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

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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 \(\Upsilon(4S)\to B^0\bar{B}^0\to (J/\psi\pi^0)f_{\text{tag}}\), 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 \(t_{\text{tag}}\) to a final state \(f_{\text{tag}}\) that distinguishes between \(B^0\) and \(\bar{B}^0\), the decay rate has a time dependence given by [3]

\[
\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t/\tau_{B^0}|}}{4\tau_{B^0}} \left[ 1 + q \cdot \left[ S_{J/\psi\pi^0} \sin(\Delta m_d \Delta t) + A_{J/\psi\pi^0} \cos(\Delta m_d \Delta t) \right] \right]
\]

where \(\tau_{B^0}\) is the neutral B lifetime, \(\Delta m_d\) is the mass difference between the two neutral B mass eigenstates, \(\Delta t = t_{CP} - t_{\text{tag}}\), and the \(b\)-flavor charge \(q = +1\) \((-1)\) when the tagging B meson is a \(B^0\) \((\bar{B}^0)\). The \(CP\) violation parameters \(S_{J/\psi\pi^0}\) and \(A_{J/\psi\pi^0}\) are given by

\[
S_{J/\psi\pi^0} \equiv \frac{2\Im(\lambda)}{|\lambda|^2 + 1}, \quad A_{J/\psi\pi^0} \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}
\]

where \(\lambda\) 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 \(b\to c\bar{d}d\) transition. In this decay, the tree amplitude is CKM-suppressed. Since the tree amplitude has the same weak phase as the \(b\to c\bar{s}s\) transition, \(S_{J/\psi\pi^0} = -\sin \phi_1\) and \(A_{J/\psi\pi^0} = 0\) 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 \(B^0\to J/\psi K^0_S\) 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 million \(B\bar{B}\) pairs, while the previous Belle analysis [7] was based on a data sample corresponding to 152 million \(B\bar{B}\) 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 million \(B\bar{B}\) pairs, collected with the Belle detector at the KEKB asymmetric-energy \(e^+e^-\) 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 anti-parallel to the positron beam direction. Since the \(B\bar{B}\) pairs are produced nearly at rest in the \(\Upsilon(4S)\) center-of-mass system (c.m.s.), \(\Delta t\) is determined from \(\Delta z\), the distance between the two \(B\) meson decay vertices along the z-direction: \(\Delta t \equiv \Delta z/c\beta\gamma\), 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 aero-
gel 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 $K^0_S$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [1]. 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 million $B\bar{B}$ 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 million $B\bar{B}$ pairs [11].

We reconstruct $J/\psi$ mesons in the $\ell^+\ell^-$ decay channel ($\ell = e$ or $\mu$) 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 $-0.15\text{ GeV}/c^2 < M_{ee(\gamma)} - m_{J/\psi} < +0.036\text{ GeV}/c^2$ and $-0.06\text{ GeV}/c^2 < M_{\mu\mu} - m_{J/\psi} < +0.036\text{ GeV}/c^2$, where $m_{J/\psi}$ denotes the $J/\psi$ nominal mass [11], and $M_{ee(\gamma)}$ and $M_{\mu\mu}$ are the reconstructed invariant masses from $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$, respectively.

Photon candidates are selected from clusters of up to 5 x 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 $\pi^0 \rightarrow \gamma\gamma$ 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 MeV$/c^2 < M_{\gamma\gamma} < 150\text{ MeV}/c^2$ is considered as a $\pi^0$ candidate.

