Searching for new physics in nonleptonic B decays

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We present allowed regions in the space of observables of certain nonleptonic B-meson decays that characterize these modes within the standard model. A future measurement of observables lying significantly outside of these regions would indicate the presence of new physics. Making use of $SU(3)$ arguments, we give the range for $B\to\pi K$ decays, and for the system of $B_d\to\pi^+\pi^-$, $B_s\to K^+K^-$ modes.

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As is well known, the B-meson system provides a very fertile testing ground for the standard-model description of CP violation, where this phenomenon originates from a complex phase in the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix). In order to search for new physics, one of the main methods is to overconstrain the three angles α, β and γ of the usual nonsquashed unitarity triangle of the CKM matrix, thereby searching for possible discrepancies. During recent years, many interesting strategies have been proposed to accomplish this task [1].

In this paper, we propose a simple approach, which offers the exciting possibility of immediate indications of new physics at future B-decay experiments. It relies on the fact that certain nonleptonic B-meson decays into two light pseudoscalar mesons can be characterized, within the standard model (SM), by regions arising in the space of the corresponding observables. If future measurements of these observables should result in values lying significantly outside of these regions, we would have an indication for the presence of new physics.

We show these regions for two different combinations of $B\to\pi K$ modes [2–5], as well as for the system of $B_d\to\pi^+\pi^-$ and $B_s\to K^+K^-$ decays [6]. In order to evaluate them, we have to make use of $SU(3)$ flavor-symmetry arguments in both cases. In the $B\to\pi K$ case, which is very promising for e^+–e^- B-factories, an additional dynamical assumption concerning final-state-interaction (FSI) effects has to be made [7]. This is not necessary in the $B_d\to\pi^+\pi^-$, $B_s\to K^+K^-$ system, which is ideally suited for "second-generation" B-physics experiments at hadron machines, such as LHCb or BTeV. Since flavor-changing neutral-current "penguin" processes play an important role in $B\to\pi K$, $B_d\to\pi^+\pi^-$ and $B_s\to K^+K^-$ decays, they may well be affected by new physics [5,8,9]. Moreover, the unitarity of the CKM matrix is used to evaluate the corresponding allowed regions.

Let us turn to the $B\to\pi K$ system first, which already allows us to confront the contours in the space of observables with experimental data from the CLEO Collaboration [10]. We will consider two different combinations of $B\to\pi K$ decays: the charged modes $B^\pm\to\pi^\pm K$ and $B^\pm\to\pi^0K^\pm$ [2,4,5], and the "mixed" combination $B^\pm\to\pi^\pm K$, $B_d\to\pi^\mp K^\pm$ [3]. Within the SM, we have

$$P\equiv A(B^+\to\pi^+K^0)\propto[1+\rho e^{i\vartheta}e^{i\gamma}]\mathcal{P}_{tc}, \tag{1}$$

where

$$\rho e^{i\vartheta}=\frac{\lambda^2R_b}{1-\lambda^2/2}\left[1-\left(\frac{\mathcal{P}_{uc}+\mathcal{A}}{\mathcal{P}_{tc}}\right)\right], \tag{2}$$

with $\lambda\equiv|V_{us}|=0.22$, $A\equiv|V_{cb}|/\lambda^2=0.81\pm0.06$ and $R_b\equiv|V_{ub}/(\lambda V_{cb})|=0.41\pm0.07$. The amplitudes $\mathcal{A}$ and $\mathcal{P}_{tc}\equiv|\mathcal{P}_{tc}|e^{i\delta_{tc}}$ ($\mathcal{P}_{uc}$) are due to annihilation and penguin topologies with internal top- and charm-quark (up- and charm-quark) exchanges, respectively. The $SU(2)$ isospin symmetry of strong interactions implies

