Measurement of antiproton production in p -He collisions at LHCb to constrain the secondary cosmic antiproton flux

G. Graziani* | on behalf of the LHCb collaboration

Sezione di Firenze, INFN, Sesto Fiorentino, Italy

*Correspondence

G. Graziani, Sezione di Firenze, INFN, Sesto Fiorentino, Italy.

Email: graziani@fi.infn.it

The flux of cosmic ray antiprotons is a powerful tool for indirect detection of dark matter. The sensitivity is limited by the uncertainty on the predicted antiproton flux from scattering of primary rays on the interstellar medium. This is, in turn, limited by the knowledge of production cross-sections, notably in p -He scattering. Thanks to its internal gas target, the LHCb experiment performed the first measurement of antiproton production from collisions of LHC proton beams on He nuclei at rest. The results and prospects are presented.

KEYWORDS

antiproton – fixed-target – LHCb – proton–helium collision

1 | LHCb AS A FIXED-TARGET DETECTOR

The LHCb detector (Alves et al. 2008) is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks, which are predominantly produced at high η in p - p collisions at the Large Hadron Collider (LHC). The forward geometry and excellent vertexing, tracking, and particle identification (PID) capabilities (Aaij et al. 2015), which are key features for the reconstruction of heavy flavor decays, make it also an ideal tool to study interactions of the LHC beams with a fixed target. Such a target is provided by the SMOG (System for Measuring Overlap with Gas) device (Barschel 2014), through which tiny amounts of a noble gas (He, Ne, Ar) can be injected inside the primary LHC vacuum around the LHCb vertex detector (VELO). The design gas pressure in the VELO region is 2×10^{-7} mbar, which is small enough not to significantly perturb the LHC operation. The device, originally conceived to determine the machine luminosity using a beam gas imaging technique (Aaij et al. 2014), is now being exploited to perform a set of physics runs with different beam and target configurations, allowing a wealth of unique production studies. One of the main goals of this program is the study of heavy flavor production in proton–ion collisions with different target mass numbers at $\sqrt{s_{NN}} \sim 100$ GeV, an intermediate energy between the existing data collected at SPS and RHIC/LHC accelerators. These measurements can shed light on the cold nuclear matter effects affecting the production of the most rel-

evant probes that are used for detecting quark–gluon plasma at higher energy density. Another attractive feature of the fixed-target configuration is the access to the large Bjorken- x region in the target nucleus. Nuclear probability density distributions (PDFs) in this region are sensitive to antishadowing effects and to possible contributions from intrinsic charm and beauty. The first results for charm production, obtained from a dataset of proton–argon collisions at $\sqrt{s_{NN}} = 110$ GeV corresponding to an integrated luminosity of a few nb $^{-1}$, have been recently released (LHCb 2017). Though the results are still limited by the data size, the observed differential D^0 and J/ψ yields are already expected to provide constraints on nuclear PDFs at large x . Exclusive particle production studies in this kinematic range can also provide crucial inputs to the modeling of cosmic ray showers in the atmosphere and in the cosmos.

2 | COSMIC COLLISIONS AT LHCb

The measurement discussed in the following is motivated by the high-precision determination of the $\bar{p}/p$ ratio in cosmic rays, up to the energy of 350 GeV, achieved during the last years by the spaceborne PAMELA (Adriani et al. 2013) and AMS-02 (Aguilar et al. 2016) experiments. The investigation of the antimatter content in cosmic rays is recognized as a primary tool for the understanding of high-energy astrophysical phenomena, and the measurements of the antiproton fraction outside of the Earth's atmosphere provides a sensitive,

FIGURE 1 Example of two-dimensional DLL distributions for a particular bin ($21.4 < p < 24.4 \text{ GeV}/c$, $1.2 < p_T < 1.5 \text{ GeV}/c$), illustrating the performance of the RICH detectors in separating π^- , K^- , and $\bar{p}$ particles. The distribution in data is shown on the left, while the templates for the four categories, obtained from calibration samples (from simulation for the ghost component), are shown on the right

indirect probe for dark matter. The interpretation of these measurements is currently limited by the uncertainty on the expected amount of secondary antiprotons produced by spallation of primary cosmic rays on the interstellar medium. State-of-the-art calculations (di Mauro et al. 2014; Giesen et al. 2015; Kappl et al. 2015) show that the experimental results are still compatible with the secondary $\bar{p}$ production, though data indicate a larger $\bar{p}$ flux at high energy with respect to most predictions. The largest uncertainty on the prediction is due, particularly in the 10–100 GeV range, to the limited knowledge of the $\bar{p}$ production cross-section in the relevant processes. In particular, no data for $\bar{p}$ production exist for p -He collisions.

