PROCEEDINGS OF SCIENCE

Heavy-flavour production in fixed-target mode

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LHCb is the only experiment that can operate in fixed-target mode at the LHC. In this particular setup, one of the LHC TeV-energy beams of protons or lead ions interacts with a gaseous target to reach the highest center-of-mass energies in a fixed-target experiment up-to-date. This provides unique conditions to study charm production. In this report, recent LHCb results from its heavy-flavour program in fixed-target collisions are reported. These results include production measurements of open charm (D^0, $\overline{D}^0$) and hidden charm (J/ψ, $\psi(2S)$) in pNe and PbNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$ collected during LHC Run 2. These results provide data to study nuclear structure and the charm hadronisation mechanism in a previously unexplored kinematic phase space, as well as input for the understanding of cold nuclear matter and the formation of a hot and thermalised medium. Finally, recent progress in the commissioning of the upgraded LHCb detector and the new gas injection system, SMOG2, is reported.

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1. Introduction

The LHCb experiment [1, 2], located at the Large Hadron Collider (LHC) at CERN, is a forward spectrometer fully instrumented between 2 and 5 units of pseudorapidity (η). The detector is specifically designed to have excellent tracking and vertexing capabilities for heavy-flavour states, being able to reconstruct and identify a variety of charged and neutral final-state particles. During LHC Run 2, LHCb acquired unprecedented datasets in fixed-target configuration with a TeV-energy beam. In this configuration, the LHC beam pipe pressure near to the LHCb interaction region is increased about two orders of magnitude (from $\approx 10^{-9}$ mbar to $\approx 10^{-7}$ mbar) by a constant gas injection, and the circulating proton (or lead ion) beam is exploited to produce proton(ion)-gas collisions.

In this particular setup, with a 2.5 TeV incoming beam of protons (p), the achieved center-of-mass energy is $\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$, covering the previously unexplored gap between fixed-target experiments at SPS ($\sqrt{s_{\mathrm{NN}}} = 20\,\mathrm{GeV}$) and RHIC ($\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$). The forward acceptance of LHCb in collider configuration transforms to a coverage in $y^* \in [-2.29, 0]$ at that energy, where y^* stands for the rapidity in the center-of-mass system. These conditions give access to the high Bjorken x region in the target, particularly around $x \approx 0.02 - 0.3$. This is a poorly constrained region of the nuclear parton distribution functions (nPDFs), in the limit between anti-shadowing and the EMC effect regions. Additionally, the versatility of the gas injection setup permits to change easily the target size by changing the gas type. With the Run 2 setup, noble gases like He, Ne and Ar could be injected.

This report focuses on recent results of charm hadron production. Due to their high masses, charm hadrons are necessarily produced in the early stage of the collision and therefore are ideal probes of the target nuclear structure. Additionally, hidden charm (charmonium) production is of great interest to study the formation of the state of deconfined matter named Quark Gluon Plasma (QGP).

2. Hidden and open charm production in pNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$

LHCb has recently measured the production of open (D^0, $\overline{D}^0$) and hidden (J/ψ, $\psi(2S)$) charm in proton-neon (pNe) collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$ [3, 4]. These measurements exploit the largest fixed-target sample collected by LHCb in Run 2, which accounts for $\mathcal{L}_{\mathrm{integrated}} = 21.7 \pm 1.4\,\mathrm{nb}^{-1}$. Differential cross-sections of D^0, $\overline{D}^0$ and J/ψ are determined as a function of transverse momentum (p_{T}) and y^* in the $0 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$ and $-2.29 < y^* < 0$ kinematic range.

The D^0 ($\overline{D}^0$) mesons are reconstructed in the $D^0 \to K^+\pi^-$ ($\overline{D}^0 \to K^-\pi^+$) final state. In figure 1 (right), the $D^0-\overline{D}^0$ production asymmetry is presented, defined as $\mathcal{A}_{\mathrm{prod}} = (Y_{D^0} - Y_{\overline{D}^0})/(Y_{D^0} + Y_{\overline{D}^0})$, where Y_D is the corrected D meson yield. This magnitude probes charm hadronization at high Bjorken x. Data show a negative asymmetry from $\sim 0\%$ to $\sim 15\%$ from $y^* = 0$ to $y^* = -2.29$, which correlates with a larger valence quark contribution of the neon target in the more backward rapidities. The results are compared with several model predictions, being those from MS model [5] and Vogt 1% [6] those that reproduced better the data.

