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Measurement of Time-Dependent *CP* Asymmetries and Constraints on $\sin(2\beta+\gamma)$ with Partial Reconstruction of $B^0 \to D^{*\mp}\pi^{\pm}$ Decays

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We present a measurement of time-dependent *CP*-violating asymmetries in decays of neutral B mesons to the final states $D^{*\mp}\pi^{\pm}$, using approximately 82 million $B\overline{B}$ events recorded by the *BABAR* experiment at the PEP-II e^+e^- storage ring. Events containing these decays are selected with a partial reconstruction technique, in which only the high-momentum $\pi^{\pm}$ from the B decay and the low-momentum $\pi^{\mp}$ from the $D^{*\mp}$ decay are used. We measure the amplitude of the asymmetry to be -0.063 ± 0.024 $(stat.) \pm 0.014$ $(syst.)$ and compute bounds on $|\sin(2\beta+\gamma)|$.

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The Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] gives an elegant explanation of *CP* violation and is under intense experimental investigation aimed at overconstraining its parameters. A crucial part of this program is the measurement of the angle $\gamma = \arg\left(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right)$ of the unitarity triangle related to the CKM matrix. The decay modes $B^0 \to D^{*\mp}h^{\pm}$, where $h = \pi,\ \rho,\ a_1$, have been proposed for use in measurements of $\sin(2\beta+\gamma)$ [2], where $\beta = \arg\left(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right)$. In the Standard Model the decays $B^0 \to D^{*+}\pi^-$ and $\overline{B}^0 \to D^{*+}\pi^-$ proceed through the $\overline{b} \to \overline{u}cd$ and $b \to c\overline{u}d$ amplitudes A_u and A_c. The relative weak phase between the two amplitudes in the usual Wolfenstein convention for the CKM matrix is γ, which, when combined with $B^0\overline{B}^0$ mixing, yields a weak phase difference of $2\beta+\gamma$ between the interfering amplitudes.

The decay rate distribution for $B \to D^{*\pm}\pi^{\mp}$ is

$$\mathcal{P}_{\eta}^{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left[1 \pm S^{\zeta}\sin(\Delta m\Delta t) \mp \eta C\cos(\Delta m\Delta t)\right], \quad (1)$$

where τ is the mean B^0 lifetime, Δm is the $B^0-\overline{B}^0$ mixing frequency, and Δt is the difference between the time of the $B \to D^{*\pm}\pi^{\mp}$ ($B_{\rm rec}$) decay and the decay of the other B ($B_{\rm tag}$) in the event. The upper (lower) sign in Eq. 1 indicates the flavor of the $B_{\rm tag}$ as a B^0 ($\overline{B}^0$), while $\eta = +1$ (-1) and $\zeta = +$ $(-)$ for the $B_{\rm rec}$ final state $D^{*-}\pi^+$ ($D^{*+}\pi^-$). The parameters C and $S^{\pm}$ are

$$C \equiv \frac{1-r^2}{1+r^2}, \qquad S^{\pm} \equiv \frac{2r}{1+r^2}\sin(2\beta+\gamma\pm\delta). \quad (2)$$

Here δ is the strong phase difference between A_u and A_c and $r = |A_u/A_c|$. Since A_u is doubly CKM-suppressed with respect to A_c, one expects r to be approximately 2%.

In this Letter we report a study of *CP*-violating asymmetries in $B^0 \to D^{*\mp}\pi^{\pm}$ decays using the technique of partial reconstruction, which allows us to analyse a large sample of signal events. Additional information about the techniques used in this analysis appears in Ref. [3, 4].

The data used in this analysis were recorded with the *BABAR* detector at the PEP-II storage ring, and consist of 76.4 fb^{-1} collected on the $\Upsilon(4S)$ resonance (on-resonance sample), and 7.6 fb^{-1} collected at an e^+e^- center-of-mass (CM) energy approximately 40 MeV below the resonance peak (off-resonance sample). Samples of simulated Monte Carlo (MC) events with an equivalent luminosity 3 to 4 times larger than the data are analyzed through the same analysis chain. The *BABAR* detector is described in detail in Ref. [5].

