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Λ_c physics at BESIII

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Using 567 pb^{-1} e^+e^- collision data collected with the BESIII detector at a center-of-mass energy of $\sqrt{s} = 4.599$ GeV, near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold, we present the measurements of Λ_c^+ hadronic decays and semi-leptonic decays. The absolute branching fraction $B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0)$ is determined to be $(2.11\pm0.33\pm0.14)\%$. The measurements of singly Cabibbo-suppressed decays $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^+K^-$ are performed, and the relative branching fractions with respect to the Cabibbo-favored decay $\Lambda_c^+ \to pK^-\pi^+$ are given, the absolute branching fractions are also obtained for these two decays. Evidence for the singly Cabibbo-suppressed decay $\Lambda_c^+ \to p\eta$ is found to be 4.2σ, and the upper limit for $\Lambda_c^+ \to p\pi^0$ is reported. The branching fractions for the semi-leptonic decays are determined to be $B(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.63\pm0.38(stat.)\pm0.20(syst.))\%$ and $B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.49\pm0.46(stat.)\pm0.27(syst.))\%$. In addition, we also give the ratio $B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)/B(\Lambda_c^+ \to \Lambda e^+\nu_e) = (0.96\pm0.16(stat.)\pm0.04(syst.))\%$.

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1. Introduction

Charmed baryon decays provide crucial information for the study of both strong and weak interactions. Hadronic Λ_c^+ decays provide important input to Λ_b physics as well as opening a window into the study of final state(strong) interactions [1, 2]. 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 [3]. For the semi-leptonic (SL) decay, Λ_c^+ provide a stringent test on non-perturbative theoretical models. The $\Lambda_c^+ \to \Lambda l^+ \nu_l$ (l denotes lepton) decay is dominated by the Cabibbo-favored transition $c \to s l^+ \nu_l$, which occurs independently of the spin-zero and isospin-zero spectator ud diquark, to good approximation. This leads to a simpler theoretical description and greater predictive power in the non-perturbative models than in the case for charmed mesons [4]. In addition, theoretical calculations prove to be quite challenging for lattice quantum chromodynamics (LQCD) due to the complexity of form factors in $\Lambda_c^+ \to \Lambda l^+ \nu_l$ [1]. Consequently, the model-independent measurement of hadronic and SL decays with better precision is a key ingredient in theoretical predictions and LQCD calculation, which in turn, will play an important role in understanding different Λ_c^+ decays.

In this letter, using 567 pb^{-1} data of e^+e^- collisions collected at $\sqrt{s} = 4.599$ with the BESIII detector, we present the measurements of the Λ_c^+ hadronic decays and SL decays.

2. Λ_c^+ hadronic decay

2.1 Observation of the decay $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0$

Λ_c^+ decays to the Σ^- hyperon are Cabibbo-allowed and expected to have large rates. However, no decays are measured except for $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+$. Therefore, searching for additional decay modes with Σ^- in the final state is essential to build up knowledge on Λ_c^+ decay.

The Single-tag (ST) and Double-tag (DT) technique is used in our analysis. Two variables, the energy difference, $\Delta E \equiv E - E_{\rm beam}$ and the beam-constrained mass $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam}/c^4 - p^2/c^2}$, are used to identify the Λ_c^+ candidates, where $E_{\rm beam}$ is the beam energy, and $E(p)$ is the reconstructed energy(momentum) in the e^+ and e^- center-of-mass system.

ST $\bar{\Lambda}_c^-$ baryon candidates are reconstructed in the eleven hadronic decay modes [5]. Candidates for the DT Λ_c^+ signal $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ (\pi^0)$ with $\Sigma^- \to n\pi^-$ are reconstructed from the tracks not used in the ST $\bar{\Lambda}_c^-$ reconstruction. As the neutron is not reconstructed in this analysis, we deduce its kinematic properties by four-momentum conservation. The absolute branching fraction (BF) of $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ (\pi^0)$ is derived from the probability of detecting the DT signals in the ST sample.

