PoS PROCEEDINGS OF SCIENCE

Operation and Performance of the LHCb experiment

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The LHCb experiment collected 37.7 pb^{-1} of integrated luminosity during the first year of proton collisions at 7 TeV centre of mass energy at the CERN Large Hadron Collider (LHC). This was achieved by operating the detector up to almost its designed instantaneous luminosity, with an overall operational efficiency of over 90%. In this paper, aspects of the operation of LHCb and some global performance results from the first year of data taking are reviewed. Particular attention is given to the running conditions in 2010, which were driven by the outstanding commissioning of the LHC accelerator, and to the trigger strategy, whose flexibility allowed the LHCb experiment to explore its physics potential while accumulating luminosity. The LHCb experiment proved during the first year of running to be at the forefront of physics discoveries at CERN, complementing well the physics results from the General Purpose Detectors ATLAS and CMS at the LHC.

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1. Introduction

The LHCb experiment [1] is located at Point 8 along the LHC accelerator. It is a single arm forward spectrometer, with an angular coverage of 10 to 250 mrad in the vertical plane and 10 to 300 mrad in the horizontal plane. The detector was built in order to study with extreme precision effects of CP violation, study rare *b* and *c* decays and to probe New Physics. It was built in a way that it expands the acceptance region of the other LHC experiments, covering the range between 2 and 5 in pseudo-rapidity. The particular shape of the detector and its sub-detector composition (Figure 1) therefore allows defining the LHCb experiment as a *forward* General Purpose Detector.

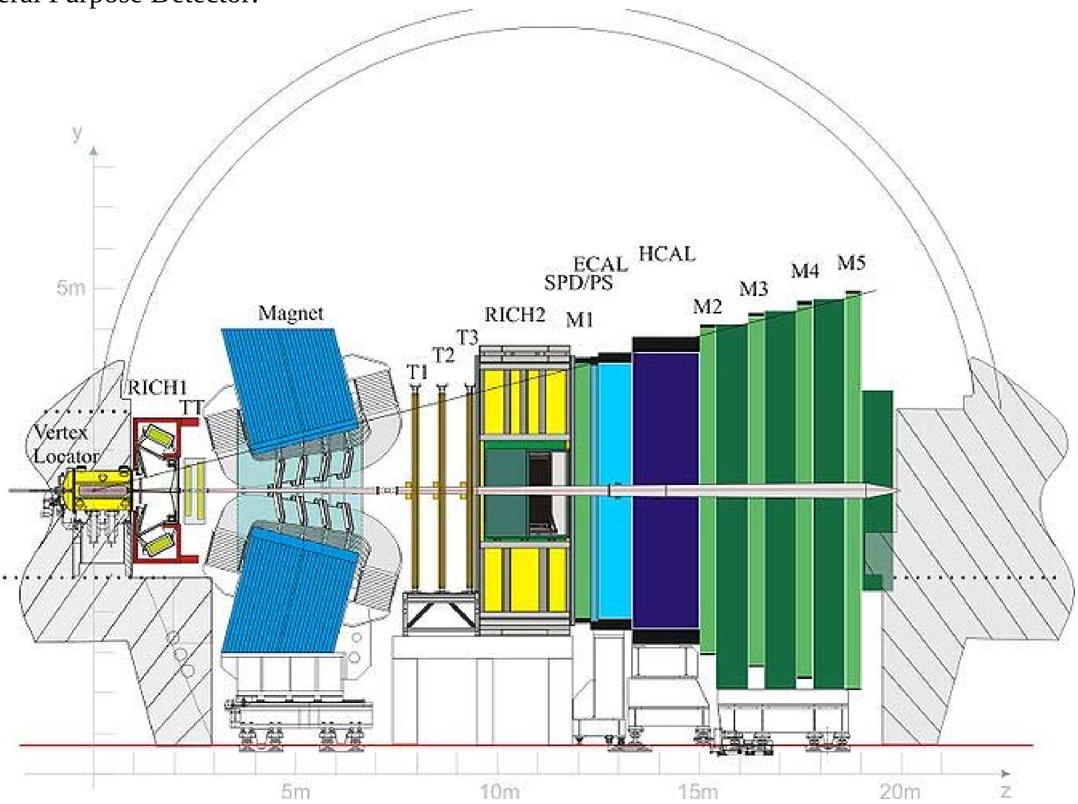

Figure 1: Schematic drawing of the LHCb detector.

