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Studies of charmed baryons at LHCb

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We report a search for the doubly charmed baryon Ξ_{cc}^{+} through the decay $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$, using a data sample corresponding to an integrated luminosity of 0.65 pb^{-1} of pp collisions at $\sqrt{s} = 7\,\text{TeV}$. In the mass range 3300–3800 MeV/c^2 no significant signal is observed. Upper limits at 95% confidence level are set on R, the ratio of the production cross section of the Ξ_{cc}^{+} times the relevant branching fraction over the Λ_c^{+} cross section, as a function of the Ξ_{cc}^{+} mass and lifetime. The largest upper limits on R over the investigated mass range are $R < 1.5 \times 10^{-2}$ for a lifetime of 100 fs and $R < 3.9 \times 10^{-4}$ for a lifetime of 400 fs.

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1 Introduction

For the four lightest quarks predicted in the constituent quark model, the baryonic states are predicted to form $SU(4)$ multiplets. For the ground states with $C = 2$, a Ξ_{cc} isodoublet (ccu, ccd) and an Ω_{cc} isosinglet are expected. There are numerous predictions of the properties of these states, with the majority yielding masses in the range 3500–3700 MeV/c^2 and a lifetime in the range 100–250 fs [1–8]. The only observed signals for any of these states are those reported by the SELEX experiment for the Ξ_{cc}^+ in its decays to $\Lambda_c^+ K^- \pi^+$ and pD^+K^- [9, 10]. The reported state had a mass measured to be 3519 ± 2 MeV/c^2 and a lifetime consistent with zero, and less than 33fs at the 90% confidence level. Subsequent searches at the BELLE [11] and BaBar [12] experiments have not observed any evidence for doubly charmed baryon production. In these proceedings, we report the results of a search for the Ξ_{cc}^+ baryon at LHCb [13].

2 Analysis method

For comparison with subsequent searches in hadronic environments we measure the Ξ_{cc}^+ production relative to that of the Λ_c^+:

$$R \equiv \frac{\sigma(\Xi_{cc}^+)\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}} \tag{1}$$

where σ and $\mathcal{B}$ represent cross sections and branching fractions, respectively, $N_{\rm sig}$ and $N_{\rm norm}$ are the extracted yields of the Ξ_{cc}^+ signal and the control Λ_c^+, and $\epsilon_{\rm sig}$ and $\epsilon_{\rm norm}$ are the efficiencies of those modes. A reasonable expectation is that $\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+) \approx \mathcal{B}(\Lambda_c^+ \to p^+ K^- \pi^+) \approx 5\%$. The LHCb Λ_c^+ cross-section at $\sqrt{\rm s} = 7$ TeV has been measured to be 230 ± 77 μb [14]. Phenomenological estimates of the Ξ_{cc}^+ production cross section in a pp environment at $\sqrt{\rm s} = 14$ TeV range between 60–1800 nb [4], and at $\sqrt{\rm s} = 7$ TeV this is expected to be approximately halved. Therefore at LHCb R is expected to be of order $10^{-5} - 10^{-4}$.

To account for the a priori unknown Ξ_{cc}^+ mass and lifetime we search for the Ξ_{cc}^+ in a wide mass range ($3300 - 3800$ MeV/c^2) and calculate efficiencies for a variety of lifetime hypotheses. For each candidate the mass difference is calculated as

$$\delta m \equiv m([pK^-\pi^-]_{\Lambda_c^+} K^- \pi^+) - m([pK^-\pi^-]_{\Lambda_c^+}) - m(K^-) - m(\pi^+) \tag{2}$$

where $m([pK^-\pi^-]_{\Lambda_c^+} K^- \pi^+)$ is the measured invariant mass of the reconstructed Ξ_{cc}^+ candidate, $m([pK^-\pi^-]_{\Lambda_c^+})$ is the measured mass of the reconstructed Λ_c^+ candidate and $m(K^-)$ and $m(\pi^+)$ are respectively the charged kaon and pion world-averaged masses. This Ξ_{cc}^+ mass window corresponds to a δm signal window of $380 < \delta m < 880$ MeV.

Our analysis is carried out using a data sample corresponding to an integrated luminosity of 0.65 pb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV, from the data gathered at LHCb during 2011. The analysis procedure was fixed before the data in the signal region was examined. Limits are on R are given as a function of both the Ξ_{cc}^{+} mass and lifetime.