In the partial reconstruction of a $B^0 \to D^{*\mp}\pi^{\pm}$ candidate (B_{rec}), only the hard (high-momentum) pion track π_h from the B decay and the soft (low-momentum) pion track π_s from the decay $D^{*-} \to \overline{D}^0\pi_s^-$ are used. This eliminates the efficiency loss associated with the neutral D meson reconstruction. Applying kinematic constraints consistent with the signal decay mode, we calculate the four-momentum of the D, obtaining its flight direction to within a few degrees and its invariant mass ($m_{\rm miss}$) [4]. Signal events peak in the $m_{\rm miss}$ distribution at the nominal D^0 mass with an r.m.s. of 3 MeV/c^2.

In addition to $B^0 \to D^{*\mp}\pi^{\pm}$ events, the selected event sample contains the following kinds of events: $B^0 \to D^{*\mp}\rho^{\pm}$; $B\overline{B}$ background peaking in $m_{\rm miss}$, composed of pairs of tracks coming from the same B meson, with the π_s originating from a charged D^* decay, excluding $B^0 \to D^{*\mp}\rho^{\pm}$ decays; combinatoric B background, defined as all remaining $B\overline{B}$ background events; and continuum $e^+e^- \to q\overline{q}$, where q represents a u, d, s, or c quark. We apply an event-shape cut and a D^* helicity-angle cut to suppress combinatoric background. We reject π_h candidates that are identified as leptons or kaons. All candidates must satisfy $1.81 < m_{\rm miss} < 1.88$ GeV/c^2. Multiple candidates are found in 5% of the events. In these instances, only the candidate with the $m_{\rm miss}$ value closest to M_{D^0} is used.

To perform this analysis, Δt and the flavor of the $B_{\rm tag}$ must be determined. We measure Δt using $\Delta t = (z_{\rm rec} - z_{\rm tag})/(\gamma\beta c)$, where $z_{\rm rec}$ ($z_{\rm tag}$) is the decay position of the $B_{\rm rec}$ ($B_{\rm tag}$) along the beam axis (z) in the laboratory frame, and the e^+e^- boost parameter $\gamma\beta$ is continuously calculated from the beam energies. To find $z_{\rm rec}$ we fit the π_h track with a beam spot constraint in the plane perpendicular to the beams. We obtain $z_{\rm tag}$ from a beam-spot-constrained vertex fit of all other tracks in the event, excluding all tracks within 1 rad of the D momentum in the CM frame. The Δt error $\sigma_{\Delta t}$ is calculated from the results of the $z_{\rm rec}$ and $z_{\rm tag}$ vertex fits.

We tag the flavor of the $B_{\rm tag}$ using lepton or kaon candidates. The lepton CM momentum is required to be greater than 1.1 GeV/c to suppress "cascade" leptons that originate from charm decays. If several flavor-tagging tracks are present in either the lepton or kaon

tagging category, the only track of that category used for tagging is the one with the largest value of θ_T, the CM angle between the track momentum and the D momentum. The tagging lepton (kaon) must satisfy $\cos\theta_T < 0.75$ ($\cos\theta_T < 0.50$), to minimize the impact of tracks originating from the D decay. If both a lepton and a kaon satisfy this requirement, the event is tagged with the lepton only.

The analysis is carried out with a series of unbinned maximum-likelihood fits, performed simultaneously on the on- and off-resonance data samples and independently for the lepton-tagged and kaon-tagged events. The probability density function (PDF) depends on the variables $m_{\rm miss}$, Δt, $\sigma_{\Delta t}$, F, $s_{\rm t}$, and $s_{\rm m}$, where F is a Fisher discriminant formed from fifteen event-shape variables that provide discrimination against continuum events [4], $s_{\rm t} = 1$ (-1) when the $B_{\rm tag}$ is identified as a B^0 ($\overline{B}^0$), and $s_{\rm m} = 1$ (-1) for "unmixed" ("mixed") events. An event is labeled unmixed if the π_h is a $\pi^-(\pi^+)$ and the $B_{\rm tag}$ is a $B^0(\overline{B}^0)$, and mixed otherwise.

