

$B \rightarrow K^{(*)}\ell^+\ell^-$ @ Low Recoil and Physics Implications

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This talk covers recent theoretical progress in exclusive semileptonic rare B -decays at low hadronic recoil. The efficient parametric suppression of the $1/m_b$ corrections in this region provides opportunities to probe the Standard Model and beyond at precision level. Notably, angular analysis allows to simultaneously access electroweak flavor physics *and* hadronic matrix elements, the latter of which constitute the leading source of theoretical uncertainty. Ratios of $B \rightarrow K^*$ form factors can already be extracted from present data. A comparison with existing theoretical determinations by lattice QCD and light cone sum rules gives a consistent picture over the whole kinematic range. In the future improved analyses will advance our understanding of non-perturbative methods for QCD *and* of $|\Delta B| = 1$ transitions.

1 Introduction

At the time of the writing of this article, several flavor changing neutral current (FCNC) exclusive semileptonic $|\Delta B| = |\Delta S| = 1$ transitions have been measured:

- $B \rightarrow K^{(*)}\mu^+\mu^-$ by BaBar¹, Belle², CDF³ (with the whole CDF data sample of 9.6 fb^{-1}), LHCb⁴ (with 1 fb^{-1}), Atlas⁵ and CMS⁶.
- $B_s \rightarrow \Phi\mu^+\mu^-$ by CDF³, LHCb⁷.
- $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ by CDF³, LHCb⁸.

The enormous increase in event rates has made branching ratios and many beyond-basic observables, such as CP and forward-backward asymmetries and other angular distributions in several dilepton mass bins available. The dominant fraction of the data originates from hadron collider experiments, and consists of $\mu^+\mu^-$ final states. Note, however LHCb's study at low dielectron mass⁹.

Different theory descriptions apply to the kinematic regions of large and low hadronic recoil. The former corresponds to small dilepton masses $\sqrt{q^2}$ below the mass of the J/Ψ and is accessible to QCD factorization¹⁰. The low recoil region corresponds to large $\sqrt{q^2} \sim \mathcal{O}(m_b)$, above the Ψ' mass, and is treated with an operator product expansion (OPE) in $1/Q$, $Q = \{m_b, \sqrt{q^2}\}$ put forward by¹¹, for recent works, see¹²; for earlier studies on inclusive decays, see¹³. Recent research directions include optimizing the physics reach of the $B \rightarrow K\ell^+\ell^-$ ¹⁴ and $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$ ¹⁵ angular distributions and working out the physics reach at low recoil^{16 17 18}. While the phenomenology of the low q^2 region has received lots of attention in the past see *e.g.*^{14 19 20 21 22 23 24 25 26 27}, the theoretical activities at low recoil are rather recent.

The angular distribution and its theory in $B_s \rightarrow \Phi(\rightarrow KK)\ell^+\ell^-$ is analogous to $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$ decays. For the former decay, however, effects from meson mixing are larger and could

be of relevance²⁰. b -baryon decays are currently not as developed theoretically as the meson ones. We note the unique properties regarding Λ_b and Λ polarization studies²⁸. We stress that the theoretical low recoil features are shared by all lepton flavors, and kinematic lepton mass effects in this region are of order m_ℓ^2/m_b^2 . Additional flavor splittings can be due to lepton flavor violating contributions to $b \rightarrow s\ell^+\ell^-$ transitions^{14 18}.

We briefly review the beneficial properties of the low recoil region in Section 2. Extractions of hadronic form factor ratios from low recoil data^{29 30} are presented in Section 3. Note the recent developments in lattice estimations of $B \rightarrow K^{(*)}$ form factors^{31 32}, which directly apply in this regime. The improved New Physics reach in selected low recoil $B \rightarrow K^{*\ell^+\ell^-}$ observables¹⁸ is demonstrated in Section 4. We conclude in Section 5.

