PHYSICAL REVIEW D **82,** 091102(R) (2010)

Correlated leading baryon-antibaryon production in $e^+e^- \to c\bar{c} \to \Lambda_c^+ \bar{\Lambda}_c^- X$

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] B. Hooberman,[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] 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] C. Buchanan,[12] B. L. Hartfiel,[12] H. Atmacan,[13] J. W. Gary,[13] F. Liu,[13] O. Long,[13] G. M. Vitug,[13] Z. Yasin,[13] V. Sharma,[14] C. Campagnari,[15] T. M. Hong,[15] D. Kovalskyi,[15] M. A. Mazur,[15] J. D. Richman,[15] T. W. Beck,[16] A. M. Eisner,[16] C. A. Heusch,[16] J. Kroseberg,[16] W. S. Lockman,[16] A. J. Martinez,[16] T. Schalk,[16] B. A. Schumm,[16] A. Seiden,[16] L. O. Winstrom,[16] C. H. Cheng,[17] D. A. Doll,[17] B. Echenard,[17] F. Fang,[17] D. G. Hitlin,[17] I. Narsky,[17] P. Ongmongkolkul,[17] T. Piatenko,[17] F. C. Porter,[17] R. Andreassen,[18] M. S. Dubrovin,[18] G. Mancinelli,[18] B. T. Meadows,[18] K. Mishra,[18] M. D. Sokoloff,[18] P. C. Bloom,[19] W. T. Ford,[19] A. Gaz,[19] J. F. Hirschauer,[19] M. Nagel,[19] U. Nauenberg,[19] J. G. Smith,[19] S. R. Wagner,[19] R. Ayad,[20,†] W. H. Toki,[20] E. Feltresi,[21] A. Hauke,[21] H. Jasper,[21] T. M. Karbach,[21] J. Merkel,[21] A. Petzold,[21] B. Spaan,[21] K. Wacker,[21] M. J. Kobel,[22] K. R. Schubert,[22] R. Schwierz,[22] D. Bernard,[23] E. Latour,[23] M. Verderi,[23] P. J. Clark,[24] S. Playfer,[24] J. E. Watson,[24] M. Andreotti,[25a,25b] D. Bettoni,[25a] C. Bozzi,[25a] R. Calabrese,[25a,25b] A. Cecchi,[25a,25b] G. Cibinetto,[25a,25b] E. Fioravanti,[25a,25b] P. Franchini,[25a,25b] E. Luppi,[25a,25b] M. Munerato,[25a,25b] M. Negrini,[25a,25b] A. Petrella,[25a,25b] L. Piemontese,[25a] V. Santoro,[25a,25b] R. Baldini-Ferroli,[26] A. Calcaterra,[26] R. de Sangro,[26] G. Finocchiaro,[26] S. Pacetti,[26] P. Patteri,[26] I. M. Peruzzi,[26,‡] M. Piccolo,[26] M. Rama,[26] A. Zallo,[26] R. Contri,[27a,27b] E. Guido,[27a,27b] M. Lo Vetere,[27a,27b] M. R. Monge,[27a,27b] S. Passaggio,[27a] C. Patrignani,[27a,27b] E. Robutti,[27a] S. Tosi,[27a,27b] M. Morii,[28] A. Adametz,[29] J. Marks,[29] S. Schenk,[29] U. Uwer,[29] F. U. Bernlochner,[30] H. M. Lacker,[30] T. Lueck,[30] A. Volk,[30] P. D. Dauncey,[31] M. Tibbetts,[31] P. K. Behera,[32] M. J. Charles,[32] U. Mallik,[32] C. Chen,[33] J. Cochran,[33] H. B. Crawley,[33] L. Dong,[33] V. Eyges,[33] W. T. Meyer,[33] S. Prell,[33] E. I. Rosenberg,[33] A. E. Rubin,[33] Y. Y. Gao,[34] A. V. Gritsan,[34] Z. J. Guo,[34] N. Arnaud,[35] M. Davier,[35] D. Derkach,[35] J. Firmino da Costa,[35] G. Grosdidier,[35] F. Le Diberder,[35] V. Lepeltier,[35] A. M. Lutz,[35] B. Malaescu,[35] P. Roudeau,[35] M. H. Schune,[35] J. Serrano,[35] V. Sordini,[35,§] A. Stocchi,[35] G. Wormser,[35] D. J. Lange,[36] D. M. Wright,[36] I. Bingham,[37] J. P. Burke,[37] C. A. Chavez,[37] J. R. Fry,[37] E. Gabathuler,[37] R. Gamet,[37] D. E. Hutchcroft,[37] D. J. Payne,[37] C. Touramanis,[37] A. J. Bevan,[38] C. K. Clarke,[38] F. Di Lodovico,[38] R. Sacco,[38] M. Sigamani,[38] G. Cowan,[39] S. Paramesvaran,[39] A. C. Wren,[39] D. N. Brown,[40] C. L. Davis,[40] A. G. Denig,[41] M. Fritsch,[41] W. Gradl,[41] A. Hafner,[41] K. E. Alwyn,[42] D. Bailey,[42] R. J. Barlow,[42] G. Jackson,[42] G. D. Lafferty,[42] T. J. West,[42] J. I. Yi,[42] J. Anderson,[43] A. Jawahery,[43] D. A. Roberts,[43] G. Simi,[43] J. M. Tuggle,[43] C. Dallapiccola,[44] E. Salvati,[44] R. Cowan,[45] D. Dujmic,[45] P. H. Fisher,[45] S. W. Henderson,[45] G. Sciolla,[45] M. Spitznagel,[45] R. K. Yamamoto,[45] M. Zhao,[45] P. M. Patel,[46] S. H. Robertson,[46] M. Schram,[46] P. Biassoni,[47a,47b] A. Lazzaro,[47a,47b] V. Lombardo,[47a] F. Palombo,[47a,47b] S. Stracka,[47a,47b] L. Cremaldi,[48] R. Godang,[48,‖] R. Kroeger,[48] P. Sonnek,[48] D. J. Summers,[48] H. W. Zhao,[48] X. Nguyen,[49] M. Simard,[49] P. Taras,[49] H. Nicholson,[50] G. De Nardo,[51a,51b] L. Lista,[51a] D. Monorchio,[51a,51b] G. Onorato,[51a,51b] C. Sciacca,[51a,51b] G. Raven,[52] H. L. Snoek,[52] C. P. Jessop,[53] K. J. Knoepfel,[53] J. M. LoSecco,[53] W. F. Wang,[53] L. A. Corwin,[54] K. Honscheid,[54] H. Kagan,[54] R. Kass,[54] J. P. Morris,[54] A. M. Rahimi,[54] S. J. Sekula,[54] N. L. Blount,[55] J. Brau,[55] R. Frey,[55] O. Igonkina,[55] J. A. Kolb,[55] M. Lu,[55] R. Rahmat,[55] N. B. Sinev,[55] D. Strom,[55] J. Strube,[55] E. Torrence,[55] G. Castelli,[56a,56b] N. Gagliardi,[56a,56b] M. Margoni,[56a,56b] M. Morandin,[56a] M. Posocco,[56a] M. Rotondo,[56a] F. Simonetto,[56a,56b] R. Stroili,[56a,56b] C. Voci,[56a,56b] P. del Amo Sanchez,[57] E. Ben-Haim,[57] G. R. Bonneaud,[57] H. Briand,[57] J. Chauveau,[57] O. Hamon,[57] Ph. Leruste,[57] G. Marchiori,[57] J. Ocariz,[57] A. Perez,[57] J. Prendki,[57] S. Sitt,[57] L. Gladney,[58] M. Biasini,[59a,59b] E. Manoni,[59a,59b] C. Angelini,[60a,60b] G. Batignani,[60a,60b] S. Bettarini,[60a,60b] G. Calderini,[60a,60b,¶] M. Carpinelli,[60a,60b,**] A. Cervelli,[60a,60b] F. Forti,[60a,60b] M. A. Giorgi,[60a,60b] A. Lusiani,[60a,60c] M. Morganti,[60a,60b] N. Neri,[60a,60b] E. Paoloni,[60a,60b] G. Rizzo,[60a,60b] J. J. Walsh,[60a] D. Lopes Pegna,[61] C. Lu,[61] J. Olsen,[61] A. J. S. Smith,[61] A. V. Telnov,[61] F. Anulli,[62a] E. Baracchini,[62a,62b] G. Cavoto,[62a] R. Faccini,[62a,62b] F. Ferrarotto,[62a] F. Ferroni,[62a,62b] M. Gaspero,[62a,62b] P. D. Jackson,[62a] L. Li Gioi,[62a] M. A. Mazzoni,[62a] S. Morganti,[62a] G. Piredda,[62a] F. Renga,[62a,62b] C. Voena,[62a] M. Ebert,[63] T. Hartmann,[63] H. Schröder,[63] R. Waldi,[63] T. Adye,[64] B. Franek,[64] E. O. Olaiya,[64] F. F. Wilson,[64] S. Emery,[65] L. Esteve,[65] G. Hamel de Monchenault,[65] W. Kozanecki,[65] G. Vasseur,[65] Ch. Yèche,[65] M. Zito,[65] M. T. Allen,[66] D. Aston,[66] D. J. Bard,[66] R. Bartoldus,[66] J. F. Benitez,[66] R. Cenci,[66] J. P. Coleman,[66] M. R. Convery,[66] J. C. Dingfelder,[66] J. Dorfan,[66] G. P. Dubois-Felsmann,[66]

