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First performance results from upgraded LHCb and SMOG2

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The LHCb experiment has recently undergone a series of major upgrades: the entire tracking system has been replaced with higher-granularity sensors, the readout electronics have been upgraded, and all hardware triggers have been replaced with a new state-of-the-art readout system. In addition, the gaseous target SMOG system has been upgraded with a dedicated storage cell to increase the rate of fixed target collisions at LHCb by up to two order of magnitude for the same gas flow as in the LHC Run 2 and to allow the injection of more gas species, including non-noble gases. We present the first performance results from the new LHCb tracking system, the streaming readout system, and SMOG II, with a focus on how these upgrades directly impact the LHCb heavy ion physics programme.

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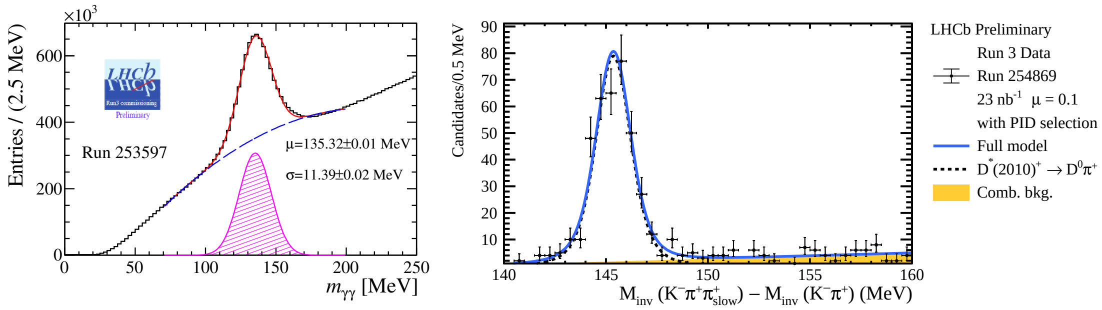

Figure 1: Distributions of invariant mass of the π^0 candidates (left) and of $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ (right), modelled with the combination (left: red solid line; right: blue solid line) of a signal (left: pink hatched area; right: black dashed line) and a background (left: blue dashed line; right: yellow area) component.

1. LHCb Run3 Upgrade

The LHCb experiment is a forward single-arm spectrometer covering the pseudorapidity range between $2 < \eta < 5$, originally designed to study heavy hadrons produced in *pp* collisions at LHC, but proven during the 2011-2018 data-taking years to be a general purpose experiment in the forward direction. During 2018-2022, LHCb detector and data-taking strategy went through a complete renovation [1] aimed to widen the physics reach towards a new range of signatures and to increase the precision on key observables, statistically limited during Run 1 and Run 2. More than 90% of the detector was updated, involving all the subsystem. The tracking system has been fully replaced, installing a new hybrid pixel detector for the vertex locator (VELO), a silicon strips upstream tracker (UT) and a scintillating fibers tracker (SciFi) downstream of the magnet. The PID detectors have been kept from Run2, while the readout systems of all subdetectors have been replaced and new optics and photodetectors have been installed for the RICH subsystem. The new detector is able to cope with increased luminosity and pile-up, reducing the occupancy and increasing the spatial resolution and PID performance, aiming to operate up to 30% centrality for PbPb. Finally, the data acquisition (DAQ) chain has been moved to a software-only paradigm, removing the hardware trigger and performing the readout at the LHC bunch crossing rate (40 MHz); the events are completely reconstructed and selected in real time through a two-levels software trigger. In order to guarantee excellent performance in term of efficiency and an offline-quality reconstruction, real-time alignment and calibration of all subdetectors are performed for every LHC fill. Two examples of preliminary results obtained with the new detector are reported in Fig.1; the first Run3 mass peak of π^0 candidates, reconstructed after the electromagnetic calorimeter (ECAL) calibration, is reported on the left [2], while the right figure shows the mass peak of $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ reconstructed with a preliminary HLT1 filtering and HLT2 reconstruction and selection [3]. In both cases, the performance shown are comparable to those obtained during Run 2 and they are constantly improving throughout the commissioning period.

