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## Observation of $CP$ Violation in $B^0 \rightarrow K^+ \pi^-$ and $B^0 \rightarrow \pi^+ \pi^-$

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We report observations of  $CP$  violation in the decays  $B^0 \rightarrow K^+ \pi^-$  and  $B^0 \rightarrow \pi^+ \pi^-$  in a sample of  $383 \times 10^6 Y(4S) \rightarrow B\bar{B}$  events. We find  $4372 \pm 82 B^0 \rightarrow K^+ \pi^-$  decays and measure the direct  $CP$ -violating charge asymmetry  $\mathcal{A}_{K\pi} = -0.107 \pm 0.018(\text{stat})_{-0.004}^{+0.007}(\text{syst})$ , which excludes the  $CP$ -conserving hypothesis with a significance of 5.5 standard deviations. In the same sample, we find

$1139 \pm 49 B^0 \rightarrow \pi^+ \pi^-$  decays and measure the  $CP$ -violating asymmetries  $S_{\pi\pi} = -0.60 \pm 0.11(\text{stat}) \pm 0.03(\text{syst})$  and  $C_{\pi\pi} = -0.21 \pm 0.09(\text{stat}) \pm 0.02(\text{syst})$ .  $CP$  conservation in  $B^0 \rightarrow \pi^+ \pi^-$  ( $S_{\pi\pi} = C_{\pi\pi} = 0$ ) is excluded at a confidence level  $1 - \text{C.L.} = 8 \times 10^{-8}$ , corresponding to 5.4 standard deviations.

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The prediction of large  $CP$ -violating effects in the  $B$ -meson system [1] has been confirmed in recent years by the *BABAR* and Belle Collaborations, both in the interference of  $B$  decays to charmonium final states with and without  $B^0$ - $\bar{B}^0$  mixing [2] and directly in the interference between the decay amplitudes in  $B^0 \rightarrow K^+ \pi^-$  [3–5]. All measurements of  $CP$  violation to date are in agreement with indirect predictions from global standard-model (SM) fits [6] based on measurements of the magnitudes of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [7] and place important constraints [8] on the flavor structure of SM extensions.

The proper-time evolution of the asymmetry between  $B^0$  and  $\bar{B}^0$  decays to  $\pi^+ \pi^-$  is characterized by sine and cosine terms with amplitudes  $S_{\pi\pi}$ , which arises from interference between decays with or without  $B^0$ - $\bar{B}^0$  mixing, and  $C_{\pi\pi}$ , which is due to interference between the  $b \rightarrow u$  “tree” and the higher-order  $b \rightarrow d$  “penguin” decay amplitudes. Similarly, the direct- $CP$ -violating asymmetry  $\mathcal{A}_{K\pi}$  between the  $\bar{B}^0 \rightarrow K^- \pi^+$  and  $B^0 \rightarrow K^+ \pi^-$  decay rates arises from interference between  $b \rightarrow u$  tree and  $b \rightarrow s$  penguin amplitudes. Negligible contributions to these asymmetry parameters would also enter from  $CP$  violation purely in  $B^0$ - $\bar{B}^0$  mixing, which has been determined to be very small [9]. The quantity  $\sin 2\alpha_{\text{eff}} = S_{\pi\pi}/\sqrt{1 - C_{\pi\pi}^2}$  can be related to  $\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$  through a model-independent analysis that uses the isospin-related decays  $B^\pm \rightarrow \pi^\pm \pi^0$  and  $B^0 \rightarrow \pi^0 \pi^0$  [10]. Contributions from new particles could affect the asymmetries in these modes primarily through additional penguin  $B$ -decay amplitudes.

Previous evidence of direct  $CP$  violation in  $B^0 \rightarrow K^+ \pi^-$  has been reported by *BABAR* [3] and Belle [4]; additional measurements of  $\mathcal{A}_{K\pi}$  have also been reported by the CDF [11] and CLEO [12] Collaborations. The Belle Collaboration recently reported [13] an observation of both time-dependent and direct  $CP$  violation in  $B^0 \rightarrow \pi^+ \pi^-$  decays using a sample of  $535 \times 10^6 B\bar{B}$  pairs, while our previous measurement [14] on a sample of  $227 \times 10^6 B\bar{B}$  pairs was statistically consistent with no  $CP$  violation. In this Letter, we present measurements of  $\mathcal{A}_{K\pi}$ ,  $S_{\pi\pi}$ , and  $C_{\pi\pi}$  in a sample of  $383 \times 10^6 B\bar{B}$  pairs using an improved analysis technique with significantly increased sensitivity compared to our previous measurements.