$$A(B^+\to\pi^+K^0)+\sqrt{2}A(B^+\to\pi^0K^+)=-[(T+C)+P_{\rm ew}], \tag{3}$$

where the amplitudes

$$T+C\equiv|T+C|e^{i\delta_{T+C}}e^{i\gamma}\ \text{and}\ P_{\rm ew}=-|P_{\rm ew}|e^{i\delta_{\rm ew}} \tag{4}$$

arise from current–current and electroweak penguin operators, respectively (the δs denote strong phases). The $SU(3)$ flavor symmetry of strong interactions allows us to fix $|T+C|$ with the help of the decay $B^+\to\pi^+\pi^0$ [2]:

$$T+C=-\sqrt{2}\,\frac{V_{us}}{V_{ud}}\,\frac{f_K}{f_\pi}A(B^+\to\pi^+\pi^0), \tag{5}$$

where the kaon and pion decay constants take into account factorizable $SU(3)$-breaking corrections. Moreover, we have in the strict $SU(3)$ limit [4]

$$\left|\frac{P_{\rm ew}}{T+C}\right|e^{i(\delta_{\rm ew}-\delta_{T+C})}=0.66\times\left[\frac{0.41}{R_b}\right]. \tag{6}$$

The factorizable $SU(3)$-breaking corrections to this relation are very small, and its theoretical accuracy is only limited by nonfactorizable effects. In a recent paper [11], an interesting approach making use of a heavy-quark expansion for nonleptonic B decays was proposed that could help to reduce these uncertainties.

The decays $B^+\to\pi^+K^0$ and $B^+\to\pi^0K^+$ provide the following observables:

$$R_{\rm c}\equiv2\left[\frac{{\rm BR}(B^+\to\pi^0K^+)+{\rm BR}(B^-\to\pi^0K^-)}{{\rm BR}(B^+\to\pi^+K^0)+{\rm BR}(B^-\to\pi^-\overline{K^0})}\right] \tag{7}$$

$$A_0^{\mathrm{c}} \equiv 2\left[\frac{\mathrm{BR}(B^+\to\pi^0K^+)-\mathrm{BR}(B^-\to\pi^0K^-)}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\overline{K^0})}\right], \quad (8)$$

where the factor of 2 has been introduced to absorb the normalization factor of the π^0. The present CLEO data imply $R_{\mathrm{c}}=1.3\pm0.5$ [10]; very recently, also the first results for CP-violating asymmetries in charmless hadronic B-meson decays were reported, leading to $A_0^{\mathrm{c}}=0.35\pm0.34$.

In order to parametrize R_{c} and A_0^{c}, it is useful to introduce

$$r_{\mathrm{c}} \equiv \frac{|T+C|}{\sqrt{\langle|P|^2\rangle}}, \quad qe^{i\omega} \equiv \left|\frac{P_{\mathrm{ew}}}{T+C}\right| e^{i(\delta_{\mathrm{ew}}-\delta_{T+C})}. \quad (9)$$

The general expressions for R_{c} and A_0^{c} in terms of these parameters and $\rho e^{i\vartheta}$ can be found in [12]. Here we restrict ourselves, for simplicity, to the case of $\rho=0$, corresponding to the neglect of rescattering processes [7], and to $\omega=0$, corresponding to Eq. (6). Then we obtain

$$R_{\mathrm{c}}=1-2r_{\mathrm{c}}(\cos\gamma-q)\cos\delta_{\mathrm{c}}+v^2r_{\mathrm{c}}^2 \quad (10)$$

$$A_0^{\mathrm{c}}=2r_{\mathrm{c}}\sin\delta_{\mathrm{c}}\sin\gamma, \quad (11)$$

where $\delta_{\mathrm{c}}\equiv\delta_{T+C}-\delta_{tc}$ and $v\equiv\sqrt{1-2q\cos\gamma+q^2}$. Since r_{c} and q can be fixed through Eqs. (5) and (6), respectively, the two observables R_{c} and A_0^{c} depend on the two ''unknowns'' δ_{c} and γ. Consequently, if we fix r_{c} and q—present data give $r_{\mathrm{c}}=0.21\pm0.06$ and $q=0.63\pm0.15$—and vary δ_{c} and γ within $[0°,360°]$, Eqs. (10) and (11) imply an allowed region in the R_{c}-A_0^{c} plane.

