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

Permalink
https://escholarship.org/uc/item/4r92w596

Journal
Physical Review D, 94(1)

ISSN
2470-0010

Authors
Lees, JP
Poireau, V
Tisserand, V
et al.

Publication Date
2016-07-18

DOI
10.1103/physrevd.94.011101

License
https://creativecommons.org/licenses/by/4.0/ 4.0

Peer reviewed
Tests of CPT symmetry in $B^0$-$\bar{B}^0$ mixing and in $B^0 \to c\bar{c}K^0$ decays

J. P. Lees,1 V. Poireau,1 V. Tisserand,1 E. Grauges,2 A. Palano,3 G. Eigen,4 D. N. Brown,5 Yu. G. Kolomensky,5 H. Koch,5 T. Schroeder,6 C. Hearty,7 T. S. Mattison,7 J. A. McKenna,7 R. Y. So,7 V. E. Blinov,8 a,b,8 c A. R. Buzyaev,8 a,b, v P. Druzhinin,8 a,b V. B. Golubev,8 a,b E. A. Kravchenko8 a,b, A. P. Onuchin,8 a,b,8 c S. I. Serednyakov8 a,b,8 c Yu. I. Skovpen,8 a,b,8 c E. P. Solodov,8 a,b K. Yu. Todyshov,8 a,b,8 c A. J. Lankford,9 J. W. Gary,10 O. Long,10 A. M. Eisner,11 W. S. Lockman,11 W. Panduro Vazquez,11 D. S. Chao,112 C. H. Cheng,112 B. Echenard,112 K. T. Flood,112 D. G. Hiltun,112 J. Kim,12 T. S. Miyashita,12 P. Ongmongkolkul,12 F. C. Porter,12 M. Röhrken,12 Z. Huard,13 B. T. Meadows,13 B. G. Pushpawela,13 M. D. Sokoloff,13 L. Sun,13,* J. G. Smith,14 S. R. Wagner,15 D. Bernard,15 M. Verderi,15 D. Bettoni,16 a G. De Nardo,16 a G. Raven,17 a, b, ¶ G. Casarosa,16 a, b, ¶, A. Bomben,16 a, b, ¶ G. R. Bonneaud,16 a, b, ¶ G. Calderini,16 a, b, ¶ J. Chauveau,16 a, b, ¶ G. Marchiori,16 a, b, ¶ J. Ocariz,16 a, b, ¶ E. Ben-Haim,16 a, b, ¶ M. Bomben16 a, b, ¶ G. R. Bonneauad,16 a, b, ¶ G. Calderini,16 a, b, ¶ J. Chauveau,16 a, b, ¶ G. Marchiori,16 a, b, ¶ J. Ocariz,16 a, b, ¶ M. Biasini,16 a, b, ¶ E. Manoni,16 a, b, ¶ A. Rossi,16 a, b, ¶ G. Batignani,16 a, b, ¶ S. Bettarini,16 a, b, ¶ G. Casarosa,16 a, b, ¶ M. Chrzaszcz,16 a, b, ¶ F. Forti,16 a, b, ¶ M. A. Giorgi,16 a, b, ¶ A. Lusiani,16 a, b, ¶ B. Oberhofer,16 a, b, ¶ E. Paoloni,16 a, b, ¶ M. Rama,16 a, b, ¶ G. Rizzo,16 a, b, ¶ J. J. Walsh,16 a, b, ¶ A. J. S. Smith,16 a, b, ¶ F. Anulli,16 a, b, ¶ R. Faccini,16 a, b, ¶ F. Ferrarotto,16 a, b, ¶ F. Ferroni,16 a, b, ¶ A. Pilloni,16 a, b, ¶ G. Priedda,16 a, b, ¶ C. Bünger,16 a, b, ¶ S. Dittrich,16 a, b, ¶ O. Grünberg,16 a, b, ¶ M. Heß,16 a, b, ¶ T. Ledlig,16 a, b, ¶ C. Voß,16 a, b, ¶ R. Wald,16 a, b, ¶ T. Adye,16 a, b, ¶ F. F. Wilson,16 a, b, ¶ S. Emery,16 a, b, ¶ G. Vasseur,16 a, b, ¶ D. Aston,16 a, b, ¶ C. Cartaro,16 a, b, ¶ M. R. Convery,16 a, b, ¶ J. Dorfan,16 a, b, ¶ W. Dunwoodie,16 a, b, ¶ M. Ebert,16 a, b, ¶ R. C. Field,16 a, b, ¶ B. G. Fulsom,16 a, b, ¶ M. T. Graham,16 a, b, ¶ K. Has,16 a, b, ¶ W. R. Innes,16 a, b, ¶ P. Kim,16 a, b, ¶ D. W. G. S. Leith,16 a, b, ¶ S. Luitz,16 a, b, ¶ D. B. MacFarlane,16 a, b, ¶ D. R. Muller,16 a, b, ¶ H. Neal,16 a, b, ¶ B. N. Ratcliff,16 a, b, ¶ M. Röhrken,16 a, b, ¶ S. Akar,16 a, b, ¶ T. Schroeder,16 a, b, ¶ C. Hearty,16 a, b, ¶ T. S. Mattison,16 a, b, ¶ J. A. McKenna,16 a, b, ¶ R. Y. So,16 a,b,16 c V. E. Blinov,16 a, b, ¶ A. R. Buzykaev,16 a,b,16 c A. R. Gritsan,16 a, ¶ F. U. Bernlochner,16 a, ¶ G. J. King,16 a, ¶ R. Kowalewski,16 a, ¶ T. Lueck,16 a, ¶ I. M. Nugent,16 a, ¶ J. M. Roney,16 a, ¶ N. Tasneem,16 a, ¶ T. J. Gershon,16 a, ¶ P. F. Harrison,16 a, ¶ T. E. Latham,16 a, ¶ R. Prepost,16 a, ¶ and S. L. Wu16 a (BABAR Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France

2Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

3INFN Sezione di Bari and Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy

4University of Bergen, Institute of Physics, N-5007 Bergen, Norway

5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

6Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

7University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

8Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia

9Novosibirsk State University, Novosibirsk 630090, Russia

10Novosibirsk State Technical University, Novosibirsk 630092, Russia

11University of California at Irvine, Irvine, California 92697, USA

12University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

13Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia

14University of Cincinnati, Cincinnati, Ohio 45221, USA

15University of Colorado, Boulder, Colorado 80309, USA

16Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France

17INFN Sezione di Ferrara, I-44122 Ferrara, Italy

18INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

19INFN Sezione di Genova, I-16146 Genova, Italy
Using the eight time dependences $e^{-\gamma}(1+C_1\cos\Delta mt+S_1\sin\Delta mt)$ for the decays $Y(4S) \rightarrow B^0 B^0 \rightarrow f_j f_k$, with the decay into a flavor-specific state $f_j = \ell^+ X$ 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 $\text{Re}(z)$ and $\text{Im}(z)$ in $B^0 B^0$ mixing and $|\bar{A}/A|$ in $B^0 \rightarrow c\bar{c}K^0$ decays. We find $\text{Im}(z) = 0.010 \pm 0.030 \pm 0.013$, Re$(z) = -0.065 \pm 0.028 \pm 0.014$, 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 $K^0\bar{K}^0$ 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 $B^0\bar{B}^0$ 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 $B^0\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays. Transitions in the $B^0\bar{B}^0$ system are well described by the quantum-mechanical evolution of a two-state wave function

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

using the Schrödinger equation

$$\dot{\Psi} = -i\mathcal{H}\Psi,$$

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, $|q/p|$, $\text{Re}(z)$, and $\text{Im}(z)$, defined by

$$|q/p| = 1 - 2\text{Im}(m_{12}\Gamma_{12})/4|m_{12}|^2 + |\Gamma_{12}|^2,\quad z = (m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2\Delta m - i\Delta\Gamma/2,$$

