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Improved measurement of time-dependent *CP* asymmetries and the *CP*-odd fraction in the decay $B^0 \to D^{*+}D^{*-}$

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We present an updated measurement of the *CP*-odd fraction and the time-dependent *CP* asymmetries in the decay $B^0 \to D^{*+}D^{*-}$ using $(383 \pm 4) \times 10^6 B\bar{B}$ pairs collected with the *BABAR* detector. We

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determine the CP-odd fraction to be $0.143 \pm 0.034(\text{stat}) \pm 0.008(\text{syst})$. The time-dependent CP asymmetry parameters are determined to be $C_+ = -0.05 \pm 0.14(\text{stat}) \pm 0.02(\text{syst})$ and $S_+ = -0.72 \pm 0.19(\text{stat}) \pm 0.05(\text{syst})$. The nonzero value of the measured S_+ indicates the evidence of CP violation at the 3.7σ confidence level.

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In the standard model (SM), CP violation is described by a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, V [1]. Measurements of CP asymmetries by the *BABAR* [2] and Belle [3] collaborations have firmly established this effect in the $b \to (c\bar{c})s$ charmonium decays [4] and precisely determined the parameter $\sin 2\beta$, where β is $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$. The amplitude of the decay $B^0 \to D^{*+}D^{*-}$ is dominated by a tree-level, color-allowed $b \to c\bar{c}d$ transition. Within the framework of the SM, the CP asymmetry of $B^0 \to D^{*+}D^{*-}$ is equal to $\sin 2\beta$ when the correction due to penguin diagram contributions is neglected. The penguin-induced correction to the CP asymmetry, estimated in models based on the factorization approximation and heavy quark symmetry, is predicted to be about 2% [5], while contributions from non-SM processes may lead to a large correction [6]. Such a deviation in the $\sin 2\beta$ measurement from that of the $B^0 \to (c\bar{c})K^{(*)0}$ decays would be evidence of physics beyond the SM.

Studies of CP violation in $B^0 \to D^{(*)\pm}D^{(*)\mp}$ 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 $C_{D^+D^-} = -0.91 \pm 0.23 \pm 0.06$ [7], in contradiction to the SM expectation. However, a large direct CP violation has not been observed in this channel by *BABAR* [8], nor in previous measurements with $B^0 \to D^{*+}D^{*-}$ decays that involve the same quark-level weak decay [9,10].

The $B^0 \to D^{*+}D^{*-}$ decay proceeds through the CP-even S and D waves and through the CP-odd P wave. In this paper, we present an improved measurement of the CP-odd fraction $R_\perp$ based on a time-integrated one-dimensional angular analysis. We also present an improved measurement of the time-dependent CP asymmetry, obtained from a combined analysis of time-dependent flavor-tagged decays and the one-dimensional angular distribution of the decay products.

The data used in this analysis comprise $(383 \pm 4) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector [11] at the PEP-II asymmetric-energy e^+e^- storage rings. We use a Monte Carlo (MC) simulation based on GEANT4 [12] to validate the analysis procedure and to study the relevant backgrounds.

We select $B^0 \to D^{*+}D^{*-}$ candidates from oppositely charged pairs of D^* mesons. The D^{*+} is reconstructed in its decays to $D^0\pi^+$ and $D^+\pi^0$. We reconstruct candidates for D^0 and D^+ mesons in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_S^0\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$. We reject the B^0 candidates for which both D^* mesons decay to $D\pi^0$ because of the smaller branching fraction and larger backgrounds. To suppress the $e^+e^- \to q\bar{q}$ ($q = u, d, s$, and c) continuum background, we require the ratio of the second and zeroth order Fox-Wolfram moments [13] to be less than 0.6.

For each $B^0 \to D^{*+}D^{*-}$ candidate, we construct a likelihood function $\mathcal{L}_{\text{mass}}$ from the masses and mass uncertainties of the D and D^* candidates [14]. In this likelihood, the D mass resolution is modeled by a Gaussian function whose variance is determined candidate-by-candidate from the mass uncertainty resulting from a vertex fit of the D meson decay products. The $D^* - D$ mass difference resolution is modeled by the sum of two Gaussian distributions whose parameters are determined from simulated events. The maximum allowed values of $-\ln\mathcal{L}_{\text{mass}}$ and $|\Delta E| \equiv |E_B^* - E_{\text{beam}}|$, the difference between the B^0 candidate energy E_B^* and the beam energy E_{beam} in the $\Upsilon(4S)$ frame, are optimized separately for each final state using simulated events to obtain the highest expected signal significance.

