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# Measurement of the Ratio of Branching Fractions of $\Xi_c^0$ Decays to $\Xi^-\pi^+$ and to $\Omega^-\mathrm{K}^+$

The *BABAR* Collaboration

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## Abstract

We have analyzed 116 $\mathrm{fb}^{-1}$ of data collected by the *BABAR* detector for $\Xi_c^0$ production. In this paper we describe the observation of $\Xi_c^0$ production from $c\overline{c}$ continuum and from B decays, with the $\Xi_c^0$ decaying into $\Xi^-\pi^+$ and $\Omega^-K^+$ modes. The ratio of the branching fractions of the $\Xi_c^0$ decays into these two final states measured in the $c\overline{c}$ continuum is:

$$\frac{\mathcal{B}(\Xi_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.296 \pm 0.018\ (\mathrm{stat.}) \pm 0.030\ (\mathrm{sys.}).$$

All results in this note are preliminary.

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# 1 INTRODUCTION

Little is known about charmed baryons today even though decades have passed since the discovery of charm. The high-luminosity $B$-factories present excellent opportunities to study the production and decay of charmed baryons with high precision.

We present the observation of the $\Xi_c^0$ (csd)[6] charmed baryon in two decay modes:

$$\Xi_c^0 \to \Omega^- K^+$$
$$\Xi_c^0 \to \Xi^- \pi^+.$$

The ratio of branching fractions of these decay modes has been predicted to be approximately 0.32 [1] using a spectator quark model calculation. This figure has a substantial theoretical uncertainty. It has been measured previously by the CLEO collaboration; their result was consistent with this prediction but had a large statistical uncertainty [2].

We measure the ratio of the branching fractions of $\Xi_c^0 \to \Omega^- K^+$ and $\Xi_c^0 \to \Xi^- \pi^+$ from the continuum production of $e^+e^- \to c\bar{c}$, where the hyperons are reconstructed through the following decays:

$$\Xi^- \to \Lambda\,\pi^-$$
$$\Omega^- \to \Lambda\,K^-$$
$$\Lambda \to p\,\pi^-.$$

Since the two final states are topologically similar, quite a few systematic uncertainties cancel in the ratio of the branching fractions. We also observe signals for $\Upsilon(4S) \to B\bar{B} \to \Xi_c^0 + X$ in both final states, where $X$ represents the rest of the event. Although copious production of $\Xi_c^0$ and $\Xi_c^+$ in $B$ decays has been predicted [3], this process has been observed previously only by CLEO, with a significance of approximately 3 $\sigma$ in the $\Xi_c^0 \to \Xi^-\pi^+$ decay mode and approximately 4 $\sigma$ in a related $\Xi_c^+$ decay mode [4].

# 2 THE *BABAR* DETECTOR AND DATASET

The data for this analysis are collected with the *BABAR* detector at the PEP-II asymmetric $e^+e^-$ collider; a total integrated luminosity of 116 fb$^{-1}$ is used. A five-layer silicon vertex detector (SVT) and a 40-layer drift chamber (DCH) form the tracking system. The drift chamber is surrounded by the DIRC, a detector of internally reflected Cherenkov light, which provides additional charged particle identification (PID). These are enclosed in a CsI(Tl) electromagnetic calorimeter (EMC). The detector assembly is embedded in a 1.5 T superconducting magnet. Further details of the *BABAR* detector are given elsewhere [5].

The data collected are processed through the standard *BABAR* reconstruction software. In the present analysis, we use an integrated luminosity of 105.4 fb$^{-1}$ collected at the $\Upsilon(4S)$ resonance, and 10.7 fb$^{-1}$ collected below the $\Upsilon(4S)$ threshold. We refer to these as the on-peak and the off-peak data samples, respectively.

