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Charmonium production in pNe collisions at $\sqrt{s_{\rm NN}} = 68.5$ GeV

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Abstract The measurement of charmonium states produced in proton-neon (pNe) collisions by the LHCb experiment in its fixed-target configuration is presented. The production of J/ψ and $\psi(2S)$ mesons is studied with a beam of 2.5 TeV protons colliding on gaseous neon targets at rest, corresponding to a nucleon-nucleon centre-of-mass energy $\sqrt{s_{\rm NN}} = 68.5$ GeV. The data sample corresponds to an integrated luminosity of $21.7 \pm 1.4\ \rm nb^{-1}$. The J/ψ and $\psi(2S)$ hadrons are reconstructed in $\mu^+\mu^-$ final states. The J/ψ production cross-section per target nucleon in the centre-of-mass rapidity range $y^\star \in [-2.29, 0]$ is found to be $506 \pm 8 \pm 46$ nb/nucleon. The ratio of J/ψ and D^0 cross-sections is evaluated to $(1.06 \pm 0.02 \pm 0.09)\%$. The $\psi(2S)$ to J/ψ relative production rate is found to be $(1.67 \pm 0.27 \pm 0.10)\%$ in good agreement with other measurements involving beam and target nuclei of similar sizes.

The production of charmonia, $c\bar{c}$ bound states, is interesting to study in proton-proton, proton-nucleus and nucleus-nucleus collisions. This process involves two scales: that of the $c\bar{c}$ pair production, which can be studied in proton-proton collisions; and that of hadronization, for which proton-nucleus collisions can bring decisive insights.

Several initial- and final-state effects occur in proton-nucleus collisions that can modify charmonium production with respect to proton-proton collisions. Charmonium production can be suppressed by nuclear absorption [1] and can be affected by multiple scattering [2], and energy loss by radiation [3] in the proton-nucleus overlapping region. Charmonium states can also be dissociated by comovers [4] or affected by the modification, namely shadowing or anti-shadowing, of the parton flux inside the nucleus [5,6]. These so-called cold nuclear-matter effects (CNM) depend on the collision energy, the transverse momentum and rapidity of the produced charmonium state, as well as the size of the target nucleus. It is therefore essential to carry out charmonium measurements over a wide range of experimental conditions. Moreover, the understanding of charmonium production and hadronization mechanisms can be significantly improved by comparison with measurements of the overall charm quark production, for which D^0 mesons are a good proxy, as their production dominates over other charm hadrons.

In this paper, a measurement of charmonium production in the LHCb fixed-target configuration is presented. The production of J/ψ mesons is studied in collisions of protons with energies of 2.5 TeV incident on neon nuclei at rest, resulting in centre-of-mass energies of $\sqrt{s_{\rm NN}} = 68.5$ GeV. It is also compared with the production of D^0 mesons measured in the same conditions [7]. In addition, the first measurement of the relative production rate of $\psi(2S)$ and J/ψ mesons in this fixed-target configuration is reported.

The LHCb detector [8,9] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. It was designed primarily 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 to precisely reconstruct the decay vertex of c and b hadrons; a tracking system with a warm magnet and tracking stations that provide a measurement of the momentum of charged particles; two ring-imaging Cherenkov detectors that provide discrimination between different species of charged hadrons; a calorimeter system consisting of scintillating-pad and preshower detectors in front of the 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) [10,11] is used to measure LHC beam profiles. It enables the injection of gases with pressure of $O(10^{-7})$ mbar in the beam-pipe section inside the VELO, allowing LHCb to operate as a fixed-target experiment. SMOG allows the injection of noble gases and therefore gives the unique opportunity to study nucleus-nucleus and proton-nucleus collisions on various targets. Due to the boost induced by the high-energy proton beam, the LHCb acceptance covers the backward rapidity hemisphere in the nucleon-nucleon centre-of-mass system of the reaction, $-2.29 < y^\star < 0$.

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Events are selected by the two-stage trigger system [12]. The first level is implemented in hardware and uses information provided by the calorimeters and the muon detectors, while the second is a software trigger. The hardware trigger requires at least one identified muon for the reconstruction of the $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decays. The software trigger requires two well-reconstructed muons having an invariant mass, $m_{\mu^+\mu^-}$, greater than $2700\,\text{MeV}/c^2$.

