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Improved Measurement of *CP* Violation in Neutral *B* Decays to $c\bar{c}s$

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We present updated measurements of time-dependent CP asymmetries in fully-reconstructed neutral B decays to several CP eigenstates containing a charmonium meson. The measurements use a data sample of $(383 \pm 4) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II B factory. We determine $\sin 2\beta = 0.714 \pm 0.032\,(\mathrm{stat}) \pm 0.018\,(\mathrm{syst})$ and $|\lambda| = 0.952 \pm 0.022\,(\mathrm{stat}) \pm 0.017\,(\mathrm{syst})$.

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The standard model (SM) of electroweak interactions describes CP violation as a consequence of an irreducible phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In the CKM framework, neutral B decays to CP eigenstates containing a charmonium and a $K^{(*)0}$ meson through tree-diagram dominated processes provide a direct measurement of $\sin 2\beta$ [2], where the angle β is defined in terms of the CKM matrix elements V_{ij} as $\arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$.

We report updated measurements, based on a sample of $(383 \pm 4) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays, of $\sin 2\beta$ and of the parameter $|\lambda|$. Here $\lambda = (q/p)(\overline{A}/A)$ [3], q and p are complex constants that relate the B-meson flavor eigenstates to the mass eigenstates, and $\overline{A}/A$ is the ratio of amplitudes of the decay of a $\overline{B}^0$ or B^0 to the final state under study. We reconstruct B^0 decays to the final states $J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}$ [4]. Since our previously published result [5], we have added 157×10^6 $B\overline{B}$ decays and applied improved event reconstruction algorithms to the entire dataset. We have also developed a new $\eta_c K^0_S$ event selection based on the Dalitz plot structure of the $\eta_c \to K^0_S K^+\pi^-$ decay, and have performed a more detailed study of the CP properties of the background events, which results in reduced systematic errors. We now include the $J/\psi K^0_L$ and $J/\psi K^{*0}$ modes in the sample to measure $|\lambda|$, and we report individual measurements of $\sin 2\beta$ and $|\lambda|$ for each of the CP decay modes used in the analysis. Finally, we present separate results for the $J/\psi K^0_S(\pi^+\pi^- + \pi^0\pi^0)$ [6], and $J/\psi K^0(K^0_S + K^0_L)$ modes.

We identify (tag) the initial flavor of the reconstructed B candidate, B_{rec}, using information from the other B meson, B_{tag}, in the event. The decay rate g_+ (g_-) for a neutral B meson decaying to a CP eigenstate accompanied by a B^0 ($\overline{B}^0$) tag can be expressed as

$$g_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ (1 \mp \Delta w) \pm (1-2w) \times \Big[\frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d \Delta t) - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d \Delta t) \Big] \Big\} \quad (1)$$

where $\Delta t \equiv t_{\mathrm{rec}} - t_{\mathrm{tag}}$ is the difference between the proper decay times of the reconstructed and tag B mesons, τ_{B^0} is the neutral B lifetime and Δm_d is the mass difference of the B meson mass eigenstates determined from $B^0 - \overline{B}^0$ oscillations [7]. We assume that the corresponding decay-width difference $\Delta\Gamma_d$ is zero. The average mistag probability w describes the effect of incorrect tags, and Δw is the difference between the mistag probabilities for B^0 and $\overline{B}^0$. The sine term in Eq. 1 results from the interference between direct decay and decay after $B^0 - \overline{B}^0$ oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct CP violation) or from CP violation in $B^0 - \overline{B}^0$ mixing. In the SM, CP violation in mixing and direct CP violation in $b \to c\overline{c}s$ decays are both negligible [3]. Under these assumptions, $\lambda = \eta_f e^{-2i\beta}$, where $\eta_f = \pm 1$ is the CP eigenvalue of the final state f. Thus, the time-dependent CP-violating asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{g_+(\Delta t) - g_-(\Delta t)}{g_+(\Delta t) + g_-(\Delta t)} = -(1-2w)\eta_f \sin 2\beta \sin(\Delta m_d\,\Delta t). \quad (2)$$

The *BABAR* detector is described in detail elsewhere [8]. We select a sample of neutral B mesons (B_{CP}) decaying to the $\eta_f = -1$ final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$ and $\eta_c K^0_S$, and to the $\eta_f = +1$ final state $J/\psi K^0_L$. We reconstruct $K^0_S \to \pi^+\pi^-$, except in $J/\psi K^0_S$, where we also include $K^0_S \to \pi^0\pi^0$. The charmonium mesons are reconstructed in the decays $J/\psi \to e^+e^-, \mu^+\mu^-$; $\psi(2S) \to e^+e^-, \mu^+\mu^-, J/\psi\pi^+\pi^-$; $\chi_{c1} \to J/\psi\gamma$ and $\eta_c \to K^0_S K^+\pi^-$. We also reconstruct the $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ final state, which can be CP-even or CP-odd due to the presence of even (L=0, 2) and odd (L=1) orbital angular momentum contributions. Ignoring the angular information in $J/\psi K^{*0}$ results in a dilution of the measured CP asymmetry by a factor $|1 - 2R_\perp|$, where $R_\perp$ is the fraction of the L=1 contribution. In Ref. [9] we have measured $R_\perp = 0.233 \pm 0.010\,(\mathrm{stat}) \pm 0.005\,(\mathrm{syst})$, which gives an effective $\eta_f = 0.504 \pm 0.033$ for $f = J/\psi K^{*0}$, after acceptance corrections.

In addition to the CP modes described above, we use a sample of B^0 mesons (B_{flav}) decaying to the flavor eigenstates $D^{(*)-}h^+$ ($h^+ = \pi^+, \rho^+, a_1^+$) and $J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$) to calibrate the flavor-tagging performance and Δt resolution. We also perform studies to measure apparent CP violation arising from CP-conserving processes using a control sample of B^+ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, and $\eta_c K^+$. The event selection and candidate reconstruction remain unchanged from those described in Refs. [5, 10, 11], with the exception of modes containing η_c mesons. In Ref. [5] we reconstructed the $B^0 \to \eta_c K^0_S$ and $B^\pm \to \eta_c K^\pm$ modes using the $\eta_c \to K^0_S K^+\pi^-$ decay, with the requirement $2.91 < m_{K^0_S K^+\pi^-} < 3.05\,\mathrm{GeV}/c^2$. We now exploit the fact that the η_c decays predominantly through a $K\pi$ resonance at around $1430\,\mathrm{MeV}/c^2$ and a $K^0_S K$ resonance close to threshold, and require that either $m_{K^0_S\pi^-}$ or $m_{K^+\pi^-}$ be in the mass-range $[1.26, 1.63]\,\mathrm{GeV}/c^2$, or that $m_{K^+K^0_S} \in [1.0, 1.4]\,\mathrm{GeV}/c^2$.

We calculate the time interval Δt between the two B decays from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision (z) axis [10]. The z position of the B_{rec} vertex is determined from the charged daughter tracks. The B_{tag} decay vertex is determined by fitting tracks not belonging to the B_{rec} candidate to a common vertex, while employing constraints from the beamspot location and the B_{rec} momentum [10]. Events are accepted if the calculated Δt uncertainty is less than 2.5 ps and $|\Delta t|$ is less than 20 ps. The fraction of all events satisfying these requirements is 95 %.

The algorithm used to determine the flavor of the B_{tag} at its decay to be either B^0 or $\overline{B}^0$ is described in detail in Ref. [5]. In brief, we define six mutually exclusive tagging categories in order of decreasing tag purity: `Lepton`, `Kaon I`, `Kaon II`, `Kaon-Pion`, `Pion` and `Other`. The figure-of-merit for tagging is the effective tagging efficiency $Q \equiv \sum_i \varepsilon_i(1-2w_i)^2$, where ε_i is the tagging efficiency of tagging category i. We measure $Q = (30.5 \pm 0.3)\,\%$, consistent with the results in Ref. [5].

We determine the composition of our final sample using the beam-energy substituted mass $m_{\mathrm{ES}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_B)^2}$, where E^*_{beam} and p^*_B are the beam energy and B momentum in the e^+e^- center-of-mass (CM) frame. For the $J/\psi K^0_L$ mode we instead use the difference ΔE between the candidate CM energy and E^*_{beam}. The composition of our final sample is shown in Fig. 1. We use events with $m_{\mathrm{ES}} > 5.2\,\mathrm{GeV}/c^2$ ($|\Delta E| < 80\,\mathrm{MeV}$ for $J/\psi K^0_L$) to determine the properties of the background contributions. We define a signal region $5.27 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$ ($|\Delta E| < 10\,\mathrm{MeV}$ for $J/\psi K^0_L$), which contains 12677 *CP* candidate events that satisfy the tagging and vertexing requirements (see Table I). For all modes except $\eta_c K^0_S$ and $J/\psi K^0_L$, we use simulated events to estimate the fractions of events that peak in the m_{ES} signal region due to cross-feed from other decay modes (peaking background). For the $\eta_c K^0_S$ mode, the cross-feed fraction is determined from a fit to the $m_{KK\pi}$ and m_{ES} distributions in data. For the $J/\psi K^0_L$ decay mode, the sample composition, effective η_f, and ΔE distribution of the individual background sources are determined either from simulation (for $B \to J/\psi X$) or from the $m_{\ell^+\ell^-}$ sidebands in data (for non-J/ψ background).

We determine $\sin2\beta$ and $|\lambda|$ from a simultaneous maximum likelihood fit to the Δt distribution of the tagged B_{CP} and B_{flav} samples. The Δt distributions of the B_{CP} sample are modeled by Eq. 1. Those of the B_{flav} sample evolve according to Eq. 1 with $\lambda = 0$. The observed amplitudes for the *CP* asymmetry in the B_{CP} sample and for flavor oscillation in the B_{flav} sample are reduced by the same factor, $1-2w$, due to flavor mistags. The Δt distributions for the signal are convolved with a resolution function common to both the B_{flav} and B_{CP} samples, modeled by the sum of three Gaussian functions [10]. The combinatorial background is incorporated with an empirical description of its Δt spectra, containing prompt and non-prompt lifetime components convolved with a resolution function [10] distinct from that of the signal. The peaking background is assigned the same Δt distribution as the signal but with no *CP* violation, with the same Δt resolution function.

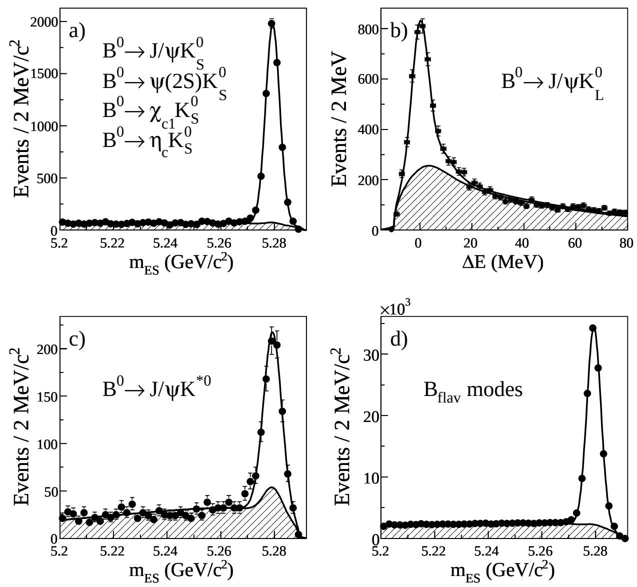

FIG. 1: Distributions for B_{CP} and B_{flav} candidates satisfying the tagging and vertexing requirements: a) m_{ES} for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, b) ΔE for the final state $J/\psi K^0_L$, c) m_{ES} for $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$, and d) m_{ES} for the B_{flav} sample. In each plot, the shaded region is the estimated background contribution.

In addition to $\sin2\beta$ and $|\lambda|$, there are 68 free parameters in the *CP* fit. For the signal, these are the parameters of the Δt resolution (7), the average mistag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mistag fractions for each tagging category (12), and the difference between B^0 and $\overline{B}^0$ reconstruction and tagging efficiencies (7). The background is described by mistag fractions (24), parameters of the Δt resolution (3) and B_{flav} time dependence (3), and parameters for the *CP* background (8), including the apparent *CP* asymmetry of non-peaking events in each tagging category. Finally, we allow for the possibility of direct *CP* violation in the $\chi_{c1}K^0_S$ background to $J/\psi K^{*0}$ (1), and in the main backgrounds to the $J/\psi K^0_L$ mode, coming from $J/\psi K^0_S$, $J/\psi K^{*0}$, and the remaining J/ψ background (3 parameters). The effective $|\lambda|$ of the non-J/ψ background is fixed from a fit to the J/ψ-candidate sidebands in $J/\psi K^0_L$. We fix $\tau_{B^0} = 1.530\,\mathrm{ps}$ and $\Delta m_d = 0.507\,\mathrm{ps}^{-1}$ [7]. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the B_{flav} sample, about 10 times more abundant than the

TABLE I: Number of events $N_{\rm tag}$ and signal purity P in the signal region after tagging and vertexing requirements, and results of fitting for *CP* asymmetries in the B_{CP} sample and various subsamples. In addition, fit results for the $B_{\rm flav}$ and B^+ control samples demonstrate that no artificial *CP* asymmetry is found where we expect no *CP* violation ($\sin2\beta = 0$, $|\lambda| = 1$). Errors are statistical only.

Sample	N_{tag}	$P(\%)$	$\sin2\beta$	$\lvert\lambda\rvert$
Full *CP* sample	12677	75	0.714 ± 0.032	0.952 ± 0.022
$J/\psi K^0_S\,(\pi^+\pi^-)$	4459	96	0.702 ± 0.042	0.976 ± 0.030
$J/\psi K^0_S\,(\pi^0\pi^0)$	1086	88	0.617 ± 0.103	0.812 ± 0.058
$\psi(2S) K^0_S$	687	83	0.947 ± 0.112	0.867 ± 0.079
$\chi_{c1} K^0_S$	313	89	0.759 ± 0.170	0.804 ± 0.102
$\eta_c K^0_S$	328	69	0.778 ± 0.195	0.948 ± 0.141
$J/\psi K^0_L$	4748	55	0.734 ± 0.074	1.061 ± 0.063
$J/\psi K^{*0}$	1056	66	0.477 ± 0.271	0.954 ± 0.083
$J/\psi K^0$	10275	76	0.697 ± 0.035	0.966 ± 0.025
$J/\psi K^0_S$	5547	94	0.686 ± 0.039	0.950 ± 0.027
$\eta_f = -1$	6873	92	0.711 ± 0.036	0.935 ± 0.024
1999-2002 data	3084	79	0.735 ± 0.063	0.987 ± 0.045
2003-2004 data	4850	77	0.728 ± 0.052	0.940 ± 0.035
2005-2006 data	4725	74	0.681 ± 0.054	0.940 ± 0.037
`Lepton`	1349	80	0.728 ± 0.066	0.901 ± 0.043
`Kaon I`	1843	76	0.689 ± 0.063	0.986 ± 0.046
`Kaon II`	2948	72	0.751 ± 0.071	0.880 ± 0.044
`Kaon-Pion`	2321	73	0.654 ± 0.112	0.999 ± 0.075
`Pion`	2551	76	0.671 ± 0.167	0.927 ± 0.104
`Other`	1665	73	0.705 ± 0.504	1.506 ± 0.483
$B_{\rm flav}$ sample	123893	85	0.018 ± 0.010	0.995 ± 0.007
B^+ sample	29598	94	0.012 ± 0.017	1.010 ± 0.012

CP sample.

The fit to the B_{CP} and $B_{\rm flav}$ samples yields $\sin2\beta = 0.714 \pm 0.032$ and $|\lambda| = 0.952 \pm 0.022$, where the errors are statistical only. The correlation between these two parameters is $-1.5\,\%$. We also perform a separate fit in which we allow different $\sin2\beta$ and $|\lambda|$ values for each charmonium decay mode, a fit to the $J/\psi K^0_S\,(\pi^+\pi^- + \pi^0\pi^0)$ mode, and a fit to the $J/\psi K^0\,(K^0_S + K^0_L)$ sample. We split the data sample by run period and by tagging category. We perform the *CP* measurements on control samples with no expected *CP* asymmetry. The results of these fits are summarized in Table I. The difference in the $\eta_c K^0_S$ $\sin2\beta$ value with respect to our previous publication [5] is partly due to the slightly different reconstruction algorithms and partly to the different selection; the two measurements are consistent when the systematic error is taken into account.

Figure 2 shows the Δt distributions and asymmetries in yields between events with 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. We also performed the *CP* fit fixing $|\lambda| = 1$, which yields $\sin2\beta = 0.713 \pm 0.032\,({\rm stat})$.

The dominant systematic errors on $\sin2\beta$ are due to limited knowledge of various background properties, incuding uncertainties in $J/\psi K^0_L$-specific backrounds and in

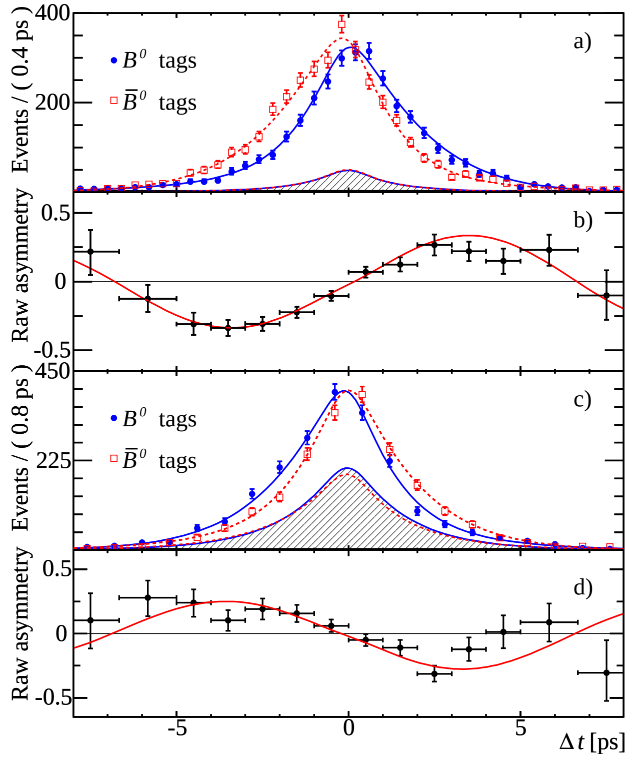

FIG. 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag (N_{B^0}) and with a $\overline{B}{}^0$ tag ($N_{\overline{B}{}^0}$), and b) the raw asymmetry, $(N_{B^0} - N_{\overline{B}{}^0})/(N_{B^0} + N_{\overline{B}{}^0})$, as functions of Δt. Figures c) and d) are the corresponding distributions for the $\eta_f = +1$ mode $J/\psi K^0_L$. To enhance the signal component, all distributions exclude `Other`-tagged events. 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.

the amounts of peaking backgrounds and their *CP* asymmetries (0.010), to possible differences between the $B_{\rm flav}$ and B_{CP} tagging performances (0.009), to the description of the Δt resolution functions (0.008), to the knowledge of the event-by-event beamspot position (0.005). The only sizeable sysyematic uncertainties on $|\lambda|$ are due to the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [12] (0.015), and to the *CP* content of the peaking backgrounds (0.006). The total systematic error on $\sin2\beta$ ($|\lambda|$) is 0.018 (0.017). The main systematic uncertainties on both $\sin2\beta$ and $|\lambda|$ for the full sample, for the seven individual modes, and for the fits to the $J/\psi K^0$ and $J/\psi K^0_S$ samples are summarized in the Table at [13].

The large B_{CP} sample allows a number of consistency checks, including separation of the data by decay mode and tagging category. The results of those checks, all consistent within the errors, are listed in Table I. We observe no statistically significant asymmetry from fits to the control samples of non-*CP* decay modes.

In summary, we report improved measurements of $\sin2\beta$ and $|\lambda|$ that supersede our previous results [5]. We measure $\sin 2\beta = 0.714 \pm 0.032\,(\mathrm{stat}) \pm 0.018\,(\mathrm{syst})$ and $|\lambda| = 0.952 \pm 0.022\,(\mathrm{stat}) \pm 0.017\,(\mathrm{syst})$, providing an improved model-independent constraint on the position of the apex of the unitarity triangle [14]. Our measurements agree within errors with the published results [15, 16] and with the theoretical estimates of the magnitudes of CKM matrix elements in the context of the SM [17]. The measured value of $|\lambda|$ is consistent with no direct *CP* violation with a significance of 1.72 standard deviations. We report the first individual measurements of $\sin 2\beta$ and $|\lambda|$ for each of the decay modes within our *CP* sample, and of the $J/\psi K^0(K^0_S + K^0_L)$ sample.

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