

Constraints on new physics from radiative B decays

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ABSTRACT: A new phase for the measurements of radiative decay modes in $b \rightarrow s$ transitions has started with new measurements of exclusive modes by LHCb and with Belle-II showing distinctive promises in both inclusive and exclusive channels. After critically reviewing the hadronic uncertainties in exclusive radiative decays, we analyze the impact of recent measurements of the branching ratio and mass-eigenstate rate asymmetry in $B_s \rightarrow \phi\gamma$ and of the angular distribution of $B \rightarrow K^*e^+e^-$ at low q^2 on new physics in the $b \rightarrow s\gamma$ transition.

KEYWORDS: Beyond Standard Model, CP violation, Heavy Quark Physics

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1 Introduction

The radiative flavour-changing neutral current (FCNC) transition $b \rightarrow s\gamma$ is a crucial probe of physics beyond the Standard Model (SM). Its strong sensitivity to new physics (NP) stems from the helicity flip required for the dipole transition, in addition to the CKM and loop suppression. Beyond the SM, new sources of chirality breaking — like the trilinear couplings in the MSSM or masses of heavy vector-like quarks — can strongly modify the $b \rightarrow s\gamma$ transition or can enhance the amplitude with a right-hand polarized photon, $b_L \rightarrow s_R\gamma_R$, that is suppressed by a factor m_s/m_b at leading order in the SM with respect to $b_R \rightarrow s_L\gamma_L$.

The strongest constraint on the $b \rightarrow s\gamma$ transition comes from the measurement of the branching ratio of the inclusive decay $B \rightarrow X_s\gamma$, which is theoretically particularly clean as the decay rate is given simply by the quark-level decay rate in the heavy b quark limit. The branching ratios of the exclusive channels $B^{0,+} \rightarrow K^*\gamma$ have been measured even more precisely, but their theoretical estimations are afflicted with considerable hadronic uncertainties. These uncertainties also affect the branching ratio of the exclusive decay $B_s \rightarrow \phi\gamma$, that has been measured recently. But branching ratios alone cannot distinguish between the different photon helicities. The most promising observables to make this

distinction are ones that vanish in the limit of purely left-handed photon polarization. A prominent example is the mixing-induced CP asymmetry in $B^0 \rightarrow K^*\gamma$ [1, 2]. The angular distribution of the exclusive decay $B \rightarrow K^*(\rightarrow K\pi)e^+e^-$ at very low invariant mass of the dielectron pair also offers observables that have this property [3]. Very recently, a previously unmeasured observable of this type has been measured by LHCb [4]: the mass-eigenstate rate asymmetry $A_{\Delta\Gamma}$ in $B_s \rightarrow \phi\gamma$, that quantifies the decay rate difference of the two B_s mass eigenstates into the $\phi\gamma$ final state [5]. All these observables have a complementary dependence on the CP phases and chirality of the new physics contributions and thus lead to powerful constraints on physics beyond the SM, when considered together. Fits of new physics in the $b \rightarrow s\gamma$ transition have been performed in the past in the context of global $b \rightarrow s$ fits (see e.g. [6–9]). Dedicated fits to radiative decays have also been performed [10, 11]; these have the advantage that they are less dependent on theory uncertainties or potential NP effects in observables that are less sensitive to the radiative dipole transition. The main novelty of our analysis with respect to the latter analyses is that we are including the new measurements of the $B \rightarrow K^*e^+e^-$ angular observables at low q^2 and the $B_s \rightarrow \phi\gamma$ mass-eigenstate rate asymmetry for the first time. We also emphasize the importance of the direct CP asymmetry in $B \rightarrow K^*\gamma$ as a constraint on new physics. Furthermore, our numerics relies completely on open source codes, which makes it possible for the interested reader to reproduce our numerical predictions and plots and to study the impact of modifying any parametrical assumptions made.

The rest of the paper is organized as follows. In section 2, we define the effective Hamiltonian and discuss the observables in inclusive and exclusive decays that are sensitive to NP. We put a particular emphasis on the theory uncertainties that affect the exclusive decays. In section 3, we present a numerical analysis of the current constraints on new physics in the $b \rightarrow s\gamma$ transition, taking into account the theoretical uncertainties. Section 4 contains our conclusions.

2 Observables

In the following sections we will define our operator basis and then move on to defining the inclusive observables that we use in this work. For discussing the exclusive observables it is important that we include a short discussion on our choice of form factors and how we treat all the hadronic uncertainties that are inherent to these observables. The subtleties of oscillations also appear in some of them and are hence discussed too.

2.1 Effective Hamiltonian

The effective Hamiltonian relevant for inclusive and exclusive decays based on the $b \rightarrow s\gamma$ transition in the SM and beyond can be written as¹

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t \left(\sum_{i=1}^8 C_i Q_i + \sum_{i=7}^8 C'_i Q'_i \right) \quad (2.1)$$

¹For simplicity, we have omitted from (2.1) — but not from our numerics — electroweak penguin operators and doubly Cabibbo-suppressed terms. We also neglect new physics in four-quark operators.

where $\lambda_i = V_{ib}V_{is}^*$ and Q_{1-6} are the SM four-quark operators (see e.g. [12] for explicit expressions) and $Q_7^{(\prime)}$ and $Q_8^{(\prime)}$, the electromagnetic and chromomagnetic dipole operators, are given by

$$Q_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}_{L(R)} \sigma_{\mu\nu} b_{R(L)}) F^{\mu\nu}, \quad Q_8^{(\prime)} = \frac{g_s}{16\pi^2} m_b (\bar{s}_{L(R)} \sigma_{\mu\nu} T^a b_{R(L)}) G^{a\mu\nu}. \quad (2.2)$$

For the Wilson coefficient C_7 , it is customary to define a regularization scheme independent “effective” coefficient

$$C_7^{\text{eff}}(\mu) = C_7(\mu) + \sum_{i=1}^6 y_i C_i(\mu) \quad (2.3)$$

where $y = (0, 0, -\frac{1}{3}, -\frac{4}{9}, -\frac{20}{3}, -\frac{80}{9})$ in a scheme with fully anti-commuting γ_5 and in the operator basis used in [13]. Its numerical value at the scale $\mu = 4.8 \text{ GeV}$ is $C_7^{\text{eff}} = -0.2915$ [12], including next-to-next-to-leading order QCD and next-to-leading order electroweak corrections,² with an uncertainty at the per mille level. The chirality-flipped coefficient C_7' is given by $C_7' = \frac{m_s}{m_b} C_7$ in the SM.

