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A critical look at hadronic $b \to s$ penguin modes

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Within the Standard Model, the time-dependent CP asymmetry $S(t)$ in hadronic $b \to s$ penguin decay modes, such as $B \to (\phi, f_0, \eta, \eta', \rho^0, \pi^0, \omega)K_S$, probes $\sin(2\beta)$ up to small corrections. Any significant deviation from the Standard Model prediction would be a clear hint for new physics. In this context, we consider the branching ratios and CP asymmetries in two theoretically clean modes, namely in $B \to f_0(980)K_S$ and $B \to \phi K_S$ decays, to the end of determining the deviation of $S(t)$ from $\sin(2\beta)$ arising from Standard Model physics. We use the QCD factorization framework for the decay amplitudes and employ a parameter scan to probe a broad range of theoretical models, exploring variations in the inputs at the 3σ level and the ill-known $\mathcal{O}(1/M_B)$ corrections with 100% uncertainty. If we demand that the theoretical model confronts the empirical branching ratios successfully, the excursions in $S(t)$ from $\sin(2\beta)$ are under sufficient theoretical control to enable the interpretation of experimental results of much higher precision.

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1. Introduction

The CKM mechanism of a single CP-violating phase has been confirmed by various B and K decay data over the last decade. However, the presence of new physics effects can not be ruled out. In the Standard Model (SM), the time-dependent CP asymmetry in hadronic B meson decays to CP eigenstates mediated by the quark-level transition $b \to sc\bar{c}$ probes $\sin(2\beta)$ [1, 2, 3, 4]. The latest measurement of the time-dependent CP asymmetry $S(t)$ in $B \to J/\psi K_S$ decays and to related charmonium final states yields $\sin(2\beta) = 0.673 \pm 0.023$ [5]. The deviation of the time-dependent asymmetry from $\sin(2\beta)$ is $\mathcal{O}(10^{-3})$ [6, 7] — it is suppressed by both CKM and loop effects. Within the SM, the time-dependent CP asymmetries in hadronic $b \to s$ penguin decay modes such as $B \to (\phi, f_0, \eta, \eta', \rho^0, \pi^0, \omega)K_S$ also probe $\sin(2\beta)$ up to small corrections [8, 9], so that determining the inferred value of $\sin(2\beta)$ in all these modes offers a window on new physics [8, 10]. The experimental results currently show no compelling deviation of the time-dependent CP asymmetry $S(t)$ from $\sin(2\beta)$, but the empirical errors, particularly in the $b \to s$ penguin modes, are still rather large [5]. We expect much larger B decay data sets to emerge from the LHCb as well as from possible very high luminosity — "super" — B-factories, so that any deviations can be determined with much improved significance. In the hope of identifying beyond the SM physics from future experiments, we focus on the SM corrections in two theoretically clean modes which can be tested against experimental results of much higher precision. In what follows we report on our work on the study of the deviations from $\sin(2\beta)$ in $B \to f_0(980)K_S$ decay [11] and in $B \to \phi K_S$ decay [12] and refer the reader to Refs. [11, 12] for all details. The study of such modes is complementary to the study of the $b \to s$ transition in B_s mixing. The hint that the empirical weak phase determined from B_s mixing is larger than the SM prediction [13], if borne out, would require new sources of CP violation beyond that contained in the CKM paradigm and should have correlated effects in $b \to s$ decays. Moreover, the study of $B \to f_0 K_S$ and $B \to \phi K_S$ are complementary to each other because $B \to f_0 K_S$ and $B \to \phi K_S$, assuming the ϕ to be ideally mixed, are the only studied $b \to s$ penguin modes which have no color-suppressed tree contributions.