3 | MEASUREMENT OF ANTIPROTON PRODUCTION IN p -He COLLISIONS

LHCb performed the first measurement of $\bar{p}$ production in p -He collisions by operating SMOG with helium during special fills with a limited number of proton bunches, accelerated to 6.5 TeV ($\sqrt{s_{NN}} = 110 \text{ GeV}$). Most of the data were collected using a single LHC fill lasting about 5 h in May 2016. Events were triggered with a minimum bias requirement, fully efficient on the collisions, producing an antiproton within the detector acceptance. The measurement was performed from collisions occurring in an 80-cm-long fiducial region, along the beam direction z , where the best reconstruction efficiency is achieved. Antiprotons were counted in narrow two-dimensional bins in momentum (p) and transverse momentum (p_T), in the range $12 < p < 110 \text{ GeV}/c$, $0.4 < p_T < 4 \text{ GeV}/c$. In this analysis, only the prompt $\bar{p}$ production was measured; the component due to hyperon decays, treated here as a background component and subtracted from the result, will be the subject of a dedicated study.

3.1 | Reconstruction and particle identification

Particles with negative charge in the kinematic range of interest were selected after applying quality requirements on the reconstruction of the track and of the collision primary vertex (PV). The PV reconstruction efficiency varies with z from 76% in the most upstream region to 95% around the nominal collision point, with a mild dependence on the p_T of the $\bar{p}$ candidate. The reconstruction efficiency for prompt antiprotons, determined in three-dimensional bins of p , p_T , and z , ranges from 40% to 80%. Systematic corrections to the efficiencies predicted by the simulation are determined from data-driven checks. Antiprotons were then identified through the response of the RICH detectors, from which two variables are built, $DLL(p-\pi)$ and $DLL(p-K)$, representing the difference of the log likelihood between the proton and pion and the proton and kaon hypotheses, respectively. The fraction of antiprotons among the negative tracks was determined from a two-dimensional extended binned maximum likelihood fit to the DLL variable distributions, where templates for the different particle species were obtained from calibration samples in data and simulation. The DLL distributions for data and calibration samples, illustrating the RICH performance, are shown in Figure 1 for an arbitrary kinematic bin.

3.2 | Backgrounds

Background from antiprotons due to hyperon decays or secondary interactions is suppressed by requiring that the impact parameter (IP), which is reconstructed through the VELO with a resolution of $(15 + 29/p_T(\text{GeV}/c))\mu\text{m}$, is compatible with zero. The residual nonprompt background, mostly due to hyperon decays, is constrained from the tail of the IP distribution in data to be $2.6 \pm 0.6\%$. The possible contamination of the gas target is evaluated by acquiring part of the data without the injected helium gas while using the same

FIGURE 2 Distributions of (left) momentum and (right) p_T for (top plot) single electron and single positron candidates; (bottom plot) background-subtracted electron candidates, compared with the distributions in simulation, which are normalized to data

FIGURE 3 Result for the $\bar{p}$ cross-section measurement, compared to the absolute predictions of the EPOS LHC model. The data points show the double differential cross-section as a function of p_T in the 18 momentum bins, with values successively scaled by a factor 0.1 to improve the readability of the plot. The EPOS LHC predictions, scaled with the same factors as the data, are shown by the solid curves. The errors bars, barely visible, show the uncorrelated uncertainty only

vacuum-pumping configuration of the data with gas. The yield measured in these special data were scaled according to the corresponding number of protons on target, and the relative average contribution from residual vacuum was evaluated to be $0.7 \pm 0.2\%$.

