The LHCb Upgrade

Simon Akar on behalf of the LHCb Collaboration

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

E-mail: `simon.akar@cppm.in2p3.fr`

Abstract. The LHCb experiment is a high-precision spectrometer searching for New Physics via measurements of CP violation and rare decays in the b- and c-quark sector. The quality of the results obtained from the data collected during the first Run of the LHC has demonstrated the excellent performance and the robustness of the detector. In order to significantly increase the statistical precision on theoretically clean observables in the heavy flavor sector, the level of collected data by the LHCb detector must be increased much beyond $1\,\mathrm{fb}^{-1}$ per year. Therefore, it is planned to upgrade the detector, which will allow a 40 MHz readout with a much more flexible software-based triggering system and redesigned sub-detectors.

1. Introduction

The LHCb experiment [1, 2] is a general-purpose forward spectrometer operating at the LHC accelerator. The detector covers a pseudo-rapidity range of $2 < \eta < 5$, which is complementary to the other LHC detector ranges. During Run 1, the detector demonstrated excellent operation performance, with about 99% of working detector channels, allowing to record more than 90% of the data delivered by the LHC adding up to a total of about $3\,\mathrm{fb}^{-1}$ of data saved to disk over the period 2010-2012. In 2011, the detector was already running at the design luminosity and number of visible interactions per bunch crossing, respectively of $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $\mu = 0.4$. In 2012, the LHC accelerator improved its performance and both $\mathcal{L}$ and μ increased above these design values. In order to cope with the delivered luminosity, the LHCb detector started to adjust constantly the beam overlap to maintain a constant instantaneous luminosity of twice the design one at $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ during a run, and with $\mu = 1.5$.

During LHC Run 3, the objective is to increase the instantaneous luminosity to $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. However, in this condition the current design of the LHCb detector does not allow to further improve the data rate as well as the efficiency. Indeed, it is limited in terms of data bandwidth to 1 MHz, instead of the LHC bunch crossing frequency of 40 MHz, due to the implementation of a first-level hardware trigger (L0). In particular, with an increased luminosity, the architecture of the L0 trigger does not allow for efficient triggering on purely hadronic channels. As shown on Fig. 1, while the physics yield for muonic channels increases with the luminosities, hadronic ones saturate above a luminosity of $3 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and is essentially half of the one for muonic channels at $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In consequence, it is mandatory to upgrade the current detector in order to increase the data rate as well as the efficiency to reach the high level of experimental precisions that is required in the flavor sector.

The upgrade of the detector is planned during the second Long Shutdown (LS2) of the accelerator in 2018-2019, and should allow LHCb to increase the yields in the muonic and hadronic channels by a factor five and ten, respectively. The objective is to operate at a constant
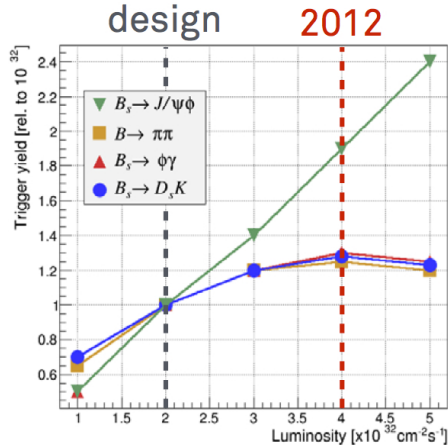
Figure 1: Trigger yield for different B decays as function of the instantaneous luminosity.

instantaneous luminosity of 2×10^{33}cm^{-2}s^{-1} during a period of ten years, corresponding to about $50\,$fb^{-1} of collected data. These running conditions correspond to ten times the current design luminosity with increased pileup of a factor 5. To reach the desired performance, all the front-end electronics as well as the detector components with embedded electronics need to be replaced. In addition, some of the detector components, in particular those closest to the interaction point, need to be redesigned to cope with the higher expected occupancies and radiation.

The plans for the LHCb upgrade are documented in the Letter of Intend [3] and in the Framework Technical Design Report of the LHCb Upgrade [4], and for each subsystem in a collection of dedicated Technical Design Reports [5, 6, 7, 8].

2. Physics motivation

Up to now, the results in heavy flavour physics are fully consistent with the CKM mechanism. However, a new source of CP violation beyond the Standard Model (SM) is needed to explain, for example, the amount of matter in the universe.

