PROCEEDINGS OF SCIENCE

LHCb upgrades

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The LHCb experiment, a single-arm forward spectrometer designed for the study of beauty and charm decays, operated successfully through the end of the Large Hadron Collider (LHC) Run 2. During this period, it collected data that resulted in numerous discoveries, challenging the boundaries of the Standard Model (SM) of particle physics and providing opportunities to explore potential new physics beyond it. During Run 3, the detector has been upgraded to run at higher instantaneous luminosity and collect large datasets, since most of the current measurements are statistically limited. Most of the LHCb subdetectors had increased the radiation hardness, the readout speed and their granularity. To fully exploit the higher luminosity delivered by the LHC, the hardware trigger has been replaced by a software trigger operating online and allowing for more flexible and complete trigger decisions. This document discusses the key features and first performances of the newly installed detector. A perspective about the future upgrades beyond Run 4, known as Upgrade II, will be provided.

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1. Introduction

The LHCb experiment [1] has successfully collected data during Run 1 and Run 2, probing the Standard Model of particle physics with precision measurements across various topics: CP violation, study of new exotic and conventional hadron states, elector-weak measurements, fixed-target physics and study of rare decay modes. Yet, no clear observation of new physics effects has been achieved and a large part of these measurements are statistically limited. To address these limitations, LHCb has undergone major upgrade to collect data at a higher instantaneous luminosity to further challenge theoretical predictions.

During Run 1 and Run 2, LHCb was limited to an instantaneous luminosity of $4\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. A direct increase of the luminosity would have not be beneficial since the hardware trigger (L0) had a maximum allowed output rate of 1 MHz. Furthermore, the L0 trigger was operating simple inclusive selections on the transverse momentum and energy of particles, reducing efficiency in a region where the bulk of hadronic states is produced and effectively preventing to fully benefit of the increased luminosity. To overcome this bottleneck, the LHCb experiment transitioned to a fully software-based trigger system, allowing real-time event reconstruction at a rate of 30 MHz. The subdetectors have been upgraded to cope with higher rates allowed by the software trigger. Furthermore, by the end of Run 2, most of the subdetectors had reached or exceeded their designed end-of-life due to radiation damage, necessitating their replacement.

In this document, the upgrade I of the LHCb experiment is presented along with prospects on the second upgrade of the experiments, foreseen for the LHC run 5 and beyond, called Upgrade II.

2. The LHCb Upgrade I: major detector enhancements

The Run 3 LHCb detector has undergone a major upgrade [2], with over 90% of channels being replaced. The upgraded detector comprises a full update of the tracking systems: the Vertex Locator (VELO), the Upstream Tracker (UT), and the Scintillating Fiber Tracker (SciFi). A brand new luminometer, PLUME, has also been installed. The electronics and part of the other sub-detector systems have been upgraded. As mentioned in the introduction, the L0 hardware trigger has been removed along with it the subdetectors mostly used by the L0 for triggering: the Pre-Shower (PS) and Scintillating Pad Detector (SPD), which were part of the previous calorimeter system, as well as the most upstream muon station. Finally the injection gas system, SMOG, has also been upgraded to improve the target gas density and allow for a wider choice of gas species. A summary of these upgrades of each subdetectors is given below.

2.1 The Vertex Locator

The goal of the VELO detector is to locate the interaction vertices and displaced decay vertices. The upgraded VELO [2] detector consists of two retractable halves, each containing 26 modules composed of hybrid silicon pixels cooled using microchannel cooling with CO_2. The detector is placed closer to the beam (3.5 mm) with respect to Run 2, to achieve a better impact parameter resolution. It is contained in a 250 μm-thick aluminium RF-box which separate the detector from the primary vacuum of the LHC. In January 2023, there was an accident in the vacuum volume and

