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Constraining new physics in $B^0 \to \pi^+\pi^-$ with reparametrization invariance and QCD factorization

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ABSTRACT

Usually, $B^0 \to \pi^+\pi^-$ decays are expressed in terms of weak amplitudes explicitly dependent on the CKM weak phase α or γ. In this Letter, we show that the weak amplitudes can be rewritten such that a manifest dependence on β emerges instead. Based on this, we constrain new-physics contributions to the CP-violating phase ϕ_d in B^0–$\bar{B}^0$ mixing. Further, we apply reparametrization invariance and use QCD factorization predictions to investigate the bounds on an additional new-physics amplitude in $B^0 \to \pi^+\pi^-$.

One of the greatest successes of the B factories BaBar and Belle is the precise determination of the CP-violating phase ϕ_d in B mixing [1]. In the Standard Model (SM), and using the Wolfenstein parametrization of the CKM matrix, ϕ_d is related to β, one of the angles of the unitarity triangle, as $\phi_d = 2\beta$. As B mixing is a loop process, the experimentally determined angle ϕ_d might in fact not equal 2β, but be polluted by the effects of new-physics (NP) particles propagating in loops, thereby contributing an additional CP violating phase, see for instance Ref. [2]. It is therefore of considerable interest to study any methods by which one can constrain an additional NP contribution to ϕ_d. In this Letter we shall show that the process $B^0 \to \pi^+\pi^-$ can be used to this effect.

The set of neutral and charged $B \to \pi\pi$ decays has been extensively studied as a means of determining the angle α (or γ) of the unitarity triangle. The lack of a theoretically clean calculation of the strong amplitudes and phases involved can be overcome by exploiting isospin symmetry, see Ref. [3], commonly referred to as the Gronau–London method. It involves relating the various experimental observables (branching ratios and CP asymmetries) in $B \to \pi\pi$ to extract both the hadronic amplitudes determining these decays and the weak phase α. As an alternative to isospin, and in order to avoid $B^0 \to \pi^0\pi^0$ decays, the use of U-spin has been explored in Refs. [4] to extract γ from $B^0 \to \pi^+\pi^-$ and the U-spin related decay $B_s \to K^+K^-$. In a conceptionally different approach the relevant strong amplitudes are calculated (as opposed to extracted from experiment), using QCD factorization (QCDF) [5–8] or effective field theory methods (SCET) [9]. The advantage here is that less experimental input is needed, the disadvantage that the calculation is performed in a limit of QCD where the b quark is assumed to be very heavy. In any case, all these analyses put the emphasis on constraining the angles γ or α.

In this Letter, we show that it is possible to express the decay amplitude in terms of ϕ_d and β, without any explicit reference to the angles α or γ. In the SM, the resulting expression allows the extraction of the relevant hadronic parameters from $B^0 \to \pi^+\pi^-$ data alone, which can be compared to the theoretical calculation in QCDF. Beyond the SM, we study the possible presence of NP in this decay, which might contribute through B^0–$\bar{B}^0$ mixing via a NP contribution to ϕ_d or through an additional NP amplitude.

We begin with a reminder of the parametrization used to extract γ. The amplitude for $\bar{B}^0 \to \pi^+\pi^-$ is given in the form:

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Table 1
CKM parameters used in this Letter.

Parameter	Value	Source
λ	$0.2257^{+0.0009}_{-0.0010}$	PDG [10]
$\lvert V_{cb}\rvert$	$(41.2 \pm 1.1) \times 10^{-3}$	PDG [10]
$\lvert V_{ub}\rvert$	$(3.93 \pm 0.36) \times 10^{-3}$	PDG [10]
$\beta_{b\to ccs}$	$(21.1 \pm 0.9)^\circ$	HFAG [1]
β_{tree}	$(23.9 \pm 3.3)^\circ$	this Letter, Eq. (16)
γ	$(77^{+30}_{-32})^\circ$	PDG [10]
R_b	0.412 ± 0.039	this Letter, Eq. (6)
$\lvert\frac{V_{td}}{V_{ts}}\rvert$	0.214 ± 0.005	[11]
R_t	0.928 ± 0.024	this Letter, Eq. (10)

