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On puzzles and non-puzzles in $B \to \pi\pi, \pi K$ decays

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Abstract. Recently, we have seen interesting progress in the exploration of CP violation in $B_d^0 \to \pi^+\pi^-$: the measurements of mixing-induced CP violation by the BaBar and Belle collaborations are now in good agreement with each other, whereas the picture of direct CP violation is still unclear. Using the branching ratio and direct CP asymmetry of $B_d^0 \to \pi^- K^+$, this situation can be clarified. We predict $\mathcal{A}_{CP}^{\rm dir}(B_d \to \pi^+\pi^-) = -0.24 \pm 0.04$, which favours the BaBar result, and we extract $\gamma = \left(70.0^{+3.8}_{-4.3}\right)^\circ$, which agrees with the unitarity triangle fits. Extending our analysis to other $B \to \pi K$ modes and $B_s^0 \to K^+ K^-$ with the help of the SU(3) flavour symmetry and plausible dynamical assumptions, we find that all observables with colour-suppressed electroweak penguin contributions are measured to be in excellent agreement with the standard model. As far as the ratios $R_{\rm c,n}$ of the charged and neutral $B \to \pi K$ branching ratios are concerned, which are sizeably affected by electroweak penguin contributions, our standard-model predictions have almost unchanged central values but significantly reduced errors. Since the new data have moved quite a bit towards these results, the "$B \to \pi K$ puzzle" for the CP conserving quantities has been significantly reduced. However, the mixing-induced CP violation of $B_d^0 \to \pi^0 K_{\rm S}$ does look puzzling; if confirmed by future measurements, this effect could be accommodated through a modified electroweak penguin sector with a large CP violating new-physics phase. Finally, we point out that the established difference between the direct CP asymmetries of $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^\mp K^\pm$ appears to be generated by hadronic and not by new physics.

1 Introduction

Since many years, the $B \to \pi\pi, \pi K$ system has received a lot of attention in the B-physics community (for a review, see [1]). Thanks to the interplay between theory and B-factory data, valuable new insights into the physics of these modes could be obtained, raising also the question of having an electroweak (EW) penguin sector that is modified by the presence of CP violating new-physics (NP) contributions [2–8]. In this paper, we shall perform an analysis of the $B \to \pi\pi, \pi K$ modes in the spirit of the strategy developed in [9–11], and we will, in particular, address the new data that were reported by the B-factory experiments BaBar (SLAC) and Belle (KEK) in the summer of 2006. The corresponding working assumptions for the treatment of the hadronic $B \to \pi\pi, \pi K$ sector can be summarised as follows:

i) SU(3) *flavour symmetry:* SU(3)-breaking effects are, however, included through the ratios of decay constants and form factors whenever they arise, and the sensitivity of the numerical results on non-factorizable SU(3)-breaking effects is explored;

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ii) *neglect of the penguin annihilation and exchange topologies:* these contributions can be probed and controlled through the $B_d \to K^+ K^-$, $B_s \to \pi^+\pi^-$ system [9, 10, 12], which can be fully exploited at the LHCb (CERN) experiment.

The data support these hypotheses, as all consistency checks that can currently be performed do not indicate any anomalous behaviour. The following analysis is essentially a study within the standard model (SM), with the goal to perform tests of the Kobayashi–Maskawa (KM) mechanism of CP violation [13]. However, also the effects of NP can straightforwardly be explored if we assume that it manifests itself only in the EW penguin sector. This scenario was, on the one hand, driven by the comparison of the B-factory data for the $B \to \pi K$ observables with their SM predictions. On the other hand, such a kind of physics beyond the SM can also be accommodated in various specific frameworks, including supersymmetry, models with extra Z' bosons, and scenarios with extra dimensions.

The outline of this paper is as follows: the starting point of our analysis, the $B \to \pi\pi$ system, is discussed in Sect. 2. In Sect. 3, we then move on to the $B \to \pi K$ decays. Finally, our main conclusions and a brief outlook are given in Sect. 4.

