Results on open-charm production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC



2015 J. Phys.: Conf. Ser. 636 012003

(http://iopscience.iop.org/1742-6596/636/1/012003)

Journal of Physics: Conference Series **636** (2015) 012003 doi:10.1088/1742-6596/636/1/012003

# Results on open-charm production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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**Abstract**. ALICE (A Large Ion Collider Experiment) is designed to study the strongly-interacting medium created in heavy-ion collisions at LHC energies, the Quark-Gluon Plasma (QGP). Charm and beauty quarks are powerful probes to study the QGP in heavy-ion collisions: produced in hard partonic scattering processes on a short time scale, they are expected to traverse the QCD medium, interacting with its constituents and losing energy through radiative and collisional processes. In ALICE, open-charm production is studied through the reconstruction of the hadronic decays of $D^0$, $D^+$, $D^{*+}$ and $D_s^+$ mesons at mid-rapidity. The high precision tracking, good vertexing capabilities and excellent particle identification offered by ALICE allow for the measurement of particles containing heavy quarks (particularly D mesons) in a wide transverse-momentum range in pp, p-Pb and Pb-Pb collisions. A review of the main results on D-meson production in pp collisions at $\sqrt{s}$ = 7 TeV, Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and the most recent results in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV will be presented. In particular, the $p_T$-differential yields and cross sections in the three collision systems, the nuclear modification factors $R_{AA}$ and $R_{pPb}$ in Pb-Pb and p-Pb collisions, and the elliptic flow in Pb-Pb collisions will be discussed. The D-meson yield in pp and p-Pb collisions will also be shown as a function of charged-particle multiplicity.

## 1. Introduction

The ALICE experiment at the LHC aims at investigating the properties of the Quark-Gluon Plasma, the hot and dense state of strongly-interacting matter produced in high-energy heavy-ion collisions. Charm and beauty quarks are among to the most powerful probes to study the QGP in heavy-ion collisions: produced in hard parton scattering processes occurring in the early stages of the collision, they traverse the QCD medium, interact with its constituents and experience the whole evolution of the medium. Open heavy-flavour hadron production is expected to be sensitive to the energy density of the system through the mechanism of in-medium energy loss of heavy quarks [1-2-3]. Quantum Chromodynamics (QCD) theoretical calculations predict a dependence of the energy loss on the colour charge and on the mass of the parton traversing the medium. This results in an expected hierarchy of the parton energy loss, with beauty quarks losing less energy than charm quarks, and charm quarks losing less energy than light quarks and gluons. One of the observables that are sensitive to the interaction of hard partons with the medium is the nuclear modification factor, $R_{AA}$, defined as the ratio of the particle yield measured in Pb–Pb collisions and the cross section in pp collisions scaled with the nuclear overlap integral. $R_{AA}$ is expected to be unity for heavy flavours in the absence of medium effects. The expected hierarchy of the energy loss described above can be probed comparing the $R_{AA}$ of different particle species, namely B-, D- and light-hadron $R_{AA}$. Further knowledge of the properties of the medium created in heavy-ion collisions can be gained from the study of the azimuthal anisotropy of open heavy flavours: the initial spatial asymmetry is transformed into an asymmetry in momentum via hydrodynamic expansion of the medium. This is quantified in terms of the second coefficient $v_2$ in a Fourier expansion of the D-meson azimuthal distribution. The elliptic flow $v_2$ brings information on the medium transport properties: on the question whether heavy quarks take part in the collective expansion of the medium, and on the path-length dependence of energy loss. The interpretation of particle production measurements in Pb-Pb collisions requires detailed studies and understanding of their production in pp and p-Pb collisions: pp collisions provide the essential reference for the nuclear modification factor and a sensitive test of perturbative QCD models describing the production of heavy flavours in elementary hadronic collisions at LHC energies. The study of p–Pb collisions is crucial to access cold nuclear matter (CNM) effects in the initial and final state (modification of the Parton Distribution Functions in nuclei nPDF [4-5], gluon saturation at low Bjorken-$x$ [6], $k_T$ broadening), assuming that an extended, long-lived QGP is not formed in these collisions.

