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Open charm production and asymmetry in pNe collisions at $\sqrt{s_{\rm NN}} = 68.5$ GeV

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Abstract A measurement of D^0 meson production by the LHCb experiment in its fixed-target configuration is presented. The production of D^0 mesons is studied with a beam of 2.5 TeV protons colliding on a gaseous neon target at rest, corresponding to a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{\rm NN}} = 68.5$ GeV. The sum of the D^0 and $\overline{D}^0$ production cross-section in pNe collisions in the centre-of-mass rapidity range $y^\star \in [-2.29, 0]$ is found to be $\sigma_{D^0}^{y^\star\in[-2.29,0]} = 48.2 \pm 0.3 \pm 4.5\,\mu$b/nucleon where the first uncertainty is statistical and the second is systematic. The $D^0 - \overline{D}^0$ production asymmetry is also evaluated and suggests a trend towards negative values at large negative $y^\star$. The considered models do not account precisely for all the features observed in the LHCb data, but theoretical predictions including 1% intrinsic charm and 10% recombination contributions better describe the data than the other models considered.

The production of D^0 charm mesons is sensitive to non-perturbative aspects of Quantum Chromodynamics (QCD). As it reflects a large fraction of the overall charm quark production, D^0 meson production can serve as a reference for the study of the modification of hidden charm ($c\bar{c}$ bound states) production in proton-nucleus and nucleus-nucleus collisions, due to the so-called cold nuclear matter (CNM) and hot and dense matter (HDM) effects [1]. Additionally, the study of D^0 and $\overline{D}^0$ mesons, $c\bar{u}$ and $\bar{c}u$ bound states, may bring new insight on the intrinsic charm content of the nucleon [2], as already performed with the proton-helium (pHe) data collected with LHCb at $\sqrt{s_{\rm NN}} = 86.6$ GeV [3], complementing the results obtained in proton–proton (pp) collisions at $\sqrt{s_{\rm NN}} = 13$ TeV via the measurement of $Z + c$ jets [4,5]. Moreover, in collisions involving a high Bjorken-x parton the charm quarks may recombine with valence quarks from the initial hadrons and lead to an asymmetry between the D^0 and $\overline{D}^0$ production cross-sections [6–8].

In this paper, a measurement of D^0 production in fixed-target proton-neon (pNe) collisions at the LHC is presented. The sum of the D^0 and $\overline{D}^0$ production, and the $D^0 - \overline{D}^0$ production asymmetry, are studied in collisions of protons with energy of 2.5 TeV incident on neon nuclei at rest, corresponding to a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{\rm NN}} = 68.5$ GeV. These measurements are performed in the negative rapidity hemisphere in the centre-of-mass frame where the proton beam and neon target have positive and negative rapidity $y^\star$, respectively.

The LHCb detector [9,10] is a single-arm forward spectrometer designed for the study of particles containing c or b quarks, covering the pseudorapidity range $2 < \eta < 5$ in the laboratory frame. The detector elements that are particularly relevant to this analysis 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; two ring-imaging Cherenkov detectors that are able to discriminate between different species 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 multi-wire proportional chambers. The system for measuring the overlap with gas (SMOG) [11] enables the injection of gases with a 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 for various gaseous targets. Due to the boost induced by the high-energy proton beam, which travels along the positive-z direction, the LHCb acceptance covers the negative rapidity hemisphere in the centre-of-mass system of the reaction $y^\star \in [-2.29, 0]$.

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 at the nominal pp interaction point. Standard pp collision events were also collected concurrently with the pNe collision data.

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Events are selected by the two-stage trigger system [12]. The first level is implemented in hardware, while the second is a software trigger. The hardware trigger requires a minimum deposited energy of 7.8 GeV in the calorimeter for the $D^0 \rightarrow K^-\pi^+$ selection.[1] The software trigger requires a well-reconstructed D^0 decay vertex formed by clearly identified kaon and pion tracks, both of which are required to have a transverse momentum greater than 250 MeV/c and a combined invariant mass in the range [1784, 1944] MeV/c^2.

