Measurement of the branching fractions for $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$

The *BABAR* Collaboration

Abstract

Using 5.2 fb^{-1} of e^+e^- annihilation data recorded with the *BABAR* detector at the PEP-II storage ring while operating on the $\Upsilon(4S)$ resonance, a sample of fully reconstructed B^0 decays in the hadronic modes $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ have been reconstructed. In this paper, a study of these events is reported, including preliminary measurements of the absolute branching fractions for these modes, which are found to be $\mathcal{B}(B^0 \to D^{*-}\pi^+) = (2.9 \pm 0.3 \pm 0.3) \times 10^{-3}$ and $\mathcal{B}(B^0 \to D^{*-}\rho^+) = (11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$.

The *BABAR* Collaboration

B. Aubert, A. Boucham, D. Boutigny, I. De Bonis, J. Favier, J.-M. Gaillard, F. Galeazzi, A. Jeremie,
Y. Karyotakis, J. P. Lees, P. Robbe, V. Tisserand, K. Zachariadou

Lab de Phys. des Particules, F-74941 Annecy-le-Vieux, CEDEX, 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, Q. Fan, M. S. Gill, S. J. Gowdy, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk,
L. T. Kerth, S. Kluth, 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, P. Strother,
A. V. Telnov, W. A. Wenzel

Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

P. G. Bright-Thomas, T. J. Champion, C. M. Hawkes, A. Kirk, S. W. O'Neale, A. T. Watson, N. K. Watson

University of Birmingham, Birmingham, B15 2TT, UK

T. Deppermann, H. Koch, J. Krug, M. Kunze, B. Lewandowski, K. Peters, H. Schmuecker, M. Steinke

Ruhr Universität Bochum, Inst. f. Experimentalphysik 1, D-44780 Bochum, Germany

J. C. Andress, N. Chevalier, P. J. Clark, N. Cottingham, N. De Groot, N. Dyce, B. Foster, A. Mass,
J. D. McFall, D. Wallom, F. F. Wilson

University of Bristol, Bristol BS8 lTL, UK

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

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

B. Camanzi, A. K. McKemey, J. Tinslay

Brunel University, Uxbridge, Middlesex UB8 3PH, UK

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

*Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Science, Novosibirsk 630090,
Russia*

A. J. Lankford, M. Mandelkern, 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, R. Faccini,[1] D. B. MacFarlane, 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. 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, D. C. Williams

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, Yu. G. Kolomensky, 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

R. Aleksan, G. De Domenico, A. de Lesquen, S. Emery, A. Gaidot, S. F. Ganzhur, G. Hamel de
Monchenault, W. Kozanecki, M. Langer, G. W. London, B. Mayer, B. Serfass, G. Vasseur, C. Yeche,
M. Zito

Centre d'Etudes Nucléaires, Saclay, F-91191 Gif-sur-Yvette, France

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

University of Cincinnati, Cincinnati, OH 45221, 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

S. Fahey, W. T. Ford, F. Gaede, D. R. Johnson, A. K. Michael, U. Nauenberg, A. Olivas, H. Park,
P. Rankin, J. Roy, S. Sen, J. G. Smith, D. L. Wagner

University of Colorado, Boulder, CO 80309, USA

T. Brandt, J. Brose, G. Dahlinger, M. Dickopp, R. S. Dubitzky, M. L. Kocian, R. Müller-Pfefferkorn,
K. R. Schubert, R. Schwierz, B. Spaan, L. Wilden

Technische Universität Dresden, Inst. f. Kern- u. Teilchenphysik, D-01062 Dresden, Germany

L. Behr, D. Bernard, G. R. Bonneaud, F. Brochard, J. Cohen-Tanugi, S. Ferrag, E. Roussot, C. Thiebaux,
G. Vasileiadis, M. Verderi

Ecole Polytechnique, Lab de Physique Nucléaire H. E., F-91128 Palaiseau, France

A. Anjomshoaa, R. Bernet, F. Di Lodovico, F. Muheim, S. Playfer, J. E. Swain

University of Edinburgh, Edinburgh EH9 3JZ, UK

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

---

[1]Jointly appointed with Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

3

R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, D. Falciai, G. Finocchiaro, P. Patteri, I. M. Peruzzi,[2]
M. Piccolo, A. Zallo

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

S. Bagnasco, A. Buzzo, R. Contri, G. Crosetti, P. Fabbricatore, S. Farinon, M. Lo Vetere, M. Macri,
M. R. Monge, R. Musenich, 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