3 Candidate selection

The selection procedure to trigger, reconstruct and select candidates must retain signal candidates and suppress three main sources of background. These backgrounds are combinations of unrelated tracks, mis-reconstructed heavy-flavour decays, and combinations of a real Λ_c^+ with unrelated tracks. The first two lead to smooth distributions in both $m([pK^-\pi^-]_{\Lambda_c^+})$ and δm, while the third background only peaks in $m([pK^-\pi^-]_{\Lambda_c^+})$ and is smooth in δm.

The selection in the software and hardware triggers for the signal and normalisation mode ($\Lambda_c^+ \to pK^-\pi^+$) is identical to reduce systematic uncertainties. A candidate must fulfil the criteria that one of the three Λ_c^+ daughter tracks must be associated with a calorimeter cluster with a measured transverse energy greater than 3500 MeV to fire the hardware trigger. One of the Λ_c^+ daughter tracks must then be selected by an inclusive selection algorithm in the software trigger, which requires the track possesses a transverse momentum greater than 1700 MeV/c and $\chi^2_{\mathrm{IP}} > 16$ with respect to any primary vertex, where χ^2_{IP} is the increase to the associated primary vertex's reconstructed χ^2 when the track is included in the primary vertex fit.

The Λ_c^+ candidate must then be reconstructed by a dedicated $\Lambda_c^+ \to pK^-\pi^+$ selection algorithm which makes a variety of kinematic and geometric requirements. The candidate must be displaced from the primary vertex, the reconstructed Λ_c^+ $p_T >$ 500 MeV/c, and the tracks must have a track fit $\chi^2 < 3$ and meet at a common vertex ($\chi^2/\mathrm{N_{dof}} < 15$). The dedicated trigger algorithm was not enabled for the full 2011 period, resulting in an integrated luminosity of 0.65pb^{-1} in this analysis. The remainder of the Λ_c^+ selection is performed at the software level, and imposes a Λ_c^+ mass window of $2185 < m([pK^-\pi^-]_{\Lambda_c^+}) < 2385$ MeV/c^2 while placing a number of kinematic cuts on the candidates and particle identification (PID) requirements on the daughter tracks.

The Ξ_{cc}^{+} candidates are then reconstructed by pairing the reconstructed Λ_c^+ with two tracks which have been identified as a K^- and π^+. The particles are required to point to a common vertex which is displaced from the PV. The kaon and pion tracks should also not have originated from the direction of the primary vertex and are required to have $p_T < 250$ MeV/c. A further multivariate selection is then applied to these candidates to improve the purity of the sample. An artificial neural network is implemented utilising the TMVA package [15]. The input variables are chosen as to display minimum Ξ_{cc}^{+} lifetime dependence. The network is trained on simulated Ξ_{cc}^{+} signal samples and on δm sideband data which is within 200 MeV/c^2 of the δm signal window.

The full selection has a limited efficiency for low Ξ_{cc}^{+} lifetime hypotheses. This is primarily attributable to the requirements that the reconstructed Ξ_{cc}^{+} vertex must be displaced from the primary vertex, and that the impact parameters of the kaon and pion should be significant with respect to the primary vertex. This analysis is therefore insensitive to Ξ_c resonances which decay strongly to the same final state.

4 Yield extractions

To extract N_{norm} an extended maximum likelihood fit is performed to the $pK^-\pi^+$ mass spectrum. The signal shape is parameterised as the sum of two Gaussian functions with a shared mean and the background is parameterised as a first-order polynomial. The selected Λ_c^+ yield in the full analysis is $N_{\text{norm}} = (818 \pm 7) \times 10^3$, with a mass resolution of ≈ 6 MeV/c^2.

The Ξ_{cc}^{+} yield is extracted from the δm distribution for a number of δm hypotheses. The method requires sufficient knowledge of the signal mass resolution to define a signal window, but beyond that requires no further information on the Ξ_{cc}^{+} lineshape. This is determined with a fit to the simulated signal, parameterising the signal as the sum of two Gaussian functions with a shared mean. The resolution is determined to be $\approx 4\,\text{MeV}/c^2$. For each investigated δm a narrow signal region is defined as $2273 < m([pK^-\pi^-]_{\Lambda_c^+}) < 2303\text{MeV/c}^2$ and $|\delta m - \delta m_0| < 10\text{MeV/c}^2$. Candidates outside this window are used to estimate the expected background within the signal window, and this is subtracted from the number of candidates inside the window to calculate the signal yield for that value of δm.

