Title
Search for T, CP, and CPT violation in B0-B0 mixing with inclusive dilepton events.

Permalink
https://escholarship.org/uc/item/5s00k8nh

Journal
Physical review letters, 96(25)

ISSN
0031-9007

Authors
Aubert, B
Barate, R
Bona, M
et al.

Publication Date
2006-06-01

DOI
10.1103/physrevlett.96.251802

Copyright Information
This work is made available under the terms of a Creative Commons Attribution License, available at https://creativecommons.org/licenses/by/4.0/

Peer reviewed
Search For $T$, $CP$, and $CPT$ Violation in $B^0 - \bar{B}^0$ Mixing with Inclusive Dilepton Events

B. Aubert,1 R. Barate,1 M. Bona,1 D. Boutigny,1 F. Coudert,1 Y. Karyotakis,1 J. P. Lees,1 V. Poireau,1 V. Tisserand,1 A. Zghiche,1 E. Grauges,2 A. Palano,3 M. Pappalaggio,3 J. C. Chen,4 N. D. Qi,4 G. Rong,4 P. Wang,4 Y. S. Zhu,4 G. Eigen,5 I. Ofte,5 B. Stugu,6 G. S. Abrams,6 M. Battaglia,6 D. N. Brown,6 J. Button-Shafer,6 R. N. Cahn,6 E. Charles,6 C. T. Day,6 M. S. Gill,7 Y. Groysman,7 R. G. Jacobsen,7 J. A. Kadyk,7 L. T. Kerth,7 Yu. G. Kolomensky,7 G. Kukartsev,7 G. Lynch,8 L. M. Mir,8 P. J. Oddone,8 T. J. Orimoto,9 M. Pripstein,9 N. A. Roe,9 M. T. Ronan,9 W. A. Wenzel,9 M. Barrett,9 K. E. Ford,9 T. J. Harrison,9 A. J. Hart,7 C. M. Hawkes,7 S. E. Morgan,7 A. T. Watson,7 K. Goetz,7 T. Held,8 H. Koch,8 B. Lewandowski,8 M. Pelizaues,8 K. Peters,8 T. Schroeder,8 M. Steincke,8 J. T. Boyd,9 J. P. Burke,9 W. N. Cottingham,9 D. Walker,9 T. Cuhadar-Donszelmann,10 B. G. Fulsom,10 C. A. Heusch,10 K. E. Ford,10 A. Khan,11 P. Kyberd,11 M. Saleem,11 L. Teodorescu,11 V. E. Blinov,12 A. D. Buki,12 V. P. Druzhinin,12 V. B. Golubev,12 A. P. Onuchin,12 S. I. Serednyak,12 Yu. I. Skopyen,12 E. P. Solodov,12 K. Y. Troysh,12 D. S. Best,13 M. Bondioli,13 M. Briuinsma,13 M. Chao,13 S. Curry,13 I. Eschrich,13 D. Kirkby,13 A. J. Lankford,13 P. Luddick,13 M. Mandelkern,13 R. K. Mohmmes,13 W. Roethel,13 D. P. Stoker,13 S. Abachi,14 C. Buchanan,14 S. D. Foulkes,15 J. W. Gary,15 O. Long,15 B. C. Shen,15 K. Wang,15 L. Zhang,15 H. K. Hadavand,16 E. J. Hilly,16 H. P. Pals,16 S. Rahatlu,16 V. Sharma,16 J. W. Berryhill,17 C. Campagnari,17 C. Cunha,17 B. Dahmes,17 T. M. Hong,17 D. Kovalskyi,17 J. D. Richman,17 T. W. Beck,18 A. M. Eiser,18 C. J. Flacco,18 C. A. Heusch,18 K. E. Ford,18 W. S. Lockman,18 G. Nesomi,18 T. Schalk,18 B. A. Schumam,18 S. Seiden,18 P. Spradlin,18 D. C. Williams,18 M. G. Wilson,18 J. Albert,19 E. Chen,19 A. Dvoretski,19 D. G. Hitlin,19 I. Narsky,20 T. Piatanen,20 F. C. Porter,20 A. Ryd,20 A. Samuel,20 R. Andreassen,20 G. Mancinelli,20 B. T. Meadows,20 M. D. Sokoloff,20 F. Blanc,21 Y. P. Bloom,21 S. Chen,21 W. T. Ford,21 J. F. Hirschauer,21 A. Kreisel,21 U. Nauenberg,21 A. Olivas,21 W. O. Ruddick,21 J. G. Smith,21 A. Ulmer,21 S. R. Wagner,21 J. Zhang,21 C. A. Chen,22 E. A. Eckhart,22 A. Soffer,22 W. H. Toki,22 R. J. Wilson,22 F. Winklmeier,22 Q. Zeng,22 D. D. Altenburg,23 E. Feltresi,23 A. Hauke,23 H. J. Bauer,23 B. Spaan,23 T. Brandt,24 V. Klose,24 H. M. Lacker,24 W. F. Mader,24 R. Nogowski,24 A. Petzold,24 T. W. Beck,25 A. M. Eisner,25 C. J. Flacco,25 C. A. Heusch,25 K. E. Ford,25 G. Sciolla,25 S. J. Sekula,25 M. Spitznagel,25 F. Taylor,25 R. K. Yamamoto,25 H. Kim,26 J. C. Williams,26 J. I. Yi,26 C. Chen,27 W. D. Hulsbergen,27 A. Jawahery,27 C. K. Lae,27 D. A. Roberts,27 G. Simi,27 N. L. Blount,28 J. Brau,28 O. Igonkina,28 M. Lu,28 R. Rahmat,28 N. B. Sinev,28 D. Strom,28 J. Strube,28

