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$B \to K^* \ell^+ \ell^-$ forward-backward asymmetry and new physics

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The forward-backward asymmetry $\mathcal{A}_{\rm FB}$ in $B \to K^* \ell^+ \ell^-$ decay is a sensitive probe of new physics. Previous studies have focused on the sensitivity in the position of the zero. However, the effective Wilson coefficients (short distance effective couplings) are in principle complex, as illustrated by $B \to \rho \ell^+ \ell^-$ decay within the standard model. Allowing for this, but keeping the $B \to K^* \gamma$ and $K^* \ell^+ \ell^-$ rate constraints, we find the landscape for $\mathcal{A}_{\rm FB}(B \to K^* \ell^+ \ell^-)$ to be far richer than from entertaining just sign flips. The complex nature of effective Wilson coefficients can be explored by future high statistics experiments.

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I. INTRODUCTION

It was pointed out 20 years ago [1] that the effective bsZ coupling is enhanced by large m_t, which turns out to dominate $b \to s\ell^+\ell^-$ ($\bar{B} \to X_s \ell^+ \ell^-$) decay. The effective $bs\gamma$ coupling gives a low $q^2 \equiv m_{\ell\ell}^2$ peak in the differential rate [2], while Z and γ induced amplitudes interfere across the q^2 spectrum. One such effect is the asymmetry $\mathcal{A}_{\rm FB}$ [3] between forward and backward moving ℓ^+ versus the B meson direction in the $\ell^+\ell^-$ frame.

The first measurement of $\mathcal{A}_{\rm FB}$ in $B \to K^* \ell^+ \ell^-$ decay was recently reported [4,5]. The results are consistent with the standard model (SM), rule out the wrong handed $\ell^+\ell^-$ current, but with only $\sim$100 signal events, a sign flip of the $bs\gamma$ coupling is still allowed. However, taking the measured inclusive $b \to s\gamma$ and $s\ell^+\ell^-$ rates together, the last point is disfavored [6].

With the advent of LHC in 2008, we expect a dramatic increase in statistics. A simulation study by the LHCb experiment shows that $\sim$7700 $B \to K^* \ell^+ \ell^-$ events are expected with 2 fb^{-1} data [7]. How useful is $\mathcal{A}_{\rm FB}$ as a probe for new physics (NP)? We point out that the sensitivity of $\mathcal{A}_{\rm FB}$ to NP is greater than previously thought. The *complexity* of the associated effective Wilson coefficients can be probed by $d\mathcal{A}_{\rm FB}/dq^2$ with early LHC data, without measuring CP violation.

II. STANDARD MODEL AND MFV

The quark level decay amplitude is [1,8],

$$\mathcal{M}_{b\to s\ell^+\ell^-} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{cs}^* V_{cb}\Big\{ C_9^{\rm eff}[\bar{s}\gamma_\mu L b][\bar{\ell}\gamma^\mu \ell] + C_{10}[\bar{s}\gamma_\mu L b][\bar{\ell}\gamma^\mu\gamma_5\ell] - 2\frac{\hat{m}_b}{\hat{s}} C_7^{\rm eff}[\bar{s} i\sigma_{\mu\nu}\hat{q}^\nu R b][\bar{\ell}\gamma^\mu\ell]\Big\}, \qquad (1)$$

where $s = q^2$, and we normalize by m_B, e.g. $\hat{s} = s/m_B^2$. We factor out $V_{cs}^* V_{cb}$ instead of $V_{ts}^* V_{tb}$, which has the advantage of being the product of Cabibbo-Kobayashi-Maskawa (CKM) elements that are already measured, and real by standard convention [9]. Short distance physics, including within SM, are isolated in the Wilson coefficients $C_7^{\rm eff}$, $C_9^{\rm eff}$, and C_{10}.