We combine the $J/\psi$ and $\pi^0$ to form a neutral B meson. Signal candidates are identified by two kinematic variables defined in the $Y(4S)$ rest frame (cms): the beam-energy constrained mass $M_{bc} \equiv \sqrt{E_{beam}^2 - (\sum \vec{p}_i)^2}$ and the energy difference $\Delta E \equiv \sum E_i - E_{beam}$, where $E_{beam} = \sqrt{s}/2$ is the cms beam energy, and $E_i$ and $\vec{p}_i$ are the cms three momenta and energies of the candidate B meson decay products, respectively. In order to improve the $\Delta E$ resolution, vertex- and mass-constrained fits are applied to $J/\psi \rightarrow \ell^+\ell^-$ decays and a mass constrained fit is used for $\pi^0 \rightarrow \gamma\gamma$ decays. The B meson signal region is defined as $5.27\text{ GeV}/c^2 < M_{bc} < 5.29\text{ GeV}/c^2$ and $-0.1\text{ GeV} < \Delta E < 0.05\text{ GeV}$. The lower bound in $\Delta E$ is chosen to accommodate the negative $\Delta E$ tail of the signal due to shower leakage associated with the $\pi^0$, and to avoid background from $B^0 \rightarrow J/\psi K_S^0$ ($K_S^0 \rightarrow \pi^0\pi^0$) decays. To suppress the two-jet-like $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) 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 $B^0 \rightarrow J/\psi \pi^0$. The algorithm for flavor tagging is described in detail elsewhere [13]. We use two parameters, $q$ defined in Eq. (11) 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 $\omega$ between $B^0$ and $B^0$ decays, $\Delta w_l$, are determined from data [13]. The vertex position for the $J/\psi \pi^0$ decay is reconstructed using leptons from the $J/\psi$ decay. The vertex position of $f_{\text{tag}}$ 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 $\Delta E - M_{bc}$ fit region defined as $5.2\text{ GeV}/c^2 < M_{bc} < 5.3\text{ GeV}/c^2$ and $-0.2\text{ GeV} < \Delta E < 0.2\text{ GeV}$, of which 290 are in the signal box.

We perform an unbinned maximum likelihood fit to the $\Delta E - M_{bc}$ distribution in order to distinguish signal and backgrounds. The probability density function (PDF)
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 parameterized by a two-dimensional function that is a product of a Crystal Ball line shape [13] in $\Delta E$ and a Gaussian form in $M_{bc}$. This parameterization accounts for the fact that $\Delta E$ and $M_{bc}$ distributions are predominantly affected by the shower energy leakage in the ECL (in $\Delta E$) and the beam energy spread of the KEKB accelerator (in $M_{bc}$). 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) $B^0 \rightarrow J/\psi K^0_S$, (2) $B^0 \rightarrow J/\psi K_S^0 L$, (3) $B \rightarrow J/\psi X$ other than $B^0 \rightarrow J/\psi K^0$, (4) combinatorial background that consists of random combinations of particles in $B\overline{B}$ decays and continuum events. Using a large MC sample, the PDFs to describe (1), (2) and (3) are determined and then parameterized as two-dimensional smooth functions in $\Delta E-M_{bc}$. 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 $B \rightarrow J/\psi X$ contributions, excluding $J/\psi K^0_S$ and $J/\psi K^0_L$, come from two-body decays, with well-measured branching fractions ($B \rightarrow J/\psi K^0$). The combinatorial background shapes in $\Delta E$ and $M_{bc}$ are described by a first-order polynomial and an ARGUS function [13], respectively. The purity in the signal region is estimated to be $87.9 \pm 8.0%$. The fractions of $J/\psi K^0_S$, $J/\psi K^0_L$ 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 $\Delta E$ and $M_{bc}$ distributions after tagging and vertexing are shown in Fig. [1].

We determine $S_{J/\psi \pi^0}$ and $A_{J/\psi \pi^0}$ by performing an unbinned maximum-likelihood fit to the observed $\Delta t$ distribution:

$$L(S_{J/\psi \pi^0}, A_{J/\psi \pi^0}) = \prod_{i} \mathcal{P}(S_{J/\psi \pi^0}, A_{J/\psi \pi^0}; \Delta t_i),$$

(3)

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

$$\mathcal{P} = (1-f_{\text{ol}}) \left[ \int d(\Delta t') R(\Delta t_i - \Delta t') \right]$$

$$\times f_{\text{sig}} \mathcal{P}_{\text{sig}}(\Delta t')$$

$$+ f_{J/\psi KS} \mathcal{P}_{J/\psi KS}(\Delta t') + f_{J/\psi KL} \mathcal{P}_{J/\psi KL}(\Delta t')$$

$$+ f_{J/\psi X} \mathcal{P}_{J/\psi X}(\Delta t')$$

$$+ f_{\text{comb}} \mathcal{P}_{\text{comb}}(\Delta t_i)$$

$$+ f_{\text{ol}} \mathcal{P}_{\text{ol}}(\Delta t_i),$$

(4)