## 2. Open heavy-flavour measurements with ALICE

The ALICE detector, described in detail in [7], consists of a central barrel at mid-rapidity, a muon spectrometer at forward rapidity and a set of detectors (forward and backward rapidities) for global collision characterization and triggering purposes.
Open heavy flavours are measured in several charm hadronic decay channels and via electrons from semi-leptonic decays of charm and/or beauty hadrons at mid-rapidity. At forward rapidity, open heavy-flavour production is studied in the semi-muonic decay channel. Electrons are identified at mid-rapidity through their specific energy loss in the TPC gas combined with the information from the Time-Of-Flight (TOF) detector and from the electromagnetic calorimeter (EMCal). Muons are reconstructed in the five tracking stations of the Muon Spectrometer ($-4 < \eta < -2.5$).

### *2.1. D-meson reconstruction and selection*

D mesons are reconstructed in ALICE via their hadronic decays $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\,\pi^+ \rightarrow K^-\pi^+\pi^-$, $D^+_s \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$ and their charge conjugates.
D-meson selection is based on the reconstruction of decay vertices displaced by a few hundred μm from the interaction vertex, exploiting the high track-position resolution close to the interaction vertex provided by the Inner Tracking System (ITS). The large combinatorial background is reduced by selections applied on the decay topology and by the identification of charged kaons and pions via their specific energy loss in the TPC and their time of flight measured with the TOF detector. Raw D-meson yields are obtained from an invariant mass analysis of the pair/triplet of candidates. Then, the contribution from B-meson decay feed-down is subtracted, in order to obtain the prompt D-meson yields.

## 3. Results

Cross section measurements of prompt D mesons were performed with ALICE in pp collisions at $\sqrt{s}$ = 7 TeV and 2.76 TeV [8-10] and are well described by perturbative QCD calculations. The $p_T$-differential cross sections for $D^0$ and $D^{*+}$ at $\sqrt{s}$ = 7 TeV are shown in Fig.1, together with FONLL [11] and GM-VFNS [12] calculations. Within uncertainties, theoretical predictions and measurements agree with each other. Nevertheless, it can be noted that the measurements tend to be higher than the central value of the FONLL predictions, as it was observed at lower collision energies, at RHIC and at the Tevatron [13-14]. For GM-VFNS, instead, the data lie on the lower side of the predictions.

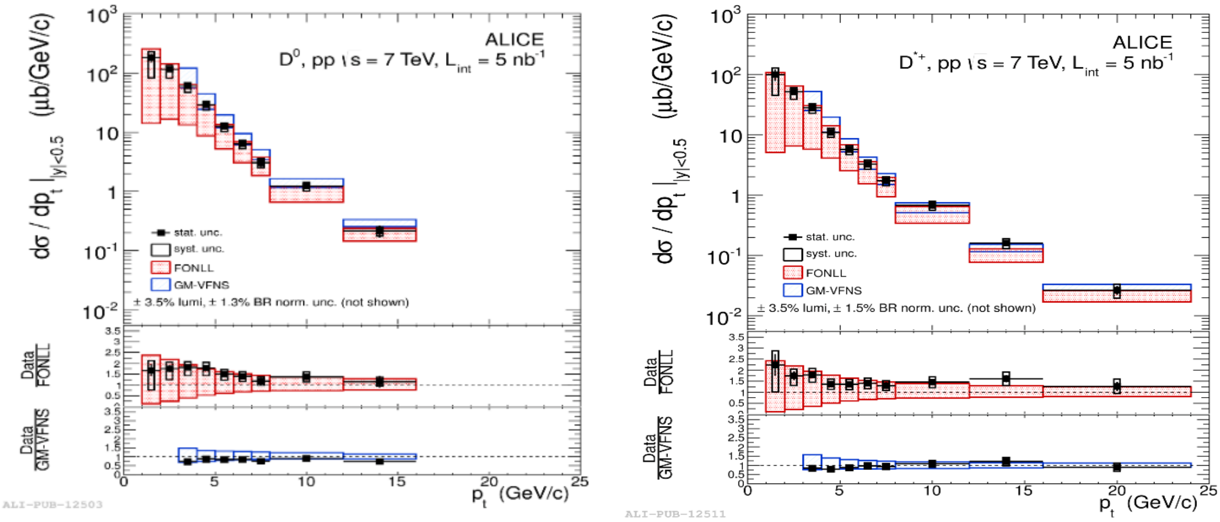


Figure 1: **Top**: $p_T$-differential cross section for prompt $D^0$ and $D^{*+}$ mesons in pp collisions at $\sqrt{s}$= 7 TeV compared with FONLL and GM-VFNS theoretical predictions. **Bottom**: the ratio of the measured cross section and the central FONLL and GM-VFNS calculations.

