

## Measurements of $\Lambda_c^+$ 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  $\Lambda_c^+ \rightarrow \Lambda^0 K^+$  and  $\Lambda_c^+ \rightarrow \Sigma^0 K^+$  relative to the Cabibbo-allowed decay modes  $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$  and  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$  to be  $0.044 \pm 0.004$  (stat.)  $\pm 0.002$  (syst.) and  $0.040 \pm 0.005$  (stat.)  $\pm 0.004$  (syst.), respectively. We also present the first observation of  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-$  and have measured the branching fraction relative to  $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$  to be  $0.266 \pm 0.027$  (stat.)  $\pm 0.032$  (syst.). The upper limit of the branching fraction into the decay  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$  relative to  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$  has been measured to be  $< 3.9 \times 10^{-2}$  at the 90% confidence level. This analysis was performed using a data sample of  $125 \text{ fb}^{-1}$  (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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# 1 INTRODUCTION

Beginning with the first observation of the charmed baryon  $\Lambda_c^+$  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  $\Lambda_c^+ \rightarrow p\phi$  by CLEO [3], and  $\Lambda_c^+ \rightarrow \Lambda^0 K^+$ ,  $\Lambda_c^+ \rightarrow \Sigma^0 K^+$  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  $\Lambda_c^+$  baryons produced in the  $e^+e^- \rightarrow q\bar{q}$  continuum at *BABAR*. We present improved measurements of the Cabibbo-suppressed decays  $\Lambda_c^+ \rightarrow \Lambda^0 K^+$  and  $\Lambda_c^+ \rightarrow \Sigma^0 K^+$ , report the first observation of  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-$ , and set an upper limit on  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$ . 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  $125 \text{ fb}^{-1}$  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  $112 \text{ fb}^{-1}$  collected at the  $\Upsilon(4S)$  (“on-resonance”) and  $13 \text{ fb}^{-1}$  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  $\Lambda^0$  are reconstructed in the decay mode  $\Lambda^0 \rightarrow p\pi^-$ . We fitted the  $p$  and  $\pi^-$  tracks to a common vertex and required the probability of  $\chi^2$  of vertex fit to be greater than 0.1 %. We also required the (three-dimensional) flight distance of each  $\Lambda^0$  candidate between its decay vertex and the primary vertex to be greater than 0.2 cm. We fitted the invariant mass of  $\Lambda^0$  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  $\sigma = \sigma_{\text{RMS}} = 1.5 \text{ MeV}/c^2$ , where  $\sigma_{\text{RMS}}$  is defined by

$$\sigma_{\text{RMS}}^2 \equiv f_1\sigma_1^2 + f_2\sigma_2^2,$$

where  $f_1$  and  $f_2$  are fractions of signal yield corresponding to Gaussian functions one and two, respectively, and  $\sigma_1$  and  $\sigma_2$  are the two corresponding widths. We required the mass of  $\Lambda^0$  candidates to be in the range  $1113 \text{ MeV}/c^2 < M_{\Lambda^0} < 1119 \text{ MeV}/c^2$ . The  $\Sigma^0$  candidates were reconstructed in the decay mode  $\Sigma^0 \rightarrow \Lambda^0\gamma$  using the  $\Lambda^0$  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  $\sigma = \sigma_{\text{RMS}} = 4.0 \text{ MeV}/c^2$  and a mean ( difference between the invariant masses) of  $767 \pm 1 \text{ MeV}/c^2$ . We accept candidates with  $M_{\Lambda^0\gamma} - M_{\Lambda^0}$  within  $\pm 10.0 \text{ MeV}/c^2$ . ( $2.5 \sigma$ ) of the measured mean value.

