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New aspects of $B \to \pi\pi, \pi K$ and their implications for rare decays

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Abstract. We analyze the $B \to \pi\pi, \pi K$ modes in the light of the most recent B-factory data, and obtain the following new results: (i) the $B_d^0 \to \pi^+\pi^-, \pi^- K^+$ modes prefer $\gamma = (74 \pm 6)^\circ$, which – together with $|V_{ub}/V_{cb}|$ – allows us to determine the "true" unitarity triangle and to search for CP-violating new-physics contributions to B_d^0–$\bar{B}_d^0$ mixing; (ii) the $B \to \pi K$ puzzle reflected in particular by the low experimental value of the ratio R_n of the neutral $B \to \pi K$ rates persists and still favors new physics in the electroweak penguin sector with a new CP-violating phase $\phi \sim -90^\circ$, although now also $\phi \sim +90^\circ$ can bring us rather close to the data; (iii) the mixing-induced $B_d^0 \to \pi^0 K_\mathrm{S}$ CP asymmetry is a sensitive probe of the sign of this phase, and would currently favor $\phi \sim +90^\circ$, as well as the direct CP asymmetry of $B^\pm \to \pi^0 K^\pm$, which suffers, however, from large hadronic uncertainties; (iv) we investigate the sensitivity of our $B \to \pi K$ analysis to large non-factorizable $SU(3)$-breaking effects and find that their impact is surprisingly small so that it is indeed exciting to speculate on new physics; (v) assuming that new physics enters through Z^0 penguins, we study the interplay between $B \to \pi K$ and rare B, K decays and point out that the most recent B-factory constraints for the latter have interesting implications, bringing us to a few scenarios for the future evolution of the data, where also the mixing-induced CP violation in $B_d^0 \to \pi^0 K_\mathrm{S}$ plays a prominent rôle.

1 Introduction

Decays of B mesons into $\pi\pi$ and πK final states offer valuable information about strong interactions, weak interactions and possible new-physics (NP) effects. In a series of recent papers [1,2], we developed a strategy to address these aspects in a systematic manner. It uses the following working hypotheses:
(i) $SU(3)$ flavor symmetry of strong interactions (but taking factorizable $SU(3)$-breaking corrections into account);
(ii) neglect of penguin annihilation and exchange topologies.

We may gain confidence in these assumptions through internal consistency checks, which worked well within the experimental uncertainties for our previous numerical analyses. Since the B-factories reported updated results for several of the input quantities, we would like to explore the implications for the picture emerging from our strategy. For a detailed overview of the current experimental status of the $B \to \pi\pi, \pi K$ observables, we refer the reader to the most recent compilation of the Heavy Flavor Averaging Group (HFAG) [3]. We will give the updated numerical values for the quantities entering our strategy below.

A somewhat surprising new development of this summer is a new world average for $(\sin 2\beta)_{\psi K_\mathrm{S}}$, which went down by about 1σ thanks to an update by the Belle collaboration [4] and is now given as follows:

$$(\sin 2\beta)_{\psi K_\mathrm{S}} = 0.687 \pm 0.032, \qquad \beta = (21.7^{+1.3}_{-1.2})^\circ. \quad (1)$$

The corresponding straight line in the $\bar{\rho}$–$\bar{\eta}$ plane of the generalized Wolfenstein parameters [5,6] is now on the lower side of the allowed region for the apex of the unitarity triangle (UT) of the Cabibbo–Kobayashi–Maskawa (CKM) matrix that follows from the usual "indirect" fits [7,8]. In view of this result, we assume that this potential discrepancy is due to NP in B_d^0–$\bar{B}_d^0$ mixing, and perform an analysis of the UT in Sect. 2. To this end, we use the data for the decays $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^- K^+$, which allow us to determine the "true" UT angle γ [9,10], serving as an input for our subsequent analysis. Complementing this information with the measurement of $|V_{ub}/V_{cb}|$ through semi-leptonic B decays, we can construct the so-called reference unitarity triangle [11,12], and are in a position to convert the possibly emerging discrepancy for the UT into a CP-violating NP physics phase in B_d^0–$\bar{B}_d^0$ mixing. Moreover, we may extract the "true" values of α and

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β, where the latter serves as an input for our analysis of rare decays.

In Sect. 3, we then extract the hadronic parameters characterizing the $B \to \pi\pi$ system with the help of the $SU(2)$ isospin symmetry of strong interactions, and predict the CP-violating observables of the $B_d^0 \to \pi^0\pi^0$ channel. The results of this section are essentially theoretically clean, and serve as a testing ground for the calculation of the dynamics of the $B \to \pi\pi$ decays directly from QCD-related approaches, such as "QCD factorization" (QCDF) [13], the perturbative QCD approach (PQCD) [14], "soft collinear effective theory" (SCET) [15], or QCD sum rules [16].

The $B \to \pi K$ system and the status of the "$B \to \pi K$ puzzle" are then the subject of Sect. 4. We find that our standard-model (SM) predictions for those decays that are only marginally affected by electroweak (EW) penguins are in accordance with the experimental picture, whereas this is not the case for the observables with prominent contributions from these topologies, in particular for the ratio R_n of the CP-averaged rates of the neutral $B \to \pi K$ modes. We show that this puzzle can still be resolved through NP effects in the EW penguin sector with a large CP-violating new phase ϕ. We have also a closer look at another hot topic – the mixing-induced CP asymmetry of the $B_d^0 \to \pi^0 K_\mathrm{S}$ channel – and point out that this quantity depends strongly on the sign of the NP phase ϕ. In particular, this asymmetry, which is found experimentally to be significantly smaller than the SM expectation, can be brought closer to the data by reversing the sign of ϕ. Moreover, we investigate whether significant non-factorizable $SU(3)$-breaking effects could have large impact on our analysis. Interestingly, we find that this is not the case, and note that such effects are also not indicated by the internal consistency checks of our working assumptions.

In Sect. 5, we explore the interplay of the NP in the EW penguin contributions to the $B \to \pi K$ system with rare B and K decays. To this end, we apply the popular scenario that NP enters the EW penguins through Z^0-penguin topologies [17–21]. In view of new experimental results, we speculate on possible future scenarios. As in our previous analysis, we find that $K \to \pi\nu\bar{\nu}$, $K_\mathrm{L} \to \pi^0 e^+e^-$ and $B_{s,d} \to \mu^+\mu^-$ are sensitive probes for these scenarios. This is also the case for the mixing-induced $B_d^0 \to \pi^0 K_\mathrm{S}$ CP asymmetry discussed in Sect. 4. Finally, we summarize our conclusions in Sect. 6.