2.2 Inclusive radiative decay

The branching ratio of the inclusive decay $B \rightarrow X_s \gamma$ can be predicted to a high accuracy, as the width is given by the width of the quark-level decay $b \rightarrow s \gamma$ up to corrections that vanish in the infinite b quark mass limit. It is to be noted that experiments only resolve photons down to a minimum energy E_0 . At present, the best compromise between experimental and theoretical sensitivity is given by $E_0 = 1.6 \text{ GeV}$. To further reduce theoretical uncertainties, the rate can be normalized to the precisely measured semi-leptonic inclusive decay $B \rightarrow X_c \ell \nu$, assuming it to be unaffected by NP. The resulting prediction reads

$$\text{BR}(B \rightarrow X_s \gamma)_{E_\gamma > E_0} = \text{BR}(B \rightarrow X_c \ell \nu) \left| \frac{\lambda_t}{V_{cb}} \right|^2 \frac{6\alpha_{\text{em}}}{\pi C} [P(E_0) + \delta_{\text{nonp.}}] \quad (2.4)$$

where $\delta_{\text{nonp.}}$ is a non-perturbative contribution that is estimated at approximately 5% of the SM branching ratio [15]. At leading order, the function $P(E_0)$ is given by

$$P(E_0)_{\text{LO}} = |C_7^{\text{eff}}|^2 + |C_7'|^2. \quad (2.5)$$

Within the SM, corrections of order α_s^2 and $(\lambda_u/\lambda_t)^2$ have been computed (see [16] for an account on the state of the art).

Apart from the (CP-averaged) branching ratio, also the direct CP asymmetry in the inclusive decay can be measured and used in principle to constrain CP-violating NP contributions. While the direct CP asymmetry in $B \rightarrow X_s \gamma$ is plagued by poorly known long-distance contributions [17], the direct CP asymmetry in the untagged decay $B \rightarrow X_{s+d} \gamma$ is free from such contributions and thus theoretically clean. Unless the NP contributions to the Wilson coefficients in the $b \rightarrow d \gamma$ transition are much larger than their counterparts in $b \rightarrow s \gamma$, the NP contribution to the untagged CP asymmetry is dominated by the $b \rightarrow s \gamma$ Wilson coefficients (see e.g. [18]). However, it turns out that even in the presence of NP,

²See [14] for an account of the contributions to this calculation.

the CP asymmetry is numerically small since the strong phases, generated first at NLO, are small. For instance, we find that even for $\text{Im}(C_7^{\text{NP}}) = 0.5$, the untagged CP asymmetry stays below 1%, to be compared to the current world average of $3.2 \pm 3.4\%$ [19]. We conclude that the inclusive CP asymmetry currently does not constitute a relevant constraint on new physics.

2.3 Exclusive radiative decays

While inclusive decay modes are theoretically cleaner and hence more accurately predictable, exclusive modes are more easily measured in experiments because of their distinctive final states. However, the observables in these exclusive modes are usually shrouded in hadronic uncertainties that are difficult to compute rendering them less conducive for prediction within a theoretical model, be it the SM or a model of new physics. These uncertainties are twofold: on one hand, predicting the observables requires the knowledge of the hadronic form factors of the relevant $B \rightarrow V$ transition. On the other hand, the radiative decays receive contributions where the photon does not participate in the — purely hadronic — hard interaction, a contribution which cannot be expressed in terms of form factors. For predicting these “non-factorizable” contributions, different approaches have been advocated. In the following, we give a general parametrization of these contributions and try to estimate their size and uncertainty, based on existing calculations and estimates.

2.3.1 General parametrization of amplitudes

The polarized amplitudes of a general $B_q \rightarrow V\gamma$ decay, where $q = u, d, \text{ or } s$, and V is a vector meson, can be written as

$$\mathcal{M}(\bar{B}_q \rightarrow \bar{V}\gamma_L) = N \left(C_7^{\text{eff}} T_1(0) + h_L \right) S_L \tag{2.6}$$

$$\mathcal{M}(\bar{B}_q \rightarrow \bar{V}\gamma_R) = N \left(C_7' T_1(0) + h_R \right) S_R \tag{2.7}$$

$$\mathcal{M}(B_q \rightarrow V\gamma_L) = N^* \left(C_7^{*\text{eff}} T_1(0) + h_R \right) S_L \tag{2.8}$$

$$\mathcal{M}(B_q \rightarrow V\gamma_R) = N^* \left(C_7^{\text{eff}*} T_1(0) + h_L \right) S_R \tag{2.9}$$

where

$$N = -\frac{4G_F}{\sqrt{2}} \lambda_t \frac{e}{8\pi^2}, \tag{2.10}$$

$$S_{L,R} = \epsilon^{\mu\nu\rho\sigma} e_\mu^* \eta_\nu^* p_\rho q_\sigma \pm i [(e^* \eta^*)(pq) - (e^* p)(\eta^* q)], \tag{2.11}$$

$T_1(0)$ is the process-dependent $B_q \rightarrow V$ tensor form factor at $q^2 = 0$, and we have neglected doubly Cabibbo-suppressed terms of order λ_u/λ_t . The process-dependent³ quantities h_L and h_R denote contributions of the weak hadronic Hamiltonian, i.e. from the operators Q_{1-6} and Q_8 . In general, they are complex quantities but enter the amplitudes without a conjugate as their phases are CP-even.

³We omit labels on process-dependent quantities like the form factors or $h_{L,R}$ in the following to avoid clutter.

Equivalently, we can express the hadronic contributions as process-dependent shifts of the Wilson coefficients,

$$\begin{aligned}\mathcal{M}(\bar{B}_q \rightarrow \bar{V}\gamma_{L(R)}) &= \left(N C_7^{(\prime)} T_1(0)\right) S_{L(R)}, \\ \mathcal{M}(B_q \rightarrow V\gamma_{R(L)}) &= \left(N^* \bar{C}_7^{(\prime)} T_1(0)\right) S_{R(L)},\end{aligned}\tag{2.12}$$

where we have defined

$$C_7 = C_7^{\text{eff}} + \Delta C_7 = C_7^{\text{eff}} + \frac{h_L}{T_1(0)}\tag{2.13}$$

$$\bar{C}_7 = C_7^{\text{eff}*} + \Delta C_7 = C_7^{\text{eff}*} + \frac{h_L}{T_1(0)}\tag{2.14}$$

and analogously for the primed coefficient.

2.3.2 Discussion of form factor uncertainties

The main source of uncertainty in the branching ratios stems from the form factor $T_1(0)$. In our numerical analysis, we use a recent update [20] of a light-cone sum rules calculation [21] of the full QCD form factors yielding

$$T_1(0) = 0.282 \pm 0.031 \quad \text{for } B \rightarrow K^*\gamma,\tag{2.15a}$$

$$T_1(0) = 0.309 \pm 0.027 \quad \text{for } B_s \rightarrow \phi\gamma,\tag{2.15b}$$

where the form factor is defined at the $\overline{\text{MS}}$ scale $\mu_b = 4.8$ GeV. A combined fit of the LCSR results and a recent lattice computation valid at high q^2 [22] yields

$$T_1(0) = 0.312 \pm 0.027 \quad \text{for } B \rightarrow K^*\gamma,\tag{2.16a}$$

$$T_1(0) = 0.299 \pm 0.012 \quad \text{for } B_s \rightarrow \phi\gamma.\tag{2.16b}$$

To be conservative, we will stick to the LCSR result in the following.