Special care is taken to suppress residual pp collisions induced by debunched protons. The PV must lie in the fiducial region $z_{\rm PV} \in [-200, -100] \cup [100, 150]$ mm, where high reconstruction efficiencies are achieved and calibration samples are available. Here $z_{\rm PV}$ is the reconstructed position along the beam axis. The region $-100 < z_{\rm PV} < 100$ mm, where most of the residual pp collisions occur, is excluded. A veto is imposed on events with activity in the backward region, with respect to the proton beam direction, based on the number of hits in the VELO stations upstream of the interaction point.

The offline selection of D^0 candidates is similar to that used in Ref. [13]. Events must contain a primary vertex with at least four tracks reconstructed in the VELO detector. The kaon and pion originating from the D^0 decay are required to be of good quality and to come from a common displaced vertex relatively to the associated PV position to which the D^0 candidate has the smallest impact parameter. Tight requirements are set on the kaon and pion particle identification information. The D^0 candidates are required to have a proper decay time greater than 0.5 ps. The measurements are performed in the range of D^0 transverse momentum $p_{\rm T} < 8$ GeV/c and $2.0 < y < 4.29$, where y is the rapidity in the laboratory frame.

The detection efficiencies are determined using samples of simulated pNe collisions. In the simulation, D^0 mesons are generated in simulated proton–proton collisions using Pythia 8 [14], which has implemented the Lund string fragmentation model [15], with a specific LHCb configuration [16] and with colliding-proton beam momenta equal to the momenta per nucleon of the beam and target in the centre-of-mass frame. The decays are generated by EvtGen [17], in which final-state radiation is handled by Photos [18]. The four-momenta of the D^0 decay products are embedded into pNe minimum bias events that are produced with the Epos event generator [19] using beam parameters obtained from the data. The event obtained after embedding is then boosted to the laboratory frame to get the fixed-target configuration. Decays of hadronic particles generated with Epos are also implemented with EvtGen. The interaction of the generated particles with the detector and its response, are handled with the Geant4 toolkit [20,21] as described in Ref. [22]. After reconstruction, the simulated events are assigned weights to ensure that the VELO cluster multiplicity distribution matches the distribution in the data.

The D^0 signal yields are obtained from extended unbinned maximum likelihood fits to their mass distributions. The signals are described by Gaussian functions while the background contributions are described by exponential functions. Figure 1 shows the $K^-\pi^+$ and $K^+\pi^-$ invariant mass distributions obtained after all selection criteria are applied to the entire pNe data set, with the fit functions superimposed. Additionally, the signal yields are determined in intervals of $p_{\rm T}$ with edges (0, 0.5, 1, 1.5, 2, 3, 8 GeV/c) and $y^\star$ with edges (−2.29, −1.5, −1.0, −0.5, 0). These yields are corrected for the total efficiencies, which account for the geometrical acceptance of the detector, and the efficiencies of the trigger, event selection including the D^0 selection, PV and track reconstruction, and particle identification. Particle identification [23] and tracking [24] efficiencies are obtained from control samples of pp collision data. All other efficiencies are determined using samples of simulated data.

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 contributions that are correlated and uncorrelated between the kinematic intervals. Systematic uncertainties on the signal determination include the contribution from b-hadron decays and the maximum contamination from residual pp collisions. More precisely, the fraction of signal from b-hadrons, included in the extracted yield and determined through the study of the impact parameter distribution of the D^0 candidates with respect to the primary vertex, is 1.1%. Contributions from residual pp collisions are estimated using samples of pure pNe collisions and pure pp collisions, both samples being collected using dedicated LHC beam configurations. These contributions result in a total 2.3% uncertainty assigned to the signal determination. 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. Overall, systematic uncertainties of 3.0% and 3.6% are assigned due to tracking and particle identification efficiencies, respectively. The PV reconstruction systematic uncertainty is determined by considering the variation of the efficiency over the whole $z_{\rm PV}$ range and the difference between the simulation and a data-driven approach to evaluate the PV efficiency. Possible contamination from collisions between the beam and atoms different from neon is quantified using data samples recorded with no neon injection, resulting in an upper limit of 1.2%, identified as the neon purity uncertainty. Two uncorrelated systematic uncertainties are also considered. First, the uncertainty related to the mass fit is evaluated using alternative models for signal and back-