2 Benefits of low recoil

When combined with the improved Isgur-Wise heavy quark form factor relations the OPE¹¹ predicts a simple structure for the $B \rightarrow K^{*\ell^+\ell^-}$ transversity amplitudes in terms of universal short-distance coefficients $C^{L,R}$ and form factors f_i as

$$A_i^{L,R}(q^2) \propto C^{L,R}(q^2) \cdot f_i(q^2) + \mathcal{O}(\alpha_s \Lambda/m_b, [\mathcal{C}_7/\mathcal{C}_9]\Lambda/m_b), \quad i = \perp, \parallel, 0. \quad (1)$$

As can be seen, the power corrections receive additional parametric suppressions, and are below the few percent level. Eq. (1) has powerful phenomenological consequences^{16 18}. It allows to define new observables which do not depend on form factors^a, as

$$H_T^{(1)}(q^2) \equiv \frac{\sqrt{2}J_4}{\sqrt{-J_2^c(2J_2^s - J_3)}}, \quad (2)$$

$$H_T^{(2)}(q^2) \equiv \frac{\beta_l J_5}{\sqrt{-2J_2^c(2J_2^s + J_3)}}, \quad (3)$$

$$H_T^{(3)}(q^2) \equiv \frac{\beta_l J_{6s}}{2\sqrt{(2J_2^s)^2 - J_3^2}}, \quad (4)$$

$$H_T^{(4)}(q^2) \equiv \frac{2J_8}{\sqrt{-2J_{2c}(2J_{2s} + J_3)}}, \quad (5)$$

$$H_T^{(5)}(q^2) \equiv \frac{-J_9}{\sqrt{(2J_{2s})^2 - J_3^2}}, \quad (6)$$

and corresponding CP asymmetries. Here $\beta_l = \sqrt{1 - 4m_\ell^2/q^2}$. The angular coefficients $J_k = J_k(q^2)$ can be extracted from the $B \rightarrow K^{*}(\rightarrow K\pi)\ell^+\ell^-$ angular distribution. Briefly, $H_T^{(4,5)}$ are SM null tests and sensitive to right-handed FCNCs, whereas $H_T^{(2,3)}$ probe similar flavor couplings as the forward-backward asymmetry $A_{\text{FB}} \propto [J_{6s} + J_{6c}/2]/[d\Gamma/dq^2]$, however, with much reduced hadronic uncertainties, see Section 4.

While present data are consistent with the SM and the low recoil framework, the machinery behind Eq. (1) can be cross-checked model-independently. To do so we introduce the (complex-valued) parameters ϵ_i , $i = \perp, \parallel, 0$, and write $A_i^{L,R} \propto C^{L,R} f_i(1 + \epsilon_i)$. As indicated in Eq. (1), the generic size of the ϵ_i from the in principle known power corrections is a few percent. While these next-to-leading order $1/m_b$ corrections have been worked out¹¹, only little is known presently on the additional heavy quark form factors they depend on. The ϵ_i -ansatz allows further to

^aNote that this holds in the most general dimension six $s\bar{b}\bar{\ell}\ell$ operator basis except for $H_T^{(2)}$ which becomes form factor dependent in the presence of scalar contributions¹⁸.

quantify corrections from beyond the OPE, such as duality violating effects. Specifically, the size of the ϵ_i can be probed with the null tests

$$J_7 = \mathcal{O}(\text{Im}[\epsilon]) + \mathcal{O}(\text{Im}[C_{T(T5)} C_{S(P)}^*]) + \mathcal{O}(m_\ell/Q C_{S,T5}), \quad (7)$$

$$|H_T^{(1)}| - 1 = \mathcal{O}(\epsilon^2) + \mathcal{O}(\Lambda^2/Q^2 |C_{T(5)}|^2). \quad (8)$$

As indicated, a potential New Physics background arises in the presence of tensor $C_{T(5)}$ and/or scalar contributions $C_{S,P}$. The best reach is found to be in J_7 , which can probe ϵ_i at the few percent level. If tensors are neglected $|H_T^{(1)}| - 1$ becomes comparable or better¹⁸.

Presently, none of the $H_T^{(i)}$ has been measured yet, however, once more information on the angular distribution becomes available they are very useful observables due to their high sensitivity to the $|\Delta B| = 1$ transitions. All $H_T^{(i)}$ maintain good sensitivity at large recoil²⁶.

Eq. (1) allows further to identify observables which are independent of short-distance coefficients. These include the already measured fraction of longitudinally polarized K^* , F_L , and the transverse asymmetry $A_T^{(2)}$ ¹⁹. Both can be used to extract hadronic matrix elements from $B \rightarrow K^* \ell^+ \ell^-$ data²⁹, see Section 3. Note that the short-distance independence of F_L and $A_T^{(2)}$ at low recoil would be spoiled by beyond the SM right-handed FCNCs. However, at low q^2 $A_T^{(2)}$ is highly receptive to the latter, while being a SM null test. Since data on $A_T^{(2)}$ are consistent with the SM and there is no other observation of such effects we neglect them here. Improved data and global analyses will reveal whether such effects are contributing to $b \rightarrow s$ transitions.

