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

The *BABAR* Collaboration

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Abstract

We report on the evidence for the decays $B^0 \to D_s^+\pi^-$ and $B^0 \to D_s^-K^+$ and the results of a search for the decays $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D_s^{*-}K^+$ from a sample of 84 million $\Upsilon(4S)$ decays into B meson pairs collected with the *BABAR* detector at the PEP II asymmetric-energy e^+e^- collider. The measured $B^0 \to D_s^+\pi^-$ yield has a probability of less than 10^{-3} to be a fluctuation of the background and we measure the branching fraction $\mathcal{B}(B^0 \to D_s^+\pi^-) = (3.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.}))\ \times 10^{-5}$. The measured $B^0 \to D_s^-K^+$ yield has a probability of less than 5×10^{-4} to be a fluctuation of the background and we measure the branching fraction $\mathcal{B}(B^0 \to D_s^-K^+) = (3.2 \pm 1.0\,(\text{stat.}) \pm 1.0\,(\text{syst.}))$ $\times 10^{-5}$. We also set 90% C.L. limits $\mathcal{B}(B^0 \to D_s^{*+}\pi^-) < 4.1 \times 10^{-5}$ and $\mathcal{B}(B^0 \to D_s^{*-}K^+) < 2.5 \times 10^{-5}$. All results are preliminary.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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The *BABAR* Collaboration,

B. Aubert, D. Boutigny, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, P. Robbe, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France

A. Palano, A. Pompili

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. 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. LeClerc, 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. Shelkov, A. V. Telnov, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

T. J. Harrison, C. M. Hawkes, D. J. Knowles, S. W. O'Neale, R. C. Penny, A. T. Watson, N. K. Watson

University of Birmingham, Birmingham, B15 2TT, United Kingdom

T. Deppermann, K. Goetzen, H. Koch, B. Lewandowski, K. Peters, H. Schmuecker, M. Steinke

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

N. R. Barlow, W. Bhimji, J. T. Boyd, N. Chevalier, P. J. Clark, W. N. Cottingham, C. Mackay, F. F. Wilson

University of Bristol, Bristol BS8 1TL, United Kingdom

K. Abe, C. Hearty, T. S. Mattison, J. A. McKenna, D. Thiessen

University of British Columbia, Vancouver, BC, Canada V6T 1Z1

S. Jolly, A. K. McKemey

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, A. R. Buzykaev, V. B. Golubev, V. N. Ivanchenko, A. A. Korol, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, A. N. Yushkov

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. Best, M. Chao, D. Kirkby, A. J. Lankford, M. Mandelkern, S. McMahon, D. P. Stoker

University of California at Irvine, Irvine, CA 92697, USA

C. Buchanan, S. Chun

University of California at Los Angeles, Los Angeles, CA 90024, USA

H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. Paar, S. Prell, Sh. Rahatlou, G. Raven, U. Schwanke, V. Sharma

University of California at San Diego, La Jolla, CA 92093, USA

J. W. Berryhill, C. Campagnari, B. Dahmes, P. A. Hart, N. Kuznetsova, S. L. Levy, O. Long, A. Lu, M. A. Mazur, J. D. Richman, W. Verkerke

University of California at Santa Barbara, Santa Barbara, CA 93106, USA

J. Beringer, A. M. Eisner, M. Grothe, C. A. Heusch, W. S. Lockman, T. Pulliam, T. Schalk, R. E. Schmitz, B. A. Schumm, A. Seiden, M. Turri, W. Walkowiak, D. C. Williams, M. G. Wilson

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, F. C. Porter, A. Ryd, A. Samuel, S. Yang

California Institute of Technology, Pasadena, CA 91125, USA

S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff

University of Cincinnati, Cincinnati, OH 45221, USA

T. Barillari, P. Bloom, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. Roy, J. G. Smith, W. C. van Hoek, L. Zhang

University of Colorado, Boulder, CO 80309, USA

J. L. Harton, T. Hu, M. Krishnamurthy, A. Soffer, W. H. Toki, R. J. Wilson, J. Zhang

Colorado State University, Fort Collins, CO 80523, USA

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

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, F. Brochard, J. Cohen-Tanugi, S. Ferrag, S. T'Jampens, Ch. Thiebaux, G. Vasileiadis, M. Verderi