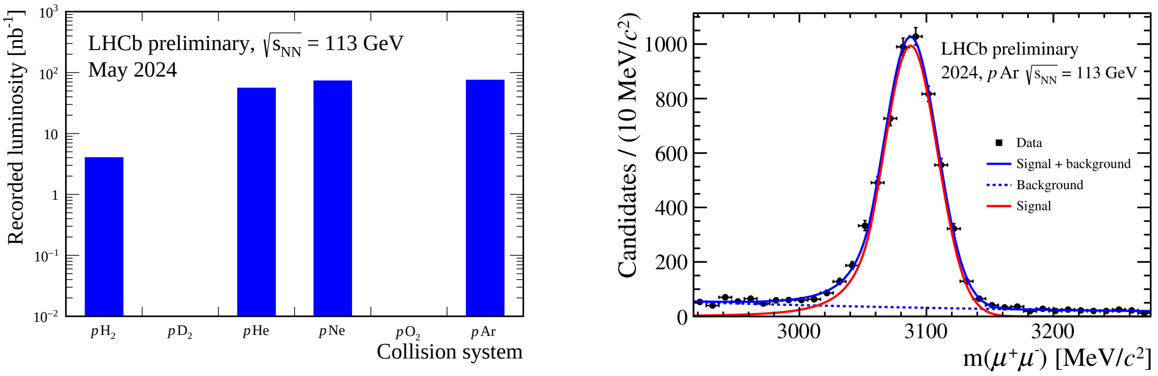

Figure 1: Left: collected online luminosities with SMOG2 in the different collision systems up to May 2024 (for runs 290411 to 294520). Right: invariant mass distribution for $J/\psi \to \mu^+\mu^-$ in pAr collisions collected during 1h40. The signal is modelled with a Crystal Ball function, the background with an exponential function. From [11].

the detector was damaged. The RF-box has been successfully replaced and, in 2024, the detector is now operating at nominal gap.

2.2 System for Measuring Overlap with Gas - SMOG

The SMOG system was initially designed for luminosity measurements using beam-gas imaging. It consisted of a pump allowing to inject gas inside the VELO vessel. During Run 2, LHCb has started exploiting SMOG to study fixed-target collisions, resulting in a series of unique measurements. For Run 3, a new SMOG2 system has been installed [2]. It is made of a dedicated storage cell which allows to reach up to two orders of magnitude higher areal density than SMOG, which was $O(10^{-7})$ mbarn. The cell is installed upstream of the VELO detector, in a region between -541 mm and -341 mm, far from the nominal pp interaction, situated at ±200 mm. A better defined interaction region enable the possibility to take fixed-target data in parallel to the nominal pp physics, thus increasing significantly the size of the dataset collected.

The new gas feed system allows for a precise determination of the target density and for injection of H_2 and D_2 in addition to the other noble gases. The collected luminosity for fixed-target datasets, as of May 2024, is shown in Figure 1 (left), for the different gas species. An example of invariant mass of J/ψ mesons in pAr collisions during approximately two hours of data-taking is given in Figure 1 (right), showing the already excellent performance of the system.

2.3 PLUME

The PLUME detector [2] is the main LHCb luminometer, used for levelling of the instantaneous luminosity which is key for stable operation of the experiment. It is composed of 48 PMTs placed around the beam pipe upstream the collision region, in a double cross structure made of two-layers. Charged particles produce Cherenkov light when impinging on a a quartz tabled glued to the PMTs and the light produced is read out by the PMTs. PLUME measures rates every 3 seconds and compute luminosity using the logzero method [5]. It provide real-time feedback to the LHC to level the luminosity at IP8 and luminosity measurement per bunch crossing. The achieved online

