Observation of the baryonic B-decay B-bar--> Lambda c+p-barK- pi +

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Observation of the baryonic B-decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$

B. Aubert,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] M. Martinelli,[3a,3b] A. Palano,[3a,3b] M. Pappagallo,[3a,3b] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] M. Battaglia,[5] D. N. Brown,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. J. Asgeirsson,[8] B. G. Fulsom,[8] C. Hearty,[8] T. S. Mattison,[8] J. A. McKenna,[8] M. Barrett,[9] A. Khan,[9] A. Randle-Conde,[9] V. E. Blinov,[10] A. D. Bukin,[10,*] A. R. Buzykaev,[10] V. P. Druzhinin,[10] V. B. Golubev,[10] A. P. Onuchin,[10] S. I. Serednyakov,[10] Yu. I. Skovpen,[10] E. P. Solodov,[10] K. Yu. Todyshev,[10] M. Bondioli,[11] S. Curry,[11] I. Eschrich,[11] D. Kirkby,[11] A. J. Lankford,[11] P. Lund,[11] M. Mandelkern,[11] E. C. Martin,[11] D. P. Stoker,[11] H. Atmacan,[12] J. W. Gary,[12] F. Liu,[12] O. Long,[12] G. M. Vitug,[12] Z. Yasin,[12] V. Sharma,[13] C. Campagnari,[14] T. M. Hong,[14] D. Kovalskyi,[14] M. A. Mazur,[14] J. D. Richman,[14] T. W. Beck,[15] A. M. Eisner,[15] C. A. Heusch,[15] J. Kroseberg,[15] W. S. Lockman,[15] A. J. Martinez,[15] T. Schalk,[15] B. A. Schumm,[15] A. Seiden,[15] L. Wang,[15] L. O. Winstrom,[15] C. H. Cheng,[16] D. A. Doll,[16] B. Echenard,[16] F. Fang,[16] D. G. Hitlin,[16] I. Narsky,[16] T. Piatenko,[16] F. C. Porter,[16] R. Andreassen,[17] G. Mancinelli,[17] B. T. Meadows,[17] K. Mishra,[17] M. D. Sokoloff,[17] P. C. Bloom,[18] W. T. Ford,[18] A. Gaz,[18] J. F. Hirschauer,[18] M. Nagel,[18] U. Nauenberg,[18] J. G. Smith,[18] S. R. Wagner,[18] R. Ayad,[19,†] W. H. Toki,[19] R. J. Wilson,[19] E. Feltresi,[20] A. Hauke,[20] H. Jasper,[20] T. M. Karbach,[20] J. Merkel,[20] A. Petzold,[20] B. Spaan,[20] K. Wacker,[20] M. J. Kobel,[21] R. Nogowski,[21] K. R. Schubert,[21] R. Schwierz,[21] A. Volk,[21] D. Bernard,[22] E. Latour,[22] M. Verderi,[22] P. J. Clark,[23] S. Playfer,[23] J. E. Watson,[23] M. Andreotti,[24a,24b] D. Bettoni,[24a] C. Bozzi,[24a] R. Calabrese,[24a,24b] A. Cecchi,[24a,24b] G. Cibinetto,[24a,24b] E. Fioravanti,[24a,24b] P. Franchini,[24a,24b] E. Luppi,[24a,24b] M. Munerato,[24a,24b] M. Negrini,[24a,24b] A. Petrella,[24a,24b] L. Piemontese,[24a] V. Santoro,[24a,24b] R. Baldini-Ferroli,[25] A. Calcaterra,[25] R. de Sangro,[25] G. Finocchiaro,[25] S. Pacetti,[25] P. Patteri,[25] I. M. Peruzzi,[25,‡] M. Piccolo,[25] M. Rama,[25] A. Zallo,[25] R. Contri,[26a,26b] E. Guido,[26a,26b] M. Lo Vetere,[26a,26b] M. R. Monge,[26a,26b] S. Passaggio,[26a] C. Patrignani,[26a,26b] E. Robutti,[26a] S. Tosi,[26a,26b] K. S. Chaisanguanthum,[27] M. Morii,[27] A. Adametz,[28] J. Marks,[28] S. Schenk,[28] U. Uwer,[28] F. U. Bernlochner,[29] V. Klose,[29] H. M. Lacker,[29] D. J. Bard,[30] P. D. Dauncey,[30] M. Tibbetts,[30] P. K. Behera,[31] M. J. Charles,[31] U. Mallik,[31] J. Cochran,[32] H. B. Crawley,[32] L. Dong,[32] V. Eyges,[32] W. T. Meyer,[32] S. Prell,[32] E. I. Rosenberg,[32] A. E. Rubin,[32] Y. Y. Gao,[33] A. V. Gritsan,[33] Z. J. Guo,[33] N. Arnaud,[34] J. Béquilleux,[34] A. D'Orazio,[34] M. Davier,[34] D. Derkach,[34] J. Firmino da Costa,[34] G. Grosdidier,[34] F. Le