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

B. Aubert, D. Boutigny, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, P. Robbe, V. Tisserand, A. Zghiche, A. Palano, A. Pompili, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu, G. Eigen, I. Offe, B. Stugu, G. S. Abrams, A. W. Borgland, A. B. Breon, N. D. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, J. F. Kral, C. LeClere, M. E. Levi, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, A. Romosan, M. T. Ronan, V. G. Shlovskaya, V. A. Telnov, W. A. Wenzel, T. J. Harrison, C. M. Hawkes, D. J. Knowles, S. W. O’Neale, R. C. Penny, A. T. Watson, N. K. Watson, T. Deppermann, K. Goetzen, K. Koch, B. Lewandowski, K. Peters, H. Schumecker, M. Steinke, N. R. Barlow, W. Bhimji, J. T. Boyd, N. Chevalier, P. J. Clark, W. N. Cottingham, C. Mackay, F. F. Wilson, K. Abe, C. Hearty, T. S. Mattison, J. A. McKenna, D. Thiessen, S. Jolly, A. K. McKenney, V. E. Blinov, A. D. Bukin, A. R. Buzyaev, V. B. Golubev, V. N. Ivanchenko, A. A. Korol, A. Kravchenko, A. P. Onuchin, S. I. Seredyukov, Yu. I. Skovpen, A. N. Yushkov, D. Best, M. Chao, D. Kirby, A. J. Lankford, M. Mandelkern, S. McMahan, D. P. Stoker, C. Buchanan, S. Chun, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. Paar, S. Prell, Sh. Rahatlon, G. Raven, U. Schwane, V. Sharma, J. W. Berryhill, C. Campagnari, B. Dahmes, P. A. Hart, N. Kuznetsova, S. L. Levy, O. Long, A. L. M. Mazur, J. D. Richman, W. Verkerke, J. Beringer, A. M. Eiser, M. Grothe, A. C. Heusch, W. S. Lockman, T. Pulliam, T. Schalk, R. E. Schmitz, B. A. Schum, A. Seiden, M. Turri, W. Walkowiak, D. C. Williams, M. G. Wilson, E. Chen, G. P. Dubois-Felsmann, A. Dvoretzki, D. G. Hitlin, F. C. Porter, J. A. Ryd, A. Samuel, S. Yang, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, T. Barillari, P. Bloom, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. Roy, J. G. Smith, W. C. van Hoek, L. Zhang, J. L. Harton, T. Hu, M. Krishnamurthy, A. Soffer, W. H. Toki, R. J. Wilson, J. Zhang, D. Altenburg, T. Brandt, J. Brose, T. Colberg, M. Dickopp, R. S. Dubitzky, A. Hauke, E. Maly, R. Müller-Pfefferkorn, S. Otto, K. R. Schubert, R. Schwierz, B. Spaan, L. Wilden, D. Bernard, G. R. Bonneau, F. Brochard, J. Cohen-Tanugi, S. Ferrag, S. T. Jampens, G. Asiegh, M. Verderi, A. Anjomshoaa, B. Rernet, A. Khan, D. Lavin, F. Muheim, S. Plafer, J. E. Swain, J. Tinslay, M. Falbo, C. Borean, C. Bozzi, L. Piemontese, A. Sarti, E. Treadwell, F. Amill, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, D. Falclai, G. Finocchiaro, P. Patteri, M. Peruzzi, M. Piccolo, A. Zallo, S. B. Bazzou, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, F. C. Pastore, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, S. Bailey, M. Morii, R. Bartoldus, G. J. Greiner, U. Mallik, J. Cochran, B. H. Crawford, J. Lamsa, W. T. Meyer, E. I. Rosenberg, J. J. Yi, M. David, G. Grosdidier, A. Hocker, H. M. Lackner, S. Laplace, F. Le Diberder, V. Lepeltier, A. M. Lutz, T. C. Petersen, S. Plaszczynski, M. H. Schune, L. Tantot, S. Trincavin-Duvoid, G. Wormser, R. M. Bionta, V. Brigljevic, D. J. Lange, A. K. van Bibber, D. M. Wright, A. J. Bevan, J. R. Fry, E. Gabathuler, R. Gamet, M. George, M. Kay, D. J. Payne, R. J. Sloane, C. Touramanis, M. L. Aspinwall, D. A. Bowerman, W. P. Dauncey, U. Egged, I. Eschrich, G. W. Morton, J. A. Nash, P. Sanders, D. Smith, G. P. Taylor, J. J. Back, G. Bellodi, P. Dixon, P. F. Harrison, R. J. L. Potter, H. W. Shorthouse, P. Strother, P. B. Vidal, G. Cowan, H. U. Fiecher, S. George, M. G. Green, A. Kurup, C. E. Marker, T. R. McMahon, S. Ricciardi, F. Salvatore, G. Vaitis, M. A. Winter, D. Brown, C. L. Davis, J. Allison, R. J. Barlow, A. C. Forthi, F. Jackson, G. D. Lafferty, A. J. Lyon, N. Savvas, J. H. Weatherall, J. C. Williams, A. Farbin, A. Jawahery, A. Ogilvie, V. Lillard, A. D. Roberts, J. R. Schieck, G. Blaylock, D. Dullapiccola, K. T. Flood, S. S. Hertzbach, R. Kofler, V. B. Koptchek, J. T. Moore, H. Staengle, S. Willocq, B. Braun, R. Cowan, G. Sciolli, F. Taylor, R. K. Yamamoto, M. Mileik, P. M. Patel, F. Palombo, J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Kroege, J. Reiff, D. A. Sanders, D. J. Summers, H. C. Cartaro, N. Cavallo, G. De Nardo, F. Fabozzi, C. Gatto, L. Lista, P. Paolucci, D. Piccolo, C. Sciaccia, J. M. LoSecco,
