Measurements of open-charm production in pp and p–Pb collisions with the ALICE detector at the LHC

Chitrasen Jena, for the ALICE Collaboration[*][†]

Università degli Studi di Padova and INFN Sezione di Padova

E-mail: jena@pd.infn.it

Hadrons containing heavy quarks, i.e. charm and beauty, are effective probes to investigate the properties of the hot, dense and strongly-interacting medium formed in high-energy nuclear collisions. The relatively large masses of heavy quarks ensure that they are predominantly produced in the early stages of the collision and probe the complete space-time evolution of the expanding medium. The measurements of D-meson production in pp collisions provide an important test of pQCD calculations and serve as an essential baseline for the comprehensive studies in heavy-ion collisions. The study of D-meson production in p–Pb collisions is necessary to disentangle the cold nuclear matter effects from hot nuclear matter effects. The measurement of heavy-flavour production as a function of charged-particle multiplicity in pp and p–Pb collisions could provide insight into the role of multi-parton interactions at LHC energies.

We present ALICE results on D-meson production in pp collisions at $\sqrt{s} = 7$ TeV and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The D-meson yields per event, measured in different multiplicity intervals and normalized to their multiplicity-integrated values, are presented for pp and p–Pb collisions. The p_{T}-differential production cross section and nuclear modification factor of prompt D mesons are measured in p–Pb collisions. The nuclear modification factor, R_{pPb}, is compatible unity within uncertainties, indicating that cold nuclear matter effects are small for $p_{\text{T}} \gtrsim 3$ GeV/c. The D-meson transverse momentum distributions in p–Pb collisions relative to pp collisions, measured in several multiplicity classes, are also discussed.

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[*]Speaker.

[†]Presently at School of Physical Sciences, National Institute of Science Education and Research, Jatni - 752050, India

1. Introduction

The primary goal of the ALICE experiment at the LHC is to study the strongly-interacting matter created in high-energy heavy-ion collisions. This state of matter with deconfined quarks and gluons, called Quark-Gluon Plasma (QGP), is predicted by Quantum Chromodynamics (QCD) to exist at high temperatures and/or high energy densities [1]. Heavy quarks are a powerful probe for investigating the properties of the QGP, since they are predominantly produced in initial hard scattering processes and experience all the stages of medium evolution. The measurements of heavy-flavour production in pp collisions allow for precision tests of perturbative QCD (pQCD) calculations and provide an essential reference for understanding the results from heavy-ion collisions [2]. Several cold nuclear matter (CNM) effects, such as the modification of parton distribution functions and momentum broadening due to parton scattering in the nucleus, can affect heavy-quark production and cannot be accounted for based only on pp data [3]. It is therefore necessary to study p–Pb collisions, where an extended hot and dense strongly-interacting medium is not expected to form, to quantify these CNM effects. In addition, heavy-flavour production as a function of charged-particle multiplicity in pp and p–Pb collisions is expected to be sensitive to the interplay between hard and soft QCD processes and could provide insight into the relevance of Multi-Parton Interactions (MPIs) on heavy-flavour production [4, 5, 6].

2. D-meson reconstruction with ALICE

The measurement of charm production in ALICE is performed by reconstructing D^0, D^+, D^{*+} and D_s^+ via their hadronic decays $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$, $D^{*+} \to D^0 \pi^+$ and $D_s^+ \to \phi \pi^+ \to K^+ K^- \pi^+$ and their charge conjugates. The analysis strategy for the D mesons in the central rapidity region is based on the invariant mass analysis of fully reconstructed decay topologies originating from displaced vertices. The Inner Tracking System (ITS) detector provides high spatial resolution of the track impact parameter allowing the reconstruction of secondary vertices from heavy-flavour decays. The study of the decay topology allows for an efficient rejection of the combinatorial background from uncorrelated tracks. In order to further suppress the combinatorial background, the Time Projection Chamber (TPC) and the Time Of Flight (TOF) detectors are used to identify pions and kaons. Details of the analysis procedure in pp and p–Pb collisions are reported in [7] and [8], respectively.

