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Fixed-target measurements contributing to cosmic ray studies

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LHCb can be seen as the fixed-target experiment operating at the highest energy ever reached, thanks to its capability, unique among the experiments at the LHC, to collide the TeV-energy LHC beams on an internal gas target. Owing to its forward geometry, the detector is ideally suited to observe such collisions, exploiting the excellent vertexing, tracking and particle identification capabilities. This setup offers unique possibilities for production measurements needed to improve the interpretation of cosmic ray observations in the space or through extensive atmospheric showers. In particular, collisions of primary cosmic rays with the interstellar medium can be reproduced using a helium target, at an energy scale relevant for the measurements of the antimatter content in cosmic rays ongoing at space payloads like AMS-02. We review the latest results from this program and the near-future prospects with the upgraded gas target device SMOG2.

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1. Introduction

In the last years, experimental astroparticle physics entered a precision era, calling for an improved understanding of interactions of cosmic rays during their propagation through the galaxy and through the atmosphere. Notably, the background to dark matter searches through cosmic antimatter is due to secondary production of antimatter particles in collisions between primary cosmic rays and hydrogen or helium nuclei, the main components of the interstellar medium. The modeling of extensive atmospheric showers produced by ultra-high-energy cosmic rays also requires accurate understanding of hadron-nucleus interactions in the non-perturbative regime over a wide range of projectile energy, from 10^{12} down to 10 GeV. For all of these cases, accelerator data are much needed to complement cosmic rays observations.

The LHCb experiment [1] was conceived with the main goal of studying heavy flavour physics in pp collisions at the LHC. The distinctive features of the detector are the forward geometry, covering the pseudorapidity region $2 < \eta < 5$; the excellent vertexing, tracking and particle identification capabilities optimised for the reconstruction of heavy flavour decays; and a flexible high-bandwidth online selection system.

During the LHC Run 2 LHCb started to operate also in fixed-target mode using its internal gas target SMOG, through which a noble gas target (He, Ne or Ar) with pressures of about 10^{-7} mbar could be injected in the LHC vacuum. Fixed-target collisions at the highest energy ever recorded, up to $\sqrt{s_{\rm NN}}$ =110 GeV in the nucleon-nucleon rest frame, could be studied, exploiting the "fixed-target-like" geometry of the LHCb detector.

Measurements of great relevance to cosmic ray physics, notably of antimatter production in pHe collisions, have been performed from the collected samples and are reviewed in the following.

The major upgrade of the LHCb experiment implemented for the LHC Run 3 included the installation of a new gas target device, called SMOG2, based on a storage cell. The integrated luminosity of fixed-target samples is expected to increase by three orders of magnitude. The first demonstration of the SMOG2 concept and the prospects for the cosmic program are discussed.

2. Latest results from "cosmic" collisions with SMOG

The main goal of Run 2 data-taking with pHe collisions was the measurement of antiproton production, motivated by the ongoing precise measurements of the antiproton cosmic flux in space, notably by AMS-02. For antiprotons with momentum above 10 GeV, the largest uncertainty on the expected flux of secondary antiprotons produced in the interstellar medium is due to the limited knowledge of the corresponding production cross-sections. LHCb has performed the first $\overline{p}$ production measurement in pHe collisions at an unique energy scale of $\sqrt{s_{\rm NN}} = 110$ GeV. The results for the prompt production [2] are a key input to the modeling of the secondary cosmic $\overline{p}$ production, as they constrain the amount of scaling violation when extrapolating the cross-section toward high energy[4, 5].

More recently, the production of antiprotons from antihyperon decays was measured [3]. Two complementary approaches were followed, as illustrated in Fig. 1. The dominant contribution, namely $\overline{\Lambda} \to \overline{p}\pi^+$ decays from promptly produced $\overline{\Lambda}$ baryons, was measured by selecting secondary decays solely on the basis of the topology and kinematics of reconstructed tracks. An inclusive