2 The $B \to \pi\pi$ system

The system of $B \to \pi\pi$ decays consists of the decays $B_d^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ and $B_d^0 \to \pi^0\pi^0$, and their charge conjugates. As is well known, the corresponding decay amplitudes can be related to one another with the help of the SU(2) isospin symmetry [14], which allows us also to take the effects of EW penguin topologies into account [15,16]. We shall come back to this feature below.

2.1 CP violation in $B_d^0 \to \pi^+\pi^-$

Let us first have a closer look at CP violation in the $B_d^0 \to \pi^+\pi^-$ channel, which receives contributions from tree and penguin diagrams in the SM. The corresponding decay amplitude can be written in the following form [17,18]:

$$A(B_d^0 \to \pi^+\pi^-) = -|\tilde{T}|e^{i\delta_{\tilde{T}}} \left[e^{i\gamma} - d e^{i\theta} \right] , \qquad (1)$$

where the $\tilde{T}$ amplitude is governed by the colour-allowed tree topologies, γ is the usual angle of the unitarity triangle, and the CP conserving hadronic parameter $d e^{i\theta}$ describes – sloppily speaking – the ratio of penguin to tree contributions. The interference between the different weak amplitudes in (1) leads to a *direct CP* asymmetry $\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-)$, whereas the interference between B_d^0–$\bar{B}_d^0$ mixing and the $B_d^0, \bar{B}_d^0 \to \pi^+\pi^-$ decay processes generates a *mixing-induced CP* asymmetry $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^+\pi^-)$. These observables enter the following time-dependent CP asymmetry [1]:

$$\frac{\Gamma(B_d^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}{\Gamma(B_d^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}$$
$$= \mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) \cos(\Delta M_d t)$$
$$+ \mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) \sin(\Delta M_d t) . \qquad (2)$$

As in [9–11], we shall use a sign convention similar to that of (2) also for self-tagging neutral B_d and charged B decays.[1]

Concerning the measurement of CP violation in $B_d^0 \to \pi^+\pi^-$, there has been interesting recent progress. There is now – for the first time – nice agreement between the BaBar and Belle results for the mixing-induced CP asymmetry:

$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) = \begin{cases} 0.53 \pm 0.14 \pm 0.02 \ (\text{BaBar [20]}) \\ 0.61 \pm 0.10 \pm 0.04 \ (\text{Belle [21]}) , \end{cases}$$
$$(3)$$

which yields the average of $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) = 0.59 \pm 0.09$ [19]. On the other hand, the picture of direct CP violation is still *not* settled:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = \begin{cases} -0.16 \pm 0.11 \pm 0.03 \ (\text{BaBar [20]}) , \\ -0.55 \pm 0.08 \pm 0.05 \ (\text{Belle [21]}) . \end{cases}$$
$$(4)$$

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[1] Our definition of $\mathcal{A}_{CP}^{\mathrm{dir}}$ coincides with $C_{CP} = -A_{CP}$, but our $\mathcal{A}_{CP}^{\mathrm{mix}}$ differs in sign from S_{CP} [19].

2.2 Clarifying the picture through $B_d^0 \to \pi^- K^+$

This unsatisfactory situation can be resolved with the help of the $B_d^0 \to \pi^- K^+$ mode, which receives – in analogy to the $B_d^0 \to \pi^+\pi^-$ channel – also contributions from the tree and penguin topologies. However, since $B_d^0 \to \pi^- K^+$ is caused by $\bar{b} \to \bar{s}u\bar{u}$ quark-level transitions, it exhibits an amplitude hierarchy which is different from that of the $\bar{b} \to \bar{d}u\bar{u}$ decay $B_d^0 \to \pi^+\pi^-$, and is actually dominated by the QCD penguin topologies. Direct CP violation in this decay, which is generated through the interference between the penguin and tree contributions, is now experimentally well established:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm)$$
$$= \begin{cases} 0.108 \pm 0.024 \pm 0.008 \ (\text{BaBar [20]}) , \\ 0.093 \pm 0.018 \pm 0.008 \ (\text{Belle [22]}) , \\ 0.04 \pm 0.16 \pm 0.02 \quad (\text{CLEO [23]}) , \\ 0.086 \pm 0.023 \pm 0.009 \ (\text{CDF [24]}) , \end{cases}$$
$$(5)$$

