

## Evidence for $B$ semileptonic decays into the charmed baryon $\Lambda_c^+$

The *BABAR* Collaboration

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### Abstract

We present the first evidence for  $B$  semileptonic decays into the charmed baryon  $\Lambda_c^+$  based on  $420 \text{ fb}^{-1}$  of data collected at the  $\Upsilon(4S)$  resonance with the *BABAR* detector at the PEP-II  $e^+e^-$  storage rings. Events are tagged by fully reconstructing one of the  $B$  mesons in a hadronic decay mode. We measure the relative branching fraction  $\mathcal{B}(\overline{B} \rightarrow \Lambda_c^+ X \ell^- \overline{\nu}_\ell) / \mathcal{B}(\overline{B} \rightarrow \Lambda_c^+ / \overline{\Lambda}_c^- X) = (3.2 \pm 0.9_{\text{stat.}} \pm 0.9_{\text{syst.}})\%$ . The significance of the signal including the systematic uncertainty is 4.9 standard deviations.

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# 1 Introduction

The  $B$  decays to charmed baryons are not as well understood as the decays into charmed mesons. In particular, there is limited knowledge, both theoretical and experimental, about the  $B$  semileptonic decays into charmed baryons. If the charmed baryonic production is dominated by the emission of an external  $W$  boson, as in the case of the mesonic production  $B \rightarrow DX$ , then we can expect the rate of the semileptonic events to be about the same for the baryonic and mesonic processes:

$$\frac{\mathcal{B}(\bar{B} \rightarrow DX\ell^-\bar{\nu}_\ell)}{\mathcal{B}(\bar{B} \rightarrow D/\bar{D}X)} \sim \frac{\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X\ell^-\bar{\nu}_\ell)}{\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X)} \quad (1)$$

where  $\ell = e$  or  $\mu$ . For the mesonic process, the ratio is  $\mathcal{B}(\bar{B} \rightarrow DX\ell^-\bar{\nu}_\ell)/\mathcal{B}(\bar{B} \rightarrow D/\bar{D}X) \approx 10\%$  [1]. If the baryonic ratio is found to be smaller than the mesonic ratio, there is a significant contribution from internal  $W$  emission in the baryonic production. The Feynman diagrams of  $B$  decays with internal and external  $W$  emissions are shown in Fig. 1.

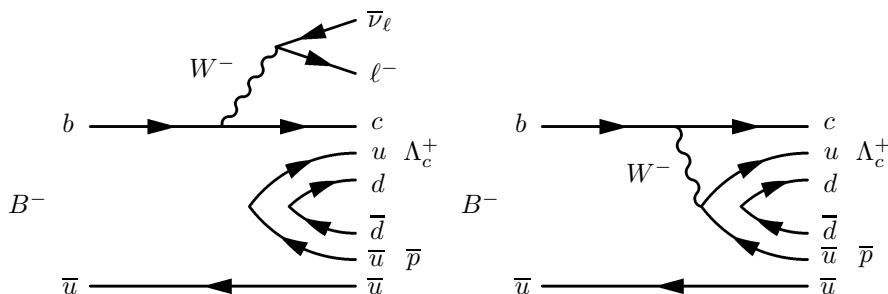


Figure 1:  $B$  decays with an external  $W$  emission (left) and an internal  $W$  emission (right).

About 90% of the inclusive semileptonic  $\bar{B} \rightarrow X\ell^-\bar{\nu}_\ell$  branching fraction [2] can be accounted for by summing the branching fractions from exclusive  $\bar{B} \rightarrow D^{(*)}(\pi)\ell^-\bar{\nu}_\ell$  decays. Semileptonic  $\bar{B}$  decays to charmed baryons may account for some of the remaining difference. These decays have not yet been observed. A previous search for  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  by the CLEO collaboration [3] obtained an upper limit of  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e)/\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X) < 0.05$  at the 90% confidence level.

In this paper, we present the first evidence for  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  decays<sup>8</sup>, where  $X$  can be any particle(s) from the  $B$  semileptonic decay other than the leptons and the  $\Lambda_c^+$ . The  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  signal yield is obtained by a fit to the  $\Lambda_c^+$  invariant mass. We perform a blind analysis using Monte-Carlo (MC) samples and the  $\Lambda_c^+$  invariant mass sidebands on data to optimize the selection criteria and estimate the backgrounds. We also present the results for a similar search for  $\bar{B} \rightarrow \Lambda_c^+ X \mu^- \bar{\nu}_\mu$ .