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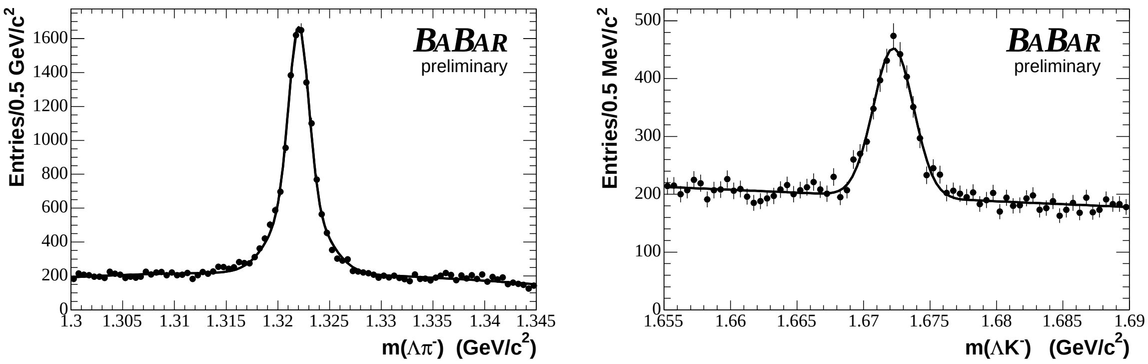
[6] All channels imply the charge conjugates as well, unless otherwise specified.



(a) (b)

Figure 1: Invariant masses of reconstructed and preselected (a) $\Xi^-$ and (b) $\Omega^-$ candidates from subsamples of data.

# 3 ANALYSIS METHOD

The two decay modes $\Omega^- \to \Lambda K^-$ and $\Xi^- \to \Lambda\pi^-$ are topologically similar. The hyperons involved are long-lived. The $\Xi_c^0$ decays close to the production vertex: $c\tau = 34^{+4}_{-2}\ \mu$m [6].

## 3.1 Selection of Events

The $\Xi_c^0$ reconstruction takes place in three stages:

- pre-selection of events containing a $\Lambda$,
- pre-selection of events containing either $\Xi^-$ or $\Omega^-$ from the $\Lambda$ sample, and
- construction of $\Xi_c^0$ candidates.

The $\Lambda$ is reconstructed by identifying a proton and combining it with an oppositely charged track. $\Lambda$ candidates within a $3\sigma$ ($\sigma$ is the fitted mass resolution) range of the central value are then used for reconstruction of $\Xi^-$ and $\Omega^-$ by vertexing it with a negatively charged track; and the $\Lambda$ mass is constrained at the nominal value [6]. For $\Omega^-$ reconstruction, the $K^-$ is required to be identified as a kaon.

To improve signal-to-noise ratio, a minimum decay distance of 2.5 mm between the primary vertex and the $\Xi^-$ decay vertex in the plane perpendicular to the beam direction is required; for the $\Omega^-$, the required distance is 1.5 mm. In addition, the "signed" flight distance[7] between the $\Lambda$ and the $\Omega^-$ decay vertex is required to be at least 3 mm.

Figures 1 (a) and (b) show invariant mass distributions of $\Lambda\pi^-$ and $\Lambda K^-$ respectively, from subsamples of the data. Superimposed on the plots are fits to a double Gaussian (single Gaussian) for the $\Xi^-(\Omega^-)$ together with a linear background. The fitted masses and resolutions of data and Monte Carlo are consistent within known systematic effects.

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[7] A "signed" flight length is where the displacement and the momentum vector of the particle are required to be less than 90° apart, i.e., $\mathrm{p} \cdot \mathrm{r} > 0$, where r denotes the distance from the production point to the decay point of particle X in the xy-plane.

Table 1: Fit results for $\Xi_c^0$.

| Yield in | $\Xi^-\pi^+$ | $\Omega^-K^+$ |
|---|---|---|
| On-peak Data | $7614 \pm 545$ | $906 \pm 54$ |
| Off-peak Data | $450 \pm 39$ | $78 \pm 10$ |
| On- and off-peak Data, $p^* > 1.8$ GeV/c, in $\cos\theta^*$ range: | $4058 \pm 319$<br>$(-0.8 \leq \cos\theta^* \leq 0.8)$ | $655 \pm 43$<br>$(-0.8 \leq \cos\theta^* \leq 0.6)$ |

### 3.2 $\Xi_c^0$ Reconstruction

The selection criteria are finalized using subsamples of the data as a precaution against selection bias. The subsamples used are of size 20 fb$^{-1}$ and 40 fb$^{-1}$ for the $\Xi^-\pi^+$ and $\Omega^-K^+$ modes respectively. The final results are obtained using the entire 116 fb$^{-1}$ sample, including these subsamples. In each case a $3\sigma$ mass range around the central value is used.

