PROCEEDINGS OF SCIENCE

LHCb upgrades

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The LHCb detector is a single-arm forward spectrometer dedicated to the study of beauty and charm decays. It has been operated successfully up to the end of the Large Hadron Collider (LHC) Run 2 and the collected data led to a series of significant discoveries in the flavour physics field. Flavour observables can probe energy scales well beyond the reach of current and future particle accelerators and are thus of fundamental importance in the quest for New Physics.

Since most of the key observables are still statistically limited, upgrades of the LHCb detector have been foreseen to fully exploit the physics reach of the LHC. During the LHC Long Shutdown 2, the LHCb detector underwent a major upgrade, known as Upgrade I, that will allow running at an instantaneous luminosity five times higher than that of the previous running periods. In these proceedings, the key features of the newly installed detector will be discussed at length and a brief perspective about the next foreseen upgrade, known as Upgrade II and expected to be installed before LHC Run 5, will be provided.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

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PoS(LHCP2023)224

1. Introduction

The LHCb experiment [1] is one of the four major detectors installed at the Large Hadron Collider (LHC) at CERN. Its primary purpose is to study *CP* violation and rare decays of beauty and charm hadrons in order to search for New Physics evidences. The LHCb detector also demonstrated its excellent performance by producing several world class results in originally unexpected areas, such as electroweak physics, fixed target and heavy ions physics.

Many of the key flavour observables are still statistically limited [2] and thus it is important to exploit as much as possible the physics potential offered by the LHC. The LHCb detector was upgraded during LHC Long Shutdown (LS) 2 and this upgrade, known as Upgrade I [3], has been designed to cope with an instantaneous luminosity five times greater that then previous running periods. The LHCb Run 3 detector has been renewed in almost all its parts, with completely rebuilt tracking systems, improved performances in the particle identification (PID) department and a new trigger strategy relying on a full software high-level trigger to enhance the selection efficiency. This detector should collect an integrated luminosity of about 40 fb^{-1} by the end of the LHC Run 4, to be compared with the 9 fb^{-1} collected so far. Another upgrade, named Upgrade II, is foreseen to be installed during LS 4 and it will allow to fully exploit the High Luminosity LHC potential, by collecting an integrated luminosity of about 300 fb^{-1}.

In the following, the main characteristics of the LHCb Run 3 detector will be discussed in detail for each subsystem.

2. Tracking systems

The LHCb Vertex Locator (VELO) [4] has been completely redesigned to cope with the luminosity increase and the trigger-less 40 MHz readout required. The $r - \phi$ silicon strips present in the Run 1 and 2 VELO have been replaced by square silicon pixels with a 55 μm pitch. In total, 52 modules are installed on two movable halves, that allow the sensors to get as close as 5.1 mm from the beam during stable beams operation. This is needed to improve the impact parameter resolution. Figure 1 shows a schematic view of the $x - z$ plane and of the $x - y$ projection of one module.

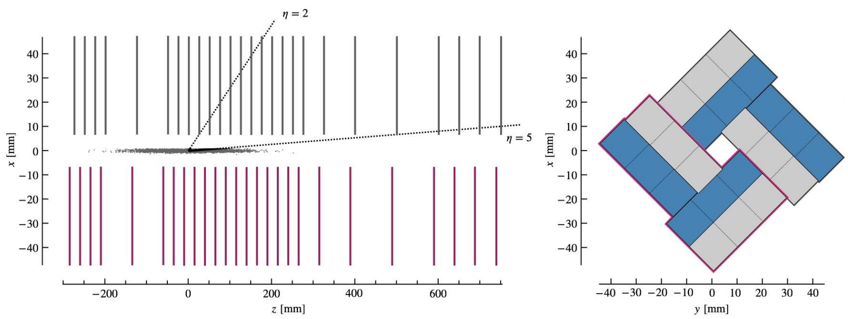


Figure 1: (Left) View of the $x - z$ plane showing the VELO modules and the pp interaction region and (right) $x - y$ projection of one module showing the layout of the ASICs around the z axis in the closed VELO configuration. The ASICs are placed both in the upstream (grey) and downstream (blue) face. In both figures, the C side is highlighted in purple.