We include candidates with an energy-substituted mass, $m_{\text{ES}} \equiv \sqrt{E_{\text{beam}}^2 - p_B^{*2}}$, greater than $5.23\ \text{GeV}/c^2$, where p_B^* is the B^0 candidate momentum in the $\Upsilon(4S)$ frame. On average, we have 1.8 B^0 candidates per event in data after all the selection requirements. In cases where more than one candidate is reconstructed in an event, the candidate with the smallest value of $-\ln\mathcal{L}_{\text{mass}}$ is chosen. Studies using MC samples show that this procedure results in the selection of the correct B^0 candidate more than 95% of the time.

The total probability density function (PDF) of the m_{ES} distribution is the sum of the signal and background components. The signal PDF is modeled by a Gaussian function and the combinatorial background is described by a threshold function [15]. Studies based on MC simulation show that there is a small peaking background from $B^+ \to \bar{D}^{*0}D^{*+}$ in which a $\bar{D}^0$ originating from a $\bar{D}^{*0}$ decay is combined with a random soft π^- to form a D^{*-} candidate. This background is described by the same PDF as the signal, and its fraction with respect to the signal yield is fixed to $(1.8 \pm 1.8)\%$, as determined in MC simulation. An unbinned maximum likelihood (ML) fit to the m_{ES} distri-

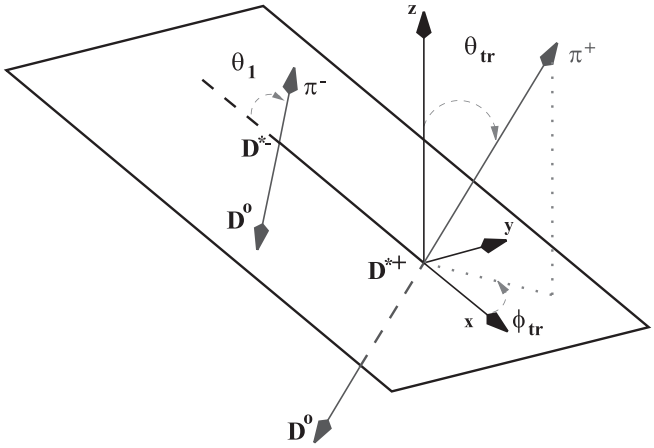

FIG. 1. Depiction of the $B^0 \to D^{*+}D^{*-}$ decay in the transversity basis. The three transversity angles are defined in the text.

bution yields 617 ± 33(stat) signal events, where the mean and width of the signal Gaussian function and the threshold function shape parameters are allowed to vary in the fit. The signal purity in the region of $m_{\rm ES} \geq 5.27$ GeV$/c^2$ is approximately 65%.

Following [16], we define three angles depicted in Fig. 1 within the transversity framework: the angle θ_1 between the momentum of the slow pion from the D^{*-} and the direction opposite the D^{*+} flight in the D^{*-} rest frame; the polar angle $\theta_{\rm tr}$ and azimuthal angle $\phi_{\rm tr}$ of the slow pion from the D^{*+} evaluated in the D^{*+} rest frame, where the coordinate system is defined with the z axis normal to the D^{*-} decay plane and the x axis opposite to the D^{*-} momentum.

The time-dependent angular distribution of the decay products is given in Ref. [17]. Taking into account the detector efficiency as a function of the transversity angles and integrating over the decay time and the angles θ_1 and $\phi_{\rm tr}$, we obtain a one-dimensional differential decay rate:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm tr}} = \frac{9}{32\pi}\Big\{(1-R_\perp)\sin^2\theta_{\rm tr} \times \Big[\frac{1+\alpha}{2}I_0(\cos\theta_{\rm tr}) + \frac{1-\alpha}{2}I_\parallel(\cos\theta_{\rm tr})\Big] + 2R_\perp\cos^2\theta_{\rm tr} \times I_\perp(\cos\theta_{\rm tr})\Big\}, \quad (1)$$

