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Measurements of Λ_c^+ Branching Fractions of Cabibbo-Suppressed Decay Modes.

The *BABAR* Collaboration

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Abstract

We have measured the branching fractions of the Cabibbo-suppressed decays $\Lambda_c^+ \to \Lambda^0 K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$ relative to the Cabibbo-allowed decay modes $\Lambda_c^+ \to \Lambda^0 \pi^+$ and $\Lambda_c^+ \to \Sigma^0 \pi^+$ to be 0.044 ± 0.004 (stat.) $\pm$ 0.002 (syst.) and 0.040 ± 0.005 (stat.) $\pm$ 0.004 (syst.), respectively. We also present the first observation of $\Lambda_c^+ \to \Lambda^0 K^+ \pi^+ \pi^-$ and have measured the branching fraction relative to $\Lambda_c^+ \to \Lambda^0 \pi^+$ to be 0.266 ± 0.027 (stat.) $\pm$ 0.032 (syst.). The upper limit of the branching fraction into the decay $\Lambda_c^+ \to \Sigma^0 K^+ \pi^+ \pi^-$ relative to $\Lambda_c^+ \to \Sigma^0 \pi^+$ has been measured to be $< 3.9 \times 10^{-2}$ at the 90% confidence level. This analysis was performed using a data sample of 125 fb^{-1} (integrated luminosity) collected by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at the Stanford Linear Accelerator Center. All results presented in this conference contribution are preliminary.

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

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The *BABAR* Collaboration,

B. Aubert, R. Barate, D. Boutigny, F. Couderc, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, V. Tisserand, A. Zghiche

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

A. Palano, A. Pompili

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

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

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

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

G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, V. G. Shelkov, W. A. Wenzel

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

M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson

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

M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, M. Steinke

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

J. T. Boyd, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. E. Latham, F. F. Wilson

University of Bristol, Bristol BS8 1TL, United Kingdom

T. Cuhadar-Donszelmann, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna, D. Thiessen

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

A. Khan, P. Kyberd, L. Teodorescu

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

A. E. Blinov, V. E. Blinov, V. P. Druzhinin, V. B. Golubev, V. N. Ivanchenko, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. Best, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

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

C. Buchanan, B. L. Hartfiel

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

S. D. Foulkes, J. W. Gary, B. C. Shen, K. Wang

University of California at Riverside, Riverside, CA 92521, USA

D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, Sh. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, CA 92093, USA

J. W. Berryhill, C. Campagnari, B. Dahmes, O. Long, A. Lu, M. A. Mazur, J. D. Richman, W. Verkerke
University of California at Santa Barbara, Santa Barbara, CA 93106, USA

T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel, S. Yang
California Institute of Technology, Pasadena, CA 91125, USA

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

T. Abe, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. G. Smith, J. Zhang, L. Zhang
University of Colorado, Boulder, CO 80309, USA

A. Chen, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng
Colorado State University, Fort Collins, CO 80523, USA

D. Altenburg, T. Brandt, J. Brose, M. Dickopp, E. Feltresi, A. Hauke, H. M. Lacker, R. Müller-Pfefferkorn, R. Nogowski, S. Otto, A. Petzold, J. Schubert, K. R. Schubert, R. Schwierz, B. Spaan, J. E. Sundermann
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, F. Brochard, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi
Ecole Polytechnique, LLR, F-91128 Palaiseau, France

D. J. Bard, P. J. Clark, D. Lavin, F. Muheim, S. Playfer, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese, A. Sarti
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

E. Treadwell
Florida A&M University, Tallahassee, FL 32307, USA

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

A. Buzzo, R. Capra, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi
Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Morii, E. Won
Harvard University, Cambridge, MA 02138, USA

R. S. Dubitzky, U. Langenegger
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor
Imperial College London, London, SW7 2AZ, United Kingdom

M. J. Charles, G. J. Grenier, U. Mallik
University of Iowa, Iowa City, IA 52242, USA

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

M. Biasini, R. Covarelli, M. Pioppi
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

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

C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

A. J. Bevan, C. A. Chavez, J. P. Coleman, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, R. J. Parry, D. J. Payne, R. J. Sloane, C. Touramanis
University of Liverpool, Liverpool L69 72E, United Kingdom

J. J. Back,[1] C. M. Cormack, P. F. Harrison,[1] F. Di Lodovico, G. B. Mohanty[1]
Queen Mary, University of London, E1 4NS, United Kingdom

