PROCEEDINGS OF SCIENCE

Performance of LHCb Upgrade I in Run 3

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LHCb is a general-purpose forward detector at the LHC which is particularly suited to precision measurements in the beauty and charm sectors. During the LHC Long Shutdown 2 the experiment went through a massive upgrade, namely Upgrade I, to cope with the increase of the instantaneous luminosity $\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^2\ \mathrm{s}^{-1}$ in Run 3. A fully software based trigger was implemented and most of the subdetectors were upgraded. The upgraded tracking system, together with the particle identification subdetectors, will be presented. Early 2022 data has been used to perform a full validation of the detector, improving alignment and calibration. First Run 3 performance extracted will be shown.

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*Speaker

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1. LHCb experiment upgrade layout

The LHCb experiment is one of the four large detectors at the Large Hadron Collider (LHC) accelerator at CERN, performing searches for new physics through studies of CP-violation and decays of heavy-flavour hadrons. In order to maintain high performance and cope with a higher delivered instantaneous luminosity significant improvements in granularity, readout speed, radiation hardness, and trigger innovations have been implemented. In particular, LHCb has successfully introduced a fully software-based trigger system, complemented by comprehensive upgrades to a majority of its subdetectors [1].

The LHCb Upgrade detector layout is shown in Fig.1. Track reconstruction is possible thanks to the combined performance of the Vertex Locator (VELO), Upstream Tracker (UT) and Scintillating Fibre Tracker (SciFi). Particle identification (PID) is reliably achieved through the use of two Ring Imaging Cherenkov (RICH) detectors designed for charged hadron identification, situated upstream and downstream of the dipole magnet. Additionally, the system includes two calorimeters, one for identifying electromagnetic particles (ECAL) and the other for hadronic particles (HCAL). The identification of muons is facilitated by a muon system consisting of four stations.

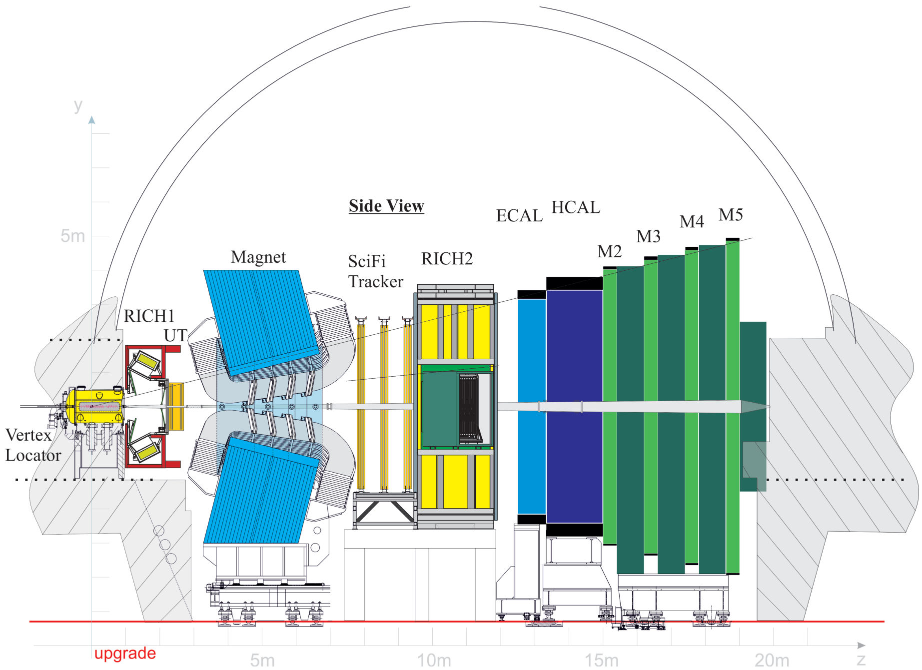

Figure 1: LHCb Upgrade detector layout, side view.

1.1 Trigger and real time analysis

One of the most significant changes pertains to the trigger mechanism: the removal of the hardware trigger, with a transition to a fully software-based trigger.

