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Improved Measurement of CP Asymmetries in $B^0 \to (c\overline{c})K^{(*)0}$ Decays

The *BABAR* Collaboration

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Abstract

We present an 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 $(347.5 \pm 3.8) \times 10^6\, \Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II B factory between 1999 and 2006. We determine $\sin 2\beta = 0.710 \pm 0.034(\text{stat}) \pm 0.019(\text{syst})$ and $|\lambda| = 0.932 \pm 0.026(\text{stat}) \pm 0.017(\text{syst})$. Both of these results are preliminary.

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1 INTRODUCTION

Charge conjugation-parity (CP) violation in the B meson system has been established by the *BABAR* [1] and Belle [2] collaborations. The Standard Model (SM) of electroweak interactions describes CP violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. 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 sin2β [4]. The angle β is defined as $\arg[-(V_{\rm cd}V_{\rm cb}^*)/(V_{\rm td}V_{\rm tb}^*)]$, where the V_{ij} are CKM matrix elements.

In this paper, we report on an updated measurement of sin2β in $(347.5\pm3.8)\times10^6\,\Upsilon(4S)\to B\overline{B}$ decays collected with the *BABAR* detector using B^0 decays to the final states $J/\psi\,K^0_S$, $J/\psi\,K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_cK^0_S$, and $J/\psi\,K^{*0}(K^{*0}\to K^0_S\pi^0)$. Since our previous measurement [5], we have added a sample of $120\times10^6\,\Upsilon(4S)\to B\overline{B}$ decays, and applied an improved event reconstruction to the complete dataset. A new $\eta_cK^0_S$ event selection has been developed based on the Dalitz structure of the $\eta_c\to K^0_SK^+\pi^-$ decay. We have also performed a more detailed study of the CP properties of our background events resulting in a reduced systematic error.

2 THE *BABAR* DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring from 1999 to 2006. This represents a total integrated luminosity of (316.2 ± 3.5) fb^{-1} taken at the $\Upsilon(4S)$ resonance (onpeak), corresponding to a sample of $(347.5\pm3.8)\times10^6\,\Upsilon(4S)\to B\overline{B}$ decays.

The *BABAR* detector is described in detail elsewhere [6]. Charged particles are selected and their momenta are measured by a combination of a vertex tracker consisting of five layers of double-sided silicon microstrip detectors and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter (EMC). Charged particle identification (PID) is provided by an internally reflected ring imaging Cherenkov detector (DIRC) covering the central region of the detector, the average energy loss (dE/dx) in the tracking devices, and by the EMC. In addition, the instrumented flux return (IFR) containing resistive plate chambers are used for muon and long-lived neutral hadron identifications. We use the GEANT4 [7] software to simulate interactions of particles traversing the *BABAR* detector.

3 ANALYSIS METHOD

We use information from the other B meson, $B_{\rm tag}$, in the event to tag the initial flavor of the fully reconstructed B candidate. The decay rate $f_+(f_-)$ for a neutral B meson decaying to a CP eigenstate accompanied by a $B^0(\overline{B}^0)$ tag can be expressed in terms of a complex parameter λ [8] as

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

where $\Delta t=t_{\rm rec}-t_{\rm tag}$ is the difference between the proper decay times of the reconstructed ($B_{\rm rec}$) and tagged ($B_{\rm tag}$) B mesons. τ_{B^0} is the B^0 lifetime and Δm_d is the mass difference determined from B^0-$\overline{B}^0$ oscillations [9]. The average mistag probability ω describes the effect of incorrect tags, and $\Delta\omega$ is the difference between the mistag rate for B^0 and $\overline{B}^0$. Here we assume that the decay width difference $\Delta\Gamma_d$ between the neutral B mass eigenstates is zero. The sine term in Eq. 1 is due to the interference between the direct decay and the 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 is negligible, as is direct CP violation for $b \to c\overline{c}s$ decays that contain a charmonium meson [8]. 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

$$A_{CP}(\Delta t) \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} \propto -(1-2\omega)\eta_f \sin 2\beta \sin(\Delta m_d \, \Delta t). \qquad (2)$$

