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Investigation of $B \rightarrow D^{(*)}\overline{D}^{(*)}K$ decays with the *BABAR* detector

The *BABAR* Collaboration

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Abstract

Using about 23M $B\overline{B}$ events collected in 1999-2000 with the *BABAR* detector, we report the observation of several hundred $B \rightarrow D^{(*)}\overline{D}^{(*)}K$ decays with two completely reconstructed D mesons. The preliminary branching fractions of the low background decay modes $B^0 \rightarrow D^{*-}D^{(*)0}K^+$ are determined to be $\mathcal{B}(B^0 \rightarrow D^{*-}D^0K^+) = (2.8 \pm 0.7 \pm 0.5) \times 10^{-3}$ and $\mathcal{B}(B^0 \rightarrow D^{*-}D^{*0}K^+) = (6.8 \pm 1.7 \pm 1.7) \times 10^{-3}$. Observation of a significant number of candidates in the color-suppressed decay mode $B^+ \rightarrow D^{*+}D^{*-}K^+$ is reported with a preliminary branching fraction $\mathcal{B}(B^+ \rightarrow D^{*+}D^{*-}K^+) = (3.4 \pm 1.6 \pm 0.9) \times 10^{-3}$.

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

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

G. P. Chen, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu
Institute of High Energy Physics, Beijing 100039, China

G. Eigen, P. L. Reinertsen, B. Stugu
University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

B. Abbott, G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, A. R. Clark, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, S. Kluth, Yu. G. Kolomensky, J. F. Kral, C. LeClerc, M. E. Levi, T. Liu, G. Lynch, A. B. Meyer, M. Momayezi, P. J. Oddone, A. Perazzo, 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

P. G. Bright-Thomas, 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, J. Krug, M. Kunze, B. Lewandowski, K. Peters, H. Schmuecker, M. Steinke
Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

J. C. Andress, N. R. Barlow, W. Bhimji, N. Chevalier, P. J. Clark, W. N. Cottingham, N. De Groot, N. Dyce, B. Foster, J. D. McFall, D. Wallom, 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, J. Tinslay
Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, D. A. Bukin, A. R. Buzykaev, V. B. Golubev, V. N. Ivanchenko, A. A. Korol, E. A. Kravchenko, A. P. Onuchin, A. A. Salnikov, S. I. Serednyakov, Yu. I. Skovpen, V. I. Telnov, A. N. Yushkov
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. Best, A. J. Lankford, M. Mandelkern, S. McMahon, D. P. Stoker
University of California at Irvine, Irvine, CA 92697, USA

A. Ahsan, K. Arisaka, C. Buchanan, S. Chun
University of California at Los Angeles, Los Angeles, CA 90024, USA

J. G. Branson, D. B. MacFarlane, S. Prell, Sh. Rahatlou, G. Raven, V. Sharma
University of California at San Diego, La Jolla, CA 92093, USA

C. Campagnari, B. Dahmes, P. A. Hart, N. Kuznetsova, S. L. Levy, O. Long, A. Lu, J. D. Richman,
W. Verkerke, M. Witherell, S. Yellin
University of California at Santa Barbara, Santa Barbara, CA 93106, USA

J. Beringer, D. E. Dorfan, A. M. Eisner, A. Frey, A. A. Grillo, M. Grothe, C. A. Heusch, R. P. Johnson,
W. Kroeger, W. S. Lockman, T. Pulliam, H. Sadrozinski, 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, S. Metzler, J. Oyang, F. C. Porter, A. Ryd,
A. Samuel, M. Weaver, S. Yang, R. Y. Zhu
California Institute of Technology, Pasadena, CA 91125, USA

S. Devmal, T. L. Geld, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff
University of Cincinnati, Cincinnati, OH 45221, USA

T. Barillari, P. Bloom, M. O. Dima, S. Fahey, W. T. Ford, D. R. Johnson, U. Nauenberg, A. Olivas,
H. Park, P. Rankin, J. Roy, S. Sen, J. G. Smith, W. C. van Hoek, D. L. Wagner
University of Colorado, Boulder, CO 80309, USA

J. Blouw, J. L. Harton, M. Krishnamurthy, A. Soffer, W. H. Toki, R. J. Wilson, J. Zhang
Colorado State University, Fort Collins, CO 80523, USA

T. Brandt, J. Brose, T. Colberg, G. Dahlinger, 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

L. Behr, D. Bernard, G. R. Bonneaud, F. Brochard, J. Cohen-Tanugi, S. Ferrag, E. Roussot, S. T'Jampens,
Ch. Thiebaux, G. Vasileiadis, M. Verderi
Ecole Polytechnique, F-91128 Palaiseau, France

A. Anjomshoaa, R. Bernet, A. Khan, D. Lavin, F. Muheim, S. Playfer, J. E. Swain
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Falbo
Elon University, Elon University, NC 27244-2010, USA

C. Borean, C. Bozzi, S. Dittongo, M. Folegani, L. Piemontese
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,[2]1 M. Piccolo, Y. Xie, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

---

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

S. Bagnasco, A. Buzzo, R. Contri, G. Crosetti, P. Fabbricatore, S. Farinon, M. Lo Vetere, M. Macri, M. R. Monge, R. Musenich, M. Pallavicini, R. Parodi, S. Passaggio, F. C. Pastore, C. Patrignani, M. G. Pia, C. Priano, E. Robutti, A. Santroni