The number of readout channels has increased by nearly two orders of magnitude, going from 172'000 to 41 millions and the total data rate changed from 152 Gbit/s to around 2 Tbit/s. The heat dissipation is provided by a silicon substrate built with micro channels that will carry CO_2 for evaporative cooling.

The second tracking system placed upstream of the LHCb magnet is the Upstream Tracker (UT) [5]. The UT hits, combined with the VELO tracks, allow to have a first estimate of the particles momentum with a precision around 15%. The UT detector is composed of 4 planes of 250 μm thick silicon strip detectors, with pitches varying between 190 and 95 μm according to the expected occupancy. The silicon detectors are arranged in staves, shown in Fig. 2 forming 4 detection planes, called stations.

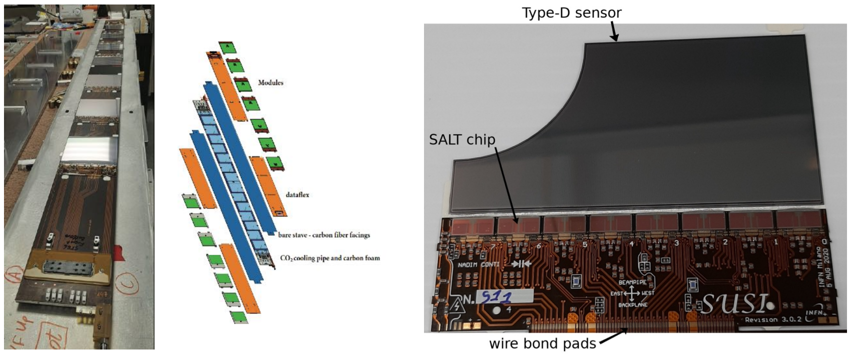


Figure 2: (Left) A mounted UT stave together with (center) an exploded view of the various components forming the stave and (right) one of the hybrids, called SUSI, used to readout the detector.

The first station (labeled *a*) is composed of an x-measuring layer (UTaX) with vertical strips and a stereo layer (UTaU) with strips inclined by 5°. The second stations (labeled *b*) is similar, with first a stereo layer (UTbV) with opposite inclination, and a layer with vertical strips (UTbX). As for the VELO, the UT sensors are cooled by a system based on bi-phase CO_2. The readout is performed by hybrids mounted in the detector acceptance accommodating several SALT chips bonded to the silicon strips. One of the hybrids is shown in the right part of Fig. 2.

The Scintillating Fibres (SciFi) tracker [5] is the last of the upgraded LHCb detector tracking systems and it is located after the magnet. It has to detect particles with an efficiency above 99% and a spatial resolution better than 100 μm. It is a completely new detector and it is based on scintillating fibres detecting the charged particles traversing them. Each fibre is 2.4 m long and has a diameter of 250 μm. The fibres are arranged in layers (6 fibres per layer) that are in turn organized into stations (4 layers per station). A sketch of the SciFi tracker is shown in Fig. 3. The layout of the layers within the stations is similar to that adopted by the UT. The fibres yield around 8000 photons per MeV of ionization energy deposited and produce light with a maximum in the wavelength spectrum around 450 nm.

The light produced in the fibres is detected by silicon photomultipliers (SiPMs) installed outside the detector acceptance. Mirrors are installed between the top and bottom fibre mats to reflect the light towards the SiPMs. The SiPMs pixel size is 57.5 μm × 62.5 μm and they are readout by custom ASICs named PACIFIC that digitize the hits and then forward them to clusterisation boards

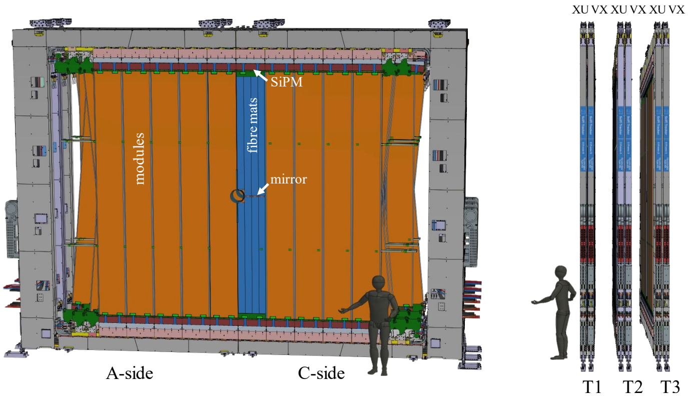


Figure 3: Representation of the SciFi tracker as seen (left) from the front and (right) from the side.

that perform the zero-suppression and clustering of the signal. The SiPMs are cooled via a single phase thermal transfer fluid and their temperature can be adjusted between +30° and −50° C.