In Fig. 1, we show this region for the currently allowed values of the parameters r_{c} and q. The small dependence on the latter parameter [see Fig. 1(b)] is due to the suppression through r_{c} in Eq. (10). A similar suppression is also effective for the terms of $\mathcal{O}(\rho)$ in R_{c}, which are related to FSI effects. If we use the observable

$$B_0^{\mathrm{c}} \equiv A_0^{\mathrm{c}}-\left[\frac{\mathrm{BR}(B^+\to\pi^+K^0)-\mathrm{BR}(B^-\to\pi^-\overline{K^0})}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\overline{K^0})}\right] \quad (12)$$

instead of A_0^{c}, the terms of $\mathcal{O}(\rho)$ are suppressed by r_{c} as well, as was also noted in Ref. [5]. In the case of Fig. 1, the FSI effects are neglected, leading to $B_0^{\mathrm{c}}=A_0^{\mathrm{c}}$. If we choose $r_c=0.21$, $q=0.63$, and assume that $\rho=0.15$, which would correspond to very large rescattering effects, while keeping $\vartheta\in[0°,360°]$ as a free parameter, we obtain the allowed region shown in Fig. 2. This figure shows nicely that the impact of FSI effects on the allowed region in the R_{c}-B_0^{c} plane is very small. Let us nevertheless note that the FSI effects can be probed—and in principle even included in Fig. 1—with the help of additional experimental data [12,13], for example on $B^\pm\to K^\pm K$ modes.

The dotted range in Fig. 1 corresponds to the present CLEO results for R_{c} and A_0^{c}. If future measurements of R_{c} and A_0^{c} should give values lying significantly outside the allowed region shown in Fig. 1, we would have an indication for new physics. On the other hand, if we should find values lying inside this region, this would not automatically imply a ''confirmation'' of the SM. In this case, it would be possible to extract a value of γ by following the strategies proposed in [4,12], which may well lead to discrepancies with the values of γ that are implied by theoretically clean strategies, using pure ''tree'' decays, such as $B\to DK$ or $B_s\to D_s^\mp K^\pm$, or by the usual ''indirect'' fits of the unitarity triangle. In a recent paper [9], several specific models were employed to explore the impact of new physics on $B\to\pi K$ decays. For example, in models with an extra Z' boson or in SUSY models with broken R-parity, the resulting electroweak penguin coefficients can be much larger than in the SM, since they arise already at the tree level. In this paper, it is not our

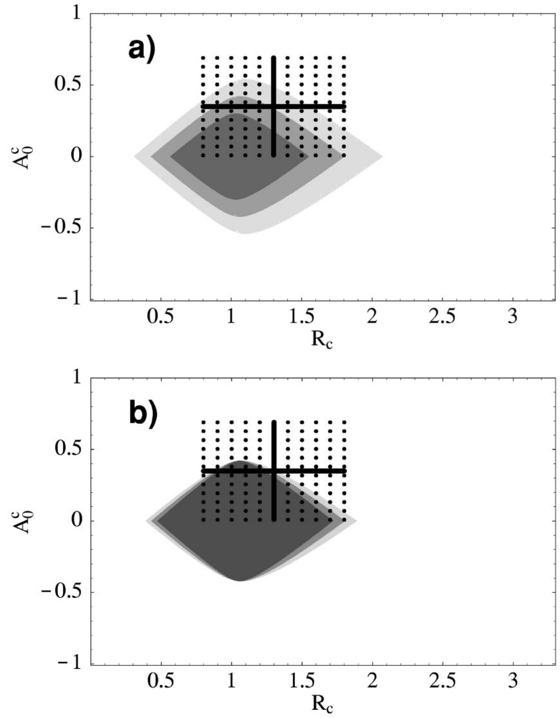

FIG. 1. Allowed region in the R_{c}-A_0^{c} plane, characterizing $B^\pm\to\pi^\pm K$, $\pi^0K^\pm$ in the SM: (a) $0.15\leq r_{\mathrm{c}}\leq0.27$, $q=0.63$; (b) $r_{\mathrm{c}}=0.21$, $0.48\leq q\leq0.78$. FSI effects are neglected.

