Commissioning and first collisions with the LHCb SMOG2 system

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Abstract. Owing to the injection of gas in the CERN LHC accelerator beam-pipe through the System for Measuring Overlap with Gas (SMOG), the LHCb experiment has been pioneering since 2015 fixed-target physics at the highest energy ever reached. Within the upgrade of the experiment, a confinement cell for the gas, SMOG2, and a new gas injection system were installed. This dedicated setup opens unique possibilities for extensive measurements for heavy-ion, hadron, spin and astroparticle physics. In this contribution, the SMOG2 system is presented, focussing on its validation and first outcome as obtained from the exploitation of the proton-gas data collected in 2022.

1 The SMOG2 system at LHCb

The LHCb experiment [1] at CERN is a single-arm spectrometer instrumenting the pseudorapidity range $2 < \eta < 5$. Leveraging on the forward detector geometry, and the possibility to inject gas in the LHC accelerator beam-pipe, LHCb is the only LHC experiment capable of operating in collider and in fixed-target mode. During the LHC Run 2 (2015-2018), gas was injected through SMOG [2] and was free to spread in ± 20 m around the nominal LHCb interaction point, which limited the species of injectable gases to the lightest noble ones only and the pressure to $\mathcal{O}(10^{-7})$ mbar. Moreover, with the overlapping of the beam-beam and beam-gas interaction regions, the beam-gas data could only be acquired either in dedicated periods or simultaneously with beam-beam data, but only exploiting the small fraction, about 10%, of the LHC bunch crossings where only the LHC clockwise beam contains particles. By analysing the samples collected in 2015-2018 with injected helium, neon and argon and circulating protons or lead ions, unique inputs to theoretical models in different research fields [3] such as nucleon characterization, heavy-ion physics and astroparticles, are being provided in the poorly explored high-x and intermediate Q^2 region.

In preparation for the LHC Run 3, started in 2022, LHCb was upgraded by the replacement of most detectors and the removal of the hardware level trigger [4]. The full read-out, calibration, alignment, collision reconstruction and selection now all happen in real time via a software application. Within the experiment upgrade, a dedicated system for fixed-target physics, SMOG2 [5], was implemented. This mainly consists of a new gas feed system (GFS) and a 20-cm-long and 1-cm-diameter confinement cell for the gas, installed between -541 mm and -341 mm upstream of the nominal LHCb interaction point. A picture of the SMOG2 cell is shown in left Fig. 1. The gas is injected through a capillary at the centre of the cell, in

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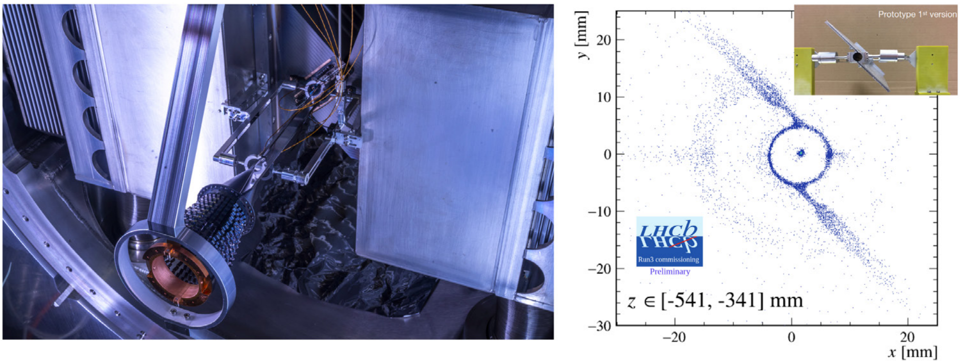

Figure 1. Picture (left) of the SMOG2 cell after installation and its visualization (right) through the reconstruction of secondary interactions in the detector material.

