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Measurement of CP-Violating Asymmetries in $B^0 \to D^{(*)\pm}D^{\mp}$

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We present updated measurements of CP-violating asymmetries in the decays $B^0 \rightarrow D^{*\pm}D^{\mp}$ and $B^0 \rightarrow D^+D^-$ using $(383 \pm 4) \times 10^6 B\bar{B}$ pairs collected by the *BABAR* detector at the SLAC PEP-II B factory. We determine the time-integrated CP asymmetry $\mathcal{A}_{D^{*\pm}D^{\mp}} = 0.12 \pm 0.06 \pm 0.02$, and the time-dependent asymmetry parameters to be $C_{D^{*+}D^-} = 0.18 \pm 0.15 \pm 0.04$, $S_{D^{*+}D^-} = -0.79 \pm 0.21 \pm 0.06$, $C_{D^{*-}D^+} = 0.23 \pm 0.15 \pm 0.04$, $S_{D^{*-}D^+} = -0.44 \pm 0.22 \pm 0.06$, $C_{D^+D^-} = 0.11 \pm 0.22 \pm 0.07$, and $S_{D^+D^-} = -0.54 \pm 0.34 \pm 0.06$, where the first uncertainty is statistical and the second is systematic.

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In the standard model (SM), CP violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix V [1]. Measurements of CP asymmetries in $B^0 \to (c\bar{c})K^{(*)0}$ decays [2] by the *BABAR* [3] and Belle [4] Collaborations have firmly established this effect and precisely determined the parameter $\sin 2\beta$, where β is $\arg[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*]$. Another way to measure $\sin 2\beta$ is to use decays whose amplitudes are dominated by a tree-level, color-allowed $b \to c\bar{c}d$ transition, such as $B^0 \to D^{(*)\pm}D^{\mp}$. Within the framework of the SM, the time-dependent CP asymmetries of $B^0 \to D^{(*)\pm}D^{\mp}$ are directly related to $\sin 2\beta$ when corrections due to penguin diagram contributions are neglected. The penguin-induced corrections have been estimated in models based on the factorization approximation and heavy quark symmetry and are predicted to be a few percent [5,6]. However, contributions from non-SM processes may lead to a large shift [7]. A significant deviation in the $\sin 2\beta$ measurement from that of the $B^0 \to (c\bar{c})K^{(*)0}$ decays would be evidence involving new physics beyond the SM.

Studies of the CP violation in $b \to c\bar{c}d$ transitions have been carried out by both the *BABAR* and Belle Collaborations. Most recently, the Belle Collaboration reported evidence of large direct CP violation in $B^0 \to D^+D^-$ where $C_{D^+D^-} = -0.91 \pm 0.23 \pm 0.06$ [8], in contradiction to the SM expectation. However, such a large direct CP violation has not been observed in previous measurements with $B^0 \to D^{(*)\pm}D^{(*)\mp}$ decays, involving the same quark-level weak decay [9–12].

In this Letter, we present an updated measurement of CP-violating asymmetries in the decays $B^0 \to D^{*+}D^-$, $B^0 \to D^{*-}D^+$, and $B^0 \to D^+D^-$. The data used in this analysis comprise $(383 \pm 4) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected by the *BABAR* detector at the PEP-II storage rings. The *BABAR* detector is described in detail elsewhere [13]. Monte Carlo (MC) simulation based on GEANT4 [14] is used to validate the analysis procedure and to study the relevant backgrounds.

The decay rate $f_+(f_-)$ for a neutral B meson decay to a common final state accompanied by a $B^0(\bar{B}^0)$ tag is given by

$$f_\pm(\Delta t) = e^{-|\Delta t|/\tau_{B^0}}/4\tau_{B^0}\{(1 \mp \Delta w) \pm (1 - 2w) \times [S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)]\}, \quad (1)$$

where $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay time of the reconstructed B meson ($B_{\rm rec}$) and that of the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the difference between the heavy and light mass eigenstates determined from the $B^0 - \bar{B}^0$ oscillation frequency [15]. The average mistag probability w describes the effect of incorrect tags, and Δw is the difference between the mistag probabilities for B^0 and $\bar{B}^0$. Since $D^{*+}D^-$ and $D^{*-}D^+$ are not CP eigenstates, we can define a time-integrated asymmetry $\mathcal{A}_{D^{*\pm}D^{\mp}}$ between the rate of $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$, calculated as

$$\mathcal{A}_{D^{*\pm}D^{\mp}} = \frac{N_{D^{*+}D^-} - N_{D^{*-}D^+}}{N_{D^{*+}D^-} + N_{D^{*-}D^+}}, \quad (2)$$

where N is the signal event yield.

