Study of prompt D$^{0}$ meson production in $p$Pb collisions at $\sqrt{s_{\mathrm{NN}}}=5$ TeV

Citation for published version:

Digital Object Identifier (DOI):
10.1007/JHEP10(2017)090

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Journal of High Energy Physics

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Study of prompt $D^0$ meson production in $p$Pb collisions at $\sqrt{s_{NN}} = 5$ TeV

The LHCb collaboration

E-mail: Giulia.Manca@cern.ch

ABSTRACT: Production of prompt $D^0$ mesons is studied in proton-lead and lead-proton collisions recorded at the LHCb detector at the LHC. The data sample corresponds to an integrated luminosity of $1.58\pm0.02\text{nb}^{-1}$ recorded at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5$ TeV. Measurements of the differential cross-section, the forward-backward production ratio and the nuclear modification factor are reported using $D^0$ candidates with transverse momenta less than 10 GeV/c and rapidities in the ranges $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$ in the nucleon-nucleon centre-of-mass system.

KEYWORDS: Charm physics, Heavy Ion Experiments, Heavy-ion collision, Particle and resonance production

ArXiv ePrint: 1707.02750
1 Introduction

Charm hadrons produced in hadronic and nuclear collisions are excellent probes to study nuclear matter in extreme conditions. The differential cross-sections of $c$-quark production in $pp$ or $p\bar{p}$ collisions have been calculated based on perturbative quantum chromodynamics (QCD) and collinear or $k_T$ factorisation [1-6]. These phenomenological models [7] are also able to predict the differential cross-section of $c$-quark production including most of the commonly assumed “cold nuclear matter” (CNM) effects in nuclear collisions, where CNM effects related to the parton flux differences and other effects come into play. Since heavy quarks are produced in hard scattering (with momentum transfer squared $Q^2 \gtrsim 2m_c$) typically at a short time scale, they are ideal to examine hot nuclear matter, the so-called “quark-gluon plasma” (QGP), by studying how they traverse this medium and interact with it right after their formation.

These studies require a thorough understanding of the CNM effects, which can be investigated in systems where the formation of QGP is not expected. In addition, a precise quantification of CNM effects would significantly improve the understanding of charmonium and open-charm production by confirming or discarding the possibility that the suppression pattern in the production of quarkonium states, like $J/\psi$, at the SPS, RHIC and LHC is due to QGP formation [7].

The study of CNM effects is best performed in collisions of protons with heavy nuclei like lead, where the most relevant CNM effects, such as nuclear modification of the parton densities [8, 9] and in-medium energy loss [10] in initial- and final-state radiation [11, 12],
are more evident. Phenomenologically, collinear parton distributions are often used to
describe the nuclear modification of the parton flux in the nucleus. The modification with
respect to the free nucleon depends on the parton fractional longitudinal momentum \(x\),
\(Q^2\) and the atomic mass number of the nucleus \(A\) \cite{13, 14}. In the low-\(x\) region, down to
\(x \approx 10^{-5} \sim 10^{-6}\), which is accessible at LHC energies at forward rapidity, a possible onset of
gluon saturation may occur \cite{15–19}. Its effect can be quantified by studying production of
\(D^0\) mesons at low transverse momentum \(p_T\) \cite{20}, ideally down to zero \(p_T\). The in-medium
energy loss occurs when the partons lose energy in the cold medium through both initial-
and final-state radiation.

CNM effects have been investigated in detail at the RHIC collider in \(dAu\) collisions \cite{7, 21} at a nucleon-nucleon centre-of-mass energy of \(\sqrt{s_{\text{NN}}} = 200\text{ GeV}\). Recently, CNM
effects were measured in \(p\Pb\) collisions at the LHC for quarkonium and heavy flavour
production \cite{22–39}. The ALICE experiment studied \(D\) meson productions in \(p\Pb\) collisions
\cite{25, 27, 31} at \(\sqrt{s_{\text{NN}}} = 5\text{ TeV}\) in the region \(-0.96 < y^* < 0.04\), where \(y^*\) is the
rapidity of the \(D\) meson defined in the centre-of-mass system of the colliding nucleons.
Their results suggest that the suppression observed in \(\Pb\Pb\) collisions is due to hot nuclear
matter effects, i.e. QGP formation. Results on leptons from semileptonic heavy-flavour
decays at various rapidities are also available \cite{40–42}.

In this paper the measurement of the cross-section and of the nuclear modification
factors of “prompt” \(D^0\) mesons, i.e. those directly produced in proton-lead collisions and
not coming from decays of \(b\)-hadrons, is presented. The measurement is performed at
\(\sqrt{s_{\text{NN}}} = 5\text{ TeV}\) with the LHCb \cite{43} detector at the LHC. Depending on the direction of the
proton and \(208\Pb\) beams and due to the different energies per nucleon in the two beams, the
LHCb detector covers two different acceptance regions in the nucleon-nucleon rest frame,

\begin{itemize}
  \item \(1.5 < y^* < 4.0\), denoted as “forward” beam configuration,
  \item \(-5.0 < y^* < -2.5\), denoted as “backward” beam configuration,
\end{itemize}

where the rapidity \(y^*\) is defined with respect to the direction of the proton beam. The
measurement is performed in the range of \(D^0\) transverse momentum \(p_T < 10\text{ GeV}/c\), in
both backward and forward collisions.

2 Detector and data samples

The LHCb detector \cite{43, 44} is a single-arm forward spectrometer covering the
pseudorapidity range \(2 < \eta < 5\), designed for the study of particles containing \(b\) or \(c\)
quarks. The detector includes a high-precision tracking system consisting of a silicon-strip
vertex detector surrounding the \(pp\) interaction region (VELO), a large-area silicon-strip
detector (TT) located upstream of a dipole magnet with a bending power of about 4 Tm,
and three stations of silicon-strip detectors and straw drift tubes (OT) placed downstream
of the magnet. The tracking system provides a measurement of momentum, \(p\), of charged
particles with a relative uncertainty that varies from 0.5\% at low momentum to 1.0\% at
200 GeV\(c\). The minimum distance of a track to a primary vertex (PV), the impact parameter,
is measured with a resolution of \((15 + 29/p_T)\mu\text{m}\), where \(p_T\) is the component of
the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The online event selection is performed by a trigger [45], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

The data sample used in this analysis consists of $p$Pb collisions collected in early 2013 at $\sqrt{s_{NN}} = 5$ TeV, corresponding to integrated luminosities of $(1.06 \pm 0.02)$ nb$^{-1}$ and $(0.52 \pm 0.01)$ nb$^{-1}$ for the forward and backward colliding beam configurations, respectively. The luminosity has been determined using the same method as in the LHCb measurement of $J/\psi$ production in $p$Pb collisions [46], with a precision of about 2%. The instantaneous luminosity during the period of data taking was around $5 \times 10^{27}$ cm$^{-2}$ s$^{-1}$, which led to an event rate that was three orders of magnitude lower than in nominal LHCb $pp$ operation. Therefore, the hardware trigger simply rejected empty events, while the next level software trigger accepted all events with at least one track in the VELO.