where $R_\perp = |A_\perp|^2/(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2)$, $\alpha = (|A_0|^2 - |A_\parallel|^2)/(|A_0|^2 + |A_\parallel|^2)$, A_0 is the amplitude for longitudinally polarized D^* mesons, $A_\parallel$ and $A_\perp$ are the amplitudes for parallel and perpendicular transversely polarized D^* mesons. The three efficiency moments $I_k(\cos\theta_{\rm tr})$, where $(k = 0, \parallel, \perp)$, are defined as

$$I_k(\cos\theta_{\rm tr}) = \int d\cos\theta_1 d\phi_{\rm tr} g_k(\theta_1, \phi_{\rm tr})\varepsilon(\theta_1, \theta_{\rm tr}, \phi_{\rm tr}), \quad (2)$$

where $g_0 = 4\cos^2\theta_1\cos^2\phi_{\rm tr}$, $g_\parallel = 2\sin^2\theta_1\sin^2\phi_{\rm tr}$, $g_\perp = \sin^2\theta_1$, and ε is the overall detector efficiency. The efficiency moments are parametrized as second-order even polynomials of $\cos\theta_{\rm tr}$ with parameter values determined from the MC simulation. In fact, the three I_k functions deviate only slightly from a constant, making the decay distribution [Eq. (1)] nearly independent of the amplitude asymmetry α.

The CP-odd fraction $R_\perp$ is measured in a simultaneous unbinned ML fit to the $\cos\theta_{\rm tr}$ and the $m_{\rm ES}$ distributions shown in Fig. 2. The background in the $\cos\theta_{\rm tr}$ distribution is modeled as an even, second-order polynomial, while the signal PDF is given by Eq. (1). The finite detector resolution of the $\theta_{\rm tr}$ measurement is modeled by the sum of three Gaussian functions plus a small tail component that accounts for misreconstructed events, where all the parameters are fixed to the values determined in the MC simulation. The resolution function is convolved with the signal PDF in the maximum likelihood fit. We categorize events into three types: $D^{*+}D^{*-} \to (D^0\pi^+, \bar{D}^0\pi^-)$, $(D^0\pi^+, D^-\pi^0)$, and $(D^+\pi^0, \bar{D}^0\pi^-)$, each with different

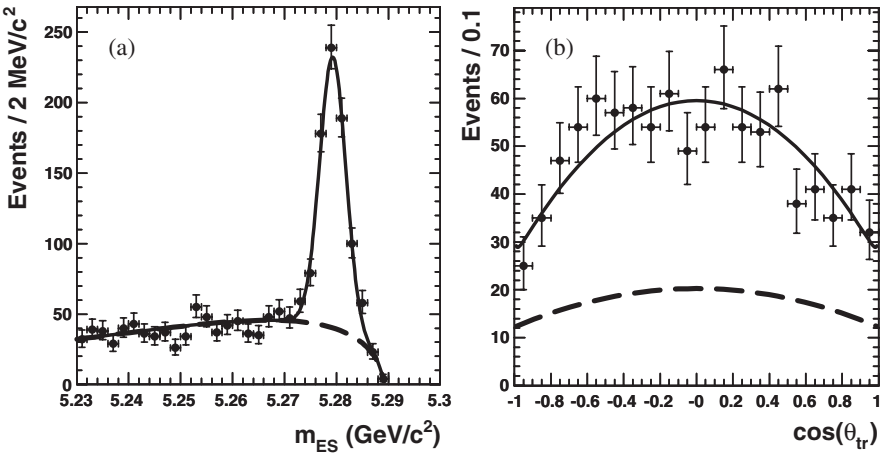

FIG. 2. Measured distribution of $m_{\rm ES}$ (a) and of $\cos\theta_{\rm tr}$ in the region $m_{\rm ES} > 5.27$ GeV$/c^2$ (b). The solid line is the projection of the fit result. The dotted line represents the background component.

signal-fraction parameters in the likelihood fit. Their efficiency moments and $\cos\theta_{\rm tr}$ resolutions are separately determined from the MC simulation. The other parameters, determined in the likelihood fit, are the $\cos\theta_{\rm tr}$ background-shape parameter, three $m_{\rm ES}$ parameters (width and mean of the signal Gaussian, and the threshold function shape parameter), as well as $R_\perp$.