Ecole Polytechnique, LLR, F-91128 Palaiseau, France

A. Anjomshoaa, R. Bernet, A. Khan, D. Lavin, F. Muheim, S. Playfer, J. E. Swain, J. Tinslay

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Falbo

Elon University, Elon University, NC 27244-2010, USA

C. Borean, C. Bozzi, L. Piemontese, A. Sarti

Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

E. Treadwell

Florida A&M University, Tallahassee, FL 32307, USA

F. Anulli,[1] R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, D. Falciai, G. Finocchiaro, P. Patteri, I. M. Peruzzi,[1] M. Piccolo, A. Zallo

Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

S. Bagnasco, A. Buzzo, 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

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

[1]Also with Università di Perugia, I-06100 Perugia, Italy

S. Bailey, M. Morii
Harvard University, Cambridge, MA 02138, USA

R. Bartoldus, G. J. Grenier, U. Mallik
University of Iowa, Iowa City, IA 52242, USA

J. Cochran, H. B. Crawley, J. Lamsa, W. T. Meyer, E. I. Rosenberg, J. Yi
Iowa State University, Ames, IA 50011-3160, USA

M. Davier, G. Grosdidier, A. Höcker, H. M. Lacker, S. Laplace, F. Le Diberder, V. Lepeltier, A. M. Lutz, T. C. Petersen, S. Plaszczynski, M. H. Schune, L. Tantot, S. Trincaz-Duvoid, G. Wormser
Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France

R. M. Bionta, V. Brigljević , D. J. Lange, K. van Bibber, D. M. Wright
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

A. J. Bevan, J. R. Fry, E. Gabathuler, R. Gamet, M. George, M. Kay, D. J. Payne, R. J. Sloane, C. Touramanis
University of Liverpool, Liverpool L69 3BX, United Kingdom

M. L. Aspinwall, D. A. Bowerman, P. D. Dauncey, U. Egede, I. Eschrich, G. W. Morton, J. A. Nash, P. Sanders, D. Smith, G. P. Taylor
University of London, Imperial College, London, SW7 2BW, United Kingdom

J. J. Back, G. Bellodi, P. Dixon, P. F. Harrison, R. J. L. Potter, H. W. Shorthouse, P. Strother, P. B. Vidal
Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, S. George, M. G. Green, A. Kurup, C. E. Marker, T. R. McMahon, S. Ricciardi, F. Salvatore, G. Vaitsas, M. A. Winter
University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. Brown, C. L. Davis
University of Louisville, Louisville, KY 40292, USA

J. Allison, R. J. Barlow, A. C. Forti, F. Jackson, G. D. Lafferty, A. J. Lyon, N. Savvas, J. H. Weatherall, J. C. Williams
University of Manchester, Manchester M13 9PL, United Kingdom

A. Farbin, A. Jawahery, V. Lillard, D. A. Roberts, J. R. Schieck
University of Maryland, College Park, MD 20742, USA

G. Blaylock, C. Dallapiccola, K. T. Flood, S. S. Hertzbach, R. Kofler, V. B. Koptchev, T. B. Moore, H. Staengle, S. Willocq
University of Massachusetts, Amherst, MA 01003, USA

B. Brau, R. Cowan, G. Sciolla, F. Taylor, R. K. Yamamoto
Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA

M. Milek, P. M. Patel
McGill University, Montréal, QC, Canada H3A 2T8

F. Palombo
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Kroeger, J. Reidy, D. A. Sanders, D. J. Summers
University of Mississippi, University, MS 38677, USA

C. Hast, P. Taras
Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7

H. Nicholson
Mount Holyoke College, South Hadley, MA 01075, USA

C. Cartaro, N. Cavallo, G. De Nardo, F. Fabozzi, C. Gatto, L. Lista, P. Paolucci, D. Piccolo, C. Sciacca
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

J. M. LoSecco
University of Notre Dame, Notre Dame, IN 46556, USA

J. R. G. Alsmiller, T. A. Gabriel
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

J. Brau, R. Frey, M. Iwasaki, C. T. Potter, N. B. Sinev, D. Strom, E. Torrence
University of Oregon, Eugene, OR 97403, USA

F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, Ph. Leruste, J. Ocariz, M. Pivk, L. Roos, J. Stark
Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France

