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Solving the $B \to \pi\pi$ and $B \to \pi K$ puzzles

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Abstract

Gravity and quantum physics become inseparable at the Planck scale. This leads to the expectation that the space-time metric itself behaves as a quantum variable. In the present work, this behavior is modeled as conformal variations about the classical background metric. The scalar field which describes these variations represents the quantum fluctuations; it is treated in lowest order by employing the classical variation principle. Variation of the gravitational action leads thus to a modified Einstein equation, where the new extra term is interpreted as a cosmological constant. The resulting equation of motion for the expanding universe is capable of accommodating the current observational data, which indicate an accelerating expansion during the current epoch.

I. INTRODUCTION

In recent years, experimental data on $B \to \pi\pi$ and $B \to \pi K$ decays has shown some unexpected peculiarities, commonly called the "$B \to \pi\pi$ puzzle" and the "$B \to \pi K$ puzzle", respectively. In a serious of papers [1–3] we have developed a formalism, where both the $B \to \pi\pi$ and $B \to \pi K$ systems are studied in a common framework. Our framework takes advantage of Isospin and SU(3)-symmetry, but no further dynamical input is used to determine hadronic parameters. Instead, the hadronic parameters are directly extracted from the experimental results after a suitable parameterization of the relevant decay amplitudes is found.

Our strategy consists of first extracting the hadronic parameters from as few observables in the $B \to \pi\pi$ system as possible. We can then use those hadronic parameters to make predictions for the other observables in the $B \to \pi\pi$ system, we find good agreement with experiment. By comparison with general results from factorization approaches, we identify which contributions should be responsible for the deviations between our results and the dynamical approaches.

Using the hadronic parameters from the $B \to \pi\pi$ system, we can then try to describe the $B \to \pi K$ decays by employing SU(3)-symmetries to determine the relevant hadronic parameters in the $B \to \pi K$ system, taking into account relevant SU(3) breaking effects. We find that the $B \to \pi K$ puzzle is actually a lot more persistent than the $B \to \pi\pi$ puzzle. Although the experimental errors are still sizeable, the current data cannot be explained in the Standard Model (SM).

Interestingly, it was observed that those channels that display peculiarities are the very ones that receive significant contributions from electroweak (EW) penguins. We therefore decided to employ a well known model of New Physics (NP) that modifies those EW penguins to explain the $B \to \pi K$ puzzle. In the *Minimal Flavor Violation* (MFV) scenario [5–8] the Z^0 penguins are enhanced and acquire a non-zero CP-violating phase. (This last feature is considered to make the scenario non-*minimal* by some authors.) The MFV scenario not only allows to solve the problems in the $B \to \pi K$ system, but also spurts a great predictivity for other processes involving EW $b \to s$ penguins (rare decays).

Some of the experimental input data used in this analysis has been modified by the experimental results presented at the summer conferences between ICHEMP'05 and the write-up of this note, an update taking into account these new developments will be presented elsewhere [4]. This note uses the same experimental input as [3].

II. THE $B \to \pi\pi$ PUZZLE

Since the overall normalisations connected with individual branching ratios are of no interest in our approach, we consider the ratios

$$R_{+-}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B^+ \to \pi^+\pi^0) + \mathrm{BR}(B^- \to \pi^-\pi^0)}{\mathrm{BR}(B_d^0 \to \pi^+\pi^-) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+\pi^-)}\right]\frac{\tau_{B_d^0}}{\tau_{B^+}} \tag{2.1}$$

$$R_{00}^{\pi\pi} \equiv 2\left[\frac{\mathrm{BR}(B_d^0 \to \pi^0\pi^0) + \mathrm{BR}(\bar{B}_d^0 \to \pi^0\pi^0)}{\mathrm{BR}(B_d^0 \to \pi^+\pi^-) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+\pi^-)}\right] \tag{2.2}$$

of the CP-averaged $B \to \pi\pi$ branching ratios, and also the the time-dependent CP–asymmetries

$$\frac{\Gamma(B_d^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}{\Gamma(B_d^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}_d^0(t) \to \pi^+\pi^-)}$$
$$= \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-)\cos(\Delta M_d t) + \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-)\sin(\Delta M_d t)\,. \tag{2.3}$$