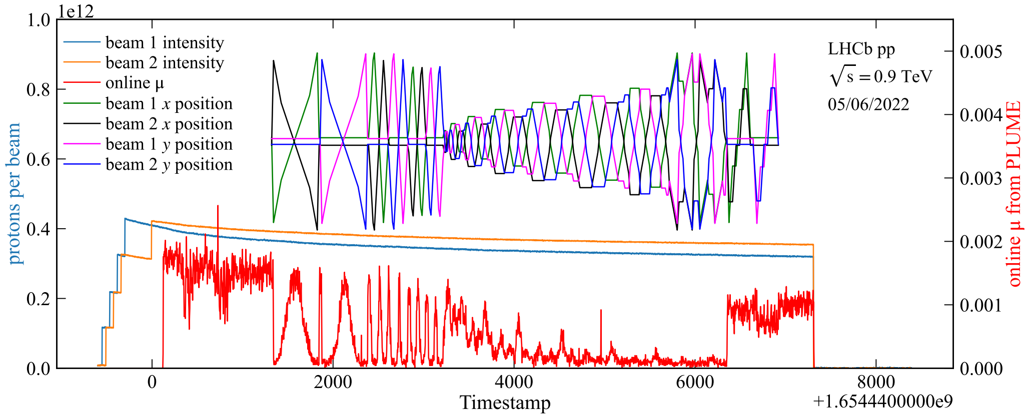

Figure 2: Van der Meer scan of June 2022. The red curves shows the evolution of the average number of interactions measured by PLUME without background subtraction. The orange and light blue curves in the middle show the beams populations measured by the 24-bit Direct Current Transformer (DCCT) A6R4. The curves on the top display the x and y positions of the two beams in arbitrary scale. From [12].

precision for Run 3 is of order 10 %. The detector is calibrated during van der Meer scans [6], an example for which can be found in Figure 2, where one and two dimensional scans are shown for the first calibration of the detector in 2022. Since then, these scan are performed regularly, for every colliding system and for different center of mass energies.

2.4 The Upstream Tracker

The Upstream Tracker (UT)[3] provides the first determination of track momentum with a precision of 15%. It consists of four layers of silicon micro-strip sensors with increasing granularity near the beam pipe, featuring sensor thicknesses of either 250 or 320 μm and pitches of 95 or 190 μm. These sensors are mounted on staves and cooled using a bi-phase CO_2 system operating at temperatures as low as -50 °C.

Fully integrated into the LHCb data acquisition chain, the UT works in conjunction with other tracking detectors to enhance momentum resolution and improve ghost-track rejection. It also facilitates downstream tracking – reconstructing tracks using only SciFi and UT hits, without VELO information – and contributes to the reconstruction of long tracks, while optimizing trigger processing speed. Figure 3 shows 50 VELO-SciFi reconstructed tracks during pp collisions. Some of these tracks lack corresponding hits in the UT layers, indicating ghost tracks that can be efficiently discarded at an early stage thanks to the UT.

2.5 Scintillating Fiber Tracker

The new SciFi tracker [3] measures particle trajectories with a spacial resolution under 100 μm. It is made of scintillating fibres readout by Silicon Photo-Multipliers (SiPMs). In order to keep the output data low, clusters are reconstructed in an FPGA with 3 different tunable thresholds.

When a signal is produced in a SiPM channel, a weight corresponding to the highest photo-electron threshold surpassed is assigned to that channel. A cluster is formed when the combined weights exceed the sum of the first two thresholds or a single weight surpasses the high threshold.

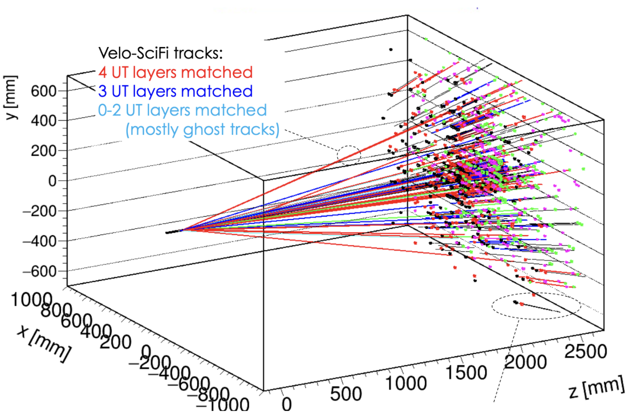

Figure 3: Velo-SciFi reconstructed tracks and matched with 4 (red), 3 (blue) or 0 to 2 (light blue) UT layers. Data from May 2024.