For the analyses presented below, simulated samples of $pp$ collisions at 8 TeV are used to determine geometrical acceptance and reconstruction efficiencies. Effects due to the different track multiplicity distributions in the $pp$ and $p$Pb collision data and the effects of the asymmetric beam energies in $p$Pb collisions are taken into account as described later. In the simulation, $pp$ collisions are generated using PYTHIA [47, 48] with a specific LHCb configuration [49]. Decays of hadronic particles are described by EvtGen [50], in which final-state radiation is generated using PHOTOS [51]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [52–54].

3 Cross-section determination

The double-differential cross-section for prompt $D^0$ production in a given $(p_T, y^*)$ kinematic bin is defined as

$$\frac{d^2\sigma}{dp_T dy^*} = \frac{N(D^0 \rightarrow K^{\pm} \pi^{\mp})}{\mathcal{L} \times \varepsilon_{\text{tot}} \times B(D^0 \rightarrow K^{\pm} \pi^{\mp}) \times \Delta p_T \times \Delta y^*},$$

where $N(D^0 \rightarrow K^{\pm} \pi^{\mp})$ is the number of prompt $D^0$ signal candidates reconstructed through the $D^0 \rightarrow K^{\pm} \pi^{\mp}$ decay channels, $\varepsilon_{\text{tot}}$ is the total $D^0$ detection efficiency, $\mathcal{L}$ is the integrated luminosity, $B(D^0 \rightarrow K^{\pm} \pi^{\mp}) = (3.94 \pm 0.04)\%$ is the sum of the branching fractions of the decays $D^0 \rightarrow K^{-} \pi^{+}$ and $D^0 \rightarrow K^{+} \pi^{-}$ [55], $\Delta p_T = 1$ GeV/c is the bin width of the $D^0$ transverse momentum, and $\Delta y^* = 0.5$ is the bin width of the $D^0$ rapidity. The rapidity $y^*$ is defined in the nucleon-nucleon centre-of-mass frame, where the positive direction is that of the proton beam. Throughout the analysis, the measurements are for the sum of $D^0$ and $\bar{D}^0$ mesons. The measurement is performed in the $D^0$ kinematic re-

\footnote{Charge conjugation is implied throughout this document if not otherwise specified.}
gion defined by $p_T < 10 \text{ GeV} / c$ and rapidities $1.5 < y^* < 4.0$ for the forward sample and $-5.0 < y^* < -2.5$ for the backward sample.

The total cross-section over a specific kinematic range is determined by integration of the double-differential cross-section. The nuclear modification factor, $R_{p\text{Pb}}$, is the ratio of the $D^0$ production cross-section in forward or backward collisions to that in $pp$ at the same nucleon-nucleon centre-of-mass energy $\sqrt{s_{NN}}$

\begin{equation}
R_{p\text{Pb}}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}(p_T, y^*)}{d p_T d y^*},
\end{equation}

where $A=208$ is the atomic mass number of the lead nucleus. The forward-backward production ratio, $R_{\text{FB}}$, is defined as

\begin{equation}
R_{\text{FB}}(p_T, y^*) \equiv \frac{d^2\sigma_{p\text{Pb}}(p_T, +|y^*|)}{d^2\sigma_{\text{Pb}}(p_T, -|y^*|)} / d p_T d y^*,
\end{equation}

where $\sigma_{p\text{Pb}}$ and $\sigma_{\text{Pb}}$ indicate the cross-sections in the forward and backward configurations respectively, measured in a common rapidity range. The $D^0$ candidates are selected according to the same requirements as used in the $D^0$ production cross-section measurements in $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$ [56] and $\sqrt{s} = 13 \text{ TeV}$ [57]. The kaon and pion tracks from the $D^0$ candidate and the vertex they form are both required to be of good quality. The requirements set on particle identification (PID) criteria are tighter than in $pp$ collisions to increase the signal-over-background ratio given the high detector occupancy observed in $p\text{Pb}$ collisions.

The signal yield is determined from an extended unbinned maximum likelihood fit to the distribution of the invariant mass $M(K^+\pi^\pm)$. The fraction of nonprompt $D^0$ mesons originating from $b$-hadron decays, called $D^0$-from-$b$ in the following, is determined from the log10($\chi^2_{IP}(D^0)$) distribution, where $\chi^2_{IP}(D^0)$ is defined as the difference in vertex-fit $\chi^2$ of a given PV computed with and without the $D^0$ meson candidate [56, 57]. On average,
prompt $D^0$ mesons have much smaller $\chi^2_{IP}(D^0)$ values than $D^0$-from-$b$. The fit is performed in two steps. First, the invariant mass distributions are fitted to determine the $D^0$ meson inclusive yield and the number of background candidates, then the $\log_{10}(\chi^2_{IP}(D^0))$ fit is performed for candidates with mass within $\pm 20\text{MeV}/c^2$ around the fitted value of the $D^0$ mass. In the $\log_{10}(\chi^2_{IP}(D^0))$ fit, the number of background candidates is constrained to the value obtained from the invariant mass fit, scaled to the selected mass range.

The distribution of $\log_{10}(\chi^2_{IP}(D^0))$ is shown in the right-hand plots of figures 1 and 2 for the forward and backward samples, respectively. The signal shape in the $M(K^+\pi^\pm)$ distributions is described by a Crystal Ball (CB) function [58] plus a Gaussian. The mean is the same for both functions, and the ratios of widths and tail parameters are fixed following simulation studies, as in previous LHCb analyses [56, 57]. The width, mean, and signal yields are left free to vary. The background is described by a linear function. The candidates are fitted in the range 1792–1942 MeV/$c^2$. The invariant mass distributions in the inclusive forward and backward samples are shown in the left-hand plots of figures 1 and 2 respectively.