3. Particle identification systems

The LHCb Run 3 detector is equipped by two Ring Imaging Cherenkov detectors, RICH 1 and 2 [6]. The first one is located upstream of the magnet and employs a C_4F_{10} radiator with refractive index $n = 1.0014$ for Cherenkov light with $\lambda = 400$ nm that provides PID for momenta between 2.6 and 60 GeV/c. The second one is located after the SciFi tracker and exploits a CF_4 gas radiator ($n = 1.0005$ for Cherenkov light with $\lambda = 400$ nm) that gives PID information for momenta between 15 and 100 GeV/c. A schematic view of both RICH detectors is shown in Fig. 4.

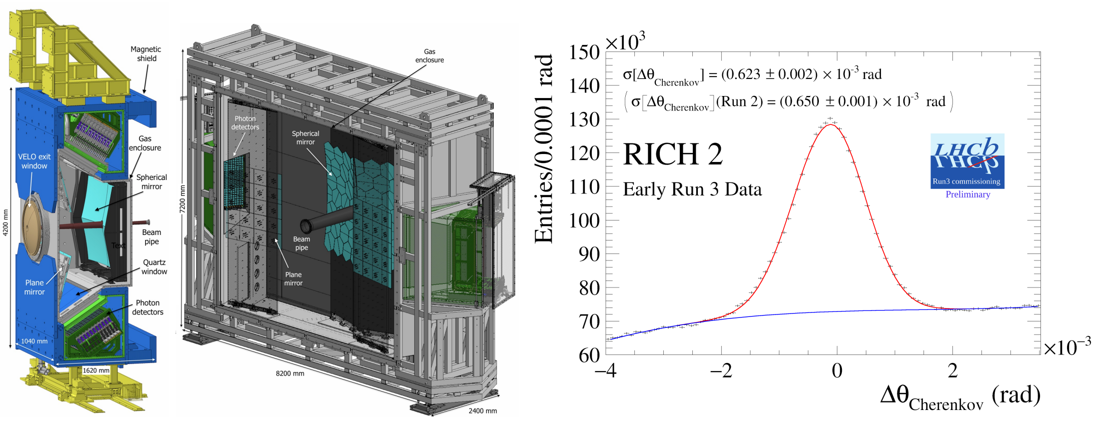


Figure 4: Schematic view of (left) RICH 1 and (center) RICH 2. (Right) Performance plot showing the value of the Cherenkov angle resolution obtained from 2023 commissioning data [7]. The Run 2 value is also reported as a comparison.

The main change concerning the RICH detectors regards the photodetection chain, as the previously employed Hybrid Photon Detectors (HPDs) had an integrated front end with a readout rate limited to 1 MHz, incompatible with the required 40 MHz of the current detector. For this reason, the HPDs have been replaced by multi-anode photomultiplier tubes (MaPMTs). Both 26.2 mm^2 and 56 mm^2 active area devices with 64 channels each have been adopted depending on the expected occupancy. In particular, RICH 1 employs only the smaller MaPMTs, while RICH 2 uses both types. In order to reduce occupancy, RICH 1 spherical mirrors curvature has also been changed.

One of the fundamental parameters to judge the performance of RICH detectors is the Cherenkov angle resolution. Both RICH 1 and RICH 2 have achieved a better resolution than in Run 2 already in the first months of operations, thus proving the capabilities of the new photodetection chain. The Cherenkov angle resolution obtained with Run 3 commissioning data is reported in the right part of Fig. 4.