3. D-meson production in pp collisions

The p_T-differential production cross sections were measured for prompt D-mesons in pp collisions at $\sqrt{s} = 7$ TeV [7] and 2.76 TeV [9]. The measured cross sections are well described by pQCD calculations [10, 11, 12].

The study of D-meson production evaluated for various multiplicity and p_T intervals, is presented via the D-meson relative yields, i.e. the ratio of the yields in each multiplicity interval to the multiplicity-integrated (average) yield:

$$\frac{(\mathrm{d}^2 N^D/\mathrm{d}y\mathrm{d}p_T)^j}{\langle \mathrm{d}^2 N^D/\mathrm{d}y\mathrm{d}p_T \rangle} = \left(\frac{1}{N_{\text{events}}^j} \frac{N_{\text{raw D}}^j}{\varepsilon_{\text{prompt D}}^j} \right) \Bigg/ \left(\frac{1}{N_{\text{MB trigger}}/\varepsilon_{\text{MB trigger}}} \frac{\langle N_{\text{raw D}} \rangle}{\langle \varepsilon_{\text{prompt D}} \rangle} \right), \qquad (3.1)$$
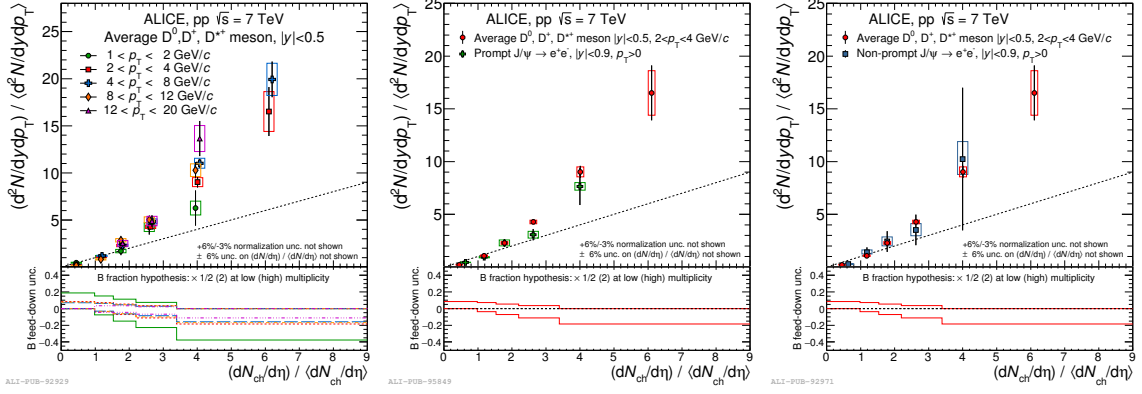
Figure 1: Average of D^0, D^+ and D^{*+} relative yields as a function of the relative charged-particle multiplicity at central rapidity in different p_T intervals (left panel). Average prompt D meson relative yield as a function of the charged-particle multiplicity at central rapidity compared with the relative yields of prompt (middle panel) and non-prompt J/ψ (right panel) [13].

