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New Decay Modes of the Λ_c^+ Charmed Baryon

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Abstract

We have observed five new decay modes of the charmed baryon Λ_c^+ using data collected with the CLEO II detector. Four decay modes, $\Lambda_c^+ \to p\bar{K}^0\eta$, $\Lambda\eta\pi^+$, $\Sigma^+\eta$, and $\Sigma^{*+}\eta$, are first observations of final states with an η meson, while the fifth mode, $\Lambda_c^+ \to \Lambda\bar{K}^0K^+$, requires the creation of an $s\bar{s}$ quark pair. We measure the branching fractions of these modes relative to $\Lambda_c^+ \to pK^-\pi^+$ to be $0.25 \pm 0.04 \pm 0.04$, $0.35 \pm 0.05 \pm 0.06$, $0.11 \pm 0.03 \pm 0.02$, $0.17 \pm 0.04 \pm 0.03$, and $0.12 \pm 0.02 \pm 0.02$, respectively.

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In the past year, CLEO has measured the exclusive decays of the Λ_c^+ into $\Lambda(n\pi)^+$, $\Sigma^0(n\pi)^+$, $\Sigma^+(n\pi)^0$, $pK^-(n\pi)^+$, and $pK_s^0(n\pi)^0$, where $n \leq 3$ and includes up to one π^0 [1–3]. In addition, CLEO has observed decays that are expected to occur solely through the W-exchange diagram (neglecting final state interactions), namely $\Lambda_c^+ \to \Sigma^+K^+K^-$, Ξ^0K^+, and $\Xi^-K^+\pi^+$ [4]. However, only $\sim 35\%$ of the Λ_c^+ hadronic decay modes have been accounted for [5]. Missing are higher multiplicity Λ_c^+ decay modes, especially those with multiple π^0's, and modes with Σ^- hyperons or neutrons in the final state, which are experimentally difficult to measure. Clearly, a substantial number of Λ_c^+ decay modes remain to be discovered.

This Letter presents results on five new Λ_c^+ decay modes. These include the first observation of four Λ_c^+ decay modes with an η meson in the final state, namely $\Lambda_c^+ \to pK_s^0\eta$, $\Lambda\eta\pi^+$, $\Sigma^+\eta$, and $\Sigma^{*+}\eta$. The fifth mode is $\Lambda_c^+ \to \Lambda K_s^0K^+$, which involves the creation of an $s\bar{s}$ quark pair. The decay modes discussed also include the charge conjugate states.

The data were collected with the CLEO II detector at the Cornell e^+e^- storage ring CESR, which operated on and just below the $\Upsilon(4S)$ resonance. The CLEO II detector [6] is a large solenoidal detector with 67 tracking layers and a CsI electromagnetic calorimeter that provides excellent π^0 and η reconstruction. We have used a total integrated luminosity of 3.25 fb^{-1}, which corresponds to ~ 4 million $c\bar{c}$ events.

The η candidates are selected through the decay $\eta \to \gamma\gamma$ from pairs of well-defined showers in the CsI calorimeter. To reduce random combinations of low energy photons, we require $E_\gamma > 0.15$ GeV for each photon candidate and $P_\eta > 0.5$ GeV/c. Photon candidates must not be associated with charged tracks and must have lateral shower shapes consistent with those expected for real photons. At least one of the photon candidates must lie in the barrel region defined by $|\cos\theta| < 0.71$, where θ is the polar angle with respect to the beam line. Photons are vetoed as η daughters if they can be paired with a second photon such that the $\gamma\gamma$ pair has an invariant mass within 2.5σ of the π^0 mass ($\sigma \sim 5$ MeV/c^2) and a momentum greater than 0.4 GeV/c. We select η candidates that are within 30 MeV/c^2 of the nominal η mass. Finally, we kinematically fit the photon momenta to the nominal η mass in order to improve the η momentum estimate.

Charged proton, kaon, and pion candidates are required to have a specific ionization loss (dE/dx) and, when available, time-of-flight information consistent with the value expected for the assumed particle type. We use a clean sample of $\Lambda \to p\pi^-$, $D^0 \to K^-\pi^+$ from D^{*+}'s, and $K_s^0 \to \pi^+\pi^-$ to measure the particle identification efficiencies directly from the data for protons, kaons, and pions, respectively.