 © 2010 The American Physical Society

W. Dunwoodie,[66] R. C. Field,[66] M. Franco Sevilla,[66] B. G. Fulsom,[66] A. M. Gabareen,[66] M. T. Graham,[66] P. Grenier,[66] C. Hast,[66] W. R. Innes,[66] J. Kaminski,[66] M. H. Kelsey,[66] H. Kim,[66] P. Kim,[66] M. L. Kocian,[66] D. W. G. S. Leith,[66] S. Li,[66] B. Lindquist,[66] S. Luitz,[66] V. Luth,[66] H. L. Lynch,[66] D. B. MacFarlane,[66] H. Marsiske,[66] R. Messner,[66,*] D. R. Muller,[66] H. Neal,[66] S. Nelson,[66] C. P. O'Grady,[66] I. Ofte,[66] M. Perl,[66] B. N. Ratcliff,[66] A. Roodman,[66] A. A. Salnikov,[66] R. H. Schindler,[66] J. Schwiening,[66] A. Snyder,[66] D. Su,[66] M. K. Sullivan,[66] K. Suzuki,[66] S. K. Swain,[66] J. M. Thompson,[66] J. Va'vra,[66] A. P. Wagner,[66] M. Weaver,[66] C. A. West,[66] W. J. Wisniewski,[66] M. Wittgen,[66] D. H. Wright,[66] H. W. Wulsin,[66] A. K. Yarritu,[66] C. C. Young,[66] V. Ziegler,[66] X. R. Chen,[67] H. Liu,[67] W. Park,[67] M. V. Purohit,[67] R. M. White,[67] J. R. Wilson,[67] M. Bellis,[68] P. R. Burchat,[68] A. J. Edwards,[68] T. S. Miyashita,[68] S. Ahmed,[69] M. S. Alam,[69] J. A. Ernst,[69] B. Pan,[69] M. A. Saeed,[69] S. B. Zain,[69] A. Soffer,[70] S. M. Spanier,[71] B. J. Wogsland,[71] R. Eckmann,[72] J. L. Ritchie,[72] A. M. Ruland,[72] C. J. Schilling,[72] R. F. Schwitters,[72] B. C. Wray,[72] B. W. Drummond,[73] J. M. Izen,[73] X. C. Lou,[73] F. Bianchi,[74a,74b] D. Gamba,[74a,74b] M. Pelliccioni,[74a,74b] M. Bomben,[75a,75b] L. Bosisio,[75a,75b] C. Cartaro,[75a,75b] G. Della Ricca,[75a,75b] L. Lanceri,[75a,75b] L. Vitale,[75a,75b] V. Azzolini,[76] N. Lopez-March,[76] F. Martinez-Vidal,[76] D. A. Milanes,[76] A. Oyanguren,[76] J. Albert,[77] Sw. Banerjee,[77] B. Bhuyan,[77] H. H. F. Choi,[77] K. Hamano,[77] G. J. King,[77] R. Kowalewski,[77] M. J. Lewczuk,[77] I. M. Nugent,[77] J. M. Roney,[77] R. J. Sobie,[77] T. J. Gershon,[78] P. F. Harrison,[78] J. Ilic,[78] T. E. Latham,[78] G. B. Mohanty,[78] E. M. T. Puccio,[78] H. R. Band,[79] X. Chen,[79] S. Dasu,[79] K. T. Flood,[79] Y. Pan,[79] R. Prepost,[79] C. O. Vuosalo,[79] and S. L. Wu[79]