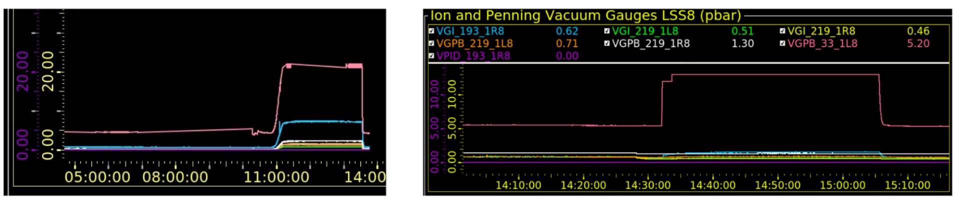

Figure 2. Evolution of the pressure with time during two injection tests in June (left) and in November (right) 2022. The coloured curves represent the readings by several gauges located at different distances from the nominal LHCb interaction point and refer to different scales.

such a way that the gas pressure in the cell is expected to follow the triangular distribution shown in the top left corner of top right Fig. 3. Thanks to the more precise definition of the beam-gas interaction region upstream of the nominal LHCb interaction point, the gas density is increased by up to two orders of magnitude for the same gas flow as in Run 2 and a simultaneous beam-beam and beam-gas data-taking exploiting all LHC bunch crossing becomes feasible. More gases, including the heaviest noble ones like krypton and xenon and non-noble species such as hydrogen, deuterium, nitrogen and oxygen, can be injected. Finally, with the new gas injection system offering a precise control and measurement of the gas flux, the direct measurement of the luminosity, dominating the systematic uncertainty for cross-section measurements in Run 2, becomes now possible with an expected uncertainty of 1-2%.

2 The SMOG2 system commissioning

During 2022, several gas injections through SMOG2 were performed to test the procedures and to validate the new system. Figure 2 shows the evolution with time of the pressure recorded by several gauges in proximity of the LHCb interaction point during an injection through SMOG2 in June (left) and in November (right) 2022. A very stable and reproducible GFS operation has been reached with all the four instrumented gas species, notably including hydrogen that was injected in LHC for the first time ever.

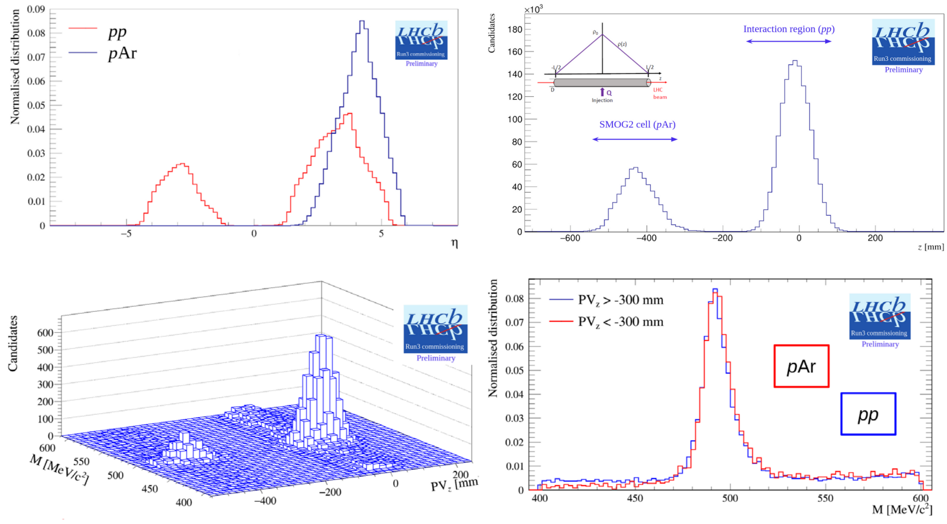

Figure 3. Reconstruction of particles in the innermost tracker detector (top left), of the beam-gas collision vertices (top right) and of $K^0_S \to \pi^+\pi^-$ decays (bottom) by the first trigger level in a 2022 data-taking with simultaneous pp + pAr collisions.

