Charm production and hadronisation in ALICE

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Heavy-flavour production is an active and highly interesting field of research. Since charm and beauty quarks are predominantly produced in the hard scattering process of colliding nuclei, they serve as unique probes to study the quark-gluon plasma in Pb–Pb collisions. In addition, recent investigations of hadronisation mechanisms have revealed interesting and unexpected features when comparing measurements in $e^+e^-$ and in hadronic collisions as in pp, p–Pb and Pb–Pb. This article summarises the latest results of charm production measured by the ALICE Collaboration. For the first time, $\Sigma_0^{0,++}$ and $\Omega_0^-$ were measured in hadronic collisions and production measurements of the $\Lambda_c^+$ and $\Xi_c^0$ are now included in the computation of the charm production cross section.

Keywords: Charm production; hadronisation; heavy ion physics; high energy physics; ALICE.

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1. Introduction

The study of hadron formation is an active field of research. Hadronisation cannot be described analytically in the framework of quantum chromodynamics (QCD) as perturbative approaches break down at the corresponding energy scales. For instance, phenomenological models based on string fragmentation [1] are commonly used to describe hadronisation in proton–proton (pp) collisions. By means of the factorisation approach [2], cross section calculations can be disentangled into different components separating terms describing the long-distance (low-energy) from the short-distance (high-energy) particle interaction. In particular, perturbative calculations based on the general-mass variable-flavour-number-scheme (GM-VFNS) [3, 4] as well as those based on fixed order with next-to-leading-logarithm resummation (FONLL) [5, 6] have shown good agreement in the case of strange and non-strange charm mesons. On the other hand, models based on collinear factorisation and fragmentation functions tuned to measurements in $e^+e^-$ and $e^-p$ collisions provide only a poor description of charm baryon production, for instance as measured in the case of $\Lambda_c^+$ production [7–10].

Production measurements of different hadron species as well as their yield ratios provide powerful observables to experimentally constrain phenomenological hadronisation models. In this article, an overview of most recent charm baryon production measurements, namely $\Lambda_c^+$, $\Sigma_c^{0,++}$, $\Xi_c^{0,++}$, and $\Omega_c^0$, conducted with the ALICE detector [11] is reported. It is worth noting that $\Sigma_c^{0,++}$ and $\Omega_c^0$ productions were measured for the first time in hadronic collisions. Comparisons to various models are discussed and the charm fragmentation fractions measured for the first time in pp collisions by the ALICE Collaboration are presented as well. The total charm production cross section has been measured in pp collisions at $\sqrt{s} = 5.02$ TeV in the rapidity region $|y| < 0.5$ also accounting for the charm baryons $\Lambda_c^+$ and $\Xi_c^0$. Its current value is measured to be $(d\sigma_{cc}/dy)|_{|y|<0.5} = 1165 \pm 44(\text{stat}) \pm 134(\text{syst}) \text{ mb}$ [8].

2. Experimental setup and data samples

A detailed description of the ALICE detector can be found in [11]. It provides excellent tracking and particle identification (PID) capabilities, especially towards low transverse momentum ($p_T$). The principal sub-detectors involved in the following presented analyses were the Inner Tracking System (ITS) used for vertex finding and tracking, the Time Projection Chamber (TPC) for tracking and PID, the Time-Of-Flight detector (TOF) for PID, as well as the V0 detector for triggering purposes and event multiplicity estimation.

Tracks were reconstructed in the barrel region within the pseudorapidity window of $|\eta| < 0.8$. Depending on the decay channel of the various baryons under study, they were reconstructed from the combination of 2 or 3 tracks that passed the selection criteria. Background was suppressed by requiring the appropriate decay topologies of interest and by requiring suitable PID criteria. For details the reader is referred to the individual cited papers.

Results presented here were obtained in different collision systems and at two centre-of-mass energies. Table I summarises the collected number of events as well as the corresponding integrated luminosity.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$N_{\text{ev}}$</th>
<th>$L_{\text{int}}$</th>
<th>baryons</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td></td>
<td></td>
<td>$\Lambda_c^+$, $\Xi_c^0$</td>
</tr>
<tr>
<td>5.02</td>
<td>$10^9$</td>
<td>19.5 nb$^{-1}$</td>
<td>$\Lambda_c^+$, $\Xi_c^0$</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>32 nb$^{-1}$</td>
<td>$\Lambda_c^+$, $\Sigma_c^{0,++}$, $\Xi_c^0$, $\Omega_c^0$</td>
</tr>
<tr>
<td>p–Pb</td>
<td>5.02</td>
<td>6 · $10^8$</td>
<td>287 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Lambda_c^+$</td>
</tr>
</tbody>
</table>

Table I. Collision systems, centre-of-mass energies and corresponding number of events and integrated luminosities of data sets used in the presented measurements of charm baryon production.
3. Charm production and hadronisation

Table II lists all charm baryons of interest in the presented analyses along with their invariant mass, decay length, and branching ratios of the studied decay channels. All values were taken as reported by the Particle Data Group [13] except for the \( \Omega \) were taken as reported by the Particle Data Group [13] except for branching ratios of the studied decay channels. All values were calculated in Ref. [14].