2 Analysis of the unitarity triangle

Let us in view of the new result for $(\sin 2\beta)_{\psi K_\mathrm{S}}$ first have a closer look at the UT. The starting point of this analysis is the assumption that the possible discrepancy between (1) and the CKM fits is due to CP-violating NP contributions to B_d^0–$\bar{B}_d^0$ mixing (although it is of course too early to say something definite on this issue at the moment) [11, 22, 23]. For other recent analyses in this context, see [7, 8, 24]. We may then extract the general B_d^0–$\bar{B}_d^0$ mixing phase

$$\phi_d = \phi_d^\mathrm{SM} + \phi_d^\mathrm{NP} = 2\beta + \phi_d^\mathrm{NP}, \tag{2}$$

where ϕ_d^NP could originate from physics beyond the SM, from the numerical value in (1), yielding $\phi_d = (43.4^{+2.6}_{-2.4})^\circ$. Here we have discarded a possible second solution around 136.6° [10, 23], which is disfavored by recent B-factory data [3]. The phase (2) enters the mixing-induced CP asymmetry of the $B_d \to \pi^+\pi^-$ channel, which arises in the following time-dependent rate asymmetry:

$$\begin{aligned}&\frac{\Gamma(B_d^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}{\Gamma(B_d^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}\\ &= \mathcal{A}_{CP}^\mathrm{dir}(B_d \to \pi^+\pi^-)\cos(\Delta M_d t)\\ &+ \mathcal{A}_{CP}^\mathrm{mix}(B_d \to \pi^+\pi^-)\sin(\Delta M_d t).\end{aligned} \tag{3}$$

In the SM, these observables can be written as (for the explicit expressions, see [9])

$$\begin{aligned}\mathcal{A}_{CP}^\mathrm{dir}(B_d \to \pi^+\pi^-) &= G_1(d,\theta;\gamma)\\ &\overset{\mathrm{exp}}{=} -0.37 \pm 0.10,\end{aligned} \tag{4}$$

$$\begin{aligned}\mathcal{A}_{CP}^\mathrm{mix}(B_d \to \pi^+\pi^-) &= G_2(d,\theta;\gamma,\phi_d)\\ &\overset{\mathrm{exp}}{=} +0.50 \pm 0.12,\end{aligned} \tag{5}$$

where we have also given the most recent experimental numbers, and $d\mathrm{e}^{\mathrm{i}\theta}$ is a CP-conserving hadronic parameter, which measures – sloppily speaking – the ratio of the $B_d \to \pi^+\pi^-$ penguin to tree contributions.

Let us now use the additional information which is provided by the $B_d \to \pi^\mp K^\pm$ decays. The assumptions listed at the beginning of Sect. 1 allow us then to derive

$$\begin{aligned}H_\mathrm{BR} &\equiv \underbrace{\frac{1}{\epsilon}\left(\frac{f_K}{f_\pi}\right)^2\left[\frac{\mathrm{BR}(B_d \to \pi^+\pi^-)}{\mathrm{BR}(B_d \to \pi^\mp K^\pm)}\right]}_{7.5 \pm 0.7}\\ &= \underbrace{-\frac{1}{\epsilon}\left[\frac{\mathcal{A}_{CP}^\mathrm{dir}(B_d \to \pi^\mp K^\pm)}{\mathcal{A}_{CP}^\mathrm{dir}(B_d \to \pi^+\pi^-)}\right]}_{6.7 \pm 2.0} \equiv H_{\mathcal{A}_{CP}^\mathrm{dir}},\end{aligned} \tag{6}$$

where $\epsilon \equiv \lambda^2/(1-\lambda^2) = 0.053$, and the ratio $f_K/f_\pi = 160/131$ of the kaon and pion decay constants takes factorizable $SU(3)$-breaking corrections into account. In (6), we have indicated the numerical values following from the current data. Consequently, within the experimental uncertainties, this relation is also well satisfied by the new data, which gives us further confidence in our working assumptions.

The quantities H_BR and $H_{\mathcal{A}_{CP}^\mathrm{dir}}$, which are fixed through the branching ratios and direct CP asymmetries, respectively, can be written as follows:

$$H_\mathrm{BR} = G_3(d,\theta;\gamma) = H_{\mathcal{A}_{CP}^\mathrm{dir}}. \tag{7}$$

If we complement this expression with (4) and (5), we have sufficient information to determine γ, as well as (d,θ) [9, 10]. Following these lines yields

$$\gamma|_\mathrm{BR} = (44.0^{+4.3}_{-3.7})^\circ \quad \vee \quad (70.1^{+5.6}_{-7.2})^\circ, \tag{8}$$

$$\gamma|_{\mathcal{A}_{CP}^\mathrm{dir}} = (42.1^{+3.4}_{-3.6})^\circ \quad \vee \quad (73.9^{+5.8}_{-6.5})^\circ. \tag{9}$$

Consequently, H_{BR} and $H_{\mathcal{A}_{CP}^{\mathrm{dir}}}$ give results that are in good agreement with one another. As we discussed in [1], the solutions around 40° can be excluded through an analysis of the whole $B \to \pi\pi, \pi K$ system, which is also the case for the most recent data. In the following analysis, we will use

$$\gamma = (73.9^{+5.8}_{-6.5})^\circ, \tag{10}$$

corresponding to $H_{\mathcal{A}_{CP}^{\mathrm{dir}}}$, as this is theoretically cleaner than the avenue offered by H_{BR}. As we will see in Sect. 4.4, even large non-factorizable $SU(3)$-breaking corrections have a remarkably small impact on the numerical result in (10). The value for γ in (10) is somewhat larger than in [1]; a significant part of the numerical shift can be explained by the new value for $(\sin 2\beta)_{\psi K_{\mathrm{S}}}$, as shown in Fig. 1.

Before having a closer look at the whole set of hadronic parameters characterizing the $B \to \pi\pi$ system, let us first explore the implications of (10) for the apex of the UT in the $\bar\rho$–$\bar\eta$ plane. The interesting feature of this value of γ following from the CP asymmetries of the $B_d \to \pi^+\pi^-$, $B_d \to \pi^\mp K^\pm$ system is that it does not receive – in our scenario of NP – any significant NP contributions. Consequently, it is the "true" angle γ of the UT. In order to complete the determination of the "true" UT, i.e. of the so-called reference UT [11,12], we use the ratio $|V_{ub}/V_{cb}|$ extracted from semi-leptonic tree-level B decays. Although its values extracted from exclusive and inclusive decays are markedly different from each other, we use the following average [7]:

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.102 \pm 0.005. \tag{11}$$

In the second column of Table 1, we list the values of $\bar\rho$, $\bar\eta$, and "β_{true}" for this value of $|V_{ub}/V_{cb}|$ and γ in (10). For completeness, we also give the values of the lengths of the UT sides R_b and R_t and of the angle α. We observe that the value of β_{true} that we obtain this way is significantly higher than the one in (1). It corresponds to $(\sin 2\beta)_{\mathrm{true}} = 0.78 \pm 0.03$.