The status of the $B \to \pi\pi$ data as of ICHEMP'05 together with the relevant references is given in Table I. The value of $\mathrm{BR}(B_d \to \pi^0\pi^0)$ is significantly larger than expected, whereas the value of $\mathrm{BR}(B_d \to \pi^+\pi^-)$ is smaller. This results in values of $R_{00}^{\pi\pi}$ and $R_{+-}^{\pi\pi}$ that are both larger than expected e.g. in QCD factorization (QCDF) [17]. In QCDF, central values of $R_{00}^{\pi\pi} = 0.07$ and $R_{+-}^{\pi\pi} = 1.24$ [18] are obtained. By tuning the input parameters with regard to the experimental results ("scenario S4" in [18]), values of 0.2 and 2.0, respectively, can be accommodated, but the experimental results are still puzzling, giving rise to the "$B \to \pi\pi$ puzzle".

Contrary to the "$B \to \pi K$ puzzle" (to be discussed in the next session), the $B \to \pi\pi$ data can be explained with significant non-factorizable contributions without any indication of physics beyond the SM. Since the $B \to \pi\pi$ decays are tree–dominated, it would also be rather hard to accommodate effects that could not be explained in the SM by new physics: The NP scenario employed in [1,2] has a negligible impact on the $B \to \pi\pi$ system.

Using isospin symmetry, we decompose the amplitudes of the three different decay channels into

$$\sqrt{2}A(B^+ \to \pi^+\pi^0) = -[\tilde{T} + \tilde{C}] = -[T + C] \tag{2.4}$$

$$A(B_d^0 \to \pi^+\pi^-) = -[\tilde{T} + P] \tag{2.5}$$

$$\sqrt{2}A(B_d^0 \to \pi^0\pi^0) = -[\tilde{C} - P], \tag{2.6}$$

where the amplitudes P, $\tilde{T}$ and $\tilde{C}$ are given by

$$P = \lambda^3 A(\mathcal{P}_t - \mathcal{P}_c) \equiv \lambda^3 A\mathcal{P}_{tc} \tag{2.7}$$

$$\tilde{T} = \lambda^3 A R_b e^{i\gamma}\left[\mathcal{T} - (\mathcal{P}_{tu} - \mathcal{E})\right] \tag{2.8}$$

$$\tilde{C} = \lambda^3 A R_b e^{i\gamma}\left[\mathcal{C} + (\mathcal{P}_{tu} - \mathcal{E})\right]. \tag{2.9}$$

Here λ and A are the well known Wolfenstein parameters [19, 20] $\lambda \equiv |V_{us}| = 0.2240 \pm 0.0036$ and $A \equiv |V_{cb}|/\lambda^2 = 0.83 \pm 0.02$ and R_b is given by

$$R_b \equiv \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| = 0.37 \pm 0.04 \tag{2.10}$$

The amplitudes (2.7-2.9) describe the different topologies involved in the decays: $\mathcal{P}_q$ are QCD **p**enguins with internal q-quark exchange ($q \in \{t,c,u\}$), including annihilation and exchange penguins, $\mathcal{T}$ are colour-allowed **t**ree-diagram-like topologies and $\mathcal{C}$ are **c**olour-suppressed tree-diagram-like topologies. The $\mathcal{E}$ amplitude corresponds to the **e**xchange topology.

The usual definition of the tree and colour-suppressed amplitudes, T and C, differs from our $\tilde{T}$ and $\tilde{C}$ through the $(\mathcal{P}_{tu}-\mathcal{E})$ terms, which have been suggested to be significant [21] but are absent in (naïve) factorisation approaches. These terms also contain the "GIM penguins" with internal up-quark exchanges, whereas their "charming penguin" counterparts enter in P through $\mathcal{P}_c$ (c.f. (2.7)) [21–24].

Taking into account the isospin symmetry and disregarding the overall normalization, we can describe the $B \to \pi\pi$ with just two parameters, d and x, and their complex phases θ and Δ defined through

$$de^{i\theta} = -\left|\frac{P}{\tilde{T}}\right| e^{i(\delta_P-\delta_{\tilde{T}})}, \quad xe^{i\Delta} = \left|\frac{\tilde{C}}{\tilde{T}}\right| e^{i(\delta_{\tilde{C}}-\delta_{\tilde{T}})}, \tag{2.11}$$

with δ_i being strong phases. We can express the $R^{\pi\pi}$ ratios and the asymmetries using only these parameters,

