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Penguin Zoology in $B \to \pi\pi$ and the Extraction of the CKM Angle α

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Abstract

We reanalyze the decay $B_d \to \pi^+\pi^-$ without assuming dominance of QCD penguins with internal top-quark exchanges. In that case the weak phase of the $\bar{b} \to \bar{d}$ QCD penguin amplitude is not related in a simple way to the CKM angle β. Nevertheless it is still possible to extract the CKM angle α in a transparent and almost model-independent way from the time-dependent CP-violating asymmetry of the transition $B_d \to \pi^+\pi^-$. Aside from that CP asymmetry this approach needs as an input only amplitudes of decays with branching ratios of order 10^{-5} and will thus be well within reach at future B-factories.

Among the central goals of the planned dedicated B-physics experiments is the direct measurement of the angles α, β and γ arising in the unitarity triangle (UT) [1] of the Cabibbo–Kobayashi–Maskawa matrix (CKM matrix) [2]. Besides the "gold-plated" decay $B_d \to J/\psi K_S$ to determine $\sin(2\beta)$, the transition $B_d \to \pi^+\pi^-$ plays a very important role to accomplish this task [3].

It is well-known that the time-dependent CP-violating asymmetry of this decay defined by

$$\begin{aligned} a_{\rm CP}(t) &\equiv \frac{\Gamma(B_d^0(t) \to \pi^+\pi^-) - \Gamma(\overline{B_d^0}(t) \to \pi^+\pi^-)}{\Gamma(B_d^0(t) \to \pi^+\pi^-) + \Gamma(\overline{B_d^0}(t) \to \pi^+\pi^-)} \\ &= \mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_d\, t) + \mathcal{A}_{\rm CP}^{\text{mix-ind}}\sin(\Delta M_d\, t) \end{aligned} \tag{1}$$

probes the angle α of the UT, where $\Delta M_d > 0$ denotes the mass splitting of the $B_d^0 - \overline{B_d^0}$ mass eigenstates. In this expression we have separated direct from mixing-induced CP-violating contributions which are characterized by

$$\mathcal{A}_{\rm CP}^{\rm dir} \equiv \frac{1 - \left|\xi_{\pi^+\pi^-}^{(d)}\right|^2}{1 + \left|\xi_{\pi^+\pi^-}^{(d)}\right|^2}, \quad \mathcal{A}_{\rm CP}^{\text{mix-ind}} \equiv \frac{2\,{\rm Im}\,\xi_{\pi^+\pi^-}^{(d)}}{1 + \left|\xi_{\pi^+\pi^-}^{(d)}\right|^2}. \tag{2}$$

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The observable $\xi^{(d)}_{\pi^+\pi^-}$ containing essentially all the information that is needed to evaluate these quantities takes the following form:

$$\xi^{(d)}_{\pi^+\pi^-} = -e^{-2i\beta}\left[\frac{e^{-2i\gamma}A_{\rm CC}+\overline{A}_{\rm PEN}}{A_{\rm CC}+A_{\rm PEN}}\right], \tag{3}$$

where $A_{\rm CC}$ is the contribution of the current-current operators including the tree process as well as the exchange contribution and $A_{\rm PEN}$ ($\overline{A}_{\rm PEN}$) are the contributions of the penguin type to $B^0_d \to \pi^+\pi^-$ ($\overline{B^0_d} \to \pi^+\pi^-$).

If there were no penguin contributions present in $B_d \to \pi^+\pi^-$, i.e. $A_{\rm PEN} = \overline{A}_{\rm PEN} = 0$, we would simply have [3]

$$a_{\rm CP}(t) = -\sin(2\alpha)\sin(\Delta M_d\, t) \tag{4}$$

and could determine α from that expression. However, penguins contribute and disturb the relation (4) between $\sin(2\alpha)$ and the CP-violating asymmetry arising in $B_d \to \pi^+\pi^-$. The corresponding hadronic uncertainties have been investigated by many authors in the previous literature (see e.g. [4]).