In our scenario, this difference is attributed to a non-vanishing value of the NP phase ϕ_d^{NP} in (2), where β corresponds to β_{true}. As seen in Table 1, our value of ϕ_d^{NP} is compatible with the one found in [7,8], but our value of γ obtained here in a different manner is significantly higher. An even larger value of γ following from $B \to \pi\pi$, in the ballpark of 80°, has been reported from an analysis using SCET [25]. In Table 1, we also show the results for the reference unitarity triangle (RUT) obtained in [7], where only CP violation in $B \to DK$ and $|V_{ub}/V_{cb}|$ in (11) have been used as input. The agreement between our analysis and the one in [7] is almost too good. In obtaining the values in the column "UTfit RUT" we have used $\bar\rho$ and $\bar\eta$ from [7]. In the last two columns in Table 1 we collect the results from [7] within the SM and for the universal unitarity triangle (UUT) in models with minimal flavor violation [26,27], where (1), $|V_{ub}/V_{cb}|$ and $\Delta M_d/\Delta M_s$ serve as inputs. As already stated above, the values of γ are in both cases significantly smaller, while the values of α are significantly larger than in the case of the RUT.

The visibly increased value of R_t relatively to the standard UT fits found by us in the case of the RUT would

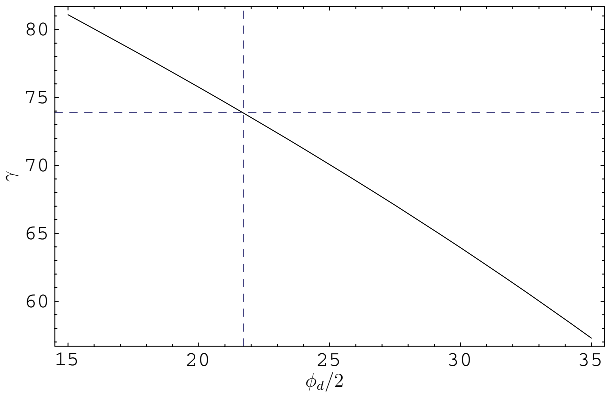

Fig. 1. The value of γ as determined in our strategy as a function of $\phi_d/2$ with all other experimental input parameters kept at their central values. The lines correspond to the values in (1) and (10)

Table 1. Parameters of the reference UT (RUT) determined through $|V_{ub}/V_{cb}|$ in (11) and the CP asymmetries of the $B_d \to \pi^+\pi^-$, $B_d \to \pi^\mp K^\pm$ system, yielding the value of γ in (10), compared with the results of [7]. We show also the results of the full UT fit and of the universal unitarity triangle obtained in [7]

Quantity	Our value	UTfit RUT	Full UT	UUT
γ	$(73.9^{+5.8}_{-6.5})^\circ$	$(65 \pm 18)^\circ$	$(57.6 \pm 5.5)^\circ$	$(51 \pm 10)^\circ$
$\bar\rho$	0.127 ± 0.046	0.18 ± 0.12	0.216 ± 0.036	0.259 ± 0.068
$\bar\eta$	0.422 ± 0.025	0.41 ± 0.05	0.342 ± 0.022	0.320 ± 0.042
R_b	0.44 ± 0.02	0.45 ± 0.07	0.40 ± 0.03	0.42 ± 0.05
R_t	0.97 ± 0.05	0.92 ± 0.11	0.86 ± 0.03	0.81 ± 0.06
β_{true}	$(25.8 \pm 1.3)^\circ$	$(26.1 \pm 3.0)^\circ$	$(23.8 \pm 1.5)^\circ$	$(23.4 \pm 1.3)^\circ$
α	$(80.3^{+6.6}_{-5.9})^\circ$	$(87 \pm 15)^\circ$	$(98.5 \pm 5.7)^\circ$	$(105 \pm 11)^\circ$
$(\sin 2\beta)_{\mathrm{true}}$	0.782 ± 0.029	0.782 ± 0.065	0.735 ± 0.024	0.728 ± 0.031
ϕ_d^{NP}	$-(8.2 \pm 3.5)^\circ$	$-(8.9 \pm 6.0)^\circ$	$-(4.1 \pm 3.9)^\circ$	$-(3.3 \pm 3.6)^\circ$

require a small *negative* NP contribution to the B_d^0–$\bar{B}_d^0$ mass difference ΔM_d and/or a slightly increased value of the non-perturbative parameter ξ relevant for the ratio $\Delta M_d/\Delta M_s$. We look forward to improved data on the $B \to \pi\pi$, $B \to \pi K$ system, $|V_{ub}/V_{cb}|$, $\sin 2\beta$ and ΔM_s in order to see whether the difference between the large value of γ found here and the one resulting from the UUT and full UT fits could be interpreted as a clear signal of NP.

3 The $B \to \pi\pi$ system

Let us now continue the analysis of the $B \to \pi\pi$ system. In addition to the CP-violating observables in (3), we use the following ratios of CP-averaged branching ratios:

$$\begin{aligned} R_{+-}^{\pi\pi} &\equiv 2\left[\frac{\mathrm{BR}(B^+\to\pi^+\pi^0)+\mathrm{BR}(B^-\to\pi^-\pi^0)}{\mathrm{BR}(B_d^0\to\pi^+\pi^-)+\mathrm{BR}(\bar{B}_d^0\to\pi^+\pi^-)}\right] \\ &\overset{\mathrm{exp}}{=} 2.04\pm0.28, \qquad (12) \\ R_{00}^{\pi\pi} &\equiv 2\left[\frac{\mathrm{BR}(B_d^0\to\pi^0\pi^0)+\mathrm{BR}(\bar{B}_d^0\to\pi^0\pi^0)}{\mathrm{BR}(B_d^0\to\pi^+\pi^-)+\mathrm{BR}(\bar{B}_d^0\to\pi^+\pi^-)}\right] \\ &\overset{\mathrm{exp}}{=} 0.58\pm0.13. \qquad (13) \end{aligned}$$

Using the isospin symmetry of strong interactions, these quantities can be written as

$$R_{+-}^{\pi\pi} = F_1(d,\theta,x,\Delta;\gamma), \quad R_{00}^{\pi\pi} = F_2(d,\theta,x,\Delta;\gamma), \quad (14)$$

where $x\mathrm{e}^{\mathrm{i}\Delta}$ is another hadronic parameter, which was introduced in [1]. Using now, in addition, the CP-violating observables in (4) and (5) and the value of γ in (10), we arrive at the following set of hadronic parameters:

$$\begin{aligned} d &= 0.52^{+0.09}_{-0.09} \quad [0.51^{+0.26}_{-0.20}], \\ \theta &= (146^{+7.0}_{-7.2})^\circ \quad [(140^{+14}_{-18})^\circ] \qquad (15) \\ x &= 0.96^{+0.13}_{-0.14} \quad [1.15^{+0.18}_{-0.16}], \\ \Delta &= -(53^{+18}_{-26})^\circ \quad [-(59^{+19}_{-26})^\circ], \qquad (16) \end{aligned}$$

which is in excellent agreement with the picture of our last analysis in [2], corresponding to the numbers in parentheses. As in this paper, we include also the EW penguin effects in the $B \to \pi\pi$ system [28,29], although these topologies have a tiny impact [30]. Let us emphasize that the results for the hadronic parameters listed above, which are consistent with the analyses of other authors (see, for instance, [31–33]), are essentially theoretically clean and serve as a testing ground for calculations within QCD-related approaches, such as QCDF [13], PQCD [14], SCET [15], or QCD sum rules [16].