3 $B \rightarrow K^*$ form factors data versus theory

At low recoil the transversity amplitudes $A_i^{L,R}$, $i = \perp, \parallel, 0$ are related, see Eq. (1). It follows that the short-distance coefficients $C^{L,R}$ drop out in specific observables:

$$F_L(q^2) = \frac{|A_\perp^L|^2 + |A_\parallel^R|^2}{\sum_{X=L,R} (|A_0^X|^2 + |A_\perp^X|^2 + |A_\parallel^X|^2)} = \frac{f_0^2}{f_0^2 + f_\perp^2 + f_\parallel^2}, \quad (9)$$

$$A_T^{(2)}(q^2) = \frac{|A_\perp^L|^2 + |A_\parallel^R|^2 - |A_\perp^L|^2 - |A_\parallel^R|^2}{|A_\perp^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\parallel^R|^2} = \frac{f_\perp^2 - f_\parallel^2}{f_\perp^2 + f_\parallel^2}, \quad (10)$$

and form factor ratios f_i/f_j can be extracted from the corresponding data. For other observables with this property see¹⁸. Last year first measurements of F_L and $A_T^{(2)}$ have become available, leading to first data-driven fits of $B \rightarrow K^*$ form factor ratios over the whole kinematic region²⁹, see Fig. 1. Here, the lattice and light cone sum rules (LCSR) results are shown for comparison only (they are not included in the fit) and stem from^{32,33} and³⁴, respectively. The q^2 -shape in the fit is based on a series expansion in $z = z(q^2, t_0)$ where $|z| \leq 1$ as

$$f_i(q^2) \propto \frac{(\sqrt{-z(q^2, 0)})^m (\sqrt{z(q^2, t_-)})^l}{z(q^2, m_{R_i}^2)} \sum_k \alpha_{i,k} z^k, \quad z(t, t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}. \quad (11)$$

Here $t_\pm = (m_B \pm m_{K^*})^2$ and $l = 1, 0, 0$ and $m = 1, 1, 0$ for $i = \perp, \parallel, 0$, respectively. The latter adjusts the kinematic behaviour, $f_\perp \propto \sqrt{q^2} \lambda V$, $f_\parallel \propto \sqrt{q^2} A_1$ etc. in terms of the standard form factors $V, A_{1,2}$. The factor $z(q^2, m_{R_i}^2)^{-1}$ corresponds to the off-shell poles from axial $m_R = 5.83$ GeV ($i = \parallel, 0$) and vector $m_R = 5.42$ GeV ($i = \perp$) B_s^* mesons, respectively. The best-fit result in the lowest order series expansion (SE) is obtained as $\alpha_\parallel/\alpha_\perp = 0.43^{+0.11}_{-0.08}$, $\alpha_0/\alpha_\perp = 0.15^{+0.03}_{-0.02}$ ²⁹. The t_0 -dependence drops out at this order.

The fitted form factor ratios at $q^2 = 0$ along with LCSR predictions^{34,35} are compiled in Table 1. The preliminary fit SE2013³⁰ includes the most recent data^{3,4,5,6} and supersedes the

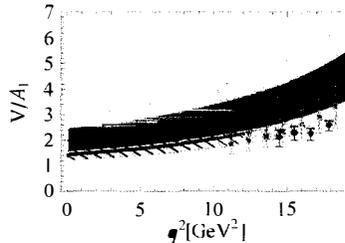


Figure 1: The data-extracted form factor ratio V/A_1 at 1σ (dark) and 2σ (lighter colored band). The data points and the hatched region denote lattice^{32,33} and LCSR³⁴ estimations, respectively, see text. Figure taken from²⁹.

Table 1: Form factor ratios at $q^2 = 0$ from $B \rightarrow K^* \mu^+ \mu^-$ data at low recoil versus theory estimations, see text. The fits are to the lowest order series expansion (SE). The (preliminary) result SE2013³⁰ includes the most recent data^{3,4,5,6} and supersedes SE. Table adapted from²⁹, see text. *Errors symmetrized and added in quadrature.

