Acta Physica Polonica B Proceedings Supplement **16**, 1-A140 (2023)

EXPECTED PERFORMANCE RESULTS FROM UPGRADED LHCb AND SMOG2*

Saverio Mariani

on behalf of the LHCb Collaboration

Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze
via Giovanni Sansone 1, Sesto Fiorentino (FI), Italy

Received 29 July 2022, accepted 16 September 2022, published online 14 December 2022

The LHCb experiment at CERN is a forward spectrometer with a unique heavy-ion physics programme exploiting the collisions of circulating proton and lead beams and, since 2015, is pioneering fixed-target physics at the LHC with the injection of helium, neon, and argon in the accelerator beam-pipe. A further extension of both programmes is now expected along with the experiment upgrade. In this document, the expected performance for data reconstruction and the related physics opportunities are discussed.

DOI:10.5506/APhysPolBSupp.16.1-A140

1. Introduction

The LHCb experiment [1, 2] at CERN is a single-arm spectrometer instrumenting the pseudorapidity region of $\eta \in [2, 5]$. The reconstruction of particles is performed by a vertex detector, VELO, and by tracking stations installed upstream and downstream of a magnet; their identification is made by two calorimeters, two ring imaging Cherenkov detectors, and muon chambers. Leveraging on the forward acceptance, complementary to the other experiments operating at the LHC, and on the excellent reconstruction and identification performance, the LHCb physics also embraces a unique heavy-ion programme. In particular, as summarised in figure 1, the LHCb took part in the LHC Run 2 heavy-ion data-taking periods. Proton–lead samples were collected at two energy scales with both the proton (pPb) and the lead beam (Pbp) entering the LHCb from the vertex detector, which gave access to Bjorken-x values down to $\mathcal{O}(10^{-6})$ and up to $\mathcal{O}(10^{-1})$, respectively.

* Presented at the 29$^{\text{th}}$ International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

Lead–lead (PbPb) data were also acquired in the 60–100% centrality range. The high track density in the forward region and the related hardware saturation effects prevented more central collisions from being probed.

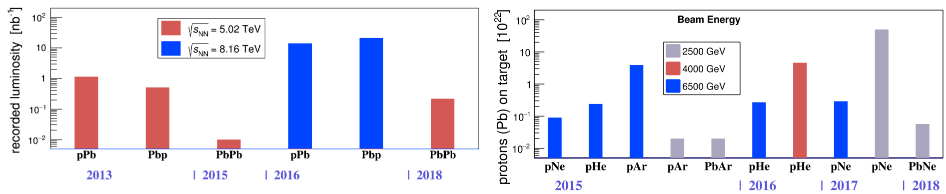

Fig. 1. Ion samples collected by the LHCb experiment during the LHC Run 2 in its collider (left) and fixed-target (right) configuration. The collision system, the energy, and the recorded statistics are indicated.

The LHCb has also the unique opportunity to study beam–gas collisions, operating as the highest-energy fixed-target experiment ever. The gas was injected in the accelerator beam-pipe by the System for Measuring Overlap with Gas (SMOG), originally conceived to decrease the uncertainty in the LHC luminosity measurement [3], with a typical pressure of $\mathcal{O}(10^{-7})$ mbar and was free to flow in a wide region around the LHCb nominal interaction point. Figure 1 shows the samples collected in the LHC Run 2 by exploiting the circulation of proton and lead beams and the injection of helium, neon, and argon. The high-x and moderate Q^2 region, poorly constrained by previous experiments, could be probed with high precision for the first time.

In view of the LHC Run 3, the LHCb experiment has been largely upgraded [4]. Most of the detectors, electronic and data acquisition channels have been removed or replaced to increase their granularity or radiation resistance. *De facto*, a brand-new detector is operating at the LHC. In parallel, the data acquisition strategy was also reviewed [5]. The hardware trigger level was removed and the full detector read-out, calibration, alignment, and the event reconstruction and selection will take place at 40 MHz via software. The first trigger level will completely run on GPUs as the first complete high-throughput GPU trigger proposed for a large high-energy physics experiment [6].