For $B \to K^* \ell^+ \ell^-$, hadronic matrix elements of quark bilinears give well-defined $B \to K^*$ form factors. In Eq. (1), $C_7^{\rm eff}$ and C_{10} are at m_B scale, with C_7 receiving large additive contributions from other Wilson coefficients through operator mixing [10], $C_7^{\rm eff} = \xi_7 C_7 + \xi_8 C_8 + \sum_{i=1}^{6} \xi_i C_i$, where ξ_i are QCD evolution factors. However, $C_9^{\rm eff}(\hat{s}) = C_9 + Y(\hat{s})$ is also a function of the dilepton mass through $Y(\hat{s})$ [8] that depends on long distance ($c\bar{c}$) effects.

Within the SM, $V_{ts}^* V_{tb}$ is almost real in the standard phase convention, and the Wilson coefficients $C_7^{\rm eff}$, C_9, and C_{10} are real up to higher order corrections, with $C_9^{\rm eff}(\hat{s})$ becoming very slightly complex through $Y(\hat{s})$. The "minimal flavor violation" (MFV) scenario [11] asserts that there are no further sources of flavor and CP violation, other than what is already present in the SM. Many popular extensions of the SM, such as a minimal supersymmetric SM [12] or two Higgs doublet models [13], follow this pattern. Thus, numerical studies of $\mathcal{A}_{\rm FB}$ in the literature often use nearly real Wilson coefficients. See e.g. [14,15]. Because of its relative insensitivity [8,16] to form factors, one focus has been the sensitivity of the zero to NP. The experimental studies have followed by considering only possible sign flips of real coefficients [4,5], or sensitivities to the zero [7].

III. RATHER COMPLEX WILSON COEFFICIENTS?

As Eq. (1) is a quantum amplitude, however, one cannot assert *a priori* that $C_7^{\rm eff}$, $C_9^{\rm eff}$, and C_{10} should be close to real, especially when the NP of interest could be CP violating (CPV). It is an experimental question.

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In fact, currently there are hints [17] for "anomalies" in time-dependent and direct CPV measurements of $b \to s\bar{q}q$ transitions. One possible explanation is NP in $b \to s\bar{q}q$ electroweak penguins [18], which are the hadronic cousins of $b \to s\ell^+\ell^-$. Thus, despite their near reality in SM or with MFV, whether $C_7^{\rm eff}$, $C_9^{\rm eff}$, and C_{10} of Eq. (1) are actually real in nature should be *tested by experiment* rather than by fiat. The experimental test may come in just a few years.

In the following section, we explore how much $\mathcal{A}_{\rm FB}$ can differ from the SM by allowing the Wilson coefficients of Eq. (1) to be complex. Constraints such as decay rates, of course, should be respected, and one should check whether models exist where C_7, C_9, and C_{10} are complex. We find, even keeping the SM operator basis, the impact of complex Wilson coefficients is large, hence the usual MFV scenario may be too strong an assumption. We will comment on enlarging operator basis in the discussion section.

Our insight comes as follows. Part of the impetus for MFV is the good agreement between theory and experiment for inclusive $b \to s\gamma$, which provides a stringent constraint on NP. However, while depending on the existence of the top quark, $\mathcal{B}(b \to s\gamma)$ depends very little on the precise value of m_t, so long that it is large. For m_t in the range of 150 to 300 GeV, the $b \to s\gamma$ rate changes by only $\sim$30%. In contrast, the $b \to s\ell^+\ell^-$ rate depends very sensitively on m_t through the effective bsZ coupling, changing by a factor of $\sim$4 in the same m_t range. Thus, extra heavy quarks could mimic MFV in $b \to s\gamma$, but impact on $b \to s\ell^+\ell^-$ beyond MFV. The extra heavy quarks could be SM-like, such as the 4th generation, or vectorlike quarks that mix with the top.

Let us take the 4th generation as an example. It was recently pointed out that a 4th generation may not be as constrained by electroweak precision measurements as previously thought [19]. It is known that $\mathcal{B}(b \to s\gamma)$ is not sensitive to t' unless $|V_{t's}^* V_{t'b}|$ is very large [20]. However, "hard" amplitudes such as $b \to s\ell^+\ell^-$ would be sensitive to $V_{t's}^* V_{t'b}$ for any $m_{t'} \neq m_t$ [1]. Since $V_{t's}^* V_{t'b}$ should be in general complex [21], so would the Wilson coefficients. Thus, the 4th generation is an existence proof of deviation from MFV in $b \to s\ell^+\ell^-$.

