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Phenomenology of the exclusive rare semileptonic decay $\bar{B} \to \bar{K}\pi\ell^+\ell^-$

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I review the phenomenology of exclusive $\bar{B} \to \bar{K}\pi\ell^+\ell^-$ decays, with focus on the intermediate resonant $\bar{K}^*(892)$ mode. The status of angular observables at both ends of the dilepton mass spectrum is revisited. Constraints on the $b \to s$ Wilson coefficients $\mathcal{C}_{7,9,10}$ based on 2011 data from the B factories, CDF and LHCb are presented.

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1. Introduction

Since the first observation of the decay $B \to K\ell^+\ell^-$ by the Belle Collaboration [1] — and the subsequent measurements by BaBar [2], CDF [3], and most recently LHCb [4], ATLAS [5] and CMS [6] — exclusive rare semileptonic decays are part of the phenomenologist's toolbox and helpful in constraining effects beyond the Standard Model. However, from a theorist's point of view the exclusive decays prove to be challenging.

The starting point for a theoretical calculation is given by the framework of an effective Hamiltonian of the form

$$\mathcal{H}^{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}V_{tb}V_{ts}^* \sum_i \mathcal{C}_i\mathcal{O}_i + O\left(V_{ub}V_{us}^*\right) + \text{ h.c.}, \tag{1.1}$$

for which we follow the conventions of reference [7]. When considering only factorizable contributions, the set of local operators can be restricted to the complete basis of semileptonic operators

$$\mathcal{O}_i = [\bar{s}\Gamma_i b][\bar{\ell}\Gamma_i'\ell], \qquad i = 9, 9', 10, 10', S, S', P, P', T, T5 \tag{1.2}$$

and the radiative operators $\mathcal{O}_{7,7'}$. In the Standard Model (SM), one obtains to Next-to-Next-to-Leading Logarithm (NNLL) [8]

$$\mathcal{C}_7 \simeq -0.3\,, \quad \mathcal{C}_9 \simeq +4.3\,, \quad \mathcal{C}_{10} \simeq -4.2\,, \tag{1.3}$$

and the Wilson coefficients of the remaining radiative and semileptonic operators are either suppressed by m_s/m_b, m_ℓ/M_W or vanish. The understanding of long-distance effects introduced by four-quark operators $\mathcal{O}_{1,\dots,6}$ and the chromomagnetic operator $\mathcal{O}_8$ are crucial to precision studies of exclusive semileptonic rare $\bar{B}$ decays.

In the following I will revisit the calculational approaches to the decay $\bar{B} \to \bar{K}\pi\ell^+\ell^-$ with special regard to the long-distance contributions in two regions of the dilepton mass, and discuss the powerful constraints on the $b \to s$ Wilson coefficients $\mathcal{C}_{7,9,10}$ that can be obtained from experimental data on exclusive radiative and (semi)leptonic decays.

2. The Angular Distribution of $\bar{B} \to \bar{K}\pi\ell^+\ell^-$ Decays

The decay

$$\bar{B}(p) \to \bar{K}(k_1)\pi(k_2)\ell^+(q_1)\ell^-(q_2), \qquad q = q_1 + q_2, k = k_1 + k_2 \tag{2.1}$$

can be fully described by means of five kinematic variables: q^2 the dilepton mass squared, k^2 the $\bar{K}\pi$ mass squared, the angle θ_ℓ between the ℓ^- momentum and the $\bar{B}$ momentum in the dilepton rest frame, the angle θ_{K^*} between the $\bar{K}$ momentum and the opposite $\bar{B}$ momentum in the $\bar{K}\pi$ rest frame, and the angle ϕ between the $\bar{K}\pi$ and dilepton decay planes. The differential decay width

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can then be decomposed into 18 angular observables $J_n \equiv J_n(q^2, k^2)$ [7, 9, 10, 11]

$$\begin{aligned}\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2\,dk^2\,d\cos\theta_\ell\,d\cos\theta_{K^*}\,d\phi} = \\ (J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_{K^*} + (J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_{K^*} \\ + (J_{1i} + J_{2i}\cos 2\theta_\ell)\cos\theta_{K^*} + (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_{K^*}\sin^2\theta_\ell \\ + (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_{K^*}\sin 2\theta_\ell + (J_{4i}\cos\phi + J_{8i}\sin\phi)\sin\theta_{K^*}\sin 2\theta_\ell \\ + (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_{K^*}\sin\theta_\ell + (J_{5i}\cos\phi + J_{7i}\sin\phi)\sin\theta_{K^*}\sin\theta_\ell\,.\end{aligned} \tag{2.2}$$

The distribution eq. (2.2) is sufficient to describe model-independently the effects of the complete basis of $b \to s\ell^+\ell^-$ operators as given in section 1. It also incorporates pure P-wave states ($n = 3, 4, 5, 6s, 6c, 7, 8, 9$), combined P- and S-wave states ($n = 1s, 1c, 2s, 2c$), as well as S-P interference terms ($n = 1i, 2i, 4i, 5i, 7i, 8i$) [10, 11].