C. L. Brown, G. Cowan, R. L. Flack, H. U. Flaecher, M. G. Green, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, M. A. Winter
University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

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

J. Allison, N. R. Barlow, R. J. Barlow, P. A. Hart, M. C. Hodgkinson, G. D. Lafferty, A. J. Lyon, J. C. Williams
University of Manchester, Manchester M13 9PL, United Kingdom

A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, V. Lillard, D. A. Roberts
University of Maryland, College Park, MD 20742, USA

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

---

[1] Now at Department of Physics, University of Warwick, Coventry, United Kingdom

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

D. J. J. Mangeol, P. M. Patel, S. H. Robertson
McGill University, Montréal, QC, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

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

S. Brunet, D. Côté, P. Taras
Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7

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

N. Cavallo,[2] F. Fabozzi,[2] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

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

T. Allmendinger, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong
Ohio State University, Columbus, OH 43210, USA

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

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

M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, M. J. J. John, Ph. Leruste, J. Malcles, J. Ocariz, M. Pivk, L. Roos, S. T'Jampens, G. Therin
Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France

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

---

[2] Also with Università della Basilicata, Potenza, Italy

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

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F. Bucci, G. Calderini, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal,[3] M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

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

N. Danielson, P. Elmer, Y. P. Lau, C. Lu, V. Miftakov, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, NJ 08544, USA

F. Bellini, G. Cavoto,[4] R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, M. Pierini, G. Piredda, F. Safai Tehrani, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

S. Christ, G. Wagner, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, N. I. Geddes, G. P. Gopal, E. O. Olaiya
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, P.-F. Giraud, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. W. London, B. Mayer, G. Schott, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

M. V. Purohit, A. W. Weidemann, J. R. Wilson, F. X. Yumiceva
University of South Carolina, Columbia, SC 29208, USA

D. Aston, R. Bartoldus, N. Berger, A. M. Boyarski, O. L. Buchmueller, R. Claus, M. R. Convery, M. Cristinziani, G. De Nardo, D. Dong, J. Dorfan, D. Dujmic, W. Dunwoodie, E. E. Elsen, S. Fan, R. C. Field, T. Glanzman, S. J. Gowdy, T. Hadig, V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, M. L. Kocian, D. W. G. S. Leith, J. Libby, S. Luitz, V. Luth, H. L. Lynch, H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, S. Petrak, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, G. Simi, A. Snyder, A. Soha, J. Stelzer, D. Su, M. K. Sullivan, J. Va'vra, S. R. Wagner, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, C. C. Young
Stanford Linear Accelerator Center, Stanford, CA 94309, USA

P. R. Burchat, A. J. Edwards, T. I. Meyer, B. A. Petersen, C. Roat
Stanford University, Stanford, CA 94305-4060, USA

S. Ahmed, M. S. Alam, J. A. Ernst, M. A. Saeed, M. Saleem, F. R. Wappler
State University of New York, Albany, NY 12222, USA

---

[3] Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain

[4] Also with Princeton University, Princeton, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier
University of Tennessee, Knoxville, TN 37996, USA

R. Eckmann, H. Kim, J. L. Ritchie, A. Satpathy, R. F. Schwitters
University of Texas at Austin, Austin, TX 78712, USA

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

F. Bianchi, M. Bona, F. Gallo, D. Gamba
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, S. Grancagnolo, L. Lanceri, P. Poropat,[5]
L. Vitale, G. Vuagnin
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

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

Sw. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, M. Graham, J. J. Hollar, J. R. Johnson,
P. E. Kutter, H. Li, R. Liu, A. Mihalyi, A. K. Mohapatra, Y. Pan, R. Prepost, P. Tan, J. H. von
Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu
University of Wisconsin, Madison, WI 53706, USA

M. G. Greene, H. Neal
Yale University, New Haven, CT 06511, USA

---

[5] Deceased

1 INTRODUCTION

Beginning with the first observation of the charmed baryon Λ_c^+ in 1979 by MARK-II and BNL [1, 2], our knowledge of the physics of charmed baryons developed less rapidly than that of the charmed mesons. This is due to the smaller baryon production cross section, shorter life time, and, in e^+e^- storage rings, the absence of a cleanly observable $\Lambda_c\ \bar{\Lambda}_c$ resonance. During the last few years there has been significant progress in the experimental study of the hadronic decays of charmed baryons. Recent results on masses, widths, lifetimes, production rates and the decay asymmetry parameters have been published by different experiments; among them the discoveries of Cabibbo-suppressed decays $\Lambda_c^+ \to p\phi$ by CLEO [3], and $\Lambda_c^+ \to \Lambda^0 K^+$, $\Lambda_c^+ \to \Sigma^0 K^+$ by Belle [4].

