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New measurements in fixed-target collisions at LHCb

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The LHCb spectrometer has the unique capability to function as a fixed-target experiment by injecting gas into the LHC beam pipe while proton or ion beams are circulating. The resulting beam+gas collisions cover an unexplored energy range that is above previous fixed-target experiments, but below the top RHIC energy for AA collisions. Here we present new results on open charm, J/ψ, and ψ(2S) production from pNe and PbNe fixed-target collisions at LHCb. Comparisons with various theoretical models of particle production and transport through the nucleus will be discussed.

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1. The fixed-target program at LHCb

The LHCb detector at the LHC is a single-arm spectrometer covering the forward pseudorapidity region between $2 < \eta < 5$ [1]. Optimized for the study of hadrons containing beauty or charm quarks, the detector features precision vertex reconstruction, tracking, particle identification, calorimetry, and muon identification over its full forward acceptance [1, 2]. In addition to its unique kinematic coverage, the LHCb detector is also novel in its ability to operate as both a collider and fixed-target experiment thanks to its System for Measuring Overlap with Gas (SMOG), a gas injection system originally developed for luminosity measurements [3]. During the LHC Run 2, SMOG was used to inject small amounts of noble gases into the LHC beam pipe near the LHCb interaction point and one of the circulating LHC beams was used to create proton-gas and Pb-gas collisions. The resulting fixed-target collisions in LHCb provide access to rapidity in the center of mass system y^* between -2.29 and 0 and cover a larger Bjorken x ($\sim 10^{-1}$) and lower Q^2 phase space than that probed in collider-mode collisions [3]. Depending on the energy of the circulating LHC beam, the center of mass energy $\sqrt{s}$ ranges from 41 to 115 GeV. The unique phase space coverage of the LHCb fixed-target program, combined with the ability to produce both pA and PbA collisions with gases of different nuclear species A, provides excellent opportunities to study and constrain cold nuclear matter effects in a variety of nuclear systems.

Recent measurements of charmonium and D^0 production in pNe and PbNe collisions were performed using fixed-target datasets collected by LHCb in 2017 and 2018, respectively [4]-[6]. Both datasets were collected using a 2.5 TeV beam from the LHC (2.5 TeV for the p beam, 2.5 TeV/nucleon for the Pb beam) incident on Neon gas atoms, resulting in a center of mass energy $\sqrt{s}$ of 68.5 GeV. These measurements are compared to various theoretical models and are also used to study cold nuclear matter effects on hidden and open charm mesons.

2. Charm production in *pNe* collisions

Measurements of hidden and open charm meson production in pNe collisions were performed with the 2017 dataset, which has an integrated luminosity of $\mathcal{L} = 21.7 \pm 1.4$ nb^{-1}. D^0 meson candidates were reconstructed in the decay channel $D^0 \rightarrow K^-\pi^+$, while the J/ψ and $\psi(2S)$ candidates were reconstructed in the dimuon decay channel [4, 5]. All three hadrons were selected with $p_T < 8$ GeV/c and rapidity in the laboratory frame $2.0 < y < 4.29$. Since the pNe data was collected simultaneously with pp collisions during the 2017 LHCb data-taking, an additional cut on the reconstructed primary vertex was applied to exclude contamination from debunched pp collision events. Only candidates with a primary vertex located in z_{PV} between [-200, -100] or [100, 150] mm were retained for the measurement.

The differential cross sections for D^0 meson production were measured as a function of the D^0 y^* and p_T and are shown in Figure 1. The LHCb measurements, shown in the black data points, are compared to theoretical models that take into account a variety of cold nuclear matter effects. The predictions from Vogt include nuclear shadowing effects and are shown with and without a 1% intrinsic charm (IC) contribution included [7]. The MS predictions include a 1% IC contribution and 10% recombination contributions [8]. The parton-hadron-string dynamics (PHSD) prediction [9] is a transport model calculation, and the FONLL predictions [10, 11] are