It should be further noted that the three $[\bar{s}b][\bar{\ell}\ell]$ terms in Eq. (1) are four fermion operators. The possible new physics underlying them is precisely what we wish to probe at B factories and at the LHC. Hence, these coefficients should be kept as full parameters to be probed, which should in principle be complex. Thus, despite the apparent success of MFV, we find the usual assumption of near reality of the Wilson coefficients is unfounded. When sufficient data comes, the experiments are well advised to keep these parameters complex in doing their fit, enlarging the scope at little extra cost.

We remark that the possibility of complex Wilson coefficients has been considered in the literature, and some attempts to study the associated phenomenology have been made, see e.g. [22,23]. These have tended to be, however, coefficient by coefficient studies, with emphasis often towards the zero of the forward-backward asymmetry; or, emphasis has been placed on further observables. To the best of our knowledge, a systematic study on the impact of such complexities on the forward-backward asymmetry by combining branching ratio constraints, has not been pursued. We emphasize that our interest is in possible *large* complexities in the Wilson coefficients arising from new physics at short distance, not the very small complexity already present in the SM due to higher order effects or resonance contributions.

IV. NUMERICAL EXAMPLES

In this study we shall keep the operator set as in Eq. (1), since this is what the experiments are already using, but allow the Wilson coefficients to be complex. We will comment on enlarging the operator basis later. Although inclusive $b \to s\ell^+\ell^-$ (and $b \to s\gamma$) is theoretically cleaner, it may be less feasible at the LHC. Further, experimental studies of inclusive processes usually apply cuts that complicate theoretical correspondence. We therefore discuss the experimentally more accessible $B \to K^*\ell^+\ell^-$ (and $B \to K^*\gamma$). The $b \to s\gamma$ rate constrains $|C_7^{\rm eff}|$, and we shall take a one sigma experimental range [9] for $\mathcal{B}(B \to K^*\gamma)$. Likewise, exclusive $\mathcal{B}(B \to K^*\ell^+\ell^-)$ constrains $C_7^{\rm eff}$, $C_9^{\rm eff}$, and C_{10}. Since measurements are not yet precise enough, we use only the one sigma experimental range of the integrated rate. With high statistics in the future, one could also fit the differential $d\mathcal{B}/d\hat{s}$ rate, which is more powerful.

Our main focus is $\mathcal{A}_{\rm FB}$ in exclusive $B \to K^*\ell^+\ell^-$ decay. Assuming the form factors are real, we have

$$\frac{d\mathcal{A}_{\rm FB}}{d\hat{s}} \propto \left\{ {\rm Re}(C_9^{\rm eff} C_{10}^*) V A_1 + \frac{\hat{m}_b}{\hat{s}} {\rm Re}(C_7^{\rm eff} C_{10}^*)[(VT_2)_- + (A_1 T_1)_+] \right\}, \tag{2}$$

where $(VT_2)_- = VT_2(1 - \hat{m}_{K^*})$, $(A_1T_1)_+ = A_1T_1(1 + \hat{m}_{K^*})$, and V, A_1, T_i are form factors [8]. We use the light-cone sum rule (LCSR) [24] form factors in our numerical analysis. In Eq. (2) we have exhibited only the dependence on $C_9^{\rm eff}$, C_{10}, and $C_7^{\rm eff}$, since it is customary to plot $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ which is normalized by the differential rate $d\Gamma/d\hat{s}$. The zero of $\bar{\mathcal{A}}_{\rm FB}$ is often considered quite stable against form factor variations [8,16].

