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Measurements of CP Asymmetries at BaBar

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ABSTRACT

We present preliminary measurements of CP–violating asymmetries in B decays. These include new results on the CKM angle α based on studies of the decay $B \to \rho^+\rho^-$ and several charmonium and hadronic penguin modes, sensitive to the CKM angle β, including results on $B \to \phi K^0_S$, $B \to K^+K^-K^0$, $B \to \eta' K^0_S$, $B \to f_0 K^0_S$, and $B \to \pi^0 K^0_S$. We also report on several of results related to the extraction of γ and $(2\beta+\gamma)$ and present limits on CPT violation in B decays.

1. Introduction

The unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix yields several relationships for its components, as $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$. This describes the extent of CP violation in the Standard Model (SM) in the B meson system and can be represented in the imaginary plane as a triangle, where the angles (α, β and γ) can be written in terms of the couplings between quarks:

$$\alpha \equiv \arg\left[-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right] \quad , \quad \beta \equiv \arg\left[-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right] \quad , \quad \gamma \equiv \arg\left[-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right]. \tag{1}$$

These angles can be extracted via CP asymmetries measured in several decay modes of the B meson. We report on recent analyses which aim to measure these angles with data collected at the BaBar detector [1]. All results are preliminary unless otherwise stated.

1.1. *Measurement of β*

The angle β can be and has been measured via time dependent asymmetry of B and $\overline{B}$ decays into charmonium modes. The decay rate $B^0 \to f$, where f is a CP-eigenstate, is described by:

$$f_{\frac{B^0}{\overline{B}^0}tag}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times [1 \mp (C\cos(\Delta m_{B^0}\Delta t) - S\sin(\Delta m_{B^0}\Delta t))] \tag{2}$$

where Δt is the time difference between the decays of the B meson studied and the other B meson (B_{tag}), whose decay products are used in a partial reconstruction to infer its B^0 or $\overline{B}^0$ flavor. For charmonium modes, where the penguin diagrams are small and carry

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Table 1: S and C CP parameters (Eq.(2)) measured for various B decay modes. The first uncertainty is statistical, the second one systematic. The "f_{even}" uncertainty for S of $K^+K^-K^0_S$ comes from the uncertainty on f_{even} itself.

B decay	S	C
ϕK^0	$+0.47 \pm 0.34^{+0.08}_{-0.06}$	$+0.01 \pm 0.33 \pm 0.10$
$K^+K^-K^0_S$	$-0.56 \pm 0.25 \pm 0.04^{+0}_{-0.17}(f_{even})$	$-0.10 \pm 0.19 \pm 0.09$
$\pi^0 K^0_S$	$+0.48^{+0.38}_{-0.47} \pm 0.19$	$+0.40^{+0.27}_{-0.28} \pm 0.06$
$f_0(980)K^0_S$	$-1.62^{+0.56}_{-0.51} \pm 0.09 \pm 0.04(model)$	$+0.27 \pm 0.36 \pm 0.10 \pm 0.07(model)$
$\eta' K^0_S$	$+0.10 \pm 0.22 \pm 0.03$	$+0.02 \pm 0.34 \pm 0.03$

the same weak phase as the tree diagrams, $C = 0$ and $S \propto \sin 2\beta$. *BaBar* measured $\sin 2\beta = 0.741 \pm 0.067 \pm 0.034$[2]. The $\sin 2\beta$ measurement assumes that the decay rates of the two mass eigenstates are the same ($\Delta\Gamma = 0$), that $q/p = 1$, and that *CPT* is conserved. All these assumptions have been tested with a measurement which uses flavor and *CP* eigenstates. The *CP* sample is more important for the measurement of $\Delta\Gamma$ as its contribution is effectively linear in this observable, while the flavor contribution is quadratic. The results are $|\Delta\Gamma/\Gamma| = 0.008 \pm 0.037 \pm 0.018$ and $q/p = 1.029 \pm 0.013 \pm 0.011$, with all other results consistent with *CPT* conservation. Hence all measurements are in agreement with the assumptions made and with the SM predictions [3]. *BaBar* also measures $\cos 2\beta = +2.72^{+0.50}_{-0.79}(\text{stat}) \pm 0.27(\text{syst})$, thus a *positive* cos2$\beta$ value, in agreement with the SM expectation. We estimate, using Monte Carlo (MC), that we exclude the negative cos2β solution at 89% Confidence Level (C.L.).