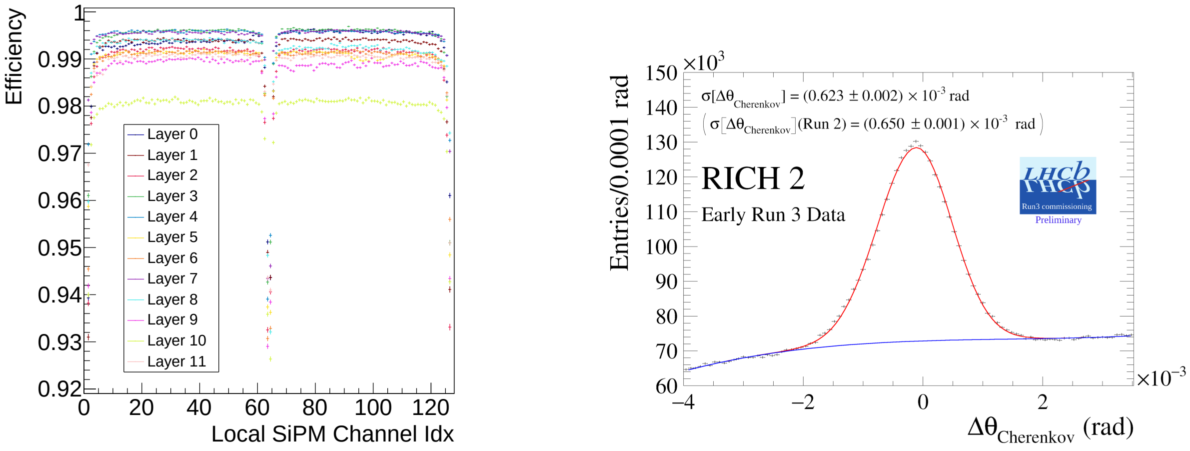

Figure 4: Left: the average hit efficiency across an SiPM in each layer of the SciFi Tracker [14]. Some regions have slightly reduced efficiency due to a few percent of channels requiring further threshold calibration. Right: Cherenkov angle resolution for reconstructed photons detected by the RICH 2 detector using early Run 3 data [13].

This clustering algorithm effectively reduces noise in hit reconstruction. However, to ensure the required tracking performance, the fake hit rate must remain below 2 MHz per SiPM array. To achieve this, the detector is cooled to -40 °C, keeping the noise cluster rate within acceptable limits. The detector has been fully operational in 2024, with over 99 % of channels having calibrated thresholds and efficiently taking data. In Figure 4, the hit efficiency of the SciFi detector layers is shown as a function of the 128 SiPM channels. The dip in the middle corresponds to the dead region between the two SiPM's dies and the drops on layer 10 is due to some SiPMs excluded from data taking in this LHC fill.

2.6 Particle identification with the RICH system

The RICH detectors perform hadron identification across a broad momentum range (2.6 − 100 GeV/c) [4]. Both detectors have seen significant upgrades, including replacing Hybrid Photon Detectors (HPDs) with Multianode PMTs (MaPMTs) for better timing and spatial resolution. Optimized mirrors curvature for RICH1 to reduce occupancy on the PMTs (a factor two less). Finally, a new readout ASIC has been developed, the CLARO ASIC, to cope with the need of an increased readout speed. In Figure 4, the RICH 2 Cherenkov angle resolution is shown. A resolution of $(0.623 \pm 0.002) \times 10^{-3}$ rad has been achieved, compared to $(0.650 \pm 0.001) \times 10^{-3}$ rad in Run 2, meaning that the upgraded detector is operated successfully and it has already outcome the performances of Run 1 and 2.