The Wilson coefficients are parametrized as

$$C_7(M_W) = C_7^{\rm SM}(M_W)(1 + \Delta_7 e^{i\phi_7}), \tag{3}$$

$$C_9(M_W) = C_9^{\rm SM}(M_W)(1 + \Delta_9 e^{i\phi_9}), \tag{4}$$

$$C_{10}(M_W) = C_{10}^{\rm SM}(M_W)(1 + \Delta_{10} e^{i\phi_{10}}), \tag{5}$$

with $\Delta_i = 0$ corresponding to the SM. As indicated, these Wilson coefficients are evaluated at the M_W scale, then evolved down to the m_B scale to be used in Eq. (2). We do not include any complexity from other Wilson coefficients. The tree-level C_1 and C_2 are unchanged by NP, but as a simplifying assumption, we ignore possible NP induced complexities through the gluonic $C_{3\text{-}6}$ and C_8 coefficients, which enter $C_7^{\rm eff}$ and $C_9^{\rm eff}$ through operator mixing and long distance effects. In practice, this should not change our point.

We remark that, although the general form of parametrization in Eqs. (3)–(5), $C_i(1 + \Delta_i e^{i\phi_i})$, gives back the SM result for $\Delta_i = 0$, this does not mean that when effective Wilson coefficients are of SM strength, they must have (close to) zero phase. For $\Delta_i = -\cos\phi_i$, the effective Wilson coefficients would be of the same magnitude as SM, but with nontrivial phase $-2\phi_i$.

A. New physics through bsZ and $bs\gamma$ couplings

Let us first illustrate with a SM-like framework, i.e. viewing $B \to K^*\ell^+\ell^-$ as induced by effective bsZ and $bs\gamma$ couplings (and box diagrams). We then expect

$$\Delta \equiv \Delta_9 \cong \Delta_{10}, \qquad \phi \equiv \phi_9 \cong \phi_{10}, \tag{6}$$

in Eqs. (4) and (5), and one effectively has the parameters Δ, Δ_7, ϕ, and ϕ_7, which covers the usual case of the wrong sign $C_7^{\rm eff}$. The 4th generation also belongs to this scenario, with $V^*_{t's}V_{t'b}$ bringing in complexity. Thus, Eq. (6) represents a broad class of models.

We plot $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ and $d\mathcal{B}/d\hat{s}$ in Figs. 1(a) and 1(b), respectively, for SM and 4th generation model (SM4). For SM4, we take the CKM parameters which yield the correct B_s-$\bar{B}_s$ mixing [25], predict large time-dependent CPV in B_s decay, as well as accommodating [18] the NP hints in CPV in $b \to s\bar{q}q$ decays. Thus, there is good motivation for keeping interest in the 4th generation in the study of $b \to s$ transitions. Note that *the zero of* $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ *has shifted* by a significant amount, with only a small positive value below the zero. While the latter could be obscured by form factor dependence, these effects are due to the enrichment of (mostly) the ϕ phase. For larger $\hat{s}$, one has little difference in $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ from the SM, as the effect of $C_7^{\rm eff}$ has damped away, while $C_9^{\rm eff}$ and C_{10} carry almost the same phase. The general appearance of $d\mathcal{B}/d\hat{s}$ for the SM and SM4 is very similar.

A broader range is actually allowed by Eq. (6). Keeping $B \to K^*\gamma$ and $K^*\ell^+\ell^-$ rates in 1σ experimental range, the range of variation allowed by Eq. (6) is shown in Fig. 1 as the shaded area, which is just for illustration and should not be taken as precise boundaries. For instance, we see that below the SM zero, $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ could even vanish, while the shaded region for $d\mathcal{B}/d\hat{s}$ in Fig. 1(b) just reflects the 1σ constraints on $B \to K^*\gamma$ and $K^*\ell^+\ell^-$. $d\mathcal{B}/d\hat{s}$ should also be fitted in the future, where formulas can be found, e.g. in Ref. [8], but it depends on the overall scale of $B \to K^*$ form factors.

