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J/ψ and D^0 production in $\sqrt{s_{\rm NN}} = 68.5$ GeV PbNe collisions

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Abstract The first measurement of J/ψ and D^0 production in PbNe collisions by the LHCb experiment in its fixed-target configuration is reported. The production of J/ψ and D^0 mesons is studied with a beam of lead ions with an energy of 2.5 TeV per nucleon colliding on gaseous neon targets at rest, corresponding to a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\rm NN}} = 68.5$ GeV. The $J/\psi/D^0$ production cross-section ratio is studied as a function of rapidity, transverse momentum and collision centrality. These data are compared with measurements from pNe collisions at the same energy and show no difference in the observed J/ψ suppression trend when comparing pNe and PbNe peripheral collisions with PbNe central collisions.

In the high-density and high-temperature regime of quantum chromodynamics (QCD), the production of heavy quarks in nucleus-nucleus interactions is well suited to study the transition between ordinary hadronic matter and the hot and dense quark-gluon plasma (QGP). Since heavy quark masses are large compared to the QGP critical temperature, $T_c \sim 156$ MeV [1], their production occurs in primary nucleon-nucleon collisions, at an early stage of the interaction. They can therefore experience the full evolution of the created nuclear medium. Moreover, at sufficiently high temperature, larger than T_c, lattice QCD calculations predict that the production of charmonium ($c\bar{c}$ bound states) decreases with respect to the overall $c\bar{c}$ production, due to the modification of their binding mechanism [2]. Consequently, the proper interpretation of the charmonium suppression, observed in nucleus-nucleus collisions at various energies [3,4], requires the measurement of charmonium yields together with the overall charm quark production [5]. Since most of the charm quarks hadronise into open charm D^0 mesons, the D^0 production yield should provide a suitable reference for the study of the charmonium yield modification, assuming that D^0 production is not modified by the medium.

In this paper, the first measurement of J/ψ and D^0 production in fixed-target nucleus-nucleus collisions at the LHC is presented.[1] Lead ions with an energy per nucleon of 2.5 TeV are incident on neon nuclei at rest, corresponding to a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 68.5$ GeV. The J/ψ and D^0 mesons are measured via their $\mu^+\mu^-$ and $K^\mp\pi^\pm$ decays, respectively.

The LHCb detector [6,7] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. It has been designed for the study of particles containing c or b quarks. The main detector elements are: the silicon-strip vertex locator (VELO) surrounding the interaction region that allows c and b hadrons to be identified from their characteristic flight distance; a tracking system that provides a measurement of the momentum of charged particles, with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV; two ring-imaging Cherenkov detectors that are able to discriminate among different types of charged hadrons; a calorimeter system consisting of scintillating-pad and preshower detectors, electromagnetic and hadronic calorimeters; and a muon detector composed of alternating layers of iron and multiwire proportional chambers. The system for measuring the overlap with gas (SMOG) [8], which enables the injection of gases with pressures of $O(10^{-7})$ mbar in the beam pipe section inside the VELO, is used to operate LHCb as a fixed-target experiment. The SMOG allows the injection of noble gases and therefore gives the unique opportunity to study nucleus-nucleus and proton-nucleus collisions with various targets. Due to the boost of the centre-of-mass frame induced by the high-energy lead ion beam, the LHCb acceptance extends over the backward rapidity hemisphere in the centre-of-mass system of the reaction covering the region $-2.29 \lesssim y^\star \lesssim 0$.

Selected events are recorded by a two-stage trigger system [9]. The first level is implemented in hardware and uses information provided by the calorimeters and the muon detectors,

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[1] The inclusion of charge-conjugate processes is implied throughout the paper.