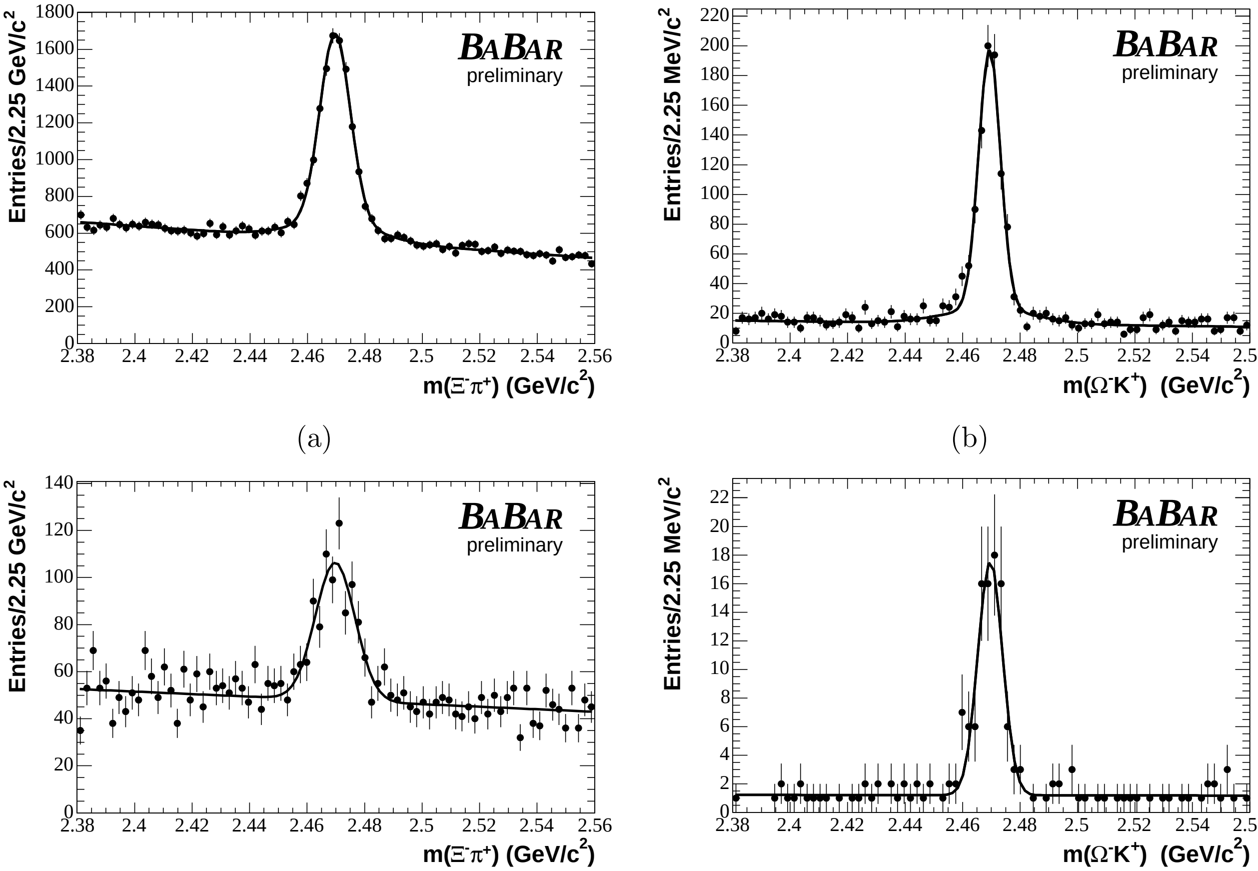
Each resulting $\Xi^-$ candidate is then vertexed with an oppositely charged pion for the $\Xi^-\pi^+$ final state. Likewise, each $\Omega^-$ candidate is vertexed with a positively charged track identified as a kaon for the $\Omega^-K^+$ final state. The resulting invariant mass distributions for the $\Xi_c^0$ candidates from the on-peak data sample are shown in Figures 2 (a) and (b) for $\Xi^-\pi^+$ and $\Omega^-K^+$ combinations, respectively. The mass distributions from the off-peak data sample are shown in Figures 2 (c) and (d) again for $\Xi^-\pi^+$ and $\Omega^-K^+$ combinations, respectively. A clear $\Xi_c^0$ peak is evident in all four spectra. The fitted distributions are superimposed on the plots. In each case we use a single Gaussian shape on a linear background, except for (b) in which a much better fit is obtained by using a double Gaussian shape on a linear background. The fit results are listed in Table 1.