(*BaBar* Collaboration)

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, 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 Los Angeles, Los Angeles, California 90024, USA*
[13]*University of California at Riverside, Riverside, California 92521, USA*
[14]*University of California at San Diego, La Jolla, California 92093, USA*
[15]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[16]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[17]*California Institute of Technology, Pasadena, California 91125, USA*
[18]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[19]*University of Colorado, Boulder, Colorado 80309, USA*
[20]*Colorado State University, Fort Collins, Colorado 80523, USA*
[21]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[22]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[23]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[24]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[25a]*INFN Sezione di Ferrara, I-44100 Ferrara, Italy*
[25b]*Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy*
[26]*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[27a]*INFN Sezione di Genova, I-16146 Genova, Italy*
[27b]*Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy*
[28]*Harvard University, Cambridge, Massachusetts 02138, USA*
[29]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[30]*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany*
[31]*Imperial College London, London, SW7 2AZ, United Kingdom*
[32]*University of Iowa, Iowa City, Iowa 52242, USA*
[33]*Iowa State University, Ames, Iowa 50011-3160, USA*
[34]*Johns Hopkins University, Baltimore, Maryland 21218, USA*

[35]Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 Orsay Cedex, France
[36]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[37]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[38]Queen Mary, University of London, London, E1 4NS, United Kingdom
[39]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[40]University of Louisville, Louisville, Kentucky 40292, USA
[41]Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
[42]University of Manchester, Manchester M13 9PL, United Kingdom
[43]University of Maryland, College Park, Maryland 20742, USA
[44]University of Massachusetts, Amherst, Massachusetts 01003, USA
[45]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[46]McGill University, Montréal, Québec, Canada H3A 2T8
[47a]INFN Sezione di Milano, I-20133 Milano, Italy
[47b]Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
[48]University of Mississippi, University, Mississippi 38677, USA
[49]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
[50]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[51a]INFN Sezione di Napoli, I-80126 Napoli, Italy
[51b]Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
[52]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[53]University of Notre Dame, Notre Dame, Indiana 46556, USA
[54]Ohio State University, Columbus, Ohio 43210, USA
[55]University of Oregon, Eugene, Oregon 97403, USA
[56a]INFN Sezione di Padova, I-35131 Padova, Italy
[56b]Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy
[57]Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
[58]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[59a]INFN Sezione di Perugia, I-06100 Perugia, Italy
[59b]Dipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy
[60a]INFN Sezione di Pisa, I-56127 Pisa, Italy
[60b]Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy
[60c]Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy
[61]Princeton University, Princeton, New Jersey 08544, USA
[62a]INFN Sezione di Roma, I-00185 Roma, Italy
[62b]Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy
[63]Universität Rostock, D-18051 Rostock, Germany
[64]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[65]CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
[66]SLAC National Accelerator Laboratory, Stanford, California 94309 USA
[67]University of South Carolina, Columbia, South Carolina 29208, USA
[68]Stanford University, Stanford, California 94305-4060, USA
[69]State University of New York, Albany, New York 12222, USA
[70]Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
[71]University of Tennessee, Knoxville, Tennessee 37996, USA
[72]University of Texas at Austin, Austin, Texas 78712, USA
[73]University of Texas at Dallas, Richardson, Texas 75083, USA
[74a]INFN Sezione di Torino, I-10125 Torino, Italy
[74b]Dipartimento di Fisica Sperimentale, Università di Torino, I-10125 Torino, Italy
[75a]INFN Sezione di Trieste, I-34127 Trieste, Italy
[75b]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[76]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[77]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[78]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[79]University of Wisconsin, Madison, Wisconsin 53706, USA

(Received 15 June 2010; published 9 November 2010)

We present a study of 649 ± 35 $e^+e^- \to c\bar{c}$ events produced at $\sqrt{s} \approx 10.6$ GeV containing both a Λ_c^+ baryon and a $\bar{\Lambda}_c^-$ antibaryon. The number observed is roughly 4 times that expected if the leading charmed hadron types are uncorrelated, confirming an observation by the CLEO Collaboration. We find a 2-jet topology in these events but very few additional baryons, demonstrating that the primary c and $\bar{c}$ are predominantly contained in a correlated baryon-antibaryon system. In addition to the charmed baryons we observe on average 2.6 ± 0.2 charged intermediate mesons, predominantly pions, carrying 65% of the remaining energy.