The fits to the invariant mass and $\log_{10}(\chi^2_{IP}(D^0))$ distributions are performed independently in each bin of $(p_T, y^*)$ of the $D^0$ meson. The contribution of the $D^0$-from-$b$ component increases with transverse momentum up to 10%. The $\log_{10}(\chi^2_{IP}(D^0))$ shapes for the prompt $D^0$ meson signal candidates are estimated using the simulation and modelled with a modified Gaussian function

$$f(x; \mu, \sigma, \epsilon, \rho_L, \rho_R) = \begin{cases} \frac{e^{\frac{-(x-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} & x < \mu - (\rho_L\sigma(1-\epsilon)), \\ e^{-\frac{-(x-\mu)^2}{\sigma^2(1-\epsilon)}} & \mu - (\rho_L\sigma(1-\epsilon)) \leq x < \mu, \\ e^{-\frac{-(x-\mu)^2}{\sigma^2(1+\epsilon)}} & \mu \leq x < \mu + (\rho_R\sigma(1+\epsilon)), \\ e^{\frac{-(x-\mu)^2}{\rho_R^2\sigma^2(1+\epsilon)^2}} \frac{e^{\frac{-(x-\mu)^2}{\rho_R^2\sigma^2(1+\epsilon)^2}}}{\rho_R^2\sigma^2(1+\epsilon)^2} & x \geq \mu + (\rho_R\sigma(1+\epsilon)), \\ \end{cases}$$

(3.4)

where the values of $\epsilon$, $\rho_L$ and $\rho_R$ are fixed to the values obtained in the simulation and $\mu$
Table 1. Summary of systematic and statistical uncertainties on the cross-section. The ranges indicate the variations between bins, with the uncertainty on average increasing with rapidity and momentum.

and $\sigma$ are free parameters. The $\log_{10}(\chi^2_{IP}(D^0))$ distribution for the $D^0$-from-$b$ component is described by a Gaussian function, following previous analyses [56, 57]. The shape of the combinatorial background is estimated using the distribution of candidates with mass in the ranges 1797–1827 MeV/c$^2$ and 1907–1937 MeV/c$^2$, i.e. between 40 and 70 MeV/c$^2$ away from the observed $D^0$ meson mass.

The total efficiency $\varepsilon_{\text{tot}}$ in eq. (3.1) includes the effects of geometrical acceptance and the efficiencies of the trigger, of the reconstruction and of the PID criteria used in the analysis. The analysis uses a minimum activity trigger, whose efficiency for events containing a $D^0$ meson is found to be 100%. The geometrical acceptance and reconstruction efficiencies are estimated using $pp$ simulated samples, validated with data. The difference between the distributions of the track multiplicity in the $p$Pb and $pp$ collisions is accounted for by studying the efficiency in bins of the track multiplicity, and weighting the efficiency according to the multiplicity distributions seen in $p$Pb and Pb$\bar{p}$ data. The related systematic uncertainties are discussed in section 4. The PID efficiency is estimated using a calibration sample of $D^0$ meson decays selected in data without PID requirements [44], and collected in the same period as the $p$Pb sample used for the analysis. The PID selection efficiency is calculated by using the $K^\pm$ and $\pi^\pm$ single-track efficiencies from calibration data, and averaging them according to the kinematic distributions observed in the simulation in each $D^0 (p_T, y^*)$ bin.

4 Systematic uncertainties

The systematic uncertainties affecting the cross-sections are listed in table 1. They are evaluated separately for the backward and forward samples unless otherwise specified. The systematic uncertainty associated to the determination of the signal yield has contributions
from the signal and background models. The uncertainty associated to the modelling of the signal is studied by using alternative models of single or sum of two Gaussian functions to fit the invariant mass in the forward and backward samples. A variation of the parameters which are fixed in the default model, within the ranges indicated by the simulation, is also explored. The largest difference between the nominal and the alternative fits is taken as the uncertainty on the method, which results in a bin-dependent uncertainty, not exceeding 5%. The effect due to background modelling in the invariant mass fit is studied by using an exponential as an alternative to the linear function. This uncertainty is found to be negligible. For the fit to the $\log_{10}(\chi^2_{IP}(D^0))$ distribution, the $\rho_L$ and $\rho_R$ parameters of the prompt signal component are varied within the ranges studied in simulation. The distribution of combinatorial backgrounds is studied with candidates in different background mass regions. The shape of the distribution for the $D^0$-from-$b$ component is fixed when studying the variation of its fraction. The same procedure is followed to estimate the uncertainty on the $\log_{10}(\chi^2_{IP}(D^0))$ fits. The systematic uncertainty on the prompt signal yields, determined by the $\log_{10}(\chi^2_{IP}(D^0))$ fit, depends on the kinematic bin and is estimated to be less than 5% in all cases.

The systematic uncertainty associated with the tracking efficiency has the components described in the following. The efficiency measurement is affected by the imperfect modelling of the tracking efficiency by simulation, which is corrected using a data-driven method [59], and the uncertainty of the correction is propagated into an uncertainty on the $D^0$ yield. The limited sizes of the simulated samples affect the precision of the efficiency, especially in the high multiplicity region. Another source of uncertainty is introduced by the choice of variable representing the detector occupancy, used to weight the distributions. The number of tracks and the number of hits in the VELO and in the TT and OT are all considered separately. The largest difference between the efficiencies when weighted by each of these variables and their average, which is the default, is taken as systematic uncertainty. An additional uncertainty comes from the detector occupancy distribution estimated in backward and forward data. The effects are summed in quadrature, yielding a total uncertainty on the tracking efficiency of 3% and 5% for the forward and backward collision sample respectively.

The limited size of the calibration sample, the binning scheme and the signal fit model used to determine the $\pi$ and $K$ PID efficiency from the calibration sample, all contribute to the systematic uncertainty. The first is evaluated by estimating new sets of efficiencies through the variation of the $\pi$ and $K$ PID efficiencies in the calibration sample within the statistical uncertainties, the second by using alternative binning schemes and the third by varying the signal function used to determine the signal. The uncertainty is taken to be the quadratic sum of the three components. The total PID systematic uncertainty ranges between 1% and 30% depending on the kinematic region and the collision sample.

The relative uncertainty associated with the luminosity measurement is approximately 2% for both forward and backward samples. The relative uncertainty of the branching fraction $B(D^0 \rightarrow K^\pm \pi^\mp)$ is 1% [55]. The limited size of the simulation sample introduces uncertainties on the efficiencies which are then propagated to the cross-section measurements; this effect is negligible for the central rapidity region but increases in the regions close to the boundaries of $p_T$ and $y^*$, ranging between 1% and 5%.
Figure 3. Double-differential cross-section $\frac{d^2\sigma}{dp_Tdy}$ (mb/(GeV/c)) of prompt $D^0$ meson production in $p$Pb collisions in the (left) forward and (right) backward collision samples. The uncertainty is the quadratic sum of the statistical and systematic components.