In p–Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV, CNM effects such as the modifications of the PDFs due to the presence of the nucleus are expected to affect the heavy-quark yield and $p_T$ distributions relative to pp collisions. In particular, by measuring heavy-flavour hadron production in different $p_T$ ranges it is possible to access different Bjorken-$x$ regimes. The nuclear modification factor $R_{pPb}$ quantifies the D-meson cross section in p–Pb collisions relative to the one in pp collisions scaled by the atomic mass number A = 208 of the lead nucleus. The average of the $R_{pPb}$ for $D^0$, $D^+$ and $D^{*+}$ in the $p_T$ range $1 < p_T < 24$ GeV/c, is shown in Fig. 2 together with the comparison with theoretical calculations. It can be observed that the $R_{pPb}$ of prompt D mesons is described within uncertainties by different models including initial-state effects [15]. The measurements confirm that initial- and final-state effects due to the presence of CNM are small in the measured $p_T$ range. The measurements are well described by

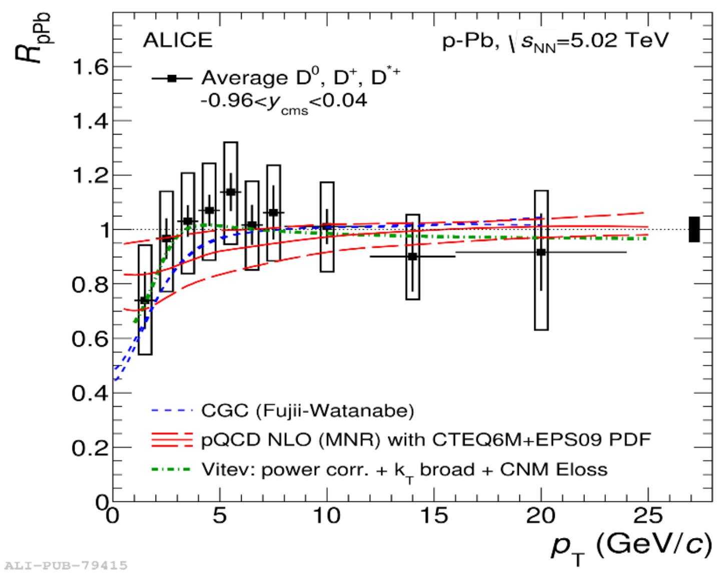


Figure 2: Average $R_{pPb}$ as a function of $p_T$ for prompt $D^0$, $D^+$ and $D^{*+}$ mesons in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, compared with models. Statistical (bars), systematic (empty boxes) and normalization (full box) uncertainties are shown.

theoretical predictions based on pQCD calculations including the EPS09 [16] nPDFs parametrisation, with calculations based on the Color Glass Condensate (CGC) and with a model including cold-nuclear matter energy loss, nuclear shadowing and $k_T$-broadening [17-18].

It has been observed that Multi-Parton Interactions, MPIs, multiple hard scatterings occurring between incoming partons in the same hadronic collision, play a relevant role in particle production at LHC energies. In particular, CMS results on jets and underlying event production rates and $\langle p_T \rangle$ as a function of the charged-particle multiplicity show a better agreement with models including MPI contribution [19]; measurements with ALICE of minijets, interpreted in the PYTHIA model, indicate an increase of MPIs with increasing multiplicity of charged particles in pp collisions [20]. Studies as a function of the event multiplicity were also performed by the ALICE Collaboration for prompt D mesons, inclusive J/Ψ in both pp and p-Pb collisions and for non-prompt J/Ψ in pp collisions. In Fig. 3 (left), average $D^0$, $D^+$, $D^{*+}$ yield per-event in pp collisions, in multiplicity intervals normalized to the same yield obtained in the multiplicity-integrated sample is reported as a function of the charged-particle multiplicity normalized by its average measured in multiplicity-integrated events [21]. The results in the different $p_T$ ranges shown in the figure are in agreement within the uncertainties. An increasing trend of the D-meson yield as a function of charged-particle multiplicity in pp collisions is observed, suggesting that MPIs, which substantially contribute to high-multiplicity events, are affecting heavy-flavour production. A similar trend is observed in p–Pb collisions, as shown in the right panel of Fig. 3 for the average $D^0$, $D^+$, $D^{*+}$ $D^0$ meson, although in this case a higher number of binary nucleon-nucleon collisions is also expected to contribute to high-multiplicity events.