The K_s^0 and Λ candidates are selected through their decays $K_s^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ by reconstructing a secondary decay vertex from the intersection of two oppositely charged tracks in the $r - \phi$ plane. The Σ^+ hyperon candidates are selected from $p\pi^0$ combinations that are consistent with coming from a decay vertex displaced from the primary interaction point [2]. The invariant masses of the K_s^0, Λ, and Σ^+ candidates must lie within 15, 5, and 15 MeV/c^2 of their nominal values, respectively.

Charmed baryons from $e^+e^- \to c\bar{c}$ interactions are produced with a hard momentum spectrum, so we reduce the combinatoric background by requiring $x_p > 0.4 - 0.6$, depending on the decay mode. Here, $x_p = P_{\Lambda_c^+}/\sqrt{E_{beam}^2 - M_{\Lambda_c^+}^2}$ is the scaled momentum of the Λ_c^+. The x_p cut eliminates Λ_c^+ baryons that arise from B meson decays. In addition, we require that the daughter particles of the Λ_c^+ lie within 90 degrees of the candidate Λ_c^+ momentum vector.

The invariant mass distribution for $\Lambda_c^+ \to pK_s^0\eta$ candidates with $x_p > 0.5$ is shown in Figure 1. For this mode only, we tightened the particle identification criteria for the proton by requiring that the probability the candidate is a proton be at least 90% of the sum of probabilities for the proton, kaon, and pion hypotheses. We parametrize the mass distribution by a Gaussian signal and a 3rd order Chebyshev polynomial background. The width of the Gaussian is taken from Monte Carlo studies to be $\sigma = 6.6$ MeV/c^2. We observe 57 ± 10 $\Lambda_c^+ \to pK_s^0\eta$ events at a mass of 2286.7 ± 1.3 MeV/c^2 (statistical error only), consistent with the nominal Λ_c^+ mass.

The invariant mass distribution for $\Lambda_c^+ \to \Lambda\eta\pi^+$ candidates with $x_p > 0.5$ is shown in Figure 2. The signal is fit to a Gaussian whose width is fixed to the Monte Carlo expectation of 8.6 MeV/c^2; the background is parametrized by a quadratic polynomial. We observe 116 ± 16 events at a mass of 2288.5 ± 1.4 MeV/c^2.

A search was made for the two-body decay $\Lambda_c^+ \to \Sigma^{*+}(1385)\eta$ by examining the resonant substructure of the $\Lambda\eta\pi^+$ mode. Figure 5 shows the invariant mass for $\Lambda\pi^+$ pairs in the $\Lambda_c^+ \to \Lambda\eta\pi^+$ mass signal region ($\pm2\sigma$) after subtracting combinations from the Λ_c^+ sideband region ($2.5-4.5\sigma$). A clear Σ^{*+} peak is visible, which we fit to a Breit-Wigner distribution of width 36 MeV/c^2 plus the $\Lambda\pi^+$ mass distribution from the non-resonant decay of $\Lambda_c^+ \to \Lambda\eta\pi^+$. The fit yields 54 ± 14 events at a mass of 1381 ± 5 MeV/c^2. This implies roughly half of the $\Lambda_c^+ \to \Lambda\eta\pi^+$ decays are due to the two-body decay $\Lambda_c^+ \to \Sigma^{*+}\eta$, neglecting any interference effects from other decay modes such as $\Lambda_c^+ \to \Lambda a_0(980)$ where $a_0 \to \eta\pi^+$. We searched for the Λa_0 decay. However, because the a_0 width is quite large and not well measured (50–300 MeV/c^2) [5], we could not constrain the Λa_0 decay component.

The invariant mass distribution for the two-body decay $\Lambda_c^+ \to \Sigma^+\eta$ is shown in Figure 3. We demand that the η, Σ^+, and $\Sigma^+\eta$ candidates have high momenta: $P_\eta > 0.8$ GeV/c, $P_{\Sigma^+} > 1.0$ GeV/c, and $x_p(\Lambda_c^+) > 0.6$, respectively. The π^0 veto on photons from η mesons is not imposed because the combinatoric background for higher momenta η's is less severe. The $\Sigma^+\eta$ mass distribution is fit to the sum of a Gaussian whose width is constrained to the Monte Carlo prediction of 13.6 MeV/c^2 and a quadratic background. We observe a $\Lambda_c^+ \to \Sigma^+\eta$ signal of 26 ± 7 events at a mass of 2286 ± 4 MeV/c^2.