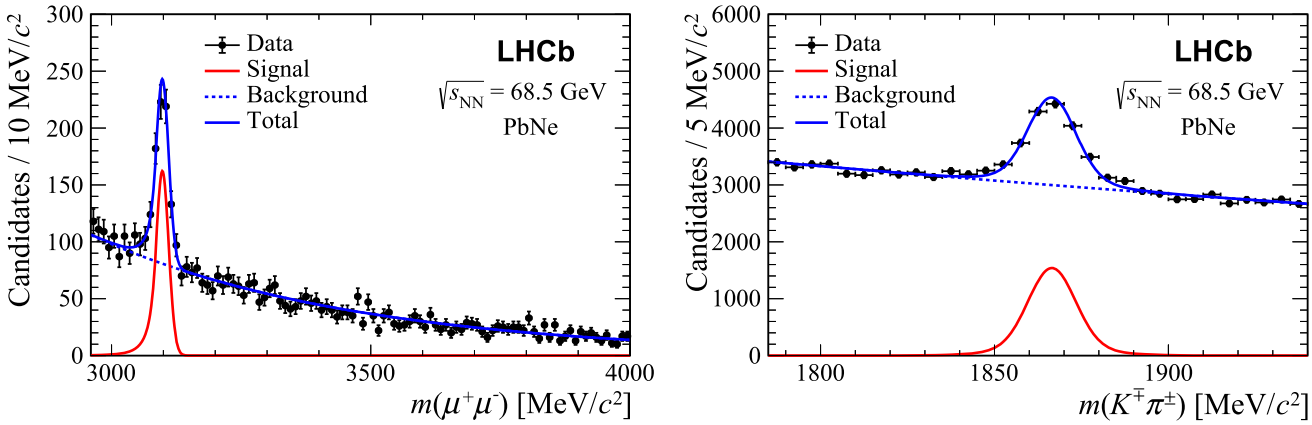

Fig. 1 Mass distributions of (left) $J/\psi \to \mu^-\mu^+$ and (right) $D^0 \to K^\mp\pi^\pm$ candidates. The data are overlaid with the fit function

while the second is a software trigger. The hardware trigger requires at least one identified muon for the selection of the $J/\psi \to \mu^+\mu^-$ decay and energy deposit in the calorimeter for the $D^0 \to K^\mp\pi^\pm$ selection. The software trigger requires two well-reconstructed muons for the J/ψ mode, while for the D^0 channel, the software trigger requires a track with transverse momentum larger than 500 MeV/c.

The data samples are collected under dedicated beam conditions where lead ion bunches moving towards the detector do not cross any bunch moving in the opposite direction at the nominal lead-lead (PbPb) interaction point. Events must have a reconstructed primary vertex (PV) z position (along the beam direction) within the fiducial region $z_{PV} \in [-200, 150]$ mm where high reconstruction efficiencies are achieved and calibration samples are available. In order to suppress residual PbPb collisions occuring at $z_{PV} = 0$ mm, events with activity in the backward region, with respect to the PV position, are vetoed, based on the number of hits in the VELO stations upstream of the interaction region.

The offline selection of J/ψ and D^0 candidates is similar to that used in Ref. [10]. Events must contain a primary vertex with at least four tracks reconstructed in the VELO detector. The J/ψ candidates are formed from two oppositely charged muons forming a vertex. The muons must have transverse momentum, p_{T}, larger than 500 MeV/c and are required to be consistent with originating from the primary interaction point. Each D^0 candidate is formed from an oppositely charged pair of charged particles that come from a common displaced vertex. One of these particles must be identified as a kaon and the other as a pion. The D^0 candidates are required to have a decay time larger than 0.4 ps. The measurements are performed in the range of D^0 and J/ψ transverse momentum $p_{\mathrm{T}} < 8$ GeV/c and rapidity $2.0 < y < 4.29$.

