Preliminary Physics Summary:

Measurement of prompt $D^0$, $D^+$, $D^{*+}$ and $D^+_s$ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Abstract

We report preliminary measurements of the production of prompt $D^0$, $D^+$, $D^{*+}$ and $D^+_s$ mesons in p–Pb collisions, recorded in late 2016, at the centre-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV per nucleon–nucleon collision. Differential production cross sections are measured at mid-rapidity ($-0.96 < y_{\text{cms}} < 0.04$) as a function of transverse momentum ($p_T$) in the intervals $0 < p_T < 36$ GeV/c for $D^0$, $1 < p_T < 36$ GeV/c for $D^+$ and $D^{*+}$, and $2 < p_T < 24$ GeV/c for $D^+_s$ mesons. The fraction of prompt D mesons is estimated using a perturbative QCD calculation of beauty production and verified in the case of $D^+$ and $D^{*+}$ mesons using fits to their impact parameter distributions. The nuclear modification factors $R_{pPb}$ are calculated using a proton–proton reference at $\sqrt{s} = 5.02$ TeV obtained by scaling the D-meson cross sections measured at $\sqrt{s} = 7$ TeV. The $D^0$ nuclear modification factor is further measured as a function of the collision centrality, $Q_{pPb}$, offering the possibility to compute the central-to-peripheral ratio, $Q_{CP}$. 

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1 Introduction

Measurements of heavy-flavour hadron production in proton–nucleus collisions allow an assessment of the various effects related to the presence of nuclei in the colliding system and denoted as cold-nuclear-matter (CNM) effects (see Ref. [1] for a recent review). In the initial state, the Parton Distribution Functions (PDFs) might be modified in bound nucleons as compared to free nucleons, depending on the parton momentum fraction $x$ and on the momentum transfer in the hard scattering $Q^2$ [2, 3]. At LHC energies, the most relevant effect is shadowing: a reduction of the parton densities at low $x$, which becomes stronger when $Q^2$ decreases and the nucleus mass number $A$ increases. This effect can be described by means of phenomenological parametrisations of the modification of the PDFs [4–7]. The resultant PDFs in bound nucleons are denoted as nPDFs. If the parton phase-space reaches saturation, PDF evolution equations are not applicable and the most appropriate theoretical description is the Colour Glass Condensate effective theory (CGC) [8–12]. The modification of the small-$x$ parton dynamics can significantly reduce D-meson production at low transverse momentum ($p_T$). Furthermore, the multiple scattering of partons in the nucleus before and/or after the hard scattering can modify the kinematic distribution of the produced hadrons: partons can lose energy in the initial stages of the collision via initial-state radiation [13], or experience transverse momentum broadening due to multiple soft collisions before the heavy-quark pair is produced [14–16]. Also these initial-state effects can induce a significant modification of D-meson production at low $p_T$. In addition to the initial-state effects discussed above, also final-state effects may be responsible for a modification of heavy-flavour hadron yields and momentum distributions. If a collective expansion in the final state were present, the medium could also impart a flow to heavy-flavour quarks or hadrons, or modify the hadronisation dynamics of heavy quarks [17–19].

We report preliminary measurements of the production cross sections and nuclear modification factors of D mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV recorded in 2016 with the ALICE detector. The sample used for this analysis is larger by a factor about six with respect to the sample collected in 2013 and used for previous publications for these observables [20–22].

The nuclear modification factor, $R_{p\text{Pb}}$, is defined as the ratio of the $p_T$-differential cross section in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV to the cross section in pp collisions at the same energy scaled by the Pb mass number $A = 208$:

$$ R_{p\text{Pb}} = \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}^{\text{promptD}}/dp_Tdy}{d^2\sigma_{pp}^{\text{promptD}}/dp_Tdy}. $$

(1)

In addition, the measurement was done in centrality intervals, where the centrality is defined using the energy deposited in the zero-degree neutron calorimeter in the Pb-going side (ZNA) as described in Ref. [23]. For each centrality class the nuclear modification factor, $Q_{p\text{Pb}}$, is defined by:

$$ Q_{p\text{Pb}}^{\text{cent}} = \frac{\langle d^2N^{\text{promptD}}/dp_Tdy \rangle_{p\text{Pb}}^{\text{cent}}}{\langle T_{p\text{Pb}} \rangle_{\text{cent}} \times \langle d^2\sigma_{pp}^{\text{promptD}}/dp_Tdy \rangle_{pp}}. $$

(2)

where $\langle d^2N/dp_Tdy \rangle_{p\text{Pb}}^{\text{cent}}$ is the yield of prompt D mesons in p–Pb collisions in a given centrality class, and $\langle T_{p\text{Pb}} \rangle_{\text{cent}}$ is the average nuclear overlap function in a given centrality class (see Ref. [23]).

Finally, the ratio of the nuclear modification factor in the 0–10% class to that in the 60–100% centrality class, $Q_{CP}$, was evaluated as:

$$ Q_{CP} = \frac{\langle d^2N^{\text{promptD}}/dp_Tdy \rangle_{p\text{Pb}}^{0-10}}{\langle T_{p\text{Pb}} \rangle_{0-10}} \times \frac{\langle T_{p\text{Pb}} \rangle_{60-100}^{-10}}{\langle T_{p\text{Pb}} \rangle_{60-100}}. $$

(3)
2 Experimental apparatus and data sample

The ALICE experimental apparatus \cite{24} is composed of various detectors for particle reconstruction and identification at mid-rapidity ($|\eta| < 0.9$), a forward muon spectrometer ($-4 < \eta < -2.5$) and a set of forward-backward detectors for triggering and event characterization. Typical detector performance in pp, p–Pb and Pb–Pb collisions is presented in \cite{25}. The main detector components used in this analysis are the V0 detector, the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Zero Degree Calorimeter (ZDC), located ±5 m from the interaction point.

Proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV were recorded with a minimum-bias (MB) interaction trigger that required coincident signals in both scintillator arrays of the V0 detector, which covers the full azimuth in the pseudorapidity intervals $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. The V0 timing information was used together with that from the ZDCs for offline rejection of interactions happening outside of the nominal slots for collisions.

The MB trigger was estimated to be sensitive to about 96.4% of the p–Pb inelastic cross section. For the data samples considered in this analysis, the probability of collision pile-up in the same-bunch crossing was below 0.5% per triggered p–Pb event. The probability of having a second interaction in a different bunch crossing superimposed with the triggered event within the readout window of 300 ns of the Silicon Pixel Detector (SPD, the two innermost ITS layers) was of about 1%. The piled-up events were largely rejected using an algorithm to detect multiple interaction vertices using tracklets defined with the SPD layers. The remaining undetected pile-up is negligible in the present analysis. Only events with a primary vertex reconstructed within ±10 cm from the centre of the detector along the beam line were considered.

