PHYSICAL REVIEW D **77,** 071101(R) (2008)

Improved measurement of time-dependent CP violation in $B^0 \to J/\psi\pi^0$ decays

S. E. Lee,[35] K. Miyabayashi,[22] H. Aihara,[42] T. Aushev,[17,12] T. Aziz,[38] A. M. Bakich,[37] V. Balagura,[12] E. Barberio,[20] A. Bay,[17] K. Belous,[11] V. Bhardwaj,[32] U. Bitenc,[13] S. Blyth,[24] A. Bondar,[1] A. Bozek,[26] M. Bračko,[19,13] T. E. Browder,[7] P. Chang,[25] A. Chen,[23] K.-F. Chen,[25] B. G. Cheon,[6] R. Chistov,[12] I.-S. Cho,[47] S.-K. Choi,[5] Y. Choi,[36] J. Dalseno,[20] M. Dash,[46] S. Eidelman,[1] D. Epifanov,[1] N. Gabyshev,[1] H. Ha,[15] J. Haba,[8] K. Hara,[21] T. Hara,[31] H. Hayashii,[22] M. Hazumi,[8] D. Heffernan,[31] T. Higuchi,[8] Y. Hoshi,[40] W.-S. Hou,[25] H. J. Hyun,[16] T. Iijima,[21] K. Inami,[21] A. Ishikawa,[33] H. Ishino,[43] R. Itoh,[8] M. Iwasaki,[42] D. H. Kah,[16] J. H. Kang,[47] S. U. Kataoka,[22] H. Kawai,[2] T. Kawasaki,[28] H. J. Kim,[16] S. K. Kim,[35] Y. J. Kim,[4] K. Kinoshita,[3] S. Korpar,[19,13] P. Križan,[18,13] R. Kumar,[32] C. C. Kuo,[23] A. Kuzmin,[1] Y.-J. Kwon,[47] J. S. Lee,[36] M. J. Lee,[35] T. Lesiak,[26] S.-W. Lin,[25] Y. Liu,[4] D. Liventsev,[12] S. McOnie,[37] T. Medvedeva,[12] W. Mitaroff,[10] H. Miyata,[28] R. Mizuk,[12] T. Mori,[21] E. Nakano,[30] M. Nakao,[8] H. Nakazawa,[23] Z. Natkaniec,[26] S. Nishida,[8] O. Nitoh,[45] S. Noguchi,[22] T. Nozaki,[8] S. Ogawa,[39] T. Ohshima,[21] S. Okuno,[14] S. L. Olsen,[7,9] H. Ozaki,[8] P. Pakhlov,[12] G. Pakhlova,[12] H. Park,[16] K. S. Park,[36] R. Pestotnik,[13] L. E. Piilonen,[46] H. Sahoo,[7] Y. Sakai,[8] O. Schneider,[17] A. J. Schwartz,[3] A. Sekiya,[22] K. Senyo,[21] M. Shapkin,[11] C. P. Shen,[9] H. Shibuya,[39] S. Shinomiya,[31] J.-G. Shiu,[25] B. Shwartz,[1] J. B. Singh,[32] A. Sokolov,[11] A. Somov,[3] S. Stanič,[29] M. Starič,[13] K. Sumisawa,[8] T. Sumiyoshi,[44] S. Suzuki,[33] O. Tajima,[8] F. Takasaki,[8] K. Tamai,[8] M. Tanaka,[8] G. N. Taylor,[20] Y. Teramoto,[30] I. Tikhomirov,[12] K. Trabelsi,[8] S. Uehara,[8] K. Ueno,[25] T. Uglov,[12] Y. Unno,[6] S. Uno,[8] P. Urquijo,[20] Y. Ushiroda,[8] Y. Usov,[1] G. Varner,[7] K. E. Varvell,[37] S. Villa,[17] C. C. Wang,[25] C. H. Wang,[24] P. Wang,[9] X. L. Wang,[9] Y. Watanabe,[14] E. Won,[15] A. Yamaguchi,[41] Y. Yamashita,[27] M. Yamauchi,[8] C. Z. Yuan,[9] Y. Yusa,[46] C. C. Zhang,[9] Z. P. Zhang,[34] V. Zhilich,[1] V. Zhulanov,[1] and A. Zupanc[13]

