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Absolute branching fractions for Λ_c^+ decays at BESIII

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The BESIII detector accumulated 567 pb^{-1} data at the center-of-mass energy of 4.599 GeV, which is the world's largest e^+e^- collision sample at the $\Lambda_c^+\bar{\Lambda}_c^-$ pair threshold. By analyzing this data sample, we present the straightforward branching fraction measurements for twelve hadrnoic decays of pK_S^0, $pK^-\pi^+$, $pK_S^0\pi^0$, $pK_S^0\pi^+\pi^-$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^+\pi^-$, $pK^-\pi^+\pi^0$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$, $\Sigma^+\pi^+\pi^-$ and $\Sigma^+\omega$ with much significant improved precision. We also report the determinations of the absolute branching fractions of the Λ_c^+ semi-leptonic decays $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$, Λ_c^+ decay involving a neutron $\Lambda_c^+ \to nK_S^0\pi^+$ and singly-Cabibbo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$ for the first time.

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1. Introdution

Hadronic decays of Λ_c^+ , the lightest charmed baryon with quark configuration udc, provide important input to Λ_b physics and an ideal laboratory to understand the interplay of the weak and strong interaction. Improved measurements of the Λ_c^+ hadronic decays can be used to constrain fragmentation functions of charm and bottom quarks by counting inclusive heavy flavor baryons. Semileptonic (SL) decay $\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$, dominated by the Cabibbo-favored (CF) transition $c \to s\ell^+\nu_\ell$ occurs, to a good approximation, independently of the spin-zero spectator ud diquark. This leads to a simpler theoretical description and greater predictive power in modeling the SL decays of the charmed baryons than the case for mesons. In addition, the lepton universality can be tested by comparing the branching fractions (BFs) of the electronic and muonic modes. Compared to charmed mesons, the progress in the studies of charmed baryons is relatively slow since the first observation of the charmed baryon ground state Λ_c^+ in 1979, due to lack of experimental data. Most Λ_c^+ branching fractions (BF) have until now been obtained by combining measurements of ratios with a single branching fraction of the golden reference mode $\Lambda_c^+ \to pK^-\pi^+$, thus introducing strong correlations and compounding uncertainties. The experimentally averaged BF, $\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)$ [2], has large uncertainty due to the introduction of model assumptions on Λ_c^+ inclusive decays in these measurements. Recently, the Belle experiment reported $\mathscr{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})$ with a precision improved by a factor of 5 over previous results [1]. However, most hadronic BFs still have poor precision [2].

Our analyses are based on a data sample with an integrated luminosity of 567pb^{-1} with the BESIII detector at the center-of-mass energy of $\sqrt{s}$=4.599 GeV. At this energy, no additional hadrons accompanying the $\Lambda_c^+\bar{\Lambda}_c^-$ pairs are produced. Thus the double-tag technique, which relies on fully reconstructing both Λ_c^+ and $\bar{\Lambda}_c^-$ decays are employed. We present the first straightforward BF measurements for twelve hadrnoic decays [4] of pK_S^0, $pK^-\pi^+$, $pK_S^0\pi^0$, $pK_S^0\pi^+\pi^-$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^+\pi^-$, $pK^-\pi^+\pi^0$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$, $\Sigma^+\pi^+\pi^-$ and $\Sigma^+\omega$ with much significant improved precision. We also report the determinations of the absolute BFs of the Λ_c^+ semi-leptonic decays into $\Lambda\ell^+\nu_\ell$ [5], Λ_c^+ decay involving a neutron $\Lambda_c^+ \to nK_S^0\pi^+$and singly-Cabibbo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$ [6] for the first time. Throughout the context, charge-conjugate modes are always implied, unless explicitly mentioned.

2. Hadronic decays

2.1 twelve Cabibbo-Favored decays

To identify the $\Lambda_c^+\bar{\Lambda}_c^-$ signal candidates, we first reconstruct one $\bar{\Lambda}_c^-$ baryon [called a single tag (ST)] through the final states of any of the 12 hadronic decay modes. Then we define double-tag (DT) events as those where the partner Λ_c^+ reconstructed from the remaining tracks and showers in one of the ST $\bar{\Lambda}_c^-$.