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

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

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

University of Iowa, Iowa City, IA 52242, USA

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani,
M. Morganti, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, G. Simi, G. Triggiani

Università di Pisa, Scuola Normale Superiore, and INFN, I-56010 Pisa, Italy

M. Benkebil, G. Grosdidier, C. Hast, A. Hoecker, V. LePeltier, A. M. Lutz, S. Plaszczynski, M. H. Schune,
S. Trincaz-Duvoid, A. Valassi, G. Wormser

LAL, F-91898 ORSAY Cedex, France

R. M. Bionta, V. Brigljević, O. Fackler, D. Fujino, D. J. Lange, M. Mugge, X. Shi, 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, S. McMahon, T. R. McMahon,
D. J. Payne, C. Touramanis

University of Liverpool, Liverpool L69 3BX, UK

M. L. Aspinwall, P. D. Dauncey, I. Eschrich, N. J. W. Gunawardane, R. Martin, J. A. Nash, P. Sanders,
D. Smith

University of London, Imperial College, London, SW7 2BW, UK

D. E. Azzopardi, J. J. Back, P. Dixon, P. F. Harrison, P. B. Vidal, M. I. Williams

University of London, Queen Mary and Westfield College, London, E1 4NS, UK

G. Cowan, M. G. Green, A. Kurup, P. McGrath, I. Scott

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, UK

D. Brown, C. L. Davis, Y. Li, J. Pavlovich, A. Trunov

University of Louisville, Louisville, KY 40292, USA

J. Allison, R. J. Barlow, J. T. Boyd, J. Fullwood, A. Khan, G. D. Lafferty, N. Savvas, E. T. Simopoulos,
R. J. Thompson, J. H. Weatherall

University of Manchester, Manchester M13 9PL, UK

---

[2]Jointly appointed with Univ. di Perugia, I-06100 Perugia, Italy

4

C. Dallapiccola, A. Farbin, A. Jawahery, V. Lillard, J. Olsen, D. A. Roberts

University of Maryland, College Park, MD 20742, USA

B. Brau, R. Cowan, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Lab for Nuclear Science, Cambridge, MA 02139, USA

G. Blaylock, K. T. Flood, S. S. Hertzbach, R. Kofler, C. S. Lin, S. Willocq, J. Wittlin

University of Massachusetts, Amherst, MA 01003, USA

P. Bloom, D. I. Britton, M. Milek, P. M. Patel, J. Trischuk

McGill University, Montreal, PQ, Canada 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, R. Kroeger, J. Reidy, D. Sanders, D. J. Summers

University of Mississippi, University, MS 38677, USA

J. F. Arguin, J. P. Martin, J. Y. Nief, R. Seitz, P. Taras, A. Woch, V. Zacek

Université de Montreal, Lab. Rene J. A. Levesque, Montreal, QC, Canada, H3C 3J7

H. Nicholson, C. S. Sutton

Mount Holyoke College, South Hadley, MA 01075, USA

N. Cavallo, G. De Nardo, F. Fabozzi, C. Gatto, L. Lista, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126 Napoli, Italy

M. Falbo

Northern Kentucky University, Highland Heights, KY 41076, USA

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

F. Colecchia, F. Dal Corso, G. Michelon, M. Morandin, M. Posocco, 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, C. De la Vaissière, L. Del Buono, O. Hamon, F. Le Diberder, Ph. Leruste, J. Lory, F. Martinez-Vidal, L. Roos, J. Stark, S. Versillé

Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, Cedex 05, 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

M. Haire, D. Judd, K. Paick, L. Turnbull, D. E. Wagoner

Prairie View A&M University, Prairie View, TX 77446, USA

5

J. Albert, C. Bula, M. H. Kelsey, 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, F. Ferrarotto, F. Ferroni, K. Fratini, E. Lamanna, E. Leonardi, M. A. Mazzoni, S. Morganti,
G. Piredda, F. Safai Tehrani, M. Serra

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

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, U. Egede, B. Franek, N. I. Geddes, G. P. Gopal

