Branching Fraction, Polarization and
$CP$-Violating Asymmetries in $B^0 \to D^*+D^*$-
Decays

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Abstract
We present measurements of the branching fraction, the polarization parameters and CP-violating asymmetries in $B^0 \to D^{*+}D^{*-}$ decays using a 140 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric $e^+e^-$ collider. We obtain $B(B^0 \to D^{*+}D^{*-}) = [0.81 \pm 0.08({\text{stat}}) \pm 0.11({\text{syst}})] \times 10^{-3}$, $R_\perp = 0.19 \pm 0.08({\text{stat}}) \pm 0.01({\text{syst}})$, $R_0 = 0.57 \pm 0.08({\text{stat}}) \pm 0.02({\text{syst}})$, $S = -0.75 \pm 0.56({\text{stat}}) \pm 0.12({\text{syst}})$ and $A = -0.26 \pm 0.26({\text{stat}}) \pm 0.06({\text{syst}})$. Consistency with Standard Model expectations is also discussed.

Key words: $B$ decay, CP violation, $\sin 2\phi_1$

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1 Introduction

In the Standard Model (SM), CP violation arises from an irreducible complex phase, the Kobayashi-Maskawa (KM) phase [1], in the weak-interaction quark-mixing matrix. In particular, the SM predicts CP asymmetries in the time-dependent rates for $B^0$ and $\bar{B}^0$ decays to a common CP eigenstate $f_{CP}$ [2]. Recent measurements of the CP-violation parameter $\sin 2\phi_1$ by the Belle [3,4] and BaBar [5] collaborations established CP violation in $B^0 \to J/\psi K^0_S$ and related decay modes [6], which are governed by the $b \to c\bar{c}s$ transition, at a level consistent with KM expectations. Here $\phi_1$ is one of the three interior angles of the Unitarity Triangle [3,4].

Despite this success, many tests remain before it can be concluded that the KM phase is the only source of CP violation. The $B^0 \to D^{*+}D^{*-}$ decay, which is dominated by the $b \to c\bar{c}d$ transition, provides an additional test of the SM. Within the SM, measurements of CP violation in this mode should yield the $\sin 2\phi_1$ value to a good approximation if the contribution from the penguin diagram is neglected. The correction from the penguin diagram is expected to be small [7]. Thus, a significant deviation in the time-dependent CP asymmetry in these modes from what is observed in $b \to c\bar{c}s$ decays would be evidence for a new CP-violating phase.

In the decay chain $\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP}f_{\text{tag}}$, where one of the $B$ mesons decays at time $t_{\text{CP}}$ to a final state $f_{CP}$ and the other decays at time $t_{\text{tag}}$ to a final state $f_{\text{tag}}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has a time dependence given by [2]

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau_{BP}}}{4\tau_{BP}} \left\{ 1 + q \left[ S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t) \right] \right\},$$

(1)

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Here $S$ and $A$ are $CP$-violation parameters, $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{tag}$, and $q = +1 \ (-1)$ when the tagging $B$ meson is a $B^0 \ (B^0)$. The parameter $S$ corresponds to the mixing-induced $CP$ violation and is related to $\sin 2\phi_1$, while $A$ represents direct $CP$ violation that normally arises from the interference between tree and penguin diagrams.

In $B^0 \to D^{*+}D^{*-}$ decays the final state $D^*$ mesons may be in a state of $s$-, $p$- or $d$-wave relative orbital angular momentum. Since $s$- and $d$-waves are even under the $CP$ transformation while the $p$-wave is odd, the $CP$-violation parameters in Eq. (1) are diluted. In order to determine the dilution, one needs to measure the $CP$-odd fraction. This can be accomplished with a time-integrated angular analysis. The BaBar collaboration has measured the polarization and $CP$ asymmetries [8], and find the $CP$-odd contribution to be small, consistent with theoretical expectations [7]. The $CP$ asymmetries are found to differ slightly from the expectation that neglects the contribution from the penguin diagram.

In this Letter we report measurements of the branching fraction, the polarization parameters and $CP$ asymmetries in $B^0 \to D^{*+}D^{*-}$ decays based on a 140 fb$^{-1}$ data sample, which corresponds to 152 million $B\overline{B}$ pairs. At the KEKB energy-asymmetric $e^+e^-$ collider [9], the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ antiparallel to the positron beamline ($z$).

Since the $B^0$ and $\overline{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), $\Delta t$ can be determined from the displacement in $z$ between the $f_{CP}$ and $f_{tag}$ decay vertices: $\Delta t \simeq (z_{CP} - z_{tag})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$.