leading to the average of $\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm) = 0.095 \pm 0.013$ [24]. In the SM, we may write

$$A(B_d^0 \to \pi^- K^+) = P' \left[1 - r e^{i\delta} e^{i\gamma} \right] , \qquad (6)$$

where the penguin amplitude P' and $r e^{i\delta}$, which measures – sloppily speaking – the ratio of tree to penguin contributions, are CP conserving strong quantities. Using the SU(3) flavour symmetry and the dynamical assumptions specified in Sect. 1, we obtain

$$r e^{i\delta} = \frac{\epsilon}{d} e^{i(\pi-\theta)} , \qquad (7)$$

where $\epsilon \equiv \lambda^2/(1-\lambda^2) = 0.05$ involves the usual Wolfenstein parameter [25], which implies the following relation [17,18,26,27]:

$$H_{\mathrm{BR}} \equiv \frac{1}{\epsilon} \left(\frac{f_K}{f_\pi} \right)^2 \left[\frac{\mathrm{BR}(B_d \to \pi^+\pi^-)}{\mathrm{BR}(B_d \to \pi^\mp K^\pm)} \right]$$
$$= -\frac{1}{\epsilon} \left[\frac{\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm)}{\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-)} \right] . \qquad (8)$$

Since the CP averaged branching ratios and the direct CP violation in $B_d^0 \to \pi^- K^+$ are well measured [19], we may use this relation to *predict* the direct CP asymmetry

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = -0.24 \pm 0.04 , \qquad (9)$$

which favours the BaBar result in (4). Furthermore, as the B_d^0–$\bar{B}_d^0$ mixing phase

$$\phi_d = (42.4 \pm 2)^\circ \qquad (10)$$

is known through the CP violation measurements in $B \to J/\psi K^{(*)}$ [19], the quantities H_{BR}, $\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm)$ and $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^+\pi^-)$ can be expressed in terms of γ and d, θ. Consequently, these parameters can be extracted from the data. As far as the angle γ is concerned, we obtain

$$\gamma = \left(70.0^{+3.8}_{-4.3} \right)^\circ , \qquad (11)$$

which is in nice agreement with the SM fits of the unitarity triangle [28,29], as can be seen in Fig. 1. For the remainder of this analysis, we will use the value of γ in (11).
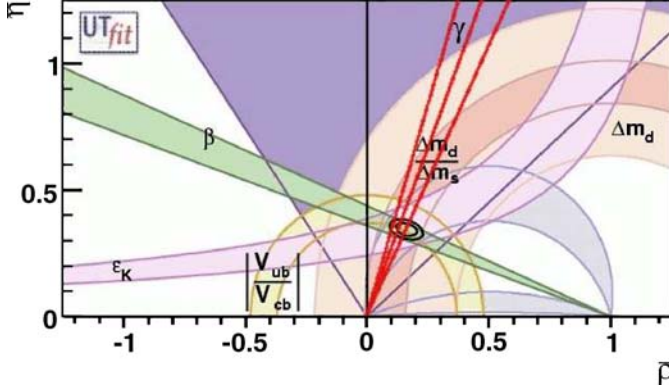
Fig. 1. Comparison of the value of γ in (11) with the SM fit of the unitarity triangle obtained by the UTfit collaboration [28]; the situation is analogous for the corresponding analysis of the CKMfitter collaboration [29]

