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## Evidence for CP violation in $B^0 \rightarrow J/\psi \pi^0$ decays

BABAR Collaboration

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Evidence for  $CP$  Violation in  $B^0 \rightarrow J/\psi\pi^0$  Decays

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We present measurements of the branching fraction and time-dependent  $CP$  asymmetries in  $B^0 \rightarrow J/\psi\pi^0$  decays based on  $466 \times 10^6 Y(4S) \rightarrow B\bar{B}$  events collected with the BABAR detector at the SLAC PEP-II asymmetric-energy  $B$  factory. We measure the  $CP$  asymmetry parameters  $S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$  and  $C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst})$ , where the measured value of  $(S, C)$  is 4.0 standard deviations from  $(0, 0)$  including systematic uncertainties. The branching fraction is determined to be  $\mathcal{B}(B^0 \rightarrow J/\psi\pi^0) = [1.69 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})] \times 10^{-5}$ .

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]. Measurements of  $CP$  asymmetries in the proper-time distribution of neutral  $B$  decays to  $CP$  eigenstates containing a  $J/\psi$  and  $K^0$  meson provide a precise measurement of  $\sin 2\beta$  [4], where  $\beta$  is  $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$  and the  $V_{ij}$  are CKM matrix elements with  $i, j$  quark indices.

The decay  $B^0 \rightarrow J/\psi\pi^0$  is a Cabibbo-suppressed  $b \rightarrow c\bar{c}d$  transition to a  $CP$ -even final state whose tree amplitude has the same weak phase as the  $b \rightarrow c\bar{c}s$  modes, e.g., the decay  $B^0 \rightarrow J/\psi K_S^0$ . The  $b \rightarrow c\bar{c}d$  loop (penguin) amplitudes have different weak phases than the tree amplitude. If there is a significant penguin amplitude in  $B^0 \rightarrow J/\psi\pi^0$ , then the measured values of the  $CP$  asymmetry coefficients  $S$  and  $C$  will differ from the tree level expectations of  $-\sin 2\beta$  and 0, respectively, and this mode could be sensitive to physics beyond the SM [5]. The coefficient  $S$  is related to  $CP$  violation in interference between amplitudes of direct decay, and decay after mixing, and  $C$  is related to direct  $CP$  violation. An additional motivation for measuring  $S$  and  $C$  from  $B^0 \rightarrow J/\psi\pi^0$  is that they can provide a model-independent constraint on the penguin contamination within  $B^0 \rightarrow J/\psi K_S^0$  [6].

The data used in this analysis were collected with the *BABAR* detector [7] at the PEP-II asymmetric  $e^+e^-$  storage ring [8]. This represents an integrated luminosity of  $425 \text{ fb}^{-1}$  collected on the  $\Upsilon(4S)$  resonance (on-peak), which corresponds to  $(466 \pm 5)$  million  $B\bar{B}$  pairs. In this Letter, we present an update of our previous measurements of the branching fraction  $\mathcal{B}$  and  $CP$  asymmetries of  $B^0 \rightarrow J/\psi\pi^0$  [9], which had been performed using an integrated luminosity of  $232 \text{ fb}^{-1}$ . Belle has also studied this mode and has published a branching fraction and a time-dependent  $CP$  violating asymmetry result using  $29.4 \text{ fb}^{-1}$  and  $484.3 \text{ fb}^{-1}$  of integrated luminosity, respectively [10,11].

We reconstruct  $B^0 \rightarrow J/\psi\pi^0$  decays from combinations of  $J/\psi \rightarrow \ell^+\ell^-$  ( $\ell = e, \mu$ ) and  $\pi^0 \rightarrow \gamma\gamma$  candidates. A detailed description of the charged particle reconstruction and identification can be found elsewhere [12]. For the  $J/\psi \rightarrow e^+e^-$  ( $\mu^+\mu^-$ ) channel, the invariant mass of the lepton pair is required to lie between 3.06 and 3.12  $\text{GeV}/c^2$  (3.07 and 3.13  $\text{GeV}/c^2$ ). Each lepton candidate must be consistent with the electron (muon) signature in the detector. We form  $\pi^0 \rightarrow \gamma\gamma$  candidates from clusters in the electromagnetic calorimeter with an invariant mass,  $m_{\gamma\gamma}$ , satisfying  $100 < m_{\gamma\gamma} < 160 \text{ MeV}/c^2$ . These clusters are required to be isolated from any charged tracks, carry a minimum energy of 30 MeV, and have a lateral energy distribution consistent with that of a photon. Each  $\pi^0$

candidate is required to have a minimum energy of 200 MeV and is constrained to the nominal mass [13].