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

M. Morii

Harvard University, Cambridge, MA 02138, USA

R. Bartoldus, T. Dignan, R. Hamilton, U. Mallik

University of Iowa, Iowa City, IA 52242, USA

J. Cochran, H. B. Crawley, P.-A. Fischer, J. Lamsa, W. T. Meyer, E. I. Rosenberg

Iowa State University, Ames, IA 50011-3160, USA

M. Benkebil, G. Grosdidier, C. Hast, A. Höcker, H. M. Lacker, S. Laplace, V. Lepeltier, A. M. Lutz, S. Plaszczynski, M. H. Schune, S. Trincaz-Duvoid, A. Valassi, G. Wormser

Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France

R. M. Bionta, V. Brigljević , D. J. Lange, M. Mugge, X. Shi, K. van Bibber, T. J. Wenaus, D. M. Wright, C. R. Wuest

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

M. Carroll, 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, N. J. W. Gunawardane, J. A. Nash, P. Sanders, D. Smith

University of London, Imperial College, London, SW7 2BW, United Kingdom

D. E. Azzopardi, J. J. Back, P. Dixon, P. F. Harrison, R. J. L. Potter, H. W. Shorthouse, P. Strother, P. B. Vidal, M. I. Williams

Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, S. George, M. G. Green, A. Kurup, C. E. Marker, P. McGrath, T. R. McMahon, S. Ricciardi, F. Salvatore, I. Scott, G. Vaitsas

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, J. T. Boyd, A. C. Forti, J. Fullwood, F. Jackson, G. D. Lafferty, N. Savvas, E. T. Simopoulos, J. H. Weatherall

University of Manchester, Manchester M13 9PL, United Kingdom

A. Farbin, A. Jawahery, V. Lillard, J. Olsen, 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, 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, J. Trischuk
McGill University, Montréal, Canada QC H3A 2T8

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

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

J. P. Martin, J. Y. Nief, R. Seitz, P. Taras, A. Woch, V. Zacek
Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Canada QC H3C 3J7

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

C. Cartaro, N. Cavallo,[3] 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, T. Handler
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

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

F. Colecchia, F. Dal Corso, A. Dorigo, F. Galeazzi, M. Margoni, G. Michelon, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, E. Torassa, 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, F. Le Diberder, Ph. Leruste, J. Lory, L. Roos, J. Stark, S. Versillé
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

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

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

---

[3] Also with Università della Basilicata, I-85100 Potenza, Italy

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

J. Albert, C. Bula, P. Elmer, C. Lu, K. T. McDonald, V. Miftakov, S. F. Schaffner, A. J. S. Smith, A. Tumanov, E. W. Varnes
Princeton University, Princeton, NJ 08544, USA

G. Cavoto, D. del Re, R. Faccini,[4] F. Ferrarotto, F. Ferroni, K. Fratini, E. Lamanna, 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, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

P. F. Jacques, M. Kalelkar, R. J. Plano
Rutgers University, New Brunswick, NJ 08903, USA

T. Adye, B. Franek, N. I. Geddes, G. P. Gopal, S. M. Xella
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, G. De Domenico, S. Emery, A. Gaidot, S. F. Ganzhur, P.-F. Giraud, G. Hamel de Monchenault, W. Kozanecki, M. Langer, G. W. London, B. Mayer, B. Serfass, G. Vasseur, Ch. Yèche, M. Zito
DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France

N. Copty, M. V. Purohit, H. Singh, F. X. Yumiceva
University of South Carolina, Columbia, SC 29208, USA

I. Adam, P. L. Anthony, D. Aston, K. Baird, J. P. Berger, E. Bloom, A. M. Boyarski, F. Bulos, G. Calderini, R. Claus, M. R. Convery, D. P. Coupal, D. H. Coward, J. Dorfan, M. Doser, W. Dunwoodie, R. C. Field, T. Glanzman, G. L. Godfrey, S. J. Gowdy, P. Grosso, 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, K. C. Moffeit, R. Mount, D. R. Muller, C. P. O'Grady, M. Perl, S. Petrak, H. Quinn, B. N. Ratcliff, S. H. Robertson, L. S. Rochester, A. Roodman, T. Schietinger, R. H. Schindler, J. Schwiening, V. V. Serbo, A. Snyder, A. Soha, S. M. Spanier, J. Stelzer, D. Su, M. K. Sullivan, H. A. Tanaka, J. Va'vra, S. R. Wagner, 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, D. Kirkby, T. I. Meyer, C. Roat
Stanford University, Stanford, CA 94305-4060, USA

R. Henderson
TRIUMF, Vancouver, BC, Canada V6T 2A3

W. Bugg, H. Cohn, A. W. Weidemann
University of Tennessee, Knoxville, TN 37996, USA

---

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

J. M. Izen, I. Kitayama, X. C. Lou, M. Turcotte
University of Texas at Dallas, Richardson, TX 75083, USA

F. Bianchi, M. Bona, B. Di Girolamo, D. Gamba, A. Smol, D. Zanin
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

L. Bosisio, G. Della Ricca, L. Lanceri, A. Pompili, P. Poropat, M. Prest, E. Vallazza, G. Vuagnin
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

R. S. Panvini
Vanderbilt University, Nashville, TN 37235, USA

C. M. Brown, A. De Silva, R. Kowalewski, J. M. Roney
University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, E. Charles, S. Dasu, F. Di Lodovico, A. M. Eichenbaum, H. Hu, J. R. Johnson, R. Liu, J. Nielsen, Y. Pan, R. Prepost, I. J. Scott, S. J. Sekula, J. H. von Wimmersperg-Toeller, S. L. Wu, Z. Yu, H. Zobernig
University of Wisconsin, Madison, WI 53706, USA

T. M. B. Kordich, H. Neal
Yale University, New Haven, CT 06511, USA

1 Introduction

Decays of B mesons that include a charmed and an anti-charmed meson are expected to occur through the b to c quark transitions $\overline{b} \rightarrow \overline{c}W^{+}$, where the W^{+} materializes as a $c\overline{s}$ pair. These transitions are responsible for most of the D_s production in B decays. D_s production has been thoroughly studied in experiments running at the $\Upsilon(4S)$ resonance [1, 2, 3]. The inclusive rate for D_s production in B decays was recently measured by *BABAR*, where a preliminary branching fraction [4]:

$$\mathcal{B}(B \rightarrow D_s X) = (10.93 \pm 0.19_{stat} \pm 0.58_{syst} \pm 2.73_{\phi\pi})\%$$

is reported.