The measurements of *CP* asymmetries in modes dominated by penguin diagrams are particularly interesting as New Physics (NP) can show up in the penguin loops. When the tree contribution is negligible, we are effectively measuring $\sin 2\beta$ in $b \to s$ transitions. A large departure from the sin2β value measured with charmonium modes will indicate contribution of NP. All the analyses on penguin modes reported here perform time dependent *CP* asymmetry measurements using maximum likelihood fits. In the SM, contributions beyond the leading penguin may be difficult to estimate, depending on the channel. The "effective sin2β" measured in these channels may then differ from sin2β, but bounds on these differences are known [4].

The decay $B^0 \to \phi K^0$ is a $b \to s\bar{s}s$ quark level decay. In the SM, the expected asymmetry $S_{\phi K^0_S}(S_{\phi K^0_L})$ is very close to $\sim +\sin 2\beta(-\sin 2\beta)$. The *CP* asymmetry parameters S and C measured by *BaBar* are reported in Table 1 [5] and are in agreement with the SM expectation, but *BaBar* and Belle's values present an almost 3 standard deviations (s.d.) discrepancy in the value of S. We can also measure the non resonant part of the previous decay, selecting K^+K^- pairs outside the ϕ mass window, and benefit from larger statistics. In contrast to $B^0 \to \phi K^0_S$, the *CP* content is not known *a priori* for this mode, but can be measured from $B \to KKK$ branching ratios (BRs) of charged and neutral B mesons as: $f_{even} = 2\Gamma(B^+ \to K^+K^0_SK^0_S)/\Gamma(B^0 \to K^+K^-K^0_S)$. *BaBar* measures $f_{even} = 0.98 \pm 0.15 \pm 0.04$, which is compatible with a pure *CP* even state. In the SM, the expected $B^0 \to K^+\, K^-\, K^0_S$ *CP* asymmetry is then $S_{K^+K^-K^0_S} \sim -\sin 2\beta$. The results are shown in Table 1 [6]. *BaBar* has also performed the first measurement of the *CP* asymmetry (A_{CP})

Invited talk presented at 12th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 04), Tsukuba, Japan, 6/17/2004 - 6/23/2004

in the $B^{\pm} \to K^{\pm} K^0_S K^0_S$ decay ($A_{CP}(B^{\pm} \to K^{\pm} K^0_S K^0_S) = -0.04 \pm 0.11(\text{stat}) \pm 0.02(\text{syst})$). The decay $B^0 \to \pi^0 K^0_S$ has also been studied at BABAR. This is a $b \to s\bar{d}d$ quark level decay. The SM expectation for $S_{\pi^0 K^0_S}$ is $\sim +\sin 2\beta$. As we are in the presence of a π^0 in the final state, the position of the reconstructed B is taken constraining the K^0_S to come from the beam spot in the plane perpendicular to the beam direction. This requires a very good knowledge of the beam position at all times. The results of the first measurement of the CP asymmetry for this decay are reported in Table 1 [7], while the decay rates plots are shown in Figure 1. The decay $B^0 \to f_0(980)K^0_S$ should be dominated by the $b \to s\bar{s}s$ penguin, since the $s\bar{s}$ component is significant and the $b \to u\bar{u}s$ tree is doubly Cabibbo suppressed compared to the leading penguin. The $B^0 \to f_0(980)K^0_S$ CP asymmetry expected in the SM is then $\sim -\sin 2\beta$. The CP fit result is reported in Table 1, with decay rates distributions shown in Figure 2. The value found for S is 1.2 s.d. from the physical limit and 1.7 from the SM predictions. This is the first observation of the $B^0 \to f_0(980)K^0_S$ decay. The results for $B^0 \to \eta' K^0_S$ are also reported. The η' is reconstructed in the $\eta\pi^+\pi^-$ and $\rho^0\gamma$ modes, with the η decaying into two photons and the ρ^0 into two charged pions. The results are reported in Table 1 [8]. Combining results from all modes and from BABAR and Belle, $\sin 2\beta$ from charmonium modes is almost 3 s.d. away from the value obtained from penguin modes.

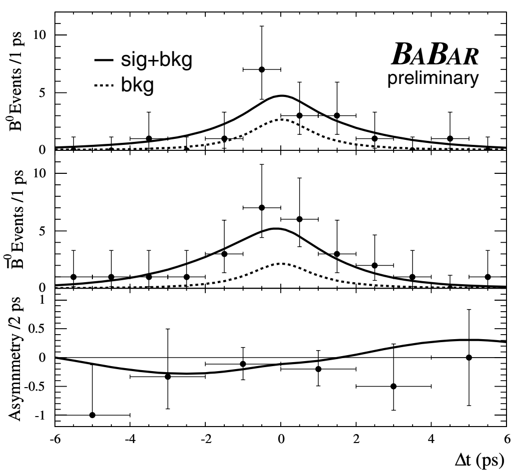

Figure 1: Δt distributions and asymmetry of $B^0 \to \pi^0 K^0_S$ candidates (122 ± 16, found out of a 110 fb^{-1} sample).

