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SELEX: Recent Progress in the Analysis of Charm-Strange and Double-Charm Baryons

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1   Introduction

SELEX (Fermilab Experiment 781) [1] employs beams of Σ^-, π^-, and protons at around $600\,\mathrm{GeV}/c$ to study production and decay properties of charmed baryons. It took data in the 1996/7 fixed target run and is currently analyzing those data.

Here we will focus on recently obtained results concerning the Ω_c^0 lifetime and the doubly-charmed baryons Ξ_{cc}^+ and Ξ_{cc}^{++}.

2   New Results on the Ω_c^0

SELEX observes the Ω_c^0 in three decay modes, namely $\Omega_c^0 \to \Omega^-\pi^+$, $\Omega_c^0 \to \Omega^-\pi^+\pi^+\pi^-$, and $\Omega_c^0 \to \Xi^- K^-\pi^+\pi^+$. The invariant mass distributions for these modes are shown in fig. 1. The total sample contains 107 ± 22 events, nearly half of them in $\Omega 3\pi$. At this moment we are working on the systematics of the mass and branching ratio measurements of these modes [2].

We use the $\Omega\pi$ and $\Omega 3\pi$ channels to determine the lifetime of the Ω_c^0. We calculate the reduced proper time ct, given by $ct = (L-N\sigma)/\gamma$, requiring $L/\sigma > N$ with $N = 6$, for each event within the mass region of the Ω_c^0. The proper lifetime resolution is $\sim 20\,\mathrm{fs}$. We make a maximum likelihood fit to a probability distribution having an exponential decay for the signal and two exponentials for the fast and slow components of the background:

$$N_s(1-\alpha)f(t)\tau^{-1}e^{-t/\tau} + \alpha N_B(\beta\tau_1^{-1}e^{-t/\tau_1} + (1-\beta)\tau_2^{-1}e^{-t/\tau_2})$$

where τ, α, β, τ_1, τ_2 are the fit parameters describing the lifetime and the relative contributions of the background to the ct distribution, and $f(t)$ is the acceptance
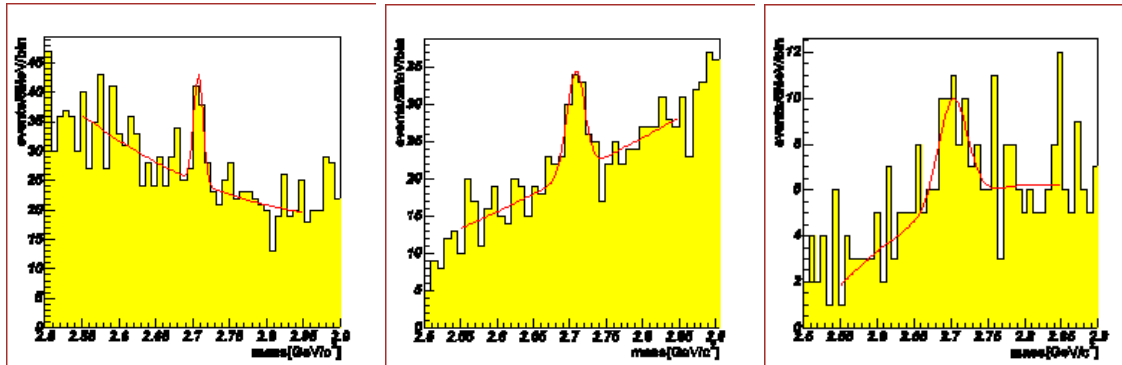
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Figure 1: Invariant mass distributions for different decay modes of the Ω_c^0. Left: $\Omega^-\pi^+$, Signal: 35 ± 12 events; center: $\Omega^-\pi^+\pi^+\pi^-$, 44 ± 14 events; right: $\Xi^- K^-\pi^+\pi^+$, 28 ± 12 events

function. We do this for each mode separately, and obtain for the $\Omega\pi$ mode $\tau = 62.6 \pm 22.0$ fs and for the $\Omega 3\pi$ mode $\tau = 65.8 \pm 16.0$ fs. Combining the two results yields $\tau_{\Omega_c} = 65 \pm 13\,(stat) \pm 9\,(sys)$ fs. More details can be found in [3]. This result should be compared to the current PDG average [4] of 69 ± 12 fs, using a total of 175 events from three different experiments.