For a given decay mode j, the ST yield, DT events and absolute BF are determined to be

$$N_j^{\rm ST} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathscr{B}_j \cdot \varepsilon_j, \quad N_{ij}^{\rm DT} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathscr{B}_i \cdot \mathscr{B}_j \cdot \varepsilon_{ij}, \quad \mathscr{B}_i = \frac{N_{ij}^{\rm DT}}{N_j^{\rm ST}} \frac{\varepsilon_j}{\varepsilon_{ij}}. \qquad (2.1)$$

where $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is the total number of produced $\Lambda_c^+\bar{\Lambda}_c^-$ pairs, ε_j is the corresponding efficiency and ε_{ij} is the efficiency for simultaneously reconstructing modes i and j.

Because of the large acceptance of the BESIII detector and the low multiplicities of Λ_c hadronic decays, $\varepsilon_{ij} \approx \varepsilon_i\varepsilon_j$. Hence, the ratio $\varepsilon_j/\varepsilon_{ij}$ is insensitive to most systematic effects associated with the decay mode j, and a signal BF $\mathscr{B}_i$ obtained using this procedure is nearly independent of the efficiency of the tagging mode.

To discriminate Λ_c candidates from background, we define two variables, the energy difference $\Delta E \equiv E - E_{\rm beam}$ and beam-constrained mass $M_{\rm BC} \equiv \sqrt{E_{\rm beam}^2 - \overrightarrow{p}^2}$, where E is the total measured energy of the Λ_c candidate, $E_{\rm beam}$ is the average value of the e^+ and e^- beam energies, and p is the measured Λ_c momentum in the center-of-mass system of the e^+e^- collision.

We perform unbinned extended maximum likelihood fits to the beam-constrained mass $M_{\rm BC}$ distributions to obtain the ST yields, as illustrated in Fig.1(a). The $M_{\rm BC}$ distributions of the DT signal candidates over the 12 ST modes is shown in Fig. 1(b). A least-squares fitter, which considers

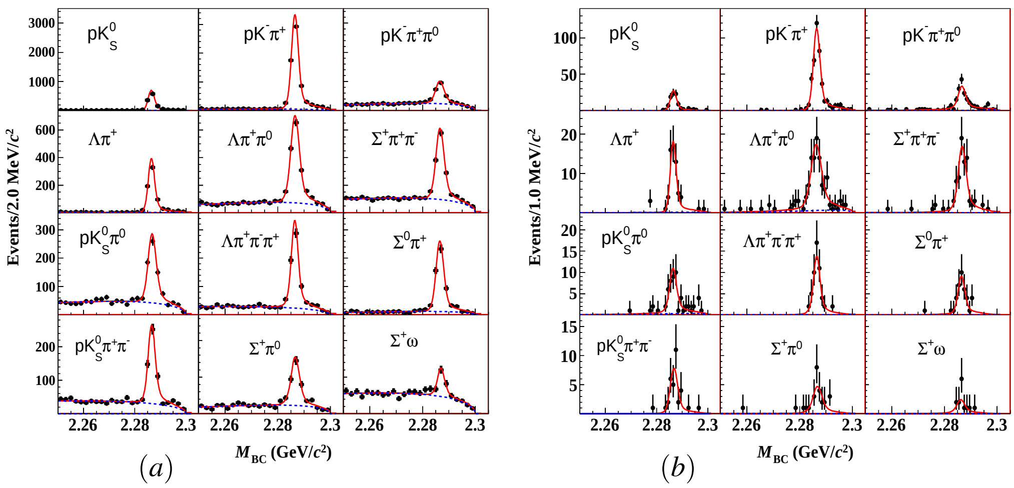

Figure 1: Fits to the ST (a) and DT (b) $M_{\rm BC}$ distributions in data for the different decay modes. Points with error bars are data, solid lines are the sum of the fit functions, and dashed lines are the background shapes.

statistical and systematic correlations among the different hadronic modes, is used to obtain the BFs of the 12 $\bar{\Lambda}_c^-$ decay modes globally [3]. The extracted BFs of Λ_c^+ are listed in Table 1, and the total number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced is obtained to be $N_{\Lambda_c^+\bar{\Lambda}_c^-} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$.