The PDF for on-resonance data is a sum over the PDFs of the different event types, $\mathcal{P} = \sum_i f_i \mathcal{P}_i$, where the index $i = \{D^*\pi, D^*\rho, peak, comb, q\overline{q}\}$ indicates one of the event types described above, f_i is the relative fraction of events of type i in the data sample, and $\mathcal{P}_i$ is the PDF for these events. The PDF for off-resonance data is $\mathcal{P}_{q\overline{q}}$. The parameter values for $\mathcal{P}_i$ are different for each event type, except where indicated otherwise. Each $\mathcal{P}_i$ is a product of the PDFs $\mathcal{M}_i(m_{\rm miss})$, $\mathcal{F}_i(F)$, and $\mathcal{T}_i'(\Delta t, \sigma_{\Delta t}, s_{\rm t}, s_{\rm m})$.

The $m_{\rm miss}$ PDF $\mathcal{M}_i$ for each event type i is the sum of a bifurcated Gaussian and an ARGUS function [4]. The Fisher PDF $\mathcal{F}_i$ is a bifurcated Gaussian. The parameter values for $\mathcal{F}_{D^*\pi}$, $\mathcal{F}_{D^*\rho}$, $\mathcal{F}_{peak}$, and $\mathcal{F}_{comb}$ are identical.

The Δt PDF is a convolution, $\mathcal{T}_i' = \int d\Delta t_{\rm tr}\, \mathcal{T}_i(\Delta t_{\rm tr}, s_{\rm t}, s_{\rm m})\, \mathcal{R}_i(\Delta t - \Delta t_{\rm tr}, \sigma_{\Delta t})$, where $\mathcal{T}_i$ is the distribution of the true decay-time difference $\Delta t_{\rm tr}$ and $\mathcal{R}_i$ is a three-Gaussian resolution function that accounts for detector resolution and effects such as systematic offsets in the measured positions of vertices [4].

The PDF $\mathcal{T}_{D^*\pi}(\Delta t_{\rm tr}, s_{\rm t}, s_{\rm m})$ for signal events corresponds to Eq. 1 with $O(r^2)$ terms neglected, and with additional parameters that account for imperfect flavor tagging:

$$\begin{aligned}\mathcal{T}_{D^*\pi} \;=\; & E_\tau(\Delta t_{\rm tr})\,\{\alpha(1+s_{\rm m}\kappa) + (1-\alpha)\,[(1-s_{\rm t}\,\Delta\omega) \\ & + s_{\rm m}\,(1-2\omega)\,\cos(\Delta m \Delta t_{\rm tr}) \\ & - s_{\rm t}\,(1-2\omega)\,S^{\xi}\,\sin(\Delta m \Delta t_{\rm tr})\,]\,\}\,, \end{aligned} \qquad (3)$$

where the mistag rate ω is the probability to misidentify the flavor of the $B_{\rm tag}$ averaged over B^0 and $\overline{B}^0$, $\Delta\omega$ is the B^0 mistag rate minus the $\overline{B}^0$ mistag rate, α is the probability that the tagging track is a daughter of the signal D meson, $\kappa = 1 - 2\rho$, where ρ is the probability that the daughter of the D results in a mixed flavor event, and $\xi = +(-)$ for $s_{\rm t}s_{\rm m} = +1(-1)$.

The $B_{\rm tag}$ may undergo a $b \to u\bar{c}d$ decay, and the kaon produced in the subsequent charm decay might be used for tagging. This effect is not described by Eq. 3. To account for it, we use a different parameterization [6] for kaon tags, in which the coefficient of the $\sin(\Delta m \Delta t_{\rm tr})$ term in Eq. 3 is

$$-\left[(1-2\omega)\,(s_{\rm t}a + s_{\rm m}c) + s_{\rm t}s_{\rm m}b(1 - s_{\rm t}\Delta\omega)\right], \qquad (4)$$

where $a \equiv 2r\sin(2\beta+\gamma)\cos\delta$, $b \equiv 2r'\sin(2\beta+\gamma)\cos\delta'$, and $c \equiv 2\cos(2\beta+\gamma)(r\sin\delta - r'\sin\delta')$. Here r' (δ') is the effective magnitude ratio (strong phase difference) between the $b \to u\bar{c}d$ and $b \to c\bar{u}d$ amplitudes in the tag-side decays. This parameterization is good to first order in r and r'.