One distinguishes between two types of penguin topologies: QCD and electroweak penguins related to strong and electroweak interactions, respectively. Consequently the penguin amplitude $A_{\rm PEN}$ can be decomposed as

$$A_{\rm PEN} = P + P_{\rm EW}, \tag{5}$$

where P describes the $\bar{b} \to \bar{d}$ QCD penguins and $P_{\rm EW}$ denotes the $\bar{b} \to \bar{d}$ electroweak penguin contributions. Whereas there are certain non-leptonic B decays where electroweak penguins play an important role [5], in the transitions considered in this letter electroweak penguins enter only in color-suppressed form and hence lead to small effects [6, 7]. Therefore we may omit the electroweak penguin contributions in the following discussion.

There are strategies that allow to eliminate the QCD penguin uncertainties in $B_d \to \pi^+\pi^-$ thereby providing a clean extraction of α. Probably the best known example is the isospin approach based on triangle constructions that was proposed by Gronau and London [8] and requires in addition to a time-dependent measurement of $B_d(t) \to \pi^+\pi^-$ also the branching ratios $\mathrm{BR}(B^+ \to \pi^+\pi^0)$ and $\mathrm{BR}(B_d \to \pi^0\pi^0)$. Since the branching ratio of $B_d \to \pi^0\pi^0$ is expected to be of $\mathcal{O}(10^{-6})$ or even smaller [7], this approach is – despite of its attractiveness – rather difficult from an experimental point of view. For alternative methods to determine α see e.g. [9].

In this note we reanalyze the contributions of the QCD penguin type to the time-dependent CP asymmtery (1). To the best of our knowledge it has been assumed in all previous studies of the hadronic uncertainties affecting the determination of α that the QCD penguins are dominated by internal top-quark exchanges. Under this assumption the $\bar{b} \to \bar{d}$ QCD penguin amplitude P takes the very simple form

$$P = e^{-i\beta}e^{i\delta_P}|P|, \tag{6}$$

where δ_P is a CP-conserving strong phase.

However, as was shown in [10], also QCD penguins with up- and charm-quarks running as virtual particles in the loops may play an important role and cannot be neglected. In particular these penguin topologies contain long-distance contributions such as $B_d^0 \to \{D^+D^-\} \to \pi^+\pi^-$ (see e.g. [11]) which are very hard to estimate. In the following discussion we shall include these contributions into the definition of the $\bar{b} \to \bar{d}$ QCD penguin amplitudes and hence we relax the condition of top-quark dominance.

Using the notation of [10] the contributions of the $\bar{b} \to \bar{d}$ QCD penguin type read

$$P = \sum_{q=u,c,t} V_{qd} V_{qb}^* P_q\,, \tag{7}$$

where P_q is the amplitude of a QCD penguin process with internal quark q omitting the CKM factors. Note that $\overline{P}$ (the $b \to d$ QCD penguin amplitude) is related to P by reversing the signs of the weak phases. For the observable $\xi_{\pi^+\pi^-}^{(d)}$ one may write using (3)

$$\xi_{\pi^+\pi^-}^{(d)} = -\left[\frac{e^{2i\alpha} + e^{-2i\beta}\frac{\overline{P}}{\overline{A}_{\rm CC}}}{1 + \frac{P}{A_{\rm CC}}}\right]. \tag{8}$$

We shall exploit the fact that the penguin contributions P and $\overline{P}$ are expected to be much smaller than the current-current amplitude $A_{\rm CC}$ [12, 13]. In fact, using the operator basis for the $|\Delta B| = 1$ Hamiltonian as given in [14], one can obtain a simple estimate for this ratio. To this end we shall retain only the top-quark contribution (*only* for this estimate!) and write

$$\overline{P} = -\frac{G_{\rm F}}{\sqrt{2}} V_{td}^* V_{tb} \sum_{k=3}^{6} C_k \langle \pi^+\pi^- | Q_k | \overline{B_d^0} \rangle \tag{9}$$