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

N. Copty, M. V. Purohit, F. X. Yumiceva

University of South Carolina, Columbia, SC 29208, USA

I. Adam, P. L. Anthony, F. Anulli, D. Aston, K. Baird, E. Bloom, A. M. Boyarski, F. Bulos, G. Calderini,
M. R. Convery, D. P. Coupal, D. H. Coward, J. Dorfan, M. Doser, W. Dunwoodie, T. Glanzman,
G. L. Godfrey, P. Grosso, J. L. Hewett, T. Himel, M. E. Huffer, W. R. Innes, C. P. Jessop, P. Kim,
U. Langenegger, D. W. G. S. Leith, S. Luitz, V. Luth, H. L. Lynch, G. Manzin, H. Marsiske, S. Menke,
R. Messner, K. C. Moffeit, M. Morii, R. Mount, D. R. Muller, C. P. O'Grady, P. Paolucci, S. Petrak,
H. Quinn, B. N. Ratcliff, S. H. Robertson, L. S. Rochester, A. Roodman, T. Schietinger, R. H. Schindler,
J. Schwiening, G. Sciolla, V. V. Serbo, A. Snyder, A. Soha, S. M. Spanier, A. Stahl, D. Su, M. K. Sullivan,
M. Talby, H. A. Tanaka, J. Va'vra, S. R. Wagner, A. J. R. Weinstein, W. J. Wisniewski, 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

A. De Silva, R. Henderson

TRIUMF, Vancouver, BC, Canada V6T 2A3

W. Bugg, H. Cohn, E. Hart, A. W. Weidemann

University of Tennessee, Knoxville, TN 37996, USA

T. Benninger, 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, P. D. Jackson, R. Kowalewski, J. M. Roney

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

H. R. Band, E. Charles, S. Dasu, P. Elmer, J. R. Johnson, J. Nielsen, W. Orejudos, Y. Pan, R. Prepost, I. J. Scott, J. Walsh, S. L. Wu, Z. Yu, H. Zobernig

University of Wisconsin, Madison, WI 53706, USA

1   Introduction

The dominant hadronic decay modes of the B meson leading to open charm in the final state involve tree-level diagrams where the $b \to c$ transition leads to a charmed meson and an external W, which often emerges as a charged π, ρ, or a_1. In this study, we report a new measurement of the branching fractions for $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ [1]. The former is known to about 10% from previous measurements, while the latter has proven more difficult to determine due to the helicity of the ρ [1, 2, 3].

2   The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector while operating in the PEP-II storage ring at the Stanford Linear Accelerator Center. For this analysis, we use a sample equivalent to 5.22 ± 0.16 fb^{-1} of integrated luminosity, collected while running on the $\Upsilon(4S)$ resonance. This corresponds to $(5.93 \pm 0.21) \times 10^6$ $B\overline{B}$ pairs, assuming the $\Upsilon(4S)$ decays only to B mesons.

The *BABAR* detector is described in detail elsewhere [4]. Charged particle tracking is provided by a 5-layer silicon microstrip detector, capable of stand-alone pattern recognition, and a 40-layer cylindrical drift chamber. This is followed outward in radius by a specialized particle identification system, based on detection of Cherenkov light generated in quartz. A calorimeter consisting of thallium-doped cesium iodide crystals provides detection for photons, and particle identification for electrons. These devices sit inside the superconducting coil, which provides a 1.5 T field with 3% uniformity over the tracking volume. The flux return for the magnet is finely segmented and instrumented with resistive-plate chambers to provide both muon identification and crude hadronic calorimetry for the detection of K_L^0 mesons.

3   *B* reconstruction method

Hadronic events for this study are selected by a set of simple requirements designed to minimize systematic errors in B counting. We require more than three charged tracks forming a primary vertex within 0.5 cm of the beam spot in both transverse directions, a sum of charged and neutral energy greater than 5 GeV, and the normalized second Fox-Wolfram moment for the event, R_2, calculated from charged tracks and neutrals in the $\Upsilon(4S)$ frame, less than 0.5. Neutrals are clusters in the calorimeter with no associated tracks, more than 30 MeV in energy, and a lateral moment of the shower distribution less than 0.8. The R_2 requirement is designed to reject the jet-like continuum events over the more uniformly distributed $\Upsilon(4S)$ decays. A fiducial requirement of $0.410 < \theta_{Lab} < 2.540$ for charged tracks and $0.410 < \theta_{Lab} < 2.409$ for neutrals, where θ_{Lab} is the polar angle to the beam line, is made in calculating these quantities and in the subsequent steps of the study.