After fitting to data and taking into account possible systematic uncertainties, we find

$$R_\perp = 0.143 \pm 0.034(\text{stat}) \pm 0.008(\text{syst}). \tag{3}$$

Figure 2 shows the projections of the data and the fit result onto $m_{\rm ES}$ and $\cos\theta_{\rm tr}$.

In the fit described above, the value of α, the asymmetry between the two CP-even amplitudes in the transversity framework, is fixed to zero. We estimate the corresponding systematic uncertainty by varying its value from -1 to $+1$ and find negligible change (0.003) in the fitted value of $R_\perp$. Other systematic uncertainties arise from varying fixed parameters within their errors: the parametrization of the angular resolution (0.006), the determination of the efficiency moments (0.004), and the background parametrization (0.004). The total systematic uncertainty on $R_\perp$ is 0.008.

We perform a combined analysis of the $\cos\theta_{\rm tr}$ distribution and its time dependence to extract the time-dependent CP asymmetry, using the event sample described previously. We use information from the other B meson ($B_{\rm tag}$) in the event to tag the initial flavor of the fully reconstructed $B^0 \to D^{*+}D^{*-}$ candidate ($B_{\rm rec}$). The multivariate flavor tagging algorithm is described in detail elsewhere [18]. We define six mutually exclusive tagging categories in order of expected tag purity from lepton to hadron, which includes kaon and pion tags. The total effective tagging efficiency of this algorithm is $(30.5 \pm 0.4)\%$.

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

$$f_\pm(\Delta t, \cos\theta_{\rm tr}) \propto e^{-|\Delta t|/\tau_{B^0}}\{G(1 \mp \Delta\omega) \pm (1-2\omega) \times [F\sin(\Delta m_d \Delta t) - H\cos(\Delta m_d \Delta t)]\}, \tag{4}$$

where $\Delta t = t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay time of the $B_{\rm rec}$ and $B_{\rm tag}$ mesons, $\tau_{B^0} = (1.530 \pm 0.009)$ ps is the B^0 lifetime, and $\Delta m_d = (0.507 \pm 0.005)$ ps^{-1} is the mass difference between the B^0-$\bar{B}^0$ mass eigenstates [19]. The average mistag probability ω describes the effect of incorrect tags, and $\Delta\omega$ is the difference between the mistag rate for B^0 and $\bar{B}^0$. The G, F, and H coefficients are defined as:

$$\begin{aligned} G &= (1-R_\perp)\sin^2\theta_{\rm tr} + 2R_\perp\cos^2\theta_{\rm tr}, \\ F &= (1-R_\perp)S_+\sin^2\theta_{\rm tr} - 2R_\perp S_\perp\cos^2\theta_{\rm tr}, \\ H &= (1-R_\perp)C_+\sin^2\theta_{\rm tr} + 2R_\perp C_\perp\cos^2\theta_{\rm tr}, \end{aligned} \tag{5}$$

where we allow the three transversity amplitudes to have different $\lambda_k = (q/p)(\bar{A}_k/A_k)(k = 0, \parallel, \perp)$ [17] due to possibly different penguin-to-tree amplitude ratios, and define the CP asymmetry parameters $C_k = (1 - |\lambda_k|^2)/(1 + |\lambda_k|^2)$, $S_k = 2\mathcal{I}m(\lambda_k)/(1 + |\lambda_k|^2)$. Here, we also define:

$$C_+ = \frac{C_\parallel|A_\parallel|^2 + C_0|A_0|^2}{|A_\parallel|^2 + |A_0|^2}, \qquad S_+ = \frac{S_\parallel|A_\parallel|^2 + S_0|A_0|^2}{|A_\parallel|^2 + |A_0|^2}. \tag{6}$$

In the absence of penguin contributions, we expect that $C_0 = C_\parallel = C_\perp = 0$, and $S_0 = S_\parallel = S_\perp = -\sin 2\beta$ [5].

In Eq. (4), the small detector efficiency effects are not taken into account and instead are absorbed into the value of $R_\perp$, which is allowed to vary in the final fit. Any bias in the resulting values of C_+, $C_\perp$, S_+, and $S_\perp$ is below the sensitivity of our MC validation sample and is accounted for in the MC statistics systematic. Hence, a dedicated method to correct for detector efficiency is not required. However, the "effective" value of $R_\perp$ obtained in this way is not identical to the value measured from the time-integrated analysis that includes the efficiency correction. This approach incorporates the uncertainty in $R_\perp$ directly into the determination of the CP parameters in the ML fit.