## 2 The *BABAR* Detector and Dataset

This analysis is based on data collected with the *BABAR* detector at the PEP-II storage rings. The total integrated luminosity of the dataset is  $420 \text{ fb}^{-1}$  collected on the  $\Upsilon(4S)$  resonance. The

<sup>8</sup>Charge-conjugate modes are implied throughout this paper.



corresponding number of produced  $B\bar{B}$  pairs is roughly 460 million. An additional  $42 \text{ fb}^{-1}$  data sample taken at a center-of-mass (CM) energy 40 MeV below the  $\Upsilon(4S)$  resonance is used to study background from  $e^+e^- \rightarrow f\bar{f}$  ( $f = u, d, s, c, \tau$ ) events (continuum production). The *BABAR* detector is described in detail elsewhere [4]. Charged-particle trajectories are measured by a 5-layer double-sided silicon vertex tracker and a 40-layer drift chamber, both operating in a 1.5-T magnetic field. Charged-particle identification is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter. Muons are identified by the instrumented magnetic-flux return. A detailed GEANT4-based MC simulation [5] of  $B\bar{B}$  and continuum events has been used to study the detector response, its acceptance, and to test the analysis techniques.

### 3 Simulation of $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$ Decays

Due to a lack of available theoretical models for semileptonic  $B$  decays to charmed baryons, we use an ad-hoc model to study selection optimization in our analysis. In our model, the  $B$  decays semileptonically into charmed baryons through an intermediate massive particle  $Y$  as  $\bar{B} \rightarrow Y \ell^- \bar{\nu}_\ell$ , according to a phase space model [6]. The  $Y$  subsequently decays into a  $\Lambda_c^+$ , an anti-nucleon (anti-proton or anti-neutron), and  $n_1$  ( $n_2$ ) charged (neutral) pions, with  $n_1$  and  $n_2$  distributed as Poissonians with a common mean of 1.25. We apply isospin symmetry in the final states of the  $Y$  decay.

Due to the ad-hoc nature of the signal model, we tune its parameters as part of the analysis. We perform a first optimization of the selection criteria using a pseudo-particle  $Y$  mass  $m_Y$  of  $4.0 \text{ GeV}/c^2$  and a width  $\Gamma_Y$  of  $0.6 \text{ GeV}/c^2$ , with the  $Y$  decay constrained by  $n_1 + n_2 \leq 4$ . After unblinding the  $\Lambda_c^+$  invariant mass signal region, we compare the sideband-subtracted signal distributions of the  $\Lambda_c^+$  and lepton momentum spectra, and the charged and neutral pion multiplicity, with the corresponding ones from the signal MC simulation. We then tune the signal model parameters to resemble the observed distributions on data. For instance, by adjusting the mass and width of the pseudo-particle  $Y$ , we can control the shape of the lepton momentum spectrum. We find a good agreement with the electron spectrum in data for  $m_Y = 4.5 \text{ GeV}/c^2$ ,  $\Gamma_Y = 0.2 \text{ GeV}/c^2$ , and  $n_1 + n_2 \leq 6$ . We use the retuned signal model to re-optimize the selection criteria and to estimate signal efficiency. We check *a posteriori* that the two-pass selection criteria optimization does not strongly depend on the initial signal model parameters used. The  $\Lambda_c^+$  and lepton momentum spectra for a sample of signal MC events are shown in Fig. 2 for two the models before and after tuning.

### 4 Event Selection

We select  $B$  semileptonic decays in events containing a fully reconstructed  $B$  meson ( $B_{\text{tag}}$ ), which allows us to constrain the kinematics, to reduce the combinatorial background, and to determine the charge and flavor of the signal  $B$ , up to flavor-changing mixing.

