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Study of Time-Dependent *CP* Asymmetry in Neutral *B* Decays to $J/\psi\,\pi^0$

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We present the first study of the time-dependent CP-violating asymmetry in $B^0 \to J/\psi\,\pi^0$ decays using e^+e^- annihilation data collected with the *BABAR* detector at the $\Upsilon(4S)$ resonance during the years 1999–2002 at the PEP-II asymmetric-energy B Factory at SLAC. Using approximately 88 million $B\overline{B}$ pairs, our results for the coefficients of the cosine and sine terms of the CP asymmetry are $C_{J/\psi\,\pi^0} = 0.38 \pm 0.41$ (stat) $\pm\, 0.09$ (syst) and $S_{J/\psi\,\pi^0} = 0.05 \pm 0.49$ (stat) $\pm\, 0.16$ (syst).

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The Standard Model of electroweak interactions describes CP violation in B-meson decays by a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The $b \to c\overline{c}s$

modes such as $B^0 \to J/\psi K^0_S$ yield precise measurements of the quantity $\sin 2\beta$, where $\beta \equiv \arg\left[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right]$ (see for example Refs. [2–4]). The decay $B^0 \to J/\psi \pi^0$ is a Cabibbo-suppressed $b \to c\bar{c}d$ transition. In the Standard Model both $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi \pi^0$ have penguin amplitudes with the same weak phase as the tree amplitude, and an additional penguin amplitude with a different phase. In $B^0 \to J/\psi K^0_S$, the penguin amplitude with a different weak phase is suppressed by λ^2_{CKM}, where λ_{CKM} is the sine of the Cabibbo angle, while in $B^0 \to J/\psi \pi^0$, the tree and each penguin amplitude are equal to leading order in λ_{CKM}. Therefore, $B^0 \to J/\psi \pi^0$ may have a *CP* asymmetry that differs from that of $B^0 \to J/\psi K^0_S$, with the size of the asymmetry serving as a probe of the penguin decay amplitudes in both modes.

BABAR has previously measured the $B^0 \to J/\psi \pi^0$ branching fraction, $(2.0\pm 0.6\,(\mathrm{stat})\pm 0.2\,(\mathrm{syst}))\times 10^{-5}$ [5], using $\Upsilon(4S) \to B\overline{B}$ decays. For the *CP* asymmetry measurement, the flavor (B^0 or $\overline{B}{}^0$) of the B meson that decays to $J/\psi\pi^0$ is inferred, or tagged, using properties of the other B meson and the time evolution of the $B\overline{B}$ system. The decay time distributions, $\mathrm{f}_+(\mathrm{f}_-)$, of B decays to a *CP* eigenstate with a B^0 ($\overline{B}{}^0$) flavor tag, are given by

$$\mathrm{f}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Bigg[1 \pm S_{J/\psi\pi^0}\sin(\Delta m_d \Delta t) \mp C_{J/\psi\pi^0}\cos(\Delta m_d \Delta t)\Bigg], \quad (1)$$

where $\Delta t = t_{\mathrm{rec}} - t_{\mathrm{tag}}$ is the difference between the proper decay time of the reconstructed B meson and the proper decay time of the tagging B meson, τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}{}^0$ oscillation frequency. The coefficients can be expressed in terms of a complex parameter λ, which depends on both the B^0-$\overline{B}{}^0$ oscillation amplitude and the B^0 and $\overline{B}{}^0$ decay amplitudes to this final state [6]: $S_{J/\psi\pi^0} = 2\mathcal{I}m\lambda/(1+|\lambda|^2)$ and $C_{J/\psi\pi^0} = (1-|\lambda|^2)/(1+|\lambda|^2)$. A decay amplitude with only a tree component would give $S_{J/\psi\pi^0} = -\sin 2\beta$ and $C_{J/\psi\pi^0} = 0$.

The data used in this measurement were collected with the *BABAR* detector [7] at the PEP-II storage ring in the years 1999 to 2002. Approximately 81 fb^{-1} of e^+e^- annihilation data recorded at the $\Upsilon(4S)$ resonance are used, corresponding to a sample of approximately 88 million $B\overline{B}$ pairs. An additional 5 fb^{-1} of data collected approximately 40 MeV below the $\Upsilon(4S)$ resonance are used to characterize non-$B\overline{B}$ background sources.

