BABAR-CONF-02/08
SLAC-PUB-9231
hep-ex/0205102

Evidence for the $b \to u$ transition $B^0 \to D_s^+ \pi^-$ and a search for $B^0 \to D_s^{*+} \pi^-$

The *BABAR* Collaboration

May 30, 2002

Abstract

We report evidence for the $b \to u$ transition $B^0 \to D_s^+ \pi^-$ and the results of a search for $B^0 \to D_s^{*+} \pi^-$ from a sample of 61.6×10^6 $\Upsilon(4S)$ decays into B meson pairs collected with the *BABAR* detector at the PEP II asymmetric e^+e^- collider. The observed $B^0 \to D_s^+ \pi^-$ yield has a probability of 4.4×10^{-4} to be a fluctuation of the background (3.5 σ) and we measure the branching fraction $\mathcal{B}(B^0 \to D_s^+ \pi^-) = (3.1 \pm 1.0\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-5}$. We also set a limit $\mathcal{B}(B^0 \to D_s^{*+} \pi^-) < 4.3 \times 10^{-5}$ at 90% C.L.

Presented at the Flavor Physics and CP Violation Conference,
5/16—5/18/2002, Philadelphia, PA

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Work supported in part by Department of Energy contract DE-AC03-76SF00515.

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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, more than one angle must be measured to demonstrate that the CKM mechanism is the correct explanation of this phenomenon. There are already several theoretically clean measurements of the angle β [3] but there is no such measurement of the other two angles (α and γ). A theoretically clean measurement of $\sin(2\beta+\gamma)$ can be obtained from the study of the time evolution of the $B^0 \to D^{(*)+}\pi^-$ and $B^0 \to D^{(*)-}\pi^+$[4] decays. This measurement requires a knowledge of the ratio between the decay amplitudes of these two processes. Unfortunately $B^0 \to D^{(*)+}\pi^-$ decays, which are Cabibbo suppressed, cannot be efficiently isolated from $\overline{B}^0 \to D^{(*)+}\pi^-$ decays. Since the amplitude of the decay $B^0 \to D^{(*)+}\pi^-$ can be related to the decay $B^0 \to D_s^{(*)+}\pi^-$[4], the measurement of $\sin(2\beta+\gamma)$ will require the knowledge of $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)$. Decays of this type have also been proposed to be used for the measurement of $|V_{ub}/V_{cb}|$ [5]. In this paper we present the results of the measurement of the branching fractions of the decays $B^0 \to D_s^{(*)+}\pi^-$.

The data were collected in the years 2000-2001 with the *BABAR* detector at the PEP-II asymmetric $e^+(3.1\,\mathrm{GeV}) - e^-(9\,\mathrm{GeV})$ storage ring [6]. Since the *BABAR* detector is described in detail elsewhere [7], only a brief description is given here. Surrounding the beam-pipe is a Silicon Vertex Tracker (SVT), which provides precise measurements of the trajectories of charged particles as they leave the e^+e^- interaction point. Outside of the SVT, a 40-layer drift chamber (DCH) allows measurements of track momenta in a 1.5 T magnetic field as well as energy-loss measurements, which contribute to charged particle identification. Surrounding the DCH is a Detector of Internally Reflected Cherenkov radiation (DIRC), which provides charged hadron identification. Outside of the DIRC is a CsI(Tl) electromagnetic calorimeter (EMC) that is used to detect photons, provide electron identification and reconstruct neutral hadrons. The EMC is surrounded by a superconducting coil, which creates the magnetic field for momentum measurements. Outside of the coil, the flux return is instrumented with resistive plate chambers interspersed with iron (IFR) for the identification of muons and long-lived neutral hadrons. We use the GEANT [8] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds.

We select hadronic events with a minimum of three reconstructed charged tracks having an impact parameter in the plane transverse to the beam less than 0.5 cm from the beam-line. The event must have a total measured energy in the laboratory greater than 4.5 GeV within the fiducial regions for charged tracks and neutral clusters with energy above 30 MeV. To help reject continuum background, the ratio of the second-to-zeroth Fox-Wolfram moment [10] must be less than 0.5.

