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D-meson production in pp and p-Pb collisions measured with ALICE at the LHC

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Abstract. The open heavy-flavour production studied with ALICE at the LHC in pp collisions at \( \sqrt{s} = 7 \) TeV and p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV is presented. Focus is given to the dependence of the production on the multiplicity of charged particles produced in the collision.

1. Introduction
Heavy quarks (charm and beauty) can be used to study several aspects of QCD in high-energy hadronic collisions. They are produced in hard partonic scattering processes occurring in the initial stage of the collisions with large momentum transfer. Therefore, the study of their production in pp collisions provides a precision test of perturbative QCD (pQCD) calculations. In proton-nucleus collisions, heavy-flavour production could be modified by the presence of a nucleus in the colliding system. The cross section and \( p_T \) distributions of heavy-flavour hadrons could be influenced by the modification of the parton distributions functions in the nucleus (nPDF), especially at small Bjorken \( x \) (see e.g. [1]), by the \( k_T \)-broadening caused by soft scatterings of the partons in the incoming nucleus [2], and by possible energy loss of the produced heavy quarks in the nucleus [3]. These effects are commonly called Cold Nuclear Matter (CNM) effects. They are explored through the measurement of the nuclear modification factor \( R_{pPb} \), i.e. the comparison of p–Pb measurements with pp results, to test whether the yield and the transverse momentum distributions follow or not a scaling with the number of binary nucleon-nucleon collisions in p–Pb collisions.

The study of the nuclear modification factor in different event multiplicity classes is also interesting to assess the possible modification of the \( p_T \) spectrum in high multiplicity events. Moreover, the measurement of heavy-flavour production, both in pp and p–Pb collisions, as a function of the multiplicity of charged particles produced in hadronic collisions can improve our understanding of their production mechanisms and could give insight into the role of Multi-Parton Interactions (MPI), i.e. several partonic interactions occurring in a single collision between two nucleons. If the production of heavy quarks is affected by the presence of additional hard scatterings between incoming partons, their yield should increase with multiplicity. The shape of the increasing trend depends on how the MPI contribute to the production of particles: if they equally contribute to soft and hard production, from small to large multiplicities, the increase would be linear. Indications of the relevance of MPI in heavy-quark production have been observed by NA27 [4] and recently by ALICE in the \( J/\psi \) and D-meson production measurement as a function of charged-particle multiplicity [5, 6].
Figure 1. Self-normalized average D-meson yields as a function of multiplicity in pp collisions for different $p_T$ ranges [6]. Left: multiplicity estimates at mid rapidity. Middle: multiplicity estimate at forward rapidity. Right: D-meson (red) and $J/\psi$ (black) yields as a function of the relative charged-particle multiplicity at mid rapidity.

2. D-meson reconstruction in ALICE

pp collisions at $\sqrt{s} = 7$ TeV ($3 \times 10^8$ events) and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($10^8$ events) collected by the ALICE detector [7], with a minimum-bias trigger, in 2010 and 2013, respectively, were analyzed. Prompt $D^0$, $D^+$, $D^{*+}$ were reconstructed via their hadronic decay channels and selected via the reconstruction of decay vertices displaced by a few hundred $\mu$m from the interaction vertex. Events were divided in classes using the charged-particle multiplicity measured at mid rapidity through the number of tracklets with $|\eta| < 1$ reconstructed by associating pairs of hits in the Silicon Pixel Detector (SPD) or at forward and backward rapidity using the charge collected by the V0 scintillator array.

3. D-meson production in pp collisions

D-meson $p_T$-differential cross sections were measured in pp collisions at $\sqrt{s} = 7$ TeV [8] and $\sqrt{s} = 2.76$ TeV [9]. They are well described by pQCD calculations [10, 11]. A pQCD-based energy scaling of the 7 TeV cross section to 2.76 TeV is in good agreement with the measured cross section at the same energy, confirming the robustness of the $\sqrt{s}$ extrapolation needed to define the references for Pb–Pb and p–Pb measurements.

The study of D-meson production, evaluated for various multiplicity and $p_T$ intervals, is presented via the D-meson self-normalized yield, i.e. the corrected per-event yield normalized to the multiplicity-integrated value:

$$\frac{d^2N^D/dydp_T^j}{\langle d^2N/D/dydp_T \rangle} = \left( \frac{1}{\langle N^j_{\text{events}} \rangle} \frac{N^j_{\text{raw }D}}{\epsilon^j_{\text{prompt }D}} \right) \left( \frac{1}{N_{\text{MB trigger}}/\epsilon_{\text{MB trigger}} \langle N_{\text{raw }D} \rangle} \right) \left( \epsilon_{\text{prompt }D} \right)$$