J. R. G. Alsmiller,50 T. A. Gabriel,50 J. Brau,51 R. Frey,51 M. Iwasaki,51 C. T. Potter,51 N. B. Sinev,51 D. Strom,51 E. Torrence,51 F. Colecchia,52 A. Dorigo,52 F. Galeazzi,52 M. Margoni,52 M. Morandini,52 M. Posocco,52 M. Rotondo,52 F. Simonetto,52 R. Stroili,52 C. Voci,52 M. Benayoun,53 H. Briand,53 J. Chauveau,53 P. David,53 Ch. de la Vaissière,53 L. Del Buono,53 O. Hamon,55 Ph. Leruste,53 J. Ocariz,53 M. Pivk,53 L. Roos,53 J. Stark,53 P. F. Manfredi,54 V. Re,54 V. Speziali,54 J. L. Gladney,55 Q. H. Guo,55 J. Panetta,55 C. Angelini,56 G. Batignani,56 S. Bettarini,56 M. Bondioli,56 F. Bucci,56 G. Calderini,56 E. Campagna,56 M. Carpinelli,56 F. Forti,56 M. A. Giorgi,56 A. Lusiani,56 G. Marchiori,56 F. Martinez-Vidal,56 M. Morganti,56 N. Neri,56 E. Paoloni,56 M. Rama,56 G. Rizzo,56 F. Sandrelli,56 G. Triggiani,56 J. Walsh,56 M. Haire,57 D. Judd,57 K. Paick,57 L. Turnbull,57 D. E. Wagoner,57 J. Albert,58 N. Danielson,58 P. Elmer,58 C. Lu,58 V. Miftakov,58 J. Olsen,58 S. F. Schaffner,58 A. J. S. Smith,58 A. Tumanov,58 E. W. Varnes,58 F. Bellini,59 G. Cavoto,58,59 D. del Re,59 R. Faccini,14,59 F. Ferrarotto,59 F. Ferroni,59 E. Leonardi,59 M. A. Mazzoni,59 S. Morganti,59 G. Piredda,59 F. Safai Tehrani,59 M. Serra,59 C. Voena,59 S. Christ,60 G. Wagner,60 R. Waldi,60 T. Adye,61 N. De Groot,61 B. Franek,61 N. L. Geddes,61 G. P. Gopal,61 S. M. Xella,61 R. Aleksov,62 S. Emery,62 A. Gaidot,62 P.-F. Giraud,62 G. Hamel de Monchenault,62 W. Kozanecki,62 M. Langer,62 G. W. London,62 B. Mayer,62 G. Schott,62 B. Serfass,62 G. Vasquez,62 Ch. Yeele,62 M. Zito,62 M. V. Purohit,63 A. W. Weidemann,63 F. X. Yumiceva,63 J. Adam,64 D. Aston,64 N. Berger,64 A. M. Boyarski,64 M. R. Convery,64 D. P. Coupland,64 D. Dong,64 J. Dorfan,64 W. Dunwoodie,64 R. C. Field,64 T. Glanzman,64 S. J. Gowdy,64 E. Grauges,64 T. Haas,64 T. Hadig,64 V. Halyo,64 T. Himel,64 T. Hryn’ova,64 M. E. Huffer,64 W. R. Innes,64 C. P. Jessop,64 M. H. Kelsey,64 P. Kim,64 M. L. Kocian,64 U. Langenegger,64 D. W. G. S. Leith,64 S. Luitz,64 V. Luth,64 H. L. Lynch,64 H. Marsiske,64 S. Menke,64 R. Messner,64 D. R. Muller,64 C. P. O’Grady,64 V. E. Ozcan,64 A. Perazzo,64 M. Perl,64 S. Petrak,64 H. Quinn,64 B. N. Ratcliff,64 S. H. Robertson,64 A. Roodman,64 A. A. Saidnikov,64 T. Schietinger,64 R. H. Schindler,64 J. Schwiening,64 G. Simi,64 A. Snyder,64 A. Soha,64 S. M. Spanier,64 J. Stelzer,64 D. Su,64 M. K. Sullivan,64 H. A. Tanaka,64 J. Va’vra,64 S. R. Wagner,64 M. Weaver,64 A. J. R. Weinstein,64 W. J. Wisniewski,64 D. H. Wright,64 C. C. Young,64 P. R. Burchat,65 C. H. Cheng,65 T. I. Meyer,65 C. Roat,65 R. Henderson,66 W. Bugg,67 H. Cohn,67 J. M. Izen,68 I. Kitayama,68 X. C. Lou,68 F. Bianchi,69 M. Bona,69 D. Gamba,69 L. Bosio,70 G. Della Ricca,70 S. Dittongo,70 L. Lanceri,70 P. Poropat,70 L. Vitale,70 G. Viagnin,70 R. S. Panvini,71 Sw. Banerjee,71 L. Bosisio,71 M. Carpinelli,71 H. Briand,71 Ph. Leruste,71 P. David,71 R. Dittori,71 C. T. Potter,71 M. Posocco,71 D. Strom,72 R. P. Jackson,72 R. Kowalewski,72 J. M. Roney,72 H. R. Band,73 S. Dasu,73 M. Datta,73 A. M. Eichenbaum,73 H. Hu,73 J. R. Johnson,73 R. Liu,73 F. Di Lodovico,73 A. Mohapatra,73 Y. Pan,73 R. Prepost,73 I. J. Scott,73 S. J. Sekula,73 J. H. von Wimmersperg-Toeller,73 J. Wu,73 S. L. Wu,73 Z. Yu,73 and H. Neal74
(The BABAR Collaboration)

1Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France
2Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy
3Institute of High Energy Physics, Beijing 100039, China
4University of Bergen, Inst. of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA
6University of Birmingham, Birmingham, B15 2TT, United Kingdom
7Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8University of Bristol, Bristol BS8 1TL, United Kingdom
9University of British Columbia, Vancouver, BC, Canada V6T 1Z1
10Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
11Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
12University of California at Irvine, Irvine, CA 92697, USA
13University of California at Los Angeles, Los Angeles, CA 90024, USA
14University of California at San Diego, La Jolla, CA 92039, USA
15University of California at Santa Barbara, Santa Barbara, CA 93106, USA
16University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA
17California Institute of Technology, Pasadena, CA 91125, USA
18University of Cincinnati, Cincinnati, OH 45221, USA
19University of Colorado, Boulder, CO 80309, USA
20Colorado State University, Fort Collins, CO 80523, USA
21Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
22École Polytechnique, LLR, F-91128 Palaiseau, France
23University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
24Elon University, Elon University, NC 27244-2010, USA
25Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
26Florida A&M University, Tallahassee, FL 32307, USA
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 $B\bar{B}$ pairs collected with the BABAR detector at the PEP II asymmetric-energy $e^+e^-$ storage ring. We measure the branching fractions $B(B^0 \to D^+_s \pi^-) = (3.2 \pm 0.9 \text{ (stat.}) \pm 1.0 \text{ (syst.)}) \times 10^{-5}$ and $B(B^0 \to D^+_s K^+) = (3.2 \pm 1.0 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-5}$. We also set 90% C.L. limits $B(B^0 \to D^+_s \pi^-) < 4.1 \times 10^{-5}$ and $B(B^0 \to D^+_s K^+) < 2.5 \times 10^{-5}$.