Only upper limits on these modes have been reported [9] and therefore the selection criteria are optimized, prior to looking at the signal yield in data, to maximize $\epsilon_S/\sqrt{n_B}$. The signal efficiency ϵ_S is evaluated from Monte Carlo, while the background n_B is evaluated with data sidebands and confirmed by Monte Carlo simulation. The criteria are then made uniform among decay modes when appropriate.

The decays $B^0 \to D_s^{(*)+}\pi^-$ are reconstructed in the modes $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to \phi\pi^+$, $K_S^0 K^+$ 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^+ and π^- track candidates are required to originate from a vertex consistent with the e^+e^- interaction point. The K_S^0 candidates are reconstructed from two oppositely-charged tracks with an invariant mass $493 < M_{\pi^+\pi^-} < 501\,\mathrm{MeV}/c^2$. The ϕ candidates are reconstructed from two oppositely-charged kaons with an invariant mass $1009 < M_{K^+K^-} < 1029\,\mathrm{MeV}/c^2$. A track is identified as a kaon using the information from the energy-loss measurement in the SVT (only for tracks for momentum $p < 0.5\,\mathrm{GeV}/c$), the DCH (if $p \leq 0.6\,\mathrm{GeV}/c$) and the measured Cherenkov angle in the DIRC (if $p > 0.6\,\mathrm{GeV}/c$). Two likelihood selections based on these quantities are used in this analysis: either very loose criteria with 95% efficiency and 20% pion contamination, or tight criteria with 85% efficiency and 5% pion contamination. If not otherwise specified the former is adopted. To reconstruct K^{*0} candidates, a K^+ and a π^- are required to have an invariant mass $856 < M_{K^+\pi^-} < 936\,\mathrm{MeV}/c^2$. The polarization of the K^{*0} and ϕ mesons in the D_s^+ decays is also utilized to reject backgrounds through the use of the helicity angle θ_H, defined as the angle between one of the decay products and the direction of flight of the meson, in the meson rest frame. Background events are distributed uniformly in $|\cos\theta_H|$, while signal events are distributed as $|\cos\theta_H|^2$. 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 $K^{*0}\,\pi^+$, the additional kaon in the reconstruction of $D_s^+ \to K_S^0\,K^+$ or $\overline{K}^{*0}\,K^+$ is required to pass the tight criteria. Finally, the D_s^+ candidates are required to have an invariant mass within 10 MeV/c^2 of the nominal mass [11].

D_s^{*+} candidates are reconstructed by combining D_s^+ and photon candidates. The D_s^+ selection is re-optimized for the $B^0 \to D_s^{*+}\pi^-$ case, but the resulting selection criteria are very similar to that of the $B^0 \to D_s^+\pi^-$ case. Photons that form a π^0 candidate in combination with any other photon with energy greater than 70 MeV are not considered. The mass difference between the D_s^{*+} and the the D_s^+ candidate is required to be within 14 MeV/c^2 of the nominal value [11].

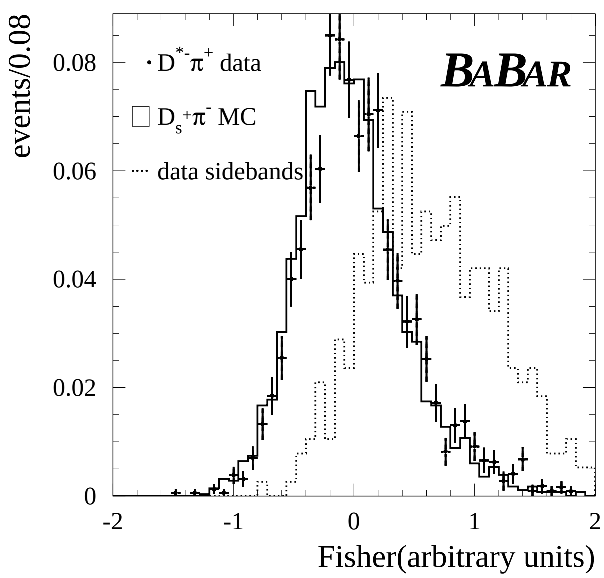

Figure 1: Distribution of the Fisher discriminant $\mathcal{F}$ in $B^0 \to D_s^+\pi^-$ Monte Carlo, $B^0 \to D^{*-}\pi^+$ data, which has the same form as the signal, and ΔE^* sideband data, which has the same form as the background.

