

**Tests of  $CPT$  symmetry in  $B^0\text{--}\bar{B}^0$  mixing and in  $B^0 \rightarrow c\bar{c}K^0$  decays**

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(Received 16 May 2016; published 18 July 2016)

Using the eight time dependences  $e^{-\Gamma t}(1 + C_i \cos \Delta m t + S_i \sin \Delta m t)$  for the decays  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow f_j f_k$ , with the decay into a flavor-specific state  $f_j = \ell^\pm X$  before or after the decay into a  $CP$  eigenstate  $f_k = c\bar{c}K_{S,L}$ , as measured by the *BABAR* experiment, we determine the three  $CPT$ -sensitive parameters  $\text{Re}(\mathbf{z})$  and  $\text{Im}(\mathbf{z})$  in  $B^0\text{-}\bar{B}^0$  mixing and  $|\bar{A}/A|$  in  $B^0 \rightarrow c\bar{c}K^0$  decays. We find  $\text{Im}(\mathbf{z}) = 0.010 \pm 0.030 \pm 0.013$ ,  $\text{Re}(\mathbf{z}) = -0.065 \pm 0.028 \pm 0.014$ , and  $|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017$ , in agreement with  $CPT$  symmetry.

DOI: 10.1103/PhysRevD.94.011101

## I. INTRODUCTION

The discovery of  $CP$  violation in 1964 [1] motivated searches for  $T$  and  $CPT$  violation. Since  $CPT = CP \times T$ , violation of  $CP$  means that  $T$  or  $CPT$  or both are also violated. For the  $K^0$  system, the two contributions were first determined [2] in 1970, by using the Bell-Steinberger unitarity relation [3] for  $CP$  violation in  $K^0\text{-}\bar{K}^0$  mixing:  $T$  was violated with about  $5\sigma$  significance and no  $CPT$  violation was observed. Large  $CP$  violation in the  $B^0$  system was discovered in 2001 [4,5] in the interplay of  $B^0\text{-}\bar{B}^0$  mixing and  $B^0 \rightarrow c\bar{c}K^0$  decays, but an explicit demonstration of  $T$  violation was given only recently [6]. In the present analysis, we test  $CPT$  symmetry quantitatively in  $B^0\text{-}\bar{B}^0$  mixing and in  $B^0 \rightarrow c\bar{c}K^0$  decays.

Transitions in the  $B^0\text{-}\bar{B}^0$  system are well described by the quantum-mechanical evolution of a two-state wave function

$$\Psi = \psi_1|B^0\rangle + \psi_2|\bar{B}^0\rangle, \quad (1)$$

using the Schrödinger equation

$$\dot{\Psi} = -i\mathcal{H}\Psi, \quad (2)$$

where the Hamiltonian  $\mathcal{H}$  is given by two constant Hermitian matrices,  $\mathcal{H}_{ij} = m_{ij} + i\Gamma_{ij}/2$ . In this evolution,  $CP$  violation is described by three parameters,  $|q/p|$ ,  $\text{Re}(\mathbf{z})$ , and  $\text{Im}(\mathbf{z})$ , defined by

$$|q/p| = 1 - \frac{2\text{Im}(m_{12}^*\Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2}, \quad (3)$$

$$\mathbf{z} = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta\Gamma/2},$$

where  $\Delta m = m(B_H) - m(B_L) \approx 2|m_{12}|$  and  $\Delta\Gamma = \Gamma(B_H) - \Gamma(B_L) \approx +2|\Gamma_{12}|$  or  $-2|\Gamma_{12}|$  are the mass and the width differences of the two mass eigenstates ( $H$  = heavy,  $L$  = light) of the Hamiltonian,

$$B_H = (p\sqrt{1+\mathbf{z}}B^0 - q\sqrt{1-\mathbf{z}}\bar{B}^0)/\sqrt{2},$$

$$B_L = (p\sqrt{1-\mathbf{z}}B^0 + q\sqrt{1+\mathbf{z}}\bar{B}^0)/\sqrt{2}. \quad (4)$$