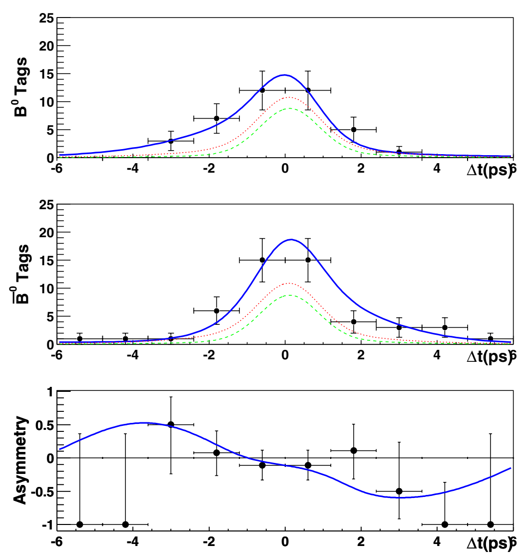

Figure 2: Δt distributions and asymmetry of $B^0 \to f_0(980)K^0_S$ candidates (94 ± 14, found out of a 111 fb^{-1} sample).

1.2. Measurement of α

For the main B decay modes which have been investigated for the measurement of α, $\pi^+\pi^-$ and $\rho^+\rho^-$, both tree and penguin diagrams contribute, hence we can only measure an α effective. BABAR's results with the $\pi^+\pi^-$mode are: $C = -0.19 \pm 0.19 \pm 0.05$ and $S = -0.40 \pm 0.22 \pm 0.03$, which are both 2 s.d. apart from Belle's.

Invited talk presented at 12th International Conference on Supersymmetry and
Unification of Fundamental Interactions (SUSY 04), Tsukuba, Japan, 6/17/2004 - 6/23/2004

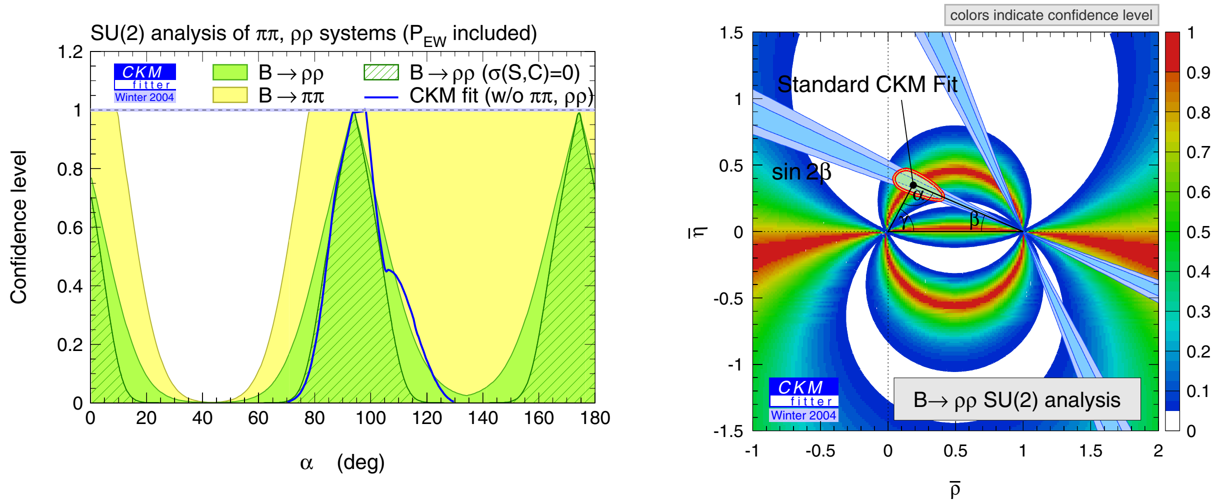

Figure 3: The $B \to \rho\rho$ analysis constrains the possible values of α. The left-hand plot shows the C.L. for different values of α, given the current measurements of $B \to \pi\pi$ from BaBar and Belle and $B \to \rho\rho$ from BaBar (with and without experimental errors). Overlaid is the global CKM fit without these two analyses included. The right-hand plot shows the constraint on the $\rho - \eta$ plane due to the $B \to \rho\rho$ analysis, which is shown overlaid by the Standard CKM fit.