### Table II. Charm baryons measured in the analyses presented in this article.

<table>
<thead>
<tr>
<th>( m_{\text{inv}} ) [GeV/c(^2)]</th>
<th>( c_T ) [( \mu )m]</th>
<th>decay (BR [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_c^+ )</td>
<td>( \approx 2.826 )</td>
<td>( \approx 60 )</td>
</tr>
<tr>
<td>( \Sigma_c^{0,+} )</td>
<td>( \approx 2.454 )</td>
<td>-</td>
</tr>
<tr>
<td>( \Xi_c^0 )</td>
<td>( \approx 2.468 )</td>
<td>( \approx 46 )</td>
</tr>
<tr>
<td>( \Xi_c^+ )</td>
<td>( \approx 2.470 )</td>
<td>( \approx 136 )</td>
</tr>
<tr>
<td>( \Omega_c^0 )</td>
<td>( \approx 2.605 )</td>
<td>( \approx 80 )</td>
</tr>
</tbody>
</table>

(7.39 above \( \Lambda_c^+ \) decay channels)

(From theoretical calculations)

#### 3.1. \( \Lambda_c^+ \) production

\( \Lambda_c^+ \) production was measured in pp collisions at a centre-of-mass energy of \( \sqrt{s} = 13 \text{ TeV} \) as a function of primary-particle multiplicity [15]. The bottom row of Fig. 1 shows the baryon-to-meson production ratio \( \Lambda_c^+ / D^0 \) as a function of transverse momentum \( p_T \).

#### 3.2. \( \Sigma_c^{0,+} \) production

The first measurement of \( \Sigma_c^{0,+} \) production in hadronic collisions was achieved by the ALICE collaboration in pp collisions,

![Figure 1](image1.png)

**Figure 1.** Meson-to-meson ratio \( D_s^+ / D^0 \) (top row) and baryon-to-meson ratio \( \Lambda_c^+ / D^0 \) (bottom row) in the lowest (left column) and highest (right column) multiplicity interval and as a function of transverse momentum. Experimental results are compared to different theory predictions (see text for discussion).

It is clearly underestimated by the prediction of Pythia8 [16] with Monash tune [17] which is approximately flat at \( \approx 0.1 \). In that case, hadronisation is tuned to results obtained in \( e^- \) and electron–proton \((e^- p)\) collisions and its description is based on standard string fragmentation. On the other hand, models including colour reconnection beyond leading colour (CR-BLC) [18] are able to describe the shape as well as the observed trend with multiplicity of the experimental data although they tend to overestimate the data at lower \( p_T \). A good agreement with the measured \( \Lambda_c^+ / D^0 \) yield ratios is observed with the Canonical-Ensemble Statistical Hadronisation (CE-SH) model [19], which is based on a statistical hadronisation model, including augmented excited charm baryon states according to the relativistic quark model (RQM) [20], and it can also better describe the low \( p_T \) region.

On the contrary, the meson-to-meson ratio \( D_s^+ / D^0 \), shown in the top row of Fig. 2, is flat within uncertainties and well described by the theoretical prediction, even if overestimated at high multiplicities by the CE-SH model. Both results together point to modified hadronisation mechanisms beyond pure in-vacuum fragmentation in the case of charm hadron production. In addition, the \( \Lambda_c^+ / D^0 \) ratio develops a shape that becomes steeper with increasing multiplicity, which hints at an increasing modification of the \( p_T \) spectra with multiplicity. As observed with the recent measurement from ALICE of the \( \Lambda_c^+ / D^0 \) ratio in pp and p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) [8], the \( \Lambda_c^+ / D^0 \) at low-intermediate \( p_T \) are higher than measurements performed with \( e^- \) collisions, also in the lowest multiplicity classes.

![Figure 2](image2.png)

**Figure 2.** Baryon-to-meson ratio \( \Sigma_c^{0,+} / D^0 \) as a function of transverse momentum. Experimental results are compared to different theory predictions (see text for discussion).
sions at $\sqrt{s} = 13$ TeV [10]. The ratio with respect to the $D^0$ was computed as shown in Fig. 2.