Note that we use the convention with  $+q$  for the light and  $-q$  for the heavy eigenstate. If  $|q/p| \neq 1$ , the evolution violates the discrete symmetries  $CP$  and  $T$ . If  $\mathbf{z} \neq 0$ , it violates  $CP$  and  $CPT$ . The normalizations of the two eigenstates, as given in Eq. (4), are precise in the lowest order of  $r$  and  $\mathbf{z}$ , where  $r = |q/p| - 1$ . Throughout the following, we neglect contributions of orders  $r^2$ ,  $\mathbf{z}^2$ ,  $r\mathbf{z}$ , and higher.

The  $T$ -sensitive mixing parameter  $|q/p|$  has been determined in several experiments, the present world average [7] being  $|q/p| = 1 + (0.8 \pm 0.8) \times 10^{-3}$ . The  $CPT$ -sensitive parameter  $\text{Im}(\mathbf{z})$  has been determined by analyzing the time dependence of dilepton events in the decay  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow (\ell^+ \nu X)(\ell^- \bar{\nu} X)$ ; the *BABAR* result [8] is  $\text{Im}(\mathbf{z}) = (-13.9 \pm 7.3 \pm 3.2) \times 10^{-3}$ . Since  $\Delta\Gamma$  is very small, dilepton events are only sensitive to the product  $\text{Re}(\mathbf{z})\Delta\Gamma$ . Therefore,  $\text{Re}(\mathbf{z})$  has so far only been determined by analyzing the time dependence of the decays  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$  with one  $B$  meson decaying into  $\ell \nu X$  and the other one into  $c\bar{c}K$ . With  $88 \times 10^6 B\bar{B}$  events, *BABAR* measured  $\text{Re}(\mathbf{z}) = (19 \pm 48 \pm 47) \times 10^{-3}$  in 2004 [9], while Belle used  $535 \times 10^6 B\bar{B}$  events to measure  $\text{Re}(\mathbf{z}) = (19 \pm 37 \pm 33) \times 10^{-3}$  in 2012 [10].

In our present analysis, we use the final data set of the *BABAR* experiment [11,12] with  $470 \times 10^6 B\bar{B}$  events for a new determination of  $\text{Re}(\mathbf{z})$  and  $\text{Im}(\mathbf{z})$ . As in Refs. [9,10], this is based on  $c\bar{c}K$  decays with amplitudes  $A$  for  $B^0 \rightarrow c\bar{c}K^0$  and  $\bar{A}$  for  $\bar{B}^0 \rightarrow c\bar{c}\bar{K}^0$ , using the following two assumptions:

- (1)  $c\bar{c}K$  decays obey the  $\Delta S = \Delta B$  rule, i.e.,  $B^0$  states do not decay into  $c\bar{c}\bar{K}^0$ , and  $\bar{B}^0$  states do not decay into  $c\bar{c}K^0$ ;

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- (2)  $CP$  violation in  $K^0$ - $\bar{K}^0$  mixing is negligible, i.e.,  
 $K_S^0 = (K^0 + \bar{K}^0)/\sqrt{2}$ ,  $K_L^0 = (K^0 - \bar{K}^0)/\sqrt{2}$ .

The  $CPT$ -sensitive parameters are determined from the measured time dependences of the four decay rates  $B^0, \bar{B}^0 \rightarrow c\bar{c}K_S^0, K_L^0$ . In  $\Upsilon(4S)$  decays,  $B^0$  and  $\bar{B}^0$  mesons are produced in the entangled state  $(B^0\bar{B}^0 - \bar{B}^0B^0)/\sqrt{2}$ . When the first meson decays into  $f = f_1$  at time  $t_1$ , the state collapses into the two states  $f_1$  and  $B_2$ . The later decay  $B_2 \rightarrow f_2$  at time  $t_2$  depends on the state  $B_2$  and, because of  $B^0$ - $\bar{B}^0$  mixing, on the decay-time difference

$$t = t_2 - t_1 \geq 0. \quad (5)$$

Note that  $t$  is the only relevant time here; it is the evolution time of the single-meson state  $B_2$  in its rest frame.