Two methods following this procedure are used. The first is an analytic two dimensional sideband subtraction, which uses a 5×5 array of non-overlapping, variable size tiles centred on the signal region with total width of $80\,\text{MeV}/c^2$ in $m([pK^-\pi^-]_{\Lambda_c^+})$ and total width $200\,\text{MeV}/c^2$ in δm. The combinatoric background is parameterised by a two-dimensional quadratic function while the Λ_c^+ component is described by the product of a signal peak in $m([pK^-\pi^-]_{\Lambda_c^+})$ and a quadratic function in δm. The background distribution is then extracted from the 24 non-central bins and the integral of this distribution over the signal box (central bin) is evaluated, extracting the background and associated statistical error. A second, cross check method is also employed by imposing a narrow Λ_c^+ mass window on all candidates and reducing the problem to a one-dimensional δm distribution.

5 Efficiency corrections and systematics

The efficiency ratios in the analysis are calculated using a variety of data-driven methods and methods utilising simulated data. The kinematic distributions of Ξ_{cc}^+ at the LHC are unknown. The simulation used in this analysis is generated according to the `GENXICC` [16] model, and with $m(\Xi_{cc}^+ = 3500\ \mathrm{MeV}/c^2)$ and $\tau_{\Xi_{cc}^+} = 333$ fs. The efficiency ratio may be factorised into the following components:

$$\frac{\epsilon_{\mathrm{norm}}}{\epsilon_{\mathrm{sig}}} = \frac{\epsilon_{\mathrm{norm}}^{\mathrm{acc}}}{\epsilon_{\mathrm{sig}}^{\mathrm{acc}}} \frac{\epsilon_{\mathrm{norm}}^{\mathrm{sel|acc}}}{\epsilon_{\mathrm{sig}}^{\mathrm{sel|acc}}} \frac{\epsilon_{\mathrm{norm}}^{\mathrm{PID|sel}}}{\epsilon_{\mathrm{sig}}^{\mathrm{PID|sel}}} \frac{1}{\epsilon_{\mathrm{sig}}^{\mathrm{ANN|PID}}} \frac{\epsilon_{\mathrm{norm}}^{\mathrm{trig|PID}}}{\epsilon_{\mathrm{sig}}^{\mathrm{trig|ANN}}} \tag{3}$$

where the efficiencies correspond to the acceptance (acc), the reconstruction and selection excluding the PID and ANN requirements (sel), the particle identification requirements (PID), the ANN selection for the signal mode only (ANN), and the trigger (trig). Most of these are evaluated with the use of simulated Ξ_{cc}^+ and Λ_c^+ decays. Due to known discrepancies between the data and simulation corrections to these efficiencies are required. The efficiency of the PID requirements, the tracking and the calorimeter hardware trigger are evaluated with the use of data-driven calibration techniques.

As the Ξ_{cc}^+ mass and lifetime are *a priori* unknown, it is necessary to re-weight the simulated events to evaluate the efficiencies for a variety of potential Ξ_{cc}^+ properties. In the case of the Ξ_{cc}^+ lifetime, the simulated events are re-weighted with a different exponential distribution and the efficiency is recalculated. In the case of the Ξ_{cc}^+ mass, simulated data is generated under two other mass hypotheses, $m(\Xi_{cc}^+ = 3300\,\mathrm{MeV})$ and $m(\Xi_{cc}^+ = 3700\,\mathrm{MeV})$ without simulating interactions with the detector. The kinematics of the Ξ_{cc}^+ daughters in the primary simulated data are re-weighted to match the distributions of the low and high mass simulation data and the efficiency is redetermined. Defining the event sensitivity α as

$$\alpha \equiv \frac{\epsilon_{\mathrm{norm}}}{N_{\mathrm{norm}}\epsilon_{\mathrm{sig}}} \tag{4}$$

such that $R = \alpha N_{\mathrm{sig}}$, it was found that α varies strongly with Ξ_{cc}^+ lifetime and weakly with Ξ_{cc}^+ mass.

The dominant uncertainty in the analysis is the statistical uncertainty on the measured signal yield, and systematic uncertainties on α have limited effects on the expected upper limits. The dominant systematic uncertainty in the analysis is due to the limited sample size of simulated events used in the efficiency corrections. Smaller systematic effects are also associated with the data-driven efficiency calibration methods. The systematic uncertainty depends on the Ξ_{cc}^+ lifetime and mass hypotheses used. Adding these effects in quadrature an overall systematic for the analysis of 26% is assigned.