3   Doubly Charmed Baryons

3.1   The Discovery of Double Charm Baryons

In 2002 the SELEX collaboration reported the first observation of a candidate for a double charm baryon, decaying as $\Lambda_c^+ K^-\pi^+$ [5, 6]. The state had a mass of $3519 \pm 2\,\mathrm{MeV}/c^2$, and its observed width was consistent with experimental resolution, less than $5\,\mathrm{MeV}/c^2$. The final state contained a charmed baryon and negative strangeness (Λ_c^+ and K^-), consistent with the Cabibbo-allowed decay of a Ξ_{cc}^+ configuration. In order to confirm the interpretation of this state as a double charm baryon, it is essential to observe the same state in some other way. Other experiments with large charm baryon samples, e.g., the FOCUS [7] and E791 fixed target charm experiments at Fermilab or the B-factories, have not confirmed the double charm signal. This is not inconsistent with the SELEX results. The report in Ref. [5] emphasized that this new state was produced by the baryon beams (Σ^-, proton) in SELEX, but not by the π^- beam. It also noted that the apparent lifetime of the state was significantly shorter than that of the Λ_c^+, which was not expected in model calculations [8]. A more detailed discussion can be found in [9].

2

3.2   Features and Problems in the Original Analysis, and Possible Solutions

All the signals observed so far are statistically significant, but have only a few signal events. The signals are clean, e.g. there is very little background, but the background itself is also difficult to estimate. SELEX only observes events from the baryon (Σ^-, proton) beams, and the number of observed events is larger than some production models (see for example [10,11]) predict. As mentioned before, the lifetime seems to be very short, and no other experiment has confirmed our observations.

Another way to confirm the Ξ_{cc}^+ is to observe it in a different decay mode that also involves a final state with baryon number and charm (not anti-charm). One such mode involving only stable charged particles is the channel pD^+K^-, another one $\Xi_c^+\pi^+\pi^-$. SELEX developed a new method for a more reliable background determination. We also improved the resolution on the secondary vertex position by including the single-charm track into the vertex fit, and we redid our full analysis chain to increase our statistics. In the following we will describe these step in details.

3.3   New Analysis Features within SELEX

The Cabibbo-allowed decay of the Ξ_{cc}^+ is shown in the following figure.
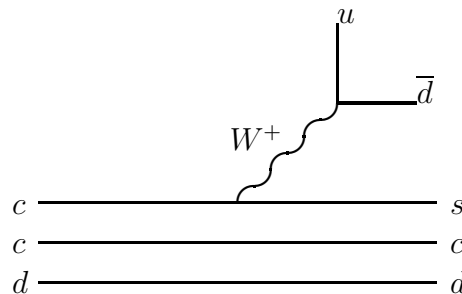
In the final state we expect a baryon, and the quarks $csdu\overline{d}$ plus eventually some pairs from the sea. We also expect a cascaded decay chain, with the first, and later the second charm quark undergoing a weak decay.

For SELEX, the easily accessible decay modes for the different doubly charmed baryons are: $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$, $\Xi_{cc}^+ \to pD^+K^-$, $\Xi_{cc}^+ \to \Xi_c^+\pi^-\pi^+$, $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$, $\Xi_{cc}^{++} \to pD^+K^-\pi^+$ (depending on the mass of the Ξ_{cc}^{++}), $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$, $\Xi_{cc}^{++} \to \Xi_c^+\pi^+\pi^+\pi^-$, $\Omega_{cc}^+ \to \Xi_c^+ K^-\pi^+$, and $\Omega_{cc}^+ \to \Xi_c^+ K^-\pi^+\pi^+\pi^-$. The first two modes are already published [5,12] by SELEX, and work on the other modes is in progress; here we will report on a first observation of the third decay mode listed.