(The Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chiba University, Chiba*
[3]*University of Cincinnati, Cincinnati, Ohio 45221*
[4]*The Graduate University for Advanced Studies, Hayama*
[5]*Gyeongsang National University, Chinju*
[6]*Hanyang University, Seoul*
[7]*University of Hawaii, Honolulu, Hawaii 96822*
[8]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[9]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[10]*Institute of High Energy Physics, Vienna*
[11]*Institute of High Energy Physics, Protvino*
[12]*Institute for Theoretical and Experimental Physics, Moscow*
[13]*J. Stefan Institute, Ljubljana*
[14]*Kanagawa University, Yokohama*
[15]*Korea University, Seoul*
[16]*Kyungpook National University, Taegu*
[17]*Ecole Polytécnique Fédérale Lausanne, EPFL, Lausanne*
[18]*University of Ljubljana, Ljubljana*
[19]*University of Maribor, Maribor*
[20]*University of Melbourne, School of Physics, Victoria 3010*
[21]*Nagoya University, Nagoya*
[22]*Nara Women's University, Nara*
[23]*National Central University, Chung-li*
[24]*National United University, Miao Li*
[25]*Department of Physics, National Taiwan University, Taipei*
[26]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[27]*Nippon Dental University, Niigata*
[28]*Niigata University, Niigata*
[29]*University of Nova Gorica, Nova Gorica*
[30]*Osaka City University, Osaka*
[31]*Osaka University, Osaka*
[32]*Panjab University, Chandigarh*
[33]*Saga University, Saga*
[34]*University of Science and Technology of China, Hefei*
[35]*Seoul National University, Seoul*

 © 2008 The American Physical Society

[36]Sungkyunkwan University, Suwon
[37]University of Sydney, Sydney, New South Wales
[38]Tata Institute of Fundamental Research, Mumbai
[39]Toho University, Funabashi
[40]Tohoku Gakuin University, Tagajo
[41]Tohoku University, Sendai
[42]Department of Physics, University of Tokyo, Tokyo
[43]Tokyo Institute of Technology, Tokyo
[44]Tokyo Metropolitan University, Tokyo
[45]Tokyo University of Agriculture and Technology, Tokyo
[46]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[47]Yonsei University, Seoul

(Received 2 August 2007; published 1 April 2008)

We report improved measurements of time-dependent CP violation parameters for $B^0(\bar{B}^0) \to J/\psi\pi^0$ decay. This analysis is based on 535×10^6 $B\bar{B}$ pairs accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. From the distribution of proper time intervals between the two B decays, we obtain the following CP violation parameters $\mathcal{S}_{J/\psi\pi^0} = -0.65 \pm 0.21(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ and $\mathcal{A}_{J/\psi\pi^0} = +0.08 \pm 0.16(\mathrm{stat}) \pm 0.05(\mathrm{syst})$, which are consistent with standard model expectations.

DOI: 10.1103/PhysRevD.77.071101 PACS numbers: 12.15.Hh, 13.25.Hw

The Kobayashi-Maskawa (KM) quark-mixing matrix [1] has an irreducible complex phase that gives rise to CP-violating asymmetries in the time-dependent rates of B^0 and $\bar{B}^0$ decays into a common CP eigenstate such as $J/\psi\pi^0$ [2]. In the decay chain $\Upsilon(4S) \to B^0\bar{B}^0 \to (J/\psi\pi^0)f_{\mathrm{tag}}$, where one of the B mesons decays at time t_{CP} to the final state $J/\psi\pi^0$ and the other decays at time t_{tag} to a final state f_{tag} that distinguishes between B^0 and $\bar{B}^0$, the decay rate has a time dependence given by [3]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q \cdot [\mathcal{S}_{J/\psi\pi^0}\sin(\Delta m_d \Delta t) + \mathcal{A}_{J/\psi\pi^0}\cos(\Delta m_d \Delta t)]\}, \tag{1}$$