The number of events passing these selection criteria was about $6 \times 10^5$. The corresponding integrated luminosity, $L_{\text{int}} = N_{\text{MB}}/\sigma_{\text{MB}}$, is equal to $292 \pm 11 \mu b^{-1}$, $\sigma_{\text{MB}} = 2.09 \text{ b}$ being the MB-trigger (i.e. visible) cross section measured via a van der Meer scan, with negligible statistical uncertainty and a systematic uncertainty of 3.7% \cite{26}. During the p–Pb run, the beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei. With this beam configuration, the nucleon–nucleon centre-of-mass system moves in rapidity by $\Delta y_{\text{cms}} = 0.465$ in the direction of the proton beam. The D-meson analyses were performed in the laboratory-frame interval $|y_{\text{lab}}| < 0.5$, which leads to a shifted centre-of-mass rapidity coverage of $-0.96 < y_{\text{cms}} < 0.04$.

3 Data analysis

3.1 Analysis with D-meson decay vertex reconstruction

The D mesons and their charge conjugates were reconstructed in the decay channels $D^0 \rightarrow K^-\pi^+$ (with branching ratio, BR, of $3.93 \pm 0.04\%$), $D^+ \rightarrow K^-\pi^+\pi^+$ (BR of $9.46 \pm 0.24\%$), $D^{*+} \rightarrow D^0\pi^+$ (BR of $67.7 \pm 0.5\%$) and $D^{*+} \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR of $2.27 \pm 0.08\%$) \cite{27}. The analysis was based on the reconstruction of decay vertices displaced from the interaction vertex, exploiting the separation of a few hundred $\mu$m induced by the weak decays of the $D^0$, $D^+$ and $D^{*+}$ mesons. The $D^0$, $D^+$ and $D^{*+}$ candidates were defined using pairs and triplets of tracks with proper charge sign combination with $|\eta| < 0.8$, $p_T > 0.3$ GeV/$c$, at least 70 (out of 159) associated space points in the TPC and at least two hits (out of six) in the ITS, out of which at least one should be in one of the two innermost layers. $D^+$ candidates were formed by combining $D^0$ candidates with tracks with $|\eta| < 0.8$, $p_T > 0.1$ GeV/$c$ and at least three associated hits in the ITS. The selection of tracks with $|\eta| < 0.8$ limits the D-meson acceptance in rapidity, which, depending on $p_T$, varies from $|y_{\text{lab}}| < 0.5$ at low $p_T$ to $|y_{\text{lab}}| < 0.8$ at $p_T > 5$ GeV/$c$. A $p_T$-dependent fiducial acceptance region was therefore defined as $|y_{\text{lab}}| < y_{\text{fid}}(p_T)$, with $y_{\text{fid}}(p_T)$ increasing from 0.5 to 0.8 in the transverse momentum range 0 < $p_T$ < 5 GeV/$c$ according to a second-order polynomial function, and $y_{\text{fid}} = 0.8$ for $p_T > 5$ GeV/$c$. The selection strategy is the same as
in previous analyses [22]. The main variables used to select the D candidates are the separation between primary and secondary vertex, the displacement of the tracks from the primary vertex, the pointing of the reconstructed D-meson momentum to the primary vertex, and, for the D^+, the impact parameter of the D meson with respect to the primary vertex in the transverse plane. For the D_{s}^{+} candidate selection, one of the two pairs of opposite-sign tracks is required to have an invariant mass compatible with the PDG world average for the φ mass. Further background reduction is obtained by applying particle identification for charged pions and kaons with the TPC and TOF detectors. A typical ±3σ window around the expected mean values of specific ionisation energy loss dE/dx in the TPC gas and of time-of-flight from the interaction point to the TOF detector is used for the identification. For D^{∗+} candidates, a 2σ window around the expected mean values is considered. For D_{s}^{+} candidates, a 3σ selection is used, but tracks without a TOF signal (mostly at low momentum) are identified using only the TPC information and requiring a 2σ compatibility with the expected dE/dx. The selections described above allow to reach S/B values in the interval 0.03–1.6 for D^{0} and 0.4–2 for D_{s}^{+} mesons, from low to high p_{T}.

The D-meson raw yields were obtained from fits to the candidate invariant-mass distributions M(Kπ) for D^{0}, M(Kππ) for D^{+}, M(KKπ) for D_{s}^{+}, and the mass difference ΔM = M(KKπ) − M(Kπ) for D^{∗+}. Examples for these distributions are shown in Fig. [1]. The D^{0}, D^{+} and D_{s}^{+} candidate invariant-mass distributions were fitted with a function composed of a Gaussian for the signal and an exponential term to describe the background shape. The ΔM distribution of the D^{∗+} candidates was fitted with a Gaussian function for the signal and a threshold function multiplied by an exponential for the background: 

\[ a \sqrt{ΔM} − m_{π} \cdot e^{b(ΔM−m_{π})} \]

To account for the contribution of signal candidates that are present in the invariant-mass distribution of the D^{0} meson with the wrong decay-particle mass assignment (reflection), an additional term, obtained from the fit with a double Gaussian function of the simulated reflections invariant-mass distributions, was included in the fit function. For the M(KKπ) distribution, an additional Gaussian was used to describe the signal of the decay D^{+} → K^{+}K^{−}π^{+} (BR of (9.51 ± 0.34) · 10^{-3} [27]), present on the left side of the D_{s}^{+} signal. The statistical significance of the observed signals S/\sqrt{S+B} varies from 5 to 62, depending on the meson species and the p_{T} interval.

The D-meson raw yields extracted in each p_{T} interval were corrected to obtain the prompt D-meson cross sections according to

\[ \frac{d^{2}\sigma_{\text{PromptD}}}{dp_{T}dy} = \frac{1}{1} \cdot \frac{f_{\text{Prompt}} \cdot \frac{1}{2} \cdot N_{D^{∗+}\text{raw}}(p_{T})}{c_{Δy}(p_{T})} \cdot \frac{1}{(\text{Acc} \times \varepsilon)_{\text{Prompt}}(p_{T})} \cdot \frac{1}{\text{BR} \cdot L_{\text{int}}}. \tag{4} \]

