Search for direct $CP$ violation in $B$ decays at $BaBar$

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Abstract. We report on new and updated BABAR measurements of direct $CP$-violating quantities in charmless $B$-decays. They have been performed using a sample of about 383 million $\Upsilon(4S) \to BB$ decays collected at the PEP-II asymmetric $B$ Factory at SLAC. No evidence of direct $CP$ violation is found in these measurements, all statistically limited.

1. Introduction
Charmed $B$ decays proceed through $b \to u$ CKM-suppressed tree diagrams and $b \to \{s, d\}$ loop (‘penguin’) diagrams. Trees and penguins can have similar amplitudes and their interference potentially lead to significant direct $CP$ violation. Such modes are also useful to look for New Physics whose effects would be seen via new particles entering in the loop diagrams. In addition, interferences between $b \to u$ decays with and without $B_0^\pm \to B_0^\mp$ mixing help constraining the $\alpha \equiv 2 \arg [V_{td}^* V_{ub} / V_{td} V_{ub}^*]$ angle of the CKM matrix $[1],[2]$. Finally, charmless decays allow one to test and validate the accuracy of theoretical models and estimation methods.

For $B^\pm \to f^\pm$ decays, direct $CP$ violation would correspond to a non-zero charge asymmetry

$$A_{ch} \equiv \frac{\Gamma (B^- \to f^-) - \Gamma (B^+ \to f^+)}{\Gamma (B^- \to f^-) + \Gamma (B^+ \to f^+)}$$

For neutral $Bs$ decaying into a non-$CP$ eigenstate (such as $B_0^0 \to b_1^- h^+$, $h = \{\pi, K\}$), a similar charge asymmetry $A_{ch}$ can be defined based on the charge $q = \{\pm 1\}$ of the $b_1$. In addition, the time-integrated $CP$ asymmetry $C$ can be computed – such as the non $CP$-violating dilution term $\Delta C$ – using a multivariate tagging technique $[4]$ to determine the flavor $\eta$ of the other $B$ meson (+1 for $B^0$ and -1 for $\bar{B}^0$). With $\chi_d = 0.188 \pm 0.003$ $[5]$ the time-integrated mixing probability, $\omega$ the mistag fraction, $\Delta \omega$ the $B-B$ difference in mistag rate (in tagging efficiency) and $N_{tot}$ the total number of signal events, the 4 yields $n_{q\eta}$ are given by

$$n_{q\eta} = \frac{1}{4} N_{tot} (1 + q A_{ch}) \left( 1 - \eta \Delta \omega + \eta \mu (1 - 2 \omega) - \eta (1 - 2 \chi_d) [1 - 2 \omega + \mu (\eta - \Delta \omega)] (C + q \Delta C) \right)$$

For $B_0^0$ decaying into a $CP$-eigenstate $f_{CP}$, the time-integrated $CP$ asymmetry is

$$C \equiv \frac{\Gamma (B_0^0 \to f_{CP}) - \Gamma (\bar{B}_0^0 \to f_{CP})}{\Gamma (B_0^0 \to f_{CP}) + \Gamma (\bar{B}_0^0 \to f_{CP})}$$
2. Analysis overview

The results presented here are based on a BABAR [3] data sample of 347 fb⁻¹ (about 383 million $B\bar{B}$ pairs), collected at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV) in $e^+e^-$-annihilation. In addition, 37 fb⁻¹ of data were recorded 40 MeV below the resonance to allow one to study the dominant $q\bar{q}$ (‘continuum’ $q = \{u, d, s, c\}$) background. Tracking is performed with a 5-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), both operating in the 1.5 T magnetic field of a superconducting solenoid. Particle identification (PID) is done with an electromagnetic calorimeter (EMC).

Two kinematic variables are used to discriminate between signal and background: the energy difference $\Delta E = E_B - \sqrt{s}/2$ and the beam-energy substituted mass $m_{ES} = \sqrt{s}/4 - (\vec{p}_B)^2$ where $(E_B, \vec{p}_B)$ is the $B$ 4-momentum vector in the $\Upsilon(4S)$ rest frame. $\Delta E$ ($m_{ES}$) peaks at 0 ($m_B$) for signal with a resolution of a few tens of (a few) MeV. Event-shape variables aim at rejecting random combinations of particles coming from continuum events which have a ‘jet-like’ structure whereas real $B$ decays are more uniform. To improve the signal-background separation, some of these variables are combined in a multivariate algorithm (MVA, a Fisher discriminant or a neural network) which is trained on signal MC and $q\bar{q}$ background and used in the fits.

Physical quantities (e.g. yields and $CP$ asymmetries) are determined from extended and unbinned maximum likelihood (ML) fits. The likelihood function $L$ has the generic shape

$$L = \exp \left( - \sum_{\text{species } k} n_k \right) \prod_{\text{events } i} \left( \sum_{\text{species } k} n_k P_k(\vec{x}_i; \vec{\alpha}_k) \right),$$

where $n_k$ is the yield for species $k$ and $P_k(\vec{x}_i; \vec{\alpha}_k)$ the complete probability density function (PDF) for event $i$, species $k$ and variables $\vec{x}_i$ ($\Delta E$, $m_{ES}$, MVA, etc.), given the set of parameters $\vec{\alpha}_k$. The complete PDF is the product of several individual PDFs whose shapes are based on MC or data (sidebands or off resonance). Their most important parameters are left free. In addition to signal and continuum, $B$-background categories (either gathering exclusive decays with similar PDF shapes or inclusive) are included in the fits.

