P H Y S I C A L   R E V I E W   L E T T E R S

$B_s \to K^{(*)0} \bar{K}^{(*)0}$ *CP* Asymmetries: Golden Channels for New Physics Searches

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We point out that time-dependent *CP* asymmetries in $B_s \to K^{*0}\bar{K}^{*0}$ decays probe the presence of new physics in $b \to s$ transitions with an unprecedented theoretical accuracy. We show that, contrary to the case of $B_d \to \phi K_S$, it is possible to obtain a model-independent prediction for the coefficient $S(B_s \to K^{*0}\bar{K}^{*0})$ in the standard model. We give an estimate of the experimental precision achievable with the next generation of *B* physics experiments. We also discuss how this approach can be extended to the case of $B_s \to \bar{K}^{*0}K^0$, $B_s \to K^{*0}\bar{K}^0$, and $B_s \to K^0\bar{K}^0$ decays and the different experimental challenges for these channels.

The measurement of *CP* asymmetries in flavor changing neutral current processes represents a crucial test of the standard model (SM). In particular, time-dependent *CP* asymmetries in $b \to s$ penguin-dominated modes are considered among the most sensitive probes of new physics (NP) [1]. Measuring these asymmetries is one of the highlights of the *B*-factory physics program [2–4]. In this context, the study of $B_d \to \phi K_S$ has been considered for a long time the *golden mode* for NP searches in nonleptonic *B* decays, since it is a pure penguin mode [5]. Indeed, writing the amplitude in terms of renormalization group invariant (RGI) parameters, defined in Ref. [6], one obtains

$$A(B_d \to \phi K^0) = V_{tb}^* V_{ts} P - V_{ub}^* V_{us} P^{\text{GIM}}, \quad (1)$$

where *P* contains penguin contractions of charmed current-current operators together with the matrix elements of $b \to s$ penguin operators, while P^{GIM} represents the Glashow-Iliopoulos-Maiani (GIM)-suppressed difference of penguin contractions of current-current operators containing charm and up quarks, respectively.

Neglecting the contribution of P^{GIM} on the basis of plausible dynamical arguments, the $B_d \to \phi K_S$ decay is mediated by a single amplitude, so that under this assumption no direct *CP* violation can be produced and the time-dependent *CP* asymmetry probes the phase 2β of $B_d - \bar{B}_d$ mixing. In terms of the coefficients *S* and *C* of sine and cosine terms in the time-dependent *CP* asymmetry, this means that in the SM one expects $S(B_d \to \phi K^0) = \sin 2\beta$ and $C(B_d \to \phi K^0) = 0$. The theoretical error associated to this prediction is related to the ratio of P^{GIM}/P.

The average of currently available experimental measurements by *BABAR* [3] and Belle [4] gives $S(B_d \to \phi K^0) = 0.39 \pm 0.18$ and $C(B_d \to \phi K^0) = 0.01 \pm 0.13$ [7]. Even though the experimental errors are still large, it is interesting to observe that the value of $S(B_d \to \phi K^0)$ deviates from the world average $\sin 2\beta = 0.675 \pm 0.026$ [7]. If confirmed in the future with a smaller error, this measurement might provide a hint of NP in *B* decays. On

the other hand, this interpretation should consider the theoretical uncertainty introduced by neglecting P^{GIM}. Even though several model-dependent approaches, based on factorization or on flavor symmetries, have been proposed in literature [8,9], a model-independent evaluation of the error is not available yet. Considering that the next generation of *B* physics experiments [10] is expected to reduce the error on $S(B_d \to \phi K_S)$ down to a few percent, the lack of a model-independent evaluation of the theoretical error is a strong limitation for a complete and meaningful test of the SM.

In this Letter, we propose to overcome this problem by using $B_d \to K^{(*)0}\bar{K}^{(*)0}$ decays to predict $S(B_s \to K^{*0}\bar{K}^{*0})$ within the SM, including the theoretical error associated to hadronic uncertainties, in particular, to the GIM-suppressed penguin contractions. Considering the experimental precision that is expected at LHCb [11] and at a future super *B* factory [12], we give a theoretical estimate of the deviation from zero of $S(B_s \to K^{*0}\bar{K}^{*0})$ within the SM. This is a crucial ingredient to search for NP effects in this decay mode: a deviation from zero much larger than the estimated SM error would be a strong signal of NP.

For a given polarization of the final state [13], we can write the decay amplitude of $B_s \to K^{*0}\bar{K}^{*0}$ decays as

$$A(B_s \to K^{*0}\bar{K}^{*0}) = -V_{tb}^* V_{ts} P_s - V_{ub}^* V_{us} P_s^{\text{GIM}}, \quad (2)$$

in the same notation of Eq. (1). Comparing Eqs. (1) and (2), it is clear that the same NP in $b \to s$ penguin diagrams enters both this channel and the *golden mode* $B_d \to \phi K_S$.