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

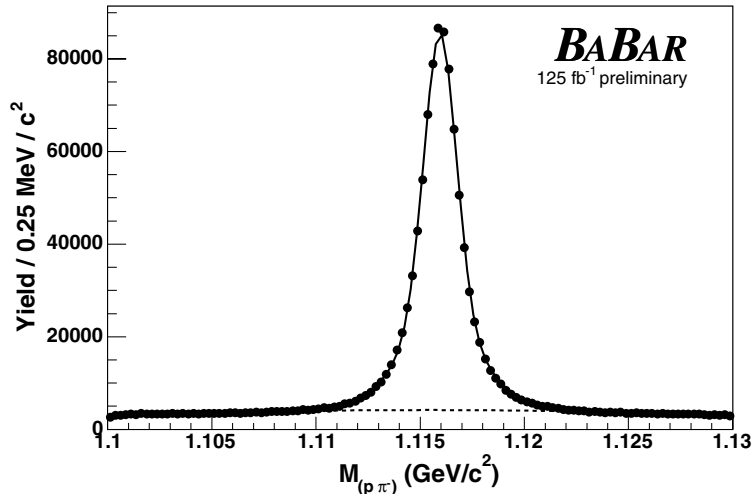


Figure 1: The invariant mass of  $p\pi$  combinations ( $\text{GeV}/c^2$ ).

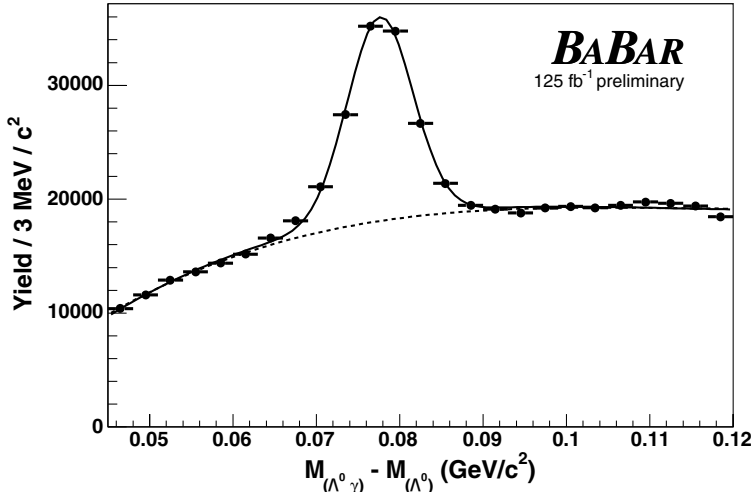


Figure 2: The invariant mass difference between  $\Lambda^0\gamma$  combinations and  $\Lambda^0$  candidates ( $\text{GeV}/c^2$ ).

## 4 PHYSICS RESULTS

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

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

For our analysis, the  $\Lambda^0$  and  $K^+$  were combined to form  $\Lambda_c^+$  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  $1164 \pm 107$  (stat.) events, with a 10.9 standard deviations significance and with fitted width  $\sigma = 5.5 \pm 0.7 \text{ MeV}/c^2$ , consistent with the MC prediction of  $6.0 \text{ MeV}/c^2$ .

For normalization, we used the decay  $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$ . The invariant mass distribution of  $\Lambda^0 \pi^+$  combinations is shown in Fig. 4. At mass values below the peak centered at the  $\Lambda_c^+$  mass a broad distribution at  $2.2 \text{ GeV}/c^2$  is visible which is a reflection due to  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$  with a missing  $\gamma$ . Additionally, at  $2.3 \text{ GeV}/c^2$  we see a shoulder, the upper edge of a  $\Xi_c$  reflection whose full shape extends through the entire  $\Lambda_c^+$  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  $\sigma = 8.2 \text{ MeV}/c^2$ , which is consistent with the experimental resolution of about  $8.0 \text{ MeV}/c^2$ , and a raw yield of  $33594 \pm 367$  (stat.) events. We calculate the ratio  $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 K^+)/\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+)$  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  $\epsilon(\Lambda_c^+ \rightarrow \Lambda^0 K^+) / \epsilon(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+) = 0.781 \pm 0.004$  (stat.). With this value we calculate:

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

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  $\Lambda_c^+ \rightarrow \Sigma^0 K^+$  was first measured by the Belle collaboration [4],

