Search for CP Violation in B^0- $\bar{B}^0$ Mixing Using Partial Reconstruction of $B^0 \to D^{*-} X \ell^+ \nu_\ell$ and a Kaon Tag

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(*BABAR* Collaboration)

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We present results of a search for CP violation in B^0-$\bar{B}^0$ mixing with the *BABAR* detector. We select a sample of $B^0 \to D^{*-}X\ell^+\nu$ decays with a partial reconstruction method and use kaon tagging to assess the flavor of the other B meson in the event. We determine the CP violating asymmetry $\mathcal{A}_{CP} \equiv [N(B^0B^0) - N(\overline{B}^0\overline{B}^0)]/[N(B^0B^0) + N(\overline{B}^0\overline{B}^0)] = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$, corresponding to $\Delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$.

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Experiments at B factories have observed CP violation in direct B^0 decays [1] and in the interference between B^0 mixing and decay [2]. CP violation in mixing has so far eluded observation.

The weak-Hamiltonian eigenstates are related to the flavor eigenstates of the strong interaction Hamiltonian by $|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$. The value of the ratio $|q/p|$ can be determined from the asymmetry between the two oscillation probabilities $\mathcal{P} = P(B^0 \to \bar{B}^0)$ and $\bar{\mathcal{P}} = P(\bar{B}^0 \to B^0)$ through $\mathcal{A}_{CP} = (\bar{\mathcal{P}} - \mathcal{P})/(\bar{\mathcal{P}} + \mathcal{P}) = (1 - |q/p|^4)/(1 + |q/p|^4) \approx 2\Delta_{CP}$, where $\Delta_{CP} = 1 - |q/p|$ and the Standard Model (SM) prediction is $\mathcal{A}_{CP} = -(4.0 \pm 0.6) \times 10^{-4}$ [3]. Any observation with the present experimental sensitivity $[\mathcal{O}(10^{-3})]$ would therefore reveal physics beyond the SM.

Experiments measure $\mathcal{A}_{CP}$ from the dilepton asymmetry, $\mathcal{A}_{\ell\ell} = [N(\ell^+\ell^+) - N(\ell^-\ell^-)]/[N(\ell^+\ell^+) + N(\ell^-\ell^-)]$, where an ℓ^+ (ℓ^-) tags a B^0 ($\bar{B}^0$) meson, and ℓ refers to either an electron or a muon [4]. These measurements benefit from the large number of produced dilepton events. However, they rely on the use of control samples to subtract the charge-asymmetric background originating from hadrons wrongly identified as leptons or leptons from light hadron decays and to compute the charge-dependent lepton identification asymmetry that may produce a false signal. The systematic uncertainties associated with the corrections for these effects constitute a severe limitation to the precision of the measurements.

Using a sample of dimuon events, the D0 Collaboration measured a value of $\mathcal{A}_{CP}$ for a mixture of B_s and B^0 decays that deviates from the SM by 3.9 standard deviations [5]. Measurements of $\mathcal{A}_{CP}$ for $B_s \to D_s\mu X$ decays are consistent with the SM [6].

We present a measurement of $\mathcal{A}_{CP}(B^0)$ with a new technique. We reconstruct B^0 mesons (hereafter called B_R; charge conjugation is implied) from semileptonic

$B^0 \to D^{*-}X\ell^+\nu$ events with a partial reconstruction of the $D^{*-} \to \pi^-\bar{D}^0$ decay [7]. The observed asymmetry between the number of events with an ℓ^+ versus an ℓ^- is

$$A_\ell \approx \mathcal{A}_{r\ell} + \mathcal{A}_{CP}\chi_d, \quad (1)$$

where $\chi_d = 0.1862 \pm 0.0023$ [8] is the integrated mixing probability for B^0 mesons and $\mathcal{A}_{r\ell}$ is the detector-induced charge asymmetry in the B_R reconstruction.