2.2 $\Lambda_c^+ \to pK^+K^-/p\pi^+\pi^-$

Single-tag method is employed in this analysis because of statistic limitation. That is, candidates for Λ_c^+ decays are reconstructed by considering all combinations of charged tracks in the final states of interest $pK^-\pi^+$, pK^+K^- and $p\pi^+\pi^-$. Here, two variables ΔE and $M_{\rm BC}$ are used to identify the reconstructed Λ_c^+ candidates. To obtain the signal yields for the decay modes $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^+K^-$, we perform a fit to the $M_{\rm BC}$ distributions of the accepted Λ_c^+ candidates, as shown in Fig. 2. The measured relative and absolute branching fractions of the singly-Cabibbo-suppressed decays with respect to the CF decay $\Lambda_c^+ \to pK^-\pi^+$, are summarized in Table 2.

Table 1: Comparison of the measured BFs in this work with previous results from PDG [2]. For our results, the first uncertainties are statistical and the second are systematic.

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

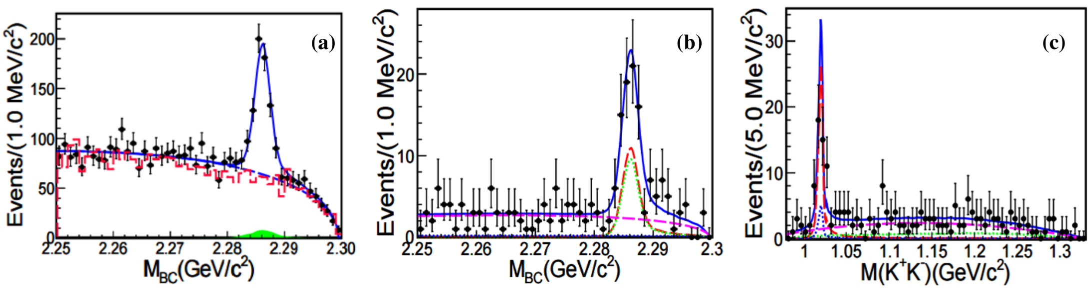

Figure 2: (a) is the fit to $M_{\rm BC}$ distribution for $\Lambda_c^+ \to p\pi^+\pi^-$. (b)(c) is the two dimensional unbinned simultaneous fit for $\Lambda_c^+ \to pK^+K^-$. Data are shown as the dots with error bars and the blue solid lines show the total fit. In (a), the green shaded area is peaking background from the CF decays $\Lambda_c^+ \to pK_S^0$ and $\Lambda_c^+ \to \Lambda\pi^+$, while the blue long-dashed line shows the continuum backgrounds. In (b, c), the red and green dashed lines show the $\Lambda_c^+ \to p\phi(\phi \to K^+K^-)$ and $\Lambda_c^+ \to pK^+K^-_{\rm non-\phi}$ signals, respectively, the blue dashed lines are the background with ϕ production, and the magenta dashed lines are the non-ϕ background described by a 3rd-order polynomial function.

Table 2: Measured relative and absolute branching fractions comparing with the previous results from PDG [2]. Uncertainties are statistic, experimental systematic, and reference mode uncertainty.