From an experimental point of view, the K^{*0} mesons can be reconstructed as $K^{*0} \to K^+\pi^-$ and $\bar{K}^{*0} \to K^-\pi^+$. Since the final state is a *CP* eigenstate, it is possible to measure the *CP* asymmetry parameters *S* and *C* from the time-dependent study of the tagged decay rates. The information on the flavor of the decaying B_s is provided by the usual tagging techniques. Since in this case the B_s meson decays only to charged tracks directly originating from the vertex, the reconstruction and vertexing of the B_s mesons

should be possible at LHCb, allowing to measure the parameters of the time-dependent CP asymmetry.

With the same approximation of $B_d \to \phi K_S$, i.e., neglecting the Cabibbo-Kobayashi-Maskawa (CKM)-suppressed contribution of $P_{s,d}^{\mathrm{GIM}}$, the SM expectation values for the coefficients of the CP asymmetry are simply given by $S(B_s \to K^{*0}\bar{K}^{*0}) = 0$ and $C(B_s \to K^{*0}\bar{K}^{*0}) = 0$, as

$$\lambda_{CP}(B_s \to K^{*0}\bar{K}^{*0}) = e^{2i\beta_s}\frac{A(\bar{B}_s \to K^{*0}\bar{K}^{*0})}{A(B_s \to K^{*0}\bar{K}^{*0})} = 1.$$

This is a null test of the SM, but an estimate of the error induced by neglecting P_s^{GIM} is needed.

The advantage of this mode, with respect to the case of $B_d \to \phi K^0$, is represented by the possibility of calculating the theoretical error in a model-independent way, using the measurement of $BR(B_s \to K^{*0}\bar{K}^{*0})$ and $C(B_s \to K^{*0}\bar{K}^{*0})$, together with the information on the order of magnitude of P_s^{GIM} provided by the time-dependent study of $B_d \to K^{*0}\bar{K}^{*0}$ decays.

The idea follows the calculation of the error on $\sin2\beta$ in $B_d \to J/\psi K^0$ presented in Ref. [14]. The expression for the decay amplitude of $B_d \to K^{*0}\bar{K}^{*0}$ in the same notation of Eqs. (1) and (2) is given by

$$A(B_d \to K^{*0}\bar{K}^{*0}) = -V_{tb}^* V_{td} P_d - V_{ub}^* V_{ud} P_d^{\mathrm{GIM}}, \quad (3)$$

which is equivalent to Eq. (2), except that in this case the two combinations of CKM matrix elements have the same order of magnitude. As a consequence, the sensitivity to P_d^{GIM} is maximal in this case. From the measurement of the BR and the CP parameters S and C, fixing the CKM elements to their SM values obtained by the UTfit Collaboration [15], one can determine $|P_d|$, $|P_d^{\mathrm{GIM}}|$, and the relative strong phase δ_d. In the SU(3)-symmetric limit, $P_d^{(\mathrm{GIM})} = P_s^{(\mathrm{GIM})}$ and $\delta_d = \delta_s$. Imposing these relations, as done in Ref. [16], would introduce a (difficult to estimate) error associated to SU(3) breaking [17]. To be conservative, we instead allow for a SU(3) breaking up to 100%, much larger than any known breaking effect.

Starting from these considerations, the estimate of the theoretical expectation for the deviation of $S(B_s \to K^{*0}\bar{K}^{*0})$ from zero proceeds through three steps, in analogy to Ref. [14]: (i) a fit to determine P_s from $BR(B_s \to K^{*0}\bar{K}^{*0})$; (ii) a fit of $|P_d|$, $|P_d^{\mathrm{GIM}}|$, and δ_d from the experimental values of BR, S, and C of $B_d \to K^{*0}\bar{K}^{*0}$. In the fit, only the solution that gives $|P_d|$ compatible with $|P_s|$ is considered; (iii) a fit of the $B_s \to K^{*0}\bar{K}^{*0}$ decay amplitude

from the experimental values of BR and C, performed forcing the absolute value $|P_s^{\mathrm{GIM}}|$ in the range obtained allowing 100% SU(3) breaking effects around the central value of $|P_d^{\mathrm{GIM}}|$. To be conservative, no information from $B_d \to K^{*0}\bar{K}^{*0}$ is used for constraining $|P_s|$ and δ_s.