2. Expected LHCb performance on heavy-ion data

Due to the installation of more granular detectors, a maximum of 30% centrality is expected to be reached for PbPb collisions already in the LHC Run 3. Figure 2 illustrates the simulation of the distributions of the total energy left in the electromagnetic calorimeter (ECAL) and the number of energy deposits (left) in the VELO, upgraded from a strip to a pixel detector, and (right) in the scintillating-fibres (SciFi) stations downstream of the

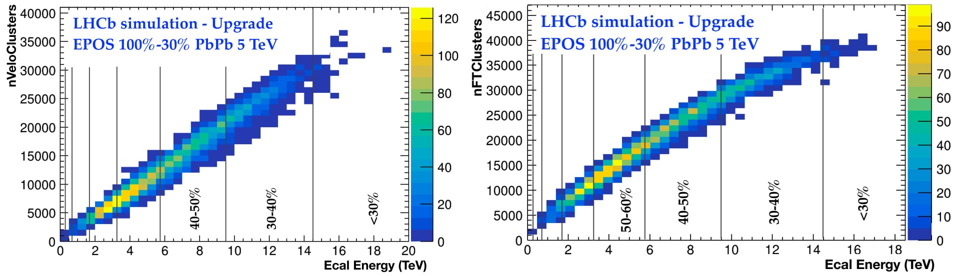

Fig. 2. Distributions on simulated PbPb collisions of the total energy left in ECAL and the number of energy deposits in (left) the VELO and in (right) the SciFi Run 3 detectors. No hardware saturation effects are observed up to 30% centrality.

magnet. No saturation pattern is observed neither in the VELO nor in the SciFi up to 30% centrality. At this scale, as shown in figure 3, a drop in the tracking efficiency can be seen. The improved reconstruction performance will allow the experiment to extend its physics reach, providing unique constraints to theoretical models in the forward region [7]. In the expected future LHCb upgrades, the heavy-ion programme will be further boosted with the installation of tracking stations inside of the magnet and with the replacement of the innermost SciFi modules with silicon trackers [8]. By then, no more centrality limitation will affect the PbPb data reconstruction.

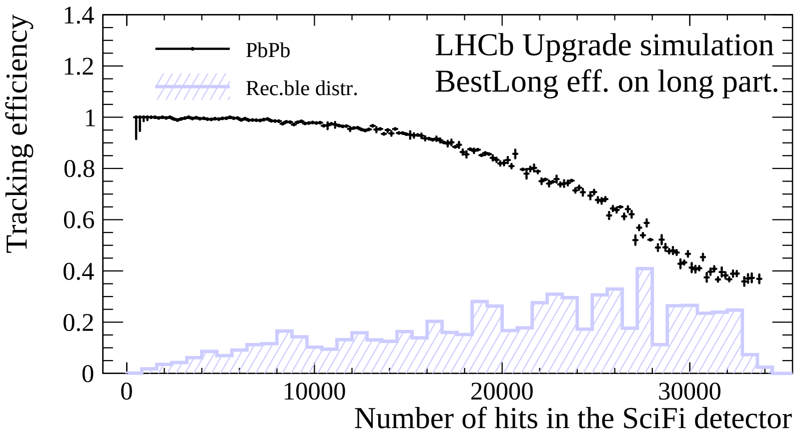

Fig. 3. LHCb upgrade track reconstruction efficiency for Run 3 simulated PbPb collisions as a function of the number of SciFi energy deposits in the event.

3. Expected LHCb performance on beam-gas data

Within the experiment upgrade in view of the LHC Run 3, a confinement cell for the gas, SMOG2 [9], was installed between 30 and 50 cm upstream of the LHCb interaction point. Following the precise definition of the beam–gas interaction region, the gas target areal density will be increased by up to two orders of magnitude with the same gas flow as in Run 2 and heavier noble gases, such as krypton and xenon and non-noble species such as hydrogen, deuterium, oxygen, and nitrogen might be injected. The detached cell position with respect to the nominal beam–beam interaction point and the expected negligible increase in the detector multiplicity due to the beam–gas collisions also open the possibility to simultaneously operate the LHCb as a collider and a fixed-target experiment.

