Primary BAD

1667, version 5

Improved measurement of $\CP$ violation in neutral $\B$ decays to $\ccbar\ K^{\{(*)0\}}$

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Review Committee

comm299, members: Eigen, Gerald; Kirkby, David (chair); Lange, David J.

Target

Physical Review Letters

Result type

Supporting BAD(s)

BAD #1447
Measurement of the CP Asymmetry amplitude $\sin(2\beta)$
BAD #1448
Aspects of the Summer 2006 $\sin2\beta$ analysis specific to the decay mode $\J/\Psi\ KL$.

Changes since preliminary result

Include $KL,K^*$ modes in simultaneous $\sin2\beta,|\lambda|$ fit and make this the new baseline (previously $|\lambda|=1$ was fixed for the baseline). Provide full systematic errors on $\sin2\beta,|\lambda|$ by mode, as requested at summer conferences.

BAIS/CWR Comments

This CWR has been shortened by a few days in order to meet a conference deadline, since the physics results were already reviewed for ICHEP.

Institutional Reading Groups

5b. Birmingham, Bochum, Caltech, Cincinnati, Karlsruhe, Louisville
6b. Edinburgh, Liverpool, Milan, Stanford, UT Austin, Wisconsin

Cover page generated by BAIS on February 27, 2007
Improved measurement of CP violation in neutral B decays to $c\bar{c}K^{(*)}$. 

The Standard Model (SM) of electroweak interactions describes charge conjugation-parity (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, measurements of CP asymmetries in the proper-time distribution of neutral B decays to tree-dominated CP eigenstates containing a charmonium and $K^{(*)0}$ meson provide a direct measurement of sin2$\beta$ [2]. The angle $\beta$ is defined in terms of the CKM matrix elements $V_{ij}$ as $\arg[-(V_{cb}V_{tb}^*)/(V_{ub}V_{tb}^*)]$. The presence of higher-order processes may shift the measured sin2$\beta$ from the SM value [3-5].

We report here on updated measurements of sin2$\beta$ and of the parameter $|\lambda|$ [6], based on a sample of $(384 \pm 4) \times 10^6 \Upsilon(4S) \to B\bar{B}$ decays. Since our previous published result [8] we have added about $157 \times 10^6$ decays and applied an improved event reconstruction to the complete dataset. We have also developed a new $\eta_c K^0_S$ event selection based on the Dalitz structure of the $\eta_c \to K^0_S K^+\pi^- \to B$ decay and we have performed a more detailed study of the CP properties of our background events, resulting in a reduced systematic error. We now include the $J/\psi K^0_S$ and $J/\psi K^{*0}$ modes in the sample to measure $|\lambda|$, and we report individual measurements of sin2$\beta$ and $|\lambda|$ for each of the seven men
day modes. Finally, we present separate results for the $J/\psi K^0_S(\pi^+\pi^- + \pi^0\pi^0)$ mode [9], and for the $J/\psi K^0_S(K^0_S + K^0_L)$ mode.

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

$$f_\pm (\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4T_{B^0}} \left\{ (1 \mp 2w) \pm (1 - 2w) \times \right.$$}

$$\left[ \frac{2Im \lambda}{1 + |\lambda|^2} \sin(\Delta m_d \Delta t) - \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos(\Delta m_d \Delta t) \right] \right\}$$

where $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the difference between the proper decay times of the reconstructed and tag B mesons, $\tau_{B^0}$ is the neutral B lifetime and $\Delta m_d$ is the mass difference determined from $B^0-\bar{B}^0$ oscillations [7]. We assume that the corresponding mistag decay-width difference $\Delta \Gamma_d$ is zero. The average mistag probability $w$ describes the effect of incorrect tags, and $\Delta w$ is the difference between the mistag rate for $B^0$ and $\bar{B}^0$. The sine term in Eq. 1 results from the interference between the direct decay and the decay after $B^0-\bar{B}^0$ 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 $B^0-\bar{B}^0$ mixing. In the SM, CP violation in mixing and $b \to c\bar{s}\bar{s}$ decays are both negligible [6]. Under these assumptions, $\lambda = (1/2)\eta_f e^{-2i\beta}$ where $\eta_f = \pm 1$ is the CP eigenvalue of the final state $f$. Thus, the time-dependent CP-violating asymmetry is:

$$A_{CP}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = (2)$$

$$- (1 - 2w)\eta_f \sin 2\beta \sin(\Delta m_d \Delta t).$$

The $\text{BABAR}$ detector is described in detail elsewhere [10]. We select a sample of neutral B mesons, $B_{CP}$, decaying to the $\eta_f = -1$ final states $J/\psi K^0_S(\pi^+\pi^-)$, $J/\psi K^0_S(\pi^0\pi^0)$, $\psi(2S)K^0_S$, $\chi_c1K^0_S$ and $\eta_cK^0_S$, and to the $\eta_f = +1$ final state $J/\psi K^0_S[11]$. The charmonium mesons are reconstructed in the decays $J/\psi \to e^+e^-$, $\mu^+\mu^-$, $\psi(2S) \to e^+e^-$, $\mu^+\mu^-$, $J/\psi\pi^+\pi^-$; $\chi_c \to J/\psi\gamma$ and $\eta_c \to K^0_SK^+\pi^-$. We also reconstruct the $J/\psi K^{(*)0}\to K^0_S(\pi^0\pi^0)$ 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 reduction of the measured CP asymmetry by a factor [1-2$R_L$], where $R_L$ is the fraction of the $L=1$ contribution. We have measured [12] $R_L = 0.233 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$, which gives an effective $\eta_f = 0.504 \pm 0.033$, after acceptance corrections, for $f = J/\psi K^{*0}$.

In addition to the CP modes described above, a large sample of $B^0$ decays to the flavor eigenstates $D^{(*)+}h^{\pm}$ ($h^{\pm} = \pi^{\pm}, \rho^{\pm},$ and $a_1^{\pm}$) and $J/\psi K^{*0}$ ($K^{*0} \to K^{\pm}\pi^\mp$) ($B_{f\pi\nu}$) is used to calibrate the flavor-tagging performance and $\Delta t$ resolution. We also perform studies to measure apparent CP violation from unphysical sources using the control sample of $B^0$ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^{\pm}$, $\chi_c K^{\pm}$, and $\eta_c K^{\pm}$. The event selection and candidate reconstruction are unchanged from those described in Refs. [8, 13, 14] with the exception of modes containing $\eta_c$ mesons. In [8] we reconstructed the $B^0 \to \eta_c K^0_S$ and $B^\pm \to \eta_c K^\pm$ modes using the $\eta_c \to K^0_SK^+\pi^-$ decay with the requirement $2.91 < m_{K^0_SK^+\pi^-} < 3.05 \text{GeV}/c^2$. We now exploit the fact that the $\eta_c$ decays predominantly through a $K\pi$ resonance at around 1430 MeV$/c^2$ and a $K^0_S$ resonance close to threshold, and require that either $m_{K^0_SK^+\pi^-}$ or $m_{K^+\pi^-}$ be in the range [1.26, 1.63] GeV$/c^2$, or that $1.0 < m_{K^+\pi^-} < 1.4$ GeV$/c^2$. 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 $(384 \pm 4) \times 10^6 \Upsilon(4S) \to B\bar{B}$ decays collected with the $\text{BABAR}$ detector at the PEP-II B factory between 1999 and 2006. We determine sin2$\beta = 0.714 \pm 0.032(\text{stat}) \pm 0.018(\text{syst})$ and $|\lambda| = 0.952 \pm 0.022(\text{stat}) \pm 0.017(\text{syst})$.