Diberder,[34] V. Lepeltier,[34] A. M. Lutz,[34] B. Malaescu,[34] S. Pruvot,[34] P. Roudeau,[34] M. H. Schune,[34] J. Serrano,[34] V. Sordini,[34,§] A. Stocchi,[34] G. Wormser,[34] D. J. Lange,[35] D. M. Wright,[35] I. Bingham,[36] J. P. Burke,[36] C. A. Chavez,[36] J. R. Fry,[36] E. Gabathuler,[36] R. Gamet,[36] D. E. Hutchcroft,[36] D. J. Payne,[36] C. Touramanis,[36] A. J. Bevan,[37] C. K. Clarke,[37] F. Di Lodovico,[37] R. Sacco,[37] M. Sigamani,[37] G. Cowan,[38] S. Paramesvaran,[38] A. C. Wren,[38] D. N. Brown,[39] C. L. Davis,[39] A. G. Denig,[40] M. Fritsch,[40] W. Gradl,[40] A. Hafner,[40] K. E. Alwyn,[41] D. Bailey,[41] R. J. Barlow,[41] G. Jackson,[41] G. D. Lafferty,[41] T. J. West,[41] J. I. Yi,[41] J. Anderson,[42] C. Chen,[42] A. Jawahery,[42] D. A. Roberts,[42] G. Simi,[42] J. M. Tuggle,[42] C. Dallapiccola,[43] E. Salvati,[43] R. Cowan,[44] D. Dujmic,[44] P. H. Fisher,[44] S. W. Henderson,[44] G. Sciolla,[44] M. Spitznagel,[44] R. K. Yamamoto,[44] M. Zhao,[44] P. M. Patel,[45] S. H. Robertson,[45] M. Schram,[45] A. Lazzaro,[46a,46b] V. Lombardo,[46a] F. Palombo,[46a,46b] S. Stracka,[46a,46b] J. M. Bauer,[47] L. Cremaldi,[47] R. Godang,[47,∥] R. Kroeger,[47] P. Sonnek,[47] D. J. Summers,[47] H. W. Zhao,[47] M. Simard,[48] P. Taras,[48] H. Nicholson,[49] G. De Nardo,[50a,50b] L. Lista,[50a] D. Monorchio,[50a,50b] G. Onorato,[50a,50b] C. Sciacca,[50a,50b] G. Raven,[51] H. L. Snoek,[51] C. P. Jessop,[52] K. J. Knoepfel,[52] J. M. LoSecco,[52] W. F. Wang,[52] L. A. Corwin,[53] K. Honscheid,[53] H. Kagan,[53] R. Kass,[53] J. P. Morris,[53] A. M. Rahimi,[53] J. J. Regensburger,[53] S. J. Sekula,[53] Q. K. Wong,[53] N. L. Blount,[54] J. Brau,[54] R. Frey,[54] O. Igonkina,[54] J. A. Kolb,[54] M. Lu,[54] R. Rahmat,[54] N. B. Sinev,[54] D. Strom,[54] J. Strube,[54] E. Torrence,[54] G. Castelli,[55a,55b] N. Gagliardi,[55a,55b] M. Margoni,[55a,55b] M. Morandin,[55a] M. Posocco,[55a] M. Rotondo,[55a] F. Simonetto,[55a,55b] R. Stroili,[55a,55b] C. Voci,[55a,55b] P. del Amo Sanchez,[56] E. Ben-Haim,[56] G. R. Bonneaud,[56] H. Briand,[56] J. Chauveau,[56] O. Hamon,[56] Ph. Leruste,[56] G. Marchiori,[56] J. Ocariz,[56] A. Perez,[56] J. Prendki,[56] S. Sitt,[56] L. Gladney,[57] M. Biasini,[58a,58b] E. Manoni,[58a,58b] C. Angelini,[59a,59b] G. Batignani,[59a,59b] S. Bettarini,[59a,59b] G. Calderini,[59a,59b,¶] M. Carpinelli,[59a,59b,**] A. Cervelli,[59a,59b] F. Forti,[59a,59b] M. A. Giorgi,[59a,59b] A. Lusiani,[59a,59c] M. Morganti,[59a,59b] N. Neri,[59a,59b] E. Paoloni,[59a,59b] G. Rizzo,[59a,59b] J. J. Walsh,[59a] D. Lopes Pegna,[60] C. Lu,[60] J. Olsen,[60] A. J. S. Smith,[60] A. V. Telnov,[60] F. Anulli,[61a] E. Baracchini,[61a,61b] G. Cavoto,[61a] R. Faccini,[61a,61b] F. Ferrarotto,[61a] F. Ferroni,[61a,61b] M. Gaspero,[61a,61b] P. D. Jackson,[61a] L. Li Gioi,[61a] M. A. Mazzoni,[61a] S. Morganti,[61a] G. Piredda,[61a] F. Renga,[61a,61b] C. Voena,[61a] M. Ebert,[62] T. Hartmann,[62] T. Leddig,[62] H. Schröder,[62] R. Waldi,[62] T. Adye,[63] B. Franek,[63] E. O. Olaiya,[63] F. F. Wilson,[63] S. Emery,[64] L. Esteve,[64] G. Hamel de Monchenault,[64] W. Kozanecki,[64] G. Vasseur,[64] Ch. Yèche,[64] M. Zito,[64] M. T. Allen,[65] D. Aston,[65] R. Bartoldus,[65] J. F. Benitez,[65] R. Cenci,[65] J. P. Coleman,[65] M. R. Convery,[65]