The LHCb ugraded data flow is shown in Fig. 2. The High-Level Trigger (HLT) is split into two levels: HLT1 and HLT2. HLT1 uses GPUs for track reconstruction, which is more cost-effective and scalable than using CPUs. HLT2, the second stage of the high-level trigger, handles reconstruction and selection for each event, and this part runs on CPUs. Real-time alignment and calibration procedures conducted for various detectors ensure the optimal performance and precision of the LHCb experiment. The centralized offline data processing focuses mainly on the preparation of the data for use in physics analysis. The process referred to as *sprucing* involves the application of additional selection criteria to the FULL data stream. It functions as a mechanism for fine-tuning the information that will be retained for analysis, with the goal of reducing data size, achieved through what is known as the *Turbo mechanism*. Figure 3 shows two mass spectra obtained after imposing the HLT1 trigger selection.

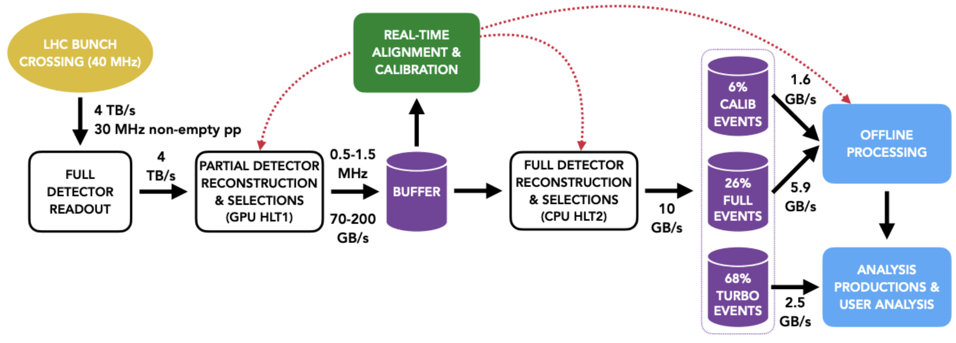

Figure 2: LHCb data flow.

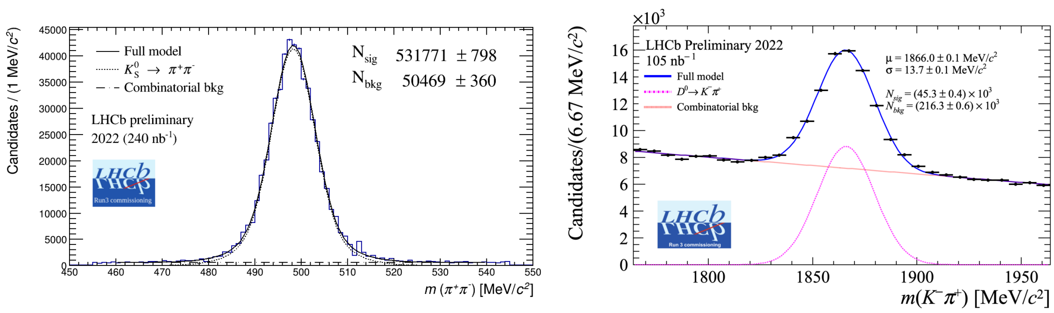

Figure 3: Mass peaks respectively of $K^0_S \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ extracted directly from HLT1 selection [2],[3].

1.2 Vertex Locator (VELO)

The VELO detector has the important role of detecting and precisely measuring trajectories of charged particles originating from the collision region. It facilitates the measurement of both the primary vertex and displaced decay vertices' positions. The redesign of the VELO detector was undertaken to ensure compatibility with the increased luminosity and the imperative for trigger-less readout capabilities. This sub-detector comprises pixelated hybrid silicon detectors, organized into 52 modules and cooled by two-phase CO_2 within microchannels in the silicon support substrates.

These modules are structured into two movable halves, which serve the purpose of beam centering, from 3 mm aperture up to 27 mm. RF foils are employed to separate the secondary VELO vacuum from that of the LHC. The delicate closing procedure requires precise knowledge of the RF foils, monitoring of vacuum and detector conditions.