3.3 | Normalization

The SMOG device does not presently allow a precise calibration of the injected gas pressure. Instead, the normalization is provided by observing a process with a well-known cross-section. Single electrons elastically scattered by the proton beam can be observed within the LHCb acceptance. The cross-section in the polar angle range $3 < \theta < 27$ mrad, outside of which the electrons cannot be reconstructed in LHCb, is $180.6 \mu\text{b}$. Though this is three orders of magnitude below the total nuclear inelastic cross-section, events are expected to have a distinct signature, with a single low-momentum and low- p_T electron track visible in the detector, with little or no other activity. Background events that could mimic this signature are expected to be charge-symmetric, since they are mostly due to soft nuclear interactions where the candidate is either the product of a photon conversion or a light hadron from a central exclusive production event. Background is thus modeled and subtracted using events with a single positively charged track. Candidate events are selected through a loose kinematic selection on the track and applying veto requirements on any detector activity not compatible with the elastic scattering hypothesis. The selection yields 16 569 single e^- candidates and 9548 e^+ candidates. The background-subtracted kinematic distributions are shown in Figure 2, where an excellent agreement with the simulation is observed. The luminosity is determined to be $\mathcal{L} = 0.443 \pm 0.011 \pm 0.027 \text{ nb}^{-1}$, where the first uncertainty is statistical and the second is systematic, dominated by the uncertainty on the electron reconstruction efficiency.

FIGURE 4 Result for the $\bar{p}$ cross-section measurement, compared to absolute predictions from different models. The plots show the ratio of data over simulation as a function of p_T in the 18 momentum bins, for EPOS LHC (black round closed symbols), EPOS 1.99 (red squared closed symbols), HIJING 1.38 (green squared open symbols), and QGSJETII-04 (violet round open symbols). The error bars represent the uncorrelated uncertainty for each measurement. The additional correlated uncertainty, shown only for EPOS LHC but also relevant to the other cases, is indicated by the red dashed lines

3.4 | Uncertainties and results

The precision of the measurement is limited by systematic uncertainty. The largest uncertainty that is correlated among all kinematic bins is the aforementioned relative 6% on the normalization. The uncorrelated uncertainty is dominated for most bins by the error on the $\bar{p}$ fraction from the PID analysis. The relative total uncertainty amounts to 10% or less for most of the accessible p_T regions. The antiprotons candidates are counted from a sample of 33.7 million selected p -He collisions, from which a sample of 1.4 million antiprotons is

determined by the PID analysis. The double differential $\bar{p}$ production cross-section ($d^2\sigma/dp dp_T$) is computed in each kinematic bin after correcting for the reconstruction efficiency and the background. The results are compared in Figure 3 with the predictions of the EPOS LHC (Pierog et al. 2015) model, which is used in the LHCb simulation. The double differential shape, notably in the momentum spectrum, is found to be in good agreement with the simulation, while the absolute production rate is larger, on average, by about a factor 1.5. In Figure 4, data are also compared with three other models

implemented in the CRMC¹ package v1.5.6. The values predicted by the pre-LHC version of EPOS (Pierog & Werner 2009) are in better agreement with data, and good agreement is also observed with HIJING 1.38 (Gyulassy & Wang 1994). QGSJET II-04 (Ostapchenko 2011) matches the measured values at low p_T , while it exhibits a harder p_T spectrum than data.

4 | PROSPECTS

The LHCb experiment has opened the way to the use of the LHC beams for fixed-target physics. The measurement of antimatter production in p -He collisions is one of the first results of this novel program. Developments of this study in the near future are foreseen, with the inclusion of the contribution due to hyperon decays, accounting for 20–30% of the $\bar{p}$ production. The measurement will be also performed on additional data collected at $\sqrt{s_{NN}} = 86.6$ GeV during November 2016, allowing us to constrain scaling violation in the computation of the secondary antiproton flux in cosmic rays.

The production studies can be extended to other light particles, pion and kaons, allowing the prediction of also the positron production cross-section. Ratios of particle species that are not affected by the uncertainty on the normalization will provide precise tests of soft QCD models.

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¹ <https://web.ikp.kit.edu/rulrich/crmc.html>