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Charmed baryons from LHCb

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The vast amount of $c\bar{c}$ production which can be recorded by the LHCb detector makes it an ideal environment to study the hadronic production of charmed baryons, along with the properties of their decays. We briefly describe the LHCb experiment, and the triggering mechanisms it uses for recording charm production. Previous charmed baryon results from LHCb are detailed, with a description of the future plans for the charmed baryon programme.

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[1]on behalf of the LHCb collaboration.

1 Introduction

Recent years have seen great advances in our understandings of the charmed baryons. The B-factories, in particular the Belle and BaBar collaborations, have been successful in making a wide variety of first observations of excited singly-charmed baryons [1, 2, 3, 4, 5, 6, 7, 8]. The current best knowledge of the spectra of singly-charmed baryons is given in Figure 1. The spin-parity assignments of many of the observed states are still to be discovered.

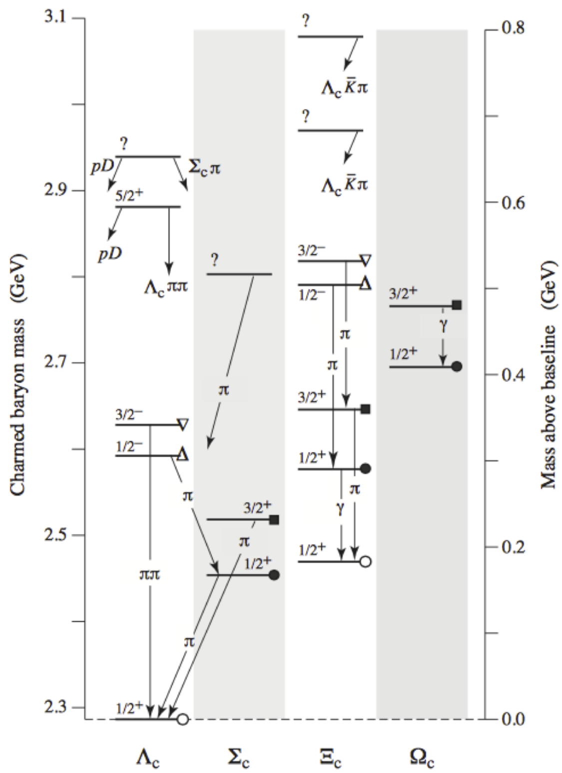


Figure 1: The spectra of known singly-charmed baryons and their mass splittings. Reproduced from [9].

In the $SU(4)$ formalism we find states in the quark model corresponding to ccd (Ξ_{cc}^{+}), ccu (Ξ_{cc}^{++}) and ccs (Ω_{cc}^{+}). Theoretical calculations generally agree that the $C = 1$ states should have lifetimes between $100 - 250$ fs, with the $C = 2$ state having a lifetime between $500 - 700$ fs [10, 11]. Evaluations for the particle mass generally predict that the Ξ_{cc} isodoublet will have a mass between $3.5 - 3.7$ GeV/c^2, with the mass of the Ω_{cc}^{+} predicted to be between $3650 - 3800$ GeV/c^2 [12, 13, 14, 15].

The SELEX collaboration has reported an observation of the Ξ_{cc}^{+} in its decays to $\Lambda_c^{0+} K^- \pi^+$ [16] and to pD^+K^- [17]. The reported state has a measured mass of 3519 ± 2 MeV/c^2, consistent with predictions from the theory community. Its measured lifetime, however, was consistent with zero, and less than 33 fs at the 90 % confidence level. This is in strong disagreement with predictions of HQET and lattice QCD, and is very different to the well-established lifetime of the Λ_c^+ ($\tau \approx 200$ fs).

If such an observation is legitimate, then much can be learned from the study of the baryon, and why its lifetime is so uncharacteristically short. Subsequent searches at notably BELLE [1], BaBar [18] and other experiments have not shown evidence for doubly-charmed baryon production. As such, the matter is still very much open to discussion, and the theory community eagerly awaits a second experimental observation of the state.