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The measurement of the $CP$-violating phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix \cite{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 \cite{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 $\beta$ exist $[3]$, but there is no such measurement of the two other angles $\alpha$ and $\gamma$. A theoretically clean measurement of $\sin(2\beta + \gamma)$ can be obtained from the study of the time evolution for $B^0 \to D^{(*)} \pi^+\pi^-$ $[4]$ 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) $B^0 \to D_s^{(*)-} K^+$. $[6]$

This measurement requires a knowledge of the ratio of the decay amplitudes $R^{(*)} = \left| A(B^0 \to D^{(*)+} \pi^-) / A(B^0 \to D^{(*)-} \pi^+) \right|$. $[7]$ Unfortunately a determination of $\left| A(B^0 \to D^{(*)+} \pi^-) / A(B^0 \to D^{(*)-} \pi^+) \right|$ 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 $B^0 \to D^{(*)+} \pi^-$. However it has been suggested $[8]$ 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 $|V_{ub}/V_{cb}|$ $[8]$. $[9]$ $[10]$ $[11]$

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 $[8]$. 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 $B^0 \to D_s^{(*)-} K^+$. $[11]$$[9]$

In this Letter we present measurements of the branching fractions for the decays $B^0 \to D_s^{(*)+} \pi^-$ and $B^0 \to D_s^{(*)-} K^+$. $[12]$

The analysis uses a sample of 84 million $\Upsilon(4S)$ decays into $B\bar{B}$ pairs collected in the years 1999-2002 with the $BABAR$ detector at the PEP-II asymmetric-energy $B$-factory $[3]$. Since the $BABAR$ detector is described in detail elsewhere $[13]$ 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 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. $[14]$

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 $D^+_s \to \phi \pi^+$, $K^0_s K^+$ and $K^{*0} K^+$, with $\phi \to K^+ K^-$, $K^0_s \to \pi^+ \pi^-$, and $K^{*0} \to K^- \pi^+$. The $K^0_s$ candidates are reconstructed from two oppositely-charged tracks with an invariant mass $493 < M_{\pi^+ \pi^-} < 501 \text{MeV}/c^2$. 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. $[15]$

The $\phi$ candidates are reconstructed from two oppositely-charged kaons with an invariant mass $1009 < M_{K^+ K^-} < 1029 \text{MeV}/c^2$. $[16]$ All the $K^0_s$ candidates are reconstructed from two oppositely-charged kaons with an invariant mass $856 < M_{\pi^+ \pi^-} < 936 \text{MeV}/c^2$. The polarization of the $K^{*0}$ ($\phi$) mesons in the $D^+_s$ decays are also utilized to reject backgrounds through the use of the helicity angle $\theta_H$, defined as the angle between one of the decay products of the $K^{*0}$ ($\phi$) and the direction of flight of the $D_s^+$, in the $K^{*0}$ ($\phi$) rest frame. Background events are distributed uniformly in $\cos \theta_H$ since they originate from random combinations, while signal events are distributed as $\cos^2 \theta_H$. $[17]$ The $K^{*0}$ candidates are therefore required to have $|\cos \theta_H| > 0.4$, while for the $\phi$ candidates we require $|\cos \theta_H| > 0.5$. In order to reject background from $D^+ \to K^0_s \pi^+$ or $K^{*0} \pi^+$, the $K^+$ in the reconstruction of $D^+_s \to K^0_s K^+$ or $K^{*0} K^+$ is re-
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 $D^{*+}_s \rightarrow D^+_s \gamma$, by combining $D^+_s$ and photon candidates. Photons that form a $\pi^0$ candidate, with $122 < M_{\gamma \gamma} < 147$ 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 $B^0 \rightarrow D^{(*)+}_s K^-$ mode if the track satisfies the tight kaon selection and to the $B^0 \rightarrow D^{(*)+}_s \pi^-$ 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 $q \bar{q}$ production. This source is suppressed based on event topology. We compute the angle ($\theta_T$) 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.), $B \bar{B}$ pairs are produced approximately at rest and form a uniform $\cos \theta_T$ distribution. In contrast, $q \bar{q}$ 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 $F$ 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 $F$. We require $F$ 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 $m_{ES} = \sqrt{E_b^2 - (\sum \vec{p}_i^2)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + \vec{p}_i^2 - E_b^2}$, where $E_b$ is the beam energy in the c.m. frame, $\vec{p}_i$ 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 $\Delta E$ peaks near zero, indicating that the candidate system of particles has total energy consistent with the beam energy in the c.m. frame. The $\Delta E$ signal band is defined by $|\Delta E - 5| < 36$ MeV and within the band we define the events with $m_{ES} > 5.27$ 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 $\frac{dN}{dx} = x \sqrt{1 - x^2/E_b^2} \exp \left[-\xi (1 - x^2/E_b^{*2})\right]$, characterized by the shape parameter $\xi$ [15].