The kinematic variable $M_n = \sqrt{(E_{beam} - E_{\pi^+\pi^+\pi^-(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+\pi^-(\pi^0)}|^2}$ is computed to characterize the reconstructed mass of the undetected neutron. We construct the variable $M_{n\pi^-} = \sqrt{(E_{beam} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$ to represent the reconstructed mass of the Σ^-. We perform an unbinned maximum likelihood fit the $M_{n\pi^-} - M_n$ spectra, as shown in Fig. 1 to extract the signal yield.

The first absolute BF $B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0)$ is determined to be $(2.11 \pm 0.33(stat.) \pm 0.14(syst.))\%$. In addition, an improved measurement of $B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+)$ is determined as $(1.81 \pm 0.17(stat.) \pm 0.09(syst.))\%$.

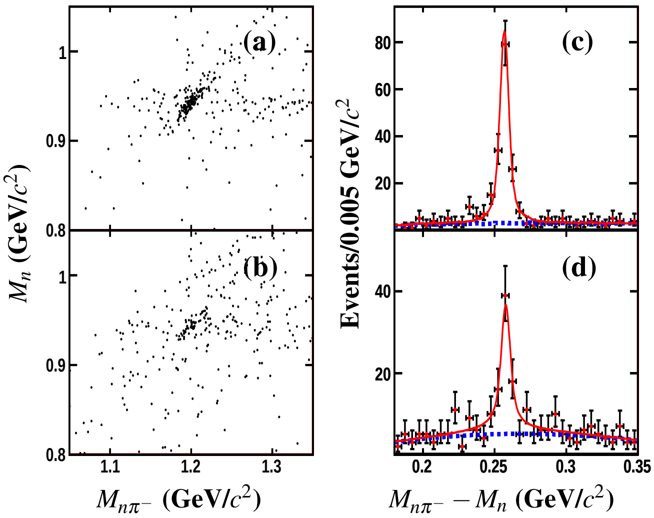

Figure 1: Scatter plots of M_n versus $M_{n\pi^-}$ for candidates in data for (a) $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and (b) $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$. Also shown are fits to the distributions of $M_{n\pi^-} - M_n$ for (c) $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and (d) $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ in data. Solid lines are the results of a complete fit while dashed lines reflect the background components.

2.2 Measurement of Singly Cabibbo Suppressed Decays $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^+K^-$

The Singly Cabibbo Suppressed (SCS) decays $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^+K^-$ proceed via the external W-emission, internal W-emission and W-exchange processes. A measurement of the SCS mode $\Lambda_c^+ \to p\phi$ is of particular interest, because it receives contributions only from the internal W-emission diagrams, which can reliably be obtained by a factorization approach [6]. An improved measurement of the $\Lambda_c^+ \to p\phi$ BF is thus essential to validate theoretical models and test the application of large-N_c factorization in the charmed baryon sector [7], where N_c is the number of colors.

In this analysis, we present BF measurements of SCS decays relative to the golden mode $\Lambda_c^+ \to pK^-\pi^+$. The ST method is used to reconstruct Λ_c^+ candidates. To obtain the signal yields of the decays $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to p\pi^+\pi^-$, a maximum likelihood fit is performed to the $M_{\rm BC}$ distributions, as shown in Fig. 2. For the decay $\Lambda_c^+ \to pK^+K^-$, a two-dimensional unbinned extended maximum likelihood fit is performed to the $M_{\rm BC}$ versus $M_{\rm K^+K^-}$ distributions for events in the ΔE signal region and sideband region simultaneously. The fitting results are illustrated in Fig. 3.