0031-9007/06/96(25)/251802(7) 251802-1 © 2006 The American Physical Society
25 Ecole Polytechnique, LLR, F-91128 Palaiseau, France
26 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
27 Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy
28 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29 Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy
30 Harvard University, Cambridge, Massachusetts 02138, USA
31 Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
32 Imperial College London, London, SW7 2AZ, United Kingdom
33 University of Iowa, Iowa City, Iowa 52242, USA
34 Iowa State University, Ames, Iowa 50011-3160, USA
35 Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street Baltimore, Maryland 21218, USA
36 Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
37 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 ORSAY Cedex, France
38 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
39 University of Liverpool, Liverpool L69 7ZE, United Kingdom
40 Queen Mary, University of London, E1 4NS, United Kingdom
41 Royal Holloway and Bedford New College, University of London, Egham, Surrey TW20 0EX, United Kingdom
42 University of Louisville, Louisville, Kentucky 40292, USA
43 University of Manchester, Manchester M13 9PL, United Kingdom
44 University of Maryland, College Park, Maryland 20742, USA
45 University of Massachusetts, Amherst, Massachusetts 01003, USA
46 Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
47 McGill University, Montréal, Québec, Canada H3A 2T8
48 Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
49 University of Mississippi, University, Mississippi 38677, USA
50 Physique des Particules, Université de Montréal, Montréal, Québec, Canada H3C 3J7
51 Mount Holyoke College, South Hadley, Massachusetts 01075, USA
52 Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, I-80126, Napoli, Italy
53 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
54 University of Notre Dame, Notre Dame Indiana 46556, USA
55 Ohio State University, Columbus, Ohio 43210, USA
56 University of Oregon, Eugene, Oregon 97403, USA
57 Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy
58 Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
59 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
60 Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy
61 Dipartimento di Fisica, Scuola Normale Superiore and INFN, Università di Pisa, I-56127 Pisa, Italy
62 Prairie View A&M University, Prairie View, Texas 77446, USA
63 Princeton University, Princeton, New Jersey 08544, USA
64 Dipartimento di Fisica e INFN, Università di Roma La Sapienza, I-00185 Roma, Italy
65 Universität Rostock, D-18051 Rostock, Germany
66 Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
67 DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
68 University of South Carolina, Columbia, South Carolina 29208, USA
69 Stanford Linear Accelerator Center, Stanford, California 94309, USA
70 Stanford University, Stanford, California 94305-4060, USA
71 State University of New York, Albany, New York 12222, USA
72 University of Tennessee, Knoxville, Tennessee 37996, USA
73 University of Texas at Austin, Austin, Texas 78712, USA
74 University of Texas at Dallas, Richardson, Texas 75083, USA
75 Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy
76 Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy
77 IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
78 University of Victoria, Victoria, British Columbia, Canada V8W 3P6
79 Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
80 University of Wisconsin, Madison, Wisconsin 53706, USA
81 Yale University, New Haven, Connecticut 06511, USA
(Received 29 March 2006; published 28 June 2006)