We identify ("tag") the flavor of the other B^0 meson (labeled B_T) using events with a charged kaon (K_T). An event with a K^+ (K^-) usually arises from a state that decays as a B^0 ($\bar{B}^0$) meson. When mixing occurs, the ℓ and K_T have the same electric charge. The observed asymmetry in the rate of mixed events is

$$A_T = \frac{N(\ell^+K_T^+) - N(\ell^-K_T^-)}{N(\ell^+K_T^+) + N(\ell^-K_T^-)} \approx \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}, \quad (2)$$

where $\mathcal{A}_K$ is the detector charge asymmetry in kaon reconstruction. A kaon with the same charge as the ℓ might also arise from the Cabibbo-favored decays of the D^0 meson produced with the lepton from the partially reconstructed side (K_R). The asymmetry observed for these events is

$$A_R = \frac{N(\ell^+K_R^+) - N(\ell^-K_R^-)}{N(\ell^+K_R^+) + N(\ell^-K_R^-)} \approx \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}\chi_d. \quad (3)$$

Equations (1)–(3) can be used to extract $\mathcal{A}_{CP}$ and the detector-induced asymmetries ($\mathcal{A}_{r\ell}$ and $\mathcal{A}_K$).

A detailed description of the *BABAR* detector is provided elsewhere [9]. We use a sample with an integrated luminosity of 425.7 fb^{-1} [10] collected on the peak of the $\Upsilon(4S)$ resonance. A 45 fb^{-1} sample collected 40 MeV below the resonance ("off peak") is used for background studies. We also use a simulated sample of $B\bar{B}$ events [11] with an integrated luminosity equivalent to approximately 3 times the data.

We preselect a sample of hadronic events requiring the number of charged particles to be at least four. We reduce non-$B\bar{B}$ (continuum) background by requiring the ratio of the second to the zeroth order Fox-Wolfram moments [12] to be less than 0.6.

We select the B_R sample by searching for combinations of a charged lepton (in the momentum range $1.4 < p_\ell < 2.3$ GeV/c) and a low momentum pion π_s^- ($60 < p_{\pi_s^-} < 190$ MeV/c), which is taken to arise from $D^{*-} \to \bar{D}^0\pi_s^-$ decay. Here and elsewhere momenta are calculated in the center-of-mass frame. The ℓ^+ and the π_s^- must have opposite electric charge. Their tracks must be consistent with originating from a common vertex, which is constrained to the beam collision point in the plane transverse to the beam axis. Finally, we combine p_ℓ, $p_{\pi_s^-}$, and the probability of the vertex fit in a likelihood ratio variable (η) optimized to reject combinatorial $B\bar{B}$ events. If more than one candidate is found in the event, we choose the one with the largest value of η.

We determine the square of the unobserved neutrino mass as

$$\mathcal{M}_\nu^2 = (E_{\text{beam}} - E_{D^*} - E_\ell)^2 - (\mathbf{p}_{D^*} + \mathbf{p}_\ell)^2,$$

where we neglect the momentum of the B^0 ($p_B \approx 340$ MeV/c) and identify the B^0 energy with the beam energy E_{beam} in the e^+e^- center-of-mass frame; E_ℓ and $\mathbf{p}_\ell$ are the energy and momentum of the lepton and $\mathbf{p}_{D^*}$ is the estimated momentum of the D^*. As a consequence of limited phase space in the D^{*+} decay, the soft pion is emitted nearly at rest in the D^{*+} rest frame. The D^{*+} four-momentum can therefore be computed by approximating its direction as that of the soft pion, and parametrizing its momentum as a linear function of the soft-pion momentum. All B^0 semileptonic decays with $\mathcal{M}_\nu^2$ near zero are considered to be signal events, including $B^0 \to D^{*-}X^0\ell^+\nu_\ell$ (primary), $D^{*-}X^0\tau^+\nu_\tau$, $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$ (cascade), and $D^{*-}h^+$ (misidentified), where $h = \pi, K$ is misidentified as a lepton. B^0 decays to flavor-insensitive CP eigenstates, $B^0 \to D^{*\pm}DX, D \to \ell^\mp X$, and $B^+ \to D^{*-}X^+\ell^+\nu_\ell$ accumulate at $\mathcal{M}_\nu^2 \sim 0$ and are called "peaking background." The uncorrelated background consists of continuum and combinatorial $B\bar{B}$ events.

