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# Charmless 2- and 3-body B decays and the angle $\alpha(\phi_2)$

Markus Cristinziani
(representing the *BABAR* collaboration)
Stanford Linear Accelerator Center
Menlo Park, CA 94025
E-mail: markus@slac.stanford.edu

## Abstract

We present preliminary measurements of branching fractions and *CP*-asymmetry parameters in two- and three-body charmless hadronic $B$ decays. The available data sample consists of 227 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC. We establish the observation of the decays $B^0 \to \pi^0\pi^0$ and $B^0 \to K^0\overline{K}^0$ and constrain the CKM angle $\alpha$ with a full SU(2) isospin analysis in the $B \to \pi\pi$ system and with a $B^0 \to \pi^+\pi^-\pi^0$ time-dependent Dalitz plot analysis.

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*Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309*

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# 1 Introduction

According to the Standard Model *CP* violation is attributed to the presence of one complex phase in the CKM quark-mixing matrix. The relations between the matrix elements $V_{ij}$ are usually represented as a triangle in the complex plane, the Unitarity Triangle. The program of the $B$ factories aims at overconstraining its sides and angles. Most measurements of branching fractions and *CP* parameters presented in this talk can be used to extract information about the angle $\alpha = \arg\left[-V_{\rm td}V_{\rm tb}^*/V_{\rm ud}V_{\rm ub}^*\right]$.

More detail about the analyses presented here can be found in the conference contributions[1].

# 2 Hadronic Charmless $B$ Decays

These results are based on the analysis of 227 million $B\overline{B}$ decays recorded by the *BABAR* detector at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC. The *BABAR* detector is described in detail elsewhere[2].

Decays of a $B$ meson into final states with two or three charmless particles are rare, with branching fractions typically of $\mathcal{O}(10^{-5})$. Signal decays are identified using two kinematic variables: (1) the difference $\Delta E$ between the energy of the $B$ candidate in the $e^+e^-$ center-of-mass (CM) frame and $\sqrt{s}/2$ and (2) the beam-energy substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where $\sqrt{s}$ is the total CM energy, and the B momentum $\mathbf{p_B}$ and the four-momentum of the initial state $(E_i, \mathbf{p_i})$ are defined in the laboratory frame.

The main common background consists of continuum ($e^+e^- \to q\overline{q}$) events where two or three mesons combine kinematically to mimic a $B$ decay. To suppress this jet-like background, a cut on the sphericity of the event is applied. Additionally, a Fisher discriminant $\mathcal{F}$ is defined as an optimized linear combination of $\sum_i p_i$ and $\sum_i p_i \cos^2\theta_i$, where $p_i$ is the momentum and $\theta_i$ is the angle with respect to the thrust axis of the $B$ candidate, both in the CM frame, for all tracks and neutral clusters not used to reconstruct the $B$ meson. Alternatively a neural network is trained on those two variables and the angles with respect to the beam axis of the $B$ momentum and $B$ thrust axis in the $\Upsilon(4S)$ frame. Background sources from $B$ decays are vector-pseudoscalar decays, where one of the decay products remains undetected, and cross-feed among the charmless modes.

The determination of *CP* parameters relies on the tagging technique and a precise measurement of the flight time. Those particles in the event that are not used to reconstruct the decay mode under study provide information about whether the other $B$ meson decayed as a $B^0$ or $\overline{B}^0$. The *CP* asymmetry parameters in $B^0 \to \pi^+\pi^-$ decays are determined with a maximum likelihood fit including information about the $B$ flavor and the difference $\Delta t$ between the decay times. The decay rate distribution $f_+$ ($f_-$) for the tagged $B = B^0$ ($\overline{B}^0$) is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S_{\pi\pi}\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}\cos(\Delta m_d \Delta t)],$$

where $\tau$ is the mean $B^0$ lifetime and $\Delta m_d$ is the mixing frequency due to the neutral-$B$-meson eigenstate mass difference.

All new results described here are summarized in the two tables showing branching fractions and *CP* parameters.

### 2.1 $B \to \pi\pi$ modes

We updated the time-dependent *CP* asymmetry measurement in the decay $B^0 \to \pi^+\pi^-$. After selection of events with two charged tracks, a maximum-likelihood fit is performed using $m_{\rm ES}$, $\Delta E$, $\mathcal{F}$ and $\theta_C$, the Čerenkov angle measured by the detector of internally reflected Čerenkov light which provides good $K-\pi$ separation in the relevant momentum region. Signal and background yields of the four related $h^+h^-$ modes ($h \equiv \pi, K$) are determined in a first fit and fixed in the final fit where information about $B$-flavor and decay-time is added. We measure the *CP* parameters in the decay $B^0 \to \pi^+\pi^-$ to be $C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$ and $S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$ which does not indicate presence of significant *CP* violation. As shown in Fig. 1 this result is not compatible with Belle's measurement with 152 million $B^0$'s[3].