Until 1994, it was believed that the $c\overline{s}$ quarks would hadronize dominantly as $D_s^{+(*)}$ mesons. Therefore, the branching fraction $b \rightarrow c\overline{c}s$ was computed from the inclusive $B \rightarrow D_s X$, $B \rightarrow (c\overline{c})\,X$ and $B \rightarrow \Xi_c\,X$ branching fractions, leading to $\mathcal{B}(b \rightarrow c\overline{c}s) = 15.8 \pm 2.8\%$ [5]. Theoretical calculations are unable to simultaneously describe this low branching fraction and the semileptonic branching fraction of the B meson [6]. It has been conjectured [7] that $\mathcal{B}(b \rightarrow c\overline{c}s)$ is in fact larger and that decays $B \rightarrow D\overline{D}K\,(X)$ (where D can be either a D^0 or a $D^{\pm}$) could contribute significantly. This might also include possible decays to orbitally-excited D_s mesons, $B \rightarrow \overline{D}^{(*)}D_s^{**}$, followed by $D_s^{**} \rightarrow D^{(*)}\,K$.

Some experimental support for this picture has been published in the last few years. The most significant results are the evidence for wrong-sign D production in B decays (CLEO), yielding $\mathcal{B}(B \rightarrow D\,X) = 7.9 \pm 2.2\%$ [8], and the observation of a small number of completely reconstructed $B \rightarrow D^{(*)}D^{(*)}K$ decays, by both CLEO [9] and ALEPH [10].

$B \rightarrow D^{(*)}D^{(*)}K$ decays can occur through three different processes: pure external diagrams, pure internal (color-suppressed) diagrams and the sum of both. Fig. 1 shows the three possible types of decays for charged and neutral B's.

In *BABAR*, the high statistics available allow comprehensive investigations to be made of the $b \rightarrow c\overline{c}s$ transitions. In the analysis described in this paper, we present evidence for the decays $B \rightarrow D^{(*)}\overline{D}^{(*)}K_S^0$ and $B \rightarrow D^{(*)}\overline{D}^{(*)}K^{\pm}$, using events in which both D's are completely reconstructed. After describing the data sample and the event selection, we show the $D^{(*)}\overline{D}^{(*)}K$ signals for the sum of all B submodes. The branching fractions for some of the cleanest modes, such as $B^0 \rightarrow D^{*-}D^{(*)0}K^{+}$, are computed and the main systematic errors are discussed. Observation of several candidates in the color-suppressed decay mode $B^{+} \rightarrow D^{*-}D^{*+}K^{+}$ is also reported.

2 The *BABAR* detector and dataset

The study reported here uses $20.7\,\mathrm{fb}^{-1}$ of data collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector, corresponding to $(22.7 \pm 0.4) \times 10^6$ $B\overline{B}$ pairs.

The *BABAR* detector is a large-acceptance solenoidal spectrometer (1.5 T) described in detail elsewhere [11]. The analysis described below makes use of charged track and π^0 reconstruction and charged particle identification. Charged particle trajectories are measured by a 5 layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), which also provide ionisation measurements (dE/dx) used for particle identification. Photons and electrons are measured in the electromagnetic calorimeter (EMC), made of 6580 thallium-doped CsI crystals constructed in a non-projective barrel and forward endcap geometry. Charged K/π separation up to $4\,\mathrm{GeV}/c$ in momentum is provided by a detector of internally reflected Cherenkov light (DIRC), consisting of

12 sectors of quartz bars that carry the Cherenkov light to an expansion volume filled with water and equipped with 10752 photomultipliers.

3 Analysis strategy

The B^0 and B^+ mesons[1] are reconstructed in a sample of multihadron events for all possible $D\overline{D}K$ modes, namely $B^0 \to D^{(*)-}D^{(*)0}K^+$, $D^{(*)-}D^{(*)+}K^0$, $\overline{D}^{(*)0}D^{(*)0}K^0$ and $B^+ \to \overline{D}^{(*)0}D^{(*)+}K^0$, $\overline{D}^{(*)0}D^{(*)0}K^+$, $\overline{D}^{(*)+}D^{(*)-}K^+$.

The K^0_S candidates are reconstructed from two oppositely charged tracks coming from a common vertex displaced from the interaction point by at least 0.2 cm and having an invariant mass within $\pm 9\,\mathrm{MeV}/c^2$ of the nominal K^0 mass. The π^0 candidates are reconstructed from pairs of photons, each with an energy greater than $30\,\mathrm{MeV}$, which are required to have a mass $115 < M_{\gamma\gamma} < 150\,\mathrm{MeV}/c^2$. The π^0 from D^{*0} must have a momentum $70 < p^*(\gamma\gamma) < 450\,\mathrm{MeV}/c$ in the $\Upsilon(4S)$ frame, while the π^0 from $D^0 \to K^-\pi^+\pi^0$ must have an energy $E(\pi^0) > 200\,\mathrm{MeV}$. Finally, a mass-constraint fit is applied to all the π^0 candidates to improve the energy resolution.