Let us first discuss the experimental prospects. Based on these, we then present an example of how our method might work once the relevant modes will be measured. An estimate of the level of precision reachable at LHCb is difficult to give at this stage and goes beyond the purpose of this work, since details on the reconstruction of the LHCb detector are needed. In addition, the lack of measurements of $B_d \to K^{*0}\bar{K}^{*0}$ makes any prediction harder. Nevertheless, few educated assumptions might help us to understand the order of magnitude of the experimental error on $S(B_s \to K^{*0}\bar{K}^{*0})$. We assume that (i) LHCb will provide a measurement of the S and C parameters with an error of ~ 0.02 (comparable to what is expected for $B_s \to K^+K^-$); (ii) a 5% precision on the decay rate will be obtained at LHCb or at a super B factory running at the $\Upsilon(5S)$ resonance [19]; (iii) a similar precision will be available for $B_d \to K^{*0}\bar{K}^{*0}$ rates and CP asymmetries. Concerning this last point, it is important to stress that $B_d \to K^{*0}\bar{K}^{*0}$ decays are CKM suppressed with respect to $B_s \to K^{*0}\bar{K}^{*0}$. Nevertheless, with LHCb integrating more than two years of data and/or a super B factory integrating >30 ab^{-1}, there should be no limitation given by the available statistics. For the central values, we assume that they lie in the ballpark of the calculation of Ref. [20], but we have checked that larger values of the BR's give similar results. The values we assume are summarized in Table I.

We now give an example of the precision we might expect on the theoretical prediction of $S(B_s \to K^{*0}\bar{K}^{*0})$ using the numbers given above. Using our method we obtain the distribution of $S(B_s \to K^{*0}\bar{K}^{*0})$ shown in Fig. 1, with a rms of 0.015. This corresponds to a theoretical error on $\arg(\lambda_{CP}(B_s \to K^{*0}\bar{K}^{*0}))$ of 0.8°. Clearly this estimate is only illustrative as it is based on the values in Table I inspired by factorization models. Once data become available, however, the method will provide an estimate independent of any theoretical model.

The presence of multiple polarizations in the $K^*\bar{K}^*$ final state does not change the idea we propose here, but it has a practical impact on the analysis strategy. Our procedure can be followed for each polarization (longitudinal or transverse), taking into account the relative minus sign in the CP eigenvalue. Experimentally, using an angular analysis it is possible to separate the different contributions and independently determine rates and CP parameters [21].

TABLE I. Input values used to estimate the precision on the determination of β_s.

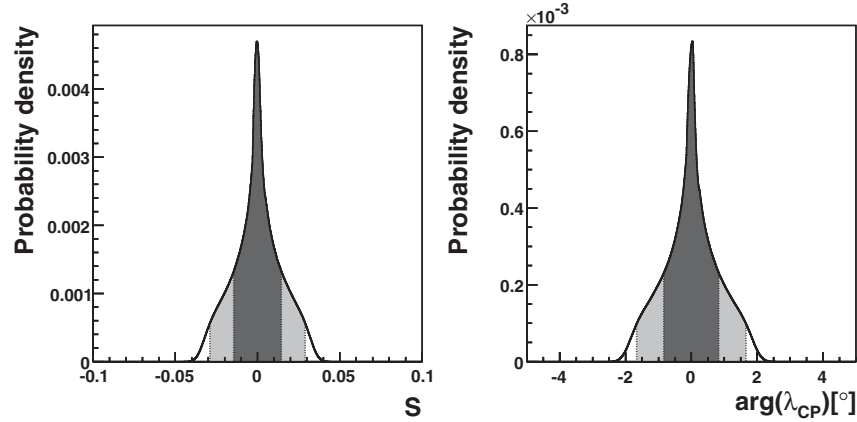| Channel	BR	S	C
$B_s \to K^{*0}\bar{K}^{*0}$	$(11.8 \pm 0.6) \times 10^{-6}$	-0.07 ± 0.02	0.01 ± 0.02
$B_d \to K^{*0}\bar{K}^{*0}$	$(5.00 \pm 0.25) \times 10^{-7}$	-0.12 ± 0.02	0.13 ± 0.02

FIG. 1.   Probability density function for S (top) and $\arg(\lambda_{CP})$ (bottom) for the decay $B_s \rightarrow K^{*0}\bar{K}^{*0}$ obtained with the procedure detailed in the text, using the input values given in Table I.

In terms of the experimental fit, the separation of the three polarizations requires one to add the angular distribution of the final state particles to the maximum likelihood fit, as it was done, for example, in the $B_d \rightarrow \rho^+\rho^-$ time-dependent analyses of *BABAR* [22].

From a practical point of view, the presence of three polarizations helps to increase the experimental precision, with respect to the case of a single polarization. In fact, the measurement is also sensitive to interference terms among the different polarizations, as for $B_d \rightarrow J/\psi K^*$ time-dependent analyses performed at the B factories [23,24]. One can define 11 parameters describing the complex B_d decay amplitudes for the three polarization states and their CP conjugates, up to an arbitrary global phase. In terms of these 11 parameters one can compute three sets of rates, S and C coefficients (one for each polarization). Since the number of unknowns is smaller than the number of observables, the presence of three polarizations in the final state will improve the precision of the analysis. The same procedure can be used for B_s decays.