5 Results

5.1 Production cross-sections

The measured values of the double-differential cross-section of prompt $D^0$ mesons in proton-lead collisions in the forward and backward regions as a function of $p_T$ and $y^*$ are given in table 2 and shown in figure 3. The one-dimensional differential prompt $D^0$ meson cross-sections as a function of $p_T$ or $y^*$ are reported in tables 3 and 4, and are displayed in figure 4. The measurements are also shown as a function of $p_T$ integrated$^2$ over $y^*$ in the common rapidity range $2.5 < |y^*| < 4.0$.

The integrated cross-sections of prompt $D^0$ meson production in $p$Pb forward data in the full and common fiducial regions are

$$\sigma_{\text{forward}}(p_T < 10\text{ GeV/c}, 1.5 < y^* < 4.0) = 230.6 \pm 0.5 \pm 13.0 \text{ mb},$$

$$\sigma_{\text{forward}}(p_T < 10\text{ GeV/c}, 2.5 < y^* < 4.0) = 119.1 \pm 0.3 \pm 5.6 \text{ mb}.$$

The integrated cross-sections of prompt $D^0$ meson production in Pb$p$ backward data in the two fiducial regions are

$$\sigma_{\text{backward}}(p_T < 10\text{ GeV/c}, -5.0 < y^* < -2.5) = 252.7 \pm 1.0 \pm 20.0 \text{ mb},$$

$$\sigma_{\text{backward}}(p_T < 10\text{ GeV/c}, -4.0 < y^* < -2.5) = 175.5 \pm 0.6 \pm 14.4 \text{ mb},$$

where the first uncertainties are statistical and the second systematic.

The cross-sections as a function of $p_T$ and $y^*$, shown in figure 4, are compared with calculations (HELAC) [60–62] validated with results of heavy-flavour production cross-section in $pp$ collisions. The absolute scale for the calculation of the $D^0$ cross-section in the

$^2$The integration over $y^*$ is performed up to $|y^*|=3.5$ for $p_T > 6\text{ GeV/c}$, neglecting the bin $3.5 < |y^*| < 4.0$ since it is not populated in the forward sample. This applies for the integrated cross-sections presented in this subsection, in tables 3, 5 and 7 and in figures 4, 5, 8 and 9.
Table 2. Double-differential cross-section \( \frac{d^2\sigma}{dp_T dy} \) (mb/(GeV/c)) for prompt \( D^0 \) meson production as functions of \( p_T \) and \( y^* \) in pPb forward and backward data, respectively. The first uncertainty is statistical, the second is the component of the systematic uncertainty that is uncorrelated between bins and the third is the correlated component. In the regions with no entries the signal is not statistically significant.
Figure 4. Differential cross-section of prompt $D^0$ meson production in $p$Pb collisions as a function of (left) $p_T$ ($\frac{d\sigma}{dp_T}$) and (right) $y^*$ ($\frac{d\sigma}{dy^*}$) in the forward and backward collision samples. The uncertainty is the quadratic sum of the statistical and systematic components. The measurements are compared with theoretical predictions including different nuclear parton distribution functions as explained in the text.

HELAC approach is obtained by fitting experimental data. The nuclear effects are considered by using three different sets of nuclear parton distribution functions (nPDFs), the leading-order EPS09 (EPS09LO) [63], the next-to-leading order EPS09 (EPS09NLO) [63] and nCTEQ15 [64]. The free nucleon PDF CT10NLO [65] is also used as a reference for the cross-section predictions in $pp$ collisions. Within large theoretical uncertainties, the HELAC calculations with all three sets of nPDFs can give descriptions consistent with the LHCb data, although a discrepancy is observed in the low $p_T$ region between the measurements and the HELAC-nCTEQ15 predictions.

5.2 Nuclear modification factors

The value of the $D^0$ meson production cross-section in $pp$ collisions at 5 TeV, needed for the measurement of the nuclear modification factor $R_{pPb}$, is taken from the LHCb measurement [66]. The systematic uncertainty related to the branching fraction cancels entirely between the measurements in $p$Pb and $pp$ data, and the systematic uncertainties associated to the signal model, the tracking and PID efficiency largely cancel between the two measurements, while the luminosity and statistical uncertainties are taken as uncorrelated. The nuclear modification factor for prompt $D^0$ meson production is shown in figure 5 in bins of $p_T$ and figure 6 in bins of $y^*$. The nuclear modification factors are calculated as a function of $p_T$ integrated over $y^*$ in the ranges described in figure 5 for both forward and backward samples. The values of $R_{pPb}$, summarised in tables 5 and 6, show a slight increase as a function of $p_T$, suggesting that the suppression may decrease with increasing transverse momentum.

The measurements are compared with HELAC calculations using EPS09LO, EPSNLO and nCTEQ15 nPDFs [60–62] as well as the Colour Glass Condensate (CGC) models CGC1 [67] and CGC2 [68]. For the results in the backward configuration, all three nPDFs predictions show reasonable agreement with each other and with LHCb data. In the forward configuration, HELAC calculations using nCTEQ15 and EPS09LO nPDFs show
Figure 5. Nuclear modification factor $R_{p\text{Pb}}$ as a function of $p_T$ for prompt $D^0$ meson production in the (left) backward data and (right) forward data, integrated over the common rapidity range $2.5 < |y^*| < 4.0$ for $p_T < 6$ GeV/$c$ and over $2.5 < |y^*| < 3.5$ for $6 < p_T < 10$ GeV/$c$. The uncertainty is the quadratic sum of the statistical and systematic components. The CGC predictions marked as CGC1 [67] and CGC2 [68] are only available for the forward region.

Figure 6. Nuclear modification factor $R_{p\text{Pb}}$ as a function of $y^*$ for prompt $D^0$ meson production, integrated up to $p_T = 10$ GeV/$c$ and compared to the $J/\psi$ measurement in the same kinematic region and to the theoretical models discussed in the text. The uncertainty is the quadratic sum of the statistical and systematic components.
Table 3. Measured differential cross-section \( \frac{d \sigma}{dp_T} \) (mb/(GeV/c)) for prompt \( D^0 \) meson production as a function of \( p_T \) in \( p\text{Pb} \) forward and backward data, respectively. The first uncertainty is statistical, the second is the component of the systematic uncertainty that is uncorrelated between bins and the third is the correlated component. The results in the last two columns are integrated over the common rapidity range \( 2.5 < |y^*| < 4.0 \) for \( p_T < 6 \text{ GeV/c} \) and over \( 2.5 < |y^*| < 3.5 \) for \( 6 < p_T < 10 \text{ GeV/c} \).