2. Formulation of ΔS_f and C_f

We follow Ref. [14] and write the amplitude for B meson decays to final CP eigenstate f as

$$A(\bar{B}^0 \to f) = \lambda_u a_f^u + \lambda_c a_f^c \propto (1 + e^{-i\gamma} d_f), \tag{2.1}$$

with $d_f = |\lambda_u/\lambda_c|(a_f^u/a_f^c)$, $\lambda_q = V_{qb}V_{qs}^*$, and V_{ij} is a CKM matrix element. In terms of the "topological" amplitudes, d_f can be expressed as $d_f \propto (\pm C + P^u)/P^c$, where C is the color-suppressed tree amplitude and $P^{u,c}$ are the (u, c) penguin amplitudes, respectively. In terms of d_f, the relevant expressions for ΔS_f and C_f are

$$\Delta S_f \equiv -\eta_f S_f - \sin(2\beta) = \frac{2\,\mathrm{Re}(d_f)\cos(2\beta)\sin\gamma + |d_f|^2\,(\sin(2\beta+2\gamma) - \sin(2\beta))}{1 + 2\,\mathrm{Re}(d_f)\cos\gamma + |d_f|^2} \tag{2.2}$$

and

$$C_f = -\frac{2\,\mathrm{Im}(d_f)\sin\gamma}{1 + 2\,\mathrm{Re}(d_f)\cos\gamma + |d_f|^2} \tag{2.3}$$

where $\eta_f = \pm 1$ depending on the transformation of the final CP eigenstate f under CP. The value of ΔS_f in the SM shows systematic trends with the particular final-state mesons considered. For example, it is small for decay modes without a color-suppressed tree contribution [14]. As described in Ref. [14], the effect of that contribution C on ΔS, however, can be either constructive or destructive depending on the final-state mesons. We emphasize that almost all the hadronic $b \to s$ penguin modes, namely $B \to (\phi, \eta, \eta', \omega, \rho^0, \pi^0)K_S$, have a color-suppressed tree contribution: one exception is the $B \to f_0 K_S$ decay mode. The non-existence of the color-suppressed tree contribution in $B \to f_0 K_S$ decay follows from charge conjugation symmetry, which sets the vacuum to scalar matrix element of the vector current to zero [15] irrespective of the structure of the $f_0(980)$. That is,

$$\langle f_0 | \bar{q}\gamma^\mu q | 0 \rangle = 0 \,, \tag{2.4}$$

so that $d_{f_0 K_S} \propto P^u/P^c$. This conclusion would follow even if the $f_0(980)$ were a non-$q\bar{q}$ state. In the case of $B \to \phi K_S$ decay, however, the deviations of $S(t)$ from $\sin(2\beta)$ qualitatively depend on the structure of the ϕ meson. That is, if the ϕ is ideally mixed, so that it is a pure $s\bar{s}$ state, then no color-suppressed tree contribution would appear. However, if the ϕ meson is not a pure $s\bar{s}$ state, so that the so-called $\phi - \omega$ mixing angle is non-zero, then the color-suppressed mode would enter giving $d_{\phi K_S} \propto (C + P^u)/P^c$. There is no reason why the $\phi - \omega$ mixing angle ought be zero, so that $\Delta S_{\phi K_S}$ can be larger than in earlier estimates [16, 17, 14]. The existence of this contribution was pointed out and estimated in the original literature [8, 9]; we find larger effects once uncertainties in the computation of the color-suppressed tree contribution are taken into account.

We compute d_f in the QCD factorization approach [18, 19] and adopt methods similar to those of Beneke [14] to assess the uncertainty in ΔS_f. The accuracy of the predictions of the different branching fractions and the different CP-violating observables in the QCD factorization approach depends on the phenomenological parameters describing the power-suppressed corrections in the hard spectator and annihilation amplitudes and on the different input parameters. The uncertainties associated with input parameters such as the scalar meson decay constants, the form factors, the quark masses, and the Gegenbauer moments of light-cone distribution amplitudes are statistical uncertainties, whereas the uncertainties associated with the $1/m_b$-suppressed corrections we refer to as systematic uncertainties. We wish to determine the impact of these various uncertainties on the value of ΔS_f.

3. Results and discussion

We expect the value of $\Delta S_{f_0 K_S}$ to be very small in our default model [18] because there is no color suppressed tree contribution, which agrees with explicit calculation [20, 11]. If ϕ is a pure $s\bar{s}$ state, there is no color-suppressed tree contribution to the $B \to \phi K_S$ decay amplitude and the value of $\Delta S_{\phi K_S}$ is also small [14].