In the formula, \( N_{D^{∗+}\text{raw}} \) is the raw yield (sum of particles and antiparticles) in the laboratory rapidity interval Δy in a p_{T} interval of width Δp_{T}. The rapidity acceptance correction factor c_{Δy} was computed with the PYTHIA 6.4.21 event generator with Perugia-0 tune as the ratio between the generated D-meson yield in Δy = 2y_{tid}, with y_{tid} varying from 0.5 at low p_{T} to 0.8 at high p_{T} and that in |y| < 0.5. It was checked that calculations of the c_{Δy} correction factor based on FONLL pQCD calculations [28] or on the assumption of uniform D-meson rapidity distribution in |y| < y_{tid} would give the same result, because both in PYTHIA and in FONLL the D-meson yield is uniform within 1% in the range |y| < 0.8. The raw yield includes contributions from both components of the D-meson population: the prompt one (i.e. produced in the charm quark fragmentation, either directly or through decays of excited open charm and charmonium states) and the non-prompt one (i.e. originating from beauty-hadron decays), labelled as feed-down in the following. The factor 1/2 accounts for the fact that the measured yields include particles and antiparticles while the cross sections are given for particles only: f_{prompt} is the fraction of prompt D mesons effectively reconstructed in the raw yield; (\text{Acc} \times \varepsilon)_{prompt} is the product of the acceptance and the efficiency of prompt D mesons, where \varepsilon accounts for primary vertex reconstruction, D-meson decay track reconstruction and selection, and for D-meson candidate selection with secondary vertex and PID cuts; BR is the branching ratio of the considered decay channel, and L_{int} is the integrated luminosity.

The acceptance and efficiency correction factors were obtained from Monte Carlo simulations including
counts per 18 MeV/
counts per 8 MeV/
counts per 8 MeV/

\begin{array}{l}
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{counts per 18 MeV} & \text{counts per 8 MeV} & \text{counts per 8 MeV} \\
\hline
100 & 120 & 140 \\
120 & 140 & 160 \\
140 & 160 & 180 \\
160 & 180 & 200 \\
\hline
\end{array}
\end{array}

\begin{array}{l}
\begin{array}{c}
(\text{a)} D^0 \text{ for } 2 < p_T < 3 \text{ GeV/c} \\
\end{array}
\end{array}

\begin{array}{l}
\begin{array}{c}
(\text{b)} D^+ \text{ for } 24 < p_T < 36 \text{ GeV/c} \\
\end{array}
\end{array}

\begin{array}{l}
\begin{array}{c}
(\text{c)} D^{*+} \text{ for } 16 < p_T < 24 \text{ GeV/c} \\
\end{array}
\end{array}

\begin{array}{l}
\begin{array}{c}
(\text{d)} D_s^+ \text{ for } 2 < p_T < 4 \text{ GeV/c} \\
\end{array}
\end{array}

\text{Figure 1: Example distributions of the invariant mass for } D^0, D^+ \text{ and } D_s^+ \text{ candidates and their charge conjugates and of the mass difference for } (D^{*+} - D^0) \text{ candidates (and charge conjugates) in p–Pb collisions. The dashed lines represent the fit to the background while the solid lines represent the total fit function. In the case of the } D^0, \text{ the contribution of signal reflections in the invariant-mass distribution is shown as well.}

detailed descriptions of the geometry of the apparatus and of the detector response. Proton-proton collisions were generated by using the PYTHIA v6.4.21 event generator with the Perugia-2011 tune; events containing a $c\bar{c}$ or $b\bar{b}$ pair were selected and an underlying p–Pb collision generated with HIJING 1.36 was superimposed to each of them in order to obtain a better description of the multiplicity distributions observed in data. The generated D-meson $p_T$ distribution was weighted in order to match the shape predicted by FONLL calculations at $\sqrt{s} = 5.02$ TeV, based on the observation that FONLL provides a good description of the measured D-meson $p_T$-differential cross sections in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. The efficiency depends on the multiplicity of charged particles produced in the collision, since the primary vertex resolution, thus the resolution for the topological selection variables, improves at high multiplicity. Therefore, the generated events were weighted on the basis of their charged-particle multiplicity in order to match the multiplicity distribution observed in data.
Acceptance 

Efficiency 

The correction factor $f_{\text{prompt}}$ was calculated with a FONLL-based method as

$$f_{\text{prompt}} = 1 - \frac{N_{\text{D feed-down}}}{N_{\text{raw}}} = 1 - A \left( \frac{d^2 \sigma}{d p_T dy} \right)^{\text{FONLL}}_{\text{feed-down}} \cdot R_{\text{ppPb}}^{\text{feed-down}} \cdot \frac{(\text{Acc} \times \varepsilon)_{\text{feed-down}} \cdot \Delta y \cdot p_T \cdot \text{BR} \cdot L_{\text{int}}}{N_{\text{D}+\text{B PpPb}}} / 2,$$

where $A$ is the mass number of the Pb nucleus. The procedure uses the B-meson production cross section in pp collisions at $\sqrt{s} = 5.02$ TeV estimated with FONLL calculations, the $B \to D + X$ decay kinematics from the EvtGen package [35], the efficiencies for D mesons from beauty-hadron decays and a hypothesis on the nuclear modification factor $R_{\text{ppPb}}$ of D mesons from B decays. On the basis of calculations including initial state effects via the EPS09 nuclear PDF parametrisations [4] or the Color Glass Condensate formalism [12], it was assumed that the $R_{\text{ppPb}}$ of prompt and feed-down D mesons are equal and their ratio was varied in the range $0.9 < R_{\text{ppPb}}^{\text{feed-down}} / R_{\text{ppPb}}^{\text{prompt}} < 1.3$ to evaluate the systematic uncertainties. The resulting $f_{\text{prompt}}$ values and their uncertainties are shown in the right-hand panels of Fig. 3 for $D^+$ and $D^{*+}$ mesons in the $|y_{\text{lab}}| < y_{\text{fid}}(p_T)$ interval.

Figure 2: Product of acceptance and efficiency for D mesons in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The values for prompt and feed-down D mesons are shown.
D-meson production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

3.2 Measurement of the prompt D-meson fraction

The prompt fractions in the raw yields of $D^+$ and $D^{*+}$ mesons, $f_{\text{prompt}}$, calculated with the FONLL-based method of Eq. (5) were cross-checked with a data-driven method that exploits the different shapes for the distributions of the transverse-plane impact parameter to the primary vertex ($d_0$) of prompt and feed-down D mesons. The prompt fraction was estimated via an unbinned likelihood fit of the $d_0$ distribution of $D^+$-meson candidates with invariant mass $|M - M_{D^+}| < 1.5\sigma$ (where $\sigma$ is the standard deviation of the Gaussian function describing the D-meson signal in the invariant-mass fits) and of $D^{*+}$-meson candidates with a mass difference $|\Delta M - \Delta M_{D^{*+}}| < 2.5\sigma$, using the fit function

$$F(d_0) = S \cdot [(1-f_{\text{prompt}})F_{\text{feed-down}}(d_0) + f_{\text{prompt}}F_{\text{prompt}}(d_0)] + B \cdot F_{\text{backgr}}(d_0).$$

