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First hint of nonstandard *CP* violation from $B\to\phi K_S$ decay

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We comment on the implications of the recently measured CP asymmetry in $B\to\phi K_S$ decay. The data disfavor the standard model at 2.7σ and, if the trend persists in the future with higher statistics, require the existence of CP violation beyond that in the CKM matrix. In particular, the $b\to s\bar{s}s$ decay amplitude would require new contributions of comparable size to the standard model ones with an order one phase. While not every model can deliver such a large amount of CP and flavor violation, those with substantial FCNC couplings to the Z can reproduce the experimental findings.

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I. INTRODUCTION

The breakdown of CP symmetry in the b system has been established from measurements of time-dependent asymmetries in[1] $B\to J/\psi K$ decays [1,2]. In the standard model (SM) the phenomenon of CP violation originates from the Cabibbo-Kobayashi-Maskawa (CKM) three generation quark mixing matrix [3]. It is an impressive success of this CKM picture of CP and flavor violation that the world average of the asymmetry in $B\to J/\psi K$ decays [4],

$$\sin[2\beta(J/\psi K_{S,L})]_{world\text{-}ave}=+0.734\pm0.054, \quad (1)$$

agrees with the value extracted from experimental constraints from very different processes such as those in the kaon sector, $\sin[2\beta(J/\psi K)]_{fit}=+0.64\ldots+0.84$ at 95% Confidence level (C.L.) [5]. However, this CKM paradigm is now challenged by the recently reported measurements of CP asymmetries in $B\to\phi K_S$ decays by BaBar [6],

$$\sin[2\beta(\phi K_S)]_{BaBar}=-0.19^{+0.52}_{-0.50}\pm0.09 \quad (2)$$

and Belle [7],

$$\sin[2\beta(\phi K_S)]_{Belle}=-0.73\pm0.64\pm0.18, \quad (3)$$

with the resulting error weighted average

$$\sin[2\beta(\phi K_S)]_{ave}=-0.39\pm0.41 \quad (4)$$

with errors added in quadrature. The value in Eq. (3) corresponds to the coefficient of the sine term in the time-dependent CP asymmetry, see, e.g., [8]. Belle also quotes a value for the direct CP asymmetry, i.e., the cosine term $A_{\phi K_S}=-0.56\pm0.41\pm0.12$ [7], which is consistent with zero. In view of the current large experimental uncertainties, we neglect direct CP violating effects on the decay amplitudes in reporting the result of Eq. (4). With increasing precision they will become sensible and yield additional information [9].

In the SM the above decay modes are related such that the difference D_{CP} of their asymmetries obeys [10–13],

$$D_{CP}=|\sin[2\beta(\phi K)]-\sin[2\beta(J/\psi K)]|\lesssim O(\lambda^2), \quad (5)$$

where $\lambda\simeq0.2$ appears in Wolfenstein's parametrization of the CKM matrix. Evaluation of Eqs. (1) and (4) yields $D_{CP}=1.12\pm0.41$ and hence violates the SM at 2.7σ. The impact of these experimental results on the validity of CKM and SM is currently statistics limited. Future prospects at the B factories are that the statistical error $\sigma_{\phi K_S}(stat)$ can be expected to improve roughly by a factor of three with an increase of integrated luminosity from $0.1ab^{-1}$ to $1ab^{-1}$ [15] and it will take some time before we know D_{CP} with sufficient significance to draw final conclusions.

In the following we entertain the possibility of a would-be measurement of $\sin[2\beta(\phi K_S)]=-0.39$ or a similar value which departs drastically from the SM expectation of Eq. (5). We discuss the generic requirements to new physics (NP) models to explain these values in Sec. II. In Sec. III we work out and discuss the reach of specific models in the observable $\sin[2\beta(\phi K_{S,L})]$ and conclude in Sec. IV.