The LHCb detector has an efficient trigger for many B decays topologies and efficient particle identification. It has good tracking and mass resolution and extremely precise vertexing. One of the LHCb sub-detector, the Vertex Locator (VELO), is a movable device which is moved to only 5mm of distance from the beams as the interaction point is located inside the VELO. For data taking, this has some important operational consequences as the VELO can move towards the beams only if a set of well defined safety conditions are met.

A two-level trigger architecture reduces the event rate from 40 MHz to 1 MHz at the Front-End via a hardware-based *L0 Trigger*. The L0 Trigger receives input from the calorimeter and muon detectors and selects events based on their multiplicity and number of tracks. The rate is decreased further to about 2 kHz at the Event Filter Farm (EFF) which consists of 50x27 processing nodes. A software-based *High Level Trigger* (HLT) composed of more than 24000 trigger tasks in total processes the data performing cuts, global event reconstruction and selections at an average speed of O(20ms) per event. The HLT tasks need to know the configuration of the L0 Trigger in order to perform correlated event selections. Due to the highly distributed architecture of the EFF, this is achieved by transmitting a *Trigger Configuration Key* (TCK) along with the data from the central *Readout Supervisor*.

2. LHCb operational aspects

Ever since first proton-proton collisions at the LHC, the LHCb detector has been operated routinely by only two people on duty during eight hours shifts in the LHCb control room. Experts on each sub-system are on-call weekly in order to solve the most urgent matters. Such an experiment organization was possible thanks to a highly reliable and automated centralized *Experiment Control System* (ECS) developed in PVSS [2]. In fact, the whole LHCb detector is mainly controlled by means of two graphical user interface panels (Figure 2) [3]. Through these panels, it is possible to control every DAQ sub-systems, the detector and the trigger configuration. Easy access and control of every channel of the Front-End, Back-End and High Voltage/Low Voltage systems are also available through the highly integrated control hierarchy. This allows for fast diagnose and fast recovery, and increases the level of safety and reliability of global operations, directly increasing the global experiment performance.

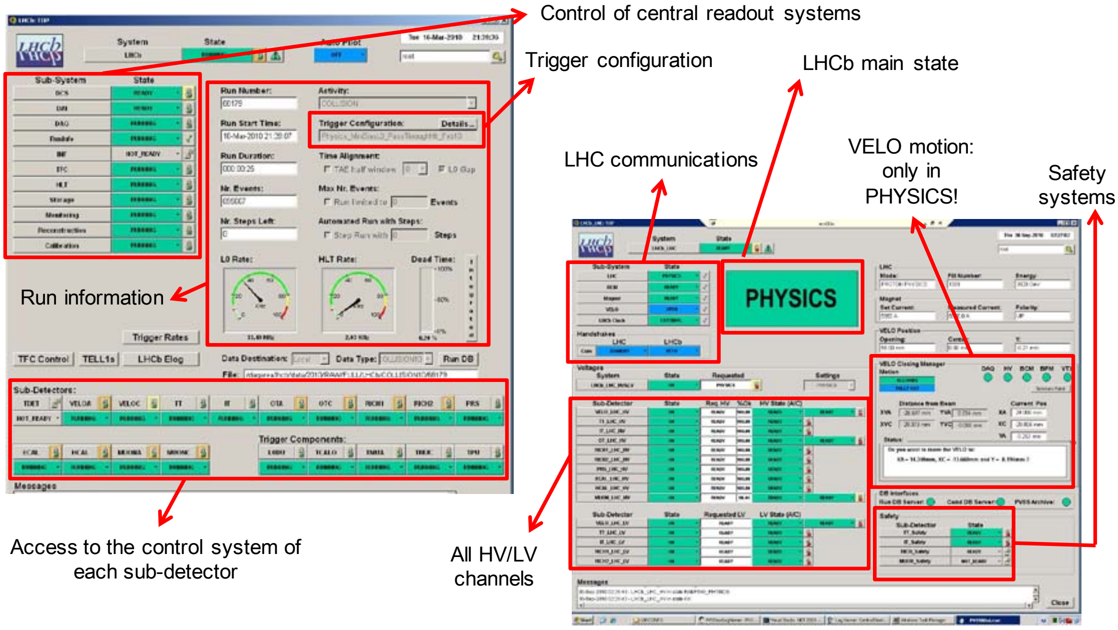

Figure 2: Screenshots of the two main graphical user interfaces which are used to control and operate the whole LHCb detector. The possibility to access every sub-system from a single location allows for a high level of automation and reliability, limiting the human interaction to supervision and actions only if needed.