For $B^0 \to D^{*\pm}D^{\mp}$, the general relations are $S_{D^{*\pm}D^{\mp}} = -\sqrt{1 - C^2_{D^{*\pm}D^{\mp}}}\sin(2\beta_{\rm eff} \pm \delta)$, where δ is the strong phase difference between $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$ [16]. Under the assumption of negligible penguin contribution, $\beta_{\rm eff} = \beta$, $\mathcal{A}_{D^{*\pm}D^{\mp}} = 0$, and $C_{D^{*+}D^-} = -C_{D^{*-}D^+}$. For $B^0 \to D^+D^-$ and in the case of negligible penguin contribution, $C_{D^+D^-}$ measures direct CP violation and is zero, while $S_{D^+D^-}$ is $-\sin 2\beta$.

The selections of $B^0 \to D^{*\pm}D^{\mp}$ and $B^0 \to D^+D^-$ candidates are similar to those of our previous analysis [10]. We reconstruct D^{*+} in its decay to $D^0\pi^+$. We reconstruct candidates for D^0 and D^+ mesons in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$, $K^0_S\pi^+$. We reconstruct $B^0 \to D^+D^-$ candidates only through the decay $D^\pm \to K^\mp\pi^\pm\pi^\pm$. We require the reconstructed masses of the D^0 and D^+ candidates to be within 20 MeV/c^2 of their respective nominal masses [15], except for the $D^0 \to K^-\pi^+\pi^0$ candidate, where we use a looser requirement of 40 MeV/c^2. We apply a mass-constrained fit to the selected D^0 and D^+ candidates and combine D^0 candidates with a π^+ track, with momentum below 450 MeV/c in the $\Upsilon(4S)$ frame, to form D^{*+} candidates.

We reconstruct the K^0_S candidates from two oppositely charged tracks with an invariant mass within 20 MeV/c^2 of the nominal K^0_S mass [15]. The χ^2 probability of the track vertex fit must be greater than 0.1%. We require charged kaon candidates to be identified as such using a likelihood technique based on the Cherenkov angle measured by the Cherenkov detector and the ionization energy loss measured by the charged-particle tracking systems [13]. We form neutral pion candidates from two photons detected in the electromagnetic calorimeter [13], each with energy above 30 MeV. The invariant mass of the pair must be within 30 MeV/c^2 of the nominal π^0 mass [15], and we require their summed energy to be greater than 200 MeV. In addition, we further apply a mass-constrained fit to the π^0 candidates.

To suppress the $e^+e^- \to q\bar{q}$ ($q = u$, d, s, and c) continuum background, we exploit the contrast between the spherical shape of $B\bar{B}$ events and the more jetlike nature of continuum events. We require the ratio of the second to the zeroth order Fox-Wolfram moments [17] to be less than

0.6. We also use a Fisher discriminant, constructed as an optimized linear combination of 11 event shape variables [18]: the momentum flow in nine concentric cones around the thrust axis of the reconstructed B^0 candidate, the angle between that thrust axis and the beam axis, and the angle between the line of flight of the B^0 candidate and the beam axis. In addition, we employ a combined D flight-length significance variable, derived from the sum of flight lengths of the two D candidates [19], to reduce background.

For each $B^0 \to D^{(*)\pm}D^{\mp}$ candidate, we construct a likelihood function $\mathcal{L}_{\rm mass}$ from the masses and mass uncertainties of the D and D^* candidates [19]. The D mass resolution is modeled by a Gaussian whose variance is determined on a candidate-by-candidate basis from its mass uncertainty before the mass-constrained fit. The $D^* - D$ mass difference resolution is modeled by the sum of two Gaussian distributions whose parameters are determined from simulated events. The values of $\mathcal{L}_{\rm mass}$ and $\Delta E \equiv E_B^* - E_{\rm beam}$, the difference between the B^0 candidate energy E_B^* and the beam energy $E_{\rm beam}$ in the $\Upsilon(4S)$ frame, are used to reduce the combinatoric background. From the simulated events, we optimize the maximum allowed values of $-\ln\mathcal{L}_{\rm mass}$ and $|\Delta E|$ for each individual final state to obtain the highest expected signal significance.