B^0 candidates in the channels $D^{*-}\pi^+$ and $D^{*-}\rho^+$ are reconstructed using the mode $D^{*-} \to \overline{D}^0\pi^-$, followed by $\overline{D}^0 \to K^+\pi^-$. The ρ^+ is seen in its decay to $\pi^+\pi^0$. All charged tracks are required to originate close to the beam spot; the distance of closest approach in the transverse plane, is required to be less than 1.5 cm and along the beam line to be less than 3 cm. The daughters of the $\overline{D}^0$ must have a transverse momentum, p_T, greater than 100 MeV/c, and include

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[1]Here, and throughout this document, we use the convention that a particular candidate state also implies the charge conjugate state is included.

at least 20 drift chamber hits. The soft pion track is only required to have p_T greater than 70 MeV/c, taking advantage of stand-alone track finding in the silicon detector to improve acceptance. No particle identification is used for this analysis. Neutral pions are formed from pairs of photons with energy greater than 30 MeV and having a lateral shower moment less than 0.8. The invariant mass of the candidate must lie within ±25 MeV/c^2 of the nominal π^0 mass.

$\overline{D}^0$ candidates are formed from $K^+\pi^-$ combinations, where the kaon and pion are required to have a minimum momentum of 200 MeV/c, and the invariant mass of the candidate must be within $\pm2.5\sigma$ of the nominal $\overline{D}^0$ mass [5]. All $\overline{D}^0$ candidates are required to have momentum greater than 1.3 GeV/c in the $\Upsilon(4S)$ frame. A vertex constraint fit is performed, for which the χ^2 probability must be greater than 0.1%.

The reconstructed $\overline{D}^0$ is then combined with a soft pion having charge opposite to the kaon to form D^{*-} candidates. A vertex constraint fit is applied to improve the angular resolution for the soft pion, using a fixed effective vertical beam spot size of 40 μm. In those cases where the fit converges, D^{*-} candidates are selected by the requirement that $\Delta m = m(\overline{D}^0\pi^-) - m(\overline{D}^0)$ lies within $\pm2.5\sigma$ of the nominal mass difference [5]. The width is taken from a weighted average of the two-Gaussian distribution that is required to fit the Δm distribution.

$B^0 \to D^{*-}\pi^+$ candidates are reconstructed by combining a D^{*-} and a π^+ with momentum greater than 500 MeV/c. The decay $B^0 \to D^{*-}\pi^+$ involves a pseudoscalar initial-state particle decaying into a vector and pseudoscalar, so that the final-state D^{*-} is polarized. Therefore, the helicity angle θ_H between the soft pion direction and the D^{*-} direction in the D^{*-} rest frame should be distributed as $\cos^2\theta_H$. In contrast, combinatorial background is uniform in $\cos\theta_H$. Therefore, B meson candidates are selected with the additional requirement $|\cos\theta_H| > 0.4$. This requirement removes 40% of the background and only 5% of signal events.

For the $B^0 \to D^{*-}\rho^+$ mode, ρ^+ candidates are formed by combining a π^0 meson and a charged pion with momentum greater than 200 MeV/c. We require the momentum of the ρ^+ to be greater than 1 GeV/c and the $\pi^+\pi^0$ mass to lie within 150 MeV/c^2 of the ρ^+ mass. Finally, the opening angle, θ_T, between the thrust angle of the B candidate and the thrust axis of the remaining charged and neutrals in the event is required to satisfy $|\cos\theta_T| < 0.9$ in order to remove continuum backgrounds.

In the case of a correctly reconstructed B meson produced by the decay of an $\Upsilon(4S)$, within the experimental resolution, the measured sum of neutral and charged energies, E_m^*, must be equal to the beam energy, E_b^*, both evaluated in the $\Upsilon(4S)$ frame. We define ΔE to be the difference between the measured B candidate energy and beam energy in the $\Upsilon(4S)$ frame, $\Delta E = E_m^* - E_b^*$. The resolution on $\sigma_{\Delta E}$ is predicted to be 16.0 ± 0.6 MeV for $D^{*-}\pi^+$ and 28 MeV for $D^{*-}\rho^+$. The beam-energy substituted mass, m_{ES}, is defined as $m_{ES}^2 = (E_b^*)^2 - (\sum_i \boldsymbol{p}_i)^2$, where the $\boldsymbol{p}_i$ is the momentum of the ith daughter of the B candidate. The predicted resolution in m_{ES} is typically about 2.5 MeV/c^2 for $D^{*-}\pi^+$ and 3.1 MeV/c^2 for $D^{*-}\rho^+$. This is about a factor of 10 better than the resolution in the reconstructed invariant mass. The resolution for m_{ES} is dominated by the beam energy spread rather than by the detector resolution. It is largely uncorrelated with the error on ΔE.