Many underlying software frameworks act independently in order to operate each element of the detector coherently with the status of the LHC machine, the global LHCb status and the trigger configuration. These systems have to also ensure the highest level of experiment protection. An example of safety matter is the movement of the VELO detector towards the beams. This is done only when the LHC operators have declared the beams to be *stable* and it is not possible to move the detector unless this condition is satisfied.

A complete framework for beam, background and luminosity monitoring at LHCb has also been developed [4]. According to the required level of reliability, this framework consists of both software and hardware. It is aimed at monitoring beam and background characteristics, trigger rates, perform online monitoring of experimental conditions and ageing as a function of beam characteristics and machine settings. The final goal is to maximize the ratio of luminosity over background. This framework has also helped the LHC operators to commission the LHC machine extensively, providing real-time information on beam losses, and quality of injection of the anti-clockwise beam. It is however both important and impressive to note here that no significant background was ever observed in the first year of running at the LHC.

3. 2010 running conditions

The LHCb experiment was designed to run at an average instantaneous luminosity of $2*10^{32}$ $cm^{-2}s^{-1}$ with an average number of visible proton-proton interactions per bunch crossing (μ) of 0.4 at 14 TeV centre of mass energy. In the LHC Technical Design Report, it was specified that these conditions would nominally be achieved by colliding 2622 bunches per beam, with $1.15*10^{11}$ protons-per-bunch (ppb), a squeezing function $\beta* = 30$ m and a normalized emittance $\varepsilon_N = 3.75$ µm.

However, the running conditions in 2010 were different thanks to the outstanding performance of the accelerator. In fact, LHCb reached ~80% of its nominal luminosity with eight times fewer colliding bunches (344) and extremely efficient beam characteristics ($\beta* = 3.5$ m, $\varepsilon_N = 2.4$ µm) with respect to the nominal LHC conditions. Figure 3 left shows the trend of the instantaneous peak luminosity over LHC fill number during 2010. The maximum instantaneous luminosity reached about $1.7*10^{32}$ $cm^{-2}s^{-1}$. In particular, the average number of visible pp interactions per bunch crossing, commonly referred as μ, constantly stayed above the nominal LHCb value and even reached the value of 2.5 (Figure 3 right), which is almost six times the designed value.

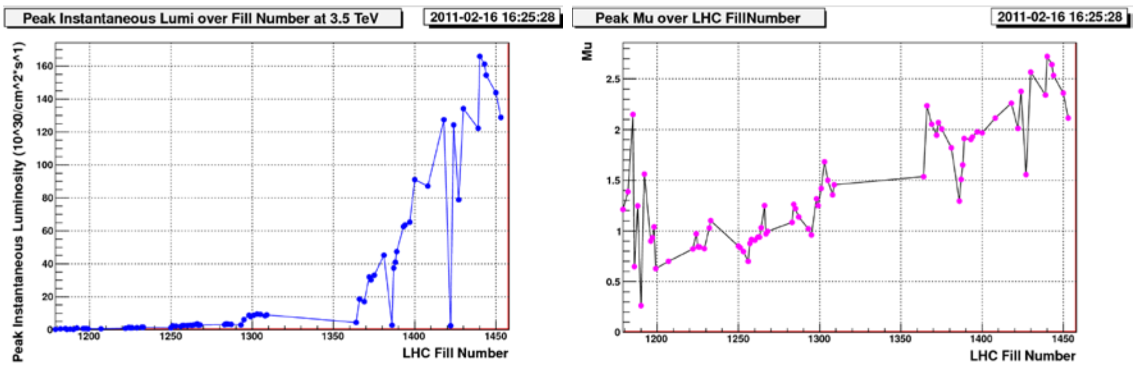

Figure 3: Plots of the peak instantaneous luminosity at LHCb (left) and μ (right) as a function of the LHC fill number. The steep trend was extremely efficient for the commissioning of the LHC machine and the LHCb experiment. However this had strong impacts on the global operations of the detector.

