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Searching for new physics with $B \to K\pi$ decays

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ABSTRACT

We propose a method to quantify the Standard Model uncertainty in $B \to K\pi$ decays using the experimental data, assuming that power counting provides a reasonable estimate of the subleading terms in the $1/m_b$ expansion. Using this method, we show that present $B \to K\pi$ data are compatible with the Standard Model. We analyze the pattern of subleading terms required to reproduce the $B \to K\pi$ data and argue that anomalously large subleading terms are not needed. Finally, we find that $S_{K_S\pi^0}$ is fairly insensitive to hadronic uncertainties and obtain the Standard Model estimate $S_{K_S\pi^0} = 0.74 \pm 0.04$.

A decade of physics studies at the B factories produced the impressive set of results on $B \to K\pi$ decays summarized in Table 1. As data became more and more accurate, phenomenological analyses based on flavour symmetries and/or hadronic models were not able to fully reproduce the data. This led several authors to introduce the $K\pi$ *puzzle* in its different incarnations [1,2]. In particular, the difference $\Delta A_{CP} = A_{CP}(K^+\pi^0) - A_{CP}(K^+\pi^-)$ has recently received considerable attention, following the new measurement $\Delta A_{CP} = 0.164 \pm 0.037$ published by the Belle Collaboration [3]. It has been argued that ΔA_{CP} could be a hint of New Physics (NP), but alternative explanations within the Standard Model (SM) have also been considered.

To understand whether $B \to K\pi$ decays are really puzzling, possibly calling for NP, one has to control the SM expectations for the $B \to K\pi$ amplitudes with a level of accuracy dictated by the size of the potential NP contributions. Thanks to the progress of theory in the last few years, we know that two-body non-leptonic B decay amplitudes are factorizable in the infinite b-quark mass limit, i.e. computable in terms of a reduced set of universal non-perturbative parameters [7–9]. However, the accuracy of the predictions obtained with factorization is limited by the uncertainties on the non-perturbative parameters on the one hand and by the uncalculable subleading terms in the $1/m_b$ expansion on the other. The latter problem is particularly severe for $B \to K\pi$ decays where some power-suppressed terms are doubly Cabibbo-enhanced with respect to factorizable terms [10]. Indeed factorization typically predicts too small $B \to K\pi$ branching ratios, albeit with large uncertainties. The introduction of subleading terms, certainly present at the physical value of the b quark mass, produces large effects in branching ratios and CP asymmetries, leading to a substantial model dependence of the SM predictions. Given this situation, NP contributions to $B \to K\pi$ amplitudes could be easily misidentified.

Table 1
Experimental inputs and fit results for $B \to K\pi$. For each observable, we report experimental results ($\mathrm{BR}^{\mathrm{exp}}$ and A_{CP}^{exp}) [3–5] taken from HFAG [6], the results of the fit using all the constraints (third column) and the prediction obtained using all constraints except the considered observable (fourth column). For ΔA_{CP}, the prediction is obtained by removing both $A_{CP}(K^+\pi^0)$ and $A_{CP}(K^+\pi^-)$ from the fit.

Decay mode	HFAG average	Global fit	Fit prediction
10^6 BR$(K^+\pi^-)$	19.4 ± 0.6	19.5 ± 0.5	19.7 ± 1.0
10^6 BR$(K^+\pi^0)$	12.9 ± 0.6	12.7 ± 0.5	12.4 ± 0.7
10^6 BR$(K^0\pi^+)$	23.1 ± 1.0	23.8 ± 0.8	24.9 ± 1.2
10^6 BR$(K^0\pi^0)$	9.8 ± 0.6	9.3 ± 0.4	8.7 ± 0.6
$A_{CP}(K^+\pi^-)$ [%]	-9.8 ± 1.2	-9.5 ± 1.2	3.9 ± 6.8
$A_{CP}(K^+\pi^0)$ [%]	5.0 ± 2.5	3.6 ± 2.4	-6.2 ± 6.0
$A_{CP}(K^0\pi^+)$ [%]	0.9 ± 2.5	1.8 ± 2.1	6.2 ± 4.5
$C(K_S\pi^0)$	0.01 ± 0.10	0.09 ± 0.03	0.10 ± 0.03
$S(K_S\pi^0)$	0.57 ± 0.17	0.73 ± 0.04	0.74 ± 0.04
ΔA_{CP} [%]	14.8 ± 2.8	13.1 ± 2.6	1.7 ± 6.1

In this Letter, we suggest a method to estimate the SM uncertainty given the experimental data, assuming that subleading terms are at most of order $1/m_b$.[1] This procedure provides a solid starting point for NP searches. Clearly, we are not sensitive to the presence of NP contributions of the same size as the subleading corrections to factorization.