$$R_{+-}^{\pi\pi} = \frac{1+2x\cos\Delta+x^2}{1-2d\cos\theta\cos\gamma+d^2} \tag{2.12}$$

$$R_{00}^{\pi\pi} = \frac{d^2+2dx\cos(\Delta-\theta)\cos\gamma+x^2}{1-2d\cos\theta\cos\gamma+d^2} \tag{2.13}$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d\to\pi^+\pi^-) = -\left[\frac{2d\sin\theta\sin\gamma}{1-2d\cos\theta\cos\gamma+d^2}\right] \tag{2.14}$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d\to\pi^+\pi^-) = \frac{\sin(\phi_d+2\gamma)-2d\cos\theta\sin(\phi_d+\gamma)+d^2\sin\phi_d}{1-2d\cos\theta\cos\gamma+d^2}. \tag{2.15}$$

Using the data for $R_{+-}^{\pi\pi}$, $R_{00}^{\pi\pi}$, $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}$ and $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}$ and additionally $\gamma = (65\pm7)^\circ$, $\phi_d = 2\beta = \left(46.5^{+3.2}_{-3.0}\right)^\circ$ we can solve the set of four equations with the four unknowns d, θ, x and Δ. Our results are

$$d = 0.51^{+0.26}_{-0.20}, \quad \theta = \left(140^{+14}_{-18}\right)^\circ, \quad x = 1.15^{+0.18}_{-0.16}, \quad \Delta = -\left(59^{+19}_{-26}\right)^\circ. \tag{2.16}$$

These results are at variance with expectations from QCDF, especially large values of the strong phases θ and Δ and x are not present in QCDF descriptions of the $B\to\pi\pi$ system. Looking at (2.11), we see that — if it was not for the $(\mathcal{P}_{tu}-\mathcal{E})$ term that distinguishes the amplitudes with a tilde from those without — x would correspond to the ratio of the colour–suppressed to the colour–allowed amplitude, a ratio that is certainly not expected to be close to unity. We therefore find that the $(\mathcal{P}_{tu}-\mathcal{E})$ term is important and suppresses (enhances) $\tilde{T}$ ($\tilde{C}$). In this way, BR($B_d\to\pi^+\pi^-$) and BR($B_d\to\pi^0\pi^0$) are suppressed and enhanced, respectively. With the hadronic parameters determined as in (2.16) we can predict the direct and mixing-induced CP asymmetries of the $B_d\to\pi^0\pi^0$ channel. These predictions, while still subject to large uncertainties, are very nicely consistent with recent data.

Quantity	Input	Exp. reference
BR($B^\pm\to\pi^\pm\pi^0$)/10^{-6}	5.5 ± 0.6	[9,10]
BR($B_d\to\pi^+\pi^-$)/10^{-6}	4.6 ± 0.4	[10,11]
BR($B_d\to\pi^0\pi^0$)/10^{-6}	1.51 ± 0.28	[9,12]
$R_{+-}^{\pi\pi}$	2.20 ± 0.31	
$R_{00}^{\pi\pi}$	0.67 ± 0.14	
$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d\to\pi^+\pi^-)$	-0.37 ± 0.11	[13,14]
$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d\to\pi^+\pi^-)$	$+0.61\pm0.14$	[13,14]

TABLE I. The $B\to\pi\pi$ input data for our strategy, with averages taken from [15]. For the evaluation of $R_{+-}^{\pi\pi}$, we have used the life-time ratio $\tau_{B^+}/\tau_{B_d^0} = 1.086\pm0.017$ [16].

The large non-factorizable effects found in [1] have been discussed at length in [2,3], they have been confirmed in [24–29]. In section III we will use the values of the hadronic parameters d, θ, x and Δ in (2.16). and employ $SU(3)$ flavor symmetry to determine the corresponding hadronic parameters of the $B \to \pi K$ system.

A. Determination of γ

In our original strategy, the CKM-angle γ is treated as an input parameter. Complementing the $B_d \to \pi^+\pi^-$ observables with either the ratio of the CP-averaged branching ratios $\mathrm{BR}(B_d \to \pi^\mp K^\pm)$ and $\mathrm{BR}(B_d \to \pi^+\pi^-)$ or the direct CP-asymmetry $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^\mp K^\pm)$, we can actually determine γ [30,31]. The result is

$$\gamma|_{\mathrm{BR}} = \left(63.3\,^{+7.7}_{-11.1}\right)^\circ, \quad \gamma|_{\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}} = \left(66.6\,^{+11.0}_{-11.1}\right)^\circ, \tag{2.17}$$

where the subscript indicates which additional input was used in the determination. This method of extracting γ is explained in detail in [2]. The results are very nicely consistent with each other and with standard UT analyzes [32], giving us confidence in the general validity of our approach.