[1] Inclusion of charge-conjugate processes is implied throughout, unless otherwise said.

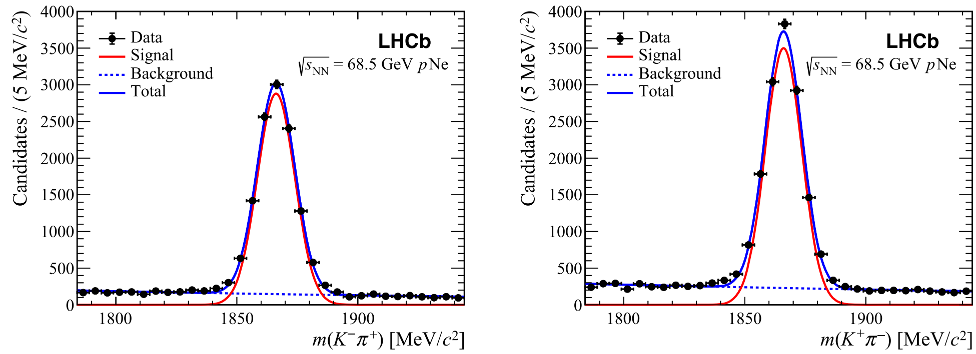

Fig. 1 Invariant mass distributions of (left) $K^-\pi^+$ and (right) $K^+\pi^-$ candidates. The data are overlaid with the result of the fit

ground shapes that reproduce the mass shapes equally well. Another source of uncertainty is associated with the accuracy of the simulation used to compute the acceptances and efficiencies. This uncertainty accounts for the finite size of the simulation sample and observed discrepancies between the data and the simulation, in the rapidity and $p_{\rm T}$ distributions.

The integrated luminosity is determined to be $\mathcal{L}_{p\rm Ne} = 21.7 \pm 1.4\ \rm nb^{-1}$ from the yield of electrons elastically scattering off the target atoms as presented in Ref. [25]. The measured D^0 and $\overline{D}{}^0$ cross-section per target nucleon within $y^\star \in [-2.29, 0]$, after taking into account the known branching fraction of $D^0 \to K^-\pi^+$ [26], is

$$\sigma_{D^0}^{y^\star\in[-2.29,0]} = \frac{Y_{D^0\to K^-\pi^+}}{\mathcal{B}_{D^0\to K^-\pi^+} \times \varepsilon_{D^0} \times \mathcal{L}_{p\rm Ne}} = 48.2 \pm 0.3\,(\text{stat.}) \pm 4.5\,(\text{syst.})\,\mu\text{b/nucleon},$$

where $Y_{D^0\to K^-\pi^+}$, $\mathcal{B}_{D^0\to K^-\pi^+}$ and ε_{D^0} are D^0 yield, branching fraction and total efficiency respectively. No correction is applied to account for the small fraction (1.1%) of signal from b-hadron decay. The cross-section per target nucleon, extrapolated to the full phase-space using Pythia 8 with a specific LHCb tuning and with the CT09MCS parton distribution functions [27], assuming forward-backward symmetry in the rapidity distribution, thus neglecting a possible small asymmetry induced by nuclear Parton Distribution Functions, is

$$\sigma_{D^0}^{4\pi} = 97.6 \pm 0.7\,(\text{stat.}) \pm 9.1\,(\text{syst.})\,\mu\text{b/nucleon}.$$