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 ($H = \text{heavy}$, $L = \text{light}$) of the Hamiltonian,

$$B_H = (p\sqrt{1 + zB^0} - q\sqrt{1 - z\bar{B}^0})/\sqrt{2},\quad B_L = (p\sqrt{1 - zB^0} + q\sqrt{1 + z\bar{B}^0})/\sqrt{2}.$$ (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 $z \neq 0$, 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 $z$, where $r = |q/p| - 1$. Throughout the following, we neglect contributions of orders $r^2, z^2, rz$, 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 $\text{Im}(z)$ has been determined by analyzing the time dependence of dilepton events in the decay $Y(4S) \rightarrow B^0\bar{B}^0 \rightarrow (\ell^+\nu X)(\ell^-\bar{\nu}X)$; the BABAR result [8] is $\text{Im}(z) = (-13.9 \pm 7.3 \pm 3.2) \times 10^{-3}$. Since $\Delta\Gamma$ is very small, dilepton events are only sensitive to the product $\text{Re}(z)\Delta\Gamma$. Therefore, $\text{Re}(z)$ has so far only been determined by analyzing the time dependence of the decays $Y(4S) \rightarrow B^0\bar{B}^0$ with one $B$ meson decaying into $\ell\nu X$ and the other one into $c\bar{c}K$. With $8 \times 10^6 BB$ events, BABAR measured $\text{Re}(z) = (19 \pm 48 \pm 7) \times 10^{-3}$ in 2004 [9], while Belle used $535 \times 10^6 BB$ events to measure $\text{Re}(z) = (19 \pm 37 \pm 33) \times 10^{-3}$ in 2012 [10].

In our present analysis, we use the final data set of the BABAR experiment [11,12] with $470 \times 10^6 BB$ events for a new determination of $\text{Re}(z)$ and $\text{Im}(z)$. As in Refs. [9,10], this is based on $c\bar{c}K$ decays with amplitudes $\lambda$ for $B^0 \rightarrow c\bar{c}K^0$ and $\bar{\lambda}$ for $\bar{B}^0 \rightarrow c\bar{c}K^0$, 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 $c\bar{c}K^0$, and $\bar{B}^0$ states do not decay into $c\bar{c}\bar{K}^0$;
(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 $B^0, \bar{B}^0 \to c\bar{c}K^0_S, K_L^0$. 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 $B_2 \to f_2$ at time $t_2$ depends on the state $B_2$, and because of $B^0-\bar{B}^0$ mixing, on the decay-time difference

$$t = t_2 - t_1 \geq 0.$$  \hfill (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

$$R(B_j \to B_i) - R(\bar{B}_i \to B_j),$$  \hfill (6)

where $B_i = B^0$ or $\bar{B}^0$, and $B_j = B_+ \text{ or } B_-$. The two states $B_j$ were defined by flavor-specific decays [13] denoted as $B^0 \to \epsilon^+X$, $\bar{B}^0 \to \epsilon^-X$. The state $B_+$ was defined as the remaining state $B_2$ after a $c\bar{c}K^0_S$ 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) $\langle \bar{A}/A \rangle = 1$.

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

$$R(B_j \to B_i) - R(B_i \to B_j).$$  \hfill (7)

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

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

$i = 1...8$, were fitted to the four time-dependent rates where the $\epsilon^X$ 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 $\Delta r$, equal to $t_{\epsilon^+X} - t_{\epsilon^-X}$ if the $\epsilon^X$ decay occurred first, and equal to $t_{\epsilon^-X} - t_{\epsilon^+X}$ 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 CP violation, i.e., it was compatible with $z = 0$, but no results for Re($z$) and 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 Re($z$) and 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 Im($q\bar{A}/pA$) are required in addition to $|q/p|$ and $z$ for a full description of CP violation in time-dependent $B^0 \to c\bar{c}K^0$ decays. In this framework, $T$ symmetry requires 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 $B^0, \bar{B}^0 \to c\bar{c}K$ are sensitive to both symmetries $CP$ and $T$ in $B^0, \bar{B}^0$ mixing and in $B^0$ decays. For decays into final states $f$ with amplitudes $A_f = A(B^0 \to f)$ and $\bar{A}_f = A(\bar{B}^0 \to f)$, using $\lambda_f = q\bar{A}_f/(pA_f)$ and approximating $\sqrt{1 - z^2} = 1$, the rates are given by

$$R(B^0 \to f) = \frac{|A_f|^2 e^{-\Gamma_f}}{4} |(1 + z + \lambda_f) e^{\Delta m t} e^{\Delta \Gamma /4} + (1 - z - \lambda_f) e^{-\Delta \Gamma /4}|^2,$$

$$R(\bar{B}^0 \to f) = \frac{|\bar{A}_f|^2 e^{-\Gamma_f}}{4} |(1 + z + 1/\lambda_f) e^{\Delta m t} e^{\Delta \Gamma /4} + (1 - z - 1/\lambda_f) e^{-\Delta \Gamma /4}|^2.$$  \hfill (9)