For the analysis of the modes $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ candidate $\pi^0$ mesons are reconstructed as pair of photons in the electromagnetic calorimeter with requirements on minimum energy and lateral shower shape. For high momentum $\pi^0$'s the two-photon mass resolution is approximately 8 MeV/$c^2$. For both the $B^0 \to \pi^0\pi^0$ signal and the $B^\pm \to \rho^\pm\pi^0$ background the $m_{\rm ES}$ and $\Delta E$ variables are correlated and therefore a two-dimensional PDF from a smoothed, simulated distribution is used. To eliminate systematic uncertainties associated with the choice of fit function of the $\mathcal{F}$ distribution, a parametric step function is used[4]. The result of the maximum likelihood fit for $B^0 \to \pi^0\pi^0$ is $n(B^0 \to \pi^0\pi^0) = 61 \pm 17$. The significance of the event yield is found to exceed $5.0\sigma$ including systematic effects. The event yield is transformed into a measurement of the branching fraction $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$. Considering the improved understanding of the $\pi^0$ detection efficiency and the additional data this result is consistent with our previous measurement[4]. In the same fit the time-integrated *CP* asymmetry, defined as $C_{\pi^0\pi^0} = (|A_{00}|^2 - \left|\overline{A}_{00}\right|^2)/(|A_{00}|^2 + \left|\overline{A}_{00}\right|^2)$, where $A_{00}$ ($\overline{A}_{00}$) is the $B^0(\overline{B}^0) \to \pi^0\pi^0$ decay amplitude is measured. We find $C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$. Finally the charge asymmetry and branching fraction for the decay $B^+ \to \pi^+\pi^0$ are measured and shown in the tables.

### 2.2 Twobody charmless decays with kaons

$B \to K\pi$ decays are dominated by $b \to s$ penguin transitions and are interesting modes to look for possible new physics or constrain the CKM angle $\gamma$[5]. New results presented here are included in the tables. We note that the charge asymmetry $\mathcal{A}_{K^+\pi^0} = (6 \pm 6 \pm 1)\%$ is consistent with zero, while the measured direct asymmetry $\mathcal{A}_{K^+\pi^-} = (-13.3 \pm 3.0 \pm 0.9)\%$ is not[6]. The time-dependent *CP* parameters of $B \to K^0_S\pi^0$ are related to the angle $\beta$ and discussed in[7].

The branching fraction and asymmetry of the previously unobserved decay $B^0 \to K^0\overline{K}^0$ is measured with a significance of $4.5\sigma$ including systematic uncertainties. Figure 2 shows the background-subtracted $\Delta E$ distributions. The background subtraction is performed by weighting events using the ${}_s\mathcal{P}lot$ technique[8].

### 2.3 $B^0 \to \rho^\pm\pi^\mp$

The final state of the decay $B^0 \to \rho^\pm\pi^\mp$ is not a *CP* eigenstate and the decay $B^0 \to \rho^0\pi^0$ has not yet been observed. A direct extraction of $\alpha$ using simple isospin relations like in the $B \to \pi\pi$ system does not appear promising. Instead, we performed a full time-dependent Dalitz analysis of the charmless three-body system $B^0 \to \pi^+\pi^-\pi^0$ with 213 million $B\overline{B}$ pairs, which allows a theoretically cleaner extraction of the angle $\alpha$[9] compared to the previously adopted quasi-twobody approach.

The 16 coefficients of the bilinear form factor terms occurring in the time-dependent decay rate of the $B^0$ meson are determined in a maximum-likelihood fit with an event yield of $n(B^0 \to \pi^+\pi^-\pi^0) = 1184 \pm 58$. The physically relevant quantities are derived from these coefficients, resulting in the measurement of the direct *CP*-violation $\mathcal{A}_{\rho\pi} = -0.088 \pm 0.049 \pm 0.013$ and $C = 0.34 \pm 0.11 \pm 0.05$ and the mixing-induced *CP*-violation parameter $S = -0.10 \pm 0.14 \pm 0.04$. For the dilution and strong phase shift we obtain $\Delta C = 0.15 \pm 0.11 \pm 0.03$ and $\Delta S = 0.22 \pm 0.15 \pm 0.03$, respectively. These results can be expressed in terms of the asymmetries $\mathcal{A}_{\rho\pi}^{+-}$ ($\mathcal{A}_{\rho\pi}^{-+}$), which involve only diagrams where the $\rho(\pi)$ meson is emitted by the W boson, and are shown in Tab. 2. For the relative strong phase $\delta_{+-}$ between the $B^0 \to \rho^-\pi^+$ and $B^0 \to \rho^+\pi^-$ transitions we find $(-67^{+28}_{-31} \pm 7)^\circ$.