2.3 Hadronic parameters and CP violation in $B_d^0 \to \pi^0\pi^0$

Concerning the determination of the ratio of the penguin to tree amplitudes of the $B_d^0 \to \pi^+\pi^-$ decay as described above, we find

$$d = 0.46 \pm 0.02, \quad \theta = (155 \pm 4)^\circ. \tag{12}$$

The $B \to \pi\pi$ system offers two more channels. Using the isospin symmetry of strong interactions, their decay amplitudes can be written as follows [9, 10]:

$$\sqrt{2}A(B^+ \to \pi^+\pi^0) = -|\tilde{T}|e^{i\delta_{\tilde{T}}}e^{i\gamma}\left[1 + xe^{i\Delta}\right], \tag{13}$$

$$\sqrt{2}A(B_d^0 \to \pi^0\pi^0) = |P|e^{i\delta_P}\left[1 + (x/d)e^{i\gamma}e^{i(\Delta-\theta)}\right], \tag{14}$$

where the hadronic parameter $xe^{i\Delta}$ denotes the ratio of "colour-suppressed" to "colour-allowed tree" amplitudes. Since we have two more $B \to \pi\pi$ observables at our disposal,

$$R_{+-}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B^\pm \to \pi^\pm\pi^0)}{\mathrm{BR}(B_d \to \pi^+\pi^-)}\right]\frac{\tau_{B_d^0}}{\tau_{B^+}} = 2.02 \pm 0.16, \tag{15}$$

$$R_{00}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B_d \to \pi^0\pi^0)}{\mathrm{BR}(B_d \to \pi^+\pi^-)}\right] = 0.50 \pm 0.08, \tag{16}$$

where we have also given the most recent experimental averages [19], x and the strong phase Δ can be determined:

$$x = 0.92^{+0.08}_{-0.09}, \quad \Delta = -\left(50^{+11}_{-14}\right)^\circ. \tag{17}$$

If we use (14) and complement (17) with the numbers in (10), (11) and (12), the CP asymmetries of the $B_d^0 \to \pi^0\pi^0$ channel can be *predicted* in the SM. Following these lines, we obtain the numbers

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0\pi^0)|_{\mathrm{SM}} = -\left(0.40^{+0.14}_{-0.21}\right), \tag{18}$$

$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0\pi^0)|_{\mathrm{SM}} = -\left(0.71^{+0.16}_{-0.17}\right), \tag{19}$$

which offer the exciting perspective of observing *large CP* violation in this decay. So far, only data for the direct CP asymmetry are available from the BaBar [20] and Belle [30] collaborations, yielding the following average [19]:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0\pi^0) = -\left(0.36^{+0.33}_{-0.31}\right). \tag{20}$$

Although this result is still compatible with zero at the 1.1σ level, the agreement with (18) (note the sign) is nevertheless very encouraging and gives us further confidence in our analysis. Let us finally note that also the EW penguin contributions are included in our numerical values with the help of the isospin symmetry [11, 15, 16], although they have a tiny impact on the $B \to \pi\pi$ system.

3 The $B \to \pi K$ system

Let us now turn to our main target, which is the $B \to \pi K$ system. In addition to the $B_d^0 \to \pi^- K^+$ mode, it consists of $B^+ \to \pi^+ K^0$, $B_d^0 \to \pi^0 K^0$ and $B^+ \to \pi^0 K^+$, as well as their charge conjugates. In the SM, all these decays are governed by their QCD penguin contributions. However, also EW penguins may play an important rôle. We distinguish between the following cases.

– *Colour-suppressed* case: EW penguins with tiny effects, $B_d^0 \to \pi^- K^+$, $B^+ \to \pi^+ K^0$.
– *Colour-allowed* case: EW penguins with sizeable effects, $B_d^0 \to \pi^0 K^0$, $B^+ \to \pi^0 K^+$.

In the latter case, the EW penguin contributions are even comparable to those of the colour-allowed tree topologies. Let us first have a closer look at those $B \to \pi K$ observables that are marginally affected by EW penguins.

