PROCEEDINGS OF SCIENCE

LHCb fixed-target results and prospects

Saverio Mariani[a,*]

[a] *Università degli studi e INFN Firenze,*
via Sansone 1, 50019 Sesto Fiorentino (FI), Italy

E-mail: saverio.mariani@cern.ch

Among the LHC experiments, LHCb has, starting from 2015, the unique possibility to exploit the injection of noble gases into the LHC accelerator to acquire in fixed-target configuration the collisions between protons or lead ions and gas atoms. These give access to poorly-constrained kinematic regions and provide an example of extending the diversity of the LHC physics reach, stressed as a key requirement for the future in the 2020 update of the European strategy for Particle Physics. Two examples of analyses also motivated by open problems in the cosmic rays community and the respective ongoing extensions are reviewed: the first charm production measurement at fixed-target LHC in the pHe and pAr systems with $\sqrt{s_{\rm NN}} = 87$ GeV and $\sqrt{s_{\rm NN}} = 110$ GeV nucleon-nucleon centre-of-mass energies, respectively, and the first determination of the prompt antiproton production cross-section in pHe collisions at $\sqrt{s_{\rm NN}} = 110$ GeV. The fixed-target system is now being upgraded with the installation of a confinement cell for the gas upstream the nominal beam-beam interaction point. The gas areal density will be increased by up to two orders of magnitude, also non-noble gases like oxygen and hydrogen could be injected and the separation between the beam-beam and beam-gas collision regions will open the possibility to simultaneously operate the LHCb detector in collider and fixed-target mode. All of this will result in a unique laboratory for QCD studies at the LHC.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(EPS-HEP2021)396

1. Introduction

As acknowledged in the 2020 update of the European Strategy for Particle Physics [1], the multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target experiments ever performed, significantly contributing to the diversity of the LHC physics reach and to its connections to other high-energy physics fields in common research items, such as the search for Dark Matter (DM). At the LHCb experiment [2, 3] at CERN, originally conceived for precision flavour physics measurements in pp collisions, the detector geometry instrumenting the forward region ($2 < \eta < 5$), its excellent tracking, vertexing and particle identification performance, the flexibility of its data acquisition system and the possibility to inject noble gases in the LHC accelerator thanks to a system called SMOG (System for Measuring Overlap with Gas) have been exploited from 2015 to study proton-gas collisions in fixed-target configuration. Some highlights of the results and operations of this programme in the LHC Run2 (2015-2018) and the opportunities and the preparation of the ongoing upgrade that will operate from 2022 are reviewed in this document.

2. The Run2 fixed-target programme

A system called SMOG for the injection of noble gases into the LHC accelerator with a $O(10^{-7})$ mbar pressure and in ± 20 m from the LHCb nominal interaction point ($z = 0$) was conceived and installed in 2011 to measure the LHC luminosity. Proton-gas collisions are employed to reconstruct the LHC beams transverse profiles and, combined with the Van Der Meer scans, decreased the measurement uncertainty to the lowest one among all LHC experiments. Starting from 2015, the SMOG gaseous target has also been exploited in a unique fixed-target programme at the LHC and samples with both proton and lead beams and injected helium, argon or neon have been collected in 2015-2018, as presented in top Fig. 1. The accessible kinematic region is unique. As an example, the LHCb acceptance for pHe collisions with a 6.5 TeV proton beam energy, corresponding to a nucleon-nucleon centre-of-mass $\sqrt{s_{\rm NN}} = 110$ GeV energy, is presented and compared to the pp one in bottom Fig. 1. The high-x and low-Q^2 region, poorly constrained from previous experimental data, can be accessed with SMOG. Also, the collisions energy scale is intermediate between the ones of SpS and LHC or RHIC experiments and collision systems with an atomic number between the proton and lead ones can be studied. Among the ongoing analyses of the collected data, two recent results and their ongoing extensions exemplifying the LHC physics reach diversity are:

- the first determination of the J/ψ and D^0 particles production in pHe and pAr collision with $\sqrt{s_{\rm NN}} = 87$ GeV and $\sqrt{s_{\rm NN}} = 110$ GeV [4], respectively. The obtained results are compared to the theoretical expectations and, at negative centre-of-mass rapidities, exclude a large contribution from an intrinsic charm content of the nucleon. The results are also important to model the main background due to charmed particle decays for PeV-energy neutrinos observation at ground. Extensions of the measurement addressing heavier charmonia states in the SMOG highest-statistics 2017 pNe sample are ongoing;

