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New Physics constraints from rare $b \to s + (\gamma,\, \ell^+\ell^-)$ decays

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Abstract. The experimental measurements of flavor-changing neutral-current B-meson decays governed by $b \to s + (\gamma,\, \ell^+\ell^-)$ transitions have entered a new level of precision. Recent results by Belle, CDF, Babar, and LHCb on $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ decays are used in model-(in)dependent analyses to test the Standard Model predictions and to derive stronger constraints on nonstandard contributions. While in agreement with the Standard Model, they still leave sizable room for new physics.

1 Introduction

Nowadays, flavor-changing neutral-current (FCNC) decays of B mesons, mediated by the transitions $b \to s + (\gamma,\, \ell^+\ell^-)$, are probed experimentally with unprecedented precision. The results of Belle [1], CDF [2] and BaBar [3] with about 200 events for $B \to K^{(*)}\ell^+\ell^-$ ($\ell = e, \mu$) are currently supplemented with LHCb measurements [4], based on 1 fb^{-1} from 2011 with about 1000 events. Whereas BaBar and CDF have already analyzed their final data sets, the Belle results are from a partial data set only. Furthermore, the 2012 data set of LHCb with $\gtrsim 2$ fb^{-1} will hopefully allow first measurements of angular observables in $B \to K^*\ell^+\ell^-$ and the precision will improve further with data of about 5 fb^{-1} in the years 2015 - 2018 [5], before a shutdown for the planned upgrade. With the start of data taking in 2015, also the super-flavor factory Belle II will collect a substantial data set with $(1.0 - 1.5) \cdot 10^4$ events [6] in the next decade. Very recently, LHCb found first evidence for the very rare decay $B_s \to \mu^+\mu^-$ [7], known as an ideal probe of scalar and pseudo-scalar nonstandard interactions combining 2 fb^{-1} data from 2011 and 2012.

Currently, the measured observables in the exclusive channels $B \to K^*\gamma$, $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ comprise branching ratios ($\mathcal{B}$), lepton forward-backward asymmetries ($A_{\rm FB}$), longitudinal K^*-polarization fraction (F_L), the flat term (F_H), the angular observables $A_T^{(2)}$, S_3 and $A_{\rm im}$, S_9, isospin asymmetries (A_I) and rate CP asymmetries ($A_{\rm CP}$) in various bins of the dilepton invariant mass q^2 as well as the mixing-induced (S) and direct (C) CP asymmetry in $B \to K^*\gamma$, see table 1.

Theory predictions for $B \to K^{(*)}\ell^+\ell^-$ focus on the two regions in q^2 above and below the two narrowly peaking $c\bar{c}$-resonances J/ψ and ψ'. At low q^2, the large recoil energy of the light meson allows to apply QCD factorization (QCDF) [8] and resonances can be included with the help of a non-local OPE in combination with dispersion relations [9]. At high q^2, nonfactorizable contributions are treated within a local OPE [10]. Consequently, in the studies, only measurements in q^2-bins are used that reside in these regions, i.e., $q^2 \lesssim (6 - 7)$ GeV^2 and $q^2 \gtrsim (14 - 15)$ GeV^2, respectively. A smaller q^2 binning of future data will allow to benefit from the spectral information, as for example positions of the zero crossings or maxima and minima.

Form factors are a crucial ingredient for observables like $\mathcal{B}$, $A_{\rm FB}$, F_L and form the bulk of theoretical uncertainties. Currently, they are obtained from lightcone sum rules (LCSRs) [9, 11], restricted to the low-q^2 region. At high q^2, ongoing efforts aim at the first unquenched predictions from the lattice [12]. Current predictions of observables at high q^2 rely on extrapolations of the low-q^2 LCSR results.