The precision in the measurements of branching fractions is only about 40% for many Cabibbo-favored modes [5], while for Cabibbo-suppressed decays the precision is even worse. As a consequence, we are not yet able to distinguish between the decay rate predictions made by different models, e.g., the quark model approach to non-leptonic charm decays and the Heavy Quark Effective Theory(HQET) [6, 7, 8].

In this paper we present a study of Λ_c^+ baryons produced in the $e^+e^- \to q\overline{q}$ continuum at *BABAR*. We present improved measurements of the Cabibbo-suppressed decays $\Lambda_c^+ \to \Lambda^0 K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$, report the first observation of $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$, and set an upper limit on $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$. Here and throughout this paper, inclusion of charge-conjugate states is implied.

2 THE *BABAR* DETECTOR AND DATASET

The data sample used in this analysis consists of 125 fb^{-1} integrated luminosity recorded between October 1999 and June 2003 with the *BABAR* detector at the SLAC PEP-II storage ring. The PEP-II facility operates nominally at the $\Upsilon(4S)$ resonance, providing collisions of 9.0 GeV electrons on 3.1 GeV positrons. The data set includes 112 fb^{-1} collected at the $\Upsilon(4S)$ ("on-resonance") and 13 fb^{-1} collected below the $B\bar{B}$ threshold ("off-resonance").

A detailed description of the *BABAR* detector can be found elsewhere [9]; only detector components most relevant to this analysis are mentioned here. Charged-particle trajectories are measured by a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), operating in the field of a 1.5-T solenoid. Charged particles are identified by combining measurements of ionization energy loss (dE/dx) in the DCH and SVT with angular information from a detector of internally reflected Cherenkov light (DIRC). Photons are identified as isolated electromagnetic showers in a CsI(Tl) electromagnetic calorimeter.

We have used Monte Carlo simulations (MC) of the *BABAR* detector based on GEANT4 [10] to optimize our selection criteria and to determine signal efficiencies. These simulations take into account the varying detector conditions and beam backgrounds during the data-taking period.

3 ANALYSIS METHOD

For this analysis, the particle identification is important. A track is identified as a kaon, pion, or proton if it is projected to pass through the fiducial volume of the DIRC and the reconstructed cone of Cerenkov light is consistent in time and angle with the measured track momentum. This information is augmented with dE/dx measured with the SVT and DCH. Photons are detected in the CsI calorimeter.

Candidates for Λ^0 are reconstructed in the decay mode $\Lambda^0 \to p\pi^-$. We fitted the p and π^- tracks to a common vertex and required the probability of χ^2 of vertex fit to be greater than 0.1 %. We also required the (three-dimensional) flight distance of each Λ^0 candidate between its decay vertex and the primary vertex to be greater than 0.2 cm. We fitted the invariant mass of Λ^0 candidates, with a double-Gaussian function of common mean to represent the signal and a second-order polynomial to represent the background. This fit is shown in Fig. 1. The fitted resolution is $\sigma = \sigma_{\rm RMS} = 1.5$ MeV/c^2, where $\sigma_{\rm RMS}$ is defined by

$$\sigma^2_{\rm RMS} \equiv f_1\sigma_1^2 + f_2\sigma_2^2,$$

where f_1 and f_2 are fractions of signal yield corresponding to Gaussian functions one and two, respectively, and σ_1 and σ_2 are the two corresponding widths. We required the mass of Λ^0 candidates to be in the range 1113 MeV/c^2 $< M_{\Lambda^0} <$ 1119 MeV/c^2. The Σ^0 candidates were reconstructed in the decay mode $\Sigma^0 \to \Lambda^0\gamma$ using the Λ^0 sample and photons with a calorimeter cluster energy greater than 0.1 GeV. The mass difference($M_{\Lambda^0\gamma} - M_{\Lambda^0}$) is shown in Fig. 2. Fitting with two Gaussian functions of common mean for the signal contribution, and with a third-order polynomial for background, we obtained a resolution $\sigma = \sigma_{\rm RMS} = 4.0$ MeV/c^2 and a mean (difference between the invariant masses) of 767 ± 1 MeV/c^2. We accept candidates with $M_{\Lambda^0\gamma} - M_{\Lambda^0}$ within ± 10.0 MeV/c^2. (2.5 σ) of the measured mean value.