Running as such high-μ has non-negligible impacts on operational aspects at LHCb:

- ✓ Events at high-μ have higher effective collision rate per bunch crossing and they are more complicated, because they contain more than one interaction vertex on average. This saturates the available bandwidth of the LHCb readout system if events are not selected properly.
- ✓ Events with more than one interaction vertex contain also more tracks. The track finding algorithm in the HLT takes more time to process events in this condition and therefore reducing the available processing nodes.
- ✓ Events with many tracks have higher particle flux which would degrade the performance of the trigger. Eventually global upper cuts on events observables such as track multiplicity are needed in order to select only the events more interesting for the LHCb physics program.
- ✓ Having a higher particle flux could also lead to detector stability problems like detector voltage trips and to have a long-term impact on accumulated radiation dose. Ultimately it

will have an impact on the efficiency of each LHCb sub-detector if not monitored continuously at luminosities $> 2*10^{32}cm^{-2}s^{-1}$.

Figure 4 shows a recorded event at high-μ at LHCb. This particular event had six vertices and despite the difficult operational conditions the performance proved extremely good and the detector response excellent.

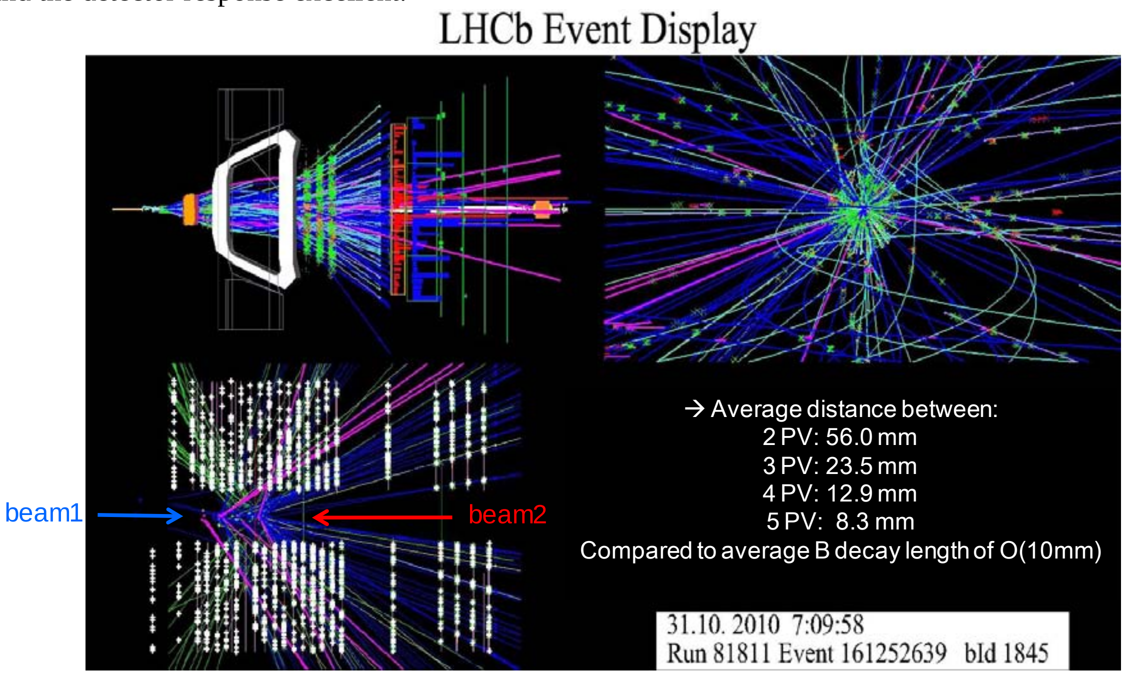

Figure 4: Example of a high-μ event seen with the Online LHCb Event Display. The pink lines are the tracks associated to each of the distinguished vertices inside the VELO (bottom left). On the top left, these tracks are shown as they traverse the full detector layout. On the top right image, the 3D event is shown in its complexity. The excellent performance of the detector allowed distinguishing properly event with even six primary vertices.