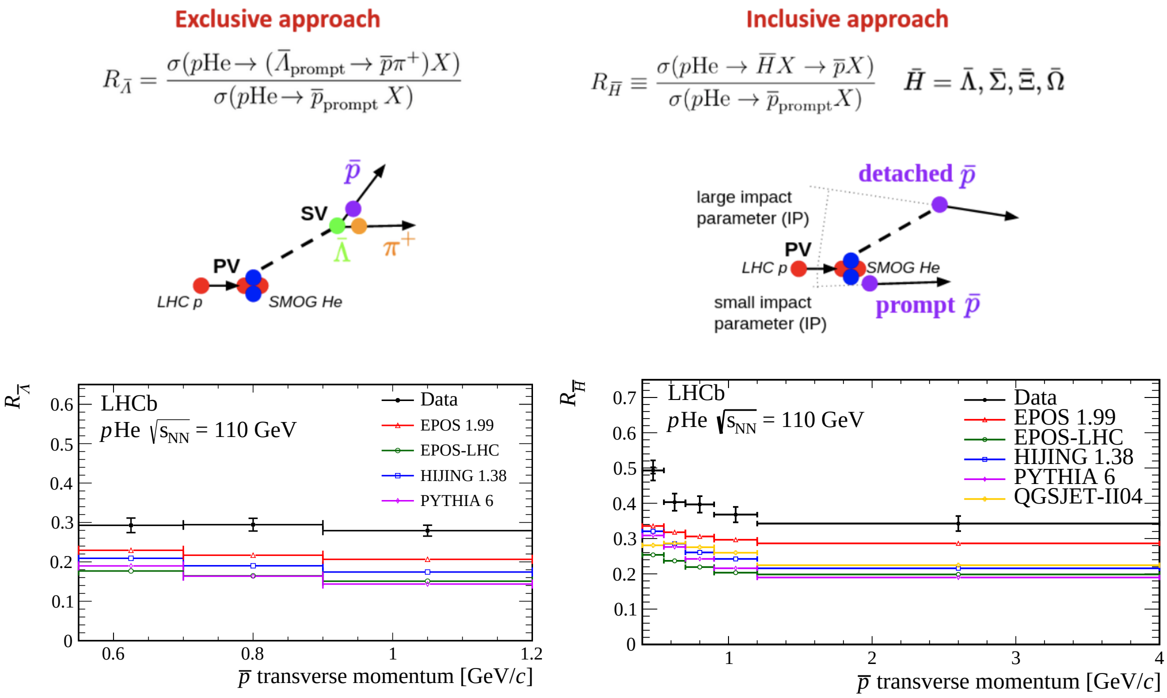

Figure 1: Results for the ratios of antiprotons produced in antihyperon decays to prompt production, as a function of the $\bar{p}$ transverse momentum. The left plot is for exclusive $\bar{\Lambda} \to \bar{p}\pi^+$ decays, the right one for inclusive production.

measurement of all antiprotons produced with large impact parameter with respect to the collision primary vertex was also performed, relying on the $\bar{p}$ particle identification capability of the LHCb detector. The results of the two analyses are consistent with the expected $\bar{\Lambda}$ to antihyperon production ratio of about 0.75 predicted in hadronization models. In both cases the predictions from the most commonly used models in cosmic ray physics, tuned on data at lower energy, significantly undershoot the observed production yields. This is consistent with the strangeness enhancement observed at higher energy at RHIC and LHC. These measurements probe the onset of this strangeness enhancement and provide strong constraints on the antihyperon contribution to the cosmic $\bar{p}$ flux, reducing one of the major residual uncertainties on its modeling.

3. The SMOG2 upgrade and its prospects

The upgraded LHCb detector for the LHC Run 3 includes an upgraded target device called SMOG2 [6]. This consists of a storage cell containing the injected gas in a 20 cm long region located just upstream the LHCb vertex detector. An increase in fixed-target instanteneous luminosity by up to two orders of magnitude with the same injected gas flow is anticipated, and the clean separation between the beam-gas and beam-beam interaction regions will enable regular simultaneous acquisition of the two collision systems. This concept has been demonstrated with the first commissioning data acquired in November 2022 (see Fig. 2 left), where clean samples of charmed particles have been reconstructed from just 18 minutes of data-taking [7].

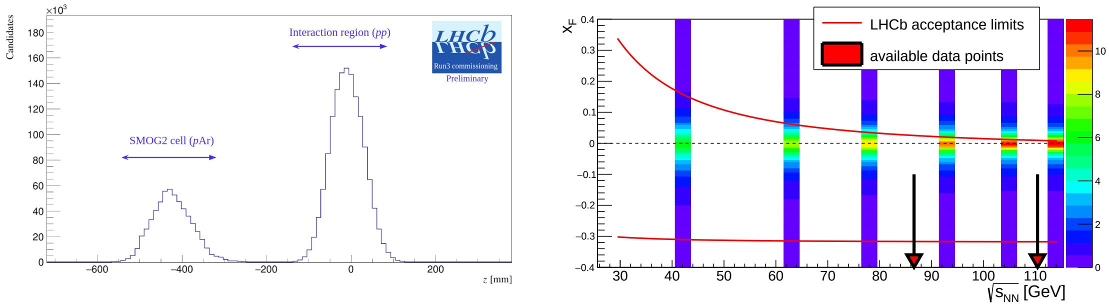

Figure 2: On the left, longitudinal position of the reconstructed collision vertices during tests of the SMOG2 injection system [7]. The left peak follows the expected triangular profile of the gas density inside the storage cell, while the right peak corresponds to beam-beam collisions. On the right, acceptance of the LHCb detector for $\overline{p}$ production in fixed-target configuration in terms of Feynman-x, as a function of energy [8].

Furthermore, it will be possible to inject more gas species, notably hydrogen and deuterium. Comparing $\overline{p}$ production with the three light targets (H, He, D) will constrain nuclear effects and isospin-related asymmetry between pp and pn collisions. This is needed to improve the model for antineutron production, accounting for about half of the cosmic $\overline{p}$ flux. A scan in beam energy is also foreseen to improve the determination of Feynman scaling violation and extend the detector acceptance toward positive values of Feynman-x, which are not covered at the highest LHC beam energy, as illustrated in Fig. 2 right.

During a run with oxygen ion beams foreseen in 2025, pO collisions corresponding to cosmic rays of the highest energy ($\sqrt{s_{\rm NN}}$ up to 10 TeV) will be recorded by in LHCb. By colliding O nuclei on an hydrogen target, production in pO collisions at an almost unexplored scale of $\sqrt{s_{\rm NN}} \sim 100$ GeV can also be studied. A wide kinematic coverage will be possible combining this sample with data obtained from proton beams colliding on an oxygen target in SMOG2.

In conclusion, LHCb is exploiting its fixed-target configuration to pursue a program of measurements of great relevance to cosmic ray physics, contributing to the extension and diversification of the physics reach of the LHC complex.

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