$B^0 \to J/\psi\pi^0$ candidates are selected (details are given in Ref. [5]) by identifying $J/\psi \to e^+e^-$ or $J/\psi \to \mu^+\mu^-$ decays and $\pi^0 \to \gamma\gamma$ decays. For the $J/\psi \to e^+e^-$ ($J/\psi \to \mu^+\mu^-$) channel, each lepton candidate must be consistent with the electron (muon) hypothesis. The invariant mass of the lepton pair is required to be between 2.95 and 3.14 GeV/c^2, and 3.06 and 3.14 GeV/c^2, for the electron and muon channels, respectively. The photon candidates used to reconstruct the π^0 candidate are identified as clusters in the electromagnetic calorimeter (EMC) with polar angles between 0.410 and 2.409 rad, that are spatially separated from every charged track, and have a minimum energy of 30 MeV. The lateral energy distribution in the cluster is required to be consistent with that of a photon. The invariant mass of the photon pair is required to between 100 and 160 MeV/c^2. Finally, the J/ψ and π^0 candidates are assigned their nominal masses and combined using 4-momentum addition.

TABLE I: Efficiencies for the requirement on the Fisher discriminant and flavor tagging, given independently, with statistical uncertainties.

Type of event	Efficiency (%)	
	Fisher	Tagging
$B^0 \to J/\psi\pi^0$	99.2 ± 0.1	65.6 ± 0.6
$B^0 \to J/\psi K^0_S(\pi^0\pi^0)$ bkg.	98.9 ± 0.1	65.6 ± 0.6
Inclusive J/ψ bkg.	94.9 ± 0.7	70.4 ± 1.4
$B\overline{B}$ generic bkg.	98.5 ± 0.4	61.1 ± 1.6
Continuum bkg.	28.6 ± 0.7	52.3 ± 0.8

Two kinematic consistency requirements are applied to each B candidate. The difference, ΔE, between the B-candidate energy and the beam energy in the e^+e^- center-of-mass (CM) frame must be $-0.4 < \Delta E < 0.4$ GeV. The beam-energy-substituted mass, $m_{\mathrm{ES}} = \sqrt{(\sqrt{s}/2)^2 - (p^*_B)^2}$, must be greater than 5.2 GeV/c^2, where $\sqrt{s}$ is the total CM energy and p^*_B is the B-candidate momentum in the CM frame.

A linear combination of several kinematic and topological variables, determined with a Fisher discriminant, provides additional separation between signal and $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum background events. The Fisher discriminant uses the following inputs: the zeroth- and second-order Legendre polynomial momentum moments ($L_0 = \sum_i |\mathbf{p}^*_i|$ and $L_2 = \sum_i |\mathbf{p}^*_i|\,\frac{3\cos^2\theta_i - 1}{2}$, where $\mathbf{p}^*_i$ are the CM momenta for the tracks and neutral calorimeter clusters that are not associated with the signal candidate, and θ_i are the angles between $\mathbf{p}^*_i$ and the thrust axis of the signal candidate); the ratio of the second-order to zeroth-order Fox-Wolfram moments, again using just tracks and clusters not associated with the signal candidate; $|\cos\theta_T|$, where θ_T is the angle between the thrust axis of the B candidate and the thrust axis of the remaining tracks and clusters in the event; and $|\cos\theta_\ell|$, where θ_ℓ is defined as the angle between the negative lepton and B candidate directions in the J/ψ rest frame. The requirement placed on the Fisher discriminant is 99% efficient for signal and rejects 71% of the continuum background. The efficiencies for satisfying this requirement are summarized in Table I.

We split the backgrounds into four mutually exclusive categories, two of which have a J/ψ from B decays ($B \to J/\psi$ X). The first background category is $B^0 \to J/\psi K^0_S(\pi^0\pi^0)$ decays where one of the π^0 mesons is nearly at rest in the e^+e^- CM frame. The second background category consists of other $B \to J/\psi$ X decays (inclusive J/ψ), which contribute through random combinations of J/ψ and π^0 candidates. The third and fourth categories consist of random combinations of particles in $B\overline{B}$ decays ($B\overline{B}$ generic) and continuum events, respectively. Monte Carlo simulation [8] is used to model aspects of the $B^0 \to J/\psi K^0_S(\pi^0\pi^0)$, inclusive J/ψ, and $B\overline{B}$ generic backgrounds. A sample ($J/\psi_{\rm fake}$) selected from data taken below the $\Upsilon(4S)$ resonance is used to model the continuum background. In this case, the J/ψ candidate is reconstructed from two tracks that are not consistent with a lepton hypothesis. Monte Carlo simulation is used to check that this procedure, which increases the size of the sample, correctly models the continuum background.