III. THE $B \to \pi K$ PUZZLE

Just like in the $B \to \pi\pi$ system, we employ suitable ratios of branching ratios to discuss the physics behind the $B \to \pi K$ system. We now have two distinguishable families of particles in the final state that can be either charged or neutral, therefore there are three ratios now:

$$R \equiv \left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right] \frac{\tau_{B^+}}{\tau_{B_d^0}} \tag{3.1}$$

$$R_{\mathrm{c}} \equiv 2\left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+) + \mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \bar{K}^0)}\right] \tag{3.2}$$

$$R_{\mathrm{n}} \equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\mathrm{BR}(B_d^0 \to \pi^0 K^0) + \mathrm{BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right]. \tag{3.3}$$

The experimental status of the branching ratios (with references) and the corresponding values of the R_i are given in Table II. The "$B \to \pi K$ puzzle" consists of the small value of R_{n} which is significantly lower than R_{c}. As already pointed out in [35], the two values should be approximately equal. With the help of the formalism developed in [1,2], we can even show that both should be larger than unity in the SM.

Quantity	Data	Exp. reference
$\mathrm{BR}(B_d \to \pi^\mp K^\pm)/10^{-6}$	18.2 ± 0.8	[10,11]
$\mathrm{BR}(B^\pm \to \pi^\pm K)/10^{-6}$	24.1 ± 1.3	[10,33]
$\mathrm{BR}(B^\pm \to \pi^0 K^\pm)/10^{-6}$	12.1 ± 0.8	[9,10]
$\mathrm{BR}(B_d \to \pi^0 K)/10^{-6}$	11.5 ± 1.0	[10,34]
R	0.82 ± 0.06	0.91 ± 0.07
R_{c}	1.00 ± 0.08	1.17 ± 0.12
R_{n}	0.79 ± 0.08	0.76 ± 0.10

TABLE II. The experimental status of the CP-averaged $B \to \pi K$ branching ratios (averages from [15]) and the corresponding values of R, R_{c} and R_{n}. For comparison with our earlier work, in the last column the values of R_i at the time of the analyzes in [1,2] are shown.

Employing $SU(3)$ flavor symmetry and neglecting colour-suppressed EW penguins, we can decompose the amplitudes of the individual decay channels as

$$A(B_d^0 \to \pi^- K^+) = P' \left[1 - re^{i\delta}e^{i\gamma}\right] \tag{3.4}$$

$$A(B_d^\pm \to \pi^\pm K^0) = -P' \tag{3.5}$$

$$\sqrt{2}A(B^+ \to \pi^0 K^+) = P' \left[1 - \left(e^{i\gamma} - qe^{i\phi}\right) r_c e^{i\delta_c}\right] \tag{3.6}$$

$$\sqrt{2}A(B_d^0 \to \pi^0 K^0) = -P' \left[1 + \rho_n e^{i\theta_n} e^{i\gamma} - qe^{i\phi} r_c e^{i\delta_c}\right]. \tag{3.7}$$

P' is a QCD penguin amplitude that constitutes an overall normalization and therefore cancels in the ratios R_i and in the CP asymmetries. The hadronic parameters r, δ, ρ_n, θ_n, r_c and δ_c can be related to the hadronic parameters d, θ, x and Δ in (2.11) through $SU(3)$ flavor symmetry (taking into account some $SU(3)$–breaking corrections, see [2] for explicit expressions and [3] for numerical results. If we were not to take advantage of this relationship, the $B \to \pi K$ puzzle would still manifest itself [35], but we would have little predictive power as to where the effects might originate.