II. CONTRIBUTIONS TO $b\to s\bar{s}s$ FROM THE WEAK SCALE AND BEYOND

Time-dependent measurements in $B_0,\bar{B}_0$ decays into a CP eigenstate f such as $J/\psi K_S,\phi K_S$ return the value of $\sin[2\beta(f)]=\sin(2\beta_{eff}+\Delta\Phi_f)$. (As commented on in the Introduction, we fix $|\bar{A}/A|=1$ to first approximation.) Here, β_{eff} is the phase from $B_0-\bar{B}_0$ mixing and is common to all $B_0,\bar{B}_0\to f$ decays, and $\Delta\Phi_f\equiv\arg(\bar{A}/A)$ is the phase from the decay amplitudes. In the SM $\beta_{eff}=\beta$ and $\Delta\Phi_{J/\psi K}$ and $\Delta\Phi\equiv\Delta\Phi_{\phi K_S}\simeq O(\lambda^2)$ [10–14]. The "golden-plated" mode $B\to J/\psi K$ is mediated at the quark level by $b\to c\bar{c}s$ decay and receives a large contribution from the tree level W exchange. Hence, we expect $\Delta\Phi_{J/\psi K}$ to be subleading even in the presence of NP. On the other hand, the rare $B\to\phi K$ decay appears in the SM only at the loop level, see Fig. 1, and therefore is generically more susceptible to (new) physics from the weak and higher scales.

Measurements of $\sin[2\beta(\phi K_S)]$ and $\sin[2\beta(J/\psi K_S)]$ fix $\Delta\Phi$ up to a four-fold ambiguity and in general have eight

[1]Throughout this paper J/ψ stands for all $c\bar{c}$ states included in the experimental analyses for $\sin[2\beta(J/\psi K)]$.

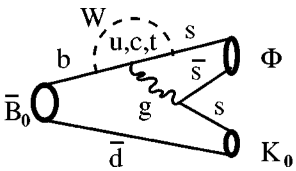

FIG. 1. SM diagram contributing to $B\to\phi K$ decay.

pairs $(\beta_{eff},\Delta\Phi)$ as solutions. For example, let us take the good O (10%) agreement between data on $\sin 2\beta[J/\psi K_{S,L}]$ and the SM fit for $\sin 2\beta$ as an indication that the value of β_{eff} extracted is in the same branch as the one from the SM fit, i.e. we assume that $b\to c\bar{c}s$ decays and B_0-$\bar{B}_0$ mixing are dominated by the SM contribution. (This concerns discrete ambiguities and barring accidental cancellations does not affect our conclusions about large phases in $b\to s\bar{s}s$ decays.) Then, $\beta_{eff}=24°$ and $\Delta\Phi=-70°,-204°$ using central values. This requires a large source of CP violation in the $b\to s\bar{s}s$ amplitude outside of the SM. We recall that there is no conflict with a small direct CP asymmetry as measured by BaBar $A_{CP}(B^{\pm}\to\phi K^{\pm})=-0.05\pm0.20\pm0.03$ [16]. While a large value for A_{CP} would unambiguously indicate the presence of NP, a small or vanishing one could be caused by small or vanishing strong phases.

Let us illustrate what kind of scales could be invoked for an interpretation of an $O(1)$ phase in the $b\to s\bar{s}s$ decay amplitude. The measured branching ratio $\mathcal{B}(B_0\to\phi K_0)=(8.1^{+3.1}_{-2.5}\pm0.8)\times10^{-6}$ [17] is in agreement with the SM assuming factorization [18], which has, however, substantial errors from hadronic physics. In the absence of a first principle precision calculation of hadronic two-body B decays into light mesons we will not perform here a detailed study of the $B\to\phi K$ matrix element. Instead we assume that $b\to s\bar{s}s$ decays proceeds via a single flavor changing neutral current (FCNC) operator with appropriate Dirac structures Γ_i,

$$O=\xi_F g_X^2\frac{\bar{s}\Gamma_1 b\bar{s}\Gamma_2 s}{M_X^2}, \tag{6}$$

generated from an interaction at scale M_X with coupling g_X and ξ_F contains all flavor mixing information. In the SM, X is the weak scale, i.e., $M_X=M_W$, $g_X=g_W$, and $\xi_F=V_{tb}V_{ts}^*$ contains the CKM angles. The operator contributes with the Wilson coefficient C_O renormalized at the $\sim m_b$ scale of size of a few times 10^{-2} [18,19]. The NP contribution to O has to be roughly of comparable size to the SM one to explain the observed $B_0\to\phi K_0$ branching ratio and has an order one CP phase in the overall mixing coefficient ξ_F to explain a large CP asymmetry induced by the $b\to s\bar{s}s$ decay amplitude.