The algorithm for B-flavor tagging assigns events to one of four hierarchical, mutually exclusive tagging categories, and is described in detail in Ref. [3]. The total tagging efficiency for the signal and each background source is given in Table I. Untagged events are excluded from further consideration. Vertex reconstruction and the determination of Δt follow the techniques detailed in Ref. [9]. We require $-20 < \Delta t < 20$ ps and an estimated uncertainty on Δt of less than 2.4 ps.

We extract the CP asymmetry by performing an unbinned extended maximum likelihood fit. The likelihood is constructed from the probability density functions (PDFs) for the variables $m_{\rm ES}$, ΔE, and Δt. The quantity that is maximized is the logarithm of

$$\mathcal{L} = \frac{e^{-\sum_{j=1}^{5} n_j}}{N!} \prod_{i=1}^{N} \sum_{j=1}^{5} \left[f_j^{\alpha_i}\ n_j \prod_{d} \mathcal{P}_j^d \right], \qquad (2)$$

where n_j is the number of events for each of the five hypotheses (one signal and four background) and N is the number of input events. The $\mathcal{P}_j^d$ are the one- or two-dimensional PDFs for variables d, for each signal or background type. The parameters $f_j^{\alpha_i}$ are the tagging fractions for each of the tagging categories α_i (assigned for each event i) and each of the signal or background types j. For the $B^0 \to J/\psi \pi^0$ signal and $B^0 \to J/\psi K^0_S(\pi^0\pi^0)$ background, the values of $f_j^{\alpha_i}$ are measured with a sample ($B_{\rm flav}$) of neutral B decays to flavor eigenstates consisting of the channels $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$ [3]. Monte Carlo simulation is used to estimate the $f_j^{\alpha_i}$ values for the inclusive J/ψ and $B\overline{B}$ generic backgrounds, while the $J/\psi_{\rm fake}$ sample is used for the continuum background.

The signal $m_{\rm ES}$ distribution is modeled as the sum of two components. The first is a modified Gaussian function that, for values less than the mean, has a width parameter that scales linearly with the distance from the mean. The second component, accounting for less than 6% of the distribution, is a threshold function [10], which is a phase-space distribution of the form $m_{\rm ES}\sqrt{(1-\frac{m_{\rm ES}{}^2}{E^2_{\rm beam}})}\exp(\xi(1-\frac{m_{\rm ES}{}^2}{E^2_{\rm beam}}))$, with a kinematic cut-off at $E_{\rm beam} = 5.289$ GeV and one free parameter ξ. The signal ΔE distribution is modeled by the sum of a Gaussian core with an asymmetric power-low tail [11] and a second order polynomial. The parameters of these PDFs are determined by fitting to a signal Monte Carlo sample. The peak position of the ΔE distribution is a free parameter of the full CP likelihood fit to allow for EMC energy scale uncertainties.

The kinematic variables $m_{\rm ES}$ and ΔE are correlated in the $B^0 \to J/\psi K^0_S(\pi^0\pi^0)$ and inclusive J/ψ backgrounds, so two-dimensional PDFs are employed for these modes. Variably-binned interpolated two-dimensional histograms of these variables are constructed from the relevant Monte Carlo samples.

The $m_{\rm ES}$ PDFs for the $B\overline{B}$ generic and continuum backgrounds are modeled by the threshold function given above, and the ΔE PDFs for these two backgrounds are modeled by second order polynomials. The parameters for these PDFs are obtained from the $B\overline{B}$ generic Monte Carlo sample and the $J/\psi_{\rm fake}$ sample.

The PDFs used to describe the Δt distributions of the signal and background sources are each a convolution of a resolution function $\mathcal{R}$ and decay time distribution $\mathcal{D}$: $\mathcal{P}(\Delta t, \sigma_{\Delta t}) = \mathcal{R}(\delta t, \sigma_{\Delta t}) \otimes \mathcal{D}(\Delta t_{\rm true})$, where Δt and $\Delta t_{\rm true}$ are the measured and true decay time differences, $\delta t = \Delta t - \Delta t_{\rm true}$, and $\sigma_{\Delta t}$ is the estimated event-by-event error on Δt.