2 The LHCb detector

The LHCb [19] detector is a dedicated forward arm spectrometer, and is the dedicated heavy-flavour physics experiment at the LHC. The detector has gathered large volumes of data from 2010 to 2012. The operating conditions of LHCb are described in Table 1. This data has already been utilised to make several important measurements in the charmed baryon sector, with many more new measurements presently being undertaken. These will be described in subsequent sections.

Year	$\sqrt{s}$ [TeV]	Instantaneous $\mathcal{L}$ [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Bunches	μ
2010	7	1×10^{32}	344	$0.5 - 2.5$
2011	7	4×10^{32}	1380	1.5
2012	8	4×10^{32}	1380	1.6
Nominal	14	2×10^{32}	2808	0.4

Table 1: The LHCb running conditions throughout the LHC Run I and the nominal conditions. The pileup, μ, is the average number of $p-p$ collisions in each visible bunch crossing.

The detector possesses powerful discrimination of secondary vertices from the decays of heavy-flavour particles produced in the primary interaction. Heavy flavour particles typically live long enough to fly around 1 cm from the location of the primary interaction. LHCb exploits a high-quality vertex resolution to isolate these particles from the production of lighter hadrons. The tracking system at LHCb provides a lifetime resolution of the order of 50 fs, precise enough to study the rapid oscillations of the B_s^0 meson. The discrimination of interesting signals from the high backgrounds present in a hadronic production environment requires a precise mass resolution and therefore a precise momentum resolution. The tracking system at LHCb provides a momentum resolution of $\delta p/p \approx 0.4 - 0.6$ %, which in the case of the decay $B_s^0 \to D_s^+ K^-$ provides a mass resolution of 16 MeV/c^2 [20].

Many decays of heavy-flavour hadrons of particular interest have a variety of topologically identical final states, obeying different CP symmetries. The discrimination of these different final states is vital to LHCb's goal to study CP-violation in the beauty and charm sectors, and also key to searches for rare decays like $B_s^0 \to \mu^+\mu^-$. The discrimination between different species of charged particle is therefore of utmost importance. The particle identification (PID) system at LHCb is able to provide strong mass hypotheses over the momentum range 1 – 100 GeV.

3 The LHCb charm triggers

3.1 Triggering in Run I

The production of $c\bar{c}$ at in LHC collisions is much higher than at the B-factories. This has been measured at LHCb to be

$$\sigma(c\bar{c})_{p_{\mathrm{T}}<8\,\mathrm{GeV}/c, 2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65(\mathrm{fragmentation})\,\mu\mathrm{b}$$

for production below 8 GeV/c transverse momentum, in the rapidity region 2.0 – 4.5, and where the last error is the theory uncertainty from the input fragmentation functions [21]. In Run I, the available retention rate for charm decays was 2 kHz. This presented a difficult challenge to retain as many interesting decays as possible while keeping down the trigger retention. To this end, prompt charm is triggered using a series of exclusive lines which exploit hadronic signiatures. A large number of secondary charm from b-hadron decays is also collected using a suite of topological triggers. Notably, semileptonic b-hadron decays with muons in the final state can be used to exploit the high efficiency, high purity muonic triggers.

The LHCb trigger is comprised of a low level hardware trigger and a high level software trigger. This schema is illustrated in Figure 2. Specifically for hadrons, a cluster must be recorded in the calorimeter exceeding 3.5 GeV/c. The first level of the software trigger, the HLT1, exploits a partial reconstruction to quickly and efficiently identify displaced tracks. For hadrons, a single charged track is required to have a transverse momentum greater than 1.7 GeV/c, an impact parameter with respect to the reconstructed primary interaction greater than 0.1 mm, and is required to fulfil a suite of track quality cuts. At the second level of the hardware trigger, the HLT2, a full event reconstruction is employed, allowing the identification of displaced primary vertices. The PID information from the RICH detectors is also available at this stage. While not used in the Run I charm triggers, direct PID information in the HLT has now been implemented in Run II.

The high production of charm necessitates a variety of requirements to be placed on candidates in order to reduce the trigger retention. These commonly consist of kinematic cuts on the c-hadron decay products, with vertex and track quality cuts.