Examples of contributions from physics beyond the SM to $b\to s\bar{s}s$ decays are shown in Fig. 2. The left diagram displays the effect of a new boson X in the FCNC loop with matter q_i in close analogy to the SM mechanism. If $g_X=g_W$, flavor angles $|\xi_F|=1$ and an $O(1)$ CP phase, and C_O is SM-like, then this requires $M_X\simeq400$ GeV to satisfy the conditions on size and CP breaking discussed above. Assuming a larger Wilson coefficient of order 1 requires $M_X\simeq2-3$ TeV. Another possibility is tree level FCNC at the weak scale, where $M_X=m_Z$, $g_X=g_W$, and $\xi_F=U_{bs}$. This is illustrated in the right diagram of Fig. 2. The sZb coupling has to be dominantly imaginary and satisfy $|U_{bs}|\simeq10^{-3}$ to be in the right place.

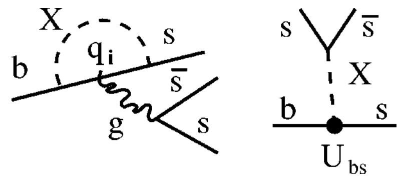

FIG. 2. Examples of contributions beyond the SM to $b\to s\bar{s}s$ decays.

III. WHICH NEW PHYSICS IN $B\to\phi K$?

In this section we examine the reach of different models in the phase of the $b\to s\bar{s}s$ decay amplitude. In particular we study the minimal supersymmetric standard model (MSSM), a variant of the two Higgs doublet model (2HDM) III which contains an extra source of CP violation and a model with a vectorlike down quark (VLDQ). The CP reach in $b\to s\bar{s}s$ is estimated using the effective Hamiltonian description and factorization [18,19]. While this latter approach contains model dependence it gives the right pattern in which NP enters the rare decays. Our findings are summarized in Table I. Only those models with $\Delta\Phi\sim O(1)$ are able to reproduce $\sin[2\beta(\phi K_S)]=-0.39$ or a value similarly different from $\sin[2\beta(J/\psi K_S)]$.

What is the explanation in supersymmetry (SUSY)? To depart significantly from the SM with $\Delta\Phi\lesssim O(\lambda^2)$ one has to go beyond the MSSM with minimal flavor violation (MFV), i.e., allow for more CP and flavor violation than the one present in the SM which is in the Yukawa couplings. Recall that gauge and anomaly mediation are MFV, whereas in general SUSY grand unified theories (GUTs) [20] and effective SUSY models [21,22] are not.

Allowing for arbitrary mixing in the down squark sector, the effect of gluino contributions in $b\to s\bar{s}s$ decay has been analyzed in Refs. [23–25]. As shown in [25], an order one NP contribution to the QCD penguins at the weak scale can give at most a 10% contribution at the scale $\mu\sim m_b$. By imposing experimental constraints from $b\to s\gamma$ a range $\Delta\Phi\lesssim0.7$ has been obtained [24]. A most important contribution in a generic MSSM without MFV stems from up squark mixing between the second and third generation which flips chirality, parametrized by δ^U_{23LR}. This parameter

TABLE I. Reach of the SM and models beyond in $\Delta\Phi=\arg(\bar{A}/A)$ in $b\to s\bar{s}s$ decays.

	SM, MSSM with MFV	Generic MSSM	2HDM III	VLDQ
$\lvert\Delta\Phi\rvert$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\lesssim0.2$	$\mathcal{O}(1)$

is essentially unconstrained $|\delta^U_{23LR}| \lesssim O(1)$, can be complex, and induces an effective sZb vertex $|Z_{sb}| \lesssim 0.1 |\delta^U_{23LR}|$ defined as [26,27]

$$\mathcal{L}_Z = \frac{g^2}{4\pi^2} \frac{g}{2\cos\theta_W} \bar{b}_L \gamma_\mu s_L Z_{sb}. \quad (7)$$

These Z penguins are constrained by $b \to s l^+ l^-$ decays $|Z_{sb}| \lesssim 0.1$ [26–29]. The contribution to $b \to \phi s$ is then $\propto (-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W)(g^2/4\pi^2) Z_{sb}$. If the penguins are sizable—indicating the presence of large, complex up squark mixing in the MSSM—they access values of $\Delta\Phi$ of $O(1)$. The effect of R-parity violating operators $\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$ is small because there are no tree level contributions to the $b \to s\bar{s}s$ operator (6) due to the symmetry properties of the superpotential [10].

