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Λ_c Physics at BESIII

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In 2014 BESIII collected a data sample of 567 pb^{-1} at $E_{cm} = 4.6$ GeV, which is just above the Λ_c^+ pair production threshold. By analyzing this data sample, we have measured the absolute branching fractions for many decays of Λ_c^+ for the first time. These decays include the semileptonic decays of $\Lambda e^+\nu$, $\Lambda\mu^+\nu$, the hadronic decays of pK_s, $pK^-\pi^+$, $pK^-\pi^+\pi^0$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Sigma^+\pi^+\pi^0$, $pK_s\pi^0$, $\Lambda\pi^+\pi^+\pi^-$, $pK_s\pi^+\pi^-$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$, $\Sigma^+\omega$, $p\phi$, pK^+K^- (non$-\phi$), $p\pi^+\pi^-$, $nK_s\pi+$, $\Sigma^-\pi^+\pi^+(\pi^0)$ and inclusive decay Λ + anything. The decays of $p\pi^+\pi^-$, $nK_s\pi^+$ and $\Sigma^-\pi^+\pi^+\pi^0$ are observed for the first time and the others are measured with significantly improved precision. These results are important to benefit the development of the related theories, and provide important inputs for both charmed baryons and B physics.

Keywords: Λ_c; BESIII; decays.

1. Λ_c^+ role in modern High Energy Physics

The knowledge of Λ_c physics is quite limited, even if is the lightest charmed baryon. Only roughly the 68% of the total branching ratio is known and most of the measured one are referred to the golden channel $\Lambda_c^+ \to pK^-\pi^+$, with the effect that the precision is very limited, as shown in Ref. 1. A more deep knowledge of the Λ_c decay, and charmed baryon in general, will help in studying the heavy quark - quark internal dynamics in a way that is complementary with respect to the charmed mesons: in fact, in the Heavy Quark Effective Theory 2, the Λ_c is modeled as a heavy quark coupled with an unexcited spin zero diquark. The absence of the degree of freedom of spin and isospin in the light quark component makes the prediction more reliable. Moreover, being the lightest charmed baryon, all the other charmed baryons will eventually decay in Λ_c, thus a better knowledge of its decay mode will also increase the possibility to study to the heavier charmed baryon states.

2. BESIII at BEPCII

BESIII is a central detector optimized for the flavour physics. It is hosted in the Beijing Electron Positron Collider II (BEPCII), at the Institute of High Energy Physics (IHEP) of Beijing, PRC. BEPCII is a double-ring symmetric collider which center of mass energy ranges in the interval between 2 and 4.6 GeV.

BESIII is composed of a series of subdetectors. Its angular coverage is 93% of 4π and it is divided in a barrel and in two endcaps. The innermost detector is the Main Drift Chamber (MDC) with spatial and the relative momentum resolution for charged particles at 1 GeV/c are 130 μm and 0.5% respectively. The Time-of-Flight (TOF) detectors are placed just outside the MDC and in the endcaps. They have a time resolution of $\sigma_t = 90(110)$ ps for the barrel (endcap). Outside the TOF walls lies the Electromagnetic Calorimeters (EMC), with energy resolution of $dE/\sqrt{E} = 2.5\%$ for a 1 GeV particle. A superconductive solenoid produces a 1 T magnetic field to allow the momentum measurement. In the yoke of the magnet, nine (eight) Resistive Plate Chambers are placed in the barrel (endcap) to operate as Muon Counters.

2.1. *Charmed baryon at threshold*

The data taken in proximity of the threshold leave BESIII with two opportunities: once one Λ_c^+ signal is reconstructed in one side of the decay, it is guaranteed that the other side of the decay must contain the charge conjugate signal, due to the quark and baryon number conservation. The two techniques are called *single-tag* and *double-tag* respectively. In the single-tag technique there are two variables that allow to check that the reconstruction is the proper one. The Mass Beam Constrained (M_{BC}) is defined as

$$M_{BC} = \sqrt{E_{beam}^2 - p_{candidate}^2}, \tag{1}$$

where E_{beam} is the nominal energy of the beam and $p_{candidate}$ is the reconstructed momentum of the Λ_c^+ candidate. The distribution is usually asymmetric, due to the ISR effect on the candidate momentum. The other variable is called ΔE, and it is defined as the difference between the energy of the candidate and the energy of the beam.

