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New measurements in fixed-target collisions at LHCb

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Owing to the injection of noble gases into the LHC accelerator beam-pipe at CERN, LHCb is developing a full-scale fixed-target experiment studying collisions of protons and lead ions on gas atoms at the as of today's highest energy ever reached in a fixed-target experiment. Such a scale, intermediate between the past experiments and the LHC ones, is mostly unexplored and the accessible physics prospects, addressing different fields of interest among which nucleon characterization and astrophysics, are unique at the LHC. The gas injection system, SMOG, has recently been upgraded in view of the LHC Run3. The gas will be confined in a 20-cm-long cell, SMOG2, installed in August 2020 40 cm upstream of the LHCb nominal interaction point. Leveraging on the precise definition of the beam-gas luminous region, the gas areal density seen by the beam will be increased by two orders of magnitude for the same gas flow as in Run2 and many gas species, notably non-noble ones such as hydrogen and oxygen, will be injected. Moreover, the separation between the beam-beam and beam-gas interaction regions opens the possibility to operate LHCb at the same time as a fixed-target and a collider experiment. In this document, two examples of the LHCb physics reach in its fixed-target configuration are presented, describing recent published results obtained from the analysis of Run2 data and the prospects for Run3.

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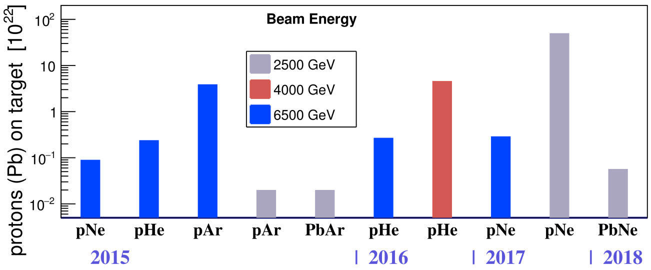

Figure 1: Samples collected by LHCb fixed-target during the LHC Run2. The collision system, the circulating beam energy and the collected statistics expressed as proton or lead ions on target are indicated.

1. LHCb as a fixed-target experiment

Among the experiments operating at the CERN LHC, LHCb [1, 2] has the unique opportunity to inject noble gases in the accelerator beam-pipe, operating as the as-of-today's highest-energy fixed-target experiment ever. The gas injection system, SMOG, was originally conceived to allow the beam transverse profiles reconstruction via imaging techniques applied to the beam-gas collisions. Leveraging on the LHCb detector fixed-target-like acceptance, pseudorapidities $\eta \in [2, 5]$, and its excellent particle reconstruction and identification performance, since 2015 SMOG has also been exploited as a gaseous target. The samples collected so far exploiting the circulation in the LHC of both protons and lead ions and the injection of helium, neon and argon are illustrated in Figure 1. The related physics opportunities are unique at the LHC [3]. The high Bjorken-x and moderate Q^2 region, mostly unexplored by previous experiments, can be firstly accessed, providing inputs to different fields of research such as heavy flavour production, nuclear structure and even astrophysics.

In preparation to the LHC Run3, the SMOG system has faced a major upgrade [4]. A 20-cm-long storage cell for the gas, SMOG2, was installed 40 cm upstream of the nominal LHCb interaction point and a new gas feed system was set up to offer a better control of the gas flow and pressure. Leveraging on the precise definition of the beam-gas interaction region, the gas areal density seen by the beam will be increased by up to two orders of magnitude for the same gas flow as in Run2 and other gases, including heavy noble ones like krypton and xenon and non-noble species such as hydrogen, deuterium, oxygen and nitrogen, can possibly be injected. Moreover, the distinct separation between the beam-beam and beam-gas interaction regions is such that a simultaneous acquisition of the two types of collisions can be feasible. At the time of writing, the system is being commissioned and the processing of the beam-gas collisions in SMOG2 is being included in the upgraded experiment overall data acquisition framework. Figure 2 exemplifies the ongoing activities to prepare for a successful SMOG2 operation [5]. The left plot, showing the primary vertex reconstruction efficiency as a function of z, demonstrates on simulation the same performance for beam-beam and beam-gas interactions was achieved and that it does not change when injecting the gas on top of the beam-beam collisions. The right plot illustrates the real-time evolution of the pressure inside the LHC beam-pipe during one of the latest gas injection tests. No showstopper has been identified so far, which means that LHCb could be the only detector operating at the same time with two collision points at two different energy scales.

