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Measurement of sin 2β with hadronic and previously unused muonic J/ψ decays

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We report a measurement of the *CP*-violation parameter sin 2β with $B^0 \to J/\psi K_S^0$ decays in which the J/ψ decays to hadrons or to muons that do not satisfy our standard identification criteria. With a sample of 88 million $B\bar{B}$ events collected by the BABAR detector at the PEP-II asymmetric-energy B factory at SLAC, we reconstruct 100 ± 17 such events, with $J/\psi \to \pi^+ \pi^- \pi^0$ being the most prevalent, and measure sin 2β=1.56 ± 0.42(stat)± 0.21(syst).

Measurement of *CP* violation in the *B*-meson system, particularly in $b \to c\bar{c}s$ transitions, has been a primary goal of the BABAR experiment. In the standard model, these decays

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exhibit a *CP* asymmetry that is proportional to sin 2β, where β is defined as $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, with V_{ij} the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. The current world average value of sin 2β is 0.731 ± 0.056 [2], with the *B* factories (BABAR at SLAC and Belle at KEK) providing the most precise measurements [3,4]. The dominant decay mode in these measurements is $B^0 \to J/\psi K_S^0$, where only leptonic decays of the J/ψ are considered. Leptonic decay modes have the advantage of low backgrounds, but account for only 12% of J/ψ decays [2]. Since the current measurements of sin 2β are statistically limited, in this

paper we extend the measurement through the use of hadronic J/ψ decays, as well as previously unused muonic decays.

At the B factories, B^0 mesons are produced via $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$. For B^0 mesons produced in this manner and decaying to the CP eigenstate $J/\psi K_S^0$, $\sin 2\beta$ appears as the amplitude of a time-dependent CP asymmetry. The standard model predicts the decay rate

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm \sin 2\beta \sin(\Delta m_d \Delta t)],$$

where the plus (minus) sign indicates that the other, "tagging," B^0 meson in the event decays as a $B^0(\bar{B}^0)$, Δt is the decay time of the CP-eigenstate B^0 meson minus the decay time of the tagging B^0 meson, τ_{B^0} is the B^0 lifetime, and Δm_d is the mass difference between the two mass-eigenstate neutral B mesons (Δm_d is also the $B^0 - \bar{B}^0$ oscillation frequency). The time-dependent CP asymmetry is

$$A_{CP} \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = \sin 2\beta \sin(\Delta m_d \Delta t).$$

Measurement of A_{CP} requires that a sample of B^0 mesons decaying to $J/\psi K_S^0$ be reconstructed, that the flavor of the other B^0 meson in the event be determined, and that Δt be measured.

A sample of 88 ± 1 million $B\bar{B}$ events recorded by the BABAR detector [5] was used in this analysis. The innermost component of BABAR is a five-layer double-sided silicon microstrip vertex detector with $90°$ stereo angle, allowing precise reconstruction of the location of the B^0 decay vertices along the beam direction. Since the $\Upsilon(4S)$ is boosted along the beam direction, the difference in position between the B^0 decay vertices in this direction allows one to measure Δt. The primary tracking device is a 40-layer drift chamber operated with a helium-based gas mixture to minimize multiple scattering. The drift chamber is surrounded by a Cherenkov particle identification device, and a CsI(Tl) calorimeter. All of the above detectors reside in a 1.5-T field generated by a superconducting solenoid. The flux is returned via layers of steel interleaved with active detectors for the identification of muons and detection of neutral hadrons.

Two types of Monte Carlo (MC) simulated events are used in the analysis. One, called the "full MC simulation," consists of events that are generated according to the known physics of $B\bar{B}$ and continuum production, passed through a detailed model of the detector response [6], and reconstructed in the same manner as the data sample. The second, called the "parametrized MC simulation," consists of events for which the relevant parameters are randomly generated according to the distributions observed in data or in detailed simulations. For any study where an accurate model of the physics or detector response is required, the full MC simulation is used. Parametrized MC simulation, which can be generated more quickly than full MC simulation, is only used to explore the statistical properties of the extraction of $\sin 2\beta$.