The data samples correspond to a collider configuration in which proton bunches moving towards the detector do not cross any bunch moving in the opposite direction. Unlike in proton-proton (pp) collisions, no nominal interaction point exists in the fixed-target case. Therefore, events are required to have a reconstructed primary vertex (PV) with its coordinate along the beam axis (z) being within the fiducial region $z_{PV} \in [-200, -100] \cup [100, 150]$ mm (where $z_{PV} = 0$ mm is the nominal position of the pp interaction point), within which high reconstruction efficiencies are achieved and calibration samples are available. Residual pp collision events, are suppressed by vetoing events with activity in the backward direction with respect to the beam direction, based on the number of hits in VELO stations upstream of the interaction region. The region $-100 < z_{PV} < 100$ mm, where most of the residual pp collisions occur, is also vetoed.

The offline selections of J/ψ and $\psi(2S)$ candidates are similar to those used in Ref. [13]. Events must contain a primary vertex with at least four tracks reconstructed in the VELO detector. The J/ψ and $\psi(2S)$ candidates are constructed from two oppositely-charged muons forming a good-quality vertex. The well-identified muons have a transverse momentum, p_{T}, larger than $500\,\text{MeV}/c$ and are required to be consistent with originating from the PV, which suppresses J/ψ and $\psi(2S)$ mesons coming from b-hadron decays. The measurements are performed in the ranges of transverse momentum $p_{\text{T}} < 8\,\text{GeV}/c$ and rapidity $2.0<y<4.29$ of J/ψ and $\psi(2S)$ mesons. Corrections for the acceptance and reconstruction efficiencies are determined using samples of simulated proton-neon (pNe) collisions. In the simulation, J/ψ and $\psi(2S)$ mesons are generated using Pythia 8 [14] with a specific LHCb configuration [15] and with colliding-proton beam momentum equal to the momentum per nucleon of the beam and target in the centre-of-mass frame. The decays are described by EvtGen [16], in which final-state radiation is generated using Photos [17]. The generated J/ψ and $\psi(2S)$ meson decay products are embedded into pNe minimum-bias events that are generated with the Epos event generator [18] using beam parameters obtained from data. Decays of hadrons 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 [19,20] as described in Ref. [21]. After reconstruction, the simulated events are assigned weights, based on the VELO cluster multiplicity. This ensures that the event multiplicity and the PV position follow the same distributions as in the data.

Table 1 Systematic and statistical uncertainties on the J/ψ meson yield. Systematic uncertainties correlated between bins affect all measurements by the same relative amount. Ranges denote the minimum and the maximum values among the $y^\star$ or p_{T} intervals while the latter value is the uncertainty integrated over $y^\star$ or p_{T}

Systematic uncertainties	
Uncorrelated between bins	
Simulation sample size	[1.4, 7.0]%; 2.3 %
Signal determination	[1.4, 11.0]%; 3.5 %
Correlated between bins	
Proton-proton collisions	2.0%
Neon purity	1.2%
Tracking efficiency	1.1%
Particle identification efficiency	1.1%
PV	3.9%
Luminosity	6.5%
Statistical uncertainty	1.6%

Figure 1 shows the invariant-mass distributions for the J/ψ and $\psi(2S)$ candidates, from which the corresponding signal yields are obtained with extended maximum-likelihood fits, after all selection criteria are applied to the entire pNe data set. The signals are described by Crystal Ball functions [22] and the background shapes are modelled by exponential functions. The total J/ψ and $\psi(2S)$ signal yields are 4542 ± 71 and 76 ± 12, respectively. The signal yields are determined independently in intervals of p_{T} and $y^\star$. These yields are corrected for the total efficiencies, evaluated to 36.6% and 38.8% for the J/ψ and $\psi(2S)$ respectively, which account for the geometrical acceptance of the detector, and the efficiencies of the trigger, event selection, PV and track reconstruction, and particle identification. Particle identification [23] and tracking efficiencies are obtained from control samples in pp collision data. All other efficiencies are determined using samples of simulated data.

