

# Search for $T$ and $CP$ Violation in $B^0\text{-}\bar{B}^0$ Mixing with Inclusive Dilepton Events

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We report the results of a search for  $T$  and  $CP$  violation in  $B^0\text{-}\bar{B}^0$  mixing using an inclusive dilepton sample collected by the BABAR experiment at the PEP-II  $B$  Factory. The asymmetry between  $\ell^+\ell^+$  and  $\ell^-\ell^-$  events allows us to compare the probabilities for  $\bar{B}^0 \rightarrow B^0$  and  $B^0 \rightarrow \bar{B}^0$  oscillations and thus probe  $T$  and  $CP$  invariance. Using a sample of 23 million  $B\bar{B}$  pairs, we measure a same-sign dilepton asymmetry of  $A_{T/CP} = (0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst}))\%$ . For the modulus of the ratio of complex mixing parameters  $p$  and  $q$ , we obtain  $|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst})$ .

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Since the first observation of  $CP$  violation in 1964 [1], the kaon system has provided many other results probing the  $CPT$  and  $T$  discrete symmetries [2]. Beyond the

investigation of  $CP$  violation through the measurements of the unitarity triangle angles  $\alpha$ ,  $\beta$  and  $\gamma$ , the BABAR experiment can investigate  $T$  and  $CP$  violation purely in

mixing.

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

$$|B_{L,H}^0\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

where  $p$  and  $q$  are complex mixing parameters with the normalization  $|p|^2 + |q|^2 = 1$ .

The  $CPT$  invariant asymmetry,  $A_{T/CP}$ , between the two oscillation probabilities  $P(\bar{B}^0 \rightarrow B^0)$  and  $P(B^0 \rightarrow \bar{B}^0)$  probes both  $T$  and  $CP$  symmetries and can be expressed in terms of  $p$  and  $q$ :

$$\begin{aligned} A_{T/CP} &= \frac{P(\bar{B}^0 \rightarrow B^0) - P(B^0 \rightarrow \bar{B}^0)}{P(\bar{B}^0 \rightarrow B^0) + P(B^0 \rightarrow \bar{B}^0)} \\ &= \frac{1 - |q/p|^4}{1 + |q/p|^4}. \end{aligned} \quad (1)$$

Standard Model calculations [3] predict the size of this asymmetry to be at or below  $10^{-3}$ . Therefore, a large measured value could be an indication of new physics.

Inclusive dilepton events representing 4% of all  $\Upsilon(4S) \rightarrow B\bar{B}$  decays provide a very large sample with which to study  $T$  and  $CP$  violation in mixing. The flavor of each  $B$  meson is tagged by the charge of the lepton. Assuming  $\Delta B = \Delta Q$  and  $CP$  invariance in the direct ( $b \rightarrow \ell$ ) semileptonic decay process, the asymmetry between same-sign lepton pairs,  $\ell^+\ell^+$  and  $\ell^-\ell^-$ , allows a comparison of the two oscillation probabilities  $P(\bar{B}^0 \rightarrow B^0)$  and  $P(B^0 \rightarrow \bar{B}^0)$ . The asymmetry  $A_{T/CP}$  for direct same-sign dileptons is time independent. However, in this analysis, the time difference  $\Delta t$  between the two  $B$  meson decays is used to discriminate the direct leptons from the cascade leptons produced in ( $b \rightarrow c \rightarrow \ell$ ) transitions.

The measurement of  $A_{T/CP}$  reported here is performed using events collected by the BABAR detector [4] from  $e^+e^-$  collisions at the PEP-II asymmetric-energy  $B$  Factory between October 1999 and October 2000. The integrated luminosity of this sample is  $20.7 \text{ fb}^{-1}$  recorded at the  $\Upsilon(4S)$  resonance (“on-resonance”) and  $2.6 \text{ fb}^{-1}$  recorded about 40 MeV below the  $\Upsilon(4S)$  resonance (“off-resonance”).  $B\bar{B}$  pairs from the  $\Upsilon(4S)$  decay move along the high-energy beam direction ( $z$ ) with a nominal Lorentz boost  $\langle\beta\gamma\rangle = 0.55$ .

Lepton candidates must have at least 12 hits in the drift chamber (DCH), at least one  $z$ -coordinate hit in the silicon vertex tracker (SVT), and a momentum in the  $\Upsilon(4S)$  center-of-mass system (CMS) between 0.7 and 2.3 GeV/ $c$ . Electrons are selected by requirements on the ratio of the energy deposited in the electromagnetic calorimeter (EMC) and the momentum measured in the DCH, on the lateral shape of the energy deposition in the calorimeter, and on the specific ionization density measured in the DCH. 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 (IFR). Lepton candidates are rejected if they are consistent with a kaon or proton hypothesis according to the Cherenkov angle measured in the detector of internally reflected Cherenkov light (DIRC) or to the ionization density measured in the DCH. The electron and muon selection efficiencies are about 92% and 75%, with pion misidentification probabilities around 0.2% and 3%, respectively.