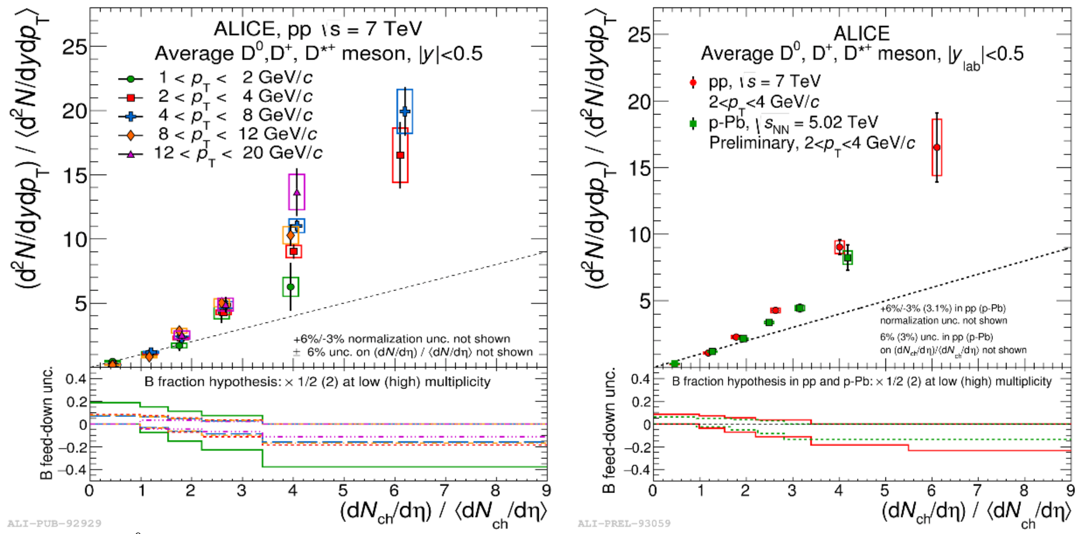


Figure 3: **Left**: $D^0$, $D^+$, $D^{*+}$ meson relative yields as a function of charged-particle multiplicity in pp collisions for different $p_T$ ranges at central rapidity. **Right**: self-normalized yield as a function of multiplicity in pp and p–Pb collisions for the average $D^0$, $D^+$, $D^{*+}$ meson with $2 < p_T < 4$ GeV/c.

In Pb–Pb collisions, the open heavy-flavour $R_{AA}$ measured with ALICE for $D^0$, $D^+$, $D^{*+}$ [22-23] shows a strong reduction of the yields at large trasverse momenta ($p_T > 5$ GeV/c) in the most central collisions relative to a binary-scaled pp reference. This suppression is interpreted as due to charm quark in-medium energy loss. The expected mass ordering of the energy loss has been also investigated: Fig. 4 (left) shows the D-meson $R_{AA}$ as a function of the average number of nucleons participating in the interaction, compared to the one of J/ψ from beauty-hadron decays measured by CMS [24]. The D-meson $p_T$ range was chosen in order to obtain a significant overlap with the $p_T$ distribution of B mesons decaying to J/ψ with $6.5 < p_T < 30$ GeV/c, thus allowing a consistent comparison. A similar trend as a function of centrality is observed, but the D-meson $R_{AA}$ is systematically lower than the one of J/ψ from B decays. This is consistent with the expectation of a smaller in-medium energy loss for beauty than for charm

Journal of Physics: Conference Series **636** (2015) 012003 doi:10.1088/1742-6596/636/1/012003

quarks. Fig. 4 (right) shows also the comparison of the D-meson $R_{AA}$ with that of charged hadrons and pions: a similar suppression is observed, but the uncertainties do not allow yet to draw a conclusion on the colour-charge and parton mass dependence of the in-medium energy loss.