Since the hadronic matrix elements for non-resonant S-wave $B \to K\pi$ transitions are not yet sufficiently understood, studies of the their interference effects rely on calculations based on resonance models [10], or resort to extraction of the S-wave contributions from data [11]. So far most calculations, however, assume a resonant on-shell P-wave $K^*(892)$ state only, which is subsequently handled in a narrow width approximation [9, 12]. The latter restricts $k^2 = M_{K^*}^2$, thereby reducing the number of independent kinematic variables from five to four. The hadronic matrix elements for such $\bar{B} \to \bar{K}^*$ transitions are traditionally expressed in terms of seven q^2-dependent form factors $V, A_{0,1,2}, T_{1,2,3}$. In the heavy quark limit one obtains the Isgur-Wise relations [13] between the dipole and vector form factors. Using the traditional form factor convention these relations read

$$\begin{aligned}T_1(q^2) = \kappa(\mu)V(q^2)\,, \quad T_2(q^2) = \kappa(\mu)A_1(q^2)\,, \\ T_3(q^2) = \frac{\kappa(\mu)M_B}{q^2}\left((M_B - M_{K^*})A_2(q^2) - (M_B + M_{K^*})A_1(q^2)\right)\end{aligned} \tag{2.3}$$

up to corrections $O(\Lambda_{\text{QCD}}/m_b)$ with $\kappa(m_b) = 1 + O\left(\alpha_s^2\right)$ [14]. They reduce the number of independent form factors to four *helicity form factors* [14, 15]

$$\begin{aligned}f_S &= \frac{2\sqrt{\lambda}}{\sqrt{q^2}}A_0 & f_0 &= \frac{(M_B^2 - M_{K^*}^2 - q^2)(M_B + M_{K^*})^2 A_1 - \lambda A_2}{2M_{K^*}(M_B + M_{K^*})\sqrt{q^2}} \\ f_\perp &= \frac{\sqrt{2\lambda}}{M_B + M_{K^*}}V & f_\parallel &= \sqrt{2}(M_B + M_{K^*})A_1\,.\end{aligned} \tag{2.4}$$

with the Källén function $\lambda = \lambda(M_B^2, M_{K^*}^2, q^2)$. Additionally, in the Large Energy Limit (LEL) for E_{K^*}, the $\bar{K}^*$ energy in the $\bar{B}$ rest frame, the four helicity form factors reduce to two universal soft form factors: $\xi_\perp$ and $\xi_\parallel$ [16, 17].

The form factors are, nevertheless, inherently non-perturbative quantities, and as such can only be calculated through non-perturbative methods. For $q^2 \simeq 0$, Light Cone Sum Rules (LCRSs) provide access [18, 19]. On the other hand, Lattice QCD (LQCD) can – in principle – be used to obtain the form factors numerically at large $q^2 \gtrsim 15\,\text{GeV}^2$ [20]. Application of a series expansion based on the analytic properties of the form factors in the complex plane allows to extrapolate the

LCSR and LQCD results to intermediate q^2 values [15]. This approach can be further improved by using experimental data to constrain ratios $f_\perp/f_\parallel$, $f_0/f_\parallel$ [21, 22, 23].

If one considers only contributions of semileptonic operators $[\bar{s}\Gamma b][\bar{\ell}\Gamma'\ell]$, the angular observables J_n take a simple form and can be expressed in terms of 14 complex-valued transversity amplitudes A_k [7], cf. eqs. (B1)-(B12) of reference [7]. This ansatz of *naive factorization* is known to be broken by the peaking background of processes $\bar{B} \to \bar{K}\pi\psi(1S, 2S, \dots)(\to \ell^+\ell^-)$. The narrow charmonium resonances $\psi(1S)$ and $\psi(2S)$ are cut from the experimental data by means of two q^2 vetoes. However, their tails as well as broader charmonium resonances still affect the theoretical predictions. It is therefore illstrustrative to compute the results in the naive factorization ansatz, and systematically extend it with known corrections.