B meson candidates are reconstructed from the D_s^+ or D_s^{*+} candidates and a charged track, which is required to fail the tight kaon criteria. Since the B mesons are produced via $e^+e^- \to \Upsilon(4S) \to B\overline{B}$, the energy of the B meson in the center-of-mass frame is the beam energy, E^*_{beam}. The distribution of $\Delta E^* = E^*_B - E^*_{beam}$ peaks at zero for the signal. The ΔE^* signal band is defined by $|\Delta E^*| < 36\,\mathrm{MeV}$ while the ΔE^* sidebands are defined as the remaining events with $|\Delta E^*| < 120\,\mathrm{MeV}$.

Backgrounds coming from other B decays, such as $B^0 \to D^-\pi^+, \rho^+$ with $D^- \to K^0_S\pi^-$ or $K^{*0}\pi^-$ deserve particular attention because their reconstructed B mass has a shape very similar to that of the signal (peaking background). In these events one of the pions in the D^- decay is misidentified as a kaon and the distribution of the reconstructed invariant mass of the D^- decay products overlaps with the signal D_s^+ mass distribution. Nonetheless, since their ΔE^* distribution does not peak at $\Delta E^* = 0$, their contribution in the signal region is small. Modes with the same final state as the signal but with no intermediate D_s^+ can also constitute a peaking background. They have the same ΔE^* distribution as the signal, but not the same distribution of the invariant mass for the D_s^+ candidate.

In order to reject events where the D_s^+ comes from a B candidate and the pion from the other B, we require the two candidates to have a probability greater than 0.25% of originating from the same vertex, which is 98% efficient on the signal. The remaining background is predominantly from continuum $q\overline{q}$ production with a D_s^+, a ϕ or a K^{*0} meson produced in the hadronization of one of the two quarks. We use event topology differences between signal and background to reduce the continuum contribution. We compute one thrust axis using only the B meson decay product candidates and one with all the other tracks. The angle between the two thrust axes (θ_T) is used to discriminate the background. In the center-of-mass frame, $B\overline{B}$ pairs are produced approximately at rest and produce a uniform $|\cos\theta_T|$ distribution. In contrast, $q\overline{q}$ pairs are produced back-to-back in the center-of-mass frame, which results in a $|\cos\theta_T|$ distribution peaking at 1. Depending on the background level of each mode we require either $|\cos\theta_T| < 0.8$ or < 0.7. We further suppress backgrounds using a Fisher discriminant $\mathcal{F}$ constructed from the scalar sum of the center-of-mass 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 [12]. The more spherical the event, the lower the value of $\mathcal{F}$. Figure 1 shows the distribution of this variable in data sidebands, which have the characteristics of the background, in simulated signal events and in a control sample of approximately 1500 $B^0 \to D^{*-}\pi^+$ fully reconstructed events with $D^{*-} \to \overline{D}^0\pi^-$ and $\overline{D}^0 \to K^+\pi^-$. This is a copious decay channel, with low background and a similar final state, and therefore well suited to investigate signal properties in data. The signal distribution is well reproduced by the simulation. We require $\mathcal{F} < 0.05$ for the $D_s^+ \to \phi\pi^+$ and $K^0_S\ K^+$ modes and $\mathcal{F} < 0.2$ for $D_s^+ \to \overline{K}^{*0}\ K^+$. The selection criteria for $B^0 \to D_s^{*+}\pi^-$ are optimized separately, but are close to the ones for $B^0 \to D_s^+\pi^-$.

As a measure of the B meson mass, the beam-energy substituted mass is defined as $m_{\mathrm{ES}} = \sqrt{E^{*2}_{beam} - \mathbf{p}^{*2}_B}$, where $\mathbf{p}^*_B$ is the momentum vector of the B meson candidate in the center-of-mass frame, calculated from the measured momenta of the decay products. The m_{ES} distribution for the signal is well described by a Gaussian distribution dominated by the resolution of the beam energy measurement, and therefore independent of the decay mode. The combinatorial background is empirically described by a threshold function (the so called "ARGUS" shape $dN/dm_{\mathrm{ES}} = A_B m_{\mathrm{ES}}\sqrt{1 - m_{\mathrm{ES}}{}^2/E^{*2}_{beam}}\exp\left[-\zeta\left(1 - m_{\mathrm{ES}}{}^2/E^{*2}_{beam}\right)\right]$, a function introduced by the ARGUS Collaboration [13]) for each mode.

