PROCEEDINGS OF SCIENCE

The LHCb upgrade

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The LHCb experiment is designed to perform high-precision measurements of CP violation observables and measurements of rare decays of beauty and charmed hadrons at the Large Hadron Collider. The results obtained with data collected in 2011 and 2012 demonstrate that the LHCb detector is functioning very well. Here we present the plan for the detector upgrade to be installed by 2018. The LHCb upgrade aims to increase the input data rate and the selection efficiency exploiting a 40 MHz flexible software-based triggering system. After the upgrade the experiment will operate at an instantaneous luminosities of 2×10^{33} cm^{-2}s^{-1}, ten times the current design luminosity, to collect 50 fb^{-1} of data over ten years.

XXI International Workshop on Deep-Inelastic Scattering and Related Subject -DIS2013,
22-26 April 2013
Marseilles,France

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PoS(DIS 2013)248

1. Introduction

During 2011 and 2012 the LHCb experiment demonstrated excellent performance, proving the effectiveness of a dedicated heavy quark experiment in the forward region at the LHC (the pseudo-rapidity range covered by LHCb is complementary to those of ATLAS and CMS). The LHCb detector is a spectrometer, optimized for heavy quark physics, instrumented to trigger leptonic and hadronic modes; to provide precision tracking and vertex reconstruction (for precision invariant mass and proper time measurements) and good particle identification. The overall LHCb detector layout is shown in Figure 1.

The vertex locator is used to measure tracks nearby the beams interaction point to precisely resolve primary and secondary vertices; the dipole magnet and the tracking stations provide accurate momentum measurements; two RICH detectors, the calorimeters and the muon system provide the particle identification. A detailed description of the LHCb sub-detectors can be found at [1]. The current trigger system is organized in two levels. The first level (L0) is an hardware trigger based on custom electronics. It selects events with high transverse momentum candidates (few GeV/c), relying on clusters in the CALO system or tracks in the MUON system. The L0 accept rate is limited to 1 MHz. The second level (HLT) is a software trigger, based on selection algorithms running on a dedicated computing farm (of about 1500 servers running 30k algorithm instances in parallel). At the beginning the ambiguity in the assignment of a secondary vertex to the primary vertex was considered problematic, therefore LHCb started running at the design luminosity of 2×10^{32} cm^{-2} s^{-1} (optimized to produce single primary interaction per bunch crossing). It was soon realized that it would have been possible to perform clean physics analysis at higher luminosities. Over 2012

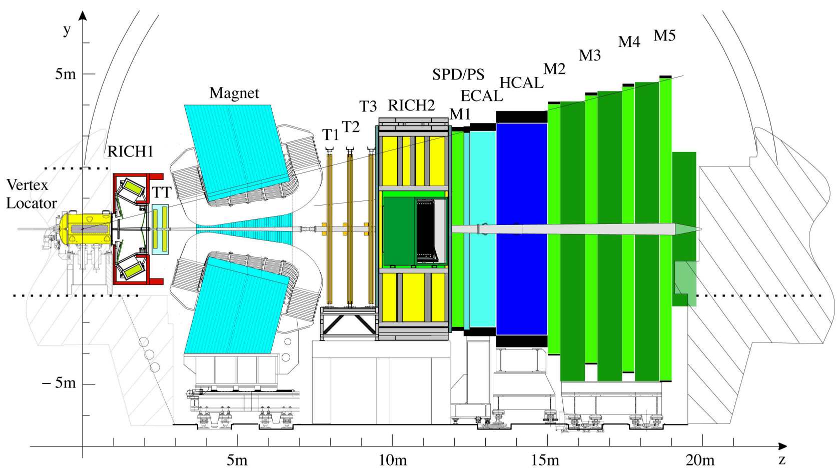

Figure 1: The LHCb detector.

Year	2011	2012
Beam energy (TeV)	3.5	4.0
Luminosity (10^{32} cm^{-2} s^{-1})	2 - 4	4
Interaction/crossing	0.4 - 1.4	1.6
Data taking efficiency (%)	>91	>95
Trigger output rate (kHz)	3.0	4.5
Recorded data (fb^{-1})	1.1	2.1

Table 1: LHCb running parameters in 2011 and 2012.