where the index $j$ identifies the multiplicity interval, $N^j_{\text{raw }D}$ is the raw yield, $\epsilon^j_{\text{prompt }D}$ represents the reconstruction and selection efficiencies for prompt D mesons and $N^j_{\text{events}}$ the number of events analysed in each multiplicity interval. The results for $D^0$, $D^+$, $D^{*+}$ are compatible with each other. The average self-normalized yield of the three species increases with increasing multiplicity and does not depend on $p_T$ within uncertainties in the interval 1-20 GeV/$c$, as shown in Fig 1. A similar trend is observed when the multiplicity is estimated at mid rapidity (Fig 1 left) or at forward rapidity, (middle), demonstrating that the trend is not connected
Figure 2. Left: Average $R_{p\text{Pb}}$ of D mesons as a function of $p_T$ compared to models [15]. Right: Average $p_T$-differential D-meson $Q_{p\text{Pb}}$ in four ZNA event activity classes.

to a possible bias due to the pseudorapidity region of the multiplicity measurements [6]. The self-normalized yield of D mesons is comparable with that of inclusive $J/\psi$ measured at mid rapidity, and the increasing trend seems to be stronger at mid rapidity than at forward rapidity, as shown in Fig 1 (right). Furthermore, an analogous trend is observed comparing D mesons and non-prompt $J/\psi$. The similar trends of charm (open and hidden) and beauty suggest that their multiplicity dependence is not, or only slightly, affected by the hadronisation stage. The yield increase can be described by calculations taking into account the influence of the interactions between colour sources in the percolation model [12], and the contribution of MPI, through the PYTHIA-8 [13] and the EPOS 3 event generators [14], that also include the effect of the initial conditions of the collision followed by a hydrodynamic evolution. However more precise measurements are needed for a conclusive discrimination of the possible origins of the effect.

4. D-meson production in p-Pb collisions

Figure 2 (left) shows the D-meson $R_{p\text{Pb}}$ (average of $D^0$, $D^+$, $D^{*+}$) as a function of $p_T$ in minimum-bias events, compared with theoretical calculations [15]. $R_{p\text{Pb}}$ is compatible with unity within uncertainties in the measured $p_T$ range. Predictions based either on Color Glass Condensate calculations [16], or next-to-leading order (NLO) pQCD calculations of D-meson production, including EPS09 nPDFs [17], or $k_T$-broadening [18] with CNM energy loss [19] can describe the measurement by considering only initial-state effects, but the comparison is not conclusive, due to the sizeable uncertainties at low $p_T$. The analysis of D-meson production was also carried out in four event activity classes and the nuclear modification factor was calculated as: $Q_{p\text{Pb}} = \frac{(dn^D/dp_T)_{\text{pp}}^{\text{cent}}}{(T_{\text{cent}}^{p\text{Pb}})/(T_{\text{cent}}^{p\text{Pb}})}$, where $(dn^D/dp_T)_{\text{pp}}^{\text{cent}}$ is the yield of D mesons in p–Pb collisions in a given event activity class, $(dn^D/dp_T)_{\text{pp}}$ is the cross section of D mesons in pp collisions at the same $\sqrt{s}$, and $\langle T_{\text{cent}}^{p\text{Pb}} \rangle$ is the average nuclear overlap function in a given event activity class. In contrast to the multiplicity-integrated $R_{p\text{Pb}}$, $Q_{p\text{Pb}}$ is influenced by potential biases in the centrality estimation that are not related to nuclear effects [20]. The least biased estimator is based on the energy deposited by nuclear fragments in the Pb-going side (ZNA), measured with the Zero Degree Neutron Calorimeter. The D-meson $Q_{p\text{Pb}}$ estimated with the ZNA is consistent within uncertainties with binary collision scaling of the yield in pp collisions, it is independent of the event activity, as it is shown in Fig 2 (right). D-meson per-event yields were also studied in p–Pb collisions as a function of the relative charged-particle multiplicity, in a similar way as for the pp data. The D-meson self-normalized yields increase with the relative charged-particle
multiplicity, and the increase is independent of $p_T$ within the measurement uncertainties, Fig 3 (left). This behavior is similar to that of the corresponding measurements in pp collisions. The increasing trend is present also in the $J/\psi$ measured in p–Pb collisions at backward and forward rapidity, Fig 3 (right). In p–Pb collisions, in addition to the MPI, the contribution from multiple binary nucleon–nucleon collisions should also be considered.

5. Conclusions
D-meson self-normalized yields show an increasing trend with increasing multiplicity, and the trend is similar for pp and p–Pb collisions. The $Q_{pp}$, measured in event-activity classes defined with the least-biased estimator (ZNA) are consistent with the multiplicity-integrated $R_{pp}$ and with unity. This suggests that there is no evidence of a deviation of D-meson production in p–Pb from binary scaling, even in high event-activity collisions.

References