To suppress combinatorial and $B\bar{B}$ backgrounds, we required Λ_c^+ candidates to have scaled momentum $x_p = p^*/p^*_{\rm max} > 0.5$; here p^* is the reconstructed momentum of the Λ_c^+ candidate in the e^+e^- center of mass, $p^*_{\rm max} = \sqrt{s/4 - M^2}$, $\sqrt{s}$ is the total center of mass energy and M is the reconstructed mass of the Λ_c^+ candidate. The signal detection efficiency is obtained from MC with particle identification efficiency corrections based on data.

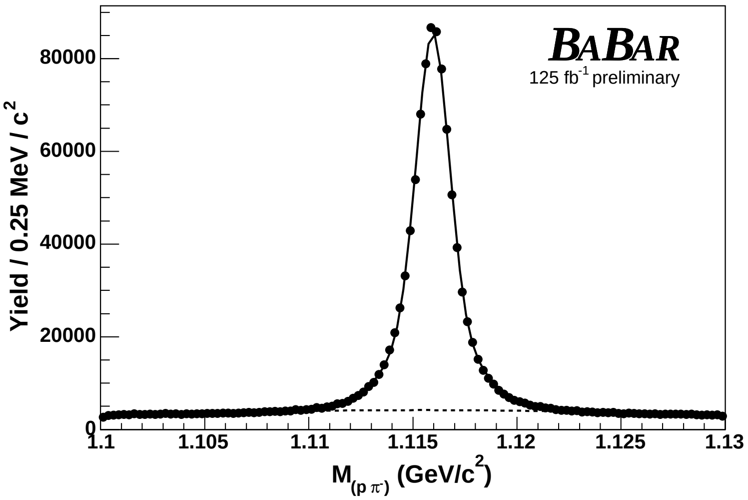

Figure 1: The invariant mass of $p\pi$ combinations (GeV/c^2).

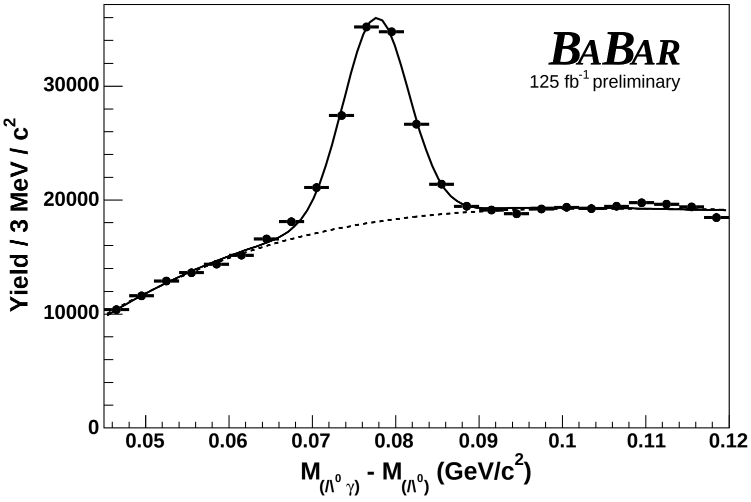

Figure 2: The invariant mass difference between $\Lambda^0\gamma$ combinations and Λ^0 candidates (GeV/c^2).

4 PHYSICS RESULTS

4.1 Measurement of the decays $\Lambda_c^+ \to \Lambda^0 K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$

The Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda^0 K^+$ was first measured by the Belle Collaboration [4].

For our analysis, the Λ^0 and K^+ were combined to form Λ_c^+ as described in Sec. 3. Invariant mass distribution of $\Lambda^0 K^+$ combinations is shown in Fig. 3. The mass distribution was fitted with a Gaussian function for the signal, and a second-order polynomial for combinatorial background. We obtain a raw yield of 1164 ± 107 (stat.) events, with a 10.9 standard deviations significance and with fitted width $\sigma = 5.5 \pm 0.7$ MeV/c^2, consistent with the MC prediction of 6.0 MeV/c^2.

