PROCEEDINGS OF SCIENCE

Charmed baryons at LHCb

Paras Naik[*] [†]
University of Bristol
E-mail: paras.naik@bristol.ac.uk

The LHCb detector is an excellent instrument for studying the production and decay of charmed baryons in pp collisions, due to efficient triggering mechanisms that capture the copious production of $c\bar{c}$ at the Large Hadron Collider. The LHCb experiment and its charmed baryon results from LHCb are detailed, with a description of our future plans.

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[*] Speaker.
[†] on behalf of the LHCb collaboration.

1. Introduction

The current best knowledge of the spectra of singly-charmed baryons is given in Figure 1. Over the past decade, a wide variety of first observations of excited singly-charmed baryons [1, 2, 3, 4, 5, 6, 7, 8] have been made by the BaBar and Belle experiments. However, the spin-parity assignments of many of the observed states are still to be determined.

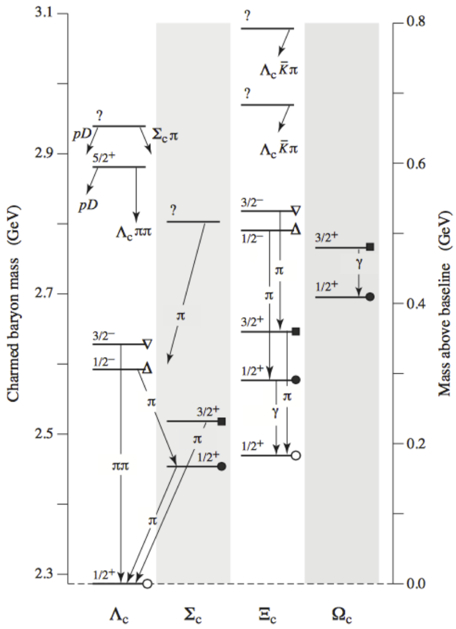

Figure 1: The spectra of known singly-charmed baryons and their mass splittings. Reproduced from [9].

The production cross section of $c\bar{c}$ in pp collisions at the LHC during Run I (2010-2012) was much higher than it was in e^+e^- collisions at BaBar and Belle, and has been measured at LHCb to be:

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

in pp collisions at $\sqrt{s} = 7$ TeV, for production below 8 GeV/c of transverse momentum (p_{T}) and in the rapidity (y) region $2.0-4.5$, where the last error given in this result is the uncertainty from the input fragmentation functions [10]. The large cross section of $c\bar{c}$ implies that copious quantities of charm baryons are produced. Indeed, in pp collisions at $\sqrt{s} = 7$ TeV we observe a large Λ_c^+ production cross section:

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

where the last error is due to the necessity of extrapolating the cross section with predictions from PYTHIA 6.4, in bins of p_{T} and y where the measurement of the cross section within the bin has a relative uncertainty larger than 50%.

Now, during Run II (2015-), the $c\bar{c}$ cross section in the same transverse momentum and rapidity regions has increased further. We measure:

$$\sigma(pp \to c\bar{c}X)_{p_{\mathrm{T}}<8\,\mathrm{GeV}/c,\ 2.0<y<4.5} = 2840 \pm 3\,(\mathrm{stat}) \pm 170\,(\mathrm{syst}) \pm 150(\mathrm{fragmentation})\,\mu\mathrm{b},$$

in pp collisions at $\sqrt{s} = 13$ TeV [11]. Thus, we can expect to obtain very large samples of charm baryon decays during Run II.

Key to the exploitation of these large charm production cross sections are the capabilities of the LHCb detector, and our ability to trigger on and reconstruct charm baryon decays. We will briefly describe the LHCb detector and the strategies used in the triggering of charmed hadron production. We then describe a search for the doubly charmed baryon Ξ_{cc}^{+} which was conducted with 0.65 pb^{-1} of 2011 LHCb data. We conclude by remarking on future analyses of charmed baryons that are planned at LHCb.

2. The LHCb detector and trigger strategies

The LHCb [12] detector is a dedicated forward arm spectrometer and is the dedicated heavy-flavour physics experiment at the LHC. 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 approximately 50 fs, and an impact parameter resolution of 20 μm for tracks with high transverse momentum. 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 $\delta p/p \approx 0.4 - 0.6\%$.

Many decays of heavy-flavour hadrons of particular interest have a variety of topologically identical final states, obeying different CP symmetries. 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.

The LHCb trigger is comprised of a low-level hardware trigger (L0) and a high-level software trigger (HLT). This schema is illustrated in Figure 2. Specifically for hadrons, a cluster must be recorded in the calorimeter exceeding 3.5 GeV. The first level of the software trigger, the HLT1, exploits a partial reconstruction to quickly and efficiently identify tracks that are displaced from the primary proton-proton interaction point. For charmed baryon decays to hadronic states a single charged track is required to fulfill a series of track quality cuts. This track must also have a transverse momentum greater than 1.7 GeV/c and an impact parameter with respect to the reconstructed primary interaction greater than 0.1 mm. At the second level of the software trigger, the HLT2, a full event reconstruction is employed, allowing the identification of displaced secondary vertices.