The $\Lambda_c^+ \to \Lambda K_s^0 K^+$ invariant mass distribution is shown in Figure 4. A less stringent Λ_c^+ momentum cut of $x_p > 0.4$ is used since the background level is low due to the clean K_s^0 and Λ signals and the limited phase space available for this decay. The Gaussian width is fixed to the Monte Carlo expectation of 4.0 MeV/c^2 and a linear background is assumed. We observe a Λ_c^+ signal of 59 ± 9 events at a mass of 2286.5 ± 0.7 MeV/c^2. There is no indication of the resonant substructure $\Lambda_c^+ \to \Lambda a_0(980)$ with a_0 decaying into $K_s^0 K^+$.

Since the Λ_c^+ cross section is unknown, we convert our observations into branching fractions relative to the well measured decay mode $\Lambda_c^+ \to pK^-\pi^+$. For each mode we apply the same proton identification and Λ_c^+ momentum cut to the $\Lambda_c^+ \to pK^-\pi^+$ sample in order to reduce the systematic errors associated with these requirements. The raw yields, efficiencies, and resultant branching fractions for all decay modes are shown in Table I. The major contributions to the systematic errors are due to K_s^0, Λ, and Σ^+ reconstruction ($5-6\%$), η reconstruction (5%), resonant substructure in the decay modes $\Lambda_c^+ \to pK^-\pi^+$ ($2-7\%$) and $\Lambda_c^+ \to \Lambda\eta\pi^+$ (10%), signal widths in the fits to the invariant mass distributions ($4-7\%$), and variations in the selection criteria ($9-15\%$). We have verified that backgrounds from

TABLE I. Summary of results on new Λ_c^+ decay modes. The efficiencies ($\mathcal{E}$) do not include branching fractions to the observed final states.

Decay Mode	Events	$\mathcal{E}$ (%)	$\mathcal{B}/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$
$p\bar{K}^0\eta$	57 ± 10	7.2	$0.25 \pm 0.04 \pm 0.04$
$\Lambda\eta\pi^+$	116 ± 16	6.4	$0.35 \pm 0.05 \pm 0.06$
$\Sigma^+\eta$	26 ± 7	7.8	$0.11 \pm 0.03 \pm 0.02$
$\Sigma^{*+}\eta$	54 ± 14	6.8	$0.17 \pm 0.04 \pm 0.03$
$\Lambda\bar{K}^0K^+$	59 ± 9	8.9	$0.12 \pm 0.02 \pm 0.02$

TABLE II. Comparison of experimental branching fractions to theoretical predictions for the two-body decays $\Lambda_c^+ \to \Sigma^+\pi^0$, $\Sigma^+\eta$, and $\Sigma^{*+}\eta$ relative to $\Lambda_c^+ \to pK^-\pi^+$.

	$\Sigma^+\pi^0$ [2]	$\Sigma^+\eta$	$\Sigma^{*+}\eta$
CLEO	0.20 ± 0.04	0.11 ± 0.04	0.17 ± 0.05
Körner & Krämer [8]	0.07	0.04	0.24
Zenczykowski [9]	0.10	0.06	—
Uppal *et al.* [10]	0.13–0.58	0.05–0.24	—

misidentified D^+ and D_s^+ decays do not peak in the Λ_c^+ signal region. For example, the $pK_s^0\eta$ and $\Lambda\eta\pi^+$ invariant mass distributions show no contribution from possible misidentified $D^+ \to K_s^0\eta\pi^+$ decays.

The decay rates for the modes with an η meson are about 2.0–2.5 times smaller than the related modes with a π^0, namely $\Lambda_c^+ \to p\bar{K}^0\pi^0$, $\Lambda\pi^+\pi^0$, and $\Sigma^+\pi^0$ [7], which is consistent with the light quark content of the η being $\sim 1/3$ that of the π^0. In addition, the relative branching fraction for $\Lambda_c^+ \to \Lambda\bar{K}^0K^+$ is roughly six times smaller than the related decay mode without the $s\bar{s}$ pair creation, $\Lambda_c^+ \to \Lambda\pi^+\pi^0$.