In the *BABAR* detector [15], charged particles are detected and their momenta measured by a combination of a five-layer silicon vertex tracker and a 40-layer drift chamber (DCH) that covers 92% of the solid angle in the  $Y(4S)$  center-of-mass (c.m.) frame, both operating in a 1.5-T

solenoidal magnetic field. Discrimination among charged pions, kaons, and protons is provided by a combination of an internally reflecting ring-imaging Cherenkov detector (DIRC), which covers 84% of the c.m. solid angle in the central region of the *BABAR* detector and has a 91% reconstruction efficiency for pions and kaons with momenta above 1.5 GeV/ $c$ , and the ionization ( $dE/dx$ ) measurements in the DCH. Electrons are explicitly removed based on a comparison of the track momentum and the associated energy deposition in a CsI(Tl) electromagnetic calorimeter and with additional information from  $dE/dx$  and DIRC Cherenkov angle ( $\theta_C$ ) measurements.

The analysis method retains many features of our previous  $B^0 \rightarrow K^+ \pi^-$  and  $B^0 \rightarrow \pi^+ \pi^-$   $CP$ -violation measurements [3,14]. We reconstruct candidate decays  $B_{\text{rec}} \rightarrow h^+ h^-$  ( $h^\pm = \pi^\pm, K^\pm$ ) from pairs of oppositely charged tracks in the polar-angle range  $0.35 < \theta_{\text{lab}} < 2.40$  that are consistent with originating from a common decay point. The remaining particles are examined to infer (flavor tag) whether the other  $B$  meson in the event ( $B_{\text{tag}}$ ) decayed as a  $B^0$  or  $\bar{B}^0$ . We perform an unbinned extended maximum-likelihood (ML) fit simultaneously for the  $CP$ -violating asymmetries and the signal and background yields and parameters. The fit uses particle-identification, kinematic, event-shape,  $B_{\text{tag}}$  flavor, and  $\Delta t$  information, where  $\Delta t$  is the difference between the  $B_{\text{rec}}$  and  $B_{\text{tag}}$  decay times. The yields for the  $K\pi$  final state are parametrized as  $n_{K^\pm \pi^\mp} = n_{K\pi}(1 \mp \mathcal{A}_{K\pi}^{\text{raw}})/2$ , and the decay-rate distribution  $f_+(f_-)$  for  $B_{\text{rec}} \rightarrow \pi^+ \pi^-$  and  $B_{\text{tag}} = B^0(\bar{B}^0)$  is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} [1 \pm S_{\pi\pi} \sin(\Delta m_d \Delta t) \mp C_{\pi\pi} \cos(\Delta m_d \Delta t)], \quad (1)$$

where  $\tau$  is the neutral  $B$  lifetime and  $\Delta m_d$  is the  $B^0$ - $\bar{B}^0$  mixing frequency, both fixed to their world averages [9].

The most significant improvement in sensitivity compared to our previous analysis comes from a 35% increase in the  $B_{\text{rec}}$  reconstruction efficiency that results from using  $dE/dx$  as a discriminating variable in the ML fit for the first time. The  $dE/dx$  measurements are used both to complement the discriminating power of  $\theta_C$  for charged particles within the DIRC acceptance and as a standalone means of particle identification for tracks that have no DIRC information and were not included in our previous measurements. The  $dE/dx$  calibration takes into account variations in the mean value and resolution of  $dE/dx$  with respect to changes in the DCH running conditions over time and each track’s charge, polar and azimuthal angles,



and the number of ionization samples. The calibration is performed with large ( $> 10^6$ ) high-purity samples of protons from  $\Lambda \rightarrow p\pi^-$ , pions and kaons from  $D^{*+} \rightarrow D^0\pi^+(D^0 \rightarrow K^-\pi^+)$ , and additional samples of pions from  $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$  decays and from  $K_S^0 \rightarrow \pi^+\pi^-$  decays that occur in the vicinity of the interaction region.