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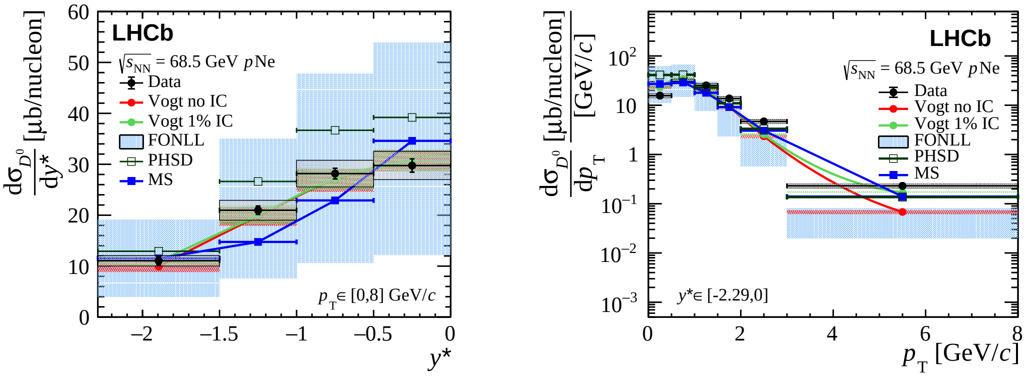

Figure 1: The differential cross sections for D^0 production in pNe collisions as a function of the D^0 (left) y^* and (right) p_T [4]. The LHCb data points in black are compared to a variety of theoretical models (see text for details).

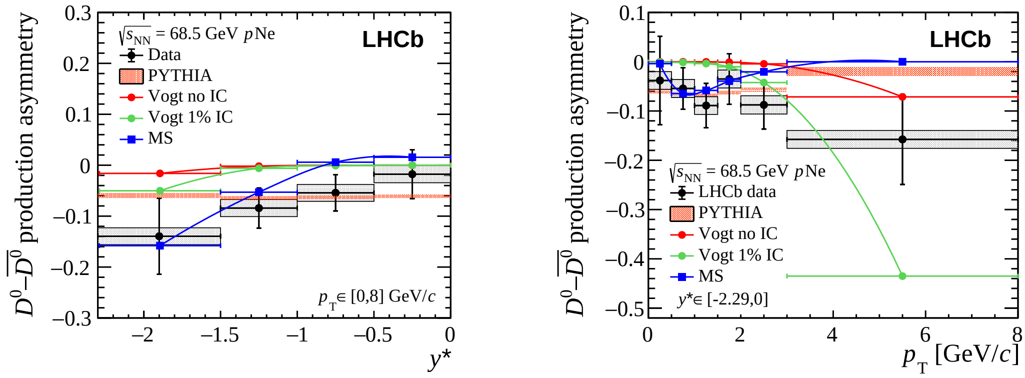

Figure 2: The $D^0 - \overline{D^0}$ production asymmetry in pNe collisions as a function of the D^0 (left) y^* and (right) p_T. [4]

a fixed-order plus next-to-leading-logarithms calculation with uncertainties from the factorization scale and parton distribution functions included. In addition to the differential cross sections, the total D^0 cross section was also measured and extrapolated to the full phase-space using PYTHIA 8 and the CT09MCS parton distribution functions [4].

The $D^0 - \overline{D^0}$ production asymmetry, which probes charm quark hadronization with a high-x valence quark, was also measured as a function of the D^0 y^* and p_T and is shown in Figure 2. The results are compared to several of the same theoretical models as described above, as well as to PYTHIA [12]. The trends seen in the data are better described by the Vogt and MS predictions than by PYTHIA [4].