LHCb increased two times the design value for the luminosity and four times the design value for the number of interactions per bunch crossing. At the end of 2012 a successful test was performed with a luminosity even high as 6×10^{32} cm^{-2}s^{-1}. Worth to mention that at the LHCb interaction point the luminosity can be tuned by adjusting the beam overlap such to maintain the predefined luminosity value constant during the entire run. An upgrade of the PC farm in 2012 allowed to increase the HLT trigger output rate to disk to 4.5 kHz (50 % more with respect to 2011). LHCb achieved to record more that 1.0 fb^{-1} of data in 2011 and in excess of 2.0 fb^{-1} in 2012 (the increase of the LHC beam energy led to an increase of 15 % in the bb production cross section in 2012 compared to 2011). In 2012 LHCb surpassed the design luminosity per year, despite the fact that the LHC was only filled with half the number of proton bunches (interacting at a rate of 20 MHz, i.e. half the design rate). The LHCb running parameters used in the 2011 and 2012 runs are summarized in Table 1. During the ongoing Long Shutdown 1 (LS1) LHCb will produce results from the recorded data sets, will consolidate the detector, will study systematic effects and improve the trigger strategies to prepare for the running periods 2015-2017. For instance, as a first step to improve the current trigger boundaries, LHCb introduced the deferred HLT, where we use storage capacity and time between LHC fills to process additional L0 selected events which otherwise would be discarded. In the period 2015-2017 the LHC will increase the centre of mass energy to $13-14$ TeV and will reach the design bunch crossing rate of 40 MHz. During this campaign we expect to collect more than 5 fb^{-1} reaching about 10% uncertainty for key measurements.

2. The LHCb upgrade

The plans for the LHCb upgrade are documented in the Letter of Intent [2] and in the Framework Technical Design Report of the LHCb Upgrade [3]. The upgrade shall take place during the Long Shutdown 2 (LS2) of the LHC in 2018. It is compatible with the high luminosity upgrade of the LHC, but does not require it. With the enhanced capabilities the LHCb upgraded detector will be unique for New Physics searches in B_s decays, will be extremely competitive in B_d decays and it will also deliver unprecedented charm hadron yields. The upgrade will allow to fully explore the LHC physics in the forward region, which also has good potential for non-flavour physics. The upgraded detector will operate at a luminosity of 2×10^{33} cm^{-2}s^{-1}, corresponding to ten times the current design luminosity. We expect to increase the yield in the decays with muons by a factor of five, and the yield for hadronic channels by a factor of ten. The plan is to collect 50 fb^{-1} over ten

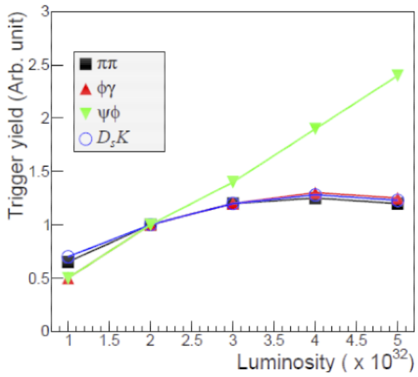

Figure 2: Simulation of current LHCb trigger yields as a function of the instantaneous luminosity. The efficiency of the hadronic channels saturates due to the L0 bandwidth limitation to 1 MHz.

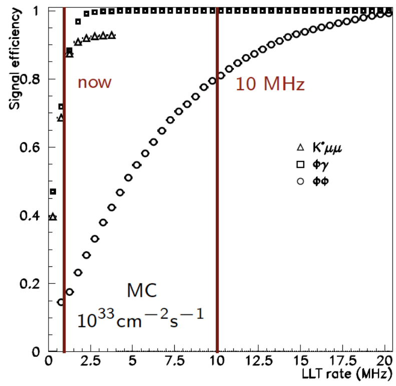

Figure 3: The LHCb upgrade. Simulation of trigger efficiency depending on the output rate of the Low Level Trigger, at the luminosity of 10^{33} cm^{-2}s^{-1}.

years, such to considerably increase the physics reach, especially for very rare decays.