We report the results of a search for $T$, $CP$, and $CPT$ violation in $B^0$-$\bar{B}^0$ mixing using an inclusive dilepton sample collected by the BABAR experiment at the PEP-II B factory. Using a sample of $232 \times 10^6$
Since the first observation of CP violation in 1964 [1], the neutral kaon system has provided many results probing the discrete symmetries CPT and T in $K^0-\bar{K}^0$ mixing [2]. Similarly, the BABAR experiment can investigate T, CP, and CPT violation in $B^0-\bar{B}^0$ mixing.

The physical states (solutions of the complex effective Hamiltonian for the $B^0-\bar{B}^0$ system) [3] can be written as

$$|B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle,$$

$$|B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle,$$

where H and L stand for heavy and light. Under CPT symmetry, the complex parameter $z$ vanishes. Similarly, T invariance implies $|q/p| = 1$. Finally, CP invariance requires both $|q/p| = 1$ and $z = 0$.

Inclusive dilepton events, where both $B$ mesons decay semileptonically ($b \to Xl\nu$, with $l = e$ or $\mu$), represent 4% of all $Y(4S) \to B\bar{B}$ decays and provide a very large sample with which to study $T$, CPT, and CP violation in mixing. In the direct semileptonic neutral $B$ decay, the flavor $B^0(\bar{B}^0)$ is tagged by the charge of the lepton $l^+$ ($l^-$).

At the $Y(4S)$ resonance, neutral $B$ mesons are produced in a coherent P-wave state. The $B$ mesons remain in orthogonal flavor states until one decays, after which the flavor of the other $B$ meson evolves with time. Neglecting second order terms in $z$, the decay rates for the three configurations ($l^+l^+$, $l^-l^-$, and $l^+l^-$) are given by

$$N^{++} \propto e^{-\Gamma_{l^+l^+}t/2} |p/q|^2 \left[ \cosh(\frac{\Delta m \Delta t}{2}) - \cos(\Delta m \Delta t) \right],$$

$$N^{--} \propto e^{-\Gamma_{l^-l^-}t/2} |p/q|^2 \left[ \cosh(\frac{\Delta m \Delta t}{2}) - \cos(\Delta m \Delta t) \right],$$

$$N^{+-} \propto e^{-\Gamma_{l^+l^-}t/2} \left[ \cosh(\frac{\Delta \Gamma \Delta t}{2}) - 2 \Re \text{Im} z \sinh(\frac{\Delta \Gamma \Delta t}{2}) + \cos(\Delta m \Delta t) + 2 \text{Im} z \sin(\Delta m \Delta t) \right],$$

where $\Delta t$ is the difference between the neutral $B$ decay times, $\Delta m$ is the $B^0-\bar{B}^0$ oscillation frequency, $\Gamma$ is the average neutral $B$ decay rate and $\Delta \Gamma$ is the decay rate difference between the two physical states. The sign of $\Delta t$ has a physical meaning only for opposite-sign dileptons and is given by $\Delta t = t^+ - t^-$ where $t^+$ ($t^-$) corresponds to $l^+$ ($l^-$), respectively.