2.7 Real time software trigger

As mentioned in the introduction, the hardware-based L0 trigger has been removed, and a completely software trigger has been implemented [8]. The L0 trigger had a limit of 1 MHz in its event output rate, where as the new full software trigger can sustain triggering rates up to 30 MHz (the inelastic proton-proton collision rate). In the upgraded trigger model, the full detector readout data are sent at 5 TB/s at 30 MHz to HLT1 (the first level of the trigger, running on GPUs). Then, events are partially reconstructed and coarse selections are applied, the output is reduced by a factor 30 and sent to a buffer (200 GB/s at 1.5 MHz). At this point, a real time alignment and calibration of the data is performed. The full detector reconstruction and further selections are applied at the second level of the trigger (HLT2), running on CPUs. Data are sent for offline processing at a rate of 10 GB/s. Offline, a further layer of centralised selections is performed, this step is called sprucing. Finally, specific physics selections designed by analysts are performed using a central system called "analysis productions". Figure 5 (left) shows a comparison between the early 2024 data (427 pb^{-1}) Trigger On Signal (TOS) efficiency using $B^\pm \to K^\pm e^+ e^-$ channel as a function of the p_T of the B candidate. For comparison, Run 2 efficiencies are shown in red, these are based on a similar decay $B^0 \to K^{*0} e^+ e^-$. A significant improvement can be observed with the new 2024 trigger strategy, particularly in the core region of b–hadron production. The paramount importance of the new real-time alignment can be seen in Figure 5 (right), where the track χ^2 of SciFi tracks included in long tracks is shown. A clear improvement due to a better calibration of SciFi per mat alignment and mat-end calibration can be seen.

3. Outlook for LHCb Upgrade II

For the Run 5 of the LHC, the current detector will have reached its end of life and a new upgraded detector will be installed. The LHCb Upgrade II detector [10] will run at a 50 times higher instantaneous luminosity than Run 1 to collect a total dataset of 300 fb^{-1}. This data will allow to measure several key flavour observables with unprecedented precision, to continue probing the Standard Model predictions. To cope with the increased luminosity, the existing subdetectors will be replaced to increase the granularity, reduce the amount of material budget and to exploit the use of new technologies including precision timing of the order of a few tens of picoseconds. As of today, most of these technologies do not exist, thus a large R&D effort will be needed to face this

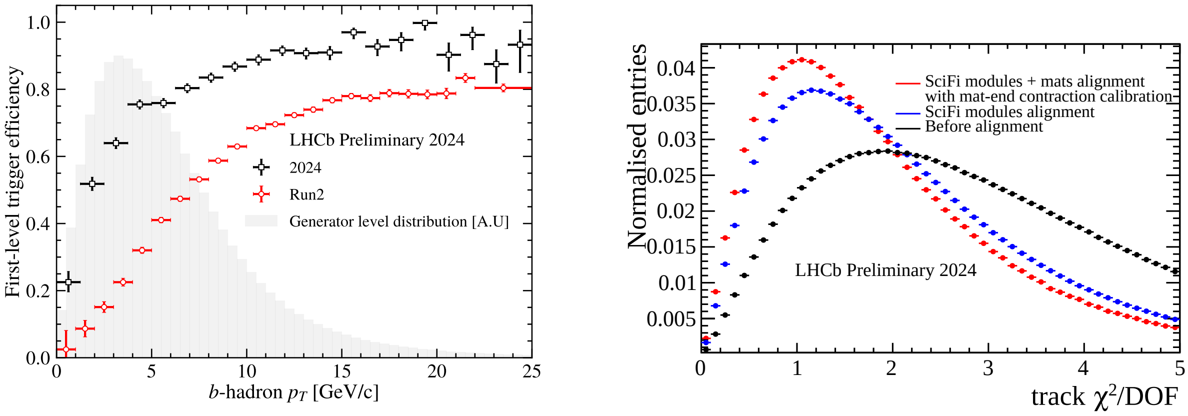

Figure 5: Left: comparison between the early 2024 data and Run 2 trigger efficiency using $B^{\pm} \to K^{\pm}e^{+}e^{-}$ channel as a function of the p_T of the B candidate [15]. Right: track χ^2 per degrees of freedom for the SciFi segment of long tracks evaluated for three different configurations of the SciFi alignment (run 292107) [16].

challenge. Equally important, the software trigger will have to be upgraded to cope with the higher rates. The increase in instantaneous luminosity implies a linear increase of HLT1 output rate but a quadratic increase of HLT2 processing, since there will be more events and they will be harder to reconstruct. The plan is to move main consumers (Track fit and RICH) of HLT2 to GPUs as well, additionally timing reconstruction algorithms will have an impact on throughput. The goal is to be able to write 50 Gb/s out of HLT2, so 5 times more than Run 3.