$$\overline{A}_{\rm CC} = \frac{G_{\rm F}}{\sqrt{2}} V_{ud}^* V_{ub} \sum_{k=1}^{2} C_k \langle \pi^+\pi^- | Q_k | \overline{B_d^0} \rangle, \tag{10}$$

where the C_k are the Wilson coefficients of the current-current ($k = 1, 2$) and QCD penguin operators ($k = 3, ..., 6$) taken at the scale $\mathcal{O}(m_b)$. The hadronic matrix elements of the four-quark operators Q_k are evaluated in factorization which implies a Fierz rearrangement for some of the operators. In that way one obtains

$$\begin{aligned} \left|\frac{\overline{P}}{\overline{A}_{\rm CC}}\right| \approx \left|\frac{P}{A_{\rm CC}}\right| &\approx \left|\frac{C_3/N_c + C_4 + \frac{2M_\pi^2}{(m_u+m_d)m_b}[C_5/N_c + C_6]}{C_1/N_c + C_2}\right| \frac{|V_{td}|}{|V_{ub}|} \\ &\approx 0.05 \cdot \frac{|V_{td}|}{|V_{ub}|} \approx 0.07 - 0.23, \end{aligned} \tag{11}$$

where $N_c = 3$ is the number of quark-colors and the factor $M_\pi^2/[(m_u + m_d)m_b]$ is due to the use of the equations of motion for the quark fields. We have used the range for the CKM-factor $|V_{td}|/|V_{ub}|$ given by Ali and London in Ref. [15].

From this simple estimate it seems to be justified to expand the observable (8) in powers of $\overline{P}/\overline{A}_{\rm CC}$ and $P/A_{\rm CC}$ and to keep only the leading term in that expansion, hence

$$\xi_{\pi^+\pi^-}^{(d)} = -\left(e^{2i\alpha} + \frac{e^{-2i\beta}\overline{P}}{\overline{A}_{\rm CC}}\right)\left(1 - \frac{P}{A_{\rm CC}}\right) + \mathcal{O}\left((P/A_{\rm CC})^2\right)$$

$$= -e^{2i\alpha}\left[1+\frac{e^{-i\delta_{\rm CC}}}{|A_{\rm CC}|}\left(e^{i\gamma}\,\overline{P}-e^{-i\gamma}P\right)\right]+\mathcal{O}\left((P/A_{\rm CC})^2\right),$$

where $\delta_{\rm CC}$ denotes the CP-conserving strong phase of the amplitude

$$A_{\rm CC}=e^{i\gamma}e^{i\delta_{\rm CC}}|A_{\rm CC}|. \tag{12}$$

As we will see in a moment, by measuring a ratio of certain branching ratios (both $\mathcal{O}(10^{-5})$) it can be tested easily whether this expansion is in fact justified.

In order to discuss the effect of the subdominant penguin contributions P_u and P_c we follow [10] and write

$$P=\left[-\frac{1}{R_t}\Delta P+e^{-i\beta}\right]|V_{td}||P_{tu}|e^{i\delta_{tu}}, \tag{13}$$

where we have introduced $P_{q_1q_2}\equiv|P_{q_1q_2}|e^{i\delta_{q_1q_2}}\equiv P_{q_1}-P_{q_2}$ and

$$R_t\equiv\frac{1}{\lambda}\frac{|V_{td}|}{|V_{cb}|}=\frac{\sin\gamma}{\sin\alpha} \tag{14}$$

with $\lambda\approx 0.22$ being the parameter in the Wolfenstein parametrization [16] of the CKM matrix. The quantity ΔP given by

$$\Delta P\equiv\frac{P_{cu}}{P_{tu}} \tag{15}$$

measures the effect of the subdominant penguins P_u and P_c. Using these relations we obtain

$$e^{i\gamma}\,\overline{P}-e^{-i\gamma}P=i\,2\,|V_{td}|\,|P_{tu}|\,(1-\Delta P)\,e^{i\delta_{tu}}\sin\alpha \tag{16}$$

from which we may express the observable (8) as

$$\xi^{(d)}_{\pi^+\pi^-}=-e^{2i\alpha}\left[1+i\,2\lambda R_t e^{i\delta}\frac{|P'|}{|A_{\rm CC}|}\sin\alpha\right]. \tag{17}$$