Non- $B\bar{B}$  events are suppressed by requiring the ratio of second to zeroth order Fox-Wolfram moments [5] to be less than 0.4. In addition, the residual contamination from radiative Bhabha and two-photon events is reduced by requiring the squared invariant mass of the event to be greater than  $20 \text{ GeV}^2/c^4$ , the event aplanarity to be greater than 0.01, and the number of charged tracks to be greater than four. Electrons from photon conversions are identified and rejected with a negligible loss of efficiency for signal events. Leptons from  $J/\psi$  and  $\psi(2S)$  decays are identified by pairing them with other oppositely-charged candidates of the same-lepton species, selected with looser criteria. We reject the whole event if any combination has an invariant mass within  $3.037 < M(\ell^+\ell^-) < 3.137 \text{ GeV}/c^2$  or  $3.646 < M(\ell^+\ell^-) < 3.726 \text{ GeV}/c^2$ .

To minimize the wrong flavor tags due to leptons from cascade charm decays, we use a neural network algorithm that combines five discriminating variables. These are calculated in the CMS (see Fig. 1) and are the momenta of the two leptons with highest momentum,  $p_1^*$  and  $p_2^*$ , the total visible energy  $E_{tot}$ , the missing momentum  $p_{miss}$  of the event, and the opening angle between the leptons,  $\theta_{12}$ . The first two variables,  $p_1^*$  and  $p_2^*$ , are very powerful in discriminating between direct and cascade leptons. The last variable,  $\theta_{12}$ , efficiently removes direct-cascade lepton pairs coming from the same  $B$  and further rejects photon conversions. Some additional discriminating power is also provided by the other two variables. In order to be insensitive to the Monte Carlo, the fraction of cascade leptons is determined from a fit to the same-sign and opposite-sign dilepton data.

In the inclusive approach used here, the  $z$  coordinate of the  $B$  decay point is the  $z$  position of the point of closest approach between the lepton candidate and an estimate of the  $\Upsilon(4S)$  decay point in the transverse plane. The  $\Upsilon(4S)$  decay point is obtained by fitting the two lepton tracks to a common vertex in the transverse plane, which is constrained to be consistent with the beam-spot position. The time difference,  $\Delta t$ , between the two  $B$  meson decays is determined from the absolute value,  $\Delta z$ , of the difference in  $z$  between the two  $B$  decays by  $\Delta t = \Delta z / \langle\beta\gamma\rangle c$ . The background events (cascade leptons from unmixed  $B^0\bar{B}^0$  events and  $B^+B^-$  events, and non- $B\bar{B}$  events) are most prominent at low  $\Delta z$  (see Fig. 2). Therefore, a requirement of  $\Delta z > 200 \mu\text{m}$  allows us to eliminate about 50% of background without

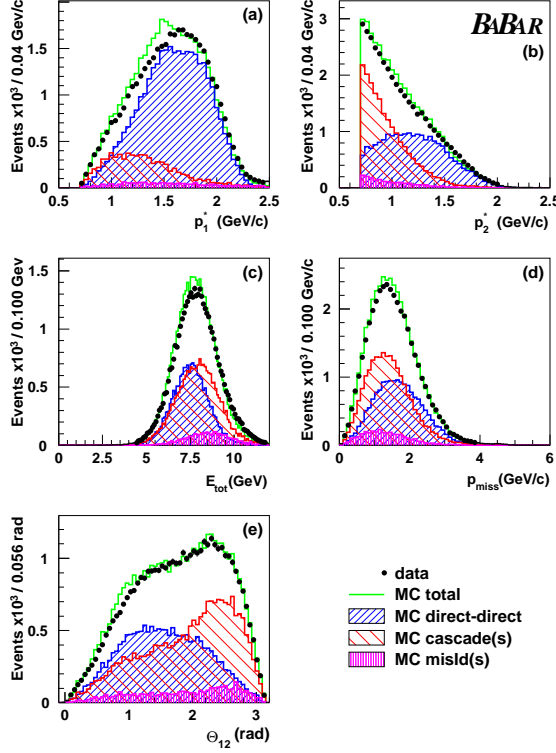


FIG. 1: Distributions of the discriminating variables (a)  $p_1^*$ , (b)  $p_2^*$ , (c)  $E_{tot}$ , (d)  $p_{miss}$  and (e)  $\theta_{12}$ , for data (dots) and Monte Carlo events (histograms). The contributions from direct-direct pairs, direct-cascade or cascade-cascade pairs, and pairs with one or more fake leptons are shown for the Monte Carlo samples.

dramatically decreasing the signal efficiency. Finally, in the measurement of  $A_{T/CP}$ , the dilution factor due to remaining background is corrected as a function of  $\Delta t$ .