We extract the signal yield from the events satisfying the selection criteria using the energy-substituted mass, $m_{\rm ES} \equiv \sqrt{E_{\rm beam}^2 - p_B^{*2}}$, where p_B^* is the B^0 candidate momentum in the $\Upsilon(4S)$ frame. We select the B^0 candidates that have $m_{\rm ES} \geq 5.23$ GeV/c^2. On average, we have 1.5 and 1.1 B^0 candidates per event for $B^0 \to D^{*\pm}D^{\mp}$ and $B^0 \to D^+D^-$, respectively. If more than one candidate is reconstructed in an event, we select the candidate with the smallest value of $-\ln\mathcal{L}_{\rm mass}$. Studies using MC samples show that this procedure results in the selection of the correct B^0 candidate more than 95% of the time.

We perform an unbinned maximum likelihood fit to the $m_{\rm ES}$ and Δt distributions to extract the CP asymmetries. We fit the events from $B^0 \to D^{*+}D^-$ and $B^0 \to D^{*-}D^+$ decays simultaneously. The probability density function (PDF) of the $m_{\rm ES}$ distribution consists of a Gaussian for the signal and a threshold function [20] for the combinatorial background. We expect some background events to peak in the $m_{\rm ES}$ signal region due to cross feed from other decay modes. We estimate the fraction of events in the signal Gaussian due to this peaking background to be $(8.8 \pm 4.4)\%$ for $B^0 \to D^{*\pm}D^{\mp}$ and $(4.8 \pm 7.4)\%$ for $B^0 \to D^+D^-$ using detailed MC simulations of inclusive B decays.

The technique used to fit the Δt distribution is analogous to that used in previous *BABAR* measurements described in Refs. [21,22]. We use information from the other B meson in the event to tag the flavor of the fully reconstructed $B^0 \to D^{(*)\pm}D^{\mp}$ candidate [21]. The signal Δt PDF in Eq. (1) is convolved with an empirical Δt resolution function [21]. The Δt is calculated from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision (z) axis [21]. The $B_{\rm tag}$ decay vertex is determined by fitting charged tracks not belonging to the $B_{\rm rec}$ candidate to a common vertex, employing constraints from the beam-spot location and the $B_{\rm rec}$ momentum [21]. Only events with a Δt uncertainty less than 2.5 ps and a measured $|\Delta t|$ less than 20 ps are accepted for the fit to the Δt distribution. Both the signal mistag probability and the Δt resolution function are determined from a large sample of neutral B decays to flavor eigenstates $B_{\rm flav}$. The combinatoric background Δt distributions are parametrized with an empirical description that includes zero and nonzero lifetime components [21]. The nonzero lifetime background is allowed to have effective CP asymmetries, and these float in the likelihood fit. By default, we assume that the peaking backgrounds have the same Δt PDF as the signal but zero CP asymmetries.

The fits to the data yield 280 ± 19 signal events for $B^0 \to D^{*+}D^-$, 219 ± 18 signal events for $B^0 \to D^{*-}D^+$, and 131 ± 14 signal events for $B^0 \to D^+D^-$, where the quoted uncertainties are statistical only. In the region of $m_{\rm ES} > 5.27$ GeV/c^2, the signal purity is approximately 41% for $B^0 \to D^{*+}D^-$, 34% for $B^0 \to D^{*-}D^+$, and 46% for $B^0 \to D^+D^-$. The fitted CP violating parameters are