The same-sign dilepton asymmetry $A_{T/CP}$, between the two oscillation probabilities $P(B^0 \to B^0)$ and $P(B^0 \to B^0)$ probes both $T$ and CP symmetries and can be expressed in terms of $|q/p|$: $A_{T/CP} = \frac{P(B^0 \to B^0) - P(B^0 \to \bar{B}^0)}{P(B^0 \to B^0) + P(B^0 \to B^0)}$, where $P(B^0 \to B^0)$ is the value reported in Ref. [3].

Standard model calculations [4] predict the magnitude of this asymmetry to be at or below $10^{-3}$. A large measured value would be an indication of new physics.

Similarly, the opposite-sign dilepton asymmetry, $A_{CP}$, between events with $\Delta t > 0$ and $\Delta t < 0$ compares the $B^0 \to B^0$ and $B^0 \to \bar{B}^0$ probabilities and is sensitive to CPT and CP violation. This asymmetry is given by

$$A_{CP} = \frac{P(B^0 \to B^0) - P(B^0 \to \bar{B}^0)}{P(B^0 \to B^0) + P(B^0 \to \bar{B}^0)}$$

where $\Delta t$ is the time difference between the events and $\Delta \Gamma$ is the decay rate difference between the two states.

As $|\Delta \Gamma|/\Gamma \ll 1$ [3], we have $\Re \text{Im} z (\Delta \Gamma \Delta t/2) = \Delta \Gamma \times \Re z \times (\Delta t/2)$ and this asymmetry is not sensitive to the CPT-violating term $\Re z$ alone, but to the product $\Delta \Gamma \times \Re z$.

In this Letter, we present measurements of $|q/p|$, $\text{Im} z$ and $\Delta \Gamma \times \Re z$ with a simultaneous likelihood fit to the observed $\Delta t$ distributions of same-sign and opposite-sign dilepton events. In the $\cosh(\Delta \Gamma \Delta t/2)$ term, we use $|\Delta \Gamma| = (5 \pm 3) \times 10^{-3}$ ps$^{-1}$, the value reported in Ref. [3].

This study is performed with data collected by the BABAR detector [5] at the PEP-II asymmetric-energy B factory between October 1999 and July 2004. The integrated luminosity of this sample is 211 fb$^{-1}$ recorded at the $Y(4S)$ resonance (“on resonance”) (232 $\times 10^6$ $B\bar{B}$ pairs) and about 16 fb$^{-1}$ recorded 40 MeV below the $Y(4S)$ resonance (“off resonance”).

The event selection is similar to that described in Ref. [6]. Non-$B\bar{B}$ events, mainly $e^+e^- \to q\bar{q}$ $(q = u\bar{d}, s\bar{c})$ continuum events, are suppressed by applying requirements on the shape and the topology of the event.

Lepton candidate tracks must have at least 12 hits in the drift chamber, at least one z-coordinate hit in the silicon vertex tracker (SVT), and a momentum in the Y(4S) center-of-mass system between 0.8 and 2.3 GeV/c. Electrons are selected by requirements on the ratio of the energy deposited in the electromagnetic calorimeter to the
momentum measured in the drift chamber. Muons are identified through the energy released in the calorimeter, as well as the strip multiplicity, track continuity, and penetration depth in the instrumented flux return. Lepton candidates are rejected if their signal in the Cherenkov detector is consistent with that of a kaon or a proton. The electron and muon selection efficiencies are about 85% and 55%, with pion misidentification probabilities around 0.2% and 3%, respectively.

Electrons from photon conversions are identified and rejected with a negligible loss of efficiency for signal events. Leptons from $J/\psi$ and $\phi(2S)$ decays are identified by pairing them with otherwise oppositely charged candidates of the same lepton species, selected with looser criteria. Events with at least two leptons are retained and the two highest momentum leptons in the $Y(4S)$ rest frame are used in the following.