While many J/ψ decays to exclusive hadronic final states have been observed [2], the sum of their measured branching fractions is less than 20%. To allow for the possibility of observing a signal in previously unmeasured decay modes, we take an inclusive approach in the first stage of event selection. Charged tracks are assigned either the electron, muon, pion, kaon, or proton mass based on particle identification information, and candidates for $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$ are formed. All neutral combinations of up to six tracks and neutral mesons are considered (a maximum of two neutral mesons is allowed), and those consistent with baryon number conservation, strangeness conservation, and Bose symmetry, and having invariant mass $m_{J/\psi}$ in the range 2.80–3.20 GeV/c^2, are retained for further analysis. Decay modes of the type $J/\psi \to KK\pi$ are excluded to ensure that the selected sample is independent of the sample used in BABAR's previous measurement of $\sin 2\beta$ [3], which included $B^0 \to \eta_c K_S^0$ events with $\eta_c \to KK\pi$.

We form K_S^0 candidates from a pair of oppositely charged tracks that have invariant mass between 489 and 507 MeV and a vertex displaced by at least 1 mm from the J/ψ candidate's vertex. The selected J/ψ and K_S^0 candidates are combined to form B^0 candidates. Two kinematic variables are used to isolate the B meson signal: the difference ΔE between the energy of the reconstructed B candidate and the beam energy in the center-of-mass frame, and the beam-energy substituted mass $m_{ES} \equiv \sqrt{E_{beam}^{*2} - p_B^{*2}}$, where p_B^* is the momentum of the reconstructed B and E_{beam}^* is the beam energy, both in the center-of-mass frame. The small variations of E_{beam}^* within the data sample are taken into account when calculating m_{ES}. Signal events will have ΔE close to 0 and values of m_{ES} close to the B^0 meson mass. Candidates are required to have $m_{ES} > 5.20$ GeV/c^2 and $|\Delta E| < 55$ MeV if the J/ψ decays entirely to charged particles, and < 105 MeV if the decay includes one or more neutral hadrons. The ΔE selection accepts candidates within 3σ of the distribution observed in simulated signal events. The resolution in m_{ES} is 3 MeV, so the selection admits a large region at low m_{ES} in addition to the region populated by signal candidates. Inclusion of this sideband region allows the magnitude of the combinatoric background to be measured.

Backgrounds arise both from continuum $q\bar{q}$ production and from B meson decays to other modes. The continuum events tend to have a two-jet topology, in contrast to the more spherically symmetric $B\bar{B}$ events. A set of 18 variables (described in Ref. [7]) that are sensitive to this difference are combined in a Fisher discriminant $\mathcal{F}$, which is defined to have an average value of 1 for signal and -1 for continuum events. The weight of each variable in the discriminant is calculated by maximizing the separation between a sample of data taken below the $B\bar{B}$ threshold (and thus composed entirely of continuum $q\bar{q}$ events) and a sample of simulated signal events. We place progressively tighter requirements on $\mathcal{F}$ as the candidate J/ψ decay multiplicity increases: for two-body decays we require $\mathcal{F} > -1.14$, for three-body decays we require $\mathcal{F} > -0.70$, and for higher-multiplicity decays we require $\mathcal{F} > -0.37$.

For three-body J/ψ decays, which have a larger combinatoric background than two-body decays, additional separation between signal and background is attained by considering the angle θ_d between the normal to the plane in which the momenta of the J/ψ daughter particles lie and the K_S^0 direction in the J/ψ rest frame. Conservation of angular momentum requires this variable to be distributed as $\cos^2 \theta_d$ for J/ψ decays to three pseudoscalars (the most common type of three-body decays), while it is uniformly distributed for $B\bar{B}$ backgrounds and peaks at $\cos \theta_d=0$ for continuum $q\bar{q}$ backgrounds. We require candidates to have $|\cos \theta_d|>0.55$. The selection in $\cos \theta_d$ and $\mathcal{F}$ was chosen to maximize $S/\sqrt{S+B}$, where S is the expected signal and B the expected background.