<table>
<thead>
<tr>
<th>( p_T [\text{GeV/c}] )</th>
<th>( 1.5 &lt; y^* &lt; 4.0 )</th>
<th>( 2.5 &lt; y^* &lt; 4.0 )</th>
<th>( 2.5 &lt; y^* &lt; 3.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0, 1])</td>
<td>54.38 \pm 0.29 \pm 0.36 \pm 3.96</td>
<td>30.31 \pm 0.22 \pm 0.22 \pm 1.59</td>
<td>–</td>
</tr>
<tr>
<td>([1, 2])</td>
<td>83.54 \pm 0.30 \pm 0.45 \pm 5.01</td>
<td>43.92 \pm 0.22 \pm 0.28 \pm 2.17</td>
<td>–</td>
</tr>
<tr>
<td>([2, 3])</td>
<td>49.72 \pm 0.16 \pm 0.27 \pm 2.45</td>
<td>25.11 \pm 0.11 \pm 0.16 \pm 1.11</td>
<td>–</td>
</tr>
<tr>
<td>([3, 4])</td>
<td>22.91 \pm 0.09 \pm 0.14 \pm 1.10</td>
<td>11.13 \pm 0.06 \pm 0.08 \pm 0.55</td>
<td>–</td>
</tr>
<tr>
<td>([4, 5])</td>
<td>10.43 \pm 0.06 \pm 0.08 \pm 0.54</td>
<td>4.92 \pm 0.04 \pm 0.05 \pm 0.32</td>
<td>–</td>
</tr>
<tr>
<td>([5, 6])</td>
<td>4.95 \pm 0.05 \pm 0.06 \pm 0.35</td>
<td>2.21 \pm 0.04 \pm 0.04 \pm 0.26</td>
<td>–</td>
</tr>
<tr>
<td>([6, 7])</td>
<td>2.37 \pm 0.05 \pm 0.04 \pm 0.21</td>
<td>–</td>
<td>0.88 \pm 0.01 \pm 0.01 \pm 0.07</td>
</tr>
<tr>
<td>([7, 8])</td>
<td>1.20 \pm 0.02 \pm 0.02 \pm 0.09</td>
<td>–</td>
<td>0.45 \pm 0.01 \pm 0.01 \pm 0.06</td>
</tr>
<tr>
<td>([8, 9])</td>
<td>6.7 \pm 0.01 \pm 0.01 \pm 0.06</td>
<td>–</td>
<td>0.24 \pm 0.01 \pm 0.01 \pm 0.04</td>
</tr>
<tr>
<td>([9, 10])</td>
<td>0.39 \pm 0.01 \pm 0.01 \pm 0.04</td>
<td>–</td>
<td>0.08 \pm 0.00 \pm 0.00 \pm 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( p_T [\text{GeV/c}] )</th>
<th>(-5.0 &lt; y^* &lt; -2.5 )</th>
<th>(-4.0 &lt; y^* &lt; -2.5 )</th>
<th>(-3.5 &lt; y^* &lt; -2.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0, 1])</td>
<td>65.83 \pm 0.70 \pm 0.40 \pm 6.85</td>
<td>42.89 \pm 0.35 \pm 0.31 \pm 5.15</td>
<td>–</td>
</tr>
<tr>
<td>([1, 2])</td>
<td>97.97 \pm 0.68 \pm 0.52 \pm 8.30</td>
<td>66.56 \pm 0.36 \pm 0.43 \pm 5.80</td>
<td>–</td>
</tr>
<tr>
<td>([2, 3])</td>
<td>52.43 \pm 0.32 \pm 0.29 \pm 3.57</td>
<td>37.96 \pm 0.20 \pm 0.25 \pm 2.56</td>
<td>–</td>
</tr>
<tr>
<td>([3, 4])</td>
<td>21.21 \pm 0.14 \pm 0.13 \pm 1.45</td>
<td>16.23 \pm 0.10 \pm 0.11 \pm 1.01</td>
<td>–</td>
</tr>
<tr>
<td>([4, 5])</td>
<td>8.62 \pm 0.09 \pm 0.06 \pm 0.62</td>
<td>6.78 \pm 0.05 \pm 0.05 \pm 0.41</td>
<td>–</td>
</tr>
<tr>
<td>([5, 6])</td>
<td>3.61 \pm 0.08 \pm 0.04 \pm 0.33</td>
<td>2.92 \pm 0.03 \pm 0.03 \pm 0.18</td>
<td>–</td>
</tr>
<tr>
<td>([6, 7])</td>
<td>1.57 \pm 0.03 \pm 0.02 \pm 0.12</td>
<td>–</td>
<td>1.12 \pm 0.02 \pm 0.02 \pm 0.07</td>
</tr>
<tr>
<td>([7, 8])</td>
<td>0.81 \pm 0.02 \pm 0.01 \pm 0.09</td>
<td>–</td>
<td>0.57 \pm 0.01 \pm 0.01 \pm 0.04</td>
</tr>
<tr>
<td>([8, 9])</td>
<td>0.41 \pm 0.02 \pm 0.01 \pm 0.07</td>
<td>–</td>
<td>0.29 \pm 0.01 \pm 0.01 \pm 0.02</td>
</tr>
<tr>
<td>([9, 10])</td>
<td>0.22 \pm 0.01 \pm 0.01 \pm 0.02</td>
<td>–</td>
<td>0.11 \pm 0.01 \pm 0.01 \pm 0.01</td>
</tr>
</tbody>
</table>
Table 4. Differential cross-section $\frac{d\sigma}{dy}$ (mb) for prompt $D^0$ meson production as a function of $|y^*|$ in $p$Pb forward and backward data, respectively. The first uncertainty is statistical, the second is the component of the systematic uncertainty that is uncorrelated between bins and the third is the correlated component.