We use two kinematic variables,  $m_{\text{ES}}$  and  $\Delta E$ , in order to isolate the signal:  $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$  is the beam-energy substituted mass and  $\Delta E = E_B^* - \sqrt{s}/2$  is the difference between the  $B$ -candidate energy and the beam energy. Here, the  $B^0 \rightarrow J/\psi\pi^0$  candidate ( $B_{\text{rec}}$ ) momentum  $\mathbf{p}_B$  and four-momentum of the initial state ( $E_i, \mathbf{p}_i$ ) are defined in the laboratory frame,  $E_B^*$  is the  $B_{\text{rec}}$  energy in the center-of-mass (c.m.) frame, and  $\sqrt{s}/2$  is the beam energy in the c.m. frame. We require  $m_{\text{ES}} > 5.2 \text{ GeV}/c^2$  and  $-0.1 < \Delta E < 0.3 \text{ GeV}$ . The asymmetric  $\Delta E$  cut is used in order to reduce background from  $B$  meson decays to final states including a  $J/\psi$  meson, where one or more of the particles in the final state is not reconstructed as part of  $B_{\text{rec}}$ .

A significant source of background is from  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) continuum events. We combine several kinematic and topological variables into a Fisher discriminant ( $\mathcal{F}$ ) to provide additional separation between signal and continuum. The three variables  $\cos(\theta_H)$ ,  $L_0$ , and  $L_2$  are inputs to  $\mathcal{F}$ , where  $\theta_H$  is the angle between the positively charged lepton and the  $B$  candidate momenta in the  $J/\psi$  rest frame. The variables  $L_0$  and  $L_2$  are the zeroth- and second-order moments:  $L_0 = \sum_i |\mathbf{p}_i^*|$  and  $L_2 = \sum_i |\mathbf{p}_i^*|(3\cos^2\theta_i - 1)/2$ , where  $\mathbf{p}_i^*$  are the c.m. momenta of the tracks and neutral calorimeter clusters that are not associated with the signal candidate. The  $\theta_i$  are the angles between  $\mathbf{p}_i^*$  and the thrust axis of the signal candidate. We use data collected 40 MeV below the  $\Upsilon(4S)$  resonance to model background from continuum events, and signal Monte Carlo (MC) simulated data to calculate the coefficients used in  $\mathcal{F}$ .

We use multivariate algorithms to identify signatures that determine (tag) the flavor of the decay of the other  $B$  in the event ( $B_{\text{tag}}$ ) to be either a  $B^0$  or  $\bar{B}^0$ . The flavor tagging algorithm has seven mutually exclusive categories of events and is described in detail elsewhere [14]. The total effective tagging efficiency of this algorithm is given by  $\sum_i \epsilon_i(1 - 2\omega_i)^2 = (30.5 \pm 0.4)\%$ , where  $\epsilon_i$  is the efficiency of a tag,  $\omega_i$  is the probability of misidentifying a tag, and  $i$  runs over the seven tag categories.

The decay rate  $f_+$  ( $f_-$ ) of neutral decays to a  $CP$  eigenstate, when  $B_{\text{tag}}$  is a  $B^0$  ( $\bar{B}^0$ ), is

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \pm S \sin(\Delta m_d \Delta t) \mp C \cos(\Delta m_d \Delta t)], \quad (1)$$

where  $\Delta t$  is the difference between the proper decay times of the  $B_{\text{rec}}$  and  $B_{\text{tag}}$  mesons,  $\tau_{B^0} = 1.530 \pm 0.009 \text{ ps}$  is the  $B^0$  lifetime, and  $\Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$  is the  $B^0$ - $\bar{B}^0$  oscillation angular frequency [13]. The decay width difference between the  $B^0$  mass eigenstates is assumed to be zero.

The time interval  $\Delta t$  is calculated from the measured separation  $\Delta z$  between the decay vertices of  $B_{\text{rec}}$  and  $B_{\text{tag}}$  along the collision axis ( $z$ ). The vertex of  $B_{\text{rec}}$  is reconstructed from the lepton tracks that come from the  $J/\psi$ ; the vertex of  $B_{\text{tag}}$  is constructed from tracks in the event that do not belong to  $B_{\text{rec}}$ , with constraints from the beam spot location and the  $B_{\text{rec}}$  momentum. We accept events with  $|\Delta t| < 20$  ps whose uncertainty  $\sigma(\Delta t)$  is less than 2.5 ps.