The PDF $\mathcal{T}'_{D^*\rho}$ for $B^0 \to D^{*\mp}\rho^\pm$ events is taken to be identical to $\mathcal{T}'_{D^*\pi}$, except for the *CP* parameters ($S^\pm$, a, b, and c), which are set to 0. The $B\overline{B}$ background PDFs $\mathcal{T}_{comb}$ and $\mathcal{T}_{peak}$ have the same functional form as Eqs. 3 and 4, with independent parameter values. The parameters of $\mathcal{T}'_{peak}$ are determined from a fit to the MC simulation sample. The *CP* parameters of all the $B\overline{B}$ backgrounds are set to 0 and are later varied to evaluate systematic uncertainties. The PDF $\mathcal{T}_{q\overline{q}}$ for the continuum background is the sum of two components, one with a finite lifetime and one with zero lifetime.

The measurement of the *CP* parameters proceeds in three steps:

1. The parameters of $\mathcal{M}_i$ and the value of $f_{D^*\pi}/(f_{D^*\pi} + f_{D^*\rho})$ are obtained from the MC simulation with the branching fractions $\mathcal{B}(B^0 \to D^{*-}\pi^+)$ and $\mathcal{B}(B^0 \to D^{*-}\rho^+)$ from Ref. [7]. Using these parameter values, we fit the data with $\mathcal{P}_i = \mathcal{M}_i(m_{\rm miss})\,\mathcal{F}_i(F)$, to determine $f_{q\overline{q}}$, f_{comb}, $f_{D^*\rho} + f_{D^*\pi}$, the parameters of $\mathcal{M}_{q\overline{q}}$, and the parameters of $\mathcal{F}_i$ for both continuum and $B\overline{B}$ events. This fit yields 6400 ± 130 (25160 ± 320) signal events for the lepton- (kaon-) tagged sample. Projections of the fit results are shown in Fig. 1. The fit is repeated to determine the relative signal yields above and below the cut on $\cos\theta_T$, which determine the values of α and ρ. We find $\alpha = (1.0 \pm 0.1)\%$ ($(5.6 \pm 0.2)\%$) for lepton- (kaon-) tagged events.

2. We fit the events in the sideband $1.81 < m_{\rm miss} < 1.84$ GeV/c^2 to obtain the parameters of $\mathcal{T}'_{comb}$ and $\mathcal{T}'_{q\overline{q}}$.

3. Using the parameter values obtained in the previous steps (except $\mathcal{T}'_{q\overline{q}}$), we fit the data in the signal region $1.845 < m_{\rm miss} < 1.880$ GeV/c^2, determining the parameters of $\mathcal{T}'_{D^*\pi}$ and $\mathcal{T}'_{q\overline{q}}$.

We use the MC samples to verify the entire analysis procedure, as well as the validity of using the same non-*CP* parameters in $\mathcal{T}'_{D^*\rho}$ and $\mathcal{T}'_{D^*\pi}$ and of using the $\mathcal{T}'_{comb}$ parameters obtained from the sideband in the signal region. For lepton-tagged events, we find a bias of ∓ 0.012 in $S^\pm$, due to the assumption that events tagged with direct and cascade leptons are described by the same

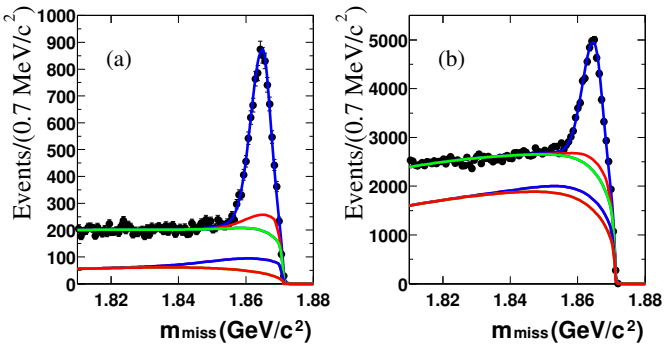

FIG. 1: The $m_{\rm miss}$ distributions for (a) lepton-tagged and (b) kaon-tagged events. The curves show, from bottom to top, the cumulative contributions of continuum, peaking $B\overline{B}$, combinatoric $B\overline{B}$, $B^0 \to D^{*+}\rho^-$, and $B^0 \to D^{*+}\pi^-$ events.

resolution function. The results presented below are corrected for this bias.