PACS numbers: 13.25.Hw, 12.15.Hh, 11.30.Er
We calculate the time interval $\Delta t$ between the two $B$ decays from the measured separation $\Delta z$ between the decay vertices of $B_{\text{rec}}$ and $B_{\text{tag}}$ along the collision (3) axis [13]. The $z$ position of the $B_{\text{rec}}$ vertex is determined from the charged daughter tracks. The $B_{\text{tag}}$ decay vertex is determined by fitting tracks not belonging to the $B_{\text{rec}}$ candidate to a common vertex, employing constraints from the beam spot location and the $B_{\text{rec}}$ momentum [13]. Events are accepted if the calculated $\Delta t$ uncertainty is less than 2.5 ps and $|\Delta t|$ is less than 20 ps. The fraction of events satisfying these requirements is 95%.

The r.m.s. $\Delta t$ resolution is 1.1 ps for the 99.7% of events that are not outliers.

The algorithm used to determine the flavor of the $B_{\text{tag}}$ at decay to be either a $B^0$ or $\bar{B}^0$ is described in detail in [8]. In brief, we define six mutually exclusive tagging categories. These are (in order of decreasing signal purity) Lepton, Kaon I, Kaon II, Kaon-Pion, Pion and Other.

The figure of merit for tagging is the effective tagging efficiency $Q = \sum_i \xi_i (1 - 2v_i)^2$. We measure $Q = (30.5 \pm 0.3)$%, consistent with the results in [8].

With the exception of the $J/\psi K_S^0$ mode, we determine the composition of our final sample using the beam-energy substituted mass $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^* - p_T^*)^2}$, where $E_{\text{beam}}^*$ and $p_T^*$ are the beam energy and $B$ momentum in the $e^+e^-$ center-of-mass frame. For the $J/\psi K_0^*$ mode we use the difference $\Delta E$ between the candidate center-of-mass energy and $E_{\text{beam}}^*$. The composition of our final sample is shown in Fig. 1. We use events with $m_{\text{ES}} > 5.2$ GeV/c$^2$ ($|\Delta E| < 80$ MeV for $J/\psi K_S^0$) to determine the properties of the background contributions.

We define a signal region $5.27 < m_{\text{ES}} < 5.29$ GeV/c$^2$ ($|\Delta E| < 10$ MeV for $J/\psi K_0^*$), which contains 12659 CP candidate events that satisfy the tagging and vertexing requirements (see Table I). For all modes except $\eta_s K_s^0$ and $J/\psi K_0^*$ we use simulated events to estimate the fractions of events that peak in the $m_{\text{ES}}$ signal region due to cross-feed from other decay modes (peaking background). For the $\eta_s K_0^*$ mode, the cross-feed is determined from a fit to the $m_{KK\pi}$ and $m_{\text{ES}}$ distributions in data.

For the $J/\psi K_0^*$ decay mode, the sample composition, effective $\eta_f$, and $\Delta E$ distribution of the individual background sources are determined either from simulation (for $B \rightarrow J/\psi X$) or from the $m_{t+\ell^-}$ sidebands in data (for non-$J/\psi$ background).

We determine $\sin^2 \beta$ and $|\lambda|$ from a simultaneous maximum likelihood fit to the $\Delta t$ distribution of the tagged $B_{\text{CP}}$ and $B_{\text{flav}}$ samples. The $\Delta t$ distributions of the $B_{\text{CP}}$ sample are modeled by Eq. 1. Those of the $B_{\text{flav}}$ sample evolve according to Eq. 1 with $\lambda = 0$. We assume that the observed amplitudes for the CP asymmetry in the $B_{\text{CP}}$ sample and for flavor oscillation in the $B_{\text{flav}}$ sample are reduced by the same factor $1 - 2\mathrm{e}^{-\Delta t}$ due to flavor mistags. The $\Delta t$ distributions for the signal are convolved with a resolution function common to both the $B_{\text{flav}}$ and $B_{\text{CP}}$ samples, modeled by the sum of three Gaussians [13]. Backgrounds are incorporated with an empirical description of their $\Delta t$ spectra, containing zero and non-zero lifetime components convolved with a resolution function [13] distinct from that of the signal.