1.3 Upstream Tracker (UT)

This tracker is made up of four planes of 1000 total 10×10 cm^2 silicon strip sensors. Readout is performed thanks to custom ASIC chips (SALT) and evaporative CO_2 cooling ensure good performance. The presence of the UT is important to reduce ghost track rate and for long lived particles. The installation of this subdetector finished during the 2022/2023 YETS and was completed in March 2023. Hence, the Data 2022 used for the plots showed in this proceeding are acquired without the UT in place.

1.4 Scintillating Fiber Tracker (SciFi)

The only tracker located downstream of the magnet, the SciFi is constructed using scintillating fibres with dimensions 2.5 m $\times$ 250 μm, organised in fibre mats. It is comprised of a total of 12 detection planes, which are further organized into 3 stations (T1, T2, T3), with each station containing 4 layers, with 128 modules in total. Signal from scintillating fibres are detected by 128-channel arrays of SiPMs made by Hamamatsu, with a channel pitch of 250 μm (524288 channels in total), readout with PACIFIC ASIC. To reduce the noise, the SiPMs are plaed inside a cold box, with temperature adjustable between -50 and +30 degrees.

1.5 Ring Imaging Cherenkov detector (RICH)

Within LHCb, the RICH subdetectors play a key role in the identification of charged hadrons. For the Upgrade RICH system new mechanics, optics, and a photodetetection chain were designed. The latter is made of multi-anode photomultiplier tubes (MAPMTs) readout by a custom front-end ASIC. The RICH 1 and RICH 2 are located respectively upstream and downstream to the dipole magnet. The first can provide charged hadron identification in the range of 2.6 – 60 GeV$/c$ making use of a C_4F_{10} gas radiator, while the second, using a CF_4 gas radiator, in the range of 15–100 GeV$/c$. The RICH1 and the central region of RICH2 are equipped with 1-inch MAPMTs modules Hamamatsu R13742 with a pixel size of 2.88×2.88 mm^2 (1888 in total), while 2-inch modules Hamamatsu R13743 with 6×6 mm^2 area were chosen for the outer region of RICH 2 (768 1-inch MAPMTs in the inner region and 384 2-inches in the outer region).

2. Calorimeters and muon system

Regarding the calorimeters and the muon system, the detectors themselves have remained largely unchanged, with no significant modifications introduced. The Scintillating Pad Detector (SPD) and the PreShower (PS) of the previous calorimeter system and the M1 station of the muon system were removed in the upgraded layout as no longer needed due to the removal of the hardware trigger. The readout electronics of the both the subdetectors have been entirely redesigned and replaced. The calorimeter electronics is based on 246 FEBs, 192 for the ECAL and 54 for the

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HCAL. For the muon system, the signals from four stations from M2 to M5 with 1104 multi-wire proportional chambers (MWPC) are digitised by the front-end CARDIAC boards with two CERN and Rio current amplifiers (CARIOCAs) and a diagnostic, time adjustment and logics (DIALOG).

3. System for Measuring the Overlap with Gas (SMOG2)

Thanks to the installation of the SMOG2 detector inside the VELO vessel, LHCb can act also as a fixed target experiment with an internal gas target (H2, Ne and Ar). The data taking can happen simultaneously with LHCb one. First mass plots produced from p-H and p-Ar collisions can be found in the LHCb public figure list [4].

4. First performance

The data taking starting in 2022 allowed to study the first performance of the upgraded LHCb detector.

4.1 Track reconstruction

Long tracks are reconstructed correlating the number of vertices reconstructed from the VELO detector with the number of SciFi clusters. Preliminary performance is shown in Fig.4. Additionally, it is evident that on increasing the average number of visible pp interactions per bunch crossing (μ) the distribution is shifted towards higher number of SciFi clusters.