Here we have defined an auxiliary quantity

$$P'\equiv|V_{cb}||P_{tu}|(1-\Delta P)e^{i\delta_{tu}} \tag{18}$$

and δ is the CP-conserving strong phase of $P'/A_{\rm CC}$. Using (9) and (10), representative values of the Wilson coefficients [14] and the factorization assumption to estimate the relevant hadronic matrix elements one finds $\delta=0°$. Therefore we expect $-90°\leq\delta\leq 90°$. Furthermore, note that $|P'|/|A_{\rm CC}|$ is of order unity since by counting the relevant CKM factors and using the estimate (11) we have

$$\frac{|P'|}{|A_{\rm CC}|}\approx\frac{|V_{cb}|}{|V_{td}|}\frac{|P|}{|A_{\rm CC}|}\approx\mathcal{O}(1). \tag{19}$$

From (17) one readily obtains the CP-violating asymmetries

$$\mathcal{A}^{\rm dir}_{\rm CP}=2\lambda R_t\frac{|P'|}{|A_{\rm CC}|}\sin\delta\sin\alpha+\mathcal{O}\left((P/A_{\rm CC})^2\right) \tag{20}$$

$$\mathcal{A}^{\text{mix-ind}}_{\rm CP}=-\sin 2\alpha-2\lambda R_t\frac{|P'|}{|A_{\rm CC}|}\cos\delta\,\cos 2\alpha\,\sin\alpha+\mathcal{O}\left((P/A_{\rm CC})^2\right). \tag{21}$$

Hence the two observables $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}$ and $\mathcal{A}_{\mathrm{CP}}^{\text{mix-ind}}$ are expressed in terms of three unknown quantities, the ratio $|P'|/|A_{\mathrm{CC}}|$, the strong phase δ and UT angle α. The presently allowed range for R_t obtained at 95% C.L. by constraining the UT using indirect strategies [15] is $0.68 \leq R_t \leq 1.55$. Thus R_t is expected to be of $\mathcal{O}(1)$ within the Standard Model. Strategies for extracting the CKM-factor R_t have been discussed e.g. in [17].

Note that we have obtained (20), (21) by expanding in $|P|/|A_{\mathrm{CC}}|$ which is of the same order as $2\lambda R_t|P'|/|A_{\mathrm{CC}}|$. Keeping only the leading term is valid as long as the relevant prefactors are of order unity such that the subleading terms can savely be neglected. Therefore the approximations made allow us to extract α and δ only in a region in which

$$\cos\delta\,\cos 2\alpha\,\sin\alpha \approx \mathcal{O}(1), \tag{22}$$

where $\mathcal{O}(1)$ means that this combination of trigonometric functions is not as small as $2\lambda R_t|P'|/|A_{\mathrm{CC}}|$.

Let us note that very similar expressions as those given in (20), (21) have been derived by Gronau in [13]. However, we did not assume dominance of QCD penguins with internal top-quarks and the physical interpretation of the amplitude P' appearing in our formulae is quite different from [13] as we will see in a moment. In order to use (20), (21) to determine α one has to have some additional input to reduce the number of unknown quantities. One commonly used input is $SU(3)$ flavor symmetry of strong interactions [18] which we shall use in our case to relate the magnitude of the auxiliary $\bar{b} \to \bar{d}$ amplitude P' (see (18)) to the $\bar{b} \to \bar{s}$ QCD penguin amplitude.

The QCD penguin amplitude involving an s-quark instead of a d-quark takes the form [10]

$$P^{(s)} = \sum_{q=u,c,t} V_{qs}V_{qb}^{*}P_q^{(s)} = -\left[1-\Delta P^{(s)}\right]|V_{cb}|\left|P_{tu}^{(s)}\right|e^{i\delta_{tu}^{(s)}} \tag{23}$$

and hence exactly corresponds to our auxiliary quantity $(-P')$ in the strict $SU(3)$ limit, i.e. if we do not distinguish between s- and d-quarks. In other words, assuming flavor $SU(3)$, $|P'|$ is simply the magnitude of the amplitude of a penguin-induced $\bar{b} \to \bar{s}$ transition such as $B^+ \to \pi^+ K^0$.