P. F. Manfredi, V. Re, V. Speziali
Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy

L. Gladney, Q. H. Guo, J. Panetta
University of Pennsylvania, Philadelphia, PA 19104, USA

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F. Bucci, G. Calderini, E. Campagna, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal, M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, G. Triggiani, J. Walsh
Università di Pisa, Scuola Normale Superiore and INFN, I-56010 Pisa, Italy

M. Haire, D. Judd, K. Paick, L. Turnbull, D. E. Wagoner
Prairie View A&M University, Prairie View, TX 77446, USA

J. Albert, G. Cavoto,[2] N. Danielson, P. Elmer, C. Lu, V. Miftakov, J. Olsen, S. F. Schaffner, A. J. S. Smith, A. Tumanov, E. W. Varnes
Princeton University, Princeton, NJ 08544, USA

[2]Also with Università di Roma La Sapienza, Roma, Italy

F. Bellini, D. del Re, R. Faccini,[3] F. Ferrarotto, F. Ferroni, E. Leonardi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Safai Tehrani, M. Serra, C. Voena

Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

S. Christ, G. Wagner, R. Waldi

Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, N. I. Geddes, G. P. Gopal, S. M. Xella

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, P.-F. Giraud, G. Hamel de Monchenault, W. Kozanecki, M. Langer, G. W. London, B. Mayer, G. Schott, B. Serfass, G. Vasseur, Ch. Yeche, M. Zito

DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France

M. V. Purohit, A. W. Weidemann, F. X. Yumiceva

University of South Carolina, Columbia, SC 29208, USA

I. Adam, D. Aston, N. Berger, A. M. Boyarski, M. R. Convery, D. P. Coupal, D. Dong, J. Dorfan, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, E. Grauges , T. Haas, T. Hadig, V. Halyo, T. Himel, T. Hryn'ova, M. E. Huffer, W. R. Innes, C. P. Jessop, M. H. Kelsey, P. Kim, M. L. Kocian, U. Langenegger, D. W. G. S. Leith, S. Luitz, V. Luth, H. L. Lynch, H. Marsiske, S. Menke, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, S. Petrak, H. Quinn, B. N. Ratcliff, S. H. Robertson, A. Roodman, A. A. Salnikov, T. Schietinger, R. H. Schindler, J. Schwiening, G. Simi, A. Snyder, A. Soha, S. M. Spanier, J. Stelzer, D. Su, M. K. Sullivan, H. A. Tanaka, J. Va'vra, S. R. Wagner, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, D. H. Wright, C. C. Young

Stanford Linear Accelerator Center, Stanford, CA 94309, USA

P. R. Burchat, C. H. Cheng, T. I. Meyer, C. Roat

Stanford University, Stanford, CA 94305-4060, USA

R. Henderson

TRIUMF, Vancouver, BC, Canada V6T 2A3

W. Bugg, H. Cohn

University of Tennessee, Knoxville, TN 37996, USA

J. M. Izen, I. Kitayama, X. C. Lou

University of Texas at Dallas, Richardson, TX 75083, USA

F. Bianchi, M. Bona, D. Gamba

Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

L. Bosisio, G. Della Ricca, S. Dittongo, L. Lanceri, P. Poropat, L. Vitale, G. Vuagnin

Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

R. S. Panvini

Vanderbilt University, Nashville, TN 37235, USA

[3]Also with University of California at San Diego, La Jolla, CA 92093, USA

S. W. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney

University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, S. Dasu, M. Datta, A. M. Eichenbaum, H. Hu, J. R. Johnson, R. Liu, F. Di Lodovico, A. Mohapatra, Y. Pan, R. Prepost, I. J. Scott, S. J. Sekula, J. H. von Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu

University of Wisconsin, Madison, WI 53706, USA

H. Neal

Yale University, New Haven, CT 06511, USA

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 of the $B^0 \to D^{(*)-}\pi^+$ [4] decays, of which a large sample is already available at the B-factories, and of the corresponding Cabibbo suppressed mode $B^0 \to D^{(*)+}\pi^-$ [5]. This measurement requires the knowledge of the ratio between the decay amplitudes $R_\lambda^{(*)} = |A(B^0 \to D^{(*)+}\pi^-)/A(B^0 \to D^{(*)-}\pi^+)|$. Unfortunately the measurement of $|A(B^0 \to D^{(*)+}\pi^-)|$ via the measurement of $\mathcal{B}(B^0 \to D^{(*)+}\pi^-)$ is not possible with the currently available data sample due to the presence of the copious background from $\overline{B}^0 \to D^{(*)+}\pi^-$. However, we can measure $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)$ and relate it to $R_\lambda^{(*)}$ using SU(3) symmetry: $R_\lambda^{(*)2} \propto \frac{\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{(*)-}\pi^+)}$, where the proportionality constant is, to first approximation, the ratio of the $D_s^{(*)+}$ and the $D^{(*)+}$ decay constants [5]. The decays $B^0 \to D_s^{(*)+}\pi^-$ have also been proposed to be used for the measurement of $|V_{ub}/V_{cb}|$ [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, theses modes can be used to investigate the role of final state rescattering since its presence can substantially increase the expected rates [7]. In this letter we present measurements of the branching fractions for the decays $B^0 \to D_s^{(*)+}\pi^-$and $B^0 \to D_s^{(*)-}K^+$.

This 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 of the detector crucial to this analysis are summarized below. 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 three reconstructed charged tracks and a total measured energy greater than 4.5 GeV as 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 on the modes studied in this letter exist [13]. Therefore the selection criteria are optimized to maximize the ratio of signal efficiency over the square-root of the expected number of background events.

The 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 a 20% pion misidentification, and a tight kaon selection with an efficiency of 85% and 5% pion misidentification probability. If not otherwise 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 the K^- and a π^+ candidates and are required to have an invariant mass in the range $856 < M_{K^-\pi^+} < 936\,\mathrm{MeV}/c^2$. The polarizations 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 meson itself, in the meson 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 $D^+\to K^0_S\,\pi^+$ or $\overline{K}^{*0}\,\pi^+$, the K^+ in the reconstruction of $D_s^+\to K^0_S\,K^+$ 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 mass [12].

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 [12].

We combine D_s^+ or D_s^{*+} candidates with a track of opposite charge to form $B^0\to D_s^{(*)-}K^+$ or $B^0\to D_s^{(*)+}\pi^-$ candidates depending on whether they pass the tight kaon selection criteria. In order to reject events where the D_s^+ comes from a B candidate and the pion or kaon from the other B, we require the two candidates 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. In order to suppress it using the event topology, we compute the angle (θ_T) between the thrust axis of the B meson decay product candidates and the thrust axis of all the other particles in the event. In the center-of-mass frame (c.m.), $B\overline{B}$ 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 c.m. frame, which results in a $|\cos\theta_T|$ distribution peaking at 1. Depending on the background level of each mode, $|\cos\theta_T|$ is required to be smaller than a value which 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 which 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 $|\Delta E| < 36\,\mathrm{MeV}$ and within it we define as signal candidates the events with $m_{\mathrm{ES}} > 5.27\,\mathrm{GeV}/c^2$.

After the aforementioned selection, three classes of backgrounds remain. First, the amount of *combinatorial background* in the signal region is estimated from the sidebands of the m_{ES} distribution and 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].