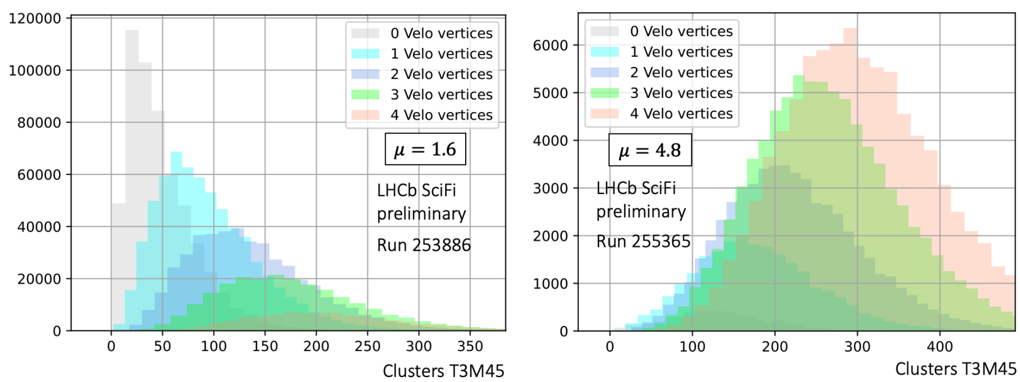

Figure 4: SciFi and VELO clusters for two different values of μ [5].

4.2 Particle identification performance

In order to validate the PID performance, invariant mass distributions were inspected for $D^0 \to K^-\pi^+$ and $J/\psi \to \mu\mu$ decays, with a preliminary alignment. Example plots are shown in Fig. 5, both without and with PID selection. It is evident that the PID cut can help to reduce the combinatorial background.

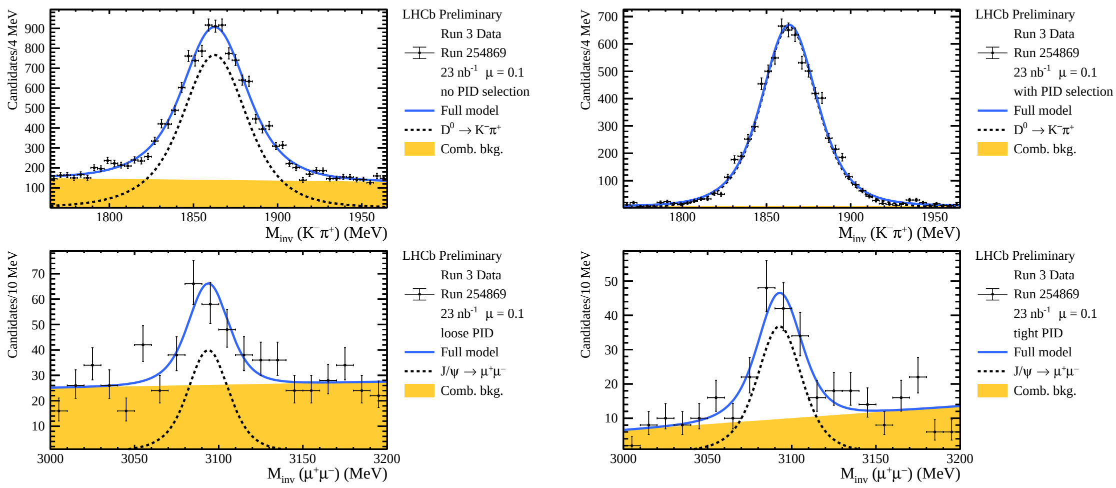

Figure 5: Top: mass spectra of $D^0 \to K^-\pi^+$ without (left) and with (right) PID selection. Bottom: mass spectra of $J/\psi \to \mu\mu$ without (left) and with (right) PID selection[6].

4.3 First mass peaks of charmed mesons and baryons

The initial mass spectra of charmed hadrons have been generated employing specific selection criteria during the second stage of the high-level trigger. In Fig. 6 the mass spectra for $D^0 \to K^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+$ are shown. These spectra serve as a valuable resource for the preliminary extraction of cross section measurements pertaining to the production of charm hadrons, using the newly upgraded detector. Mass spectra for $D^+ \to K^-\pi^+\pi^+$ are shown in Fig. 7, requiring either a loose selection (on the left) or a tight selection (on the right), with the additional condition that an event is accepted if one or two tracks are triggered on that specific signal. This leads to a substantial reduction of the background.