Mode	$\mathcal{B}_{mode}/\mathcal{B}_{ref.}$	$\mathcal{B}_{mode}$	PDG
$p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
pK^+K^-	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

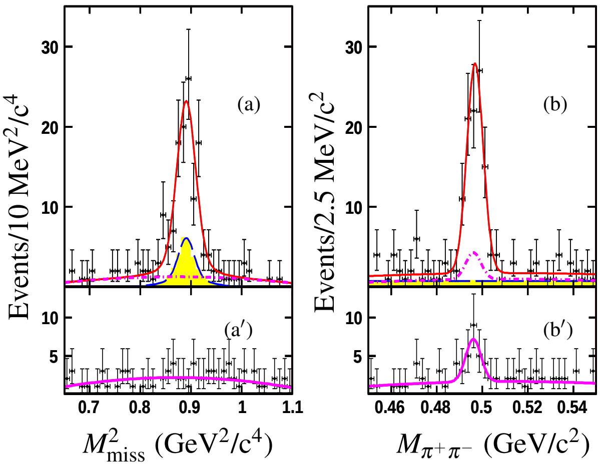

Figure 3: Simultaneous fit to $M^2_{\rm miss}$ and $M_{\pi^+\pi^-}$ of events in (a, b) the $\bar{\Lambda}_c^-$ signal region and (a′, b′) sideband regions. Data are shown as the dots with error bars. The blue long-dashed lines show the Λ_c^+ backgrounds while the pink dot-dashed lines show the non-Λ_c^+ backgrounds. The red lines show the total fit. The yellow shaded area shows the MC simulated backgrounds from Λ_c^+ decay.

2.3 $\Lambda_c^+ \to nK_S^0\pi^+$

Double-tag method is applied in the analysis, the same 11 hadronic decay modes as Sec. 2.1, except the mode $\Lambda_c^+ \to \Sigma^+\omega$, are utilized to reconstruct the $\bar{\Lambda}_c^-$ baryon as the tag side. The signal candidates for $\bar{\Lambda}_c^- \to nK_S^0\pi^+$ are selected from the remaining tracks recoiling against the ST $\bar{\Lambda}_c^-$ candidates. Since the neutron is not detected, we adopt a kinematic variable $M^2_{\rm miss} = E^2_{\rm miss} - |\overrightarrow{p}_{\rm miss}|^2$ to obtain the information of the missing neutron, where $E_{\rm miss}$ and $\overrightarrow{p}_{\rm miss}$ are the missing energy and momentum carried by the neutron, respectively, which are calculated by $E_{\rm miss} = E_{\rm beam} - E_{\rm K_S^0} - E_{\pi^+}$ and $\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \vec{p}_{\rm K_S^0} - \vec{p}_{\pi^+}$, where $\vec{p}_{\Lambda_c^+}$ is the momentum of Λ_c^+ baryon, $E_{\rm K_S^0}(\vec{p}_{\rm K_S^0})$ and $E_{\pi^+}(\vec{p}_{\pi^+})$ are the energies (momentum) of the K_S^0 and π^+, respectively. Here, the momentum $\vec{p}_{\Lambda_c^+}$ is given by $\vec{p}_{\Lambda_c^+} = -\hat{p}_{tag}\sqrt{E^2_{\rm beam} - m^2_{\bar{\Lambda}_c^-}}$, where $\hat{p}_{tag}$ is the direction of the momentum of ST $\bar{\Lambda}_c^-$ and $m_{\bar{\Lambda}_c^-}$ is the $\bar{\Lambda}_c^-$ nominal mass [2]. If the K_S^0 and π^+ from the $\Lambda_c^+ \to nK_S^0\pi^+$ are corrected, the $M^2_{\rm miss}$ is expected to be around the neutron nominal mass square.

To obtain the yield of $\Lambda_c^+ \to nK_S^0\pi^+$, we perform a two-dimensional unbinned likelihood fit to the $M^2_{\rm miss}$ and $M_{\pi^+\pi^-}$ distributions in both $M_{\rm BC}$ signal and sideband regions simultaneously, as shown in Fig. 3. The preliminary result for the absolute branching fraction is determined to be $\mathscr{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82 \pm 0.23(\text{stas.}) \pm 0.11(\text{syst.}))\%$.