DOI: 10.1103/PhysRevD.82.091102 PACS numbers: 13.66.Bc, 13.60.Rj, 13.87.Fh

Baryon production in high-energy jets from e^+e^- annihilations has presented a series of challenges to our understanding of strong interactions. Its observation led to the competing notions of "primary" and "local" baryon correlations [1]. In the former, the e^+ and e^- annihilate into a primary diquark-antidiquark, rather than a quark-antiquark, pair. The diquark and antidiquark then hadronize into jets containing a leading baryon N_1 and a leading antibaryon $\bar{N}_2$, respectively, but no other (anti)baryons. N_1 and $\bar{N}_2$ would then share two quark flavors and typically have high, antiparallel momenta and large values of variables characterizing their separation, such as invariant mass or rapidity difference $|\Delta y|$, where $y \equiv 0.5 \ln[(E + p_\parallel)/(E - p_\parallel)]$, E is the baryon energy, and $p_\parallel$ is the projection of its momentum on the thrust axis. Alternatively, an $N_1\bar{N}_2$ pair might be produced locally, in an individual step of a hadronization cascade, with a smaller value of $|\Delta y|$. Most experimental studies of baryon-antibaryon pairs have shown $|\Delta y|$ distributions that peak at small values [2].

Several mechanisms to describe baryon production and correlations have been implemented in Monte Carlo hadronization models [3]. In the JETSET [4] color-flux-tube model, a tube break can result in a diquark-antidiquark (rather than $q\bar{q}$) pair, producing an $N_1\bar{N}_2$ pair locally. An intermediate meson is introduced between N_1 and $\bar{N}_2$ with some probability (50% by default [5]) to match the measured $|\Delta y|$ distributions. In the HERWIG [6] model, an individual, color-singlet cluster may fragment into a baryon-antibaryon pair but not a multibody state with additional mesons. The model does not reproduce the measured $|\Delta y|$ distributions when tuned to other observables [2]. The UCLA [7] area-law model includes $N_1\bar{N}_2$ pairs with any number of intermediate mesons, and suppresses higher-mass intermediate meson systems by means of a tunable parameter.

Direct evidence of primary production and/or intermediate mesons would be of great interest, but previous searches for the latter using three-particle correlations [8] or baryon flavor correlations [9] were generally inconclusive.

At center-of-mass (c.m.) energies $\sqrt{s}$ much larger than four baryon masses, the assumption of local baryon number conservation implies that an $e^+e^- \to q\bar{q}$ event containing a leading baryon N_1 in the q jet and a leading antibaryon $\bar{N}_2$ in the $\bar{q}$ jet must also contain an antibaryon $\bar{N}_3$ in the q jet and a baryon N_4 in the $\bar{q}$ jet. However, if the $N_1\bar{N}_3N_4\bar{N}_2$ mass is a large fraction of $\sqrt{s}$, these four-baryon events would be suppressed and other processes might be visible—in particular, primary baryon production events with exactly two baryons, one in each jet. At $\sqrt{s} \approx$ 10 GeV, charmed (c) baryons are of particular interest, since any high-momentum c or $\bar{c}$ baryon must be a leading particle in an $e^+e^- \to c\bar{c}$ event, and any $N_{c1}\bar{N}_3N_4\bar{N}_{c2}$ mass exceeds 6.5 GeV$/c^2$. The CLEO Collaboration reported an excess by a factor of 3.5 ± 0.6 [10] in the number of events at $\sqrt{s} = 10.6$ GeV with both a Λ_c^+ and a $\bar{\Lambda}_c^-$, where their expectation is derived assuming local baryon number conservation in the JETSET model and from observed events with a Λ_c^+ and a D^- or $\bar{D}^0$ meson. This excess is evidence that the baryon production is correlated between the c and $\bar{c}$ jets and is consistent with primary baryon production, but does not exclude the possibility of local baryon production with correlation between the jets. The two cases can be distinguished experimentally: local production would require an additional baryon and antibaryon (N_4 and $\bar{N}_3$) in the event, so events with exactly one Λ_c^+, exactly one $\bar{\Lambda}_c^-$, and no additional baryons would imply primary production. CLEO investigated this and did not observe a strong signal for additional protons in the $\Lambda_c^+\bar{\Lambda}_c^-$ candidate events, but due to a limited data sample and the lack of a limit on additional neutrons they were unable to exclude local baryon production.

In this paper we exploit the particle identification capabilities of the *BABAR* detector [11] to select a sample of $\Lambda_c^+\bar{\Lambda}_c^-X$ events in which the Λ_c^+ and $\bar{\Lambda}_c^-$ are produced at high momentum in opposite hemispheres, and study their characteristics in detail. We use 220 fb^{-1} of data collected

*Deceased.

†Now at Temple University, Philadelphia, Pennsylvania 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, Alabama 36688, USA.

¶Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France.

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

at $\sqrt{s} = 10.54$–10.58 GeV. We identify the charged tracks in the X system, looking for additional (anti)protons, and search for higher-mass baryons that could be a source of the $\Lambda_c^+ \bar{\Lambda}_c^- X$ events. We consider charged tracks measured in the silicon vertex tracker (SVT) and drift chamber (DCH), and identified as pions, kaons, or protons using the DCH and the detector of internally reflected Cherenkov light. The identification algorithm used here [12,13] is over 99% efficient for pions and kaons (protons) within the acceptance with momenta between 0.15 and 0.5 (1.2) GeV$/c$, with misidentification rates below 0.5%. At higher momenta it remains over 90% efficient, with misidentification rates generally below 1%.