For the CP eigenstates $c\bar{c}K^0_L (CP = +1)$ and $c\bar{c}K^0_S (CP = -1)$ with $A_{S(L)} = A[B^0 \to c\bar{c}K^0_{S(L)}]$ and $\bar{A}_{S(L)} = A[\bar{B}^0 \to c\bar{c}K^0_{S(L)}]$, 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{align*}
A_S(t) & = A_L(t) = A/\sqrt{2}, \\
\bar{A}_S(t) & = -\bar{A}_L(t) = \bar{A}/\sqrt{2},
\end{align*}

for $r < 1$ and $z \approx 0$.
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.

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

The relations between the 16 observables $y_i = S_1 \cdots C_8$ in Eqs. (10) and (11) and the four parameters $p_1 = (1 - |\lambda|^2)/2$, $p_2 = 2 \Im(\lambda)/(1 + |\lambda|^2)$, $p_3 = \Re(\lambda)$, and $p_4 = \Re(\lambda)$ 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 $\Re(\lambda)$ and $\Im(\lambda)$ in the products $\Re(\lambda)\Re(\lambda)$, $\Im(\lambda)\Re(\lambda)$, $\Re(\lambda)\Re(\lambda)$, and $\Re(\lambda)\Re(\lambda)\Re(\lambda)\Re(\lambda)\Re(\lambda)$. After fixing these terms, the relation between the vectors $y$ and $p$ is strictly linear,

$$y = M_1 p,$$

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

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

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

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

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

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

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

$$C_{stat}(p) = M_1 C_{stat}(y) M_1^T,$$

$$C_{sys}(p) = M_1 C_{sys}(y) M_1^T,$$

with the property

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

$$p_3 = \text{Im}(z) = 0.010 \pm 0.030 \pm 0.013,$$
$$p_4 = \text{Re}(z) = -0.065 \pm 0.028 \pm 0.014,$$

with a $\chi^2$ value of 6.9 for 12 degrees of freedom. The $\text{Re}(z)$ 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

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017,$$

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 $C_{\text{stat}}(p) + C_{\text{sys}}(p) = (M^TGM)^{-1}$, where $M$ relates $y$ and $p$ after convergence of the fit. The statistical correlation coefficients are $\rho(|\bar{A}/A|, \text{Im}(z)) = 0.03$, $\rho(|\bar{A}/A|, \text{Re}(z)) = 0.44$, and $\rho(\text{Re}(z), \text{Im}(z)) = 0.03$. The systematic correlation coefficients are $\rho(|\bar{A}/A|, \text{Im}(z)) = 0.03$, $\rho(|\bar{A}/A|, \text{Re}(z)) = 0.48$, and $\rho(\text{Re}(z), \text{Im}(z)) = -0.15$.

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

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

with $\Delta \Gamma = 0$ for one simulation and $\Delta \Gamma = 0.011\Gamma$ 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 $\pm 5/\Gamma$. We then fit the two samples, binned in intervals of $\Delta t = 0.25/\Gamma$, to the expressions

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

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

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

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 $B \to c\bar{c}K$ decays. The uncertainties on $\text{Re}(z)$ are comparable with those obtained by Belle in 2012 [10] with $535 \times 10^6 B\bar{B}$ events, $\text{Re}(z) = -0.019 \pm 0.037 \pm 0.033$. The uncertainties on $\text{Im}(z)$ 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, $\text{Im}(z) = -0.014 \pm 0.007 \pm 0.003$. The result of the present analysis for $\text{Re}(z)$, $-0.065 \pm 0.028 \pm 0.014$, 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).
TESTS OF CPT SYMMETRY IN $B^0$-$\bar{B}^0$ …

[9] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 70, 012007 (2004), inserting $\text{Re}(\lambda) = -0.73$.

[13] In addition to prompt charged leptons from inclusive semileptonic decays $\ell^\pm \nu X$, Ref. [6] used charged kaons, charged pions from $D^+$ decays and high-momentum charged particles in the flavor-specific samples $\ell^\pm X$.