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CP Violation measurements in B→ charm decays at *BABAR*.

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Abstract

This article summarises measurements of time-dependent *CP* asymmetries in decays of neutral B mesons to charm final states using data collected by the *BABAR* detector at the PEP-II asymmetric-energy B factory. All results are preliminary unless otherwise stated.

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1 Introduction

The Standard Model (SM) of particle physics describes *CP* violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, measurements of *CP* asymmetries in the proper-time distribution of neutral B decays to *CP* eigenstates containing a charmonium and K^0 meson provide a direct measurement of $\sin 2\beta$ [2]. The unitarity triangle angle β is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$ where the V_{ij} are CKM matrix elements.

The BaBar detector [3] is located at the SLAC PEP-II e^+e^- asymmetric energy B-factory. Its program includes the measurement of the angle β through the measurement of time-dependent *CP*-asymmetries, A_{CP}. At the $\Upsilon(4S)$ resonance, A_{CP} is extracted from the distribution of the difference of the proper decay times, $t \equiv t_{CP} - t_{tag}$, where t_{CP} refers to the decay time of the signal B meson (B_{CP}) and t_{tag} refers to the decay time of the other B meson in the event (B_{tag}). The decay products of B_{tag} are used to identify its flavor at its decay time.

$$\begin{aligned} A_{CP}(t) \;\; &\equiv \;\; \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)} \\ &= S\sin(\Delta m_d t) - C\cos(\Delta m_d t), \end{aligned}$$

where $N(\overline{B}^0(t) \to f)$ is the number of $\overline{B}^0$ that decay into the CP-eigenstate f after a time t and Δm_d is the difference between the B mass eigenstates. The sinusoidal term describes interference between mixing and decay and the cosine term is the direct *CP* asymmetry. S and C are functions of the parameter λ and are defined as follows:

$$S = \frac{2 \cdot \mathrm{Im}\,|\lambda|}{1+|\lambda|^2},$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2},$$

$$\lambda = \frac{q}{p} \cdot \frac{A(\overline{B}^0(t) \to \overline{f})}{A(B^0(t) \to f)}. \quad (1)$$

In Eq. 1, $A(\overline{B}^0(t) \to \overline{f})$ ($A(B^0(t) \to f)$) is the decay amplitude of $\overline{B}^0$ (B^0) to the final state $\overline{f}$ (f). The physical states (solutions of the complex effective Hamiltonian for the B^0-$\overline{B}^0$ system) can be written in terms of the parameters p, q and z [4]:

$$\begin{aligned} |B_L\rangle \;\; &= \;\; p\sqrt{1-\mathsf{z}}|B^0\rangle + q\sqrt{1+\mathsf{z}}|\overline{B}^0\rangle, \\ |B_H\rangle \;\; &= \;\; p\sqrt{1+\mathsf{z}}|B^0\rangle - q\sqrt{1-\mathsf{z}}|\overline{B}^0\rangle, \end{aligned}$$

where H and L denote the Heavy and Light mass eigenstates. Under *CPT* symmetry, the complex parameter z vanishes. T invariance implies $|q/p| = 1$ and *CP* invariance requires both $|q/p| = 1$ and $\mathsf{z} = 0$. In this article the current status of measurements of *CP* violation in $B \to$ charm decays and studies of searches for T, *CPT* and *CP* violation in B^0-$\overline{B}^0$ mixing are presented. All results are preliminary unless otherwise stated.

2 $b \to c\overline{c}s$ decay modes

The determination of β from $b \to c\overline{c}s$ decay modes currently provides the most stringent constraint on the unitarity triangle. For these decay modes, the *CP* violation parameters in Eq. 1 are $S_{b\to c\overline{c}s} =$

