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Using the eight time dependences $e^{-\Gamma t}(1+C_i \cos\Delta m t+S_i \sin\Delta m t)$ for the decays $\Upsilon(4S)\to B^0\overline{B}^0\to f_j f_k$, with the decay into a flavor-specific state $f_j = \ell^\pm X$ before or after the decay into a CP eigenstate $f_k = c\overline{c}K_{S,L}$, as measured by the *BABAR* experiment, we determine the three CPT-sensitive parameters $\mathrm{Re}\,(\mathsf{z})$ and $\mathrm{Im}\,(\mathsf{z})$ in B^0-$\overline{B}^0$ mixing and $|\overline{A}/A|$ in $B^0\to c\overline{c}K^0$ decays. We find $\mathrm{Im}\,(\mathsf{z}) = 0.010\pm0.030\pm0.013$, $\mathrm{Re}\,(\mathsf{z}) = -0.065\pm0.028\pm0.014$, and $|\overline{A}/A| = 0.999\pm0.023\pm0.017$, in agreement with CPT symmetry.

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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-$\overline{K}^0$ mixing: T was violated with about 5σ 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-$\overline{B}^0$ mixing and $B^0\to c\overline{c}K^0$ decays, but an explicit demonstration of T violation was given only recently [6]. In the present analysis, we test CPT symmetry quantitavely in B^0-$\overline{B}^0$ mixing and in $B^0\to c\overline{c}K^0$ decays.

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

$$\Psi = \psi_1\,|B^0\rangle + \psi_2\,|\overline{B}^0\rangle\ , \tag{1}$$

using the Schrödinger equation

$$\dot{\Psi} = -\mathrm{i}\ \mathcal{H}\ \Psi\ , \tag{2}$$

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

$$\begin{aligned} |q/p| &= 1 - \frac{2\,\mathrm{Im}\,(m_{12}^*\Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2}\ , \\ \mathsf{z} &= \frac{(m_{11}-m_{22}) - \mathrm{i}\,(\Gamma_{11}-\Gamma_{22})/2}{\Delta m - \mathrm{i}\,\Delta\Gamma/2}\ , \end{aligned} \tag{3}$$

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,

$$\begin{aligned} B_H &= (p\sqrt{1+\mathsf{z}}\,B^0 - q\sqrt{1-\mathsf{z}}\,\overline{B}^0)/\sqrt{2}\ , \\ B_L &= (p\sqrt{1-\mathsf{z}}\,B^0 + q\sqrt{1+\mathsf{z}}\,\overline{B}^0)/\sqrt{2}\,. \end{aligned} \tag{4}$$

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 $\mathsf{z} \neq 0$, 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, $r\,\mathsf{z}$, and higher.

The T-sensitive mixing parameter $|q/p|$ has been determined in several experiments, the present world average [7] being $|q/p| = 1 + (0.8\pm0.8)\times10^{-3}$. The CPT-sensitive parameter $\mathrm{Im}\,(\mathsf{z})$ has been determined by analyzing the time dependence of di-lepton events in the decay $\Upsilon(4S)\to B^0\overline{B}^0\to(\ell^+\nu X)\ (\ell^-\overline{\nu}X)$; the *BABAR* result [8] is $\mathrm{Im}\,(\mathsf{z}) = (-13.9\pm7.3\pm3.2)\times10^{-3}$. Since $\Delta\Gamma$ is very small, di-lepton events are only sensitive to the product $\mathrm{Re}\,(\mathsf{z})\Delta\Gamma$. Therefore, $\mathrm{Re}\,(\mathsf{z})$ has so far only been determined by analyzing the time dependence of the decays $\Upsilon(4S)\to B^0\overline{B}^0$ with one B meson decaying into $\ell\nu X$ and the other one into $c\overline{c}K$. With $88\times10^6 B\overline{B}$ events, *BABAR* measured $\mathrm{Re}\,(\mathsf{z}) = (19\pm48\pm47)\times10^{-3}$ in 2004 [9], while Belle used $535\times10^6 B\overline{B}$ events to measure $\mathrm{Re}\,(\mathsf{z}) = (19\pm37\pm33)\times10^{-3}$ in 2012 [10].

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

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

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

The CPT-sensitive parameters are determined from the measured time dependeces of the four decay rates $B^0, \overline{B}^0\to c\overline{c}K^0_S, K^0_L$. In $\Upsilon(4S)$ decays, B^0 and $\overline{B}^0$ mesons are produced in the entangled state $(B^0\overline{B}^0 - \overline{B}^0B^0)/\sqrt{2}$. 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-$\overline{B}^0$ mixing, on the decay-time difference

$$t = t_2 - t_1 \geq 0\,. \tag{5}$$

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.

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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 transiton-rate differences

$$R(B_j \to B_i) - R(B_i \to B_j) \tag{6}$$

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

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

$$R(B_j \to B_i) - R(\overline{B}_i \to B_j)\,. \tag{7}$$

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

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

$i = 1\ldots8$, were fitted to the four time-dependent rates where the ℓX decay precedes the $c\overline{c}K$ 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 $t \ge 0$ in these expressions is the time between the first and the second decay of the entangled $B^0\overline{B}^0$ pair as defined in Eq. (5). In our 2012 analysis, we named it $\Delta\tau$, equal to $t_{c\overline{c}K} - t_{\ell X}$ if the ℓX decay occured first, and equal to $t_{\ell X} - t_{c\overline{c}K}$ with $c\overline{c}K$ as 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 $\mathsf{z} = 0$, but no results for $\mathrm{Re}\,(\mathsf{z})$ and $\mathrm{Im}\,(\mathsf{z})$ 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 will therefore be able to determine the decay parameter $|\overline{A}/A|$ in addition to the mixing parameters $\mathrm{Re}\,(\mathsf{z})$ and $\mathrm{Im}\,(\mathsf{z})$. As in 2012, we use $\Delta\Gamma = 0$, but we will show at the end of this analysis that the final results are independent of this constraint. Accepting the assumptions (1) and (2), and in addition