In this function, $S$ and $B$ are the signal raw yield and background in the selected invariant-mass range; $F_{\text{prompt}}(d_0)$, $F_{\text{feed-down}}(d_0)$ and $F_{\text{backgr}}(d_0)$ are functions describing the impact parameter distributions of prompt D mesons, feed-down D mesons, and background, respectively. The function $F_{\text{prompt}}$ is a detector...
resolution term modelled with a Gaussian and a symmetric exponential term, $\frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|b|}{\lambda}\right)$, describing the tails of the impact-parameter distribution of prompt D mesons. $F^{\text{feed-down}}$ is the convolution of the detector resolution term with a symmetric double-exponential function ($F^{\text{true}}_{\text{feed-down}}$) describing the intrinsic impact parameter distribution of secondary D mesons from B-meson decays, which is determined by the decay length and decay kinematics of B mesons. The parameters of the $F^{\text{prompt}}$ and $F^{\text{true}}_{\text{feed-down}}$ functions were fixed to the values obtained by fitting the distributions from Monte Carlo simulations, except for the Gaussian width of the detector-resolution term, which was kept free in the data fit to compensate for a possible imperfect description of the impact-parameter resolution in the simulation. The parameters of $F^{\text{backgr}}$ were fixed by fitting the impact parameter distribution of background candidates in the side-bands of the signal peak in the invariant-mass distributions (mass difference for D$^+$ mesons). Figure 3 (left) shows examples of fits to the impact-parameter distributions of D$^+$ and D$^{*+}$ mesons in the transverse-momentum intervals 3 < $p_T$ < 4 GeV/$c$ and 5 < $p_T$ < 6 GeV/$c$, respectively. For D$^+$ mesons, the candidates used in the impact-parameter fit were selected with the same criteria described in the previous section except for the cut on the D$^+$ impact parameter, which was not applied for this study. The prompt fraction, $f^{\text{prompt}}$, was obtained by integrating the functions obtained from the fit in the restricted impact-parameter range used in the analysis.

The prompt fraction estimated with the data-driven approach has systematic uncertainties due to i) the shape assumed for prompt D-meson, feed-down D-meson, and background impact-parameter distributions, ii) the uncertainty on the signal and background yields, and iii) the consistency of the procedure, evaluated with a Monte Carlo closure test. These uncertainties were estimated with the procedures described in Ref. [22]. The systematic uncertainty arising from the shape assumed for prompt D-meson, feed-down D-meson, and background impact parameter distributions is typically smaller than 2%. The systematic effect due to the uncertainty on the signal and background yields ranges from 1% to 5%, depending on $p_T$. Finally, a Monte Carlo closure test was carried out to verify the consistency of the procedure with simulated data by comparing the $f^{\text{prompt}}$ values recovered with the impact-parameter fit and the input ones: the difference, typically about 1%, was considered as a systematic uncertainty. The total systematic uncertainty on $f^{\text{prompt}}$ with the data-driven approach is about 2–3% for both D$^+$ and D$^{*+}$ mesons in the interval 3 < $p_T$ < 16 GeV/$c$ and about 5% in 2–3 GeV/$c$ and above 16 GeV/$c$.

The prompt fraction of D$^+$ and D$^{*+}$ mesons measured with this method is shown in Fig. 3 (right). The prompt fraction measured with the impact-parameter fits is compatible with the FONLL-based estimation within uncertainties.

### 3.3 Analysis without D-meson decay-vertex reconstruction

In order to extend the measurement of D-meson production to $p_T < 1$ GeV/$c$, a different analysis method, not based on geometrical selections on the displaced decay-vertex topology, was utilized for the two-body decay D$^0 \rightarrow K^- \pi^+$ (and its charge conjugate).

The D$^0$ yield was extracted in eight $p_T$ intervals in the range 0 < $p_T$ < 12 GeV/$c$ from an invariant-mass analysis of pairs of kaons and pions with opposite charge sign (UnLike Sign, ULS). D$^0$ candidates were defined from tracks with $|\eta| < 0.8$, $p_T > 0.4$ GeV/$c$, and passing the same quality and particle-identification criteria described above for the analyses with decay-vertex reconstruction. The resulting D$^0$ and $\bar{D}^0$ candidates were selected by applying the $p_T$-dependent fiducial acceptance cut $|\eta_{\text{lab}}| < \eta_{\text{fid}}(p_T)$ on their rapidity (same fiducial acceptance as for the analyses with decay-vertex reconstruction). No selections based on secondary-vertex displacement were applied because at very low $p_T$, the D-meson decay topology cannot be efficiently resolved due to the insufficient resolution of the track impact parameter and the small Lorentz boost. The resulting invariant-mass distribution of Kπ pairs in the transverse momentum intervals 0 < $p_T$ < 1 GeV/$c$ is shown in the top-left panel of Fig. 4.

Four different techniques were used to estimate the background distribution: (i) like-sign pairs; (ii) event
mixing; (iii) track rotation; and (iv) side-band fit. The like-sign (LS) method is based on Kπ combinations with same charge sign. In each \( p_T \) interval, the background on the ULS invariant-mass distribution was estimated from the LS ones as \( N_{K^+\pi^-} = 2 \cdot \sqrt{N_{K^+\pi^+} \cdot N_{K^-\pi^-}} \), where \( N_{K^+\pi^+} \) and \( N_{K^-\pi^-} \) are the number of like-sign Kπ pairs in a given invariant-mass interval. The event-mixing method estimates the uncorrelated background by pairing each kaon of a given event with all pions of other events having similar multiplicity and vertex position along the beam axis. In the track-rotation technique, for each \( D^0 \) (and \( \bar{D}^0 \)) candidate, up to nine combinatorial-background-like candidates were created by rotating the kaon track by different angles in the range between \( \frac{\pi}{2} \) and \( \frac{3\pi}{2} \) radians in azimuth. In the case of the event-mixing and track-rotation methods, the background is normalized to match the yield of Kπ pairs in the invariant-mass range 1.72–1.75 GeV/\( c^2 \). The invariant-mass distributions of background candidates estimated with these three methods (i–iii) are shown as lines in the top-left panel of Fig. 4. The background distribution is subtracted from the ULS Kπ invariant-mass distribution and the resulting distributions, which contain the \( D^0 \) signal and the remaining background, are shown in the other panels of Fig. 4. The \( D^0 \) raw yield (sum of particle and antiparticle contributions) was extracted via a fit to the background-subtracted invariant-mass distribution. The fit function is composed of a Gaussian term to describe the signal, a second-order polynomial function to model the remaining background and a term describing the contribution of signal candidates passing the selections with swapped mass hypotheses of the final state kaon and pion (reflections), whose invariant-mass distribution was taken from the simulation.