$-\eta_f \sin2\beta$ and $S_{b\to c\bar{c}s} = 0$, where η_f is -1 for $(c\bar{c})K^0_S$ decays (e.g. $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ [5]) and η_f is $+1$ for the $(c\bar{c})K^0_L$ (e.g. $J/\psi K^0_L$) state. We use the value $\eta_f = 0.504 \pm 0.033$ for the $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ final state since it can be both *CP* even and *CP* odd due to the presence of even and odd orbital angular momentum contributions [6]. These modes have been used to measure sin2β using 348 M $B\overline{B}$ pairs [7], where an improved event reconstruction has been applied to the complete dataset, and a new $\eta_c K^0_S$ event selection has been developed based on the Dalitz structure of the $\eta_c \to K^0_S K^+\pi^-$ decay. We measure [8]

$$
\begin{aligned}
\sin2\beta &= 0.715 \pm 0.034 \pm 0.019, \\
|\lambda| &= 0.932 \pm 0.026 \pm 0.017
\end{aligned}
$$

which is in agreement with SM expectations. Figure 1 shows the Δt distributions and asymmetries in yields between B^0 tags and $\overline{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of Δt, overlaid with the projection of the likelihood fit result.

3 cos2β measurements

The analysis of $b \to c\bar{c}s$ decay modes imposes a constraint on sin2β only, leading to a four-fold ambiguity in the determination of β. This ambiguity can leave possible new physics undetected even with very high precision measurements of sin2β. Additional constraints are obtained from the ambiguity-free measurement of cos2β using the angular and time-dependent asymmetry in $B^0 \to J/\psi K^*$ decays and the time-dependent Dalitz plot analyses of $B^0 \to D^{*0}h^0$ and $B^0 \to D^{*+}D^{*-}K^0_S$. The $B^0 \to J/\psi K^*$ analysis is published in Ref. [9].

A model-independent measurement of cos2β in $B^0 \to D^{*0}h^0$ decays has been made using a time-dependent Dalitz plot analysis of $D^0 \to K^0_S\pi^+\pi^-$, where h^0 is a light neutral meson such as π^0, η, η' or ω [10]. The strong phase variation on the $D^0 \to K^0_S\pi^+\pi^-$ Dalitz plot allows access to the angle β with only a two-fold ambiguity $(\beta + \pi)$ [11]. Using 311 M $B\overline{B}$ pairs, the following values of the *CP* asymmetry parameters are extracted:

$$
\begin{aligned}
\cos2\beta &= 0.54 \pm 0.54 \pm 0.08 \pm 0.18, \\
\sin2\beta &= 0.45 \pm 0.36 \pm 0.05 \pm 0.07, \\
|\lambda| &= 0.975^{+0.093}_{-0.085} \pm 0.012 \pm 0.002,
\end{aligned}
$$

where in addition to the statistical and systematic errors, there are also uncertainties from the signal Dalitz model. Assuming that sin2β takes the same value as the $b \to c\bar{c}s$ decay average in Ref. [12] and that there is no *CP* violation in B^0-$\overline{B}^0$ mixing, a parameterised Monte Carlo method based on the observed data finds that these measurements favour the solution of $\beta = 22^\circ$ over 68° at an 87% confidence level.

A study of the decay $B^0 \to D^{*+}D^{*-}K^0_S$ has been made using 230 M $B\overline{B}$ pairs [13]. The branching fraction $\mathcal{B}(B^0 \to D^{*+}D^{*-}K^0_S) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3}$ has been measured and evidence found for the decay $B^0 \to D^{*+}D^-_{s1}(2536)K^0_S$ with a 4.6σ statistical significance. The time-dependent decay rate asymmetry of $B^0 \to D^{*+}D^{*-}K^0_S$ can be written in terms of the parameters J_0, J_{s1}, J_{s2} and J_c which are integrals over the half Dalitz space of the decay amplitudes of $B^0 \to D^{*+}D^{*-}K^0_S$ and $\overline{B}^0 \to D^{*+}D^{*-}K^0_S$ [14]. The fits to the data yield:

$$
\frac{J_c}{J_0} = 0.76 \pm 0.18 \pm 0.07,
$$

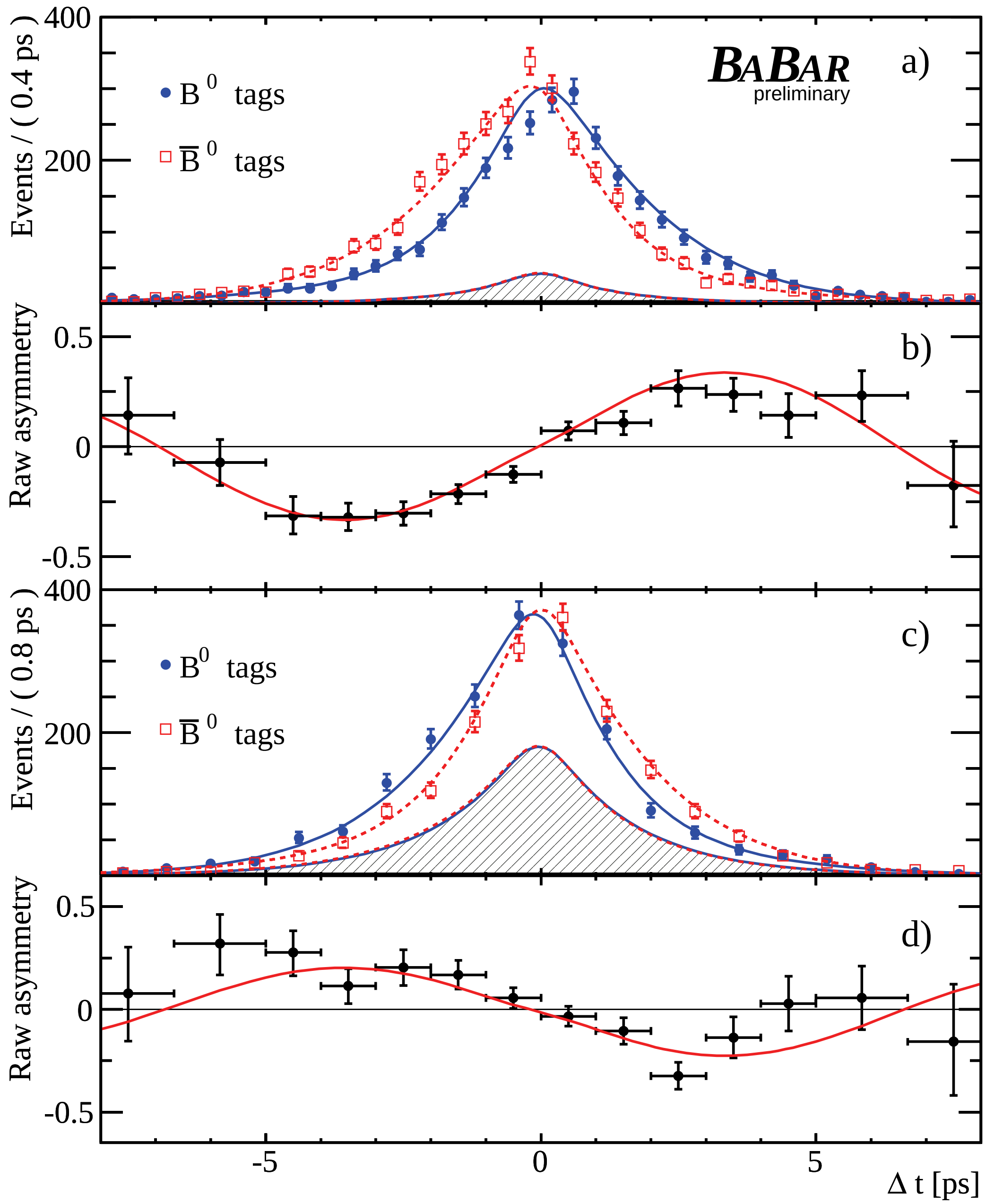

Figure 1: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K^0_L$. The solid (dashed) curves represent the fit projections in Δt for B^0 ($\overline{B}^0$) tags. The shaded regions represent the estimated background contributions.

$$\frac{2J_{s1}}{J_0}\sin 2\beta = 0.10 \pm 0.24 \pm 0.06,$$
$$\frac{2J_{s2}}{J_0}\cos 2\beta = 0.38 \pm 0.24 \pm 0.05.$$

The measured value of J_c/J_0 is significantly different from zero, which, according to Ref. [14], may indicate that there is a sizeable broad resonant contribution to the decay $B^0 \to D^{*+}D^{*-}K^0_S$ from an unknown D^+_{s1} state with an unknown width. Under this assumption then the measured value of $2J_{s2}/J_0$ implies that the sign of cos2β is preferred to be positive at a 94% confidence level.