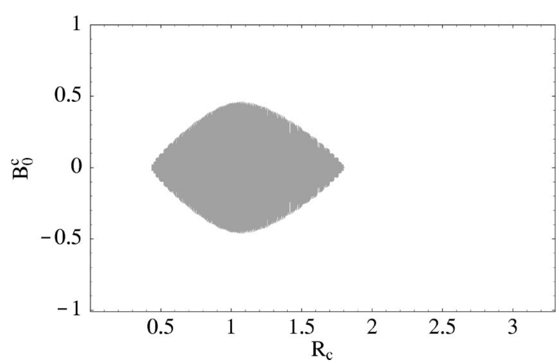

FIG. 2. Allowed region in the R_{c}-B_0^{c} plane, characterizing $B^\pm\to\pi^\pm K$, $\pi^0K^\pm$ in the SM in the presence of large FSI effects, which are described by $\rho=0.15$ ($r_{\mathrm{c}}=0.21$, $q=0.63$).

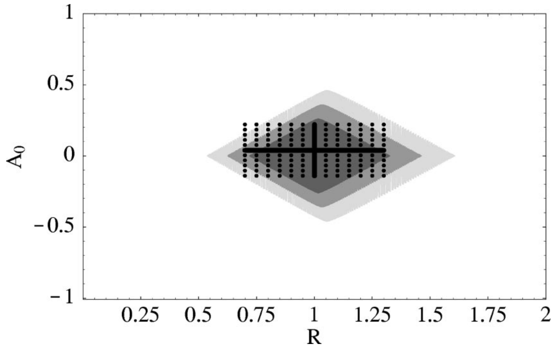

FIG. 3. Allowed region in the R-A_0 plane, characterizing $B^\pm\to\pi^\pm K$, $B_d\to\pi^\mp K^\pm$ within the SM for $0.13\leqslant r\leqslant 0.23$, $q_C e^{i\omega_C}=0.66\times 0.25$. FSI effects are neglected.

purpose to consider specific models for new physics. However, we plan to come back to this issue in a forthcoming publication.

In Fig. 3, we show the allowed region for the observables of the $B^\pm\to\pi^\pm K$, $B_d\to\pi^\mp K^\pm$ system [3], where R and A_0 correspond to R_c and A_0^c, respectively; explicit expressions can be found in [12], where also the parameters r and $q_C e^{i\omega_C}$ are defined properly. The latter describes ''color-suppressed'' electroweak penguin diagrams, which are usually expected to play a minor role [14]. In contrast to the charged case, r and $q_C e^{i\omega_C}$ cannot be fixed by using only flavor-symmetry arguments. To this end, we have to employ, in addition, certain dynamical assumptions, such as arguments involving the ''factorization'' hypothesis, and have to keep in mind that the parameters thus determined may also be affected by FSI effects, which have been neglected in Fig. 3. However, there are important experimental indicators for such rescattering processes, for example the branching ratios of $B\to KK$ modes or a sizeable direct CP asymmetry in $B^\pm\to\pi^\pm K$. In order to reduce these uncertainties, also the approach proposed in Ref. [11] may turn out to be very useful. The dotted range in Fig. 3 represents the present CLEO results $R=1.0\pm 0.3$ and $A_0=0.04\pm 0.18$, which coincides perfectly with the allowed region implied by the SM. This feature should be compared with the situation in Fig. 1. Unfortunately, the present experimental uncertainties are too large to speculate on new-physics effects. However, the experimental situation should improve considerably in the next couple of years.