where the index j identifies the multiplicity interval, $N^j_{\text{raw D}}$ is the raw yield, $\varepsilon^j_{\text{prompt D}}$ is the reconstruction and selection efficiency for prompt D mesons and N^j_{events} is the number of events analysed in each multiplicity interval. The number of events used for the normalisation of the multiplicity integrated yield are corrected for the fraction of inelastic collisions that are not selected by the minimum-bias trigger, expressed as $N_{\text{MB trigger}}/\varepsilon_{\text{MB trigger}}$. The relative yields of D^0, D^+ and D^{*+} mesons are compatible in all p_T intervals within uncertainties [13]. The left panel of Fig. 1 shows the average of the D-meson relative yield as a function of the charged-particle multiplicity at central rapidity ($dN_{\text{ch}}/d\eta$) for different p_T intervals. The relative D-meson yield increases with the charged-particle multiplicity by about a factor of 15 in the range between 0.5 and 6 times $\langle dN_{\text{ch}}/d\eta \rangle$ and the enhancement is independent of p_T within the uncertainties. The relative yields of prompt D mesons compared with the relative yields of prompt and non-prompt J/ψ, where non-prompt J/ψ are those coming from b-hadron decays, are shown in the middle and right panels of Fig. 1. A similar increase of relative yields for charm (open and hidden) and beauty with charged-particle multiplicity suggests that the increasing trend is most likely due to the $c\bar{c}$ and $b\bar{b}$ production processes, and is not significantly influenced by hadronisation. The yield enhancement as a function of the charged-particle multiplicity is qualitatively described by PYTHIA 8 calculations including MPI contributions [4], a percolation model taking into account the influence of colour charge exchanges during the interaction [5] and the EPOS 3 event generator which provides a description of the initial conditions followed by a hydrodynamical evolution [6]. More precise measurements are needed in order to further constrain the models.

4. D-meson production in p-Pb collisions

The left panel of Fig. 2 shows the p_T-differential production cross sections of prompt D^0, D^+, D^{*+}, and D_s^+ mesons in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The p_T-differential cross sections were used to compute the nuclear modification factor, R_{pPb}, defined as $R_{\text{pPb}}(p_T) = \frac{d\sigma_{\text{pPb}}/dp_T}{A \times (d\sigma_{\text{pp}}/dp_T)}$, where $d\sigma_{\text{pPb}}/dp_T$ is the p_T-differential cross section in p–Pb collisions, $d\sigma_{\text{pp}}/dp_T$ is the p_T-differential cross section in pp collisions at the same centre-of-mass energy, and A is the mass number of the Pb nucleus. The reference pp cross sections at $\sqrt{s} = 5.02$ TeV were obtained by a
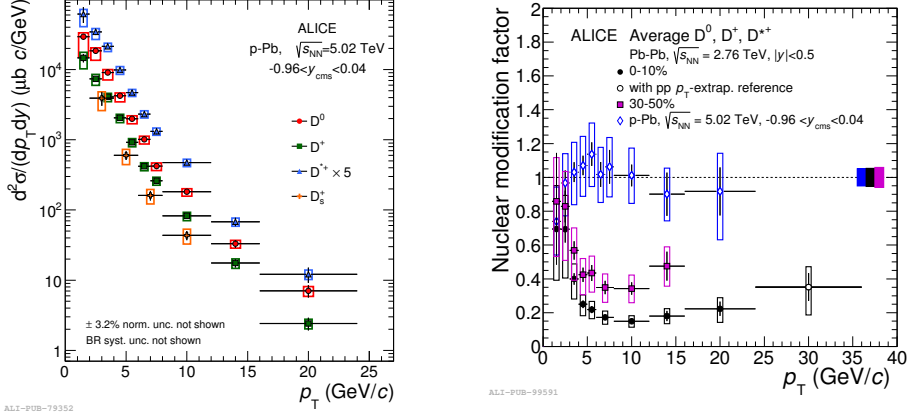
Figure 2: Left panel: p_T-differential production cross section of prompt D^0, D^+, D^{*+}, and D_s^+ mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [8]. Right panel: Average R_{pPb} of D^0, D^+ and D^{*+} mesons as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to D-meson R_{AA} in central (0–10%) and in semi-peripheral (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [2].