2.3.3 Discussion of hadronic contributions

Concerning the hadronic effects encoded in ΔC_7 , we include the following known contributions:

- $O(\alpha_s)$ vertex corrections involving matrix elements of the current-current operators $Q_{1,2}$ [23];
- hard spectator scattering involving matrix elements of Q_{1-6} and Q_8 at leading order in Λ/m_b from QCD factorization [24];
- weak annihilation at $O(\Lambda/m_b)$ from QCD factorization [25–27].

The numerical central values of all the contributions are shown in table 1 for the three relevant transitions. The vertex correction is by far the largest contribution. At $O(\alpha_s)$, it suffers from a sizable uncertainty due to the dependence on the charm quark mass scheme. This problem is known from the inclusive decay (see e.g. [28, 29]) and could be resolved

by including $O(\alpha_s)^2$ corrections. Importantly, since the vertex correction factorizes into a product of the universal part and a $B \rightarrow V$ form factor, its contribution to the shift ΔC_7 is the same for all exclusive decays based on the $b \rightarrow s$ transition. Spectator scattering turns out to be independent of the spectator quark charge at leading order in QCDF, and is, thus, also universal for all three transitions, up to small parametric differences. Our numerical results for the vertex correction and spectator scattering agree well with an alternative derivation using SCET [30]. The weak annihilation contribution is proportional to the spectator quark charge at the order considered, so it differs by a factor -2 between the charged and neutral $B \rightarrow K^*\gamma$ transitions. For $B_s \rightarrow \phi\gamma$, there is an additional penguin contribution where the $b \rightarrow s$ transition connects the initial b quark with the spectator s quark, but it is suppressed by small Wilson coefficients, so the differences with respect to $B^0 \rightarrow K^*\gamma$ remain small.

The following contributions are instead *not* included in our central values for ΔC_7 :

- QCDF power corrections to spectator scattering involving Q_8 , which are endpoint divergent [25–27];
- Contributions to weak annihilation and spectator scattering involving Q_8 beyond QCDF that have been computed with light-cone sum rules (LCSR) [31–33];
- Soft gluon corrections to quark loop spectator scattering, in particular the charm loop that comes with a large Wilson coefficient [5, 31, 34].

Of these contributions, the soft gluon correction to the charm loop is expected to be numerically dominant in view of the large Wilson coefficient C_2 . This effect has been estimated for $B \rightarrow K^*\gamma$ in [31] using LCSR and finding, in our conventions,

$$\Delta C_7|_{\text{soft}} = (-0.52 \pm 0.43) \times 10^{-2}, \quad \Delta C_7'|_{\text{soft}} = (0.13 \pm 0.20) \times 10^{-2}. \quad (2.17)$$

This calculation was refined and applied to $B_s \rightarrow \phi\gamma$ in [5], finding

$$\Delta C_7|_{\text{soft}} = (1.11 \pm 0.78) \times 10^{-2} e^{i(255 \pm 15^\circ)}, \quad \Delta C_7'|_{\text{soft}} = (0.42 \pm 0.29) \times 10^{-2} e^{i(106 \pm 15^\circ)}. \quad (2.18)$$

A different approach, also using LCSR, was taken in [34] finding⁴

$$\Delta C_7|_{\text{soft}} = (+1.2_{-1.6}^{+0.9}) \times 10^{-2}, \quad \Delta C_7'|_{\text{soft}} \approx 0. \quad (2.19)$$

Given the marginal agreement between the different estimates, we omit this effect and account for its omission — and all remaining neglected effects — by adding an uncertainty on the real and imaginary parts of ΔC_7 of $\pm 1.5 \times 10^{-2}$, which includes the central values of all three estimates and is much larger than the difference between the QCDF and LCSR computations of weak annihilation and spectator scattering.

Concerning $\Delta C_7'$, i.e. hadronic contributions to the “wrong-helicity” amplitude, we do not attempt a prediction but only parametrize our ignorance. While simple power counting

⁴The authors of [34] confirmed to us an erroneous sign in their eq. (6.3).

	$B^0 \rightarrow K^*\gamma$	$B^+ \rightarrow K^*\gamma$	$B_s \rightarrow \phi\gamma$
Vertex corrections	$-(7.8 \pm 1.0) - (1.1 \pm 0.3)i$		
Spectator scattering Q_{1-6}	$-0.7 - 1.3i$	$-0.7 - 1.3i$	$-0.7 - 1.7i$
Spectator scattering Q_8	-0.3	-0.3	-0.4
Weak annihilation	-0.4	$+0.9$	-0.5

Table 1. Contributions to ΔC_7 in units of 10^{-2} for the three decays. We only show the uncertainties for the (numerically dominant) vertex corrections that are process independent.

leads to a relatively large possible range for this quantity [35, 36], based on more refined parametric arguments implying the existence of a helicity suppression [11, 37, 38] as well as on the above numerical estimates of the soft gluon charm loop contribution to $\Delta C_7'$ from LCSR, we assume an uncertainty of $\pm 0.4 \times 10^{-2}$ on the real and imaginary parts of $\Delta C_7'$ and consider this to be a conservative choice.

2.3.4 Exclusive radiative observables

With the notation introduced in section 2.3.1, the helicity-summed and CP-averaged branching ratio can be written as

$$\text{BR}(B_q \rightarrow V\gamma) = \tau_{B_q} \frac{G_F^2 \alpha_{\text{em}} m_{B_q}^3 m_b^2}{32\pi^3} \left(1 - \frac{m_V^2}{m_B^2}\right)^3 |\lambda^t|^2 (|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2) T_1(0), \quad (2.20)$$

where the quantities α_{em} , m_b , $\mathcal{C}_7^{(l)}$, and $T_1(0)$ are to be understood as $\overline{\text{MS}}$ quantities at the scale μ_b that we take to be 4.8 GeV.

In the decay of the neutral mesons B_d and B_s to CP eigenstates, like $B_s \rightarrow \phi\gamma$ or $B^0 \rightarrow K^*(\rightarrow K_S\pi^0)\gamma$, the time-dependent CP asymmetry leads to additional observables, thanks to meson-antimeson mixing. It reads

$$A_{\text{CP}}(B_q(t) \rightarrow V\gamma) = \frac{\Gamma(\bar{B}_q(t) \rightarrow \bar{V}\gamma) - \Gamma(B_q(t) \rightarrow V\gamma)}{\Gamma(\bar{B}_q(t) \rightarrow \bar{V}\gamma) + \Gamma(B_q(t) \rightarrow V\gamma)} \quad (2.21)$$

$$= \frac{S(B_q \rightarrow V\gamma) \sin(\Delta M_q t) + A_{\text{CP}}(B_q \rightarrow V\gamma) \cos(\Delta M_q t)}{\cosh(y_q t / \tau_{B_q}) - A_{\Delta\Gamma}(B_q \rightarrow V\gamma) \sinh(y_q t / \tau_{B_q})}, \quad (2.22)$$

containing the direct CP asymmetry A_{CP} , the mixing-induced CP asymmetry S and the mass-eigenstate rate asymmetry $A_{\Delta\Gamma}$.