In the absence of precise form factor predictions, it is still possible to constrain new physics with the help of "optimized" observables, i.e., observables that exhibit reduced sensitivity to the form factors. On the experimental side, this requires an angular analysis of the 4-body final state $B \to K^*(\to K\pi)\,\ell^+\ell^-$ giving access to 12 angular observables J_i that are in principle independent. Based on the form factor symmetries at low and high q^2, a number of form factor insensitive combinations ($A_T^{(2,3,4,5,\rm re,im)}$ [13], $P_{(1,\dots,6)}$ [14] at low q^2 and $H_T^{(1,\dots,5)}$ [15] at high q^2, see also [16] for different tests within the SM operator basis) of the J_i have been identified, which will be hopefully measured in the future. In these observables, subleading corrections in $1/m_b$ expansions are the main uncertainties [9, 15]. Interestingly, at high q^2 the OPE predicts relations for optimized observables which are preserved to rather high degree also in the presence of nonstandard interactions [15]. Thus, experimental tests of these relations can serve as a test of the validity of the OPE. Moreover, at high q^2 there are also combinations of observables, which are very insensitive to short-distance contributions and allow to determine ratios of form factors [15, 17, 18].

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	Belle	Babar	CDF	LHCb
$B \to K^*\gamma$	$\mathcal{B}, S, C, A_I$	$\mathcal{B}, S, C, A_I$		
$B \to K^*\ell^+\ell^-$	$\mathcal{B}, A_{\rm FB}, F_L$	$\mathcal{B}, A_{\rm FB}, F_L$	$\mathcal{B}, A_{\rm FB}, F_L$	$\mathcal{B}, A_{\rm FB}, F_L$
	A_I	$A_I, A_{\rm CP}$	A_I	$A_I, A_{\rm CP}$
			$A_T^{(2)}, A_{\rm im}$	S_3, S_9
$B \to K\ell^+\ell^-$	$\mathcal{B}, A_I$	$\mathcal{B}, F_H, A_I$	$\mathcal{B}, A_{\rm FB}, A_I$	$\mathcal{B}, A_{\rm FB}, F_H, A_I$
$B_s \to \mu^+\mu^-$				Br

Table 1. Measured observables: branching ratio ($\mathcal{B}$), lepton forward-backward asymmetry ($A_{\rm FB}$), rate CP asymmetry ($A_{\rm CP}$), mixing-induced and direct CP asymmetries (S and C), longitudinal K^*-polarization fraction (F_L), flat term (F_H), iso-spin asymmetry (A_I), angular observables $A_T^{(2)}$, S_3 and $A_{\rm im}$, S_9.

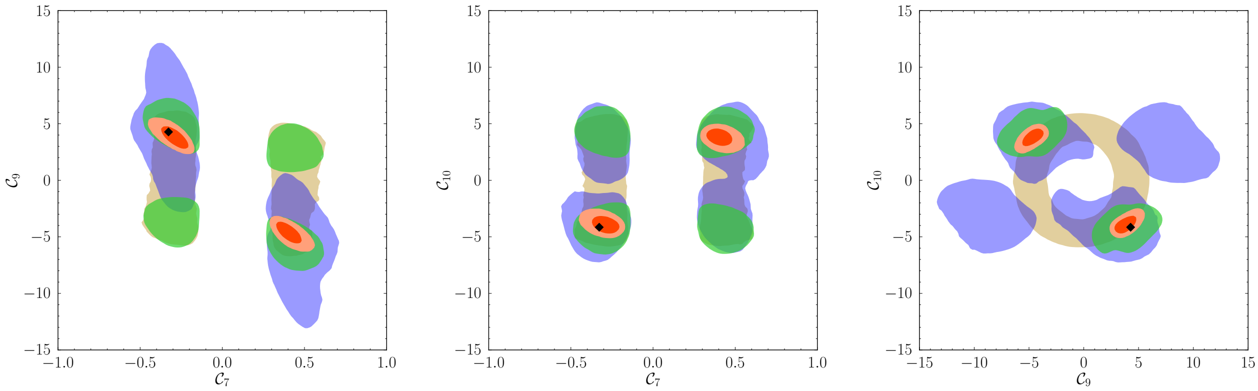

Figure 1. The marginalized 2-dim 95% credibility regions of $\mathcal{C}_{7,9,10}$ at $\mu = 4.2$ GeV are shown when combining the $B \to K^*\gamma$ constraints with data from *i)* only low- and high-q^2 $B \to K\ell^+\ell^-$ [brown]; *ii)* only low-q^2 $B \to K^*\ell^+\ell^-$ [blue]; *iii)* only high-q^2 $B \to K^*\ell^+\ell^-$ [green]; and *iv)* all the data, including also $B_s \to \mu^+\mu^-$ [light red], showing as well the 68% credibility region [red]. The SM values of $\mathcal{C}_{7,9,10}^{\rm SM}$ are indicated by ◆.