We illustrate the power of early LHC data with the 2 fb^{-1} study of LHCb, where $\sim$7700 reconstructed $B \to K^*\ell^+\ell^-$ events are expected. We take the simulated errors [7] (with signal events generated according to the SM) for $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ from three bins, one around the SM zero, one below, and one above, and plot also in Fig. 1(a) to guide the eye. It should be clear that our suggestion can be tested early on in the LHC era

B. General SM-like four-quark operators

The narrow, long "tail" at $\hat{s} \gtrsim 0.3$ for $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ in Fig. 1(a) reflects the "symmetry" imposed by Eq. (6), which we now loosen. Even if we keep the operator basis as in Eq. (1), treating these as 4-fermion interactions arising from possible NP at short distance (for instance, Z' models [15]), one should keep the full generality of Eqs. (3)–(5). We proceed to explore the parameter space as before, keeping $B \to K^*\gamma$ and $K^*\ell^+\ell^-$ within 1σ constraint. Indeed we find much richer possibilities than Figs. 1(a) and 1(b). Besides the SM and SM4, which are cases a and b, respectively, as in Fig. 1, we illustrate in Figs. 2(a) and 2(b) the further cases of c, d, and e. The Δ_i and ϕ_i values are given in Table I.

Case d has the wrong sign C_{10}, while case e has the sign flip in both $C_7^{\rm eff}$ and C_{10} (equivalent to the wrong sign C_9). Both are already ruled out [4]. The case of flipping only the

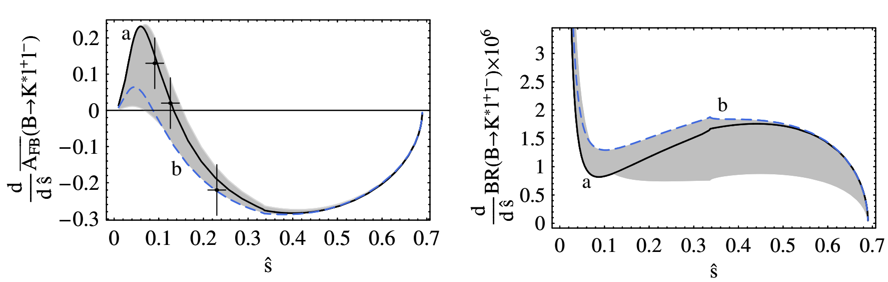

FIG. 1 (color online). $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ and $d\mathcal{B}/d\hat{s}$ for $B \to K^*\ell^+\ell^-$. The shaded region is allowed by Eq. (6), and cases a (solid line) and b (dashed line) are the SM and SM4, respectively. The three crosses correspond to three representative simulated data points from a 2 fb^{-1} study [7] of the LHCb experiment.

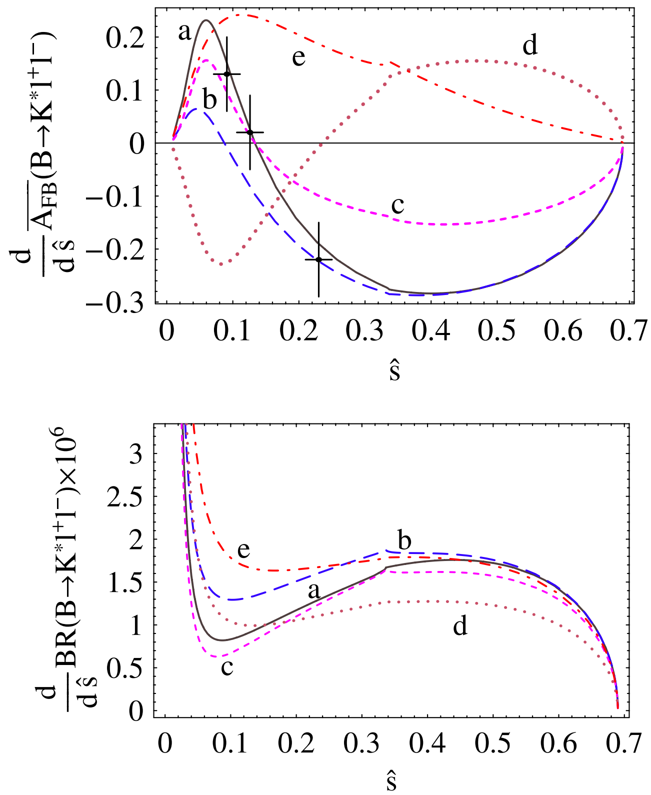

FIG. 2 (color online). $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ and $d\mathcal{B}/d\hat{s}$ for $B \to K^*\ell^+\ell^-$ allowing all Wilson coefficients to be complex as in Eqs. (3)–(5). The (simulated) data points are as in Fig. 1.