The present analysis does not start from raw data but uses intermediate results from Ref. [6] where, as mentioned above, we used our final data set for the demonstration of large  $T$  violation. This was shown in four time-dependent transition-rate differences

$$R(B_j \rightarrow B_i) - R(B_i \rightarrow B_j), \quad (6)$$

where  $B_i = B^0$  or  $\bar{B}^0$ , and  $B_j = B_+$  or  $B_-$ . The two states  $B_i$  were defined by flavor-specific decays [13] denoted as  $B^0 \rightarrow \ell^+ X$ ,  $\bar{B}^0 \rightarrow \ell^- X$ . The state  $B_+$  was defined as the remaining state  $B_2$  after a  $c\bar{c}K_S^0$  decay, and  $B_-$  as  $B_2$  after a  $c\bar{c}K_L^0$  decay. In order to use the two states for testing  $T$  symmetry in Eq. (6), they must be orthogonal;  $\langle B_+ | B_- \rangle = 0$ , which requires the additional assumption

- (3)  $|\bar{A}/A| = 1$ .

In the same 2012 analysis, we demonstrated that  $CPT$  symmetry is unbroken within uncertainties by measuring the four rate differences

$$R(B_j \rightarrow B_i) - R(\bar{B}_i \rightarrow B_j). \quad (7)$$

For both measurements in Eqs. (6) and (7), expressions

$$R_i(t) = N_i e^{-\Gamma t} (1 + C_i \cos \Delta m t + S_i \sin \Delta m t), \quad (8)$$

$i = 1 \dots 8$ , were fitted to the four time-dependent rates where the  $\ell X$  decay precedes the  $c\bar{c}K$  decay, and to the four rates where the order of the decays is inverted. The rate ansatz in Eq. (8) requires  $\Delta\Gamma = 0$ . The time  $t \geq 0$  in these expressions is the time between the first and the second decay of the entangled  $B^0\bar{B}^0$  pair as defined in Eq. (5). In our 2012 analysis, we named it  $\Delta\tau$ , equal to  $t_{c\bar{c}K} - t_{\ell X}$  if the  $\ell X$  decay occurred first, and equal to  $t_{\ell X} - t_{c\bar{c}K}$  with  $c\bar{c}K$  as the first decay. After the fits, the  $T$ -violating and  $CPT$ -testing rate differences were evaluated from the obtained  $S_i$  and  $C_i$  results. The  $CPT$  test showed no  $CPT$  violation, i.e., it was compatible with  $z = 0$ , but no results for  $\text{Re}(z)$  and  $\text{Im}(z)$  were given in 2012.

Our present analysis uses the eight measured time dependences in the 2012 analysis, i.e., the 16 results  $C_i$  and  $S_i$ , for determining  $z$ . This is possible without assumption (3) since we do not need to use the concept of states  $B_+$  and  $B_-$ . We are therefore able to determine the decay parameter  $|\bar{A}/A|$  in addition to the mixing parameters  $\text{Re}(z)$  and  $\text{Im}(z)$ . As in 2012, we use  $\Delta\Gamma = 0$ , but we show at the end of this analysis that the final results are independent of this constraint. Accepting assumptions (1) and (2), and in addition

- (4) that the amplitudes  $A$  and  $\bar{A}$  have a single weak phase,

only two more parameters  $|\bar{A}/A|$  and  $\text{Im}(q\bar{A}/pA)$  are required in addition to  $|q/p|$  and  $z$  for a full description of  $CP$  violation in time-dependent  $B^0 \rightarrow c\bar{c}K^0$  decays. In this framework,  $T$  symmetry requires  $\text{Im}(q\bar{A}/pA) = 0$  [14], and  $CPT$  symmetry requires  $|\bar{A}/A| = 1$  [15].