We require at least one of the tracks in the  $B_{\text{rec}}$  decay candidate to have  $\theta_C$  measured with at least six signal photons; for such tracks, the value of  $\theta_C$  must agree within 4 standard deviations ( $\sigma$ ) with either the pion or the kaon hypothesis. Thus, protons with six or more signal photons are removed, while proton-pion and proton-kaon combinations are possible for background candidates where one of the tracks has no usable  $\theta_C$  measurement. We construct  $\theta_C$  probability-density functions (PDFs) for the pion and kaon hypotheses and  $dE/dx$  PDFs for the pion, kaon, and proton hypotheses, separately for each charge. The  $K - \pi$  separations provided by  $\theta_C$  and  $dE/dx$  are complementary: for  $\theta_C$ , it varies from  $2.5\sigma$  at 4.5 GeV/c to  $13\sigma$  at 1.5 GeV/c [3], while for  $dE/dx$  it varies from less than  $1.0\sigma$  at 1.5 GeV/c to  $1.9\sigma$  at 4.5 GeV/c (Fig. 1).

Each  $B$  candidate is characterized by the energy difference  $\Delta E = (q_Y \cdot q_B/\sqrt{s}) - \sqrt{s}/2$ , which also provides additional discriminating power between the four possible final states ( $\pi^+\pi^-$ ,  $K^+\pi^-$ ,  $K^-\pi^+$ , and  $K^+K^-$ ) and the beam-energy-substituted mass  $m_{\text{ES}} = [(s/2 + \vec{p}_Y \cdot \vec{p}_B)^2/E_Y^2 - \vec{p}_B^2]^{1/2}$  [15]. Here  $q_Y$  and  $q_B$  are the four-momenta of the  $Y(4S)$  and the  $B$  candidate, respectively,  $s \equiv (q_Y)^2$  is the square of the c.m. energy,  $\vec{p}_Y$  and  $\vec{p}_B$  are the laboratory three-momenta of the  $Y(4S)$  and the  $B$ , respectively, and  $E_Y \equiv q_Y^0$  is the laboratory energy of the  $Y(4S)$ . For signal events, the  $m_{\text{ES}}$  and  $\Delta E$  PDFs are Gaussian functions with widths of 2.6 MeV/ $c^2$  and 29 MeV, respectively. For the background,  $m_{\text{ES}}$  is parametrized with an empirical threshold function [16], and  $\Delta E$  is parametrized with a second-order polynomial. We require  $5.2 < m_{\text{ES}} < 5.3$  GeV/ $c^2$  and  $|\Delta E| < 0.150$  GeV.

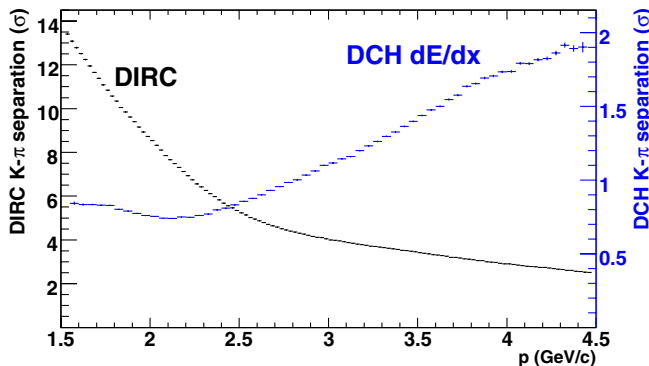


FIG. 1 (color online). The average difference between the expected values of DIRC  $\theta_C$  and DCH  $dE/dx$  for pions and kaons at  $0.35 < \theta_{\text{lab}} < 2.40$ , divided by the uncertainty, as a function of laboratory momentum in  $B^0 \rightarrow h^+h^-$  decays in BABAR.