We construct Λ_c^+ candidates in the $pK^-\pi^+$ and pK_S^0 decay modes and $\bar{\Lambda}_c^-$ in the corresponding charge-conjugate modes. We consider a pair of oppositely charged tracks as a $K_S^0 \to \pi^+\pi^-$ candidate if a vertex fit returns a χ^2 with a confidence level (C.L.) exceeding 0.01, the vertex is displaced by 2.5–60 cm from the interaction point (IP) calculated for each event from the set of well-measured tracks in the SVT, the angle θ_{K_S} between the K_S^0 candidate's momentum and the IP-to-vertex direction satisfies $\cos\theta_{K_S} > 0.97$, and the $\pi^+\pi^-$ invariant mass is in the range 491.8–503.8 MeV$/c^2$. All combinations of a K_S^0 and a well-measured (≥ 15 hits in the DCH and ≥ 5 in the SVT) proton are considered $\Lambda_c^+ \to pK_S^0$ candidates. A combination of well-measured p, K^-, and π^+ tracks is considered a $\Lambda_c^+ \to pK^-\pi^+$ candidate if its vertex fit yields C.L. > 0.001.

We require p^*, the momentum of the Λ_c^+ candidate in the e^+e^- c.m. frame, to exceed 2.3 GeV$/c$, so that the rate of Λ_c^+ from $\Upsilon(4S)$ decays [12,14] is negligible. We select events containing at least one Λ_c^+ candidate and at least one $\bar{\Lambda}_c^-$ candidate, requiring each candidate to have mass within 190 MeV$/c^2$ of the fitted Λ_c^+ peak. We then form $\Lambda_c^+\bar{\Lambda}_c^-$ pairs provided that they have no common tracks in their decay chains. For these 21 000 pairs we show the candidate $pK^-\pi^+$ and pK_S^0 invariant mass distributions in Fig. 1(a). Clear Λ_c^+ signals are visible over modest backgrounds. The peak mass values, rates, and momentum distributions are consistent with previous measurements [12,14,15]. We plot the invariant mass of the $\bar{\Lambda}_c^-$ candidate versus that of the Λ_c^+ candidate in Fig. 1(b). Horizontal and vertical bands are visible, corresponding to events with a real $\bar{\Lambda}_c^-$ or Λ_c^+, respectively, and there is a substantial enhancement where they overlap.

The opening angle θ between the Λ_c^+ and $\bar{\Lambda}_c^-$ momenta in the c.m. frame is sensitive to their production mechanism. We expect $\Lambda_c^+\bar{\Lambda}_c^-$ pairs from gluon splitting ($e^+e^- \to q\bar{q}g \to q\bar{q}c\bar{c}$) or $e^+e^- \to c\bar{c}g$ events with a very hard gluon to have relatively small θ, but also a suppressed selection efficiency due to the p^* requirement. In the 21 000 events selected, θ values are concentrated near 180°, consistent with dominance of 2-jet $e^+e^- \to c\bar{c}$

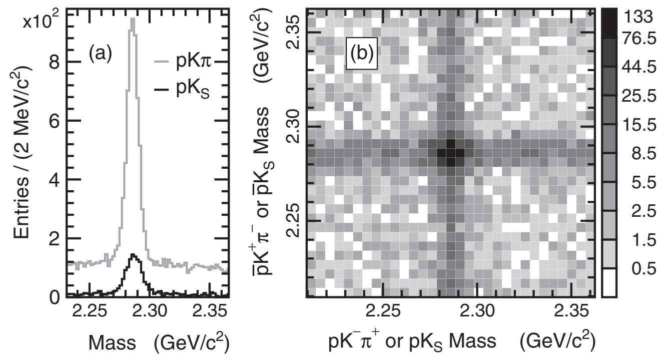

FIG. 1. (a) Invariant mass distributions for the $\Lambda_c^+/\bar{\Lambda}_c^-$ candidates in selected events, reconstructed in the $pK\pi$ (gray) and pK_S^0 (black) decay modes. (b) Invariant mass of the $\bar{\Lambda}_c^-$ candidate vs that of the Λ_c^+ candidate in the same event, in 5 MeV$/c^2$ square bins.

events. Only seven events have $\theta < 90°$, one of which is in the signal region defined below. Since the small-θ background may have different characteristics from that at large θ, we require $\theta > 90°$. This criterion also removes events with a hard initial state photon, the study of which would be interesting with a larger data sample and a different analysis approach, as has been done by Belle [16].

About 3% of the events have two Λ_c^+ (or two $\bar{\Lambda}_c^-$) candidates, due to the two $pK^-\pi^+$ combinations in the decay chains $\Sigma_c^{++} \to \Lambda_c^+(pK^-\pi^+)\pi^+$ and $\Lambda_c^{*+} \to \Lambda_c^+(pK^-\pi^+)\pi^+\pi^-$. We include all combinations in the sample and account for the kinematic overlap through the background subtraction. We define a circular $\Lambda_c^+\bar{\Lambda}_c^- X$ signal region centered at our peak mass values with a radius of 12 MeV$/c^2$, which contains 919 entries. Using the single-$\Lambda_c^+/\bar{\Lambda}_c^-$ bands [13], we estimate an expected background in the signal region of 245 ± 5 events with one real Λ_c^+ or $\bar{\Lambda}_c^-$ and one fake. Using events with both masses at least 40 MeV$/c^2$ from the fitted Λ_c^+ mass, we estimate 25 ± 1 expected background events with fake Λ_c^+ and $\bar{\Lambda}_c^-$, giving a $\Lambda_c^+\bar{\Lambda}_c^- X$ signal of $N_{\Lambda_c^+\bar{\Lambda}_c^-} = 649 \pm 35$ events.