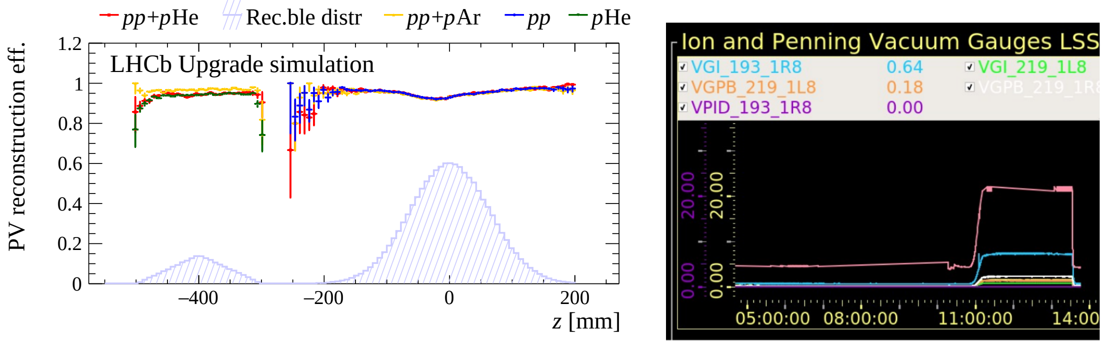

Figure 2: Two examples of the ongoing preparation towards a successful SMOG2 operation. The left plot shows the PV reconstruction efficiency for simulated events with standalone or overlapped beam-beam and beam-gas collisions and demonstrates the same performance has been achieved. The right plot shows the evolution of the pressure inside the accelerator beam-pipe during one of the latest injection tests.

2. SMOG unexpected contribution to dark matter searches in cosmic rays

By analysing data collected in Run2 with SMOG, LHCb indirectly contributed to the worldwide effort to clarify Dark Matter (DM) nature and interactions. Satellite experiments such as AMS-02 are indeed searching with increasing precision DM annihilation or decays in matter-antimatter final states by comparing the antimatter flux in Cosmic Rays (CRs) with its expected production in CRs spallation on the InterStellar Medium (ISM), mainly composed of hydrogen and helium. The interpretation of their measurements is limited by our knowledge of the antimatter production in known processes. When AMS-02 published in 2015 the antiproton flux in cosmic rays results, for example, the background description could only rely on few $\sigma(pp \to \overline{p}X)$ measurements and no data at all were available for processes involving helium [6]. Exploiting a sample of proton-helium (pHe) collisions collected with SMOG, LHCb published in 2018 a first measurement for $\sigma(p\mathrm{He} \to \overline{\mathrm{p}}_{\mathrm{prompt}}\mathrm{X})$ [7] at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV. A new result, addressing "detached" antiprotons originating in the anti-hyperon decays $\overline{\Lambda} \to \overline{p}\pi^{+}$ and $\overline{\Sigma}^{-} \to \overline{p}\pi^{0}$, with the $\overline{\Lambda}$ and $\overline{\Sigma}^{-}$ particles produced promptly or in heavier states cascade decays, has been recently finalised [8]. The detached-to-prompt antiproton production was measured following two different approaches, as presented in Figure 3. The dominant process, $\overline{\Lambda} \to \overline{p}\pi^{+}$ with $\overline{\Lambda}$ produced promptly, is exclusively reconstructed. The cross-section of the process is measured and divided by the previous prompt antiproton result, removing the uncertainty due to the luminosity. A second approach inclusively addresses all antihyperon species. Tight cuts on the particle identification variables are applied to obtain a sample enriched of antiprotons and these are classified as prompt or detached depending on their consistency with the proton-helium collision vertex. In both approaches, the measurement results are found to be in excess with respect to the predictions from the most common theoretical models [9] and will contribute to reduce the uncertainties in the modelling of the antiproton production in CRs-ISM collisions. With SMOG2, and the consequent possibility to collect data with injected hydrogen, deuterium and helium at different beam energy, possibly from the injection one of 450 GeV up to 6800 GeV, the relevance of cross-section uncertainty in the cosmic secondary antiproton flux prediction is expected to be eventually dismissed.