We reconstruct a sample of neutral B mesons, B_{CP}, decaying to the $\eta_f = -1$ final states [10] $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$ and $\eta_c K^0_S$, and the $\eta_f = +1$ final state $J/\psi K^0_L$. The J/ψ and $\psi(2S)$ mesons are reconstructed through their decays to e^+e^- and $\mu^+\mu^-$; the $\psi(2S)$ is also reconstructed through its decay to $J/\psi\pi^+\pi^-$. The χ_{c1} meson is reconstructed in the decay mode $J/\psi\gamma$. The η_c meson is reconstructed in the decay mode $K^0_S K^+\pi^-$. 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 momenta contributions. Ignoring the angular information in $J/\psi K^{*0}$ results in a reduction of the measured CP asymmetry by a factor $|1-2R_\perp|$, where $R_\perp$ is the fraction of the L=1 contribution. We have measured $R_\perp = 0.233 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$ [11], which gives an effective $\eta_f = 0.504 \pm 0.033$, after acceptance corrections.

In addition to the CP modes described above, a large sample B_{flav} of B^0 decays to the flavor eigenstates $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$ is used for calibrating the flavor tagging performance and Δt resolution. We perform studies to measure apparent CP violation from unphysical sources using a control sample of B^+ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, and $\eta_c K^+$. Since the previous *BABAR* analyses, we apply an improved event reconstruction to all the events and we find that on a subset of the data the new and old event reconstruction algorithms give consistent results. The event selection and candidate reconstruction are unchanged from those described in Refs. [5, 12, 13] with the exceptions described below. As in Ref. [5] we reconstruct the $B^0 \to \eta_c K^0_S$ and $B^\pm \to \eta_c K^\pm$ modes using only the $\eta_c \to K^0_S K^+\pi^-$ decay with $2.91 < m_{K^0_S K^+\pi^-} < 3.05\,\text{GeV}/c^2$. We now exploit the fact that the η_c decays predominantly through a $K\pi$ resonance at around $1430\,\text{MeV}/c^2$, and apply the selection criteria $1.26\,\text{GeV}/c^2 < m(K^0_S\pi^-) < 1.63\,\text{GeV}/c^2$ and $1.26\,\text{GeV}/c^2 < m(K^+\pi^-) < 1.63\,\text{GeV}/c^2$.

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 [12]. 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, employing constraints from the beam spot location and the B_{rec} momentum [12]. 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 events satisfying these requirements is 95%. The r.m.s. Δt resolution is 1.1 ps for the 99.7% of events that are not outliers.

Multivariate algorithms are used to identify signatures of B decays that determine ("tag") the flavor of the B_{tag} at decay to be either a B^0 or $\overline{B}^0$ candidate. Primary leptons from semileptonic B decays are selected from identified electrons and muons as well as isolated energetic tracks. The charges of identified kaon candidates are used in a kaon tag. Low momentum pions from D^{*+} decays are selected on the basis of their momentum and direction with respect to the thrust axis of $B_{\rm tag}$. These algorithms are combined to account for correlations among different sources of flavor information and to provide an estimate of the mistag probability for each event. Each event whose estimated mistag probability is less than 45% is assigned to one of six tagging categories. The `Lepton` category contains events with an identified lepton; the remaining events are divided into the `Kaon I`, `Kaon II`, `Kaon-Pion`, `Pion`, or `Other` categories based on the estimated mistag probability. For each category i, the tagging efficiency ε_i and fraction w_i of events having the wrong tag assignment are measured from data (Table 1). The figure of merit for tagging is the effective tagging efficiency $Q \equiv \sum_i \varepsilon_i (1-2w_i)^2 = (30.4 \pm 0.3)\,\%$, where the error shown is statistical only.

Table 1: Efficiencies ε_i, average mistag fractions w_i, mistag fraction differences $\Delta w_i \equiv w_i(B^0) - w_i(\overline{B}^0)$, and effective tagging efficiency Q_i extracted for each tagging category i from the $B_{\rm flav}$ sample.