The signal-region fit (step 3) on the data determines the CP-parameters (S^+, S^-) for lepton tags and (a, b, c) for kaon tags which are found to be

$$\begin{aligned} S^+ &= -0.078 \pm 0.052 \pm 0.021, \\ S^- &= -0.070 \pm 0.052 \pm 0.019, \\ a &= -0.054 \pm 0.032 \pm 0.017, \\ b &= -0.009 \pm 0.019 \pm 0.013, \\ c &= +0.005 \pm 0.031 \pm 0.017, \end{aligned} \quad (5)$$

where the first error is statistical and the second is systematic. The time-dependent, *CP*-violating asymmetry $\mathcal{A}_{CP} = (N_{B^0_{\rm tag}} - N_{\overline{B}^0_{\rm tag}})/(N_{B^0_{\rm tag}} + N_{\overline{B}^0_{\rm tag}})$ is shown in Fig. 2. In the absence of background and experimental effects, $\mathcal{A}_{CP} = 2r\sin(2\beta+\gamma)\cos\delta\sin(\Delta m\Delta t)$.

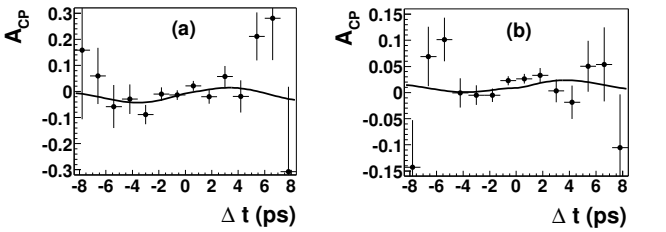

FIG. 2: The asymmetry $\mathcal{A}_{CP}$ for (a) lepton- and (b) kaon-tagged events. The curves show the projection of the PDF from the unbinned fit.

The systematic uncertainties on the *CP*-violation parameters are summarized in Table I. They include (1) the statistical errors obtained from the fits of steps 1 and 2; (2) uncertainties due to the unknown values of the *CP*-violation parameters in the background, the uncertainty in the ratio of branching fractions $\mathcal{B}(B^0 \to D^{*-}\pi)/\mathcal{B}(B^0 \to D^{*-}\rho)$, the modeling of $\mathcal{T}'_{peak}$, and possible biases introduced by the presence of background; (3) the uncertainty in the cascade lepton bias and possible biases due to the τ and Δm parameters; (4) uncertainties in the measurement of the beam spot position, the detector z length scale, and detector alignment; and (5) the statistical error in the parameters determined from the MC sample.

TABLE I: The systematic uncertainties on the *CP*-violation parameters.

Source	Error ($\times 10^{-3}$) in				
	S^+	S^-	a	b	c
(1) Step 1 & 2 statistics	1.7	0.9	1.0	0.5	0.6
(2) Backgrounds	12.1	10.0	13.7	8.4	14.2
(3) Fit procedure	6.6	5.3	5.2	1.7	0.8
(4) Detector effects	9.4	7.3	3.7	9.1	3.5
(5) MC statistics	12.8	12.8	8.0	4.0	9.0
Total	21	19	17	13	17

Combining a and $(S^+ + S^-)/2$, accounting for correlated errors, we obtain

$$2r\sin(2\beta+\gamma)\cos\delta = -0.063 \pm 0.024 \pm 0.014. \quad (6)$$

This measurement deviates from 0 by 2.3 standard deviations. It can be used to provide bounds on $|\sin(2\beta+\gamma)|$ [8].