We can calculate an expected number of signal events, $n_{\rm exp}$, under the assumption that the c and $\bar{c}$ hadron types are uncorrelated so that all signal events are four-baryon events. Then $n_{\rm exp} = Cn_1^2/4N_{c\bar{c}}$, where $n_1 = 420\,000$ is the number of single $\Lambda_c^+/\bar{\Lambda}_c^-$ observed in the data, $N_{c\bar{c}} = 3 \times 10^8$ is the number of $e^+e^- \to c\bar{c}$ events expected for our integrated luminosity, and the factor C accounts for the correlation between the Λ_c^+ and $\bar{\Lambda}_c^-$ reconstruction efficiencies. This formulation is independent of the Λ_c^+ branching fractions and average efficiencies. In the simple case where the efficiencies of the Λ_c^+ and $\bar{\Lambda}_c^-$ in $\Lambda_c^+\bar{\Lambda}_c^- X$ events are uncorrelated, no correction is needed ($C = 1$) and $n_{\rm exp} = n_1^2/4N_{c\bar{c}}$. More generally, $0 < C < 1/\varepsilon$ for an average acceptance times efficiency of ε: in the extreme case of maximal correlation $C = 1/\varepsilon$, and in the extreme case of maximal anticorrelation $n_{\rm exp} = C = 0$. At BABAR there might be correlations because of the asymmetric beam energies and detector layout. We evaluate this correction using the JETSET, HERWIG, and UCLA models, adjusting their charm fragmentation parameters and reweighting the resulting p^* distributions to reproduce our measured distribution for inclusive Λ_c^+ [12]. Combined with smooth parametrizations of our efficiencies as functions of momentum and polar angle, the models give values of C ranging from 0.63 to 1.65, with a mean of 1.05. Even allowing for the large model dependence, the full range of $n_{\rm exp} =$ 100–250 events is well below the observed 649 ± 35, confirming the enhanced rate $N_{\Lambda_c^+\bar{\Lambda}_c^-}/n_{\rm exp} \approx 4$ reported by the CLEO Collaboration [10].

We investigate the structure of the $\Lambda_c^+\bar{\Lambda}_c^- X$ events using the Λ_c^+ and $\bar{\Lambda}_c^-$ candidates along with additional charged tracks that have at least ten points measured in the DCH, five in the SVT, and extrapolate within 5 mm of the beam axis. We subtract appropriately scaled distributions in the background regions from those in the signal region to obtain distributions for $\Lambda_c^+\bar{\Lambda}_c^- X$ events. Figure 2(a) shows the distribution of the number of additional tracks, as well as the numbers of identified $K^\pm$ and $p/\bar{p}$ among them. Were each c baryon compensated by a light antibaryon, then—assuming that half the antibaryons have an antiproton in the final state and accounting for $p/\bar{p}$ detection efficiency—we would expect 45% of these events to contain one identified $p/\bar{p}$ and another 20% to contain both an identified p and a $\bar{p}$; we observe only 3.4% and 0.6%, respectively. Figure 2(b) shows the distribution of missing mass, calculated from the four-momenta of the initial e^+ and e^-, the reconstructed Λ_c^+ and $\bar{\Lambda}_c^-$, and all additional tracks interpreted as pions. A typical $N_{c1}\bar{n}Xn\bar{N}_{c2}$ event, containing both a neutron and an antineutron, would have a missing mass well in excess of 2 GeV/c^2.

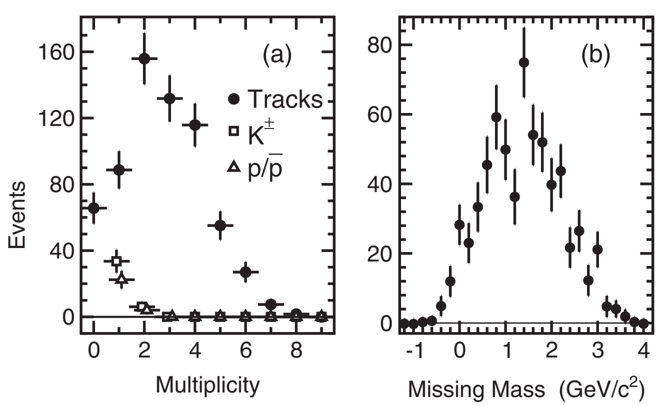

FIG. 2. Background-subtracted distributions for the 649 $\Lambda_c^+\bar{\Lambda}_c^- X$ events in the data: (a) the numbers of additional tracks, identified $K^\pm$ and identified $p/\bar{p}$; and (b) missing mass, with imaginary masses given negative real values. Most events have no identified $K^\pm$ or $p/\bar{p}$ and the corresponding zero-multiplicity points are off the vertical scale in (a).

The distributions in Fig. 2 indicate that the majority of the $\Lambda_c^+\bar{\Lambda}_c^- X$ events do not contain additional baryons, and therefore that the conservation of baryon number is realized with the primary c and $\bar{c}$ hadrons. In the background-subtracted sample of 649 ± 35 $\Lambda_c^+\bar{\Lambda}_c^- X$ signal events, there are 28 ± 6 additional identified $p/\bar{p}$ candidates. These $p/\bar{p}$ candidates include background from two main sources: interactions in the detector material and misidentified pions or kaons. We expect five protons from material interactions. We also expect about 12 pions or kaons misidentified as protons, based on the numbers and momenta of the observed additional $\pi^\pm$ and $K^\pm$ tracks. In cross-checks these expectations are found to be consistent with the data within uncertainties: there are 8 ± 4 more identified p than $\bar{p}$ (with the excess attributed to material interactions), and there are 7 ± 3 events seen with exactly one additional identified $p/\bar{p}$ and an event missing mass below 750 MeV/c^2 (inconsistent with a missing second baryon, and so attributed to a misidentified kaon or pion). Subtracting the expected contributions from these two background sources, correcting for efficiency, and assuming equal p and n production rates, we estimate that we observe 13 ± 8 true four-baryon events. This is well below the rate of 100 to 250 four-baryon events expected for uncorrelated production, let alone the observed rate of 649 ± 35 events, indicating that the four-baryon process is strongly suppressed and that the primary production process dominates.