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J. C. Dingfelder,[65] J. Dorfan,[65] G. P. Dubois-Felsmann,[65] W. Dunwoodie,[65] R. C. Field,[65] M. Franco Sevilla,[65] A. M. Gabareen,[65] M. T. Graham,[65] P. Grenier,[65] C. Hast,[65] W. R. Innes,[65] J. Kaminski,[65] M. H. Kelsey,[65] H. Kim,[65] P. Kim,[65] M. L. Kocian,[65] D. W. G. S. Leith,[65] S. Li,[65] B. Lindquist,[65] S. Luitz,[65] V. Luth,[65] H. L. Lynch,[65] D. B. MacFarlane,[65] H. Marsiske,[65] R. Messner,[65,*] D. R. Muller,[65] H. Neal,[65] S. Nelson,[65] C. P. O'Grady,[65] I. Ofte,[65] M. Perl,[65] B. N. Ratcliff,[65] A. Roodman,[65] A. A. Salnikov,[65] R. H. Schindler,[65] J. Schwiening,[65] A. Snyder,[65] D. Su,[65] M. K. Sullivan,[65] K. Suzuki,[65] S. K. Swain,[65] J. M. Thompson,[65] J. Va'vra,[65] A. P. Wagner,[65] M. Weaver,[65] C. A. West,[65] W. J. Wisniewski,[65] M. Wittgen,[65] D. H. Wright,[65] H. W. Wulsin,[65] A. K. Yarritu,[65] C. C. Young,[65] V. Ziegler,[65] X. R. Chen,[66] H. Liu,[66] W. Park,[66] M. V. Purohit,[66] R. M. White,[66] J. R. Wilson,[66] P. R. Burchat,[67] A. J. Edwards,[67] T. S. Miyashita,[67] S. Ahmed,[68] M. S. Alam,[68] J. A. Ernst,[68] B. Pan,[68] M. A. Saeed,[68] S. B. Zain,[68] A. Soffer,[69] S. M. Spanier,[70] B. J. Wogsland,[70] R. Eckmann,[71] J. L. Ritchie,[71] A. M. Ruland,[71] C. J. Schilling,[71] R. F. Schwitters,[71] B. C. Wray,[71] B. W. Drummond,[72] J. M. Izen,[72] X. C. Lou,[72] F. Bianchi,[73a,73b] D. Gamba,[73a,73b] M. Pelliccioni,[73a,73b] M. Bomben,[74a,74b] L. Bosisio,[74a,74b] C. Cartaro,[74a,74b] G. Della Ricca,[74a,74b] L. Lanceri,[74a,74b] L. Vitale,[74a,74b] V. Azzolini,[75] N. Lopez-March,[75] F. Martinez-Vidal,[75] D. A. Milanes,[75] A. Oyanguren,[75] J. Albert,[76] Sw. Banerjee,[76] B. Bhuyan,[76] H. H. F. Choi,[76] K. Hamano,[76] G. J. King,[76] R. Kowalewski,[76] M. J. Lewczuk,[76] I. M. Nugent,[76] J. M. Roney,[76] R. J. Sobie,[76] T. J. Gershon,[77] P. F. Harrison,[77] J. Ilic,[77] T. E. Latham,[77] G. B. Mohanty,[77] E. M. T. Puccio,[77] H. R. Band,[78] X. Chen,[78] S. Dasu,[78] K. T. Flood,[78] Y. Pan,[78] R. Prepost,[78] C. O. Vuosalo,[78] and S. L. Wu[78]

(*BABAR* Collaboration)

