# NEW MEASUREMENTS IN FIXED-TARGET COLLISIONS AT THE LHC*

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

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## 1. Introduction

The LHCb detector [1] is a single-arm spectrometer fully instrumented in the forward rapidity covering the pseudorapidity range of $2 < \eta < 5$. It specializes in measurements of particles containing $c$ or $b$ quarks, and possesses excellent vertexing, tracking, and particle-identification capabilities. Furthermore, The LHCb is the only LHC experiment that operates in a fixed-target configuration, providing rich physics opportunities in a largely unexplored kinematic region.

The SMOG (System for Measuring Overlap with Gas) device injects a small amount of noble gases with the pressure of $\mathcal{O}(10^{-7})$ mbar into the beam pipe close to the LHCb vertex detector (VELO) as gaseous targets, transforming the LHCb into a fixed-target experiment. This configuration allows LHCb to study $p$–Gas and Pb–Gas collisions with a center-of-mass energy between 68–110 GeV depending on the beam energy, and an acceptance in

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the center-of-mass rapidity ($y^*$) between $-2.3$ and 0. This unique kinematic coverage is of great interest to studies of heavy-ion and cosmic ray physics. LHCb has published two earlier papers on the measurements of heavy flavor and prompt antiproton production with SMOG [2, 3], demonstrating the feasibility of the project. In these proceedings, three new measurements using SMOG data are presented and discussed.

## 2. Charmonia production in $p$Ne collisions at $\sqrt{s_{NN}} = 68.5$ GeV

Heavy quarks in proton–nucleus collisions are important probes to study various nuclear effects. The production of charmonia, $c\bar{c}$ bound states, in proton–nucleus collisions suffers from cold nuclear matter (CNM) effects, including modifications from nuclear parton distribution functions (nPDFs), multiple scattering inside the nucleus, nuclear absorption, and comover dissociation. The CNM effects are dependent on the collision energy, therefore, it is essential to perform measurements over a wide range of energy to understand the mechanisms. Recently, using SMOG data recorded with a 2.5 TeV proton beam incident on neon nuclei at rest, the LHCb measured the production of charmonia states, $J/\psi$ and $\psi(2S)$ mesons, in $p$Ne collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 68.5$ GeV.

The fixed-target SMOG data samples are acquired with particular beam conditions, where a bunch moving towards LHCb crosses the nominal interaction point without a bunch moving in the opposite direction from the other beam. The charmonia states are reconstructed via $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decay channels. The total luminosity is measured to be $22.8 \pm 1.5$ nb$^{-1}$, determined from the yield of electrons elastically scattering off the target Ne atoms as described in Ref. [3].

Figure 1 shows the differential cross section of $J/\psi$ production in transverse momentum, $p_{\mathrm{T}}$, and $y^*$. The data points are compared to three different theoretical calculations. The predictions from HELAC-ONIA [4] using CT14NLO and nCTEQ15 PDF sets underestimate the data. Next-to-leading order pQCD calculations with (1%) and without an Intrinsic Charm contribution [5] are both in good agreement with the data.

The total $J/\psi$ cross section is extrapolated to full phase space using PYTHIA 8 with a specific LHCb tuning and CT09MCS PDF set [6] and assuming forward–backward symmetry in the rapidity. The result is shown as the grey/red point in Fig. 2 (left), and is compared to the previous SMOG measurement [2] and values from other measurements at different energies [7], showing a continuous increasing trend with greater energy. The $\psi(2S)/J/\psi$ ratio is measured for the first time with SMOG data. The result is displayed in grey/red in Fig. 2 (right), and shows general agreement with other measurements.

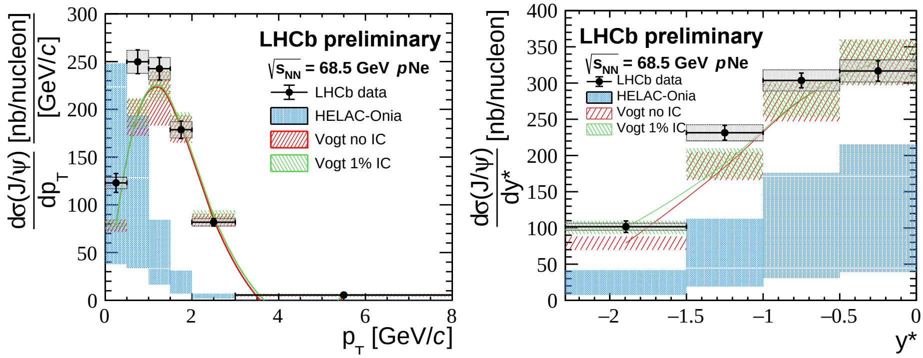


Fig. 1. Differential cross section of $J/\psi$ as functions of $p_{\mathrm{T}}$ (left) and $y^*$ (right). The statistical uncertainties are shown as vertical bars, while the systematic uncertainties are represented by the grey shaded areas.

