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A Study of the Rare Decays $B^0 \to D_s^{(*)+}\pi^-$ and $B^0 \to D_s^{(*)-}K^+$

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We report evidence for the decays $B^0 \to D_s^+ \pi^-$ and $B^0 \to D_s^- K^+$ and the results of a search for $B^0 \to D_s^{*+} \pi^-$ and $B^0 \to D_s^{*-} K^+$ in a sample of 84 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP II asymmetric-energy e^+e^- storage ring. We measure the branching fractions $\mathcal{B}(B^0 \to D_s^+ \pi^-) = (3.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-5}$ and $\mathcal{B}(B^0 \to D_s^- K^+) = (3.2 \pm 1.0\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-5}$. We also set 90% C.L. limits $\mathcal{B}(B^0 \to D_s^{*+} \pi^-) < 4.1 \times 10^{-5}$ and $\mathcal{B}(B^0 \to D_s^{*-} K^+) < 2.5 \times 10^{-5}$.

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The measurement of the *CP*-violating phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] is an important part of the present scientific program in particle physics. *CP* violation manifests itself as a non-zero area of the unitarity triangle [2]. While it is sufficient to measure one of the angles to demonstrate the existence of CP violation, the unitarity triangle needs to be overconstrained by experimental measurements, in order to demonstrate that the CKM mechanism is the correct explanation of this phenomenon. Several theoretically clean measurements of the angle β exist [3], but there is no such measurement of the two other angles α and γ. A theoretically clean measurement of $\sin(2\beta + \gamma)$ can be obtained from the study of the time evolution for $B^0 \to D^{(*)-}\pi^+$ [4] decays, which are already available in large samples at the B factories, and for the corresponding CKM-suppressed mode $B^0 \to D^{(*)+}\pi^-$ [5].

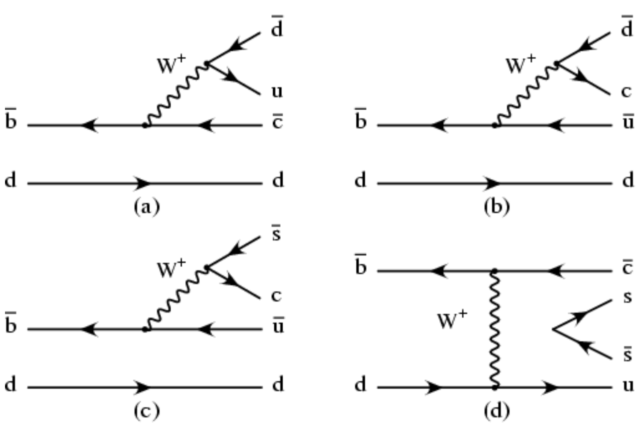

FIG. 1: The Feynman diagrams for the decays a) $B^0 \to D^{(*)-}\pi^+$, b) $B^0 \to D^{(*)+}\pi^-$, c) $B^0 \to D_s^{(*)+}\pi^-$, d) $B^0 \to D_s^{(*)-}K^+$.

This measurement requires a knowledge of the ratio of the decay amplitudes $R^{(*)} = |A(B^0 \to D^{(*)+}\pi^-)/A(B^0 \to D^{(*)-}\pi^+)|$.

Unfortunately a determination of $|A(B^0 \to D^{(*)+}\pi^-)|$ from a measurement of $\mathcal{B}(B^0 \to D^{(*)+}\pi^-)$ is not possible with the currently available data sample due to the presence of the large background from $\overline{B}^0 \to D^{(*)+}\pi^-$. However it has been suggested [5] that $R^{(*)}$ can be inferred from measurements of the ratios of the branching fractions $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)/\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$ using SU(3) symmetry relation. The decays $B^0 \to D_s^{(*)+}\pi^-$ have also been proposed as a means for measuring $|V_{ub}/V_{cb}|$ [6].

The decays $B^0 \to D_s^{(*)-}K^+$ are a probe of the dynamics in B decays because they are expected to proceed mainly via a W-exchange diagram, not observed so far. In addition, these modes can be used to investigate the role of final state rescattering, which can substantially increase the expected rates [7]. Figure 1 shows the Feynman diagrams for the decays $B^0 \to D^{(*)-}\pi^+$, $B^0 \to D^{(*)+}\pi^-$, $B^0 \to D_s^{(*)+}\pi^-$ and $B^0 \to D_s^{(*)-}K^+$.