In addition, due to the main focus on the commissioning of the LHC machine in its first year of operations, LHCb had to respond to beam conditions without knowledge about the ultimate parameters. The unexpectedly high value of μ with limited number of bunches initially followed by a successive increase allowed exploring the experiment physics potential. The detector, the trigger and the readout performance could be tuned more efficiently and their potential explored more rapidly as a function of integrated luminosity.

4. The LHCb trigger strategy during 2010

The objective of the LHCb trigger strategy evolved into a two-fold aim. The first of which was to collect luminosity for the first very important physics measurements in the field of B-physics and charm physics. Secondly, the scope was put in collecting as much luminosity as possible following a steady and steep luminosity increase by the LHC accelerator, while exploring the LHCb physics potential. In fact, as already shown in Figure 3, the delivered instantaneous luminosity at LHCb had increased steadily as a function of the LHC fill number, due to the focus put in the commissioning of the LHC accelerator. More than half of the total integrated luminosity collected by the LHCb experiment in 2010 came in the last few fills.

At the early stage of the physics running, the LHC machine was delivering physics with very few colliding bunches (< 50), thus generating a very low L0 trigger rate and therefore very low CPU consumption for processing events. Hence, the choice during this first period of running was to keep a very loose trigger and allow bandwidth and high efficiency for a very broad spectrum of physics channels dedicated to charm physics. Initially, even every bunch crossing was read out without L0 Trigger and the events were selected at the HLT only on the basis of a simple minimum bias trigger, i.e. events with at least one track in the VELO.

By the time that the machine commissioning entered a second stage, the event complexity was increased to reach nominal conditions. Each event contained more than one vertex per interaction in average. The number of colliding bunches was also increased to reach the final number of 344 in the last physics fills. In these conditions, the L0 trigger rate increased sharply, having an impact on the processing time of events at the HLT. The choice was then to apply Global Event Cuts (GECs), still giving high priority to muon-based signal channels (i.e. $B_s \rightarrow \mu\mu$) and charm physics.

The GECs were mostly based on the multiplicity of an event, which in the L0 Trigger is measured by the Preshower-ScintillatingPads Detector (PRS-SPD). Figure 5 shows the relationship between the SPD multiplicity and the number of primary vertices (PV) of an event. For less than seven primary vertices, the relationship is linear. In the first stage, the applied cut was at 900 SPD multiplicity, which means that all the events with an SPD multiplicity below 900 were accepted. By doing this, the detector could explore its full physics potential and tune the performance. In the later stage, the applied cut was at 450 SPD multiplicity, in order to reduce the trigger rate and select only those events which were of interest. Effectively, the GECs allows collecting luminosity even at high pileup interactions while maintaining the total multiplicity below an acceptable level.

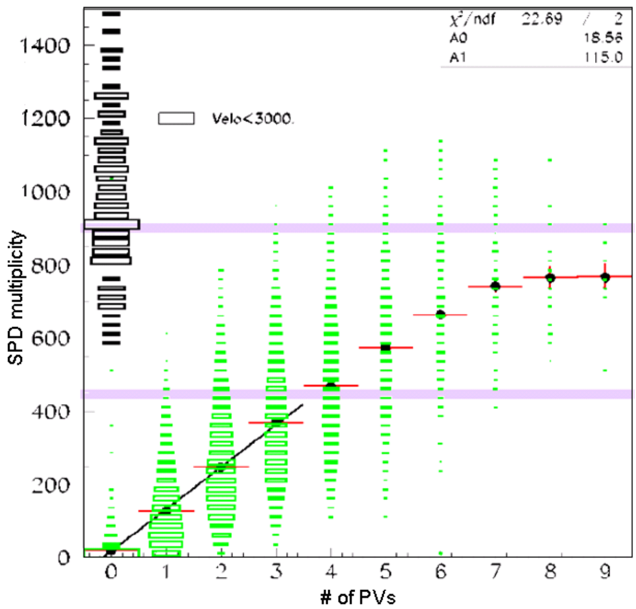

Figure 5: SPD multiplicities of events are plotted against the number of Primary Vertices (PV) as seen by the HLT algorithm. The relationship is basically linear for PV < 7. The two purple bands show the cut applied on the basis of the SPD multiplicity of an event. In the early physics run, the LHCb trigger strategy was to cut at 900 SPD multiplicity, while in the later physics run, where the experiment conditions reached their nominal values, the cut was at 450 SPD multiplicity.