The J/ψ and $\psi(2S)$ mesons were reconstructed in the dimuon final state. Figure 1 shows the differential cross-section for J/ψ as a function of p_{T}. The result is compared with several

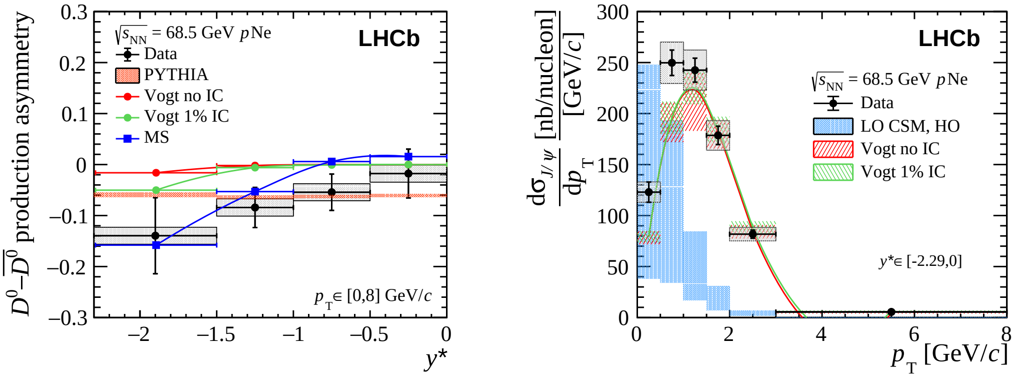

Figure 1: Left: $D^0 - \overline{D}^0$ production asymmetry in $\sqrt{s_{\rm NN}}$ = 68.5 GeV pNe collisions as a function of center-of-mass rapidity [4]. Right: differential J/ψ cross-section as a function of $p_{\rm T}$ in pNe collisions at $\sqrt{s_{\rm NN}}$ = 68.5 GeV [3].

predictions: leading-order color singlet model using Helac-onia (LO CSM HO) [7], which does not reproduce the data, and two flavours of a prediction with the colour evaporation model with and without the presence of a 1% intrinsic charm content in the nucleus, labelled as Vogt no IC and Vogt 1% [6]. These last predictions reproduce better the data and the calculation including intrinsic charm is favoured. These data are important input to understand the still open question of how to describe charmonia hadroproduction.

3. Hidden and open charm production in PbNe collisions at $\sqrt{s_{\rm NN}}$ = 68.5 GeV

LHCb has measured the J/ψ and D^0 production ratio in PbNe collisions at $\sqrt{s_{\rm NN}}$ = 68.5 GeV, using data collected during the 2018 ion run at LHC [8]. By using a large ion as projectile, the reached energy densities might be high enough for QGP formation, which can be studied by measuring charmonium production. The color screening mechanism predicts a QGP-induced suppression of charmonium formation, consistent with NA50 measurement at $\sqrt{s_{\rm NN}}$ = 20 GeV with PbPb collisions [9]. In the LHCb measurement, the yield of D^0 mesons is used to normalise the J/ψ yield, serving as a proxy of the total charm produced in the collision.

The J/ψ and D^0 are reconstructed in the $\mu^+\mu^-$ and $K^+\pi^+$ decay channels respectively. Both mesons are measured in the $0 < p_{\rm T} < 8\,{\rm GeV}/c$ and $-2.29 < y^* < 0$ kinematic range. In this way, the previously reported pNe results [3, 4] can be used as reference for cold nuclear matter effects.