Let us now focus on the decays $B_d\to\pi^+\pi^-$ and $B_s\to K^+K^-$. The latter mode is not accessible at the e^+–e^- B-factories operating at the $\Upsilon(4S)$ resonance, but is very promising for ''second-generation'' B-decay experiments at hadron machines. From a theoretical point of view, the $B_d\to\pi^+\pi^-$, $B_s\to K^+K^-$ system has some advantages in comparison with the $B\to\pi K$ approach, as we will see below. Within the SM, the $B_d^0\to\pi^+\pi^-$ decay amplitude can be parametrized, in a completely general way, as follows [6]:

$$A(B_d^0\to\pi^+\pi^-)\propto e^{i\gamma}[1-de^{i\theta}e^{-i\gamma}], \tag{13}$$

where the parameter

$$de^{i\theta}\equiv\frac{1}{(1-\lambda^2/2)R_b}\left(\frac{A_{\text{pen}}^{ct}}{A_{\text{cc}}^{u}+A_{\text{pen}}^{ut}}\right) \tag{14}$$

describes—sloppily speaking—the ratio of ''penguin'' to ''tree'' contributions. Employing a notation similar to that in Eq. (13) yields

$$A(B_s^0\to K^+K^-)\propto e^{i\gamma}\left[1+\frac{1}{\epsilon}d'e^{i\theta'}e^{-i\gamma}\right], \tag{15}$$

where $d'e^{i\theta'}$ corresponds to Eq. (14), and $\epsilon\equiv\lambda^2/(1-\lambda^2)$. The time evolution of the decay $B_s\to K^+K^-$ provides the following time-dependent CP asymmetry:

$$a_{CP}(t)\equiv\frac{\Gamma(B_s^0(t)\to f)-\Gamma(\overline{B_s^0}(t)\to f)}{\Gamma(B_s^0(t)\to f)+\Gamma(\overline{B_s^0}(t)\to f)}=\frac{2e^{-\Gamma_s t}[\mathcal{A}_{CP}^{\text{dir}}\cos(\Delta M_s t)+\mathcal{A}_{CP}^{\text{mix}}\sin(\Delta M_s t)]}{e^{-\Gamma_{\text{H}}^{(s)}t}+e^{-\Gamma_{\text{L}}^{(s)}t}+\mathcal{A}_{\Delta\Gamma}(e^{-\Gamma_{\text{H}}^{(s)}t}-e^{-\Gamma_{\text{L}}^{(s)}t})}, \tag{16}$$

where $\mathcal{A}_{CP}^{\text{dir}}$, $\mathcal{A}_{CP}^{\text{mix}}$ and $\mathcal{A}_{\Delta\Gamma}$ satisfy the relation

$$(\mathcal{A}_{CP}^{\text{dir}})^2+(\mathcal{A}_{CP}^{\text{mix}})^2+(\mathcal{A}_{\Delta\Gamma})^2=1. \tag{17}$$

Using (15), we obtain [6]

$$\mathcal{A}_{CP}^{\text{dir}}(B_s\to K^+K^-)=\frac{2\tilde{d}'\sin\theta'\sin\gamma}{1+2\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2} \tag{18}$$

$$\mathcal{A}_{CP}^{\text{mix}}(B_s\to K^+K^-)=\frac{\sin(\phi_s+2\gamma)+2\tilde{d}'\cos\theta'\sin(\phi_s+\gamma)+\tilde{d}'^2\sin\phi_s}{1+2\tilde{d}'\cos\theta'\cos\gamma+\tilde{d}'^2}, \tag{19}$$

where $\tilde{d}'\equiv d'/\epsilon$, and $\phi_s\equiv -2\delta\gamma=2\arg(V_{ts}^*V_{tb})$ denotes the B_s^0-$\overline{B_s^0}$ mixing phase. Within the SM, we have $2\delta\gamma\approx 0.03$ due to a Cabibbo suppression of $\mathcal{O}(\lambda^2)$, implying that ϕ_s is very small.