To gauge the size of the uncertainties, we perform a random scan of the allowed theoretical parameter space. For the parameter scan, we choose the range of the input parameters by taking either 1σ or 3σ deviations from the central values and include the theoretical $\mathscr{O}(1/M_B)$ corrections with 100% uncertainty. To control the latter, we impose a branching ratio constraint in such a way that we ignore those theoretical models which are not compatible within 1σ of the experimental branching ratio for 1σ parameter scans and within 3σ of the experimental branching ratio for the 3σ parameter scans, respectively [11]. We plot various combinations of $\Delta S_{f_0 K_S}$ and $C_{f_0 K_S}$ from our parameter scan with branching ratio constraint as shown in Fig. 1. The ranges of $\Delta S_{f_0 K_S}$ from our

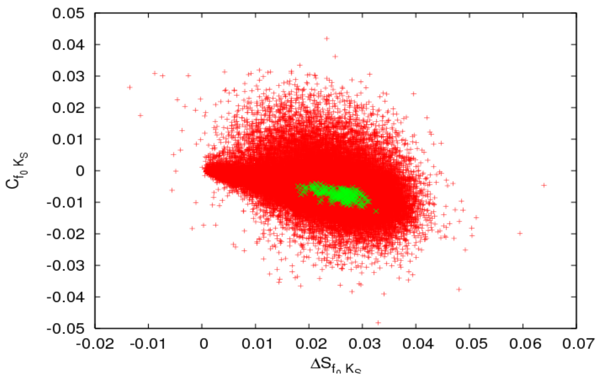

Figure 1: Range in $\Delta S_{f_0 K_S}$ and $C_{f_0 K_S}$ from a scan of 500 000 theoretical models with the empirical branching ratio constraint imposed. The darker points represent the possible range of $\Delta S_{f_0 K_S}$ and $C_{f_0 K_S}$ within 3σ whereas the lighter points represent the range for a 1σ variation.

random scan over the theory space are $[0.018, 0.033]$ for 1σ scan and $[-0.019, 0.064]$ for 3σ scan, respectively.

For the $B \to \phi K_S$ decay mode, first we perform the parameter scan for zero $\phi - \omega$ mixing angle and find the range of $\Delta S_{\phi K_S}$ to be $[0.014, 0.039]$ for 1σ scan and $[-0.062, 0.080]$ for 3σ scan shown in Fig. 2. Thus we verify that if there is no color-suppressed tree contribution, ΔS_f is small, i.e, $d_f \propto P^u/P^c$ implies small ΔS_f. Since there is no reason for the ϕ meson to be a pure $s\bar{s}$ state, we introduce a non-zero $\phi - \omega$ mixing angle θ which parametrizes the departure from ideal mixing. We thus write the $q\bar{q}$ structure of the ϕ meson as

$$\phi = \left(\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}\right) \sin\theta + s\bar{s} \cos\theta\,. \tag{3.1}$$

Just to illustrate how a non-zero mixing angle can effect the value of $\Delta S_{\phi K_S}$, we perform a random scan over all the theoretical parameter sets allowing the parameters to vary within 1σ and 3σ from their central values and θ to vary from $[2,4]^\circ$ for the 1σ scan and $[0,6]^\circ$ for the 3σ scan respectively [12]. The value of $\theta = 3^\circ \pm 1^\circ$ is chosen so that it encompasses the various results for this quantity in the literature [12]. The resulting ranges of $\Delta S_{\phi K_S}$ are $[0.0048, 0.035]$ for the 1σ scan and $[-0.074, 0.14]$ for the 3σ scan, respectively. The slightly larger range in $\Delta S_{\phi K_S}$ for a non-zero mixing angle results from the color-suppressed tree contribution to the $B \to \phi K_S$ decay amplitude. We plot the various combinations of $\Delta S_{\phi K_S}$ and $C_{\phi K_S}$ from our scan as shown in Fig. 3.

