Recent Results on Λ_c Decays at BESIII

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Abstract. As the lightest and most common charmed baryon, the Λ_c^+ plays a key role in our understanding of particles of this type. The BESIII detector has collected a 567 pb^{-1} sample of e^+e^- annihilation data near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold. Using a double-tag technique, we make absolute measurements of twelve Cabibbo-favored Λ_c^+ hadronic decay modes, including the golden reference mode $pK^-\pi^+$, for which we find $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.84 \pm 0.27(\text{stat}) \pm 0.23(\text{syst}))\%$. We also determine $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.63 \pm 0.38(\text{stat}) \pm 0.20(\text{syst}))\%$. Preliminary results for other final states, including $nK_S\pi^+$ and $\Lambda\mu\nu_\mu$, are also presented, along with future prospects.

1. Introduction

The Λ_c^+ baryon is the ground state of charmed baryons. Most excited Λ_c and Σ_c baryons eventually decay into a Λ_c^+ (with the exception of the decay to the pD final state), and the major decays of Λ_b baryons include a Λ_c^+ [1]. Thus, the study of the Λ_c^+ provides an important normalization to the measurements of Λ_b, Λ_c and Σ_c baryons, reducing the uncertainties in measurements of these heavier baryons. Since there is no lighter baryon containing a charm quark, Λ_c^+ can only decay through the weak interaction, and is the most common of the four weakly-decaying charmed baryons.

It has been more than 30 years since the Mark II experiment discovered the Λ_c^+ baryon in 1979 [2]. However, many hadronic decays have not been measured. Among the reported measurements of branching fractions, most are relative to the decay mode $\Lambda_c^+ \to pK^-\pi^+$. Recently, the Belle experiment reported $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$ [3]. The absolute branching fraction of this decay mode has not yet been measured using threshold data and many other hadronic branching fractions still have poor precision [1]. The high statistics Λ_c^+ data collected at the BESIII experiment near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold therefore provide an excellent opportunity to perform precise measurement of Λ_c^+ decays.

2. Measurements near $\Lambda_c^+\bar{\Lambda}_c^-$ threshold

In 2014, the BESIII experiment collected the largest Λ_c^+ data sample to date near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold. Utilizing e^+e^- annihilations, BESIII collected an integrated luminosity of 567 pb^{-1} of data at $\sqrt{s} = 4.599$ GeV, which is 26 MeV above the $\Lambda_c^+\bar{\Lambda}_c^-$ pair mass. This energy is not enough for the production of even one additional pion. The data taken near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold is therefore very clean and can take advantage of "tagging" techniques.

There are two types of samples used in the tagging technique: single tag (ST) and double tag (DT) samples. In the ST sample, only one Λ_c candidate is reconstructed through a chosen hadronic decay without any requirement on the remaining tracks and showers. In the DT sample, both a Λ_c^+ and a $\bar{\Lambda}_c^-$ are reconstructed, where the Λ_c^+ is reconstructed through the hadronic decay of interest and is called "the signal side" and the $\bar{\Lambda}_c^-$, called "the tag side", is usually reconstructed through well-known and clean hadronic decay modes. Charge-conjugate states are implied throughout this paper. The signal yield of the ST sample is given by $N_j^{ST} = 2N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_j\varepsilon_j$, and the signal yield of the DT sample is given by $N_{i,j}^{DT} = 2N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_i\mathcal{B}_j\varepsilon_{i,j}$, where i and j indicate a certain decay mode, $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs, $\mathcal{B}$ is the branching fraction, and ε is the corresponding efficiency. The branching fraction of the signal side is determined by isolating B_i such that $\mathcal{B}_i = N_{i,j}^{DT}\varepsilon_j/N_j^{ST}\varepsilon_{i,j}$. The total number of produced $\Lambda_c^+\bar{\Lambda}_c^-$ events cancels, and many systematic uncertainties associated with the tag side also cancel.

3. Absolute hadronic branching fractions of Λ_c^+ baryon

Most branching fractions of Λ_c^+ decays are studied by their ratios to "the golden reference mode", $\Lambda_c^+ \to pK^-\pi^+$. Hence, an absolute measurement of the golden reference mode is crucial. Using the largest $\Lambda_c^+\bar{\Lambda}_c^-$ threshold sample, the BESIII Collaboration recently reported absolute branching fractions of twelve Cabibbo-favored Λ_c^+ hadronic decay modes, including $\Lambda_c^+ \to pK^-\pi^+$ [4].