As it is shown in Figure 2, due to the 1 MHz L0 trigger output rate limitation, the present layout of the L0 trigger does not allow for an efficient triggering on hadronic decay modes as the instantaneous luminosity increases above the current design value of 2×10^{32} cm^{-2}s^{-1}: the net yield of hadronic events levels off, while the yield of events with muon scales. Figure 3, referring to a luminosity of 10^{33} cm^{-2}s^{-1}, shows that as the output rate of the L0 trigger increases signal efficiencies improve. The efficiencies improve for three benchmark channels, but the gains are most significant for the hadronic decay $B_s \to \phi\phi$, which becomes fully efficient (on reconstructable events) at the trigger output rate of about 20 MHz.

We reached the conclusion for the LHCb upgrade better to omit the L0 hardware trigger filter, reading out the full detector information at 40 MHz directly into the HLT trigger, for an optimal event selection. About 12000 optical links, driven by the CERN GBT, are required to connect the front-end electronics to the readout boards, to guarantee the aggregate bandwidth of 38 Tbit/s. To form the trigger decision the HLT will use all the sub-detector information and eventually will write down the selected events to disk at a rate of about 20 kHz. However, the new readout architecture for the upgrade still foresees a Low Level Trigger (LLT) hardware trigger, which shall provide an optional and tunable throttle mechanism, to accommodate the detector output to the HLT intake capabilities, i.e. while the HLT capabilities will grow over time as the HLT filter farm gets enlarged.

The implementation of the DAQ and the HLT trigger system for the LHCb upgrade will require the assembling of a high-performance network, exploiting the most advanced computing technology available. We think that the DAQ architecture can be effectively implemented using PCIe Gen3 based readout boards, directly plugged to the HLT server motherboards, and by exploiting the InfiniBand network protocol. The envisaged high-bandwidth, highly efficient and cost effective local area network for event building and event selection is shown in Figure 4.

The LHCb sub-detector for the upgrade have to cope with the increasing level of radiation and the increases in the detector occupancies. The vertex locator (VELO) has to maintain or improve

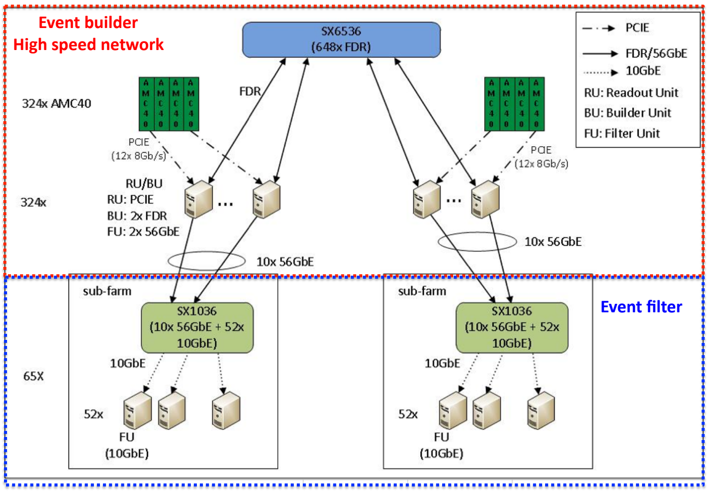

Figure 4: The DAQ architecture for the LHCb upgrade. Event fragments are injected into the event builder network by means of PCIe readout boards directly connected to the server motherboard. Assembled events are then transmitted to the HLT event filter farm for the HLT selection.