## II. B-MESON DECAY RATES

The time-dependent rates of the decays  $B^0, \bar{B}^0 \rightarrow c\bar{c}K$  are sensitive to both symmetries  $CPT$  and  $T$  in  $B^0$ - $\bar{B}^0$  mixing and in  $B^0$  decays. For decays into final states  $f$  with amplitudes  $A_f = A(B^0 \rightarrow f)$  and  $\bar{A}_f = A(\bar{B}^0 \rightarrow f)$ , using  $\lambda_f = q\bar{A}_f/(pA_f)$  and approximating  $\sqrt{1 - z^2} = 1$ , the rates are given by

$$\begin{aligned} R(B^0 \rightarrow f) &= \frac{|A_f|^2 e^{-\Gamma t}}{4} |(1 - z + \lambda_f) e^{i\Delta m t} e^{\Delta\Gamma t/4} + (1 + z - \lambda_f) e^{-\Delta\Gamma t/4}|^2, \\ R(\bar{B}^0 \rightarrow f) &= \frac{|\bar{A}_f|^2 e^{-\Gamma t}}{4} |(1 + z + 1/\lambda_f) e^{i\Delta m t} e^{\Delta\Gamma t/4} + (1 - z - 1/\lambda_f) e^{-\Delta\Gamma t/4}|^2. \end{aligned} \quad (9)$$

For the  $CP$  eigenstates  $c\bar{c}K_L^0$  ( $CP = +1$ ) and  $c\bar{c}K_S^0$  ( $CP = -1$ ) with  $A_{S(L)} = A[B^0 \rightarrow c\bar{c}K_{S(L)}^0]$  and  $\bar{A}_{S(L)} = A[\bar{B}^0 \rightarrow c\bar{c}K_{S(L)}^0]$ , assumptions (1) and (2) give  $A_S = A_L = A/\sqrt{2}$  and  $\bar{A}_S = -\bar{A}_L = \bar{A}/\sqrt{2}$ . In the

following, we only need to use  $\lambda_S = -\lambda_L = \lambda$ . Setting  $\Delta\Gamma = 0$  and keeping only first-order terms in the small quantities  $|\lambda| - 1$ ,  $z$ , and  $r = |q/p| - 1$ , this leads to rate expressions as given in Eq. (8) with coefficients



$$\begin{aligned}
S_1 &= S(\ell^- X, c\bar{c}K_L) \\
&= \frac{2\text{Im}(\lambda)}{1 + |\lambda|^2} - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) + \text{Im}(z)[\text{Re}(\lambda)]^2, \\
C_1 &= +\frac{1 - |\lambda|^2}{2} - \text{Re}(\lambda)\text{Re}(z) - \text{Im}(\lambda)\text{Im}(z), \\
S_2 &= S(\ell^+ X, c\bar{c}K_L) \\
&= -\frac{2\text{Im}(\lambda)}{1 + |\lambda|^2} - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) - \text{Im}(z)[\text{Re}(\lambda)]^2, \\
C_2 &= -\frac{1 - |\lambda|^2}{2} + \text{Re}(\lambda)\text{Re}(z) - \text{Im}(\lambda)\text{Im}(z), \\
S_3 &= S(\ell^- X, c\bar{c}K_S) \\
&= -\frac{2\text{Im}(\lambda)}{1 + |\lambda|^2} - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) + \text{Im}(z)[\text{Re}(\lambda)]^2, \\
C_3 &= +\frac{1 - |\lambda|^2}{2} + \text{Re}(\lambda)\text{Re}(z) + \text{Im}(\lambda)\text{Im}(z), \\
S_4 &= S(\ell^+ X, c\bar{c}K_S) \\
&= \frac{2\text{Im}(\lambda)}{1 + |\lambda|^2} - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) - \text{Im}(z)[\text{Re}(\lambda)]^2, \\
C_4 &= -\frac{1 - |\lambda|^2}{2} - \text{Re}(\lambda)\text{Re}(z) + \text{Im}(\lambda)\text{Im}(z). \quad (10)
\end{aligned}$$