The LHCb Run 3 detector electromagnetic and hadronic calorimeters (ECAL and HCAL, respectively) are largely unchanged [6]. The ECAL is composed of Shashlik modules, with 4 mm thick scintillator tiles and 2 mm thick lead tiles, accounting for a total of 25 radiation lengths and a Molière radius of around 36 mm. The modules have a transverse dimension of 12.1 cm × 12.1 cm and are segmented in different ways according to the expected occupancy. The energy resolution is $9\%/\sqrt{E} \oplus 0.8\% \oplus 0.003/E \sin\theta$, where E is the energy in GeV and θ is the angle between the particle and the beam axis. A schematic view of a ECAL cell is shown in the left part of Fig. 5. The HCAL is based on the Tilecal technology and is a sampling calorimeter with scintillator material interleaved with iron absorbers, accounting for a total of 5.6 interaction lengths. The outer cells have a transverse dimension of 26 cm × 26 cm, while the inner ones have a reduced size of 13 cm × 13 cm. The energy resolution is around $67\%/\sqrt{E} \oplus 9\%$, where E is again the energy in GeV. A schematic view of a HCAL cell is shown in the central part of Fig. 5.

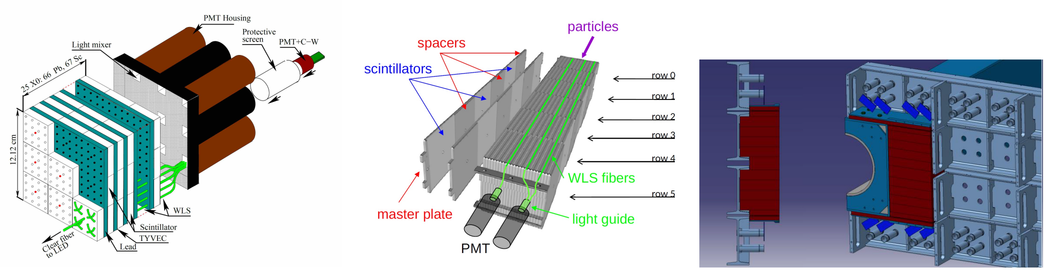


Figure 5: Schematic view of (left) a ECAL cell, (center) a HCAL cell and (right) the tungsten beam plug installed around the beam pipe.

The main changes done to the calorimeter system during the LS 2 regard the removal of the PreShower and Scintillating Pad Detector systems, needed for the hardware trigger employed during Run 1 and 2, and the upgrade of the readout electronics to cope with a 40 MHz input rate. Another small change regards the PMT gain, that has been lowered to keep the same average anode current due to the increased instantaneous luminosity. This loss has been recovered by increasing the gain of the amplifier-integrator in the newly developed front end boards.

Finally, also the LHCb Run 3 detector muon system [6] is largely unchanged with respect to Run 2 operations. The current detector is composed by 4 stations (M2-M5) equipped by multi-wire proportional chambers (MWPCs) interleaved by 80 cm thick iron absorbers to filter incoming low momentum particles. Each station is divided in 4 regions of different sizes according to the occupancy of the detector, to uniformly distribute the impinging particle flux. The only relevant changes with respect to Run 1 and 2 are the removal of the first station (M1), exploited in the hardware trigger and thus no longer needed, and the upgrade of the readout electronics to cope with the expected 40 MHz readout rate. Another change regarded the installation of a new tungsten beam plug around the beam pipe to lower the rate of incoming particles in the innermost region of M2. A schematic view of the plug is shown in the right part of Fig. 5.

4. Trigger and data processing

The trigger and data processing strategy adopted by LHCb Run 3 detector [8] is completely new and different with respect to Run 1 and 2. The most important feature of the new LHCb trigger is the removal of the hardware level-0 trigger (L0), that was employed to filter the event rate from 40 MHz down to 1 MHz. The L0 trigger used to filter events with simple requirements on the transverse momentum and energy of the particles and caused a sizeable loss of efficiency for final state involving hadrons.

The new trigger, fully based on GPUs and CPUs, offers the flexibility and the performance needed. The first level of the software trigger, called High Level Trigger 1 (HLT1), performs a first reconstruction and selection of the events using GPUs. This is the first time that a trigger fully based on GPUs is employed in a high energy physics experiment. The HLT1 output is then written on a buffer, waiting for the processing of the second trigger level based on CPUs, known as High Level Trigger 2 (HLT2). This second stage allows a full event reconstruction with offline-like quality, enabling more refined and exclusive selections to be applied to select the decays of interest. The combined effect of HLT1 and HLT2 brings down the full detector readout bandwidth (5 TB/s) to a more meneageable 10 GB/s written on disk. The online data flow just described is sketched in Fig. 6.