We first reconstruct the  $B$  semileptonic decay, selecting a lepton with momentum  $p_\ell^*$  in the CM frame higher than  $0.35 \text{ GeV}/c$ . Electrons from photon conversion and  $\pi^0$  Dalitz decay are removed using a dedicated algorithm, which uses a least-squares fit to reconstruct the vertex between two tracks of opposite charges whose kinematical parameters are compatible with a photon conversion or a  $\pi^0$  Dalitz decay. Tracks identified as electrons or muons are required to be within 0.1 cm of the the interaction point at their point of closest approach in the transverse plane. Candidate

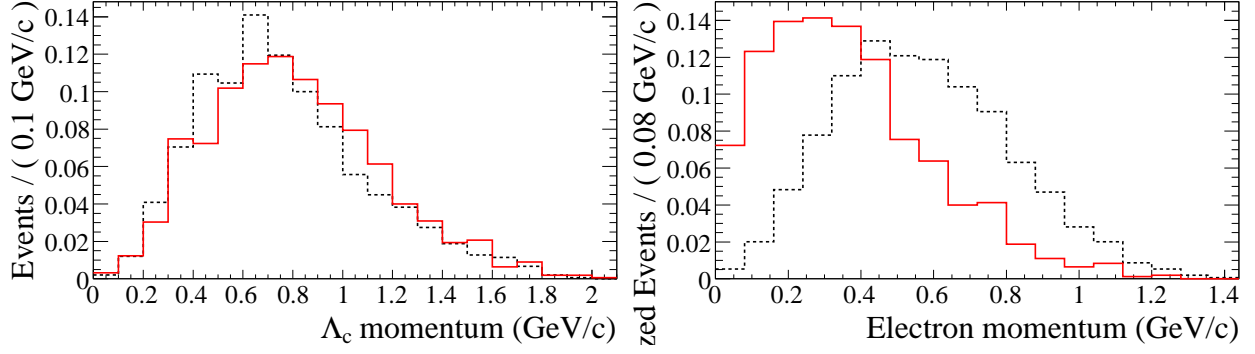


Figure 2:  $\Lambda_c^+$  and lepton momentum spectra for a sample of signal MC events using the models before tuning (dashed line) and after tuning (solid line) as described in the text.

$\Lambda_c^+$  baryons, with the correct charge-flavor correlation with the lepton, are reconstructed in the  $pK^-\pi^+$ ,  $pK_S^0$ ,  $pK_S^0\pi^+\pi^-$ ,  $\Lambda\pi^+$ ,  $\Lambda\pi^+\pi^+\pi^-$  modes.  $K_S^0$  ( $\Lambda$ ) candidates are reconstructed in the  $\pi^+\pi^-$  ( $p\pi^-$ ) decay mode.

In events with multiple  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  candidates, the candidate with the highest  $\Lambda_c^+ \ell^-$  vertex fit probability is selected.

We reconstruct  $B_{\text{tag}}$  decays of the type  $\bar{B} \rightarrow DY'$ , where  $Y'$  represents a collection of hadrons with a total charge of  $\pm 1$ , composed of  $n'_1\pi^\pm + n'_2K^\pm + n'_3K_S^0 + n'_4\pi^0$ , where  $n'_1 + n'_2 \leq 5$ ,  $n'_3 \leq 2$ , and  $n'_4 \leq 2$ . Using  $D^0$  ( $D^+$ ) and  $D^{*0}$  ( $D^{*+}$ ) as seeds for  $B^-$  ( $\bar{B}^0$ ) decays, we reconstruct about 1000 types of decay chains. For each of the  $B_{\text{tag}}$  decay modes, the purity  $\mathcal{P}$  is estimated using MC simulation.  $\mathcal{P}$  is defined as the ratio of signal over background events with  $m_{ES} \geq 5.27 \text{ GeV}/c^2$ .

The kinematic consistency of a  $B_{\text{tag}}$  candidate is checked using two variables: the beam-energy substituted mass  $m_{ES} = \sqrt{s/4 - \vec{p}_B^2}$ , and the energy difference  $\Delta E = E_B - \sqrt{s}/2$ . Here  $\sqrt{s}$  refers to the total CM energy, while  $\vec{p}_B$  and  $E_B$  denote the momentum and energy of the  $B_{\text{tag}}$  candidate in the CM frame. For correctly identified  $B_{\text{tag}}$  decays, the  $m_{ES}$  distribution peaks at the  $B$  mass, while  $\Delta E$  peaks at zero. We select a  $B_{\text{tag}}$  candidate in the signal region defined as  $5.27 \text{ GeV}/c^2 < m_{ES} < 5.29 \text{ GeV}/c^2$ , excluding  $B_{\text{tag}}$  candidates with daughter particles in common with the charmed baryon or the lepton from the  $B$  semileptonic decay.