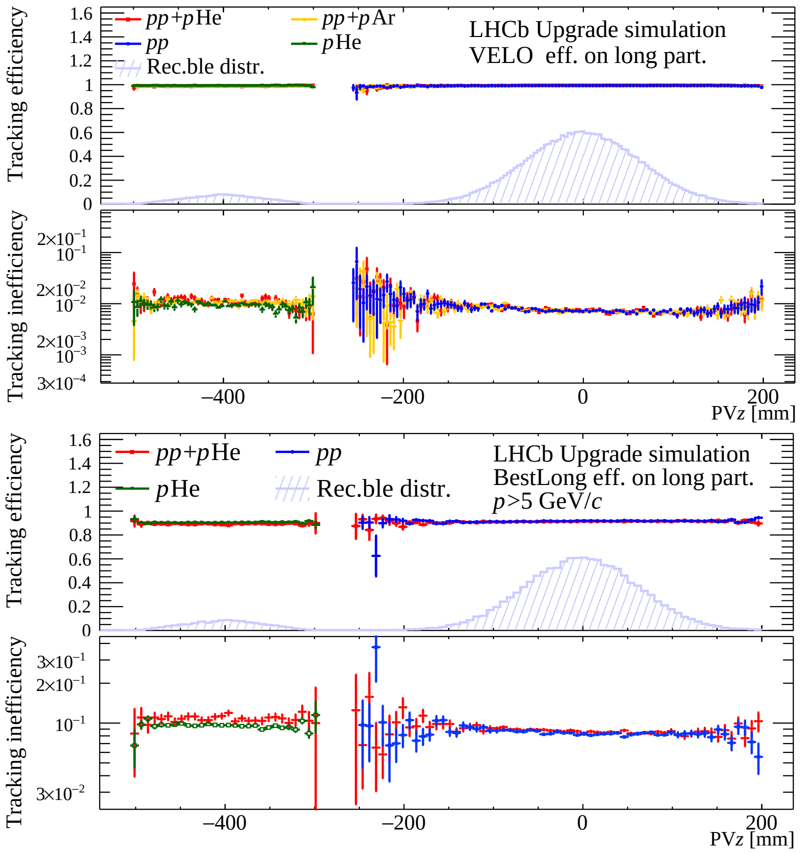

Fig. 4. Track reconstruction efficiencies and inefficiencies (top) in the VELO and (bottom) in the full tracking system as a function of the PV z coordinate for simulated stand-alone pp, pHe, and overlapped pp and pHe and pAr collisions.

The related physics opportunities [10] are unique at the LHC and cover different fields of interest, including heavy ion, astroparticle physics, and probes for the nucleon structure characterization. On the other hand, the cell displacement with respect to the nominal interaction point poses some challenges in reconstructing the particles produced in SMOG2 and dedicated activities to optimise the reconstruction algorithms were needed [11]. Figures 4 and 5 show some of the obtained results [12]. In the former, the track reconstruction efficiencies and inefficiencies are illustrated as a function of the longitudinal primary vertex (PV) coordinate for simulated samples representing stand-alone or simultaneous data-taking scenarios. As resulting from the gas confinement in the cell, the beam–beam, and beam–gas interaction regions are clearly distinguished. Despite the different topology and energy, the same performance was obtained for beam–beam and beam–gas collisions. Also, by comparing stand-alone and overlapped *pp* and proton–helium (*p*He) or proton–argon (*p*Ar) data, no efficiency loss is observed, demonstrating that the interference between the two data acquisition is minimal. The latter figure presents a similar plot for the PV reconstruction efficiency as a function of z and the same conclusions as for the tracking are valid.