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN$_2$P$_3$, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3a]*INFN Sezione di Bari, I-70126 Bari, Italy*
[3b]*Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[9]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[10]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[11]*University of California at Irvine, Irvine, California 92697, USA*
[12]*University of California at Riverside, Riverside, California 92521, USA*
[13]*University of California at San Diego, La Jolla, California 92093, USA*
[14]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[15]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[16]*California Institute of Technology, Pasadena, California 91125, USA*
[17]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[18]*University of Colorado, Boulder, Colorado 80309, USA*
[19]*Colorado State University, Fort Collins, Colorado 80523, USA*
[20]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[21]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[22]*Laboratoire Leprince-Ringuet, CNRS/IN$_2$P$_3$, Ecole Polytechnique, F-91128 Palaiseau, France*
[23]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[24a]*INFN Sezione di Ferrara, I-44100 Ferrara, Italy*
[24b]*Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy*
[25]*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[26a]*INFN Sezione di Genova, I-16146 Genova, Italy*
[26b]*Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy*
[27]*Harvard University, Cambridge, Massachusetts 02138, USA*
[28]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[29]*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany*
[30]*Imperial College London, London, SW7 2AZ, United Kingdom*
[31]*University of Iowa, Iowa City, Iowa 52242, USA*
[32]*Iowa State University, Ames, Iowa 50011-3160, USA*
[33]*Johns Hopkins University, Baltimore, Maryland 21218, USA*
[34]*Laboratoire de l'Accélérateur Linéaire, IN$_2$P$_3$/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France*

[35]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[36]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[37]Queen Mary, University of London, London, E1 4NS, United Kingdom
[38]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[39]University of Louisville, Louisville, Kentucky 40292, USA
[40]Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
[41]University of Manchester, Manchester M13 9PL, United Kingdom
[42]University of Maryland, College Park, Maryland 20742, USA
[43]University of Massachusetts, Amherst, Massachusetts 01003, USA
[44]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[45]McGill University, Montréal, Québec, Canada H3A 2T8
[46a]INFN Sezione di Milano, I-20133 Milano, Italy
[46b]Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
[47]University of Mississippi, University, Mississippi 38677, USA
[48]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
[49]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[50a]INFN Sezione di Napoli, I-80126 Napoli, Italy
[50b]Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
[51]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[52]University of Notre Dame, Notre Dame, Indiana 46556, USA
[53]Ohio State University, Columbus, Ohio 43210, USA
[54]University of Oregon, Eugene, Oregon 97403, USA
[55a]INFN Sezione di Padova, I-35131 Padova, Italy
[55b]Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy
[56]Laboratoire de Physique Nucléaire et de Hautes Energies, IN_2P_3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
[57]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[58a]INFN Sezione di Perugia, I-06100 Perugia, Italy
[58b]Dipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy
[59a]INFN Sezione di Pisa, I-56127 Pisa, Italy
[59b]Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy
[59c]Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy
[60]Princeton University, Princeton, New Jersey 08544, USA
[61a]INFN Sezione di Roma, I-00185 Roma, Italy
[61b]Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy
[62]Universität Rostock, D-18051 Rostock, Germany
[63]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[64]CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
[65]SLAC National Accelerator Laboratory, Stanford, California 94309 USA
[66]University of South Carolina, Columbia, South Carolina 29208, USA
[67]Stanford University, Stanford, California 94305-4060, USA
[68]State University of New York, Albany, New York 12222, USA
[69]Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
[70]University of Tennessee, Knoxville, Tennessee 37996, USA
[71]University of Texas at Austin, Austin, Texas 78712, USA
[72]University of Texas at Dallas, Richardson, Texas 75083, USA
[73a]INFN Sezione di Torino, I-10125 Torino, Italy
[73b]Dipartimento di Fisica Sperimentale, Università di Torino, I-10125 Torino, Italy
[74a]INFN Sezione di Trieste, I-34127 Trieste, Italy
[74b]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[75]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[76]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[77]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

[*]Deceased.

[†]Now at Temple University, Philadelphia, PA 19122, USA.

[‡]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.

[§]Also with Università di Roma La Sapienza, I-00185 Roma, Italy.

[‖]Now at University of South Alabama, Mobile, AL 36688, USA.

[¶]Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN_2P_3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France.

[**]Also with Università di Sassari, Sassari, Italy.

[78]*University of Wisconsin, Madison, Wisconsin 53706, USA*
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We report the observation of the baryonic B-decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$, excluding contributions from the decay $\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda} K^-$. Using a data sample of 467×10^6 $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II storage ring at SLAC, the measured branching fraction is $(4.33 \pm 0.82_{\rm stat} \pm 0.33_{\rm syst} \pm 1.13_{\Lambda_c^+}) \times 10^{-5}$. In addition we find evidence for the resonant decay $\bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p} K^-$ and determine its branching fraction to be $(1.11 \pm 0.30_{\rm stat} \pm 0.09_{\rm syst} \pm 0.29_{\Lambda_c^+}) \times 10^{-5}$. The errors are statistical, systematic, and due to the uncertainty in the Λ_c^+ branching fraction. For the resonant decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} \bar{K}^{*0}$ we obtain an upper limit of 2.42×10^{-5} at 90% confidence level.