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

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

II. B-MESON DECAY RATES

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

$$\begin{aligned} R(B^0 \to f) &= \frac{|A_f|^2\,\mathrm{e}^{-\Gamma t}}{4}\left|(1 - \mathsf{z} + \lambda_f)\,\mathrm{e}^{\mathrm{i}\Delta m t}\,\mathrm{e}^{\Delta\Gamma t/4} + (1 + \mathsf{z} - \lambda_f)\,\mathrm{e}^{-\Delta\Gamma t/4}\right|^2, \\ R(\overline{B}^0 \to f) &= \frac{|\overline{A}_f|^2\,\mathrm{e}^{-\Gamma t}}{4}\left|(1 + \mathsf{z} + 1/\lambda_f)\,\mathrm{e}^{\mathrm{i}\Delta m t}\,\mathrm{e}^{\Delta\Gamma t/4} + (1 - \mathsf{z} - 1/\lambda_f)\,\mathrm{e}^{-\Delta\Gamma t/4}\right|^2. \end{aligned} \tag{9}$$

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

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

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 $R_1 \ldots R_4$ 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

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

The S_i and C_i results from our 2012 analysis, including uncertainties and correlation matrices, have been published as supplemental material [18] in Tables II, III, and 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	$\sigma_{\rm stat}$	$\sigma_{\rm sys}$	C_i	$\sigma_{\rm stat}$	$\sigma_{\rm sys}$
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 $p_1 = (1-|\lambda|^2)/2$, $p_2 = 2\,\mathrm{Im}\,(\lambda)/(1+|\lambda|^2)$, $p_3 = \mathrm{Im}\,(\mathsf{z})$, and $p_4 = \mathrm{Re}\,(\mathsf{z})$ are approximately linear. Therefore, the four parameters can be determined in a two-step linear χ^2 fit using matrix algebra. The first-step fit determines p_1 and p_2 by fixing $\mathrm{Re}\,(\lambda)$ and $\mathrm{Im}\,(\lambda)$ in the products $\mathrm{Re}\,(\mathsf{z})\mathrm{Re}\,(\lambda)$, $\mathrm{Im}\,(\mathsf{z})\mathrm{Im}\,(\lambda)$, $\mathrm{Im}\,(\mathsf{z})[\mathrm{Re}\,(\lambda)]^2$, and $\mathrm{Re}\,(\mathsf{z})\mathrm{Re}\,(\lambda)\mathrm{Im}\,(\lambda)$. 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 $\mathrm{Im}\,(\lambda) = 0.67$ and $\mathrm{Re}\,(\lambda) = -0.74$, motivated by the results of analyses assuming CPT symmetry [7]. With this ansatz, χ^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

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

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

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

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

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

with the property

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

This first-step fit yields

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

This leads to

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

where the negative sign of ${\rm Re}\,(\lambda)$ 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 λ values according to the p_1 and p_2 results of the first step, i.e. to the central values in Eqs. (19). Eqs. (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

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

with a χ^2 value of 6.9 for 12 degrees of freedom.

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

$$|\overline{A}/A| = 0.999 \pm 0.023 \pm 0.017\ , \tag{21}$$

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

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

Using an accept/reject algorithm, we have performed two "toy simulations", each with $\sim 2\times10^6$ "events", i.e. t values sampled from the distributions

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

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 ${\rm Im}\,(\lambda) = 0.67$ and ${\rm Re}\,(\lambda) = -0.74$ 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

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

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 470×10^6 $B\overline{B}$ events from *BABAR*, we determine

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

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

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[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
[2] K. R. Schubert et al., Phys. Lett. B **31**, 662 (1970).
[3] J. S. Bell and J. Steinberger, Proc. Int. Conf. Elem. Part., Oxford 1965, p. 195 (Rutherford Lab. 1966).
[4] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. Lett. **87**, 091801 (2001).
[5] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001).
[6] J. P. Lees et al. (*BABAR* Collaboration), Phys. Rev. Lett. **109**, 211801 (2012).
[7] The Review of Particle Physics, K. A. Olive et al. (Particle Data Group), Chin. Phys. C **38**, 090001 (2014) and 2015 update.
[8] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. Lett. **96**, 251802 (2006).
[9] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. D **70**, 012007 (2004), inserting $\mathrm{Re}\,(\lambda) = -0.73$.
[10] T. Higuchi et al. (Belle Collaboration), Phys. Rev. D **85**, 071105 (2012).
[11] B. Aubert et al. (*BABAR* Collaboration), Nucl. Instum. and Meth. A **479**, 1 (2002).
[12] B. Aubert et al. (*BABAR* Collaboration), Nucl. Instum. and Meth. A **729**, 615 (2013).
[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 $\ell^{\pm}X$.
[14] C. P. Enz and R. R. Lewis, Helv. Phys. Acta **38**, 860 (1965).
[15] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. **106**, 340 (1957).
[16] T. B. Day, Phys. Rev. **121**, 1204 (1961).
[17] H. Lipkin, Phys. Rev. **176**, 1715 (1968).
[18] J. P. Lees et al. (*BABAR* Collaboration), Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.109.211801.
[19] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. D **71**, 032005 (2005).
[20] R. Itoh et al. (Belle Collaboration), Phys. Rev. Lett. **95**, 091601 (2005).
[21] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 231802 (2007).
[22] B. Aubert et al. (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 161802 (2007).