3.1 PID enhancement for Run 4

In vision of the Upgrade II, some of the particle identification detectors, RICH and the calorimeters, will be partially upgraded for Run 4 [17]. These upgrades aim to enhance PID performance and serve as a testbed for technologies planned for Upgrade II. Specifically, the innermost region of the electromagnetic calorimeter, which has remained unchanged since Run 1, will be replaced after Run 3 due to reaching its radiation tolerance limits. The existing shashlik modules will be replaced with SpaCal ("spaghetti calorimeter") modules, incorporating scintillating crystal fibers. Additionally, all detector modules will be restructured into a rhombic shape to better align with the occupancy profile. For the RICH detectors, new electronics with time-stamping capabilities for photon hits will be introduced. This marks the first implementation of timing measurements, a critical step toward the timing requirements of Upgrade II.

4. Conclusion

The LHCb experiment, is a story of success. In the first decade, the physics program has expanded well beyond original expectations. During the long shutdown 2, the detector has been almost fully upgraded and the installation and commissioning of it were a success. In this conference, the excellent performance with early Run 3 data have been shown. Despite the LHC incident in the VELO vacuum volume, thanks to the successfully replacement of the RF box, the detector is now collecting high quality data close to nominal conditions. Looking at the future, the first enhancement of particle identification for Run 4 have been approved by the LHCC and the R&D efforts toward the LHCb upgrade II are being finalised.

With this upgrades, the LHCb detector will reach an integrated luminosity of approximately 300 fb^{-1}, enabling measurements of numerous key flavour observables with precision capable of challenging the Standard Model expectations.

References

[1] LHCb collaboration, "The LHCb Detector at the LHC", *JINST* **3** (2008), S08005.

[2] LHCb collaboration, "The LHCb upgrade I", LHCb-DP-2022-002.

[3] LHCb collaboration, "LHCb Tracker Upgrade TDR", CERN-LHCC-2014-001.

[4] LHCb collaboration, "LHCb PID Upgrade TDR", CERN-LHCC-2013-022.

[5] Schmelling, Michael, "Luminosity calibration for the leading bunch nobias-triggered data from the 2015 early measurement runs", CERN-LHCb-INT-2017-015.

[6] S. van der Meer, "Calibration of the effective beam height in the ISR", CERN-ISR-PO-68- 31.

[7] LHCb collaboration, "RICH Performance Plots - Cherenkov Angle Resolutions for RICH1 and RICH2", LHCB-FIGURE-2023-007, `https://cds.cern.ch/record/2859118`.

[8] LHCb collaboration, "Upgrade Software and Computing", CERN-LHCC-2018-007.

[9] LHCb collaboration, "First LHCb upgrade reconstruction results on fixed-target data", LHCB-FIGURE-2023-001.

[10] LHCb collaboration, "Framework TDR for the LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era", CERN-LHCC-2021-012.

[11] LHCb collaboration, "First results from SMOG2 2024", 2024, `https://cds.cern.ch/record/2898697`.

[12] LHCb collaboration, "First absolute calibration of the PLUME online luminometer in Run 3", 2022, `https://cds.cern.ch/record/2813388`.

[13] LHCb collaboration, "RICH Performance Plots - Cherenkov Angle Resolutions for RICH 1 and RICH 2", 2023, `https://cds.cern.ch/record/2859118`.

[14] LHCb collaboration, "SciFi Performance plots July 2024", 2024, `https://cds.cern.ch/record/2904659`.

[15] LHCb collaboration, "$B \to K^{+}J/\psi(\ell\ell)$ with early 2024 data fits and efficiencies", 2024, `https://cds.cern.ch/record/2898806`.

[16] LHCb collaboration, "Alignment and calibration of the LHCb Upgrade detector with early 2024 data", 2024, `https://cds.cern.ch/record/2898813`.

[17] R. Lindner, "LHCb Particle Identification Enhancement TDR", CERN-LHCC-2023-005.