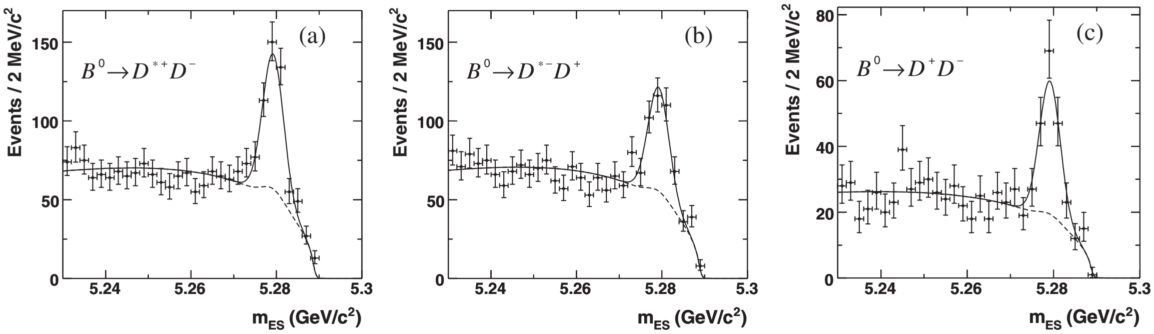

FIG. 1. Measured distribution of $m_{\rm ES}$ for (a) $B^0 \to D^{*+}D^-$, (b) $B^0 \to D^{*-}D^+$, and (c) $B^0 \to D^+D^-$ candidates. The solid line is the projection of the fit result and the dotted line represents the background components.

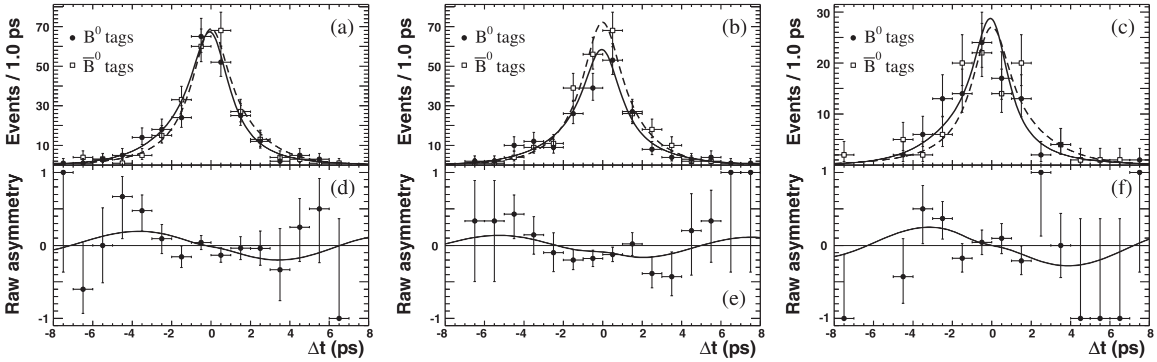

FIG. 2. The distributions of Δt and fit projections for $B^0 \to D^{*+}D^-$ (left), $B^0 \to D^{*-}D^+$ (middle), and $B^0 \to D^+D^-$ (right) candidates in the signal region $m_{\rm ES} > 5.27\ {\rm GeV}/c^2$ with a B^0 or $\bar{B}0$ tag (a)–(c). The raw time-dependent asymmetries $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$ as functions of Δt are also shown (d)–(e).

$$\begin{aligned}
\mathcal{A}_{D^{*\pm}D^{\mp}} &= 0.12 \pm 0.06 \pm 0.02,\\
C_{D^{*+}D^-} &= 0.18 \pm 0.15 \pm 0.04,\\
S_{D^{*+}D^-} &= -0.79 \pm 0.21 \pm 0.06,\\
C_{D^{*-}D^+} &= 0.23 \pm 0.15 \pm 0.04,\\
S_{D^{*-}D^+} &= -0.44 \pm 0.22 \pm 0.06,\\
C_{D^+D^-} &= 0.11 \pm 0.22 \pm 0.07,\\
S_{D^+D^-} &= -0.54 \pm 0.34 \pm 0.06,
\end{aligned} \tag{3}$$

where the first uncertainty is statistical and the second is systematic.

Projections of the fits onto $m_{\rm ES}$ for the three different samples are shown in Fig. 1. Figure 2 shows the Δt distributions and asymmetries in yields between events with B^0 and $\bar{B}^0$ tags, overlaid with the projection of the likelihood fit result. As a cross-check, we repeat the fit by allowing the B^0 lifetime to float. The obtained lifetime is in good agreement with its world average [15].