The fourth approach to the background treatment consists of a two-step fit to the ULS Kπ invariant-mass distribution. In the first step, the side bands of the \( D^0 \) peak (\(|M(K\pi) - M(D^0)| > 2.5 \sigma\), where \( \sigma \) is the Gaussian width of the \( D^0 \) peak from the simulation), were used to evaluate the background shape, which was modeled with a fourth-order polynomial for \( p_T < 2 \text{ GeV}/c \) and with a second-order polynomial for \( p_T > 2 \text{ GeV}/c \). In the second step, the invariant-mass distribution was fitted in the whole range, using a Gaussian function to model the signal and the polynomial function from the previous step to describe the background.

In the invariant-mass fits for all four methods, the width of the Gaussian was fixed to the value from the simulation, while the centroid was left as a free parameter of the fit and was found to be compatible, within uncertainties, with the PDG world-average value of the \( D^0 \) mass.

The raw-yield values from the four methods for the background subtraction were found to be consistent within 10% in all \( p_T \) intervals of the p–Pb data sample analysed. The arithmetic average of the four values was, therefore, computed and used in the calculation of the cross sections. The statistical uncertainties on these average raw-yield values were defined as the arithmetic average of the uncertainties from the four background-subtraction methods.

The acceptance and the efficiency were determined from the same Monte Carlo simulations used for the analyses with decay-vertex reconstruction. The calculation of the \( D^0 \) efficiency was performed utilizing \( p_T \) and event-multiplicity dependent weights, so as to match the D-meson \( p_T \) spectra predicted by FONLL calculations and the charged-particle multiplicity distributions measured at mid-rapidity. The resulting \( \text{Acc} \times \epsilon \) of prompt \( D^0 \) mesons is shown as a function of \( p_T \) in Fig. 5. Compared to the analysis with decay-vertex reconstruction, the efficiency is higher by a factor of about 20 at low \( p_T \) (3 at high \( p_T \)), has a less steep \( p_T \) dependence (the \( p_T \) dependence in the case of the \( \text{Acc} \times \epsilon \) in the analysis without decay-vertex reconstruction is mainly determined by the geometrical acceptance of the apparatus), and is the same for prompt \( D^0 \) and for \( D^0 \) from beauty-hadron decays.

The prompt contribution to the \( D^0 \)-meson raw yield, \( f_{\text{prompt}} \), was estimated with the same FONLL-based method used for the analysis with decay-vertex reconstruction as described above in Eq. 5. The resulting \( f_{\text{prompt}} \) values decrease with increasing \( p_T \) (from about 0.96 for \( p_T < 3 \text{ GeV}/c \) to about 0.9 in the interval \( 8 < p_T < 12 \text{ GeV}/c \)) and are larger than in the analysis with decay-vertex reconstruction, since the feed-down component is not enhanced by the selection criteria.
Figure 4: Invariant-mass distributions of $D^0 \rightarrow K^- \pi^+$ candidates (and charge conjugates) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $0 < p_T < 1$ GeV/c. The top-left panel displays the invariant-mass distribution of all ULS Kπ pairs together with the background distributions estimated with the LS, event-mixing and track-rotation techniques. The other panels show the invariant-mass distributions after subtraction of the background from the event-mixing (top-right), track-rotation (bottom-left) and LS (bottom-right) techniques. Fit functions are superimposed.

Figure 5: Product of acceptance and efficiency of $D^0 \rightarrow K^- \pi^+$ (and charge conjugates) in p–Pb collisions, for the analyses with and without topological selections.
4 Systematic uncertainties

Systematic uncertainties on the D-meson cross sections in p–Pb collisions were estimated considering the following sources: (i) extraction of the raw yield from the invariant-mass distributions; (ii) track reconstruction efficiency; (iii) D-meson selection efficiency; (iv) PID efficiency; (v) the shape of the $p_T$ spectrum generated for D mesons in the simulation; (vi) subtraction of the feed-down from beauty-hadron decays. In addition, the uncertainties on the branching ratios [27] and on the integrated luminosity were considered.

The systematic uncertainties on the raw yield extraction were evaluated for each D-meson species and in each $p_T$ interval by repeating the fits several times varying (i) the invariant-mass bin width, (ii) the lower and upper limits of the fit range, and (iii) the functional form of the background fit function. In addition, the same approach was used with a bin-counting method, in which the signal yield was obtained by integrating the invariant-mass distribution after subtracting the background estimated from a fit to the side-bands only. For $D^0$ mesons, an additional contribution due to signal reflections in the invariant-mass distribution was estimated by varying the ratio of the integral of the reflections over the integral of the signal and the shape of the templates used in the invariant-mass fits. The systematic uncertainty was defined as the R.M.S. of the distribution of the signal yields obtained from all these variations. It was verified that the raw yields extracted with the default fit settings used to compute the cross sections are in the range obtained from all these variations. The uncertainty ranges between 1% and 15% depending on the D-meson species and $p_T$ interval.

The systematic uncertainty on the track reconstruction efficiency was estimated by varying the track-quality selection criteria and by comparing the probability to match the tracks from the TPC to the ITS hits in data and simulation. The comparison of the matching efficiency in data and simulations was made after weighting the relative abundances of primary and secondary particles [36] in the simulation to match those in data, which were estimated via fits to the track impact-parameter distributions. The estimated uncertainty depends on the D-meson $p_T$ and it ranges from 2.5% to 4% for the two-body decay of $D^0$ mesons and from 3.7% to 5% for the three-body decays of $D^+$, $D^{*+}$, and $D_s^+$ mesons.

The uncertainty on $Acc \times \varepsilon$ originates from imperfections in the description of the D-meson kinematic and decay properties and of the detector resolutions and alignments in the simulation. For the analyses with decay-vertex reconstruction, it was estimated by comparing the corrected yields obtained by repeating the analysis with different sets of selection criteria, resulting in a significant modification the efficiencies, raw yield and background values. The assigned uncertainty for non-strange D mesons is 3% in most of the $p_T$ intervals and it increases to 12% at low $p_T$, where the efficiencies are low and vary steeply with $p_T$, because of the tighter geometrical selections. A larger uncertainty (ranging from 7% at high $p_T$ to 14% at low $p_T$) was estimated for $D^+_s$ mesons, for which more stringent selection criteria were utilized in the analysis as compared to non-strange D mesons. In the case of the $D^0$-meson analysis without decay-vertex reconstruction, the stability of the corrected yield was tested against variations of the single-track $p_T$ selection and no systematic effect was observed.