There are two classes of $B\bar{B}$ backgrounds. The first consists of candidates formed from a subset of a given B meson's decay products, or from a combination of decay products from the two B mesons in the event. This background and the continuum $q\bar{q}$ background are henceforth referred to as "combinatoric backgrounds." They have a linearly falling distribution in ΔE, and their distribution in m_{ES} may be parametrized by an empirical phase-space distribution [8] (henceforth referred to as the ARGUS function):

$$A(m_{\mathrm{ES}};m_0,c_{\mathrm{arg}}) \propto m_{\mathrm{ES}}\sqrt{1-(m_{\mathrm{ES}}/m_0)^2}$$
$$\times \exp\{c_{\mathrm{arg}}[1-(m_{\mathrm{ES}}/m_0)^2]\},$$

where m_0 is a cutoff mass set to 5.291 GeV (a typical center-of-mass beam energy) and c_{arg} is a fitted parameter.

The second class of $B\bar{B}$ background consists of B mesons that decay to a topology also allowed for $J/\psi K_S^0$, but without a J/ψ in the intermediate state. These "peaking" backgrounds are dominated by B decays that have a charmed meson in the intermediate state, so we remove any candidates for which a D or D^* meson within 2σ of the nominal mass can be formed from the final-state hadrons. Since these backgrounds arise from fully reconstructed B^0 mesons, they have the same distribution in m_{ES} and ΔE as the signal.

Since the branching fractions for many of the modes that contribute to the peaking backgrounds are not well measured, we must extract the peaking background magnitude from the data. We do this by performing a two-dimensional unbinned maximum likelihood fit to the m_{ES} and $m_{J/\psi}$ distributions. The likelihood function used is

$$L=[n_{\mathrm{comb}}A(m_{\mathrm{ES}};m_0,c_{\mathrm{arg}})+(n_{\mathrm{sig}}+n_{\mathrm{peak}}^0)G(m_{\mathrm{ES}})]$$
$$\times[(n_{\mathrm{comb}}+n_{\mathrm{peak}}^0)C(m_{J/\psi};p_1,p_2)+n_{\mathrm{sig}}G(m_{J/\psi})],$$

where n_{comb} is the fitted combinatoric background, n_{peak}^0 is the fitted peaking background, n_{sig} is the fitted signal, A is a normalized ARGUS function, G are normalized Gaussians, and C is a normalized second-order Chebyshev polynomial with parameters p_i. The total area of the Gaussian peak in the m_{ES} distribution represents the sum of the signal and n_{peak}^0, while the area of the Gaussian in $m_{J/\psi}$ represents the signal only. The difference between the two therefore is a direct measure of n_{peak}^0. The mean and width of $G(m_{\mathrm{ES}})$ are

TABLE I. Observed $B^0 \to J/\psi K_S^0$ signal and background. The combinatoric backgrounds reported are the integral of the fitted ARGUS function in the region $m_{\mathrm{ES}}>5.27$ GeV/c^2. Except for the rows labeled "After final selection," the numbers are measured prior to application of the final selection criteria on $m_{J/\psi}$ and ΔE. All uncertainties are statistical only.