A. Observables that do not depend on EW penguin parameters

Recently, direct CP violation has been observed in the $B \to \pi K$ system [36, 37]:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm) \equiv \frac{{\rm BR}(B_d^0 \to \pi^- K^+) - {\rm BR}(\bar{B}_d^0 \to \pi^+ K^-)}{{\rm BR}(B_d^0 \to \pi^- K^+) + {\rm BR}(\bar{B}_d^0 \to \pi^+ K^-)} = +0.113 \pm 0.019, \tag{3.8}$$

With the help of our values for r and δ, we can calculate a theoretical prediction for this quantity via (3.4), we obtain $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm) = +0.127^{+0.102}_{-0.066}$, in very good agreement with the experimental result. In our original analysis [2], we obtained $+0.140^{+0.139}_{-0.087}$ while the experimental value at the time was $+0.095 \pm 0.028$, we therefore predicted that the value should go up.

The other two observables only marginally affected by EW penguins are the ratio R (3.1) and the direct CP asymmetry of $B^\pm \to \pi^\pm K$, they could however be affected by an additional hadronic parameter $\rho_c e^{i\theta_c}$, which is expected to play a minor rôle and was neglected in (3.5) and (3.6). A non-zero value of ρ_c, θ_c could imply a non-vanishing direct CP asymmetry in $B^\pm \to \pi^\pm K$ (depending on the phase θ_c. The experimental value of this asymmetry is $+0.020 \pm 0.034$, in accordance with vanishing ρ_c or ${\rm Im} e^{i\theta_c}$. Using our values for r and δ, we obtain

$$R = 0.943^{+0.028}_{-0.021}, \tag{3.9}$$

which is sizeably larger than the experimental value. The nice agreement of the data with our prediction of $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)$, which is independent of ρ_c, suggests that ρ_c is the origin of the deviation of R, this is supported by the fact that recent results on $B \to KK$ decays also hint towards a sizeable ρ_c with $\theta_c \approx 0$ just as needed for slightly lowering R without affecting $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm)$ [38].

B. Observables that do depend on EW penguin parameters

All observables discussed up to now are not only in accordance with our theoretical values but also independent of the parameters q and ϕ that parameterize the EW penguins. We find that exactly those observables that depend on these parameters are the ones that constitute the $B \to \pi K$ puzzle, this is what prompted us to propose a new physics scenario involving modified EW penguins to solve the $B \to \pi K$ puzzle.

In the SM, the parameters q and ϕ can be determined with the help of the $SU(3)$ flavor symmetry of strong interactions [39], yielding

$$q = 0.69 \times \left[\frac{0.086}{|V_{ub}/V_{cb}|}\right], \qquad \phi = 0^\circ. \tag{3.10}$$

Using this result, we can calculate R_c and R_n [1,2], obtaining [3]:

$$R_c|_{SM} = 1.14 \pm 0.05, \quad R_n|_{SM} = 1.11^{+0.04}_{-0.05}. \tag{3.11}$$

The experimental results for these quantities are shown in Table II, we find that R_c is more or less as expected, whereas the value of R_n in (3.11) is much too large.

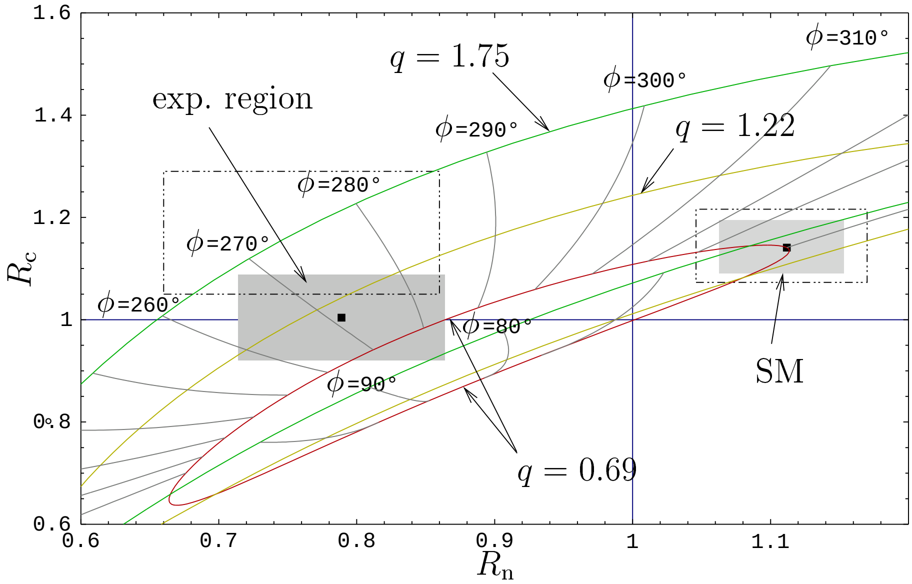

FIG. 1. The R_n–R_c plane. We show contours for values of $q = 0.69$, $q = 1.22$ and $q = 1.75$, with $\phi \in [0°, 360°]$. The experimental ranges for R_c and R_n and those predicted in the SM are indicated in grey, the dashed lines serve as a reminder of the corresponding ranges in [2].