In the case of the $B^0 \rightarrow K^*\gamma$, the direct CP asymmetry A_{CP} also coincides⁵ to excellent approximation with the *time-integrated* CP asymmetry, while $A_{\Delta\Gamma}$ can be neglected, since the normalized width difference

$$y_q = \Delta\Gamma_q / (2\Gamma_q) = \tau_{B_q} \Delta\Gamma_q / 2 \quad (2.23)$$

is tiny for B_d mesons. In terms of the quantities defined above, one can write

$$A_{\text{CP}}(B^0 \rightarrow K^*\gamma) \times \text{BR}(B^0 \rightarrow K^*\gamma) = 2 \text{Im } C_7^{\text{eff}} \text{Im } \Delta C_7 + 2 \text{Im } C_7' \text{Im } \Delta C_7' + \dots \quad (2.24)$$

⁵This fact relies on $\Delta M_d \ll \Gamma_d$ and thus does not hold in the B_s system.

where the ellipsis includes in particular the doubly Cabibbo-suppressed SM contribution. Since $\Delta C_7'$ is expected to be very small, A_{CP} mostly constrains the imaginary part of the NP contribution to C_7 [7]. As seen from table 1, spectator scattering induces a non-negligible strong phase to ΔC_7 , which in combination with the precise measurements of A_{CP} — that actually do not require a time-dependent analysis — make it a strong constraint as we will discuss in section 3.

The quantity $A_{\Delta\Gamma}$ is only relevant for the B_s decay. Due to the sizable width difference $y_s \approx 6\%$ in the B_s system, $A_{\Delta\Gamma}$ can be extracted from the *untagged* time-dependent decay rate of $B_s \rightarrow \phi\gamma$,

$$\text{BR}(B_s(t) \rightarrow \phi\gamma) = \text{BR}(B_s \rightarrow \phi\gamma) e^{-t/\tau_{B_s}} \left[\cosh\left(\frac{y_s t}{\tau_{B_s}}\right) - A_{\Delta\Gamma}(B_s \rightarrow \phi\gamma) \sinh\left(\frac{y_s t}{\tau_{B_s}}\right) \right]. \quad (2.25)$$

This also implies that the time-integrated branching ratio of the $B_s \rightarrow \phi\gamma$ decay measured experimentally does not coincide with the theoretical branching ratio in the absence of B_s - \bar{B}_s mixing given in (2.20). The two quantities are related as

$$\overline{\text{BR}}(B_s \rightarrow \phi\gamma) = \left[\frac{1 - A_{\Delta\Gamma}(B_s \rightarrow \phi\gamma) y_s}{1 - y_s^2} \right] \text{BR}(B_s \rightarrow \phi\gamma). \quad (2.26)$$

Particularly simple expressions for S and $A_{\Delta\Gamma}$ can be obtained in the approximation $|\mathcal{C}_7^{(\prime)}| \approx |\bar{\mathcal{C}}_7^{(\prime)}|$ (the violation of this relation generates A_{CP}). Then one can write $\mathcal{C}_7 = |\mathcal{C}_7| e^{i\phi_7} e^{i\delta_7}$, $|\bar{\mathcal{C}}_7| = |\mathcal{C}_7| e^{-i\phi_7} e^{i\delta_7}$, and analogously for the primed coefficients, leading to

$$S(B_s \rightarrow \phi\gamma) = \sin(2\chi) \sin(\phi_7 + \phi_7' - \phi_s^\Delta) \cos(\delta_7 - \delta_7'), \quad (2.27)$$

$$A_{\Delta\Gamma}(B_s \rightarrow \phi\gamma) = \sin(2\chi) \cos(\phi_7 + \phi_7' - \phi_s^\Delta) \cos(\delta_7 - \delta_7'), \quad (2.28)$$

where we have introduced

$$\tan \chi \equiv \left| \frac{\mathcal{C}_7'}{\mathcal{C}_7} \right| \quad (2.29)$$

and ϕ_s^Δ is a NP contribution to the B_s mixing phase. Analogously, the mixing-induced CP asymmetry in $B^0 \rightarrow K^*(\rightarrow K_S \pi^0)\gamma$ is given by

$$S(B^0 \rightarrow K^*\gamma) = \sin(2\chi) \sin(\phi_7 + \phi_7' - 2\beta - \phi_d^\Delta - 2|\beta_s|) \cos(\delta_7 - \delta_7'), \quad (2.30)$$

where $\beta = \arg(V_{tb}^* V_{td})$, $\beta_s = \arg(V_{tb}^* V_{ts})$. While we do not use these approximate expressions in our numerics, they demonstrate clearly that

- both $S(B^0 \rightarrow K^*\gamma)$ and $A_{\Delta\Gamma}(B_s \rightarrow \phi\gamma)$ measure the ratio of the amplitudes with right- and left-handed photons,
- in the case of NP contributions leading to a sizable value for these observables, the dependence on the strong phases is small, as they only enter in the cosine terms.

The latter is in contrast to the direct CP asymmetry in $B \rightarrow K^*\gamma$ which is instead strongly dependent on the strong phases as seen in (2.24).

2.4 Exclusive semi-leptonic angular observables

While strictly speaking $B^0 \rightarrow K^{*0}(\rightarrow K\pi)e^+e^-$ is not a radiative decay, the angular analysis of this rare semi-leptonic decay at a very low dilepton invariant mass squared can give complementary constraints on the Wilson coefficients C_7 and C'_7 . This is true in particular for the observables [3, 39–41]

$$P_1 = A_T^{(2)} = \frac{S_3}{2S_2^s}, A_T^{(\text{Im})} = \frac{A_9}{2S_2^s}, \tag{2.31}$$

where we use the conventions used by the LHCb collaboration (see e.g. [12] for a dictionary between different conventions). P_1 is a CP-averaged angular observable and $A_T^{(\text{Im})}$ a T-odd CP asymmetry. Both observables are quasi null tests of the SM. Importantly, both only depend on the *transverse* $B \rightarrow K^*e^+e^-$ helicity amplitudes. These helicity amplitudes also receive contributions from the weak hadronic Hamiltonian, but for $q^2 \rightarrow 0$ they coincide with the contributions to the $B^0 \rightarrow K^*\gamma$ amplitudes. Using again the approximation $|\mathcal{C}_7^{(\prime)}| \approx |\bar{\mathcal{C}}_7^{(\prime)}|$, one can thus write (cf. [11])

$$\lim_{q^2 \rightarrow 0} P_1 = \sin(2\chi) \cos(\phi_7 - \phi'_7) \cos(\delta_7 - \delta'_7), \tag{2.32}$$

$$\lim_{q^2 \rightarrow 0} A_T^{(\text{Im})} = \sin(2\chi) \sin(\phi_7 - \phi'_7) \cos(\delta_7 - \delta'_7), \tag{2.33}$$

where χ has been defined in (2.29).

In practice, the observables are measured in finite q^2 bins, as dictated by the experimental resolution and statistical precision. While (2.32) and (2.33) no longer hold exactly in this case, the impact of Wilson coefficients other than the ones contributing to radiative decays is marginal even in the presence of NP, taking into account other constraints.