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While $(6.8 \pm 0.6)\%$ [1] of all B-meson decays have baryons in their final state, very little is known about the decay mechanisms behind these decays and more generally about hadron fragmentation into baryons. One way to enhance our understanding of baryon production in B decays may be to compare decay rates to related exclusive final states.

In this paper we present a measurement of the Cabibbo-suppressed decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$ [2]. This decay can be compared with the Cabibbo-favored decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$, which has been observed by the CLEO [3] and Belle [4] collaborations. The average of the branching fraction results from these two experiments are $(12.6 \pm 1.3 \pm 3.3) \times 10^{-4}$ for $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$ and $(2.3 \pm 0.3 \pm 0.6) \times 10^{-4}$ for the resonant subchannel $\bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p} \pi^-$, where the first uncertainty is the combined statistical and systematic error and the second one is the error on the $\Lambda_c^+ \to p K^- \pi^+$ branching fraction. If only Cabibbo suppression is taken into account one expects the ratio of the corresponding Cabibbo-favored and suppressed decays to be close to $|V_{\rm us}/V_{\rm ud}|^2$, where $V_{\rm us}$ and $V_{\rm ud}$ are Cabibbo-Kobayashi-Maskawa matrix elements. Any deviation from this value indicates a contribution from the additional decay amplitudes possible in the Cabibbo-favored decays.

This analysis is based on a dataset of about 426 fb^{-1}, corresponding to 467×10^6 $B\bar{B}$ pairs, collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring, which was operated at a center-of-mass energy equal to the $\Upsilon(4S)$ mass (on resonance). In addition, a dataset of 44 fb^{-1} collected approximately 40 MeV below the $\Upsilon(4S)$ mass (off resonance) is used to study continuum background. The *BABAR* detector is described in detail elsewhere [5]. For simulated events we use EVTGEN [6] for the event generation and GEANT4 [7] for the detector simulation.

For the decay $\Lambda_c^+ \to p K^- \pi^+$ a vertex fit is performed and the invariant mass is required to fall in the interval $2.277 < m_{pK\pi} < 2.295$ GeV$/c^2$. For the reconstruction of the B-candidate, the mass of the Λ_c^+-candidate is constrained to the nominal mass of the Λ_c^+ [1] and is combined with $\bar{p}$, K^-, and π^+ candidates. Afterwards the whole decay tree is fitted to a common vertex and the χ^2 probability of this fit is required to exceed 0.2%.

The selection of proton, kaon, and pion candidates is based on measurements of the specific ionization in the silicon vertex tracker and the drift chamber, and of the Cherenkov radiation in the detector of internally reflected Cherenkov light [8]. The proton and antiproton selection uses in addition information from the electromagnetic calorimeter. The average efficiency for pion identification is about 95%, while the typical misidentification rate is 10%, depending on the momentum of the particle. The efficiency for kaon identification varies between 60% and 90%, while the misidentification rate is smaller than 5%. The efficiency for proton and antiproton identification is about 90% with a misidentification rate around 2%.

The separation of signal and background of the candidate sample is obtained using two kinematic variables, $\Delta E = E_B^* - \sqrt{s}/2$ and $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - |\mathbf{p}|_B^2}$. Here, $\sqrt{s}$ is the initial center-of-mass energy, E_B^* the energy of the B-candidate in the center-of-mass system, $(E_i, \mathbf{p}_i)$ is the four-momentum vector of the e^+e^- system and $\mathbf{p}_B$ the B-candidate momentum vector, both measured in the laboratory frame. For true B-decays $m_{\rm ES}$ is centered at the B-meson mass and ΔE is centered at zero. Throughout this analysis, B-candidates are required to have an $m_{\rm ES}$ value between 5.275 and 5.286 GeV$/c^2$.

After applying all selection criteria there are on average 1.16 candidates per event. If the B-candidates have different Λ_c^+-candidates we select the one with the invariant $pK^-\pi^+$ mass closest to the nominal Λ_c^+ mass [1]. If the candidates share the same Λ_c^+ we retain the one with the best vertex fit.

The significance of the $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$ signal is determined from a fit to the observed ΔE distribution (see Fig. 1). As the fit function we use a straight line for background and a Gaussian for signal. Fitting between -0.12 GeV and 0.12 GeV we obtain 82 ± 17 signal events and determine a significance of 8.8 standard deviations for this decay. Here, and in the following, we calculate the significance as the square root of the difference of 2 times the log likelihood of a fit with and without signal component.