The four other rates  $R_5(t) \cdots R_8(t)$  with  $c\bar{c}K$  as the first decay and  $t_{\ell X} - t_{c\bar{c}K} = t$  follow from the same two-decay-time expression [16,17] as the rates  $R_1 \cdots R_4$  with  $t_{c\bar{c}K} - t_{\ell X} = t$ . Therefore, the rates  $R_5(c\bar{c}K_L, \ell^- X)$ ,  $R_6(c\bar{c}K_L, \ell^+ X)$ ,  $R_7(c\bar{c}K_S, \ell^- X)$ , and  $R_8(c\bar{c}K_S, \ell^+ X)$  are given by Eq. (8) with the coefficients

$$S_i = -S_{i-4}, C_i = +C_{i-4} \quad \text{for } i = 5, 6, 7, \text{ and } 8. \quad (11)$$

The  $S_i$  and  $C_i$  results from our 2012 analysis, including uncertainties and correlation matrices, have been published as Supplemental Material [18] of Ref. [6] in Tables II–IV. For completeness, we include in Table I the results and the uncertainties.

TABLE I. Input values from the Supplemental Material [18] of Ref. [6]. The second column gives the two decays with their sequence in decay time.

$i$	decay pairs	$S_i$	$\sigma_{\text{stat}}$	$\sigma_{\text{sys}}$	$C_i$	$\sigma_{\text{stat}}$	$\sigma_{\text{sys}}$
1	$\ell^- X, c\bar{c}K_L$	0.51	0.17	0.11	-0.01	0.13	0.08
2	$\ell^+ X, c\bar{c}K_L$	-0.69	0.11	0.04	-0.02	0.11	0.08
3	$\ell^- X, c\bar{c}K_S$	-0.76	0.06	0.04	0.08	0.06	0.06
4	$\ell^+ X, c\bar{c}K_S$	0.55	0.09	0.06	0.01	0.07	0.05
5	$c\bar{c}K_L, \ell^- X$	-0.83	0.11	0.06	0.11	0.12	0.08
6	$c\bar{c}K_L, \ell^+ X$	0.70	0.19	0.12	0.16	0.13	0.06
7	$c\bar{c}K_S, \ell^- X$	0.67	0.10	0.08	0.03	0.07	0.04
8	$c\bar{c}K_S, \ell^+ X$	-0.66	0.06	0.04	-0.05	0.06	0.03

### III. FIT RESULTS

The relations between the 16 observables  $y_i = S_1 \cdots C_8$  in Eqs. (10) and (11) and the four parameters  $p_1 = (1 - |\lambda|^2)/2$ ,  $p_2 = 2\text{Im}(\lambda)/(1 + |\lambda|^2)$ ,  $p_3 = \text{Im}(z)$ , and  $p_4 = \text{Re}(z)$  are approximately linear. Therefore, the four parameters can be determined in a two-step linear  $\chi^2$  fit using matrix algebra. The first-step fit determines  $p_1$  and  $p_2$  by fixing  $\text{Re}(\lambda)$  and  $\text{Im}(\lambda)$  in the products  $\text{Re}(z)\text{Re}(\lambda)$ ,  $\text{Im}(z)\text{Im}(\lambda)$ ,  $\text{Im}(z)[\text{Re}(\lambda)]^2$ , and  $\text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda)$ . After fixing these terms, the relation between the vectors  $y$  and  $p$  is strictly linear,