where τ_{B^0} is the neutral B lifetime, Δm_d is the mass difference between the two neutral B mass eigenstates, $\Delta t = t_{CP} - t_{\mathrm{tag}}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a $B^0(\bar{B}^0)$. The CP violation parameters $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ are given by

$$\mathcal{S}_{J/\psi\pi^0} \equiv \frac{2\Im(\lambda)}{|\lambda|^2 + 1}, \qquad \mathcal{A}_{J/\psi\pi^0} \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \tag{2}$$

where λ is a complex parameter that depends on both the $B^0\bar{B}^0$ mixing and the amplitudes for B^0 and $\bar{B}^0$ decay to $J/\psi\pi^0$. In the standard model (SM), $|\lambda|$ is, to a good approximation, equal to the absolute value of the ratio of the $\bar{B}^0 \to J/\psi\pi^0$ to $B^0 \to J/\psi\pi^0$ decay amplitudes. At the quark level, the $B^0 \to J/\psi\pi^0$ decay proceeds via a $b \to c\bar{c}d$ transition. In this decay, the tree amplitude is CKM-suppressed. Since the tree amplitude has the same weak phase as the $b \to c\bar{c}s$ transition, $\mathcal{S}_{J/\psi\pi^0} = -\sin 2\phi_1$ and $\mathcal{A}_{J/\psi\pi^0} = 0$ are expected if other contributions to the decay amplitude can be neglected [4]. If, however, the penguin or other contributions are substantial, the CP violation parameters for this mode may deviate from these values. Employing SU(3) symmetry as well as plausible dynamical assumptions, the results obtained for $B \to J/\psi\pi^0$ decay can be used to estimate the penguin pollution in $B^0 \to J/\psi K_S^0$ decay for a very precise determination of $\sin 2\phi_1$ [5].

The most recent study of $B^0 \to J/\psi\pi^0$ decays was reported by *BABAR* [6] using a sample of 232×10^6 $B\bar{B}$ pairs, while the previous Belle analysis [7] was based on a data sample corresponding to 152×10^6 $B\bar{B}$ pairs. This measurement of time-dependent CP violation in $B^0 \to J/\psi\pi^0$ decays is based on a larger data sample that contains 535×10^6 $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [8] operating at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is produced with a Lorentz boost factor of $\beta\gamma = 0.425$ along the z-axis, which is antiparallel to the positron beam direction. Since the $B\bar{B}$ pairs are produced nearly at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt is determined from Δz, the distance between the two B meson decay vertices along the z-direction: $\Delta t \cong \Delta z / c\beta\gamma$, where c is the speed of light.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [9]. Two inner detector configurations were used. A 2.0 cm radius beam pipe and a 3-layer silicon vertex detector were used for the first sample of 152×10^6 $B\bar{B}$ pairs, while a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining 383×10^6 $B\bar{B}$ pairs [10].

We reconstruct J/ψ mesons in the $\ell^+\ell^-$ decay channel ($\ell = e$ or μ) and include up to two bremsstrahlung photons that are within 50 mrad of each of the e^+ and e^- tracks (denoted as $e^+e^-(\gamma)$). The invariant mass is required to be within $-0.15\ \mathrm{GeV}/c^2 < M_{ee(\gamma)} - m_{J/\psi} < +0.036\ \mathrm{GeV}/c^2$ and $-0.06\ \mathrm{GeV}/c^2 < M_{\mu\mu} - m_{J/\psi} < +0.036\ \mathrm{GeV}/c^2$, where $m_{J/\psi}$ denotes the J/ψ nominal mass [11], and $M_{ee(\gamma)}$ and $M_{\mu\mu}$ are the reconstructed invariant masses from $e^+e^-(\gamma)$ and $\mu^+\mu^-$, respectively.

