Measurement of Open Heavy-Flavour Production in pp and p–Pb Collisions with ALICE at the LHC

Renu Bala (for the ALICE Collaboration)
Department of Physics, University of Jammu, India
Renu.Bala@cern.ch

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The Large Hadron Collider at CERN allows us to study heavy-ion collisions at an unprecedented energy. ALICE, A Large Ion Collider Experiment, is the experiment dedicated to the investigation of heavy-ion collisions. In this contribution, recent open heavy-flavour results from pp collisions at √s = 5.02, 7, 8 and 13 TeV and p–Pb collisions at √s_{NN} = 5.02 TeV, collected with the ALICE detector during the LHC Run-1 and Run-2 are presented. The results include the production cross section, nuclear modification factor and multiplicity dependence studies of production of D mesons and electrons from heavy-flavour hadron decays at mid-rapidity and of muons from heavy-flavour hadron decays at forward rapidity. Charm production was measured down to p_T = 0 GeV/c in pp and p–Pb collisions. Recent measurements of the production cross section of heavy charmed baryons such as Λ_c (in pp and p–Pb) and Ξ_c (in pp) are discussed. The results are compared with theoretical model predictions.

Keywords: Open heavy flavour; pQCD; cross section; nuclear modification factor; CNM effect.

1. Introduction

The measurements of heavy-flavour production in pp collisions are important to test predictions from perturbative QCD and provide an essential baseline for the studies in heavy-ion collisions. Differential studies of their production as a function of the multiplicity of charged particles produced in the collisions can give insight into multi-parton interaction phenomena, and into the interplay between hard and soft processes. The study of heavy-flavour production in p–Pb collisions is also required to disentangle the influence on particle production of cold nuclear matter effects from those related to the formation of a QGP in Pb–Pb collisions.
2. Open heavy-flavour reconstruction with ALICE

The ALICE apparatus has excellent capabilities for heavy-flavour measurements. It is composed of a central barrel and a forward muon arm. A detailed description of the experimental setup can be found in [1]. At mid rapidity (|η| < 0.9), open heavy-flavour production is measured via the hadronic decays of D mesons (D^{0}, D^+, D^{*+} and D_s^+) and Λ^+_c baryon, the partial reconstruction of prompt Λ^+_c → e^+ ν_e Λ and (Ξ^0_c → e^+ Ξ^- ν_e) decays, and via the identification of electrons from semileptonic decays of charm and beauty hadrons. At forward rapidity (-4 < η < -2.5), muons from heavy-flavour hadron decays are reconstructed in the muon spectrometer.

3. Results in pp collisions

The differential production cross sections of prompt D mesons (D^{0}, D^+, D^{*+} and D_s^+), heavy-flavour decay electrons, electrons from beauty-hadron decays and heavy-flavour decay muons were measured in pp collisions at √s = 7, 2.76, 8 and 13 TeV. They are well described by pQCD calculations [5,6,7]. The first measurement of the production cross section of Λ^+_c at mid-rapidity at LHC is shown in fig.1 (left) which is also compared with model predictions [8,10,11]. Right: Ratio of Λ^+_c baryon and D^{0}-meson yields in pp collisions at √s=7 TeV and p–Pb collisions at √s_{NN} = 5.02 TeV compared with the model predictions. The open heavy flavour production is also studied as a function of multiplicity of charged particles.
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Fig. 2. Left: Average D⁰, D⁺ and D*⁺ and inclusive J/ψ relative yields as a function of charged-particle multiplicity (see text). Right: comparison of the results of D-meson production and inclusive J/ψ at √s= 7 TeV to inclusive J/ψ at √s= 13 TeV produced in the collision. In figure 2 (left) average D⁰, D⁺ and D*⁺ and inclusive J/ψ yield per multiplicity intervals normalized to the yield obtained in the multiplicity-integrated sample is shown as a function of charged-particle multiplicity normalized by its average measured in multiplicity-integrated events\(^\text{12}\). An increasing trend as a function of charged particle multiplicity is observed for both J/ψ and D mesons, suggesting that multi-parton interactions (MPI), which substantially contribute to high-multiplicity events, are important to understand heavy-flavour production rate as a function of the event multiplicity. Also the current measurement of J/ψ in pp at √s= 13 TeV are compared to the measurements of J/ψ and D-meson production at √s= 7 TeV. The results are in agreement, indicating that no significant energy dependence of the relative increase of the production with event multiplicity could be observed.

4. Results in p–Pb collisions

In p–Pb collisions, cold nuclear matter (CNM) effects such as the modification of the PDFs due to the presence of the nucleus are expected to affect the heavy-quark yield and \(p_T\) distributions relative to the pp collisions. The p–Pb spectra are quantitatively compared to the pp reference by computing the nuclear modification factor \(R_{p\text{Pb}}\), which is defined as: 

\[ R_{p\text{Pb}} = \frac{1}{\sigma_{pp}} \frac{d\sigma_{p\text{Pb}}}{d\eta} \times \frac{d\delta_{p\text{Pb}}}{d\eta} \]

where \(\Lambda\) is the Pb atomic mass number, \(\sigma_{pp}\) and \(\sigma_{p\text{Pb}}\) are the production cross section in pp and p–Pb collisions, respectively. Figure 3 shows the average of the non-strange D mesons (D⁰, D⁺ and D*⁺) \(R_{p\text{Pb}}\), compared to the D⁺ in p–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV using data from Run-2 at the LHC. The \(R_{p\text{Pb}}\) is consistent with unity for strange as well as non-strange D mesons. The results are compatible with those obtained in Run-1 results\(^\text{13}\). The data are described by models including CNM effects, as well as by models assuming the formation of QGP in p–Pb collisions, though at high \(p_T\) a suppression larger than 15% is disfavoured. The nuclear modification factor of...
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![Graphs showing average D meson $D^0$, $D^+$, $D_s^+$ in p-Pb and Pb-Pb collisions as a function of $p_T$.]