The technique used to measure the CP asymmetry is analogous to that used in *BABAR* measurements as described in Ref. [18,20]. We calculate the time interval Δt between the two B decays from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision (z) axis [20]. The z position of the $B_{\rm rec}$ vertex is determined from the charged daughter tracks. 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 [20]. Only events with a Δt uncertainty less than 2.5 ps and a measured $|\Delta t|$ less than 20 ps are accepted. We perform a simultaneous unbinned ML fit to the $\cos\theta_{\rm tr}$, Δt, and $m_{\rm ES}$ distributions to extract the CP asymmetry. The signal PDF in $\theta_{\rm tr}$ and Δt is given by Eq. (4). The signal mistag probability and the difference between the mistag rate for B^0 and $\bar{B}^0$ are determined for each tagging category from a large sample of neutral B decays to flavor eigenstates, $B_{\rm flav}$. In the likelihood fit, the expression in Eq. (4) is convolved with an empirical Δt resolution function determined from the $B_{\rm flav}$ sample. The $\theta_{\rm tr}$ resolution is accounted for in the same way as described previously.

Our increased statistics allows for better treatment of the background in this analysis. The background Δt distributions are parametrized by an empirical description that includes components that have zero lifetime, and that have an effective lifetime similar to the signal. The lifetime of the second component and its relative fraction are allowed to vary in the likelihood fit. We also allow the lifetime component to have free effective CP asymmetry parameters, $C_{\rm eff}$ and $S_{\rm eff}$, for each tagging category to take

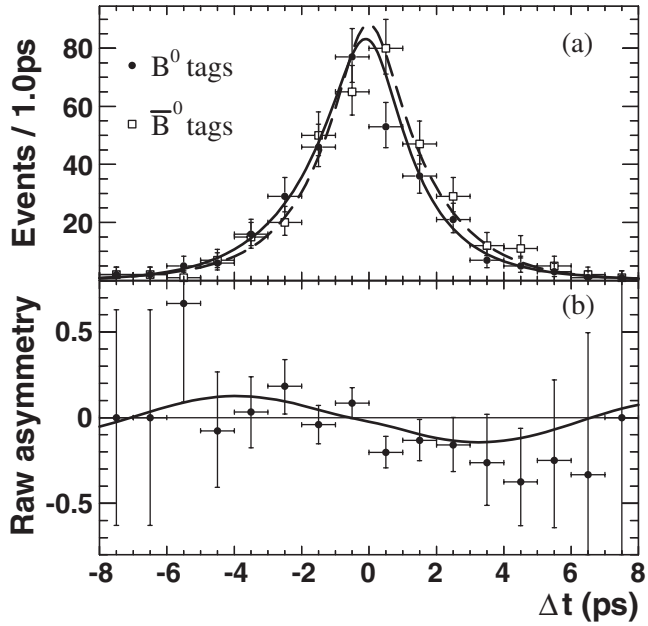

FIG. 3. The distribution in Δt of the yield in the region $m_{\rm ES} > 5.27\ {\rm GeV}/c^2$ for $B^0(\bar{B}^0)$ tagged candidates (a) and the raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of Δt (b). In (a), the solid (dashed) curves represent the fit to the data for $B^0(\bar{B}^0)$ tags.

into account a possible difference in mistag rates in the background. The background shape in $\theta_{\rm tr}$ is modeled by an even, second-order polynomial in $\cos\theta_{\rm tr}$, as in the time-integrated angular analysis.