Second, $B$ meson decays such as $B^0 \rightarrow D^{\pm} \pi^-$, $D^{\pm} \rightarrow K^\pm \pi^o$ or $K^{\ast0} \pi\pi^o$ can constitute a background for the $B^0 \rightarrow D^+_s \pi^-$ 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 $\Delta E$. The corresponding backgrounds for the $B^0 \rightarrow D^- K^+ K^{\pm} (D^0 \rightarrow D^- K^+, K^{++})$ have a branching fraction ten times smaller.

Finally, rare $B$ decays into the same final state, such as $B^0 \rightarrow \bar{K}^{(*)0} K^+ \pi^0$ or $\bar{K}^{(*)0} K^+ K^- (charmless background)$, have the same $m_{ES}$ and $\Delta E$ distributions as the $B^0 \rightarrow D^+_s \pi^-$ or $B^0 \rightarrow D^- K^+$ signal. Figure 2 shows the $\Delta E$ distribution for the $B^0 \rightarrow D^+_s \pi^-$ and $B^0 \rightarrow D^- K^+$ 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 ($M_{DS}$) while the signal has a Gaussian distribution.

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

The mean and the width of the Gaussian distribution are fixed to the values obtained in a copious sample and found to be negligible. The cross-contamination is estimated to be $3.7 \pm 2.4$ (2.7 \pm 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 $9.5 \times 10^{-4}$ (5.0 \times 10^{-4}). For a Gaussian distribution this would correspond to $\sigma = 5 \text{ MeV}/c^2$. The number of observed events, the background expectations, and the reconstruction efficiencies estimated with simulated events are summarized in Table I.

In the $B^0 \rightarrow D^{+}_s \pi^- (B^0 \rightarrow D^{0}_s K^+)$ 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 $3.7 \pm 2.4 (2.7 \pm 1.9)$ 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 $9.5 \times 10^{-4}$ (5.0 \times 10^{-4}). For a Gaussian distribution this would correspond to $3.3 \sigma (3.5\sigma)$. Given the estimated reconstruction efficiencies we measure 

\begin{align*}
B(B^0 \rightarrow D^{+}_s \pi^-) &= (3.2 \pm 0.9) \times 10^{-5} \\
B(B^0 \rightarrow D^{0}_s K^+) &= (3.2 \pm 1.0) \times 10^{-5},
\end{align*}

and 90\% C.L. limits $B(B^0 \rightarrow D^{+}_s \pi^-) < 4.1 \times 10^{-5}$ and $B(B^0 \rightarrow D^{0}_s K^+) < 2.5 \times 10^{-5}$. The systematic errors are dominated by the 25\% relative uncertainty for $B(D^{+}_s \rightarrow \phi \pi^+)$. The uncertainties on the knowledge of the background come from uncertainties in the $\xi$ parameter, for the combinatorial background, and from the limited number of events in the $M^{\text{had}}$ bands.