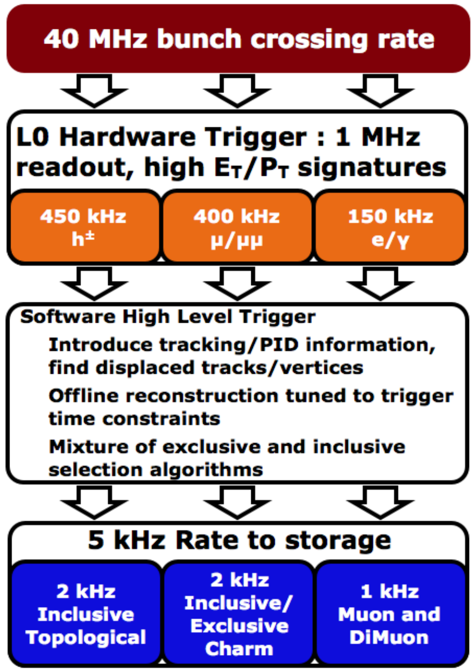
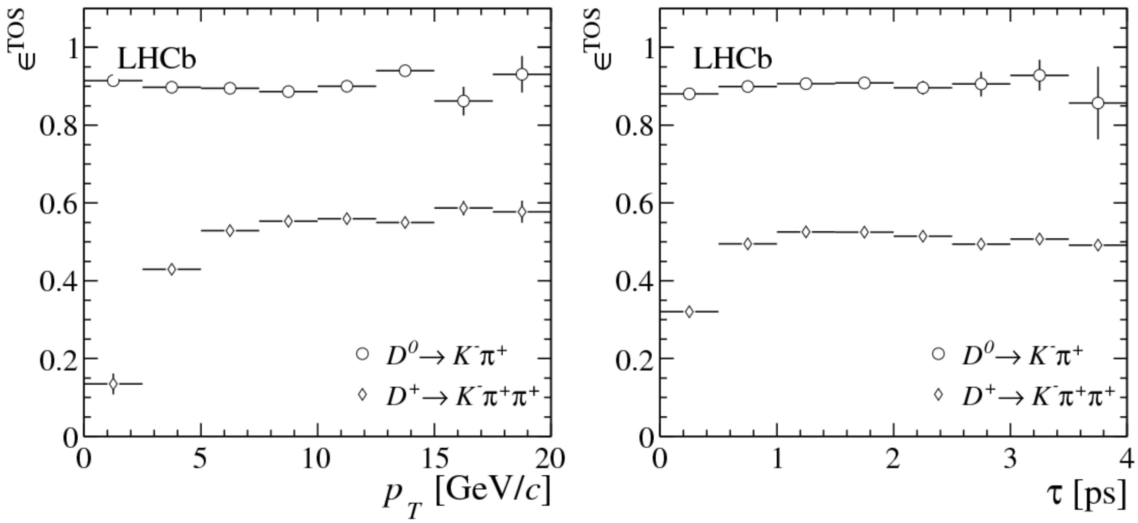


Figure 2: The LHCb trigger schema in Run I.

As shown in Figure 3, this can have the effect of biasing the selection with respect to key variables such as p_{T} and lifetime. A variety of accurate and precise data-driven techniques have been developed such that these effects can be corrected [22, 23].

3.2 Triggering in Run II

While the trigger in Run I was highly performant, a major issue was keeping the retention of the dedicated charm triggers under control. To mitigate this issue, the strategy of a "turbo" stream was developed, which eschews a full reconstruction online of signal candidates such that only part of the event must be saved to tape. This has proved to be an excellent solution in comparison to recording the full event and reconstructing signal candidates offline. In the "full" stream the typical event size is approximately 70 kbytes, whereas in turbo a signal candidate can be recorded using just 5 kbytes of data. This reduction of bandwidth allows for a vastly higher number of charm decays to be recorded with the available trigger retention. The majority of dedicated charm trigger lines have now moved to the turbo stream, enabling the recording of greatly increased signal yields with the same integrated luminosity.