Finally, we can predict the CP asymmetries of the decay $B_d \to \pi^0\pi^0$, where we obtain

$$\begin{aligned} \mathcal{A}_{CP}^{\mathrm{dir}}(B_d\to\pi^0\pi^0) &= -0.30^{+0.48}_{-0.26}, \\ \mathcal{A}_{CP}^{\mathrm{mix}}(B_d\to\pi^0\pi^0) &= -0.87^{+0.29}_{-0.19}. \qquad (17) \end{aligned}$$

On the other hand, the current experimental value for the direct CP asymmetry is [3]

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d\to\pi^0\pi^0) = -0.28^{+0.40}_{-0.39}. \qquad (18)$$

No stringent test of our predictions is provided at this stage, but the indicated agreement is very encouraging.

4 The $B \to \pi K$ system

Following our strategy developed in [1], we are now in a position to calculate the observables of the $B \to \pi K$ system in the SM. The corresponding decays fall into two classes: transitions with a negligible impact of EW penguins, and channels receiving sizable contributions from these topologies.

4.1 The decays $B_d \to \pi^\mp K^\pm$ and $B^\pm \to \pi^\pm K$

Let us first have a look at those decays that are marginally affected by contributions from EW penguin diagrams, $B_d \to \pi^\mp K^\pm$ and $B^\pm \to \pi^\pm K$. We encountered the former channel already in the SM relation (6), which is satisfied by the current data. Concerning the latter decay, it provides the CP-violating asymmetry

$$\begin{aligned} &\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm\to\pi^\pm K) \\ &\quad\equiv \frac{\mathrm{BR}(B^+\to\pi^+K^0)-\mathrm{BR}(B^-\to\pi^-\bar{K}^0)}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\bar{K}^0)} \\ &\quad\overset{\mathrm{exp}}{=} 0.02\pm0.04, \qquad (19) \end{aligned}$$

and enters in the following ratio [34]:

$$\begin{aligned} R &\equiv \left[\frac{\mathrm{BR}(B_d^0\to\pi^-K^+)+\mathrm{BR}(\bar{B}_d^0\to\pi^+K^-)}{\mathrm{BR}(B^+\to\pi^+K^0)+\mathrm{BR}(B^-\to\pi^-\bar{K}^0)}\right]\frac{\tau_{B^+}}{\tau_{B_d^0}} \\ &\overset{\mathrm{exp}}{=} 0.86\pm0.06; \qquad (20) \end{aligned}$$

the numerical values refer again to the most recent compilation of the HFAG in [3]. The $B^+ \to \pi^+K^0$ channel involves another hadronic parameter, $\rho_{\mathrm{c}}\mathrm{e}^{\mathrm{i}\theta_{\mathrm{c}}}$, which cannot be determined through the $B \to \pi\pi$ data [28,35,36]:

$$A(B^+\to\pi^+K^0) = -P'\left[1+\rho_{\mathrm{c}}\mathrm{e}^{\mathrm{i}\theta_{\mathrm{c}}}\mathrm{e}^{\mathrm{i}\gamma}\right]; \qquad (21)$$

the overall normalization P' cancels in (19) in (20). Usually, it is assumed that $\rho_{\mathrm{c}}\mathrm{e}^{\mathrm{i}\theta_{\mathrm{c}}}$ can be neglected. In this case, the direct CP asymmetry in (19) vanishes, and R can be calculated through the $B \to \pi\pi$ data with the help of the assumptions specified at the beginning of Sect. 1:

$$R|_{\mathrm{SM}} = 0.963^{+0.019}_{-0.022}. \qquad (22)$$

This numerical result is 1.6σ larger than the experimental value in (20). As we discussed in detail in [2], the experimental range for the direct CP asymmetry in (19) and the first direct signals for $B^\pm \to K^\pm K$ decays [37] favor a value of θ_{c} around 0°. This feature allows us to essentially resolve the small discrepancy concerning R for values of ρ_{c} around 0.05. The remaining small numerical difference between the calculated value of R and the experimental result, if confirmed by future data, could be due to (small) color-suppressed EW penguins, which enter R as well [1]. As we will see in Sect. 4.4, even large non-factorizable $SU(3)$-breaking effects would have a small impact on the predicted value of R. In view of these results, we would not be surprised to see an increase of the experimental value of R in the future.

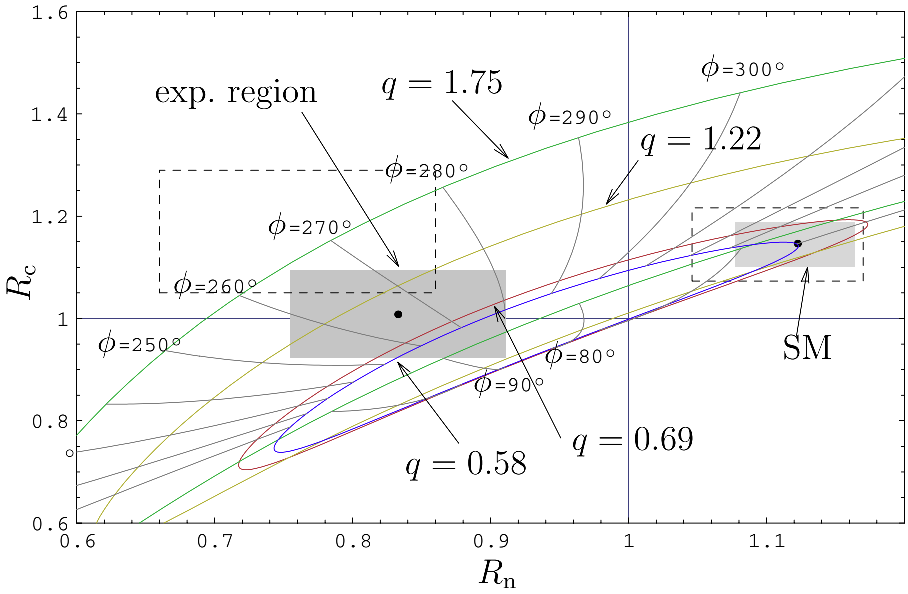

Fig. 2. The current situation in the R_n–R_c plane: the shaded areas indicate the experimental and SM 1σ ranges, the lines show the theory predictions for the central values of the hadronic parameters and various values of q with $\phi \in [0^\circ, 360^\circ]$. The plot ranges and the displayed values of q correspond to those considered in [1]