The background arises predominantly from random combinations of tracks in  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) and  $\tau^+\tau^-$  jetlike continuum events. We define the angle  $\theta_S$  in the c.m. frame between the sphericity axes [17] of the  $B$  candidate and of all remaining charged and neutral particles in the event. For background events,  $|\cos\theta_S|$  peaks sharply near 1, while for  $B$  decays the distribution is nearly flat. We require  $|\cos\theta_S| < 0.9$ , which removes approximately 64% of  $u\bar{u}$ ,  $d\bar{d}$ , and  $s\bar{s}$ , 52% of  $c\bar{c}$ , and 84% of  $\tau^+\tau^-$  background. Contamination from  $e^+e^- \rightarrow \tau^+\tau^-$  production is reduced to 2% of the total background by requiring the ratio of the second to zeroth Fox-Wolfram moments [18] to be less than 0.7, which has a negligible effect on the signal efficiency. The overall gain in signal reconstruction efficiency is 52% compared to our previous analysis. Additional continuum-background suppression in the fit is accomplished by the Fisher discriminant  $\mathcal{F}$  described in Ref. [19]. We have studied the backgrounds from higher-multiplicity  $B$  decays and find them to be negligible, particularly due to their good separation from signal in  $\Delta E$ .

The  $B_{\text{tag}}$  flavor is determined with a neural-net algorithm [20] that assigns the event to one of seven mutually exclusive tagging categories. The figure of merit for the tagging quality, measured in a data sample  $B_{\text{flav}}$  of fully reconstructed  $B^0$  decays to  $D^{(*)-}(\pi^+, \rho^+, a_1^+)$  or  $J/\psi K^{*0}$ , is the effective efficiency  $Q = \sum_k \epsilon_k (1 - 2w_k)^2 = 0.305 \pm 0.003$ , where  $\epsilon_k$  and  $w_k$  are the efficiencies and mistag probabilities for events in tagging category  $k$ . Separate values of  $\epsilon_k$  and  $w_k$  for each background category are determined in the ML fit.

The time difference  $\Delta t \equiv \Delta z/\beta\gamma c$ , where  $\beta\gamma \approx 0.56$  is the known boost of the  $Y(4S)$ , is obtained by measuring the distance  $\Delta z$  along the beam ( $z$ ) axis between the  $B_{\text{rec}}$  and  $B_{\text{tag}}$  decay vertices. We require  $|\Delta t| < 20$  ps and  $\sigma_{\Delta t} < 2.5$  ps, where  $\sigma_{\Delta t}$  is the  $\Delta t$  uncertainty estimated separately for each event. The resolution function for signal candidates is a sum of three Gaussians [20] with parameters determined from a fit to the full  $B_{\text{flav}}$  sample. The background  $\Delta t$  distribution, common to all tagging categories, is modeled as a sum of three Gaussian functions with parameters determined in the final fit.

The likelihood for candidate  $j$  tagged in category  $k$  is obtained by summing the product of event yield  $n_i$ , tagging efficiency  $\epsilon_{i,k}$ , and probability  $\mathcal{P}_{i,k}$  over all possible signal and background hypotheses  $i$ . We treat separately the cases where both or only one track has a  $\theta_C$  measurement. The extended likelihood function for tagging category  $k$  is

$$\mathcal{L}_k = \exp\left(-\sum_i n_i \epsilon_{i,k}\right) \prod_j \left[ \sum_i n_i \epsilon_{i,k} \mathcal{P}_{i,k}(\vec{x}_j; \vec{\alpha}_i) \right]. \quad (2)$$

The probabilities  $\mathcal{P}_{i,k}$  are evaluated as a product of PDFs for each of the independent variables  $\vec{x}_j = \{m_{\text{ES}}, \Delta E, \mathcal{F}, dE/dx, \theta_C, \Delta t\}$ , with parameters  $\vec{\alpha}_i$ . We use separate  $\theta_C$  and  $dE/dx$  PDFs for positively and negatively

charged tracks. The  $\Delta t$  PDF for signal  $\pi^+\pi^-$  decays is given by Eq. (1) modified to include the mistag probabilities for each tagging category and convolved with the signal resolution function. The  $\Delta t$  PDFs for signal  $K\pi$  and background  $K\pi$ ,  $\pi p$ , and  $Kp$  combinations take into account the correlation between the charge of the kaon or proton and the  $B_{\text{tag}}$  flavor; for signal  $K\pi$ ,  $B^0$ - $\bar{B}^0$  mixing is also taken into account. The total likelihood  $\mathcal{L}$  is the product of likelihoods for each tagging category and has 117 free parameters.