We identify charged kaons in the momentum range $0.2 < p_K < 4$ GeV/c with an average efficiency of about 85% and a ~3% pion misidentification rate. We determine the K production point from the intersection of the K track and the beam spot, and then determine the distance Δz between the ℓ^+ π_s^- and K vertex coordinates along the beam axis. Finally, we define the proper time difference Δt between the B_R and the B_T in the "Lorentz boost approximation" [13], $\Delta t = \Delta z/\beta\gamma$, where $\beta\gamma = 0.56$ is the average boost of the $\Upsilon(4S)$ in the laboratory frame. Since the B mesons are not at rest in the $\Upsilon(4S)$ rest frame, and in addition the K is usually produced in the cascade process $B_T \to DX, D \to KY$, Δt is only an approximation of the actual proper time difference between the B_R and the B_T. We reject events if the uncertainty $\sigma(\Delta t)$ exceeds 3 ps. This selection reduces to a negligible level the contamination from protons produced in the scattering of primary particles with the beam pipe or the detector material and wrongly identified as kaons, which would otherwise constitute a large charge-asymmetric source of background.

We define an event as "mixed" if the K and the ℓ have the same electric charge and as "unmixed" otherwise. In about 20% of the cases, the K has the wrong charge correlation with respect to the B_T, and the event is wrongly defined (mistags).

About 95% of the K_R candidates have the same electric charge as the ℓ; they constitute 75% of the mixed event sample. Because of the small lifetime of the D^0 meson, the separation in space between the K_R and the $\ell\pi_s$ production points is much smaller than for K_T. Therefore, we use Δt as a first discriminant variable. Kaons in the K_R sample are usually emitted in the hemisphere opposite to the ℓ, while genuine K_T are produced randomly, so we use in addition the cosine of the angle $\theta_{\ell K}$ between the ℓ and the K.

In about 20% of the cases, the events contain more than one K; most often we find both a K_T and a K_R candidate. As these two carry different information, we accept multiple-candidate events. Using ensembles of simulated samples of events, we find that this choice does not affect the statistical uncertainty.

The $\mathcal{M}_\nu^2$ distribution of all signal candidates in shown in Fig. 1. We determine the signal fraction by fitting the $\mathcal{M}_\nu^2$ distribution in the interval $[-10, 2.5]$ GeV$^2/c^4$ with the sum of continuum, $B\bar{B}$ combinatorial, and $B\bar{B}$ peaking events. We split peaking $B\bar{B}$ into direct ($B^0 \to D^{*-}\ell^+\nu$), "D^{**}" ($B \to D^{*-}X^0\ell^+\nu_\ell$), cascade, hadrons wrongly identified as leptons, and CP eigenstates. In the fit, we float the fraction of direct, D^{**}, and $B\bar{B}$ combinatorial background, while we fix the continuum contribution to the expectation from off-peak events, rescaled by the on-peak to off-peak luminosity ratio, and the rest (less than 2% of the total) to the level predicted by the simulation. Based on the assumption of isospin conservation, we attribute 66% of the D^{**} events to B^+ decays and the rest to B^0 decays. We use the result of the fit to compute the fractions of continuum, combinatorial, and peaking B^+ background, CP eigenstates, and B^0 signal in the sample, as a function of $\mathcal{M}_\nu^2$. We find $(5.945 \pm 0.007) \times 10^6$ peaking events (see Fig. 1).

We then repeat the fit after dividing events into the four lepton categories ($e^\pm$, $\mu^\pm$) and eight tagged samples ($e^\pm K^\pm$, $\mu^\pm K^\pm$).

We measure $\mathcal{A}_{CP}$ with a binned four-dimensional fit to Δt (100 bins), $\sigma(\Delta t)$(20), $\cos\theta_{\ell k}$(4), and p_K(5). Following Ref. [14] and neglecting resolution effects, the Δt distributions for signal events with a K_T are represented by the following expressions:

$$\mathcal{F}_{\bar{B}^0B^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) + \left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) - \left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t)\right],$$

$$\mathcal{F}_{B^0\bar{B}^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) + \left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) + \left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t)\right],$$

$$\mathcal{F}_{\bar{B}^0\bar{B}^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) - \left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) - \left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t)\right] \times \left|\frac{q}{p}\right|^2,$$

$$\mathcal{F}_{B^0B^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) - \left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) + \left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t)\right] \times \left|\frac{p}{q}\right|^2,$$

where the first index of $\mathcal{F}$ refers to the flavor of the B_R and the second to the B_T, $\Gamma_0 = \tau_{B^0}^{-1}$ is the average width of the two B^0 mass eigenstates, Δm_d and $\Delta\Gamma$ are, respectively, their mass and width differences, the parameter r' results from the interference of Cabibbo-favored and doubly Cabibbo suppressed decays on the B_T side [14] and has a very small value [$\mathcal{O}(1\%)$], and b and c are two parameters expressing the CP violation arising from that interference. In the SM, $b = 2r'\sin(2\beta+\gamma)\cos\delta'$ and $c = -2r'\cos(2\beta+\gamma)\sin\delta'$, where β and γ are angles of the unitary triangle and δ' is a strong phase. The quantities Δm_d, τ_{B^0}, b, c, and $\sin(2\beta+\gamma)$ are left free in the fit. The value of $\Delta\Gamma$ is fixed to zero. Neglecting the tiny contribution from doubly Cabibbo suppressed decays, the main contribution to the asymmetry is time independent and due to the normalization factors of the two mixed terms.