sign of $C_7^{\rm eff}$, ruled out by rate constraints [6], is not plotted. Such scenarios have been considered in the literature, which we give to illustrate the versatility of Eqs. (3)–(5). Though ruled out, case e is illuminating. Without complex phases, the large effects still survive rate constraints to give a stronger low q^2 peak in Fig. 2(b) that lies outside the shaded region of Fig. 1(b). This is because Eq. (6) no longer holds. Similar cases may exist that remain to be probed.

An interesting new scenario is illustrated by case c, where $d\mathcal{B}/d\hat{s}$ and the zero of $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ are hard to distinguish from the SM, but $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ above the zero reaches only half the SM value. Thus, a measurement of the zero does *not* pin down C_9. The scenario can be tested already with 1 ab^{-1} data at B factories expected by 2008. If such phenomena are discovered with, e.g. LHCb data, it would imply NP that feed the $(\bar{s}\gamma_\mu Lb)(\bar{\ell}\gamma^\mu\ell)$ and $(\bar{s}\gamma_\mu Lb)(\bar{\ell}\gamma^\mu\gamma_5\ell)$ operators differently.

TABLE I. Parameter values for cases b–e in Fig. 2. The SM (case a) has $\Delta_i = 0$. The last column gives direct CP violation in $b \to s\gamma$, where "—" is given for cases d and e, which are already ruled out. In our numerics [10], we use $C_7^{\rm eff} \simeq 0.67C_7 - 0.18$, with $C_7 \simeq -0.20$, $C_9 \simeq 2.1$, and $C_{10} \simeq -4.4$ at M_W scale.

Case	Δ_7	Δ_9	Δ_{10}	ϕ_7	ϕ_9	ϕ_{10}	$\mathcal{A}_{CP}(b\to s\gamma)$
b	-0.2	-0.9	-0.9	65°	65°	65°	2%
c	-0.5	1	-0.5	90°	270°	0	5%
d	0	-1.5	-2.0	0	35°	0	—
e	-4.8	-1.2	-2.2	0	0	0	—

We mark the simulated errors from the 2 fb^{-1} study at LHCb as before on Fig. 2(a), illustrating its power. The actual possibilities are far richer. The shaded area of Fig. 1(a) illustrates that, even with Eq. (6) imposed, a broad range is allowed for $\hat{s} < 0.2$. With the full freedom of Eqs. (3)–(5), the region allowed by rate constraint would likely cover a large part of Fig. 2(a), which is up to experiment to explore. One should keep the effective Wilson coefficients of Eq. (1) complex and use the general parametrization of Eqs. (3)–(5) to fit for Δ_i and ϕ_i. *Finite* ϕ_i *implies violation of MFV.*

V. DISCUSSION AND CONCLUSION

Although $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ by itself is a real measure, if fitting for complex Wilson coefficients uncovers CP violating phases, large direct CP violation could be implied. We give the expected $\mathcal{A}_{CP}(b\to s\gamma)$ in the last column of Table I. Cases d and e are already ruled out, hence marked as "—" in the table. The sizable $\mathcal{A}_{CP}$ in cases b (SM4) and c are not inconsistent with current data [9], which has an error of 4%, but can be probed at a future Super B factory.