In principle, the same approach can also be applied to $B_s \rightarrow K^{*0}\bar{K}^0$, $B_s \rightarrow \bar{K}^{*0}K^0$ and $B_s \rightarrow K^0\bar{K}^0$ decays, with the caveat that the strategy has to change in order to face the different experimental challenges.

For $B_s \rightarrow K^0\bar{K}^0$, the measurement of the BR should be possible at LHCb or at a super B factory. On the other hand, the time-dependent CP parameters S and C cannot be measured, since the extrapolation of the B_s vertex from the flight direction of two K_S does not seem possible at LHCb, while a B factory has not enough vertex resolution to follow the fast oscillations of B_s mesons [19]. Nevertheless, it is still possible to obtain a determination of λ_{CP}, measuring the tagged decay rates for $\Delta t > 0$ and $\Delta t < 0$. The sign of Δt can be measured at a super B factory, using the K_S flight direction to determine the B vertex [25]. Using a full Monte Carlo simulation, it was shown that it is possible to measure $\arg(\lambda_{CP}(B_s \rightarrow K^0\bar{K}^0))$ with an experimental error less than 20° [19]. The actual

error could be even smaller, if the improvement of the vertexing detector (due to the use of a layer zero of the silicon detector close to the beam pipe) will allow to separate primary and secondary vertices on $B \rightarrow DX$ decays [26], strongly reducing the background contamination [27]. At the same time, the rms for $\arg(\lambda_{CP})$ expected in the SM, taking into account P_s^{GIM} with our method, should be at the level of 4° [19].

The case of $B_s \rightarrow K^{*0}\bar{K}^0$ and $B_s \rightarrow \bar{K}^{*0}K^0$ is more similar to $B_s \rightarrow K^{*0}\bar{K}^{*0}$. The main difference in this case is that there are two different particles in the final state. As a consequence, the number of hadronic parameters to determine is twice the number of hadronic parameters for a single polarization in $B_s \rightarrow K^{*0}\bar{K}^{*0}$ modes. On the other hand, the number of experimental observables is larger. Reconstructing $B_s \rightarrow K^{*0}\bar{K}^0$ and $\bar{B}_s \rightarrow K^{*0}\bar{K}^0$ ($B_s \rightarrow K^0\bar{K}^{*0}$ and $\bar{B}_s \rightarrow K^0\bar{K}^{*0}$) from $K^+\pi^-K_S$ ($K^-\pi^+K_S$) final states it is possible to measure CP violating effects [28], which provide four observables (S, C, $\bar{S}$, and $\bar{C}$) in addition to two decay rates. It will be possible to use $B_s \rightarrow K^{*0}\bar{K}^0$ and $B_s \rightarrow K^0\bar{K}^{*0}$ to obtain two null tests of the SM, using the upper values on the two P_s^{GIM} contributions obtained from $B_d \rightarrow K^{*0}\bar{K}^0$ and $B_d \rightarrow K^0\bar{K}^{*0}$, respectively.

To summarize, we have proposed a new strategy to look for NP in $b \rightarrow s$ penguin decays without relying on model-dependent estimates of the hadronic uncertainties. The new *golden channel* we suggest is $B_s \rightarrow K^{(*)0}\bar{K}^{(*)0}$. We claim that the SM pollution in the null tests of the SM from time-dependent CP asymmetries in this *golden channel* can be controlled with a high accuracy in a model-independent way. The key observation is that, even allowing for SU(3) breaking effects of $\mathcal{O}(1)$, using the experimental information on the SU(3)-related channel $B_d \rightarrow K^{(*)0}\bar{K}^{(*)0}$ it is possible to put a strong constraint on the polluting CKM-suppressed penguin amplitude. The most promising channel seems to be $B_s \rightarrow K^{*0}\bar{K}^{*0}$, which can be reconstructed from four charged tracks in the final state and should be easily accessible at LHCb, together with the B_d decay to

the same final state (which can already be studied with the full dataset collected by *BABAR* and Belle). Pseudoscalar-vector and pseudoscalar-pseudoscalar final states imply the presence of K_S mesons, making the analysis harder in the environment of a hadron collider. In this respect, a super *B* factory would play a very important role.

Note added.—During the review process of our manuscript, the *BABAR* Collaboration published a first measurement of $\mathrm{BR}(B_d \rightarrow K^{*0}\bar{K}^{*0}) = (4.9^{+1.6}_{-1.3} \pm 0.5) \times 10^{-7}$, in agreement with the value we assumed, although with a large uncertainty [29].

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