For normalization, we used the decay $\Lambda_c^+ \to \Lambda^0\pi^+$. The invariant mass distribution of $\Lambda^0\pi^+$ combinations is shown in Fig. 4. At mass values below the peak centered at the Λ_c^+ mass a broad distribution at 2.2 GeV/c^2 is visible which is a reflection due to $\Lambda_c^+ \to \Sigma^0\pi^+$ with a missing γ. Additionally, at 2.3 GeV/c^2 we see a shoulder, the upper edge of a Ξ_c reflection whose full shape extends through the entire Λ_c^+ signal region. The distribution was fitted using two Gaussian functions with same mean for signal, a square wave function for each reflection, and a 7th-order polynomial for combinatorial background. We obtained the width $\sigma = 8.2$ MeV/c^2, which is consistent with the experimental resolution of about 8.0 MeV/c^2, and a raw yield of 33594 ± 367 (stat.) events. We calculate the ratio $\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+)/\mathcal{B}(\Lambda_c^+ \to \Lambda^0\pi^+)$ in on-resonance and off-resonance data. The results are comparable within uncertainties, so off-resonance data is combined with on-resonance data. Using signal MC, the relative signal reconstruction efficiency is found to be $\epsilon(\Lambda_c^+ \to \Lambda^0 K^+)$ / $\epsilon(\Lambda_c^+ \to \Lambda^0\pi^+) = 0.781 \pm 0.004$ (stat.). With this value we calculate:

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda^0\pi^+)} = 0.044 \ \pm\ 0.004\ (\text{stat.})\ \pm\ 0.002\ (\text{syst.})\ .$$

We provide a detailed description of the sources of systematic uncertainty for this and other measured decay modes in Sec. 5.

The Cabibbo-suppressed decay $\Lambda_c^+ \to \Sigma^0 K^+$ was first measured by the Belle collaboration [4],

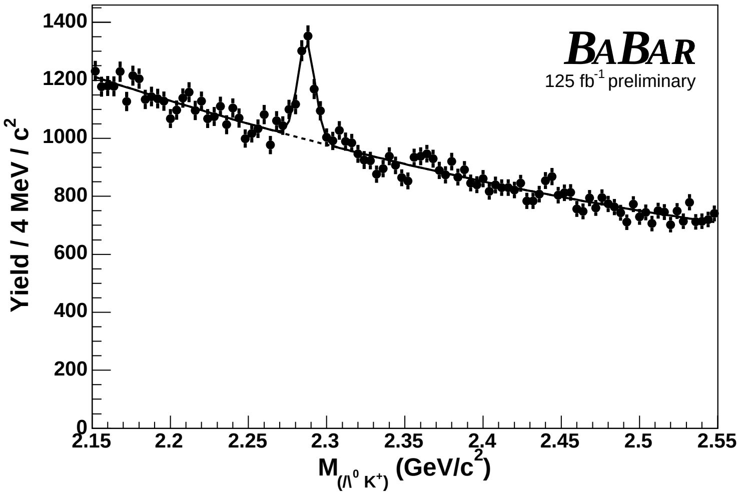

Figure 3: The invariant mass of $\Lambda^0 K^+$ combinations (GeV/c^2).

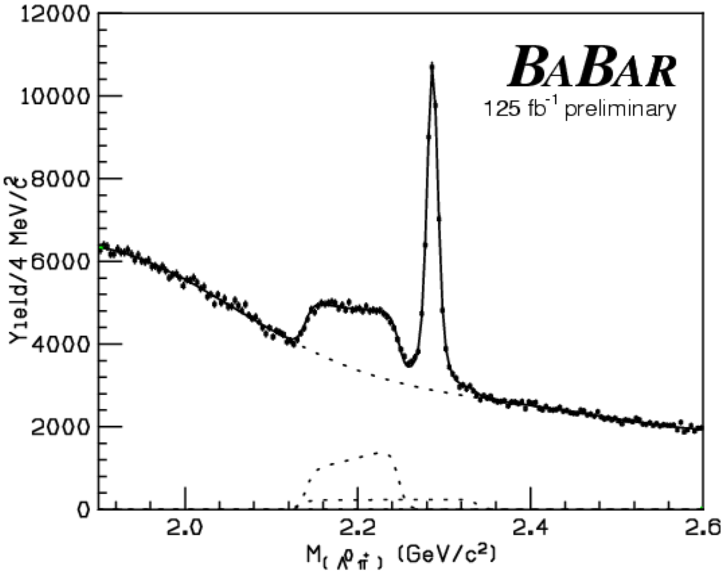

Figure 4: The invariant mass of $\Lambda^0\pi^+$ combinations (GeV/c^2).

under the restriction of the scaled momentum to the region $x_p > 0.6$. For our analysis, we combined a Σ^0 and a K^+ candidate to form Λ_c^+, requiring $x_p > 0.5$ as before. The invariant mass of $\Sigma^0 K^+$ combinations is shown in Fig. 5. We improved the invariant mass resolution by plotting the corrected mass e.g., $M_{\Sigma^0 K^+} - M_{\Sigma^0} + M_{\Sigma^0}^{PDG}$, instead of $M_{\Sigma^0 K^+}$ where M_{Σ^0} is the reconstructed mass of Σ^0 and $M_{\Sigma^0}^{PDG}$ is the mass of Σ^0 from PDG [5]. We fit the distribution using a Gaussian function with a fixed width $\sigma = 6.0$ MeV/c^2 (as determined from MC simulations) for signal and a third-order polynomial for combinatorial backgrounds. The fit yields 387 ± 48 (stat.) events with a 8.1σ statistical significance for Λ_c^+ baryons having decayed to $\Sigma^0 K^+$. For normalization, we use the Cabibbo-allowed decay mode $\Lambda_c^+ \to \Sigma^0\pi^+$. The invariant mass of $\Sigma^0\pi^+$ combinations is shown in Fig. 6. The fit uses a Gaussian function for the signal and a third-order polynomial for background. The measured width $\sigma = 6.7 \pm 0.1$ MeV/c^2, which is consistent with the MC prediction of $\sigma = 7.0$ MeV/c^2. The fitted yield is 12450 ± 170 (stat.) events. The relative reconstruction efficiency is measured to be $\epsilon(\Lambda_c^+ \to \Sigma^0 K^+)$ / $\epsilon(\Lambda_c^+ \to \Sigma^0\pi^+) = 0.780 \pm 0.001$ (stat.) using signal MC. The resulting relative branching ratio is

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)} = 0.040 \pm 0.005\ \text{(stat.)} \pm 0.004\ \text{(syst.)}\ .$$

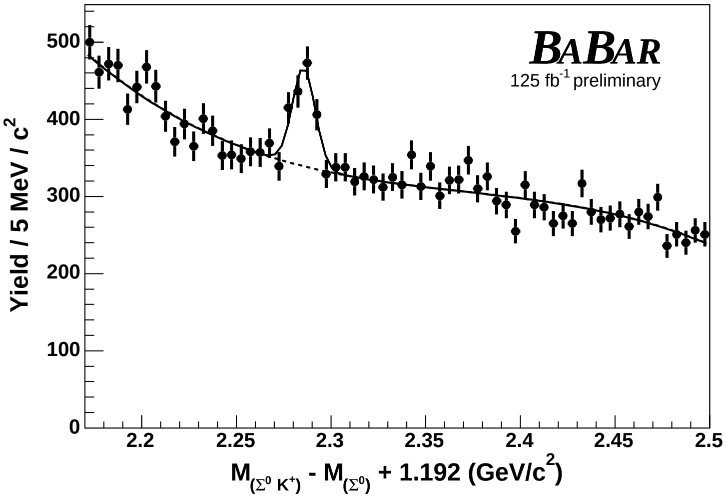

Figure 5: The invariant mass of $\Sigma^0 K^+$ combinations (GeV/c^2).

4.2 Measurement of the decay $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$

To measure the Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$ we used the selection criteria described in Sec. 3, but with scaled momentum restricted to $x_p > 0.6$. The invariant mass distribution of $\Lambda^0 K^+\pi^+\pi^-$ combinations is shown in Fig. 7. The distribution is fitted with a Gaussian function for the signal shape and a third-order polynomial for background. We obtained the width $\sigma = 9.9 \pm 1.0$ MeV/c^2 and signal yield of 2591 ± 258 (stat.) events for the $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$ decay with 10.1σ statistical significance. A small fluctuation is seen at the mass 2.26 GeV/c^2. The effect of this fluctuation on the signal yield has been included in the fitting systematic. For normalization mode we use $\Lambda_c^+ \to \Lambda^0\pi^+$ with scaled momentum at $x_p > 0.6$, for which we obtained a raw yield of 22173 ± 287 (stat.) events. The relative signal reconstruction efficiency is measured to be $\epsilon(\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-)$ / $\epsilon(\Lambda_c^+ \to \Lambda^0\pi^+) = 0.442 \pm 0.004$ (stat.). The resulting branching ratio is

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-\ )}{\mathcal{B}(\Lambda_c^+ \to \Lambda^0\pi^+)} = 0.266 \pm 0.027\ \text{(stat.)} \pm 0.032\ \text{(syst.)}.$$

This is the first measurement of the Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$.