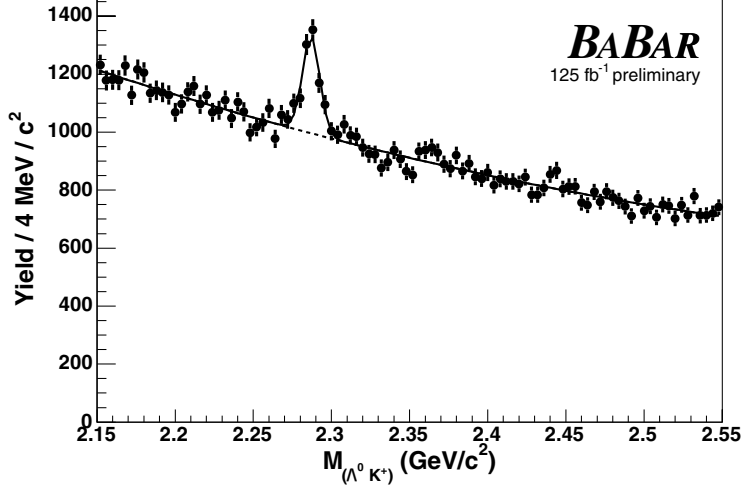


Figure 3: The invariant mass of  $\Lambda^0 K^+$  combinations ( $\text{GeV}/c^2$ ).

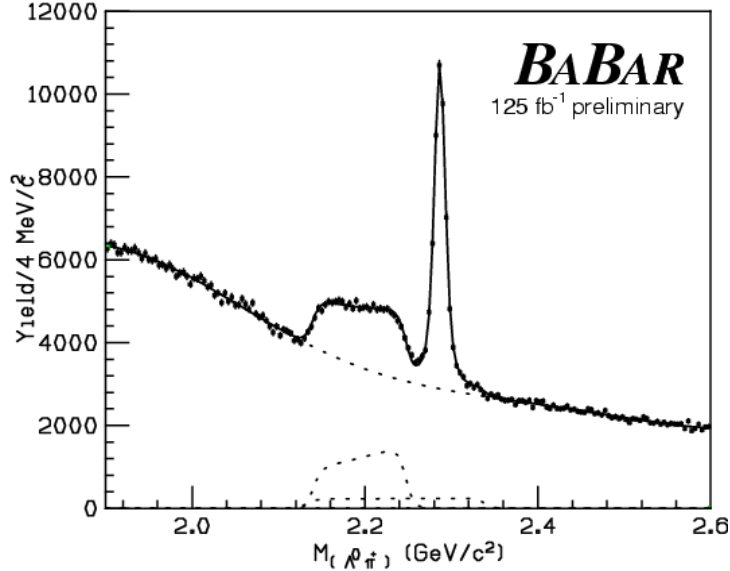


Figure 4: The invariant mass of  $\Lambda^0 \pi^+$  combinations ( $\text{GeV}/c^2$ ).

under the restriction of the scaled momentum to the region  $x_p > 0.6$ . For our analysis, we combined a  $\Sigma^0$  and a  $K^+$  candidate to form  $\Lambda_c^+$ , 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  $M_{\Sigma^0}$  is the reconstructed mass of  $\Sigma^0$  and  $M_{\Sigma^0}^{PDG}$  is the mass of  $\Sigma^0$  from PDG [5]. We fit the distribution using a Gaussian function with a fixed width  $\sigma = 6.0 \text{ MeV}/c^2$  (as determined from MC simulations) for signal and a third-order polynomial for combinatorial backgrounds. The fit yields  $387 \pm 48$  (stat.) events with a  $8.1\sigma$  statistical significance for  $\Lambda_c^+$  baryons having decayed to  $\Sigma^0 K^+$ . For normalization, we use

the Cabibbo-allowed decay mode  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ . 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  $\sigma = 6.7 \pm 0.1 \text{ MeV}/c^2$ , which is consistent with the MC prediction of  $\sigma = 7.0 \text{ MeV}/c^2$ . The fitted yield is  $12450 \pm 170$  (stat.) events. The relative reconstruction efficiency is measured to be  $\epsilon(\Lambda_c^+ \rightarrow \Sigma^0 K^+) / \epsilon(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+) = 0.780 \pm 0.001$  (stat.) using signal MC. The resulting relative branching ratio is