CP-violating effects in $b \to s$ transitions are predicted to be very small in the SM, being proportional to the doubly Cabibbo-suppressed combination $\mathrm{Im}(V_{ub}V_{us}^*)$. Here several CP asymmetries of the angular observables $J_{5,6,8,9}$ can be extracted from untagged B meson samples and moreover, CP asymmetries of $J_{7,8,9}$ are not suppressed by small QCD phases [19]. The first measurements of the CP asymmetry $A_{\rm im}$ of J_9 [2] and the rate CP asymmetry of $B \to K^*\ell^+\ell^-$ became available [4], where the latter equals to the one of $B \to K\ell^+\ell^-$ in the SM operator basis [20].

In view of the high future accuracy of measurements of $B \to K^*(\to K\pi)\ell^+\ell^-$, the $(K\pi)$ pairs not originating from the K^* decay, especially the resonant and non-resonant S-wave contributions, will affect the angular distribution. They can be controlled due to the angular analysis and require a careful treatment on the experimental side [21].

2 Model-independent constraints

A scenario of real[1] nonstandard contributions $C_{7,9,10}$ can be considered as the simplest model-independent extension of the Standard Model (SM). Here C_i denote the short-distance couplings (Wilson coefficients) of the numerically most important $b \to s\gamma$ and $b \to s\ell^+\ell^-$ mediating operators in the $|\Delta B| = |\Delta S| = 1$ effective Hamiltonian known in the SM at the next-to-next-to leading order [22]. Combining available results[2] of the exclusive channels $B \to K^*\gamma$, $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$, one obtains the 2-dim marginalized posterior distributions as shown in figure 1 [18]. Theory uncertainties have been included as nuisance parameters and are marginalized over, the fit also provides updated knowledge on them. Two solutions remain viable, one including the SM and the other with all sign-flipped Wilson coefficients. The goodness-of-fit yields satisfactory p values between 0.60 and 0.75 for both solutions. Also the SM indicates a good fit [23]. Observables sensitive to 4-quark operator contributions, such as $\mathcal{B}(B \to X_s\gamma)$, $A_{\rm FB}(B \to K^*\ell^+\ell^-)$ or $A_I(B \to K^*\gamma)$, provide means to distinguish the two solutions [14].

The experimental results also imply constraints on scenarios beyond the minimal setup, such as allowing for CP violation beyond the standard CKM picture [20, 23] and including additional operators: chirality-flipped

[1] It is customary to factor out the complex CKM combination $V_{tb}V_{ts}^*$, i.e., implying minimal flavor violation.

[2] The following measurements were not included: *i)* the CDF final data set with 9.6 fb^{-1} presented at the ICHEP-2012 conference [2], *ii)* the recent world-best measurements of $B \to K\ell^+\ell^-$ from 1 fb^{-1} of LHCb [4] and *iii)* first evidence of $B_s \to \mu^+\mu^-$ by LHCb [7].

$C_{7',9',10'}$ and/or (pseudo)-scalar $C_{S,S',P,P'}$ [23, 24, 26]. The data yield strong correlations among the allowed regions of the Wilson coefficients, including their moduli and phases, which might not be easily visualized beyond 2-dim marginalized plots. Consequently, predictions for not yet measured observables in theses scenarios are more informative. The data still allow for sizable CP-violation [23] for the CP asymmetries $A_{7,8,\rm im}$. Moreover, right-handed currents start to be constrained from the interplay of branching-ratio measurements of $B \to K^* \ell^+\ell^-$ and $B \to K\ell^+\ell^-$ [23].