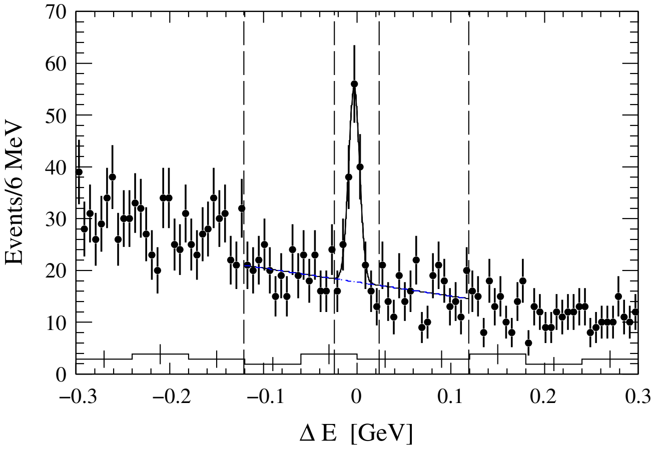

FIG. 1 (color online). Fitted ΔE distribution in data with all selection criteria applied (data points). Shown are all reconstructed events $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$. The continuum background, described by off-resonance data, is overlaid (histogram). The dashed, vertical lines indicate the signal- and sideband.

Like the Cabibbo-favored decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$ the Cabibbo-suppressed decay can proceed via different resonant subchannels. Figures 2 and 3 show the sideband subtracted $\Lambda_c^+ \pi^+$ and $K^- \pi^+$ invariant mass distributions, respectively. Here, the signal region corresponds to $|\Delta E| < 0.024$ GeV, and the sideband regions to $0.024 < |\Delta E| < 0.12$ GeV. We find evidence for the decay $\bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p} K^-$ (4.3σ) and hints on the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} K^{*0}$ (2.7σ). For the determination of the significance we use in both cases a second order polynomial for background and as signal function we use in the first case a Gaussian and in the latter a nonrelativistic Breit-Wigner.

For the determination of the efficiency corrected signal yield, we divide the phase space into smaller regions. In order to account for the resonant substructure, the following regions are used:

(1) The $\Sigma_c(2455)^{++}$ signal region in the range from 2.447 to 2.461 GeV$/c^2$ in $m(\Lambda_c^+ \pi^+)$,

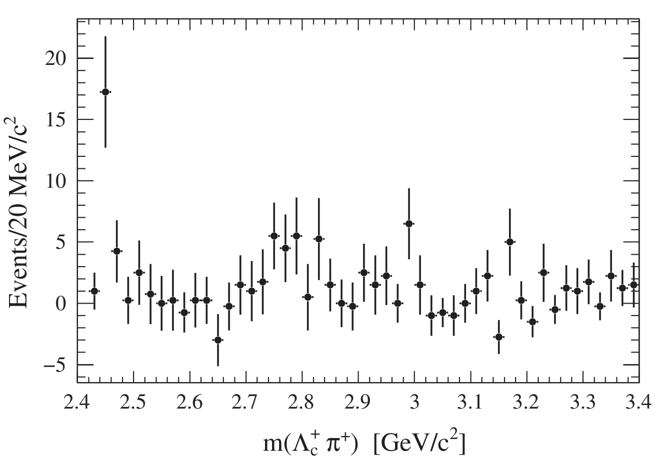

FIG. 2. Invariant $\Lambda_c^+ \pi^+$ mass in data with the ΔE sideband subtracted. A clear $\Sigma_c(2455)^{++}$ signal is visible.

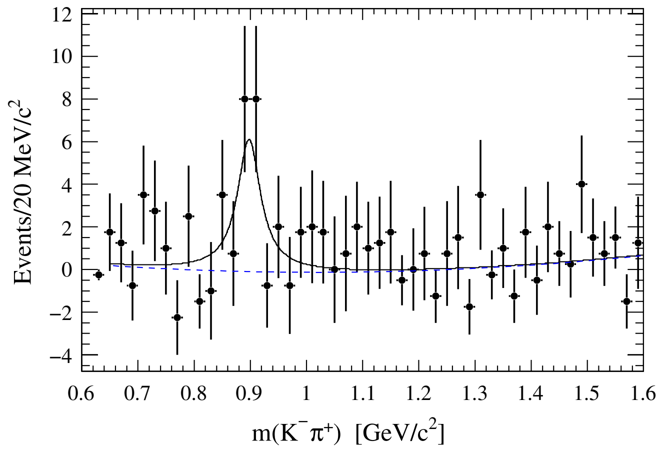

FIG. 3 (color online). Sideband subtracted invariant $K^- \pi^+$ mass with the $\Sigma_c(2455)^{++}$ signal region ($2.447 < m(\Lambda_c^+ \pi^+) < 2.461$ GeV$/c^2$) excluded. The solid curve is the fit, which is the sum of a nonrelativistic Breit-Wigner function and a second order polynomial. The dashed curve is the parabolic portion. An enhancement at the $\bar{K}^{*0}$ mass of 896 MeV$/c^2$ is visible.