Quantity	Our Prediction	Experiment
$\mathcal{A}^{\rm dir}_{\rm CP}(B_d \to \pi^0\pi^0)$	$-0.28^{+0.37}_{-0.21}$	-0.28 ± 0.39
$\mathcal{A}^{\rm mix}_{\rm CP}(B_d \to \pi^0\pi^0)$	$-0.63^{+0.45}_{-0.41}$	$-0.48^{+0.48}_{-0.40}$
$\mathcal{A}^{\rm dir}_{\rm CP}(B_d \to \pi^\mp K^\pm)$	$0.127^{+0.102}_{-0.066}$	0.113 ± 0.019
$\mathcal{A}^{\rm dir}_{\rm CP}(B^\pm \to \pi^0 K^\pm)$	$0.10^{+0.25}_{-0.19}$	-0.04 ± 0.04
$\mathcal{A}^{\rm dir}_{\rm CP}(B_d \to \pi^0 K_S)$	$0.01^{+0.15}_{-0.18}$	0.09 ± 0.14
$\mathcal{A}^{\rm mix}_{\rm CP}(B_d \to \pi^0 K_S)$	$-0.98^{+0.04}_{-0.02}$	$-0.34^{+0.29}_{-0.27}$

TABLE III. Compilation of our predictions for the CP-violating $B \to \pi\pi$, πK asymmetries.

The expected ("SM") and measured values are shown in the R_n–R_c plane in Fig. 1. Following [2], we show contours for ϕ between 0 (SM) and 360° and $q = 0.69$ (SM), 1.22 and 1.75, where the latter reproduced the central values of R_c and R_n in our previous analysis [1, 2]. We see that a q as large as 1.75 (which was not compatible with rare decay constraints) is actually not required anymore. The experimental values are reproduced for [3]:

$$q = 1.08\,^{+0.81}_{-0.73}, \qquad \phi = -(88.8^{+13.7}_{-19.0})^\circ\,, \tag{3.12}$$

where the absolute value q is compatible with the SM, but the large phase ϕ is a spectacular signal of possible NP contributions. The dashed lines in Fig. 1 show the situation in our previous analysis [1, 2], we find that the central values for the SM prediction have hardly moved, while their uncertainties have been reduced a bit. On the other hand, the central experimental values of R_c and R_n have moved in such a way that q decreased, while the weak phase ϕ remains around $-90°$. This movement of R_c and R_n had actually been anticipated in [2] for reasons of compatibility with rare decay constraints.

The predictions for the CP asymmetries in the $B \to \pi\pi$ and $B \to \pi K$ systems in our new physics scenario (3.12) are given in Table III.

IV. IMPLICATIONS FOR RARE K AND B DECAYS

As explained in the introduction, the MFV model (here parameterized by non-SM q and ϕ) has implications on other processes induced by the modified Z^0 penguins, we will study the impact of the NP needed to explain the $B \to \pi K$ puzzle on rare K and B decays. The Z^0-penguin function C can be related to our parameter q by [1, 2, 40]

$$C = |C|e^{i\theta_C} = 2.35\bar{q}e^{i\phi} - 0.82, \qquad \bar{q} = q\left|\frac{V_{ub}/V_{cb}}{0.086}\right|\,. \tag{4.1}$$

The functions X, Y, Z that govern rare decays can easily be derived from C,

$$X = |X|e^{i\theta_X} = 2.35\bar{q}e^{i\phi} - 0.09, \tag{4.2}$$

$$Y = |Y|e^{i\theta_Y} = 2.35\bar{q}e^{i\phi} - 0.64, \tag{4.3}$$

$$Z = |Z|e^{i\theta_Z} = 2.35\bar{q}e^{i\phi} - 0.94. \tag{4.4}$$

The only source of a phase for these quantities is the NP phase ϕ, in the SM and in the scenario considered in [40]), the functions X, Y, Z remain real. Studying the decay rates for various rare decays in our NP scenario, it turns out that the data on inclusive $B \to X_s l^+ l^-$ decays [41,42] are presently most powerful to constrain X, Y, Z, but due to significant experimental errors and theoretical uncertainties these bounds are only approximate. Typically, X, Y, Z are allowed to be at most 2.2 (while $X \approx 1.5$, $Y \approx 1.0$, $Z \approx 0.7$ in the SM).