In this Letter we present measurements of the branching fractions for the decays $B^0 \to D_s^{(*)+}\pi^-$and $B^0 \to D_s^{(*)-}K^+$.

The analysis uses a sample of 84 million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs collected in the years 1999-2002 with the *BABAR* detector at the PEP-II asymmetric-energy B-factory [8]. Since the *BABAR* detector is described in detail elsewhere [9], only the components that are crucial to this analysis are summarized here. Charged particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification, ionization energy loss (dE/dx) in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device are used. Photons are identified and measured using the electromagnetic calorimeter, which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5 T solenoidal superconducting magnet. We use the GEANT [10] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds.

We select events with a minimum of four reconstructed charged tracks and a total measured energy greater than 4.5 GeV, determined using all charged tracks and neutral clusters with energy above 30 MeV. In order to reject continuum background, the ratio of the second and zeroth order Fox-Wolfram moments [11] must be less than 0.5.

So far, only upper limits have been reported for the modes studied here [12]. Therefore the selection criteria are optimized to maximize the ratio of signal efficiency over the square-root of the expected number of background events.

Candidates for D_s^+ mesons are reconstructed in the modes $D_s^+ \to \phi\pi^+$, $K_S^0 K^+$ and $\overline{K}^{*0} K^+$, with $\phi \to K^+K^-$, $K_S^0 \to \pi^+\pi^-$, and $\overline{K}^{*0} \to K^-\pi^+$. The K_S^0 candidates are reconstructed from two oppositely-charged tracks with an invariant mass $493 < M_{\pi^+\pi^-} < 501\,\mathrm{MeV}/c^2$. All other tracks are required to originate from a vertex consistent with the e^+e^- interaction point. In order to identify charged kaons, two selections are used: a pion veto with an efficiency of 95% for kaons and 20% for pions, and a tight kaon selection with an efficiency of 85% and 5% pion misidentification probability. Unless the tight selection is specified, the pion veto is always adopted. The ϕ candidates are reconstructed from two oppositely-charged kaons with an invariant mass $1009 < M_{K^+K^-} < 1029\,\mathrm{MeV}/c^2$. The $\overline{K}^{*0}$ candidates are constructed from K^- and π^+ candidates and are required to have an invariant mass in the range $856 < M_{K^-\pi^+} < 936\,\mathrm{MeV}/c^2$. The polarization of the $\overline{K}^{*0}$ (ϕ) mesons in the D_s^+ decays are also utilized to reject backgrounds through the use of the helicity angle θ_H, defined as the angle between one of the decay products of the $\overline{K}^{*0}$ (ϕ) and the direction of flight of the D_s^+, in the $\overline{K}^{*0}$ (ϕ) rest frame. Background events are distributed uniformly in $\cos\theta_H$ since they originate from random combinations, while signal events are distributed as $\cos^2\theta_H$. The $\overline{K}^{*0}$ candidates are therefore required to have $|\cos\theta_H| > 0.4$, while for the ϕ candidates we require $|\cos\theta_H| > 0.5$. In order to reject background from $D^+\to K_S^0\pi^+$ or $\overline{K}^{*0}\pi^+$, the K^+ in the reconstruction of $D_s^+\to K_S^0K^+$ or $\overline{K}^{*0}K^+$ is required to pass the tight kaon identification criteria introduced above. Finally, the D_s^+ candidates are required to have an invariant mass within 10 MeV/c^2 of the nominal value [13].

We reconstruct D_s^{*+} candidates in the mode $D_s^{*+}\to D_s^+\gamma$, by combining D_s^+ and photon candidates. Photons that form a π^0 candidate, with $122 < M_{\gamma\gamma} < 147\,\mathrm{MeV}/c^2$, in combination with any other photon with energy greater than 70 MeV are rejected. The mass difference between the D_s^{*+} and the D_s^+ candidate is required to be within 14 MeV/c^2 of the nominal value [13].

We combine $D_s^{(*)+}$ candidates with a track of opposite charge to form a B candidate, and assign the candidate to the $\overline{B}^0\to D_s^{(*)+}K^-$ mode if the track satisfies the tight kaon selection and to the $B^0\to D_s^{(*)+}\pi^-$ mode otherwise. In order to reject events where the D_s^+ comes from a B decay and the pion or kaon comes from the other B, we require the two decay products to have a probability greater than 0.25% of originating from a common vertex.