5. LHCb global performance

During the full 2010 physics run, the LHCb detector worked with more than 99.5% active channels (total of 544063) and the detector hardware behaved extremely well throughout the whole year 2010. 37.7 pb^{-1} of luminosity were recorded out of 42.2 pb-1 of delivered luminosity at LHCb with an overall efficiency close to 90%. Even though the main objective of LHCb was to explore the LHCb physics potential and detector performance, the choice to follow the increasing instantaneous luminosity allowed LHCb to follow the same luminosity trend of ATLAS and CMS, which are designed to cope with two orders of magnitude higher luminosities and one order of magnitude higher μ in average.

However, a luminosity difference with ATLAS and CMS was observed. Figure 6 shows the integrated delivered and recorded luminosity as a function of the LHC fill number. More than 50% of the total integrated luminosity was collected in the last few physics fills which were delivered in the last week of the proton physics runs. This had evident impact on the LHCb operations and trigger strategy as described in Chapter 5, as the complexity of events grew quickly while most of the luminosity was being delivered.

Figure 6 also contains the efficiency of the LHCb detector and the breakdown of the different sources. The main sources of inefficiencies in LHCb are due to:

- ✓ the High Voltage (HV) of each sub-detector, which are ramped to their nominal values as soon as the beams are declared stables,
- ✓ the safety of the VELO, which allows the VELO to move to data taking positions if certain safety conditions are met only,
- ✓ the availability of the Data Acquisition system (DAQ), which needs to be configured with the proper trigger configuration in order to record and process physics data,
- ✓ the trigger deadtime, which can be influenced by high processing time or bandwidth congestion.

It is here important to note that the highest contribution was due to the DAQ availability. This was a direct consequence of the complexity of the events and continuous changing of trigger configurations in order to cope with the changing running conditions.

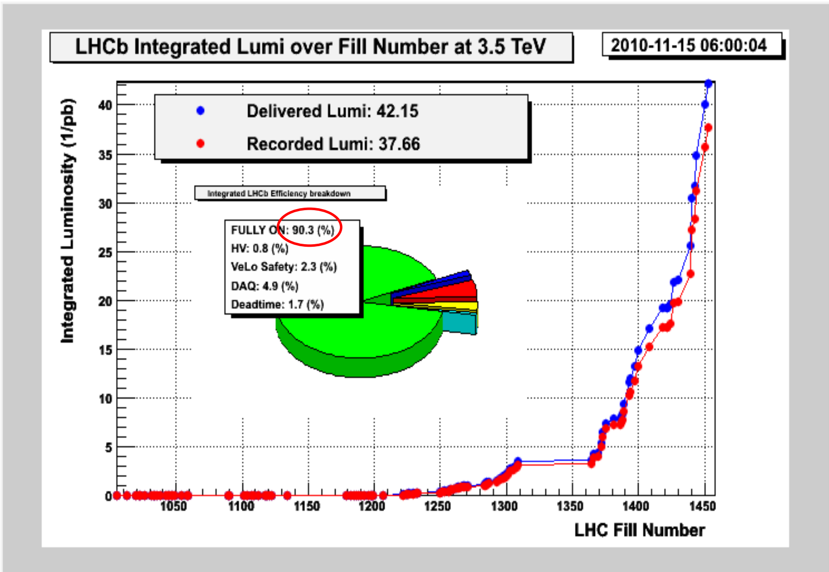

Figure 6: Integrated delivered (in blue) and recorded (in red) luminosity at LHCb with a global efficiency of about 90%.

6.Conclusions

As described in this paper, the LHCb experiment successfully accomplished its first physics run during 2010. A total of 37.7 pb^{-1} of integrated luminosity was collected and has been reprocessed for data analysis. The overall efficiency was just above 90%. The global operational challenges were overcome with success allowing the LHCb experiment to follow the growth in luminosity at the same pace as the GPD detectors.

References

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