Figure 2 illustrates the combined constraint on β in the $\overline{\rho}$-$\overline{\eta}$ plane from the Belle and *BABAR* $b \to c\bar{c}s$, $B^0 \to J/\psi K^*$, $B^0 \to D^{*0}h^0$ and $B^0 \to D^{*+}D^{*-}K^0_S$ analyses [12].

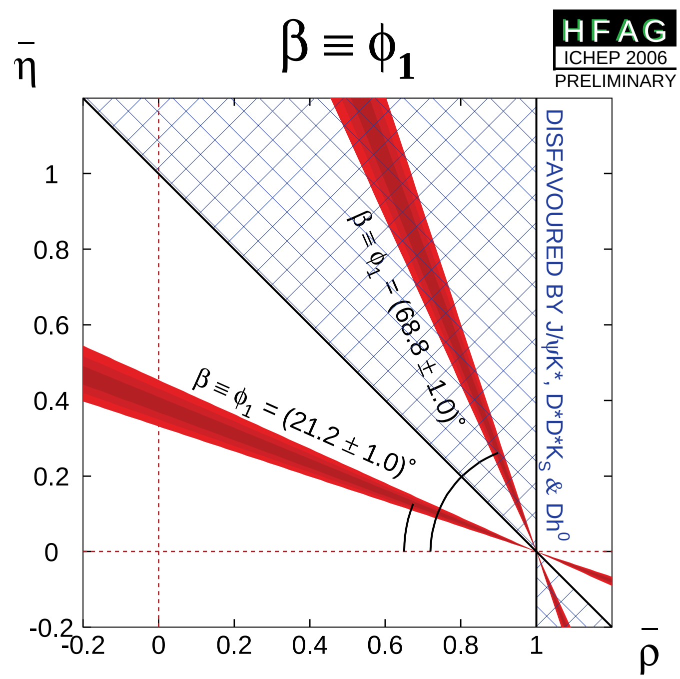

Figure 2: Constraint on β in the $\overline{\rho}$-$\overline{\eta}$ plane, obtained from the analysis of $b \to c\bar{c}s$ decays, the angular analysis of $B^0 \to J/\psi K^*$ and the time-dependent Dalitz plot analyses of $B^0 \to D^{*0}h^0$ and $B^0 \to D^{*+}D^{*-}K^0_S$. The hatched area corresponding to the solution β =68.8±1.0° where cos2β is negative, is strongly disfavoured.

4 Studies of T, CPT and CP violation in B^0-$\overline{B}^0$ mixing.

Inclusive dilepton events, where both B mesons decay semileptonically represent 4% of all $\Upsilon(4S) \to B^0\overline{B}^0$ decays and provide a very large sample with which to study T, CPT and CP violation in B^0-$\overline{B}^0$ mixing. The same-sign dilepton asymmetry $A_{T/CP}$ between the two oscillation probabilities $P(\overline{B}^0 \to B^0)$ and $P(B^0 \to \overline{B}^0)$ is sensitive to $|q/p|$ and probes both T and CP symmetries. The opposite-sign dilepton asymmetry $A_{T/CPT}$ compares the probabilities $P(B^0 \to B^0)$ and $P(\overline{B}^0 \to \overline{B}^0)$ and probes CPT and CP violation. It is sensitive to the product $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}$ where $\Delta\Gamma$ is the difference between the decay rates of the neutral B mass eigenstates. The result published in Ref. [15] uses a sample of 232 M $B\overline{B}$ pairs to measure the T and CP violation parameter

$$|q/p| - 1 = (-0.8 \pm 2.7 \pm 1.9) \times 10^{-3}$$

and the CPT and CP parameters

$$\begin{aligned} \mathrm{Im}\,\mathsf{z} &= (-13.9 \pm 7.3 \pm 3.2) \times 10^{-3}, \\ \Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z} &= (-7.1 \pm 3.9 \pm 2.0) \times 10^{-3}\, ps^{-1}. \end{aligned}$$