(a) Trigger p_{T} dependence

(b) Trigger τ dependence

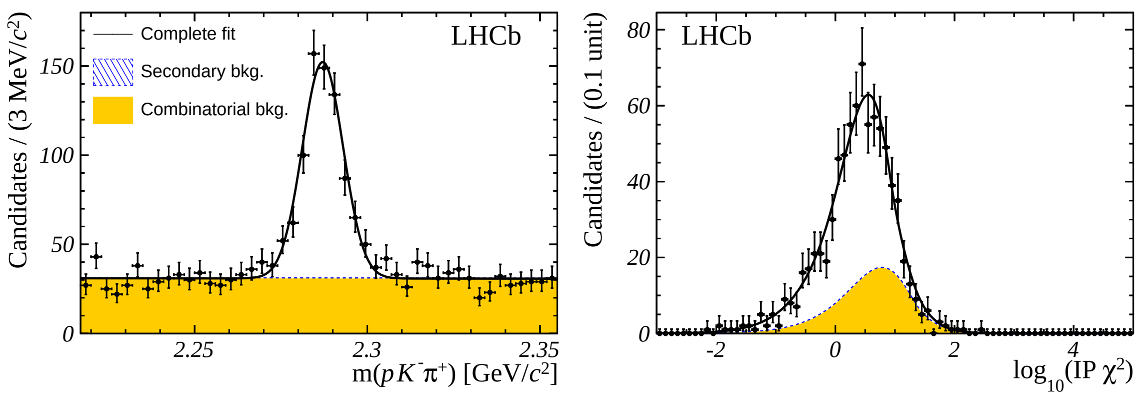
Figure 3: The trigger efficiencies of $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of the c-hadron transverse momentum (a) and its lifetime (b). The requirements necessary to keep dedicated charm trigger retention to acceptable levels can have the effect of biasing with respect to key quantities. This is handled using a variety of precise and accurate data-driven corrections.

4 Prompt charm cross sections at $\sqrt{s} = 7$ TeV

By measuring production cross sections of charmed hadrons it is possible to test the predictions of quantum chromodynamics (QCD), specifically fragmentation and hadronisation models. Calculations of charm cross sections with at next-to-leading order made with the Generalized Mass Variable Flavour Number Scheme (GMVFNS) [24, 25] and at fixed order with next-to-leading-log resummation (FONLL) [26, 27, 28] have been shown to accurately reproduce the cross-sections measured at both the Tevatron [29] and in the central region ($|\eta| < 0.5$) at the LHC [30, 31]. LHCb offers a unique opportunity to study charm production in the forward region in pp collisions.

LHCb has published a measurement of the cross sections of the D^0, D^+, D_s^+, D^{*+} and Λ_c^+ using 15 nb^{-1} of pp collisions recorded in 2010 [21]. Charm production at LHCb can be produced in a variety of ways - directly at the primary interaction, from feed-down of instantaneous decays of excited charm, and from secondary decays of b-hadrons. Those charmed hadrons produced in the first two ways are defined as "prompt", while those in the latter are defined as "secondary" and are treated as a background in this analysis.

Candidate Λ_c^+ are selected with a variety of kinematic and PID criteria, and selection efficiencies are corrected for using a variety of data-driven and simulation corrections. The signal extraction is performed using a simultaneous maximum likelihood fit to the Λ_c^+ mass and the Λ_c^+ $\log(IP\chi^2)$. The fits are capable of discriminating between the prompt signal, the secondary background, and backgrounds arising from random combinations of unrelated tracks. The results to the Λ_c^+ fit are shown in Figure 4, where the secondary contamination was shown to be consistent with zero.



(a) Λ_c^+ mass

(b) Λ_c^+ $\log(IP\chi^2)$

Figure 4: The fits used in the signal extraction of prompt Λ_c^+ from the combinatoric and secondary backgrounds.