Figure 2 shows the m_{ES} distribution for each of the modes. An unbinned maximum-likelihood fit is used to fit the m_{ES} distributions for signal and ARGUS shaped background contributions. The different D_s^+ decay modes are combined. The mean and width of the signal distribution are fixed to the values obtained in a high statistics $B^0 \to D^{(*)-}\pi^+$ sample. The ARGUS shape parameter [13] is fixed to the value fitted on the data after having released, in order to increase the statistics, the

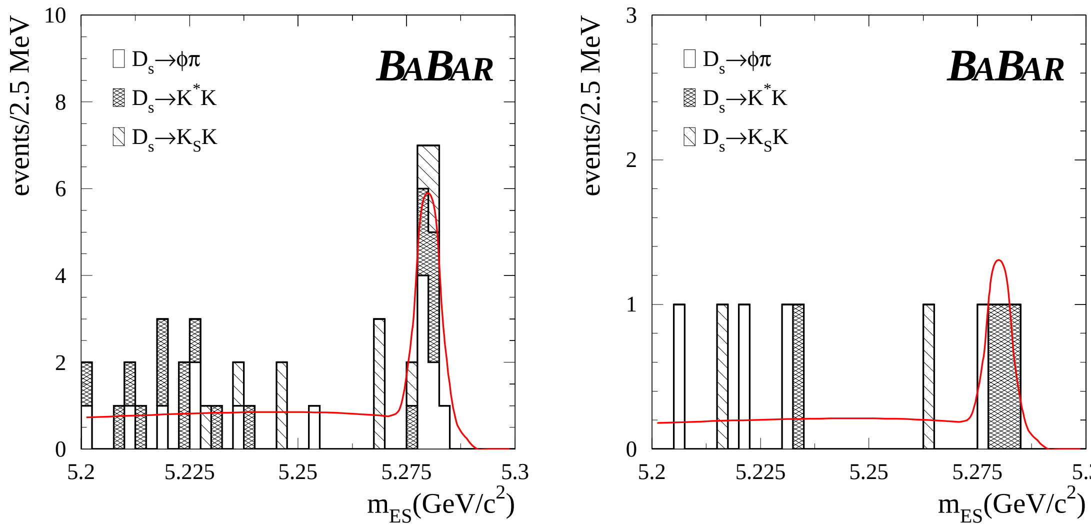

Figure 2: Distribution of $m_{\rm ES}$ for the $B^0 \to D_s^+\pi^-$ (left) and $B^0 \to D_s^{*+}\pi^-$ (right) candidates after all selection criteria, including the ΔE^* signal window. The fits used to obtain the signal yield are described in the text. The contributions from the individual modes are also shown.

requirements on the D_s^+ mass (accepted within $40\,\mathrm{MeV}/c^2$ of the nominal mass) and the ΔE^* (to $50\,\mathrm{MeV}$). The signal yields and combinatorial background, as returned from the fit, are given in Table 1.

Table 1: The number of events in the signal box (N_{sigbox}), the signal yield (N_{sig}) and the combinatorial background (N_{comb}) as extracted from the likelihood fit, the efficiency (ε), the peaking background (N_{peak}), and the measured branching fraction ($\mathcal{B}$). N_{sig}, N_{comb} and $\mathcal{B}$ are not available for modes with too few events. N_{peak} is not reported if no event is found in the D_s^+ mass sideband. Only statistical errors are quoted.

D_s^+ Mode	ε %	N_{sigbox} events	N_{sig} events	N_{comb} events	N_{peak} events	$\mathcal{B}$ 10^{-5}
		$B^0 \to D_s^+\pi^-$				
$\phi\pi^+$	16.6	7	6.4 ± 2.7	1.2 ± 0.5	-	3.5 ± 1.5
$\overline{K}^{*0}K^+$	9.7	6	5.1 ± 2.4	1.9 ± 0.6	2.3 ± 1.8	2.2 ± 1.8
$K_S^0 K^+$	12.2	4	3.4 ± 2.0	1.2 ± 0.5	-	3.7 ± 2.2
total		17	14.9 ± 4.1	4.4 ± 0.9	2.3 ± 1.8	3.1 ± 1.0
		$B^0 \to D_s^{*+}\pi^-$				
$\phi\pi^+$	7.8	1			-	
$\overline{K}^{*0}K^+$	3.3	3	2.9 ± 1.8	0.17 ± 0.17	0.20 ± 0.14	$6.5^{+3.6}_{-2.6}$
$K_S^0 K^+$	5.1	0			-	
total		4	3.5 ± 2.0	0.94 ± 0.38	0.20 ± 0.14	$2.1^{+0.8}_{-1.0}$