The remaining background is predominantly combinatorial in nature and arises from continuum $q\overline{q}$ production. This source is suppressed based on event topology. We compute the angle (θ_T) between the thrust axis of the B meson candidate and the thrust axis of all other particles in the event. In the center-of-mass frame (c.m.), $B\overline{B}$ pairs are produced approximately at rest and form a uniform $\cos\theta_T$ distribution. In contrast, $q\overline{q}$ pairs are produced back-to-back in the c.m. frame, which results in a $|\cos\theta_T|$ distribution peaking at 1. Based on the background level of each mode, $|\cos\theta_T|$ is required to be smaller than a value that ranges between 0.7 and 0.8. We further suppress backgrounds using a Fisher discriminant $\mathcal{F}$ constructed from the scalar sum of the c.m. momenta of all tracks and photons (excluding the B candidate decay products) flowing into 9 concentric cones centered on the thrust axis of the B candidate [14]. The more spherical the event, the lower the value of $\mathcal{F}$. We require $\mathcal{F}$ to be smaller than a threshold that varies from 0.04 to 0.2 depending on the background level.

We extract the signal using the kinematic variables $m_{\mathrm{ES}} = \sqrt{E_{\mathrm{b}}^{*2} - (\sum_i \mathbf{p}_i^*)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_{\mathrm{b}}^*$, where E_{b}^* is the beam energy in the c.m. frame, $\mathbf{p}_i^*$ is the c.m. momentum of daughter particle i of the B meson candidate, and m_i is the mass hypothesis for particle i. For signal events, m_{ES} peaks at the B meson mass with a resolution of about 2.5 MeV/c^2 and ΔE peaks near zero, indicating that the candidate system of particles has total energy consistent with the beam energy in the c.m. frame. The ΔE signal band is defined by $|\Delta E - 5| < 36\,\mathrm{MeV}$ and within the band we define the events with $m_{\mathrm{ES}} > 5.27\,\mathrm{GeV}/c^2$ as the signal candidates.

After the aforementioned selection, three classes of backgrounds remain. First, the amount of *combinatorial background* in the signal region is estimated from the sideband of the m_{ES} distribution which is described by a threshold function $\frac{dN}{dx} = x\sqrt{1 - x^2/E_b^{*2}}\exp\left[-\xi\left(1 - x^2/E_b^{*2}\right)\right]$, characterized by the shape parameter ξ [15].

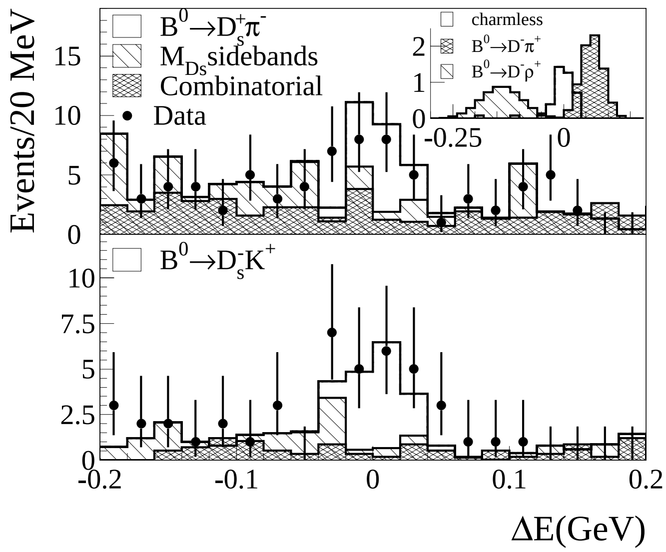

FIG. 2: The ΔE distribution for $B^0\to D_s^+\pi^-$ (top) and $B^0\to D_s^-K^+$ (bottom) candidates in data compared with the distributions of the combinatorial background, estimated from the m_{ES} sideband, the cross-contamination, estimated from the $M_{D_s}^{\mathrm{cand}}$ sidebands, and the simulation of the signal, normalized to the observed yield. The insert shows the ΔE distribution of the separate contributions to the cross contamination to the $B^0\to D_s^+\pi^-$ signal as predicted by simulation. The reflection backgrounds are normalized to the known branching fractions [13], while the normalization of the charmless background is arbitrary.