To obtain signal yields, we define the beam-constrained mass $M_{\rm BC}$ of the Λ_c candidates calculated by substituting the beam energy $E_{\rm beam}$ for the measured Λ_c energy. The fits to ST $M_{\rm BC}$ distributions are shown in Figure 1. BESIII obtains the ST and DT signal yields of the twelve Cabibbo-favored decay modes and further implements a global least-squares fit by considering the correlations to improve precision and obtain proper uncertainties. The branching fraction of $\Lambda_c^+ \to pK^-\pi^+$ is determined to be $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.84\pm0.27(\text{stat})\pm 0.23(\text{syst}))\%$. The precision of the other eleven Cabibbo-favored hadronic decay modes is also improved significantly, compared to 2014 PDG values, shown in Table 1.

Table 1. Comparison of the measured branching fractions in this work with previous results from 2014 PDG [1]. For our results, the first uncertainties are statistical and the second are systematic.

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

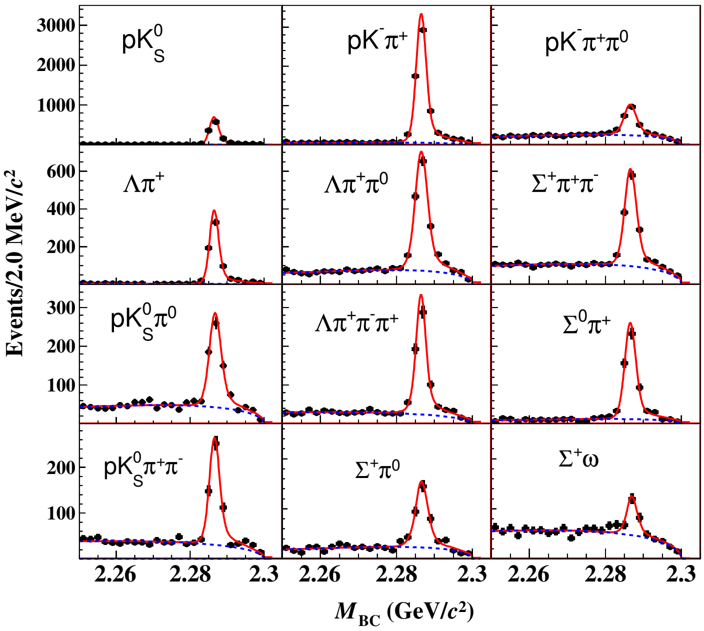

Figure 1. Fits to the ST M_{BC} distributions for the different decay modes. Points with error bars are data, solid lines are the sum of the fit functions, and dashed lines are the background shape. (Taken from [4])

4. Measurement of the absolute branching fraction for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

The BESIII Collaboration recently published the first absolute measurement of the branching fraction for the semi-leptonic decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ [5]. This semi-leptonic decay of Λ_c^+, coming from the dominant Cabibbo-favored $c \to s e^+ \nu_e$ transition, is a benchmark for all other Λ_c^+ semi-leptonic decays. However, various Λ_c^+ form-factor models result in a wide range of theoretical predictions, from 1.4% to 9.2%, for the branching fraction.

We first single-tag the $\bar{\Lambda}_c^-$ through the eleven of the hadronic decay modes in Table 1, excluding $\Sigma^+\omega$. Then, we reconstruct the Λ and e^+, leaving the neutrino undetected. To obtain the neutrino information, the variable $U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$ is used, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum carried by the neutrino, respectively. They can be calculated as $E_{\rm miss} = E_{\rm beam} - E_\Lambda - E_{e^+}$ and $\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \vec{p}_\Lambda - \vec{p}_{e^+}$, where $\vec{p}_{\Lambda_c^+}$, $\vec{p}_\Lambda$, $\vec{p}_{e^+}$ are the momenta of the Λ_c^+, the λ and the e^+, respectively, while E_Λ and E_{e^+} are the energies of the Λ and the e^+, respectively. Here, $\vec{p}_{\Lambda_c^+}$ is obtained by using the direction opposite the measured momentum of the $\bar{\Lambda}_c^-$ with the magnitude constrained to be $|\vec{p}_{\Lambda_c^+}| = \sqrt{E^2_{\rm beam} - m^2_{\Lambda_c^+}}$, where $m_{\Lambda_c^+}$ is the mass of Λ_c^+ from the PDG.

The fit to $U_{\rm miss}$ is shown in Figure 2. The branching fraction for Λ_c^+ decays to $\Lambda e^+ \nu_e$ is measured to be $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38({\rm stat}) \pm 0.20({\rm syst}))\%$. This result is a significant improvement on the PDG value of $(2.9 \pm 0.5)\%$, and provides a powerful constraint on theoretical models.