Thus one of the unknowns in (20), (21) – the ratio $|P'|/|A_{\mathrm{CC}}|$ – may be determined with a relatively mild $SU(3)$ input. The magnitude of the amplitude $|A_{\mathrm{CC}}|$ may be obtained from the decay $B^+ \to \pi^+\pi^0$ which receives only color-allowed and color-suppressed current-current and negligibly small color-suppressed electroweak penguin contributions. Because of the isospin symmetry of strong interactions, QCD penguins do not contibute to that decay [8]. If we neglect the color-suppressed current-current and electroweak penguin contributions to $B^+ \to \pi^+\pi^0$ we obtain

$$\left.\frac{|P'|^2}{|A_{\mathrm{CC}}|^2}\right|_{SU(3)} \approx \frac{1}{2}\frac{\mathrm{BR}(B^+ \to \pi^+ K^0)}{\mathrm{BR}(B^+ \to \pi^+\pi^0)}, \tag{24}$$

where phase space effects have been neglected and the factor 1/2 is due to the π^0-meson. The relevant B^+ branching ratios have been estimated using the factorization hypothesis to be $\mathrm{BR}(B^+ \to \pi^+ K^0) = 9.1 \cdot 10^{-6}$ and $\mathrm{BR}(B^+ \to \pi^+\pi^0) = 7.8 \cdot 10^{-6}$ [7] yielding

$$\left.\frac{|P'|}{|A_{\mathrm{CC}}|}\right|_{SU(3)} \approx 0.8. \tag{25}$$

In the factorization approach $SU(3)$-breaking can be taken into account by multiplying with the ratio $f_\pi/f_K \approx 0.8$ yielding

$$\frac{|P'|}{|A_{\rm CC}|} \approx \frac{f_\pi}{f_K}\sqrt{\frac{1}{2}\frac{{\rm BR}(B^+\to\pi^+K^0)}{{\rm BR}(B^+\to\pi^+\pi^0)}} \tag{26}$$

which finally allows us a determination of α and δ from the measurement of $\mathcal{A}_{\rm CP}^{\rm dir}$ and $\mathcal{A}_{\rm CP}^{\text{mix-ind}}$ using (20), (21).

Let us discuss the uncertainties and limitations of this procedure. One limitation is due to the expansion in $|P|/|A_{\rm CC}|$ and has already been given in (22). The angle α is expected to lie within the range $20^\circ \leq \alpha \leq 120^\circ$ [15] and hence $\sin\alpha$ will not become small. Furthermore, if the strong phase δ is close to the limiting values of $\pm 90^\circ$, the extraction of α may be performed by using the direct CP-violating asymmetry only since $|\mathcal{A}_{\rm CP}^{\rm dir}|$ acquires its maximal value of

$$|\mathcal{A}_{\rm CP}^{\rm dir}| = 2\lambda R_t \frac{|P'|}{|A_{\rm CC}|}\sin\alpha, \tag{27}$$

while our expansion breaks down for $\mathcal{A}_{\rm CP}^{\text{mix-ind}}$. Hence for intermediate values of δ only the $\cos 2\alpha$ factor in (22) causes trouble since it vanishes at $\alpha = 45^\circ$ and $\alpha = 135^\circ$. Consequently we have to exclude a region σ around these values in which $|\cos 2\alpha| \leq 2\lambda R_t|P'|/|A_{\rm CC}|$, i.e. the subleading terms of the expansion start to become important. From this one obtains the exclusion regions $45^\circ \pm \sigma$ and $135^\circ \pm \sigma$ with

$$\sigma \approx \frac{180^\circ}{\pi}\lambda R_t \frac{|P'|}{|A_{\rm CC}|} \approx 12^\circ R_t \frac{|P'|}{|A_{\rm CC}|}. \tag{28}$$