Photon candidates are selected from clusters of up to 5×5 crystals in the ECL. Each candidate is required to have no associated charged track and a cluster shape that is consistent with an electromagnetic shower. To select $\pi^0 \to \gamma\gamma$ decay candidates, the energy of a photon is required to be greater than 50 MeV in the ECL barrel and 100 MeV in the end-cap region. A pair of photons with an invariant mass in the range $118\ \mathrm{MeV}/c^2 < M_{\gamma\gamma} < 150\ \mathrm{MeV}/c^2$ is considered as a π^0 candidate.

We combine the J/ψ and π^0 to form a neutral B meson. Signal candidates are identified by two kinematic variables defined in the $\Upsilon(4S)$ rest frame (cms): the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - (\sum \vec{p}_i)^2}$ and the energy difference $\Delta E \equiv \sum E_i - E_{\rm beam}$, where $E_{\rm beam} = \sqrt{s}/2$ is the cms beam energy, and $\vec{p}_i$ and E_i are the cms three momenta and energies of the candidate B meson decay products, respectively. In order to improve the ΔE resolution, vertex- and mass-constrained fits are applied to $J/\psi \to \ell^+\ell^-$ decays and a mass-constrained fit is used for $\pi^0 \to \gamma\gamma$ decays. The B meson signal region is defined as $5.27\ \mathrm{GeV}/c^2 < M_{\rm bc} < 5.29\ \mathrm{GeV}/c^2$ and $-0.1\ \mathrm{GeV} < \Delta E < 0.05\ \mathrm{GeV}$. The lower bound in ΔE is chosen to accommodate the negative ΔE tail of the signal due to shower leakage associated with the π^0, and to avoid background from $B^0 \to J/\psi K_S^0$ ($K_S^0 \to \pi^0\pi^0$) decays. To suppress the two-jet-like $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum background, we require that the event shape variable, R_2, which is the ratio of the second to zeroth Fox-Wolfram moment, satisfy $R_2 < 0.4$ [12].

We identify the flavor of the accompanying B meson from inclusive properties of particles that are not associated with the reconstructed $B^0 \to J/\psi\pi^0$. The algorithm for flavor tagging is described in detail elsewhere [13]. We use two parameters, q defined in Eq. (1) and r, to represent the tagging information. The parameter r is an event-by-event Monte Carlo (MC) determined flavor-tagging quality factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only for sorting data into six intervals. The wrong tag fractions for the six r intervals, w_l ($l = 1, 6$), and the difference in ω between B^0 and $\bar{B}^0$ decays, Δw_l, are determined from data [13]. The vertex position for the $J/\psi\pi^0$ decay is reconstructed using leptons from the J/ψ decay. The vertex position of $f_{\rm tag}$ is obtained using tracks that are not assigned to the $J/\psi\pi^0$ candidate and an interaction point constraint. After all selection criteria are applied, we obtain 864 events in the $\Delta E - M_{\rm bc}$ fit region defined as $5.2\ \mathrm{GeV}/c^2 < M_{\rm bc} < 5.3\ \mathrm{GeV}/c^2$ and $-0.2\ \mathrm{GeV} < \Delta E < 0.2\ \mathrm{GeV}$, of which 290 are in the signal box.