The expression for the time-dependent $B_d \to \pi^+\pi^-$ CP asymmetry simplifies considerably, since the width difference $\Delta\Gamma_d \equiv \Gamma_{\rm H}^{(d)} - \Gamma_{\rm L}^{(d)}$ between the B_d mass eigenstates is—in contrast to the expected situation in the B_s system—negligibly small. Using Eq. (13), the corresponding CP-violating observables can be expressed as [6]

$$\mathcal{A}_{CP}^{\rm dir}(B_d \to \pi^+\pi^-) = -\left[\frac{2d\sin\theta\sin\gamma}{1-2d\cos\theta\cos\gamma+d^2}\right] \tag{20}$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d \to \pi^+\pi^-) = \frac{\sin(\phi_d+2\gamma)-2d\cos\theta\sin(\phi_d+\gamma)+d^2\sin\phi_d}{1-2d\cos\theta\cos\gamma+d^2}, \tag{21}$$

where $\phi_d = 2\beta$ denotes the B_d^0-$\overline{B_d^0}$ mixing phase. It should be emphasized that Eqs. (18),(19) and Eqs. (20),(21) are completely general parametrizations within the SM, taking also into account all kinds of penguin and FSI effects.

Since the decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other by interchanging all strange and down quarks, the U-spin flavor symmetry implies

$$d' e^{i\theta'} = d e^{i\theta}. \tag{22}$$

Interestingly, this relation is not affected by U-spin-breaking corrections within a modernized version of the ''Bander-Silverman-Soni'' mechanism [15], which relies—among other things—also on the ''factorization'' hypothesis [6]. Consequently, unless nonfactorizable effects should have a dramatic impact, the U-spin-breaking corrections to Eq. (22) are probably moderate. We are optimistic that future B-decay experiments will also provide valuable insights into $SU(3)$-breaking effects. Moreover, further work along the lines of Ref. [11] may lead to a better theoretical understanding of these effects.

If we use the U-spin relation (22), the three observables $A_s^{\rm d} \equiv \mathcal{A}_{CP}^{\rm dir}(B_s \to K^+K^-)$, $A_s^{\rm m} \equiv \mathcal{A}_{CP}^{\rm mix}(B_s \to K^+K^-)$ and $A_d^{\rm d} \equiv \mathcal{A}_{CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ depend on the two hadronic parameters d and θ, as well as on the CKM angle γ and the B_s^0-$\overline{B_s^0}$ mixing phase ϕ_s. However, the latter quantity is negligibly small in the SM, i.e., $\phi_s^{\rm SM} \approx 0$. Consequently, if we keep d as a free parameter, i.e., $0 \leqslant d \leqslant \infty$, and vary θ and γ in the interval $[0°,360°]$, Eqs. (18), (19) and (20) fix a three-dimensional region in the space of the observables $A_s^{\rm d}$, $A_s^{\rm m}$ and $A_d^{\rm d}$, characterizing the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ system within the SM. This region is shown in Fig. 4, where the circles with radius 1 fix a cylinder in the $A_d^{\rm d}$ direction, which is due to Eq. (17), implying $(A_s^{\rm d})^2 + (A_s^{\rm m})^2 \leqslant 1$. An interesting feature of the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ predicted region is a hole, which allows for new physics also inside the volume. If one restricts the penguin parameter d to be smaller than 1, which seems to be quite plausible, this hole would be enlarged. It is also interesting to note that the U-spin flavor symmetry implies, within the SM, that the direct CP asymmetries of $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$ have opposite signs; equal signs would be an indication for new physics. In contrast to the $B \to \pi K$ case, we do not have to worry about any FSI effects in the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ system, and no additional information is required to fix certain parameters such as $r_{\rm c}$ or q.