The production of hidden charm mesons was also studied in pNe collisions [5]. Figure 3 shows the measured differential cross sections for J/ψ production as a function of the J/ψ y^* and p_T. The LHCb data points are compared to Leading-Order Color Singlet Model (LO CSM) predictions computed using the HELAC-Onia generator and to predictions by Vogt [7] that were computed with the Color Evaporation Model and include contributions from nuclear absorption of the $c\overline{c}$ state and multiple scattering. The L0 CSM predictions do not describe the trends observed

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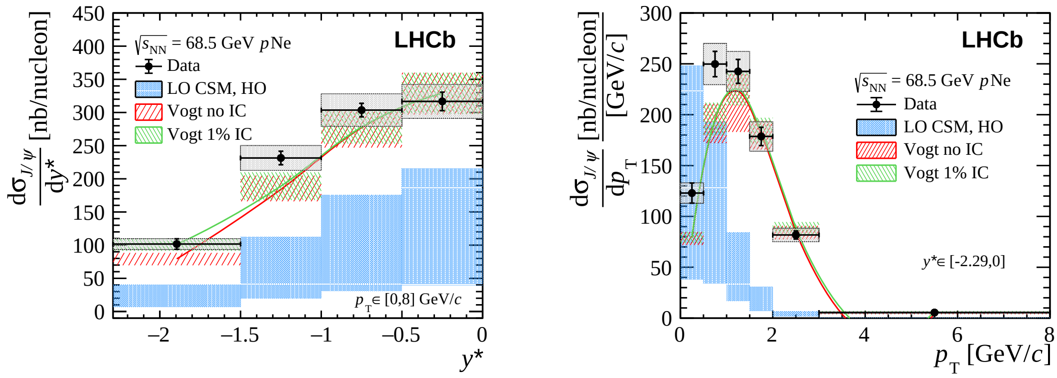

Figure 3: The differential cross sections for J/ψ production in pNe collisions as a function of the J/ψ (left) y^* and (right) p_T [5]. The LHCb data points in black are compared to several theoretical models (see text for details).

in data, indicating the need for higher-order calculations to describe the J/ψ production. The Vogt predictions describe both of the observed y^* and p_T trends, however the current precision in the data cannot yet distinguish between predictions with or without a 1% IC component. As with the D^0 measurement, the J/ψ total cross section per target nucleon was also measured and then extrapolated to the full phase space using PYTHIA 8 and the CT09MCS PDF set. The resulting cross section, $\sigma^{4\pi}_{J/\psi} = 1013 \pm 16 \pm 83$ nb/nucleon, where the first uncertainty is the statistical uncertainty and the second the systematic uncertainty, is in good agreement with previous measurements of the total J/ψ cross section as a function of $\sqrt{s_{NN}}$ [5]. Due to the limited sample size, similar cross section measurements were not made for the $\psi(2S)$ and instead the relative production rate of $\psi(2S)$ and J/ψ mesons was measured. The result, shown in red in Figure 4, was found to be in good agreement with measurements on other nuclear targets and at similar center of mass energies.

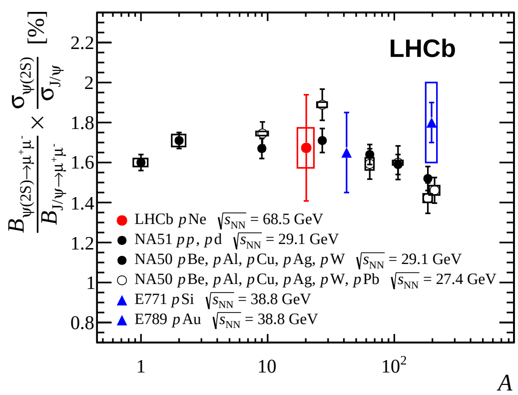

Figure 4: The relative production rate of $\psi(2S)$ and J/ψ mesons in pNe collisions (shown in red), compared to measurements from other fixed-target experiments. [5]

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3. Charm production in PbNe collisions