The D^0 and D^+ mesons are reconstructed in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, by selecting track combinations within $\pm 2\sigma$ or $\pm 3\sigma$ of the nominal D mass, where σ is the mass resolution for the D decay mode considered and the tighter 2σ mass interval is applied for B modes with a larger combinatorial background. The K and π tracks are required to be well reconstructed in the tracking detectors and to originate from a common vertex. Charged kaon identification, with information from the Cherenkov angle in the DIRC and from dE/dx measurements in the drift chamber and in the vertex detector, is required for most D decay modes, as well as for the $K^\pm$ from B's.

D^* candidates are reconstructed in the modes $D^{*+} \to D^0\pi^+$, $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$, by combining a D^0 candidate with a π^-, π^0, or photon. A $\pm 3\sigma$ interval around the nominal $\Delta M = M(D^*) - M(D^0)$ mass difference is used to select D^*'s. Partial reconstruction of D^{*0}'s (no π^0 or γ reconstruction) is also used in the $B^0 \to D^{*-}D^{*0}K^+$ mode, as explained below.

B candidates are reconstructed from the $D^{(*)}$, $\overline{D}^{(*)}$ and K candidates. A mass constraint is applied to all the intermediate particles (D^0, D^-, K^0_S). Since the B mesons are produced via $e^+e^- \to \Upsilon(4S) \to B\overline{B}$, the energy of the B in the $\Upsilon(4S)$ frame is given by the beam energy E^*_{beam}, which is measured much more precisely than the energy of the B candidate. Therefore, to isolate the B meson signal, we use two kinematic variables: ΔE, the difference between the reconstructed energy of the B candidate and the beam energy in the center of mass frame, and m_{ES}, the beam energy substituted mass, defined as

$$m_{\mathrm{ES}} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

where p^*_B is the momentum of the reconstructed B in the $\Upsilon(4S)$ frame. Signal events will have ΔE close to 0 and m_{ES} close to the B meson mass, $5.729\,\mathrm{GeV}/c^2$. When several candidates are selected per event in a specific B submode (*e.g.* $B^+ \to D^0\overline{D}^0K^+$), a χ^2 value, taking into account the difference between the measured and the PDG values of the D masses and of the ΔM (for D^*'s) is constructed and only the candidate with the lowest χ^2 value is kept for the given submode.

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[1] Charge-conjugate reactions are implied throughout this note.

4 Evidence for signal in the sum of all B submodes

We present here the distributions obtained by summing all possible $B \to D^{(*)}D^{(*)}K$ decay channels, for neutral and charged B decays respectively.

Since multiple candidates are removed only submode by submode the same event can appear several times in distributions obtained by summing over all modes. In the ΔE distribution this manifests itself as three distinct peaks, as can be seen in Figs. 2 and 3. An event will appear in the peak near 0 MeV when reconstructed correctly, in the peak around -160 MeV if it is a D^*DK (D^*D^*K) decay reconstructed as DDK (D^*DK), and near the peak around $+160$ MeV if it is a DDK (D^*DK) decay reconstructed as D^*DK (D^*D^*K).

About 120 B^0's and 180 $B^\pm$ decays have been reconstructed. The $m_{\rm ES}$ distributions (Figs. 2 and 3) contain only events with $|\Delta E| < 24$ MeV. From Monte Carlo studies, the $m_{\rm ES}$ resolutions of the different sub-modes are quite similar and the $m_{\rm ES}$ spectrum of B^0 and $B^\pm$ events can be fitted by the sum of a background shape and a Gaussian function used to extract the number of signal events. The background is empirically described by the function

$$\frac{dN}{dm_{ES}} \propto m_{ES} \times \sqrt{1-\frac{m_{ES}^2}{E_{beam}^{*2}}} \times \exp\left[-\zeta\left(1-\frac{m_{ES}^2}{E_{beam}^{*2}}\right)\right],$$

where the only free parameters are ζ and the normalization factor. This function is referred to as the ARGUS function in the following. The ΔE distributions (Figs. 2 and 3) contain only events with $m_{\rm ES} > 5.27\,{\rm MeV}/c^2$. They have been fitted by the sum of a polynomial background and three Gaussian functions for the three signal components described above. However, the fits to the ΔE distributions are only indicative since they merge many B and D sub-decay modes, which have significantly different ΔE resolutions depending on the number of π^0's or photons involved

5 Measurement of exclusive branching fractions

In this section, we present measurements of branching fraction for the three decay channels $B^0 \to D^{*-}D^0K^+$, $B^0 \to D^{*-}D^{*0}K^+$ and $B^+ \to D^{*-}D^{*+}K^+$. Several candidates are also observed in the CP conjugate modes $B^0 \to D^{(*)-}D^{(*)+}K^0_S$ but without extracting branching fractions.

5.1 Monte Carlo samples and efficiencies

The selection efficiencies for each mode were obtained from detailed Monte Carlo simulation, in which the detector response is modeled with the GEANT3 program [12]. In addition, data was used whenever possible to determine detector performance and the simulation adjusted accordingly. B meson decays to DDK were generated with a three-body phase space model. For each sub-decay mode, samples of 5000 signal events were produced. Typical efficiencies range from 10%, for $B^0 \to D^{*-}D^0K^+$ with both D^0's decaying to $K\pi$, to less than 1%, for $B^+ \to D^{*-}D^{*+}K^+$ with D^0's decaying to $K\pi\pi^0$ or $K3\pi$.

5.2 Systematic uncertainties

Systematic errors account for the uncertainties on tracking and π^0 reconstruction efficiencies, K identification efficiency, D and B vertexing requirements, efficiency of the requirement on ΔE used to define the signal box, efficiency of the D mass requirement; uncertainty on the background shape; uncertainties on the D and D^* branching fractions; uncertainties on the selection efficiencies arising from Monte Carlo statistics; and uncertainty on the number of produced $B\overline{B}$ events in the data sample. The breakdown of the different contributions to the systematic error for each mode is given in Table 1.