$$\mathcal{A}\big(\bar{B}^0 \to \pi^+\pi^-\big) = \lambda_c A_c + \lambda_u A_u, \tag{1}$$

where $\lambda_q = V^*_{qd} V_{qb}$, and A_c, A_u are strong amplitudes. A_u is dominated by tree diagrams, whereas the only contributions to A_c are from penguin diagrams. The corresponding time-dependent CP asymmetry is given by:

$$A_\pm(t) = \frac{\Gamma(B^0(t) \to \pi^+\pi^-) - \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)}{\Gamma(B^0(t) \to \pi^+\pi^-) + \Gamma(\bar{B}^0(t) \to \pi^+\pi^-)} = C_\pm \cos(\Delta m t) - S_\pm \sin(\Delta m t). \tag{2}$$

The experimental observables $C_\pm$ and $S_\pm$ can be expressed in terms of $\lambda_\pm$:

$$S_\pm = \frac{2\,\mathrm{Im}(\lambda_\pm)}{1 + |\lambda_\pm|^2}, \qquad C_\pm = \frac{1 - |\lambda_\pm|^2}{1 + |\lambda_\pm|^2}, \tag{3}$$

where $\lambda_\pm$ is given by

$$\lambda_\pm = e^{-i\phi_d} \frac{\mathcal{A}(\bar{B}^0 \to \pi^+\pi^-)}{\mathcal{A}(B^0 \to \pi^+\pi^-)}. \tag{4}$$

Parametrizing the amplitudes as in Eq. (1), we have

$$\lambda_\pm = e^{-i\phi_d} \frac{e^{-i\gamma} - r e^{i\delta}}{e^{i\gamma} - r e^{i\delta}} \tag{5}$$

with $r e^{i\delta} = A_c/(A_u R_b)$, $\gamma = \arg(-\lambda_c/\lambda_u)$ and

$$R_b = \left|\frac{\lambda_u}{\lambda_c}\right| = \frac{1 - \lambda^2/2}{\lambda} \frac{|V_{ub}|}{|V_{cb}|}. \tag{6}$$

Numerical values for these and other CKM-related quantities are collected in Table 1. The observables $S_\pm$ and $C_\pm$ are given by

$$S_\pm = -\frac{\sin(\phi_d + 2\gamma) - 2r\sin(\phi_d + \gamma)\cos\delta + r^2 \sin\phi_d}{1 - 2r\cos\gamma\cos\delta + r^2}, \tag{7}$$

$$C_\pm = -\frac{2r\sin\gamma\sin\delta}{1 - 2r\cos\gamma\cos\delta + r^2}. \tag{8}$$

In the absence of penguin contributions, $r = 0$ and the determination of $\phi_d + 2\gamma$ would be completely analogous to that of ϕ_d from $B^0 \to J/\psi K_S$. Realistically, r is expected to be a small, but non-zero number, which makes the extraction of γ more challenging.

We now show how a different parametrization of the decay amplitude (1) replaces the explicit dependence of $\lambda_\pm$ on γ by one on β. Using $\beta = \arg(-\lambda_t/\lambda_c)$, one can trade the dependence on γ for one on β by exploiting the unitarity of the CKM matrix and exchanging λ_u for $-\lambda_c - \lambda_t$:

$$\mathcal{A}\big(\bar{B}^0 \to \pi^+\pi^-\big) = \lambda_c B_c + \lambda_t B_t = \lambda_c\big(B_c - R_t e^{i\beta} B_t\big), \tag{9}$$

where $B_c = A_c - A_u$, $B_t = -A_u$ and

$$R_t = \left|\frac{\lambda_t}{\lambda_c}\right| = \frac{1}{\lambda}\frac{|V_{td}|}{|V_{ts}|}\left\{1 - \frac{1}{2}(1 - 2R_b\cos\gamma)\lambda^2 + O\big(\lambda^4\big)\right\}. \tag{10}$$

Table 2
Experimental results for $S_\pm$, $C_\pm$ from BaBar and Belle and the HFAG average.