For the background determination, we developed an event mixing method. The first decay vertex is close to the primary vertex, and we assume that all the background is purely combinatoric. We make combinatoric backgrounds by taking the first decay

vertex from one event, and the second vertex from another event; to increase statistics, we use the single-charm vertex 25 times. The resulting combinatoric background is absolutely normalized. We employed this method already in [12].
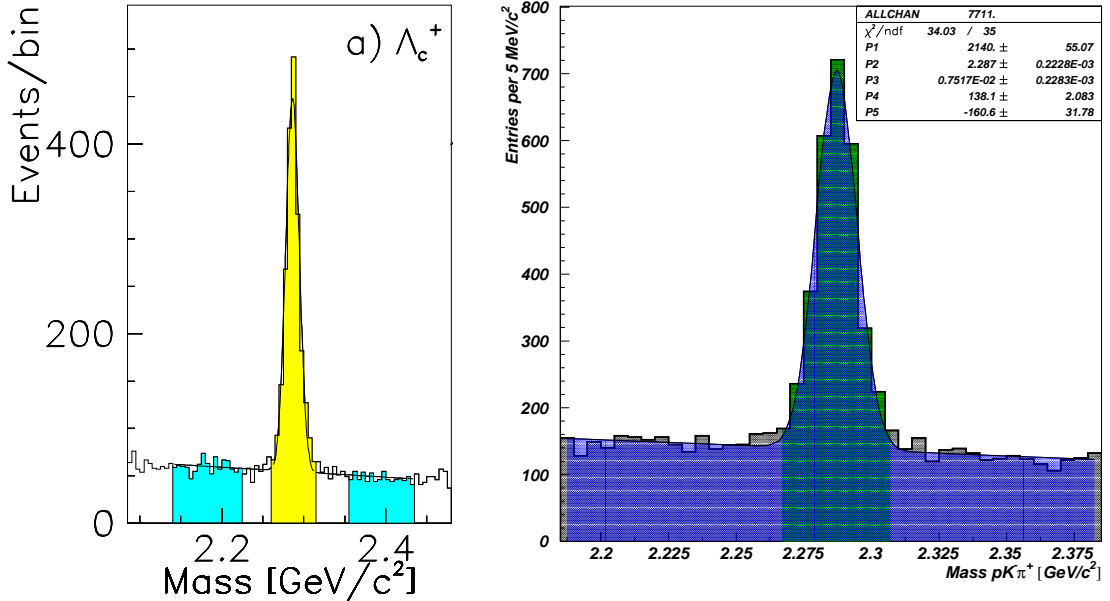
3.4 $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ – New Analysis

Figure 2: $\Lambda_c^+ \to pK^-\pi^+$ data sets of original (left) and new (right) analysis.

To increase our statistics, we re-analyzed our full data set with some softer cuts and with improved tracking software. In fig. 2 we show a comparison of the Λ_c^+ data set used for the analysis. The number of $\Lambda_c \to pK^-\pi^+$ candidates increased from 1630 to 2140.

We also improved the resolution of the decay vertex position of the Ξ_{cc}^+ candidate by including the vector of the Λ_c^+ into the vertex fit. This improved resolution reduces the background when applying a cut in L/σ, while keeping more signal events. It also increases the possibility of measuring the lifetime of double charm baryons.