The variables ΔE and m_{ES} are used to define a signal region and also sideband regions for background studies. For all modes, the region between 5.2 and 5.3 GeV/c^2 in m_{ES} and between ±300 MeV in ΔE is used to study the B candidates. The peak position, m_B^0, which should be the nominal B mass, and the resolution $\sigma_{m_{ES}}$ are extracted from the distribution of m_{ES} after requiring ΔE be consistent with zero to within $\pm2.5\sigma$. The resolution in ΔE is extracted from the ΔE distribution obtained by requiring that m_{ES} lie within $\pm2.5\sigma_{m_{ES}}$ of m_B^0.

The signal region in the two dimensional plane $m_{\rm ES}$ versus ΔE is defined as a area $\pm 2.5\sigma$ wide centered at the nominal B mass, m_B^0, and at $\Delta E = 0$. By staying below $|\Delta E| = m_\pi$, we avoid correlated background from B decays where a real final-state charged pion is either not included in the reconstruction or a random soft pion from the recoil B is added to the observed state.

Only one candidate per event is allowed to appear in the $m_{\rm ES}$ versus ΔE distribution. The criteria selected is to consider only the entry with the smallest absolute value for ΔE. The resulting two dimensional distribution of candidate events in ΔE and $m_{\rm ES}$ is shown in Fig. 1.
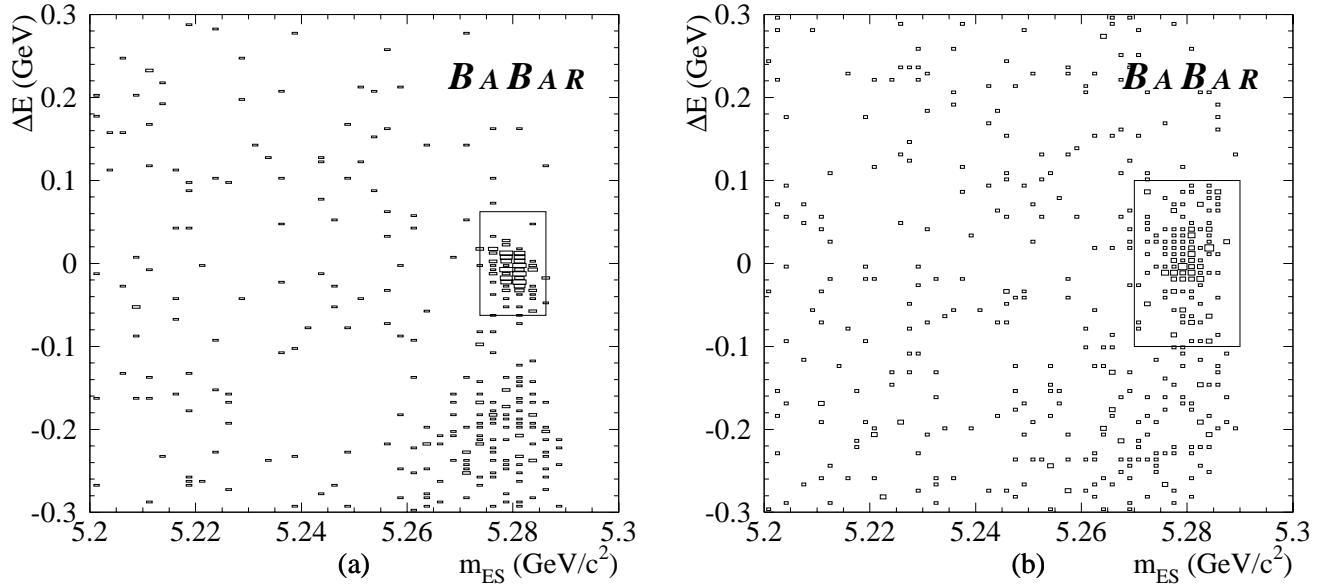
Figure 1: Distribution in data of ΔE versus $m_{\rm ES}$ for B candidates in the channels (a) $B^0 \to D^{*-}\pi^+$ and (b) $B^0 \to D^{*-}\rho^+$.