4.2 The decays $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^0 K$

Let us now turn to those $B \to \pi K$ modes that are significantly affected by EW penguin contributions, the $B^+ \to \pi^0 K^+$ and $B_d^0 \to \pi^0 K^0$ channels. The key observables for the exploration of these modes are the following ratios of their CP-averaged branching ratios [28,38]:

$$R_c \equiv 2\left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+) + \mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right] \overset{\mathrm{exp}}{=} 1.01 \pm 0.09, \quad (23)$$

$$R_n \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B_d^0 \to \pi^0 K^0) + \mathrm{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right] \overset{\mathrm{exp}}{=} 0.83 \pm 0.08. \quad (24)$$

The EW penguin effects are described by a parameter q, which measures the strength of the EW penguins with respect to tree-diagram-like topologies, and a CP-violating phase ϕ. In the SM, this phase vanishes, and q can be calculated with the help of the $SU(3)$ flavor symmetry, yielding a value of $0.69 \cdot 0.086/|V_{ub}/V_{cb}| = 0.58$ [39]. We find then

$$R_c|_{\mathrm{SM}} = 1.15 \pm 0.05, \quad R_n|_{\mathrm{SM}} = 1.12 \pm 0.05. \quad (25)$$

Following [1], we discuss the dependence of R_n and R_c on q and ϕ with the help of a plot of the R_n–R_c plane (Fig. 2). The experimental range is still far from the SM predictions; for the convenience of the reader we have indicated the experimental range and the SM predictions at the time of our original analysis [1] with dashed rectangles. Although the central values of R_n and R_c have slightly moved towards each other, the puzzle is as prominent as ever. The experimental region can now be reached without an enhancement of q, but a large CP-violating phase ϕ of the order of -90° is still required, although ϕ of the order of $+90^\circ$ can also bring us rather close to the experimental range of R_n and R_c. We will return to this alternative below. Explicitly, we find

$$q = 0.99\,^{+0.66}_{-0.70}, \quad \phi = -(94\,^{+16}_{-17})^\circ. \quad (26)$$

The impact of rare decays on these values will be discussed in Sect. 5, where various scenarios with different values of q and ϕ will be considered.

4.3 CP violation in $B_d \to \pi^0 K_S$ and $B^\pm \to \pi^0 K^\pm$

In the SM, the CP asymmetries of the decay $B_d \to \pi^0 K_S$, which can be extracted from a time-dependent rate asymmetry of the same form as (3), are expected to satisfy the following relations [30]:

$$\begin{aligned} &\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_S) \approx 0, \\ &\underbrace{\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_S)}_{\equiv -(\sin 2\beta)_{\pi^0 K_S}} \approx \underbrace{\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \psi K_S)}_{\equiv -(\sin 2\beta)_{\psi K_S}}. \end{aligned} \quad (27)$$

The most recent B-factory results read as follows [3]:

$$\begin{aligned} \mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_S) &= -0.02 \pm 0.13, \\ \mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_S) &= -0.31 \pm 0.26, \end{aligned} \quad (28)$$

where the BaBar and Belle collaborations are in agreement with each other. Comparing with (1), we see that there is a sizable departure of the experimentally measured value of $(\sin 2\beta)_{\pi^0 K_S}$ from $(\sin 2\beta)_{\psi K_S}$, which is one of the recent hot topics.

Consequently, a detailed theoretical analysis of the relations in (27) is required. In fact, our strategy developed in [1] allows us to address this issue and to *predict* the CP-violating observables of the $B_d \to \pi^0 K_S$ channel both within the SM and within our scenario of NP discussed above. A detailed analysis along these lines was already presented by us in [1], from which one can extract

$$\Delta S \equiv (\sin 2\beta)_{\pi^0 K_S} - (\sin 2\beta)_{\psi K_S} \overset{\mathrm{exp}}{=} -0.38 \pm 0.26 \quad (29)$$

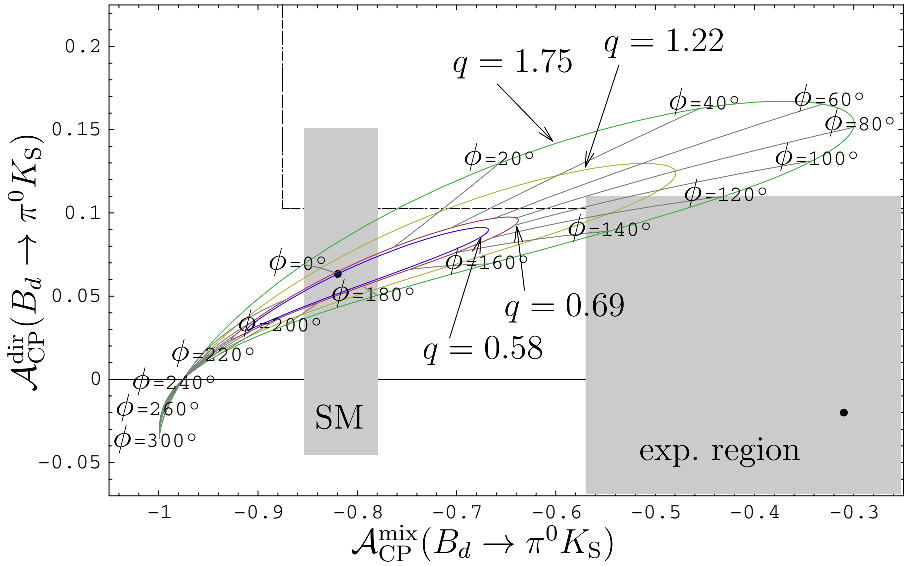

Fig. 3. The situation in the $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$–$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}})$ plane: we show contours for values of $q = 0.58$ to $q = 1.75$ with $\phi \in [0°, 360°]$. The grey area represents the 1σ experimental range (see (28)), and the central value is indicated by the black dot

to be *positive* in the SM, and in the ballpark of 0.10–0.15. The difference introduced in (29) allows a direct comparison with the results obtained in the literature, where values for ΔS in the range 0.04–0.08 can be found that were obtained within the context of dynamical approaches like QCDF [40] and SCET [25]. Moreover, bounds were derived with the help of the $SU(3)$ flavor symmetry [41]. Using the formulae of Sect. 4.5 in [1], our updated values for the CP asymmetries in $B_d \to \pi^0 K_{\mathrm{S}}$ within the SM read as follows:

$$\begin{aligned}\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}})|_{\mathrm{SM}} &= 0.06^{+0.09}_{-0.10},\\ \mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})|_{\mathrm{SM}} &= -(0.82^{+0.03}_{-0.04}).\end{aligned} \tag{30}$$

Consequently, we find

$$\Delta S|_{\mathrm{SM}} = 0.13 \pm 0.05, \tag{31}$$

in agreement with other estimates but somewhat larger. We stress that in obtaining this result we did *not* have to rely on dynamical frameworks that use ideas of factorization, in contrast to the analyses of [40, 25].