Application of the selection criteria described above results in a sample of 20,381 same-sign dilepton events, consisting of 5,252 electron pairs, 5,152 muon pairs and 9,977 electron-muon pairs. For  $\Delta z > 200 \mu\text{m}$ , the fraction of non- $B\bar{B}$  events, measured with the off-resonance data, is 4.3% with a charge asymmetry of  $(-5 \pm 10)\%$ ; the main  $B\bar{B}$  backgrounds, determined from Monte Carlo simulation, include 24% of one direct lepton paired with a cascade lepton from the other  $B$ , 10% of fake leptons from the other  $B$ , 2% of fake leptons from the same  $B$  and 2% of leptons from  $J/\psi$  or resonance decays.

Since the asymmetry  $A_{T/CP}$  is expected to be small, we have carefully determined the possible charge asymmetries induced by the detection and reconstruction of electrons and muons. The three sources of charge asymmetry in the selection of lepton candidates come from differences, for positive and negative particles, in tracking efficiency  $\varepsilon_{track}^\pm$ , in particle identification efficiency  $\varepsilon_{pid}^\pm$ , and in misidentification probability  $\eta_{pid}^\pm$ . Independent samples are used to estimate these efficiencies and

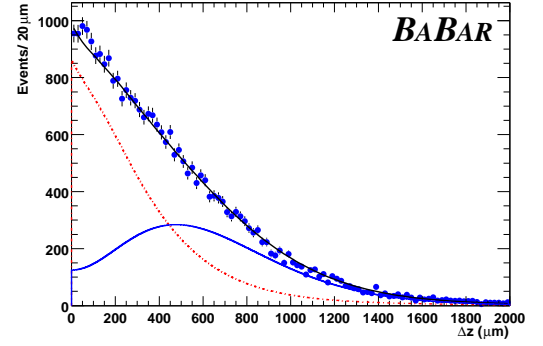


FIG. 2: Distribution of the same-sign dileptons as a function of  $\Delta z$ ; the curve superimposed on the dots is determined from a fit to the same-sign and opposite-sign dileptons; the solid and dotted lines represent respectively the signal component ( $B^0B^0$  or  $\bar{B}^0\bar{B}^0$  pairs) and the background component (cascade leptons from unmixed  $B^0\bar{B}^0$  and  $B^+B^-$  events, leptons from  $J/\psi$ , resonance decays and non- $B\bar{B}$  events).

probabilities as a function of several charged track parameters  $x_i$ : total or transverse momentum, and polar and azimuthal angles in the laboratory frame. The numbers of “detected” positive and negative leptons  $N_{det}^\pm$  are related to the numbers of true leptons  $N_{true}^\pm$  by the equation

$$N_{det}^\pm(x_i, p^*) = N_{true}^\pm(x_i, p^*) \cdot \varepsilon_{track}^\pm(x_i) \cdot [\varepsilon_{pid}^\pm(x_i) + r(\pi, p^*) \cdot \eta_{pid}^\pm(\pi, x_i) + r(K, p^*) \cdot \eta_{pid}^\pm(K, x_i) + r(p, p^*) \cdot \eta_{pid}^\pm(p, x_i)], \quad (2)$$

where  $r(\pi, p^*)$ ,  $r(K, p^*)$  and  $r(p, p^*)$  are the relative abundances of hadrons ( $\pi$ ,  $K$ , and  $p$ ) with respect to the lepton abundance for a given  $p^*$  (the momentum of the track in the CMS). These quantities are obtained from  $B\bar{B}$  Monte Carlo events, after applying the event selection criteria with perfect particle identification. To correct for charge asymmetries in the lepton detection, we apply a weight proportional to the ratio  $N_{true}^\pm(x_i, p^*)/N_{det}^\pm(x_i, p^*)$ , for each lepton in the sample.

Using tracks selected from multi-hadron events, the tracking efficiencies  $\varepsilon_{track}^\pm(x_i)$  for positive and negative particles are determined by computing the ratio of the number of SVT tracks with at least 12 DCH hits as required in the dilepton selection, divided by the initial number of SVT tracks. These tracking efficiencies are tabulated as a function of transverse momentum and polar and azimuthal angles. The charge asymmetry correction is less than 0.1% on average in the relevant momentum range.