### 3.3 Simulation

Events corresponding to the $e^+e^- \to c\overline{c} \to \Xi_c^0 + X$ process are generated, with the $\Xi_c^0$ decays into the two desired decay modes. PYTHIA [7] is used for the $c\overline{c}$ fragmentation and GEANT4 [8] is used to simulate the detector response. These events are then reconstructed and the selection criteria applied. Samples of 90,000 events for the $\Xi^-\pi^+$ final state and 60,000 events for the $\Omega^-K^+$ final state are generated. To investigate possible background contributions, generic $e^+e^- \to q\overline{q}\ \{u, d, s, c\}$ continuum Monte Carlo events are processed through the complete analysis program sequence. The $e^+e^- \to c\overline{c}$ sample corresponds to an integrated luminosity of 64 fb$^{-1}$, and the combined $u\overline{u}, d\overline{d}, s\overline{s}$ sample corresponds to 33 fb$^{-1}$. In addition, 22,000 events are generated according to $\Upsilon(4S) \to B\bar{B} \to \Xi_c^0 + X$, and processed through the complete analysis chain.

### 3.4 Background Contributions

We analyze the generic $c\overline{c}$ Monte Carlo events. No evidence of a peaking background is observed. The distribution of the background events can be fitted with a linear shape in the $\Xi^-\pi^+$ channel. For the $\Omega^-K^+$ channel, the distribution of the reconstructed events is flat. The events from generic $u\overline{u}, d\overline{d}, s\overline{s}$ Monte Carlo do not show any peaking either.



(a)

(b)

(c)

(d)

Figure 2: The invariant mass distributions for $\varXi_c^0$ candidates, shown for (a) $\varXi^-\pi^+$ in on-peak data, (b) $\varOmega^-K^+$ in on-peak data, (c) $\varXi^-\pi^+$ in off-peak data, and (d) $\varOmega^-K^+$ in off-peak data.

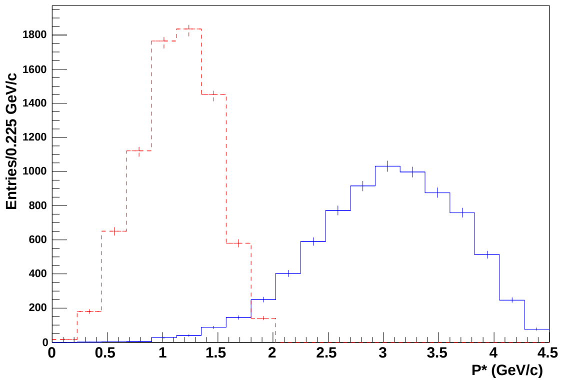


Figure 3: $p^*$ distributions from reconstructed $\Xi_c^0$ in Monte Carlo. The dashed red line shows $\Xi_c^0$ produced in B decays, and the solid blue line shows $c\bar{c}$ production of $\Xi_c^0$. Normalizations are arbitrary. No background is present.

### 3.5 $\Xi_c^0$ Production from $c\bar{c}$ Continuum and from $\Upsilon(4S) \to B\bar{B} \to \Xi_c^0 + X$

The $B \to \Xi_c^0 + X$ Monte Carlo events are instructive in separating the $\Xi_c^0$ contribution originating from B decays from those originating from the $c\bar{c}$ continuum production. Figure 3 shows the distribution of the momentum of the reconstructed $\Xi_c^0$'s in the center-of-mass frame ($p^*$) from the Monte Carlo[8]. These are also "truth-matched", i.e., where the reconstructed information matches the generated information.

The dashed red line shows the $p^*$ distribution of $\Xi_c^0$'s originating from B decays and the solid blue line shows that from $c\bar{c}$ continuum. The normalizations in this figure are arbitrary. The $p^*$ distribution from B decays does not extend beyond 2 GeV/c, purely from kinematics, whereas the distribution from the continuum peaks at much higher $p^*$ values.

The $p^*$ distributions from the $\Xi_c^0$ signal regions for the off-peak data are shown without any efficiency correction in Figures 4 (a) and (b), for the $\Xi^-\pi^+$ and the $\Omega^-K^+$ final states, respectively. These data are collected below $b\bar{b}$ production threshold, and therefore represent $\Xi_c^0$ production from continuum only. The background under the $\Xi_c^0$ signal in the data is estimated from the sidebands in the reconstructed $\Xi_c^0$ mass spectrum and then removed. These $p^*$ distributions, peaked around 3 GeV/c, clearly indicate $\Xi_c^0$ production from $c\bar{c}$ continuum.