## 3 Extraction of $\alpha$

We use the isospin relations of reference[10] to extract information on the angle difference $\delta = \alpha - \alpha_{\text{eff}}$, based on the measurement of the branching fraction[11] $\mathcal{B}(B^0 \to \pi^+\pi^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$ in conjunction with the asymmetries $C_{\pi^+\pi^-}$ and $C_{\pi^0\pi^0}$ and the $B^0 \to \pi^0\pi^0$ and $B^\pm \to \pi^\pm\pi^0$ decay rates described here. We scan over all values of $|\delta|$ and calculate a $\chi^2$ for the decay amplitudes, given these five measurements and the two isospin constraints for each value of $|\delta|$. The $\chi^2$ is converted into a confidence level, as shown in Fig. 3, from which we derive an upper bound on $|\delta|$ of 35° at the 90% C.L.

From the measured coefficients of the amplitude relations in the Dalitz analysis we can extract an independent bound on $\alpha$, with little theoretical assumptions. We find $\alpha = \left(113^{+27}_{-17} \pm 6\right)^\circ$, while only a weak constraint is achieved at the significance level of more than two standard deviations.

## Acknowledgments

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| Decay | $\mathcal{B} \times 10^{-6}$ | $N\sigma$ |
|---|---|---|
| $B^+ \to \pi^+\pi^0$ | $5.8 \pm 0.6 \pm 0.4$ | |
| $B^0 \to \pi^0\pi^0$ | $1.17 \pm 0.32 \pm 0.10$ | 5.0 |
| $B^+ \to K^+\pi^0$ | $12.0 \pm 0.7 \pm 0.6$ | |
| $B^0 \to K^0\pi^0$ | $11.4 \pm 0.9 \pm 0.6$ | |
| $B^+ \to K^0\pi^+$ | $26.0 \pm 1.3 \pm 1.0$ | |
| $B^0 \to K^0\overline{K}^0$ | $1.19 \pm 0.38 \pm 0.13$ | 4.5 |
| $B^+ \to K^+\overline{K}^0$ | $< 2.35$ 90% C.L. | |

Table 1: Summary of branching fractions measured with 227 million $B\overline{B}$ pairs. The last column ($N\sigma$) shows the significance including systematic effects.

| Parameter | Value |
|---|---|
| $S_{\pi\pi}$ | $-0.30 \pm 0.17 \pm 0.03$ |
| $C_{\pi\pi}$ | $-0.09 \pm 0.15 \pm 0.04$ |
| $\mathcal{A}_{\pi^+\pi^0}$ | $-0.01 \pm 0.10 \pm 0.02$ |
| $C_{\pi^0\pi^0}$ | $-0.12 \pm 0.56 \pm 0.06$ |
| $\mathcal{A}_{K^+\pi^0}$ | $0.06 \pm 0.06 \pm 0.01$ |
| $\mathcal{A}_{K^0\pi^+}$ | $-0.087 \pm 0.046 \pm 0.010$ |
| $\mathcal{A}_{\rho\pi}^{+-}$ | $-0.21 \pm 0.11 \pm 0.04$ |
| $\mathcal{A}_{\rho\pi}^{-+}$ | $-0.47 \pm 0.15 \pm 0.06$ |

Table 2: Summary of updated $CP$ parameters.

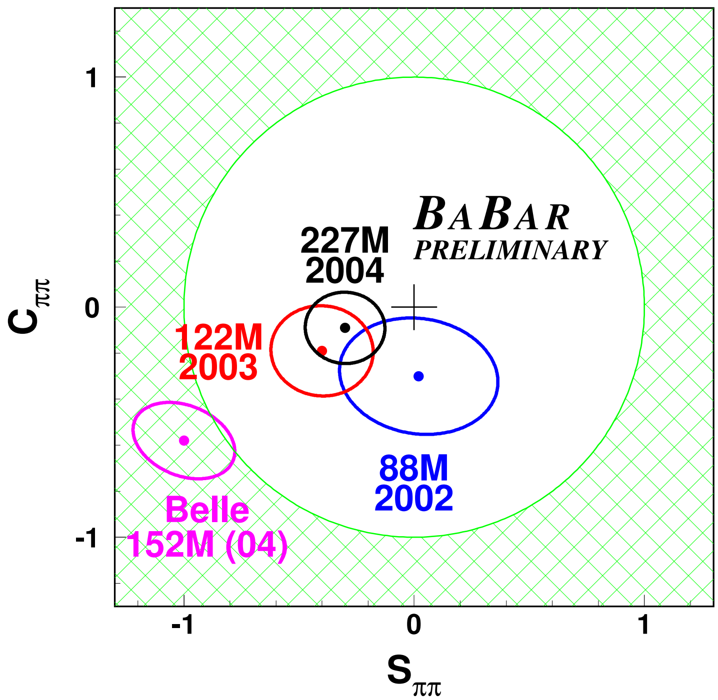


Figure 1: Central values and $1\sigma$ contours of the time-dependent $CP$ parameters $C_{\pi\pi}$ and $S_{\pi\pi}$ in the decay $B^0 \to \pi^+\pi^-$ on different *BABAR* datasets in contrast to the measurement from Belle.