3. Semi-leptonic decays $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$

Using the same strategy as Sec. 2.3, we select the signal candidates for $\bar{\Lambda}_c^- \to \Lambda\ell^+\nu_\ell$ in the remaining tracks recoiling against the 11 ST $\bar{\Lambda}_c^-$ candidates. As the neutrino is missing, we employ a kinematic variable $U_{\rm miss} = E_{\rm miss} - c|\overrightarrow{p}_{\rm miss}|$ to obtain information on the neutrino, where $E_{\rm miss}$ and $\overrightarrow{p}_{\rm miss}$ are the missing energy and momentum carried by the neutrino, respectively. For signal events, $U_{\rm miss}$ is expected to peak around zero. As shown in Fig. 4, we fit the

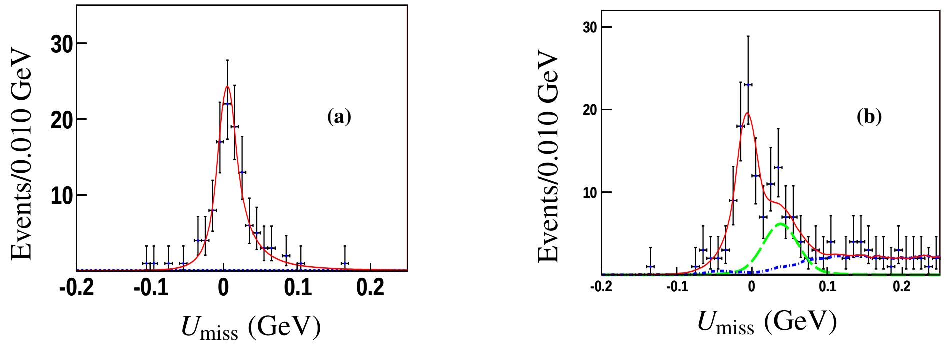

Figure 4: Fit to the $U_{\rm miss}$ distributions in the Λ signal region. (a) is $\Lambda_c^+ \to \Lambda e^+ \nu_e$ and (b) is $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$. Data are shown as dots with error bars. The red thick lines show the total fit, the blue dot-dashed lines show other Λ_c^+ decay backgrounds, and the green long-dashed line in (b) shows the $\Lambda_c^+ \to \Lambda \pi^+ \pi^0$ background.

$U_{\rm miss}$ distributions to obtain the signal events, and the absolute BF is calculated by $\mathscr{B}(\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell) = \frac{N_{\rm semi}}{N^{\rm tot}_{\bar{\Lambda}_c^-} \times \varepsilon_{\rm semi} \times \mathscr{B}(\Lambda \to p\pi^-)}$. We get $\mathscr{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38({\rm stat.}) \pm 0.20({\rm syst.}))\%$ and $\mathscr{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46({\rm stat.}) \pm 0.27({\rm syst.}))\%$. The preliminary result for the ratio of two branching fraction is determined to be $\mathscr{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/\mathscr{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = 0.96 \pm 0.16({\rm stat.}) \pm 0.04({\rm syst.})$.

4. Summary

In summary, based on 567 pb^{-1} of e^+e^- annihilation data collected at $\sqrt{s} = 4.599$ GeV with the BESIII detector, we measure the twelve CF Λ_c^+ decay rates by employing a DT technique. This is the first absolute measurements of the Λ_c^+ decay BFs at the $\Lambda_c^+\bar{\Lambda}_c^-$ production threshold, after Λ_c^+ discovered 30 years ago. BESIII has also published the first absolute BF of the semi-leptonic decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ and singly-Cabibbo-suppressed decays $\Lambda_c^+ \to pK^+K^-/p\pi^+\pi^-$. Preliminary results are presented for the first absolute BFs measurement of $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$ and Λ_c^+ decay involving a neutron $\Lambda_c^+ \to nK_S^0\pi^+$. Many other analyses of Λ_c^+, including more hadronic modes, with neutrons, semi-leptonic modes, and inclusive studies, are in progress.

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