<table>
<thead>
<tr>
<th>$y^*$</th>
<th>Forward (mb)</th>
<th>0 &lt; $p_T$ &lt; 10 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1.5, 2.0]</td>
<td>115.19 ± 0.53 ± 0.91 ± 9.99</td>
<td></td>
</tr>
<tr>
<td>[2.0, 2.5]</td>
<td>107.05 ± 0.29 ± 0.50 ± 5.73</td>
<td></td>
</tr>
<tr>
<td>[2.5, 3.0]</td>
<td>93.90 ± 0.27 ± 0.38 ± 4.14</td>
<td></td>
</tr>
<tr>
<td>[3.0, 3.5]</td>
<td>80.76 ± 0.33 ± 0.42 ± 3.71</td>
<td></td>
</tr>
<tr>
<td>[3.5, 4.0]</td>
<td>64.24 ± 0.55 ± 0.58 ± 4.79</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$y^*$</th>
<th>Backward (mb)</th>
<th>0 &lt; $p_T$ &lt; 10 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-3.0, -2.5]</td>
<td>126.35 ± 0.78 ± 0.95 ± 15.54</td>
<td></td>
</tr>
<tr>
<td>[-3.5, -3.0]</td>
<td>120.84 ± 0.53 ± 0.53 ± 8.89</td>
<td></td>
</tr>
<tr>
<td>[-4.0, -3.5]</td>
<td>104.93 ± 0.58 ± 0.47 ± 6.66</td>
<td></td>
</tr>
<tr>
<td>[-4.5, -4.0]</td>
<td>87.92 ± 0.85 ± 0.52 ± 6.13</td>
<td></td>
</tr>
<tr>
<td>[-5.0, -4.5]</td>
<td>65.32 ± 1.57 ± 0.68 ± 7.07</td>
<td></td>
</tr>
</tbody>
</table>

a function of rapidity are shown in figure 7 where a different suppression between the two charmonium states can be observed. In figures 5 and 6 the measurements are also compared with calculations in the CGC frameworks CGC1 [67] and CGC2 [68]. Both models include the effect of the saturation of partons at small $x$. The CGC models are found to be able to describe the trend of prompt $D^0$ meson nuclear modifications as a function of $p_T$ and of rapidity. The uncertainty band for CGC1 is much smaller than for CGC2 and for the nuclear PDF calculations, since CGC1 only contains the variation of charm quark masses and factorisation scale which largely cancel in this ratio of cross-sections. In the context of $p$Pb collisions, recent measurements have shown that long-range collective effects, which have previously been observed in relatively large nucleus-nucleus collision systems, may also be present in smaller collision systems at large charged particle multiplicities [71–74]. If these effects are due to the creation of a hydrodynamic system, momentum anisotropies at the quark level can arise, which may modify the final distribution of observed heavy-quark hadrons [75]. Since the measurements in this analysis do not consider a classification in charged particle multiplicity, potential modifications in high-multiplicity events are weakened as the presented observables are integrated over charged particle multiplicity.

5.3 Forward-backward ratio

In the forward-backward production ratio $R_{FB}$ the common uncertainty between the forward and backward measurements largely cancels. The uncertainties of branching fraction,
with the data within the theoretical uncertainties. Good agreement is found between measurements and theoretical predictions using up to $p_T = 10$ GeV/c, the first uncertainty is statistical and the second systematic.

<table>
<thead>
<tr>
<th>$p_T$ [GeV/c]</th>
<th>Forward</th>
<th>Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0, 1]</td>
<td>0.62 ± 0.01 ± 0.03</td>
<td>0.87 ± 0.01 ± 0.09</td>
</tr>
<tr>
<td>[1, 2]</td>
<td>0.64 ± 0.01 ± 0.03</td>
<td>0.97 ± 0.01 ± 0.07</td>
</tr>
<tr>
<td>[2, 3]</td>
<td>0.70 ± 0.01 ± 0.03</td>
<td>1.06 ± 0.01 ± 0.07</td>
</tr>
<tr>
<td>[3, 4]</td>
<td>0.72 ± 0.01 ± 0.04</td>
<td>1.06 ± 0.01 ± 0.06</td>
</tr>
<tr>
<td>[4, 5]</td>
<td>0.77 ± 0.01 ± 0.05</td>
<td>1.06 ± 0.01 ± 0.06</td>
</tr>
<tr>
<td>[5, 6]</td>
<td>0.77 ± 0.02 ± 0.08</td>
<td>1.01 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>[6, 7]</td>
<td>0.82 ± 0.02 ± 0.06</td>
<td>1.05 ± 0.03 ± 0.06</td>
</tr>
<tr>
<td>[7, 8]</td>
<td>0.78 ± 0.03 ± 0.09</td>
<td>0.99 ± 0.04 ± 0.06</td>
</tr>
<tr>
<td>[8, 9]</td>
<td>0.79 ± 0.05 ± 0.12</td>
<td>0.92 ± 0.05 ± 0.07</td>
</tr>
<tr>
<td>[9, 10]</td>
<td>0.83 ± 0.07 ± 0.09</td>
<td>1.10 ± 0.10 ± 0.09</td>
</tr>
<tr>
<td>[0, 10]</td>
<td>0.66 ± 0.00 ± 0.03</td>
<td>0.97 ± 0.01 ± 0.07</td>
</tr>
</tbody>
</table>

Table 5. Nuclear modification factor $R_{p\text{Pb}}$ for prompt $D^0$ meson production in different $p_T$ ranges, integrated over the common rapidity range $2.5 < |y^*| < 4.0$ for $p_T < 6$ GeV/c and over $2.5 < |y^*| < 3.5$ for $6 < p_T < 10$ GeV/c for the forward (positive $y^*$) and backward (negative $y^*$) samples. The first uncertainty is statistical and the second systematic.

<table>
<thead>
<tr>
<th>$y^*$</th>
<th>$R_{p\text{Pb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[−4.5, −4.0]</td>
<td>1.31 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>[−4.0, −3.5]</td>
<td>1.05 ± 0.01 ± 0.05</td>
</tr>
<tr>
<td>[−3.5, −3.0]</td>
<td>0.99 ± 0.01 ± 0.04</td>
</tr>
<tr>
<td>[−3.0, −2.5]</td>
<td>0.90 ± 0.01 ± 0.05</td>
</tr>
<tr>
<td>[2.0, 2.5]</td>
<td>0.74 ± 0.01 ± 0.04</td>
</tr>
<tr>
<td>[2.5, 3.0]</td>
<td>0.67 ± 0.00 ± 0.03</td>
</tr>
<tr>
<td>[3.0, 3.5]</td>
<td>0.66 ± 0.00 ± 0.03</td>
</tr>
<tr>
<td>[3.5, 4.0]</td>
<td>0.65 ± 0.01 ± 0.03</td>
</tr>
</tbody>
</table>

Table 6. Nuclear modification factor $R_{p\text{Pb}}$ for prompt $D^0$ meson production in different $y^*$ ranges, integrated up to $p_T = 10$ GeV/c. The first uncertainty is statistical and the second systematic.