We use two methods for interpreting our results in terms of constraints on $|\sin(2\beta+\gamma)|$. Both methods involve minimizing a χ^2 function that is symmetric under the exchange $\sin(2\beta+\gamma) \to -\sin(2\beta+\gamma)$, and applying the method of Ref. [9].

In the first method we make no assumption regarding the value of r. For different values of r we minimize the function $\chi^2 = \sum_{j,k=1}^{3} \Delta x_j V^{-1}_{jk} \Delta x_k$, where Δx_j is the difference between the result of our measurement and the theoretical value of S^+, S^-, and a, and V is the measurement error matrix, which is nearly diagonal. The parameters determined by this fit are $\sin(2\beta+\gamma)$, which is limited to lie in the range $[-1, 1]$, and δ. We then generate many parameterized MC experiments with the same sensitivity as reported here for different values of $\sin(2\beta+\gamma)$ and with $\delta = 0$, which yields the most conservative limits. The fraction of these experiments in which $\chi^2(\sin(2\beta+\gamma)) - \chi^2_{\rm min}$ is smaller than in the data is interpreted as the confidence level (CL) of the lower limit on $|\sin(2\beta+\gamma)|$. The resulting lower limit is shown as a function of r in Fig. 3. This limit is always the more conservative of the two possibilities implied by the ambiguity $|\sin(2\beta+\gamma)| \leftrightarrow |\cos\delta|$.

The second method assumes that r can be estimated from the Cabibbo angle, the ratio of branching fractions $\mathcal{B}(B^0 \to D^{*+}_s\pi^-)/\mathcal{B}(B^0 \to D^{*-}\pi^+)$ [10], and the ratio of decay constants $f_{D^*}/f_{D^*_s}$ [11], yielding $r_0 = 0.017^{+0.005}_{-0.007}$.

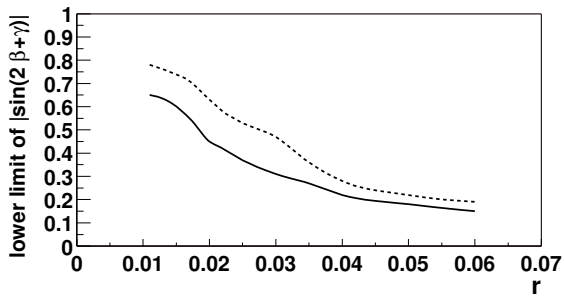

FIG. 3: 95% CL lower limit on $|\sin(2\beta+\gamma)|$ as a function of r. The solid curve corresponds to this analysis; the dashed curve includes the results of Ref. [12] for $B^0 \to D^{*\mp}\pi^{\pm}$ only.

We attribute an additional non-Gaussian 30% relative error to the theoretical assumptions involved in obtaining this value. We minimize $\tilde{\chi}^2 = \chi^2 + \Delta^2(r)$, where $\Delta^2(r) = 0$ for $|r - r_0|/r_0 \leq 0.3$ and is an offset quadratic function outside this range, corresponding to a χ^2 contribution with the uncertainties on r_0 given above. The parameters $\sin(2\beta+\gamma)$, δ, and r are determined in this fit. This method yields the limits $|\sin(2\beta+\gamma)| > 0.87$ at 68% CL and $|\sin(2\beta+\gamma)| > 0.56$ at 95% CL.

Combining this measurement with the BABAR results for fully reconstructed $B^0 \to D^{*\mp}\pi^{\pm}$ and $B^0 \to D^{\mp}\pi^{\pm}$ [12], we find, using the second method, $|\sin(2\beta+\gamma)| > 0.87$ at 68% CL and $|\sin(2\beta+\gamma)| > 0.58$ at 95% CL. The lower limit on $|\sin(2\beta+\gamma)|$ obtained with the first method, including the results of Ref. [12] for $B^0 \to D^{*\mp}\pi^{\pm}$ only, is shown in Fig. 3.

To summarize, we have studied time-dependent *CP*-violating asymmetries in $B^0 \to D^{*\mp}\pi^{\pm}$ using partial reconstruction. The amplitude of the *CP*-violating asymmetry that we measure differs from zero by 2.3 standard deviations. We interpret our results as an r-dependent lower limit on $|\sin(2\beta+\gamma)|$.

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