The Belle detector [10] is a large-solid-angle spectrometer that includes a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented with resistive plate chambers to detect $K^0_L$ mesons and to identify muons (KLM).

2 Event Selection

We reconstruct $B^0 \to D^{*+}D^{*-}$ decays in the following $D^*$ final states; $(D^0\pi^+, \overline{D}^0\pi^-)$, $(D^0\pi^+, D^-\pi^0)$ and $(D^{+}\pi^0, \overline{D}^0\pi^-)$. For the $D^0$ decays we use $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$, $K^+K^-$, $K^0_{S}\pi^+\pi^-$ and $K^0_{S}\pi^+\pi^-\pi^0$. For the $D^+$ decays we use $D^+ \to K^0_{S}\pi^+, K^0_{S}\pi^+\pi^0, K^0_{S}K^+, K^-\pi^+\pi^+$ and $K^-K^+\pi^+$. We allow all combinations of $D$ decays except for cases where both $D$ decays
include neutral kaons in the final state.

Charged tracks from $D$ meson decays are required to be consistent with originating from the interaction point (IP). Charged kaons are separated from pions according to the likelihood ratio $P_{K/\pi} \equiv \mathcal{L}(K)/[\mathcal{L}(K) + \mathcal{L}(\pi)]$, where the likelihood function $\mathcal{L}$ is based on the combined information from the ACC, CDC $dE/dx$ and TOF measurements. We require $P_{K/\pi} > 0.1$ (0.2) for kaons in 2-prong (4-prong) $D$ meson decays. The kaon identification efficiency is 96%, and 13% of pions are misidentified as kaons. Candidate charged pions are required to satisfy $P_{K/\pi} < 0.9$, which provides a pion selection efficiency of 91% with a kaon misidentification probability of 3%. Neutral pions are formed from two photons with invariant masses above 119 MeV/$c^2$ and below 146 MeV/$c^2$. To reduce the background from low-energy photons, we require $E_\gamma > 0.03$ GeV for each photon and $p_\pi > 0.1$ GeV/$c$, where $E_\gamma$ and $p_\pi$ are the photon energy and the $\pi^0$ momentum in the laboratory frame, respectively. Candidate $K^0_S \rightarrow \pi^+\pi^-$ decays are reconstructed from oppositely charged track pairs that have invariant masses within 15 MeV/$c^2$ of the nominal $K^0_S$ mass. A reconstructed $K^0_S$ is required to have a displaced vertex and a flight direction consistent with that of a $K^0_S$ originating from the IP.

Candidate $D$ mesons are reconstructed from the selected kaons and pions, and are required to have invariant masses within $6\sigma$ ($3\sigma$) of the $D$ meson mass for 2-prong (3- or 4-prong) decays, where $\sigma$ is the mass resolution that ranges from 5 to 10 MeV/$c^2$. In this selection $\sigma$ is obtained by fitting the Monte Carlo (MC) simulated $D$ meson mass. These $D^0$ ($D^+$) candidates are then combined with $\pi^+$ ($\pi^0$) to form $D^{*+}$ candidates, where the IP and pion identification requirements are not used to select $\pi^+$ candidates. The mass difference between $D^{*+}$ and $D^0$ ($D^+$) is required to be within 3.00 (2.25) MeV/$c^2$ of the nominal mass difference. We identify $B$ meson decays using the energy difference $\Delta E \equiv E_{\text{cms}} - E_{\text{beam}}$, and the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}})^2 - (p_{B_{\text{cms}}})^2}$, where $E_{\text{cms}}$ is the beam energy in the cms, and $E_{B_{\text{cms}}}$ and $p_{B_{\text{cms}}}$ are the cms energy and momentum, respectively, of the reconstructed $B$ candidate. The $B$ meson signal region is defined as $|\Delta E| < 0.04$ GeV and $M_{bc}$ within $3\sigma$ of the $B$ meson mass, where $\sigma$ is 3.5 MeV/$c^2$. In order to suppress background from the $e^+e^- \rightarrow u\bar{u}$, $d\bar{d}$, $s\bar{s}$, or $c\bar{c}$ continuum, we require $H_2/H_0 < 0.4$, where $H_2$ ($H_0$) is the second (zeroth) Fox-Wolfram moment [11]. After applying this requirement, we find that the contributions to the background from $B^+B^-, B^0\bar{B}^0$ and continuum are approximately equal. Figure 1 shows the $M_{bc}$ and $\Delta E$ distributions for the $B^0 \rightarrow D^{*+}D^{*-}$ candidates that are in the $\Delta E$ and $M_{bc}$ signal regions, respectively. In the $M_{bc}$ and $\Delta E$ signal regions there are 194 events.
Fig. 1. (Left) $M_{bc}$ and (right) $\Delta E$ distributions for $B^0 \to D^{*+}D^{*-}$ candidates within the $\Delta E$ ($M_{bc}$) signal region. Solid curves show the fit to signal plus background distributions, and dashed curves show the background contributions that comprise $B^+B^-$, $B^0\overline{B}^0$ and continuum events.