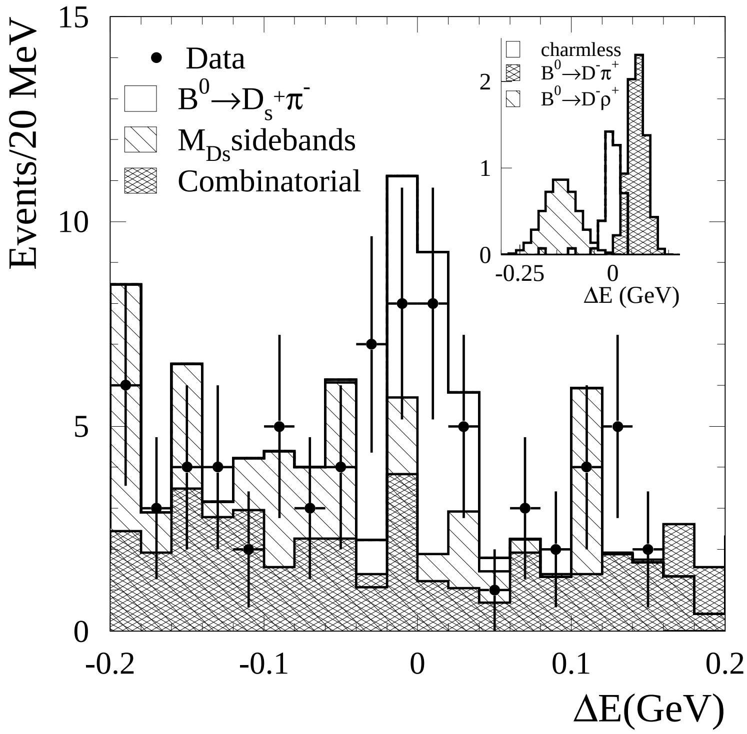

Figure 1: The ΔE distribution in data compared with the distribution in the combinatorial background, estimated from the $m_{\rm ES}$ sidebands, and with the cross-contamination, which is estimated from the $M_{D_s}^{cand}$ sidebands. The insert shows separately the ΔE distribution of the contributions to the cross contamination as expected from the simulation. The reflection background is normalized to the known branching fractions [12], while the normalization of the charmless background is arbitrary.

Next, 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*). This background has the same $m_{\rm ES}$ distributions as the signal but different distributions of ΔE. The corresponding background for the $B^0 \to D_s^- K^+$ mode ($B^0 \to D^- K^+, K^{*+}$) has 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 $m_{\rm ES}$ and ΔE distributions as the signal. Figure shows the ΔE distribution for the signal and for the various sources of background.

The branching fraction of the charmless background is not well measured and we therefore need to estimate the sum of the reflection and charmless background (referred to as *cross-contamination*) directly on data. This is possible because both of these backgrounds have a flat distribution in the D_s^+ candidate ($M_{D_s}^{cand}$) mass while the signal has a Gaussian distribution. Possible peaking background from $B \to D_s^+ X$ decays is negligible, as determined from simulation. The cross-contamination to 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 has been estimated to be less than 1%.