Our suggestion of keeping the Wilson coefficients complex is not just for NP. Even within the SM, for the CKM suppressed decay $B \to \rho\ell^+\ell^-$, one already expects [26] complex effective couplings from the u-quark and top contributions, as seen in Fig. 3 where we show $B \to K^*\ell^+\ell^-$ in the SM for comparison. The difference probably cannot be probed by 2 fb^{-1} data at LHCb, as one expects less than 200 $B \to \rho\ell^+\ell^-$ events with larger background. It can be tested with a larger data set.

We offer some remarks before closing. We have focused on $\mathcal{A}_{\rm FB}$ for exclusive $B \to K^*\ell^+\ell^-$, mostly because of experimental accessibility, and with an upgrade of statis-

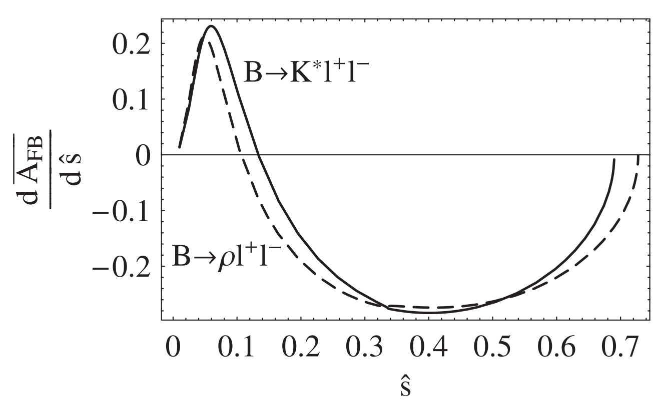

FIG. 3. $d\bar{\mathcal{A}}_{\rm FB}/d\hat{s}$ for $B \to \rho\ell^+\ell^-$ and $K^*\ell^+\ell^-$ in the SM.

tics imminent. Our discussion, starting with Eq. (1), clearly applies to the inclusive case as well. Second, it is usually stressed that the zero of $\mathcal{A}_{\rm FB}$ is insensitive to form factors. With NP sensitivities now going beyond the zero, form factor issues would have to be considered. The combined progress from form factor models, lattice, as well as experimental studies of $B \to \rho \ell \nu$ would be needed. Third, while the 4th generation model provides a good example, our approach is general for any NP that does not generate new operators. The study of $b \to s$ transitions is still in its infancy, and is the least constrained. Imposing MFV may be overstretching our experience from other areas of flavor violation. It is up to experiment to reveal what may be in store for us, and $\mathcal{A}_{\rm FB}$ is an excellent probe. Four, whether to allow C_7, C_9, and C_{10} to be complex, or to extend to opposite chirality operators, does bring in the issue of NP model dependence [27]. We have advocated the former with 4th generation as a model example. Z' models can also be another example, but in principle allow also new operators. Note that, by allowing C_7, C_9, and C_{10} to be complex, one already covers a rather large range of $\mathcal{A}_{\rm FB}$ (Fig. 2). Enlarging the operator set, the Wilson coefficients should still be allowed complex, and the most general case would have 10 operators [22] hence 20 parameters. A fit to $\mathcal{A}_{\rm FB}$ only would not be profitable, and other measurables, such as $B_s \to \mu^+ \mu^-$ for scalar operators, and K^* polarization for right-handed currents, should be employed. The optimal approach will be explored in a subsequent work. But Eq. (1) is already used by experiment, so making a complex parameter fit can be done readily. Finally, the 1 ab^{-1} final data at B factories would only give limited improvement on the existing result. The next round of major improvement would come from LHC. A Super B factory upgrade would be necessary to bring back competitiveness of e^+e^- machines, allowing one to study also the inclusive mode.

In summary, we have explored the CP conserving consequences of complex Wilson coefficients on the forward-backward asymmetry $\mathcal{A}_{\rm FB}$ in $B \to K^* \ell^+ \ell^-$ decay. The possibilities are much broader than the usual consideration of sign flips under the minimal flavor violation framework. In view of hints of CP violation anomalies in $b \to s q \bar{q}$ decays, the large increase in statistics with the advent of LHC would make $\mathcal{A}_{\rm FB}$ one of the cleanest probes for new physics in the near future.

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