Extensive searches for evidence of New Physics (NP) beyond the SM at the TeV scale are currently being performed at the LHC. The absence of positive results coming from direct searches of NP effects performed in high-energy colliders, indicates that if such NP exist, corresponding effects would arise beyond the electroweak scale. The LHCb experiment is well designed to perform searches of NP effects via indirect searches, by preforming precise measurements of specific decay processes involving loop diagrams. In the presence of NP, new heavy particles could enter the loop and provide new amplitudes and phases that could dramatically modify the observables [9, 10]. The current results in B and charm physics obtained at the LHC are, so far, consistent with the SM predictions, but the theoretical precision on flavour observables in many decay processes are still well below the experimental uncertainties [4]. The aim of the upgrade of the LHCb detector, with $50\,$fb^{-1} of collected data, is to significantly decrease the experimental uncertainties to reach values comparable to or below the theoretical precision. Some key channels are briefly presented here.

A good example of LHCb's potential in the search for NP are the rare decays $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$. LHCb's current uncertainty on $\mathcal{B}(B_s^0 \to \mu\mu)$ is 1.5×10^9 [11], while the expected statistical sensitivity with the upgraded detector reaches 0.15×10^9 , whereas the theoretical precision is 0.3×10^9. Rare decays involving $b \to s$ transitions can also be considered as key channels for the upgrade of the LHCb detector. Indeed, in $B^0 \to K^*(K)\mu\mu$ decays, the expected statistical sensitivity on many observables such as the forward-backward asymmetry, others also related to the angular distributions, as well as the isospin asymmetry are expected to reach

the theoretical uncertainties. The excepted experimental precision on CP violation parameters, especially in the B_s system, should also get close to the theoretical precision, as for example the mixing induced phase ϕ_s in $B_s^0 \to J/\psi\phi$ or $B_s^0 \to J/\psi f_0(980)$ decays.

3. The LHCb upgrade strategy

3.1. The trigger system

With the current detector, the main bottleneck for increasing the data rate as well as the efficiency at a luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is the existing readout architecture, shown in Fig. 2. The strategy for the upgrade of the LHCb experiment is to remove the L0 trigger implemented in the hardware of the individual sub-detectors. In the L0 frame, the rate of accepted events is reduced from the LHC bunch crossing frequency of 40 MHz to about 1 MHz based on the transverse energy and transverse momentum measured by the calorimeters and the muon system, respectively. In a second step, events are built in the software based Higher Level Trigger (HLT), using the information from the entire detector. The final output rate to storage on disk corresponds to 5 kHz.

In the detector upgrade the new readout architecture will be implemented as a trigger-less system [5], where the full detector information at the inelastic event rate of 30 MHz will be used in a fully-flexible software based trigger, as shown in Fig. 3. This full software trigger should apply selections as similar as possible to those applied in offline analyses to maximize trigger efficiencies and to minimize systematic uncertainties. The full software trigger will write to tape with a rate of 20 to 100 kHz.
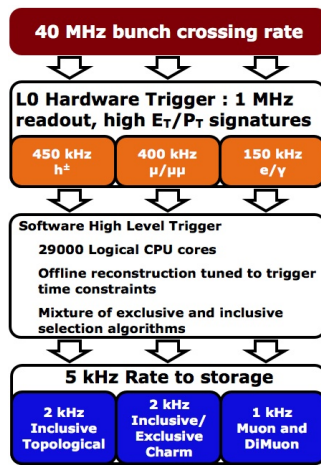
Figure 2: Schematic view of the LHCb trigger system, as implemented until 2012.
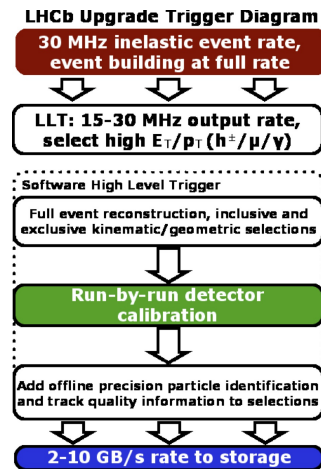
Figure 3: Schematic view of the full-software trigger scheme for the LHCb upgrade.

3.2. Detector Upgrade

In addition to the new readout system briefly discussed in Sec. 3.1, many sub-detectors must be redesigned to cope with the harsher conditions in which the LHCb upgrade detector will be running. The most significant changes concern the tracking system, including the vertex detector, which will be completely redesigned.