The separation between direct leptons ($b \rightarrow l$) and background from the $b \rightarrow c \rightarrow l$ decay chain (cascade leptons) is achieved with a neural network that combines five discriminating variables: the momenta and opening angle of the two lepton candidates, and the total visible energy and missing momentum of the event, all computed in the $Y(4S)$ rest frame. Of the original sample of $232 \times 10^6$ $B\bar{B}$ pairs, $1.4 \times 10^6$ pass this dilepton selection.

Since the asymmetry $A_{CP}$ is expected to be small, we have determined the possible charge asymmetries induced by charge-dependent differences in the reconstruction and identification of electrons and muons. The charge asymmetries are defined as $a = (\varepsilon^+ - \varepsilon^-)/(\varepsilon^+ + \varepsilon^-)$ where $\varepsilon^+$ ($\varepsilon^-$) is the efficiency for positive and negative particles. As the lepton efficiencies and purities depend mainly on their momenta, we consider separately the asymmetry for the higher and lower momentum lepton, respectively, $a_{dir}$ and $a_{casc}$.

The charge asymmetry of track reconstruction is measured in the data by comparing tracks reconstructed using only the SVT with those passing the dilepton track selection, obtaining $a_{dir} = (0.8 \pm 0.2) \times 10^{-3}$.

The lepton identification efficiencies are measured as a function of total momentum and polar and azimuthal angles, with a control sample of radiative Bhabha events for electrons, and with a $ee \rightarrow \mu\mu\gamma$ control sample for muons. The misidentification probabilities are determined with control samples of kaons produced in $D^{*+} \rightarrow \pi^+ D^{0} \rightarrow \pi^+ K^{-}\pi^+$ (and charge conjugate) decays, pions produced in $K_S \rightarrow \pi^+\pi^-$ decays, three-prong $\tau$ decays, and protons produced in $\Lambda$ decays.

The control samples show that the muon track reconstruction efficiency has a charge asymmetry reaching $~5 \times 10^{-3}$ and that positive kaons are $20\%$–$30\%$ more likely than negative kaons to be misidentified as muons. As a consequence, in the likelihood fit (described below), we float the charge asymmetries $a_{dir}^{\mu}$ and $a_{casc}^{\mu}$ for direct and cascade muons.

For electrons, the charge asymmetry averaged over the signal phase space is $a_e = (0.4 \pm 0.2) \times 10^{-3}$ and we find that antiprotons with momentum $\sim 1$ GeV/c are significantly more likely than protons to be misidentified, due to annihilation with nucleons in the calorimeter material. Based on the charge asymmetry in tracking and in identification, we fix the charge asymmetry for the direct electrons with the higher momentum to $a_{dir}^e = 1.2 \times 10^{-3}$. For the lower momentum direct electrons and the cascade electrons, for which antiproton contamination is more important, we correct the initial charge asymmetry by the fraction of antiprotons estimated with $B\bar{B}$ Monte Carlo samples and the proton control sample. This gives the following charge asymmetries: $a_{dir}^e = 0.8 \times 10^{-3}$, $a_{casc}^e = 0.5 \times 10^{-3}$, and $a_{casc}^{\mu} = 0.2 \times 10^{-3}$.

In the inclusive approach used here, the $z$ coordinate of the $B$ decay point is approximated by the $z$ position of the point of closest approach between the lepton candidate and an estimate of the $Y(4S)$ decay point in the transverse plane. The $Y(4S)$ decay point is obtained by fitting the two lepton tracks to a common vertex, constrained to be consistent with the beam-spot position in the transverse plane. The proper time difference $\Delta t$ between the two $B$ meson decays is taken as $\Delta t = \Delta z/(\beta\gamma)c$, where $\Delta z$ is the difference between the $z$ coordinates of the leptons, with the same-sign convention as for $\Delta t$, and $\gamma = 0.55$ is the nominal Lorentz boost. For same-sign dileptons, the sign of $\Delta t$ is chosen randomly.

We model the contributions to our sample from $B\bar{B}$ decays using five categories of events, $i$, each represented by a probability density function (PDF) in $\Delta t$, $P_i^{\mu,e}$. Their shapes are determined using the $B^o\bar{B}^o$ ($n$) and $B^+\bar{B}^-$ ($c$) Monte Carlo simulation separately, with the approach described in Ref. [7].

The five categories are the following. First, the pure signal events with two direct leptons (sig), which are $81\%$ of the $B\bar{B}$ events, give information on the $T$, $CPT$, and $CP$ parameters. Then, we consider two categories of cascade decays: those in which the direct lepton and the cascade lepton come from different $B$ decays (obs), and those in which the direct lepton and the cascade lepton stem from the same $B$ decay (sbc). According to $B\bar{B}$ Monte Carlo simulation, their contributions are around $9\%$ and $4\%$, respectively. In addition, $3\%$ of the dilepton events originate from the decay chain $b \rightarrow \tau^{-} \rightarrow l^{-}$ $(1d1\tau)$, which tags the $B$ flavor correctly. Finally, the remaining events (other) consist mainly of one direct lepton and one lepton from the decay of a charmonium resonance from the other $B$ decay.

The sig event PDF, $P_{sig}^{\mu,e}$, are obtained by the convolution of an oscillatory term containing the $T$, $CPT$, and $CP$ parameters [Eq. (1)] for neutral $B$ decays (or an exponential function for charged $B$ decays) with a resolution function which is the sum of three Gaussians. The widths of the core and tail Gaussians and the fractions of the core and outlier Gaussians are free parameters in the fit. The width of the outlier Gaussian is fixed to 8 ps. The means of the Gaussians are fixed to zero [8].
The obc event PDF, $P^{obc}_{n;c}$, are modeled by the convolution of $\Delta t$-dependent terms of a form similar to those of the signal with a resolution function which takes into account the effect of the charmed meson lifetimes. Since both short-lived $D^0$ and $D^+\pi^-$, and long-lived $D^+$ mesons are involved in cascade decays, the resolution function for the long-lived and short-lived components is a double-sided exponential convolved with the sum of three Gaussians. To allow for possible outliers not present in the Monte Carlo simulation, the fraction of the third Gaussian is free in the fit. The parameterization of the sbc event PDF, $P^{sbc}_{n;c}$, account for the lifetimes of charmed mesons in a similar way.

The PDF for $1d1\tau$ events, $P^{n;c}_{1d1\tau}$, are similar to that of the sig events. The resolution function used takes into account the $\tau$ lifetime and is chosen to be two double-sided exponentials convolved with two Gaussians. Finally, the PDF for the remaining events, $P^{n;c}_{other}$, are the convolution of an exponential function with an effective lifetime and two Gaussians.

The fractions $(f^{n;c}_{sbc}, f^{n;c}_{1d1\tau}, f^{n;c}_{other})$ of sbc, $1d1\tau$ and other events, are determined directly from the $B^0\bar{B}^0$ and $B^+B^-$ Monte Carlo simulation. The fraction $f^{n;c}_{obc}$ of obc events are fitted to the data, with the ratio $f^{n;c}_{obc}/f^{n;c}_{obc}$ constrained to the estimate obtained with Monte Carlo samples. The fraction $f_{++}$ of $B^+B^-$ events is determined from the data themselves.

The last component of the dilepton sample originates from non-$B\bar{B}$ events, and has been estimated using off-resonance data to be $f_{cont} = (3.1 \pm 0.1)\%$ of the data set. This PDF is modeled using off-resonance events with looser cuts and on-resonance events that fail the continuum-rejection cuts. The charge asymmetries $a^{cont}_{e,\mu}$ obtained with the two samples are consistent with zero at the 1% level and thus are fixed to zero in the likelihood.

The $T/CP$ and $CPT/CP$ violation parameters are extracted from a binned maximum likelihood fit to the events that pass the dilepton selection. The likelihood $L$ combines the detector-related charge asymmetries and the time-dependent PDFs described previously. As the charge asymmetries are significantly different for electrons and muons, we split the sample into four lepton combinations: $e_1e_2$, $e_1\mu_2$, $\mu_1\mu_2$, and $e_1\mu_1$. The obc event PDF, $P^{n;c}_{obc}$, account for the lifetimes of charmed mesons in a similar way.

The likelihood is given by

$$L(\Delta t) = (1 + q_1a^{cont}_{l_1} + q_2a^{cont}_{l_2})f_{cont}P_{cont} + (1 - f_{cont})(f_{++}P^{B^+B^-} + (1 - f_{++})P^{B^0\bar{B}^0})$$

$$P^{B^0\bar{B}^0}_{n;c} = (1 - f^{n;c}_{sbc})(1 + q_1a^{esc}_{l_1} + q_2a^{esc}_{l_2})P^{esc}_{casc} + f^{n;c}_{sbc}(1 + q_1a^{dir}_{l_1} + q_2a^{dir}_{l_2})P^{dir}_{casc}$$

$$P^{B^+B^-}_{n;c} = (1 - f^{n;c}_{sbc})(1 + q_1a^{esc}_{l_1} + q_2a^{esc}_{l_2})P^{esc}_{casc} + f^{n;c}_{sbc}(1 + q_1a^{dir}_{l_1} + q_2a^{dir}_{l_2})P^{dir}_{casc}$$

where $q_1$, $q_2$, $l_1$, and $l_2$ are the charges and the flavors $(e, \mu)$ of the two leptons.

The likelihood fit gives $|q/p| - 1 = (-0.8 \pm 2.7) \times 10^{-3}$, $\text{Im}z = (-13.9 \pm 7.3) \times 10^{-3}$, and $\Delta \Gamma \times \text{Re}z = (7.1 \pm 3.9) \times 10^{-3}$ ps$^{-1}$. The correlation between the measurements of $\text{Im}z$ and $\Delta \Gamma \times \text{Re}z$ is 76%. If we fix $\Delta \Gamma = 0$, we obtain $\text{Im}z = (-3.7 \pm 4.6) \times 10^{-3}$. The fitted fractions of $B^+B^-$ and obc events are $f_{++} = (59.1 \pm 0.3)\%$ and $f^{n;c}_{obc} = (10.7 \pm 0.1)\%$. Figure 1 shows the $A_{T/CP}$ asymmetry between $(l^+, l^+)$ and $(l^-, l^-)$ dileptons defined in Eq. (2) and the $A_{CPT/CP}$ asymmetry between $(l^+, l^-)$ dileptons with $\Delta t > 0$ and $\Delta t < 0$ defined in Eq. (3).

There are several sources of systematic uncertainty in these measurements. To determine their magnitude, we vary each source of systematic effect by its known or estimated uncertainty, and take the resulting deviations in the measured parameters as its error.

For $|q/p|$, the most important systematic uncertainties are due to the correction of electron charge asymmetries. A $1.4 \times 10^{-3}$ deviation of $|q/p|$ is observed by shifting simultaneously the electron charge asymmetries by $1.0 \times 10^{-3}$ which corresponds to the uncertainty estimated with Monte Carlo and control samples. The systematic uncertainty related to the charge asymmetry due to the tracking is estimated by randomly discarding 0.16% of the negative tracks from our data sample. This fraction has been determined from an independent data control sample. A $1.0 \times 10^{-3}$ deviation of $|q/p|$ is observed. Similarly, a possible

---

FIG. 1 (color online). (a) $A_{T/CP}$ asymmetry between $(l^+, l^+)$ and $(l^-, l^-)$. A larger charge asymmetry for cascade muons, dominant at small $|\Delta t|$, explains the nonflatness of the curve. (b) $A_{CPT/CP}$ asymmetry between $(l^+, l^-)$ dileptons with $\Delta t > 0$ and $\Delta t < 0$. 

1% charge asymmetry for non-$B\bar{B}$ backgrounds induces a systematic uncertainty of $0.6 \times 10^{-3}$.

The widths of the first and second Gaussian of the resolution function for the $bc$ and $sbc$ categories as well as the pseudolifetime for the $1d1\tau$ and other categories are varied separately by 10%. This variation is motivated by the comparison of the fitted parameters of the signal resolution function obtained on $B\bar{B}$ Monte Carlo samples and on data. The fractions of the short-lived and long-lived charmed meson components for $bc$ and $sbc$ are varied by 10%.

We have also varied the parameters $\Delta m$, $\tau_{B_s}$, and $\tau_{B_c}$ independently within their known uncertainties [9], and $\Delta \Gamma$ from $10^{-5}$ to 0.1 ps$^{-1}$. Finally, one of the dominant systematic uncertainties on $\Delta \Gamma \times \text{Re} \zeta$ is the imperfect knowledge of the absolute $\zeta$ scale of the detector and the residual uncertainties in the SVT local alignment, for which we estimate an error of $1.2 \times 10^{-3}$ ps$^{-1}$.

For each parameter, the total systematic uncertainty is the sum in quadrature of the estimated systematic uncertainties from each source, as summarized in Table I. When we assume $\Delta \Gamma = 0$, the systematic uncertainty for $\text{Re} \zeta$ is $2.9 \times 10^{-3}$.

If we compare our results to $\Delta \Gamma \times \text{Re} \zeta = 0.0$ and $\text{Im} \zeta = 0.0$ (no CPT violation case), the $\chi^2$ is 3.25 for 2 degrees of freedom, which is consistent with CPT invariance at 19.7% confidence level. Finally, assuming $\Delta \Gamma = 0$, we obtain $\text{Re} \zeta = (-3.7 \pm 4.6(\text{stat}) \pm 2.9(\text{syst.})) \times 10^{-3}$.

In summary with the 1999–2004 data ($232 \times 10^6 B\bar{B}$ pairs), we have performed a simultaneous likelihood fit of same-sign and opposite-sign dileptons. We measure the independent parameters governing $CP$ and $T$ violation, and the $CPT$ and $CP$ violation parameters. The results are

$$|q/p| - 1 = (-0.8 \pm 2.7(\text{stat}) \pm 1.9(\text{syst.})) \times 10^{-3},$$

$$\text{Im} \zeta = (-13.9 \pm 7.3(\text{stat}) \pm 3.2(\text{syst.})) \times 10^{-3},$$

$$\Delta \Gamma \times \text{Re} \zeta = (-7.1 \pm 3.9(\text{stat}) \pm 2.0(\text{syst.})) \times 10^{-3} \text{ ps}^{-1}.$$  

These measurements are a clear improvement over previously published values [3,10]. The new measurement of $|q/p|$ is consistent with the standard model predictions [4].

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 wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACYT (Mexico), Marie Curie EIF (European Union), the A.P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

*Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France.
†Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.
‡Also with Università della Basilicata, Potenza, Italy.

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
[2] A. Apostolakis et al. (CLEAR Collaboration), Phys. Lett. B 456, 297 (1999).
[3] B. Aubert at al. (BABAR Collaboration), Phys. Rev. D 70, 012007 (2004).
[4] M. Beneke et al., Phys. Lett. B 576, 173 (2003); M. Ciuchini et al., J. High Energy Phys. 08 (2003) 031.
[5] B. Aubert et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 1 (2002).
[6] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 88, 231801 (2002).
[7] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 88, 221803 (2002).
[8] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 66, 032003 (2002).
[9] K. Anikeev et al. (Heavy Flavor Averaging Group), hep-ex/0505100.
[10] E. Nakano et al. (BELLE Collaboration), Phys. Rev. D 73, 112002 (2006).