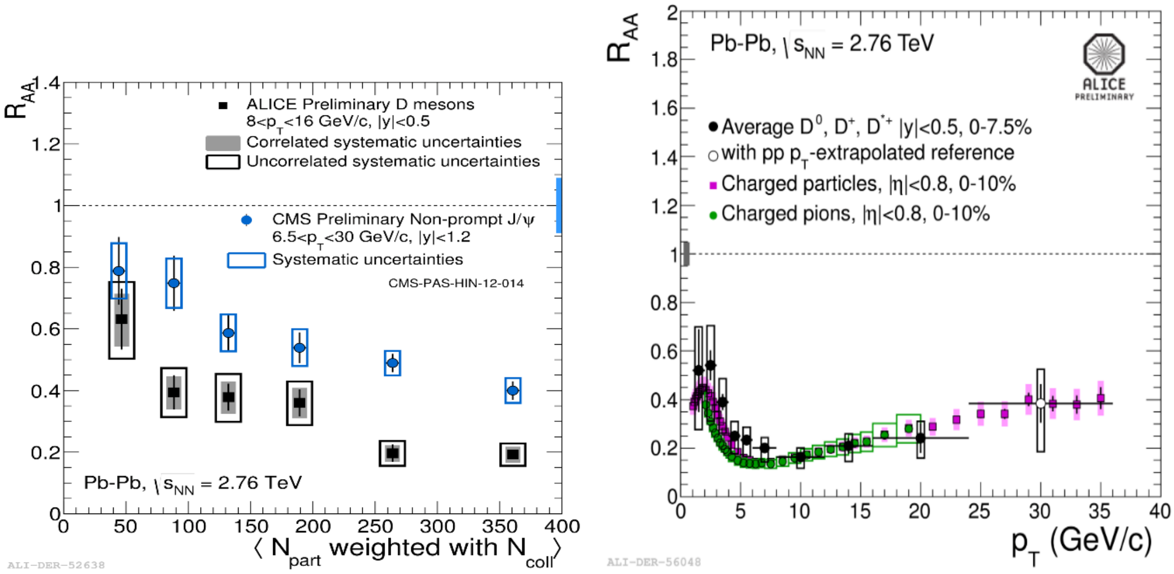


Figure 4: **Left**: $R_{AA}$ of prompt D mesons and of non-prompt J/ψ measured by CMS [24] as a function of centrality, expressed in terms of the number of nucleons participating in the interaction. **Right**: Comparison of prompt D-meson $R_{AA}$ with the $R_{AA}$ of charged hadrons and pions.

The D-meson $v_2$ measured in 30-50% central Pb-Pb collisions shown in Fig. 5, is larger than zero with a 5.7σ significance in the interval $2 < p_T < 6$ GeV/c and comparable in magnitude to the one of charged hadrons, dominated by light-flavour hadrons [25] . These results indicate that at low $p_T$ charm quarks participate in the collective motion of the system. At high $p_T$, $v_2$ results could give insight into the path-length dependence of the in-medium energy loss, but the present statistics does not allow to give a conclusion on this.

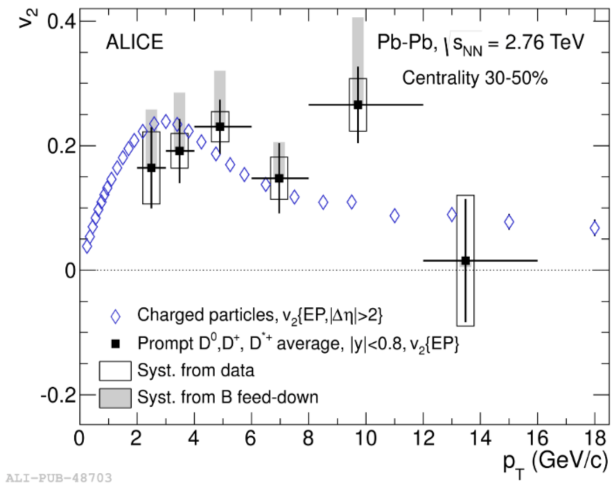


Figure 5: Comparison between $D^0$, $D^{*+}$ and $D^+$ average $v_2$ and charged hadron $v_2$ measured in 30-50% central Pb-Pb collisions [25].

## 4. Conclusions

Measurements of open charm production have been carried out successfully with the ALICE experiment at the LHC. $p_T$-differential cross sections for prompt D mesons in pp collisions are reproduced within uncertainties by theoretical predictions based on pQCD calculations. The D-meson self-normalized yields exhibit an increasing trend with increasing charged-particle multiplicity in pp collisions, suggesting that MPIs affect the hard momentum scale relevant for heavy-flavour production. A similar increase is observed in p–Pb collisions, but in this case a higher number of binary nucleon-nucleon collisions also contributes to high-multiplicity events. $R_{pPb}$ of prompt D mesons in p-Pb collisions is consistent with unity within uncertainties, providing evidence that CNM effects are small in the measured $p_T$ range. In Pb-Pb collisions a strong suppression of heavy-flavour yields is observed at intermediate and high $p_T$. As the influence of CNM effects is small in the measurement $p_T$ range, these results in Pb–Pb collisions can be interpreted as a final-state effect due to in-medium parton energy loss. The $v_2$ measured in Pb–Pb semi-central collisions is larger than zero at low $p_T$, suggesting that heavy quarks participate in the collective motion of the system.

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