In the case of multiple  $B_{\text{tag}}$  candidates, we select the one with the largest purity  $\mathcal{P}$  of the  $B_{\text{tag}}$  mode; in the case of multiple candidates with the same  $B_{\text{tag}}$  mode we select the one with the smallest  $|\Delta E|$  value.

The  $B_{\text{tag}}$ ,  $\Lambda_c^+$ , and  $\ell^-$  candidates are required to have the correct charge-flavor correlation.

By fully reconstructing one  $B$  in the event and by requiring the presence of a proton or  $\Lambda$  candidate, used for the  $\Lambda_c^+$  reconstruction, the resulting sample shows a high purity, as is generally the case for a tagged analysis. In order to minimize model-dependent effects that can be introduced by a specific set of selection criteria, we only require the lepton momentum to be greater than  $0.35 \text{ GeV}/c$ , as described above, and the missing momentum to be greater than  $0.2 \text{ GeV}/c$ . This last cut removes background from hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  decays in which all the particles in the  $X$  system have been reconstructed and one hadron is misidentified as a lepton. We also require the total charge of the reconstructed event to be zero, in order to reduce combinatorial background in the  $B_{\text{tag}}$  reconstruction from missing particles.

To obtain the  $B$  semileptonic signal yields, we perform a one-dimensional binned maximum likelihood fit to the  $\Lambda_c^+$  invariant mass distribution. Backgrounds to the process of interest can

be divided according to whether they contain a correctly-reconstructed  $\Lambda_c^+$  with a mass value in the signal region (peaking), and those that do not. MC studies of generic  $B\bar{B}$  and continuum events show that the peaking background comes mainly from hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  decays, with a fake electron from gamma conversions or  $\pi^0$  Dalitz decays, or a hadron misidentified as a muon. The number of peaking background events from hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  decays is estimated from the simulation, as:

$$N_{\text{peak}} = 2 \cdot \epsilon_{\text{peak}} \cdot \mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X) \cdot N_{B\bar{B}}$$

where  $\epsilon_{\text{peak}}$  is the efficiency of reconstructing fake  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  events in a hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  sample computed as the ratio of reconstructed and generated events, and  $N_{B\bar{B}}$  is the number of  $B\bar{B}$  pairs corresponding to the data luminosity. We use  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X) = (3.9 \pm 1.2)\%$ , which is the statistical average of the charged and neutral  $B$  branching fractions [1]. We estimate  $N_{\text{peak}} = 5.2 \pm 1.0_{\text{stat.}} \pm 1.7_{\text{syst.}}$  events and  $N_{\text{peak}} = 15.3 \pm 1.4_{\text{stat.}} \pm 4.9_{\text{syst.}}$  events for the electron and muon samples, respectively. The sources of systematic error are described in Sec. 6.

The  $\Lambda_c^+$  invariant mass distribution is fitted with the sum of three probability density functions (PDFs): one Gaussian for semileptonic  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  events, another Gaussian for peaking background events from hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  decays, and a first order polynomial for combinatorial  $B\bar{B}$  and continuum background events. The two Gaussians share the same mean and width, and the width is fixed to the value obtained by fitting the hadronic  $\bar{B} \rightarrow \Lambda_c^+ X$  data sample, as described in Sec. 5. The amount of peaking background PDF is fixed to the MC prediction. We first fit the  $\Lambda_c^+$  invariant mass sidebands, defined as the mass window of  $2.23 - 2.26$ ,  $2.31 - 2.34$   $\text{GeV}/c^2$ , to constrain the background PDF parameters. We then fit the  $\Lambda_c^+$  invariant mass including the signal region, where the free parameters are the signal and background yields, and the  $\Lambda_c^+$  mass mean value.

## 5 Measurement of Branching Fractions

The  $\Lambda_c^+$  invariant mass distribution is compared with the results of the fit in Figure 3 for the  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  decays, where we show separately the electron and muon sample.