(2) the $\bar{K}^{*0}$ signal region from 0.8 to 1.1 GeV$/c^2$ in $m(K^- \pi^+)$, excluding region 1), and

(3) all events that are not in region 1) or 2).

The events in region 3 show no further significant resonant structure, but are also not uniformly distributed in phase space. Since we use a phase space model in our Monte Carlo simulation we correct the efficiency as a function of $m(\Lambda_c^+ \bar{p} \pi^+)$. We determine the signal yield in the different regions by subtracting the extrapolated background from the observed number of B-candidates in the ΔE signal region. The background is determined with a linear fit to the ΔE distribution in the ΔE sidebands, $0.024 < |\Delta E| < 0.12$ GeV. For the efficiency estimation we use the same fit strategy as for the signal yields, but instead of a straight line we use a second order polynomial as fit function to account for the small combinatoric background in the signal Monte Carlo simulation. Here, we use nonresonant Monte Carlo events for regions 2 and 3 and for region 1 we use $\bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p} K^-$ Monte Carlo events since this region is almost saturated by resonant events. The number of signal events $N_{\rm sig}$, as well as the efficiencies ε, for the three regions are listed in Table I.

Using these values the overall branching fraction is calculated as

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+) = \frac{1}{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) \cdot N_{B\bar{B}}} \cdot \sum_{i=1}^{3} \frac{N_{{\rm sig},i}}{\varepsilon_i} = (4.33 \pm 0.82_{\rm stat} \pm 1.13_{\Lambda_c^+}) \times 10^{-5}, \quad (1)$$

with $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = (5.0 \pm 1.3)\%$ [1] and $N_{B\bar{B}} = N_{\bar{B}^0} + N_{B^0} = (467 \pm 5) \times 10^6$, assuming equal production of $B^0 \bar{B}^0$ and $B^+ B^-$ in the decay of the $\Upsilon(4S)$. In Eq. (1) and in the following branching fractions, the first

TABLE I. Number of signal events, $N_{\rm sig}$, and efficiencies ε for the three regions used to obtain the signal yield.

Region	$N_{\rm sig}$	ε
1 (Σ_c^{++})	17.3 ± 4.6	$(6.64 \pm 0.04)\%$
2 ($\bar{K}^{*0}$)	26.5 ± 9.7	$(8.60 \pm 0.07)\%$
3	39.7 ± 12.2	$(8.94 \pm 0.25)\%$

uncertainty is statistical, while the second one arises from the branching fraction of the Λ_c^+. The final state $\Lambda_c^+ \bar{p} K^- \pi^+$ may also include contributions from the decay $\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda} K^-$. Our cut on the vertex fit probability, however, would strongly suppress this contribution, hence the branching fraction (1) is understood to not include this decay. This is corroborated by the fact that the $\bar{p}\pi^+$ invariant mass distribution shows no $\bar{\Lambda}$ peak.

For the $\Sigma_c(2455)^{++}$ subchannel we determine the signal yield with a fit to the ΔE sideband subtracted $m(\Lambda_c^+\pi^+)$ distribution. We obtain the signal yield by subtracting from the number of events observed in the $\Sigma_c(2455)^{++}$ signal region the background yield extrapolated from a fit of a second order polynomial to the $\Sigma_c(2455)^{++}$ mass sidebands. Here, the signal region is defined as $2.447 < m(\Lambda_c^+\pi^+) < 2.461\ \mathrm{GeV}/c^2$, while the mass sidebands are $2.426 < m(\Lambda_c^+\pi^+) < 2.447\ \mathrm{GeV}/c^2$ and $2.461 < m(\Lambda_c^+\pi^+) < 2.7\ \mathrm{GeV}/c^2$. The efficiency is estimated by using the same fit strategy on $\bar{B}^0 \to \Sigma_c(2455)^{++}\bar{p}K^-$ Monte Carlo events. Both, the signal yield as well as the efficiency for this resonant subchannel are given in Table II. Using these values we obtain a branching fraction of $(1.11 \pm 0.30_{\rm stat} \pm 0.29_{\Lambda_c^+}) \times 10^{-5}$ for this subchannel, under the assumption that the $\Sigma_c(2455)^{++}$ decays entirely into $\Lambda_c^+\pi^+$.