J/ψ decay mode	Signal	Peaking bkg.	Comb. bkg.
$\pi^+\pi^-$	28 ± 8	84 ± 17	206 ± 12
K^+K^-	5 ± 3	-1 ± 6	42 ± 5
$p\bar{p}$	6 ± 3	1 ± 6	34 ± 5
Total h^+h^-	40 ± 9	86 ± 19	279 ± 13
After final selection	28 ± 8	13 ± 3	15 ± 3
$\pi^+\pi^-\pi^0$	58 ± 17	104 ± 29	652 ± 23
$p\bar{p}\pi^0$	11 ± 6	9 ± 9	77 ± 7
Total $h^+h^-\pi^0$	69 ± 18	113 ± 30	716 ± 22
After final selection	72 ± 13	19 ± 5	74 ± 8

fixed to the values observed in high-statistics hadronic B-decay samples, and the mean and width of $G(m_{J/\psi})$ are fixed to the values observed in our $J/\psi \to \mu^+\mu^-$ sample for two-body decay modes, and to the values observed in full MC simulation events for higher-multiplicity modes. The photon-energy resolution in the simulated events is degraded to match that observed in data. The additional smearing required is 3% of the measured photon energy for photons below 100 MeV, and decreases with increasing photon energy (no additional smearing is required for photons above 1 GeV).

The J/ψ decay modes for which the measured signal magnitude is less than its statistical uncertainty are removed from the analysis. The surviving modes and their contribution to the signal are listed in Table I. Note that no modes including an η meson are observed, and also that no decays with a multiplicity of greater than 3 are visible above background.

The observation of 28 candidates in the $J/\psi \to \pi^+\pi^-$ channel is inconsistent with our expectation of observing about one event given the known branching fraction of $(1.47\pm 0.23)\times 10^{-4}$ [2] for this mode. We interpret the excess candidates as $J/\psi \to \mu^+\mu^-$ decays in which both muons fail the standard muon selection criteria. Studies using simulated events with muon identification efficiencies measured in data confirm that the observed signal magnitude is consistent with the $J/\psi \to \mu^+\mu^-$ hypothesis. Since these events do measure $\sin 2\beta$, and are independent of the events used in our previous measurements [3], we retain them for this analysis.

After n_{peak}^0 is determined, the following final selection criteria are imposed to improve the purity of the sample: We recalculate ΔE with the J/ψ candidate constrained to the nominal mass, and define the result as ΔE_c. The resolution in ΔE_c is 11 MeV for two-body J/ψ decay candidates, and 12 MeV for three-body candidates. For two-body J/ψ decay candidates we require $3.06<m_{J/\psi}<3.12$ GeV/c^2 and $|\Delta E_c| <33$ MeV, and for three-body J/ψ decay candidates we re-
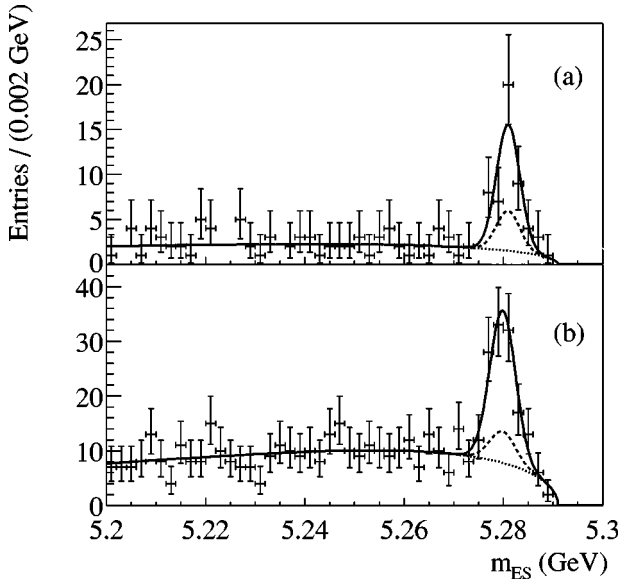
FIG. 1. m_{ES} distributions for candidates for $B^0 \to J/\psi K_S^0$ with the J/ψ decaying to (a) two and (b) three particles. The dotted line represents the fitted combinatoric background distribution. The dashed line represents the total background distribution, while the solid line represents the signal plus background distribution.

quire $3.05 < m_{J/\psi} < 3.15$ GeV/c^2 and $|\Delta E_c| < 35$ MeV.