The Λ_c^+ data was divided into bins of rapidity with one bin of p_T, and also into bins of p_T with one bin of rapidity, to allow comparison with the predictions from the GMVFNS scheme. The differential cross section for Λ_c^+ in p_T bin i is calculated as

$$\frac{\mathrm{d}\sigma_i(\Lambda_c^+)}{\mathrm{d}p_\mathrm{T}} = \frac{1}{\Delta p_\mathrm{T}} \cdot \frac{N_i(\Lambda_c^+ \to pK^-\pi^+ + \text{c.c.})}{\epsilon_i(\Lambda_c^+ \to pK^-\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) \cdot \mathcal{L}_\text{int}}$$

where $N_i(\Lambda_c^+ \to pK^-\pi^+ + \text{c.c.})$ is the number of $\Lambda_c^+ \to pK^-\pi^+$ decays (and the charge conjugate mode) recorded in the bin, $\epsilon_i(\Lambda_c^+ \to pK^-\pi^+)$ is the selection efficiency in that bin, $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ is the branching fraction of the decay (taken from the PDG as $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3)$ % [9]), and $\mathcal{L}_\text{int}$ is the integrated luminosity of the data sample.

In extracting the total cross sections, we discount bins with a relative uncertainty larger than 50 % and extrapolate the cross section with predictions from Pythia 6.4. We measure a total cross section in the acceptance for the Λ_c^+ of

$$\sigma(\Lambda_c^+)_{p_\mathrm{T}<8\,\mathrm{GeV}/c, 2.0<y<4.5} = 233 \pm 26\,(\text{stat}) \pm 71\,(\text{syst}) \pm 14(\text{extrapolation})\ \mu\text{b}$$

The Λ_c^+ cross section as a function of p_T is shown in Figure 5. The cross sections for all modes in the analysis are combined with the fragmentation functions from [25] to provide a $c\bar{c}$ cross section. The combination of all five measurements, taking into account correlations between the modes, yields

$$\sigma(c\bar{c})_{p_{\mathrm{T}}<8\,\mathrm{GeV}/c, 2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65(\mathrm{fragmentation})\ \mu\mathrm{b}$$

where the final uncertainty is due to fragmentation functions.

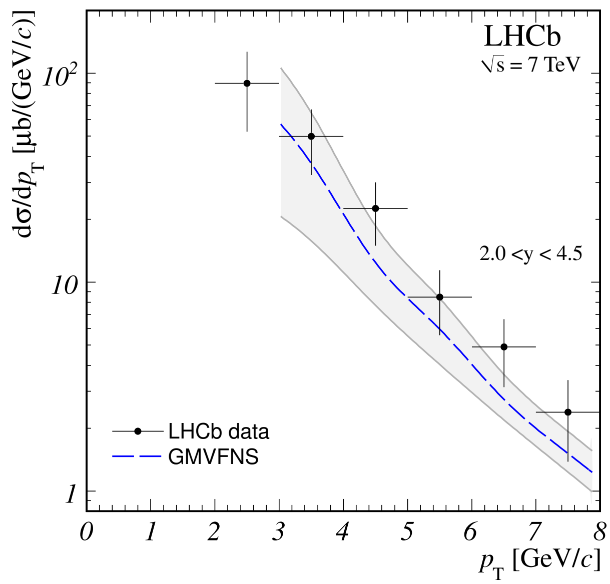


Figure 5: The measured Λ_c^+ cross section as a function of the Λ_c^+ p_{T}, compared with predictions from the GMVFNS scheme. The error bars show the combined statistical and systematic uncertainty on the measurements and the shaded region indicates the uncertainty on the theoretical predictions.

5 Search for Ξ_{cc}^+ with 2011 data

LHCb has conducted the first search for doubly charmed baryon production at a *pp* collider [32]. This search was performed on 0.65 pb^{-1} of *pp* data gathered in 2011 at a centre-of-mass energy $\sqrt{s} = 7$ TeV. We specifically measure the ratio of Ξ_{cc}^+ production relative to Λ_c^+ production:

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

where σ and $\mathcal{B}$ are the relevant cross sections and branching fractions, N_{sig} and N_{norm} are the extracted yields of the Ξ_{cc}^+ signal and the control Λ_c^+, and ϵ_{sig} and ϵ_{norm} are selection efficiencies.