The kinematic acceptance and reconstruction efficiencies are determined using simulated lead-neon (PbNe) collision events. In the simulation, J/ψ and D^0 mesons are generated using PYTHIA 8 [11] with a specific LHCb configuration [12] and with colliding lead-ion beam momenta equal to the momentum per nucleon of the beam and target in the centre-of-mass frame. Particle decays are described by EVTGEN [13], in which final-state radiation is generated using PHOTOS [14]. The four-momenta of the J/ψ and D^0 decay products are embedded into PbNe minimum bias events that are generated with the EPOS event generator [15] using beam parameters obtained from data. Decays of hadronic particles generated with EPOS are also described by EVTGEN. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [16,17] as described in Ref. [18]. After reconstruction, the simulated events are assigned weights using a gradient boosted reweighter [19] to reproduce the data with respect to the multiplicity in the scintillating pad detector (denoted hereafter as hit multiplicity) and the transverse momentum distribution of the J/ψ and D^0 candidates. The overall efficiencies, including the kinematic acceptance, the efficiencies of the trigger, event selection, primary vertex reconstruction, tracking and particle identification, are 13.9% and 1.1% for the J/ψ and D^0 decays, respectively.

The J/ψ and D^0 signal yields are obtained from extended unbinned maximum-likelihood fits to their mass distributions. The J/ψ signal is described by a Crystal Ball function[20] while the D^0 signal is described by the sum of two Gaussian functions. The background components are modelled by exponential functions. Figure 1 shows the mass distribution obtained after all selection criteria are applied to the entire PbNe data set, with the fit functions superimposed. The overall yields for the J/ψ and D^0 channels are about 550 and 5700 respectively. The signal yields are determined in intervals of p_{T}, $y^\star$ and hit multiplicity. The yields determined from the mass fit are corrected for the geometrical acceptance of the detector and the efficiencies of the trigger, event selection, primary vertex reconstruction, tracking and particle identification. The efficiencies for particle identification [21] and tracking are obtained from a control sample of

Table 1 Summary of the systematic uncertainties affecting the $J/\psi/D^0$ production ratio. Those that are correlated between bins affect all measurements by the same relative amount. Ranges denote the minimum and the maximum values among the y, p_{T} or hit multiplicity bins

Systematic uncertainties	$J/\psi/D^0$
Correlated bin uncertainties	
Simulation weighting	16.0%
MC-truth matching efficiency	4.1%
PV efficiency	0.3%
Tracking efficiency	2.9%
Particle identification	1.2%
Overall $J/\psi/D^0$ determination	7.8%
Uncorrelated bin uncertainties	
Signal mass model	[1.1, 14.7]%
Simulation statistical error	[0.5, 1.8]%
Tracking calibration sample stat	$< 0.1\%$
Particle identification calibration stat	[6.5, 6.9]%
Overall systematic uncertainty	19.6%

lead-proton (Pbp) collision data. All the other efficiencies are determined from simulation. Several sources of systematic uncertainties are considered, affecting either the determination of the signal yields or the total efficiencies. They are summarised in Table 1 separately for correlated and uncorrelated systematic uncertainties among the bins.

The contamination from residual PbPb collisions, evaluated to be 0.23%, is considered negligible in the $J/\psi/D^0$ production ratio. The fraction of signal from b-hadron decays at $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV is estimated to be less than 0.1%, which is also considered to be negligible. The PV efficiency systematic uncertainty is determined by considering the difference between the PV efficiency computed using the J/ψ and D^0 simulations. The systematic uncertainty related to the mass fit is evaluated using alternative models for signal and background shapes that reproduce the mass shapes well. Another source of uncertainty arises from the finite size of the simulation sample used to compute the acceptances and efficiencies. Systematic uncertainties in the tracking and particle identification efficiencies are mainly related to the differences between the track multiplicity in PbNe and Pbp collisions, and to the size of the Pbp samples. The tracking systematic uncertainty also takes into account the difference in tracking efficiency between the data and the simulation. The MC-truth matching procedure is also tested and its inefficiency is considered a systematic uncertainty. Alternative sets of event weights are produced to evaluate the uncertainty associated with the reweighting procedure. The main variation is obtained by different random splitting of the training/testing samples and with different multiplicity input variables (such as the number of long tracks, or the multiplicity hits, or the clusters or tracks in the VELO). The largest discrepancy between the data and simulation is in the primary vertex position distribution. This discrepancy mostly cancels in the $J/\psi/D^0$ ratio. To obtain the residual discrepancy, the difference between the overall $J/\psi/D^0$ efficiency ratio evaluated using the default weights and the same ratio computed with the alternative weights is studied with respect to the primary vertex position, leading to another systematic uncertainty affecting the weighting. These tests result in a correlated 16% systematic uncertainty to be applied in the $J/\psi/D^0$ production ratio. A last correlated systematic uncertainty of 7.8% takes into account the difference between the overall $J/\psi/D^0$ ratio, which is the average of the results integrated over $y^\star$ or p_{T} and multiplicity, and the individual results.