The vertex detector (VELO) upgrade [6], which is essential for vertices identification and track reconstruction, will benefit from a new pixel detector with smaller cells of $55 \times 55\,\mu\mathrm{m}^2$. In order to minimize the production of secondary particles, the thickness of the sensors will be reduced, down to $200\,\mu\mathrm{m}$. Additionally, to improve the impact parameter resolution and to increase the track acceptance, the distance between the first sensors and the beam will be

reduced from 5.5 to 3.5 mm in the fully closed configuration of the VELO. Simulation studies, presented in Ref [6], show that the expected performance of the upgraded VELO should be maintained, if not improved, compared to the already excellent performance obtained with the current VELO.

The rest of the current tracker system is composed of the Trigger Tracker (TT) and the T-stations, placed upstream and downstream the magnet, respectively. The TT will be replaced by the Upstream Tracker (UT), using the same technology as in the TT, i.e. silicon micro-strips, but with finer granularity, especially in the inner part, in order to reduce the occupancy and ghost tracks rate. The materiel budget will also be lowered, with sensors of reduced thickness: $300 \,\mu$m compared to $500 \,\mu$m in the TT. The T-stations, currently using silicon strips in the inner-most part and straw tubes in the outer part will be replaced by a single technology using layers of scintillating fibres with a diameter of $250 \,\mu$m. The readout, made of silicon photo-multipliers, will be placed outside the acceptance at the edge of each of the three $5 \times 6 \,\text{m}^2$ panels. Details and expected performance of both the UT and the T-stations upgrade can be found in Ref. [7].

The particle identification (PID) system, which is composed of two Ring Imaging Cherenkov (RICH) detectors, one upstream and the other downstream the magnet, the electromagnetic and hadronic calorimeters as well as five muon chambers, will also undergo modifications during the upgrade. Indeed, in the case of the RICH placed upstream the magnet, the optics will be redesigned and the aerogel will be replaced by a CF_4 radiator, in order to cope with the higher expected occupancies. For the same reason and due to the removal of the L0 trigger, the Scintillating Pad Detector and the Preshower detectors, as well as the first muon chamber, all placed in front of the electromagnetic calorimeter, will be removed. Details and expected performance of the upgraded PID system can be found in Ref. [8].

4. Conclusion

During the first Run of data taking at the LHC, the LHCb detector demonstrated excellent performance, leading to impressive results with a high-precision level on many heavy flavor observables. An upgrade of the LHCb detector is proposed, with a new readout system and a full software trigger, in order to enhance the physics yields, especially in the purely hadronic channels, which will increase by a factor ten with respect to the foreseen yields in Run 2. A total dataset of at least $50 \,\text{fb}^{-1}$ will be collected during a period of ten years. This will allow to significantly decrease the statistical uncertainties on many key measurements, some of which will be reaching the current theoretical precisions, which is required in order to investigate small deviations from the SM. All the documents concerning the LHCb upgrade have now been released by the LHCb collaboration and approved by the CERN Research Board. The road-map is on schedule for an installation of the LHCb upgrade that will start with the LS2 in 2018.

References

[1] LHCb Collaboration, *LHCb technical design report: Reoptimized detector design and performance*, CERN-LHCC-2003-030 (2003).

[2] LHCb Collaboration, *The LHCb Detector at the LHC*, JINST 3, S08005 (2008).

[3] LHCb Collaboration, *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001 (2011).

[4] LHCb Collaboration, *Framework TDR for the LHCb Upgrade: Technical Design Report*, CERN-LHCC-2012-007 (2012).

[5] LHCb Collaboration, *LHCb Trigger and Online Upgrade Technical Design Report*, CERN-LHCC-2014-016 (2014).

[6] LHCb Collaboration, *LHCb VELO Upgrade Technical Design Report*, CERN-LHCC-2013-021 (2013).

[7] LHCb Collaboration, *LHCb Tracker Upgrade Technical Design Report*, CERN-LHCC-2014-001 (2014).

[8] LHCb Collaboration, *LHCb PID Upgrade Technical Design Report*, CERN-LHCC-2013-022 (2013).

[9] Y. Grossman and M. P. Worah, Phys. Rev. **B395**, 241-249 (1997).

[10] I. Y. Bigi and A. I. Sanda, *CP Violation*, Cambridge, UK: Cambridge University Press, 2000.

[11] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 021801 (2013).