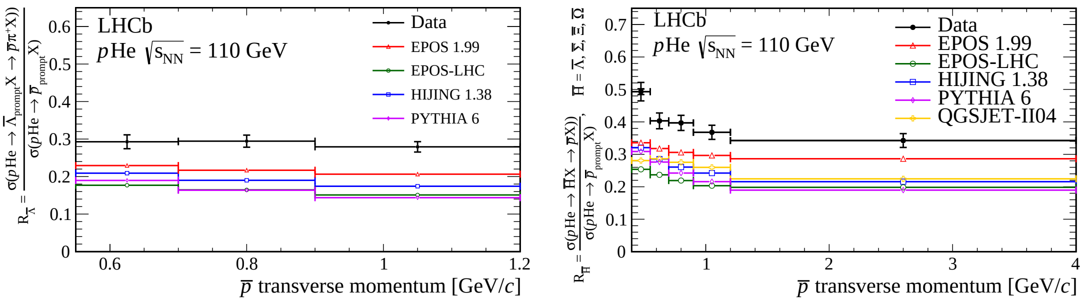

Figure 3: Results for the detached-to-prompt antiproton ratio measurement as a function of the transverse momentum following the exclusive (left) and inclusive (right) approach. In both cases, the measurement results are in large excess with respect to the predictions of common theoretical models.

3. Charming fixed-target LHCb

Charm physics is also largely profiting from the LHCb fixed-target unique programme. The production of charm states is indeed an excellent probe for nuclear matter effects such as PDF nuclear modification, nuclear absorption or multiple scattering. A more precise description of these phenomena, requiring to study samples with different collision systems and energies, is crucial to shade light on the mechanisms of cold and hot nuclear matter effects. Moreover, by exploiting the high-x regime accessible to LHCb fixed target, a possible intrinsic charm contribution in the proton can be quantified. After a first measurement for J/ψ and D^0 production in pHe and pAr collisions [10], published in 2018, the analysis was recently repeated on the largest SMOG sample of pNe and in PbNe collisions, both with $\sqrt{s_{\mathrm{NN}}}$ =68.5 GeV. Some of the obtained results are shown in Figure 4. The top left one shows the results for the J/ψ differential cross-section as a function of the centre-of-mass rapidity and are found to be in excess with respect to HELAC-ONIA calculations [11]. The results are also compared to other predictions [12] including no or a 1% intrinsic charm contribution, but are found not to be discriminative enough to draw a certain conclusion: an increased statistics and a better control of some systematics such as the luminosity, both offered in Run3 by the SMOG2 system, are thus desirable. Thanks to the available large size of the pNe sample, the $\psi(2S)$ state production was also studied. Top right Figure 4 shows (in red) the results for the ratio between the $\psi(2S) \to \mu^+\mu^-$ and J/$\psi \to \mu^+\mu^-$ decays branching fractions. An agreement with previous experiments is found, but large uncertainties, dominated by the statistical contribution, affect the results, providing further motivation for the SMOG2 upgrade. Bottom Figures 4 present some of the results for charm measurements in the PbNe system, only available at LHCb fixed-target with this energy scale. Left (right) plot shows the J/ψ-to-D^0 cross-section ratio as a function of the centre-of-mass rapidity (number of binary nucleon-nucleon collisions, obtained by applying the Glauber model to the energy deposits in the calorimeter). The latter J/ψ evolution is modelled as $\sigma_{\mathrm{J}/\psi}/\sigma_{\mathrm{D}^0} \propto N_{\mathrm{coll}}^{\alpha'-1}$. The fitted value is $\alpha' = 0.82 \pm 0.07$, indicating that J/ψ is affected by additional nuclear effect than D^0 and no anomalous suppression is found in most central collisions, differently than previous NA50 results [13]. No evidence for deconfined medium formation in PbNe is hence observed here.