The Δt distribution for the decays of the B^+ mesons is parametrized by an exponential function, $\mathcal{F}_{B^+} = \Gamma_+ e^{-|\Gamma_+\Delta t|}$, where the B^+ decay width is computed as the inverse of the lifetime $\Gamma_+^{-1} = \tau_{B^+} = (1.641 \pm 0.008)$ ps.

When the K_T comes from the decay of the B^0 meson to a CP eigenstate (as, for example, $B^0 \to D^{(*)}\bar{D}^{(*)}$ [8]), a different expression applies:

$$\mathcal{F}_{CPe}(\Delta t) = \frac{\Gamma_0}{4}e^{-\Gamma_0|\Delta t|}[1 \pm S\sin(\Delta m_d\Delta t) \pm C\cos(\Delta m_d\Delta t)],$$

where the plus (minus) sign applies if the B_R decays as a B^0 ($\bar{B}^0$). The fraction of these events (about 1%) and the parameters S and C are fixed in the fits and are taken from simulation.

We obtain the Δt distributions for K_T in $B\bar{B}$ events, $\mathcal{G}_i(\Delta t)$, by convolving the theoretical ones with a resolution function, which consists of the superposition of several Gaussian functions, convolved with exponentials to account for the finite lifetime of charmed mesons in the cascade decay $b \to c \to K$. Different sets of parameters are used for peaking and for combinatorial background events.

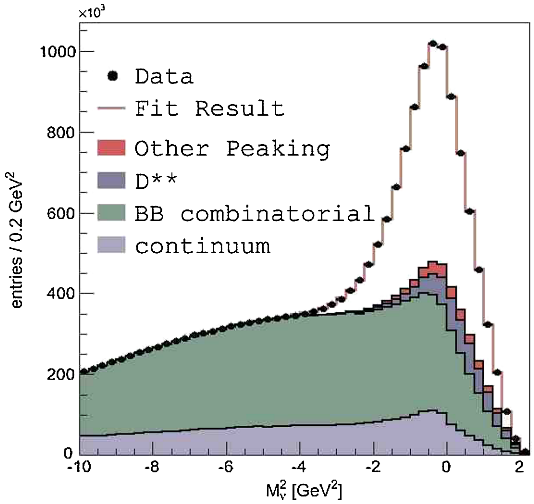

FIG. 1 (color online). $\mathcal{M}_\nu^2$ distribution for selected events. The data are represented by the points with error bars. The fitted contributions from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, other peaking background, D^{**} events, $B\bar{B}$ combinatorial background, and rescaled off-peak events are overlaid.

To describe the Δt distributions for K_R events, $\mathcal{G}_{K_R}(\Delta t)$, we select a subsample of data containing fewer than 5% K_T decays and use background-subtracted histograms in our likelihood functions. As an alternative, we apply the same selection to the simulation and correct the simulated Δt distribution by the ratio of histograms from data and simulation. The $\cos\theta_{\ell K}$ shapes are obtained from the histograms of the simulated distributions for $B\bar{B}$ events. The Δt distribution of continuum events is represented by a decaying exponential convolved with Gaussians parametrized by fitting simultaneously the off-peak data.