Interestingly, the expressions (2.32) and (2.33) are very similar to the expressions (2.28) and (2.27) for $A_{\Delta\Gamma}$ and $S(B_s \rightarrow \phi\gamma)$, but there is an important difference: while the latter depend on the sum of the weak phases of C_7 and C'_7 , the former depend on their difference. In scenarios with complex contributions to both Wilson coefficients, they are thus complementary. Moreover, the semi-leptonic angular observables are not affected by NP in meson-antimeson mixing.

Before proceeding to the numerical analysis, a comment is in order about the processes not discussed so far. While *baryonic* exclusive radiative decays such as $\Lambda_b \rightarrow \Lambda\gamma$ are promising but still awaiting to be measured, LHCb has recently measured [42] a triple product asymmetry in $B \rightarrow K_1(\rightarrow K\pi\pi)\gamma$ that is sensitive to the photon polarization [43–45]. However at present this observable does not constitute a relevant constraint on NP as it is plagued by large hadronic uncertainties. In our notation, this asymmetry is proportional to $\cos(2\chi)$, so it is less sensitive to small χ than the observables discussed above.

3 Numerical analysis

In our numerical analysis we will primarily use `flavio` [50] and cross-check all the results with `HEPfit` [51]. While all the analysis in this work will be made available as a standard

Observable	SM prediction	Measurement
$10^4 \times \text{BR}(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}}$	3.36 ± 0.23 [16]	3.27 ± 0.14 [46]
$10^5 \times \text{BR}(B^+ \rightarrow K^* \gamma)$	3.43 ± 0.84	4.21 ± 0.18 [19]
$10^5 \times \text{BR}(B^0 \rightarrow K^* \gamma)$	3.48 ± 0.81	4.33 ± 0.15 [19]
$10^5 \times \overline{\text{BR}}(B_s \rightarrow \phi \gamma)$	4.31 ± 0.86	3.5 ± 0.4 [47, 48]
$S(B^0 \rightarrow K^* \gamma)$	-0.023 ± 0.015	-0.16 ± 0.22 [19]
$A_{\text{CP}}(B^0 \rightarrow K^* \gamma)$	0.003 ± 0.001	-0.002 ± 0.015 [19]
$A_{\Delta\Gamma}(B_s \rightarrow \phi \gamma)$	0.031 ± 0.021	-1.0 ± 0.5 [4]
$\langle P_1 \rangle(B^0 \rightarrow K^* e^+ e^-)_{[0.002, 1.12]}$	0.04 ± 0.02	-0.23 ± 0.24 [49]
$\langle A_T^{\text{Im}} \rangle(B^0 \rightarrow K^* e^+ e^-)_{[0.002, 1.12]}$	0.0003 ± 0.0002	0.14 ± 0.23 [49]

Table 2. SM predictions vs. experimental world averages of observables sensitive to the $b \rightarrow s\gamma$ transition.

part of a `flavio` release, the necessary modifications for `HEPfit`, tuned to match the numerics generated by `flavio`, can be made available on request. The details of the `flavio` implementation can be found in appendix A. In the following sections we will look at the SM predictions for the observables that we have discussed previously. We will also see how these observables can constrain contributions to C_7 and C_7' generated by new physics. As a separate exercise we try to fit for the values of the form factors assuming the experimental numbers to be SM signals.

3.1 Standard Model predictions facing measurements

The CP and isospin averaged branching ratio of the inclusive $B \rightarrow X_s \gamma$ decay has been measured at CLEO [52], Belle [53, 54] and BaBar [55–58]. The HFAG world average for a minimum photon energy of 1.6 GeV is shown in table 2 and is in excellent agreement with the SM prediction shown in the same table.

Measurements of the exclusive $B \rightarrow K^* \gamma$ branching ratio have been reported by CLEOII [59], Belle [60] and BaBar [61]. The current HFAG world averages for the charged and neutral modes are shown in table 2 along with our SM predictions.⁶

The first measurement of the (time-integrated) branching ratio of $B_s \rightarrow \phi \gamma$ has been performed by Belle [63]. LHCb has presented a measurement of the ratio of branching ratios of $B_s \rightarrow \phi \gamma$ and $B^0 \rightarrow K^* \gamma$ [47], which can be converted to a measurement of $\text{BR}(B_s \rightarrow \phi \gamma)$ by using the world average of $\text{BR}(B^0 \rightarrow K^* \gamma)$ from other experiments. Again, table 2 compares our SM prediction with the HFAG world average obtained in this way.

⁶By including the branching ratios of both the charged and neutral mode, we implicitly include the isospin asymmetry as a constraint, which is generated by the interference of weak annihilation and C_7 . Note however that the current HFAG averages do not take into account the different treatment of the B^+/B^0 production asymmetry at B factories, which leads to a bias on the asymmetry [62].

Comparing the SM predictions with the measurements of the three exclusive branching ratios, one notices that, although they agree at the level of 1σ , the SM predictions tend to be on the low side for $B \rightarrow K^*\gamma$ and on the high side for $B_s \rightarrow \phi\gamma$. Such a pattern — if it were significant — could *not* be explained by NP, which would affect both decays in the same way. Likewise, it is unlikely to be explained by a hadronic effect encoded in $\Delta C_7^{(\prime)}$ since it would either affect all three branching ratios in a similar way (for spectator-independent effects) or one would expect a larger difference between the B^+ and B^0 decay than between the B^0 and B_s decay (for effects depending on the spectator charge). Consequently, if this pattern persists with more precise measurements, it would point towards a higher value for the $B \rightarrow K^*$ form factor $T_1(0)$ and a lower value for the corresponding $B_s \rightarrow \phi$ form factor than in eqs. (2.15a) and (2.15b), respectively.

To quantify this statement, we have performed two Bayesian fits of the relevant hadronic quantities to the measured exclusive branching ratios $\text{BR}(B^0 \rightarrow K^*\gamma)$, $\text{BR}(B^+ \rightarrow K^*\gamma)$, and $\text{BR}(B_s \rightarrow \phi\gamma)$ using a Markov Chain Monte Carlo (with `flavio` and `emcee` [64]), assuming the validity of the SM. For the first fit, we assumed flat priors for the form factors $T_1(0)$, for the second fit we used the LCSR priors, (2.15). The posterior distribution for the form factors for both fits are shown in figure 1, compared to the LCSR prior. For the fit with *flat priors*, we find the following mean and variance of the form factors,

$$T_1(0) = 0.316_{-0.015}^{+0.016} \quad \text{for } B \rightarrow K^*\gamma, \quad (3.1)$$

$$T_1(0) = 0.280_{-0.022}^{+0.020} \quad \text{for } B_s \rightarrow \phi\gamma. \quad (3.2)$$

These can be seen as fit predictions given the data, if the SM holds.

The mixing-induced CP asymmetry $S_{K^*\gamma}$ has been measured⁷ by both Belle and BaBar [65, 66], the HFAG average is shown in table 2. While these measurements are still far from the small SM prediction, Belle-II is expected to measure $S_{K^*\gamma} \sim 3\%$ with 50 ab^{-1} of data [67].