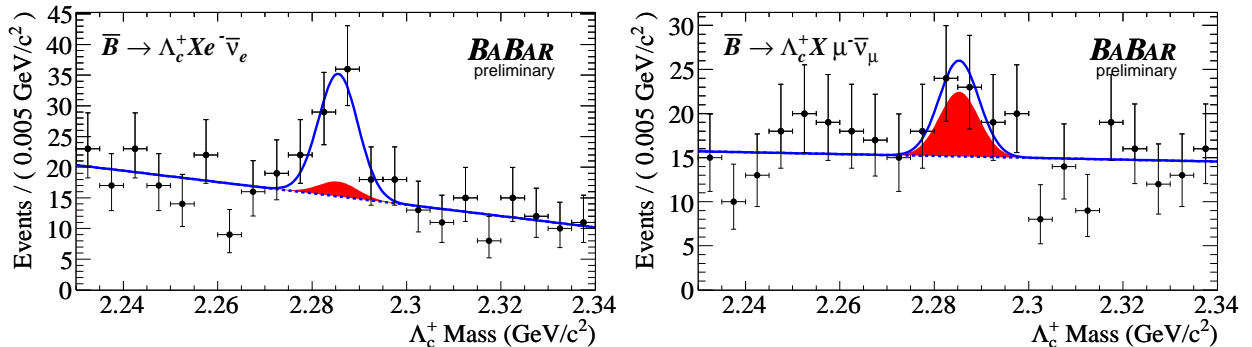


Figure 3: Fit to the  $\Lambda_c^+$  distribution for  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  (left) and  $\bar{B} \rightarrow \Lambda_c^+ X \mu^- \bar{\nu}_\mu$  (right): the data (points with error bars) are compared to the results of the overall fit (solid line). The peaking background contribution is shown with a shaded area. The combinatorial  $B\bar{B}$  and continuum background is shown with a dashed line.

In Fig. 4 and 5, we show the distributions for the  $\Lambda_c^+$  and electron momentum spectrum, and the charged and neutral pion multiplicity in the  $X$  system for the  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  sample.

These distributions are sideband-subtracted, by selecting events in the  $\Lambda_c^+$  invariant mass signal region, and subtracting the combinatorial  $B\bar{B}$  and continuum background using the invariant mass sidebands, and then corrected bin-by-bin by the efficiency estimated from the signal MC. The peaking background contribution is subtracted using the MC prediction.

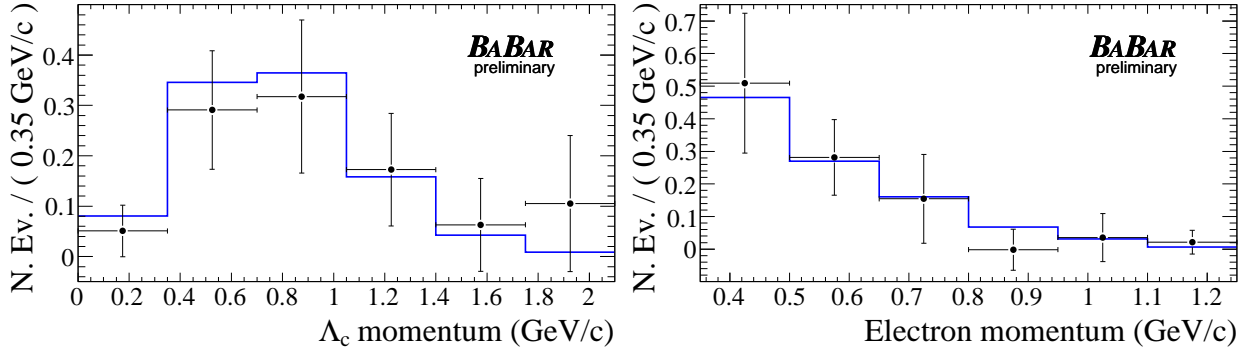


Figure 4: Sideband-subtracted, efficiency-corrected, normalized distributions for the  $\Lambda_c^+$  and electron momentum spectrum in  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  decays: the data (points with error bars) are compared to the signal MC prediction.