2. LHCb fixed-target programme

Among the experiments operating at LHC, LHCb has the unique opportunity to inject gases in the accelerator beam-pipe, in order to use the proton-gas collisions to reconstruct the LHC beam

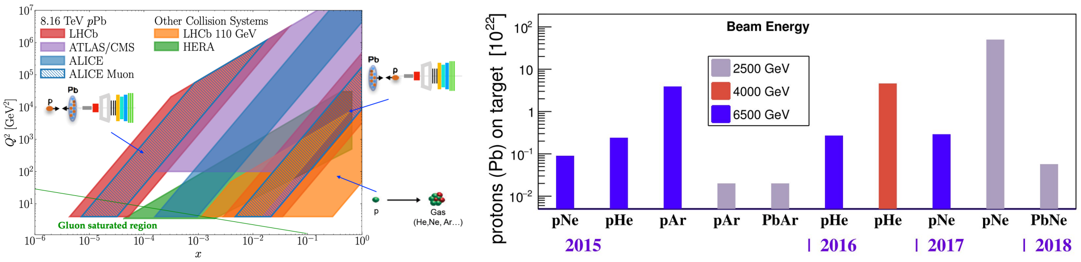

Figure 2: Figures of merit for LHCb fixed-target programme in Run 2. The left plot compares LHCb acceptance in the Q^2/ Bjorken-x plane with other experiments exemplifying the uniqueness of its coverage. The right plot presents the samples collected with SMOG between 2015 and 2018, indicating the collision system, the energy and the statistics as p (Pb) on target.

transverse profiles and measure the luminosity. Exploiting the forward geometry of the detector and its excellent particle reconstruction and identification performance, since 2015 the gas injection system SMOG has also been used as a gaseous target, turning LHCb into the as-of-today's highest-energy fixed-target experiment ever. During Run 2, samples both with proton and lead ions were collected injecting noble gases (He, Ne, Ar), covering a rapidity region in the centre of mass system ($-3 < y^* < 0$) complementary to the ones covered by the collider mode samples. The related physics opportunities are unique at the LHC. The high Bjorken-x and moderate Q^2 region, mostly unexplored by previous experiments, can be accessed with SMOG and collision systems with atomic numbers between the proton and lead can be studied, providing inputs to many research fields such as heavy flavour production, nuclear structure and cosmic rays astrophysics (Fig. 2).
Since SMOG was not originally conceived for production measurements, it suffered from some limitations:

- The gas was injected directly into the VELO tank and it could flow 40 m around the interaction point in the LHC beam pipe; in order not to significantly perturb the LHC operation, only noble gases could be injected with a maximum pressure in the interaction region of 10^{-7} mbar, limiting the statistics and variety of the collected samples.
- The beam-gas and beam-beam luminous region overlapped, requiring dedicated periods and data-taking strategies for the fixed-target physics programme, further limiting the available statistics.
- The SMOG system was not equipped with precise enough gauges to measure the pressure of the injected gas, preventing a direct measurement of the luminosity. The elastic scattering of LHC protons on the gas electrons was used instead, with a systematic uncertainty that turned out to be the dominant one affecting the measurements precision.

In order to overcome these limitations, during LHCb upgrade a new gas injection system, SMOG2, was installed. It consists of a 20 cm-long storage cell installed 44 cm upstream of the nominal LHCb interaction point and a new gas feed system that allows a finer and automatized control of the gas flow, pressure and injected species [4, 5]. Thanks to the confined interaction region, the gas density can be increased by to two orders of magnitude with the same gas flow as in SMOG.

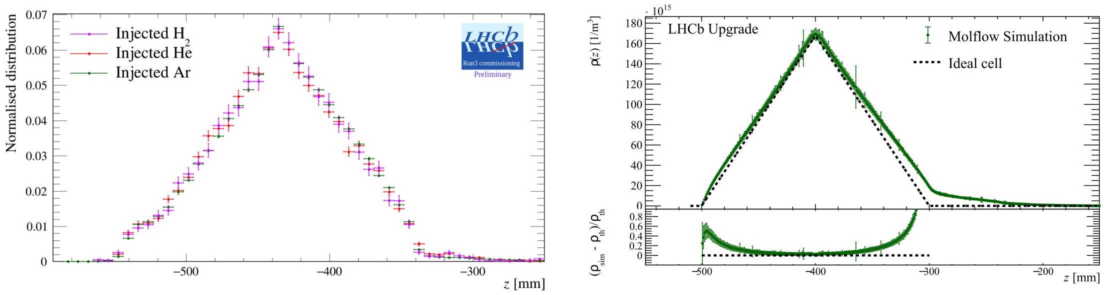

Figure 3: Gas density profile in data and simulation. In the left plot, the gas density profile is obtained as the normalised distribution of the longitudinal coordinate for the primary vertices; the profile is obtained for hydrogen (pink), helium (red) and argon (green) injections and no dependence on the gas species is found. The right plot shows the simulated gas density profile for helium as a function of the longitudinal coordinate; the profile for the ideal isolated cell is also shown (black dashed line). An overall agreement between data and simulation is observed.