general yield and tracking are considered fully correlated, while the PID uncertainty is considered 90% correlated since it is a mixture of statistical uncertainty (uncorrelated) and the uncertainties due to the binning scheme and yield determination (correlated). All other uncertainties are uncorrelated. The measured $R_{\text{FB}}$ values are shown in figure 8, as a function of $p_T$ integrated over the range $2.5 < |y^*| < 4.0$, and as a function of $y^*$ integrated up to $p_T = 10$ GeV/c. The $R_{\text{FB}}$ values in different kinematic bins are also summarised in table 7. Good agreement is found between measurements and theoretical predictions using EPS09LO and nCTEQ15 nPDFs. The calculation using EPS09NLO nPDF also agrees with the data within the theoretical uncertainties.
In the common kinematic range $p_T < 10\text{ GeV/c}$, $2.5 < |y^*| < 4.0$, the forward-backward ratio $R_{FB}$ is $0.71 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$, indicating a significant asymmetry. The predictions for $R_{FB}$ integrated over the same kinematic range are $0.71^{+0.21}_{-0.24}$ for the HELAC-EPS09LO calculation, $0.81^{+0.10}_{-0.09}$ for the HELAC-EPS09NLO calculation and $0.69^{+0.07}_{-0.07}$ for the HELAC calculation using the nCTEQ15 nPDF set, which are all in good agreement with the measured value. The forward-backward production ratio increases slightly with increasing $p_T$, and decreases strongly with increasing rapidity $|y^*|$, a trend that becomes significant when one considers the large correlation among the systematic uncertainties discussed in section 4. This behaviour is consistent with the expectations from the QCD calculations. The $R_{FB}$ measurement of muons from heavy-flavour decays in a similar kinematic region reported by the ALICE experiment [42] shows a qualitatively similar trend.

In order to compare the production of open charm and charmonium, the ratio of $R_{FB}$ for prompt $J/\psi$ mesons divided by $R_{FB}$ for prompt $D^0$ mesons is shown in figure 9. The measurement shows that $R_{FB}$ has the same size for prompt $D^0$ and prompt $J/\psi$ mesons within the uncertainties in the LHCb kinematic range.

\begin{table}[h]
\begin{tabular}{|c|c|c|}
\hline
\$p_T[\text{GeV/c}]$ & $R_{FB}$ \\
\hline
$[0, 1]$ & $0.71 \pm 0.01 \pm 0.06$ \\
$[1, 2]$ & $0.66 \pm 0.00 \pm 0.04$ \\
$[2, 3]$ & $0.66 \pm 0.00 \pm 0.03$ \\
$[3, 4]$ & $0.69 \pm 0.01 \pm 0.03$ \\
$[4, 5]$ & $0.73 \pm 0.01 \pm 0.04$ \\
$[5, 6]$ & $0.76 \pm 0.02 \pm 0.08$ \\
$[6, 7]$ & $0.79 \pm 0.02 \pm 0.05$ \\
$[7, 8]$ & $0.79 \pm 0.03 \pm 0.09$ \\
$[8, 9]$ & $0.86 \pm 0.04 \pm 0.12$ \\
$[9, 10]$ & $0.75 \pm 0.06 \pm 0.09$ \\
$[0, 10]$ & $0.68 \pm 0.00 \pm 0.04$ \\
\hline
\$|y^*|\$ & $R_{FB}$ \\
\hline
$[2.5, 3.0]$ & $0.74 \pm 0.01 \pm 0.07$ \\
$[3.0, 3.5]$ & $0.67 \pm 0.00 \pm 0.03$ \\
$[3.5, 4.0]$ & $0.61 \pm 0.01 \pm 0.03$ \\
\hline
\end{tabular}
\end{table}

\textbf{Table 7.} Forward-backward ratio $R_{FB}$ for prompt $D^0$ meson production in different $p_T$ ranges, integrated over the common rapidity range $2.5 < |y^*| < 4.0$ for $p_T < 6\text{ GeV/c}$ and over $2.5 < |y^*| < 3.5$ for $6 < p_T < 10\text{ GeV/c}$, and in different $y^*$ ranges integrated up to $p_T = 10\text{ GeV/c}$. The first uncertainty is the statistical and the second is the systematic component.
Figure 7. Ratio of nuclear modification factors $R_{p\text{Pb}}$ of $J/\psi$ and $\psi(2S)$ to $D^0$ mesons in bins of rapidity integrated up to $p_T = 10\,\text{GeV}/c$ in the common rapidity range $2.5 < |y^*| < 4.0$. The uncertainty is the quadratic sum of the statistical and systematic components.

Figure 8. Forward-backward ratio $R_{FB}$ for prompt $D^0$ meson production (left) as a function of $p_T$ integrated over the common rapidity range $2.5 < |y^*| < 4.0$ for $p_T < 6\,\text{GeV}/c$ and over $2.5 < |y^*| < 3.5$ for $6 < p_T < 10\,\text{GeV}/c$ (right) as a function of $y^*$ integrated up to $p_T = 10\,\text{GeV}/c$. The uncertainty is the quadratic sum of the statistical and systematic components.
Figure 9. Relative forward-backward production ratio $R_{FB}$ for prompt $D^0$ mesons over that for prompt $J/\psi$ mesons (left) as a function of $p_T$ integrated over the common rapidity range $2.5 < |y^*| < 4.0$ for $p_T < 6\text{ GeV}/c$ and over $2.5 < |y^*| < 3.5$ for $6 < p_T < 10\text{ GeV}/c$; (right) as a function of $y^*$ integrated up to $p_T = 10\text{ GeV}/c$. The red inner bars in the uncertainty represent the statistical uncertainty and the black outer bars the quadratic sum of the statistical and systematic components.

6 Conclusion

The prompt $D^0$ production cross-section has been measured with LHCb proton-lead collision data at $\sqrt{s_{NN}} = 5\text{ TeV}$. The measurement is performed in the range of $D^0$ transverse momentum $p_T < 10\text{ GeV}/c$, in both backward and forward collisions covering the ranges $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$. This is the first measurement in this rapidity region down to zero transverse momentum of the $D^0$ meson. Nuclear modification factors and forward-backward production ratios are also measured in the same kinematic range. Both observables are excellent probes to constrain the PDF uncertainties, which are currently significantly larger than the uncertainties on the experimental results. A large asymmetry in the forward-backward production is observed, which is consistent with the expectations from nuclear parton distribution functions, and colour glass condensate calculations for the forward rapidity part. The results are found to be consistent with the theoretical predictions considered.