We perform an unbinned maximum likelihood fit to the $\Delta E - M_{\rm bc}$ distribution in order to distinguish signal and backgrounds. The probability density function (PDF) of signal is composed of two parts: one is for the candidates that are correctly reconstructed combinations of daughter particles coming from a single neutral B meson, the other corresponds to combinations in which one of the final state particles is incorrectly reconstructed (i.e. one of the daughter particles originates from the other B meson). The former is parametrized by a two-dimensional function that is a product of a Crystal Ball line shape [14] in ΔE and a Gaussian form in $M_{\rm bc}$. This parametrization accounts for the fact that ΔE and $M_{\rm bc}$ distributions are predominantly affected by the shower energy leakage in the ECL (in ΔE) and the beam energy spread of the KEKB accelerator (in $M_{\rm bc}$). On the other hand, the latter is described by a MC-determined two-dimensional smooth function. In the signal box, the correct combination is estimated to describe $87 \pm 2\%$ of the signal events. The background is composed of four components: (1) $B^0 \to J/\psi K_S^0$, (2) $B^0 \to J/\psi K_L^0$, (3) $B \to J/\psi X$ other than $B^0 \to J/\psi K^0$, (4) combinatorial background that consists of random combinations of particles in $B\bar{B}$ decays and continuum events. Using a large MC sample, the PDFs to describe (1), (2), and (3) are determined and then parametrized as two-dimensional smooth functions in $\Delta E - M_{\rm bc}$. In the fit, we fix each yield of the three components, (1), (2), and (3), to the values obtained from the MC sample. The dominant $B \to J/\psi X$ contributions, excluding $J/\psi K_S^0$ and $J/\psi K_L^0$, come from two-body decays, with well-measured branching fractions ($B \to J/\psi K^{(*)}$). The combinatorial background shapes in ΔE and $M_{\rm bc}$ are described by a first-order polynomial and an ARGUS function [15], respectively. The purity in the signal region is estimated to be $87.9 \pm 8.0\%$. The fractions of $J/\psi K_S^0$, $J/\psi K_L^0$ and other $J/\psi X$ events are $2.6 \pm 0.2\%$, $2.0 \pm 1.2\%$ and $3.2 \pm 0.2\%$, respectively, while the combinatorial event fraction is $4.3 \pm 0.5\%$. The ΔE and $M_{\rm bc}$ distributions after tagging and vertexing are shown in Fig. 1.

We determine $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ by performing an unbinned maximum-likelihood fit to the observed Δt distribution:

$$\mathcal{L}(\mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}) = \prod_i^N \mathcal{P}(\mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}; \Delta t_i), \quad (3)$$

where the product is over all events in the signal region. The PDF $\mathcal{P}$ is given by

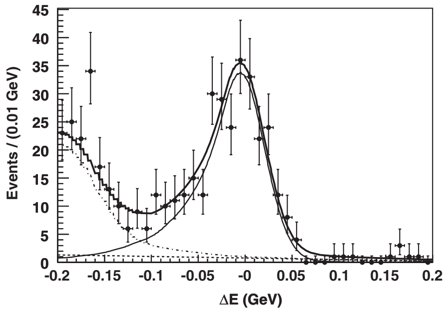

FIG. 1. ΔE distribution for events in the $M_{\rm bc}$ signal region (top) and $M_{\rm bc}$ distribution in the ΔE signal region (bottom). The superimposed curves show the signal (solid line), $B \to J/\psi X$ (dot-dashed line), combinatorial background (dashed line) and the sum of all the contributions (thick solid line).

$$\begin{aligned}\mathcal{P} =& (1-f_{\rm ol})\bigg\{\int d(\Delta t')R(\Delta t_i - \Delta t')[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t') \\ &+ f_{J/\psi K_S}\mathcal{P}_{J/\psi K_S}(\Delta t') + f_{J/\psi K_L}\mathcal{P}_{J/\psi K_L}(\Delta t') \\ &+ f_{J/\psi X}\mathcal{P}_{J/\psi X}(\Delta t')] + f_{\rm comb}\mathcal{P}_{\rm comb}(\Delta t_i)\bigg\} \\ &+ f_{\rm ol}P_{\rm ol}(\Delta t_i), \end{aligned} \quad (4)$$