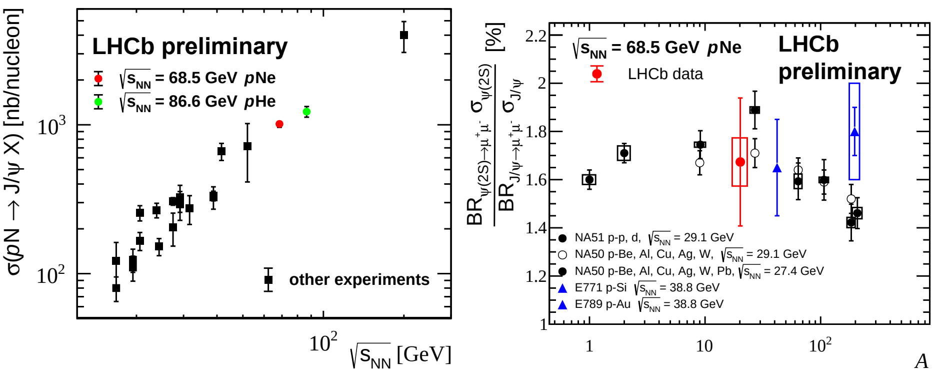


Fig. 2. (Colour on-line) Left: total $J/\psi$ cross section per target nucleon as a function of center-of-mass energy $\sqrt{s_{NN}}$. The grey/red point represents the present work, the light grey/green point an earlier SMOG result from LHCb [2], and the black points are measurements from other experiments [7]. Right: $\psi(2S)/J/\psi$ ratio as a function of the target atomic mass number $A$. The grey/red point corresponds to the present analysis.

## 3. Charm production in PbNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV

In nucleus–nucleus collisions, the production of heavy quarks can be used to study the transition from ordinary hadronic matter to the hot and dense quark–gluon plasma (QGP). Due to colour screening inside the QGP, charmonium-bound states suffer additional suppression in the presence of the QGP compared to normal nuclear matter. Using a SMOG dataset of PbNe collisions, the LHCb measured the production of heavy-flavour hadrons, $J/\psi$ and $D^0$ mesons, at $\sqrt{s_{NN}} = 68.5$ GeV. This is the first measurement of nucleus–nucleus collisions with the fixed-target mode at the LHCb.

The production cross-section ratios of $J/\psi$ and $D^0$ as a function of $p_{\mathrm{T}}$ and $y^*$ are shown in Fig. 3. The ratio shows a strong increasing trend with increasing $p_{\mathrm{T}}$, and shows little dependence on $y^*$. The bottom panel of Fig. 3 displays the ratio as a function of $N_{\mathrm{coll}}$, the number of binary nucleon–nucleon collisions [8]. The $J/\psi$ meson is more suppressed in comparison to the $D^0$ mesons when the collisions become more central. Assuming that the $J/\psi$ and $D^0$ production follows the form of $\sigma^{AB}_{J/\psi} = \sigma^{pp}_{J/\psi} \times AB^{\alpha}$ and $\sigma^{AB}_{D^0} = \sigma^{pp}_{D^0} \times AB$, an $\alpha$ value of $0.82 \pm 0.07$ is obtained by fitting the data as shown in Fig. 3. This value is in good agreement with similar values found in proton–nucleus collisions by the NA50 experiment [9], where no QGP formation is expected. Therefore, no anomalous $J/\psi$ suppression that could indicate the presence of the QGP formation is observed within uncertainties.

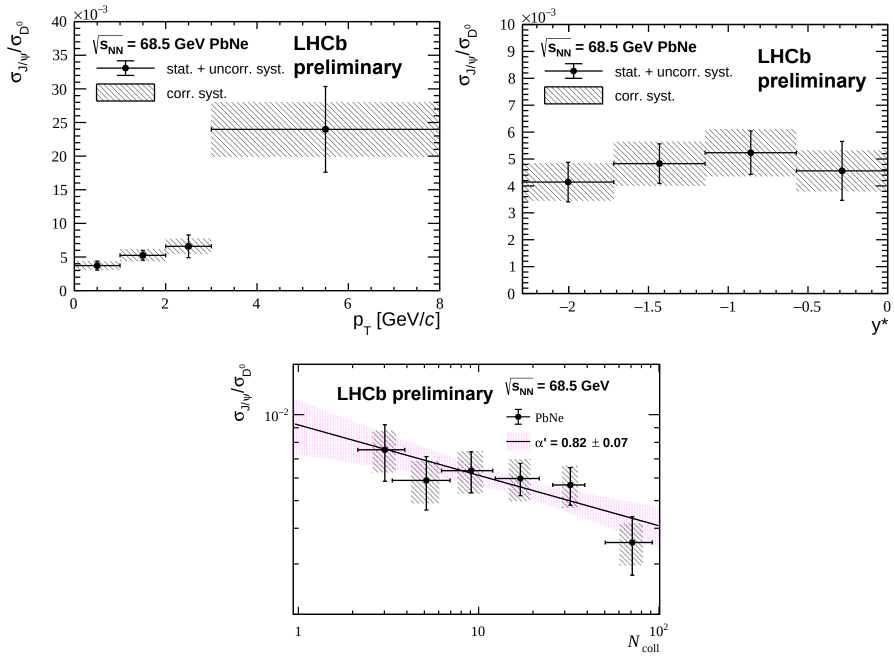


Fig. 3. The production cross-section ratio of $J/\psi$ and $D^0$ as functions of $p_{\mathrm{T}}$ (upper left), $y^*$ (upper right), and $N_{\mathrm{coll}}$ (bottom).