For the signal, the resolution function consists of the sum of three Gaussian distributions, the parameters of which are determined from the $B_{\rm flav}$ sample, as in the $B^0 \to J/\psi K^0_S$ measurement [9]. The decay time distribution is given by Eq. 1 modified for the effects of B-flavor tagging:

$$\begin{aligned}\mathcal{D}^{\pm}_{\alpha,f}(\Delta t) = & \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{(1 \mp \Delta w_\alpha) \\ & \pm S_f\ (1-2w_\alpha)\sin(\Delta m_d \Delta t) \\ & \mp C_f\ (1-2w_\alpha)\cos(\Delta m_d \Delta t)\}, \qquad (3)\end{aligned}$$

where $\mathcal{D}^{+}_{\alpha,f}(\mathcal{D}^{-}_{\alpha,f})$ is for a $B^0(\overline{B}^0)$ tagging meson. The variable w_α is the average probability of incorrectly tagging a B^0 as a $\overline{B}^0$ ($w_\alpha^{B^0}$) or a $\overline{B}^0$ as a B^0 ($w_\alpha^{\overline{B}^0}$), and $\Delta w_\alpha = w_\alpha^{B^0} - w_\alpha^{\overline{B}^0}$. Both w_α and Δw_α are determined using the $B_{\rm flav}$ data sample [3]. We use the values $\Delta m_d = 0.489\,{\rm ps}^{-1}$ and $\tau_{B^0} = 1.542$ ps [12].

The PDF used to model the Δt distribution for the $B^0 \to J/\psi K^0_S(\pi^0\pi^0)$ background, which also includes a CP asymmetry, takes the same form as that for signal, but with $S_{J/\psi K^0_S} = \sin 2\beta = 0.74$ [3] and $C_{J/\psi K^0_S} = 0$.

The parameterizations of the Δt PDFs for the inclu-

TABLE II: Results of the *CP* likelihood fit, for the full region $-0.4 < \Delta E < 0.4\,\text{GeV}$ and $m_{\text{ES}} > 5.2\,\text{GeV}/c^2$. Errors are statistical only. The global correlation coefficient is 0.14 for $C_{J/\psi\,\pi^0}$ and 0.15 for $S_{J/\psi\,\pi^0}$.

	Fit results
$C_{J/\psi\,\pi^0}$	0.38 ± 0.41
$S_{J/\psi\,\pi^0}$	0.05 ± 0.49
Signal ΔE peak position (MeV)	-13.2 ± 7.2
$B^0 \to J/\psi\,\pi^0$ signal (events)	40 ± 7
$B^0 \to J/\psi\,K^0_S(\pi^0\pi^0)$ background (events)	140 ± 19
Inclusive J/ψ background (events)	109 ± 35
$B\overline{B}$ generic background (events)	52 ± 25
Continuum background (events)	97 ± 22

sive J/ψ and $B\overline{B}$ generic backgrounds each consist of prompt and exponential decay components. Decays appear to be prompt when particles from the reconstructed B are erroneously included in the tagging B vertex. For the $B\overline{B}$ generic background, the prompt and exponential components correspond to the cases where the two decay products forming the J/ψ come from both or just one of the B mesons, respectively. The fraction that is in the exponential component, the decay lifetime parameter, and the resolution parameters are determined from the Monte Carlo simulation.

The Δt PDF for the continuum background has only a prompt component and the resolution parameter values are obtained by fitting the J/ψ_{fake} sample.

The results of the *CP* asymmetry fit, for all free parameters, are shown in Table II. There are 40 ± 7 signal events in the total sample of 438 selected events. The projection in m_{ES} is shown in Fig. 1. The yields and asymmetry as functions of Δt, overlaid with projections of the likelihood fit results, are shown in Fig. 2. Repeating the fit with the added constraint $C_{J/\psi\,\pi^0} = 0$ does not significantly change the result for $S_{J/\psi\,\pi^0}$.

The dominant contributions to the systematic errors in $C_{J/\psi\,\pi^0}$ and $S_{J/\psi\,\pi^0}$ are summarized in Table III. The first class of uncertainties are those obtained by variation of the parameters used in the m_{ES}, ΔE, and Δt PDFs, where the dominant sources are the uncertainties in the signal ΔE PDF parameters. A systematic error to account for a correlation between the tails of the signal m_{ES} and ΔE distributions is obtained by using a two-dimensional PDF. Another contribution stems from the impact of EMC energy scale uncertainties on the modeling of the $B^0 \to J/\psi\,K^0_S(\pi^0\pi^0)$ background. An additional systematic uncertainty comes from the choice of the binning of the two-dimensional PDFs for the $B^0 \to J/\psi\,K^0_S(\pi^0\pi^0)$ and inclusive J/ψ backgrounds.