We know that, in principle, there are two ways to have a large excursion in ΔS_f: a small $|P^c|$ amplitude or a large $|\pm C + P^u|$ amplitude. A large excursion in ΔS_f due to a small $|P^c|$ amplitude can be controlled using the experimental branching ratio constraint, as in this case the theoretical branching ratio becomes too small in comparison to its experimental value. Although the uncertainties associated with the hard spectator interaction terms can enhance the $|\pm C + P^u|$ amplitude, it is, however, not possible in QCD factorization to make $|P^u|$ large without making $|P^c|$

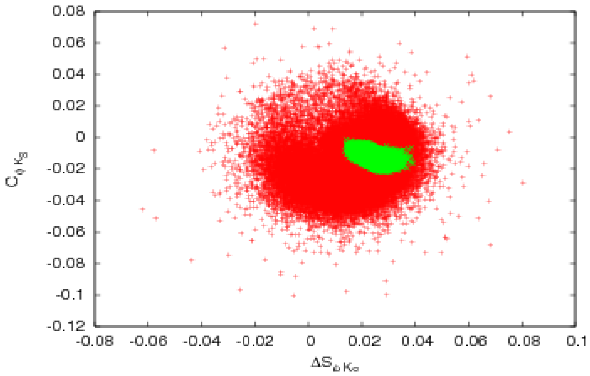

Figure 2: Range in $\Delta S_{\phi K_S}$ and $C_{\phi K_S}$ from a scan of 500,000 theoretical models. The lighter interior region corresponds to a scan of parameter space at 1σ, whereas the darker region corresponds to a scan at 3σ. We assume ideal mixing here.

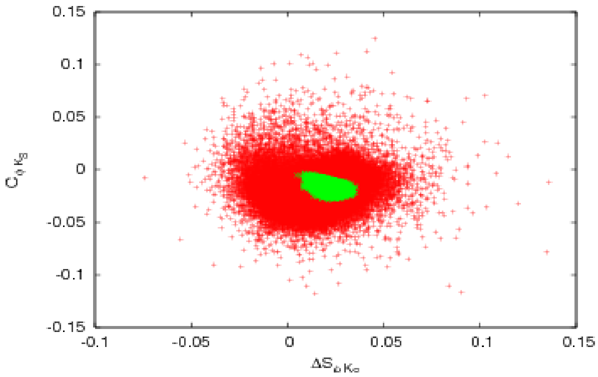

Figure 3: Range in $\Delta S_{\phi K_S}$ and $C_{\phi K_S}$ from a scan of 500,000 theoretical models. The lighter interior region corresponds to a scan of parameter space at 1σ, whereas the darker region corresponds to a scan at 3σ. Here we vary the value of the $\phi - \omega$ mixing angle θ as well.

large at the same time. Thus, ΔS_f is small if $d_f \propto P^u/P^c$. However, it is in fact possible to have a large excursion in ΔS_f if a color-suppressed tree contribution is present because the uncertainty associated with the hard spectator interaction term can enhance the color-suppressed tree amplitude and make $|a_f^u|$ much larger than $|a_f^c|$. We note that a large excursion in ΔS_f can come from the inverse moment of B meson distribution amplitude, λ_B. However, these large excursions can be controlled using the empirical branching ratio constraint. To test the accuracy of our NLO analysis, we also change the renormalization scale μ from $m_b/2$ to m_b, and we find very little variation in ΔS_f and C_f; for the ϕK_S mode we consider the zero mixing angle case. The weak μ dependence we observe follows as the observables involve ratios of computed amplitudes in each case.

4. Conclusion

We have investigated the size of the SM corrections in two theoretically clean hadronic $b \longrightarrow s$ penguin decay modes, namely, $B \longrightarrow f_0 K_S$ and $B \longrightarrow \phi K_S$ decay modes, within the QCD factorization approach of Refs. [18, 19]. Our discussion of CP asymmetries in these $b \to s$ penguin dominated modes are aimed at constraining ΔS_f within the SM, such that the size of the window for new physics can be assessed. We find that the $B \to f_0 K_S$ decay mode is the theoretically cleanest $b \to s$ penguin mode as the $B \to f_0 K_S$ decay amplitude does not contain any color-suppressed tree contribution, irrespective of the structure of the f_0. We note that the empirical errors are still large and that they are larger than our largest estimated values of ΔS_f so that further refinement of the experimental results is warranted.

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