The LHCb Upgrade

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Abstract. During the LHC Run 1 the LHCb experiment has successfully performed a large number of high precision measurements in heavy flavour physics using 3 fb$^{-1}$ of data collected at centre-of-mass energies of 7 TeV and 8 TeV. In LHC Run 2 the LHCb is expected to integrate an additional 5 fb$^{-1}$ data, however many of the measurements will remain limited by statistics. For this reason LHCb will undergo in 2020 a major upgrade during the Long Shutdown 2 of LHC, with the aim to collect 50 fb$^{-1}$ of data by 2028. To achieve this goal the LHCb detector readout rate will be upgraded from the current 1 MHz to the LHC bunch crossing rate of 40 MHz. The luminosity delivered to the experiment will increase by a factor five, up to $2 \cdot 10^{33}$ cm$^{-2}$ s$^{-1}$. The online selection of events will be uniquely performed by a pure software trigger, improving the trigger efficiencies. In order to sustain the increased luminosity and readout rate, all the sub-detectors will be upgraded. The architecture of the upgraded DAQ system and trigger strategy will be presented, as well an overview of the sub-detector upgrades.

1. Introduction
The LHCb experiment apparatus [1] is a single-arm forward spectrometer dedicated to the study of heavy flavour physics, installed on the Large Hadron Collider (LHC). Its physics program includes precise measurement of CP violation and rare decays of B and charm hadrons, study of electroweak and QCD processes, hadron spectroscopy and heavy ion collisions.

During the Run 1 of the LHC, the LHCb experiment collected 3 fb$^{-1}$ of data and performed many important measurement in the heavy flavour sector, such as the first observation of the $B^0_s \rightarrow \mu^+\mu^-$ [2] joint with the CMS collaboration, the measurement of a flavour changing neutral current anomaly in the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay [3], and the observation of pentaquark states [4] in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay.

However, many crucial measurements are statistically limited [5], with experimental precisions not directly comparable to the uncertainties of the theoretical predictions. The scenario will only partially improve with the LHC Run 2, during which LHCb is expected to reach an integrated luminosity of 8 fb$^{-1}$. For this reason LHCb will undergo in 2020, during the LHC Long Shutdown 2, a major upgrade [6] that will make it feasible to collect at least 50 fb$^{-1}$ of data by 2028. With such a large dataset, the measurements will finally have comparable precision as the theoretical predictions.

2. The LHCb Upgrade
To be able to record at least 50 fb$^{-1}$ of data, during the LHC Run 3 the luminosity delivered to the experiment will be increased by a factor five with respect to the current conditions, to $2 \cdot 10^{33}$ cm$^{-2}$ s$^{-1}$. Moreover, the online selection of events will be revolutionised, fully-reconstructing...
all the events at the LHC inelastic event rate exploiting a fully software-based trigger. To sustain the new experimental conditions, all the LHCb sub-detectors will be upgraded as well the detector readout system.

2.1. The LHCb trigger and readout upgrade
The current trigger strategy at LHCb is based on a first hardware-based trigger step, called Level 0 (L0), followed by a selection performed by a software-based High Level Trigger (HLT). The L0 reduces the event rate from the LHC bunch crossing rate of 40 MHz up to 1 MHz, basing on measurements performed by the calorimeters and the muon chambers. The HLT then performs a first partial event reconstruction at the rate of 1 MHz, that is the LHCb detector readout rate. Then, a full reconstruction of events with offline-like quality is performed at the rate of 150 KHz. Finally, the selected events are stored at a rate of 12.5 KHz.

However, the current readout and triggering scheme is a limiting factor for the trigger effectiveness at Upgrade conditions. Figure 1 shows that the trigger yield on many hadronic channels already saturates at the current luminosity of LHCb, not increasing for higher values of the luminosity.

To be able to efficiently run at increased luminosity, the L0 hardware-based trigger will be removed, and events will be selected by the software-based HLT alone. The HLT will perform a full reconstruction of events at the LHC inelastic event rate of 30 MHz. Offline precision particle identification and track quality information will be exploited to reduce the rate down to 20-100 KHz. The new trigger strategy will increase the triggering efficiency on the hadronic channels by a factor 2 to 4 with respect to Run 1 [7], corresponding to an increase by a factor 10 to 20 of the hadronic yields.

The detector readout scheme will be upgraded, in order to process events at 40 MHz rate. The readout signals will be sent to the surface by 300 m long optical links to an event builder farm. An uniform infrastructure based on PCIe40 cards will be used for data readout, slow and fast control. Events will be distributed by data-centre technology networking to the triggering farm, composed by standard dual-socket x86 servers.