Category	ε (%)	w (%)	Δw (%)	Q (%)
`Lepton`	8.67 ± 0.08	3.0 ± 0.3	-0.2 ± 0.6	7.67 ± 0.13
`Kaon I`	10.96 ± 0.09	5.3 ± 0.4	-0.6 ± 0.7	8.74 ± 0.16
`Kaon II`	17.21 ± 0.11	15.5 ± 0.4	-0.4 ± 0.7	8.21 ± 0.19
`Kaon-Pion`	13.77 ± 0.10	23.5 ± 0.5	-2.4 ± 0.8	3.87 ± 0.14
`Pion`	14.38 ± 0.10	33.0 ± 0.5	5.2 ± 0.8	1.67 ± 0.10
`Other`	9.61 ± 0.08	41.9 ± 0.6	4.6 ± 0.9	0.25 ± 0.04
All	74.60 ± 0.12			30.4 ± 0.3

With the exception of the $J/\psi\, K^0_L$ mode, we use the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$ to determine the composition of our final sample, where $E^*_{\rm beam}$ and p^*_B are the beam energy and B momentum in the e^+e^- center-of-mass frame. For the $J/\psi\, K^0_L$ mode we use the difference ΔE between the candidate center-of-mass energy and $E^*_{\rm beam}$. The composition of our final sample is shown in Fig. 1. We use events with $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ ($\Delta E < 80\,{\rm MeV}$ for $J/\psi\, K^0_L$) in order to determine the properties of the background contributions. We define a signal region $5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ ($|\Delta E| < 10\,{\rm MeV}$ for $J/\psi\, K^0_L$) that contains *CP* candidate events that satisfy the tagging and vertexing requirements as listed in Table 2.

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 $m_{\rm ES}$ 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 $m_{\rm ES}$ 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 fake $J/\psi \to \ell^+\ell^-$).

We determine sin2β with a simultaneous maximum likelihood fit to the Δt distribution of the tagged B_{CP} and $B_{\rm flav}$ samples. The Δt distributions of the B_{CP} sample are modeled by Eq. 1 with $|\lambda| = 1$. Those of the $B_{\rm flav}$ sample evolve according to the known frequency for flavor oscillation in B^0 mesons. We assume that the observed amplitudes for the *CP* asymmetry in the B_{CP} sample and for flavor oscillation in the $B_{\rm flav}$ 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

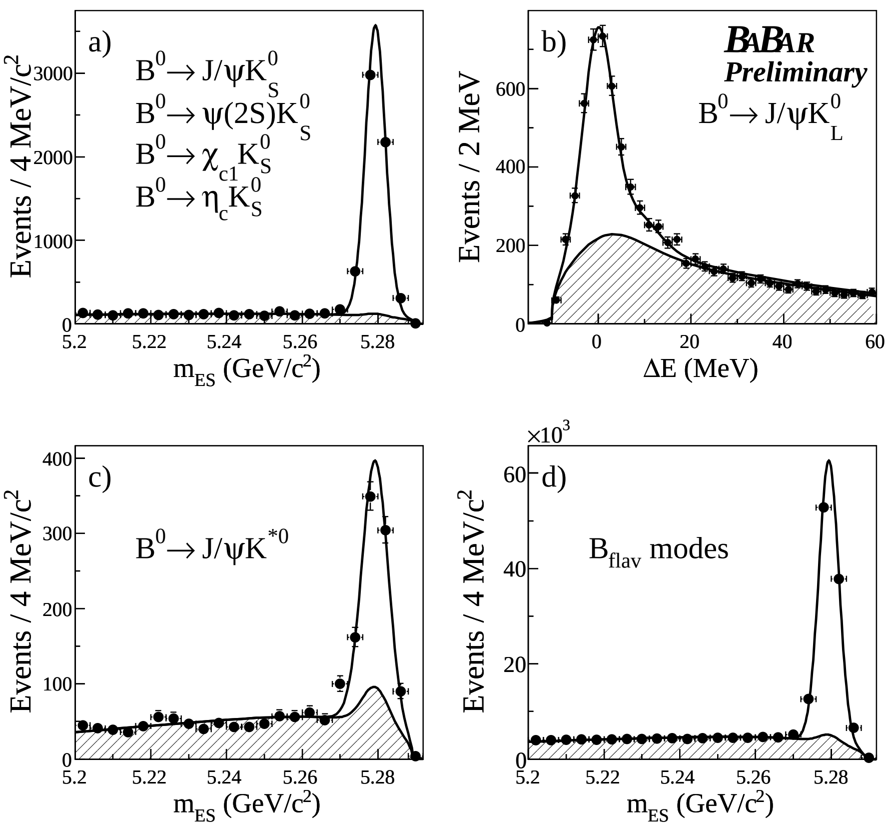

Figure 1: Distributions for B_{CP} and $B_{\rm flav}$ candidates satisfying the tagging and vertexing requirements: a) $m_{\rm ES}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, b) ΔE for the final state $J/\psi K^0_L$, c) $m_{\rm ES}$ for $J/\psi K^{*0}(K^{*0}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

$B_{\rm flav}$and B_{CP} samples, modeled by the sum of three Gaussians [12]. Backgrounds are incorporated with an empirical description of their Δt spectra, containing zero and non-zero lifetime components convolved with a resolution function [12] distinct from that of the signal.