The efficiency of this selection for peaking backgrounds ($\varepsilon_{\mathrm{peak}}$) is estimated using full MC simulation events. We define $\varepsilon_{\mathrm{peak}}$ as the ratio of the area of the fitted Gaussian in m_{ES} after the final selection to the area before the final selection. For two-body decay candidates $\varepsilon_{\mathrm{peak}} = 0.15 \pm 0.01(\mathrm{stat})$ and for three-body decay candidates $\varepsilon_{\mathrm{peak}} = 0.17 \pm 0.02(\mathrm{stat})$. An unbinned maximum likelihood fit to the sum of a Gaussian distribution and an ARGUS function is performed on the m_{ES} distributions of the surviving candidates. The integral of the ARGUS function measures the combinatoric background, while the integral of the Gaussian measures the sum of the signal and peaking background. Subtracting $n_{\mathrm{peak}} \equiv \varepsilon_{\mathrm{peak}} n_{\mathrm{peak}}^0$ from the latter provides an estimate of the signal. The m_{ES} distributions are shown in Fig. 1, and the signal and background magnitudes in the final sample are reported in Table I.

Once the sample of $B^0 \to J/\psi K_S^0$ candidates has been isolated, the extraction of $\sin 2\beta$ proceeds in the same manner as for BABAR's other recent measurements [3]. Information from the final-state particles recoiling against the $J/\psi K_S^0$ meson candidate is used to determine whether the other B meson in the event was a B^0 or $\bar{B}^0$ at the time of its decay. This is referred to as the flavor "tag." The variables used for tagging include the charge of any high-momentum identified electron or muon, the charge of any identified kaon, and the charge of a slow pion consistent with arising from D^* meson decay. The efficiency ε and mistag rate w are measured using the data as described below, and reported in Ref. [3]; the overall figure of merit for the flavor-tagging performance, $\varepsilon(1 - 2w)^2$, is $(28.1 \pm 0.7)\%$.

The extraction of $\sin 2\beta$ is done using an unbinned maximum likelihood fit to the Δt distribution of the candidate
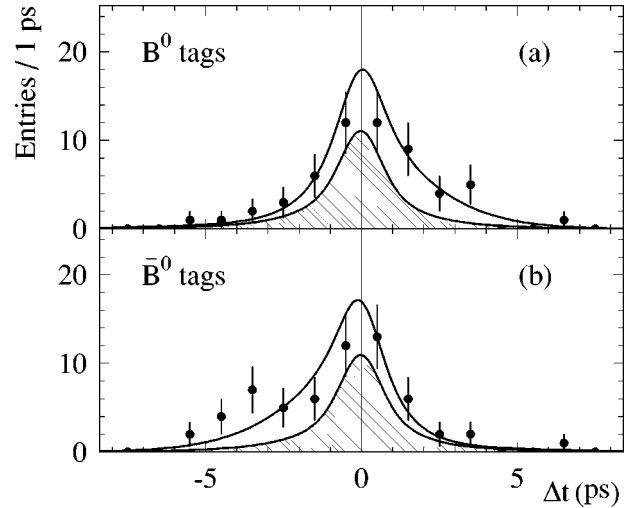

FIG. 2. Δt values observed in the $B^0 \to J/\psi K_S^0$ candidates. The plots show the distribution for events in which the recoiling B meson is tagged as (a) B^0 and (b) $\bar{B}^0$. In each plot the solid line represents the result of the maximum likelihood fit, and the shaded area the contribution of background.