The PID information from the RICH detectors is also available at this stage. For decays of the short lived Λ_c^+, where the candidate decay vertex is less displaced from the primary proton-proton interaction point than in D hadron decays, this was of key importance to reject combinations of unrelated tracks. The dedicated $\Lambda_c^+ \to pK^-\pi^+$ trigger in the HLT was one of a limited number of trigger lines which used PID information, to reject candidates where the proton track is a misidentified hadron of another species. Following the success of this technique in Run I, direct PID information in the HLT has now been implemented in a much wider variety of charm exclusive triggers for Run II.

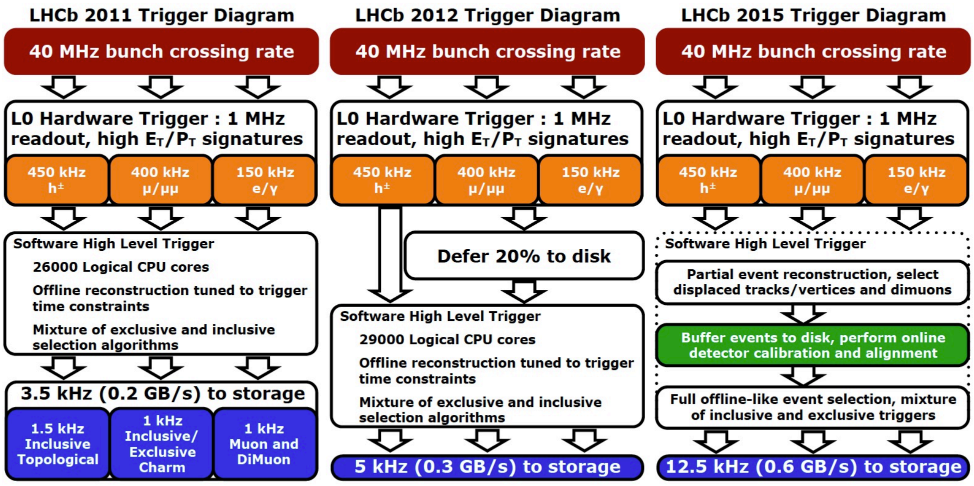

Figure 2: From left to right: The LHCb trigger schema in Run I/2011, Run I/2012 (20% of events passing the hardware trigger deferred for a later processing), and Run II (all HLT1 accepted events deferred).

Prompt charm is triggered with a series of exclusive lines which exploit hadronic signatures. A large number of secondary charm from b-hadron decays is also collected with a suite of inclusive b-hadron 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 high production rate 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.

In Run I, approximately 40% of the 5 kHz trigger output rate was allotted to triggers for charmed hadrons. This presented a difficult challenge to retain as many interesting decays as possible given the constraints on trigger retention. A quasi real-time alignment and calibration was installed and made operational for Run II, which allows offline-quality reconstruction to be produced online. To exploit this, the strategy of a "Turbo" trigger stream was developed, where events for specific analyses could be collected, the reconstruction of signal candidates occurs online, and are then available for physics analyses only a few hours after having been recorded, with optimal calibration and alignment. Data are already made ready for user analysis, and the sub-detector information already discarded. Thus events being provided by the Turbo stream are an order of magnitude smaller in size than data following the traditional trigger stream. Most charm trigger lines now take advantage of the Turbo stream. The significantly reduced bandwidth allows substantially more charm decays to be recorded within the same amount of integrated luminosity.

3. Search for Ξ_{cc}^{+} with 2011 data

For the $SU(4)$ multiplets of baryons composed of the u, d, s and c quarks 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 Ξ_{cc}^{+} state should have lifetimes between 100 – 250 fs, with the Ξ_{cc}^{++} state having a lifetime between 500 – 1550 fs [13, 14]. 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 [15, 16, 17, 18].

The SELEX collaboration has reported an observation of the Ξ_{cc}^+ in its decay to $\Lambda_c^+ K^- \pi^+$ [19] and evidence of the Ξ_{cc}^+ in the mode pD^+K^- [20]. 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).

A Ξ_{cc}^+ baryon with such a short lifetime would be critically important to study, in order to understand the mechanisms that lead to its uncharacteristically short lifetime. However, subsequent searches at notably Belle [1], BaBar [21] 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.