There are 65 free parameters in the fit: sin2β (1), the average mistag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mistag fractions for each tagging category (12), parameters for the signal Δt resolution (7), parameters for *CP* background time dependence (8), and the difference between B^0 and $\overline{B}^0$ reconstruction and tagging efficiencies (7); for $B_{\rm flav}$ background, time dependence (3), Δt resolution (3), and mistag fractions (24). For the *CP* modes (except for $J/\psi K^0_L$), the apparent *CP* asymmetry of the non-peaking background in each tagging category is allowed to be a free parameter in the fit.

We fix $\tau_{B^0} = 1.530$ ps, $\Delta m_d = 0.507$ ps^{-1} [9], $|\lambda| = 1$, and $\Delta\Gamma_d = 0$. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the large $B_{\rm flav}$ sample. We determine background parameters mainly from events outside the peaks in the

Table 2: Number of events $N_{\rm tag}$ in the signal region after tagging and vertexing requirements, signal purity P including the contribution from peaking background, and results of fitting for CP asymmetries in the B_{CP} sample and various subsamples. In addition, results on the $B_{\rm flav}$ and charged B control samples test that no artificial CP asymmetry is found where we expect no CP violation ($\sin 2\beta = 0$). Errors are statistical only. The signal region is $5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ ($|\Delta E| < 10\,{\rm MeV}$ for $J/\psi K^0_L$).

Sample	$N_{\rm tag}$	$P(\%)$	$\sin 2\beta$
Full CP sample	11496	76	0.710 ± 0.034
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$,$\eta_c K^0_S$	6028	92	0.713 ± 0.038
$J/\psi K^0_L$	4323	55	0.716 ± 0.080
$J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$	965	68	0.526 ± 0.284
1999-2002 data	3084	79	0.755 ± 0.067
2003-2004 data	4850	77	0.724 ± 0.052
2005-2006 data	3562	74	0.663 ± 0.062
$J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$)			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	4076	96	0.715 ± 0.044
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	988	88	0.581 ± 0.105
$\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$)	622	83	0.892 ± 0.120
$\chi_{c1}K^0_S$	279	89	0.709 ± 0.174
$\eta_c K^0_S$	243	75	0.717 ± 0.229
`Lepton` category	703	97	0.754 ± 0.068
`Kaon I` category	900	93	0.713 ± 0.066
`Kaon II` category	1437	91	0.711 ± 0.075
`Kaon-Pion` category	1107	89	0.635 ± 0.117
`Pion` category	1238	91	0.587 ± 0.175
`Other` category	823	89	0.454 ± 0.469
$B_{\rm flav}$ sample	112878	83	0.016 ± 0.011
B^+ sample	27775	93	0.008 ± 0.017

$m_{\rm ES}$ and ΔE distribtions, as shown in Fig. 1.

The fit to the B_{CP} and $B_{\rm flav}$ samples yields

$$\sin 2\beta = 0.710 \pm 0.034({\rm stat}) \pm 0.019({\rm syst}).$$

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 perform a separate fit with only the cleanest $\eta_f = -1$ sample, in which we treat both $|\lambda|$ and $\sin 2\beta$ as free parameters. We do not use the modes $J/\psi K^{*0}$ and $J/\psi K^0_L$ to minimize the dependence of the results on the background parametrization. We obtain $|\lambda| = 0.932 \pm 0.026({\rm stat}) \pm 0.017({\rm syst})$. The correlation between the coefficients multiplying the $\sin(\Delta m_d \Delta t)$ and $\cos(\Delta m_d \Delta t)$ terms in Eq. 1 is -1.2%.