The identification efficiencies  $\varepsilon_{pid}^\pm(x_i)$  are measured as a function of total momentum and polar and azimuthal angles, with two control samples consisting of  $ee \rightarrow eeee$  (with  $\gamma\gamma \rightarrow ee$ ) and radiative Bhabha events for electrons, and with a  $ee \rightarrow ee\mu\mu$  (with  $\gamma\gamma \rightarrow \mu\mu$ ) control

sample for muons. The misidentification probabilities  $\eta_{pid}^{\pm}(\text{hadron}, x_i)$  are determined using control samples of kaons produced in  $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ K^- \pi^+$  decays (and charge conjugate), pions produced in  $K_S \rightarrow \pi^+ \pi^-$  decays, and one-prong and three-prong  $\tau$  decays, and protons produced in  $\Lambda$  decays.

For the electrons, the charge asymmetry in the particle identification efficiency reaches (0.5–1.0)% in some regions of the lepton phase space. The impact of the charge asymmetry in misidentification is negligible because the absolute misidentification probability for pions is extremely small ( $\sim 0.2\%$ ). However, the  $\Lambda$  control sample indicates a very large misidentification probability for antiprotons with momentum  $\sim 1 \text{ GeV}/c$ . Such an effect is due to the annihilation of antiprotons with nucleons in the calorimeter, which produces a signature similar to that of an electron. The impact of this effect is balanced by the low relative abundance of antiprotons in  $B$  decays. Overall, antiprotons induce a charge asymmetry of order 0.1% and a correction is applied for this effect.

For the muons, the  $ee\mu\mu$  control sample shows that the charge asymmetry in the efficiency reaches 0.5%. The misidentification probability for pions is much larger ( $\sim 3\%$ ) than in the case of electrons but there is no indication of any charge asymmetry induced. On the other hand, the kaon misidentification distribution shows a charge asymmetry at the level of (10–20)% due to the difference between cross sections for  $K^+$  and  $K^-$  meson interactions with matter for momenta around 1 GeV/c.

Equation 1 is applicable for pure signal (direct leptons from  $B^0 B^0$  and  $\bar{B}^0 \bar{B}^0$  events). However, the dilepton sample is contaminated by cascade leptons from  $B^+ B^-$  and unmixed  $B^0 \bar{B}^0$  events, non- $B\bar{B}$  events, and  $J/\psi$  decays (see Fig. 2). Assuming no charge asymmetry in the background and assuming  $CP$  invariance holds in direct semileptonic  $B$  decays, we can write the measured asymmetry  $A_{T/CP}^{meas}$  (see Fig. 3) in terms of the number of events  $N$  as

$$\begin{aligned} A_{T/CP}^{meas}(\Delta t) &= \frac{N(\ell^+ \ell^+, \Delta t) - N(\ell^- \ell^-, \Delta t)}{N(\ell^+ \ell^+, \Delta t) + N(\ell^- \ell^-, \Delta t)} \\ &= A_{T/CP} \cdot \frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}, \end{aligned} \quad (3)$$

where  $S(\Delta t)$  and  $B(\Delta t)$  are the numbers of signal and background events respectively. Therefore, extraction of a value for  $A_{T/CP}$  requires a determination of the dilution factor  $S(\Delta t)/[S(\Delta t) + B(\Delta t)]$ . The asymmetry between same-sign dileptons is corrected for the background dilution using the time dependent probability density functions shown in Fig. 2. These probability density functions are obtained with a fit to data for the same-sign and opposite-sign dilepton samples with the value of  $\Delta m_d$  fixed to the world average value [6]. This fit is similar to that used in the measurement of  $\Delta m_d$

with dilepton events [7]: it determines the corrections to the resolution function extracted from Monte Carlo simulations, the fraction of cascade leptons, the average lifetime of the charm component for cascade leptons, the fraction of cascade leptons, and the fraction of charged  $B$  events. In addition, the fraction of non- $B\bar{B}$  events is measured from off-resonance data. From a  $\chi^2$  fit to the distribution of the asymmetry as a function of  $\Delta t$  for the same-sign dileptons with  $\Delta z > 200 \mu\text{m}$  (see Fig. 3), we extract  $A_{T/CP} = (0.5 \pm 1.2)\%$ .