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[1] An early attempt at this method was presented in Ref. [11].

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We now describe our method in detail. We start with a general parametrization of the $B \to K\pi$ amplitudes derived from the one in Ref. [12]. The decay amplitudes are given by:

$$\begin{aligned}
A\big(B^+ \to K^0\pi^+\big) &= -V_{ts}V_{tb}^* P + V_{us}V_{ub}^* A,\\
A\big(B^+ \to K^+\pi^0\big) &= \frac{1}{\sqrt{2}}\big(V_{ts}V_{tb}^*(P + \Delta P_1 + \Delta P_2)\\
&\quad - V_{us}V_{ub}^*(E_1 + E_2 + A)\big),\\
A\big(B^0 \to K^+\pi^-\big) &= V_{ts}V_{tb}^*(P + \Delta P_1) - V_{us}V_{ub}^* E_1,\\
A\big(B^0 \to K^0\pi^0\big) &= -\frac{1}{\sqrt{2}}\big(V_{ts}V_{tb}^*(P - \Delta P_2) + V_{us}V_{ub}^* E_2\big). \qquad (1)
\end{aligned}$$

In terms of the parameters of Ref. [12], our parameters read

$$\begin{aligned}
E_1 &= E_1(s,q,q;B,K,\pi) - P_1^{\mathrm{GIM}}(s,q;B,K,\pi),\\
E_2 &= E_2(q,q,s;B,\pi,K) + P_1^{\mathrm{GIM}}(s,q;B,K,\pi),\\
A &= A_1(s,q,q;B,K,\pi) - P_1^{\mathrm{GIM}}(s,q;B,K,\pi),\\
P &= P_1(s,d;B,K,\pi),\\
\Delta P_1 &= P_1(s,u;B,K,\pi) - P_1(s,d;B,K,\pi),\\
\Delta P_2 &= P_2(s,u;B,\pi,K) - P_2(s,d;B,\pi,K). \qquad (2)
\end{aligned}$$

With respect to the most general parametrization, we have neglected isospin breaking in the hadronic matrix elements of the effective weak Hamiltonian, yet fully retaining the effects of the electroweak penguins (EWP). This assumption reduces the number of independent parameters and removes the dependence on meson charges in the arguments of the parameters on the r.h.s. of Eqs. (2), where q denotes the light quarks.

Our procedure is to fit the hadronic parameters to the experimental data, taking into account the hierarchy between leading and subleading terms in the $1/m_b$ expansion by imposing an upper bound to subleading corrections. Only the correction to the dominant penguin amplitude is well determined by the fit. The information on the subdominant terms is limited, while their presence contributes to the theoretical uncertainty. The theoretical error on the predicted observables is thus determined by the allowed range for the subleading parameters. While quantifying this range is somewhat arbitrary, extreme situations in which the leading and subleading terms are comparable would imply a failure of the infinite mass limit. Of course, one has to be careful about possible parametric or dynamical enhancements which could invalidate the power counting. Chirally-enhanced terms in $B \to K\pi$ amplitudes are well-known examples of terms that are formally subleading but numerically of $\mathcal{O}(1)$. We have therefore included them in the leading factorized amplitudes. We now quantify the allowed ranges we use for subleading corrections. To this aim, we write each parameter as follows:

$$\begin{aligned}
E_1 &= E_1^{\mathrm{F}} + Fr(E_1),\\
E_2 &= E_2^{\mathrm{F}} + Fr(E_2)e^{i\delta(E_2)},\\
A &= A^{\mathrm{F}} + Fr(A)e^{i\delta(A)},\\
P &= P^{\mathrm{F}} + Fr(P)e^{i\delta(P)},\\
\Delta P_1 &= \Delta P_1^{\mathrm{F}} + F\alpha_{\mathrm{em}} r(\Delta P_1)e^{i\delta(\Delta P_1)},\\
\Delta P_2 &= \Delta P_2^{\mathrm{F}} + F\alpha_{\mathrm{em}} r(\Delta P_2)e^{i\delta(\Delta P_2)}, \qquad (3)
\end{aligned}$$