We present the first observation of the SCS decay $\Lambda_c^+ \to p\pi^+\pi^-$ and improved (or comparable) measurements of the $\Lambda_c^+ \to p\phi$ and $\Lambda_c^+ \to pK^+K^-_{\rm non-\phi}$. The relative BFs with respect to the CF decay $\Lambda_c^+ \to pK^-\pi^+$ are measured to be $B(\Lambda_c^+ \to p\pi^+\pi^-)/B(\Lambda_c^+ \to pK^-\pi^+) = (6.70 \pm 0.48 \pm 0.25)\%$, $B(\Lambda_c^+ \to p\phi)/B(\Lambda_c^+ \to pK^-\pi^+) = (1.81 \pm 0.33 \pm 0.13)\%$ and $B(\Lambda_c^+ \to pK^+K^-_{\rm non-\phi})/B(\Lambda_c^+ \to pK^-\pi^+) = (9.36 \pm 2.22 \pm 0.71)\%$. We also obtain absolute BFs for the SCS decays $B(\Lambda_c^+ \to p\pi^+\pi^-) = (3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$, $B(\Lambda_c^+ \to p\phi) = (1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$ and $B(\Lambda_c^+ \to pK^+K^-_{\rm non-\phi}) = (5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$.

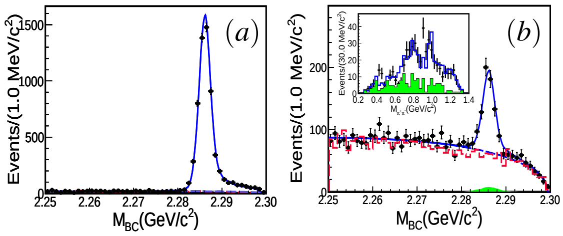

Figure 2: Distributions of $M_{\rm BC}$ for the decays (a) $\Lambda_c^+ \to pK^-\pi^+$ and (b) $\Lambda_c^+ \to p\pi^+\pi^-$. Points with an error bar are data, the blue solid lines show the total fits, the blue long dashed lines are the combinatorial background shapes, and the red long dashed histograms are data from the ΔE sideband region for comparison. In (b), the green shaded histogram is the peaking background from the CF decays $\Lambda_c^+ \to pK_S^0$ and $\Lambda_c^+ \to \Lambda\pi^+$. The inset plot in (b) shows the $\pi^+\pi^-$ invariant mass distribution with the additional requirement $|\Delta E| < 8$ MeV and $2.2836 < M_{\rm BC} < 2.2894$ GeV/c^2, where the dots with an error bar are for the data, the blue solid histogram shows the fit curve from Partial Wave Analysis, and the green shaded histogram shows background estimated from the $M_{\rm BC}$ sideband region.

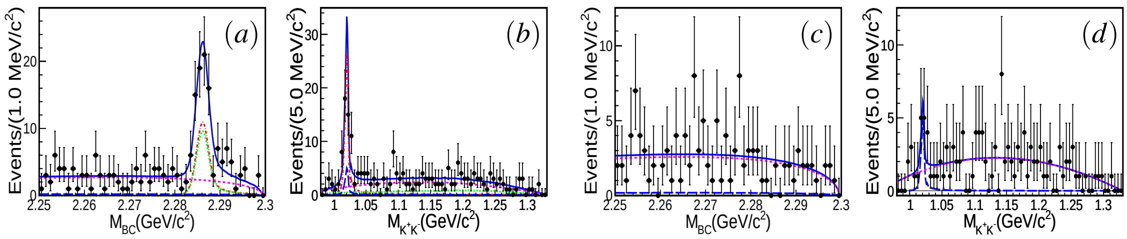

Figure 3: Distributions of $M_{\rm BC}$ and $M_{K^+K^-}$ for data in the ΔE signal region ((a) and (b)) and sideband region ((c) and (d)) for the decay $\Lambda_c^+ \to pK^+K^-$. The blue solid curves are for the total fit results, the red dash-dotted curves show the $\Lambda_c^+ \to p\phi \to pK^+K^-$ signal, the green dotted curves show the $\Lambda_c^+ \to pK^+K^-_{\rm non-\phi}$ signal, the blue long-dashed curves are the background with ϕ production, and the magenta dashed curves are the non-ϕ background.