4 Branching fraction measurements

The measurement of branching fractions requires an estimate of the combinatorial background in the $m_{\rm ES}$ distribution near the nominal B mass. For the channel $B^0 \to D^{*-}\pi^+$, the $m_{\rm ES}$ distribution, shown in Fig. 2, is fitted with a background function [3] which parameterizes how the phase space approaches zero as the energy approaches E_b^*:

$$f_{BG}(\xi) = N\xi\sqrt{1 - \xi^2}\exp(\kappa(1 - \xi^2)) \tag{1}$$

where $\xi = m_{\rm ES}/E_b^*$, and the normalization and the shape are determined by the parameters N and κ. The signal is characterized by a Gaussian distribution with free mass, m_B, and width, $\sigma_{m_{\rm ES}}$. The projection of the signal as a function of ΔE, also shown in Fig. 2, is fitted using a linear background function plus a single Gaussian distribution with free mean and width, $\sigma_{\Delta E}$. The region $-0.3 < \Delta E < -0.13$ GeV, containing feeddown from $D^{*-}\rho$ where a pion is left out of the reconstruction, is excluded from the fit. The observed width of the signal in $m_{\rm ES}$ is $2.45 \pm 0.18\,{\rm MeV}/c^2$ while the
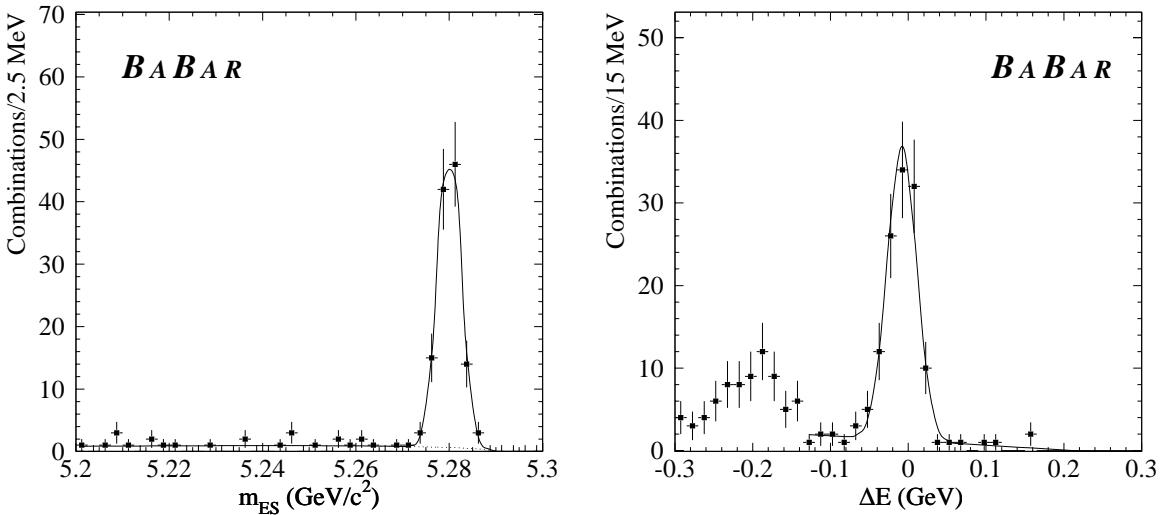
Figure 2: Distribution of m_{ES} for $|\Delta E| < 2.5\sigma_{\Delta E}$ (left), and ΔE for $|m_{\mathrm{ES}} - m_B^0| < 2.5\sigma_{m_{\mathrm{ES}}}$ (right) in the channel $B^0 \to D^{*-}\pi^+$. The fits are described in the text.

Table 1: Observed and expected yields and efficiencies for B^0 decay modes.

B^0 mode	Observed yield	Efficiency (%)
$D^{*-}\pi^+$	119 ± 11	27.0 ± 1.0
$D^{*-}\rho^+$	131 ± 13	7.6 ± 0.6

ΔE resolution is observed to be $18.8 \pm 0.9\,\mathrm{MeV}$. Acceptances are calculated in terms of the fitted widths observed in data and Monte Carlo simulation.

For the channel, $B^0 \to D^{*-}\rho^+$ the observed m_{ES} distribution is shown in Fig. 3. This has been fitted with the same background function and signal function described above. The projection of the signal as a function of ΔE, also shown in Fig. 3, is fitted using a linear background function plus a single Gaussian distribution with free mean and width, $\sigma_{\Delta E}$, with the region $-0.3 < \Delta E < -0.13\,\mathrm{GeV}$ once more excluded. The width of the signal in m_{ES} is $3.5 \pm 0.3\,\mathrm{MeV}/c^2$ while the ΔE resolution is observed to be $39.5 \pm 4.7\,\mathrm{MeV}$.