The direct CP asymmetry $A_{\text{CP}}(B^0 \rightarrow K^*\gamma)$ has been measured on the one hand in the time-dependent CP asymmetry in $B^0 \rightarrow K^*(\rightarrow K_S\pi^0)\gamma$ by BaBar and Belle. On the other hand, as discussed in section 2.3.4, it coincides with the *time-integrated* CP asymmetry, which has been measured much more precisely. The HFAG world average shown in table 2 includes measurements from BaBar [61] and LHCb [47].

Angular observables of the decay $B^0 \rightarrow K^*e^+e^-$ at low q^2 have been measured only by LHCb so far [49]. The same holds for the mass-eigenstate rate asymmetry $A_{\Delta\Gamma}$ in $B_s \rightarrow \phi\gamma$, that has been measured very recently for the first time [4], with a large negative central value but still large uncertainty. While this measurement is two standard deviations away from the SM expectation, we stress that values below -1 are actually unphysical as seen from (2.28).

For all the observables that vanish in the limit of purely left-handed photon polarization, i.e. $S(B^0 \rightarrow K^*\gamma)$, $A_{\Delta\Gamma}(B_s \rightarrow \phi\gamma)$, and the binned angular observables $\langle P_1 \rangle$ and $\langle A_T^{\text{Im}} \rangle$ in $B^0 \rightarrow K^*e^+e^-$, the measurements are still far away from the small SM predictions. From eqs. (2.30), (2.28), (2.32), and (2.33), it can be seen that the SM predictions

⁷Belle and BaBar have also measured $S_{K_S\pi^0\gamma}$ including the resonant regions of $K^*\gamma$. The HFAG average for this quantity is $S_{K_S\pi^0\gamma} = -0.15 \pm 0.20$. We do not use it in our numerics.

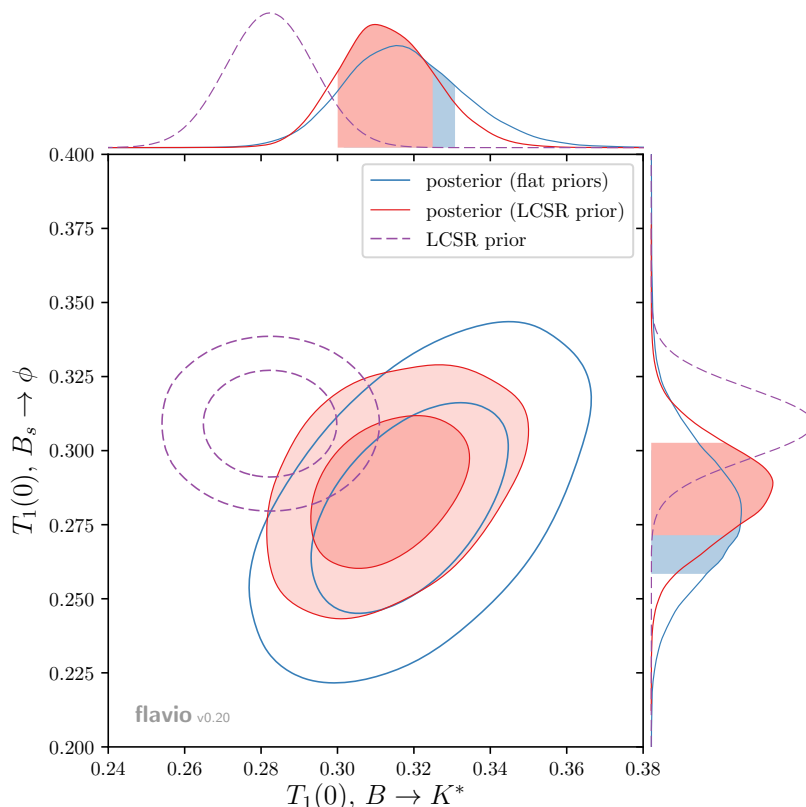


Figure 1. Posterior probability distribution of the tensor form factors $T_1(0)$ in $B \rightarrow K^*$ and $B_s \rightarrow \phi$ transitions from two Bayesian fits to the three exclusive radiative branching ratios, assuming flat priors (blue, empty contours) or the LCSR priors, (2.15) (red, filled contours). The dashed contours show the LCSR priors, (2.15), for comparison. Contours correspond to 68.3 and 95.5% posterior probability. The curves along the top and right axes show the one-dimensional marginal (posterior or prior) distributions for the individual form factors; the shaded bands correspond to 68.3% marginal probability.

are proportional to $C'_7 = (m_s/m_b)C_7 + \Delta C_7$ and thus depend crucially on the assumption made on the hadronic contribution ΔC_7 , that we have discussed in section 2.3.3.

3.2 Constraints on Wilson coefficients

To constrain the parameter space of NP models, it is crucial to know the allowed values of the NP contributions to the Wilson coefficients C_7 and C'_7 . In this section, we discuss the constraints separately for the real and imaginary parts of C_7 as well as for C'_7 .

Real part of C_7 . In scenarios where C'_7 does not receive NP contributions and the contribution to C_7 is aligned in phase with the SM, the only observables sensitive to NP among the ones we have discussed are the branching ratios. Figure 2 shows the constraints on NP contributions to the real part of C_7 from the individual exclusive and the inclusive branching ratio, as well as the global constraint. The latter is of course dominated by the inclusive branching ratio, which has the smallest theory uncertainty. We find the following

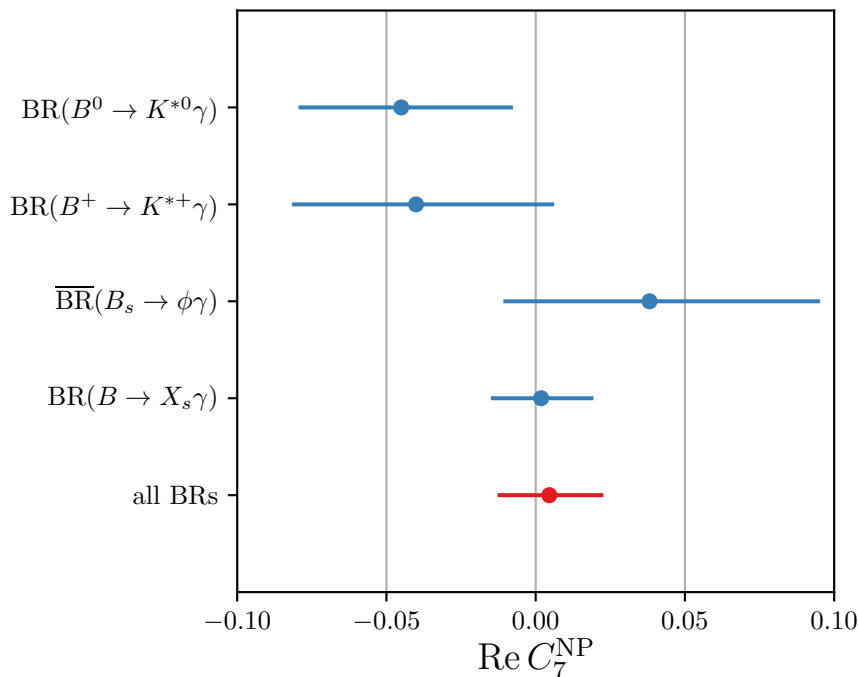


Figure 2. Constraint on NP contributions to the real part of the Wilson coefficient C_7 from exclusive and inclusive branching ratios as well as combined constraint from these branching ratios.

best-fit regions for the NP contribution,⁸

$$\text{Re } C_7^{\text{NP}}(\mu_b) \in \begin{cases} [-0.018, 0.012] & @ 1\sigma, \\ [-0.032, 0.027] & @ 2\sigma, \end{cases} \quad (3.3)$$

where $\mu_b = 4.8$ GeV.