3.1 Tiny electroweak penguin effects

3.1.1 $B_d^0 \to \pi^- K^+$ and $B^+ \to \pi^+ K^0$

In Sect. 2.2, we have already used the CP averaged branching ratio and the direct CP asymmetry of the $B_d^0 \to \pi^- K^+$ channel. As we saw in Fig. 1, the resulting value of γ in (11) agrees nicely with the SM fits of the unitarity triangle. However, there is another decay with tiny (colour-suppressed) EW penguin contributions at our disposal, the $B^+ \to \pi^+ K^0$ channel. In the SM, its decay amplitude can be written as

$$A(B^+ \to \pi^+ K^0) = -P'\left[1 + \rho_c e^{i\theta_c}e^{i\gamma}\right], \tag{21}$$

where the CP conserving hadronic parameter $\rho_c e^{i\theta_c}$ is doubly Cabibbo-suppressed and, hence, usually neglected. In this limit, we obviously have vanishing direct CP violation in $B^+ \to \pi^+ K^0$. This feature is fully supported by the following experimental average [19]:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^\pm K) = -0.009 \pm 0.025. \tag{22}$$

Finally, using the working assumptions specified in Sect. 1, we can predict the following ratio of CP averaged branching ratios [31]:

$$R \equiv \left[\frac{\text{BR}(B_d^0 \to \pi^- K^+) + \text{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\text{BR}(B^+ \to \pi^+ K^0) + \text{BR}(B^- \to \pi^- \bar{K}^0)} \right] \frac{\tau_{B^+}}{\tau_{B_d^0}}$$

$$\stackrel{\text{SM}}{=} 0.942 \pm 0.012 \stackrel{\text{exp}}{=} 0.93 \pm 0.05 \,. \qquad (23)$$

The excellent agreement of our SM prediction with the data is impressive, and in particular no anomalous value of ρ_c is indicated. In this context it is interesting to note that a similar picture of ρ_c follows also from the recently observed $B^\pm \to K^\pm K$ decays [32,33]. Consequently, toy models of final-state interaction effects yielding a significant enhancement of the ρ_c parameter that were discussed several years ago are now strongly disfavoured by the B-factory data.

3.1.2 Another application: prediction of the $B_s^0 \to K^+ K^-$ observables

As an interesting by-product, the strategy developed in [9–11] allows us to predict the observables of the $B_s^0 \to K^+ K^-$ decay, where the (colour-suppressed) EW penguin contributions have again a tiny impact. Using the SM value of the B_s^0–$\bar{B}_s^0$ mixing phase $\phi_s = -2\lambda^2\eta = -2°$ [1], where λ and η are the usual parameters of the Wolfenstein parametrization [25], we arrive at the following predictions of the CP asymmetries:

$$\mathcal{A}_{CP}^{\text{dir}}(B_s \to K^+ K^-)|_{\text{SM}} = 0.093 \pm 0.015 \,, \qquad (24)$$

$$\mathcal{A}_{CP}^{\text{mix}}(B_s \to K^+ K^-)|_{\text{SM}} = -0.234^{+0.017}_{-0.014} \,. \qquad (25)$$

In the case of the CP averaged branching ratio, an SU(3)-breaking form-factor ratio enters the prediction, thereby increasing the uncertainties. If we use the result of a QCD sum-rule calculation [34], we obtain

$$\text{BR}(B_s \to K^+ K^-) = (28^{+7}_{-5}) \times 10^{-6} \,. \qquad (26)$$

The $B_s^0 \to K^+ K^-$ channel was recently observed by the CDF collaboration [35]; the most recent experimental result for the CP averaged branching ratio reads as follows [24]:

$$\text{BR}(B_s \to K^+ K^-) = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6} \,. \qquad (27)$$

Within the uncertainties, (26) is in nice agreement with (27), which is also support of the working hypotheses listed in Sect. 1. The $B_s \to K^+ K^-$, $B_d \to \pi^+ \pi^-$ system offers a strategy for the extraction of γ with the help of the U- spin flavour symmetry of strong interactions [17,18], which can nicely be implemented at the LHCb experiment[2]. The predictions and hadronic parameters given above are useful for further experimental studies in the preparation for the quickly approaching start of the LHC.