The ratio was scaled by the factor 1.5 to account for the $\Sigma^+_b$ baryon. Also in this case the experimental results show a slight slope, however less pronounced compared to the $\Lambda^+_b/D^0$ ratio. Pythia8 [16] with Monash tune [17] underestimates the data and does not describe the shape. Similarly to the $\Lambda^+_c/D^0$ ratio, the CR-BLC tunes [18] overestimate the ratio at low $p_T$ but different to the Monash tune they exhibit a shape which successfully describes the intermediate and high $p_T$ data points. The SH model [19] augmented with additional excited charm baryon states according to RQM [20] describes the shape and order of magnitude. Also the Catania model [21], which includes partonic coalescence in addition to in-vacuum fragmentation, is able to describe the data well within uncertainties. Another quark (re-)combination mechanism (QCM) model [22] also describes the data well within uncertainties. In this case charm quarks can combine with equal-velocity light quarks to form hadrons.

As an additional result of this analysis, a substantial feed-down fraction of $\approx 0.4$ was measured [10] which however is not sufficient to explain the increased $\Lambda^+_c/D^0$ ratio discussed in Sec. 3.1.

3.3. $\Xi_c^0$ and $\Xi_c^+$ production

$\Xi_c^0$ and $\Xi_c^+$ production was measured in pp collisions at $\sqrt{s} = 13$ TeV by the ALICE Collaboration [23]. Concerning the ratio of the branching fractions $\text{BR}(\Xi_c^0 \to \Xi^- e^+ \nu_e) / \text{BR}(\Xi_c^+ \to \Xi^- \pi^+)$, a decrease of the overall uncertainty by a factor 3 was achieved compared to the current value reported by the Particle Data Group [13]. As seen in Fig. 3, among all compared predictions the Catania model [21] is closer to the data while the others underestimate them.

This is supported by another measurement of $\Xi_c^0$ production in pp collisions at $\sqrt{s} = 5.02$ TeV by ALICE [23].

3.4. $\Omega_c^0$ production

As a preliminary result, the production of the $\Omega_c^0$ baryon was measured for the first time in hadronic collisions by ALICE. Its branching ratio $\text{BR}(\Omega_c^0 \to \Omega^- \pi^+)$ was provided by theoretical calculations [14]. As in the case of the $\Xi_c^0$/D$^0$ ratio, the Catania model [21] is closest to the experimental data while other predictions underestimate the data as shown in Fig. 4. Another observation is the approximately flat shape of the ratio compared to the ratios discussed before. In this analysis, also the baryon-to-baryon production ratio with respect to the $\Lambda_c^+$ was computed and again all predictions but the one from the Catania model [21] significantly underestimate the data.

4. Charm cross section and fragmentation fractions

The charm production cross section per unit of rapidity in the fiducial rapidity window of $|y| < 0.5$ was measured in pp collisions at $\sqrt{s} = 5.02$ TeV [12], for the first time accounting for charm baryon production measurements of $\Lambda_c^+$ and $\Xi_c^0$. Its value is found to be $\langle d\sigma c^+/dy\rangle_{|y|<0.5} = 1165\pm14$(stat)$^{+134}_{-101}$(syst) $\mu$b. Here, the $\Xi_c^0$ was accounted for by scaling the contribution of $\Xi_c^0$ by a factor of 2 and asymmetric errors were derived to account for a potentially sizeable contribution of $\Omega_c^0$. In addition, the previously measured values obtained at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV were updated accounting for the latest measurements of baryon-to-meson ratios presented above. This results in an increase...
Figure 5: Charm production cross section as a function of centre-of-mass energy compared to FONLL and NNLO calculations.

Figure 6: Fragmentation fractions measured in pp collisions at $\sqrt{s} = 5.02$ TeV compared to previous measurements in smaller collision system such as $e^+e^-$ and $e^-p$.

5. Conclusion

Various production measurements of charm baryons were presented. In particular the $\Sigma_c^{0,+}$ and the $\Omega_c^0$ productions were measured in hadronic collisions for the first time. The most recent measurement of the total charm cross section also incorporates results from charm baryon measurements of $\Lambda_c^+$ and $\Xi_c^0$ and it was shown that the FF of the $\Xi_c^0$, which has been accounted for the first time, is seen to indeed have a sizeable contribution to the total charm cross section. Note that the $D^*$ feeds into the $D^0$ and $D^+$ contributions via its decays.

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10. ALICE Collaboration, Measurement of prompt $D^0$, $\Lambda_c^+$, and $\Sigma_c^{++}(2455)$ production in p--p collisions at $\sqrt{s} = 13$ TeV, e-Print arxiv:2106.08278 (2021).


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