Fig. 3. Left: Average of D-meson ($D^0$, $D^+$, $D_s^+$) $R_{pPb}$ and $D_s^+$ $R_{pPb}$ as a function of $p_T$. Right: averaged D-mesons ($D^0$, $D^+$, $D_s^+$) $R_{pPb}$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to model calculations.

Prompt D-mesons was also computed as a function of centrality, where centrality is determined using the energy deposited in the zero-degree neutron calorimeter in the Pb-going side (ZNA) i.e $Q_{pPb}$

$$Q_{pPb} = \frac{\langle d^2N^{\text{prompt } D}/d^3p_T \rangle}{\langle d^2N^{\text{mult}}/d^3p_T \rangle_{pPb}}$$

where $\langle d^2N/d^3p_T \rangle_{pPb}$ and $\langle d^2N/d^3p_T \rangle_{\text{mult}}$ are the yield of prompt D mesons in p-Pb collisions and the average nuclear overlap function in a given centrality class, respectively. The $Q_{pPb}$ was evaluated in the most central collisions in the 0–10% class and in the most peripheral collisions in the 60–100% centrality class, offering the possibility to compute the central-to-peripheral ratio $Q_{CP}$.

$$Q_{CP} = \frac{\langle d^2N^{\text{prompt } D}/d^3p_T \rangle_{pPb}^{0-10}}{\langle d^2N^{\text{prompt } D}/d^3p_T \rangle_{pPb}^{60-100}} \times \frac{\langle d^2N^{\text{mult}}/d^3p_T \rangle_{pPb}^{0-10}}{\langle d^2N^{\text{mult}}/d^3p_T \rangle_{pPb}^{60-100}}$$

Figure 4 (left panel) presents the $Q_{pPb}$ results for average of prompt D-mesons as a function of $p_T$ for the 0–10% and 60–100% centrality classes. The results in the two centrality classes are consistent with unity within the uncertainties, although the central values of the $Q_{pPb}$ are generally larger than unity in the 0–10% class and slightly lower than unity in the 60–100% class. The right panel of figure 4 shows the average D-mesons $Q_{CP}$ superimposed to the one obtained from charged particles. A similar trend is observed for both the particles: the $Q_{CP}$ increases in the interval 1–5 GeV/c, reaching values of about 1.3 and then tends to decrease in the interval 7–16 GeV/c. The average value of the D-meson $Q_{CP}$ in the interval $3 < p_T < 8$ GeV/c is larger than unity by 1.5 standard deviations of the statistical and systematic uncertainty. In figure 5, the first measurement at the LHC of the $\Lambda_c$ $R_{pPb}$, is shown. It is consistent with unity and with that of D mesons within uncertainties. Predictions including POWHEG+PYTHIA with EPS09 nuclear PDF and a prediction
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Fig. 4. Left: Averaged nuclear modification factor of D-mesons as a function of $p_T$ in 0–10 % and 60–100 % centrality classes. Right: D-meson central to peripheral nuclear modification factor.

Fig. 5. Left: $R_{p\Pb}$ of prompt $\Lambda_c$ baryon in p–Pb collisions as a function of $p_T$ compared with that of D-mesons (left panel) and with model calculations\(^7,\,14\) (right panel).

for charmed hadrons which assumes a small size QGP formed\(^{14}\), are presented in the right panel of the figure. The precision achieved with the current measurement does not allow us to distinguish between calculations with and without hot medium effects. Figure 6 shows the $p_T$-differential cross section times branching ratio of the $\Xi_c^0$ baryon (including prompt and non-prompt contributions), and the baryon-to-meson ratio $\Xi_c^0/D_0$ in comparison to predictions from PYTHIA. The shaded band for the models spans the range of theoretical predictions for the $\Xi_c^0$ branching ratio\(^{16,\,17,\,18}\). As for the $\Lambda_c^+/D_0$ ratio, all predictions significantly underestimate the data.

5. Summary

Recent results on open charm and baryon production in pp and p–Pb collisions has been reported. The $p_T$-differential cross sections for open-charm mesons in pp collisions are reproduced within uncertainties by theoretical predictions based on

\(^{14}\) Reference to further details.
pQCD calculations, where as for the baryon production, all models underestimates the data. $R_{pPb}$ of charm and baryon in $p$–$Pb$ collisions is consistent with unity within uncertainties, providing evidence that CNM effects are small in the measured $p_T$ range. The average value of the D-meson $Q_{CP}$ in the interval $3 < p_T < 8$ GeV/$c$ is larger than unity by 1.5 standard deviations of the statistical and systematic uncertainty, that could derive from the initial- or final-state effects, including the possible presence of radial flow in $p$–$Pb$ collisions.

References