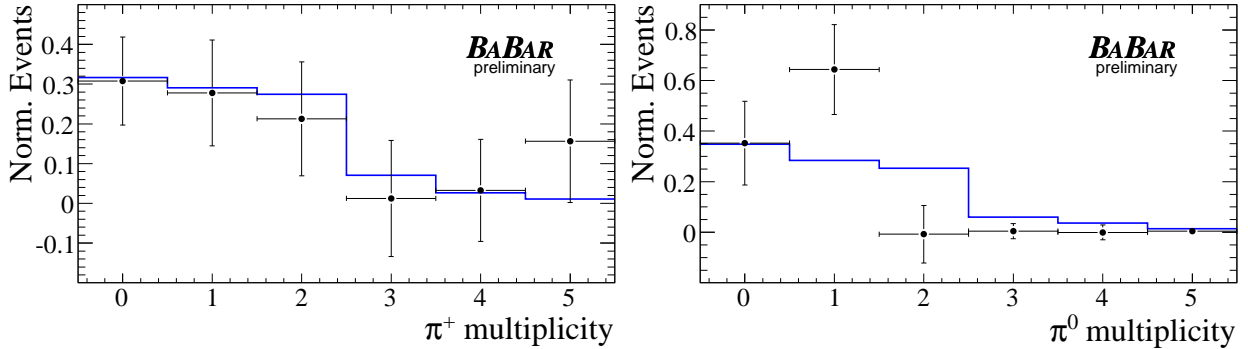


Figure 5: Sideband-subtracted, efficiency-corrected, normalized distributions for the charged and neutral pion multiplicity in the  $X$  system in  $\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$  decays: the data (points with error bars) are compared to the signal MC prediction.

In order to reduce the systematic uncertainty, the exclusive  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell)$  branching fractions are measured relative to the hadronic  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)$  branching fraction. To determine the hadronic branching fraction, we use a sample of  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)$  events selected similarly to the semileptonic channel. We select the reconstructed  $\Lambda_c^+$  candidate with the highest vertex probability, and a  $B_{\text{tag}}$  candidate in the signal region defined as  $5.27 \text{ GeV}/c^2 < m_{ES} < 5.29 \text{ GeV}/c^2$ , excluding  $B_{\text{tag}}$  candidates with daughter particles in common with the charmed baryon. In the case of multiple  $B_{\text{tag}}$  candidates, we select the one with the largest *a priori* purity of the  $B_{\text{tag}}$  mode; in the case of multiple candidates with the same  $B_{\text{tag}}$  mode (same *a priori* purity), we select the one with the smallest  $|\Delta E|$  value.

To obtain the  $\bar{B} \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X$  signal yield, we perform a one-dimensional binned maximum likelihood fit to the  $\Lambda_c^+$  invariant mass distribution with the sum of two PDFs: a single Gaussian for hadronic  $\bar{B} \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X$  events, and a first order polynomial background for combinatorial

$B\bar{B}$  and continuum background events. The  $\Lambda_c^+$  invariant mass distribution is compared with the results of the fit in Figure 6.

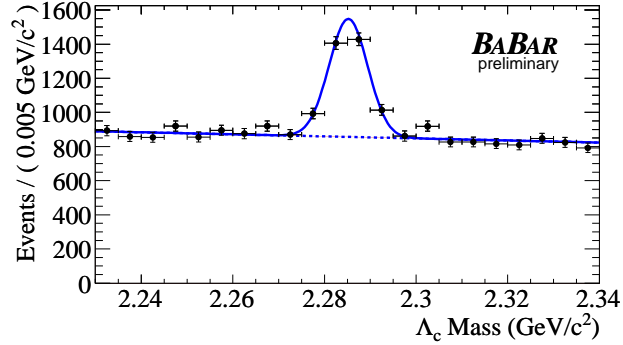


Figure 6: Fit to the  $\Lambda_c^+$  distribution for  $\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X$ : the data (points with error bars) are compared to the results of the overall fit (solid line). The combinatorial  $B\bar{B}$  and continuum background is shown with a dashed line.

Table 1: Signal yields and reconstruction efficiencies for the  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  and  $\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X$  decays with statistical errors.