Figure 3 shows the results of our new analysis, for various cuts in L/σ of the first decay vertex. Re-analyzing and relaxing some cuts in the single charm sample increased the number of signal events, but also resulted in a somewhat higher background level; but the background is nicely reproduced and well understood from the combinatoric analysis. The improved secondary vertex resolution yields in cleaner signals and allows access to other decay modes, which we will pursue in the future. Measuring the lifetime now seems possible, but is still challenging. As seen from the yields for different cuts in L/σ, the lifetime seems to be around $1\,\sigma$.
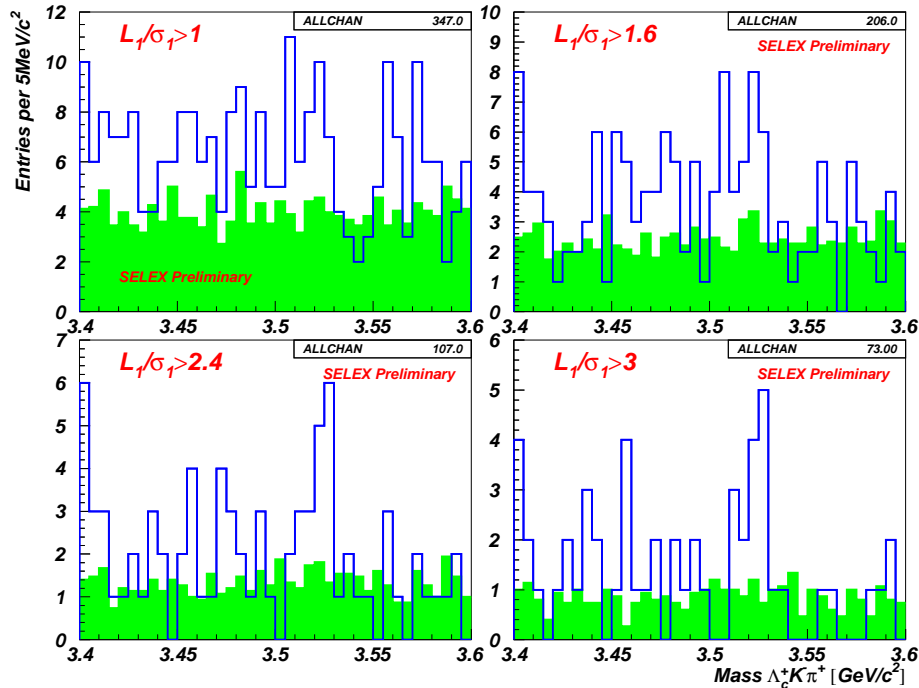
Figure 3: $\Lambda_c^+ K^- \pi^+$ ($\Lambda_c^+ \to pK^- \pi^+$) invariant mass distributions (blue) for various cuts in L/σ on the first decay vertex. In green we show the estimated combinatoric background from the event mixing procedure described in the text.

3.5 $\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

We also revisited with our re-analyzed data set the first double-charm baryon state we found in SELEX [6], the $\Xi_{cc}(3780)^{++}$. In fig. 4 is shown the $\Lambda_c^+ \pi^+ \pi^+$ invariant mass distribution, restricting ourselves to Σ^- induced events. The peak at $3780\,\text{MeV}/c^2$ is statistically significant, and is wider than our experimental resolution, as shown by Monte Carlo. The background is well described by our mixed event procedure. By removing the slower of the π^+'s, we observe that about half of the $\Xi_{cc}(3780)^{++}$ decay to $\Xi_{cc}^+(3520)$. At this moment we are finishing up the analysis for this state.