Fitting the final sample of 309 540 events, we find  $n_{\pi\pi} = 1139 \pm 49$ ,  $n_{K\pi} = 4372 \pm 82$ ,  $n_{KK} = 10 \pm 17$ , where all errors are statistical only, and measure the following asymmetries:

$$\begin{aligned} \mathcal{A}_{K\pi} &= -0.107 \pm 0.018(\text{stat})_{-0.004}^{+0.007}(\text{syst}), \\ S_{\pi\pi} &= -0.60 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}), \\ C_{\pi\pi} &= -0.21 \pm 0.09(\text{stat}) \pm 0.02(\text{syst}). \end{aligned} \quad (3)$$

Here  $\mathcal{A}_{K\pi}$  is the fitted value of the  $K^\pm\pi^\pm$  event-yield asymmetry  $\mathcal{A}_{K\pi}^{\text{raw}}$  shifted by  $+0.005_{-0.003}^{+0.006}$  to account for a bias that arises from the difference between the cross sections of  $K^+$  and  $K^-$  hadronic interactions within the *BABAR* detector. We determine this bias from a detailed Monte Carlo simulation based on GEANT4 [21] version 7.1; it is independently verified with a calculation based on the known material composition of the *BABAR* detector [15]

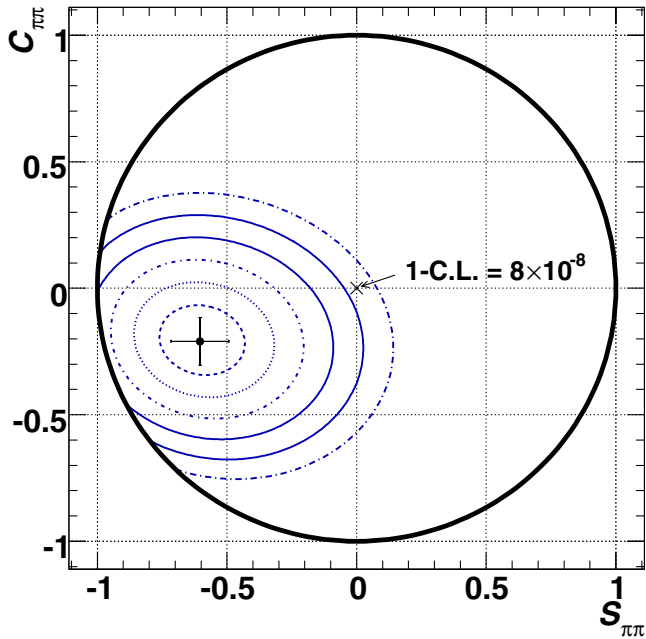


FIG. 2 (color online).  $S_{\pi\pi}$  and  $C_{\pi\pi}$ : the central values, errors, and confidence-level (C.L.) contours for  $1 - \text{C.L.} = 0.317$  ( $1\sigma$ ),  $4.55 \times 10^{-2}$  ( $2\sigma$ ),  $2.70 \times 10^{-3}$  ( $3\sigma$ ),  $6.33 \times 10^{-5}$  ( $4\sigma$ ),  $5.73 \times 10^{-7}$  ( $5\sigma$ ), and  $1.97 \times 10^{-9}$  ( $6\sigma$ ), calculated from the square root of the change in the value of  $-2\ln\mathcal{L}$  compared with its value at the minimum. The systematic errors are included.

and the cross sections and material properties tabulated in Ref. [9]. The corrected  $K^\pm\pi^\pm$  event-yield asymmetry in the background, where no observable  $CP$  violation is expected, is consistent with zero:  $-0.006 \pm 0.004(\text{stat})_{-0.003}^{+0.006}(\text{syst})$ .

A contour plot of the  $(S_{\pi\pi}, C_{\pi\pi})$  confidence levels is shown in Fig. 2. The correlation between  $S_{\pi\pi}$  and  $C_{\pi\pi}$  is  $-0.07$ . Performing a fit that excludes  $\Delta t$  and using an event-weighting technique [22], in Fig. 3 we show the distributions of  $\Delta t$  for signal  $\pi^+\pi^-$  events with  $B_{\text{tag}}$  tagged as  $B^0$  or  $\bar{B}^0$ , and the asymmetry as a function of  $\Delta t$ , overlaid with the PDF curves that represent the result of the full fit.