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[2] For a recent study, see [36]

3.2 Sizeable electroweak penguin effects

3.2.1 CP conserving observables

Let us now focus on those CP conserving $B \to \pi K$ observables that are sizeably affected by EW penguin contributions. In this context, the following ratios [15] have received a lot of attention in the literature:

$$R_{\text{c}} \equiv 2 \left[\frac{\text{BR}(B^+ \to \pi^0 K^+) + \text{BR}(B^- \to \pi^0 K^-)}{\text{BR}(B^+ \to \pi^+ K^0) + \text{BR}(B^- \to \pi^- \bar{K}^0)} \right]$$

$$= 1.11 \pm 0.07 \,, \qquad (28)$$

$$R_{\text{n}} \equiv \frac{1}{2} \left[\frac{\text{BR}(B_d^0 \to \pi^- K^+) + \text{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\text{BR}(B_d^0 \to \pi^0 K^0) + \text{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)} \right]$$

$$= 0.99 \pm 0.07 \,, \qquad (29)$$

where we have also given the experimental averages [19], taking the most recent measurements by the BaBar [20] and Belle [37] collaborations into account. In these quantities, the EW penguin effects enter in colour-allowed form through the modes involving neutral pions, and they are theoretically described by the parameter q that measures the "strength" of the EW penguin with respect to the tree contributions, and by the CP violating phase ϕ. In the SM, the SU(3) flavour symmetry allows for the prediction $q = 0.60$ [38], and ϕ *vanishes.* As has been known for many years (see, for instance, [39,40]), EW penguin topologies offer an interesting avenue for NP to manifest itself in the B-factory data. In the case of CP violating NP effects of this kind, ϕ would take a value different from zero.

As can be seen in Fig. 2, which illustrates the time evolution of the measurements of R_{c} and R_{n}, the central values have significantly moved up with respect to the 2005 data (partly due to radiative corrections affecting final states with charged particles [41]), while the errors were only marginally reduced. Following [9–11], let us now discuss the situation in the plane of R_{n} and R_{c}, as shown in Fig. 3. Here the various contours correspond to different values of q, and the position on the contour is parametrized through the CP violating phase ϕ. We observe that the SM prediction (on the right-hand side) is
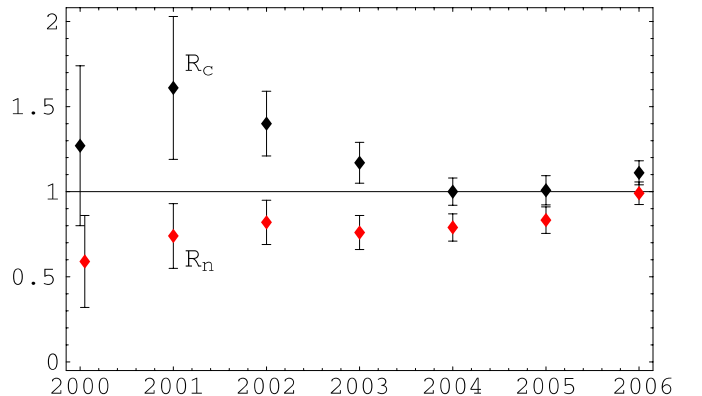
Fig. 2. The time evolution of the experimental values of R_{c} and R_{n}
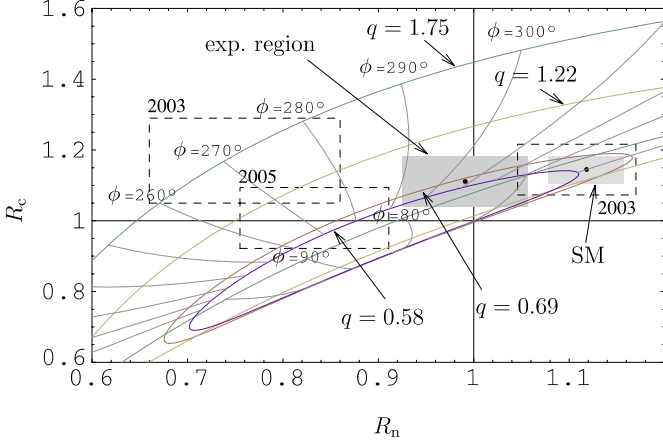
Fig. 3. The situation in the R_{n}–R_{c} plane, as discussed in the text