The statistical correlation between the measurements of $\mathrm{Im}\,\mathsf{z}$ and $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}$ is 76%. A search is then made for time-dependent variations in the complex CPT parameter $\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1 \cos(\Omega\hat{t} + \phi)$ where Ω is the Earth's sidereal frequency and $\hat{t}$ is sidereal time [16]. We measure:

$$\begin{aligned} \mathrm{Im}\,\mathsf{z}_0 &= (-14.1 \pm 7.3 \pm 2.4) \times 10^{-3}, \\ \Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_0 &= (-7.2 \pm 4.1 \pm 2.1) \times 10^{-3}\,\mathrm{ps}^{-1}, \\ \mathrm{Im}\,\mathsf{z}_1 &= (-24.0 \pm 10.7 \pm 5.9) \times 10^{-3}, \\ \Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_1 &= (-18.8 \pm 5.5 \pm 4.0) \times 10^{-3}\,\mathrm{ps}^{-1}. \end{aligned}$$

The statistical correlation between the measurements of $\mathrm{Im}\,\mathsf{z}_0$ and $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_0$ is 76%; and between $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_1$ is 79%. Figure 3 shows confidence level contours for the parameters $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_1$ including both statistical and systematic errors. A significance of 2.2σ is found for periodic variations in the CPT violation parameter z at the sidereal frequency, characteristic of Lorentz violation.

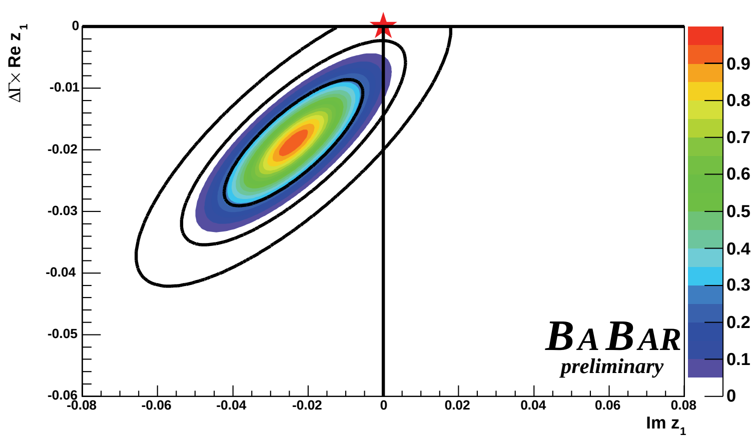

Figure 3: Confidence level contours for the parameters $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_1$. The line contours indicate 1σ, 2σ, and 3σ significance. The star at $\mathrm{Im}\,\mathsf{z}_1 = \Delta\Gamma \cdot \mathrm{Re}\,\mathsf{z}_1 = 0$ indicates the condition for no sidereal-time dependence in z.

A measurement of the parameter $|q/p|$ has also been made using the partial reconstruction of one of the B mesons in the semileptonic channel $D^{*-}\ell^+\nu_\ell$, where only the hard lepton and the soft pion from the $D^{*-} \to \overline{D}^0\pi^-$ decay are reconstructed [17]. A data sample of 220 M $B\overline{B}$ pairs are used. We measure

$$|q/p| - 1 = (6.5 \pm 3.4 \pm 2.0) \times 10^{-3}$$

which is consistent with SM expectations.

5 Conclusion

An improved measurement of sin2β has been made using $B^0 \to$ charmonium + K^0 decays. This is consistent with SM expectations and continues to provide the most stringent constraint on the unitarity triangle. Analysis of the $b \to c\bar{c}s$, $B^0 \to J/\psi K^*$, $B^0 \to D^{*0}h^0$ and $B^0 \to D^{*+}D^{*-}K^0_S$ modes indicate that the solution $\beta = 21.1 \pm 1.0^\circ$ is strongly preferred. The measurements of $|q/p|$ from analyses of inclusive dilepton and $D^{*-}\ell^+\nu_\ell$ events are in agreement with SM predictions.

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