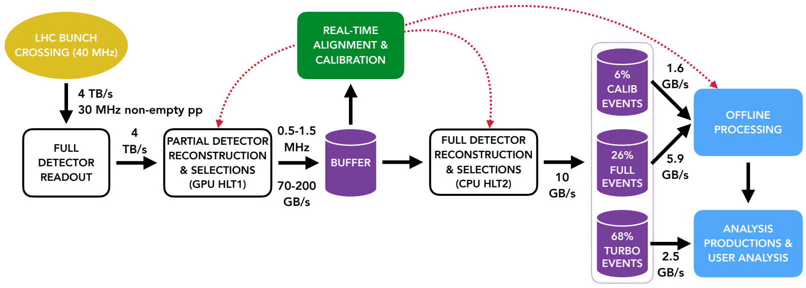
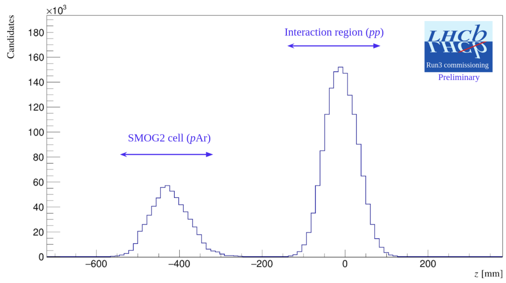


Figure 6: Online data flow [8].

5. Other subsystems

During LS 2, other subsystems have been installed in order to enhance the LHCb performance and physics reach. An internal gas target, called SMOG2 [9], has been installed upstream of the VELO vacuum vessel. The system features a storage cell that can be used to inject noble gasses via a capillary. Since the storage cell is located upstream of the VELO, the proton-gas interaction point is well separated from the nominal *pp* luminous region. This enables the LHCb experiment to run in fixed target mode in parallel with nominal *pp* operation, as shown in the left part of Fig. 7, thus allowing very large datasets of fixed target collisions to be collected. Another subsystem not present during Run 2 operation is the so-called Probe for Luminosity Measurement (PLUME) [10]. The PLUME detector is a brand new luminometer composed by 48 PMTs located upstream of the VELO. Its task is to provide online luminosity measurements with a precision better than 5% to the experiment, as well as continuous feedback to the LHC. A photograph of the PLUME subsystem is shown in the right part of Fig. 7



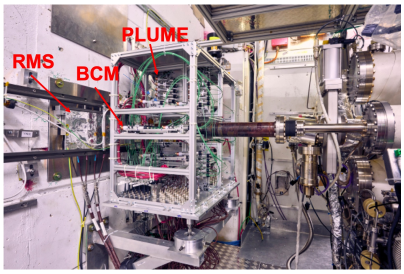


Figure 7: (Left) Distribution of the primary vertex longitudinal coordinate for vertices reconstructed by HLT1 [11]. Two well separated peaks representing *pp* (right peak) and *p*Ar (left peak) interactions are visible. (Right) Picture of the PLUME detector.

6. Upgrade II of the LHCb experiment

Another upgrade of the LHCb detector, named Upgrade II, is expected to be installed before LHC Run 5 [12]. This upgraded detector aims at collecting an integrated luminosity of around 300 fb^{-1}, that will allow to measure several key flavour observables with unprecedented precision, reaching in several cases the level of Standard Model (SM) predictions. To meet this challenge, it is foreseen to replace all of the existing spectrometer components to increase the granularity, reduce the amount of material in the detector and to exploit the use of new technologies including precision timing of the order of a few tens of picoseconds. Since such technologies generally do not exist at the present day, a vigorous R&D effort will be needed to face this challenge.

7. Conclusions

The LHCb detector performed remarkably well during the LHC Run 1 and Run 2, producing several important and unexpected results in several fields beyond the original scope of the experiment. A large upgrade of the detector, named Upgrade I, has been installed during LS 2 and started its operations during Run 3. The technologies employed have been described and some first performance plots have been shown in these proceedings. Moreover, an additional upgrade, known as Upgrade II, is currently under study and is foreseen to be installed before LHC Run 5, to fully profit from the planned upgrade of the accelerator. This upgrade will enable the LHCb detector to harvest an integrated luminosity of around 300 fb^{-1} and to measure several key flavour observables with a precision comparable to SM predictions.

References

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