Decay Mode	$N_{\text{data}}$	$\epsilon (\times 10^{-5})$
$\bar{B} \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e$	$38 \pm 10$	$2.06 \pm 0.17$
$\bar{B} \rightarrow \Lambda_c^+ X \mu^- \bar{\nu}_\mu$	$7.4 \pm 8.4$	$1.07 \pm 0.12$
$\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X$	$1432 \pm 81$	$3.02 \pm 0.13$

The relative branching fraction  $\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell)/\mathcal{B}(\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X)$  is obtained by correcting the signal yields obtained from the fit by the reconstruction efficiency ratio:

$$\frac{\mathcal{B}(B \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell)}{\mathcal{B}(B \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X)} = \left( \frac{N_{\text{semil}}}{N_{\text{had}}} \right) \left( \frac{\epsilon_{\text{had}}}{\epsilon_{\text{semil}}} \right).$$

Here,  $N_{\text{semil}}$  ( $N_{\text{had}}$ ) is the number of  $\bar{B} \rightarrow \Lambda_c^+ X$  signal events for the semileptonic (hadronic) mode, reported in Table 1 together with the corresponding reconstruction efficiencies  $\epsilon$ .

## 6 Systematic Uncertainties

By measuring the  $\bar{B} \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell$  branching fraction relative to the  $\bar{B} \rightarrow \Lambda_c^+/\bar{\Lambda}_c^- X$  branching fraction, many uncertainties in the reconstruction efficiency ratio cancel out. In particular, the uncertainties in the  $\Lambda_c^+$  and  $B_{\text{tag}}$  reconstruction efficiencies and the  $\Lambda_c^+$  decay branching fractions do not contribute.

We categorize the remaining systematic uncertainties into additive uncertainties which directly affect the signal yield, and multiplicative uncertainties which affect only the branching fraction ratio. The systematic uncertainties that have been considered are described below and summarized in Tab. 2.

Table 2: Table of systematic uncertainties. The additive errors (errors on the signal yield) are shown in units of events. The multiplicative errors (errors on the reconstruction efficiency) are shown in units of percent.

Additive systematics	$\overline{B} \rightarrow \Lambda_c^+ X e^- \overline{\nu}_e$	$\overline{B} \rightarrow \Lambda_c^+ X \mu^- \overline{\nu}_\mu$
Peaking background statistics (ev.)	1.0	1.4
Uncertainty in $\mathcal{B}(\overline{B} \rightarrow \Lambda_c^+ X)$ (ev.)	1.6	4.7
Lepton misidentification rate (ev.)	0.7	2.0
Fit bias (ev.)	0.3	1.2
Total additive (ev.)	2.0	5.4
Multiplicative systematics	$\overline{B} \rightarrow \Lambda_c^+ X e^- \overline{\nu}_e$	$\overline{B} \rightarrow \Lambda_c^+ X \mu^- \overline{\nu}_\mu$
Reconstruction efficiency statistics (%)	8.4	11.4
Model dependence (lepton momentum) (%)	22.6	71.8
Model dependence ( $\Lambda_c^+$ momentum) (%)	7.5	7.5
Lepton identification efficiency (%)	1.1	2.7
Selection order (%)	3.7	44.6
Total multiplicative (%)	25.5	85.7

## 6.1 Additive Systematics

Systematic uncertainties in the signal yield are dominated by the peaking-background yield estimate. We evaluate this uncertainty by propagating the uncertainty in the  $\overline{B} \rightarrow \Lambda_c^+ X$  branching fraction, and the Poisson error due to the limited hadronic MC statistics. We also vary the lepton misidentification probabilities by 15% for both electrons and muons, and add in quadrature the corresponding variation in the peaking background rate. To evaluate the effect of a bias in the fit technique, we perform ensembles of MC experiments, in which events are generated according to the PDF shapes measured on data, varying the signal to background rate, and fitting for the signal as in the full analysis. The difference between the fitted value of the yield and the true value is taken as a systematic error.