3. Presented results

3.1. *First direct measurements of Λ_c Branching Fraction at threshold*

The first published work of BESIII on the Λ_c^+ decays aim to study the branching fraction of 12 different decay mode and, using the double-tag technique, to improve the precision of the branching ratio. Moreover, it sets the decay mode that will be used in the following double-tag analysis. In Ref. 3 the branching fraction (BF) are extracted in the following way: first, the single-tag analysis for a particular tag mode final state is performed and the number of events N_{ST} and the efficiency ε_{ST} are extracted; then the number of events N_{DT} and the efficiency ε_{DT} reconstructing the tag final state plus the final state of interest are extracted. The BF is then:

$$BF(\Lambda_c \to X) = N_{DT}/N_{ST} \times \varepsilon_{ST}/\varepsilon_{DT}, \tag{2}$$

where X is the state of interested reconstructed in the double-tag analysis. To improve the result quality, a simultaneous fit to all the final state is applied. The results for double-tag analysis are shown in Fig. 1.

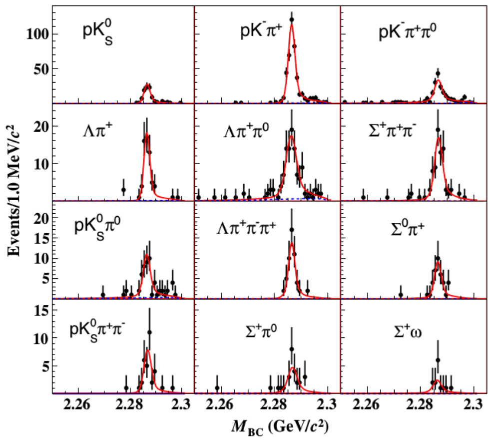

Fig. 1. Fits to the double-tag M_{bc} distributions.

At the same time, the total number of Λ_c pairs produced in the data taking is extracted and it is $N_{\Lambda_c} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$, where the two errors are the statistical and systematic one respectively.

3.2. *Observation of* $\Lambda_c^+ \to nK_s^0\pi^+$

The Λ_c^+ are reconstructed mainly with the Λ and proton final state, since in both case the proton (from the direct decay or from the subsequent Λ decay) can be easily reconstructed. The possibility to close the kinematic allows BESIII to search for neutron final state analyzing the missing mass that was completely missing in the PDG table 1.

In Ref. 4 BESIII reports the first direct measurement of a final state with a neutron. To obtain the branching ratio, a simultaneous 2D fit is applied to sideband and signal, as shown in Fig. 2.

The resonant structure that appears in the M^2_{miss} plot is the $\Lambda_c^+ \to \Sigma^-(n\pi^-)\pi^+\pi^+$ signal, but both the neutron and the K_s^0 signals are quite clear from the fit. The result of the branching ratio is BF$(\Lambda_c^+ \to nK_s^0\pi^+) = (1.82 \pm 0.23 \pm 0.11)\%$, where the errors are statistical and systematic respectively.

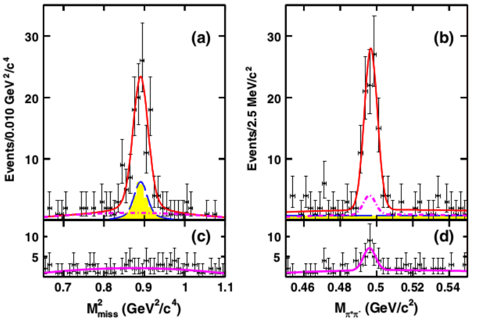

Fig. 2. Projections of the two dimensional simultaneous fit to the missing mass (left) and of the $\pi^+\pi^-$ invariant mass (right). The bottom parts shows the fit to the sidebands.

3.3. *Study of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$*

The observation of a decay mode with a neutron in the final state of Ref. 4 has shown that there is the possibility to use the double-tag technique to search for other decay modes.

In Ref. 5, BESIII reports the measurement of other two decay modes with a neutron in the final state: the first observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ and the first direct measurement of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$. The two analyzes have similar features so they will be described together.