Second, B meson decays such as $\overline{B}^0\to D^+\pi^-, \rho^-$ with $D^+\to K_S^0\pi^+$ or $\overline{K}^{*0}\pi^+$ can constitute a background for the $B^0\to D_s^+\pi^-$ mode if the pion in the D decay is misidentified as a kaon (*reflection background*). These backgrounds have the same m_{ES} distributions as the signal but different distributions in ΔE. The corresponding backgrounds for the $B^0\to D_s^-K^+$ mode ($B^0\to D^-K^+, K^{*+}$) have a branching fraction ten times smaller.

Finally, rare B decays into the same final state, such as $B^0\to\overline{K}^{(*)0}K^+\pi^-$ or $\overline{K}^{(*)0}K^+K^-$ (*charmless background*), have the same m_{ES} and ΔE distributions as the $B^0\to D_s^+\pi^-$ or $B^0\to D_s^-K^+$ signal. Figure 2 shows the ΔE distribution for the $B^0\to D_s^+\pi^-$ and $B^0\to D_s^-K^+$ signal and for various sources of background. The branching fraction of the charmless background is not well measured; therefore we need to estimate the sum of the reflection and charmless background (referred to as *cross-contamination*) directly with data. This is possible because both of these background sources have a flat distribution in the D_s^+ candidate mass ($M_{D_s}^{\rm cand}$) while the signal has a Gaussian distribution.

Possible contamination from $B \to D_s^{(*)} X$ decays is determined with simulation and found to be negligible. The cross-contamination for the decays $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D_s^{*-}K^+$ is dominated by the reflection background, which we estimate from simulation. Cross-feed between $B^0 \to D_s^{(*)+}\pi^-$ and $B^0 \to D_s^{(*)-}K^+$ modes is estimated to be less than 1%.

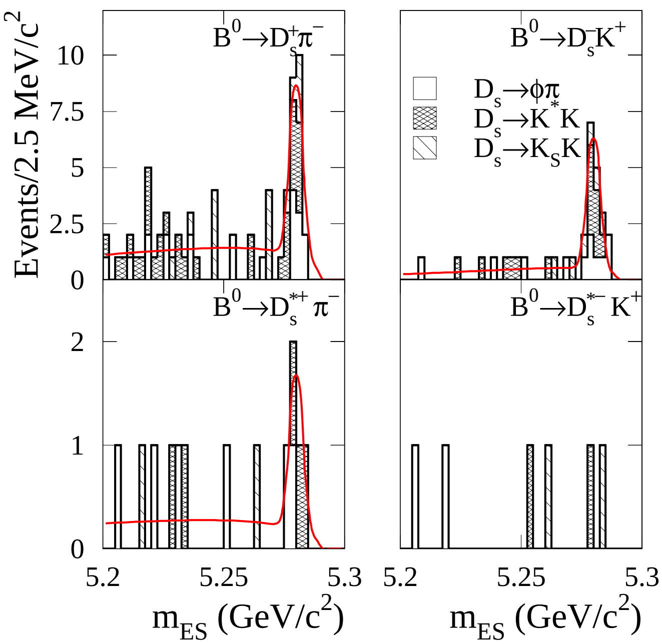

FIG. 3: The $m_{\rm ES}$ distributions for the $B^0 \to D_s^+\pi^-$ (top left), $B^0 \to D_s^- K^+$ (top right), $B^0 \to D_s^{*+}\pi^-$ (bottom left), and $B^0 \to D_s^{*-}K^+$ (bottom right) candidates within the ΔE band in data after all selection requirements. The fits used to obtain the signal yield are described in the text. The contribution from each D_s^+ mode is shown separately.

Figure 3 shows the $m_{\rm ES}$ distribution in the ΔE signal band for each of the modes. We perform an unbinned maximum-likelihood fit to each $m_{\rm ES}$ distribution with a threshold function to characterize the combinatorial background and a Gaussian distribution to describe the sum of the signal and cross-contamination contributions. The mean and the width of the Gaussian distribution are fixed to the values obtained in a copious $B^0 \to D^{(*)-}\pi^+$ control sample. For the $B^0 \to D_s^+\pi^-$ and $B^0 \to D_s^- K^+$ analyses, we obtain the threshold parameter ξ from a fit to the distributions of $m_{\rm ES}$ in data, after loosening the $M_{D_s}^{\rm cand}$ and ΔE requirements. In the case of $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D_s^{*-}K^+$, due to the low background level, we use simulated events to estimate ξ.