LHCb has conducted the first search for doubly charmed baryon production at a pp collider [22]. 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, using the decay mode $\Xi_{cc}^+ \to \Lambda_c^+(pK^-\pi^+)K^-\pi^+$ and the normalisation channel $\Lambda_c^+ \to pK^-\pi^+$. We specifically measure the ratio of Ξ_{cc}^+ production relative to Λ_c^+ production:

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

where σ and $\mathscr{B}$ are the relevant cross sections and branching fractions, $N_{\rm sig}$ and $N_{\rm norm}$ are the extracted yields of the Ξ_{cc}^+ signal and the control Λ_c^+, and $\varepsilon_{\rm sig}$ and $\varepsilon_{\rm norm}$ 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, misreconstructed 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 that requires that the Λ_c^+ must be displaced from the primary interaction. The algorithm also 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, trained to have as little as possible sensitivity to the Ξ_{cc}^+ lifetime.

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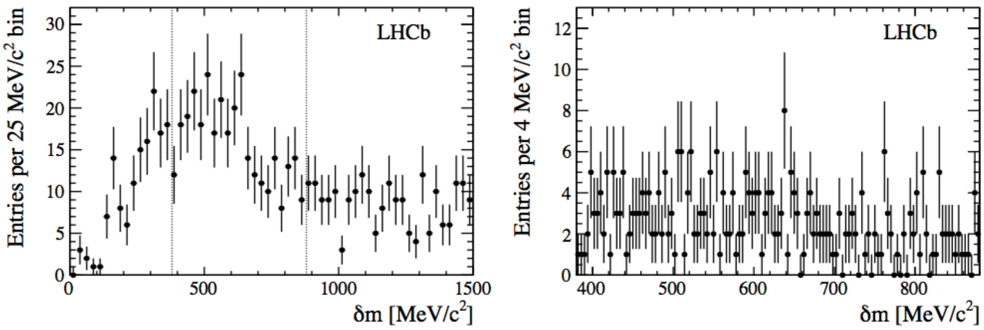

Figure 3: The full δm spectrum (left) and the Ξ_{cc}^{+} signal region (right, marked with dashed lines on the full δm spectrum).

The signal yield of the normalisation channel is extracted with a fit to the $m(pK^{-}\pi^{+})$ distribution. 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 with an analytic sideband subtraction that requires knowledge of the Ξ_{cc}^{+} mass resolution (which is taken from simulation) but requires no other information of the Ξ_{cc}^{+} lineshape.

Signal yields are calculated in 1 MeV/c^2 intervals of δm across the full signal region, shown in Figure 3. 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 "look-elsewhere effect" [23]. 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 $\mathcal{S}$ 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 $\mathcal{S} = 1.5\sigma$ at a $\delta m = 513\,\mathrm{MeV}/c^2$, corresponding to

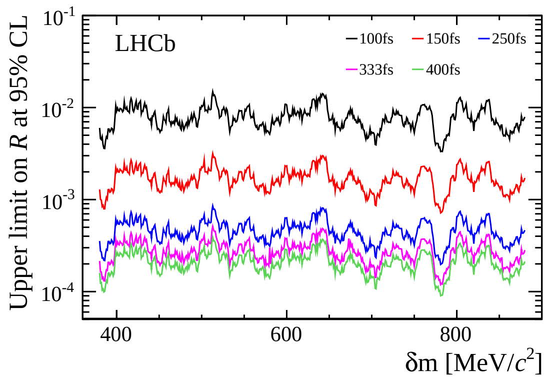

Figure 4: Upper limits on R for a number of Ξ_{cc}^{+} lifetime hypotheses.

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a global p-value for the null hypothesis of 99%. We therefore give upper limits on R as a function of δm with the CL_S method [24]. 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 4.

4. Future and ongoing projects

Several charmed baryon analyses are currently ongoing at LHCb, covering a wide range of topics. A new search for doubly charmed baryons with 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 $\Xi_{cc}^{+[+]} \to D^+(K^-\pi^+\pi^+)pK^-[\pi^+]$, 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 plan to expand charm cross section measurements at $\sqrt{s} = 13$ TeV, by providing 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.

Promising avenues of investigating new physics with charmed baryons also exist. Investigations of *CP* violation and of rare decays with charmed baryons offer searches for new physics complementary to those conducted with charmed mesons due to the different strong phases in their decays. A search for *CP* violation in Cabibbo-suppressed Λ_c^+ decays is currently underway using the Run I dataset. A search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$ is also being conducted.

In Run II we anticipate that charmed baryon *CP* violation searches will have the same sensitivity as our *CP* violation searches with charmed mesons from Run I. The suite of charmed baryon trigger lines has also been expanded for Run II to enable a wide variety of spectroscopy analyses. We also anticipate that observations of the Ξ_{cc}^{+} should be possible at LHCb with the Run II dataset. The possibility also exists to perform amplitude analyses of charm baryon decays (following the formalism of Ref. [25]), to fully explore the resonant substructure within these decays. It is also possible to search for enhanced local *CP* violation within the phase space of multi-body decays.

Looking ahead to Run III we anticipate excellent precision on *CP* violation searches with charmed baryons. We also expect the ability to conduct double charm spectroscopy, and the ability to probe for the triply charmed baryon Ω_{ccc}^{+}.

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