In order to incorporate non-factorizing effects into the description of the $\bar{B} \to \bar{K}\pi\ell^+\ell^-$ amplitudes, one turns to study the correlation function

$$\mathcal{T}_i^\mu = i \int \mathrm{d}x\, e^{iqx} \langle \bar{K}^* | T\{\mathcal{O}_i(0) j^\mu_{\text{e.m.}}(x) | \bar{B}\rangle \tag{2.5}$$

for the four-quark and chromomagnetic operators $\mathcal{O}_{1,\dots,6,8}$. Here T is the time-ordered product and $j_{\text{e.m.}}$ is the electromagnetic current. Since the quantum numbers of the correlator eq. (2.5) are compatible only with the operators $\mathcal{O}_{7('),9(')}$, one can account for intermediate $\bar{q}q$ effects by means of the replacements

$$\mathcal{C}_i \to \mathcal{C}_i + \Delta_i(q^2) \equiv \mathcal{C}_i^{\text{eff}}(q^2)\,, \qquad i = 7('), 9(') \tag{2.6}$$

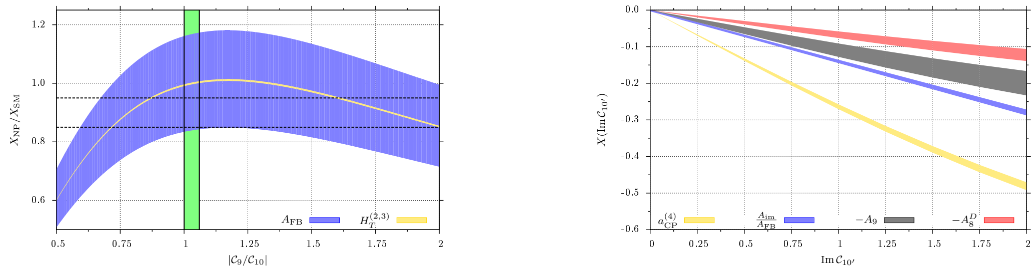
where $\mathcal{C}_i^{\text{eff}}(q^2)$ are known as the q^2-dependent *effective Wilson coefficient*. Note here that the $\Delta_i(q^2)$ in general include both factorizing, form factor independent as well as non-factorizing, form factor dependent contributions. In the following paragraphs two major approaches to the calculation of eq. (2.5) shall be revisited.

For small q^2, or equivalently for large recoil energy $E_{K^*} \sim m_b$ of the $\bar{K}^*$ in the $\bar{B}$ rest frame, one can systematically calculate certain perturbative contributions to the effective Wilson coefficients in the framework of QCD Factorization (QCDF) [24, 25]. Schematically, one obtains for projections of the correlator $\mathcal{T}_a$

$$\mathcal{T}_a \supseteq C_a \xi_a + \phi_B \otimes T_a \otimes \phi_{K^*} + O\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right), \qquad a = \perp, \parallel\,, \tag{2.7}$$

where the C_a denotes factorizable corrections that enter with the soft form factors ξ_a. The hard scattering kernels T_a enter after convolution with the $\bar{B}$ and $\bar{K}^*$ light cone distribution amplitudes (LCDAs) ϕ_B and ϕ_{K^*}, respectively. The calculation of some power-suppressed contributions is plagued by endpoint divergencies [25], a problem that can potentially be overcome with the help of LCSR methods [19, 26, 27].

On the other end of the q^2 spectrum, where $q^2 \simeq m_b^2$, a local Operator Product Expansion (OPE) can be performed simultaneosuly in $1/m_b$ and $1/\sqrt{q^2}$ [28, 29]. Combining the results of the OPE with the form factor relations eq. (2.3), one finds [14] that the correlator eq. (2.5) yields only



(a) Performance of $H_T^{(2,3)}$ vs A_{FB} in probing the ratio $|\mathcal{C}_9/\mathcal{C}_{10}|$. Both observables are shown including their theory uncertainty for the entire low recoil bin, and normalized to their respective SM values.

(b) Performance of varios CP asymmetries as functions of $\mathrm{Im}\,\mathcal{C}_{10'}$. Of the compared observables, $a_{CP}^{(4)}$, the CP asymmetry of $H_T^{(4,5)}$, is most sensitive to small deviations of the SM value $\mathrm{Im}\,\mathcal{C}_{10'} = 0$.