None of the reconstructed events is consistent with the two-body process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$. However, the signal could arise from the pair production of c baryons if one or both are excited states that decay to $\Lambda_c^+/\bar{\Lambda}_c^-$: $e^+e^- \to N_{c1}\bar{N}_{c2} \to \Lambda_c^+\bar{\Lambda}_c^- X$. Combining $\Lambda_c^+/\bar{\Lambda}_c^-$ candidates with one or two additional tracks assigned the pion mass hypothesis gives the invariant mass distributions in Fig. 3. The points represent sideband-subtracted signal events and the histograms the single-$\Lambda_c^+/\bar{\Lambda}_c^-$ sidebands with entries reweighted to reproduce the number of the $\Lambda_c^+/\bar{\Lambda}_c^-$ in signal events and their momentum and polar angle distributions in the lab frame. Peaks are visible in the sideband data for the $\Sigma_c^{++/0}(2455)$, $\Sigma_c^{++/0}(2520)$, and the excited Λ_c^+ states at 2593, 2625, 2765, and 2880 MeV/c^2. We find no unexpected peaks in our $\Lambda_c^+\pi(\pi)$, Λ_c^+K, or $\Lambda_c^+\bar{p}$ mass distributions. The points are consistent with the histograms, indicating similar c baryon compositions in the two event types. Only two events are kinematically consistent with $e^+e^- \to N_{c1}\bar{N}_{c2}$ for these known N_c. Distributions of θ and the decay angles in the $\Lambda_c^+\pi$ rest frames are consistent with multihadron events, and not with very heavy states decaying into a Λ_c^+ and more than two pions. We conclude that $e^+e^- \to N_{c1}\bar{N}_{c2}$ processes represent a small fraction of our sample. From the fits in Fig. 3, we estimate that $35 \pm 3\%$ of the Λ_c^+ and $29 \pm 2\%$ of the additional pions in our sample are decay products of heavier c baryons.

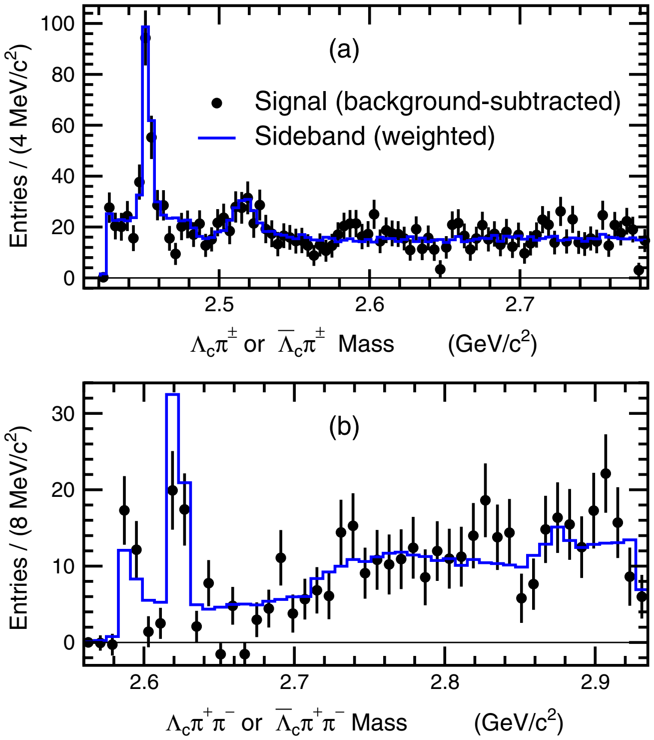

FIG. 3 (color online). Invariant mass distributions for (a) $\Lambda_c^+\pi^\pm$ and $\bar{\Lambda}_c^-\pi^\pm$ and (b) $\Lambda_c^+/\bar{\Lambda}_c^-\pi^+\pi^-$ combinations. The points with errors represent the background-subtracted $\Lambda_c^+\bar{\Lambda}_c^-X$ events, and the weighted histograms are from the single-$\Lambda_c^+/\bar{\Lambda}_c^-$ sidebands.

Having established the presence of a category of events containing a c baryon, a $\bar{c}$ baryon, no other (anti)baryons, and several intermediate mesons, we study the number and structure of these mesons. We exclude events with an identified $p/\bar{p}$ or a missing mass squared below $-0.25\ \mathrm{GeV}^2/c^4$. We estimate that the sample contains a further 5 ± 5 four-baryon events in which no $p/\bar{p}$ is detected; we take these to have the same distributions as the events with an identified $p/\bar{p}$ and subtract an appropriately scaled contribution to correct for them. In this sample of 619 ± 35 events, we study a number of quantities including the $\Lambda_c^+/\bar{\Lambda}_c^-$ and additional track momenta, polar angles, rapidities, and opening angles. Their inclusive distributions are quite similar to those in the single-$\Lambda_c^+/\bar{\Lambda}_c^-$ sample and similar to those in all hadronic events. In particular, signing the thrust axis such that the Λ_c^+ rapidity is positive, the Λ_c^+ and $\bar{\Lambda}_c^-$ rapidities cluster near $+1.1$ and -1.1 units, respectively, with the additional tracks of each charge distributed broadly and symmetrically in between.