	SE	SE2013	LCSR* ³⁴	LCSR* ³⁵	LEL
$V(0)/A_1(0)$	2.0 ± 0.4	1.6 ± 0.3	1.4 ± 0.2	1.5 ± 0.9	$1.3 + \mathcal{O}(1/m_b)$
$A_1(0)/A_2(0)$	1.2 ± 0.1	1.1 ± 0.0	1.1 ± 0.2	1.0 ± 0.7	-

SE fit. One observes that the fitted value of V/A_1 is somewhat larger than the LCSR ones and larger than the symmetry-based prediction in the large energy limit (LEL)³⁶,

$$V(q^2)/A_1(q^2) = (m_B + m_{K^*})^2 / (m_B^2 + m_{K^*}^2 - q^2), \quad (12)$$

which receives no α_s -corrections at leading power³⁷, *i.e.*, $V(0)/A_1(0) = 1.3 + \mathcal{O}(1/m_b)$. This tendency has decreased with the new 2013 data, but even before, in the SE fit, there was agreement within $\sim 1\sigma$.

Overall, the data-extracted form factor ratios and their extrapolations are found to be currently consistent with theoretical estimations by different non-perturbative means applicable to different q^2 -domains. The fits at low recoil provide direct experimental information on form factor ratios in this region; this is useful for lattice estimations as a future benchmark test. Extrapolations to the low q^2 range are more sensitive to the parametrization of the slope. Fits to a more involved shape than the lowest order series expansion require some input from large recoil to be predictive at large recoil³⁰. To proceed it would be useful if in addition to the form factors itself also their ratios could be provided in theoretical estimations. Note, that the lattice and LCSR based ratios shown in Table 1 and Fig. 1 are obtained for lack of correlation information assuming gaussian error propagation. In addition, with finer binning the sensitivity to the q^2 -shape would increase, however, this needs to be done while watching the OPE.

4 Probing New Physics

The reach in low recoil-integrated $B \rightarrow K^* \ell^+ \ell^-$ observables versus the ratio of Wilson coefficients $|C_9/C_{10}|$ is shown in Fig. 2. The blue (broad) band corresponds to A_{FB} , which is form factor dependent, whereas the thin light-colored band belongs to the form factor-free observables $H_T^{(2,3)}$. Note that $H_T^{(2)} = H_T^{(3)}$ in the SM operator basis.

The reach in low recoil-integrated CP-asymmetries versus the Wilson coefficient C'_{10} is shown in Fig. 3. All asymmetries shown are SM null tests. The gold curve with the steepest slope corresponds to the CP-asymmetry of $H_T^{(4)}$, whereas the blue curve with the next-to-steepest

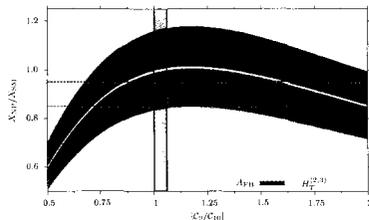


Figure 2: Sensitivity to $|C_9/C_{10}|$ in A_{FB} (blue, wide band) and $H_T^{(2,3)}$ (gold, thin band) integrated over the low recoil region $q^2 \gtrsim 14.2 \text{ GeV}^2$. The vertical (green) band denotes the SM prediction. Figure taken from ¹⁸.

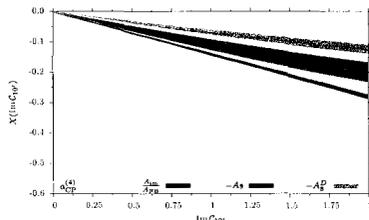


Figure 3: The sensitivity of various $B \rightarrow K^* \ell^+ \ell^-$ CP-asymmetries to New Physics in C'_{10} . Figure taken from ¹⁸.

slope to $A_{im}/A_{FB} = J_9/J_{6s} \propto H_T^{(5)}/H_T^{(3)}$, respectively. Both asymmetries are form factor-free; the other two CP asymmetries $A_{8,9}$ ²⁰ are not, and exhibit larger uncertainties than the former.

5 Conclusions

Smaller uncertainties in the measurements and access to further observables in exclusive $b \rightarrow s \ell \ell$ modes are expected to come from the LHC experiments in the nearer future, especially for muons. Belle II and a possible super flavor factory provide opportunities for other flavors in the final states as well, including inclusive decays, electrons, neutrinos and possibly taus.

For a clear interpretation of the data at precision level parametric (form factors, CKM, ...) and systematic inputs (framework, power corrections, ...) need to be disentangled from the $|\Delta B| = 1$ couplings. The important feature in $B \rightarrow V \ell^+ \ell^-$ decays at low recoil is the ability to access these inputs individually. Amended by other information, such as improved calculations of the hadronic matrix elements or complementary measurements this gives way to a map of the $b \rightarrow s$ flavor structure at the weak scale; the $b \rightarrow d$ one is already at the horizon.

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