After the selection criteria mentioned above are applied, the average number of candidates per event is approximately 1.1 in data. The multiple candidates per event result from having more than one choice of  $\pi^0$  per event, so we choose the one whose value of  $m_{\gamma\gamma}$  is closest to the  $\pi^0$  mass reported by the PDG [13]. Overall, the true signal candidate is correctly identified 99.6% of the time for signal MC simulated data. After this step, the signal efficiency is 19.3%, and a total of 1120 events are selected in on-peak data.

In addition to signal and continuum background events, there are also  $B\bar{B}$ -associated backgrounds present in the data. We consider  $B$  backgrounds from the following types of event: (i)  $B^0 \rightarrow J/\psi K_S^0$ , (ii)  $B^0 \rightarrow J/\psi K^{*0}$ , (iii)  $B^\pm \rightarrow J/\psi K^{*\pm}$ , (iv)  $B^\pm \rightarrow J/\psi \rho^\pm$ , (v)  $B^0 \rightarrow J/\psi \rho^0$ , (vi) other  $B$  decays to final states including a real  $J/\psi$  where the  $\pi^0$  either comes from the other  $B$  in the event or is the decay product of particles produced in a  $B \rightarrow J/\psi X$  decay, and (vii)  $B$  meson decays to final states including charm mesons, where the  $J/\psi$  is either real and comes from a  $\psi(2S)$  or  $\chi_{c1}$  decay, or it is fake, and the result of two semi-leptonic  $B$  decays where the invariant dilepton mass falls into the allowed window. The yields of these backgrounds are fixed to expectations (16.2, 9.4, 8.8, 2.3, 0.3, 79.4, and 60.4 events, respectively), using branching ratios from world averages [15]. We allow these to vary in turn when evaluating systematic uncertainties. Backgrounds from other  $B$  decays are small and have been neglected.

The signal yield,  $S$ , and  $C$  are simultaneously extracted from an unbinned extended maximum-likelihood (ML) fit to the on-peak data sample, where the discriminating variables used in the fit are  $m_{\text{ES}}$ ,  $\Delta E$ ,  $\mathcal{F}$ , and  $\Delta t$ . For each candidate-type (signal, continuum, and the aforementioned  $B$  backgrounds), we construct a probability density function (PDF) that is the product of PDFs in each of these variables, assuming that they are uncorrelated. These combined PDFs are used in the fit to the data sample. The continuum-background  $m_{\text{ES}}$ ,  $\Delta E$ ,  $\mathcal{F}$ , and  $\Delta t$  PDF parameters are floated in the final fit to the data. For all other types, the PDF parameters are extracted from high-statistics MC samples. The  $m_{\text{ES}}$  distributions for signal and  $B^0 \rightarrow J/\psi K_S^0$  events peak at the  $B$  mass, and are described by a Gaussian with a low side exponential tail (GE). The  $m_{\text{ES}}$  PDFs for all other backgrounds are described by ARGUS functions [16]. The signal  $\Delta E$  distribution is described by a sum of a GE distribution and a second-order polynomial. We use a smoothed histogram of MC simulated data to

describe the  $\Delta E$  PDFs for  $B^0 \rightarrow J/\psi K_S^0$ ,  $B^\pm \rightarrow J/\psi \rho^\pm$ , and  $B$  meson decays to final states including charm mesons, and second-order polynomials for the  $\Delta E$  PDFs of all other backgrounds. We parameterize the  $\mathcal{F}$  distribution for signal and continuum events using the sum of a Gaussian and a Gaussian with different widths above and below the mean. The  $\mathcal{F}$  distributions for all other background PDFs are Gaussians. The signal  $\Delta t$  distribution is described by Eq. (1) convolved with three Gaussians (core, tail, outliers) which takes into account  $\sigma(\Delta t)$  from the vertex fit and tagging dilution. The resolution is parameterized using a large sample of fully reconstructed hadronic  $B$  decays [14]. The nominal  $\Delta t$  distribution for the  $B$  backgrounds is the same as for signal, except for inclusive  $B$  and  $J/\psi K^{*0}$  backgrounds. As the  $\Delta t$  distributions for inclusive  $B$  and  $J/\psi K^{*0}$  backgrounds are narrower than those of the signal and other  $B$  backgrounds, we use the lifetime obtained by fitting samples of MC of these modes. The fitted lifetime is 1.1 ps, which is an effective parameter, as opposed to having any physical meaning. The continuum background  $\Delta t$  distribution is described by the sum of three Gaussian distributions. The  $\Delta t$  PDF parameters depend on the flavor tag category. The signal yield is fitted using known tag efficiencies listed in Ref. [14] for each tag category. The continuum yields for the seven tagging categories are allowed to vary in the ML fit, and the fractions of  $B$  background events in each category are determined from MC samples.