Several sources of systematic uncertainty are considered, affecting either the determination of the signal yields or the total efficiencies. They are summarised in Table 1 separately for contributions that are correlated and uncorrelated between different intervals of p_{T} and $y^\star$. Systematic uncertainty on the signal determination includes several contributions. A significant systematic uncertainty arises from the finite size of the simulation samples. The systematic uncertainty associated to the determination of the signal yields is related to the mass fit. This uncertainty is evaluated using alternative models for signal and background shapes, Gaussian and polynomial functions respectively, that reproduce the mass distributions equally well. The effect of the small (below 0.1%) residual contribution of signal from b hadrons

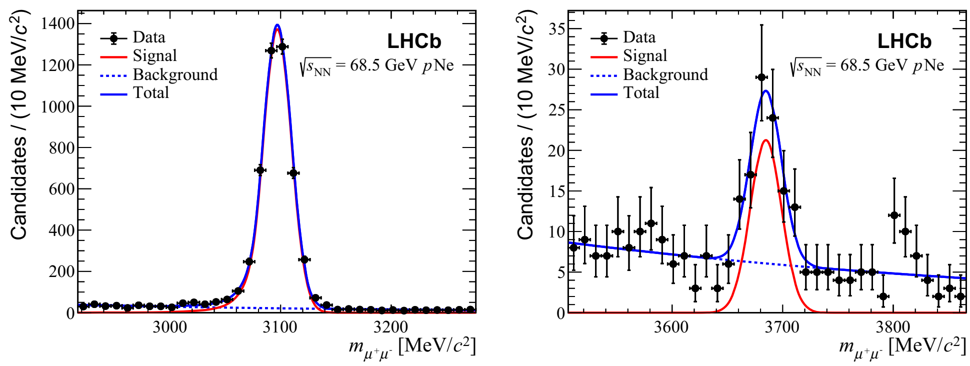


Fig. 1 Invariant mass distributions of (left) $J/\psi \rightarrow \mu^-\mu^+$ candidates and (right) $\psi(2S) \rightarrow \mu^-\mu^+$ candidates. The data are overlaid with the fit function

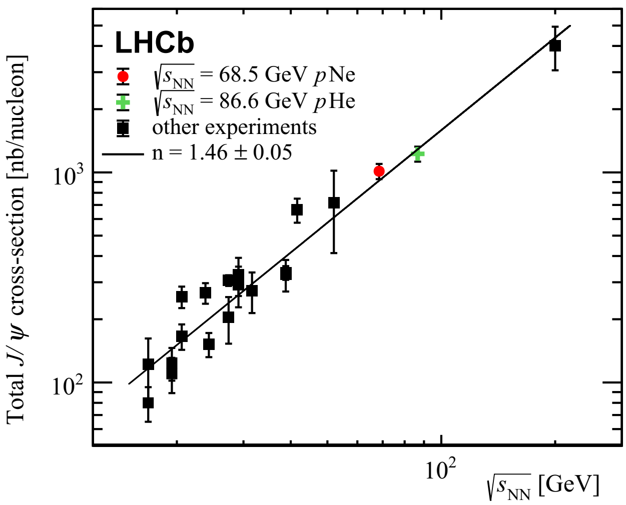


Fig. 2 Total J/ψ cross-section per target nucleon as a function of centre-of-mass energy. Experimental data, represented by black points, are taken from Ref. [24]. The red point corresponds to the pNe result from the present analysis. The green point corresponds to a measurement performed by LHCb with pHe collisions [13]

is investigated and found to be negligible. Other contributions are obtained by determining the maximum contamination from residual pp collisions with samples of pure pNe collisions and pure pp collisions. The neon purity systematic uncertainty corresponds to the contamination from collisions between the beam and elements different from neon, coming from standard outgassing. It is quantified using data samples recorded with no neon injection. Since the tracking and particle identification efficiencies are determined using pp control samples, the differences between the track multiplicity in pNe and pp collisions are considered as systematic uncertainties. The tracking and particle identification systematic uncertainties also take into account the size of the pp control samples. The PV reconstruction systematic uncertainty corresponds to the variation of the efficiency over the whole z_{PV} range, and to the difference between the PV reconstruction efficiency evaluated using the simulation and a data-driven approach exploiting the well-reconstructed $\phi \rightarrow K^+K^-$ decay. The integrated luminosity is determined to be 21.7 ± 1.4 nb^{-1} from the yield of electrons elastically scattering off the target Ne atoms as presented in Ref. [25]. The measured J/ψ production cross-section per target nucleon and within $y^\star \in [-2.29, 0]$, using the world average branching fraction of $J/\psi \rightarrow \mu^+\mu^-$ decays [26], is

$$\sigma_{J/\psi} = 506 \pm 8 \pm 46 \text{ nb/nucleon},$$

where the first uncertainty is statistical and the second systematic. To compare with previous experimental results at different energies, the J/ψ cross-section is extrapolated to the full phase space using PYTHIA 8 with the CT09MCS PDF set [27], with no additional uncertainty related to the extrapolation, assuming forward-backward symmetry in the rapidity distribution. After extrapolation, the total J/ψ cross-section is