where $f_{\rm sig}, f_{J/\psi K_S}, f_{J/\psi K_L}, f_{J/\psi X}$ and $f_{\rm comb}$ are the fractions of $B^0 \to J/\psi \pi^0$ signal, $B^0 \to J/\psi K_S^0$, $B^0 \to J/\psi K_L^0$, other $B \to J/\psi X$ background and combinatorial background, respectively. All fractions are functions of ΔE and $M_{\rm bc}$ and are determined from the fit discussed above. The PDF for the signal distribution, $\mathcal{P}_{\rm sig}$, is given by Eq. (1) and modified to account for the effect of incorrect flavor assignment; the parameters τ_{B^0} and Δm_d are fixed to PDG2006 values [11]. The signal PDF is convolved with the proper-time interval resolution function $R(\Delta t)$ [16]. The $B^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K_L^0$ background distributions are described by the same $\mathcal{P}_{\rm sig}$, respectively, called $\mathcal{P}_{J/\psi K_S}$ and $\mathcal{P}_{J/\psi K_L}$, convolved with $R(\Delta t)$. The CP-asymmetry parameters $\mathcal{S}_{J/\psi K_S^0}$, $\mathcal{A}_{J/\psi K_S^0}$, $\mathcal{S}_{J/\psi K_L^0}$ and $\mathcal{A}_{J/\psi K_L^0}$ are fixed to the recent Belle results [17]. The $B \to J/\psi X$ background excluding the $B^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K_L^0$ components ($\mathcal{P}_{J/\psi X}$) is described with an effective lifetime as

$$\mathcal{P}_{J/\psi X}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{J/\psi X}}}{4\tau_{J/\psi X}}\{1 - q\Delta\omega_l\}. \quad (5)$$

The effective lifetime $\tau_{J/\psi X}$ is 1.10 ± 0.10 (1.03 ± 0.07) ps for the 3(4)-layer-silicon vertex detector sample, which is determined by fitting a $B \to J/\psi X$ MC sample. The combinatorial component ($\mathcal{P}_{\rm comb}$) is described by a double Gaussian. The relevant parameters are obtained using events in the sideband region, $5.20\ {\rm Gev}/c^2 < M_{\rm bc} < 5.26\ {\rm GeV}/c^2$ and $|\Delta E| < 0.2$ Gev. The fraction $f_{\rm ol}$ and PDF $\mathcal{P}_{\rm ol}$ describe the outlier component, which is a small number of events that have large Δt values for both signal and background.

The unbinned maximum likelihood fit to the 290 events in the signal region results in the CP violation parameters:

$$\mathcal{S}_{J/\psi\pi^0} = -0.65 \pm 0.21({\rm stat}) \pm 0.05({\rm syst})$$

$$\text{and} \quad \mathcal{A}_{J/\psi\pi^0} = +0.08 \pm 0.16({\rm stat}) \pm 0.05({\rm syst}),$$

where the systematic uncertainties listed are described below. The Δt distributions and the time-dependent decay rate raw asymmetry $\mathcal{A}_{CP}$ are shown in Fig. 2, where $\mathcal{A}_{CP} = (N_+ - N_-)/(N_+ + N_-)$ and $N_+(N_-)$ is the number of candidate events with $q = +1\ (-1)$.

The systematic errors are listed in Table I. The main contributions to the systematic error in $\mathcal{S}_{J/\psi\pi^0}$ are due to uncertainties in the vertex reconstruction and to a small fit bias. The vertex reconstruction systematic error consists of uncertainties in the interaction point profile, charged track