A future measurement of observables lying significantly outside of the region shown in Fig. 4 would be an indication of new physics. Such a discrepancy could either be due to CP-violating new-physics contributions to B_s^0-$\overline{B_s^0}$ mixing, or to the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ decay amplitudes. The former case would also be indicated simultaneously by large CP-violating effects in the mode $B_s \to J/\psi\phi$, which would allow us to extract the B_s^0-$\overline{B_s^0}$ mixing phase ϕ_s (see, for example, [16]). A discrepancy between the measured $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ observables and the region corresponding to the value of ϕ_s thus determined would then signal new-physics contributions to the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ decay amplitudes. On the other hand, if $B_s \to J/\psi\phi$ should exhibit negligible CP-violating effects, any discrepancy between the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ observables and the volume shown in Fig. 4 would indicate new-physics contributions to the corresponding decay amplitudes. On the other hand, if the observables should lie within the

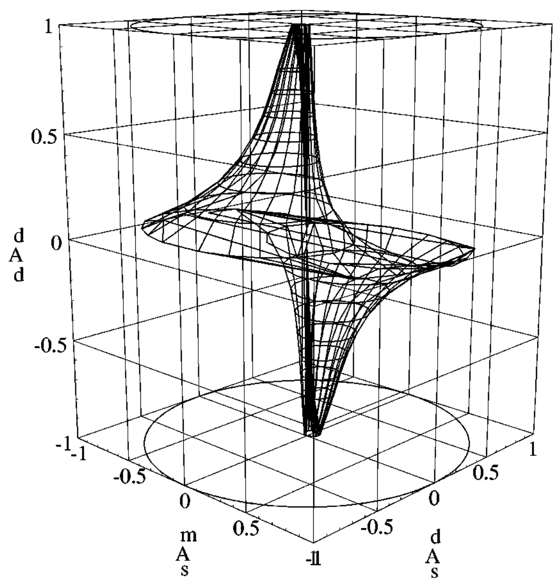

FIG. 4. The allowed region in the space of the CP asymmetries $A_s^{\rm d} \equiv \mathcal{A}_{CP}^{\rm dir}(B_s \to K^+K^-)$, $A_s^{\rm m} \equiv \mathcal{A}_{CP}^{\rm mix}(B_s \to K^+K^-)$ and $A_d^{\rm d} \equiv \mathcal{A}_{CP}^{\rm dir}(B_d \to \pi^+\pi^-)$, which characterize the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ system within the SM ($\phi_s = 0$).

SM predicted region, we can extract a value for the CKM angle γ by following the strategy presented in [6], which may well be in disagreement with those implied by theoretically clean strategies making use of pure ''tree'' decays, thereby also indicating the presence of new physics.

If we use the B_d^0-$\overline{B_d^0}$ mixing phase ϕ_d, which can be determined, for instance, with the help of the ''gold-plated'' mode $B_d\to J/\psi K_S$, as an additional input, we may also fix a three-dimensional region in the space of the observables $\mathcal{A}_{CP}^{\rm dir}(B_d\to\pi^+\pi^-)$, $\mathcal{A}_{CP}^{\rm mix}(B_d\to\pi^+\pi^-)$ and $\mathcal{A}_{CP}^{\rm dir}(B_s\to K^+K^-)$ through the standard-model expressions (18), (20) and (21). Since the decays $B_s\to K^+K^-$ and $B_d\to\pi^{\mp}K^{\pm}$ differ only in their spectator quarks, we have $\mathcal{A}_{CP}^{\rm dir}(B_s\to K^+K^-)\approx\mathcal{A}_{CP}^{\rm dir}(B_d\to\pi^{\mp}K^{\pm})$. Consequently, that figure would also be interesting for the e^+-e^- B-factories, where $B_s\to K^+K^-$ is not accessible. However, we should keep it in mind that this relation relies not only on flavor-symmetry arguments, but also on a certain dynamical input concerning ''exchange'' and ''penguin annihilation'' topologies [6], which may be enhanced in the presence of large FSI effects.

To summarize, we have presented a simple strategy, which may provide immediate indications for new physics at future B-decay experiments. We plan to discuss in more detail several of the features described briefly here in a forthcoming paper.

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