- the first determination of $\sigma(p\text{He} \to \bar{p}_{\rm prompt}X, \sqrt{s_{\rm NN}} = 110\ \text{GeV})$ [5], a key ingredient to model the antiproton production in collisions between Cosmic Rays (CRs) and the interstellar

PoS(EPS-HEP2021)396

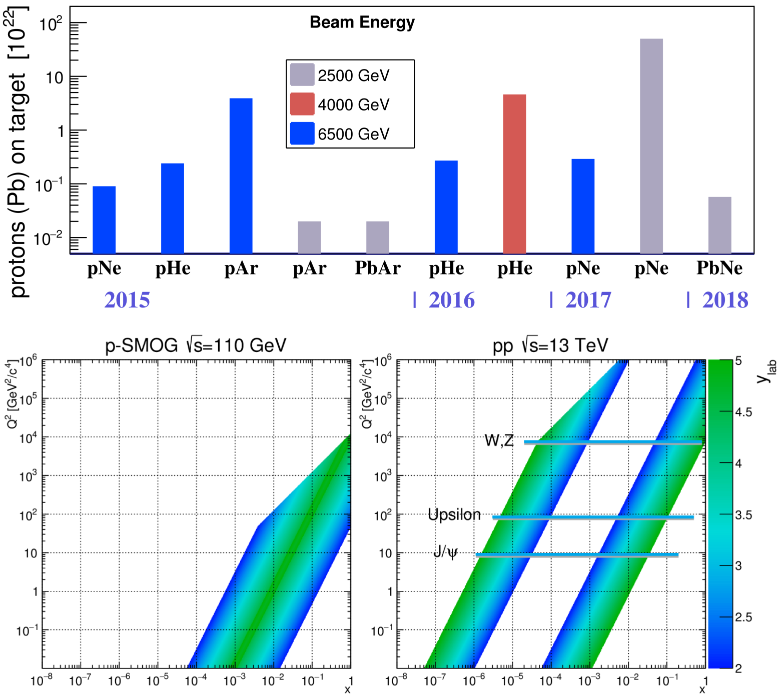

Figure 1: Figures of merit for the LHCb fixed-target programme in Run2. The top plot presents the samples collected with the SMOG system between 2015 and 2018 and also indicates the statistics as proton (or lead atoms) on target, the collision system and the energy. The bottom plot compares the LHCb acceptance in the Q^2/Bjorken$-x$ plane for pHe at $\sqrt{s_{\rm NN}}$ =110 GeV (left) and pp (right) collisions. With SMOG, the high-x and low-Q^2 region, poorly constrained by experimental data, can be accessed. Figures from [8].

medium, mainly composed of hydrogen and helium. A measured excess of the antiproton flux in CRs over this expected production could evidence a possible DM decay or annihilation process and its precise modelling is thus crucial to the interpretation of data. This only relied on poor experimental inputs and the LHCb result has indeed lower uncertainties than the spread among different theoretical models. Since only promptly-produced antiprotons are considered in this result, an extension of the measurement addressing the detached component ($\overline{\Lambda} \rightarrow \overline{p}\pi^+$, with both a prompt or a decay-produced $\overline{\Lambda}$ particle and $\overline{\Sigma} \rightarrow \overline{p}\pi^0$) is ongoing. This is expected to account for 25-40% of the total, but is poorly constrained by previous experimental data. Two complementary approaches exemplified by Fig. 2 [6] are being followed. In the left plot, the distribution for all reconstructed and selected antiproton candidates in pHe data of a variable related to the impact parameter presents three distinct peaks, corresponding to the prompt, produced in decays and in interactions with the detector material antiproton categories. By drawing on simulation templates for all particle species and fitting to the pHe data their composition with the relative abundances as free parameters, the detached-to-prompt antiproton ratio is being measured. The second approach is the measurement of $\sigma(p\text{He} \rightarrow (\overline{\Lambda}_{\rm prompt} \rightarrow \bar{p}\pi^+)X)$ decays, counted in pHe data by modelling the $\overline{\Lambda}$ candidates invariant mass, presented in right Fig. 2. The obtained results are divided by the prompt $\bar{p}$ ones, independently cross-checking the detached antiprotons dominant contribution.