5.3 $B^+ \to D^{*-} D^{*+} K^+$

The $m_{\rm ES}$ distribution obtained for events with $|\Delta E| < 24\,\rm MeV$ is shown in Fig. 4 for the sum of all the six possible $D^0 \times \overline{D}^0$ decay combinations. A fit to the data is performed with the sum of a Gaussian function for the signal and an ARGUS function for the background. The number of signal events is 8.2 ± 3.5 and the number of background events given by the ARGUS function is 1.7. The probability that the signal arises from a background fluctuation is 1.4×10^{-5} ($> 5\sigma$). The corresponding preliminary branching fraction is measured to be

$$\mathcal{B}(B^+ \to D^{*-} D^{*+} K^+) = (3.4 \pm 1.6 \pm 0.9) \times 10^{-3}$$

The first error quoted is statistical and the second is systematic. The different contributions to the systematic error are given in Table 1.

5.4 $B^0 \to D^{*-} D^{(*)0} K^+$

In this analysis we require that either the D^0 or the $\overline{D}^0$ decays to $K\pi$ and we do not explicitly reconstruct the π^0 or the photon from $D^{*0} \to D^0\pi^0$ or $D^0\gamma$. The $m_{\rm ES}$ versus ΔE distribution of $D^{*-} D^0 K^+$ combinations is shown in Fig. 5 for the sum of the three $D^0\overline{D}^0$ sub-modes considered. Despite the background level, two separate enhancements, due to the decay modes $B^0 \to D^{*-} D^0 K^+$ and $B^0 \to D^{*-} D^{*0} K^+$, are clearly visible. The enhancement in the region $\Delta E \simeq 0$, $m_{\rm ES} \simeq 5.28\,{\rm GeV}/c^2$ corresponds to decays $B^0 \to D^{*-} D^0 K^+$, while the second enhancement in the region $\Delta E \simeq -154\,\rm MeV$, $m_{\rm ES} \simeq 5.28\,{\rm GeV}/c^2$ corresponds to decays $B^0 \to D^{*-} D^{*0} K^+$.

Events containing $B^0 \to D^{*-} D^0 K^+$ decays are selected by requiring $|\Delta E| < 25\,\rm MeV$. The $m_{\rm ES}$ spectrum for these events is shown in Fig. 6 along with a fit with the sum of a Gaussian function describing the signal and an ARGUS function describing the background. The number of signal events is found to be 29.6 ± 7.2. After correcting for the selection efficiencies and for the intermediate D^0 and D^{*+} branching fractions [13], the preliminary branching fraction for $B^0 \to D^{*-} D^0 K^+$ is found to be

$$\mathcal{B}(B^0 \to D^{*-} D^0 K^+) = (2.8 \pm 0.7 \pm 0.5) \times 10^{-3},$$

where the first error quoted is statistical and the second systematic. The breakdown of the various contributions to the systematic error is given in Table 1.

Events containing $B^0 \to D^{*-} D^{*0} K^+$ decays are selected by requiring $|\Delta E + 154| < 60\,\rm MeV$. The average position and width of ΔE for $B^0 \to D^{*-} D^{*0} K^+$ is found to be in good agreement with expectations from $B^0 \to D^{*-} D^{*0} K^+$ signal Monte Carlo studies. The $m_{\rm ES}$ spectrum of the selected events is shown in Fig. 7 along with a fit with the sum of a Gaussian and an ARGUS background function. The number of signal events found is 80.2 ± 15.3.

To extract the $B^0 \to D^{*-} D^{*0} K^+$ branching fraction, the contamination from decays $B^+ \to D^{*-} D^{*+} K^+$, where the π^+ from the D^{*+} is not reconstructed, needs to be subtracted. This contribution has been estimated by performing the $B^0 \to D^{*-} D^{*0} K^+$analysis on $B^+ \to D^{*-} D^{*+} K^+$ signal Monte Carlo, assuming the $B^+ \to D^{*-} D^{*+} K^+$ branching fraction presented in Section 5.3. The $B^+ \to D^{*-} D^{*+} K^+$ background contribution is shown in Fig. 7 as a small Gaussian on top of the combinatorial background shape; it is estimated to be 20.6 ± 9.7 events. After subtracting this contribution, the preliminary $B^0 \to D^{*-}D^{*0}K^+$ branching fraction is determined to be:

$$\mathcal{B}(B^0 \to D^{*-}D^{*0}K^+) = (6.8 \pm 1.7 \pm 1.7) \times 10^{-3}$$

where the last uncertainty is systematic. The breakdown of the various contributions to the systematic error is given in Table 1.

5.5 $B^0 \to D^{(*)-}D^{(*)+}K^0_S$

The m_{ES} distribution for events reconstructed in the channels $B^0 \to D^{(*)-}D^{(*)+}K^0_S$ is shown in Fig. 8. For modes involving D^0's, at least one decay $D^0 \to K\pi$ was required. The fitted number of signal events is 10.1 ± 3.7 with an estimated background of 3.4 events. The probability that the signal is a fluctuation of the background is 1.4×10^{-5} ($> 5\sigma$). Most of the signal is due to the channels $B^0 \to D^{*+}D^-K^0_S$ (4.7 ± 2.2 events with a background of 1 event) and $B^0 \to D^{*+}D^{*-}K^0_S$ (4.8 ± 2.2 events with a background of 0.3 event). As pointed out in [14], the channel $B^0 \to D^{*+}D^{*-}K^0_S$ is a *CP* conjugate state that could be used for $\sin 2\beta$ measurements. However, given the presently observed rate for reconstructing events, large improvements in the selection efficiencies are still needed before challenging the "golden" channels $B^0 \to D^{*+}D^{*-}$ as suggested in [14].