In summary, an unbinned extended maximum likelihood fit yields 40 ± 7 signal events and the parameters of time-dependent CP asymmetry for the decay $B^0 \to J/\psi\,\pi^0$: $C_{J/\psi\,\pi^0} = 0.38 \pm 0.41$ (stat) $\pm\, 0.09$ (syst) and $S_{J/\psi\,\pi^0} = 0.05 \pm 0.49$ (stat) $\pm\, 0.16$ (syst). Within the

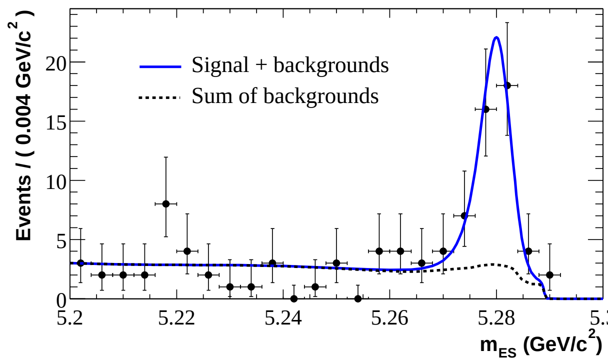

FIG. 1: Projection in m_{ES} for the results of the *CP* fit, displayed with the added requirement $-0.11 < \Delta E < 0.11\,\text{GeV}$. In contrast, the *CP* fit uses the full ΔE region. In the further restricted region $m_{\text{ES}} > 5.27\,\text{GeV}/c^2$, there are 49 data events (points), of which about 12 events are fit as background. Here, $B^0 \to J/\psi\,K^0_S(\pi^0\pi^0)$ and inclusive J/ψ decays contribute to the enhancement in the background distribution at large m_{ES}.

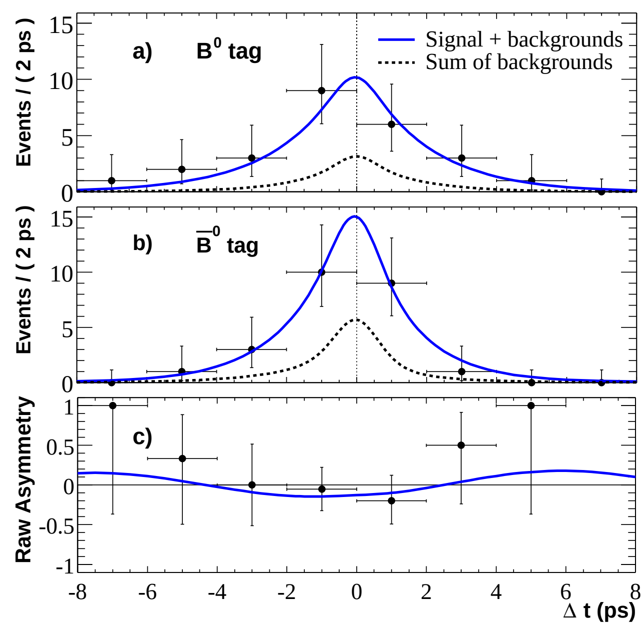

FIG. 2: Distributions of events a) with a B^0 tag (N_{B^0}), b) with a $\overline{B}^0$ tag ($N_{\overline{B}^0}$), and c) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. Candidates in these plots are required to satisfy $-0.11 < \Delta E < 0.11\,\text{GeV}$ and $m_{\text{ES}} > 5.27\,\text{GeV}/c^2$. Of the 49 signal and background events in this region, 25 have a B^0 tag and 24 have a $\overline{B}^0$ tag, with fit background contributions of approximately 5 and 7 events, respectively. The curves are projections that use the values of the other variables in the likelihood to determine the contributions to the signal and backgrounds.

Standard Model formulation of *CP* asymmetries, these results demonstrate the possibility, with additional integrated luminosity, of observing penguin contributions in

TABLE III: Summary of systematic uncertainties.

Source	$C_{J/\psi\,\pi^0}$	$S_{J/\psi\,\pi^0}$
Parameter variations		
$m_{\rm ES}$ and ΔE parameters	0.05	0.13
Tagging fractions	0.00	0.01
Δt parameters	0.03	0.02
Additional systematics		
ΔE–$m_{\rm ES}$ correlation in signal	0.07	0.08
EMC energy scale $B^0 \to J/\psi\,K^0_S(\pi^0\pi^0)$	0.01	0.00
Choice of two-D histogram PDFs	0.01	0.03
Beam spot, boost/vtx., misalignment	0.01	0.01
Total systematic uncertainty	0.09	0.16

$B^0 \to J/\psi\,\pi^0$. Such a measurement may experimentally constrain similar amplitudes in $B^0 \to J/\psi\,K^0_S$.

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