3 Branching Fraction

To determine the signal yield, we perform a two-dimensional maximum likelihood fit to the $M_{bc}$-$\Delta E$ distribution ($5.2 \text{ GeV}/c^2 < M_{bc} < 5.3 \text{ GeV}/c^2$ and $|\Delta E| < 0.2 \text{ GeV}$). We use a Gaussian signal distribution plus the ARGUS background function [12] for the $M_{bc}$ distribution. The signal shape parameters are determined from MC. The background parameters are obtained simultaneously in the fit to data. The $\Delta E$ distribution is modeled by a double Gaussian signal function plus a linear background function. We obtain shape parameters separately for candidates with and without $D^{**} \to D^+\pi^0$ decays to account for small differences between the two cases.

The fit yields $130 \pm 13$ signal events, where 20% include $D^{**} \to D^+\pi^0$ decays. To obtain the branching fraction $\mathcal{B}(B^0 \to D^{*+}D^{*-})$, we use the reconstruction efficiency and the known branching fraction for each subdecay mode. We obtain an effective efficiency of $[1.06 \pm 0.08] \times 10^{-3}$ from the sum of the products of MC reconstruction efficiencies and branching fractions for each of the subdecays. Small corrections are applied to the reconstruction efficiencies for charged tracks, neutral pions and $K^0_S$ mesons to account for differences between data and MC.

We obtain

$$\mathcal{B}(B^0 \to D^{*+}D^{*-}) = [0.81 \pm 0.08\text{(stat)} \pm 0.11\text{(syst)}] \times 10^{-3},$$

(2)

where the first error is statistical and the second is systematic. The result is consistent with the present world-average value [13].
Fig. 2. Definition of the angles in the transversity basis. Angle $\theta_{tr}$ and $\phi_{tr}$ are defined in the $D^{*+}$ rest frame (the lower plane), while $\theta_1$ is defined in the $D^{*-}$ rest frame (the upper plane).

The dominant sources of the systematic error are uncertainties in the tracking efficiency (11%) and in the subdecay branching fractions (7%). Other sources are uncertainties in the fit parameters and methods (1%), in the reconstruction efficiencies of $\pi^0$ (2%) and $K_0^0$ (1%), particle identification (1%), polarization parameters (2%), the number of $B$ mesons (1%), and MC statistics (1%), where each value in parentheses is the total contribution.

4 Polarization

The time-dependent $CP$ analysis requires knowledge of the $CP$-odd fraction. To obtain the $CP$-odd fraction without bias, we must take into account the efficiency difference between the two $CP$-even components. Therefore, we perform a time-integrated two-dimensional angular analysis to obtain the fraction of each polarization component. We use the transversity basis [14] where three angles $\theta_1$, $\theta_{tr}$ and $\phi_{tr}$ are defined in Fig. 2. The angle $\theta_1$ is the angle between the momentum of the slow pion from the $D^{*-}$ in the $D^{*-}$ rest frame and the direction opposite to $B$ momentum in the $D^{*+}$ rest frame. The angle $\theta_{tr}$ is the polar angle between the normal to the $D^{*+}$ decay plane and the direction of flight of the slow pion from the $D^{*-}$ in the $D^{*+}$ rest frame. The angle $\phi_{tr}$ is the corresponding azimuthal angle, where $\phi_{tr} = 0$ is the direction antiparallel to the $D^{*-}$ flight direction. Integrating over time and the angle $\phi_{tr}$, the two-dimensional differential decay rate is

$$\frac{1}{\Gamma} \frac{d^2\Gamma}{d\cos\theta_{tr} d\cos\theta_1} = \frac{9}{16} \sum_{i=0,\parallel,\perp} R_i H_i(\cos\theta_{tr}, \cos\theta_1),$$