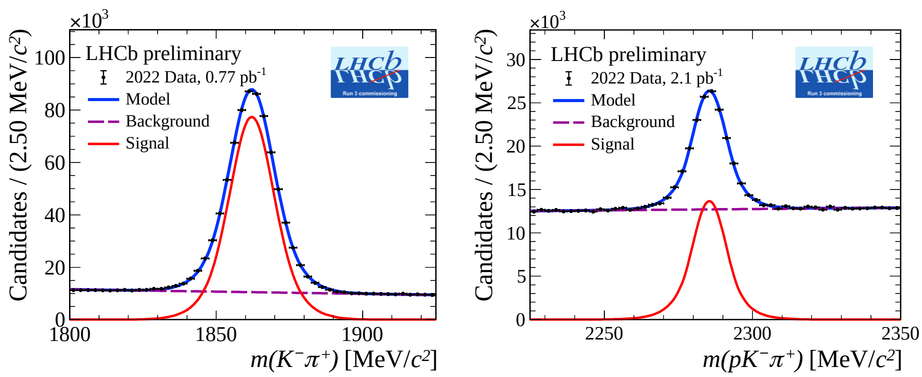

Figure 6: Mass spectra of $D^0 \to K^-\pi^+$ (left) and $\Lambda_c^+ \to pK^-\pi^+$ (right) in output from the second stage of the high level trigger [7].

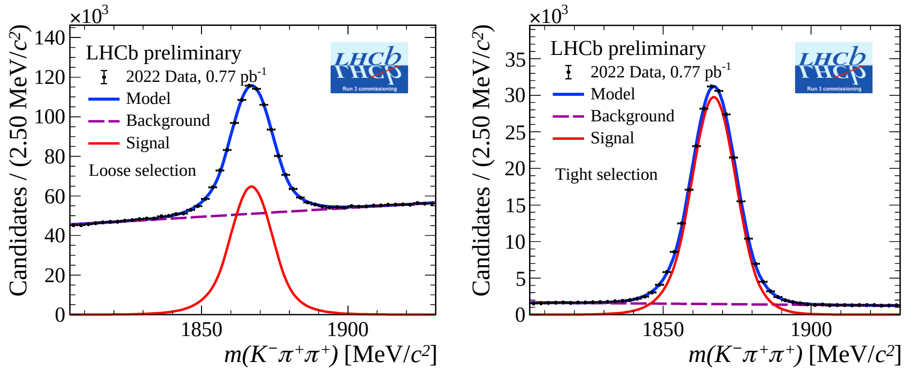

Figure 7: $D^+ \to K^-\pi^+\pi^+$ mass peak applying loose selection (left) and tight selections (right) on the first stage trigger level [7].

5. Summary

The goal of the LHCb Upgrade I is to ensure that the experiment will continue to produce high-quality data in challenging conditions in Run 3, preserving its scientific integrity and capacity to make valuable contributions to the field of particle physics. Initial performance assessments, as demonstrated in the proceedings, have shown promising results. The data collected in the upcoming year will further facilitate the extraction of important physical measurements, thereby advancing our understanding of fundamental particle interactions.

References

[1] LHCb collaboration, *The LHCb upgrade I*, arXiv 2305.10515, 2023;

[2] LHCb collaboration, $D^0 \to K^-\pi^+$ *mass plots at HLT1 level with 2022 commissioning data*, LHCb-FIGURE-2023-009, CERN, 2023;

[3] LHCb collaboration, *HLT1 TwoTrackKs and TwoKs lines invariant mass plots*, LHCb-FIGURE-2023-005, CERN, 2023;

[4] LHCb collaboration, *Invariant mass spectra from SMOG2 p-Ar and p-H collisions from 2022 data*, LHCb-FIGURE-2023-008, CERN, 2023;

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[6] LHCb collaboration, *Mass plots with early Run 3 data* , LHCb-FIGURE-2023-002, CERN, 2023;

[7] LHCb collaboration, *Invariant mass spectra of charm hadrons from 2022 data*, LHCb-FIGURE-2023-011, 2023.