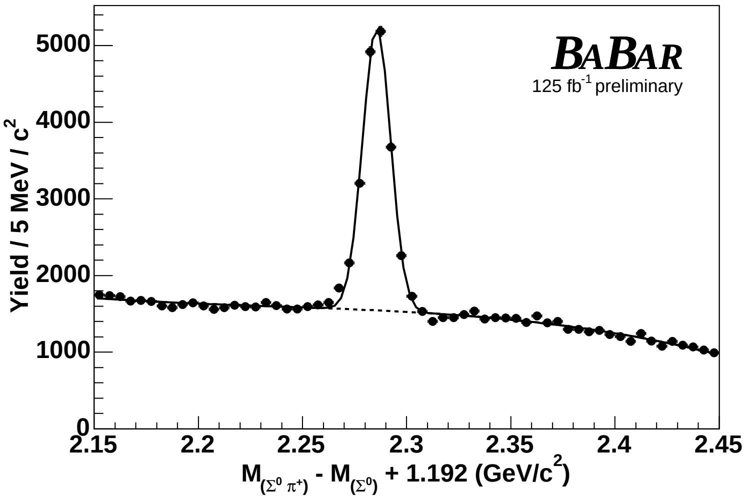

Figure 6: The invariant mass of $\Sigma^0\pi^+$ combinations (GeV/c^2).

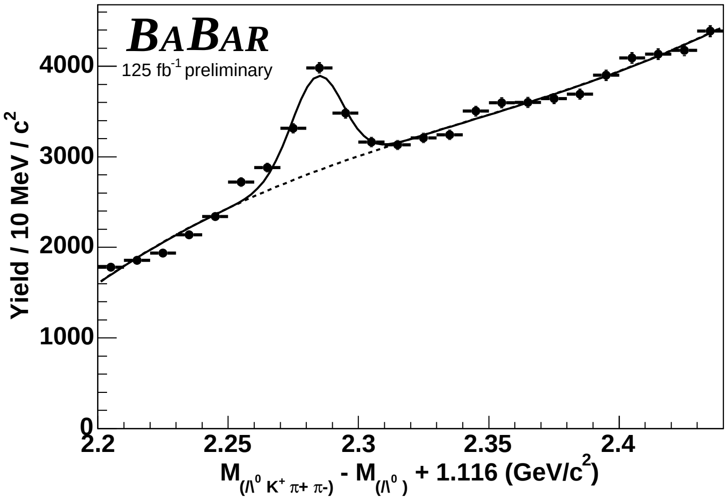

Figure 7: The invariant mass of $\Lambda^0 K^+\pi^+\pi^-$ combinations (GeV/c^2).

4.3 Search for the decay of $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$

We searched for the decay $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ using the selection described in Sec. 3 and restricting the scaled momentum to $x_p > 0.6$. The fit of the invariant mass distribution (Fig. 8) yields 41 ± 51 (stat.) events for the $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ decay with 0.8σ statistical significance. The width $\sigma = 10.0$ MeV/c^2 and mean = 2285.0 MeV/c^2 were fixed to values obtained from MC. Using the decay mode $\Lambda_c^+ \to \Sigma^0\pi^+$ for normalization, we find a raw yield of 8785 ± 131 (stat.) events for the decay $\Lambda_c^+ \to \Sigma^0\pi^+$ at $x_p > 0.6$. The relative reconstruction efficiency is measured to be $\epsilon(\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-)$ / $\epsilon(\Lambda_c^+ \to \Sigma^0\pi^+) = 0.390 \pm 0.002$ (stat.). We do not observe any significant

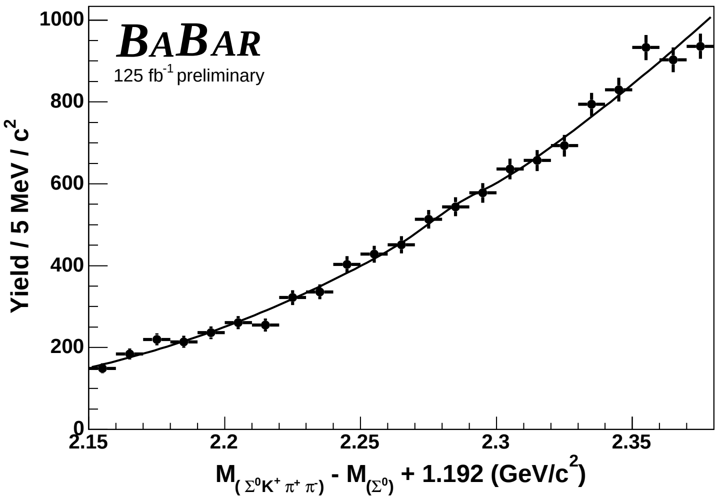

Figure 8: The invariant mass of $\Sigma^0 K^+\pi^+\pi^-$ combinations (GeV/c^2).