Figure 2 (left) shows the ratio $\sigma_{J/\psi}/\sigma_{D^0}$ in PbNe and pNe collisions at $\sqrt{s_{\rm NN}}$ = 68.5 GeV as a function of the average number of binary nucleon-nucleon collisions ($N_{\rm coll}$). This last parameter is estimated using the Glauber model [10]. The $\sigma_{J/\psi}/\sigma_{D^0}$ in nuclear collisions is assumed to have the functional form $\sigma^{AB}_{J/\psi}/\sigma^{AB}_{D^0} = (\sigma^{pp}_{J/\psi}/\sigma^{pp}_{D^0}) \times AB^{\alpha'-1}$, when describing suppression due to cold nuclear matter effects such as nuclear absorption. A decreasing trend towards high $N_{\rm coll}$ is observed, but it does not show significant deviations from the expected curve. Therefore, an anomalous suppression in PbNe collisions at $\sqrt{s_{\rm NN}}$ = 68.5 GeV is not observed. The study of larger systems with a larger maximum value of $N_{\rm coll}$ as PbAr is very promising to continue searching for QGP indications.

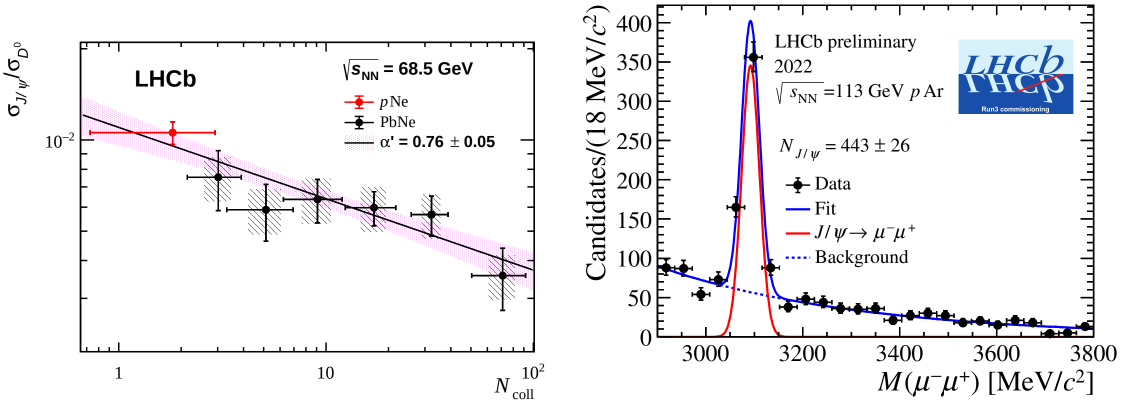

Figure 2: Left: J/ψ-to-D^0 cross-section ratio as a function of N_{coll} for $\sqrt{s_{\text{NN}}} = 68.5$ GeV PbNe and pNe collisions [8]. Right: invariant mass spectrum of the $J/\psi \to \mu^+\mu^-$ candidates from 18 min of pAr collisions collected in 2022 [11].

4. Conclusions and prospects

In this contribution, measurements of open and hidden charm in pNe and PbNe collisions at $\sqrt{s_{\text{NN}}} = 68.5$ GeV were reported. These measurements provide new insights into nuclear stucture, the charm hadronization mechanism and the study of cold nuclear matter in previously unexplored collision systems and at a never explored center-of-mass energy. The studies would benefit from larger datasets, which would allow for measurements of other open and hidden charm states. The exploration of other collision systems either small (pH$_2$, pD$_2$, ideal references for nuclear effects) or large (PbAr, to extend the probed N_{coll} range) is of uttermost interest.

For LHC Run 3, which started in 2022 and will continue to 2025, a significant improvement of the physics performance in fixed-target collisions is foreseen. This is thanks to a new dedicated gas storage cell, named SMOG2 [12], installed ≈ 400 mm upstream of the nominal pp interaction region. By injecting gas directly into the cell the local gas pressure is increased up to two orders of magnitude with the same gas flow as in Run 2 conditions. This translates to a equivalent gain in instantaneous luminosity. Also, the new setup allows for the injection of non-noble gases (H$_2$, D$_2$, O$_2$) and enables data-taking in parallel with collider mode operations. This extends the available beam time for fixed-target operations. With this improvements, the fixed-target physics program at LHCb will be greatly expanded [13].

The new system is now operational and first injections of H$_2$ and Ar were performed as part of the SMOG2 commissioning in 2022. Figure 2 (right) shows the dimuon invariant mass spectra from pAr collisions at $\sqrt{s_{\text{NN}}} = 113$ GeV collected in only ≈ 18 min of data-taking. A clean J/ψ signal with around 400 candidates is visible.

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