In conclusion, we report a 3.3\sigma signal for the $b \rightarrow u$ transition $B^0 \rightarrow D^{+}_s \pi^-$ and a 3.5\sigma signal for the decay $B^0 \rightarrow D^{0}_s K^+$, and measure

\begin{align*}
B(B^0 \rightarrow D^{+}_s \pi^-) &= (3.2 \pm 0.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-5} \\
B(B^0 \rightarrow D^{0}_s K^+) &= (3.2 \pm 1.0 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-5}.
\end{align*}

Since the dominant uncertainty comes from the knowledge of the $D^{0}_s$ branching fractions we also compute

\begin{align*}
B(B^0 \rightarrow D^{+}_s \pi^-) \times B(D^{+}_s \rightarrow \phi \pi^+) &= (1.13 \pm 0.33 \pm 0.21) \times 10^{-6} \\
B(B^0 \rightarrow D^{0}_s K^+) \times B(D^{0}_s \rightarrow \phi \pi^+) &= (1.16 \pm 0.36 \pm 0.24) \times 10^{-6}.
\end{align*}

The search for $B^0 \rightarrow D^{+}_s \pi^-$ and $B^0 \rightarrow D^{0}_s K^+$ yields the 90\% C.L. upper limits

\begin{align*}
B(B^0 \rightarrow D^{+}_s \pi^-) < 4.1 \times 10^{-5} \\
B(B^0 \rightarrow D^{0}_s K^+) < 2.5 \times 10^{-5}.
\end{align*}

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

| $B$ mode | $N_{\text{sigbox}}$ | $N_{\text{gaus}}$ | $N_{\text{comb}}$ | $N_{\text{cross}}$ | $\varepsilon(\%)$ | $P_{\text{bckg}}$ | $B(10^{-3})$ | 90% C.L. (10^{-3}) |
|---------|---------------------|-------------------|-----------------|-----------------|----------------|----------------|-------------|----------------|
| $B^0 \to D_s^+ \pi^-$ | 9 | 8.0 ± 3.0 | 2.1 ± 0.7 | < 0.7 | 16.9 | 1.4 × 10^{-3} | 3.1 ± 1.2 | - |
| $D_s^+ \to \phi \pi^+$ | 12 | 9.2 ± 3.4 | 3.8 ± 1.0 | 2.9 ± 1.8 | 9.6 | 2.3 × 10^{-2} | 3.5 ± 1.9 | - |
| $D_s^+ \to K^0 \phi K^-$ | 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 ± 0.9 | 1.0 |
| $B^0 \to D_s^+ \phi^0 K^-$ | 2 | - | 0.6 ± 0.3 | < 0.14 | 7.8 | - | - | - |
| $D_s^+ \to K^0 \phi K^-$ | 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^-1.1 | < 12 |
| $D_s^+ \to K^0 \phi K^-$ | 0 | - | 0.4 ± 0.3 | < 0.14 | 5.1 | - | - | - |
| all | 5 | 4.4^+2.7^-2.5 | 1.2 ± 0.4 | 0.3 ± 0.2 | N/A | 2.3 × 10^{-2} | 1.9^+6.3^-0.5 | < 4.1 |
| $B^0 \to D_s^+ K^-$ | 7 | 5.8 ± 2.6 | 1.3 ± 0.7 | 1.1 ± 1.2 | 13.0 | 4.5 × 10^{-2} | 2.4 ± 1.3 | - |
| $D_s^+ \to \phi \phi K^-$ | 8 | 7.3 ± 2.9 | 1.7 ± 0.7 | < 0.7 | 7.8 | 1.9 × 10^{-3} | 5.0 ± 2.0 | - |
| $D_s^+ \to K^0 S K^-$ | 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 ± 1.0 | 1.0 |
| $B^0 \to D_s^+ K^+$ | 0 | - | 0.8 ± 0.6 | < 0.14 | 5.3 | - | - | - |
| $D_s^+ \to \phi \phi K^+$ | 1 | - | 0.4 ± 0.4 | < 0.14 | 2.7 | - | - | - |
| $D_s^+ \to K^0 S K^+$ | 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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* Also with Università di Perugia, I-06100 Perugia, Italy

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