The two-body decay modes $\Lambda_c^+ \to \Sigma^+\eta$ and $\Sigma^{*+}\eta$ are expected to proceed entirely through nonfactorizable internal W-emission and W-exchange diagrams. Unlike in charmed meson decays, these nonfactorizable decays are not color or helicity suppressed and contribute to the Λ_c^+ lifetime being approximately half of the D^0 and D_s^+ meson lifetimes.

Körner and Krämer [8], Zenczykowski [9], and Uppal *et al.* [10] have used quark and pole models to make theoretical predictions for the Λ_c^+ decays into two-body final states with Σ^+ and Σ^{*+} hyperons. We have converted their decay rates into relative branching fractions, shown in Table II, using the PDG values for the Λ_c^+ lifetime and $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ [5]. The high (low) value in Uppal's prediction includes (excludes) the effect of flavor dependence on the scale $|\psi(0)|^2$. The theoretical estimates agree with our results within a factor of two. The ratio $\mathcal{B}(\Sigma^+\eta)/\mathcal{B}(\Sigma^+\pi^0)$ shows better agreement between theory and experiment.

In summary, we have observed five new decay modes of the charmed baryon Λ_c^+. Four decay modes, $\Lambda_c^+ \to p\bar{K}^0\eta$, $\Lambda\eta\pi^+$, $\Sigma^+\eta$, and $\Sigma^{*+}\eta$, contain an η meson in the final state, while the fifth decay mode, $\Lambda_c^+ \to \Lambda\bar{K}^0K^+$, requires the creation of an $s\bar{s}$ quark pair. The branching fractions are measured relative to the decay mode $\Lambda_c^+ \to pK^-\pi^+$. Altogether, these new decay modes account for $\sim 4\%$ of all Λ_c^+ decays.

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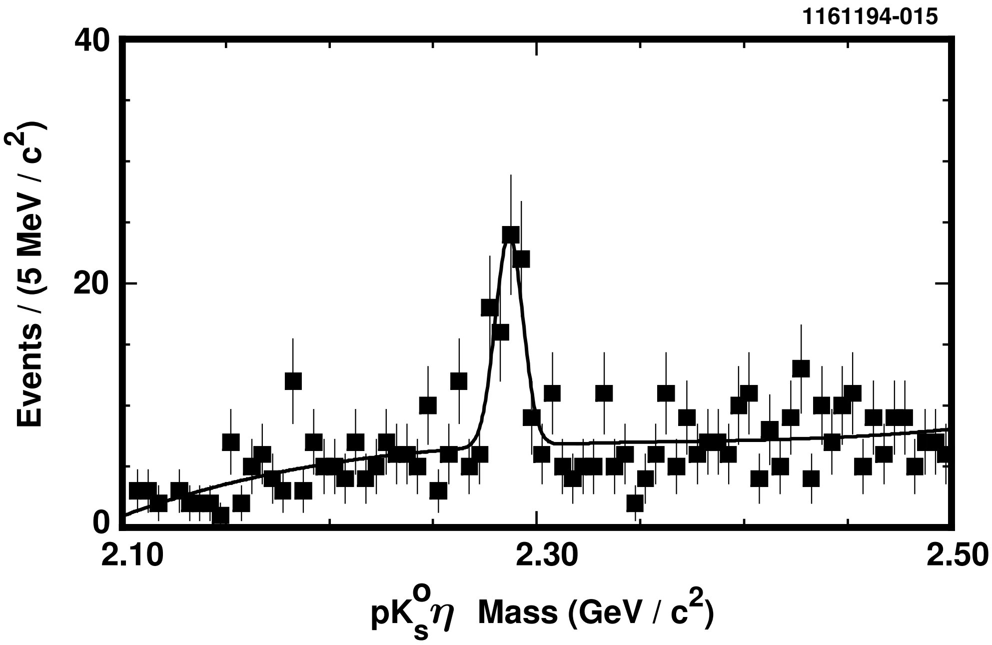

FIG. 1. Invariant mass distribution for $\Lambda_c^+ \to pK_s^0\eta$.