2.2. The LHCb detector upgrade
The LHCb detector needs to be upgraded to sustain the renewed experimental challenges due to the increased luminosity. Higher granularity and radiation tolerance are required for the sub-detectors, in particular for the tracking sub-detectors, as well as new front-end and readout electronics. Figure 2 shows a sketch of the upgraded LHCb detector.
The Vertex Locator (VELO) [8] is the tracking detector devoted to the precise measurement of primary vertices and displaced vertices of short living particles. The current VELO, based on silicon microstrips technology, will be replaced by 26 tracking layers based on 50x50 μm² pixel technology that will ensure a better hit resolution and simpler track reconstruction. Figure 3.a shows a sketch of the tracking detector. The upgraded VELO will be closer to the beam axis, from the current 8.4 mm up to 5.1 mm from it, and the particles will see substantially less detector material, from 4.6% to 1.7% radiation lengths, before the intersection of the first tracking layers which are the crucial ones to determine the resolution on the measurement of the impact parameter of the particles. These improvements will improve the impact parameter resolution by a factor of about 40%, increase the VELO tracking efficiency especially for low momentum tracks, and provide a better decay time resolution. In order to reduce the radiation damage to the sensors, the detector layers will be opened while not taking data and closed when stable beam condition is reached. The sensors will be cooled at the temperature of -20 °C exploiting an innovative microchannel CO₂ cooling technology.

The Upstream Tracker (UT) [9] will be used for downstream reconstruction of long lived particles decaying after the VELO. It will be also essential to improve the trigger timing, and the momentum resolution. The UT will be composed by 4 tracking layers based on silicon strip technology. A UT layer is sketched in Figure 3.b. The inner sensors will be closer to the beam pipe with respect to the current tracker, in order to increase the geometrical acceptance. The segmentation and technology of the sensors is driven by the expected particle occupancy and radiation dose. In the outer region, the strips will be 99.5 mm long with 180 μm pitch, and based on p⁺-in-n technology. The strips in the central region will have same length but 95 μm pitch, and they will be based on n⁺-in-p technology in order to better sustain the higher radiation dose. Finally, the strips closest to the beam will be 51.5 mm long, with 95 μm pitch and based on n⁺-in-p technology.

The Scintillating Fiber tracker (SciFi) [9] will be structured in 12 detector layers, and used for track reconstruction after the magnet region thus providing measurement of the particle momentum. Figure 3.c shows a sketch of a SciFi layer. The SciFi will be based on 2.4 m long plastic scintillating fibres with 250 μm diameter, arranged on vertical direction. Each of the detector layers will be composed of 6 layers of fibres, with a total layer thickness of 1.35 mm and transversal dimensions of about 6 m x 5 m. On vertical direction the layers will be made of two series of fibres separated by mirrors. The fibres will be readout by SiPMs placed on the top and on the bottom of the detector layers, reading arrays of 50x50 μm² sized pixels grouped in arrays of 128 channels. SiPMs will be cooled at the temperature of -40 °C in order to decrease
The VErtex LOcator (VELO) upgrade

Two moveable halves in vacuum tank

Replace Si strips with pixel sensors

Active region @ 5.1 mm from beam (instead of 8.1 mm as in the current VELO)

Rad. in the innermost region: $8 \times 10^{15} \text{neq}/\text{cm}^2$ after 50 fb$^{-1}$

Readout at 40 MHz

Tot. power consumption $>2k \text{W}$

CO$_2$ micro-channel cooling

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Figure 3: Sketches of the upgraded LHCb trackers: VELO (a), UT (b) and SciFi (c).

The radiation damage and the dark noise.

The usage of UT hits in the track extrapolation from the VELO to the SciFi detectors will allow to reduce the number of fake tracks reconstructed by the tracking algorithms, by a factor 50-70%. Consequently, the trigger timing will be largely improved. The SciFi will improve the tracking efficiency, reducing in the meanwhile the amount of reconstructed fake tracks, with respect using the current detector in the Upgrade.

The two RICH detectors of LHCb are used for $p$, $\pi$ and $K$ particle identification. The optical layout of the RICH1, which is more near to the interaction point, will be modified to handle the much higher particle occupancy of the upgrade conditions [10]. In particular, the focal length of the mirrors will be increased by a factor $\sqrt{2}$ thus halving the occupancy. The current readout of both RICH detectors, performed by HPDs at 1 MHz rate, will be replaced by Multianode PMTs working at 40 MHz.

The LHCb calorimeters and muon chambers, used for $p$, $e$, $\gamma$, $\mu$ particle identification, will not undergo substantial upgrades, apart by the replacement of the front-end electronics and the removal of some stations currently used by the L0 trigger only [10].

The installation of the LHCb upgraded detector will take place during the LHC Long Shutdown 2. In 2018 the old sub-detectors will be removed, and in 2019 the Upgrade ones will be installed in order to get ready to run for the LHC Run 3, on 2020-2021.

3. Conclusion

The LHCb experiment experienced a great success in the heavy flavour sector, during the LHC Run 1. Several crucial measurements are currently statistically limited, and will not significantly improve with the integrated luminosity of 8 fb$^{-1}$ expected to be collected until the end of the LHC Run 2.
The LHCb will undergo in 2020 a major upgrade to collect 50 fb$^{-1}$ of data by the end of LHC Run 4. The Upgrade will consists of new trackers based on completely new technologies, as well of updates of the RICH, calorimeters and muon chambers. The online selection of events will be performed by a software-based trigger only, reconstructing the full events at the LHC inelastic interaction rate of 30 MHz. The Upgrade project is fully approved and funded in its completeness, and the construction of all sub-detectors are on the way.

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