2.3 Evidence for the Singly Cabibbo Suppressed decays $\Lambda_c^+ \to p\eta$ and search for $\Lambda_c^+ \to p\pi^0$

The SCS decays $\Lambda_c^+ \to p\eta$ and $p\pi^0$ have not yet been studied experimentally. Some theoretical models [8, 9, 10, 11], predict the BFs of these two process under different assumptions (the flavor SU(3) symmetry, FSI) obtaining different results. Therefore, measurements of these BFs will help us to understand the underlying dynamics of charmed baryon decays and distinguish between the different models. Furthermore, the ratio of BFs of these two decays, which is expected to be relatively insensitive to the values of input parameters in the theoretical calculation, is an excellent probe to distinguish between the different models.

In this analysis, ST method is used to reconstruct the signal modes. In the study of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ decays, the η mesons are reconstructed in their two most prominent decay modes, $\eta \to \gamma\gamma(\eta_{\gamma\gamma})$ and $\eta \to \pi^+\pi^-\pi^0(\eta_{\pi^+\pi^-\pi^0})$, while the π^0 is reconstructed in $\pi^0 \to \gamma\gamma$.

A simultaneous fit to the $M_{\rm BC}$ distributions for the two η decay modes is performed, constraining to the same $B(\Lambda_c^+ \to p\eta)$ and taking into account the different detection efficiencies and decay BFs of η. The projections of the fit curves are illustrated in Fig. 4. The resultant BF is determined to be $B(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.28(stat.) \pm 0.10(syst.)) \times 10^{-3}$ with a statistical significance of 4.2σ. Since no significant $\Lambda_c^+ \to p\pi^0$ signal is observed, an upper limit on the BF is estimated to be $B(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4}$ at the 90% confidence level. The corresponding ratio of BFs between the two decays is also calculated to be $B(\Lambda_c^+ \to p\pi^0)/B(\Lambda_c^+ \to p\eta) < 0.24$.

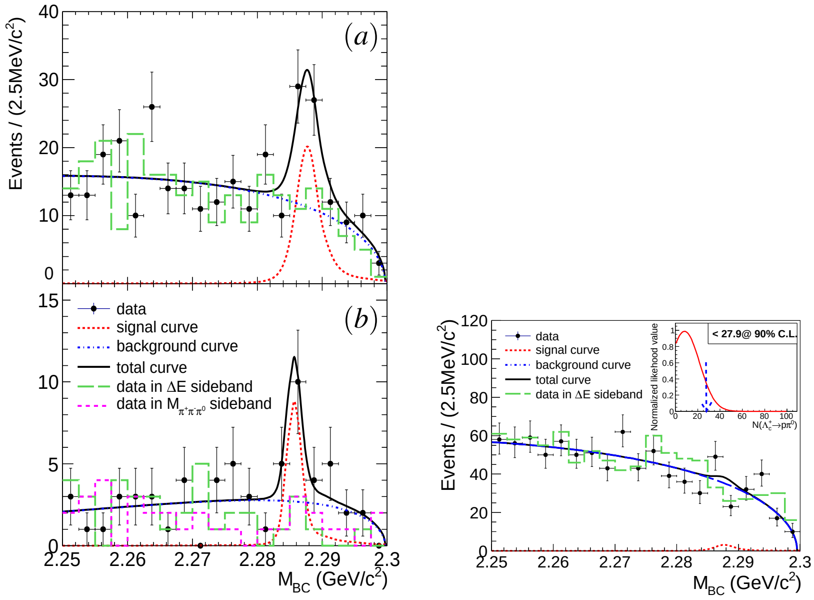

Figure 4: (color online) (left)Simultaneous fit to the M_{BC} distributions of $\Lambda_c^+ \to p\eta$ reconstructed with the decay modes (a) $\eta \to \gamma\gamma$ and (b) $\eta \to \pi^+\pi^-\pi^0$. (right) Fit to the M_{BC} distribution for the decay $\Lambda_c^+ \to p\pi^0$. The dots with error bars are data, the (black) solid curve is for the best fit, and the (blue) dashed curve is for the background. The (green) long-dashed histograms and (pink) dashed histogram (in (b) only) are the data in the ΔE and $M_{\pi^+\pi^-\pi^0}$ sideband region. The insert shows the normalized likelihood distribution, which includes the systematic uncertainty, as a function of the expected signal yield. The (blue) dashed arrow indicates the upper limit on the signal yield at 90% C.L.