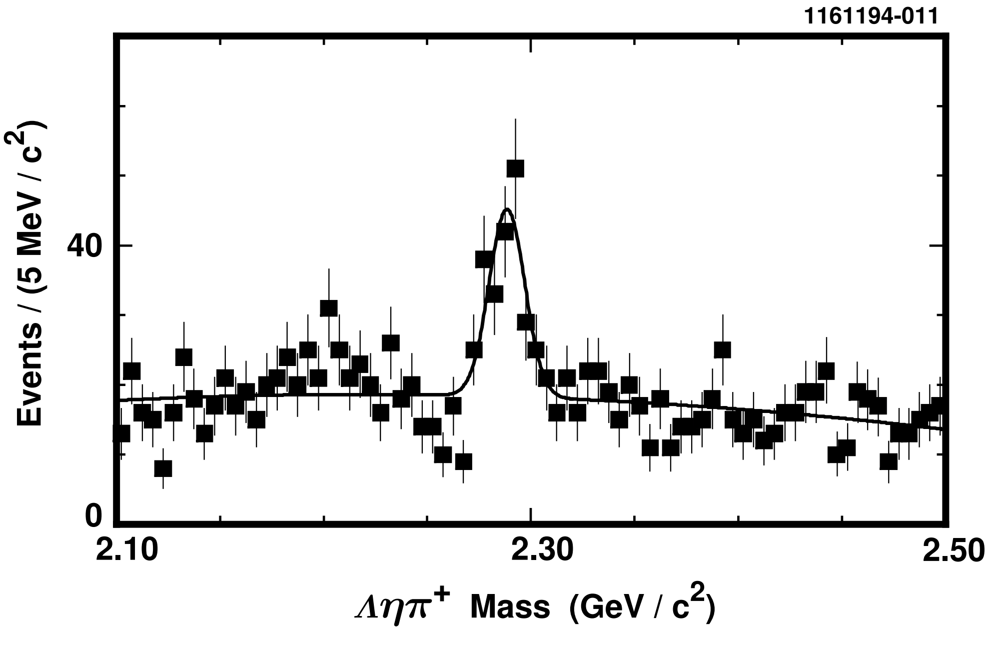

FIG. 2. Invariant mass distribution for $\Lambda_c^+ \to \Lambda\eta\pi^+$.

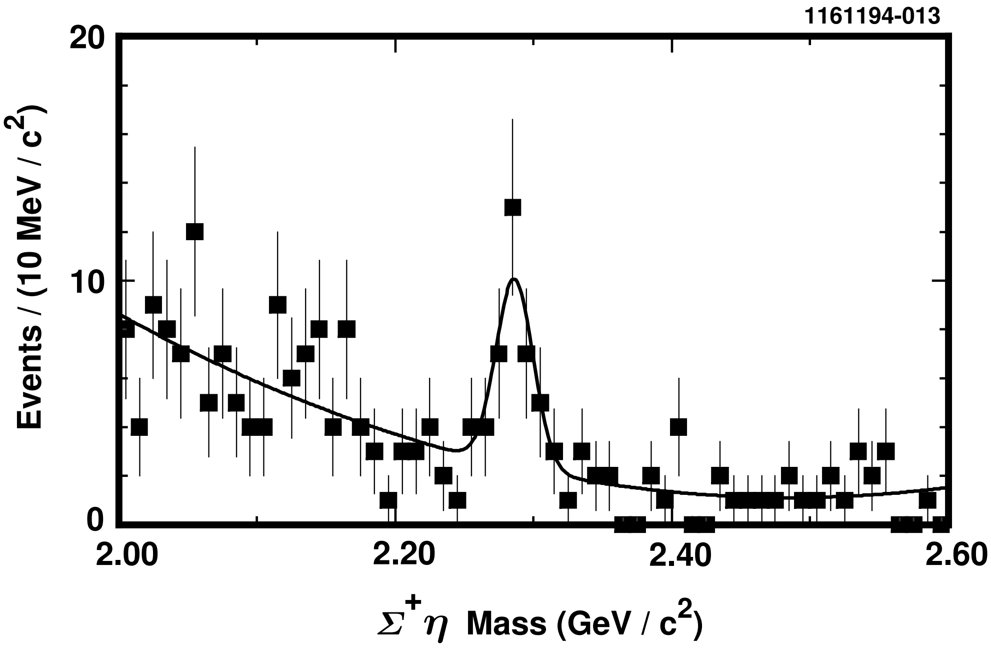

FIG. 3. Invariant mass distribution for $\Lambda_c^+ \to \Sigma^+\eta$.