Most systematics cancel out in the direct $CP$-violating ratios. Detector asymmetries (charge-dependent effect in tracking and PID or imperfect modeling of interactions in BABAR) contribute to systematics and can even produce small biases in $A_{ch}$. Other sources of systematics come from the $B$-background estimation, tagging uncertainties or PDF parameterizations. In all the reported measurements of direct $CP$ violation quantities, statistical errors dominate by far.

3. Results

For all results in these proceedings, the first error is statistical and the second one systematic.

- Ref. [6] presents the results of searches for decays of $B$ mesons to final states with an axial-vector meson $b_1$ and a charged pion or kaon. First observations of the decays $B^+ \rightarrow b_1^0K^+$, $B^0 \rightarrow b_1^-\pi^+$, $B^0 \rightarrow b_1^+K^-$ are reported, such as evidence for the decay $B^+ \rightarrow b_1^0\pi^+$. The measured charge asymmetries are given in Table 1. Two additional quantities have been measured for the decay $B^0 \rightarrow b_1^-\pi^+$: $C = -0.22 \pm 0.23 \pm 0.05$ and $\Delta C = -1.04 \pm 0.23 \pm 0.08$. The latter agrees with the suppression of $B^0 \rightarrow b_1^-\pi^-$ in the Standard Model (G-parity).

- The first observation of the inclusive decay $B^+ \rightarrow K^+K^-\pi^+$ is presented in Ref. [7]. The charge asymmetry is extracted from the signal yield by fitting separately the $B^-$ and $B^+$ samples. The result is $A_{ch} = 0.00 \pm 0.10 \pm 0.03$. The next step of this analysis will be to fully use the Dalitz Plot (DP) $m^2_{K^+K^-}$ vs. $m^2_{K^-\pi^+}$ (so far only the signal efficiency dependence
on the DP has been taken into account), in particular to understand the origin of a broad structure peaking near 1.5 GeV/c² in the \( K^+K^- \) invariant mass spectrum.

- Ref. [8] updates the analysis of the \( B^+ \rightarrow \{\eta, \eta', \omega\}h^+ \) decays. Two decay chains are constructed for the \( \eta \rightarrow \gamma\gamma \) and \( \rightarrow \pi^+\pi^-\pi^0 \) and \( \eta' \rightarrow \pi^+\pi^-\pi^0 \) and \( \rightarrow \rho^0(\rightarrow \pi^+\pi^-\gamma) \) particles. ML fits are done separately for each decay chain; the likelihood functions (including systematics errors) are then combined to provide the charge asymmetries which are given in Table 1.

- The analysis of decays \( B^\pm \rightarrow h^\pm\pi^0 \) (\( h = \{\pi, K\} \)) and \( B^0 \rightarrow \pi^0\pi^0 \) is updated in Ref. [9]. The measured charge asymmetries are shown in Table 1. \( \mathcal{A}_{\text{ch}}(B^\pm \rightarrow K^\pm\pi^0) \) is very different from \( \mathcal{A}_{\text{ch}}(B^0 \rightarrow K^0\pi^0) \) which indicates that the effect of color-suppressed tree and electroweak penguin amplitudes are significant. Finally, the time-integrated \( CP \) asymmetry for the \( B^0 \rightarrow \pi^0\pi^0 \) is measured to be \( C = -0.49 \pm 0.35 \pm 0.05 \).

### Table 1. New and updated measurements of charge asymmetries by BABAR in the modes \( B \rightarrow b_1h, B^+ \rightarrow \{\eta, \eta', \omega\}h^+ \) and \( B^\pm \rightarrow h^\pm\pi^0 \) modes, with \( h = \pi \) or \( K \).

| Decay     | \( B^+ \rightarrow b_1^+\pi^+ \)      | \( B^+ \rightarrow b_1^0K^+ \)      | \( B^0 \rightarrow b_1^-\pi^\pm \) | \( B^0 \rightarrow b_1^-K^+ \) |
|-----------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| \( \mathcal{A}_{\text{ch}} \) | \( 0.05 \pm 0.16 \pm 0.02 \)     | \( -0.46 \pm 0.20 \pm 0.02 \)     | \( -0.05 \pm 0.10 \pm 0.02 \)     | \( -0.07 \pm 0.12 \pm 0.02 \)     |

| Decay     | \( B^+ \rightarrow \eta\pi^+ \) | \( B^+ \rightarrow \eta'\pi^+ \) | \( B^+ \rightarrow \omega\pi^+ \) | \( B^\pm \rightarrow \pi^\pm\pi^0 \) |
|-----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| \( \mathcal{A}_{\text{ch}} \) | \( -0.08 \pm 0.10 \pm 0.01 \) | \( 0.21 \pm 0.17 \pm 0.01 \) | \( -0.02 \pm 0.08 \pm 0.01 \) | \( 0.03 \pm 0.08 \pm 0.01 \) |

| Decay     | \( B^+ \rightarrow \eta K^+ \) | \( B^+ \rightarrow \eta' K^+ \) | \( B^+ \rightarrow \omega K^+ \) | \( B^\pm \rightarrow K^\pm\pi^0 \) |
|-----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| \( \mathcal{A}_{\text{ch}} \) | \( -0.22 \pm 0.11 \pm 0.01 \) | \( 0.01 \pm 0.02 \pm 0.01 \) | \( -0.01 \pm 0.07 \pm 0.01 \) | \( 0.03 \pm 0.04 \pm 0.01 \) |

### 4. Conclusion

Several new or updated measurements of direct \( CP \)-violating quantities in charmless \( B \)-decays have been presented by BABAR. They do not provide any new evidence of direct \( CP \) violation.

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