To account for the 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 Ξ_{cc}^+ lifetime hypotheses. For each candidate we define a mass difference Δm as

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

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

The selection of candidates aims to reject backgrounds arising from combinations of unrelated tracks, mis-reconstructed c-hadron and b-hadron decays, and combinations of real Λ_c^+ with unrelated tracks. We first construct Λ_c^+ candidates, requiring that each passes a selection algorithm in the HLT which requires that the Λ_c^+ must be displaced from the primary interaction, and places PID, kinematic and vertex/track quality requirements on the decay. Ξ_{cc}^+ candidates are then constructed by pairing the Λ_c^+ candidates with a kaon and pion track. The bachelor kaons and pions are required not to point back to the primary interaction. This diminishes the sensitivity of the selection in the case of a very short lifetime Ξ_{cc}^+, but is necessary for the rejection of backgrounds where a real Λ_c^+ is paired with random kaons and pions. Finally, an artificial neural network is used to improve the selection purity of Ξ_{cc}^+ candidates, which is trained to have as little as possible sensitivity to the Ξ_{cc}^+ lifetime.

The signal yield of the normalisation channel is extracted using a fit to $m(pK^-\pi^+)$. The normalisation yield was found to be $(818 \pm 7) \times 10^3$, with a signal width of 6 MeV/c^2. The Ξ_{cc}^+ yield is extracted using a method which requires knowledge of the Ξ_{cc}^+ mass resolution (which is taken from simulation), but requires no other information of the Ξ_{cc}^+ lineshape. For each value of Δm a narrow signal region is defined as $2273 < m([pK^-\pi^-]_{\Lambda_c^+}) < 2303$MeV/c^2 and $|\delta m - \delta m_0| < 10$MeV/c^2. We use an analytic 2D sideband subtraction, using a 5×5 array of non-overlapping, variable size tiles centred on the signal region with total width of 80 MeV/c^2 in $m([pK^-\pi^-]_{\Lambda_c^+})$ and total width 200 MeV/c^2 in Δm. The combinatoric background is parameterised by a quadratic function, and the 24 non-central bins are used to extrapolate the background inside the signal region. The total Δm spectrum and the signal region are shown in Figure 6.

Signal yields are calculated in 1 MeV/c^2 intervals of Δm across the full signal region. Local significances at each interval are given as:

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

where σ_{S+B}^2 and σ_B^2 are the statistical uncertainties on the signal yield and the expected background. Global significances for each Δm must take into account the

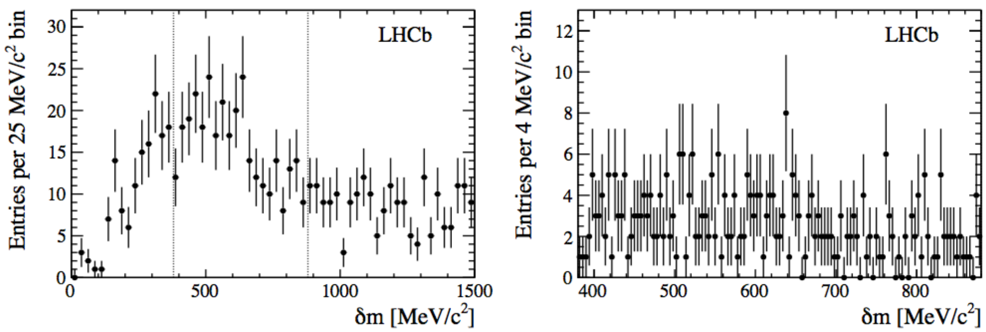


Figure 6: The full Δm spectrum (left) and the Ξ_{cc}^{+} signal region (right).

"look elsewhere effect" [33]. We do so by generating a large number of background only pseudo-experiments, with the full analysis method applied to each. We give a global p-value for a given S as the fraction of the total simulated experiments with an equal or larger local significance anywhere in the Δm spectrum.