D^0 and J/ψ production were also measured in PbNe collisions to compare hidden and open charm production between large (PbNe) and small (pNe) nuclear systems [6]. This measurement is the first fixed-target AA collision at the LHC. The charm hadron candidate selection is similar to that used for the pNe measurements. The J/ψ to D^0 cross section ratio was measured in PbNe collisions and compared to the same ratio measured in pNe collisions, using the cross section measurements described in the previous section. The ratio in collisions of nuclei with mass numbers A and B is assumed to have the functional form $\sigma^{AB}_{J/\psi}/\sigma^{AB}_{D^0} = \sigma^{pp}_{J/\psi}/\sigma^{pp}_{D^0} \times (AB)^{\alpha-1}$. If the parameter α is equal to one, then $\sigma_{J/\psi}/\sigma_{D^0}$ is the same for both pp and AB collisions. However, an α value less than one indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons. The function can be equivalently written as a function of N_{coll}, the number of binary nucleon-nucleon collisions obtained from a Glauber analysis [6]. The cross section ratios as a function of AB and N_{coll} are shown in Figure 5, with the α values from the fits to the data listed on the plots. The α values smaller than one indicate that the J/ψ mesons do experience more nuclear effects in PbNe collisions than D^0 mesons. Within the current experimental uncertainties, a linear trend is observed between pNe collisions and central PbNe collisions, preventing the conclusive observation of anomolous J/ψ suppression or the formation of a deconfined medium. Future measurements in PbA collisions with LHCb's upgraded fixed-target gas injection cell for Run 3, SMOG2, will have much smaller statistical and systematic uncertainties to enable more precise measurements of charmonia production in nuclear systems [13].

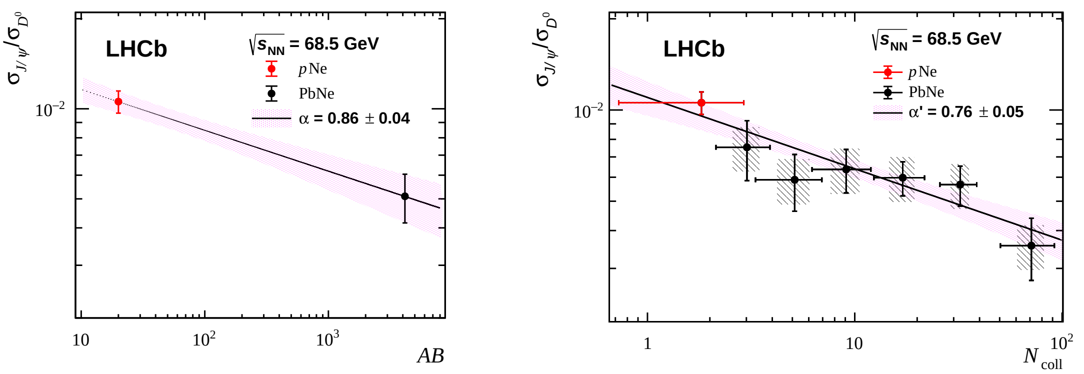

Figure 5: The J/ψ to D^0 cross section ratios as a function of (left) the atomic mass numbers A and B of the beam and target nuclei, and (right) the number of binary nucleon-nucleon collisions N_{coll} [6].

4. Conclusion

Measurements of D^0 and charmonium production have recently been performed in $\sqrt{s}$ = 68.5 GeV pNe and PbNe collisions with the LHCb detector in its fixed-target configuration. In pNe collisions, the $D^0 - \overline{D^0}$ production asymmetry and differential D^0 and J/ψ cross sections as a function of the hadron y^* and p_T were measured. The results were compared with theoretical calculations including a variety of charm hadronization mechanisms and cold nuclear matter effects. A measurement of the relative production rate of $\psi(2S)$ and J/ψ mesons was also performed and

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found to be consistent with rates measured in other fixed-target experiments. The first fixed-target AA experiment at the LHC was performed with PbNe collisions, and the J/ψ to D^0 cross section ratio was measured and compared to that in pNe collisions. The resulting trend of the ratio as a function of N_{coll} does not permit a conclusive observation of J/ψ anomolous suppression within the current experimental uncertainties. LHCb's upgraded fixed-target system, SMOG2, is now operational in Run 3 and will collect much larger samples of fixed-target collisions with a variety of nuclear targets, enabling the detailed study of charm production in a variety of nuclear systems.

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