Experiment	$S_\pm$	$C_\pm$
BaBar [14]	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$
Belle [15]	$-0.61 \pm 0.10 \pm 0.04$	$-0.55 \pm 0.08 \pm 0.05$
HFAG [1]	-0.65 ± 0.07	-0.38 ± 0.06

Note that B_c and B_t are both dominated by tree-level decays as they both contain A_u.

With this parametrization of the decay amplitude, $\lambda_\pm$ becomes

$$\lambda_\pm = e^{-i\phi_d}\left(\frac{1 - R_t R_{tc} e^{i\beta}}{1 - R_t R_{tc} e^{-i\beta}}\right) \tag{11}$$

$$= e^{-i\phi_d}\left(\frac{1 - d e^{i\theta_d} e^{i\beta}}{1 - d e^{i\theta_d} e^{-i\beta}}\right), \tag{12}$$

where $R_{tc} = B_t/B_c$ and $d = |R_t R_{tc}|$, $\theta_d = \arg(R_t R_{tc})$. Note that unlike r, d is not suppressed, but expected to be of order 1 (as R_t is also close to 1). The CP-violating observables in (3) now read

$$S_\pm = \frac{d^2\sin(2\beta - \phi_d) + 2d\cos\theta_d\sin(\phi_d - \beta) - \sin(\phi_d)}{d^2 - 2d\cos\beta\cos\theta_d + 1}, \tag{13}$$

$$C_\pm = -\frac{2d\sin\beta\sin\theta_d}{d^2 - 2d\cos\beta\cos\theta_d + 1}. \tag{14}$$

Obviously (13), (14) are not independent of (7), (8), but related by the unitarity constraint

$$R_t e^{i\beta} + R_b e^{-i\gamma} - 1 = 0. \tag{15}$$

The advantage of expressing $S_\pm$ and $C_\pm$ in terms of β instead of γ is that, at least in the SM, there is now only one manifest weak phase. This implies that, with R_t determined from B mixing, both d and θ_d can be extracted from experiment and compared to theoretical calculations, for example QCDF. This is independent of any information from the decay $B^0 \to \pi^0\pi^0$ whose branching ratio continues to be difficult to understand in the framework of QCDF or SCET.

The most accurate measurement of ϕ_d is via mixing in B^0 decays to CP eigenstates of charmonium. The CP asymmetry averaged over these channels provides a direct measurement of $\sin\phi_d = 0.673 \pm 0.023$, so that in the SM $\beta = (21.1 \pm 0.9)^\circ$ [1].[1] It is also possible to derive β from tree-process measurements only, based on γ and $|V_{ub}|$. Taking γ and $|V_{ub}|$ from Ref. [10], see Table 1, we find β_{tree} using

$$\sin\beta_{\text{tree}} = \frac{R_b\sin\gamma}{\sqrt{1 - 2R_b\cos\gamma + R_b^2}},$$

$$\cos\beta_{\text{tree}} = \frac{1 - R_b\cos\gamma}{\sqrt{1 - 2R_b\cos\gamma + R_b^2}}, \tag{16}$$

which results in $\beta_{\text{tree}} = (23.9^{+3.4}_{-3.2})^\circ$ (in the following analysis we use $\beta_{\text{tree}} = (23.9 \pm 3.3)^\circ$). Both values of β are compatible with each other, but we will use the latter one to obtain constraints on a NP contribution to ϕ_d.

From the experimental data collected in Table 2, we find the values of d and θ_d given in Table 3. The high quality of the experimental results leads to small uncertainties on d, typically 5%, and

[1] There is an ambiguity in this result, as $\beta = (68.9 \pm 1.0)^\circ$ is also a solution. However, this is excluded at the 95% confidence level by a Dalitz plot analysis of $B^0 \to \bar{D}^0 h^0$ where $h^0 = \pi^0, \omega, \eta$ [12], and by a time-dependent angular analysis of $B^0 \to J/\psi K^{*0}$ [13].