The $J/\psi/D^0$ cross-section ratio, taking into account the branching fractions, is

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = \frac{Y_{J/\psi\to\mu^+\mu^-}}{\mathcal{B}_{J/\psi\to\mu^+\mu^-}\times\varepsilon_{J/\psi}} \times \frac{\mathcal{B}_{D^0\to \mathrm{K}^\mp\pi^\pm}\times\varepsilon_{D^0}}{Y_{D^0\to \mathrm{K}^\mp\pi^\pm}} = 0.51 \pm 0.04\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.})\%,$$

where $Y_{J/\psi\to\mu^+\mu^-}$ ($Y_{D^0\to \mathrm{K}^\mp\pi^\pm}$), $\mathcal{B}_{J/\psi\to\mu^+\mu^-}$ ($\mathcal{B}_{D^0\to \mathrm{K}^\mp\pi^\pm}$) and $\varepsilon_{J/\psi}$ (ε_{D^0}) are J/ψ (D^0) yield, branching fraction and total efficiency, respectively. The $J/\psi/D^0$ cross-section ratio as a function of $y^\star$ and p_{T} is shown in Fig. 2. The ratio depends strongly on p_{T} but the data are compatible with no dependence on centre-of-mass rapidity.

The $J/\psi/D^0$ cross sections ratios in PbNe collision data are compared with measurements in pNe collisions with LHCb in similar experimental conditions [22,23]. The left panel of Fig. 3 shows the $J/\psi/D^0$ cross-section ratio for both PbNe and pNe data as a function of AB, the product of the beam (A) and target (B) atomic mass numbers. Assuming that nuclear effects, that can modify the initial $c\bar{c}$ pair production, cancel in the $J/\psi/D^0$ ratio, and that the J/ψ and D^0 production cross-sections are of the form $\sigma^{AB}_{J/\psi} = \sigma^{pp}_{J/\psi}\times AB^\alpha$ and $\sigma^{AB}_{D^0} = \sigma^{pp}_{D^0}\times AB$, respectively, the cross-section ratio dependence on AB is expected to follow

$$\frac{\sigma^{AB}_{J/\psi}}{\sigma^{AB}_{D^0}} = \frac{\sigma^{pp}_{J/\psi}}{\sigma^{pp}_{D^0}} \times (AB)^{\alpha-1} = C\times(AB)^{\alpha-1}. \quad (1)$$

A fit to the data gives $\alpha = 0.86 \pm 0.04$ (and $C = (1.59 \pm 0.26)\times10^{-2}$), which indicates that J/ψ production is affected by additional nuclear effects with respect to D^0 production.