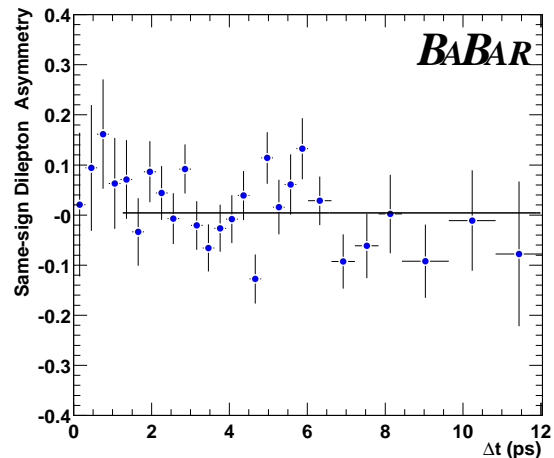


FIG. 3: Corrected same-sign dilepton asymmetry as a function of  $\Delta t$ . The line shows the result of the fit for the dileptons with  $\Delta z > 200 \mu\text{m}$ .

The systematic uncertainties related to the detection charge asymmetry both for tracking and lepton identification are determined using direct leptons from semileptonic  $B$  decays. This sample has the same topology and kinematics as the leptons from dilepton events. This single-lepton charge asymmetry, sensitive to the charge asymmetry due to detection bias, may also be affected by the real physical asymmetry  $A_{T/CP}$  in the dilepton events. But, in practice, the effect introduced by  $A_{T/CP}$  is suppressed by more than one order of magnitude and is therefore neglected. With the 1999–2000 data set, we select roughly 1.5 million electrons and 1.5 million muons. After subtraction of scaled off-resonance data and after applying a correction weight derived from Eq. 2, we measure the charge asymmetries to be  $(-0.30 \pm 0.14)\%$  for the electrons and  $(-0.35 \pm 0.17)\%$  for the muons. We assign these residual asymmetries  $\pm 0.30\%$  and  $\pm 0.35\%$  as systematic errors due to charge asymmetry in detection efficiencies. With the dilution factor correction, the total systematic errors related to the charge asymmetry in the detection are  $\pm 0.5\%$  and  $\pm 0.6\%$  for electrons and muons, respectively.

The assumption of no charge asymmetry in the background is confirmed by the off-resonance data where the charge asymmetry  $(-5 \pm 10)\%$  is consistent with zero and

leads to a  $\pm 0.7\%$  uncertainty on the  $A_{T/CP}$  measurement. In addition, the charge asymmetry of the events with  $\Delta z < 100 \mu\text{m}$ , which contain 85% background (cascade leptons from  $B^\pm$  and unmixed  $B^0$ ), is  $(1.2 \pm 1.4)\%$ , also consistent with zero. From this asymmetry, we can constrain to  $\pm 0.9\%$  the uncertainty on  $A_{T/CP}$  due to a possible charge asymmetry in the decays producing the cascade leptons. If we assume  $CP$  invariance in the decays producing the cascade, this uncertainty vanishes.

The background dilution correction is measured with the data from the full dilepton sample with the value of  $\Delta m_d$  fixed to the world average value [6]. The uncertainty on the ratio  $B/S$  leads to a  $\pm 3\%$  multiplicative error on  $A_{T/CP}$ , which is negligible. A possible dilution of  $A_{T/CP}$  due to double mistag is neglected because the probability of double mistag is at the level of only 1%.

TABLE I: Summary of systematic uncertainties on  $A_{T/CP}$ .

Type of systematic error	$\sigma(A_{T/CP})(\%)$
Electron charge asymmetry in the detection	0.5
Muon charge asymmetry in the detection	0.6
Non- $B\bar{B}$ background charge asymmetry	0.7
$B\bar{B}$ background charge asymmetry	0.9
Correction of the background dilution	0.01
Total	1.4

In conclusion, we measure  $A_{T/CP} = (0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst}))\%$  where the total systematic uncertainty is the quadratic sum of the systematic uncertainties listed in Table I. From Eq. 1, the  $A_{T/CP}$  asymmetry gives the modulus of the ratio of complex mixing parameters  $p$  and  $q$  equal to

$$|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst}).$$

This measurement can be translated into a measurement of the  $CP$  violating parameter  $\varepsilon_B = (p - q)/(p + q)$ . We obtain  $\text{Re}(\varepsilon_B)/(1 + |\varepsilon_B|^2) = (1.2 \pm 2.9(\text{stat}) \pm 3.6(\text{syst})) \times$

$10^{-3}$ , which is the most stringent test of  $T$  and  $CP$  violation in  $B^0$ - $\bar{B}^0$  mixing to date and is consistent with previous measurements [8].

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