Fig. 4. The situation in the $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$–$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}})$ plane

very stable in time, having now significantly reduced errors. On the other hand, the B-factory data have moved quite a bit towards the SM, thereby reducing the "$B \to \pi K$ puzzle" for the CP averaged branching ratios. A similar trend is also seen in the measurements of CP violation in $b \to s$ penguin-dominated decays [19], where in particular the average value of $(\sin 2\beta)_{\phi K_{\mathrm{S}}}$ has moved towards the reference value of $(\sin 2\beta)_{J/\psi K_{\mathrm{S}}}$. If we convert the experimental values of R_{n} and R_{c} into q and ϕ, we obtain

$$q = 0.65^{+0.39}_{-0.35}, \quad \phi = -\left(52^{+21}_{-50}\right)^\circ. \tag{30}$$

In comparison with the situation of the ratio R discussed in Sect. 3.1.1, the agreement between the new data for the $R_{\mathrm{c,n}}$ and their SM predictions is not as perfect. However, a case for a modified EW penguin sector cannot be made through the new measurements of these quantities.

3.2.2 CP violating observables

In addition to the CP conserving observables discussed above, we can also analyse the CP violating asymmetries of the $B_d^0 \to \pi^0 K_{\mathrm{S}}$ and $B^\pm \to \pi^0 K^\pm$ channels [9–11]. Let us first turn to the neutral decay, which offers an interesting probe for NP [42]. Within the SM, we obtain the following predictions:
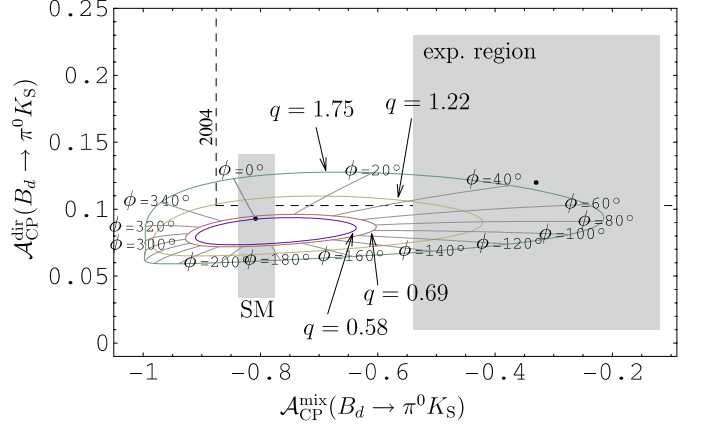
$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}})|_{\mathrm{SM}} = 0.091^{+0.048}_{-0.059}, \tag{31}$$

$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})|_{\mathrm{SM}} = -0.81 \pm 0.03, \tag{32}$$

which are much sharper than the current B-factory data:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}}) = \begin{cases} 0.20 \pm 0.16 \pm 0.03 \,(\text{BaBar [43]}), \\ 0.05 \pm 0.14 \pm 0.05 \,(\text{Belle [44]}), \end{cases} \tag{33}$$

$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}}) = \begin{cases} -0.33 \pm 0.26 \pm 0.04 \,(\text{BaBar [43]}), \\ -0.33 \pm 0.35 \pm 0.08 \,(\text{Belle [44]}), \end{cases} \tag{34}$$

yielding the following averages [19]:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}}) = 0.12 \pm 0.11,$$
$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}}) = -0.33 \pm 0.21. \tag{35}$$

In analogy to Fig. 3, we show the situation in the $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$–$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}})$ plane in Fig. 4. We see that $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$ offers a particularly interesting observable, and that the experimental central values can be reached for large *positive* values of ϕ. Concerning direct CP violation in $B^\pm \to \pi^0 K^\pm$, we obtain the following prediction:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm)|_{\mathrm{SM}} = -0.001^{+0.049}_{-0.041}, \tag{36}$$

which is in good agreement with the experimental average [19]

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm) \overset{\mathrm{exp}}{=} -0.047 \pm 0.026 \tag{37}$$

within the errors. For the new input data, this feature turns out to be almost independent of the presence of CP violating NP contributions to the EW penguin sector. Consequently, the non-vanishing experimental value of

$$\Delta A \equiv \mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm) - \mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm)$$
$$\overset{\mathrm{exp}}{=} -0.140 \pm 0.030, \tag{38}$$

which differs from zero at the 4.7σ level, is likely to be generated through hadronic effects, i.e. not through the impact of physics beyond the SM. A similar conclusion was drawn in [45, 46], where it was also noted that the measured values of R_{c} and R_{n} are now in accordance with the SM.