The decays $B \to K\,\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ provide complementary information on chirality-flipped Wilson coefficients which enter both modes as $(C_i + C_{i'})$ and $(C_i - C_{i'})$, respectively. Their interplay has been explored in some detail for $C_{S,P,10}$ in [24]. The decay $B \to K\,\ell^+\ell^-$ allows also to constrain (pseudo-)scalar and tensor operators with the help of the observables $A_{\rm FB}$ and F_H that are accessible in the angular analysis [8]. In this respect, latest data from LHCb on F_H at high q^2 [4] provide updated constraints on $|C_T|^2 + |C_{T5}|^2 \lesssim 0.5$ [15].

The transition $b \to s\,\tau^+\tau^-$ is experimentally not constrained except for the upper bound $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$ from BaBar [25]. Due to mixing of $b \to s\,\tau^+\tau^-$ operators into $b \to s\,(\gamma, \ell^+\ell^-)$ ($\ell = e, \mu$), the latter processes imply indirect constraints on large nonstandard $b \to s\,\tau^+\tau^-$ contributions [26]. When combined with the direct constraint on $\mathcal{B}(B^+ \to K^+\tau^+\tau^-)$, they rule out an enhancement of the decay width difference $\Delta\Gamma_s$ of the B_s-meson of more than 35% compared to the SM prediction, assuming single operator dominance [26].

At the moment, the measured observables in exclusive $b \to s\,\ell^+\ell^-$ decays can be explained within the SM and they push the scale of tree-level-mediated new FCNC interactions in this sector above $\mathcal{O}(20\,\text{TeV})$ – for some even above $\mathcal{O}(100\,\text{TeV})$ – assuming single operator dominance and order-one couplings [18, 20, 23]. The measurement of additional observables, especially angular observables in $B \to K^*(\to K\pi)\,\ell^+\ell^-$, will allow to further scrutinize nonstandard interactions. The absence of any new-physics signal in the future, within uncertainties, will put strong constraints on model parameter spaces in model-dependent analyses.

3 Model-dependent constraints

In the past, the most frequently considered $|\Delta B| = |\Delta S| = 1$ FCNC observables were $\mathcal{B}(B \to X_s\gamma)$ and the upper bound on $\mathcal{B}(B_s \to \mu^+\mu^-)$ in order to place constraints on parameter spaces of extensions of the SM, especially for the supersymmetric ones (MSSM, NMSSM, ...). The $b \to s\gamma$ mediated decays test especially chirality-changing effects, whereas $B_s \to \mu^+\mu^-$ is very sensitive to (pseudo-) scalar contributions as for example neutral Higgs penguins. To less extent, analyses of tree-level FCNC's have resorted to $B \to X_s\ell^+\ell^-$. However, the new data on exclusive $B \to K^{(*)}\ell^+\ell^-$ decays allow also to test flavor-changing Z and Z'-couplings to b and s quarks as well as modifications of left- and right-handed W couplings that are present in many extensions of the SM. In the effective theory they modify the Wilson coefficients $C_{7,9,10}$ and their chirality-flipped counterparts $C_{7',9',10'}$.

In the framework of the MSSM, the latest $b \to s\,\ell^+\ell^-$ data constrain flavor-changing left-right mixing $(\delta^u_{23})_{LR}$ in the up-squark sector, which in turn places constraints on various FCNC decays $t \to c\gamma$, $t \to cg$ and $t \to cZ$ of the top quark [27]. The interplay of $B_s \to \mu^+\mu^-$ at large $\tan\beta$ and angular observables in $B \to K^*\ell^+\ell^-$ at moderate $\tan\beta$ has been investigated in constrained scenarios such as the CMSSM and NUHM [28].

LeptoQuark interactions, which induce scalar and pseudo-scalar operators $\mathcal{O}_{S,S',P,P'}$, have been constrained with recent data from $B \to (X_s, K)\,\ell^+\ell^-$, and $B_s \to \mu^+\mu^-$ [29].

The latest data of exclusive $b \to s\,\ell^+\ell^-$ decays provide also constraints on models with extended gauge-sectors Z' [30], especially beyond minimal flavor-violating scenarios, but also in some models of partial compositeness where they probe interactions with Z bosons [31].

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