where the factorized amplitudes in the limit $m_b \to \infty$ are

$$\begin{aligned}
E_1^{\mathrm{F}} &= A_{\pi K}\big(-\alpha_1 - \alpha_4^u + \alpha_4^c - \alpha_{4,\mathrm{EW}}^u + \alpha_{4,\mathrm{EW}}^c\big),\\
E_2^{\mathrm{F}} &= A_{K\pi}\left(-\alpha_2 - \frac{3}{2}\big(\alpha_{3,\mathrm{EW}}^u - \alpha_{3,\mathrm{EW}}^c\big)\right)\\
&\quad + A_{\pi K}\left(\alpha_4^u - \alpha_4^c - \frac{1}{2}\big(\alpha_{4,\mathrm{EW}}^u - \alpha_{4,\mathrm{EW}}^c\big)\right),\\
A^{\mathrm{F}} &= A_{\pi K}\left(-\alpha_4^u + \alpha_4^c + \frac{1}{2}\big(\alpha_{4,\mathrm{EW}}^u - \alpha_{4,\mathrm{EW}}^c\big)\right),\\
P^{\mathrm{F}} &= A_{\pi K}\left(-\alpha_4^c + \frac{1}{2}\alpha_{4,\mathrm{EW}}^c\right),\\
\Delta P_1^{\mathrm{F}} &= -A_{\pi K}\frac{3}{2}\alpha_{4,\mathrm{EW}}^c,\\
\Delta P_2^{\mathrm{F}} &= -A_{K\pi}\frac{3}{2}\alpha_{3,\mathrm{EW}}^c, \qquad (4)
\end{aligned}$$

Table 2
Input values used in the analysis. Form factors are taken from lattice QCD calculations [14]. CKM parameters have been taken from Ref. [15]. Wave function parameters can be found in Table 1 of Ref. [13].

f_π	0.1307 GeV	f_K	0.1598 GeV
$F^{B\to\pi}$	0.27 ± 0.08	$F^{B\to K}/F^{B\to\pi}$	1.20 ± 0.10
τ_{B^0}	1.546×10^{-12} ps	τ_{B^+}	1.674×10^{-12} ps
m_B	5.2794 GeV	f_B	0.189 ± 0.027 GeV
m_π	0.14 GeV	m_K	0.493677 GeV
λ	0.2258 ± 0.0014	A	0.810 ± 0.011
$\bar\rho$	0.154 ± 0.022	$\bar\eta$	0.342 ± 0.014

in terms of the parameters α defined in Eq. (31) of Ref. [13]. We note that we have discarded non-factorizable contributions to the chirally enhanced terms. Furthermore,

$$\begin{aligned}
A_{\pi K} &= G_F/\sqrt{2}m_B^2 f_K F_\pi(0),\\
A_{K\pi} &= G_F/\sqrt{2}m_B^2 f_\pi F_K(0). \qquad (5)
\end{aligned}$$

The coefficient F in Eqs. (3) sets the normalization of subleading corrections and is equal to $A_{\pi K}$ computed using the central value of the form factor. The phase convention is chosen such that the power correction to E_1 is real.

The subleading terms in units of F are given by $r(X) = [0, 0.5]$ for $X = \{E_1, E_2, A, \Delta P_1, \Delta P_2\}$. Since $r(P)$ is very well determined by the fit, for computational efficiency we used $r(P) = [0, 0.2]$. For the sake of comparison, Ref. [13] quotes a value of $0.09^{+0.32}_{-0.09}$ for the contribution to $r(P)$ from penguin annihilation, compatible with the range we use. All strong phases vary in the range $[-\pi, \pi]$.

Using the ranges above for the hadronic parameters and the input parameters reported in Table 2, we perform a fit to the data in Table 1 using the method described in Ref. [16]. Flat priors are used for the hadronic parameters. Two sets of results are summarized in Table 1. On one hand, when using all the experimental information as input we test the consistency of the SM description of the decay amplitudes in a *global fit*. On the other hand, by removing one of the inputs from the fit we obtain a *prediction* of the corresponding experimental observable, using all the other inputs to constrain the hadronic parameters.

Two main results are obtained from the *global fit*: (i) the BR values are well reproduced, and they are fairly insensitive to the $1/m_b$ contributions, but for the CKM-enhanced charming penguin P. (ii) The values of the A_{CP} are well reproduced, thanks to the $1/m_b$ contributions. In particular, the presence of ΔP_2 ($E_2 + A$) in the CKM-enhanced (CKM-suppressed) part of the $B^+ \to K^+\pi^0$ amplitude (see Eq. (1)) allows to obtain simultaneously a positive value of $A_{\mathrm{CP}}(K^+\pi^0)$ and a negative value of $A_{\mathrm{CP}}(K^+\pi^-)$. This is shown in the left plot of Fig. 1, where the output distribution of ΔA_{CP} is fully consistent with the experimental world average $\Delta A_{\mathrm{CP}} = 0.148 \pm 0.028$.

The results for the hadronic parameters are shown in Figs. 2–4. Both the charming penguin parameters $r(P)$ and $\delta(P)$ are well determined, in agreement with the old results of Ref. [10]. In particular, $r(P)$ is found to be of $\mathcal{O}(1/m_b)$, as expected from the power expansion in QCD factorization. Small values of $r(A)$ are favoured,