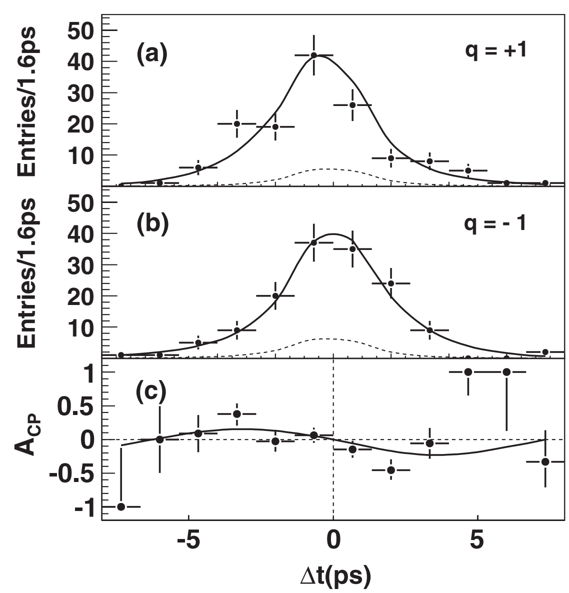

FIG. 2. Δt distribution of $B^0 \to J/\psi \pi^0$ candidate events for $q = +1$ (a) and $q = -1$ (b). The dashed lines are the sum of backgrounds while the solid lines are the sum of signal and backgrounds. (c) is the raw asymmetry ($\mathcal{A}_{CP}$) distribution. The curve is the projection of the fit result.

TABLE I. Systematic uncertainties

Parameter	$\Delta\mathcal{S}_{J/\psi\pi^0}$	$\Delta\mathcal{A}_{J/\psi\pi^0}$
Vertexing	± 0.050	± 0.034
Wrong tag fraction	± 0.009	± 0.009
Resolution function	± 0.008	± 0.007
Fit bias	± 0.013	± 0.010
Physics parameters	± 0.004	± 0.001
$B \to J/\psi X$ *CP* asymmetry	± 0.004	± 0.001
PDF Shape and fraction	± 0.009	± 0.005
Background Δt shape	± 0.006	± 0.001
Tag side interference	± 0.001	± 0.038
Total	± 0.054	± 0.054

selection based on the track helix error, helix parameter corrections, event selection based on Δt and goodness of fit in the vertex reconstruction, and the small SVD misalignment. The systematic uncertainties due to the parameters w_l and Δw_l are estimated by varying the parameters by their 1 standard deviation (σ) errors. We vary each resolution function parameter by $\pm 1\sigma$ and assign a systematic error as the quadratic sum of the resulting deviations in $\mathcal{S}$ and $\mathcal{A}$. The fit bias systematic error is evaluated from an ensemble of MC samples as the difference between the input and fitted values of $\mathcal{S}$ and $\mathcal{A}$. The errors in the physics parameters τ_{B^0} and Δm_d are taken into account. To estimate the systematics from $B^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K_L^0$, we vary their fractions and *CP* asymmetry parameters, $\mathcal{S}$ and $\mathcal{A}$ by $\pm 1\sigma$. We estimate the systematic uncertainty from the $B \to J/\psi X$ backgrounds other than $J/\psi K^0$ by scaling the systematic errors due to $J/\psi K_S^0$ and $J/\psi K_L^0$ according to the amount of background contamination. The ΔE and $M_{\rm bc}$ parameters and fractions of signal and backgrounds are varied to estimate the systematic errors. We vary the MC-determined parameters by $\pm 2\sigma$ to take account of possible imperfect modeling in MC. We include the effect of tag side interference [18]. The tag side interference is caused by the interference between the two amplitudes of B decays into charmed mesons, i.e. caused by $V_{\rm cb}$ and $V_{\rm ub}$. Therefore it is expressed by four parameters, $r_{\rm int}$ (size of interference between $V_{\rm cb}$ and $V_{\rm ub}$ amplitudes), ϕ_1, ϕ_3 and δ (strong phase difference between $V_{\rm cb}$ and $V_{\rm ub}$ mediated amplitudes). Since this interference results in a potential direct *CP* violation, $\mathcal{A}_{J/\psi\pi^0}$ is much more affected than $\mathcal{S}_{J/\psi\pi^0}$. We sum each of the contributions in quadrature to obtain the total systematic error.

The confidence regions of our measurement in the $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ plane are shown in Fig. 3. We evaluate the statistical significance of this *CP* asymmetry measurement using a two-dimensional Feldman and Cousins method [19], taking both statistical and systematic uncertainties into account. We found that our $\mathcal{S}_{J/\psi\pi^0}$ measurement has a significance greater than 2.4σ for any $\mathcal{A}_{J/\psi\pi^0}$ value.