PoS(EPS-HEP2021)396

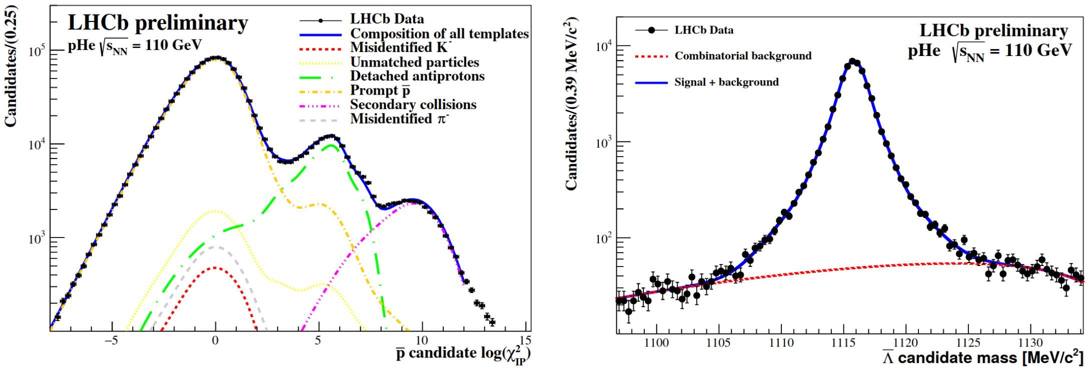

Figure 2: Figures of merit for the approaches that are being followed for the measurement of the non-prompt antiproton production. In the left plot the impact parameter separation between prompt and detached antiprotons is exploited to measure the detached-to-prompt $\bar{p}$ ratio with a template fit to data. The right plot presents the invariant mass peak of the $\overline{\Lambda}$ particles, whose exclusive reconstruction and selection allows the dominant contribution of detached antiprotons to be counted. Figures from [6].

3. The SMOG2 upgrade

The Run2 SMOG injection system, not originally conceived for production measurements, suffered from some limitations:

- the 40 m gas spread limited the maximum injectable gas pressure and species and, as a consequence, the statistics and variety of the collected samples;
- the overlap between the beam-beam and beam-gas interaction regions suggested a fixed-target data-taking strategy with short and dedicated periods. Only during a special *pp* run at $\sqrt{s}$ = 5 TeV, beam-beam and beam-gas collisions were acquired simultaneously for physics, the latter for the only beam bunches not colliding in the LHCb interaction point. This increased the size of the collected beam-gas sample, but a significant contamination of the nominal beam-empty events from beam-beam collisions due to bunch-by-bunch protons migrations was observed. On the other hand, beam-beam data are affected by an additional background from beam-gas collisions;
- the SMOG system was not equipped with precise-enough gauges for the gas pressure and a direct measurement of the luminosity of the beam-gas samples was not possible. The elastic scatterings between LHC protons and the gas electrons were thus employed, with a systematic uncertainty that turned out to be the dominant one affecting the measurements precision;
- since the gas injection system was only equipped with one gas recipient, an intervention was needed for each gas replacement.

An upgrade of the gas injection system, SMOG2 [7], is currently taking place to solve all these limitations and to operate from 2022. It mainly consists in the installation of a 20 cm-long confinement cell for the gas covering $z \in [-50, -30]$ cm, as shown in top and bottom left Figs.3. With a well-defined region for the beam-gas collisions, the gas target areal density can be increased