Let us now turn to our NP scenario. Using the modified parameters of (q, ϕ) in (26) yields the following results:

$$\begin{aligned}\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^0 K_{\mathrm{S}}) &= 0.01\,^{+0.14}_{-0.18},\\ \mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}}) &= -(0.96\,^{+0.04}_{-0.08}).\end{aligned} \tag{32}$$

Consequently, as already noticed in [1], these specific EW penguin parameters imply an enhancement of ΔS with respect to the SM case:

$$\Delta S = 0.27\,^{+0.05}_{-0.09}. \tag{33}$$

Thus the best values for (q, ϕ) that are required to confront the small value of R_{n} with the theoretical interpretation within our strategy make the disagreement with the data for $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$ even larger than in the SM. The question then arises whether there exist values of (q, ϕ) for which ΔS could be smaller than in the SM or even reverse the sign. As seen already in Fig. 10 of [1] and in its updated version in Fig. 3 here, such values of (q, ϕ) can indeed be found. We will return to this issue after the constraints from rare decays have been taken into account. In view of the large experimental errors of the mixing-induced CP asymmetry of the $B_d \to \pi^0 K_{\mathrm{S}}$ channel, it is unfortunately not possible to draw definite conclusions at the moment.

Finally, there is still one CP asymmetry of the $B \to \pi K$ system left:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm) \overset{\mathrm{exp}}{=} -0.04 \pm 0.04. \tag{34}$$

This quantity received also a lot of attention, in particular as its experimental value differs from

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm) \overset{\mathrm{exp}}{=} 0.115 \pm 0.018, \tag{35}$$

which we have used in (6). On the other hand, both asymmetries are expected to be equal in the naive limit of vanishing color-suppressed tree and electroweak penguin topologies. The lifted color suppression shown through the large value of x could, in principle, be responsible for this difference, but, calculating this asymmetry in the SM and our NP scenario (26), we find

$$\begin{aligned}\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm)|_{\mathrm{SM}} &= 0.04\,^{+0.09}_{-0.07},\\ \mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm)|_{\mathrm{NP}} &= 0.09\,^{+0.20}_{-0.16},\end{aligned} \tag{36}$$

so that the SM still prefers a positive value of $\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm)$. In view of the large uncertainties, no stringent test is provided at this point. Nevertheless, it is tempting to play a bit with this asymmetry. In analogy to Fig. 3, we show in Fig. 4 the situation in the $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$–$\mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm)$ plane for various values of q with $\phi \in [0°, 360°]$. We observe that also the current experimental value of the CP asymmetry of the charged $B^\pm \to \pi^0 K^\pm$ mode seems to show a preference for positive values of ϕ around +90°. It will be interesting to monitor these topics as the data improve. We will return to this issue in Sect. 5.

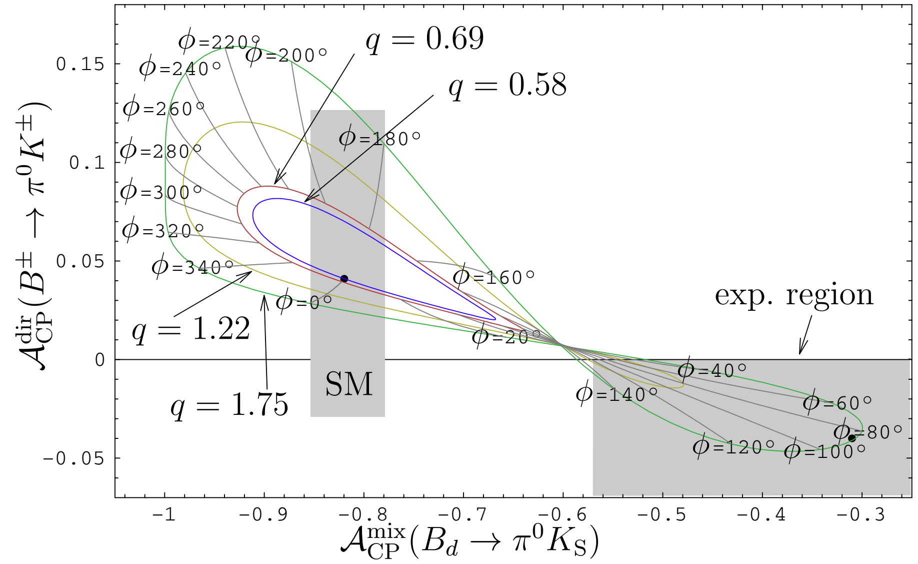

Fig. 4. The situation in the $\mathcal{A}_{CP}^{\rm mix}(B_d \to \pi^0 K_{\rm S})$–$\mathcal{A}_{CP}^{\rm dir}(B^\pm \to \pi^0 K^\pm)$ plane, in analogy to Fig. 3

4.4 A closer look at $SU(3)$-breaking effects

Before leaving the $B \to \pi K$ system, let us have a critical look at the sensitivity of our results on large (non-factorizable) corrections to the working assumptions listed in Sect. 1. As we discussed in detail in [1,2], internal consistency checks of these assumptions are provided within our strategy. An example is relation (6). These checks are currently satisfied at the 25% level, and can be improved systematically with better experimental data. Consequently, no violation of our working assumptions is indicated. On the other hand, since sizable non-factorizable $SU(3)$-breaking effects cannot yet be excluded, let us investigate their impact on our numerical results.

In our analysis of the $B \to \pi\pi, \pi K$ system, we include factorizable $SU(3)$-breaking corrections through appropriate form-factor and decay-constant ratios. The relevant relation is (3.55) of [2], which relates the parameters (x, Δ) of the $B \to \pi\pi$ system to their $B \to \pi K$ counterparts:

$$x' e^{i\Delta'} = \left[\frac{f_\pi F_{BK}(M_\pi^2; 0^+)}{f_K F_{B\pi}(M_K^2; 0^+)}\right] x e^{i\Delta} \equiv \rho_{SU(3)}\, x e^{i\Delta}\,. \quad (37)$$

From light-cone sum-rules [42], it was found that $\rho_{SU(3)}^{\rm fact} = 1.05 \pm 0.18$. This factor is also included in the updated analysis presented in this paper. In order to explore the impact of large non-factorizable $SU(3)$-breaking effects on our analysis, we will use $|\rho_{SU(3)}| = 1.05 \pm 0.36$, i.e. enlarge the error of $|\rho_{SU(3)}^{\rm fact}|$ by 100%, and also allow for a CP-conserving strong phase of $\rho_{SU(3)}$ between $-15°$ and $+15°$. Concerning the relation of the $B_d^0 \to \pi^+\pi^-$ parameters (d, θ) to their $B_d^0 \to \pi^- K^+$ counterparts (d', θ'), we follow [9,10], and introduce $SU(3)$-breaking parameters through

$$d' = \xi d, \quad \theta' = \theta + \Delta\theta. \quad (38)$$

In the numerical analysis, we consider then $\xi = 1.0 \pm 0.18$, and allow the strong phase $\Delta\theta$ to vary freely between $-15°$ and $+15°$.