Imaginary part of C_7 . As discussed in section 2.3.4, the only stringent constraint on the imaginary part of C_7^{NP} is expected to come from $A_{\text{CP}}(B \rightarrow K^*\gamma)$. Using the experimental measurement in table 2, we find

$$\text{Im } C_7^{\text{NP}}(\mu_b) \in [-0.064, 0.094] \times \left[\frac{-0.027}{\text{Im } \Delta C_7} \right] \quad @ 95\% \text{ C.L.} \quad (3.4)$$

Using our numerics and theory error estimates detailed in section 2.3.3, we find

$$\text{Im } \Delta C_7(\mu_b) = -0.027 \pm 0.016 \quad \text{for } B^0 \rightarrow K^*\gamma, \quad (3.5)$$

where the central value is dominated by vertex corrections and spectator scattering (cf. table 1) and the uncertainty by our estimate of neglected contributions, including the soft gluon correction to the charm loop. From (3.5) it is clear that an accidental cancellation in the imaginary part of ΔC_7 , that would make A_{CP} tiny even in the presence of NP in

⁸With the one-dimensional 1 and 2 σ regions, we refer to regions where the logarithm of the likelihood is within 1 and 4 of the best-fit value, respectively.

$\text{Im } C_7$, is not entirely excluded. We note that the estimate of the soft gluon contribution in (2.18), that we omitted, would make the constraint even stronger. In any case, a better understanding of the hadronic contributions is crucial to better constrain this Wilson coefficient.

Constraints on C_7' . The virtues of the exclusive observables come to play in models predicting a NP contribution to the “wrong-chirality” Wilson coefficient C_7' . In figure 3, we show the constraints in the plane of NP contributions to $\text{Re } C_7$ vs. $\text{Re } C_7'$ and $\text{Re } C_7'$ vs. $\text{Im } C_7'$. The contours correspond to constant values of $\Delta\chi^2$ with respect to a best fit point, obtained by combining (correlated) experimental and theoretical uncertainties.⁹ In each of the plots, we have assumed NP to only affect the two quantities plotted (e.g., in the first plot, both coefficients are assumed to be real). In addition to the global 1 and 2σ constraints, we also show the 1σ constraints from individual exclusive observables as well as from the combination of all branching ratios. These plots highlight the complementarity of the exclusive observables: while the imaginary part of C_7' is constrained by A_T^{Im} , the real part is constrained by $A_{\Delta\Gamma}$ and P_1 , while $S_{K^*\gamma}$ leads to a constraint in the complex C_7' plane that is “rotated” by the B^0 mixing phase 2β . The new measurement of $A_{\Delta\Gamma}$ shows a preference for non-zero $\text{Re } C_7'$, but given its large uncertainties, it is not in disagreement with the measurement of P_1 .

Since the experimental central value of $A_{\Delta\Gamma}$ is at the border of the physical domain, we provide best fit values and correlated errors on the real and imaginary parts of C_7' in a fit without $A_{\Delta\Gamma}$ and in a fit including it, obtained by approximating the likelihood in the vicinity of the best fit point as a multivariate Gaussian. We find

$$\begin{pmatrix} \text{Re } C_7'^{\text{NP}}(\mu_b) \\ \text{Im } C_7'(\mu_b) \end{pmatrix} = \begin{pmatrix} 0.018 \pm 0.037 \\ 0.001 \pm 0.037 \end{pmatrix}, \quad \rho = 0.34 \quad (\text{without } A_{\Delta\Gamma}), \quad (3.6)$$

$$\begin{pmatrix} \text{Re } C_7'^{\text{NP}}(\mu_b) \\ \text{Im } C_7'(\mu_b) \end{pmatrix} = \begin{pmatrix} 0.038 \pm 0.035 \\ 0.006 \pm 0.036 \end{pmatrix}, \quad \rho = 0.29 \quad (\text{with } A_{\Delta\Gamma}), \quad (3.7)$$

where ρ are the correlation coefficients.

4 Conclusions and outlook

The $b \rightarrow s\gamma$ transition belongs to the most important probes of NP in the flavour sector. While the most stringent constraint on new contributions with left-handed photon helicity comes from the branching ratio of the inclusive decay $B \rightarrow X_s\gamma$, the exclusive radiative decays $B_q \rightarrow V\gamma$ and the semileptonic decays $B_q \rightarrow Ve^+e^-$ at low q^2 are complementary probes that are sensitive to the photon helicity. In this paper, after having critically reviewed all the hadronic uncertainties in exclusive radiative and semi-leptonic decays, we have updated the numerical analysis of new physics in the Wilson coefficients C_7 and C_7' of the electromagnetic dipole operators, taking into account the recent measurements of the $B \rightarrow K^*e^+e^-$ angular distribution and the untagged time-dependent $B_s \rightarrow \phi\gamma$ decay rate by LHCb and emphasizing the role played by the direct CP asymmetry in $B \rightarrow K^*\gamma$.

⁹See [7] and the documentation of the `FastFit` class in `flavio` for details on the procedure.

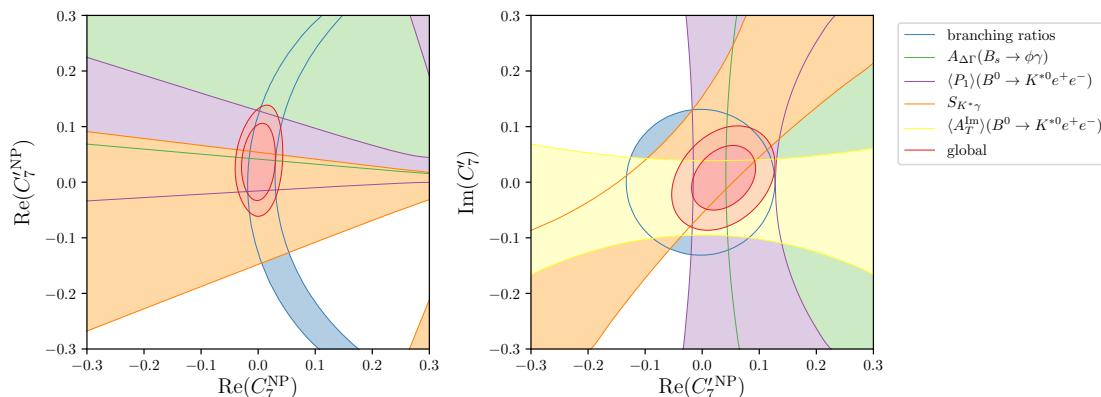


Figure 3. Constraints on NP contributions to the Wilson coefficients C_7 and C_7' . For the global constraints, 1 and 2σ contours are shown, while the individual constraints are shown at 1σ level.