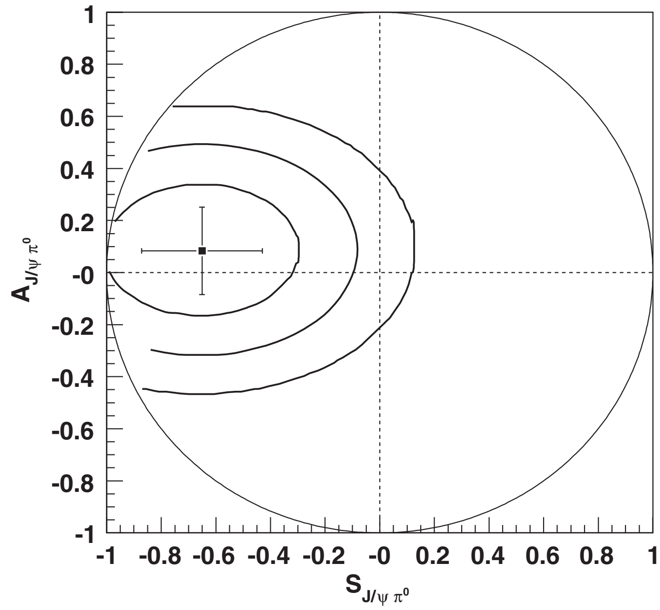

FIG. 3. The confidence regions for $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$. The contours correspond to 1-C.L. $= 3.17 \times 10^{-1}$ (1σ), 4.55×10^{-2} (2σ), and 2.70×10^{-3} (3σ). The point with error bars corresponds to the measured $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ values. The circle is a boundary derived from Eq. (2).

In summary, we measure the *CP* violation parameters in $B^0 \to J/\psi\pi^0$ decays using $535 \times 10^6 B\bar{B}$ pairs: $\mathcal{S}_{J/\psi\pi^0} = -0.65 \pm 0.21(\text{stat}) \pm 0.05(\text{syst})$ and $\mathcal{A}_{J/\psi\pi^0} = +0.08 \pm 0.16(\text{stat}) \pm 0.05(\text{syst})$. We measure mixing-induced *CP* violation with 2.4σ significance. This result supersedes our previous measurement [7] and exhibits significant improvement in precision compared to the latest *BABAR* measurement [6]. It is consistent with the measured value of $\sin 2\phi_1$ in $b \to c\bar{c}s$ decays [17,20], as expected in the standard model.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and Super-SINET network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Science Foundation of China and the Knowledge Innovation Program of the Chinese Academy of Sciences under contract No. 10575109 and IHEP-U-503; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State

Committee for Scientific Research; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).

[3] A general review of the formalism is given in I. I. Bigi, V. A. Khoze, N. G. Uraltsev, and A. I. Sanda, in *CP Violation*, edited by C. Jarlskog (World Scientific, Singapore, 1989), p. 175.

[4] Y. Grossman and M. Worah, Phys. Lett. B **395**, 241 (1997).

[5] M. Ciuchini, M. Pierini, and L. Silvestrini, Phys. Rev. Lett. **95**, 221804 (2005).

[6] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **74**, 011101(R) (2006).

[7] S. U. Kataoka *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 261801 (2004).

[8] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.

[9] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).

[10] Z. Natkaniec *et al.* (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A **560**, 1 (2006).

[11] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).

[12] G.C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[13] H. Kakuno *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 516 (2004).

[14] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, Krakow 1986; DESY DESY Internal Report F31-86-02, 1986.

[15] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).

[16] H. Tajima *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 370 (2004).

[17] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 031802 (2007).

[18] O. Long, M. Baak, R. N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).

[19] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998); Appendix A of K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **68**, 012001 (2003).

[20] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 171803 (2007).