6 Summary

Using about 23M $B\overline{B}$ events, we have observed several hundred completely reconstructed $B \to D^{(*)}\overline{D}^{(*)}K$ decays. The following preliminary branching fractions have been measured:

$$\mathcal{B}(B^0 \to D^{*-}D^0K^+) = (2.8 \pm 0.7 \pm 0.5) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*-}D^{*0}K^+) = (6.8 \pm 1.7 \pm 1.7) \times 10^{-3}$$

in good agreement with the CLEO measurements $\mathcal{B}(B^0 \to D^{*-}D^0K^+) = (4.5^{+2.5}_{-1.9} \pm 0.8) \times 10^{-3}$ and $\mathcal{B}(B^0 \to D^{*-}D^{*0}K^+) = (13.0^{+7.8}_{-5.8} \pm 3.6) \times 10^{-3}$ [9].

We have observed an excess of 8.2 ± 3.5 events over a background of 1.7 events in the color-suppressed decay mode $B^+ \to D^{*+}D^{*-}K^+$, where no significant number of candidates has been previously seen. The corresponding preliminary branching fraction is measured to be

$$\mathcal{B}(B^+ \to D^{*-}D^{*+}K^+) = (3.4 \pm 1.6 \pm 0.9) \times 10^{-3}$$

Finally, several candidates have also been observed in the *CP* conjugate states $B^0 \to D^{(*)+}D^{(*)-}K^0_S$. This study confirms that the transitions $b \to c\overline{c}s$ can proceed through the decays $B \to D^{(*)}\overline{D}^{(*)}K$. To quantify more precisely this statement, we intend to measure all the individual $B \to D^{(*)}\overline{D}^{(*)}K$ branching fractions and study the decay kinematics of these decays in the near future.

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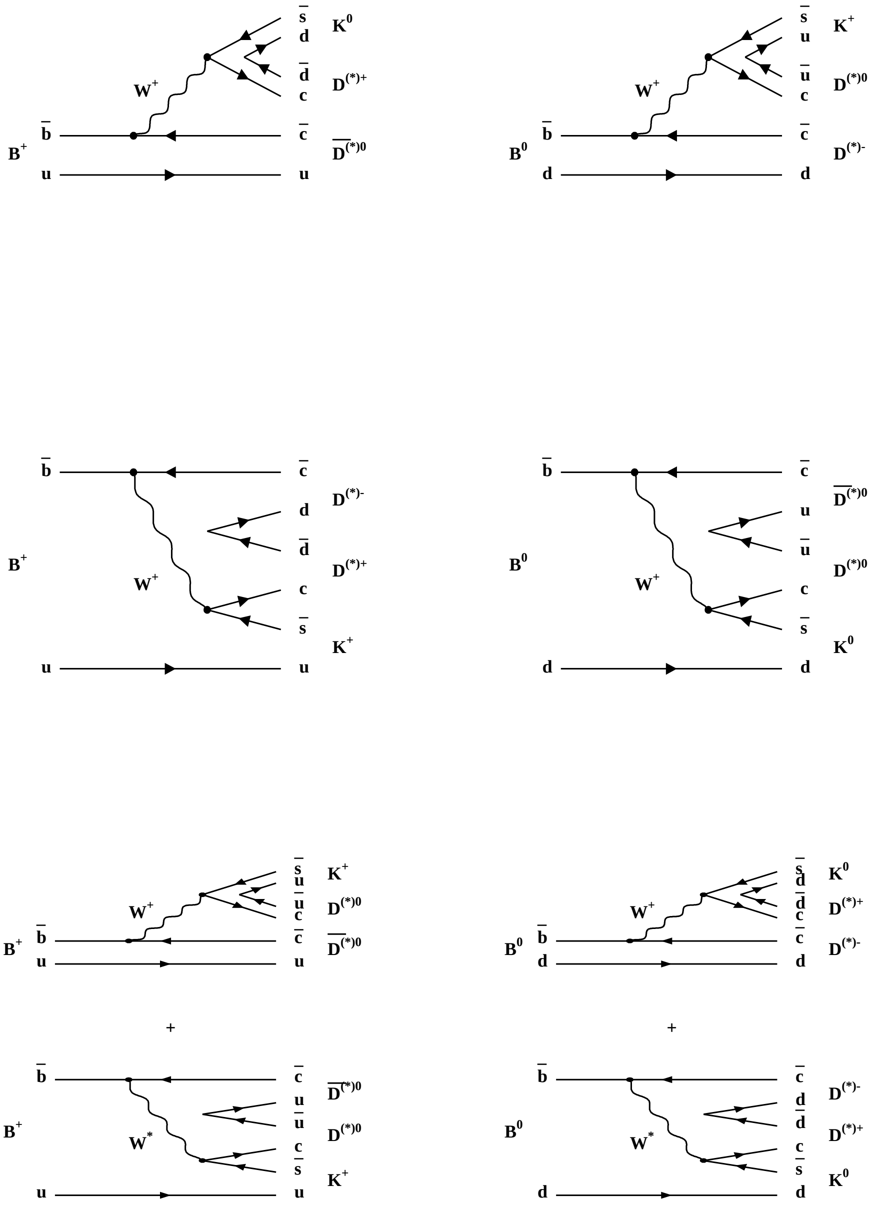

Figure 1: *DDK* decays proceed through external only diagrams (top), internal only diagrams (2nd line) and both (last lines)