(3)
where \( i = 0, \|, \text{ or } \perp \) denotes longitudinal, transverse parallel, or transverse perpendicular components, \( R_i \) is its fraction that satisfies

\[
R_0 + R_\| + R_\perp = 1,
\]

and \( H_i \) is its angular distribution defined as

\[
\begin{align*}
H_0(\cos \theta_\text{tr}, \cos \theta_1) &= 2 \sin^2 \theta_\text{tr} \cos^2 \theta_1, \\
H_\|(\cos \theta_\text{tr}, \cos \theta_1) &= \sin^2 \theta_\text{tr} \sin^2 \theta_1, \\
H_\perp(\cos \theta_\text{tr}, \cos \theta_1) &= 2 \cos^2 \theta_\text{tr} \sin^2 \theta_1.
\end{align*}
\]

The fraction \( R_\perp \) corresponds to the \( CP \)-odd fraction.

Eq. (3) is affected by the detector efficiency, in particular due to the correlations between transversity angles and slow pion detection efficiencies. To take these effects into account, we replace \( H_i(\cos \theta_\text{tr}, \cos \theta_1) \) with distributions of reconstructed MC events \( H_i(\cos \theta_\text{tr}, \cos \theta_1) \), which are prepared separately for candidates with and without \( D^{*+} \rightarrow D^+ \pi^0 \) decays as is done in the branching fraction measurement. We also introduce effective polarization parameters \( R'_i \equiv \epsilon_i R_i / (\epsilon_0 R_0 + \epsilon_\| R_\| + \epsilon_\perp R_\perp) \), where \( \epsilon_i \) is a total reconstruction efficiency for each transversity amplitude. As a result, the signal probability density function (PDF) for the fit is defined as

\[
H_{\text{sig}} = \sum_i R'_i H_i(\cos \theta_\text{tr}, \cos \theta_1).
\]

We determine the following likelihood value for each event:

\[
L = f_{\text{sig}} H_{\text{sig}} + (1 - f_{\text{sig}}) H_{\text{bg}},
\]

where \( f_{\text{sig}} \) is the signal probability calculated on an event-by-event basis as a function of \( \Delta E \) and \( M_{bc} \). The background PDF \( H_{\text{bg}} \) is determined from the sideband region \((5.20 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2, |\Delta E| < 0.2 \text{ GeV})\). A fit that maximizes the product of the likelihood values over all events yields

\[
\begin{align*}
R_\perp &= 0.19 \pm 0.08(\text{stat}) \pm 0.01(\text{syst}), \\
R_0 &= 0.57 \pm 0.08(\text{stat}) \pm 0.02(\text{syst}).
\end{align*}
\]

Figure 3 shows the angular distributions with the results of the fit.

We study the uncertainties of the following items to determine the systematic errors: background shape parameters, angular resolutions, and slow pion detection efficiencies. Also included are a possible fit bias, MC histogram bin size

\[
9
\]
dependence and misreconstruction effects. These systematic errors are much smaller than the statistical errors.

5 \textit{CP} Asymmetries

We perform an unbinned maximum likelihood fit to the three dimensional $\Delta t$, $\cos \theta_{tr}$ and $\cos \theta_1$ distributions for $B^0 \to D^{*+}D^{*-}$ candidates to measure the $CP$-violation parameters.

The $B^0$ meson decay vertices are reconstructed using the $D$ meson trajectory and an IP constraint. We do not use slow pions from $D^{*+}$ decays. We require that at least one $D$ meson has two or more daughter tracks with a sufficient number of the SVD hits to precisely measure the $D$ meson trajectory. The $f_{\text{tag}}$ vertex determination is the same as for other $CP$-violation measurements [4].

The $b$-flavor of the accompanying $B$ meson is identified from inclusive properties of particles that are not associated with the reconstructed $B^0 \to f_{CP}$ decay [3]. We use two parameters, $q$ and $r$, to represent the flavor tagging information. The first, $q$, is already defined in Eq. (1). The parameter $r$ is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. This assignment is used only to sort data into six $r$ intervals. The wrong tag fractions for the six $r$ intervals, $w_l$ ($l = 1, 6$), and differences between $B^0$ and $B^0$ decays, $\Delta w_l$, are determined from the data; we use the same values that were used for the sin 2$\phi_1$ measurement [4].
The signal PDF is given by

$$\mathcal{P}_{\text{sig}} = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \sum_{i=0,||,\perp} R'_i \mathcal{H}_i(\cos \theta_{tr}, \cos \theta_1) \times \left[ 1 - q\Delta w + q(1 - 2w)(A \cos \Delta m \Delta t + \xi_i S \sin \Delta m \Delta t) \right],$$

(9)

where $CP$ parity $\xi_i$ is +1 for $i = 0$ and $||$, and −1 for $i = \perp$. We assume universal $CP$-violation parameters in Eq. (9), i.e. $S_0 = S_|| = S_\perp$ and $A_0 = A_|| = A_\perp$. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}(\Delta t)$ [4], which takes into account the finite vertex resolution.