Figures 5 (a) and (b) show the $p^*$ distribution in on-peak data from the $\Xi_c^0$ candidates in the $\Xi^-\pi^+$ and $\Omega^-K^+$ final states, respectively, after background subtraction, again without any efficiency correction. The peaks below 1.5 GeV/c in both plots clearly represent $\Xi_c^0$ production from B decays, as evident from Figures 3 and 4.

### 3.6 Analysis and Efficiency Correction for $c\bar{c} \to \Xi_c^0 + X$

For further analysis the on- and off-peak data samples are combined; to isolate the $c\bar{c}$ production of $\Xi_c^0$, events with $p^* > 1.8$ GeV/c are selected. In order to avoid large fluctuations from the edges of the phase-space and detector acceptance effects, we also require $-0.8 \leq \cos\theta^* \leq 0.8$ for the $\Xi^-\pi^+$

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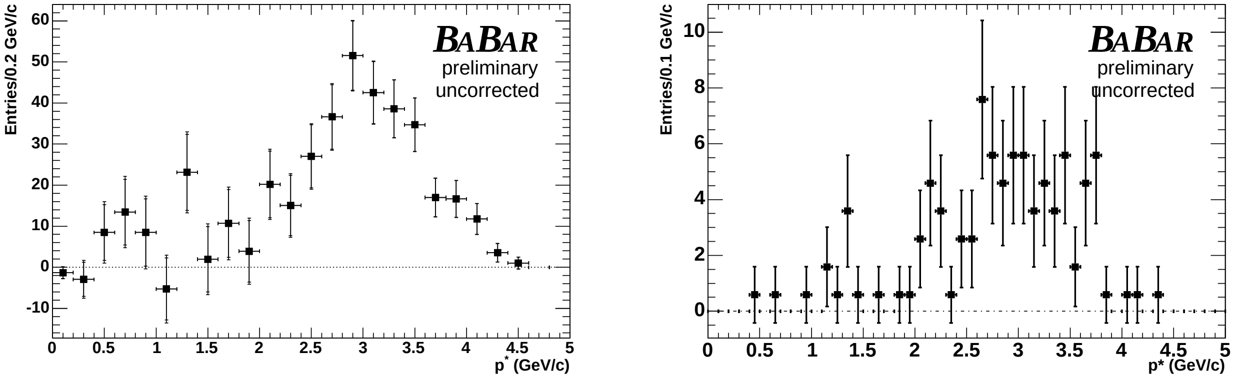
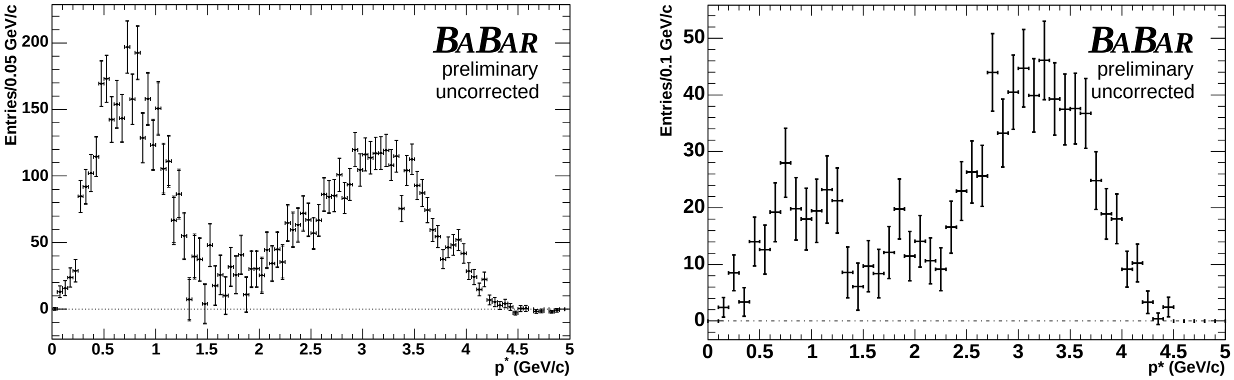
[8] The decay of the $B$ into $\Xi_c^0$ is modelled using PYTHIA [7] fragmentation.