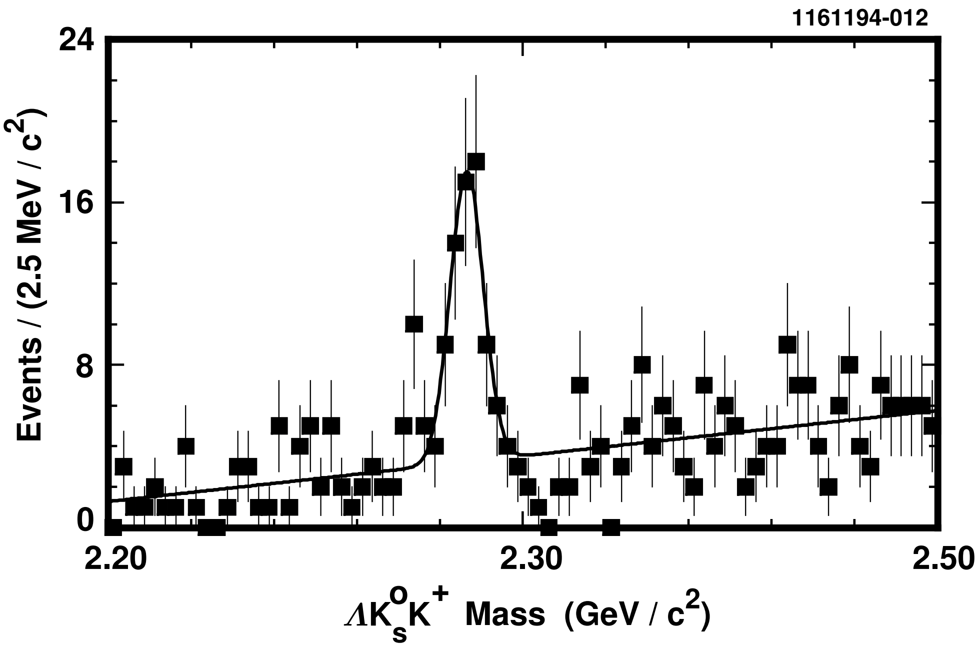

FIG. 4. Invariant mass distribution for $\Lambda_c^+ \to \Lambda K_s^0 K^+$.

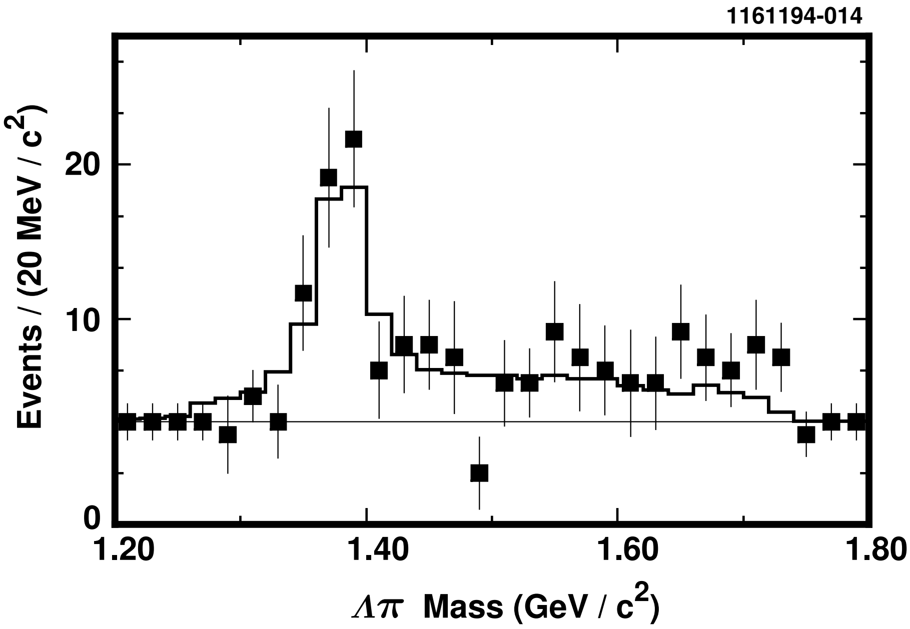

FIG. 5. The $\Lambda\pi^+$ invariant mass distribution for $\Lambda_c^+ \to \Lambda\eta\pi^+$ candidates showing the $\Sigma^{*+}(1385)$ resonance. The points are data and the histogram is a fit to a Breit-Wigner signal and a phase space background.