The D^0 differential cross-sections per target nucleon, as functions of $y^\star$ and $p_{\rm T}$, are shown in Fig. 2. These results are compared with the fixed-order plus next-to-leading-logarithms resummation model calculations (FONLL) [28, 29], and a parton-hadron-string dynamics (PHSD) transport calculation [30]. Both predictions fail to reproduce either the low (PHSD) or high (FONLL) $p_{\rm T}$ region, while the rapidity shapes are in better agreement with the data. Most features of the LHCb measurements are well described by alternative predictions with (Vogt 1% IC) or without (Vogt no IC) intrinsic charm contributions, both taking into account the shadowing effect [31], and by predictions (MS) including 1% intrinsic charm and 10% recombination contributions

Table 1 Systematic and statistical uncertainties on the signal yields. Systematic uncertainties correlated between $y^\star$ or $p_{\rm T}$ bins affect all measurements by the same relative amount. Ranges denote the minimum and the maximum values among the $y^\star$ or $p_{\rm T}$ bins

Systematic uncertainties	
Correlated between bins	
Signal determination	2.3%
Tracking efficiency	3.0%
Particle identification efficiency	3.6%
PV reconstruction efficiency	4.1%
Neon purity	1.2%
Luminosity	6.5%
Uncorrelated between bins	
Signal and background model	[0.3, 5.6]%
Simulation sample	[0.7, 8.0]%
Total correlated uncertainty	9.3%
Total uncorrelated uncertainty	[1.1, 9.2]%
Total statistical uncertainty	[2.3, 7.7]%

[6]. Note that only the FONLL predictions include the factorization scale and parton distribution function uncertainties, while the bands in Vogt's predictions represent the variation due to the shadowing, and PHSD or MS models have no uncertainty. Note also that D^0 and D^* measurements have been performed by the STAR experiment in $\sqrt{s} = 200$ GeV pp collisions at midrapidity [32], showing a better agreement with FONLL predictions at moderate and large $p_{\rm T}$.

Finally, the $D^0 - \overline{D}{}^0$ production asymmetry is presented. It is quantified as

$$\mathcal{A}_{\rm prod} = \frac{Y_{\rm corr}(D^0) - Y_{\rm corr}(\overline{D}{}^0)}{Y_{\rm corr}(D^0) + Y_{\rm corr}(\overline{D}{}^0)}, \tag{1}$$

where $Y_{\rm corr}(D^0)$ and $Y_{\rm corr}(\overline{D}{}^0)$ correspond to the $D^0 \to K^-\pi^+$ and $\overline{D}{}^0 \to K^+\pi^-$ efficiency corrected yields respectively. The uncertainties associated with the luminosity determination, neon purity and particle identification efficiency cancel in the asymmetry. Furthermore, uncertainties related to the tracking efficiency and simulation samples partially cancel. A conservative systematic uncertainty of 2.8% is

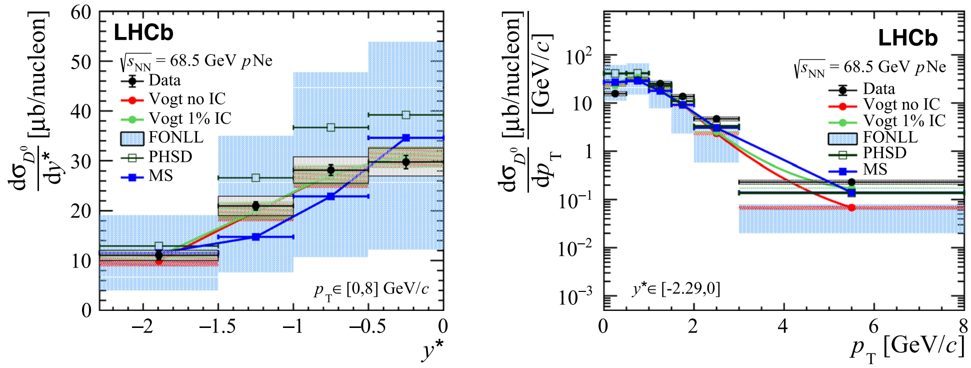

Fig. 2 Measured D^0 cross-section in $\sqrt{s_{NN}} = 68.5$ GeV pNe collisions as function of (left) $y^{\star}$ and (right) p_T. The quadratic sums of statistical and uncorrelated systematic uncertainties are given by the bars, while the grey boxes represent the correlated systematic uncertainties. The data are overlaid with theoretical predictions as described in the text