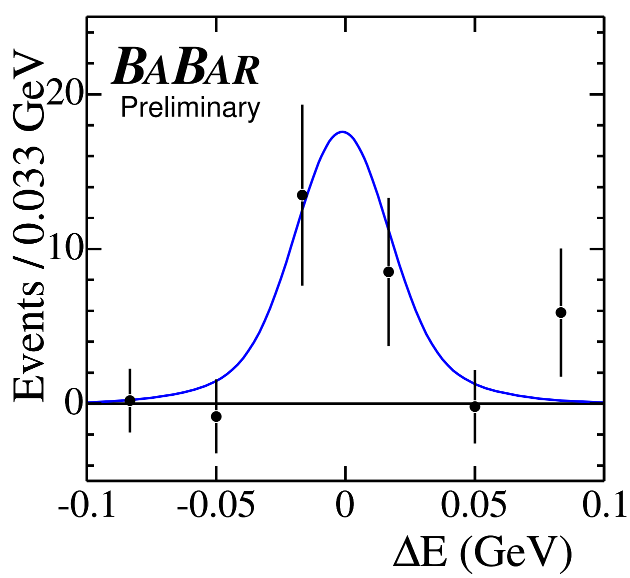


Figure 2: $\Delta E$ distribution for background subtracted $B^0 \to K^0\overline{K}^0$ events (see text).

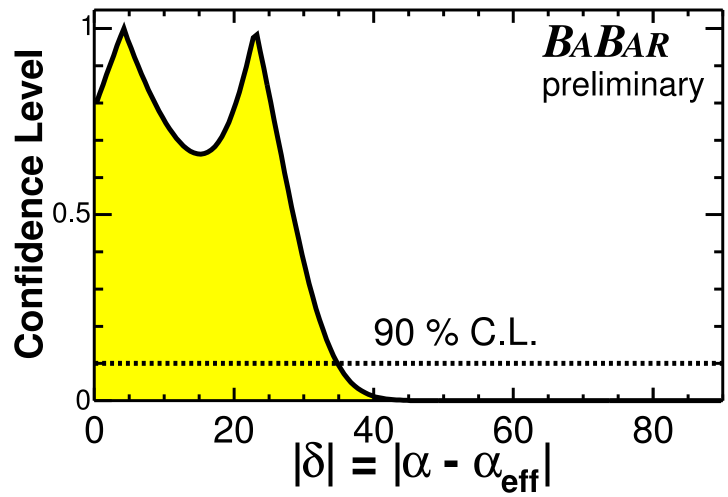


Figure 3: Confidence level for the parameter $\delta$ from the full $B \to \pi\pi$ isospin analysis.

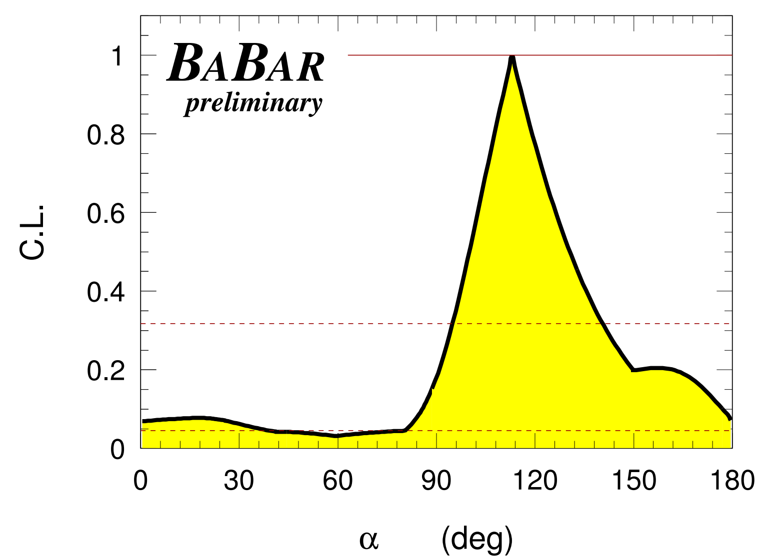


Figure 4: Confidence level for the CKM angle $\alpha$ from the $B^0 \to \pi^+\pi^-\pi^0$ Dalitz analysis.