events, where the assumed functional form is $f_\pm(\Delta t)$ convolved with the resolution of the Δt measurement, with the mistag probability taken into account. The input to the fit consists of both the signal sample and a large sample of fully reconstructed B^0 decays to $D^{(*)+}\pi^-$, $D^{(*)+}\rho^-$, $D^{(*)+}a^-$, and $J/\psi K^{0*}$ with $K^{0*} \to K^+\pi^-$. The B^0 flavor is known for these modes, so this sample constrains a set of parameters describing the flavor-tagging performance and vertex resolution. The simultaneous fit takes into account any correlations between these parameters and the value of $\sin 2\beta$. The result is

$$\sin 2\beta = 1.56 \pm 0.42(\mathrm{stat}).$$

The Δt distribution for flavor-tagged signal events is shown in Fig. 2, and the *CP* asymmetry observed before correction for backgrounds and mistag probability is shown in Fig. 3. In each case a projection of the best-fit model is superimposed.
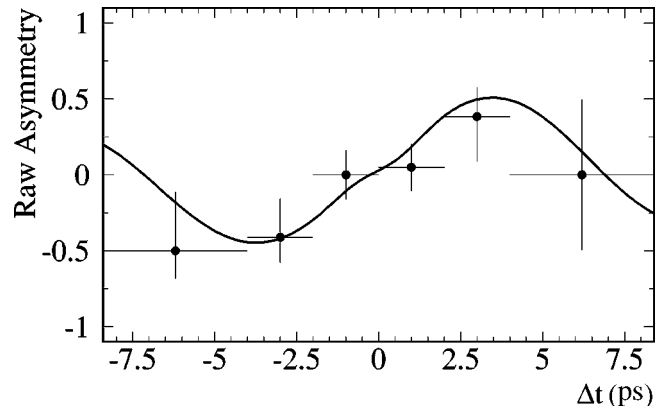

FIG. 3. Δt asymmetry observed before correction for backgrounds and mistag probability in $B^0 \to J/\psi K_S^0$ candidates, with best-fit asymmetry displayed.

As a cross check, the analysis was repeated using a sample of $B^{\pm} \to J/\psi K^{\pm}$ events selected in a manner analogous to the CP sample, and with the same J/ψ decay modes considered. This sample yields an apparent $\sin 2\beta$ of $-0.13 \pm 0.20(\text{stat})$, consistent with the expected null result.

Systematic uncertainties arise from several sources. In performing the fit for $\sin 2\beta$ it is assumed that the background has no CP asymmetry. Since some of the background is composed of real B^0 mesons this may not be true. Fitting for $\sin 2\beta$ on a sample composed of candidates in the $m_{J/\psi}$ or ΔE_c sidebands yields 0.18 ± 0.46. The signal sample is then refit with the CP asymmetry of the peaking background fixed to the $\pm 1\sigma$ limits of the measured asymmetry, and the observed variation of ± 0.15 in $\sin 2\beta$ is taken as a systematic uncertainty.

The next most significant systematic uncertainty arises from the estimation of the background magnitudes. When the $\sin 2\beta$ fit is performed, the parameter c_{arg} of the ARGUS distribution describing the combinatoric background is fixed to the central value determined from fitting the m_{ES} distribution. The $\sin 2\beta$ fit is repeated with this value fixed to its $\pm 1\sigma$ limits, and the observed variation in $\sin 2\beta$ of ± 0.13 is taken as a systematic uncertainty.