4 First Observation of $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$

SELEX published [13] the first observation of the Cabibbo-suppressed decay of $\Xi_c^+ \to pK^- \pi^+$; this is the same final state as we used before for the reconstruction of the Λ_c^+. Our sample of Ξ_c^+ in the mode is much smaller than our Λ_c^+ sample, but the branching fraction of $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$ should be larger than to $\Lambda_c^+ K^- \pi^+$. We applied
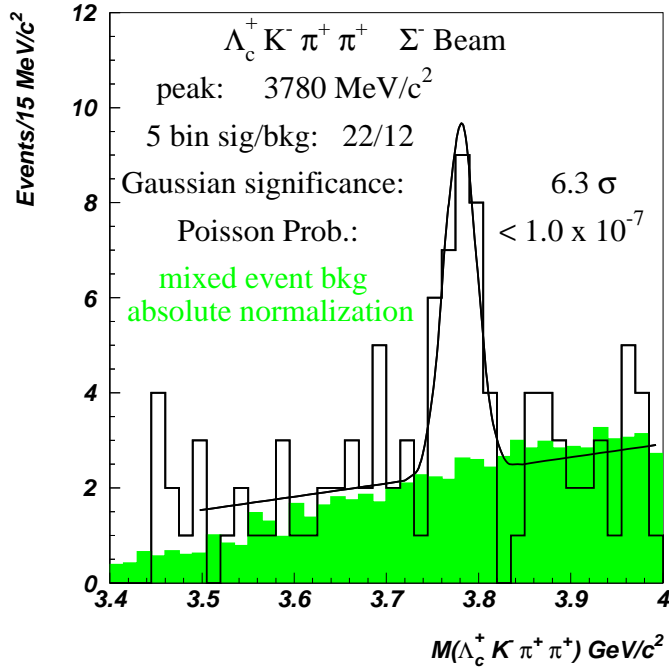
Figure 4: The $\Lambda_c^+ K^- \pi^+ \pi^+$ invariant mass distribution, for Σ^- beam only.

the same cuts and procedure as to the previously described analyzes, and obtained [14] the $\Xi_c^+ \pi^+ \pi^-$ invariant mass distribution shown in fig. 5. A clear peak at about $3520\,\mathrm{MeV}/c^2$ is seen in the figure. This constitutes the first observation of this decay mode of the $\Xi_{cc}^+(3520)$.

5   Summary

SELEX is still the only experiment observing double charm baryons. We published observations on two different decays modes, $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ [5] and $\Xi_{cc}^+ \to pD^+K^-$ [12]. After a re-analysis of our full data set, with improved efficiency and resolution, we presented here a higher-statistics observation of $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, and a re-analysis of the $\Xi_{cc}(3780)^{++}$. The new analysis also allows access to additional decay modes, and we presented here the first observation of $\Xi_{cc}^+ \to \Xi_c^+ \pi^- \pi^+$.

SELEX will continue the line of analysis, by first publishing these preliminary results. We will try to measure the lifetime of the Ξ_{cc}^+. We will also seek the isospin-partner of the Ξ_{cc}^+, the Ξ_{cc}^{++} in all corresponding decay modes around $3500\,\mathrm{MeV}/c$.
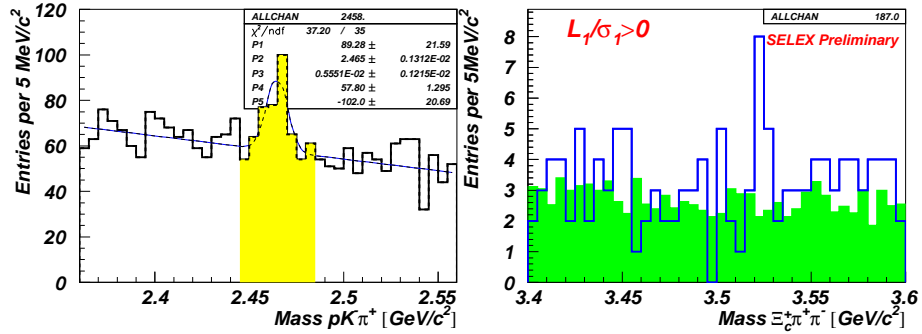
Figure 5: Left: $pK^-\pi^+$ invariant distribution and Ξ_c^+ sample (yellow) used. Right: $\Xi_c^+\pi^+\pi^-$ invariant mass distribution. The green histogram is our estimate of the combinatoric background.

6   Acknowledgment

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