Our main findings can be summarized as follows.

- The inclusive and exclusive branching ratios strongly constrain NP contributions to the real part of C_7 , cf. (3.3).
- Assuming the SM to hold, the exclusive branching ratios can also be used to extract the form factors, cf. (3.2).
- The observable most sensitive to the imaginary part of C_7 is the direct CP asymmetry in $B \rightarrow K^*\gamma$, cf. (3.4). However, the contribution is proportional to the sine of a strong phase that is rather uncertain, adopting our conservative error estimates. Improved determinations of this phase would be useful to better constrain this Wilson coefficient.
- The Wilson coefficient C_7' is constrained by a number of theoretically clean¹⁰ observables with complementary dependence on the Wilson coefficients: the mixing-induced CP asymmetry in $B \rightarrow K^*\gamma$, the angular observables P_1 and A_T^{Im} in $B \rightarrow K^*e^+e^-$ at low q^2 , and the mass-eigenstate rate asymmetry $A_{\Delta\Gamma}$ in $B_s \rightarrow \phi\gamma$ measured recently for the first time. The new measurement of $A_{\Delta\Gamma}$ shows a slight preference for non-standard C_7' , but the global fit does not show a significant tension.

While we have only presented one- and two-dimensional constraints on Wilson coefficients, a global Bayesian fit simultaneously fitting all Wilson coefficients as well as the hadronic contributions would be interesting to quantify the agreement of different hypothesis on NP or hadronic contributions given the data. We leave this exercise to a future update of this work.

In our numerical analysis, we have purely relied on open source codes, in particular `flavio`¹¹ and `HEPfit`.¹² appendix A contains some details on how to modify `flavio` to

¹⁰Given present experimental uncertainties.

¹¹<https://flav-io.github.io>.

¹²<http://hepfit.roma1.infn.it>.

study the impact of different parameter choices. These public codes can also play an instrumental role in improving the constraints on new physics in $C_7^{(\prime)}$ by future measurements, e.g. by LHCb or Belle-II. In addition to improved measurements of the $B \rightarrow K^*\gamma$ and $B_s \rightarrow \phi\gamma$ branching ratios, this includes in particular

- measurements of the radiative baryonic decays $\Lambda_b \rightarrow \Lambda^{(*)}\gamma$ [68, 69],
- a more precise measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^*\gamma$ to zero in on $S_{K^*\gamma}$,
- Improved measurements of the $B \rightarrow K^*e^+e^-$ angular analysis at very low q^2 and the analogous measurement in $B_s \rightarrow \phi e^+e^-$.

On the theory side, the main limiting factor in exclusive decays is the form factor uncertainty, impeding the exploitation of the precise branching ratio measurements. A moderate improvement might be possible in the future from extrapolations of improved lattice calculations of the form factors at high q^2 , in particular in the $B_s \rightarrow \phi$ case, while the $B \rightarrow K^*$ form factors are more challenging due to the large K^* width [70]. Concerning angular observables, mixing-induced CP asymmetries and $A_{\Delta\Gamma}$, these observables are instead virtually unaffected by the form factor uncertainty. Their uncertainty is dominated by poorly known contributions to the hadronic quantities $\Delta C_7^{(\prime)}$ that would profit from more precise estimates in the future. Nevertheless, given their smallness within the SM, these uncertainties will be subdominant compared to the experimental uncertainties for the next few years, unless a sizable deviation from the SM expectation is observed.

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A Reproducing numerics with flavio

The Standard Model predictions and plots in this paper have been obtained with the open source Python package `flavio`, version 0.20. For usage documentation and details on this code, see its web site.¹³ The central values and uncertainties of all parameters discussed in this paper correspond to the default values of this version, with the exception of the $B \rightarrow V$ form factors, that we take from a LCSR calculation, while `flavio` by default uses a combined fit to lattice and LCSR results. The LCSR form factors can be loaded as default in any script or session, after invoking `import flavio`, with the commands

```
from flavio.physics.bdecays.formfactors.b_v import bsz_parameters
bsz_parameters.bsz_load_v2_lcsr(flavio.default_parameters)
```

¹³<https://flav-io.github.io>.

The SM central values and uncertainties of the radiative decay observables can be computed with the commands

```
flavio.sm_prediction(<obs>)
flavio.sm_uncertainty(<obs>)
```

where <obs> has to be replaced by

- 'BR(B->Xsgamma)' for $\text{BR}(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{ GeV}}$,
- 'BR(B0->K*gamma)' for $\text{BR}(B^0 \rightarrow K^{*0} \gamma)$,
- 'BR(B+>K*gamma)' for $\text{BR}(B^+ \rightarrow K^{*+} \gamma)$,
- 'BR(Bs->phigamma)' for $\overline{\text{BR}}(B_s \rightarrow \phi \gamma)$,
- 'S_K*gamma' for $S_{K^* \gamma}$,
- 'ADeltaGamma(Bs->phigamma)' for $A_{\Delta\Gamma}(B_s \rightarrow \phi \gamma)$.

For the $B \rightarrow K^* e^+ e^-$ observables, the analogous commands read

```
flavio.sm_prediction(<obs>, q2min=0.002, q2max=1.12)
flavio.sm_uncertainty(<obs>, q2min=0.002, q2max=1.12)
```

where <obs> is

- '<P1>(B0->K*ee)' for $\langle P_1 \rangle$,
- '<ATIm>(B0->K*ee)' for $\langle A_T^{\text{Im}} \rangle$.

The easiest way to study the impact of different parameter or theory uncertainty choices is to modify the default parameter values. For instance, to set the $B \rightarrow K^*$ form factor $T_1(0)$ to 0.3 ± 0.1 , use

```
flavio.default_parameters.set_constraint('B->K* BSZ a0_T1', '0.3 +- 0.1')
```

The other most relevant parameters for exclusive radiative decays are

- 'Bs->phi BSZ a0_T1' – $B_s \rightarrow \phi$ form factor $T_1(0)$
- 'B0->K*0 deltaC7p a_+ Re' – $\text{Re}(\Delta C_7^{(p)})$ in $B^0 \rightarrow K^{*0} \gamma$
- 'B0->K*0 deltaC7 a_- Re' – $\text{Re}(\Delta C_7)$ in $B^0 \rightarrow K^{*0} \gamma$
 - analogously for 'B+>K*+' and 'Bs->phi'
 - analogously for the imaginary parts of $\Delta C_7^{(l)}$ using 'Re' \rightarrow 'Im'.

A Jupyter notebook to reproduce the plots in figure 3 can be found in a public repository: [71].

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