After performing tests on the fitting procedure as described in Ref. [17], we fit the data. The results, corrected for fit bias (see below), are  $184 \pm 15(\text{stat})$  signal events,  $S = -1.23 \pm 0.21(\text{stat})$ , and  $C = -0.20 \pm 0.19(\text{stat})$ . Figure 1 shows distributions of  $m_{\text{ES}}$ ,  $\Delta E$ , and  $\mathcal{F}$  for the data, where the signal is enhanced by selecting  $\Delta E < 0.1$  GeV for the  $m_{\text{ES}}$  distribution, and  $m_{\text{ES}} > 5.275$  GeV/ $c^2$  for the other distributions. These requirements have a relative signal efficiency of 98.8% (92.3%) and background efficiency of 64% (10.4%) for  $m_{\text{ES}}$  ( $\Delta E$  and  $\mathcal{F}$ ). Figure 2 shows the  $\Delta t$  distributions for signal  $B^0$  and  $\bar{B}^0$  tagged events. The signal is enhanced by excluding events from the tagging category with the largest value of  $\omega$ , and by requiring  $m_{\text{ES}} > 5.275$  GeV/ $c^2$  and  $\Delta E < 0.1$  GeV. These requirements have a relative efficiency of 70.0% (4.4%) for signal (background). The time-dependent decay rate asymmetry  $[N(\Delta t) - \bar{N}(\Delta t)]/[N(\Delta t) + \bar{N}(\Delta t)]$  is also shown, where  $N$  ( $\bar{N}$ ) is the decay rate for  $B^0$  ( $\bar{B}^0$ ) tagged events.

Table I summarizes the systematic uncertainties on the signal yield,  $S$ , and  $C$ . These include the uncertainty due to the PDF parameterization (including the resolution function), evaluated by varying the signal and background PDF parameters within the uncertainties of their nominal values. The PDF parameter uncertainties are determined from MC samples of signal and background events. The uncertainties associated with the Lorentz boost, the  $z$ -scale of the

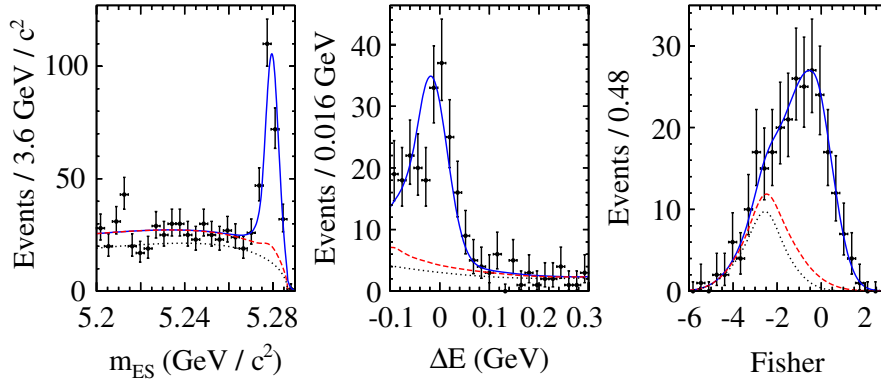


FIG. 1 (color online). Signal enhanced distribution (see text) of (left)  $m_{ES}$ , (middle)  $\Delta E$ , and (right)  $\mathcal{F}$  for the data (points), sum of signal and backgrounds (solid line), sum of backgrounds (dashed line), and the continuum background (dotted line).

tracking system, and the event-by-event beam spot position are found to be small. We determine the fit bias on signal parameters from ensembles of generated experiments using signal MC simulated data, which is generated using the GEANT4-based [18] *BABAR* MC simulation, embedded into MC samples of background simulated from the PDFs as described in Ref. [17]. We apply corrections to account for the observed fit bias on the signal yield,  $S$ , and  $C$  of  $-2.7$  events,  $-0.034$ , and  $-0.022$ , respectively. The uncertainty coming from this correction is taken as half of the correction added in quadrature with the error on the correction. Most, but not all, of the inclusive charmonium final states that dominate the inclusive  $B$  background are precisely known from previous measurements. Their yields are fixed in the fit. As a cross check, yields for the  $B$  backgrounds are allowed to vary one at a time. The sum in quadrature of deviations from the nominal result is taken as a systematic