Figure 1: Both figures taken from reference [7].

factorizable contributions to the transversity amplitudes up to corrections $O\left(\alpha_s \frac{\Lambda}{m_b}, \frac{\mathcal{C}_7}{\mathcal{C}_9}\frac{\Lambda}{m_b}\right)$, where $\Lambda = O(\Lambda_{\mathrm{QCD}})$. Thus, the transversity amplitudes $A_{0,\perp,\parallel}^{L(R)}$ factorize to that order,

$$A_{0,\parallel}^{L(R)}(q^2) = -\mathcal{C}_{-,L(R)}(q^2) \times f_{0,\parallel}(q^2)\,, \qquad A_{\perp}^{L(R)}(q^2) = +\mathcal{C}_{+,L(R)}(q^2) \times f_{\perp}(q^2)\,, \tag{2.8}$$

into helicity form factors $f_{0,\perp,\parallel}$ and effective short-distance coefficients $\mathcal{C}_{\pm,L(R)}$. (In the SM basis, i.e., for $\mathcal{C}_{9',10'} = 0$ one obtains $\mathcal{C}_{+,L(R)} = \mathcal{C}_{-,L(R)}$). Matrix elements other than those parametrized by the $\bar{B} \to \bar{K}^*$ form factor enter only at order Λ^2/m_b^2 [29]. Subleading corrections to the transversity ampltiudes A_k are parametrically suppressed and can be parametrized as [30]

$$r_k = \frac{\Lambda_k}{M_B}\left(\mathcal{C}_7 + \alpha_s e^{i\delta_k}\right). \tag{2.9}$$

Beyond probing electro-weak and hadronic quantities, observables at low hadronic recoil also provide quantitative tests of the OPE. The latter are constructed from terms ε_k that could break the factorization of the transversity amplitudes A_k,

$$A_k^{L(R)} \propto \mathcal{C}_{L(R)} f_k (1 + \varepsilon_k)\,, \qquad k = 0, \perp, \parallel\,. \tag{2.10}$$

Based on this ansatz, one finds that $J_7 \neq 0$ probes $\mathrm{Im}\,\varepsilon_{0,\parallel}$ (and thus the OPE) at the percent level, while contributions from Beyond the SM (BSM) are helicity suppressed [7].

The theoretical uncertainties in $\bar{B} \to (\bar{K}\pi)_P \ell^+\ell^-$ observables are driven by the lack of knowledge of the $\bar{B} \to \bar{K}^*$ form factors. This dilutes the constraining power of experimental data on observables such as the branching ratio $\mathcal{B}$, the longitudinal polarization F_L and the lepton forward-backward asymmetry A_{FB}. In order to reduce the impact of form factor uncertaintes, several analyses [7, 14, 31, 32, 33] have been carried out that introduce *optimized observables*. The latter are designed so that form factors cancel to leading order.

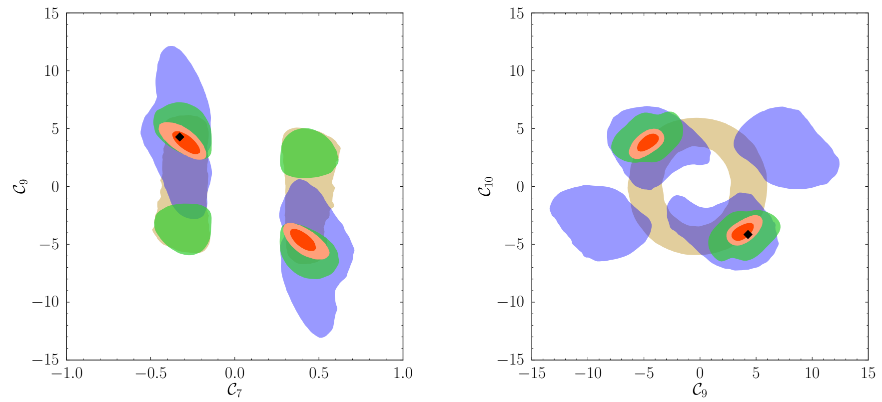


Figure 2: SM values (◆) and 95% credibility regions for the Wilson coefficients $\mathcal{C}_{7,9,10}$ as obtained from the analysis in reference [22].