$$\sigma^{4\pi}_{J/\psi} = 1013 \pm 16 \pm 92 \text{ nb/nucleon},$$

where the first uncertainty is statistical and the second systematic. An overview of J/ψ cross-section measurements performed at different centre-of-mass energies by different experiments [24], including this measurement and the previous LHCb measurement in pHe collisions at $\sqrt{s_{NN}} = 86.6$ GeV [13], is shown in Fig. 2. The data are well reproduced with the function $\sigma_{J/\psi} = C \times (\sqrt{s_{NN}})^n$, with $n = 1.46 \pm 0.05$ ($\chi^2/n_{dof} = 64.6/18$ and p-value $= 4 \times 10^{-7}$), indicating a power-law dependence of the cross-section on the centre-of-mass energy, between $\sqrt{s_{NN}} \sim 20$ GeV and $\sqrt{s_{NN}} = 200$ GeV.

The J/ψ differential cross-sections per target nucleon, as functions of $y^\star$ and p_T, are shown in Fig. 3. These results are compared with predictions of the HELAC-Onia (HO) generator [28–30], using QCD leading order (LO) calculations within the Color Singlet Model (CSM), with the proton CT14NLO and nuclear nCTEQ15 PDF [31] sets. The error band is obtained by varying the renormalization and factorization scales from 0.5 to 2. These predictions underestimate the measured total cross-sections. The data are better described by alternative predictions (Vogt), using calculations in the Color Evaporation Model carried out at next-to-

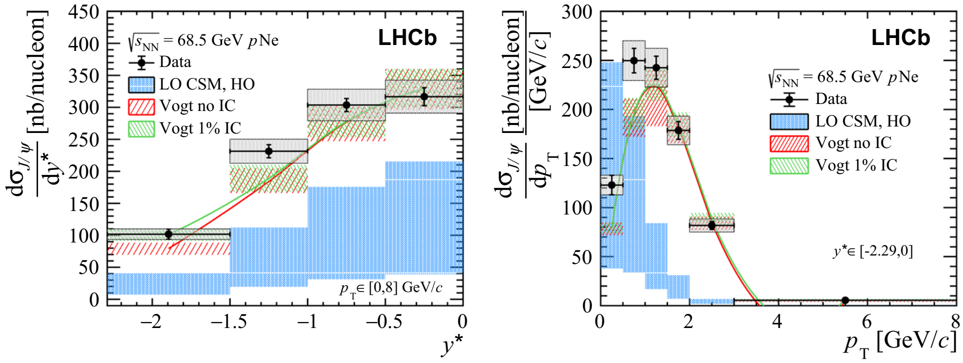
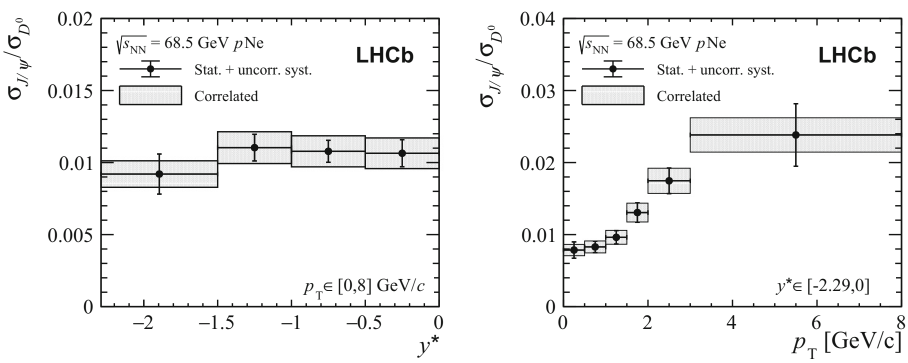


Fig. 3 Differential J/ψ cross-section as a function of (left) $y^\star$ and (right) p_T. The quadratic sums of statistical and uncorrelated systematic uncertainties are given by the error bars, while the grey boxes represent the correlated systematic uncertainties. Blue boxes (LO CSM, HO) correspond to predictions using the CT14NLO and nCTEQ15 PDF sets [28–31]. Green and red boxes correspond to predictions (Vogt) from [32] with and without a 1% intrinsic charm (IC) contribution respectively (green and red lines indicate the central values)

Fig. 4 Ratio of J/ψ and D^0 cross-sections as a function of (left) $y^\star$ and (right) p_T. The quadratic sums of the statistical and uncorrelated systematic uncertainties are given by the error bars, while the grey boxes represent the correlated systematic uncertainties



leading order (NLO) in the heavy-flavour cross-section, with or without a 1% intrinsic charm (IC) contribution [32].