The systematic uncertainty of the time-integrated CP asymmetry $\mathcal{A}_{D^{*\pm}D^{\mp}}$ is dominated by the potential differences in the reconstruction efficiencies of the positively and negatively charged tracks (0.014). Other sources that contribute to the systematic error include the estimate of the peaking background fraction (< 0.001), the uncertainty in the $m_{\rm ES}$ resolution for the $B^0 \to D^{*\pm}D^{\mp}$ signal events (0.005), and a possible fit bias (0.004).

The systematic uncertainties on C and S are evaluated separately for each of the decay modes. Their sources and estimates are summarized in Table I. The systematic uncertainties arise from the amount of possible background that tends to peak under the signal and its CP asymmetry, the assumed parametrization of the Δt resolution function, the possible differences between the $B_{\rm flav}$ and signal mistag fractions, the knowledge of the event-by-event beam-spot position, the uncertainties from the finite MC sample used, the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ and the favored $b \to c\bar{u}d$ amplitudes in some tag-side decays [23], and the uncertainty in the $m_{\rm ES}$ resolution for the signal events. All of the systematic uncertainties are found to be much smaller than the statistical uncertainties.

Since $D^{*+}D^-$ and $D^{*-}D^+$ are not CP eigenstates, it is also illustrative to express the measured CP-violating parameters C and S in a slightly different parametrization [24]: $C_{D^*D} = (C_{D^{*+}D^-} + C_{D^{*-}D^+})/2$, $\Delta C_{D^*D} = (C_{D^{*+}D^-} - C_{D^{*-}D^+})/2$, $S_{D^*D} = (S_{D^{*+}D^-} + S_{D^{*-}D^+})/2$, and $\Delta S_{D^*D} = (S_{D^{*+}D^-} - S_{D^{*-}D^+})/2$. The quantities C_{D^*D} and S_{D^*D} parametrize flavor-dependent direct CP violation and mixing-induced CP violation re-

TABLE I. Sources of systematic error on time-dependent CP asymmetry parameters for the decays $B^0 \to D^{*\pm}D^{\mp}$ and $B^0 \to D^+D^-$.

Source	$C_{D^{*+}D^-}$	$S_{D^{*+}D^-}$	$C_{D^{*-}D^+}$	$S_{D^{*-}D^+}$	$C_{D^+D^-}$	$S_{D^+D^-}$
Peaking backgrounds	0.026	0.041	0.027	0.031	0.044	0.042
Δt resolution parametrization	0.011	0.021	0.013	0.012	0.015	0.020
Mistag fraction differences	0.014	0.011	0.016	0.012	0.023	0.013
Beam-spot position	0.004	0.006	0.007	0.036	0.005	0.002
Δm_d, τ_B	0.002	0.003	0.003	0.004	0.001	0.004
MC statistics	0.011	0.015	0.011	0.015	0.036	0.023
Tag-side interference and others	0.016	0.025	0.017	0.020	0.020	0.013
Total	0.037	0.056	0.040	0.056	0.066	0.055

lated to the angle β, respectively. The parameters ΔC_{D^*D} and ΔS_{D^*D} are insensitive to *CP* violation. ΔC_{D^*D} describes the asymmetry between the rates $\Gamma(B^0 \to D^{*+}D^-) + \Gamma(\bar{B}^0 \to D^{*-}D^+)$ and $\Gamma(B^0 \to D^{*-}D^+) + \Gamma(\bar{B}^0 \to D^{*+}D^-)$, while ΔS_{D^*D} is related to the strong phase difference δ. We find

$$\begin{aligned} C_{D^*D} &= 0.21 \pm 0.11 \pm 0.03, \\ S_{D^*D} &= -0.62 \pm 0.15 \pm 0.04, \\ \Delta C_{D^*D} &= -0.02 \pm 0.11 \pm 0.03, \\ \Delta S_{D^*D} &= -0.17 \pm 0.15 \pm 0.04, \end{aligned} \tag{4}$$

where the first uncertainty is statistical and the second is systematic.

In summary, this Letter reports updated measurements of the *CP*-violating asymmetries for the decays $B^0 \to D^{*\pm}D^{\mp}$ and $B^0 \to D^+D^-$. These measurements supersede the previous *BABAR* results [10], with a more than 50% reduction in the statistical uncertainties. The time-dependent asymmetries are consistent with the SM predictions within their statistical uncertainties. We do not see evidence of large direct *CP* violation in the decay $B^0 \to D^+D^-$ as reported by the Belle Collaboration [8].

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