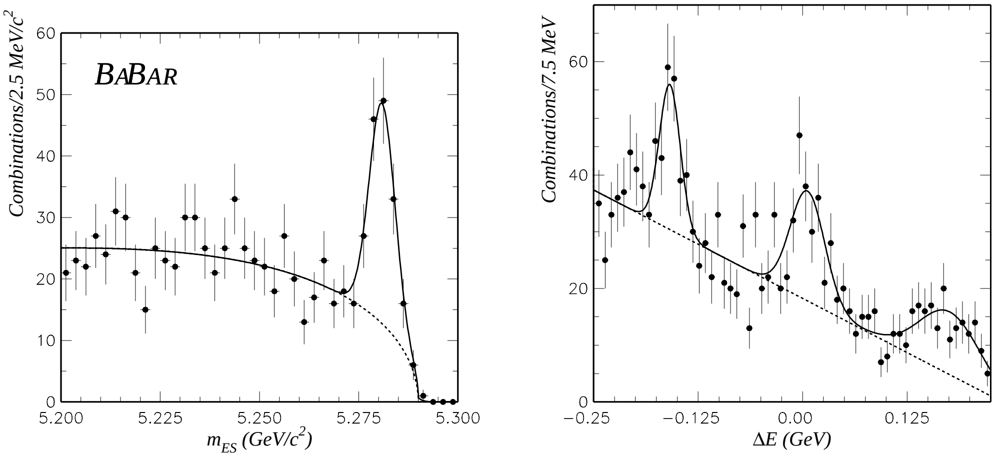

Figure 2: m_{ES} and ΔE distributions for the sum of all neutral modes

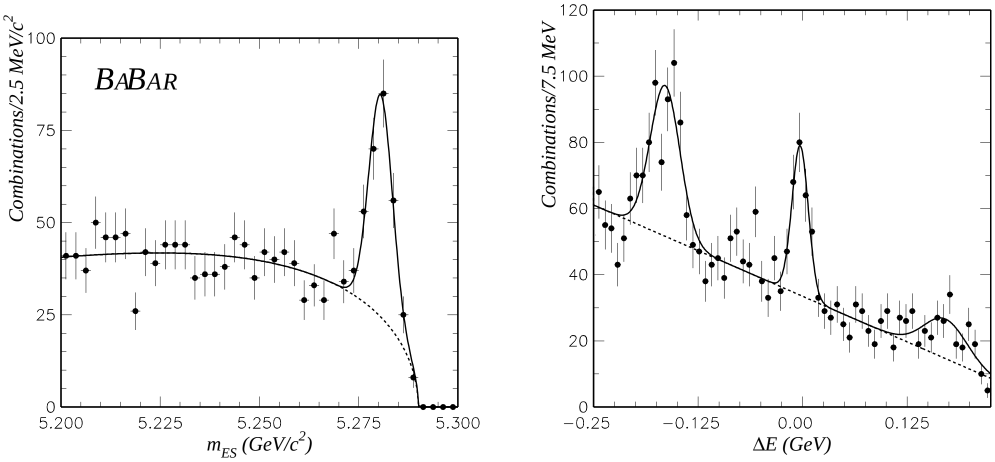

Figure 3: m_{ES} and ΔE distributions for the sum of all charged modes

Table 1: Breakdown of the various contributions to the relative systematic uncertainty on the $B^+ \to D^{*-}D^{*+}K^+$, $B^0 \to D^{*-}D^0K^+$ and $B^0 \to D^{*-}D^{*0}K^+$ branching fraction measurements.

Source	$B^+ \to D^{*-}D^{*+}K^+$ error(%)	$B^0 \to D^{*-}D^0K^+$ error(%)	$B^0 \to D^{*-}D^{*0}K^+$ error(%)
Tracking + Neutral efficiency	9.7	8.8	8.8
Vertexing efficiency	10	5.6	8.3
PID efficiency	9	5.3	5.3
ΔE requirements	2	7.7	2.4
D meson mass requirements	13.4	-	-
Intermediate BF	5.6	5.6	7.5
Background shape	-	4.9	2.9
Monte Carlo statistics	16	3.5	4.3
$N_{B\overline{B}}$	1.6	1.6	1.6
$B^+ \to D^{*-}D^{*+}K^+$ bkg	-	-	19.4
Total	**27**	**16.3**	**25.4**