No fit is performed with the $B^0 \to D_s^{*-}K^+$ sample due to the small number of events. Whenever there are enough events, we fit each D_s^+ decay mode separately, as well as the combination of all modes. The cross-contamination is estimated by performing the same fit on the events in the data $M_{D_s}^{\rm cand}$ sidebands ($4\sigma < |M_{D_s}^{\rm cand} - 1968.6\,{\rm MeV}/c^2| < 8\sigma$, where the resolution is $\sigma = 5\,{\rm MeV}/c^2$). The number of observed events, the background expectations, and the reconstruction efficiencies estimated with simulated events are summarized in Table I.

In the $B^0 \to D_s^+\pi^-$ ($B^0 \to D_s^- K^+$) mode the fit yields a Gaussian contribution of 21.4$\pm$5.1 (16.7$\pm$4.3) events and a combinatorial background of 7.8$\pm$1.7 (3.5$\pm$1.3) events. The cross-contamination is estimated to be 3.7 ± 2.4 (2.7 ± 1.9) events. The probability of the background to fluctuate to the observed number of events, taking into account both Poisson statistics and uncertainties in the background estimates, is 9.5×10^{-4} (5.0×10^{-4}). For a Gaussian distribution this would correspond to 3.3σ (3.5σ). Given the estimated reconstruction efficiencies we measure $\mathcal{B}(B^0 \to D_s^+\pi^-) = (3.2 \pm 0.9) \times 10^{-5}$ ($\mathcal{B}(B^0 \to D_s^- K^+) = (3.2 \pm 1.0) \times 10^{-5}$), where the quoted error is statistical only. We also set the 90% C.L. limits $\mathcal{B}(B^0 \to D_s^{*+}\pi^-) < 4.1 \times 10^{-5}$ and $\mathcal{B}(B^0 \to D_s^{*-}K^+) < 2.5 \times 10^{-5}$.

The systematic errors are dominated by the 25% relative uncertainty for $\mathcal{B}(D_s^+ \to \phi\pi^+)$. The uncertainties on the knowledge of the background come from uncertainties in the ξ parameter, for the combinatorial background, and from the limited number of events in the $M_{D_s}^{\rm cand}$ sidebands for the cross-contamination. They amount to 14%, 16%, 7%, and 36% of the measured branching fractions in the $B^0 \to D_s^+\pi^-$, $B^0 \to D_s^- K^+$, $B^0 \to D_s^{*+}\pi^-$, and $B^0 \to D_s^{*-}K^+$ modes, respectively. The rest of the systematic errors, which include the uncertainty on tracking, K_S^0 reconstruction, and charged-kaon identification efficiencies, range between 11% and 14% depending on the mode.

In conclusion, we report a 3.3σ signal for the $b \to u$ transition $B^0 \to D_s^+\pi^-$ and a 3.5σ signal for the decay $B^0 \to D_s^- K^+$, and measure

$$\mathcal{B}(B^0 \to D_s^+\pi^-) = (3.2 \pm 0.9\,({\rm stat.}) \pm 1.0\,({\rm syst.})) \times 10^{-5},$$
$$\mathcal{B}(B^0 \to D_s^- K^+) = (3.2 \pm 1.0\,({\rm stat.}) \pm 1.0\,({\rm syst.})) \times 10^{-5}.$$

Since the dominant uncertainty comes from the knowledge of the D_s^+ branching fractions we also compute $\mathcal{B}(B^0 \to D_s^+\pi^-) \times \mathcal{B}(D_s^+ \to \phi\pi^+) = (1.13 \pm 0.33 \pm 0.21) \times 10^{-6}$ and $\mathcal{B}(B^0 \to D_s^- K^+) \times \mathcal{B}(D_s^- \to \phi\pi^-) = (1.16 \pm 0.36 \pm 0.24) \times 10^{-6}$. The search for $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D_s^{*-}K^+$ yields the 90% C.L. upper limits

$$\mathcal{B}(B^0 \to D_s^{*+}\pi^-) < 4.1 \times 10^{-5},$$
$$\mathcal{B}(B^0 \to D_s^{*-}K^+) < 2.5 \times 10^{-5}.$$