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

$$\mathcal{P}_{J/\psi X}(\Delta t) = \frac{e^{-\Delta t/t_{J/\psi X}}}{4t_{J/\psi X}} \left[ 1 - q\Delta \omega \right].$$

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

$$S_{J/\psi \pi^0} = -0.65 \pm 0.21(\text{stat}) \pm 0.05(\text{syst})$$

$$A_{J/\psi \pi^0} = +0.08 \pm 0.16(\text{stat}) \pm 0.05(\text{syst}),$$

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

The systematic errors are listed in Table [1]. The main contributions to the systematic error in $S_{J/\psi \pi^0}$ 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 selection based on the track helix error, helix parameter corrections, event selection based on $\Delta t$ and goodness of fit in the vertex reconstruction, and the small SVD misalignment. The systematic uncertainties due to the parameters $w_l$ and $\Delta w_l$ are estimated by varying the parameters by their one standard deviation ($\sigma$) 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 $S$ and $A$. The fit bias
side interference is caused by the interference between the two amplitudes of $B$ decays into charmed mesons, i.e. caused by $V_{cb}$ and $V_{ub}$. Therefore it is expressed by four parameters, $r_{\text{int}}$ (size of interference between $V_{cb}$ and $V_{ub}$ amplitudes), $\phi_1$, $\phi_3$ and $\delta$ (strong phase difference between $V_{cb}$ and $V_{ub}$ mediated amplitudes). Since this interference results in a potential direct $CP$ violation, $A_{J/\psi\pi^0}$ is much more affected than $S_{J/\psi\pi^0}$. We sum each of the contributions in quadrature to obtain the total systematic error.

The confidence regions of our measurement in the $S_{J/\psi\pi^0}$ and $A_{J/\psi\pi^0}$ 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 $S_{J/\psi\pi^0}$ measurement has a significance greater than 2.4 $\sigma$ for any $A_{J/\psi\pi^0}$ value.

In summary, we measure the $CP$ violation parameters in $B^0 \to J/\psi\pi^0$ decays using $535 \times 10^6 \bar{B}B$ pairs: $S_{J/\psi\pi^0} = -0.65 \pm 0.21(\text{stat}) \pm 0.05(\text{syst})$ and $A_{J/\psi\pi^0} = +0.08 \pm 0.16(\text{stat}) \pm 0.05(\text{syst})$. We measure mixing-induced $CP$ violation with 2.4 $\sigma$ 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 $b \to c \tau \bar{s}$ decays [17, 20], as expected in the Standard Model.

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**TABLE I: Systematic uncertainties**

| Parameter                        | $\Delta S_{J/\psi \pi^0}$ | $\Delta A_{J/\psi \pi^0}$ |
|----------------------------------|---------------------------|---------------------------|
| Vertexing                        | $\pm 0.050$               | $\pm 0.034$               |
| Wrong tag fraction               | $\pm 0.009$               | $\pm 0.009$               |
| Resolution function              | $\pm 0.008$               | $\pm 0.007$               |
| Fit bias                         | $\pm 0.013$               | $\pm 0.010$               |
| Physics parameters               | $\pm 0.004$               | $\pm 0.001$               |
| $B \to J/\psi X$ $CP$ asymmetry  | $\pm 0.004$               | $\pm 0.001$               |
| PDF Shape and fraction           | $\pm 0.009$               | $\pm 0.005$               |
| Background $\Delta t$ shape      | $\pm 0.006$               | $\pm 0.001$               |
| Tag side interference            | $\pm 0.001$               | $\pm 0.038$               |
| Total                            | $\pm 0.054$               | $\pm 0.054$               |

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**FIG. 2:** $\Delta t$ 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 ($A_{\text{CP}}$) distribution. The curve is the projection of the fit result.

**FIG. 3:** The confidence regions for $S_{J/\psi \pi^0}$ and $A_{J/\psi \pi^0}$. The contours correspond to 1-C.L. $= 3.17 \times 10^{-1}$ (1$\sigma$), $4.55 \times 10^{-2}$ (2$\sigma$), and $2.70 \times 10^{-3}$ (3$\sigma$). The point with error bars corresponds to the measured $S_{J/\psi \pi^0}$ and $A_{J/\psi \pi^0}$ values. The circle is a boundary derived from Eq.[2].
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