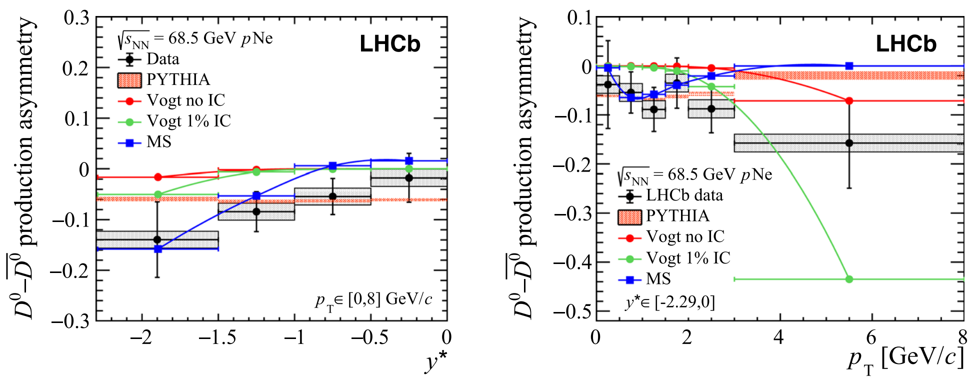

Fig. 3 The $D^0 - \overline{D}^0$ production asymmetry in $\sqrt{s_{NN}} = 68.5$ GeV pNe collisions as function of (left) centre-of-mass rapidity $y^{\star}$, and as function of (right) transverse momentum p_T. Quadratic sums of statistical and uncorrelated uncertainties are given by the error bars, while the grey boxes represent the correlated systematic uncertainties. The data are overlaid with theoretical predictions as described in the text

assigned to account for the uncertainty on the simulated material budget of the detector.

The results are presented in Fig. 3 and indicate a negative asymmetry from ~ 0 down to $\sim -15\%$ from $y^{\star} = 0$ to $y^{\star} = -2.29$. The largest asymmetry is obtained at $y^{\star} = -2.29$, where the valence quark contribution of the neon target is more significant than at $y^{\star} \sim 0$. The data are compared with Pythia 8 predictions which show a $D^0 - \overline{D}^0$ asymmetry of about -6%. This asymmetry, which may be caused by the fragmentation models included in Pythia [33,34], is compatible with the data, but mostly independent of $y^{\star}$ and p_T. While the Vogt predictions from Ref. [31], which represent an upper limit, do not perfectly reproduce the asymmetry scale, they indicate trends compatible with the data for both the rapidity and transverse momentum ratios. The MS predictions including 1% IC and 10% recombination contributions [6] are also generally consistent with the data.

In summary, a study of D^0 meson production in $\sqrt{s_{NN}} = 68.5$ GeV pNe collisions with the LHCb experiment is presented. The sum of the D^0 and $\overline{D}^0$ production cross-section per target nucleon, measured in the centre-of-mass rapidity range $y^{\star} \in [-2.29, 0]$, is found to be $\sigma_{D^0}^{y^{\star}\in[-2.29,0]} = 48.2 \pm 0.3\,(\text{stat.}) \pm 4.5\,(\text{syst.})$ μb/nucleon. The $D^0 - \overline{D}^0$ production asymmetry tends towards a negative value of roughly -15% in the $y^{\star} \sim -2$ region, where the valence quark contribution of the neon target is more significant than at $y^{\star} \sim 0$.

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