For the $\bar{K}^{*0}$ subchannel we determine the signal yield by a fit to the ΔE sideband subtracted $m(K^-\pi^+)$ distribution, excluding the $\Sigma_c(2455)^{++}$ signal region. Here, we use the sum of a second order polynomial and a nonrelativistic Breit-Wigner function in the range from 0.64 to $1.6\ \mathrm{GeV}/c^2$ as the fit function. The nonrelativistic Breit-Wigner distribution is added in order to get a proper background description from the fit. For the fit we fix the width and the mean of the Breit-Wigner function to its measured values [1], and determine the signal yield by subtracting the integral of the background function between 0.8 and $1.0\ \mathrm{GeV}/c^2$ from the number of events in this region. The efficiency is estimated applying the same fit procedure to $\bar{B}^0 \to \Lambda_c^+\bar{p}\bar{K}^{*0}$ Monte Carlo events. With the obtained values, which are listed in Table II, we estimate a branching fraction of $(1.60 \pm 0.61_{\rm stat} \pm 0.42_{\Lambda_c^+}) \times 10^{-5}$ for this subchannel taking into account that $2/3$ of the $\bar{K}^{*0}$ decay into $K^-\pi^+$.

TABLE II. Number of signal events, $N_{\rm sig}$, and the efficiency ε for the resonant decays via the $\Sigma_c(2455)^{++}$ and the $\bar{K}^{*0}$.

Resonance	$N_{\rm sig}$	ε
$\Sigma_c(2455)^{++}$	16.0 ± 4.3	$(6.15 \pm 0.04)\%$
$\bar{K}^{*0}$	20.9 ± 7.9	$(8.38 \pm 0.05)\%$

Several sources of systematic uncertainties have been investigated. Most of these are derived from studies of data control samples and by comparison between data and Monte Carlo events. The systematic uncertainties arise from the reconstruction of charged tracks (1.4%), the charged particle identification (2.4%), and the number of $B\bar{B}$ pairs (1.1%). The uncertainty due to the ΔE background parametrization in data is determined by extracting the signal yield with a second order polynomial instead of a straight line (4.7%). The influence of the signal- and sideband definitions is estimated by changing their definitions to $|\Delta E| < 0.036$ GeV and $0.036 < |\Delta E| < 0.12$ GeV, respectively, and extracting the signal yields with these new definitions (3.3%). A further systematic uncertainty is the phase space model used for the Monte Carlo simulation (1.0%), which is determined by reweighting the Monte Carlo events to match the observed $m(\Lambda_c^+\bar{p}\pi^+)$ distribution in data. In order to estimate the uncertainties arising from the applied $m(\Lambda_c^+)$ (3.4%) and χ^2 probability (0.8%) selection criteria we vary the criteria by $0.5\ \mathrm{MeV}/c^2$ and 0.001, respectively. The overall systematic uncertainty is 7.5%.

For the low significance $\Lambda_c^+\bar{p}\bar{K}^{*0}$ signal, we determine an upper limit of 2.42×10^{-5} at 90% confidence level. This limit is calculated assuming a Gaussian *a posteriori* probability density with $\sigma = 0.63 \times 10^{-5}$, which includes statistical and systematic errors, and evaluating 90% of the integral in the physical region.

In summary, we observe the decay $\bar{B}^0 \to \Lambda_c^+\bar{p}K^-\pi^+$ with a significance of 8.8σ and measure a branching fraction of

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+\bar{p}K^-\pi^+) = (4.33 \pm 0.82_{\rm stat} \pm 0.33_{\rm syst} \pm 1.13_{\Lambda_c^+}) \times 10^{-5}. \quad (2)$$

The ratio of the branching fraction of this decay to that of $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^-\pi^+$ [3,4] is 0.038 ± 0.009, which is smaller than $|V_{us}/V_{ud}|^2 = 0.0536 \pm 0.0020$ [1]. This is a possible indication that additional decay amplitudes for the Cabibbo-favored decay are not negligible. Here, and in the following, the error on the ratio includes statistical and systematic uncertainties, while the uncertainty on the Λ_c^+ branching fraction cancels.

The branching fraction of the decay $\bar{B}^0 \to \Sigma_c(2455)^{++}\bar{p}K^-$ is determined to be

$$\mathcal{B}(\bar{B}^0 \to \Sigma_c(2455)^{++}\bar{p}K^-) = (1.11 \pm 0.30_{\rm stat} \pm 0.09_{\rm syst} \pm 0.29_{\Lambda_c^+}) \times 10^{-5}. \quad (3)$$

The ratio of this branching fraction to that of $\bar{B}^0 \to \Sigma_c(2455)^{++}\bar{p}\pi^-$ [3,4] is 0.048 ± 0.016, compatible with $|V_{us}/V_{ud}|^2$.

For the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} \bar{K}^{*0}$ the branching fraction is determined to be

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \bar{K}^{*0}) = (1.60 \pm 0.61_{\rm stat} \pm 0.12_{\rm syst} \pm 0.42_{\Lambda_c^+}) \times 10^{-5}. \tag{4}$$

The 90% confidence level upper limit for this decay is

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \bar{K}^{*0}) < 2.42 \times 10^{-5}. \tag{5}$$

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