Acknowledgments

We would like to thank Andrea Dainese, Bertrand Ducloué, Jean-Philippe Lansberg and Huasheng Shao for providing the theoretical predictions for our measurements. We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF
and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (U.S.A.). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (U.S.A.). We are indebted to the communities behind the multiple open source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil Général de Haute-Savoie, Labex ENIGMASS and OCEVU, Région Auvergne (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, The Royal Society, Royal Commission for the Exhibition of 1851 and the Leverhulme Trust (United Kingdom).

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References


[32] ALICE collaboration, Suppression of high transverse momentum \( D \) mesons in central \( Pb-Pb \) collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV, JHEP 09 (2012) 112 [arXiv:1203.2160] [inSPIRE].


[34] LHCb collaboration, Study of \( \psi(2S) \) production and cold nuclear matter effects in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5 \) TeV, JHEP 03 (2016) 133 [arXiv:1601.07878] [inSPIRE].

[35] LHCb collaboration, Study of \( \Upsilon \) production and cold nuclear matter effects in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5 \) TeV, JHEP 07 (2014) 094 [arXiv:1405.5152] [inSPIRE].

[36] ALICE collaboration, \( J/\psi \) production as a function of charged-particle pseudorapidity density in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, JHEP 06 (2016) 050 [arXiv:1603.02816] [inSPIRE].

[37] ALICE collaboration, \( \Upsilon \) production in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV and in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV, Phys. Rev. C 94 (2016) 054908 [arXiv:1605.07569] [inSPIRE].

[38] ALICE collaboration, Centrality dependence of \( \psi(2S) \) suppression in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, JHEP 06 (2016) 050 [arXiv:1603.02816] [inSPIRE].

[39] ALICE collaboration, Measurement of \( D \)-meson production versus multiplicity in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, JHEP 08 (2016) 078 [arXiv:1602.07240] [inSPIRE].

[40] ALICE collaboration, Centrality dependence of inclusive \( J/\psi \) production in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, JHEP 11 (2015) 127 [arXiv:1506.08808] [inSPIRE].

[41] ALICE collaboration, Rapidity and transverse-momentum dependence of the inclusive \( J/\psi \) nuclear modification factor in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, JHEP 06 (2015) 055 [arXiv:1503.07179] [inSPIRE].

[42] ALICE collaboration, Production of inclusive \( \Upsilon(1S) \) and \( \Upsilon(2S) \) in \( p\bar{p} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, Phys. Lett. B 740 (2015) 105 [arXiv:1410.2234] [inSPIRE].

[32] ALICE collaboration, $J/\psi$ production and nuclear effects in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, JHEP 02 (2014) 073 [arXiv:1308.6726] [nSPIRE].

[33] ALICE collaboration, Suppression of $\psi(2S)$ production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, JHEP 12 (2014) 073 [arXiv:1405.3796] [nSPIRE].


[35] CMS collaboration, Event activity dependence of $Y(nS)$ production in $\sqrt{s_{NN}} = 5.02$ TeV pPb and $\sqrt{s} = 2.76$ TeV pp collisions, JHEP 04 (2014) 103 [arXiv:1312.6300] [nSPIRE].


[38] CMS collaboration, Transverse momentum spectra of inclusive $b$ jets in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 754 (2016) 59 [arXiv:1510.03373] [nSPIRE].


[41] ALICE collaboration, Measurement of electrons from beauty-hadron decays in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, JHEP 07 (2017) 052 [arXiv:1609.03898] [nSPIRE].


[43] LHCb collaboration, The LHCb detector at the LHC, 2008 JINST 3 S08005 [nSPIRE].


I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
10 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
11 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
12 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
13 School of Physics, University College Dublin, Dublin, Ireland
14 Sezione INFN di Bari, Bari, Italy
15 Sezione INFN di Bologna, Bologna, Italy
16 Sezione INFN di Cagliari, Cagliari, Italy
17 Universita e INFN, Ferrara, Ferrara, Italy
18 Sezione INFN di Firenze, Firenze, Italy
19 Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
20 Sezione INFN di Genova, Genova, Italy
21 Universita e INFN, Milano-Bicocca, Milano, Italy
22 Sezione di Milano, Milano, Italy
23 Sezione INFN di Padova, Padova, Italy
24 Sezione INFN di Pisa, Pisa, Italy
25 Sezione INFN di Roma Tor Vergata, Roma, Italy
26 Sezione INFN di Roma La Sapienza, Roma, Italy
27 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
28 AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
29 National Center for Nuclear Research (NCBJ), Warsaw, Poland
30 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
31 Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
32 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
33 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
34 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
35 Yandex School of Data Analysis, Moscow, Russia
36 Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
37 Institute for High Energy Physics (IHEP), Protvino, Russia
38 ICCUB, Universitat de Barcelona, Barcelona, Spain
39 Universidad de Santiago de Compostela, Santiago de Compostela, Spain
40 European Organization for Nuclear Research (CERN), Geneva, Switzerland
41 Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
42 Physik-Institut, Universität Zürich, Zürich, Switzerland
43 Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
44 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
45 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
46 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
47 University of Birmingham, Birmingham, United Kingdom
48 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
49 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
50 Department of Physics, University of Warwick, Coventry, United Kingdom
51 STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
52 School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
53 School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
55 Imperial College London, London, United Kingdom
56 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
57 Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Maryland, College Park, MD, United States
Syracuse University, Syracuse, NY, United States
Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to
University of Chinese Academy of Sciences, Beijing, China, associated to
School of Physics and Technology, Wuhan University, Wuhan, China, associated to
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to
Departamento de Fisica, Universidad Nacional de Colombia, Bogotá, Colombia, associated to
Institut für Physik, Universität Rostock, Rostock, Germany, associated to
National Research Centre Kurchatov Institute, Moscow, Russia, associated to
National Research Tomsk Polytechnic University, Tomsk, Russia, associated to
Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to
Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to
Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
Laboratoire Leprince-Ringuet, Palaiseau, France
P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Genova, Genova, Italy
Università di Milano Bicocca, Milano, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Roma La Sapienza, Roma, Italy
AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland
LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain
Hanoi University of Science, Hanoi, Viet Nam
Università di Padova, Padova, Italy
Università di Pisa, Pisa, Italy
Università degli Studi di Milano, Milano, Italy
Università di Urbino, Urbino, Italy
Università della Basilicata, Potenza, Italy
Scuola Normale Superiore, Pisa, Italy
Università di Modena e Reggio Emilia, Modena, Italy
IIT, IIT Roorkee, India
Novosibirsk State University, Novosibirsk, Russia
Deceased