$$y = M_1 p, \quad (12)$$

where  $M_1$  uses  $\text{Im}(\lambda) = 0.67$  and  $\text{Re}(\lambda) = -0.74$ , motivated by the results of analyses assuming  $CPT$  symmetry [7]. With this ansatz,  $\chi^2$  is given by

$$\chi^2 = (M_1 p - \hat{y})^T G (M_1 p - \hat{y}), \quad (13)$$

where  $\hat{y}$  is the measured vector of observables, and the weight matrix  $G$  is taken to be

$$G = [C_{\text{stat}}(y) + C_{\text{sys}}(y)]^{-1}, \quad (14)$$

where  $C_{\text{stat}}(y)$  and  $C_{\text{sys}}(y)$  are the statistical and systematic covariance matrices, respectively. The minimum of  $\chi^2$  is reached for

$$\hat{p} = \mathcal{M}_1 \hat{y} \quad \text{with} \quad \mathcal{M}_1 = (M_1^T G M_1)^{-1} M_1^T G, \quad (15)$$

and the uncertainties of  $\hat{p}$  are given by the covariance matrices

$$\begin{aligned}
C_{\text{stat}}(p) &= \mathcal{M}_1 C_{\text{stat}}(y) \mathcal{M}_1^T, \\
C_{\text{sys}}(p) &= \mathcal{M}_1 C_{\text{sys}}(y) \mathcal{M}_1^T, \quad (16)
\end{aligned}$$

with the property

$$C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M_1^T G M_1)^{-1}. \quad (17)$$

This first-step fit yields

$$\begin{aligned}
p_1 &= 0.001 \pm 0.023 \pm 0.017, \\
p_2 &= 0.689 \pm 0.030 \pm 0.015. \quad (18)
\end{aligned}$$

This leads to

$$\begin{aligned}
|\lambda| &= 1 - p_1 = 0.999 \pm 0.023 \pm 0.017, \\
\text{Im}(\lambda) &= (1 - p_1)p_2 = 0.689 \pm 0.034 \pm 0.019, \\
\text{Re}(\lambda) &= -(1 - p_1)\sqrt{1 - p_2^2} \\
&= -0.723 \pm 0.043 \pm 0.028, \quad (19)
\end{aligned}$$

where the negative sign of  $\text{Re}(\lambda)$  is motivated by four measurements [19–22]. The results of all four favor  $\cos 2\beta > 0$ , and in Ref. [22]  $\cos 2\beta < 0$  is excluded with  $4.5\sigma$  significance.

In the second step, we fix the two  $\lambda$  values according to the  $p_1$  and  $p_2$  results of the first step, i.e. to the central values in Eqs. (19). Equations (12) to (17) are then applied again, replacing  $M_1$  with the new relations matrix  $M_2$ . This gives the same results for  $p_1$  and  $p_2$  as in Eq. (18), and

$$\begin{aligned} p_3 = \text{Im}(\mathbf{z}) &= 0.010 \pm 0.030 \pm 0.013, \\ p_4 = \text{Re}(\mathbf{z}) &= -0.065 \pm 0.028 \pm 0.014, \end{aligned} \quad (20)$$

with a  $\chi^2$  value of 6.9 for 12 degrees of freedom.

The  $\text{Re}(\mathbf{z})$  result deviates from 0 by  $2.1\sigma$ . The result for  $|\lambda|$  can be easily converted into  $|\bar{A}/A|$  by using the world average of measurements for  $|q/p|$ . With  $|q/p| = 1.0008 \pm 0.0008$  [7], we obtain