We determine the following likelihood value for the $j$-th event:

$$P_j = (1 - f_{\text{ol}}) \int \left[ f_{\text{sig}} \mathcal{P}_{\text{sig}}(\Delta t') R_{\text{sig}}(\Delta t_i - \Delta t') \right. \left. + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t_i - \Delta t') \right] d(\Delta t') + f_{\text{ol}} P_{\text{ol}}(\Delta t_i),$$

(10)

where $P_{\text{ol}}(\Delta t)$ is a broad Gaussian function that represents an outlier component [3] with a small fraction $f_{\text{ol}}$. The $f_{\text{sig}}$ calculation is explained in the previous section. The PDF for background events, $\mathcal{P}_{\text{bkg}}(\Delta t)$, is expressed as a sum of exponential and prompt components, and is convolved with $R_{\text{bkg}}$ that is a sum of two Gaussians. All parameters in $\mathcal{P}_{\text{bkg}}(\Delta t)$ and $R_{\text{bkg}}$ are determined by a fit to the $\Delta t$ distribution of a background-enhanced control sample; i.e. events outside of the $\Delta E-M_{bc}$ signal region. We fix $\tau_{B^0}$ and $\Delta m_d$ to their world-average values [13]. The only free parameters in the final fit are $S$ and $A$, which are determined by maximizing the likelihood function $L = \prod_j P_j(\Delta t_j, \cos \theta_{tr,j}, \cos \theta_{1,j}; S, A)$, where the product is over all events. The fit yields

$$S = -0.75 \pm 0.56(\text{stat}) \pm 0.12(\text{syst}),$$
$$A = -0.26 \pm 0.26(\text{stat}) \pm 0.06(\text{syst}),$$

(11)

where the first errors are statistical and the second errors are systematic. These results are consistent with the SM expectations for small penguin contributions.

We define the raw asymmetry in each $\Delta t$ bin by $(N_{q=+1} - N_{q=-1})/(N_{q=+1} + N_{q=-1})$, where $N_{q=+1(-1)}$ is the number of observed candidates with $q = +1(-1)$. Figure 4 shows the raw asymmetries in two regions of the flavor-tagging parameter $r$. While the numbers of events in the two regions are similar, the effective tagging efficiency is much larger and the background dilution is smaller in the region $0.5 < r \leq 1.0$. Note that these projections onto
Fig. 4. Raw $B^0 \rightarrow D^{*+} D^{*-}$ asymmetry in bins of $\Delta t$ for (top) $0 < r \leq 0.5$ and $0.5 < r \leq 1.0$ (bottom). The solid curves show the result of the unbinned maximum-likelihood fit.

The sources of the systematic errors include uncertainties in the vertex reconstruction (0.05 for $S$ and 0.03 for $A$), in the flavor tagging (0.04 for $S$ and 0.02 for $A$), in the resolution function (0.05 for $S$ and 0.01 for $A$), in the background fractions (0.04 for $S$ and 0.02 for $A$), in the tag-side interference [4] (0.01 for $S$ and 0.03 for $A$), and in the polarization parameters (0.06 for $S$ and 0.01 for $A$). Other contributions for $S$ come from a possible fit bias (0.04) and from uncertainties in $\tau_{B^0}$ and $\Delta m_d$ (0.02). We add each contribution in quadrature to obtain the total systematic uncertainty.