The efficiency for the selection requirements is given in Table 1 as obtained from simulation. The measurement of the branching fractions for the individual modes are shown as a cross check but they are not used to obtain the result. The branching fraction is determined from the signal yield (N_{sig}), the peaking background (N_{peak}), the efficiency (ε) and the total number of $B\overline{B}$ events in the sample ($N_{BB} = 61.6 \pm 0.6 \times 10^6$). The fit separates the combinatoric background (N_{comb}) from N_{sig} which is the sum of the signal and the peaking background. We estimate the total peaking background by fitting the $m_{\rm ES}$ distribution in the D_s^+ mass sidebands. The observed yield is rescaled to the signal region based on the D_s^+ mass distribution in background events. The only peaking background that would not be included in this estimate comes from B decays with a D_s^+ in the final state. Simulation of a large number of events in these decay modes shows their contribution to be negligible.

Within a 3σ $m_{\rm ES}$ window we find 17 $B^0 \to D_s^+\pi^-$ and 4 $B^0 \to D_s^{*+}\pi^-$ events, and a Gaussian component (signal and peaking background) of 14.9±4.1 and 3.5±2.0 events, respectively. The $B^0 \to D_s^+\pi^-$ yield has a probability of 4.4×10^{-4} to be a fluctuation of the background (3.5σ) and we measure a branching fraction $\mathcal{B}(B^0 \to D_s^+\pi^-) = (3.1 \pm 1.0\,(\text{stat.}))\times 10^{-5}$. The $B^0 \to D_s^{*+}\pi^-$ yield has a probability of 2.2σ to be a background fluctuation and the measured branching fraction is $\mathcal{B}(B^0 \to D_s^{*+}\pi^-) = (2.1^{+0.8}_{-1.0}\,(\text{stat.}))\times 10^{-5}$. Probabilities are computed including all the uncertainties on the backgrounds.

As a consistency check for the $B^0 \to D_s^+\pi^-$ search, we plot in Figure 3 the ΔE^* projection for the $D_s^+\pi^-$ and the $D_s^{*+}\pi^-$ modes after requiring $m_{\rm ES}$ lie within a 3σ window of the known B mass. A comparison of the observed ΔE^* distribution with the expectations from the combinatorial background, the component of the peaking background from $B^0 \to D^-\pi^+$ and $B^0 \to D^-\rho^+$, and the signal itself shows good agreement. The other peaking components with the same final state as the signal are included in the signal.