the current performance. The VELO electronics will have to withstand radiation of up to 0.3×10^{16} neutron equivalents/cm^2. In order to limit the number or produced secondary particles its material budget has to be reduced by thinning down the sensors to a thickness of 200 μm. Thermal run-away has to be prevented by CO_2 cooling. At present two detection technologies are still considered. The first is of a strip detector layout, with a r- and ϕ-geometry as in the current detector. The layout will be improved in case to better balance the occupancies, featuring a reduced pitch of 30 μm and shorter strip lengths than present. This option would employ a new readout chip which should be shared with the Inner Tracker. The second technology employs a novel pixel detector solution at a size of 55μm $\times$ 55μm, leading to a low occupancy. The readout chip is implemented in the 130 nm technology, based on the VELOPIX readout chip featuring a matrix of 256 $\times$ 256 pixels, radiation hard up to 500 MRad and tolerant to single-event-upsets. The current tracker consists of silicon strip detector at the location of the TT tracking station (upstream the magnet). For the inner-most part of the tracking stations (downstream the magnet), where the so-called Inner Tracker (IT) covers the area with the highest occupancy close to the beam-pipe, we still foresee two options: a silicon strip or a scintillating fibres detector. The design of the scintillating fiber tracker features 5 layers of 250 μm diameter, 2.5 m long fibres, read by multi-channel SiPM located outside the acceptance. The Outer Tracker (OT), surrounding the IT, is made up from straw tubes as for the present detector. The occupancy for the OT increases strongly around the beam pipe. Therefore, in order to limit the occupancy (to less than 20 %), the size of the IT will be scaled up, increasing its current area by about a factor of four. The silicon-strip detectors face similar challenges as the VELO, with radiation levels up to to $2. \times 10^{14}$ neutron equivalents/cm^2. Like for the VELO, sensors will be designed to balance the occupancy and to reduce the budget material. Both the IT-strip option and

TT tracking systems will share the same readout chip. The current RICH system is made up of two detectors, RICH1 featuring two radiators, Aerogel and C_4F_{10}, and RICH2 featuring CF_4 as single radiator. In order to limit the occupancy the Aerogel radiator will be removed and the RICH1 optics changed. The front-end electronics is embedded into the vacuum of the Hybrid Photon Detectors, which therefore need to be replaced to allow reading out the detector at 40 MHz. Baseline solution for the new photon detectors is the 64-channel Multianode Photomultiplier tubes R11265, which features an active area of 80 % and can be used without projecting lenses. R&D on the design of the readout electronics is underway. Performance studies demonstrate that the occupancy can be kept below 10 % and particle identification will work well to beyond luminosities of 2×10^{33} cm^{-2} s^{-1}. The electromagnetic and the hadronic calorimeters can keep the detector modules and the photo-multipliers since they can withstand the radiation. The gain of the photo-multipliers need to be reduced to keep the anode currents constant despite the higher occupancies. The new front end boards will compensate the reduced gain with a higher amplification. It has been demonstrated that the signal-to-noise ratio and the energy resolution can be maintained, despite the reduced gain of the photo-multipliers. It is foreseen removing the Scintillating Pad and the Parton Shower Detectors: they have no use with high occupancies. The Multi-Wire Proportional Chambers and the front-end electronics of the muon chambers are almost compatible with the LHCb upgrade. Part of them, in the innermost region of the chambers, may need to be replaced with GEM detectors. The electronics needs minor modifications. The first Muon chamber (M1), located in front of the calorimeters, will be removed due to the high occupancy and its tasks will be taken over by the tracking stations.

3. Conclusions

LHCb results have shown excellent detector performance and the strength of the flavour Physics programme at the LHC. The LHCb upgrade is in preparation. The new detector will run at a luminosity of 2×10^{32} $cm^{-2}s^{-1}$, ten times the current design value. The key element of the new LHCb detector is the readout of all sub-detectors at the full rate of 40 MHz directly into a versatile software trigger. The LHCb upgrade will be a general purpose experiment in the LHC forward region, covering beauty, charm, lepton flavour violation, QCD and exotic searches. The installation is planned in the long LHC shutdown by 2018.

References

[1] The LHCb Detector at CERN; The LHCb Collaboration, JINST 3, S08005 (2008)

[2] Letter of Intent for the LHCb Upgrade; The LHCb Collaboration, CERN/LHCC-2011-001, LHCC-I-018-2011

[3] Framework TDR for the LHCb Upgrade: Technical Design Report; The LHCb Collaboration, CERN/LHCC-2012-007, LHCb-TDR-12 - 2012