We study the 2HDM III as an example of a NP scenario with an extended Higgs sector. The relevant model parameters are the charged Higgs boson mass and the "wrong" Higgs couplings of the third generation [we neglect all entries except the (3,3) one] and their relative phase. This new CP phase enters predominantly the dipole operators such as the one with a gluon $O_8 \simeq \bar{s} \sigma_{\mu\nu} b G^{\mu\nu}$, see [30] for details. This operator contributes to the $b \to s\bar{s}s$ amplitude, though in the SM at a subleading level compared to the QCD penguin diagrams, e.g., [24]. The 2HDM III model is constrained by nonobservation of the charged Higgs boson $m_{H^\pm} > 80$ GeV, the $b \to s\gamma$ branching ratio, B_0-$\bar{B}_0$ mixing, the ρ parameter, and the neutron electric dipole moment. We scan over the allowed parameter space and obtain $\Delta\Phi \lesssim 0.2$.

A simple model beyond the SM with an enlarged matter sector is the one with an additional vectorlike down quark D_4. The (3×4) dimensional extended CKM matrix V includes mixing between D_4 and the SM quark doublets and causes tree level FCNC couplings to the Z [31]. These are given as $U_{bs} = -V^d_{b4} V^{d*}_{s4}$ for $b \to s$ transitions, where V^d diagonalizes the down sector. This gives also the amount of CKM unitarity violation $U_{bs} = \Sigma_{i=u,c,t} V^*_{ib} V_{is}$ which vanishes in the SM. Following the discussion for the SUSY models with Z penguins, we relate $U_{bs} = -g^2/(4\pi^2) Z_{sb}$ and get $|U_{bs}| \lesssim 10^{-3}$, slightly better than the bound from [32]. The reach of the VLDQ model in $\Delta\Phi$ is $O(1)$ in agreement with the estimates at the end of Sec. II.

IV. CONCLUDING REMARKS

We have examined the implications of the experimental results [6,7] on CP violation from interference between mixing and decay in $B \to \phi K_s$ decays. These data are in conflict with the SM at 2.7σ *and* with many NP scenarios without $\Delta\Phi$ of $O(1)$, as compiled in Table I, such as the MSSM with MFV. As we find, models with sizable and complex sZb couplings do have the required CP reach in $b \to s\bar{s}s$ decays. Note that anomalous couplings generically lead to large effects in the sZb vertex [33]. The Z penguins contribute also to $b \to s\ell^+\ell^-$ decays, $b \to s\nu\bar{\nu}$ decays, and B_s-$\bar{B}_s$ mixing [26].

A new CP violating NP contribution to the operator (6) will leak into other decays such as $B \to K\eta, K\eta'$ which do have a $s\bar{s}$ admixture. Belle reported for the time-dependent asymmetry parameters $\sin[2\beta(\eta' K_S)] = 0.76 \pm 0.36^{+0.05}_{-0.06}$ and $A_{\eta' K_S} = +0.26 \pm 0.22 \pm 0.03$ [34,7]. Because of the anomalously large branching ratio of $B \to (K, X_s)\eta'$ decays [18,35] the effect of NP in the $(\bar{s}b)(\bar{s}s)$ vertex can be diluted in these channels by an enhanced SM contribution. Hence, it is conceivable that $\sin[2\beta(\eta' K_S)]$ is closer to $\sin[2\beta(J/\psi K_S)]$ than $\sin[2\beta(\phi K_S)]$ in agreement with the data and the hypothesis of sizable NP in $B \to \phi K_S$ decays. There might be as well already NP in the CP asymmetry in $B \to J/\psi K_{S,L}$ decays (1). Excluding the possibility that NP in $b \to c\bar{c}s$ and/or B_0-$\bar{B}_0$ mixing conspires such that the fit β lives on a different branch than β_{eff}, this effect is at the 10% level. Since $\mathcal{B}(B \to \phi K)/\mathcal{B}(B \to J/\psi K) \simeq 10^{-2}$ [17] and assuming approximate flavor universality an order one NP contribution to $B \to \phi K_S$ is roughly a 10% correction to $B \to J/\psi K$, which is within the errors. Sensitivity to NP from measuring β in different decays is limited by the error on $\sin 2\beta_{fit}$, which can be improved if the error on $|V_{ub}|$ decreases and the SM background from $b \to u\bar{u}s$ contributions to $B \to \phi K$, which has been suggested to bound by $SU(3)$ analysis [13].

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