## 6.2 Multiplicative Systematics

Systematic uncertainties which affect the reconstruction efficiency ratio are dominated by the uncertainty in the signal model. To estimate this, we look for deviations in the reconstruction efficiency as we vary the tuning parameters of the signal model. The deviation in the electron spectrum is taken as the  $\Delta\chi^2/\text{n.d.f.} = 1$  difference, where  $\Delta\chi^2$  is the data-MC difference divided by the statistical error on data, added in quadrature for each bin of momentum, and n.d.f. = 6 is the number of bins. The deviation in the  $\Lambda_c^+$  spectrum is taken as the variation in the efficiency as a function of  $\Lambda_c^+$  momentum. We also include the Poisson error contribution of the limited signal MC statistics. We estimate the systematic uncertainty due to particle identification by varying the electron (muon) identification efficiency by 2% (3%). Because the event selection order is slightly different in the semileptonic and hadronic sample selections, the reconstruction efficiency systematics do not exactly cancel. We evaluate the corresponding systematic uncertainty by reversing the order of the lepton and  $B_{\text{tag}}$  selection, taking the difference in the signal yield, corrected by the reconstruction efficiency, as the systematic error. The large systematic uncertainty coming from the selection order in the muon channel is due to the low statistics of the muon sample.

## 7 Results

We measure the following branching ratios:

$$\frac{\mathcal{B}(B \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e)}{\mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)} = (3.9 \pm 1.0_{\text{stat.}} \pm 1.1_{\text{syst.}})\% \quad (2)$$

$$\frac{\mathcal{B}(B \rightarrow \Lambda_c^+ X \mu^- \bar{\nu}_\mu)}{\mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)} = (1.5 \pm 1.7_{\text{stat.}} \pm 1.7_{\text{syst.}})\%. \quad (3)$$

The result for the electron channel is compatible with the CLEO result [3] of  $\mathcal{B}(B \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e) / \mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X) < 0.05$ . Despite the lower value of the muon result, the two channels are compatible within their errors. Taking the weighted average of the two channels, we obtain:

$$\frac{\mathcal{B}(B \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell)}{\mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)} = (3.2 \pm 0.9_{\text{stat.}} \pm 0.9_{\text{syst.}})\%. \quad (4)$$

By using the hadronic branching fraction  $\mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X) = (4.5 \pm 1.2)\%$  [1], we obtain:

$$\mathcal{B}(B \rightarrow \Lambda_c^+ X e^- \bar{\nu}_e) = (1.8 \pm 0.5_{\text{stat.}} \pm 0.7_{\text{syst.}}) \times 10^{-3} \quad (5)$$

$$\mathcal{B}(B \rightarrow \Lambda_c^+ X \mu^- \bar{\nu}_\mu) = (6.6 \pm 7.5_{\text{stat.}} \pm 7.6_{\text{syst.}}) \times 10^{-4} \quad (6)$$

$$\mathcal{B}(B \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell) = (1.5 \pm 0.4_{\text{stat.}} \pm 0.6_{\text{syst.}}) \times 10^{-3}. \quad (7)$$

We evaluate the significance  $\mathcal{S}$  of our result using the log likelihood ratio  $-2 \log(\mathcal{L}_{\text{max}}/\mathcal{L}_0)$  where  $\mathcal{L}_{\text{max}}$  is the maximum likelihood and  $\mathcal{L}_0$  is the likelihood value fixing the signal yield to be zero, including statistical and systematic errors:

$$\mathcal{S}_e = \sqrt{-2 \log(\mathcal{L}_{\text{max}}/\mathcal{L}_0)} = 4.6 \quad (8)$$

$$\mathcal{S}_\mu = \sqrt{-2 \log(\mathcal{L}_{\text{max}}/\mathcal{L}_0)} = 0.8 \quad (9)$$

where the subscript  $e$  and  $\mu$  denotes the electron and muon channels, respectively. The probability  $P$  that our measured signal results from a background fluctuation are computed from these  $\mathcal{S}$  values to be  $P_e = 2.2 \times 10^{-6}$  and  $P_\mu = 0.22$ . In order to compute the significance for the combined result, we take the product of these two probabilities:  $P_\ell = 4.8 \times 10^{-7}$ . Converting this back to the significance, we obtain  $\mathcal{S}_\ell = 4.9$  for the combined result.

In conclusion, we present the first evidence for  $B$  semileptonic decays into the charmed baryon  $\Lambda_c^+$ . The relative branching fraction  $\mathcal{B}(B \rightarrow \Lambda_c^+ X \ell^- \bar{\nu}_\ell) / \mathcal{B}(B \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X)$  is found to be smaller than the corresponding one for the  $D$  charmed meson. We measure the  $\Lambda_c^+$  and electron momentum spectrum in the  $B$  semileptonic decay, which could be of guidance to further development in the theoretical modeling of these decays.

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