uncertainty. In order to evaluate the uncertainty coming from  $CP$  violation in the  $B$  background, where appropriate, we introduce nonzero  $S$  and  $C$  for each background in turn. The uncertainty due to  $CP$  violation in  $B^0 \rightarrow J/\psi K_S^0$  is determined by varying  $S$  and  $C$  within current experimental limits [14,19]. For  $B$  background events decaying into final states with charm, we allow for a 20% asymmetry, and we allow for 100% asymmetries in all other  $B$  backgrounds. We study the possible interference between the suppressed  $\bar{b} \rightarrow \bar{u}c\bar{d}$  amplitude with the favored  $b \rightarrow c\bar{u}d$  amplitude for some tag-side  $B$  decays [20]. Systematic uncertainties from the effect of misalignment of the vertex detector and the use of an effective lifetime for inclusive  $B$  and  $J/\psi K^{*0}$  backgrounds are found to be negligible. There are additional systematic uncertainties that contribute only to the branching fraction. These come from uncertainties for  $\pi^0$  meson reconstruction efficiency (3%), the  $J/\psi \rightarrow \ell^+ \ell^-$  branching fractions (1.4%), the number of  $B$  meson pairs (1.1%), and tracking efficiency (1.0%). We apply a correction for charged particle identification efficiency ( $-1.3 \pm 0.7\%$  for  $J/\psi \rightarrow e^+ e^-$ , and  $-3.3 \pm 1.0\%$  for

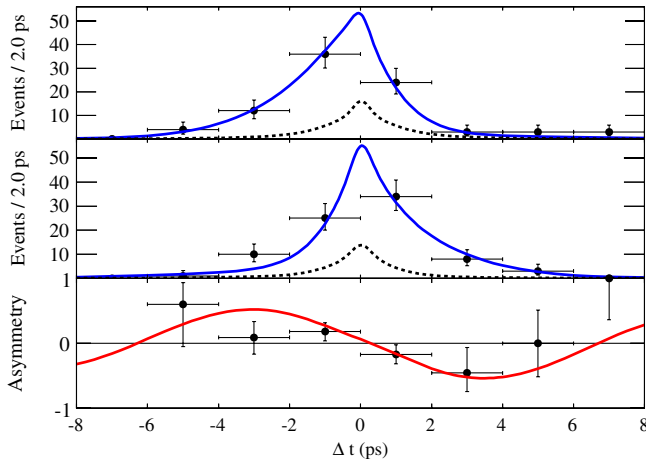


FIG. 2 (color online). The  $\Delta t$  distribution for a sample of signal enhanced events (see text) tagged as  $B^0$  (top) and  $\bar{B}^0$  (middle), where dotted lines are the sum of backgrounds and solid lines are the sum of signal and backgrounds. The time-dependent  $CP$  asymmetry (see text) is also shown (bottom), where the curve represents the measured asymmetry.

TABLE I. Contributions to the systematic errors on the signal yield,  $S$ , and  $C$ , where the signal yield errors are given as number of events. The total systematic uncertainty is the quadratic sum of the individual contributions listed. Additional systematic uncertainties that are applied only to the branching fraction are discussed in the text.

Contribution	Yield	$S$	$C$
PDF parameterization	+0.5 -1.6	+0.010 -0.012	+0.002 -0.011
Boost and $z$ -scale	$\pm 1.1$	$\pm 0.001$	$\pm 0.002$
Beam spot position	$\dots$	$\pm 0.004$	$\pm 0.002$
Fit bias	$\pm 1.5$	$\pm 0.021$	$\pm 0.014$
$B$ background yields	$\pm 1.2$	$\pm 0.029$	$\pm 0.013$
$CP$ content of $B$ background	$\pm 0.4$	$\pm 0.002$	$\pm 0.002$
Tag-side interference	$\dots$	$\pm 0.004$	$\pm 0.014$
Total	+2.3 -2.7	$\pm 0.04$	$\pm 0.03$

$J/\psi \rightarrow \mu^+ \mu^-$  decays) based on the results of control sample studies using  $B$  decays with  $J/\psi$  mesons in the final state. The systematic error contribution from MC statistics is negligible.

We measure

$$\mathcal{B} = [1.69 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})] \times 10^{-5},$$

$$S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst}),$$

$$C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst}),$$

where the correlation between  $S$  and  $C$  is 19.7%. We determine the significance, including systematic uncertainties, of nonzero values of  $S$  and  $C$  using ensembles of MC simulated experiments as outlined in Ref. [21]. The significance of  $S$  or  $C$  being nonzero is  $4.0\sigma$ , which constitutes evidence for  $CP$  violation in  $B^0 \rightarrow J/\psi \pi^0$  decays. The numerical values of  $S$  and  $C$  are consistent with the SM expectations for a tree-dominated  $b \rightarrow c\bar{c}d$  transition. All results presented here are consistent with previous measurements [9–11].

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