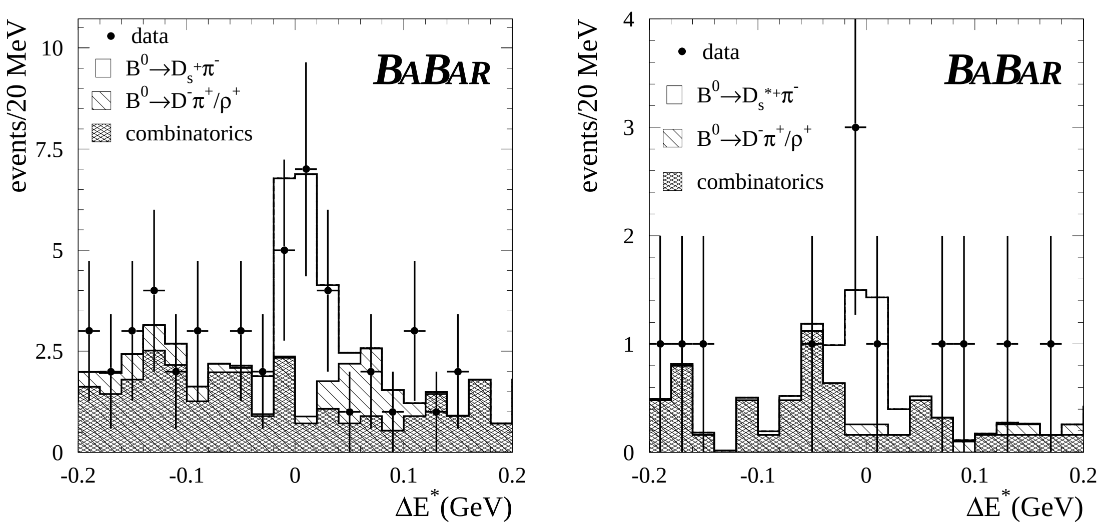

Figure 3: ΔE^* projection for $B^0 \to D_s^+\pi^-$ (left) and $B^0 \to D_s^{*+}\pi^-$ (right) events in a 3σ $m_{\rm ES}$ window around the B mass. The signal from the Monte Carlo simulation (open histogram), the combinatorial background (cross hatched histogram), and the $B^0 \to D^-\pi^+$ and $B^0 \to D^-\rho^+$ components (hatched histogram) are overlaid.

The total systematic error is the sum in quadrature of the contributions shown in Table 2. The systematic uncertainty on the combinatorial background subtraction derives from varying the background ARGUS shape within the statistical uncertainty on its determination. The uncertainty on the peaking background accounts for the limited size of the sample used to estimate it. The uncertainties on the D_s^+ and D_s^{*+} branching fractions are taken from [11]: the dominant source is $\mathcal{B}(D_s^+ \to \phi\pi^+)$, a 25% relative error correlated among all modes, since the other branching fractions are measured relative to it. The uncertainty due to the possibility that the simulation does not appropriately reproduce the shape of the event selection variables is estimated by comparing the corresponding distributions for signal simulation and a copious and pure $B^0 \to D^{*-}\pi^+$ control sample. The tracking efficiency is computed from a sample of $e^+e^- \to \tau^+\tau^-$ events, with one τ decaying into three tracks and one neutrino, and one decaying into one track and one neutrino. We estimate the K_S^0 efficiency uncertainty by comparing the momentum and flight-distance distributions in data and Monte Carlo simulation. The kaon identification efficiency is derived from a sample of $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$ decays.

Table 2: The systematic uncertainties in the measurement of the branching fraction $\mathcal{B}$.

	Uncertainty ($\times 10^{-5}$)	
	$D_s^+ \pi^-$	$D_s^{*+} \pi^-$
D_s^+ and D_s^{*+} branching fractions	0.82	0.53
Peaking Background	0.44	0.09
Selection variables	0.30	0.18
Tracking and K_S^0 efficiency	0.17	0.11
Kaon identification	0.14	0.09
Combinatoric background	0.09	0.06
Simulation statistics	0.05	0.07
N_{BB}	0.04	0.02
Photon efficiency	-	0.03
Total	1.01	0.59

In conclusion, we observe 17 $B^0 \to D_s^+\pi^-$ and 4 $B^0 \to D_s^{*+}\pi^-$ candidates in the signal region. We therefore report a 3.5σ signal for the $b \to u$ transition $B^0 \to D_s^+\pi^-$, with $\mathcal{B}(B^0 \to D_s^+\pi^-) = (3.1 \pm 1.0\,(\text{stat.}) \pm 1.0\,(\text{syst.}))\ \times 10^{-5}$. Given that the dominant uncertainty comes from the knowledge of the D_s^+ branching fractions we also compute $\mathcal{B}(B^0 \to D_s^+\pi^-) \times \mathcal{B}(D_s^+ \to \phi\pi^+) = (1.11 \pm 0.37 \pm 0.22) \times 10^{-6}$. The search for $B^0 \to D_s^{*+}\pi^-$ yields a result of 2.2σ significance, and a 68% confidence interval $\mathcal{B}(B^0 \to D_s^{*+}\pi^-) = (2.1^{+0.8}_{-1.0}\,(\text{stat.}) \pm 0.6\,(\text{syst.}))\ \times 10^{-5}$, which can be translated into an upper limit $\mathcal{B}(B^0 \to D_s^{*+}\pi^-) < 4.3 \times 10^{-5}$ at 90% C.L.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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