6 Results and conclusions

Tests for Ξ_{cc}^{+} signals are carried out at $1\,\text{MeV}/c^2$ steps across the full δm range. For each value, yields for signal and background are extracted as in Sec. 4. Local significances are then calculated as

$$\mathcal{S}(\delta m) \equiv \frac{N_{S+B} - N_B}{\sqrt{\sigma_{S+B}^2 + \sigma_B^2}} \tag{5}$$

where σ_{S+B}^2 and σ_B^2 are the statistical uncertainties on the signal yield and the expected background. The look elsewhere effect [17] is taken into account to correct for a global significance. A large number of simulated background-only pseudo-experiments are generated and the full analysis procedure is applied to each. The global p-value for a given S is then the fraction of the total simulated experiments which contained an equal or larger local significance at any value of δm. If no signal excess corresponding to a global significance of 3σ is observed, upper limits on R are quoted using the CL_S method [18].

The δm distribution is shown in Fig. 1, and the estimated signal yield in Fig. 2. The largest local significance observed is at $\delta m = 513\,\text{MeV}$ corresponding to a local significance $\mathcal{S} = 1.5\ \sigma$ ($2.2\ \sigma$ in the 1D cross-check fit). This corresponds to a global p-value of 99 % (53 %). It is therefore concluded that no significant excess is observed. Upper limits on R are given in Fig. 3 across the δm distribution for a variety of lifetime hypotheses.

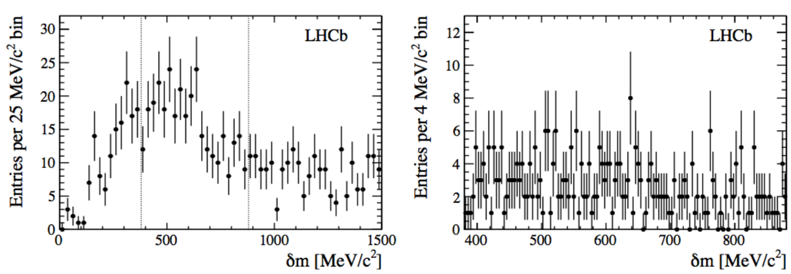

Figure 1: The δm distribution requiring $2273 < m([pK^-\pi^-]_{\Lambda_c^+}) < 2303\,\text{MeV}$. The right plot shows the highlighted range in the left with a finer binning.

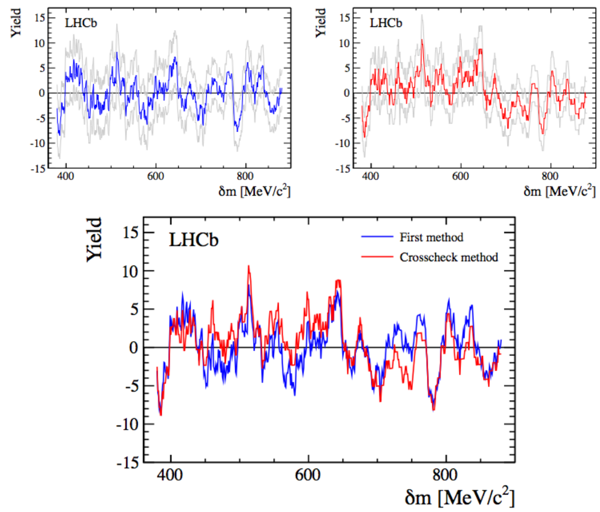

Figure 2: The measured signal yields in δm. The upper plots show the yields for the primary extraction method (left) and the cross-check method (grey lines are $\pm 1\ \sigma$ statistical error bands). Lower plot shows both methods plotted together, indicating good agreement.

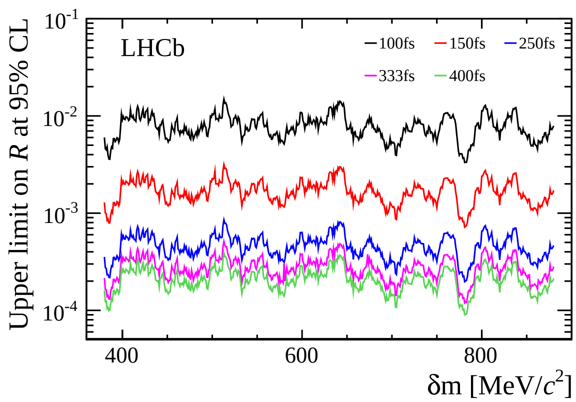

Figure 3: Upper limits on R for a number of Ξ_{cc}^{+} lifetime hypotheses.

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