A detailed Monte Carlo simulation is used to determine the acceptance for the signal events. Control samples are used to determine the uncertainties on crucial performance characteristics of the simulation. The fitted yields for signal events and estimated efficiencies for each channel are listed in Table 1.

A variety of sources contribute to the systematic errors on the final branching fraction results. The number of produced B mesons is extracted from the ratio of multihadron-to-muon pair events on- and off-resonance, after application of the simple event selection criteria described above. After extrapolation from accepted to produced numbers of $B\overline{B}$ pairs, the estimated uncertainty is 3.6% [4].

11
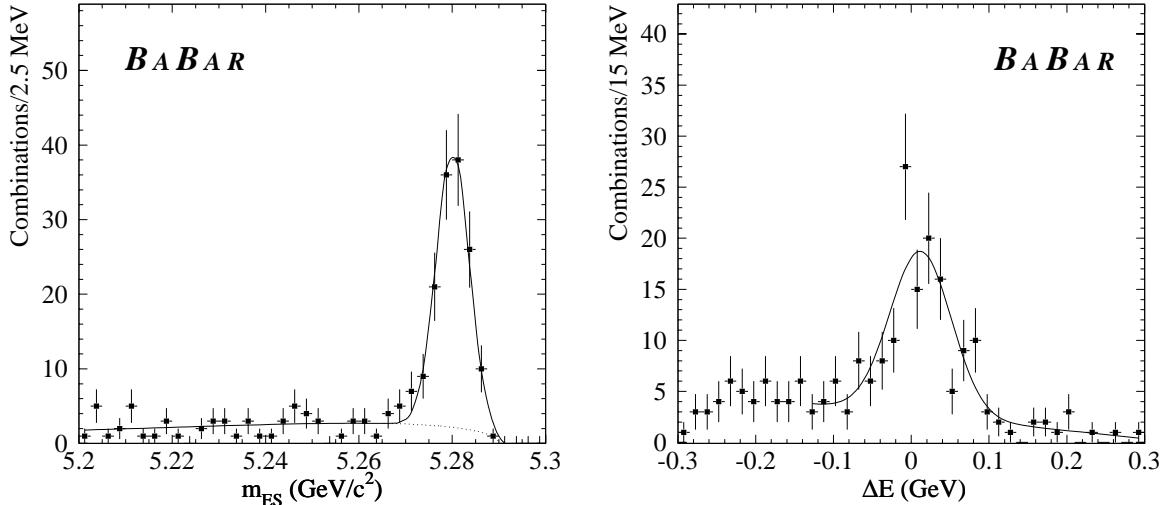
Figure 3: Distribution of m_{ES} for $|\Delta E| < 2.5\sigma_{\Delta E}$ (left), and ΔE for $|m_{\mathrm{ES}} - m_B^0| < 2.5\sigma_{m_{\mathrm{ES}}}$ (right) in the channel $B^0 \to D^{*-}\rho^+$. The fits are described in the text.

The primary check on charged track efficiency is obtained by studying the probability for observing drift chamber versus silicon detector-only tracks in inclusive $D^0 \to K^-\pi^+\pi^+\pi^-$. This is compared with the rate for finding the third track in one-versus-three topology tau-pair decays. A final check is the observed multiplicity distribution in $\Upsilon(4S)$ events. A systematic error of 2.5% per track with $p_T > 1\,\mathrm{GeV}/c$ on the overall efficiency scale is determined by comparing the three methods. The soft pion efficiency is determined from a study of the forward-backward asymmetry in observed D^{*-} decays, and is also constrained to some extent by the same charm and tau-pair studies. The p_T resolution in the Monte Carlo events is adjusted to reproduce the resolution seen in cosmic ray muons. The overall systematic uncertainty in the final result due to tracking efficiency is estimated to be 7.9% for the final states considered in this study. An additional systematic error contribution come from changes in the ratio of observed and predicted efficiencies as the selection requirements are varied within a reasonable range (3%).

In the case of the $B^0 \to D^{*-}\rho^+$ channel, there are additional systematic errors due to the ρ^+ and its polarization. The reconstruction efficiency for the π^0, as modeled in our Monte Carlo simulation, is verified to be accurate to within 5% [4]. The width of the signal in the ΔE projection is modestly larger than predicted by the Monte Carlo simulation. Therefore, we have varied the ΔE requirement for the signal band over a wide range around the nominal 2.5σ, and estimate a further 10% uncertainty due to this requirement. Finally, we have extracted the branching fraction separately in the two hemispheres of the ρ helicity angle, $\theta_H(\rho)$, greater and less than zero. A further 15% systematic error is assigned on the basis of the observed difference in branching fraction. The helicity distributions for the ρ and the D^{*-} are consistent with expectations based on previous measurements [2] and our Monte Carlo efficiency calculation, although we have not yet attempted to determine the polarization from the data.