To estimate the uncertainty on the PID selection efficiency, for the three non-strange D-meson species the analysis was repeated without PID selection. The resulting cross sections for $D^0$ and $D^+$ were found to be compatible with those obtained with the PID selection and therefore no systematic uncertainty was assigned. For $D^{*+}$ mesons, that use a 2$\sigma$ PID selection, a 2% systematic uncertainty was assigned from the difference of the cross sections evaluated with and without PID selection. For $D^+_s$ mesons, the lower signal yield and the larger combinatorial background prevented a signal estimation without particle identification. In this case, a 3$\sigma$ PID selection, looser with respect to the PID strategy adopted in the analysis, was used to estimate the systematic uncertainty, which was found to be 2% at low $p_T$ and negligible for $p_T > 12$ GeV/c. Also for the $D^0$-meson reconstruction without decay-vertex reconstruction, an analysis without applying PID selections could not be performed due to the insufficient statistical significance of
the signal. It was verified that the cross sections obtained with more stringent PID criteria were compatible with those with the default selection. Based on this result and on the fact that the PID selections are the same used in the D\(^0\) analysis with decay-vertex reconstruction, for which no systematic effect was observed, no uncertainty due to PID was assigned.

In addition, the Acc \( \times \) \( \epsilon \) values could also be sensitive to the generated shapes of the D-meson transverse momentum distributions and of the multiplicity of particles produced in the collision. The systematic uncertainty due to the generated D-meson \( p_T \) shape was estimated by considering different input distributions (PYTHIA, FONLL) and was found to be negligible. The effect of possible differences between the charged-multiplicity distributions in data and multiplicity-reweighted simulations was also found to be negligible.

The systematic uncertainty on the subtraction of feed-down from B decays (i.e. the calculation of the \( f_{\text{prompt}} \) fraction) was estimated by varying the FONLL parameters (b-quark mass, factorisation and renormalisation scales) as prescribed in [28] and by varying the hypothesis on the nuclear modification factor of feed-down D mesons in the range \( 0.9 < \frac{R_{\text{feed-down}}}{R_{\text{prompt}}} < 1.3 \), as explained in Sec. 3. It ranges between \( \pm 2\% \) and \( \pm 5\% \) depending on the D-meson species and \( p_T \) interval.

The \( p_T \)-differential cross sections have a systematic uncertainty on the overall normalisation induced by the uncertainties on the integrated luminosity (3.7\% [26]) and on the branching ratios of the considered D-meson decays [27].

The systematic uncertainties on the \( R_{\text{ppb}} \) measurement include those on the measured D-meson cross sections and those on the proton–proton cross section reference. For the \( Q_{\text{ppb}} \) measurement, the systematic uncertainties are those on the measured D-meson cross sections, those on the proton–proton cross section reference, and the uncertainties on the average nuclear overlap function. The systematic uncertainties on the \( Q_{\text{CP}} \) include those on the measured D-meson cross sections and the uncertainties on the average nuclear overlap functions.

The uncertainty on the pp reference used for the calculation of \( R_{\text{ppb}} \) and \( Q_{\text{ppb}} \) has two contributions. The first is the systematic uncertainty on the measured \( p_T \)-differential D-meson cross section at \( \sqrt{s} = 7 \) TeV. The second contribution is the scaling to \( \sqrt{s} = 5.02 \) TeV, which will be discussed in Section 5.

In the calculation of the nuclear modification factor, the systematic uncertainty on the feed-down subtraction deriving from the variation of the parameters of the FONLL calculation was considered to be correlated in the p–Pb and pp measurements, while all the other sources of systematic uncertainties were treated as uncorrelated.

5 Proton–proton reference for \( R_{\text{ppb}} \)

The \( p_T \)-differential cross section of prompt D mesons in pp collisions at \( \sqrt{s} = 5.02 \) TeV, used as reference for the nuclear modification factor, was obtained by applying a \( p_T \)- and D-species-dependent scaling factor to the cross sections measured at \( \sqrt{s} = 7 \) TeV [34]. These measurements reach up to \( p_T = 36 \) GeV/c for D\(^0\), 24 GeV/c for D\(^+\) and D\(^{++}\), and 12 GeV/c for D\(^+_s\) mesons. The scaling factor was defined as the ratio of the cross sections at 5.02 TeV (in \( -0.96 < y_{\text{cms}} < 0.04 \)) and 7 TeV (in \( |y_{\text{cms}}| < 0.5 \)) from the FONLL calculation [28], as described in Ref. 37. The systematic uncertainty on the scaling factor was determined by consistently varying the charm-quark mass, the values of the factorisation and renormalisation scales, and the CTEQ6.6 PDF uncertainties in the FONLL calculations at the two energies [37]. The uncertainty decreases with increasing \( p_T \), with values of, e.g., \( +15\% \) for \( 0 < p_T < 1 \) GeV/c, \( -13\% \) for \( 3 < p_T < 4 \) GeV/c and \( \pm 2\% \) for \( p_T > 12 \) GeV/c. For the intervals \( 24 < p_T < 36 \) GeV/c for D\(^+\) and D\(^{++}\), and \( 12 < p_T < 24 \) GeV/c for D\(^+_s\) mesons, the FONLL calculation at \( \sqrt{s} = 5.02 \) TeV [28] was used as a reference by scaling the values of each meson species by the ratio of data/FONLL in the interval \( p_T > 5 \) GeV/c (2 GeV/c for D\(^+_s\)), which has a value of about 1.4. This procedure is described
6 Results

6.1 $p_T$-differential cross sections

Figure 6: $p_T$-differential production cross section of $D^0$ mesons with $-0.96 < y_{\text{cms}} < 0.04$ in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Left: comparison of prompt and inclusive $D^0$ mesons (the latter including also $D^0$ mesons from beauty-hadron decays) from the analysis without decay-vertex reconstruction. Right: comparison between the prompt $D^0$ cross sections measured with and without decay-vertex reconstruction. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively.

Figure 6 shows the $p_T$-differential production cross section for $D^0$ mesons with $-0.96 < y_{\text{cms}} < 0.04$ in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the left-hand panel of the figure, the cross section obtained from the analysis without decay-vertex reconstruction is shown for inclusive and for prompt $D^0$ mesons, while in the right-hand panel the cross section for prompt $D^0$ mesons is compared with that obtained with decay-vertex reconstruction. The results are consistent within statistical uncertainties, with only two points with deviations between 2 and 3 standard deviations.

The most precise measurement of the prompt $D^0$ production cross section is obtained using the results of the analysis without decay-vertex reconstruction in the interval $0 < p_T < 1$ GeV/$c$ and those of the analysis with decay-vertex reconstruction for $p_T > 1$ GeV/$c$. The resulting cross section is shown in the top-left panel of Fig. 7.