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

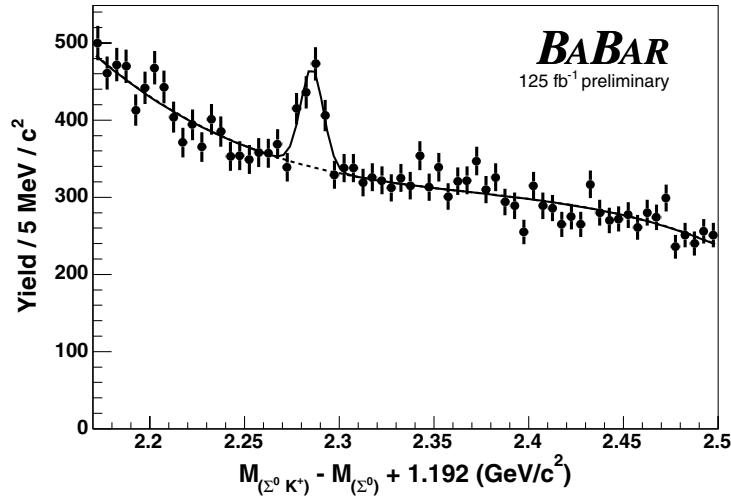


Figure 5: The invariant mass of  $\Sigma^0 K^+$  combinations ( $\text{GeV}/c^2$ ).

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

To measure the Cabibbo-suppressed decay  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-$  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  $\sigma = 9.9 \pm 1.0 \text{ MeV}/c^2$  and signal yield of  $2591 \pm 258$  (stat.) events for the  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-$  decay with  $10.1\sigma$  statistical significance. A small fluctuation is seen at the mass  $2.26 \text{ GeV}/c^2$ . The effect of this fluctuation on the signal yield has been included in the fitting systematic. For normalization mode we use  $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$  with scaled momentum at  $x_p > 0.6$ , for which we obtained a raw yield of  $22173 \pm 287$  (stat.) events. The relative signal reconstruction efficiency is measured to be  $\epsilon(\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-) / \epsilon(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+) = 0.442 \pm 0.004$  (stat.). The resulting branching ratio is

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

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

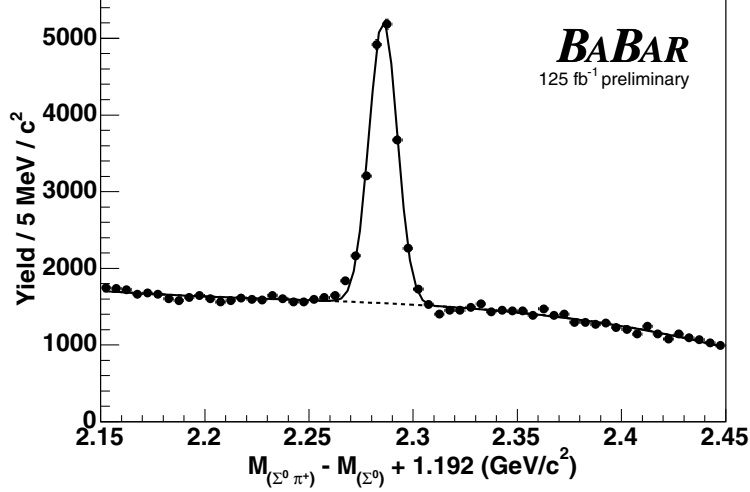


Figure 6: The invariant mass of  $\Sigma^0\pi^+$  combinations ( $\text{GeV}/c^2$ ).

