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Chapter 13

LHCb Upgrades for the high-luminosity heavy-flavour programme

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1. LHCb Upgrades

The very successful operation of LHCb during Run 1 and Run 2 of LHC vindicated the concept and design of a dedicated heavy flavour physics experiment at a hadron collider. The detector was able to run at an instantaneous luminosity of 4×10^{32} cm^{-2}s^{-1}, twice the design value, and to collect 9 fb^{-1} of data by the end of Run 2.

In order to be able to continue the LHCb physics programme, a first upgrade of the detector (Upgrade I) was approved in 2012,[1] which is now in its first year of operation with colliding beams. The key concept of this upgrade is that the bottleneck of the level 0 hardware trigger is removed. By reading out the full detector at the LHC bunch crossing rate of 40 MHz and implementing all trigger decisions in software, it is possible to increase the luminosity without suffering a compensating loss in efficiency. By increasing the instantaneous luminosity by a factor of five, to 2×10^{33} cm^{-2}s^{-1}, and improving the trigger efficiency for hadronic modes by a factor of two, the annual yields in most channels will be an order of magnitude larger than during Run 2. The target integrated luminosity for the Upgrade I phase is around 35 and 65 fb^{-1} by the end of Run 3 and Run 4, respectively (Fig. 1). The upgraded detector has been designed to meet these specifications, and to withstand the higher occupancies foreseen at Run 3, while keeping performance comparable to Run 2.

Further data collection with the Upgrade I detector beyond Run 4 will not be attractive, on account of the excessive "data-doubling" time, and

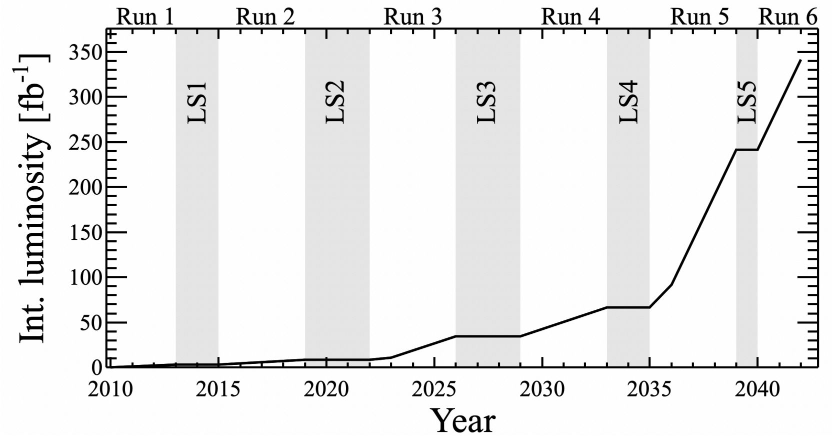

Fig. 1. Integrated luminosity profile for the original LHCb (Runs 1 and 2), and the one expected for Upgrade I (Runs 3 and 4) and Upgrade II (Runs 5 and 6).

also due to the fact that many of its components will have reached the end of their natural lifespan in terms of radiation exposure. There is therefore a strong motivation to perform a second upgrade (Upgrade II) of the detector,[2] in order to fully realise the flavour physics potential of the HL-LHC. Upgrade II is proposed for installation during LS4, and it is expected to take data at a maximum instantaneous luminosity of 1.5×10^{34} cm^{-2}s^{-1}, with the target of accumulating $\sim$ 300 fb^{-1} during Run 5 and Run 6 of LHC (Fig. 1). The flavour physics data sample will be at this point significantly larger than that of any other planned experiment, and will lead to improvements in the precision of a large number of key observables without being limited by systematic uncertainties.[3]

In the following sections more details are given on the Upgrade I detector and on the proposed design for the Upgrade II detector, respectively.

1.1. *The Upgrade I detector*

A new detector has been installed to cope with the increase in luminosity and pile-up by a factor of five, reaching values of 2×10^{33} cm^{-2}s^{-1} and 6, respectively. Particular focus has been put on increasing the detector granularity and radiation tolerance. An exception is represented by the calorimeter modules and the muon chambers, which have been recycled from the previous run. The readout scheme has also been upgraded for all subdetectors, in order to be able to readout the events at 40 MHz and

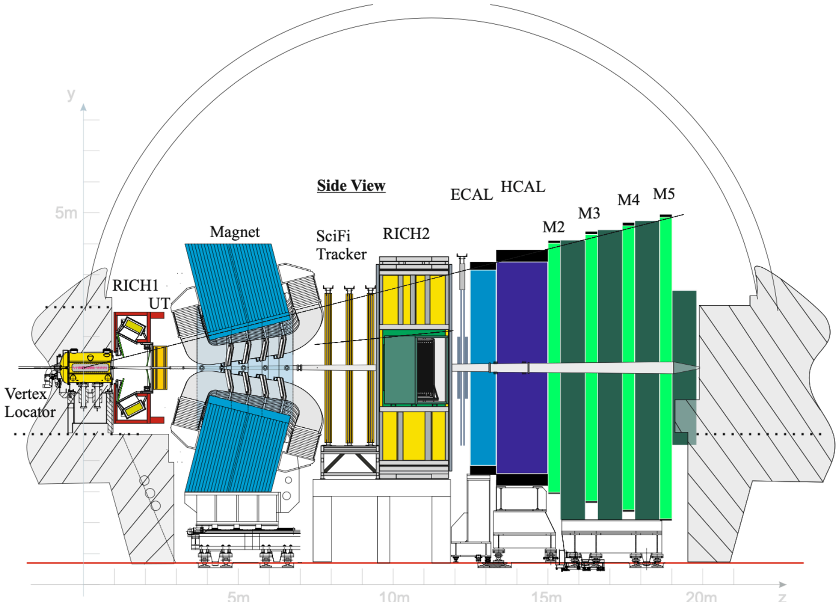

Fig. 2. Layout of the LHCb Upgrade I detector.

implement the new software trigger concept. Figure 2 shows a sketch of the upgraded detector.