An additional check of the result for $B^0 \to D^{*-}\pi^+$ is to relax the $\cos\theta_H$ requirement, and extract the fitted signal as a function of $\cos\theta_H$ instead. The distribution of the B candidates
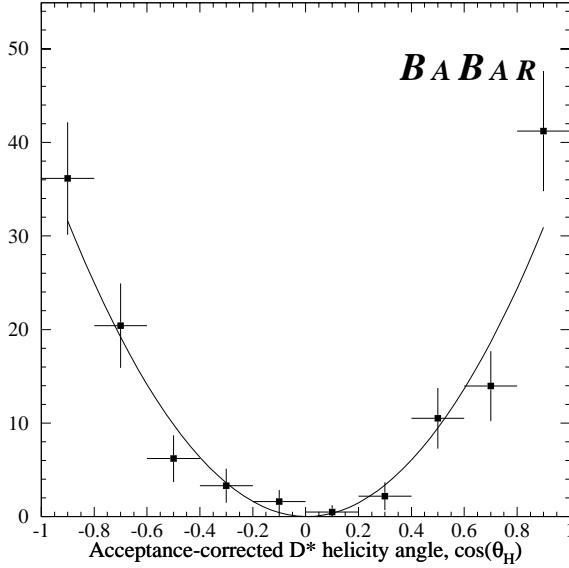
Figure 4: Distribution of $B^0 \rightarrow D^{*-}\pi^+$ as a function of the helicity angle of the soft pion, $\cos\theta_H$, in the D^{*-} rest frame after acceptance correction. The vertical axis has arbitrary units.

within $\pm 2.5\sigma m_{\mathrm{ES}}$ of the nominal B mass and $\pm 2.5\sigma_{\Delta E}$ of $\Delta E = 0$ exhibits no forward-backward asymmetry after acceptance corrections as can be seen in Figure 4. This confirms our understanding of the soft pion efficiency in the D^{*-} decay. Overlayed on the 126 signal candidates, with an estimated background of 4 events, is a fit with $\cos^2\theta_H$, yielding a χ^2 for goodness-of-fit of 8.6 for 7 degrees of freedom.

The PDG compilation [5] of measured branching fractions for the $D^{*+} \rightarrow D^0\pi^+$, $(68.3 \pm 1.4)\%$, and $D^0 \rightarrow K^-\pi^+$, $(3.83 \pm 0.09)\%$, are used in computing our final results. The measurement errors on these branching fractions are included in the systematic error on our final result. We also assume the $\Upsilon(4S)$ decays into $B^0\overline{B}^0$ pairs with a 50% fraction; no systematic error is assigned to this value.

Based on fitted yield of signal events, the estimated efficiency, and the number of produced B mesons in our sample, the preliminary results for the branching fractions for $B^0 \rightarrow D^{*-}\pi^+$ and $B^0 \rightarrow D^{*-}\rho^+$ are $(2.9 \pm 0.3 \pm 0.3) \times 10^{-3}$ and $(11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$ respectively. The branching fraction for $B^0 \rightarrow D^{*-}\rho^+$ includes all non-resonant and quasi-two-body contributions that lead to a $\pi^+\pi^0$ invariant mass in the ρ band. However, the acceptance for non-resonant $D^{*-}\pi^+\pi^0$ decays is about 15% of $D^{*-}\rho^+$ so that, combined with the known branching fraction for this mode, the non-resonant contribution to our result for $B^0 \rightarrow D^{*-}\rho^+$ is expected to be quite small. Both branching fraction results compare well with previous measurements and with the world average [5].

5 Summary

B^0 decays to $D^{*-}\pi^+$ and $D^{*-}\rho^+$ have been studied using the decay chain $D^{*-} \rightarrow \overline{D}^0\pi^-$, followed by $\overline{D}^0 \rightarrow K^+\pi^-$. The preliminary branching fractions obtained for these channels, $(2.9 \pm 0.3 \pm 0.3) \times$

10^{-3} and $(11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$ respectively, are compatible with previous observations [1, 2, 3].

6   Acknowledgments

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