FONLL-based energy scaling of the p_T-differential cross sections measured at $\sqrt{s} = 7$ TeV [14]. The right panel of Fig. 2 shows the average R_{pPb} of prompt D mesons as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to the average R_{AA} of prompt D meson in central (0–10%) and semi-peripheral (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [2]. The R_{pPb} is close to unity within uncertainties, indicating that the suppression of D mesons for $p_T \gtrsim 3$ GeV/c observed in Pb-Pb collisions cannot be explained in terms of CNM effects but is due to strong final-state effects induced by hot and dense QCD matter.
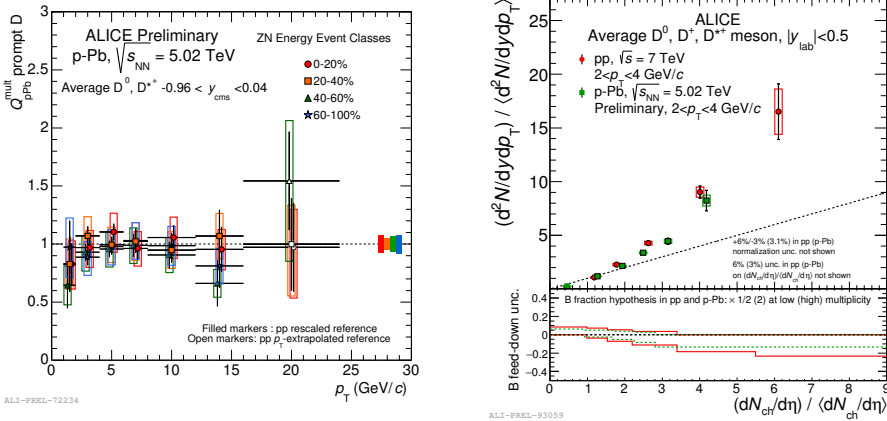

Figure 3: Left panel: Average D^0, D^+ and D^{*+} nuclear modification factors as a function of p_T in the 0–20%, 20–40%, 40–60% and 60–100% event classes selected with the ZNA estimator. Right panel: Relative D^0 yield as a function of multiplicity for $2 < p_T < 12$ GeV/c in p–Pb collisions, compared with the results from pp collisions.

The production of prompt D^0, D^+ and D^{*+} mesons is also studied in four event classes using different centrality estimators. The nuclear modification factor is calculated as $Q_{pPb}(p_T) = \frac{dN_{pPb}^{cent}/dp_T}{\langle T_{pPb}^{cent}\rangle \times (d\sigma_{pp}/dp_T)}$, where dN_{pPb}^{cent}/dp_T is the yield of prompt D mesons in p–Pb collisions in a given event class, $d\sigma_{pp}/dp_T$ is the p_T-differential cross section of prompt D mesons in pp collisions, and $\langle T_{pPb}^{cent}\rangle$ is the average nuclear overlap function in a given centrality class. In contrast to the

multiplicity-integrated R_{pPb}, Q_{pPb} is influenced by potential biases in the centrality estimation that are not related to nuclear effects [15]. The least biased estimator is based on the energy deposited by nuclear fragments in the Zero Degree Neutron Calorimeter in the Pb-going direction (ZNA). The D-meson Q_{pPb} estimated with the ZNA is consistent with unity within uncertainties and is independent of the event activity, as shown in the left panel of Fig. 3. The relative yields of D-mesons were also studied in p–Pb collisions as a function of charged-particle multiplicity and compared with the corresponding measurements in pp collisions, as shown in the right panel of Fig. 3. A similar relative increase of the D-meson yield with charged-particle multiplicity is observed in both pp and p–Pb collisions. It is worth noting that, in addition to the MPI, multiple binary nucleon-nucleon interactions occur in most p–Pb collision events and the collision initial conditions are also modified.

5. Conclusions

The measurements of D-meson production at central rapidity in pp and p–Pb collisions, performed with the ALICE detector, have been presented. The D-meson relative yields are found to increase with increasing charged-particle multiplicity in both pp and p–Pb collisions. Charm (open and hidden) and beauty hadron relative yields exhibit a similar increase with increasing charged-particle multiplicity at central rapidity in pp collisions at $\sqrt{s} = 7$ TeV. The Q_{pPb} of the D mesons measured in several event classes, defined with the least-biased estimator ZNA, are consistent with unity and also with the multiplicity-integrated R_{pPb}. Therefore, from our data there is no evidence of a multiplicity dependence of D-meson production in p–Pb collisions with respect to that of pp collisions at the same centre-of-mass energy within the uncertainties.

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