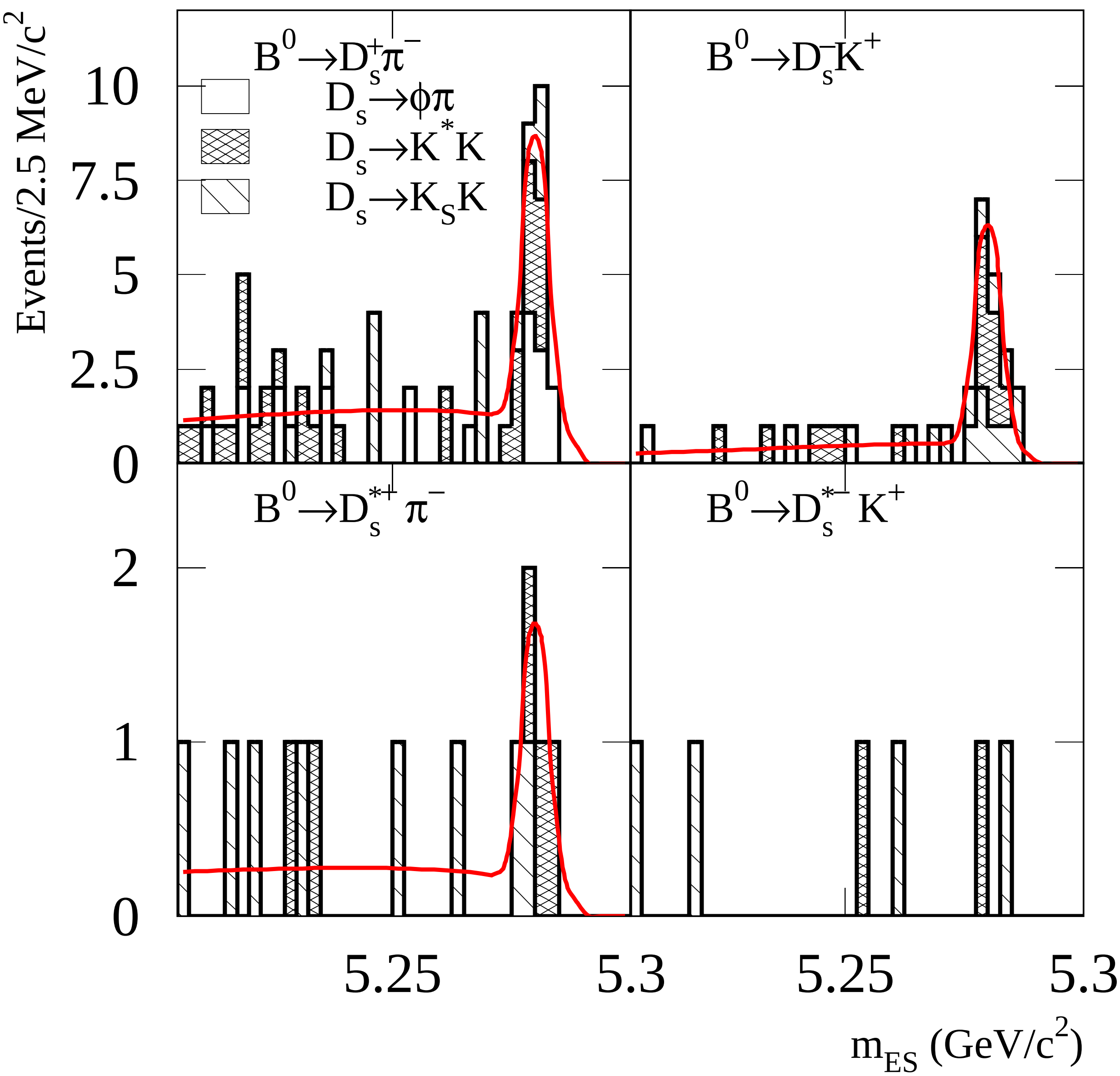

Figure 2: The $m_{\rm ES}$ distributions for the $B^0 \to D_s^+ \pi^-$ (top left), $B^0 \to D_s^{*+} \pi^-$ (top right), $B^0 \to D_s^- K^+$ (bottom left), and $B^0 \to D_s^{*-} K^+$ (bottom right) candidates on data after the selection, within the ΔE band. The fits used to obtain the signal yield are described in the text. The contribution from each D_s^+ mode is shown.

Figure shows the $m_{\rm ES}$ distribution for each of the modes in the ΔE signal band. We perform an unbinned maximum-likelihood fit to each $m_{\rm ES}$ distribution with the threshold function to characterize the combinatorial background and a Gaussian function to describe the sum of the signal and cross-contamination contributions. The mean and the width of the Gaussian distribution are

Table 1: The number of signal candidates (N_{sigbox}), the Gaussian yield (N_{gaus}) and the combinatorial background (N_{comb}) as extracted from the likelihood fit, the reconstruction efficiency (ε), the cross-contamination (N_{cross}), the probability (P_{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_{gaus}, N_{comb} and $\mathcal{B}$ are not available for modes with too few events. N_{cross} is not reported if no event is found in the D_s^+ mass sideband.

B mode	N_{sigbox}	N_{gaus}	N_{comb}	N_{cross}	ε(%)	P_{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

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 data distributions of $m_{\rm ES}$ after loosening the $M_{D_s}^{cand}$ 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 to the $B^0 \to D_s^{*-}K^+$sample, due to the low number of events. Whenever there are enough events we perform a fit to each D_s^+ decay mode separately, as well as on the combination of all modes. The cross-contamination is estimated performing the same fit on the events in the data $M_{D_s}^{cand}$ sidebands ($4\sigma < |M_{D_s}^{cand} - 1968.6\,\mathrm{MeV}/c^2| < 8\sigma$, where the resolution is $\sigma_{M_{D_s}^{cand}} = 5\,\mathrm{MeV}/c^2$). The number of observed events, the background expectations and the reconstruction efficiencies as estimated on simulated events are summarized in Table 1.

In the $B^0 \to D_s^+\pi^-$($B^0 \to D_s^- K^+$) mode the fit yields a Gaussian contribution of 21.4 ± 5.1 (16.7 ± 4.3) events and a combinatorial background of 7.8 ± 1.7 (3.5 ± 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 fluctuations 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 $\mathcal{B}(B^0 \to D_s^{*-}K^+) < 2.5 \times 10^{-5}$. All results are preliminary.

The systematic errors are dominated by the 25% relative uncertainty in $\mathcal{B}(D_s^+ \to \phi\pi^+)$. 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 $M_{D_s}^{cand}$ 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 and charged kaons 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 $B^0 \to D_s^- K^+$ decay, and we determine the preliminary results

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

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 preliminary 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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