Table 2. The impact of large non-factorizable $SU(3)$-breaking effects on our SM analysis. The "default" results of our analysis include factorizable $SU(3)$-breaking corrections, as described in the text

Quantity	Default values	Non-fact. $SU(3)$ breaking
γ	$(73.9^{+5.8}_{-6.5})°$	$(73.9^{+9.4}_{-9.0})°$
R	0.96 ± 0.02	$0.96\,^{+0.03}_{-0.04}$
$R_{\rm c}$	1.15 ± 0.05	1.15 ± 0.07
$R_{\rm n}$	1.12 ± 0.05	1.12 ± 0.06
$\mathcal{A}_{CP}^{\rm dir}(B^\pm \to \pi^0 K^\pm)$	$0.04\,^{+0.08}_{-0.07}$	$0.04\,^{+0.13}_{-0.11}$
$\mathcal{A}_{CP}^{\rm dir}(B_d \to \pi^0 K_{\rm S})$	$0.06\,^{+0.09}_{-0.10}$	$0.06\,^{+0.13}_{-0.16}$
ΔS	0.13 ± 0.05	$0.13\,^{+0.06}_{-0.07}$

The impact of this conservative treatment of non-factorizable $SU(3)$-breaking corrections on our SM analysis of the $B \to \pi K$ system is surprisingly small, as can be seen in Table 2. Even with significantly enhanced uncertainties, it is not possible to accommodate the whole $B \to \pi K$ data in a satisfactory manner within the SM, and the $B \to \pi K$ puzzle persists. Consequently, it is in fact very exciting to speculate on NP effects, as we have done in Sects. 4.2 and 4.3. Let us next explore the interplay with rare K and B decays.

5 Interplay with rare B and K decays and possible future scenarios

An attractive feature of the approach in [1,2] is a direct connection between non-leptonic B decays and rare B and K decays [43]. Assuming that the dominant NP contributions enter through the Z^0-penguin function C, and using the renormalization-group evolution from scales $\mathcal{O}(M_W, m_t)$ to scales $\mathcal{O}(m_b)$, we can directly investigate the impact of the modified EW penguin contributions in the $B \to \pi K$ modes on rare B and K decays.

Proceeding in this manner we find that the value of (q, ϕ) in (26), which is preferred by the $B \to \pi K$ observables $R_{\mathrm{n,c}}$, requires the one-loop short-distance functions X and Y to be at least as high as

$$|X|_{\min} \approx |Y|_{\min} \approx 2.2, \tag{39}$$

to be compared with $X \approx 1.5$ and $Y \approx 1.0$ in the SM.

The values in (39) appear to violate the 95% probability upper bounds

$$X \leq 1.95, \qquad Y \leq 1.43, \tag{40}$$

obtained recently in the context of minimal flavor violation (MFV) [44]. While our scenario of NP having new complex phases goes beyond MFV, the inspection of the known formulae for $B \to X_s l^+ l^-$ shows that the upper bound on Y in (40) is difficult to avoid if the only NP contribution resides in the EW penguins and the operator basis is the same as in the SM. For our analysis below we will, therefore, use an only slightly more generous bound and impose $|Y| \leq 1.5$. Taking then those values of (q, ϕ) from (26) that also satisfy $|Y| = 1.5$ leaves us with

$$q = 0.48 \pm 0.07, \quad \phi = -(93 \pm 17)^\circ. \tag{41}$$

Note that this corresponds to a modest *suppression* of the magnitude of the EW penguin parameter relative to its new SM value of 0.58.

Another possible solution to the clash between (39) and (40) would be the introduction of new complex phases in the photon magnetic penguin contribution that has no impact on the $B \to \pi K$ decays but can influence $B \to X_s l^+ l^-$. This could weaken the tension between (39) and (40) subject to the bounds on the CP asymmetry in the $B \to X_s \gamma$ decay, where the photon magnetic penguin plays an important rôle [45]. Another avenue one could explore would be the introduction of new operators in $B \to X_s l^+ l^-$ that would invalidate the bounds in (40). For instance, new operators originating in Higgs penguins in the MSSM with a large $\tan\beta$ could help here. The impact of these new operators on $B \to X_s l^+ l^-$ turns out to be moderate when the constraints on their Wilson coefficients from $B_s \to \mu^+ \mu^-$ are taken into account [46]. Still their presence can definitely weaken the bounds in (40), so that the values in (39) are compatible with rare decay constraints in such a more complicated NP scenario.

In spite of these possibilities, we will not explore them in the present paper because the predictive power of this more general NP scenario is significantly smaller than of our scenario, unless a specific model is considered. Instead we will investigate how various modifications of (q, ϕ), which allow us to satisfy the bounds in (40), influence our results for the observables of the $B \to \pi K$ system presented in Sect. 4, and the predictions for rare decays discussed in detail in [1,2]. For this purpose, we have introduced three scenarios that represent possible future measurements of R_{n} and R_{c}.

(1) Scenario A: $q = 0.48$, $\phi = -93^\circ$, which is compatible with the present $B \to \pi K$ data and the rare decay bounds (see (41)).

(2) Scenario B: we assume that R_{n} goes up, and take $q = 0.66$, $\phi = -50^\circ$, which leads to $R_{\mathrm{n}} = 1.03$, $R_{\mathrm{c}} = 1.13$ and some interesting effects in rare decays, as we shall see below. This would, for example, occur if radiative corrections to the $B_d^0 \to \pi^- K^+$ branching ratio enhance R_{n} [47], though this alone would probably account for only about 5%.

(3) Scenario C: assume that both R_{n} and R_{c} move towards 1; taking $R_{\mathrm{n}} = R_{\mathrm{c}} = 1$ leads to $q = 0.54$, $\phi = 61^\circ$. The *positive* sign of the phase in this scenario distinguishes it strongly from both others.

The result of this exercise is contained in Tables 3 and 4: in Table 3, we show the values of a number of observables of the $B \to \pi K$ system in the three scenarios, while in Table 4, we show the corresponding values of the most interesting branching ratios for rare K and B decays. To this end, we have used for the angle β the value of β_{true} in Table 1. We observe that, in particular, the interplay of the $K \to \pi \bar{\nu} \nu$ modes is a very good and clean indication of which kind of NP scenario to look for. Due to the interference of charm and top contributions in $K^+ \to \pi^+ \bar{\nu} \nu$, it is also the decay that can most naturally be suppressed (though this is in contrast to the present experimental value). On the other hand, $\mathrm{BR}(K_{\mathrm{L}} \to \pi^0 \bar{\nu} \nu)$ is always enhanced due to the large values of ϕ and the absence of the charm contribution. Concerning the observables of the $B \to \pi K$ system, $\mathcal{A}_{CP}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$ offers a particularly interesting probe. This CP asymmetry comes out very large in Scenarios A and B, where the NP phase is negative. On the other hand, the positive sign in Scenario C brings this value closer to the data, in accordance with the features pointed out in Sect. 4.3. Similarly the experimental value of

$$\begin{aligned} \Delta A \; &\equiv \; \mathcal{A}_{CP}^{\mathrm{dir}}(B^\pm \to \pi^0 K^\pm) - \mathcal{A}_{CP}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm) \\ &\overset{\mathrm{exp}}{=} -0.16 \pm 0.04 \end{aligned} \tag{42}$$

favors a positive value of ϕ.