To validate our results, we perform a number of consistency checks and systematic-error studies similar to those reported in Refs. [3,14]. For  $\mathcal{A}_{K\pi}$ , the dominant source of systematic uncertainty is the bias due to kaon hadronic interactions. We find that the systematic errors due to potentially imperfect understanding of the DIRC and DCH particle-identification performance are small for  $\mathcal{A}_{K\pi}$  (0.002),  $S_{\pi\pi}$  (0.007), and  $C_{\pi\pi}$  (0.006). The dominant sources of systematic uncertainty on  $S_{\pi\pi}$  are the signal  $\Delta t$  model (0.020) and flavor-tagging parameters (0.015), while for  $C_{\pi\pi}$  the dominant uncertainties arise from tagging

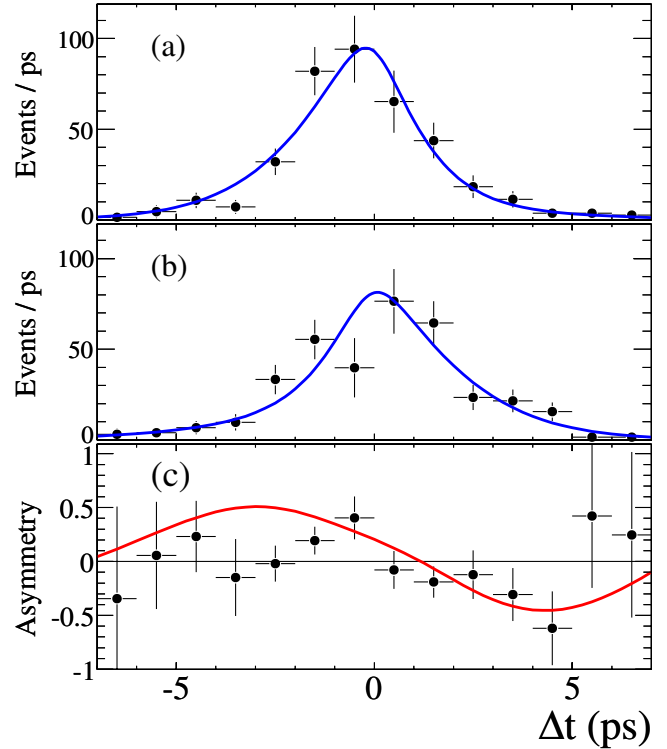


FIG. 3 (color online). The background-subtracted distributions of the decay-time difference  $\Delta t$  in signal  $B \rightarrow \pi^+\pi^-$  events. The points with errors show the events where  $B_{\text{tag}}$  is identified as (a)  $B^0$  or (b)  $\bar{B}^0$ . The asymmetry, defined as  $(n_{B^0} - n_{\bar{B}^0}) / (n_{B^0} + n_{\bar{B}^0})$ , for signal events in each  $\Delta t$  bin, is shown in (c). The solid curves are the projection of the fit.

(0.014) and the potential effect [23] of doubly CKM-suppressed decays of the  $B_{\text{tag}}$  meson (0.016). As a final cross-check, we perform a fit allowing the mixing frequency and lifetime to vary simultaneously with  $S_{\pi\pi}$  and  $C_{\pi\pi}$ . We find  $\Delta m_d = 0.506 \pm 0.017 \text{ ps}^{-1}$  and  $\tau_{B^0} = 1.523 \pm 0.026 \text{ ps}$ , where the errors are statistical only, consistent with the world-average values, and the resulting shifts in the  $CP$  parameters are negligible. The total systematic uncertainties are calculated by summing all individual contributions in quadrature.

In summary, we observe direct  $CP$  violation in the decay  $B^0 \rightarrow K^+ \pi^-$  with a statistical significance of  $5.5\sigma$  and  $CP$  violation in the time distribution of  $B^0 \rightarrow \pi^+ \pi^-$  decays with a significance of  $5.4\sigma$ . We also determine that the mixing-induced  $CP$ -violating asymmetry  $S_{\pi\pi}$  is nonzero with a significance of  $5.1\sigma$  or greater for any value of  $C_{\pi\pi}$ . All results are consistent with, and supersede, our previously published measurements [3,14].

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