Flavor $SU(3)$ is generally believed to be good at a level of about ten to twenty percent. However, as far as $SU(3)$ is concerned, we only need it for the relation between branching ratios, while we do not use $SU(3)$ for any of the strong phases. Quantitatively we may use (20), (21) to give an explicit expression for the uncertainty $\Delta\alpha$ of α that is induced by the uncertainty of $|P'|/|A_{\rm CC}|$. We obtain

$$|\Delta\alpha| = \frac{r\sin^2\alpha}{2\sqrt{r^2\sin^2\alpha - \left(\mathcal{A}_{\rm CP}^{\rm dir}\right)^2}}|\Delta r|, \tag{29}$$

where we have used the abbreviation

$$r \equiv 2\lambda R_t \frac{|P'|}{|A_{\rm CC}|}. \tag{30}$$

For the following discussion we shall assume that the measurement of the branching ratios appearing in (26) yields a value of 0.6 for $|P'|/|A_{\rm CC}|$. This value is in correspondence with (25) if we include factorizable $SU(3)$-breaking through f_π/f_K.

The ratio $|P'|/|A_{\rm CC}|$ enters our expressions only through r. In relating the measured branching ratios to r we have to deal with uncertainties arising from non-factorizable $SU(3)$-breaking, the neglected color-suppressed current-current contributions to $B^+ \to$

$\pi^+\pi^0$ and from the CKM-factor R_t. Assuming an uncertainty in r of 30%, which includes the one from using (26) as well as possible uncertainties in R_t, is clearly quite conservative. In our examples we shall use $r = 0.26$ as the central value corresponding to $|P'|/|A_{\rm cc}| = 0.6$, $R_t = 1$ and shall not consider any experimental uncertainties.

As the first example let us consider a case where no direct CP violation is detected, i.e. $\mathcal{A}_{\rm CP}^{\rm dir} = 0$, and the measurement yields $\mathcal{A}_{\rm CP}^{\rm mix\text{-}ind} = -0.25$. Ignoring the presence of penguins one would extract from these values $\alpha = 83°$; including the penguins along the lines suggested here one obtains $\alpha = (76 \pm 1)°$, where the uncertainty of one degree is obtained form (29). Note that in this example the QCD penguin contributions shift the extracted value of α by seven degrees.

Let us now consider a case with non-vanishing direct CP violation. Specifically, we assume that the CP asymmetries are measured to be $\mathcal{A}_{\rm CP}^{\rm mix\text{-}ind} = -0.25$ and $\mathcal{A}_{\rm CP}^{\rm dir} = +0.1$. In that case one obtains $\alpha = (76 \pm 1)°$. The non-vanishing direct CP violation implies a non-trivial CP-conserving phase δ which in this example turns out to be $\delta = (24 \pm 4)°$.

In summary, for a 30% theoretical uncertainty in r and for the central value $r = 0.26$ the method suggested here is expected to allow an extraction of α with an uncertainty of $\pm 3°$ if α lies in the allowed regions, i.e. not too close to $45°$ or $135°$. For values of α far away from these singular points one may even have an uncertainty of $\pm 1°$ as has been shown in the above examples. Even for larger values of r the method is still quite reliable, at least for "save" values of α.

Another source of uncertainty is the expansion in $|P|/|A_{\rm cc}| = \mathcal{O}(r)$. To give some idea of the effect of the higher order terms in $|P|/|A_{\rm cc}|$ we shall use our first example. Here the linear terms in $|P|/|A_{\rm cc}|$ induced a shift of seven degrees which amounts to roughly ten percent. Therefore we expect the corrections from second order terms to be of the order of a percent, i.e. in absolute values of about one degree.

Since the approach presented in this letter requires neither difficult measurements of very small branching ratios nor complicated geometrical constructions it may turn out to be very useful for the early days of the B-factory era beginning at the end of this millennium.

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