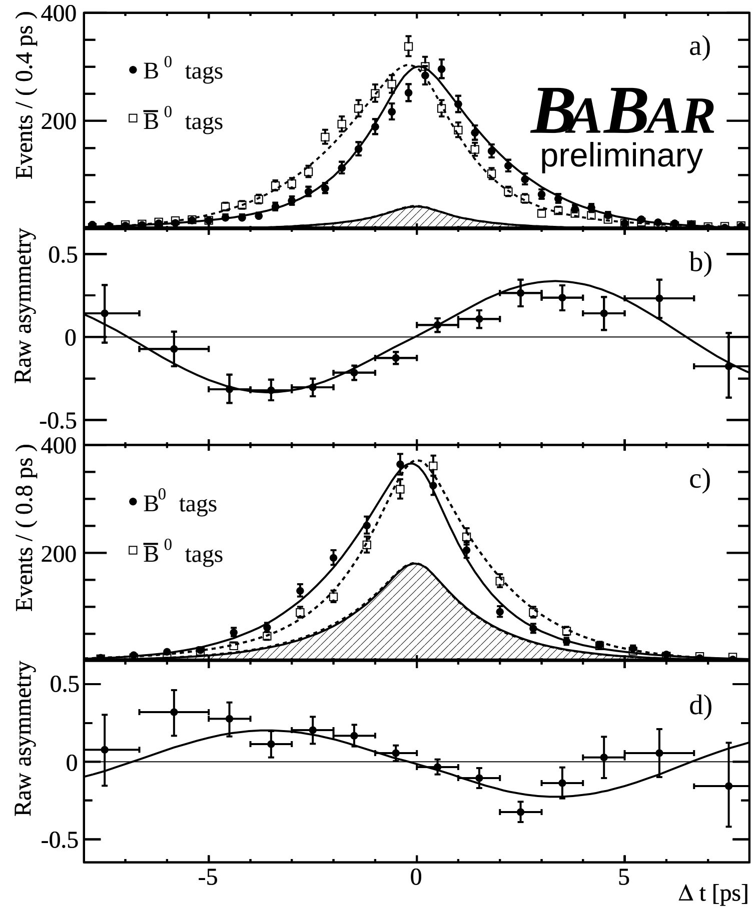

Figure 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag (N_{B^0}) and with a $\overline{B}^0$ tag ($N_{\overline{B}^0}$), and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$,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

4 SYSTEMATIC UNCERTAINTIES

The systematic uncertainties on $\sin2\beta$ and $|\lambda|$ are summarized in Table 3. These include the uncertainties in the level and CP asymmetry of the peaking background, the assumed parameterization of the Δt resolution function, possible differences between the $B_{\rm flav}$ and B_{CP} tagging performances and Δt resolution functions, knowledge of the event-by-event beam spot position, and 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 [14]. In addition, we include the variation due to the assumed values of Δm_d and τ_B [9]. We also assign the change in the measured $\sin 2\beta$ as the corresponding systematic uncertainties when we let $|\lambda|$ to be a free parameter in the fit and when we set $\Delta\Gamma_d/\Gamma_d = \pm 0.02$, the latter being considerably larger than SM estimates [15]. The total systematic error on $\sin 2\beta$ ($|\lambda|$) is 0.019 (0.017).

Table 3: Systematic uncertainties on $\sin 2\beta$ and $|\lambda|$.

Source	$\sigma(\sin 2\beta)$	$\sigma(\lvert\lambda\rvert)$
CP backgrounds	0.007	0.002
Δt resolution function	0.008	0.002
$J/\psi K_L^0$ backgrounds	0.007	N/A
Mistag fraction differences	0.009	0.007
Beam spot	0.008	0.004
Δm_d, τ_B, $\Delta\Gamma_d/\Gamma_d$, $\lvert\lambda\rvert$	0.003	0.001
Tag-side interference	0.002	0.014
MC statistics	0.003	0.005
Total systematic error	0.019	0.017

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 listed in Table 2. We observe no statistically significant asymmetry from fits to the control samples of non-CP decay modes.

5 SUMMARY

In summary, we report on improved measurements of $\sin 2\beta$ and $|\lambda|$ that supersede our previous result [5]. We measure $\sin 2\beta = 0.710 \pm 0.034(\text{stat}) \pm 0.019(\text{syst})$ and $|\lambda| = 0.932 \pm 0.026(\text{stat}) \pm 0.017(\text{syst})$. The updated value of $\sin 2\beta$ is consistent with the current world average [16] and the theoretical estimates of the magnitudes of CKM matrix elements in the context of the SM [17]. The theoretical uncertainty on the interpretation of the measurement of $\sin 2\beta$ in these modes is approximately 0.01 [18].

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