5. Measurement of the absolute branching fraction for $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$

We also studied $\Lambda \mu^+ \nu_\mu$ decays of the Λ_c^+. With the result of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ in hand, the ratio $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)/\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)$ tests lepton universality in baryonic decays. We use a technique analogous to that of $\Lambda_c^+ \to \Lambda e^+ \nu_e$, with $U_{\rm miss}$ used as the final signal

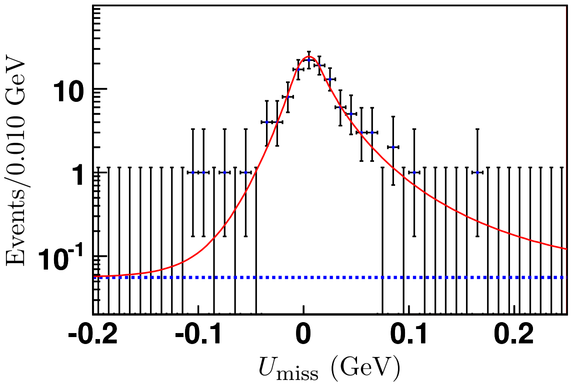

Figure 2. Fit to the $U_{\rm miss}$ distribution. The points with error bars are data, the (red) solid curve shows the total fit, and the (blue) dashed curve is the background shape. (Taken from [5])

variable. However, the background is higher in the case of $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$, due to the ambiguity in separating μ and π. Thus, a cut on the mass of the $\Lambda\mu^+$ system is used to suppress $\Lambda_c^+ \to \Lambda\pi^+$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ processes. A cut on extra energy deposits in the electro magnetic calorimeter is applied to suppress the $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ background. The fitting model includes MC-drive background shapes to simulate the remaining background, shown in Figure 3. The preliminary result for the branching fraction is determined to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.49 \pm 0.46(\text{stat}) \pm 0.26(\text{syst}))\%$, and the ratio is determined to be $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)/\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (0.96 \pm 0.16(\text{stat}) \pm 0.04(\text{syst}))\%$.

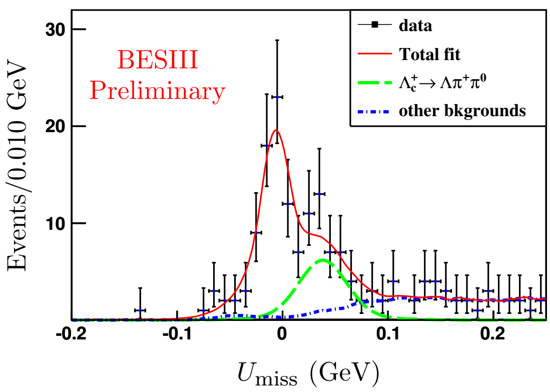

Figure 3. Fit to the $U_{\rm miss}$ distribution. Data are shown as the dots with error bars. The long-dashed curve (green) shows the $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ background while the dot-dashed curve (blue) shows other Λ_c^+ decay backgrounds. The thick line (red) shows the total fit.

6. Observation of $\Lambda_c^+ \to nK_S^0\pi^+$

Comparing branching fractions for $\Lambda_c^+ \to p(K\pi)^0$ and $\Lambda_c^+ \to nK_S^0\pi^+$ provides an excellent opportunity to test final state interactions and isospin symmetry in the charmed baryon sector

[6]. Hence, the BESIII Collaboration performed the first direct measurement of $\Lambda_c^+ \to nK_S^0\pi^+$, which is also the first direct measurement of any Λ_c^+ decay involving a neutron in the final state.

The eleven hadronic decay modes in Table 1 (excluding $\Sigma^+\omega$) are used to reconstruct the $\bar{\Lambda}_c^-$ baryons as the tag side. Since the neutron is not detected, we define missing mass squared, $M^2_{\rm miss} = E^2_{\rm miss} - c^2|\vec{p}_{\rm miss}|^2$, to access to the missing neutron, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum carried by the neutron, respectively. They are calculated as $E_{\rm miss} = E_{\rm beam} - E_{K_S^0} - E_{\pi^+}$ and $\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \vec{p}_{K_S^0} - \vec{p}_{\pi^+}$, where $\vec{p}_{\Lambda_c^+}$, $\vec{p}_{K_S^0}$, and $\vec{p}_{\pi^+}$ are the momenta of the Λ_c^+, the K_S^0 and the π^+, respectively, while $E_{K_S^0}$ and E_{π^+} are the energies of the K_S^0 and the π^+, respectively. The momentum, $\vec{p}_{\Lambda_c^+}$, is obtained from the tag by the same method as in the previous analysis.