$B \to \rho^+\rho^-$ is similar to $B \to \pi^+\pi^-$ but it is a vector–vector decay and can in principle proceed via three partial waves depending on the angular moments. "s" and "d" waves have CP even while "d" waves have CP odd. Hence, of the three helicity amplitudes, only the state corresponding to longitudinal polarization is a pure CP eigenstate. $B \to \rho^+\rho^-$ has been observed in BaBar with a BR $(3.0\pm4\pm5)\times10^{-6}$ and with completely longitudinal polarization, $(99 \pm 3 \pm 3)\%$ [9]. A theoretical limit on the shift between α and $\alpha_{\rm eff}$ is described by the Grossman-Quinn bound [10], which for $B \to \rho\rho$ is written:

$$|\alpha - \alpha_{\rm eff}| < \frac{\mathcal{B}(B^0 \to \rho^0\rho^0)}{\mathcal{B}(B^0 \to \rho^+\rho^-)}. \tag{3}$$

It provides a reasonably tight theoretical constraint on the value of $|\alpha - \alpha_{\rm eff}|$ of 12.9^o at 68.3% C.L. From a SU(2) analysis, choosing the result nearest to the CKM best fit[11], we measure $\alpha = (96\pm10\pm4\pm13)^o$, where the last error is due to the penguin contamination. Fig. 3 shows that this measurement is more effective than any for the $\pi^+\pi^-$ mode, that it is consistent with independent limits from other measurements as found with CKM fitter[12], and that not much improvement is possible, even with more statistics, without a better bound on the BR of $B \to \rho^0\rho^0$.

1.3. Measurement of γ

γ measurements can be made in modes which have both $b \to c$ and $b \to u$ tree diagrams, which interfere. The magnitude of the interference is determined by the ratio of the two methods of decay.

$B^0 \to D^{(*)+}\pi^-$ is sensitive to $\sin{(2\beta+\gamma)}$. It is possible for a B^0 to decay into $D^{(*)+}\pi^-$

Invited talk presented at 12th International Conference on Supersymmetry and
Unification of Fundamental Interactions (SUSY 04), Tsukuba, Japan, 6/17/2004 - 6/23/2004

either via a $b \to c$ transition or via a CKM–suppressed decay with B–mixing. The phase 2β arises from the mixing and the phase γ from the $b \to u$ transition. The expected asymmetry is small. The analysis is performed with a sample of fully reconstructed B mesons and a sample of B mesons where the D^0 is not explicitly reconstructed. We measure $|\sin(2\beta+\gamma)| > 0.58$ (95% C.L.) [14].

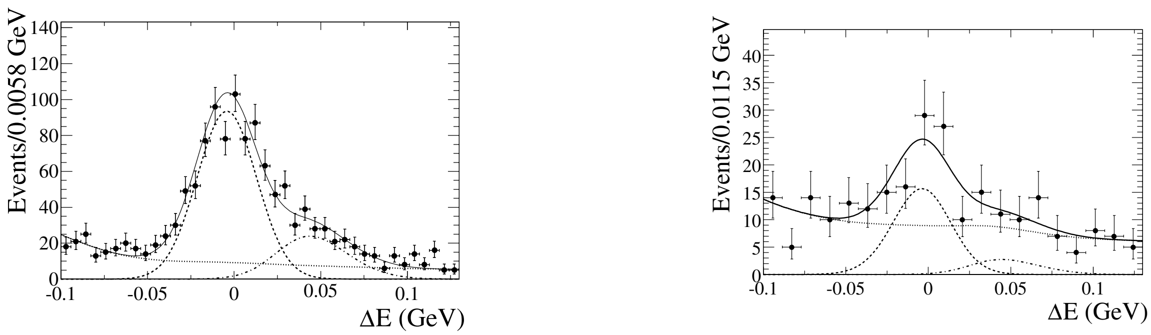

Figure 4: $B^-\to D^0K^-$ signal after requiring that the prompt track be consistent with the kaon hypothesis for the flavor (left) and CP (right) eigenstates. The quasi–gaussian peaks on the left (right) of each plot are the $B^-\to D^0K(\pi)^-$ contributions.

