Measurements of $Λ_c^+$ in pp, p–Pb and Pb–Pb collisions with ALICE at the LHC

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Abstract. The baryon-to-meson ratio $Λ_c^+/D^0$ and the nuclear modification factor $R_{AA}$ in the charm sector are important observables to gain an understanding of how charm quarks hadronise and lose energy in the Quark-Gluon Plasma produced in heavy-ion collisions. In this contribution, recent measurements performed with the ALICE detector in pp, p–Pb and Pb–Pb collisions at 5.02 TeV are presented and compared with previous measurements in pp collisions at 7 TeV, measurements by the LHCb Collaboration and theoretical model predictions.

1. Introduction

Heavy quarks (charm and beauty) act as unique probes of the Quark-Gluon Plasma (QGP) produced in high-energy heavy-ion collisions [1]. Due to their large masses with respect to the QCD energy scale, they are produced early in the collision in hard partonic scatterings. This means that they experience the full evolution of the medium and can provide information on transport mechanisms inside the QGP [2]. Measurements of the baryon-to-meson ratio (e.g. $Λ_c^+/D^0$) give sensitivity to the dominance of different hadronisation processes for charm quarks. The hot and dense QGP medium is expected to enhance the production of charmed baryons, at low to intermediate transverse momentum, $p_T$, via recombination of charm quarks with other quarks in the medium. To provide context to results from heavy-ion collisions, smaller systems must also be studied. Measurements in pp collisions can be used to test perturbative QCD calculations and act as a clean baseline for larger collision systems. Results from p–Pb collisions allows us to study effects caused by the presence of a nucleus in the initial state to be separated from those due to the presence of the QGP. One experimental observable is the nuclear modification factor, $R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{d^2N_{AA}}{d^2p_T} \times \frac{d^2σ_{pp}}{d^2p_T}$, which is the ratio of the differential yield in heavy-ion collisions to the differential cross section in pp collisions scaled by the nuclear overlap function, $<T_{AA}>$. Deviations from unity are typically explained by energy loss in the medium or by cold nuclear matter effects. Although, it is important to note that $R_{AA}$ is affected by many other effects such as hadronisation or collective flow.

In this contribution, we report on measurements made of the charmed baryon $Λ_c^+$ in pp, p–Pb and Pb–Pb collisions at 5.02 TeV, performed with the ALICE experiment [3].

2. Data Analysis

A description of the ALICE detector can be found in Ref [3]. For the relevant data analyses, three detectors located at mid-rapidity were used. The Inner Tracking System (ITS) was used...
for vertexing and track reconstruction. The Time Projection Chamber (TPC), the main tracking
detector, also provided \(dE/dx\) information for the particle identification (PID). The Time Of
Flight (TOF) detector provided further complementary PID information.

The measurement of \(\Lambda_c^+\) production was performed by reconstructing two hadronic decay
modes: \(\Lambda_c^+ \rightarrow pK_{s}^{0}\) with branching ratio (BR) \((1.59 \pm 0.08)\%\) and \(\Lambda_c^+ \rightarrow pK^-\pi^+\) with BR
\((6.28 \pm 0.33)\%). The \(\Lambda_c^+ \rightarrow pK_{s}^{0}\) decay channel was reconstructed from combining a bachelor
track with a \(K_{s}^{0}\) candidate. Whereas the \(\Lambda_c^+ \rightarrow pK^-\pi^+\) decays were built up from triplets of
reconstructed tracks with appropriate charge sign combinations. To reduce large combinatorial
background, PID information from the TPC and TOF detectors was used. A Bayesian approach
\cite{4} was used to combine the signals from the TPC and TOF detectors and assign conditional
probabilities associated to different particle species to each track. For the \(pK^-\pi^+\) channel, the
particle species with the highest probability was consequently assigned to that track. For the
\(pK_{s}^{0}\) channel, the bachelor track had a \(|n_\sigma| < 3\) pre-selection followed by a cut on the posterior
probability of the track being a proton at 80%.

Three different analyses were performed with different optimisation of the selection procedures
of the \(\Lambda_c^+\) candidates. The first method relied on standard selections ("rectangular cuts")
on kinematic and geometric variables and this approach was tuned on Monte Carlo (MC)
simulations to optimise the statistical significance. This method was used for both decay
channels in pp and p–Pb analyses. The other two methods used a multivariate approach with
Boosted Decision Trees (BDTs) that utilised either the Adaboost \cite{5} or XGBoost boosting
algorithms, for the \(pK_{s}^{0}\) decay channel, in p–Pb (Adaboost-based BDTs only) and Pb–Pb
collisions. The different analyses for each collision system were then merged, incorporating
the different decay channels and selection methods used, into a single measurement.