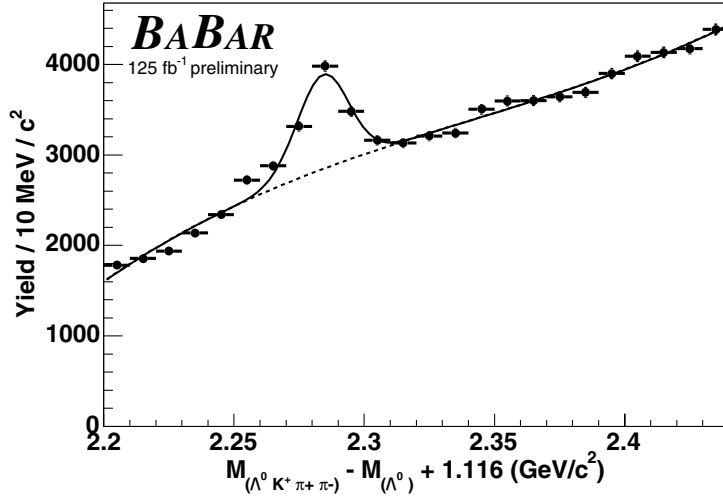


Figure 7: The invariant mass of  $\Lambda^0 K^+ \pi^+ \pi^-$  combinations ( $\text{GeV}/c^2$ ).

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

We searched for the decay  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$  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  $41 \pm 51$  (stat.) events for the  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$  decay with  $0.8\sigma$  statistical significance. The width  $\sigma = 10.0 \text{ MeV}/c^2$  and mean  $= 2285.0 \text{ MeV}/c^2$  were fixed to values obtained from MC. Using the decay mode  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$  for normalization, we find a raw yield of  $8785 \pm 131$  (stat.) events for the decay  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$  at  $x_p > 0.6$ . The relative reconstruction efficiency is measured to be  $\epsilon(\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-) / \epsilon(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+) = 0.390 \pm 0.002$  (stat.). We do not observe any significant

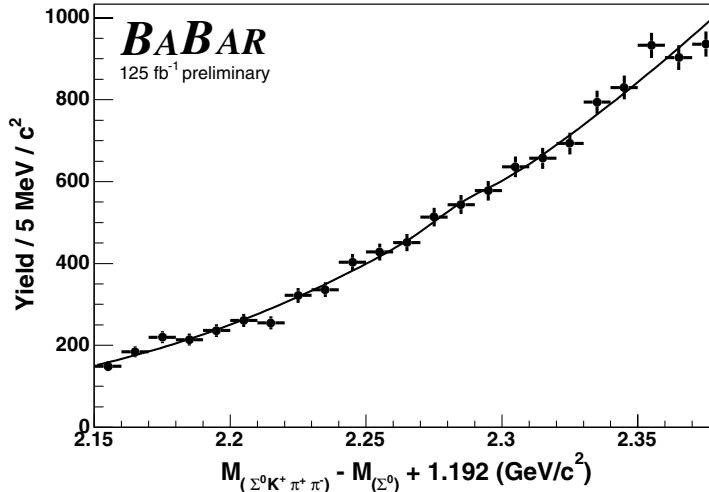


Figure 8: The invariant mass of  $\Sigma^0 K^+ \pi^+ \pi^-$  combinations ( $\text{GeV}/c^2$ ).

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

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

## 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  $\sim 1\%$ . 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 ( $\Lambda_c^+ \rightarrow \Sigma^0 K^+ / \Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ ).

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  $\Sigma$  and  $\Xi_c$  reflections (in case of  $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$  decay). Any change in signal yields is being taken as a systematic uncertainty. We also varied the signal width ( $\sigma$ ) 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  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ / \Lambda_c^+ \rightarrow \Lambda^0 \pi^+$ , 8.0% for  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ / \Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ , and 10.1% for  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^- / \Lambda_c^+ \rightarrow \Lambda^0 \pi^+$ . 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  $\Lambda_c^+ \rightarrow \Lambda^0 K^+$  and  $\Lambda_c^+ \rightarrow \Sigma^0 K^+$  with improved accuracy. We also report the first observation of the Cabibbo-suppressed decay  $\Lambda_c^+ \rightarrow \Lambda^0 K^+ \pi^+ \pi^-$ , and we set an upper limit on the  $\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$  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  $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 K^+)/\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+) = [0.039-0.056]$  and  $\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^0 K^+)/\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+) = [0.033-0.036]$ . The results are in agreement with the predictions.

## 7 ACKNOWLEDGMENTS

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