In Table 4, we show the effect of the various scenarios on selected rare decays. Our SM results differ slightly from the standard values because we use the CKM input from the first column in Table 1. Larger values of R_t and $\bar{\eta}$ than found in [7,8] result in higher values of $\mathrm{BR}(K^+ \to \pi^+ \bar{\nu} \nu)$ and $\mathrm{BR}(K_{\mathrm{L}} \to \pi^0 \bar{\nu} \nu)$, respectively, than found in [48] and [49]. The great sensitivity of the rare decay branching ratios to the parameters (q, ϕ) demonstrates clearly the impressive power of rare K and B decays to search for NP effects in the EW penguin sector.

6 Conclusions

In this paper, we have reconsidered our analysis of $B \to \pi\pi, \pi K$ and rare B and K decays in view of the new B-factory data for $(\sin 2\beta)_{\psi K_{\mathrm{S}}}$ and the two-body modes as well as more stringent bounds on rare decays. The main new messages from our analysis are as follows.

(1) The $B_d \to \pi^+ \pi^-$ and $B_d \to \pi^\mp K^\pm$ modes, which

Table 3. The $B \to \pi K$ observables for the three scenarios introduced in the text

Quantity	SM	Scen. A	Scen. B	Scen. C	Experiment
R_{n}	1.12	0.88	1.03	1	0.83 ± 0.08
R_{c}	1.15	0.96	1.13	1	1.01 ± 0.09
$\mathcal{A}_{CP}^{\mathrm{dir}}(B^{\pm}\to\pi^0 K^{\pm})$	0.04	0.07	0.06	0.02	-0.04 ± 0.04
$\mathcal{A}_{CP}^{\mathrm{dir}}(B_d\to\pi^0 K_{\mathrm{S}})$	0.06	0.04	0.03	0.09	-0.02 ± 0.13
$\mathcal{A}_{CP}^{\mathrm{mix}}(B_d\to\pi^0 K_{\mathrm{S}})$	−0.82	−0.89	−0.91	−0.70	-0.31 ± 0.26
ΔS	0.13	0.21	0.22	0.01	-0.38 ± 0.26
ΔA	−0.07	−0.04	−0.05	−0.09	-0.16 ± 0.04

Table 4. Rare decay branching ratios for the three scenarios introduced in the text

Decay 90% C.L.	SM	Scen. A	Scen. B	Scen. C	Exp. bound
$\mathrm{BR}(K^+ \to \pi^+\bar{\nu}\nu)/10^{-11}$	9.3	2.7	8.3	8.4	$(14.7^{+13.0}_{-8.9})$
$\mathrm{BR}(K_{\mathrm{L}} \to \pi^0\bar{\nu}\nu)/10^{-11}$	4.4	11.6	27.9	7.2	$< 2.9 \cdot 10^4$
$\mathrm{BR}(K_{\mathrm{L}} \to \pi^0 e^+e^-)/10^{-11}$	3.6	4.6	7.1	4.9	< 28
$\mathrm{BR}(B \to X_s\bar{\nu}\nu)/10^{-5}$	3.6	2.8	4.8	3.3	< 64
$\mathrm{BR}(B_s \to \mu^+\mu^-)/10^{-9}$	3.9	9.2	9.1	7.0	$< 1.5 \cdot 10^2$
$\mathrm{BR}(K_{\mathrm{L}} \to \mu^+\mu^-)_{\mathrm{SD}}/10^{-9}$	0.9	0.9	0.001	0.6	< 2.5

are marginally affected by EW penguins, allow us to determine $\gamma = (74 \pm 6)^\circ$. Complementing this value with $|V_{ub}/V_{cb}|$, we can determine the true unitarity triangle, allowing us to search for NP contributions to B_d^0–$\bar{B}_d^0$ mixing; we find a NP phase $\phi_d^{\mathrm{NP}} = -(8.2 \pm 3.5)^\circ$.

(2) The $B \to \pi K$ puzzle, which is in particular reflected by the low experimental value of the ratio R_{n} of the neutral $B \to \pi K$ branching ratios, persists. It still points to NP in the EW penguin sector, and favors a large NP phase $\phi \sim -90^\circ$, although now also a value around $+90^\circ$ can bring us rather close to the current experimental ranges of $R_{\mathrm{n,c}}$.

(3) $\phi \sim +90^\circ$ would allow us to accommodate also the pattern of $(\sin 2\beta)_{\pi^0 K_{\mathrm{S}}} < (\sin 2\beta)_{\psi K_{\mathrm{S}}}$, which may be indicated by the B-factory data and received recently a lot of attention, although the measurements suffer still from large uncertainties. A similar comment applies to the difference ΔA in (42) of the direct CP asymmetries of the $B_d \to \pi^{\mp}K^{\pm}$ and $B^{\pm} \to \pi^0 K^{\pm}$ modes, which could be increased for $\phi \sim +90^\circ$. However, the latter CP asymmetry suffers from large uncertainties in our approach and does therefore not (yet) allow a stringent test.

(4) The internal consistency checks of the working assumptions of our strategy are satisfied at the level of 25%, and can be improved through better data. We studied the sensitivity of our numerical predictions of the $B \to \pi K$ observables on non-factorizable $SU(3)$-breaking effects of this order of magnitude, and found that the impact is surprisingly small. Consequently, it is in fact very exciting to speculate on NP effects in the EW penguin contributions to the $B \to \pi K$ decays.

(5) In view of the fact that the parameters (q, ϕ) needed for the explanation of the low value of R_{n} appear to imply rare decay branching ratios that violate the experimental bound from $B \to X_s l^+ l^-$, we have explored various scenarios for (q, ϕ) that allow us to satisfy the rare decay constraints, but still give interesting results for both the $B \to \pi K$ decays and the rare K and B decays. Needless to say, our analysis of the $B \to \pi\pi$ modes and the determination of the angle γ described above are not affected by these modifications. On the other hand, we find again that reversing the sign of the NP phase ϕ brings the mixing-induced asymmetry of $B_d \to \pi^0 K_{\mathrm{S}}$ closer to the data.

Our analysis demonstrates that the simultaneous study of non-leptonic B-decay branching ratios, the corresponding direct and mixing-induced CP asymmetries and rare K and B decays within a consistent phenomenological framework developed in [1], can with improved data shed light on new physics and the structure of QCD dynamics in non-leptonic B decays.

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