## 4. Detached antiproton production in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV

The SMOG program can also provide valuable input to cosmic-ray physics. The new measurement of the production of antiprotons originating from antihyperons, referred to as detached ($\bar{p}$), in proton–helium collisions at $\sqrt{s_{NN}} = 110$ GeV [10] is an extension of the earlier SMOG measurement of prompt $\bar{p}$ production in the same collisions [3]. These measurements offer important information to improve the modelling of $\bar{p}$ flux in cosmic rays, where theoretical uncertainties on the $\bar{p}$ production cross section in collisions between cosmic rays and the interstellar medium limit the interpretation of cosmic ray data from space-borne experiments.

The analysis of the detached $\bar{p}$ is performed in two complementary approaches. The exclusive approach measures the detached $\bar{p}$ via the dominant process, $\bar{\Lambda} \to \bar{p}\pi^+$, and calculates the ratio $R_{\bar{\Lambda}}$, defined as the ratio of the cross section of $\bar{p}$ originating from $\bar{\Lambda}$ to that of the promptly produced $\bar{p}$. In the inclusive approach, antiprotons are identified with the particle identification capabilities of the LHCb detector. The prompt and detached $\bar{p}$ are separated by the impact parameter, the minimum distance of reconstructed $\bar{p}$ track to the primary vertex. The ratio of the cross section of $\bar{p}$ from all antihyperon decays to that of the prompt $\bar{p}$, denoted by $R_{\bar{H}}$, is then derived.

The measured ratios $R_{\bar{\Lambda}}$ and $R_{\bar{H}}$ are shown in the upper panels of Fig. 4 as functions of $\bar{p}$ transverse momentum. The data is significantly larger than predictions from widely used hadronic collision generators, showing an underestimation of the antihyperon contribution to $\bar{p}$ production by current models. In the bottom panel, the double ratio of $R_{\bar{\Lambda}}$ to $R_{\bar{H}}$, which is theoretically more reliably predicted, is compared to the EPOS-LHC estimation, and shows good agreement.

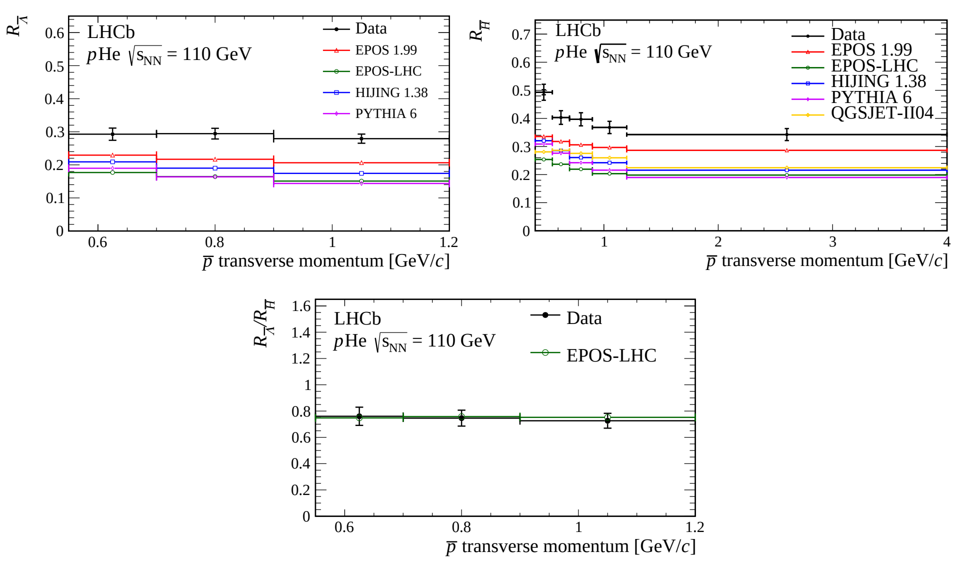


Fig. 4. The ratios $R_{\bar{\Lambda}}$ (upper left) and $R_{\bar{H}}$ (upper right) as functions of $\bar{p}$ transverse momentum. In the bottom panel, the $R_{\bar{\Lambda}}$ to $R_{\bar{H}}$ double ratio *versus* $\bar{p}$ transverse momentum.

## 5. Summary

LHCb's unique SMOG program offers rich physics opportunities in a relatively unexplored kinematic region. In these proceedings, three new measurements in the fixed-target configuration are presented and discussed, including the first result from fixed-target nucleus–nucleus collisions. For Run 3, the system has undergone a significant upgrade to the new SMOG2 system including a Storage Cell and a Gas Feed System [11]. It can use more flexible gas species and is able to provide high statistics fixed-target data. The SMOG2 system will become one of the highlights of LHCb's future heavy-ion and cosmic-ray physics program.

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