3. Results in pp and p–Pb collisions

In Figure 1 showing measurements of the baryon-to-meson ratio as a function of \(p_T\), there
appears to be an indication that measurements of \(\Lambda_c^+/D^0\) in pp (\(\sqrt{s} = 5.02, 7\) TeV) and p–Pb
(\(\sqrt{s_{NN}} = 5.02\) TeV) by ALICE at mid-rapidity are higher than those made in p–Pb (\(\sqrt{s_{NN}} =
5.02\) TeV) by LHCb, in forwards and backwards rapidities, at low \(p_T\) up to about 8 GeV/c. For
larger \(p_T\) values, the measurements become consistent within uncertainties. Figure 2 shows a
comparison of \(\Lambda_c^+/D^0\) in pp collisions at \(\sqrt{s} = 5.02\) TeV and \(\sqrt{s} = 7\) TeV with predictions by
MC model predictions. Several of the predictions fail to describe the decreasing trend with \(p_T\)
seen in the data, remaining constant at a value around 0.1. The predictions which implement
colour reconnection \cite{9} (indicated by Mode 0) describe the data more closely, exhibiting a notable
enhancement at low \(p_T\). PYTHIA 8 \cite{8} with soft QCD effects enabled gives the closest description
albeit underestimation.
Figure 1: Comparison of $\Lambda_c^+ / D^0$ ratios measured at mid-rapidity with ALICE and forwards and backwards rapidities with LHCb.

Figure 2: Comparison of $\Lambda_c^+ / D^0$ ratio measured at ALICE in pp collisions at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV with theoretical models.

Figure 3 compares the baryon-to-meson ratios for charm ($\Lambda_c^+ / D^0$), strange ($\Lambda / pK^0$) and light ($p/\pi$) sectors. These three ratios share a decreasing trend in the range of $3 < p_T < 24$ GeV/c with the charm and strange ratios being consistent in shape and magnitude within uncertainties. The light-flavour ratios in all collision systems peak at around $p_T = 3$ GeV/c and, in p–Pb collisions there is a hint of a similar peak for the $\Lambda_c^+ / D^0$ ratio. More precise measurements at low-$p_T$ will be necessary for a more complete comparison. The similarities between these ratios may hint at the common mechanism for the hadronisation of light, strange and charm quarks in small systems.

Figure 4 shows the corresponding $\Lambda_c^+ / D^0$ ratios for pp collisions at $\sqrt{s} = 5.02$ TeV and two different centrality ranges (0-10% and 30-50%) of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. There is a hint of an enhancement for Pb–Pb collisions with respect to pp collisions at $p_T$ around 4-6 GeV/c. In Figure 5 the results for central collisions are compared to theoretical models. The data gives good agreement to the Catania prediction where both coalescence and fragmentation occur [6] and to the statistical hadron model [7]. Similar agreement is seen between the data and model predictions in the 30-50% centrality class.

4. Results in Pb–Pb

Figure 4 shows the corresponding $\Lambda_c^+ / D^0$ ratios for pp collisions at $\sqrt{s} = 5.02$ TeV and two different centrality ranges (0-10% and 30-50%) of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. There is a hint of an enhancement for Pb–Pb collisions with respect to pp collisions at $p_T$ around 4-6 GeV/c. In Figure 5 the results for central collisions are compared to theoretical models. The data gives good agreement to the Catania prediction where both coalescence and fragmentation occur [6] and to the statistical hadron model [7]. Similar agreement is seen between the data and model predictions in the 30-50% centrality class.
In Figure 6, the preliminary results for \( R_{AA} \) in \( \text{Pb} - \text{Pb} \) collisions obtained from the data sample collected in 2018 are shown as a function of \( p_T \) and compared against previously published results by ALICE. A large suppression of \( \Lambda^+ (R_{AA} < 1) \) is seen up to a factor 5 at high \( p_T \). While the two preliminary measurements are consistent within uncertainties, there is a hint for a smaller nuclear modification factor for central collisions (up to 1.5 times smaller at high \( p_T \).) In Figure 7, the \( R_{AA} \) measurement for the 0-10% centrality range is compared to theoretical models. The data is better described by the Catania prediction when both coalescence and fragmentation mechanisms are present in both pp and Pb–Pb systems. Similar agreement is seen between the data and model predictions in the 30-50% centrality class.
5. Summary and Outlook

The baryon-to-meson ratio, $\Lambda_+^+ / D^0$ and the nuclear modification factor $R_{AA}$ of $\Lambda_+^+$ were measured in pp, p–Pb and Pb–Pb collisions at centre-of-mass energy 5.02 TeV with the ALICE detector. A larger $\Lambda_+^+ / D^0$ ratio is measured in pp and p–Pb collisions at mid-rapidity by ALICE than at forwards and backwards rapidities as measured by LHCb in p-Pb collisions. Striking similarities between the light, strange and charm sector baryon-to-meson ratios, hinting at a potential common hadronisation mechanism. In Pb–Pb, the new measurements, based on the large 2018 data sample, with their extended $p_T$ range give hints of an enhancement of the $\Lambda_+^+ / D^0$ ratio with respect to pp collisions. The $\Lambda_+^+ / D^0$ ratio and $R_{AA}$ measurements are consistent with model predictions where both fragmentation and coalescence are present.

These measurements are expected to be significantly improved from ongoing detector upgrades. In particular, the Inner Tracking System upgrade will enable better tracking and vertexing, more precise measurements, and enable new measurements of heavy flavour observables including the $\Lambda^0_b$.

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