The results are given in terms of two variables, that are defined as

$$M_n = \sqrt{(E_{beam} - E_{\pi^+\pi^+\pi^-(\pi^0)})^2 - |\overrightarrow{p}_{\Lambda_c^+} - \overrightarrow{p}_{\pi^+\pi^+\pi^-(\pi^0)}|^2} \tag{3}$$

$$M_{n\pi^-} = \sqrt{(E_{beam} - E_{\pi^+\pi^+(\pi^0)})^2 - |\overrightarrow{p}_{\Lambda_c^+} - \overrightarrow{p}_{\pi^+\pi^+(\pi^0)}|^2} \tag{4}$$

Since the two variables are highly correlated, the $M_{n\pi} - M_n$ variable is used to extract the total number of signal events. The distributions are shown in Fig. 3.

The resulting branching fraction are calculated with the double-tag approach and they are $BF(\Lambda_c^+ \to= \Sigma^-\pi^+\pi^+) = (1.81 \pm 0.17)\%$ and $BF(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0) = (2.11 \pm 0.33)\%$.

3.4. *Evidence of $\Lambda_c^+ \to p\eta$ and search for $\Lambda_c^+ \to p\pi^0$*

To search for rare decays it is possible to use the single-tag technique to improve the efficiency and thus access to lower branching ratio. On the other hand, the background level will raise. Single Cabibbo Suppress decays help to address the feature of the charmed baryon. In literature there are several theoretical predictions (Refs. 6, 7, 8, 9) for the decays $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$, that shall proceed predominantly through internal W-emission and W-exchange diagrams, that are not-factorizable in the Heavy Quark Effective Theory.

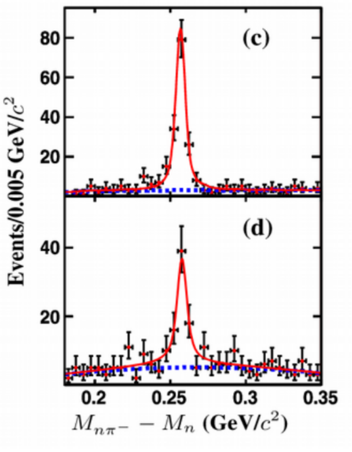

Fig. 3. Fit to the $(M_{n\pi^-} - M_n)$ distributions, where $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ final state are presented in the top and bottom plot respectively.

BESIII reports in Ref. 10 the first evidence of $\Lambda_c^+ \to p\eta$ and the upper limit of the process $\Lambda_c^+ \to p\pi^0$.

The two dominant η decay mode were analyzed and are shown in Fig. where the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ are presented in the top and bottom part respectively. The measured branching fraction is $BF(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$, where the first error is statistical and the second one is due to the systematics.

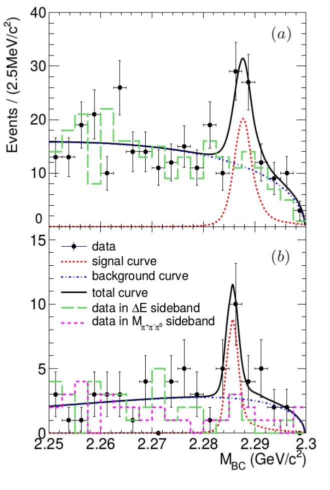

Fig. 4. Fit to the M_{BC} distribution for the two η final state. (Top) $\eta \to \gamma\gamma$. (Bottom) $\eta \to \pi^+\pi^-\pi^0$

For the $\Lambda_c^+ \to p\pi^0$ process, the π^0 is reconstructed in the $\pi^0 \to \gamma\gamma$, but, as shown in Fig. , no clear signal arise. The upper limit is calculated to be $BF(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4}$ at 90% of C.L.

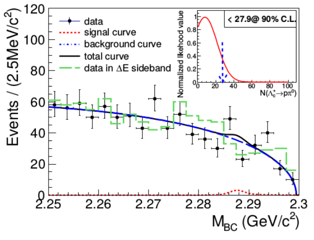

Fig. 5. Fit to the M_{bc} distribution for the process $\pi^0 \to \gamma\gamma$. In the left corner box, the function to extract the upper limit.

Based on the both results and on the ratio, the theoretical prediction of Sharma *et al* (Ref. 6) is the one that agrees more with the experimental data of BESIII, assuming that the sign of the p-wave decay of $\Lambda_c \to \Xi^0 K^+$ is negative.

4. Summary

This work aimed to give a brief description of some of the most interesting results of the BESIII physics program on the Λ_c. As it can be seen, most of the results, although being the most precise one, are still statistically limited. So, BESIII is currently planning to collect $3\,\text{fb}^{-1}$ data to improve largely the present statistic and thus, the precision of the known measurements and to access to further decay modes.

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