The uncertainty on the peaking background arises from several sources, the largest of which is the statistical uncertainty on n_{peak}^0. The next most significant source is uncertainty in $\varepsilon_{\text{peak}}$. We estimate the magnitude of this uncertainty by observing the variations in $\varepsilon_{\text{peak}}$ among samples of different simulated B^0 decay modes. In addition, one could define $\varepsilon_{\text{peak}}$ as the efficiency for any candidate with $m_{\text{ES}} > 5.27$ GeV to pass the final selection, rather than defining it as the ratio of fitted Gaussian areas. We take the difference between the two definitions as a systematic. The estimate of n_{peak}^0 is also subject to uncertainty in the distribution of peaking backgrounds in $m_{J/\psi}$, which is modeled as a second-order Chebyshev polynomial. The variation in n_{peak}^0 when the order is changed by ± 1 is propagated to the systematic uncertainty. The accuracy of the fit used to extract the signal is verified using background-only samples, such as data recorded below the $B\bar{B}$ threshold or samples of candidates reconstructed in modes not accessible to the J/ψ. No statistically significant signal yields are reported in fits to these samples. We assign the largest artificial signal yield consistent with these tests as a systematic uncertainty. The final source is the uncertainty on the resolution of the J/ψ peak (which is held fixed in the fit that determines n_{peak}^0). Variation of this assumed width between values observed in different decay modes yields a variation in n_{peak}^0. The sum in quadrature of all these effects totals 25% of the magnitude of n_{peak}. Repeating the fit on many samples of parametrized MC simulation events, each of which has the same size and background as the sample observed in data, shows that the variation in $\sin 2\beta$ resulting from a 25% uncertainty in the peaking background is ± 0.07.

There are potentially differences in the flavor-tagging performance and vertex resolution between events with hadronic J/ψ decays and the other fully reconstructed B decays used to measure these parameters. Performing a $\sin 2\beta$ fit to

TABLE II. Summary of systematic uncertainties on the measurement of $\sin 2\beta$.

Source	Uncertainty
Peaking background CP	0.15
Combinatoric background magnitude	0.13
Peaking background magnitude	0.07
Tagging and vertexing differences	0.04
Common to leptonic modes	0.03
Misreconstructed signal	0.01
Total	0.21

a large sample of full MC simulation signal events with $J/\psi \to \pi^+ \pi^- \pi^0$ with the flavor tagging and vertex resolution fixed to the measured values yields a result consistent with the generated value. The statistical uncertainty of the result (± 0.04) is taken as a systematic uncertainty.

Another systematic uncertainty arises from events in which one or more of the final state particles assigned to the reconstructed B^0 in fact originated from the other B^0 in the event. The fraction of such events is negligible for two-body J/ψ decays, and about 5% for three-body decays. Performing $\sin 2\beta$ fits on full MC simulation samples with and without including the incorrectly reconstructed candidates yields a variation of ± 0.01 in $\sin 2\beta$.

Finally we take into account all the sources of systematic uncertainty that apply to BABAR's previous measurements of $\sin 2\beta$ [3], except for those specific to the $B^0 \to J/\psi K_L^0$ mode, that have not already been specifically addressed here. These uncertainties primarily arise from limits on our understanding of flavor-tagging and vertex reconstruction performance, and yield a variation of ± 0.03 in $\sin 2\beta$.

The systematic uncertainties are summarized in Table II. The sum in quadrature of all contributions is 0.21.

The value of $\sin 2\beta$ reported in this analysis is higher than the world average value of 0.731 ± 0.056. To estimate the consistency of this result with the world average, 10 000 parametrized MC samples with the same signal and background magnitudes as observed in the data were generated with a true $\sin 2\beta$ of 0.731. To simulate the systematic uncertainty in this analysis and the total uncertainty on the world average, a random number with Gaussian distribution and $\sigma = 0.22$ is added to the $\sin 2\beta$ result for each sample. Of the 10 000 samples, 629 fluctuated to a value of 1.56 or greater, indicating that the probability of such a fluctuation is 6.3%.

In summary, we have extended BABAR's previous $\sin 2\beta$ measurement by including $J/\psi K_S^0$ modes where the J/ψ decays to hadronic final states. The result is

$$\sin 2\beta = 1.56 \pm 0.42(\text{stat}) \pm 0.21(\text{syst}).$$

Although we searched for many hadronic J/ψ decay modes, signals were observed only in modes that have been previously seen [2]. Further, only in hadron multiplicities of 2 and 3 was it possible to observe a signal above background. Extending the analysis to the χ_c and $\psi(2S)$ mass

regions does not yield additional significant signals, nor is an η_c signal observed after elimination of $KK\pi$ modes.

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