The rate of events in each bin (j) and for each tagged sample is then expressed as the sum of the predicted contributions from peaking events, $B\bar{B}$ combinatorial, and continuum background. Accounting for mistags and K_R events, the peaking B^0 contributions to the same-sign samples are

$$\begin{aligned}\mathcal{G}_{\ell^+K^+}(j) = {} & (1+\mathcal{A}_{r\ell})(1+\mathcal{A}_K)\{(1-f_{K_R}^{++}) \\ & \times[(1-\omega^+)\mathcal{G}_{B^0B^0}(j)+\omega^-\mathcal{G}_{B^0\bar{B}^0}(j)] \\ & + f_{K_R}^{++}(1-\omega'^+)\mathcal{G}_{K_R}(j)(1+\chi_d\mathcal{A}_{\ell\ell})\}, \\ \mathcal{G}_{\ell^-K^-}(j) = {} & (1-\mathcal{A}_{r\ell})(1-\mathcal{A}_K)\{(1-f_{K_R}^{--}) \\ & \times[(1-\omega^-)\mathcal{G}_{\bar{B}^0\bar{B}^0}(j)+\omega^+\mathcal{G}_{\bar{B}^0B^0}(j)] \\ & + f_{K_R}^{--}(1-\omega'^-)\mathcal{G}_{K_R}(j)(1-\chi_d\mathcal{A}_{\ell\ell})\},\end{aligned}$$

where the reconstruction asymmetries have separate values for the e and μ samples. We allow for different mistag probabilities for K_T ($\omega^\pm$) and K_R ($\omega'^\pm$). The parameters $f_{K_R}^{\pm\pm}(p_k)$ describe the fractions of K_R tags in each sample as a function of the kaon momentum.

A total of 168 parameters are determined in the fit. By analyzing simulated events as data, we observe that the fit reproduces the generated values of $1-|q/p|$ (zero) and of the other most significant parameters ($\mathcal{A}_{r\ell}$, $\mathcal{A}_K$, Δm_d, and τ_{B^0}). We then produce samples of simulated events with $\Delta_{CP} = \pm 0.005, \pm 0.010, \pm 0.025$ and $\mathcal{A}_{r\ell}$ or $\mathcal{A}_K$ in the range of $\pm 10\%$, by removing events. A total of 67 different simulated event samples are used to check for biases. In each case, the input values are correctly determined, and an unbiased value of $|q/p|$ is always obtained. The fit to the data yields $\Delta_{CP} = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$, where the first uncertainty is statistical and the second systematic. The values of the detector charge asymmetries are $\mathcal{A}_{r,e} = (3.0 \pm 0.4) \times 10^{-3}$, $\mathcal{A}_{r,\mu} = (3.1 \pm 0.5) \times 10^{-3}$, and $\mathcal{A}_K = (13.7 \pm 0.3) \times 10^{-3}$. The frequency of the oscillation $\Delta m_d = 508.5 \pm 0.9\ \mathrm{ns}^{-1}$ is consistent with the world average, while $\tau_{B^0} = 1.553 \pm 0.002$ ps is somewhat larger than the world average, which we account for in the systematic uncertainties. Figure 2 shows the fit projection for Δt.

The systematic uncertainty is computed as the sum in quadrature of several contributions, described below and summarized in Table I.

Peaking sample composition.—We vary the sample composition by the statistical uncertainty of the $\mathcal{M}_\nu^2$ fit, the fraction of B^0 to B^+ in the D^{**} peaking sample in the range $50 \pm 25\%$ to account for possible violation of isospin symmetry, the fraction of the peaking contributions

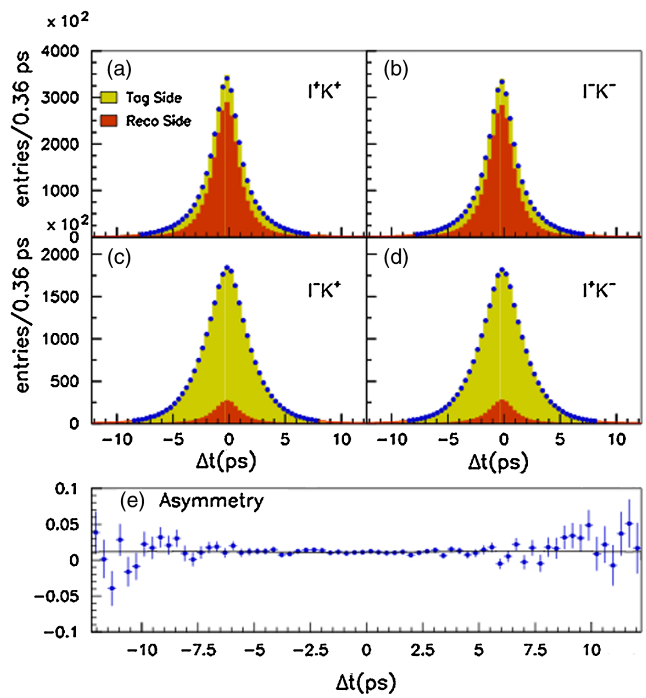

FIG. 2 (color online). Distribution of Δt for the continuum-subtracted data (points with error bars) and fitted contributions from K_R (dark) and K_T (light), for (a) ℓ^+K^+ events, (b) ℓ^-K^- events, (c) ℓ^-K^+ events, (d) ℓ^+K^- events, (e) raw asymmetry between ℓ^+K^+ and ℓ^-K^- events.