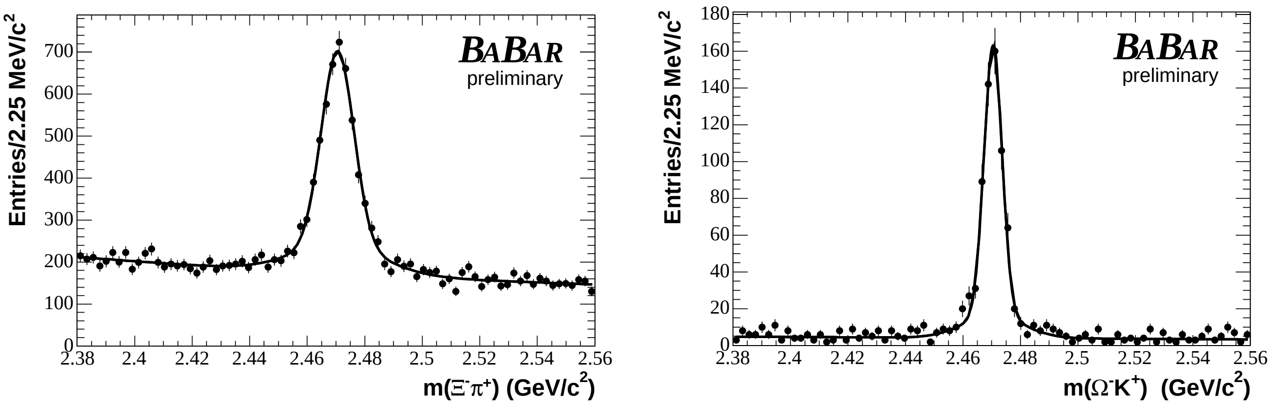
(a) (b)

Figure 4: Sideband-subtracted $p^*$ distribution of reconstructed $\Xi_c^0$ candidates in off-peak data without efficiency correction in (a) $\Xi^-\pi^+$ and (b) $\Omega^-K^+$ mode. Most of the signal is produced at higher $p^*$ as expected.



(a) (b)

Figure 5: Sideband-subtracted $p^*$ distribution from $\Xi_c^0$ candidates in on-peak data without efficiency correction in (a) $\Xi^-\pi^+$ and (b) $\Omega^-K^+$ mode. The lower peak below $p^* < 1.5$ GeV/c is primarily from the $\Xi_c^0$ production from B decays as evident from Figure 3 and Figure 4.



(a) (b)

Figure 6: Invariant mass spectra for $\Xi_c^0$ with $p^* > 1.8$ GeV/c from (a) $\Xi^-\pi^+$ final state with $-0.8 \leq \cos\theta^* \leq 0.8$, and (b) $\Omega^-K^+$ final state with $-0.8 \leq \cos\theta^* \leq 0.6$ using on- and off-peak data. Both spectra are fitted with a double Gaussian for signal and a linear background shape.

mode and $-0.8 \leq \cos\theta^* \leq 0.6$ the for $\Omega^-K^+$ mode, where $\theta^*$ is the polar angle of the $\Xi_c^0$ candidate with respect to the collision axis in the center-of-mass frame.

Figures 6 (a) and (b) show the $\Xi_c^0$ invariant mass spectra in these $\cos\theta^*$ ranges with $p^* >$ 1.8 GeV/c for the combined on- and off-peak data sample, for $\Xi^-\pi^+$ and $\Omega^-K^+$ decay modes, respectively. The fit results are presented in Table 1.

The efficiency is calculated from signal Monte Carlo events as a function of $p^*$ and cos$\theta^*$ in each of the two decay modes. For each decay mode, a fifteen-parameter two-dimensional fit gives a smooth parameterization of the efficiency with small statistical unceratinty. We then correct the data distribution by weighting each event in the spectrum inversely by its efficiency according to the event's position in ($p^*$, cos$\theta^*$) space. After correcting for efficiency we obtain $19375 \pm 393$ events in the $\Xi^-\pi^+$ mode and $4866 \pm 283$ events in the $\Omega^-K^+$ mode[9].