These 619 events contain only 45 ± 10 identified $K^\pm$ of which about 20 are expected to be misidentified pions. The events show no mass peak for K_S^0 candidates reconstructed from pairs of tracks not included in the Λ_c^+ or $\bar{\Lambda}_c^-$ (including tracks that do not extrapolate within 5 mm of the beam axis). The K:π ratio is thus much lower than the value 0.3 typical of hadronic events, which might be due to the limited energy available and the fact that our c baryons are nonstrange (the lighter c-s baryons do not decay into Λ_c^+). The $\pi^+\pi^-$, $K^\pm\pi^\mp$, and K^+K^- invariant mass distributions show no significant resonant structure; in particular, there is no evidence for the ρ^0. This implies a vector:pseudoscalar meson ratio much lower than the value near one typical of hadronic events, and suggests that most tracks not from c baryon decays represent distinct intermediate mesons.

The intermediate meson multiplicity is distributed broadly. We verify that the contribution from decays of heavier c baryons is not concentrated in any particular region in Fig. 2(a), but due to the limited sample size we do not attempt to correct the distribution. We observe an average of 2.7 additional charged tracks per event. Correcting for c baryon decays and tracking efficiency gives 2.6 ± 0.2 charged intermediate mesons per event, where the uncertainty includes both statistical and systematic effects. The uncertainty is dominated by the track acceptance in these events, evaluated with a set of simulations based on the observed $\pi^\pm$ and $K^\pm$ distributions. On average, the c and $\bar{c}$ baryons carry 75% of the event energy, and the intermediate charged mesons account for about 65% of the remainder. This and the broad distribution of missing masses in Fig. 2(b) suggest the presence of additional neutral mesons. If intermediate π^0 are produced at half the $\pi^\pm$ rate, as in typical hadronic events, the average intermediate meson multiplicity would be 3.9 ± 0.3.

The new type of event observed in our data might be explained by either primary diquark-antidiquark production or the production of multiple intermediate mesons between a baryon and antibaryon. Neither the JETSET nor the HERWIG model produces events of the type observed, although both might be adapted to include one or both of the above processes. JETSET does produce $N_{c1}M\bar{N}_{c2}$ events, where M is a single meson, often a vector decaying into two or three pions, but the event characteristics are far from consistent with the data. Multiple intermediate meson processes occur naturally in the UCLA model, which also predicts an enhanced $\Lambda_c^+\bar{\Lambda}_c^-X$ fraction due to events of this type, with suppressions of kaons and vector mesons. The version of the UCLA model used does not describe the observed events in detail, having an average of only 1.8 intermediate mesons with a distribution peaked at low values, but the results presented here should encourage development of this and other relevant models.

In summary, we isolate a sample of 649 ± 35 $e^+e^- \to c\bar{c}$ events containing both a Λ_c^+ and a $\bar{\Lambda}_c^-$ with high momentum in opposite hemispheres, and study these events in detail. The number of events is estimated to be about 4 times that expected if the leading c and $\bar{c}$ hadron types are uncorrelated, confirming an observation by the CLEO Collaboration. Taking advantage of the particle identification capabilities of the *BABAR* detector and the large data sample, we are further able to establish that almost all of these events contain no additional baryons. They do contain 2.6 ± 0.2 additional charged intermediate mesons on average, and events with zero additional mesons do not contribute significantly. Our event sample exhibits distributions of momentum, angle, rapidity, and c baryon type similar to those in typical hadronic events, but contains fewer kaons and vector mesons. This is direct evidence for a new class of multihadron events, in which baryon number is conserved by a leading baryon and antibaryon, rather than locally along the hadronization chain.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

[1] See, e.g., P. Oddone, in Proceedings of the 12th SLAC Summer Institute on Particle Physics: The Sixth Quark (SSI 84), Stanford, California, 1984, edited by A. Mosher (SLAC-R-281), p. 442.

[2] M. Althoff *et al.* (TASSO Collaboration), Phys. Lett. **139B**, 126 (1984); H. Aihara *et al.* (TPC Collaboration), Phys. Rev. Lett. **57**, 3140 (1986); D. Buskulic *et al.* (ALEPH Collaboration), Z. Phys. C **64**, 361 (1994); P. Abreu *et al.* (DELPHI Collaboration), Phys. Lett. B **416**, 247 (1998); G. Abbiendi *et al.* (OPAL Collaboration), Eur. Phys. J. C **13**, 185 (2000).

[3] We use default parameter values for all models unless otherwise noted.

[4] In PYTHIA v. 6.22, T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[5] B. Andersson, Cambridge Monogr. Part. Phys., Nucl. Phys., Cosmol. **7**, 1 (1997).

[6] G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).

[7] S. Chun and C. Buchanan, Phys. Rep. **292**, 239 (1998); S. Abachi *et al.*, Eur. Phys. J. C **49**, 569 (2007).

[8] P. Abreu *et al.* (DELPHI Collaboration), Phys. Lett. B **318**, 249 (1993).

[9] P. D. Acton *et al.* (OPAL Collaboration), Phys. Lett. B **305**, 415 (1993); P. Abreu *et al.* (DELPHI Collaboration), Phys. Lett. B **490**, 61 (2000); G. Abbiendi *et al.* (OPAL Collaboration), Eur. Phys. J. C **64**, 609 (2009).

[10] A. Bornheim *et al.* (CLEO Collaboration), Phys. Rev. D **63**, 112003 (2001).

[11] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).

[12] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **75**, 012003 (2007).

[13] B. L. Hartfiel, Ph.D. thesis, University of California-Los Angeles, 2005; SLAC-R-823 (unpublished).

[14] R. Seuster *et al.* (Belle Collaboration), Phys. Rev. D **73**, 032002 (2006).

[15] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **72**, 052006 (2005).

[16] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. Lett. **101**, 172001 (2008).