In order to obtain signal yields, we perform a simultaneous fit of the two-dimensional $M^2_{\rm miss}$ vs. $M_{\pi^+\pi^-}$ distributions in both M_{BC} signal and sideband regions of the tag side, shown in Figure 4. The purpose of fitting the two-dimensional $M^2_{\rm miss}$ vs. $M_{\pi^+\pi^-}$ distributions is to simulate the background from $\Lambda_c^+ \to \Sigma^\pm\pi^+\pi^\mp$ with $\Sigma^\pm \to n\pi^\pm$, which has same final state as the signal process when the K_S^0 is reconstructed through $K_S^0 \to \pi^+\pi^-$. These background events form a peaking background in $M^2_{\rm miss}$ but, unlike the K_S^0, are distributed flat along $M_{\pi^+\pi^-}$. The purpose of performing simultaneous fits in both the M_{BC} signal and sideband regions of the tag side is to constrain the non-Λ_c^+ decay background under the M_{BC} peak to that of the M_{BC} sideband. The preliminary result for the absolute branching fraction is determined to be $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82 \pm 0.23({\rm stat}) \pm 0.11({\rm syst}))\%$. With the measurement of $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ and $\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0)$ [4], we determine $\mathcal{B}(\Lambda_c^+ \to n\bar{K}^0\pi^+)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.62\pm0.09$ and $\mathcal{B}(\Lambda_c^+ \to n\bar{K}^0\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0\pi^0) = 0.97 \pm 0.16$. These ratios are a key input to test isospin symmetry and extract strong phases of final states in the charmed baryon sector.

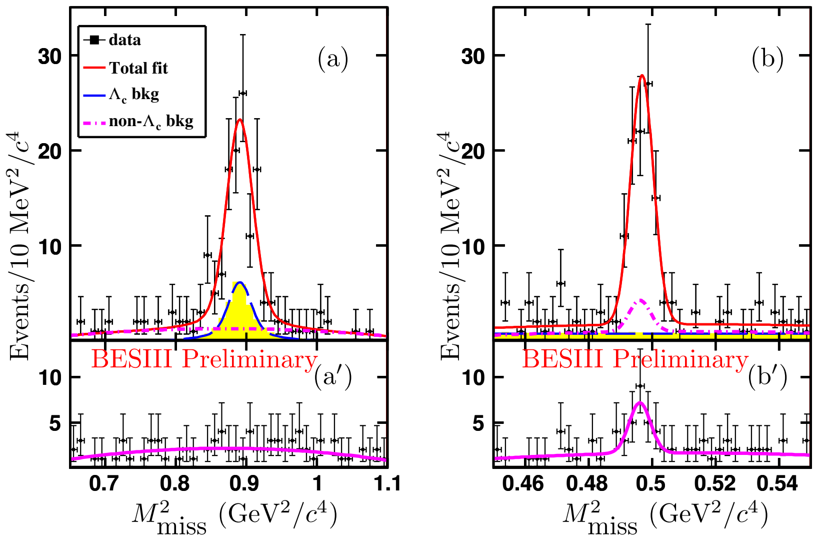

Figure 4. Simultaneous fit to $M^2_{\rm miss}$ and $M\pi^+\pi$ of events in (a, b) the $\bar{\Lambda}_c^-$ signal region and (a′, b′) sideband regions. Data are shown as the dots with error bars. The long-dashed lines (blue) show the Λ_c^+ backgrounds while the dot-dashed curves (pink) show the non-Λ_c^+ backgrounds. The red curves show the total fit. The (yellow) shaded area show the MC simulated backgrounds from Λ_c^+ decay.

7. Summary

The $\Lambda_c^+\bar{\Lambda}_c^-$ near-threshold data at BESIII have proven to be an effective sample to study the Λ_c^+ baryon. BESIII has published the first absolute measurement of twelve Cabibbo-favored Λ_c^+ hadronic decay modes, including $\Lambda_c^+ \to pK^-\pi^+$. BESIII has also published the first absolute measurement of $\Lambda_c^+ \to \Lambda e\nu_e$. Preliminary results are also given for the first absolute measurement of $\Lambda_c^+ \to \Lambda\mu\nu_\mu$ and Λ_c^+ decays involving a neutron, $\Lambda_c^+ \to nK_S^0\pi^+$. Many other analyses of Λ_c^+, including more hadronic modes, more modes with neutrons, more semi-leptonic modes, and inclusive studies, are in progress.

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