We perform various cross checks. A fit to the same sample with $A$ fixed at zero yields $S = -0.69 \pm 0.56$ (stat). We check with an ensemble of MC pseudo-experiments that the fit has no sizable bias and the expected statistical errors are consistent with the measurement. We also select the following decay modes that have similar properties to the $B^0 \rightarrow D^{**} D^{*-}$ decay: $B^0 \rightarrow D^{*-} D_s^{*+}$, $D^- D_s^{*+}$, $D^{*-} D_s^+$, $D^- D_s^+$, and $B^+ \rightarrow D^{**0} D_s^{*+}$, $D^{**0} D_s^+$, $D^{*0} D_s^+$ and $D^{*0} D_s^+$. Fits to the control samples yield $S[B^0 \rightarrow D^{(*)} D_s^{(*)}] = -0.12 \pm 0.08$, $A[B^0 \rightarrow D^{(*)} D_s^{(*)}] = +0.02 \pm 0.05$, $S[B^+ \rightarrow D^{(*)} D_s^{(*)}] = -0.10 \pm 0.07$, and $A[B^+ \rightarrow D^{(*)} D_s^{(*)}] = -0.001 \pm 0.050$, where errors are statistical only. All results are consistent with zero. We also measure the $B$ meson lifetime using $B^0 \rightarrow D^{**} D^{*-}$ candidates as well as the control samples. All results are consistent with the present world-average values. A fit to the $\Delta t$ distribution of the $B^0 \rightarrow$
without using polarization angle information yields $S = -0.57 \pm 0.45$, $\mathcal{A} = -0.29 \pm 0.26$; this result suggests that the $CP$-odd component is small, supporting our polarization measurement.

Although the statistics are not sufficient to provide tight constraints, we also consider polarization-dependent values for $S$ and $\mathcal{A}$, which may arise from possible differences in the contributions of the penguin diagrams. We assume that the $CP$ asymmetries for the $CP$-odd component are consistent with the SM expectations, and fix $S_\perp$ at the world-average value of $\sin 2\phi_1$ [13] and $\mathcal{A}_\perp$ at zero. A fit with this assumption yields $S = -0.72 \pm 0.50$ and $\mathcal{A} = -0.42 \pm 0.30$ for the $CP$-even component, also consistent with the SM expectations.

6 Conclusion

In summary, we have performed measurements of the branching fraction, the polarization parameters and the $CP$-violation parameters for $B^0 \to D^{*+}D^{*-}$ decays. The results are

\[
\begin{align*}
\mathcal{B}(B^0 \to D^{*+}D^{*-}) &= [0.81 \pm 0.08\text{(stat)} \pm 0.11\text{(syst)}] \times 10^{-3}, \\
R_\perp &= 0.19 \pm 0.08\text{(stat)} \pm 0.01\text{(syst)}, \\
R_0 &= 0.57 \pm 0.08\text{(stat)} \pm 0.02\text{(syst)}, \\
S &= -0.75 \pm 0.56\text{(stat)} \pm 0.12\text{(syst)}, \\
\mathcal{A} &= -0.26 \pm 0.26\text{(stat)} \pm 0.06\text{(syst)}. \\
\end{align*}
\]

The polarization parameters and $CP$-violation parameters are consistent with the SM expectations and theoretical predictions for small penguin contributions [15].

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References

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[2] A. B. Carter and A. I. Sanda, Phys. Rev. D 23, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B193, 85 (1981).

[3] Belle Collaboration, K. Abe et al., Phys. Rev. Lett. 87, 091802 (2001); Phys. Rev. D 66, 032007 (2002); Phys. Rev. D 66, 071102 (2002).

[4] Belle Collaboration, K. Abe et al., hep-ex/0408111.

[5] BaBar Collaboration, B. Aubert et al., Phys. Rev. Lett. 87, 091801 (2001); Phys. Rev. D 66, 032003 (2002); Phys. Rev. Lett. 89, 201802 (2002).

[6] Throughout this paper, the inclusion of the charge conjugate decay mode is implied unless otherwise stated.

[7] X. Y. Pham and Z. Z. Xing, Phys. Lett. B 458, 375 (1999).

[8] BaBar Collaboration, B. Aubert et al., Phys. Rev. Lett. 91, 131801 (2003).

[9] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods A 499, 1 (2003).

[10] Belle Collaboration, A. Abashian et al., Nucl. Instrum. Methods A 479, 117 (2002).

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

[12] ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B 241, 278 (1990).

[13] Particle Data Group, K. Hagiwara et al., Particle Listings in the 2003 Review of Particle Physics, http://www-pdg.lbl.gov/2003/contents_listings.html.

[14] I. Dunietz, H. R. Quinn, A. Snyder, W. Toki and H. J. Lipkin, Phys. Rev. D 43, 2193 (1991).

[15] If penguin contributions are small, the theoretical predictions within the SM are $A \simeq 0$ and $S \simeq -\sin 2\phi_1$, where $\sin 2\phi_1$ is measured in $b \to c\bar{c}s$ transitions to be $0.731 \pm 0.056$ [13].