The three functions X, Y, Z are important for different decays: X governs decays with $\nu\bar{\nu}$ in the final state like $K \to \pi\nu\bar{\nu}$, Y those with l^+l^- in the final state and Z is relevant for $K_L \to \pi^0 l^+ l^-$ and ϵ'/ϵ. In our scenario of physics all these decays are modified, but all stay within experimental bounds. The most prominent signature of our scenario is [1, 2]

$$\frac{\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})}{\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})_{\mathrm{SM}}} = \left|\frac{X}{X_{\mathrm{SM}}}\right|^2 \left[\frac{\sin(\beta-\theta_X)}{\sin(\beta)}\right]^2,$$

with the two factors on the right-hand side in the ball park of 2 and 5, respectively. Consequently, $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ can be enhanced over the SM prediction even by an order of magnitude and is expected to be roughly by a factor of 4 larger than $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$. In the SM and most MFV models the pattern is totally different with $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ smaller than $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ by a factor of 2–3 [32, 43, 44]. On the other hand a recent analysis shows that a pattern of $BR(K \to \pi\nu\bar{\nu})$ expected in our NP scenario can be obtained in a general MSSM [45]. The branching ratio of $K_L \to \pi^0\nu\bar{\nu}$ is actually predicted to be rather close to its model-independent upper bound [46], $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \leq 4.4\,\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$.

We show some of the numerical results of the implications of our NP scenario (with the parameters q and ϕ determined so that R_c and R_n agree with their experimental values) in Table IV. As mentioned above, in our original analysis [2] the value for q needed to exactly reproduce the experimental values for R_c and R_n was 1.75. This q violated some of the rare decay constraints and we therefore considered a smaller q that could still reasonably explain R_c and R_n without violating the rare decay constraints. With the new values for R_c and R_n, the required q has come down to almost exactly the size allowed by rare decay constraints, therefore we can directly use the q from R_c and R_n and the values in Table IV are very similar to the ones in [2].

Decay	SM prediction	Our scenario	Exp. bound (90% C.L.)
$K^+ \to \pi^+\bar{\nu}\nu$	$(7.8 \pm 1.2) \cdot 10^{-11}$	$(7.5 \pm 2.1) \cdot 10^{-11}$	$(14.7^{+13.0}_{-8.9}) \cdot 10^{-11}$ [47]
$K_L \to \pi^0\bar{\nu}\nu$	$(3.0 \pm 0.6) \cdot 10^{-11}$	$(3.1 \pm 1.0) \cdot 10^{-10}$	$< 5.9 \cdot 10^{-7}$ [48]
$K_L \to \pi^0 e^+ e^-$	$(3.7^{+1.1}_{-0.9}) \cdot 10^{-11}$	$(9.0 \pm 1.6) \cdot 10^{-11}$	$< 2.8 \cdot 10^{-10}$ [49]
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.5 \pm 0.3) \cdot 10^{-11}$	$(4.3 \pm 0.7) \cdot 10^{-11}$	$< 3.8 \cdot 10^{-10}$ [50]
$B \to X_s \bar{\nu}\nu$	$(3.5 \pm 0.5) \cdot 10^{-5}$	$\approx 7 \cdot 10^{-5}$	$< 6.4 \cdot 10^{-4}$ [51]
$B_s \to \mu^+ \mu^-$	$(3.42 \pm 0.53) \cdot 10^{-9}$	$\approx 17 \cdot 10^{-9}$	$< 5.0 \cdot 10^{-7}$ [52]

TABLE IV. Predictions for various rare decays in the scenario considered compared with the SM expectations and experimental bounds.

Summary

We have shown how the $B \to \pi\pi$ puzzle can be solved within the Standard Model by significant non-factorisable contributions to the decay amplitudes and how New Physics is necessary to explain the current experimental data on the $B \to \pi K$ system. We have presented a New Physics scenario that reproduces the observed features in the $B \to \pi K$ system and studied the impact of this scenario on rare B and K decays.

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V. REFERENCES

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