From our fit to data we determine

$$\begin{aligned} C_+ &= -0.05 \pm 0.14({\rm stat}) \pm 0.02({\rm syst}), \\ C_\perp &= 0.23 \pm 0.67({\rm stat}) \pm 0.10({\rm syst}), \\ S_+ &= -0.72 \pm 0.19({\rm stat}) \pm 0.05({\rm syst}), \\ S_\perp &= -1.83 \pm 1.04({\rm stat}) \pm 0.23({\rm syst}). \end{aligned} \tag{7}$$

The correlations between C_+ and C_- and between S_+ and S_- are -0.46 and 0.39, respectively. All other correlations are negligible. Figure 3 shows the Δt distributions and asymmetry in yield between B^0 and $\bar{B}^0$ tags, overlaid with the result of the likelihood fit. Because $R_\perp$ is small, we have rather large statistical uncertainties for the measured $C_\perp$ and $S_\perp$ values. We repeat the fit assuming that both *CP*-even and *CP*-odd states have the same *CP* asymmetry, i.e. $C_+ = C_\perp = C$ and $S_+ = S_\perp = S$. We find

$$\begin{aligned} C &= -0.02 \pm 0.11({\rm stat}) \pm 0.02({\rm syst}), \\ S &= -0.66 \pm 0.19({\rm stat}) \pm 0.04({\rm syst}). \end{aligned} \tag{8}$$

In both cases, the effective *CP* asymmetries in the background are found to be consistent with zero. To further test the consistency of the fitting procedure, the same analysis is applied to the $B^0 \to D_s^{*+} D^{*-}$ control sample. The result is consistent with no *CP* violation as expected.

The sources of systematic uncertainty on the *CP* asymmetries and their estimated magnitudes are summarized in Table I. We vary the yield and *CP* asymmetries of possible backgrounds that peak under the signal. We also vary fixed parameters in the fit for the assumed parameterization of the Δt resolution function, the possible differences between the $B_{\rm flav}$ and B_{CP} mistag fractions, and knowledge of the event-by-event beam-spot position. We evaluate the uncertainty due to possible interference between the suppressed $b \to u\bar{c}d$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag side decays [21]. We also include systematic uncertainties incurred from the finite MC sample used to verify the fitting method. All of the systematic uncertainties are much smaller than the statistical uncertainties.

In summary, we have reported measurements of the *CP*-odd fraction, $R_\perp$, and time-dependent *CP* asymmetries for the decay $B^0 \to D^{*+} D^{*-}$. The measurement is consistent with and supersedes the previous *BABAR* result [9]. The time-dependent asymmetries are found to be consistent with the SM predictions. The nonzero value of the measured S_+ indicates the evidence of *CP* violation at the 3.7σ confidence level.

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 organiza-

TABLE I. Systematic errors on time-dependent *CP* asymmetry parameters for the decay $B^0 \to D^{*+} D^{*-}$.

Source	C_+	S_+	$C_\perp$	$S_\perp$	C	S
Peaking backgrounds	0.008	0.028	0.037	0.110	0.003	0.028
Δt resolution parametrization	0.009	0.011	0.018	0.022	0.008	0.010
Mistag fraction differences	0.008	0.024	0.016	0.035	0.008	0.024
Beam-spot position	0.004	0.007	0.019	0.042	0.003	0.005
Δm_d, τ_B	0.004	0.006	0.016	0.004	0.001	0.006
Angular resolution	0.009	0.031	0.076	0.116	0.008	0.012
Tag-side interference and others	0.014	0.009	0.017	0.021	0.014	0.009
MC statistics	0.005	0.013	0.031	0.150	0.001	0.013
Total	0.024	0.053	0.098	0.229	0.021	0.044

tions 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), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[2] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **89**, 201802 (2002).
[3] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **66**, 071102 (2002).
[4] We imply charge conjugate modes throughout the paper.
[5] X. Y. Pham and Z. Z. Xing, Phys. Lett. B **458**, 375 (1999).
[6] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997).
[7] S. Fratina *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 221802 (2007).
[8] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 071801 (2007).
[9] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 151804 (2005).
[10] H. Miyake *et al.* (Belle Collaboration), Phys. Lett. B **618**, 34 (2005).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
[12] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[13] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
[14] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **73**, 112004 (2006).
[15] H. Albrecht *et al.* (ARGUS Collaboration), Z. Phys. C **48**, 543 (1990).
[16] I. Dunietz, H. R. Quinn, A. Snyder, W. Toki, and H. J. Lipkin, Phys. Rev. D **43**, 2193 (1991).
[17] The *BABAR* Collaboration Physics Book, edited by P. F. Harrison and H. R. Quinn, SLAC-R504 (1998), pp. 213–220.
[18] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **94**, 161803 (2005).
[19] W. M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[20] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **66**, 032003 (2002).
[21] O. Long, M. Baak, R. N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).