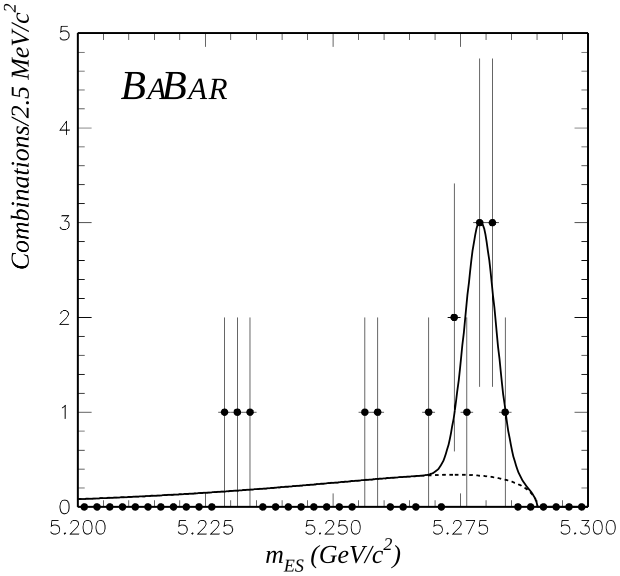

Figure 4: $B^+ \to D^{*-}D^{*+}K^+$ $m_{\rm ES}$ distribution

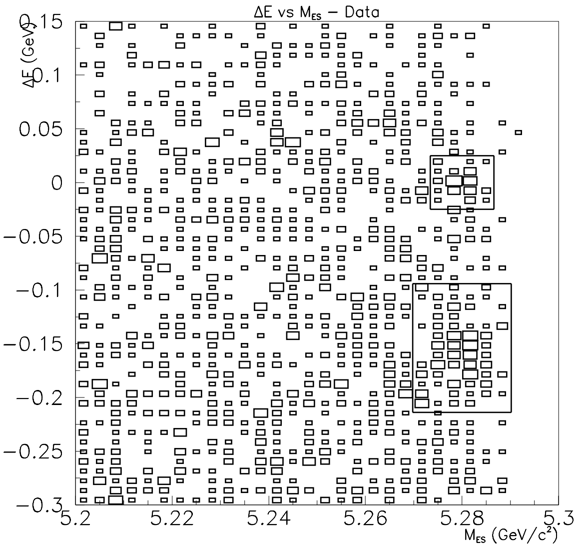

Figure 5: Distribution of ΔE versus m_{ES} for $D^{*-}D^0K^+$ combinations in the data. The signal boxes are defined by a $\pm3\sigma$ requirement on m_{ES}. The box $|\Delta E| < 25\,\mathrm{MeV}$ corresponds to $B^0 \rightarrow D^{*-}D^0K^+$ decays, while the box $|\Delta E + 154| < 60\,\mathrm{MeV}$ corresponds dominantly to decays $B^0 \rightarrow D^{*-}D^{*0}K^+$ (The π^0 or γ from $D^{*0} \rightarrow D^0\pi^0$ or $D^0\gamma$ is not reconstructed here)

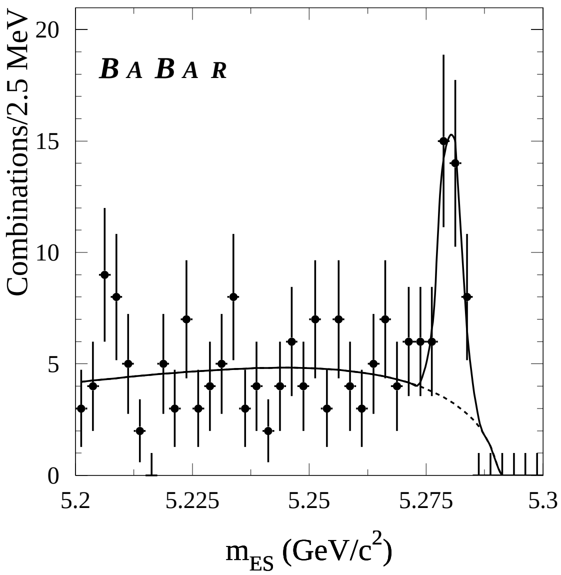

Figure 6: Distribution of m_{ES} for $D^{*-}D^0K^+$ combinations with $|\Delta E| < 25\,\mathrm{MeV}$. An ARGUS background function is used together with a Gaussian for the signal shape to fit the data.

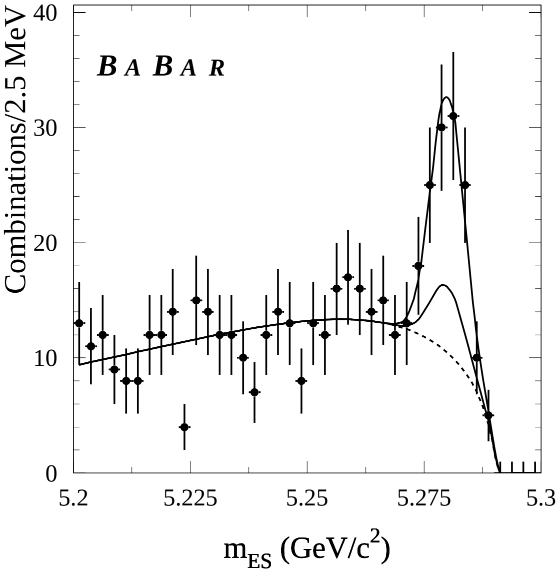

Figure 7: Distribution of m_{ES} for $D^{*-}D^{0}K^{+}$ combinations with $|\Delta E + 154| < 60\,\mathrm{MeV}$ ($B \to D^{*-}D^{*0}K^{+}$ signal region). An ARGUS background function is used together with a Gaussian for the signal shape to fit the data. The $B^{+} \to D^{*-}D^{*+}K^{+}$ background contribution is shown as a small Gaussian on top of the combinatorial background shape.

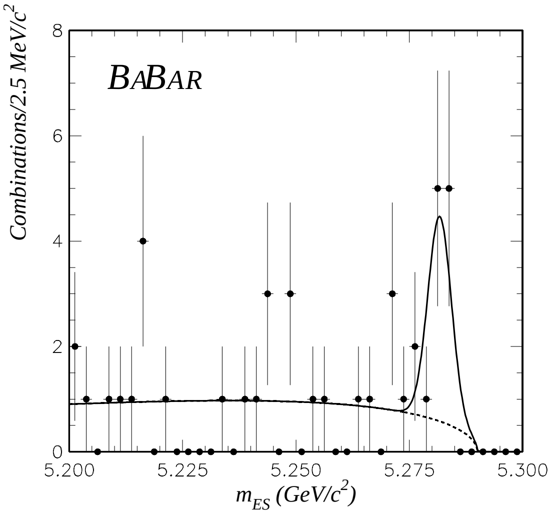

Figure 8: $B^{0} \to D^{(*)-}D^{(*)+}K^{0}_{S}$ m_{ES} distribution