The J/ψ production cross-section is also compared to the D^0 production cross-section extracted from the same dataset, in the same kinematical conditions [7]. Several systematic uncertainties cancel in the $J/\psi/D^0$ cross-section ratio, related to the PV and track reconstruction efficiencies, the contamination from residual pp collisions, the neon purity and the luminosity determination. The ratio of J/ψ and D^0 cross-sections is

$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = (1.06 \pm 0.02 \pm 0.09)\%,$$

where the first uncertainty is statistical and the second systematic. The ratio takes into account the branching fractions [26] of $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$. The J/ψ-to-D^0 cross-section ratio as a function of $y^\star$ and p_T is shown in Fig. 4. Although this ratio shows a strong dependence on p_T, the data show no significant rapidity dependence.

The $\psi(2S)$ production cross-section is also measured. Due to the limited size of the $\psi(2S)$ sample, only the relative production rate of $\psi(2S)$ and J/ψ mesons is presented, where most of the efficiencies and systematic uncertainties cancel out. The remaining systematic uncertainties are evaluated to be 0.01% for the finite size of the simulation sample, 0.09% for the total efficiency differences between J/ψ and $\psi(2S)$ and 0.05% for the signal extraction. The relative production rate of $\psi(2S)$ and J/ψ mesons is

$$\frac{\mathcal{B}_{\psi(2S)\to\mu^+\mu^-}}{\mathcal{B}_{J/\psi\to\mu^+\mu^-}} \times \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = (1.67 \pm 0.27 \pm 0.10)\%,$$

where $\mathcal{B}_{\psi(2S)\to\mu^+\mu^-}$ and $\mathcal{B}_{J/\psi\to\mu^+\mu^-}$ are the branching fractions of $\psi(2S) \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decays, respectively, and the first uncertainty is statistical and the second systematic. Figure 5 compares this result to measurements performed at various centre-of-mass energies by other experiments as a function of the target atomic mass number A [33–37]. Measurement is in agreement with other proton-nucleus measurements at similar values of A.

In summary, the study of charmonium production in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV recorded by the LHCb experiment is presented. The J/ψ production cross-section is measured in the centre-of-mass rapidity range $y^\star \in [-2.29, 0]$. The comparison of this new measurement with earlier data supports a power-law dependence of the J/ψ production cross-section on centre-of-mass energy. The J/ψ-to-D^0 cross-section ratio is found to be independent of rapidity and the $\psi(2S)$-to-J/ψ cross-section ratio is found to be

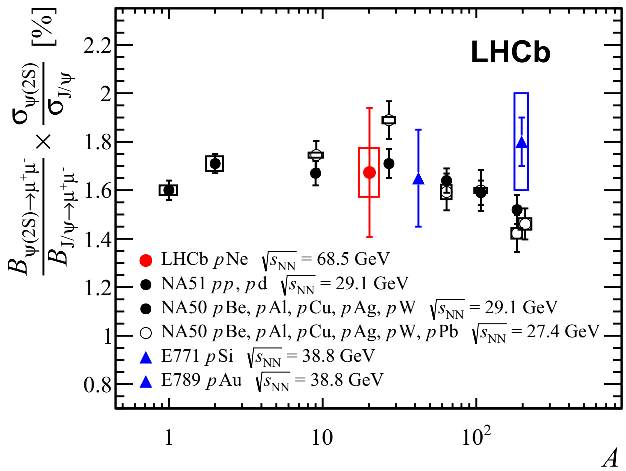


Fig. 5 The $\psi(2S)$-to-J/ψ production ratio as a function of the target atomic mass number A. The red point corresponds to the $\sqrt{s_{NN}} = 68.5$ GeV pNe result from the present analysis, vertical error bar corresponds to the statistical uncertainty and the box to the systematic uncertainty. The other points show previous fixed-target experimental data at various centre-of-mass energies [33–37]

$(1.67 \pm 0.27 \pm 0.10)\%$. This result is in a good agreement with other measurements involving beam and target nuclei of similar sizes, and performed at different centre-of-mass energies.

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