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TABLE I: The number of signal candidates ($N_{\rm sigbox}$), the Gaussian yield ($N_{\rm gaus}$) and the combinatorial background ($N_{\rm comb}$) extracted from the likelihood fit, the cross-contamination ($N_{\rm cross}$), the reconstruction efficiency (ε), the probability ($P_{\rm bckg}$) of the data being consistent with the background fluctuating up to the level of the data in the absence of signal, the measured branching fraction ($\mathcal{B}$), and the 90% confidence-level upper limit. $N_{\rm gaus}$, $N_{\rm comb}$, and $\mathcal{B}$ are not available for modes with too few events. $N_{\rm cross}$ is not reported if no event is found in the D_s^+ mass sideband.

B mode	$N_{\rm sigbox}$	$N_{\rm gaus}$	$N_{\rm comb}$	$N_{\rm cross}$	$\varepsilon(\%)$	$P_{\rm bckg}$	$\mathcal{B}(10^{-5})$	90% C.L. (10^{-5})
$B^0 \to D_s^+\pi^-$								
$D_s^+ \to \phi\pi^+$	9	8.0 ± 3.0	2.1 ± 0.7	< 0.7	16.9	1.4×10^{-3}	3.1 ± 1.2	-
$D_s^+ \to \overline{K}^{*0}K^+$	12	9.2 ± 3.4	3.8 ± 1.0	2.9 ± 1.8	9.6	2.3×10^{-2}	3.5 ± 1.9	-
$D_s^+ \to K_S^0 K^+$	5	4.2 ± 2.2	1.9 ± 0.6	1.2 ± 1.4	12.3	8.3×10^{-2}	2.4 ± 1.8	-
all	26	21.4 ± 5.1	7.8 ± 1.7	3.7 ± 2.4	N/A	9.5×10^{-4}	$3.2 \pm 0.9 \pm 1.0$	-
$B^0 \to D_s^{*+}\pi^-$								
$D_s^+ \to \phi\pi^+$	2	-	0.6 ± 0.3	< 0.14	7.8	-	-	-
$D_s^+ \to \overline{K}^{*0}K^+$	3	$2.8^{+2.7}_{-1.8}$	0.4 ± 0.3	0.3 ± 0.2	3.3	3.9×10^{-2}	$4.3^{+4.7}_{-3.1}$	< 12
$D_s^+ \to K_S^0 K^+$	0	-	0.4 ± 0.3	< 0.14	5.1	-	-	-
all	5	$4.4^{+2.7}_{-2.8}$	1.2 ± 0.4	0.3 ± 0.2	N/A	2.3×10^{-2}	$1.9^{+1.2}_{-1.3} \pm 0.5$	< 4.1
$B^0 \to D_s^- K^+$								
$D_s^+ \to \phi\pi^+$	7	5.8 ± 2.6	1.3 ± 0.7	1.1 ± 1.2	13.0	4.5×10^{-2}	2.4 ± 1.3	-
$D_s^+ \to \overline{K}^{*0}K^+$	8	7.3 ± 2.9	1.7 ± 0.7	< 0.7	7.8	1.9×10^{-3}	5.0 ± 2.0	-
$D_s^+ \to K_S^0 K^+$	4	3.7 ± 2.0	0.6 ± 0.4	1.3 ± 1.0	9.2	1.7×10^{-2}	2.5 ± 2.1	-
all	19	16.7 ± 4.3	3.5 ± 1.3	2.7 ± 1.9	N/A	5.0×10^{-4}	$3.2 \pm 1.0 \pm 1.0$	-
$B^0 \to D_s^{*-} K^+$								
$D_s^+ \to \phi\pi^+$	0	-	0.8 ± 0.6	< 0.14	5.3	-	-	-
$D_s^+ \to \overline{K}^{*0}K^+$	1	-	0.4 ± 0.4	< 0.14	2.7	-	-	-
$D_s^+ \to K_S^0 K^+$	1	-	0.4 ± 0.4	< 0.14	4.3	-	-	-
all	2	-	1.6 ± 0.8	< 0.14	N/A	0.48	-	< 2.5

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