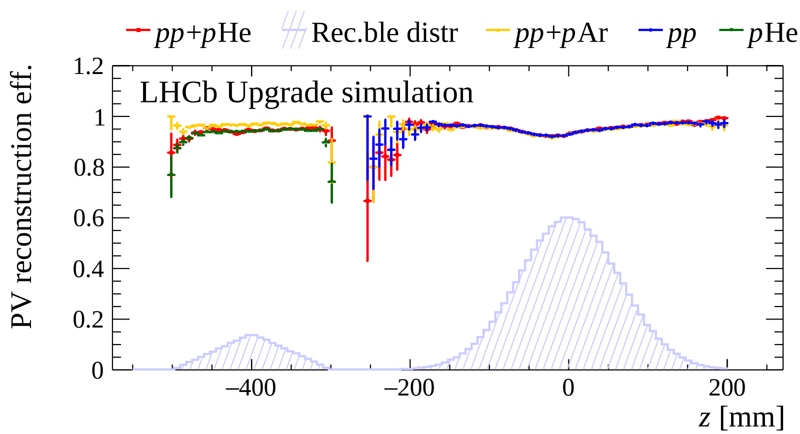

Fig. 5. PV reconstruction efficiency as a function of z for simulated stand-alone *pp*, *p*He and overlapped *pp* and *p*He and *p*Ar collisions.

4. Conclusions

In parallel to the study of *pp* collisions, the LHCb is developing a unique heavy-ion programme and is pioneering since 2015 fixed-target physics at the LHC. Both programmes, providing already in Run 2 unique constraints to theoretical models in poorly explored kinematic regions, are fully profiting from the ongoing upgrade of the LHCb experiment. Thanks to the increased granularity of the newly installed subdetectors, a 30% maximum centrality is expected to be accessed already in Run 3 and further improvements are foreseen for the future. Concerning the fixed-target programme, a storage cell for the gas has been installed, allowing more gas species and increased pressure to be exploited. Thanks to the separation between the beam–beam and beam–gas interaction regions, the LHCb will operate at the same time as a collider and a fixed-target experiment. This is supported by dedicated activities on the event reconstruction software, which achieved the same performance and excluded a major interference between the two data types. As explicitly stressed in the 2020 European Strategy for Particle Physics Update [13], "the physics reach of the LHC complex can be greatly extended at a very limited cost".

REFERENCES

[1] LHCb Collaboration, «The LHCb detector at the LHC», *J. Instrum.* **3**, S08005 (2008).

[2] LHCb Collaboration, «LHCb detector performance», *Int. J. Mod. Phys. A* **30**, 1530022 (2015).

[3] LHCb Collaboration, «Precision luminosity measurement at LHCb», *J. Instrum.* **9**, P12005 (2014).

[4] LHCb Collaboration, «Framework TDR for the LHCb Upgrade: Technical Design Report», CERN-LHCC-2012-007.

[5] LHCb Collaboration, «Computing Model of the Upgrade LHCb experiment», CERN-LHCC-2018-014.

[6] LHCb Collaboration, «LHCb Upgrade GPU High Level Trigger Technical Design Report», CERN-LHCC-2020-006.

[7] LHCb Collaboration, «LHCb projections for proton-lead collisions during LHC Runs 3 and 4», CERN-LHCb-CONF-2018-005.

[8] LHCb Collaboration, «Framework TDR for the LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era», CERN-LHCC-2021-012.

[9] LHCb Collaboration, «LHCb SMOG Upgrade», CERN-LHCC-2019-005.

[10] A. Bursche *et al.*, «Physics opportunities with the fixed-target program of the LHCb experiment using an unpolarized gas target», LHCb-PUB-2018-015.

[11] S. Mariani, «Fixed-target physics with the LHCb experiment at CERN», CERN-THESIS-2021-313.

[12] LHCb Collaboration, «LHCb Upgrade expected reconstruction performance with ions and fixed-target data», LHCb-FIGURE-2022-002.

[13] R.K. Ellis *et al.*, «Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020», CERN-ESU-004.