For the region of low hadronic recoil, five observables $H_T^{(i)}$,

$$H_T^{(1)} = \frac{\sqrt{2}J_4}{\sqrt{-J_{2c}(2J_{2s}-J_3)}}, \quad H_T^{(2)} = \frac{\beta_\ell J_5}{\sqrt{-2J_{2c}(2J_{2s}+J_3)}}, \quad H_T^{(3)} = \frac{\beta_\ell J_{6s}}{2\sqrt{4J_{2s}^2 - J_3^2}},$$
$$H_T^{(4)} = \frac{2J_8}{\sqrt{-2J_{2c}(2J_{2s}+J_3)}}, \quad H_T^{(5)} = \frac{-J_9}{\sqrt{4J_{2s}^2 - J_3^2}}, \tag{2.11}$$

can be constructed that fulfill the cancellation requirement. While $|H_T^{(1)}| \simeq 1$ almost model indepedently, $H_T^{(2,3)}$ are effective in probing the ratio $|\mathcal{C}_9/\mathcal{C}_{10}|$ [7]; their increased BSM sensitivity in comparison to A_{FB} can be inferred from fig. 1(a). Finally, $H_T^{(4,5)}$ and their CP asymmetries probe CP-violating right-handed Wilson coefficients $\mathcal{C}_{9',10'}$, see fig. 1(b). As a consequence of the LEL all of the $H_T^{(i)}$ stay also free of form factors to leading order at large hadronic recoil [34]. A complete basis of optimized observables for the large recoil region, with focus on the extraction of $\mathcal{C}_{7'}$ is also given in reference [34].

3. Constraining $b \to s\gamma$ and $b \to s\ell^+\ell^-$ Wilson Coefficients from Exclusive Decays

The Wilson coefficients $\mathcal{C}_i$ can be constrained in a model-independent framework, i.e., one fits their values from all available experimental $|\Delta B| = |\Delta S| = 1$ data in a global analysis. For the complete basis of semileptonic operators with — in general — complex-valued Wilson coefficients, this means to perform a fit with 20 real-valued parameters of interest. Taking into account the Wilson coefficients of four-quark and radiative operators $\mathcal{O}_{1,\dots,6}$ and $\mathcal{O}_{7('),8(')}$ respectively on arrives at 40 degrees of freedom.

It it therefore necessary to lower the number of parameters of interest. One option is to restrict the Wilson coefficients $\mathcal{C}_{1,\dots,6,8(')}$ to their SM values, and set the non-SM-like coefficient $\mathcal{C}_{7',9',10',S,P,T,T5}$ to zero. This scenario corresponds to the *SM basis of operators* and was considered in several analyses [22, 35, 36, 37]. It was shown in reference [22] that this basis of operators suffices to describe the available data on exclusive rare (semi)leptonic and radiative decays. I refer the reader to the original work for details on experimental inputs and the statistical method. Two best-fit points $(\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10})$ are obtained,

$$\text{SM-like:}(-0.293, +3.69, -4.19)\,, \qquad \text{sign-flipped:}(+0.416, -4.59, +4.05)\,. \tag{3.1}$$

Both of these points yield p-values of 60% and 75%, depending on the definition of the p-value. The SM-like solution is compatible with the SM point eq. (1.3) at 68% credibility [22]. The 95% credibility regions for $\mathcal{C}_{7,9,10}$ obtained from this analysis are shown in fig. 2.

Beyond obtaining information on the nature of the Wilson coefficients, the analysis at hand also provides information on the hadronic quantities such as form factor values. Their treatment as nuisance parameters in a Bayesian analysis allows to compare their prior and posterior probability distributions. In the particular analysis, it was informative to see that a slight ($\lesssim 1\sigma$) tension arises between the priors and posteriors of the form factors V_1 and A_2 at $q^2 = 0$ [22]. This behaviour has also been seen in an analysis dedicated to extracting the form factors from low recoil data [21].

4. Conclusion

The theoretical understanding and the experimental handling of the decay $\bar{B} \to \bar{K}\pi\ell^+\ell^-$ have both advanced tremendously over the last decade. Still, there is room for improvements. Global analyses of exclusive rare semileptonic decays find good agreement with the SM, but leave plenty of room for physics beyonds the SM. The emergence of precision data on exclusive rare semileptonic decays from LHCb and the prospect of inclusive measurements from Belle II will not only allow to constrain BSM effects further. It will also aide in improving our understanding of hadronic models and non-perturbative methods.

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