In addition to $\sin 2\beta$ and $|\lambda|$, there are 68 free parameters in the $CP$ fit. For the signal, these are the parameters of the $\Delta t$ resolution (7), the average mistag fractions $w$ and the differences $\Delta w$ between $B^0$ and $\bar{B}^0$ mistag fractions for each tagging category (12), and the difference between $B^0$ and $\bar{B}^0$ reconstruction and tagging efficiencies (7). The background is described by mistag fractions (24), parameters of the $\Delta t$ resolution (3) and $B_{\text{flav}}$ time dependence (3), and 8 parameters for the CP background, 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 $\chi_{c1} K_0^0$ background to $J/\psi K_0^*$ (1), and in the main backgrounds to the $J/\psi K_0^*$ mode: $J/\psi K_0^*$, $J/\psi K^*$, and the remaining $J/\psi$ background (3 parameters). The effective $|\lambda|$ of the non-$J/\psi$ background is fixed from a fit to the $J/\psi$ sidebands in $J/\psi K_0^*$. We fix $\tau_{B^0} = 1.530$ ps, $\Delta m_d = 0.507$ ps$^{-1}$, and $\Delta t_d = 0$. The determination of the mistag fractions and $\Delta t$ resolution function parameters for the signal is dominated by the large $B_{\text{flav}}$ sample.

The fit to the $B_{\text{CP}}$ and $B_{\text{flav}}$ samples yields $\sin^2 \beta = 0.714 \pm 0.032$ 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 $\sin^2 \beta$ and $|\lambda|$ values for each
TABLE I: Number of events $N_{\text{tag}}$ 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, results on the $B_{flav}$ and charged $B$ control samples test that no artificial CP asymmetry is found where we expect no CP violation ($\sin2\beta = 0$, $|\lambda| = 1$). Errors are statistical only.

| Sample                  | $N_{\text{tag}}$ ($\%$) | $\sin2\beta$ | $|\lambda|$ |
|------------------------|--------------------------|--------------|-----------|
| Full CP sample         | 12659 75                 | 0.714 ± 0.032 | 0.952 ± 0.027 |
| $J/\psi K^0_s (\pi^+\pi^-)$ | 1241 89              | 0.725 ± 0.066 | 0.901 ± 0.043 |
| $J/\psi K^0_s (\pi^0\pi^0)$ | 5547 94              | 0.686 ± 0.039 | 0.950 ± 0.027 |
| $J/\psi K^0_{s0}$       | 1999-2002 data 3084 79   | 0.735 ± 0.063 | 0.987 ± 0.045 |
| $J/\psi K^0_{s0}$       | 2003-2004 data 4850 77   | 0.728 ± 0.052 | 0.940 ± 0.035 |
| $J/\psi K^0_{s0}$       | 2005-2006 data 4725 74   | 0.681 ± 0.054 | 0.940 ± 0.037 |
| $\eta_f = -1$          | 4730 55                 | 0.735 ± 0.074 | 1.065 ± 0.063 |
| $\eta_f = +1$          | 1056 66                 | 0.477 ± 0.271 | 0.954 ± 0.083 |
| $J/\psi K^0_{s0}$       | 16860 90                | 0.697 ± 0.035 | 0.966 ± 0.025 |
| $\gamma_c = 1$         | 6873 92                 | 0.711 ± 0.036 | 0.935 ± 0.024 |
| $\gamma_c = 1$         | 1999-2002 data 3084 79   | 0.735 ± 0.063 | 0.987 ± 0.045 |
| $\gamma_c = 1$         | 2003-2004 data 4850 77   | 0.728 ± 0.052 | 0.940 ± 0.035 |
| $\gamma_c = 1$         | 2005-2006 data 4725 74   | 0.681 ± 0.054 | 0.940 ± 0.037 |
| $\eta_f = -1$          | 4730 55                 | 0.735 ± 0.074 | 1.065 ± 0.063 |
| $\eta_f = +1$          | 1056 66                 | 0.477 ± 0.271 | 0.954 ± 0.083 |
| $J/\psi K^0_{s0}$       | 16860 90                | 0.697 ± 0.035 | 0.966 ± 0.025 |
| $\gamma_c = 1$         | 6873 92                 | 0.711 ± 0.036 | 0.935 ± 0.024 |