Figure 3 (right) also shows the $J/\psi/D^0$ cross-section ratio as a function of the number of binary nucleon-nucleon collisions, N_{coll}. The PbNe data sample is divided into intervals of N_{coll} corresponding to different centrality intervals related to the overlap region between the two colliding nuclei. The larger the N_{coll} the larger is the overlap region. Since small overlap regions correspond to small N_{coll} values (similar to

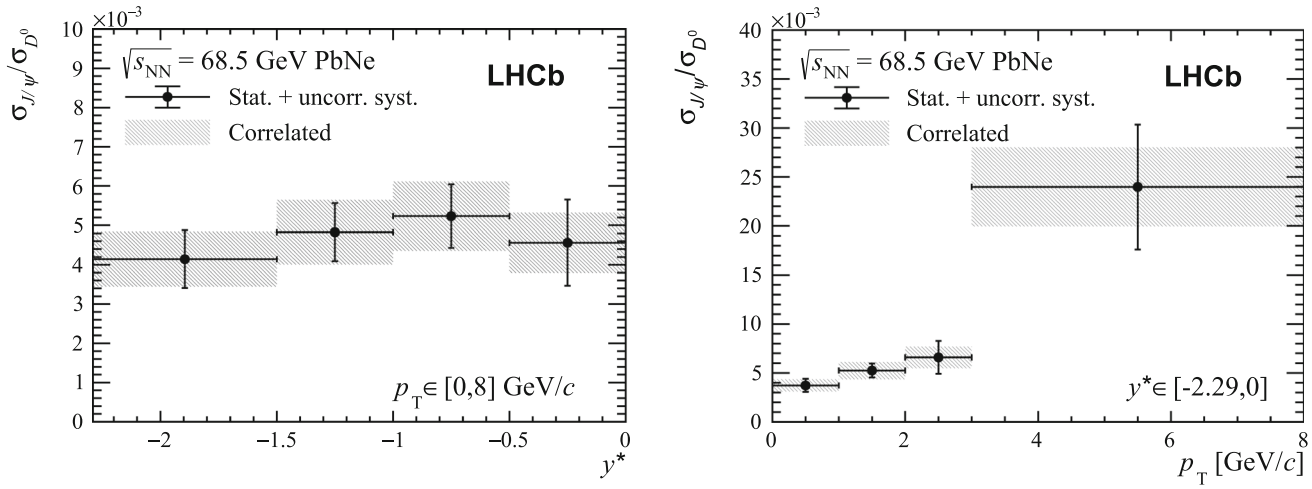

Fig. 2 Ratios of J/ψ to D^0 cross-sections as a function of (left) $y^\star$ and (right) transverse momentum. The error bars represent uncertainties that are uncorrelated bin-to-bin while the boxes represent the correlated uncertainties