The Vertex Locator (VELO) is the tracking detector devoted to the precise reconstruction of primary vertices and displaced vertices of short-lived particles. The previous version of the VELO, made of silicon microstrips, has been replaced by 26 tracking layers based on 50×50 μm^2 pixel technology, that will ensure a better hit resolution and simpler track reconstruction. The upgraded VELO is closer to the beam axis, from the 8.4 mm of the previous detector down to 5.1 mm of the present one, and the particles will see substantially less material before the first measured point, from 4.6% to 1.7% radiation length. This design is expected to improve the impact parameter resolution by $\sim$40%, to increase the tracking efficiency, especially for low momentum tracks, and to provide a better decay time resolution.

The Upstream Tracker (UT) will be used for reconstruction of long-lived particles decaying after the VELO, and consists of 4 layers based on silicon strip technology. The tracking system is completed by the Scintillating

Fibre tracker (SciFi), placed downstream the magnet, and consisting of 12 detector planes with transversal dimension of about 6×5 m^2. Each plane is made of 6 layers of plastic scintillating fibres, 2.4 m length and 250 μm diameter, arranged along the vertical direction. The fibres are readout by SiPMs placed on the top and the bottom of the detector planes, which are cooled to a temperature of $-40°$C in order to decrease the radiation damage and the dark noise. The usage of UT hits in the track extrapolation from VELO to SciFi detector will allow the number of fake tracks reconstructed by the tracking algorithms to be reduced, thus improving the trigger timing.

The two RICH detectors of LHCb are used for p, π and K particle identification. The optical layout of the RICH1, which is closer to the interaction point, has been modified to handle the higher particle occupancy of the upgrade conditions. In particular, the focal length of the mirrors has been increased by a factor $\sqrt{2}$, thus halving the occupancy. The readout of both RICH detectors, previously performed by HPDs at 1 MHz rate, has been replaced by multi-anode PMTs, working at 40 MHz.

Finally, for the software trigger a fast reconstruction entirely running on GPUs, that aims at selecting inclusive signatures of beauty and charm decays as well as high p_T muons has been implemented. This is followed by a full reconstruction on CPUs, that indicate the signals of interest.

1.2. *The Upgrade II detector*

Performing flavour physics in the forward region at a peak luminosity of 1.5×10^{34} cm^{-2}s^{-1} presents significant experimental challenges. The expected number of interactions per crossing is around 40, producing ~ 2000 charged particles within the LHCb acceptance. Radiation damage also becomes a greater concern for most detectors, *e.g.* with neutron fluences reaching 6×10^{16} 1 MeV n_{eq}/cm^2 in the innermost region of the VELO. The design proposed in Ref. 2 is based on the present spectrometer footprint, with all the detector components being upgraded in order to meet the desired specifications.

Among the distinctive features of the new design is the capability of providing fast-timing information with resolution of few tens of ps per particle, which at very high pile-up becomes an essential attribute for suppressing combinatorial background. As an example, a new VELO detector will be designed to provide a similar spatial resolution as in Upgrade I, but with a 50 ps resolution time-stamp per hit, thus becoming the first 4D-tracking device of this type. To meet the above challenges, the VELO ASIC will be designed in 28 nm technology, and new radiation-hard silicon sensors will be developed, with R&D results identifying already 3D sensors as a promising candidate for this purpose.

For the tracking system, high granularity pixel sensors appear as a solution to cope with high particle density in the UT and in the central region of downstream tracker, and to minimise the incorrect matching of upstream and downstream track segments. The emerging radiation-hard MAPS technology is a strong candidate for the above detectors. The outer region of the downstream tracker will be still covered by scintillating fibres, as in Run 3. However significant developments are required to cope with the increased radiation damage.

The RICH system will be a natural evolution of the current detector, with SiPMs replacing the multi-anode PMTs due to their higher granularity and excellent timing performances. In particular, this will allow a significant suppression of the combinatorial background. The new ECAL will implement a SpaCal design for the innermost highly irradiated region, while keeping Shashlik modules for the outer part. For SpaCal, a combination of tungsten absorber coupled with novel very radiation-hard crystals fibres or lead absorber coupled with polysterene fibres will be used for expected doses above and below 200 kGy, respectively. In order to achieve a timing resolution of few tens of ps, a double readout with longitudinal segmentation of the modules is foreseen on the whole calorimeter, which will guarantee the needed background reduction. Finally, for the muon system, new detectors will be needed to replace MWPCs in the innermost region of all stations, with a design possessing both high granularity and high rate capability. A promising candidate for this purpose is the μ-RWELL, a new type of Micro-Pattern Gaseous Detector based on the same principle as the GEM, and exploiting a very similar manufacturing process.

The examples discussed above give some ideas of the technological developments needed to face the very challenging experimental conditions of HL-LHC moving forward. That will certainly represent a bridge towards projects based at future accelerators.

References

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