The study of $B^-\to D^{(*)0}K^{(*)-}$ decays will play an important role in our understanding of CP violation, as they can be used to constrain the angle γ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix in a theoretically clean way [13]. In the SM, in the absence of $D^0\overline{D^0}$ mixing, $R_{CP\pm}/R_{\mathrm{non}-CP} \simeq 1 + r^2 \pm 2r\cos\delta\cos\gamma$, where

$$R_{\mathrm{non}-CP/CP\pm} \equiv \frac{\Gamma(B^- \to D^0_{\mathrm{non}-CP/CP\pm}K^-)}{\Gamma(B^- \to D^0_{\mathrm{non}-CP/CP\pm}\pi^-)}, \quad (4)$$

r is the ratio of the color suppressed $B^+ \to D^0K^+$ and color allowed $B^- \to D^0K^-$ amplitudes ($r \sim 0.1 - 0.3$), and δ is the CP-conserving strong phase difference between these amplitudes. Furthermore, defining the direct CP asymmetry

$$A_{CP\pm} \equiv \frac{\Gamma(B^-\to D^0_{CP\pm}K^-) - \Gamma(B^+\to D^0_{CP\pm}K^+)}{\Gamma(B^-\to D^0_{CP\pm}K^-) + \Gamma(B^+\to D^0_{CP\pm}K^+)}, \quad (5)$$

we have: $A_{CP\pm} = \pm 2r\sin\delta\sin\gamma/(1 + r^2 \pm 2r\cos\delta\cos\gamma)$. The unknowns δ, r, and γ can be constrained from the measurements of $R_{\mathrm{non}-CP}$, $R_{CP\pm}$, and $A_{CP\pm}$. The smaller r is, the more difficult is the measurement of γ with this method. At BABAR we have studied the $B^\pm \to D^0K^\pm$ mode in the flavor ($D^0 \to K^-\pi^+, K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$, and the charged conjugate decays) and $CP = 1$ states ($D^0 \to K^+K^-$ and $\pi^+\pi^-$). Two quantities are used to discriminate between signal and background: the beam-energy-substituted mass $m_{\mathrm{ES}} \equiv \sqrt{(E_i^{*2}/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B^* - E_i^*/2$, where the subscripts i and B refer to the initial e^+e^- system and the B candidate respectively, the asterisk denotes the CM frame, and the kaon mass hypothesis of the prompt track is used to calculate ΔE. Figure 4 shows the $B^-\to D^0K^-$ signal after requiring that the prompt track be consistent with the kaon hypothesis for the flavor and CP eigenstates. Using datasets of $56\,\mathrm{fb}^{-1}$ for the measurement of R, and

Invited talk presented at 12th International Conference on Supersymmetry and
Unification of Fundamental Interactions (SUSY 04), Tsukuba, Japan, 6/17/2004 - 6/23/2004

82 fb^{-1} for R_{CP+} and A_{CP+}, BaBar measures[15]: $R = (8.31 \pm 0.35 \pm 0.20)\%$, $R_{CP+} = (8.8 \pm 1.6 \pm 0.5)\%$, $A_{CP+} = 0.07 \pm 0.17 \pm 0.06$, and $R_{CP+}/R = 1.06 \pm 0.19 \pm 0.06$. No meaningful γ measurement is yet possible from these results.

We can also use the Atwood, Dunietz and Soni method[16], which exploits the interference between the decay chain combining the CKM and color suppressed $B^+ \to D^0 K^+$ decay and the CKM allowed $D^0 \to K^- \pi^+$ decay and the one with a color allowed $B^+ \to \overline{D^0} K^+$ decay and the doubly CKM suppressed $\overline{D^0} \to K^- \pi^+$ decay. We find no signal in the suppressed decay mode, and, using a Bayesian model, we measure: $r < 0.22$ at 90% C.L. [17], result which makes a measurement of γ quite difficult.

2. Conclusions

We measure $\cos 2\beta < 0$ at 89% C.L. and find no evidence of *CPT* violation, in agreement with SM expectation. Measurements of *CP* asymmetries in the penguin dominated modes are also found compatible with SM expectations at the present level of statistics. The BaBar experiment has also conducted several analyses with the aim of extracting α and γ. In the $B^0 \to \rho^+ \rho^-$ system, we measure $\alpha = (96 \pm 10 \pm 4 \pm 13)^o$. Using $B^0 \to D^{(*)+} \pi^-$ decays, we find $|\sin(2\beta + \gamma)| > 0.58$ at 95% C.L. Other decays and methods to extract the angle γ are under investigation, and tighter constraints on its value will be found once larger data sets become available from both BaBar and Belle, though these measurements appear quite hard as BaBar also measures: $r < 0.22$ at 90% C.L.

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