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017, \quad (21)$$

in agreement with *CPT* symmetry. Using the matrix algebra in Eqs. (12) to (17) allows us to determine the separate statistical and systematic covariance matrices of the final results, in agreement with the condition  $C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M^T G M)^{-1}$ , where  $M$  relates  $y$  and  $p$  after convergence of the fit. The statistical correlation coefficients are  $\rho[|\bar{A}/A|, \text{Im}(\mathbf{z})] = 0.03$ ,  $\rho[|\bar{A}/A|, \text{Re}(\mathbf{z})] = 0.44$ , and  $\rho[\text{Re}(\mathbf{z}), \text{Im}(\mathbf{z})] = 0.03$ . The systematic correlation coefficients are  $\rho[|\bar{A}/A|, \text{Im}(\mathbf{z})] = 0.03$ ,  $\rho[|\bar{A}/A|, \text{Re}(\mathbf{z})] = 0.48$ , and  $\rho[\text{Re}(\mathbf{z}), \text{Im}(\mathbf{z})] = -0.15$ .

#### IV. ESTIMATING THE INFLUENCE OF $\Delta\Gamma$

Using an accept/reject algorithm, we have performed two “toy simulations,” each with  $\sim 2 \times 10^6$  events, i.e.  $t$  values sampled from the distributions

$$e^{-\Gamma t} [1 + \text{Re}(\lambda) \sinh(\Delta\Gamma t/2) + \text{Im}(\lambda) \sin(\Delta m t)], \quad (22)$$

with  $\Delta\Gamma = 0$  for one simulation and  $\Delta\Gamma = 0.01\Gamma$  for the other one, corresponding to one standard deviation from the present world average [7]. For both simulations we use  $\text{Im}(\lambda) = 0.67$  and  $\text{Re}(\lambda) = -0.74$  and sample  $t$  values between 0 and  $+5/\Gamma$ . We then fit the two samples, binned in intervals of  $\Delta t = 0.25/\Gamma$ , to the expressions

$$Ne^{-\Gamma t} [1 + C \cos(\Delta m t) + S \sin(\Delta m t)], \quad (23)$$

with three free parameters  $N$ ,  $C$  and  $S$ . The fit results agree between the two simulations within 0.002 for  $C$  and 0.008 for  $S$ . We, therefore, conclude that omission of the  $\sinh$  term in Ref. [6] has a negligible influence on the three final results of this analysis.

#### V. CONCLUSION

Using  $470 \times 10^6 B\bar{B}$  events from *BABAR*, we determine

$$\begin{aligned} \text{Im}(\mathbf{z}) &= 0.010 \pm 0.030 \pm 0.013, \\ \text{Re}(\mathbf{z}) &= -0.065 \pm 0.028 \pm 0.014, \\ |\bar{A}/A| &= 0.999 \pm 0.023 \pm 0.017, \end{aligned}$$

where the first uncertainties are statistical and the second uncertainties are systematic. All three results are compatible with *CPT* symmetry in  $B^0$ - $\bar{B}^0$  mixing and in  $B \rightarrow c\bar{c}K$  decays. The uncertainties on  $\text{Re}(\mathbf{z})$  are comparable with those obtained by Belle in 2012 [10] with  $535 \times 10^6 B\bar{B}$  events,  $\text{Re}(\mathbf{z}) = -0.019 \pm 0.037 \pm 0.033$ . The uncertainties on  $\text{Im}(\mathbf{z})$  are considerably larger, as expected, than those obtained by *BABAR* in 2006 [8] with dilepton decays from  $232 \times 10^6 B\bar{B}$  events,  $\text{Im}(\mathbf{z}) = -0.014 \pm 0.007 \pm 0.003$ . The result of the present analysis for  $\text{Re}(\mathbf{z})$ ,  $-0.065 \pm 0.028 \pm 0.014$ , supersedes the *BABAR* result of 2004 [9].

#### ACKNOWLEDGMENTS

We thank H.-J. Gerber (ETH Zurich) and T. Ruf (CERN) for very useful discussions on  $T$  and *CPT* symmetry. We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (Netherlands), NFR (Norway), MES (Russia), MINECO (Spain), STFC (United Kingdom), and BSF (USA-Israel). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation (USA).

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