Improved Evidence for Direct CP Violation in $B^0 \to \pi^+ \pi^-$ Decays and Model-Independent Constraints on $\phi_2$


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We present a new measurement of the time-dependent CP-violating parameters in $B^0 \to \pi^+ \pi^-$ decays with $275 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy $e^+ e^-$ collider operating at the $Y(4S)$ resonance. We find $666 \pm 43$ $B^0 \to \pi^+ \pi^-$ events and measure the CP-violating parameters: $S_{\pi \pi} = -0.67 \pm 0.16\text{(stat)} \pm 0.06\text{(syst)}$ and $A_{\pi \pi} = +0.56 \pm 0.12\text{(stat)} \pm 0.06\text{(syst)}$. We find evidence for large direct CP violation with a significance greater than 4 standard deviations for any $S_{\pi \pi}$ value. Using isospin relations, we obtain $95.4\%$ confidence intervals for the Cabibbo-Kobayashi-Maskawa quark-mixing matrix angle $\phi_2$ of $0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$.

Kobayashi and Maskawa (KM) pointed out in 1973 that CP violation can be incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix in the standard model framework \cite{1}. The KM model predicts CP-violating asymmetries in the time-dependent rates of neutral $B$ meson decays to the CP eigenstate $\pi^+ \pi^-$ \cite{2}. In the decay chain of $Y(4S) \to B^0 \bar{B}^0 \to (\pi^+ \pi^-)(f_{\text{tag}})$, one of the neutral $B$ mesons decays into $\pi^+ \pi^-$ at time $t_{\pi \pi}$ and the other decays at time $t_{\text{tag}}$ to a final state $f_{\text{tag}}$ that distinguishes its flavor. The time-dependent decay rate is given by

$$
\mathcal{P}_{\pi \pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B^2} \left[ 1 + q\{S_{\pi \pi} \sin(\Delta m_d \Delta t) + A_{\pi \pi} \cos(\Delta m_d \Delta t)\} \right],
$$

where $\Delta t = t_{\pi \pi} - t_{\text{tag}}$, $\tau_B$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two neutral $B$ mass eigenstates, and $q = +1 (-1)$ for $f_{\text{tag}} = B^0 (\bar{B}^0)$. We measure $S_{\pi \pi}$ and $A_{\pi \pi}$, which are the mixing-induced and direct CP-violating parameters, respectively. In the case where only a $b \to u$ “tree” transition contributes to the decay $B^0 \to \pi^+ \pi^-$ \cite{3}, we would have $S_{\pi \pi} = \sin 2\phi_2$ and $A_{\pi \pi} = 0$. Because of possible contributions from $b \to d$ “penguin” transitions that have different weak and strong phases, $S_{\pi \pi}$ may deviate from $\sin 2\phi_2$, and direct CP violation, $A_{\pi \pi} \neq 0$, may occur. Our previous measurement based on a 140 fb$^{-1}$ data sample indicated large $S_{\pi \pi}$ and $A_{\pi \pi}$ values \cite{4}, while no significant CP asymmetry was observed by the BABAR Collaboration \cite{5}. It is therefore important to measure the CP-violating parameters with larger statistics.

The measurement in this Letter is based on a 253 fb$^{-1}$ data sample containing $275 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector at the KEKB $e^+ e^-$ asymmetric-energy (3.5 on 8 GeV) collider \cite{6} operating at the $Y(4S)$ resonance. The $Y(4S)$ is produced with a Lorentz boost factor of $y_B = 0.425$ along the $z$ axis, which is antiparallel to the positron beam direction. Since the two $B$ mesons are produced nearly at rest in the $Y(4S)$ center-of-mass system (CMS), the decay time difference $\Delta t$ is determined from the distance between the two $B$ meson decay positions along the $z$ direction ($\Delta z$): $\Delta t \equiv \Delta z/c\beta y$, where $c$ is the velocity of light.

The Belle detector \cite{7} is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like ar-
rangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect $K^0_S$ mesons and to identify muons. A sample containing $152 \times 10^6 B\bar{B}$ pairs (Set I) was collected with a 2.0 cm radius beam pipe and a 3-layer silicon vertex detector, while a sample with $123 \times 10^6 B\bar{B}$ pairs (Set II) was collected with a 1.5 cm radius beam pipe, a 4-layer silicon detector, and a small-cell inner drift chamber [8].

We employ the identical analysis procedure as the previous publication [4]. We reconstruct $B^0 \rightarrow \pi^+ \pi^-$ candidates using oppositely charged track pairs that are positively identified as pions by combining information from the ACC and the CDC $dE/dx$ measurements. The pion detection efficiency is 90%, and 11% of kaons are misidentified as pions. We select $B$ meson candidates using the energy difference $\Delta E = E_B - E_\text{beam}$ and the beam-energy constrained mass $M_{bc} = \sqrt{(E_\text{beam})^2 - (p_B^*)^2}$, where $E_\text{beam}$ is the CMS beam-energy, and $E_B$ and $p_B^*$ are the CMS energy and momentum of the $B$ candidate. We define the signal region as 5.271 GeV/c$^2 < M_{bc} < 5.287$ GeV/c$^2$ and $|\Delta E| < 0.064$ GeV, which corresponds to $\pm 3$ standard deviations ($\sigma$) from the central values.

We identify the flavor of the accompanying $B$ meson from inclusive properties of particles that are not associated with the reconstructed $B^0 \rightarrow \pi^+ \pi^-$ decay. We use $q$ 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 dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six $r$ intervals. The wrong tag fractions for the six $r$ intervals, $w_i$ ($i = 1,6$), and the differences between $B^0$ and $\bar{B}^0$ decays, $\Delta w_i$, are determined from data [9,10].

To suppress the continuum background ($e^+e^- \rightarrow q\bar{q}; q = u, d, s, c$), we apply the technique used in Ref. [4]. We form a likelihood function $L_{S(B)}$ for the signal (background) based on event topology variables and impose requirements on a likelihood ratio $LR = L_S/(L_S + L_B)$ to suppress continuum events. The LR requirement is determined by optimizing the expected sensitivity using MC signal events and events in the sideband region in 5.20 GeV/c$^2 < M_{bc} < 5.26$ GeV/c$^2$ or $+0.1$ GeV $< \Delta E < +0.5$ GeV. We accept events having LR > 0.86. In order to include additional events with LR < 0.86, we optimize LR separately for each of the $r$ bins, as the $r$ also suppresses continuum events. We then lower the LR thresholds of 0.50, 0.45, 0.45, 0.45, 0.45, and 0.20 for the six $r$ bins. There are thus 12 distinct bins of LR $r$ for selected events.

We extract 2820 signal candidates by applying the above requirements and the vertex reconstruction algorithm used in Ref. [10] to the data sample. Figure 1 shows the $\Delta E$ distributions for the events with (a) LR > 0.86 and (b) LR < 0.86 in the $M_{bc}$ signal region. The $B^0 \rightarrow \pi^+ \pi^-$ signal yield is determined from an unbinned two-dimensional maximum likelihood fit to the $\Delta E-M_{bc}$ distribution in the range of $M_{bc} > 5.20$ GeV/c$^2$ and $-0.3$ GeV $< \Delta E < +0.5$ GeV with signal events plus contributions from misidentified $B^0 \rightarrow K^+ \pi^-$ events, the continuum background, and three-body $B$ decays. We use a single Gaussian for the signal and $B^0 \rightarrow K^+ \pi^-$ events in $\Delta E$ and $M_{bc}$. The continuum background shapes in $\Delta E$ and $M_{bc}$ are described by a first-order polynomial and an ARGUS function [11], respectively. For the three-body $B$ decay background shape, we employ a smoothed two-dimensional histogram obtained from a large MC sample. The fit to the subset with LR > 0.86 yields 415 $\pm 27 \pi^+ \pi^-$ events and 154 $\pm 19 K^+ \pi^-$ events in the signal region, where the errors are statistical only. The $K^+ \pi^-$ contamination is consistent with the $K \rightarrow \pi$ misidentification probability, which is measured independently. Extrapolating from the size of the continuum background in this fit, we expect 315 $\pm 3$ continuum events in the signal region. We use MC-determined fractions as in [4] to calculate the numbers of decays for LR < 0.86, since the fit to the low LR events gives large statistical fluctuation because of the poor signal-to-noise ratio. We expect 251 $\pm 16 \pi^+ \pi^-$, 93 $\pm 12 K^+ \pi^-$, and 1592 $\pm 15$ continuum events in the signal region. The contribution from three-body $B$ decays is negligibly small in the signal region.

We determine $S_{\pi\pi}$ and $A_{\pi\pi}$ by applying an unbinned maximum likelihood fit to the distribution of proper-time difference $\Delta t$. The probability density function (PDF) for the signal events is given in Eq. (1) modified to incorporate the effect of incorrect flavor assignment $w_i$ and $\Delta w_i$. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}(\Delta t)$ in order to take into account the finite position resolution [10,12]. The PDF for $B^0 \rightarrow K^+ \pi^-$ is $P_{K^+\pi^-}^{\text{eff}}(\Delta t, w_i, \Delta w_i) = (1/4\sqrt{\pi})e^{-|\Delta t|/\tau_{CP}}[1-qw_i + q(1-2w_i)A_{\text{eff}}^{\pi+, \pi^-}\cos(\Delta m_\pi \Delta t)]$. We use $A_{\text{eff}}^{\pi+, \pi^-} = (A_{K^+ \pi^-} + A_{\pi^-})/(1 + A_{K^+ \pi^-}A_{\pi^-})$, where $A_{K^+ \pi^-} = -0.109 \pm 0.019$ is the measured direct $CP$-violating parameter in $B^0 \rightarrow K^+ \pi^-$ decays [13], and $A_{\pi^-}$ is the difference in the product of the pion efficiency and kaon misidentification probability between $\pi^+(K^-)$ and $\pi^-(K^+)$ divided by

![Figure 1. $\Delta E$ distributions in the $M_{bc}$ signal region for $B^0 \rightarrow \pi^+ \pi^-$ candidates with (a) LR > 0.86 and (b) LR < 0.86.](101801-3)
their sum [14]. The inclusion of $A_{\epsilon}$ changes the $A_{K\pi}$ value by 11%. We make use of the same resolution function $R_{q\pi}(\Delta t)$ for the $B^0 \to K^+\pi^-$ events. The PDF for the continuum background events is $P_{q\pi}(\Delta t) = 1/2(1 + qA_{q\pi}|(f_1 + 2f_2)e^{-|\Delta t/\tau_{q\pi}|}(1 - \delta(\Delta t)))$, where $f_1$ is the fraction of the background with effective lifetime $\tau_{q\pi}$, and $\delta$ is the Dirac delta function. We use $A_{q\pi} = 0$ as a default. A fit to the sideband events yields $A_{q\pi} = +0.01 \pm 0.01 (-0.00 \pm 0.01)$ for the data in Set I (II). This uncertainty in the background asymmetry is included in the systematic error for the $S_{\pi\pi}$ and $A_{\pi\pi}$ measurement. The background PDF $P_{q\pi}$ is convolved with a background resolution function $R_{q\pi}$. All parameters in $P_{q\pi}$ and $R_{q\pi}$ are determined from sideband events.

We define a likelihood value for each (ith) event as a function of $S_{\pi\pi}$ and $A_{\pi\pi}$:

$$L_i = (1 - f_{\text{stat}}) \int_{-\infty}^{+\infty} \left[ (f_{\pi\pi} P_{\pi\pi}(\Delta t', w_i, \Delta w_i; S_{\pi\pi}, A_{\pi\pi}) 
+ f_{\text{sig\pi}} P_{\text{sig\pi}}(\Delta t', w_i, \Delta w_i) R_{q\pi}(\Delta t_0 - \Delta t') 
+ f_{q\pi} P_{q\pi}(\Delta t') R_{q\pi}(\Delta t_0 - \Delta t') \right] d\Delta t' + f_{\text{sys\pi\pi}} P_{\text{sys\pi\pi}}(\Delta t).$$

(2)

Here, the probability functions $f_{\pi\pi}(k = \pi\pi, K\pi, \text{or q\pi})$ are determined on an event-by-event basis as functions of $\Delta E$ and $M_{bc}$ for each LR-$r$ bin ($m = 1, 12$). A small number of signal and background events that have large values of $\Delta t$ is accommodated by the outlier PDF, $P_{\text{ol}}$, with a fractional area $f_{\text{ol}}$. In the fit, $S_{\pi\pi}$ and $A_{\pi\pi}$ are the only free parameters and are determined by maximizing the likelihood function $L = \Pi_i L_i$, where the product is over all the $B^0 \to \pi^+\pi^-$ candidates.

The unbinned maximum likelihood fit to the 2820 $B^0 \to \pi^+\pi^-$ candidates containing $666 \pm 43\pi^+\pi^-$ signal events (1486 $B^0$ tags and 1334 $B^{-}$ tags) yields $S_{\pi\pi} = -0.67 \pm 0.16\text{(stat)} \pm 0.06\text{(sys)}$ and $A_{\pi\pi} = +0.56 \pm 0.12\text{(stat)} \pm 0.06\text{(sys)}$. The correlation between $S_{\pi\pi}$ and $A_{\pi\pi}$ is $+0.09$. In this Letter, we quote the usual fit errors from the likelihood functions, called the MINOS errors, as statistical uncertainties [15]. Figures 2(a) and 2(b) show the $\Delta t$ distributions for the 470 $B^0$- and 414 $B^-\tagged$ events in the subset of data with LR $> 0.86$. We define the raw asymmetry $A_{CP}$ in each $\Delta t$ bin by $A_{CP} = (N_+ - N_-)/(N_+ + N_-)$, where $N_+(-)$ is the number of observed candidates with $q = +1(-1)$. Figures 2(c) and 2(d) show the raw asymmetries for two regions of the flavor-tagging parameter $r$.

The main contributions to the systematic error are due to the uncertainties in the vertex reconstruction ($\pm 0.04$ for $S_{\pi\pi}$ and $\pm 0.03^{+0.00}_{-0.01}$ for $A_{\pi\pi}$) and event fraction ($\pm 0.02$ for $S_{\pi\pi}$ and $\pm 0.04$ for $A_{\pi\pi}$); the latter includes the uncertainties in $A_{q\pi}$ and final state radiation. We include the effect of tag side interference [16] on $S_{\pi\pi}(\pm 0.01)$ and $A_{\pi\pi}(\pm 0.02)$. Other sources of systematic error are the uncertainties in

![FIG. 2. $\Delta t$ distributions for the 884 $B^0 \to \pi^+\pi^-$ candidates with LR $> 0.86$ in the signal region: (a) 470 candidates with $q = +1$, (b) 414 candidates with $q = -1$. Raw asymmetry, $A_{CP}$, in each $\Delta t$ bin with (c) $0 < r < 0.5$ and (d) $0.5 < r < 1.0$. The solid lines show the results of the unbinned maximum likelihood fit to the $\Delta t$ distribution of the 2820 $B^0 \to \pi^+\pi^-$ candidates.](image-url)
Ref. [4] that takes into account both statistical and systematic errors. The hypothesis of CP symmetry conservation, \( S_{\pi^+\pi^-} = A_{\pi^+\pi^-} = 0 \), is ruled out at a confidence level (C.L.) of 1 - C.L. = 5.6 \times 10^{-8}, equivalent to a 5.4\sigma significance for one-dimensional Gaussian errors. The case of no direct CP violation, \( A_{\pi^+\pi^-} = 0 \), is also ruled out with a significance greater than 4.0\sigma for any \( S_{\pi^+\pi^-} \) value.

Figure 3 shows the \( \Delta E \) distributions for \( B^0 \rightarrow \pi^+\pi^- \) candidates with \( LR > 0.86 \) and \( 0.5 < r \leq 1.0 \) for (a) \( q = +1 \) and (b) \( q = -1 \) in the \( M_{bc} \) signal region. An unbinned two-dimensional maximum likelihood fit to the \( q = +1 \) (\( q = -1 \)) subset yields 107 ± 13(69 ± 11)\( \pi^+\pi^- \), 42 ± 9(43 ± 9)\( K^+\pi^- \), and 38 ± 1(38 ± 1) continuum events in the signal box. The \( K^+\pi^- \) and continuum background yields are consistent between the two subsets as expected, while the \( \pi^+\pi^- \) yields are appreciably different; direct CP violation in \( B^0 \rightarrow \pi^+\pi^- \) decays is visible in the contrast of the two subsets. These results also support the expectation from SU(3) symmetry that \( A_{\pi^+\pi^-} \approx -3A_{K^+\pi^-} \) [18].

To constrain \( \phi_2 \), we employ isospin relations [20] and the approach of Ref. [21] for the statistical treatment. We use the measured branching ratios of \( B^0 \rightarrow \pi^+\pi^- \), \( \pi^0\pi^0 \), and \( B^+ \rightarrow \pi^+\pi^0 \), and the direct CP asymmetry for \( B^0 \rightarrow \pi^0\pi^0 \) [13] as well as our measured values of \( S_{\pi^+\pi^-} \) and \( A_{\pi^+\pi^-} \) taking into account their correlation. Figure 4 shows the obtained C.L. as a function of \( \phi_2 \). We find an allowed range for \( \phi_2 \) at 95.4% C.L. of \( 0^\circ < \phi_2 < 19^\circ \) and \( 71^\circ < \phi_2 < 180^\circ \).

In summary, we have performed a new measurement of the CP-violating parameters in \( B^0 \rightarrow \pi^+\pi^- \) decays using a 253 fb\(^{-1} \) data sample. We obtain \( S_{\pi^+\pi^-} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst}) \) and \( A_{\pi^+\pi^-} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst}) \). We rule out the CP-conserving case, \( S_{\pi^+\pi^-} = A_{\pi^+\pi^-} = 0 \), at the 5.4\sigma level. We find compelling evidence for direct CP asymmetry with 4.0\sigma significance. The results confirm the previous Belle measurement of the CP-violating parameters as well as the earlier evidence for direct CP violation in \( B^0 \rightarrow \pi^+\pi^- \) decays [4].

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[3] Throughout this Letter, the inclusion of the charge conjugate decay mode is implied unless otherwise stated.
[4] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 93, 021601 (2004); see also K. Abe et al. (Belle Collaboration), Phys. Rev. D 68, 012001 (2003) for results based on a 78 fb\(^{-1} \) data sample. The results reported here supersede those of these two publications.


[15] The rms values of the $S_{\pi\pi}$ and $A_{\pi\pi}$ distributions of MC pseudoexperiments were quoted as the statistical uncertainties in the previous publications [4]. With improved statistics, we find that MINOS errors are approximately symmetric and agree well with the rms values (0.15 for $S_{\pi\pi}$ and 0.11 for $A_{\pi\pi}$).