The $p_T$-differential cross sections for the other three D-meson species ($D^+$, $D^{**+}$ and $D^{++}$) are shown in the other panels of Fig. 7. In the same figure, the cross sections in p–Pb collisions are compared with the corresponding pp reference cross sections, scaled by the Pb mass number $A = 208$.

In Fig. 8 the preliminary measurements of the $D^0$, $D^+$, $D^{**+}$ and $D^{++}$ cross sections with the 2016 p–Pb data sample ($L_{\text{int}} = 292 \pm 10.8 \mu b^{-1}$) are compared with the published measurements that used the 2013 data sample ($L_{\text{int}} = 48.6 \pm 1.6 \mu b^{-1}$) \cite{20, 21}. The new results are compatible with the published ones and have significantly lower uncertainties and extended $p_T$ reach.

The ratios of the $p_T$-differential cross sections of the D-meson species were calculated taking into account the correlation of the systematic uncertainties induced by the corrections for tracking efficiency and feed-down from beauty decays. In Fig. 9 these ratios are shown together with those for pp collisions

in Ref. \cite{38}.
Figure 7: $p_T$-differential production cross sections of prompt $D^0$ (top-left), $D^+$ (top-right), $D^{++}$ (bottom-left) and $D_s^+$ (bottom-right) mesons with $-0.96 < y_{\text{CMS}} < 0.04$ in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, compared with the respective pp reference cross sections scaled by the Pb mass number $A = 208$. For the $D^0$ meson, the results in $0 < p_T < 1$ GeV/$c$ are obtained from the analysis without decay-vertex reconstruction, while those in $1 < p_T < 36$ GeV/$c$ are taken from the analysis with decay-vertex reconstruction. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The systematic uncertainty of the feed-down correction is shown separately as filled shaded boxes.
**Figure 8**: $p_T$-differential production cross sections of prompt $D^0$ with (top-left) and without (top-right) decay-vertex reconstruction, $D^+$ (mid-right), $D^{++}$ (mid-left) and $D_s^+$ (bottom) mesons with $-0.96 < y_{\text{cms}} < 0.04$ in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using the 2016 p–Pb data sample compared with the measurements that used the 2013 data sample [20–22]. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The systematic uncertainty of the feed-down correction is shown separately as filled shaded boxes.
Figure 9: Ratios of prompt D-meson production cross sections as a function of $p_T$ and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($-0.96 < y_{cm} < 0.04$). The results are compared with those of pp collisions at $\sqrt{s} = 7$ TeV [34]. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively.

at $\sqrt{s} = 7$ TeV [34]: within uncertainties, the relative abundances of the four species are unmodified in p–Pb with respect to pp collisions.

6.2 $p_T$-differential nuclear modification factor

The nuclear modification factor was computed using Eq. 1. The systematic uncertainties of the p–Pb and pp measurements were considered as independent and propagated quadratically, except for the uncertainty on the feed-down correction, which was recalculated for the ratio of cross sections by consistently varying the FONLL calculation parameters in the numerator and in the denominator.

The nuclear modification factor of prompt $D^0$ mesons in the interval $0 < p_T < 12$ GeV/c was also computed using the cross sections in pp [22, 34] and p–Pb collisions resulting from the corresponding analyses without decay-vertex reconstruction. In Fig. 10 it is compared with the result obtained from the analysis with decay-vertex reconstruction, which covers the interval $1 < p_T < 36$ GeV/c. The two measurements are consistent within statistical uncertainties.

Figure 11 shows the nuclear modification factors $R_{pPb}$ of prompt $D^0$, $D^+$ and $D^{*+}$ mesons in the left-hand panel and their average, along with the $R_{pPb}$ of $D^+_s$ mesons, in the right-hand panel. The average of the nuclear modification factors of the three non-strange D-meson species was calculated using the inverse of the relative statistical uncertainties as weights. The systematic uncertainty of the average was calculated by propagating the uncertainties through the weighted average, where the contributions from tracking efficiency, beauty feed-down correction, and scaling of the pp reference were considered as fully correlated among the three species. The $R_{pPb}$ is compatible with unity over the $p_T$ interval covered by
Figure 10: Comparison of the nuclear modification factors of prompt $D^0$ mesons as obtained in the analysis with decay-vertex reconstruction [20] and in the analysis without decay-vertex reconstruction. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The black-filled box at $R_{pPb} = 1$ represents the normalisation uncertainty.

Figure 12 shows the combined measurement of the nuclear modification factor of prompt (non-strange) $D$ mesons, as obtained by using the $D^0$ measurement without decay-vertex reconstruction for the interval $0 < p_T < 1$ GeV/$c$ and the average of the measurements for $D^0$, $D^+$ and $D^{++}$ mesons in the interval $1 < p_T < 24$ GeV/$c$. For $24 < p_T < 36$ GeV/$c$ the $D^0$ measurement was used as is the only meson for which the pp reference could be obtained without transverse momentum extrapolation. The data are compared with theoretical results. In the left-hand panel of this figure, four models including only CNM effects are displayed: a calculation based on the Color Glass Condensate formalism [12, 39], a FONLL calculation [28] with CTEQ6M PDFs [40] and EPPS16 NLO nuclear modification [7], a LO pQCD calculation with intrinsic $k_T$ broadening, nuclear shadowing and energy loss of the charm quarks in cold nuclear matter (Vitev et al.) [41], and a higher-twist calculation based on incoherent multiple scatterings (Kang et al.) [42]. The three former calculations describe the data within uncertainties in the entire $p_T$ range, although for the CGC calculation the compatibility with the data in 3–12 GeV/$c$ is at the limit of the uncertainties of the data and of the calculations. The calculation by Kang et al., which has a different trend with respect to the others, is disfavoured by the data for $p_T < 3–4$ GeV/$c$. CNM effects are expected to be largest for small $p_T$, where, in addition, the predictions of the different theoretical approaches differ. The statistical uncertainty of the present measurement for the lowest $p_T$ interval is about 30% and does not allow us to draw a conclusion. However, the analysis technique without decay-vertex reconstruction, applied on future larger pp data samples, should provide access to the physics-rich range down to $p_T = 0$.

In the right-hand panel of Fig. 12, the data are compared with the results of two transport model calculations, Duke [18] and POWLANG [19], both of them assuming that a Quark–Gluon Plasma is formed in p–Pb collisions. Both models are based on the Langevin approach for the transport of heavy quarks through an expanding deconfined medium described by relativistic viscous hydrodynamics. The Duke model includes both collisional and radiative energy loss. The POWLANG model considers only collisional processes with two choices for the transport coefficients, based on hard-thermal-loop (HTL) and lattice-QCD (lQCD) calculations. In both the Duke and POWLANG results the D-meson nuclear
Figure 11: Nuclear modification factor $R_{pPb}$ of prompt D mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Left: $R_{pPb}$ of $D^0$, $D^+$ and $D^{++}$ mesons. Right: average $R_{pPb}$ of the three non-strange D-meson species and $R_{pPb}$ of $D_s^+$ mesons. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The black-filled box at $R_{pPb} = 1$ represents the normalisation uncertainty.