Figure 2 shows the $\Delta t$ distributions and asymmetries in yields between events with $B^0$ tags and $\bar{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of $\Delta t$, overlaid with the projection of the likelihood fit result. We also performed the CP fit fixing $|\lambda| = 1$. This yields $\sin2\beta = 0.713 ± 0.032(\text{stat})$. The systematic uncertainties on $\sin2\beta$ and $|\lambda|$ for the full sample, for the seven individual modes and for the fits to the $J/\psi K^0$ and $J/\psi K^0_s$ sample are summarized in Table II. We study the uncertainties in the amount of peaking backgrounds and their CP asymmetries, the assumed parameterization of the $\Delta t$ resolution functions, possible differences between the $B_{flav}$ and $B_{CP}$ tagging performances and $\Delta t$ resolution functions, knowledge of the event-by-event beam spot position, and the possible interference between the suppressed $b \rightarrow u\bar{c}d$ amplitude with the favored $b \rightarrow c\bar{u}d$ amplitude for some tag-side $B$ decays [15]. In addition, we include the variation due to the assumed values of $\Delta m_d$ and $\tau_B$ [7]. We also assign the change in the measured $\sin2\beta$ as the corresponding systematic uncertainties when we set $\Delta \Gamma_d/\Gamma_d = ±0.02$, the latter being considerably larger than SM estimates [16]. The total systematic error on $\sin2\beta$ ($|\lambda| = 0.018(0.017)$ 

![FIG. 2:](image-url) a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_s$, $\psi(2S)K^0_s$, $\chi_c K^0_s$, and $\eta K^0_s$) in the signal region with a $B^0$ tag ($N_{B^0}$) and with a $\bar{B}^0$ tag ($N_{\bar{B}^0}$), and b) the raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of $\Delta t$. Figures c) and d) are the corresponding distributions for the $\eta_f = +1$ mode $J/\psi K^0_s$. All distributions exclude Other-tagged events. The solid (dashed) curves represent the fit projections in $\Delta t$ for $B^0$ ($\bar{B}^0$) tags. The shaded regions represent the estimated background contributions.

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 are also summarized in Table I. We observe no statistically significant asymmetry from fits to the control samples of non-$CP$ decay modes.

In summary, we report on improved measurements of $\sin2\beta$ and $|\lambda|$ that supersede our previous result [8]. We measure $\sin2\beta = 0.714 ± 0.032(\text{stat}) ± 0.018(\text{syst})$ and $|\lambda| = 0.952 ± 0.022(\text{stat}) ± 0.017(\text{syst})$, providing an improved model-independent constraint on the position of the apex of the Unitarity Triangle [17]. The updated value of $\sin2\beta$ is consistent with the current world average [18] and the theoretical estimates of the magnitudes of CKM matrix elements in the context of the SM [17]. We report the first measurements of $\sin2\beta$ and $|\lambda|$ for each of the decay modes within our $CP$ sample, and of the $J/\psi K^0_s (K^0_s + K^0_{s0})$ sample. We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its sup-
TABLE II: Systematic uncertainties on sin2β and |λ| for the full CP sample, for the J/ψ K₀⁺(π⁺π⁻), J/ψ K₀⁺(π⁰π⁰), J/ψ K₁⁺, ψ(2S)K₀, χc1 K₀, ηc K₀, and J/ψ K^0 (K^+ → K₀^0π^0) decay modes, and for the fit to the J/ψ K⁰ and J/ψ K⁰ samples. For each systematic source the first line is σ(sin2β), the second line is σ(|λ|).

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port and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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[6] See, for example, D. Kirkby and Y. Nir in Ref. [7].
[17] See e.g. A. Ciccio, Z. Ligeti and Y. Sakai, in Ref. [7].