The largest local significance observed is $S = 1.5\sigma$ at a $\Delta m = 513\,\mathrm{MeV}/c^2$, corresponding to a global p-value for the null hypothesis of 99 %. We therefore give upper limits on R as a function of Δm using the CL_S method [34]. We do so for a variety of Ξ_{cc}^{+} lifetime hypotheses (arrived at by re-weighting the simulation-derived efficiencies with different generated Ξ_{cc}^{+} lifetimes). These are given in Figure 7.

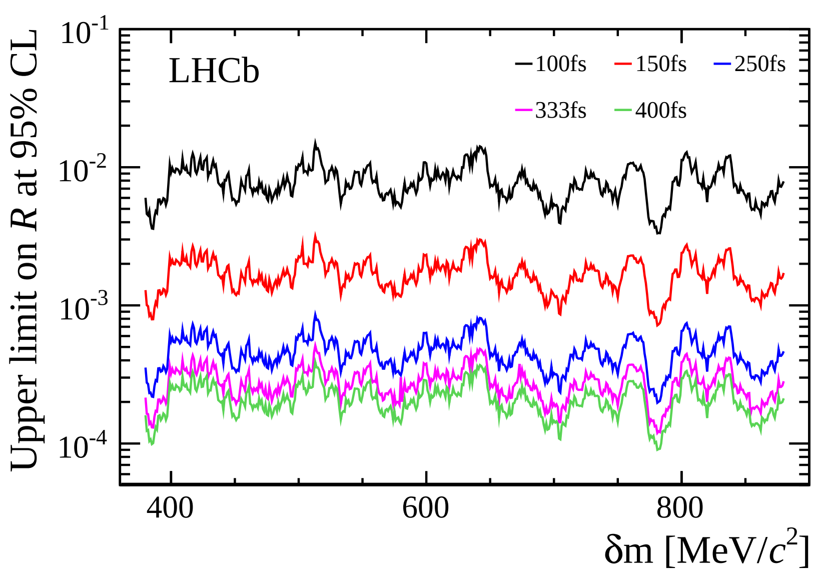


Figure 7: Upper limits on R for a number of Ξ_{cc}^{+} lifetime hypotheses.

6 Future and ongoing projects

A great many charmed baryon analyses are currently underway at LHCb, covering a wide range of topics. We briefly describe some of these, including updates to the analyses presented herein. We also detail some future prospects for future LHCb datasets which will be taken over the LHC Run II and Run III.

Charm cross section measurements at $\sqrt{s} = 13$ TeV are in the process of being evaluated using the 2015 LHCb dataset. We plan a vastly expanded suite of measurements, including differential cross sections of the Λ_c^+, Σ_c^0, Σ_c^{++}, Ξ_c^+ and Ξ_c^0 baryons. Work is also ongoing in improving the description of the proton detection asymmetry at LHCb, which is a limiting factor in prospective production asymmetry studies of these baryons. We hope to include these measurements using $\sqrt{s} = 13$ TeV data, complementary to our published results on D and D_s production asymetries at LHCb [35].

A new search for the doubly charmed baryons using the full Run I dataset is underway. In addition to the Ξ_{cc}^+, we now also search for the Ξ_{cc}^{++}. The analysis is able to take advantage of improvements to the dedicated $\Lambda_c^+ \to pK^-\pi^+$ triggers made in 2012 to enhance sensitivity. An expanded suite of Cabibbo-favoured decay modes will be used to search for these particles, including $\Xi_{cc}^{+[+]} \to D^+(K^-\pi^+\pi^+)pK^-[\pi^+]$ and $\Xi_{cc}^{+[+]} \to D^0(K^-\pi^+)pK^-[\pi^+]$ which can take advantage of LHCb's excellent D reconstruction. We tentatively expect to improve our current upper limits on R by an order of mangitude.

We conclude by reiterating that the LHCb detector's ability to perform charmed baryon spectroscopy has thus far been excellent. Over the course of the experiment's lifetime we anticipate a wide number of measurements of charmed baryon branching fractions, masses and lifetimes. We also plan to search for the remaining charmed baryon states, and are optimistic we can contribute to the open questions of doubly charmed baryon production.

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