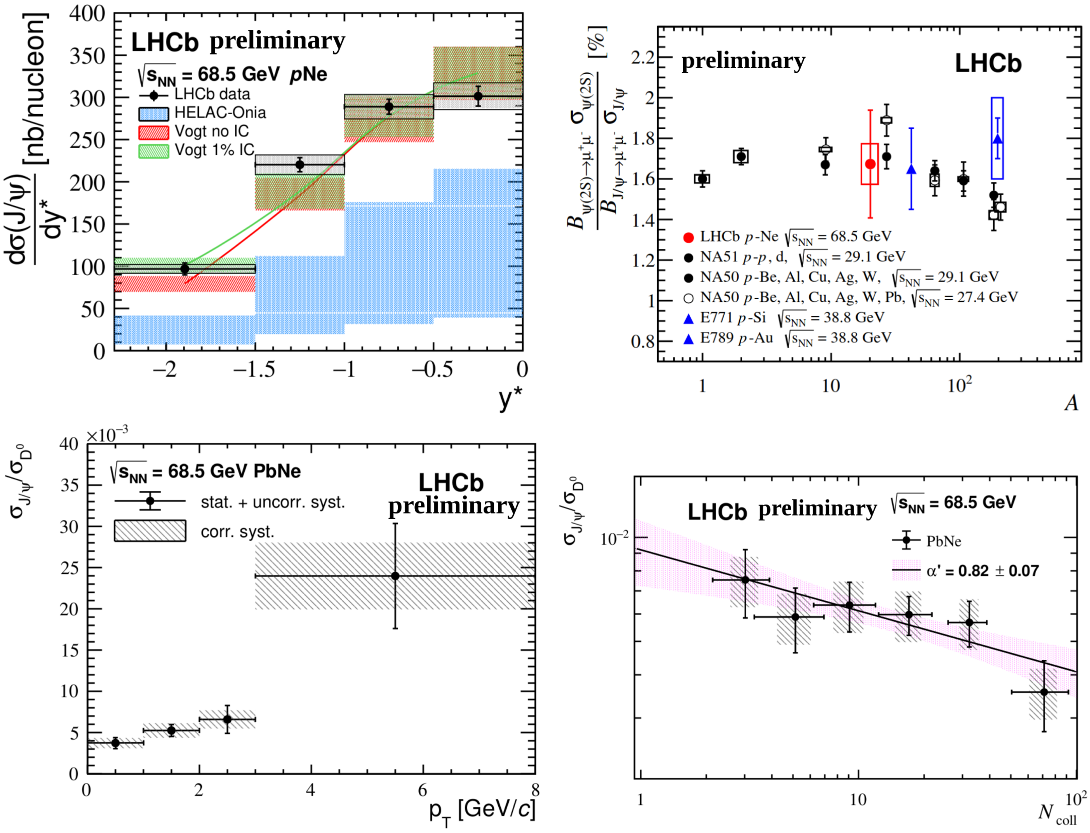

Figure 4: Some LHCb fixed-target charm results. Top left plot compares the J/ψ differential production cross-section in a sample of pNe collisions with theoretical predictions including no or a 1% intrinsic charm contribution in the nucleon. The top right plot shows the LHCb result for the $\psi(2S)$-to-J/ψ branching fraction ratio, compared with previous experiments. Bottom plots illustrate the J/ψ-to-D^0 cross-section ratio as a function of (left) the centre-of-mass rapidity and (right) the number of binary collisions.

4. Conclusions

In parallel to collider physics, LHCb is developing a unique and full-scale fixed-target programme. The high-x and moderate Q^2 region can be firstly precisely accessed, providing unprecedented inputs to theoretical models for different fields of interest. A further boost of the programme is expected with the ongoing SMOG2 upgrade, offering a wider choice of injectable gases, a better control of the systematic uncertainties, notably the sample luminosity, and the possibility to acquire at the same time beam-beam and beam-gas collisions. In this document, two examples of the LHCb fixed-target physics reach are presented. By exploiting light gases such as hydrogen, deuterium and helium, the unforeseen LHCb space mission can be completed, dismissing the uncertainties, nowadays dominant, in the description of the antimatter production in space. By injecting instead heavier gases, large statistics of heavy charm states will be available, giving insights into a more accurate description of the nucleon and nuclear structure. All of this perfectly fits into the 2020 European Strategy for Particle Physics Update, acknowledging fixed-target experiments at the LHC for "providing a great extension of the physics reach of the complex at a limited cost" [14].

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