The angular distribution of the data is well-described by a $(1 + \cos^2\theta^*)$ function; we use this to estimate the fractions of the $\Xi_c^0$ which are expected to lie in the selected angular regions for each mode. Extrapolating from the fiducial region into the full range $-1 \leq \cos\theta^* \leq +1$, we obtain the total numbers of signal events for $p > 1.8$ GeV/$c$ are $26621 \pm 540$ and $7874 \pm 458$ for the $\Xi^-\pi^+$ and $\Omega^-K^+$ modes, respectively. We thus obtain the ratio of branching fractions:

$$\frac{B(\Xi_c^0 \to \Omega^-K^+)}{B(\Xi_c^0 \to \Xi^-\pi^+)} = 0.296 \pm 0.018 \text{ (stat.)}.$$

# 4 STUDY OF SYSTEMATIC UNCERTAINTIES

We evaluate several sources of systematic uncertainties, described below and summarized in Table 2. Adding all of these uncertainties[10] in quadrature, we obtain a total absolute systematic uncertainty of 0.030 on the ratio of the branching fractions.

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[9] The $\Lambda$ branching fraction is not taken into account in these numbers, since this cancels in the ratio.

[10] No baryon polarization is considered in the present analysis and any systematic uncertainty due to this is neglected.

- We vary the signal shape, the background shape, and the fit range, and use a simple event-counting method. From the deviations observed, we assign systematic uncertainties for the use of a binned fit and for the particular technique used, adding them in quadrature.
- We repeat the analysis with (a) a parameterization of the efficiency with a similar function with nine parameters, and (b) a simple efficiency calculation in two dimensional bins from Monte Carlo. The discrepancy observed between the main result and the result from (a) is assigned as the systematic uncertainty.
- We vary the range in $\cos\theta^*$ used for the two final states. We also vary the $\cos\theta^*$ distribution used for the extrapolation. The combined systematic uncertainty is taken to be the sum in quadrature of the uncertainty due to using different $\cos\theta^*$ ranges for the two modes and the uncertainty due to the choice of extrapolation function.
- We take into account an uncertainty due to the finite size of the Monte Carlo sample used to estimate the efficiencies.
- Approximately 1% of selected events contain multiple candidates in the $\Xi_c^0$ signal range with one or more tracks in common. We retain all such candidates, and therefore assign a systematic uncertainty in case these form a peaking background.
- $\Xi_c^0$ and $\bar{\Xi}_c^0$ are studied separately; the ratios are found to be consistent. We assign the difference as the systematic uncertainty due to detector charge asymmetry.
- We assign an uncertainty of 1% on the efficiency for each track required to be identified as a kaon.
- The uncertainty in the branching fraction of $\Omega^-$, $(67.8 \pm 0.7)\%$ [6], is included.

We make the following additional checks:

- The desired ratio of the branching fractions is calculated from off-peak data only, and is measured to be $0.259 \pm 0.044$, consistent with the main result.
- The data are divided up into three $p^*$ ranges: (1.8–2.7) GeV/c, (2.7–3.6) GeV/c, and (3.6–4.5) GeV/c; the yields and ratios calculated for each range are $0.269 \pm 0.030$, $0.295 \pm 0.019$, and $0.263 \pm 0.031$, respectively. These are consistent with being independent of $p^*$ within statistical uncertainties.

# 5 PHYSICS RESULTS AND SUMMARY

In summary, we observe $\Xi_c^0$ production from the $c\overline{c}$ continuum and from $\Upsilon(4S) \to B\bar{B} \to \Xi_c^0 + X$ using the *BABAR* detector at SLAC. This represents the first observation of $\Xi_c^0 \to \Omega^- K^+$ in $B$ decays. We present a preliminary measurement of the ratio of branching fractions of $\Xi_c^0$ to $\Omega^- K^+$ and $\Xi^- \pi^+$, determined using the $c\overline{c}$ continuum data:

$$\frac{B(\Xi_c^0 \to \Omega^- K^+)}{B(\Xi_c^0 \to \Xi^- \pi^+)} = 0.296 \pm 0.018 \text{ (stat.)} \pm 0.030 \text{ (sys.)}.$$

This represents a significant improvement on the existing value of $(0.50 \pm 0.21 \pm 0.05)$ [2].

Table 2: Systematic uncertainties.

| Source | Uncertainty |
|---|---|
| Fits to mass spectrum | 0.019 |
| Efficiency | 0.015 |
| $\cos\theta^*$ Distribution | 0.016 |
| Limited Monte Carlo Statistics | 0.004 |
| Multiple candidates | 0.004 |
| Charge asymmetry | 0.001 |
| Particle ID | 0.006 |
| $\mathit{\Omega}^-$ branching fraction | 0.003 |
| Total systematic uncertainty | 0.030 |

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