PoS(EPS-HEP2021)396

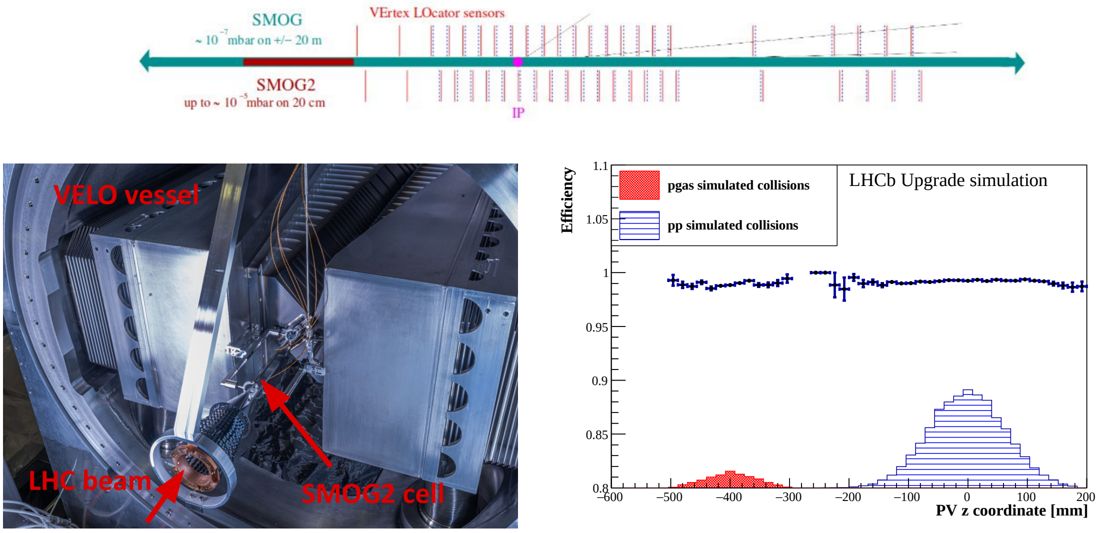

Figure 3: Illustration for the SMOG2 upgrade that will operate from 2022. Top figure shows the z region covered by the confinement cell, whose center is located 40 cm upstream the LHCb nominal interaction point. The bottom left is a picture of the cell installation, accomplished in August 2020; the bottom right one a preliminary result for the tracking efficiency on simulated *pp* and *p*He collisions as a function of the primary vertex longitudinal coordinate. The two components can be seen clearly separated and, despite the different collision conditions, the same tracking performance has been achieved. Bottom-right figure from [9].

by up to two orders of magnitude with respect to SMOG and more gas species, notably hydrogen, deuterium, oxygen and nitrogen, can possibly be injected. Thanks to the installation of precise gauges for the temperature and to an accurate control of the gas flow, the luminosity can be directly measured, decreasing the dominant systematic uncertainty to 1-2%. Also, thanks to the separation between the beam-beam and beam-gas interaction regions, the feasibility to simultaneously operate LHCb in collider and fixed-target mode with all LHC bunches is being investigated. An example of this is presented in bottom right of Fig. 3, showing the tracking efficiency as a function of the longitudinal coordinate of the primary vertex. The beam-gas (in red) and beam-beam (in blue) components can be clearly seen separated and, despite the different type of collision, tracks are efficiently reconstructed for all PVz. For the moment, no showstopper for a simultaneous beam-beam and beam-gas data acquisition has been found. The projected physics opportunities [8], pending the definition of the data-taking strategy, will further widen the LHCb-SMOG physics reach and comprehend:

- measurements of heavy-ion interests, such as the extension of the studies on the charm and bottom systems that, profiting from the larger available statistics, will advance our understanding of the Quark-Gluon Plasma;

- measurements of QCD interests, aiming to a better description of the nucleon structure through for example the study of low-mass Drell-Yan states and photo-peripheral-produced ρ and ω particles. Studies for the inclusive quarkonia production, a key process to get access to the yet unmeasured gluon TDMs, will also be possible;

PoS(EPS-HEP2021)396

- measurements of CRs interest, such as the extension of the antiproton production measurements to lower beam energies, possibly up to the LHC injection one of 450 GeV. By comparing the production cross-sections with injected hydrogen and deuterium, also the antiproton from antineutron production can be constrained, while oxygen and nitrogen will reproduce the systems of the atmospheric showers.

4. Conclusions

The LHCb experiment at CERN has being pioneering a unique fixed-target programme studying collisions between the LHC beams and injected noble gases. The analysis of Run2 data already provided results in poorly-explored kinematic and energy regions and is having an impact in different fields of interests. In parallel to the measurement extensions, the limitations affecting the Run2 injection system are being faced with a major upgrade mainly consisting in the installation of a confinement cell for the gas allowing its areal density to be increased by up to two orders of magnitude with respect to SMOG. The consequent increase in the statistics, together with the explored possibilities to also inject non-noble gases and to simultaneously operate LHCb in detector and collider mode, will result into an unprecedented laboratory for QCD studies at the LHC.

References

[1] Ellis, Richard Keith *et al.* (2019), Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020, CERN-ESU-004

[2] LHCb (2008), The LHCb detector at the LHC, JINST 3, LHCb-DP-2008-001

[3] LHCb (2014), The LHCb detector performance, Int. J. Mod. Phys. A30, LHCb-DP-2014-002

[4] LHCb (2018), First measurement of charm production in fixed-target configuration at the LHC, PRL 122, LHCb-PAPER-2018-023

[5] LHCb (2018), Measurement of antiproton production in pHe collisions at $\sqrt{s_{\rm NN}} = 110$ GeV, PRL 122, LHCb-PAPER-2018-031

[6] LHCb (2020), Antiprotons from $\overline{\Lambda} \to \overline{p}\pi^+$ and $\overline{\Sigma} \to \overline{p}\pi^0$ decays in pHe collisions, LHCb-FIGURE-2020-004

[7] LHCb (2019), LHCb SMOG Upgrade, LHCb-TDR-020

[8] Bursche, Albert *et al.* (2018), Physics opportunities with the fixed-target programme of the LHCb experiment using an unpolarized gas target, LHCb-PUB-2018-015

[9] LHCb (2019), SMOG2 VELO tracking efficiency, LHCb-FIGURE-2019-007

PoS(EPS-HEP2021)396