Finally, performing a simultaneous fit to R_{n}, R_{c} and the CP violating observables of $B_d^0 \to \pi^0 K_{\mathrm{S}}$, we arrive at

$$q = 1.7^{+0.5}_{-1.3}, \quad \phi = +\left(73^{+6}_{-18}\right)^\circ. \tag{39}$$

Interestingly, these parameters – in particular the large *positive* phase – would also allow us to accommodate the

experimental values of $(\sin 2\beta)_{\phi K_S}$ and the CP asymmetries of other $b \to s$ penguin modes with central values smaller than $(\sin 2\beta)_{\psi K_S}$. The large value of q would be excluded by constraints from rare decays in simple scenarios where NP enters only through Z penguins [9–11], but it could still be accommodated in other scenarios, e.g. in models with leptophobic Z' bosons.

3.3 Sensitivity to SU(3)-breaking effects

In analogy to the detailed discussion in [11], we have also explored the sensitivity of our new numerical results to SU(3)-breaking effects. The resulting picture is essentially the same: even if we allow for very conservative uncertainties in the SU(3)-breaking effects, the resulting uncertainties on our predictions are only very moderately increased with respect to our standard analysis; the SU(3)-breaking corrections never become dominant over the other sources of uncertainty. For numerical details, we refer the reader to the discussion in [11]. We would like to stress that even our standard analysis takes into account a reasonable estimate of SU(3)-breaking related uncertainties, which are included in all the theoretical errors quoted in this paper.

4 Conclusions and outlook

The $B \to \pi\pi, \pi K$ system remains a particularly interesting playground for the testing of the KM mechanism of CP violation, and the systematic strategy developed in [9–11] continues to provide a powerful tool for the theoretical interpretation of the corresponding B-factory data. The recent experimental progress allows us now to use only data for which the results of the BaBar and Belle collaborations are in full agreement with each other. Interestingly, the resulting SM picture is very stable, with central values almost unchanged since the original analysis of 2003, having significantly reduced errors.

In our new analysis, we pointed out that the branching ratio and direct CP asymmetry of the $B_d^0 \to \pi^- K^+$ decay allow us to clarify the still unsatisfactory situation of the measurements of the direct CP violation in $B_d^0 \to \pi^+\pi^-$.

– We predict $\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = -0.24 \pm 0.04$, which favours the BaBar result.
– We extract $\gamma = \left(70.0^{+3.8}_{-4.3}\right)^\circ$, in agreement with the SM fits of the unitarity triangle.

Moreover, we find hadronic parameters characterizing the $B \to \pi\pi$ system that show large CP conserving strong phases, thereby establishing large deviations from the naive factorization hypothesis.

The current status of the $B \to \pi K$ system can be summarized as follows:

– All modes with colour-suppressed EW penguins are found in excellent agreement with the SM.
– The data for the $R_{\mathrm{n,c}}$ have moved quite a bit towards the SM predictions, which are almost unchanged, thereby strongly reducing the "$B \to \pi K$ puzzle" for CP averaged branching ratios.

– On the other hand, the mixing-induced CP violation in $B_d^0 \to \pi^0 K_S$ still looks puzzling, and it can straightforwardly be accommodated through a modified EW penguin sector with a large, positive value of the CP violating NP phase ϕ.
– The non-zero experimental value of ΔA in (38) seems to be caused by hadronic and not by NP effects.

Unfortunately, we still cannot draw definite conclusions about the presence of NP in the $B \to \pi K$ system (and other $b \to s$ penguin decays, such as $B_d^0 \to \phi K_S$). It will be interesting to keep track of the picture of these decays once the data improve further.

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