3. Λ_c^+ semi-leptonic decay

Using the similar strategy in hadronic decay measurements, we select a data sample of $\bar{\Lambda}_c^-$ baryons by reconstructing exclusive hadronic decays, we call this ST sample.

The signal candidates for $\Lambda_c^+ \to \Lambda l^+ \nu_l$ (l denotes e or μ) are selected from the remaining tracks recoiling against the ST $\bar{\Lambda}_c^-$ candidates. As the neutrino is missing, we employ a kinematic variable

$$U_{\text{miss}} = E_{\text{miss}} - c|\vec{p}_{\text{miss}}|$$

to obtain information on the neutrino, where E_{miss} and $\vec{p}_{\text{miss}}$ are the missing energy and momentum carried by the neutrino, respectively. They are calculated by $E_{\text{miss}} = E_{\text{beam}} - E_\Lambda - E_{l^+}$ and $\vec{p}_{\text{miss}} = \vec{p}_{\Lambda_c^+} - \vec{p}_\Lambda - \vec{p}_{l^+}$, where $\vec{p}_{\Lambda_c^+}$ is the momentum of Λ_c^+ baryon, $E_\Lambda(\vec{p}_\Lambda)$ and E_{l^+} ($\vec{p}_{l^+}$) are the energies (momenta) of the Λ and the positron, respectively. Here, the momentum $\vec{p}_{\Lambda_c^+}$ is given by $\vec{p}_{\Lambda_c^+} = -\hat{p}_{\text{tag}}\sqrt{E_{\text{beam}}^2 - m_{\bar{\Lambda}_c^-}^2}$, where $\hat{p}_{\text{tag}}$ is the direction of the momentum of the ST $\bar{\Lambda}_c^-$ and $m_{\bar{\Lambda}_c^-}$ is the nominal $\bar{\Lambda}_c^-$ mass [12]. For signal events, U_{miss} is expected to peak around zero.

Fig. 5(a) illustrates the fit result to $U_{\rm miss}$ for $\Lambda_c^+ \to \Lambda e^+ \nu_e$, and Fig. 5(b) for $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$. We get $B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38(stat.) \pm 0.20(syst.))\%$, $B(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46(stat.) \pm 0.27(syst.))\%$. In addition, we also calculate the ratio $B(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (0.96 \pm 0.16(stat.) \pm 0.04(syst.))\%$, which could tests lepton universality in baryon decays.

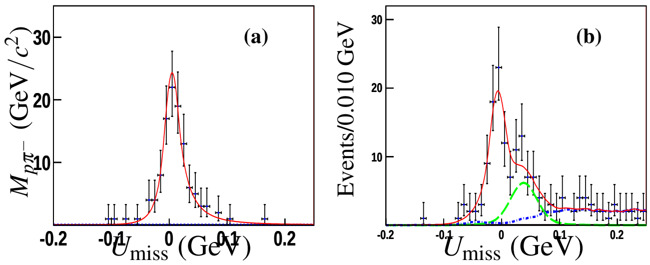

Figure 5: Fit to the $U_{\rm miss}$ distribution within the Λ signal region. (a) $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decay mode. The points with error bars are data, the (red) solid curve shows the total fit and the (blue) dashed curve is the background shape. (b) $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$ decay mode. 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.

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 report the measurement of Λ_c^+ hadronic decays and semi-leptonic decays. 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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