The nuclear modification factor shows a structure with a maximum at $p_T \approx 2.5$ GeV/$c$, possibly followed by a moderate ($< 20–30\%$) suppression at higher $p_T$, resulting from the interplay of CNM effects and interactions of charm quarks with the radially expanding medium. The trend predicted by these models is disfavoured by the data, which in particular disfavour a suppression larger than 10–15\% in the interval $3 < p_T < 12$ GeV/$c$.

6.3 $p_T$- and centrality-dependent nuclear modification factor at $\sqrt{s_{NN}} = 5.02$ TeV

The nuclear modification factor of prompt $D^0$ was also computed in centrality intervals defined by the zero-degree energy (ZNA), $Q_{pPb}$, similarly to what had been performed in Ref.\[21\] using Eq.\[2\] As for the $R_{pPb}$ calculation, for $Q_{pPb}$ the systematic uncertainties of the p–Pb and pp measurements were considered as independent and propagated quadratically, with the exception of the uncertainty on the feed-down correction; the latter was recalculated for the ratio of cross sections by consistently varying the FONLL calculation parameters in the numerator and in the denominator. The hypothesis used for the variation of the nuclear modification factor of D mesons from beauty decays was $0.9 < R^{\text{feed-down}}_{pPb}/R^{\text{prompt}}_{pPb} < 1.3$ for the 0–10\% centrality class and $0.9 < R^{\text{feed-down}}_{pPb}/R^{\text{prompt}}_{pPb} < 1.1$ for the 60–100\% centrality class.

Figure 13 (left) presents the $Q_{pPb}$ results for $D^0$ 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 $Q_{CP}$ observable, defined in Eq.\[3\] was used to compare with better precision the $p_T$-differential yields of the $D^0$ meson in central and peripheral p–Pb collisions. Figure 13 (right) shows $Q_{CP}$, as obtained using 0–10\% as central class and 60–100\% as peripheral class. $Q_{CP}$ is independent of the pp cross section and uses the p–Pb measured yields in peripheral events as a reference. Therefore, it has reduced systematic uncertainties with respect to $Q_{pPb}$, because the contributions from the track reconstruction, selection and PID efficiency cancel in the ratio. The systematic uncertainties on the signal yield extraction were estimated by applying the modified fit procedures described in section\[4\] on the invariant-mass distributions in 0–10\% and 60–100\% consistently. The treatment for the feed-down correction uncertainty is analo-
Figure 12: Nuclear modification factor $R_{pPb}$ of prompt D mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV: average $R_{pPb}$ of $D^0$, $D^+$ and $D^{*+}$ mesons in the interval $1 < p_T < 24$ GeV/c [20], shown together with the $D^0$ $R_{pPb}$ in $0 < p_T < 1$ GeV/c. In the left-hand panel, the data are compared with results of theoretical calculations including only CNM effects: CGC [39], FONLL [28] with EPPS16 nPDFs [7], a LO pQCD calculation with CNM effects (Vitev et al.) [41] and a calculation based on incoherent multiple scatterings (Kang et al.) [42]. In the right-hand panel, the results of the Duke [18] and POWLANG [19] transport models are compared with the measured D-meson $R_{pPb}$. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The black-filled box at $R_{pPb} = 1$ represents the normalisation uncertainty.

Figure 13: Left: $D^0$ meson nuclear modification factors as a function of $p_T$ in the 0–10%, 60–100% centrality classes. Right: $D^0$ central-to-peripheral nuclear modification factor. The vertical error bars and the empty boxes represent the statistical and systematic uncertainties, respectively. The colour-filled boxes at $Q_{pPb}(Q_{CP}) = 1$ represent the normalisation uncertainties.
gous to that for the $R_{pPb}$ and $Q_{pPb}$ calculations, but the contributions from the hypothesis on the nuclear modification factor of D mesons from B decays were considered independent in 0–10% and 60–100% and added in quadrature. The resulting $Q_{CP}$ increases in the interval 1–4 GeV/$c$, reaching values of about 1.25 and then tends to decrease in the interval 7–24 GeV/$c$. The average value of the $D^{0}$-meson $Q_{CP}$ in the interval $3 < p_{T} < 8$ GeV/$c$ is larger than unity by 1.7 standard deviations (of the statistical and systematic uncertainty).

7 Summary

The production cross sections of the prompt charmed mesons $D^{0}$, $D^{+}$, $D^{*+}$ and $D_{s}^{+}$ in p–Pb collisions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV were measured as a function of $p_{T}$ in the rapidity interval $-0.96 < y_{\text{cms}} < 0.04$ exploiting the data sample collected in 2016 ($L_{\text{int}} = 292 \pm 10.8 \mu b^{-1}$). The $p_{T}$-differential production cross sections were reported in the transverse momentum range $0 < p_{T} < 36$ GeV/$c$ for $D^{0}$ mesons, $1 < p_{T} < 36$ GeV/$c$ for $D^{+}$ and $D^{*+}$ mesons, and $2 < p_{T} < 24$ GeV/$c$ for $D_{s}^{+}$ mesons. The ratios of the cross sections of the four D-meson species were determined as a function of $p_{T}$ and were found to be compatible with those measured in pp collisions at $\sqrt{s} = 7$ TeV in the rapidity interval $|y_{\text{cms}}| < 0.5$.

The $p_{T}$-differential nuclear modification factor $R_{pPb}$ was found to be compatible with unity for $0 < p_{T} < 36$ GeV/$c$. The results are described within uncertainties by theoretical calculations that include initial-state effects, which are expected to be small for $p_{T} > 2$ GeV/$c$ but significant for $p_{T}$ close to 0, where the predictions of the different theoretical approaches differ. The observed $R_{pPb}$ is also described by transport calculations assuming the formation of a deconfined medium in p–Pb collisions, even though the data seem to disfavour a suppression larger than 10–15% in the interval $3 < p_{T} < 12$ GeV/$c$. The current precision of the measurement does not allow us to draw conclusions on the role of the different CNM effects and on the possible presence of additional hot-medium effects.

The centrality dependence of the D-meson yields was also studied. The $D^{0}$-meson $Q_{pPb}$ measurements are consistent with unity within the uncertainties in the measured $p_{T}$ interval. The $D^{0}$-meson $Q_{CP}$ average value in the $3 < p_{T} < 8$ GeV/$c$ interval is larger than unity by 1.7 standard deviations (of the statistical and systematic uncertainty).

References


D-meson production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV