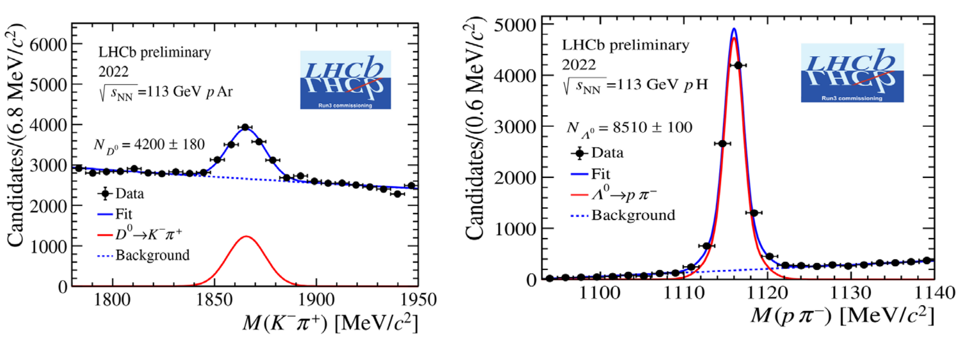

Figure 4. Invariant mass distributions for $D^0 \to K^-\pi^+$ (left) and $\Lambda \to p\pi^-$ (right) decay candidates in 2022 data-takings with simultaneous pp + pAr and pp + pH$_2$ collisions, respectively.

The acquired data have then been processed to validate the tunings applied to the collision reconstruction sequence optimising beam-gas performance [6]. Firstly, the distribution of the SMOG2 cell material has been obtained by reconstructing secondary interactions in the detector. By selecting $z \in [-541, -341]$ mm, as shown in right Fig. 1, a clear picture of the LHC beamspot, the cell in its closed position, the two wings and the support for the capillary where the injection goes through can be clearly seen. The cell position and alignment with respect to the LHC beam and to the rest of LHCb has hence be validated with data.

The data reconstruction in the first trigger level was then studied. The distribution of the particles pseudorapidity as reconstructed in the innermost detector (VELO), surrounding the nominal interaction point, is shown in left Fig. 3. As expected, pp collisions present a nearly symmetric distribution, with backward and forward differences only due to the lower number of VELO modules upstream of the LHCb nominal collision point. Particles produced in pAr collisions, instead, only have positive η values, as expected from the large Lorentz boost due to the momentum asymmetry between the laboratory and the centre of mass frames. Top right Fig. 3 illustrates then the reconstructed collision vertex z distribution. As expected from the confinement of the gas in the SMOG2 cell, two clearly distinct peaks appear, following a Gaussian distribution in z for pp and a triangular one for pAr collisions. Hadron decays have also been reconstructed and studied. Bottom plots of Fig. 3 illustrate the invariant mass distributions for $K^0_S \rightarrow \pi^+\pi^-$ candidates as a function of the z coordinate of the collision vertex associated to the K^0_S particle. When projecting to overlap candidates from pp and pAr collisions, peak widths are observed to be comparable, indicating that the momentum resolution does not drastically change with the collision type.

In order to validate the full reconstruction and selection sequence, some other decay channels have then been studied offline. Two examples of the obtained results are reported in Fig. 4, illustrating the invariant mass distributions for reconstructed $D^0 \rightarrow K^-\pi^+$ and $\Lambda \rightarrow p\pi^-$ candidates in data-takings with simultaneous $pp + p$Ar and $pp + pH_2$ collisions, respectively. It is worth to notice that the two data acquisitions lasted 18 and 20 minutes, respectively, yet contained more than four thousands D^0 and eight thousands Λ candidates. A very high-statistics production of charm states can hence be expected during routine LHCb simultaneous beam-beam and beam-gas operations in Run 3.

3 Conclusions

In conclusions, LHCb has been pioneering since 2015 fixed-target physics at the highest energy ever reached. While in 2015-2018 the gas was free to spread in a wide region around the LHCb interaction point, a 20-cm-long dedicated gas storage cell, SMOG2, was installed as part of the LHCb experiment upgrade. By the better definition of the beam-gas interaction region upstream of the nominal LHCb interaction point, more gases can be exploited with higher densities compared to the LHC Run 2 and beam-gas data can be acquired together with the beam-beam ones. The validation of the system took place in 2022. Several gas injections have been performed, with great stability and reproducibility of the GFS. The reconstruction of the particles produced in beam-gas collisions, as well as of the collision vertices and of decay chains, has been studied, confirming the results already found in the simulation. With the incoming LHC data periods, the analysis of the collected beam-gas data will provide a unique laboratory for QCD studies at the LHC, allowing the high-x and intermediate Q^2 kinematic region to be accessed and explored with high precision. As mentioned in the physics briefing inputting the 2020 European Strategy for Particle Physics Update [7], with this “the physics reach of the LHC complex can greatly be extended at a very limited cost".

References

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