signal for $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$. Therefore, we calculate the upper limit using the Feldman and Cousins method [11] including systematic uncertainties. We find:

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)} < 3.9 \times\ 10^{-2} \text{ @ } 90\% \text{ CL.}$$

5 SYSTEMATIC STUDIES

We have considered several possible sources of systematic uncertainties in our measurements. The systematic uncertainty due to each cut used in candidate selection is ~ 1 %. The photon spectrum is different in measured and reference decay modes, so we studied the effect by changing the photon energy and assigned a systematic uncertainty of 2.8 % to the branching ratio ($\Lambda_c^+ \to \Sigma^0 K^+$ / $\Lambda_c^+ \to \Sigma^0\pi^+$).

We have studied possible biases due to our fitting procedure. The shape of background has been varied by changing the degree of the polynomial function as well as the shapes of Σ and Ξ_c reflections (in case of $\Lambda_c^+ \to \Lambda^0\pi^+$ decay). Any change in signal yields is being taken as a systematic uncertainty. We also varied the signal width (σ) by one standard deviation, with an change in yields interpreted as a systematic uncertainty. We assign a systematic uncertainty due to fit bias of 5.1 % for $\Lambda_c^+ \to \Lambda^0 K^+$ / $\Lambda_c^+ \to \Lambda^0\pi^+$, 8.0 % for $\Lambda_c^+ \to \Sigma^0 K^+$ / $\Lambda_c^+ \to \Sigma^0\pi^+$, and 10.1 % for $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$ / $\Lambda_c^+ \to \Lambda^0\pi^+$. The systematic uncertainty associated with the fitting is the dominant one.

6 SUMMARY

We report on a measurement of the branching ratio of the Cabibbo-suppressed decays $\Lambda_c^+ \to \Lambda^0 K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$ with improved accuracy. We also report the first observation of the Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda^0 K^+\pi^+\pi^-$, and we set an upper limit on the $\Lambda_c^+ \to \Sigma^0 K^+\pi^+\pi^-$ decay.

The results for these decay modes are summarized in Table 1. All results reported in this paper are preliminary. The expectations from the quark model [6] are $\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+)/\mathcal{B}(\Lambda_c^+ \to \Lambda^0 \pi^+) = [0.039-0.056]$ and $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)/\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+) = [0.033-0.036]$. The results are in agreement with the predictions.

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Signal Mode	Signal Yield	Reference Mode	Reference Yield	Relative Efficiency	$\frac{\mathcal{B}_{\mathrm{signal}}}{\mathcal{B}_{\mathrm{reference}}}$	Other Measurements
$\Lambda^0 K^+$	1164 ± 107	$\Lambda^0 \pi^+$	33594 ± 367	0.781 ± 0.004	$0.044 \pm 0.004 \pm 0.002$ $(x_p > 0.5)$	$0.074 \pm 0.010 \pm 0.012$ [4] $(x_p > 0.5)$
$\Lambda^0 K^+ \pi^+ \pi^-$	2591 ± 258	$\Lambda^0 \pi^+$	22173 ± 287	0.442 ± 0.004	$0.266 \pm 0.027 \pm 0.032$ $(x_p > 0.6)$	—
$\Sigma^0 K^+$	387 ± 48	$\Sigma^0 \pi^+$	12450 ± 170	0.780 ± 0.001	$0.040 \pm 0.005 \pm 0.004$ $(x_p > 0.5)$	$0.056 \pm 0.014 \pm 0.008$ [4] $(x_p > 0.6)$
$\Sigma^0 K^+ \pi^+ \pi^-$	41 ± 51	$\Sigma^0 \pi^+$	8785 ± 131	0.390 ± 0.002	$< 3.9 \times 10^{-2}$ @ 90% CL $(x_p > 0.6)$	—

Table 1: Summary of results obtained in this analysis. The last column shows the current other measurements of each decay mode, where available.