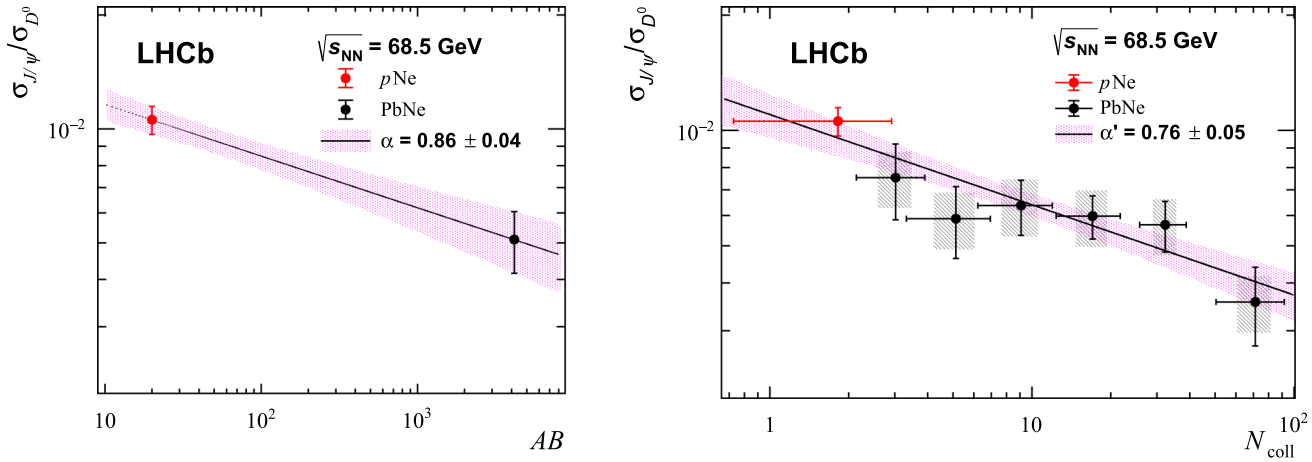

Fig. 3 Left: $J/\psi/D^0$ cross-section ratio as a function of AB, the product of the beam (A) and target (B) atomic mass numbers; the error bars represent the quadratic sum of statistical and systematic uncertainties. Right: $J/\psi/D^0$ cross-section ratio as a function of $N_{\rm coll}$; the error bars represent the quadratic sum of statistical and uncorrelated systematic uncertainties while the boxes correspond to the correlated systematic uncertainty. The red and black points correspond to pNe [22] and PbNe collisions, respectively

$N_{\rm coll}$ values in proton-nucleus collisions), any suppression related to the formation of a deconfined medium should occur at large $N_{\rm coll}$ values.

The number of binary collisions is not directly observable but it can be mapped to the actual data using a Glauber model. In LHCb, this mapping, reported in Table 2, is performed based on the hit multiplicity, as detailed in Ref. [24]. For pNe collisions, the result is integrated over the impact parameter of the collision. Assuming that the J/ψ and D^0 production cross-sections scale as $\langle N_{\rm coll}\rangle^{\alpha'}$ and $\langle N_{\rm coll}\rangle$ respectively, the cross-section ratio $\sigma_{J/\psi}/\sigma_{D^0}$ scales as $\langle N_{\rm coll}\rangle^{\alpha'-1}$. A fit to the data (where the PbNe correlated systematic uncertainty is not taken into account) gives $\alpha' = 0.76 \pm 0.05$, compatible with α when relating $N_{\rm coll}$ to AB with the Glauber model. This confirms that J/ψ meson production is affected by additional nuclear effects with respect to D^0 production. Moreover, within uncertainties, no difference in the J/ψ suppression trend is observed when comparing the PbNe largest $N_{\rm coll}$ bin with the pNe and PbNe smaller $N_{\rm coll}$ bins.

In summary, we report on the J/ψ to D^0 production ratio in $\sqrt{s_{\rm NN}} = 68.5$ GeV PbNe collisions with the LHCb experiment. The $J/\psi/D^0$ cross-section ratio is found to be $\sigma_{J/\psi}/\sigma_{D^0} = 0.51 \pm 0.04\,(\text{stat.}) \pm 0.10\,(\text{syst.})\%$ for $y^\star \in [-2.29, 0]$ and $p_{\rm T} \in [0, 8]$ GeV/c. When compared with results obtained in pNe collisions, the dependence of this ratio with $(AB)^{\alpha-1}$ gives $\alpha = 0.86 \pm 0.04$. Finally, the study of this ratio, divided into intervals of $N_{\rm coll}$, shows no difference in the J/ψ suppression trend, when comparing pNe and PbNe peripheral collisions with PbNe central collisions.

Table 2 The mapping from intervals of the hit multiplicity to intervals of N_{coll}; $\langle N_{\text{coll}} \rangle$ and RMS(N_{coll}) correspond to the N_{coll} distribution mean and root mean square values respectively

	Hit multiplicity	$\langle N_{\text{coll}} \rangle$	$RMS(N_{\text{coll}})$
*p*Ne		1.81	1.10
PbNe	0–200	3.02	0.88
	200–300	5.13	1.81
	300–446	9.09	2.87
	446–715	17.04	4.67
	715–960	32.26	6.51
	960–1700	71.12	20.70

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