TABLE I. Principal sources of systematic uncertainties.

Source	$\sigma(\Delta_{CP})$
Peaking sample composition	$^{+1.50}_{-1.17} \times 10^{-3}$
Combinatorial sample composition	$\pm 0.39 \times 10^{-3}$
Δt resolution model	$\pm 0.60 \times 10^{-3}$
K_R fraction	$\pm 0.11 \times 10^{-3}$
K_R Δt distribution	$\pm 0.65 \times 10^{-3}$
Fit bias	$^{+0.58}_{-0.46} \times 10^{-3}$
CP eigenstate description	± 0
Physical parameters	$^{+0}_{-0.28} \times 10^{-3}$
Total	$^{+1.88}_{-1.61} \times 10^{-3}$

(taken from the simulation) by $\pm 20\%$, and the fraction of CP eigenstates by $\pm 50\%$.

$B\bar{B}$ combinatorial sample composition.—We vary the fraction of B^+ events in the $B\bar{B}$ combinatorial sample by $\pm 4.5\%$, which corresponds to the uncertainty in the inclusive branching fraction for $B^0 \to D^{*-}X$.

Δt resolution model.—We quote the difference between the result when all resolution parameters are determined in the fit and those obtained when those that exhibit a weak correlation with $|q/p|$ are fixed.

K_R fraction.—We vary the ratio of $B^+ \to K_R X$ to $B^0 \to K_R X$ by $\pm 6.8\%$, which corresponds to the uncertainty of the fraction $BR(D^{*0} \to K^- X)/BR(D^{*+} \to K^- X)$.

$K_R \Delta t$ distribution.—We use half the difference between the results obtained using the two different strategies to describe the $K_R \Delta t$ distribution.

Fit bias.—Parametrized simulations are used to check the estimate of the result and its statistical uncertainty. We add the statistical uncertainty on the validation test using the detailed simulation and the difference between the nominal result and the central result determined from the ensemble of parametrized simulations.

CP eigenstates description.—We vary the S and C parameters describing the CP eigenstates by their statistical uncertainties as obtained from simulation.

Physical parameters.—We repeat the fit setting the value of $\Delta\Gamma$ to 0.02 ps^{-1}. The lifetimes of the B^0 and B^+ mesons and Δm_d are floated in the fit. Alternatively, we check the effect of fixing each parameter in turn to the world average.

In summary, we present a new measurement of the parameter governing CP violation in B^0-$\bar{B}^0$ oscillations. With a partial $B^0 \to D^{*-}X\ell^+\nu$ reconstruction and kaon tagging, we find $\Delta_{CP} = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$ and $\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$. These results are consistent with, and more precise than, dilepton-based results from B factories [4]. No deviation is observed from the SM expectation [3].

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[1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **93**, 131801 (2004).

[2] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **79**, 072009 (2009); I. Adachi *et al.* (Belle Collaboration), Phys. Rev. Lett. **108**, 171802 (2012).

[3] A. Lenz, U. Nierste, J. Charles, S. Descotes-Genon, H. Lacker, S. Monteil, V. Niess, and S. T'Jampens, Phys. Rev. D **86**, 033008 (2012); J. Charles *et al.*, Phys. Rev. D **84**, 033005 (2011); A. Lenz and U. Nierste, J. High Energy Phys. 06 (2007) 072.

[4] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **96**, 251802 (2006); E. Nakano *et al.* (Belle Collaboration), Phys. Rev. D **73**, 112002 (2006).

[5] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **84**, 052007 (2011).

[6] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **110**, 011801 (2013).

[7] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **100**, 051802 (2008).

[8] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).

[9] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).

[10] J. P. Lees *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **726**, 203 (2013).

[11] D. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[12] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[13] D. Boutigny *et al.*, SLAC Report No. SLAC-R-504, 1998.

[14] O. Long, M. Baak, R. N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).