Also, non-noble gases, like hydrogen, deuterium, oxygen and nitrogen, can be injected, as well as heavier noble gases like krypton and xenon, further expanding the LHCb fixed-target physics reach [5]. Moreover, thanks to the installation of precise gauges for the temperature and to an accurate control of the gas flow, the luminosity will be directly measured with an estimated precision of the 1-2 %. Finally, thanks to the separation between the beam-beam and beam-gas interaction regions, a simultaneous acquisition of the two type of collisions can be feasible, vastly increasing the collected statistics.

3. SMOG2 first performance results

In 2022, during the first data acquisition campaign of Run 3 for the LHCb experiment commissioning, several gas injections at different pressures in SMOG2 have been performed to validate the new apparatus and test its performance [6]. Data were recorded simultaneously to *pp* collisions and the collisions were reconstructed in real-time through the new software trigger.
SMOG2 operation results to be completely transparent for LHC operation, with no visible reduction of the beam life-time (estimated to be less than 2% from simulations); the contribution to the total data flow appears to be small compared to the regular *pp* data-taking, but, at the same time, beam-gas interactions proved to be fundamental to increase the activity during BGI (*Beam-Gas Imaging*) and material mapping measurements when the beam-beam interactions were scarce. In order to commission the gas feed system, both noble gases (Argon, Neon and Helium) and non-noble gases have been injected; in particular, Hydrogen has been injected for the first time in the LHC, showing the same behaviour as noble gases. Comparing the beam-gas vertices distributions obtained with the different gases, corresponding to their density distribution, no differences are observed between species; the longitudinal profile follows a triangular distribution, as expected from the cell geometry, in agreement with the gas flow simulation [7] (Fig. 3). Studying the primary vertices longitudinal distribution for the complete dataset, two clearly separated distributions can be seen, respectively centered around the nominal interaction point ($z = 0$ mm) and confined in the SMOG2 cell (-541 mm $< z < -341$ mm) (Fig. 4); the interaction regions confirm to be

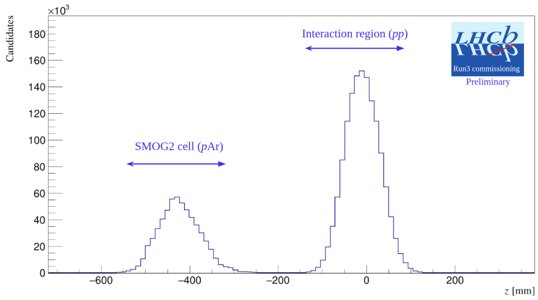

Figure 4: Distribution of the primary vertex longitudinal coordinate; two clearly separated regions for pp and pAr collisions can be seen, around the nominal interaction point and confined in the SMOG2 cell.

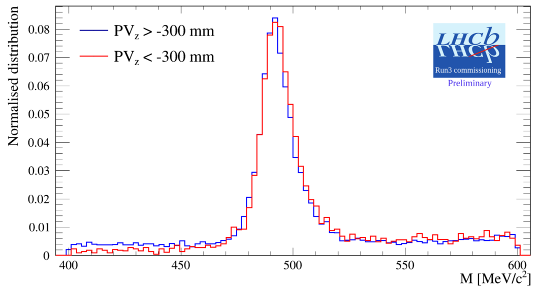

Figure 5: Reconstruction performance for K^0_S, as an example of decaying particle. Considering the normalised invariant mass distributions for K^0_S candidates with a primary vertex compatible with pAr (red) or pp (blue) region, the mass resolution is found to be comparable.

efficiently separated, allowing LHCb to operate simultaneously in collider and fixed-target mode with two interaction points at two different centre of mass energies. Finally, the reconstruction performance for decaying particles has been studied considering K^0_S candidates; as shown in Fig. 5, decaying particles coming from beam-gas interactions can be efficiently reconstructed obtaining a mass resolution that is comparable to the one for pp events.

4. Conclusions

The LHCb experiment at CERN went through a complete upgrade of its detector, including its unique fixed-target apparatus that allows to study collisions between the LHC beams and injected gases. The new apparatus, consisting of a gas confinement cell upstream of the nominal interaction point and of a finely controlled gas feed system, will allow to overcome the limitations affecting Run 2 injections, offering a wider choice of injectable gases, a better control of the systematic uncertainties and the possibility to acquire at the same time beam-beam and beam-gas collisions. The first data acquired during 2022 commissioning showed comparable performance between beam-gas and beam-beam events and confirmed the ability to acquire simultaneously with two interaction points for beam-beam and fixed target, without compromising either performance. As a result, during Run 3 LHCb will be the only experiment at the LHC acquiring data with two simultaneous interaction points at two different energy scales. The resulting physics prospects will contribute, as stated in the 2020 ESPPU [8], "to significantly extend the LHC physics reach at a limited cost".

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