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The LHCb Upgrade

Maurizio Martinelli[∗†]
Nikhef, Amsterdam
E-mail: maurizio.martinelli@nikhef.nl

The main goal of the LHCb Experiment is to measure *CP* violation in the decays of beauty and charm mesons and search for the effects of new particles beyond the Standard Model. The first years of data taking have been fruitful, even though effects beyond the Standard Model have not been observed yet, and the collaboration is looking forward to make a step further to widely increase the search potential of the detector by recording 50fb^{-1} after 2019 with an improved trigger system. This amount of data could put the LHCb collaboration in the advantageous position of being able to extend its search potential to a sensitivity approaching the theoretical error for many Flavor Physics observables.

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[∗]Speaker.
[†]On behalf of the LHCb collaboration

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PoS(Beauty 2013)058

1. Introduction

The LHCb detector [1] has been producing excellent Physics results since the beginning of the data taking in 2010. Most of them are in line with the Physics program for which the detector has been designed for, and in some cases they are even better than the expectations.

These results have been achieved because the detector behaved as predicted during its design, allowing the operations to be pushed to their limit. Among the outstanding results of the operations it's worth mentioning the recorded instantaneous luminosity that is double the design, and the number of interactions per beam crossing that has been on average 1.6, four times the 0.4 of the design.

This excellent performance has been the basis for high quality results in many different fields of Flavor Physics. LHCb rapidly overtook the B factories in the hadronic decays of beauty and charm mesons, allowing for the most precise measurements of CP violation and mixing in many channels [2, 3, 4]. A successful program of rare decay studies has been also possible, as shown by the evidence for the $B^0_s \to \mu^+\mu^-$[5] and the most precise results to date on the $B^0 \to K^{*0}\mu^+\mu^-$ angular distributions [6]. Last but not least, LHCb is leaving its mark in spectroscopy as well, see for example the determination of the $X(3872)$ quantum numbers [7].

All the mentioned results were produced with the 3 fb^{-1} of pp data collected during 2011 and 2012 run at the center of mass energy of 7 TeV and 8 TeV, respectively. A successful pA run has also taken place at the beginning of 2013, before the long shutdown of the LHC. When LHCb will turn on again in 2015, the plan is to record around 7 fb^{-1} of pp data at the center of mass energy of 14 TeV, and reach a target of 10 fb^{-1} data recorded with the current detector.

Starting 2018, there will be an eighteen months shutdown, during which LHCb collaboration plans to upgrade its detector. The upgrade is required to meet the target of recording 50 fb^{-1} pp data in the following years. The means for reaching this purpose are a higher instantaneous luminosity and an improved trigger. Specifically, the target is to improve the detector to cope with the factor 5 increase in luminosity (from 4×10^{32}cm^{2}s^{-1} to 2×10^{33}cm^{2}s^{-1}), and to double the efficiency of the hadron trigger, gaining a factor 10 in instantaneous signal yield for decays not involving muons.

2. Physics Motivation

The LHCb detector is already unique for searching effects beyond the Standard Model (SM) in the B^0_s decays, and the upgrade will allow it to remain competitive with Belle-II in B^+ and B^0 studies [8]. The LHCb upgrade will also allow to record unprecedented quantity of charm decays. Furthermore, the LHCb geometry makes it unique for Electroweak and QCD measurements, complementary to ATLAS and CMS.

Specific meetings with theorists have been held to discuss the capabilities of the LHCb detector and the opportunities offered by the upgrade. The outcome of this discussion is that the LHCb upgrade could make it possible to approach the theoretical uncertainty in many different measurements of interest in Flavor Physics, such as B^0_s mixing, gluonic penguin diagrams, right-handed currents, Electroweak penguins, Higgs penguins, Unitarity triangle angles and CP violation in Charm decays [9, 10].

PoS(Beauty 2013)058

A few specific examples are now given. LHCb recently showed the first evidence of the $B_s^0 \to \mu^+\mu^-$ decay, consistent with the SM. This measurement reduced the room for effects beyond the SM, but the measurement of the $B^0 \to \mu^+\mu^-$ decay, together with a precise measurement of the $B_s^0 \to \mu^+\mu^-$ branching ratio is needed to enlighten the picture. While the $B_s^0 \to \mu^+\mu^-$ observation is possible with the current plan, the $B^0 \to \mu^+\mu^-$ branching ratio is expected to be measured with an error of 100% with 10 fb^{-1} of LHCb data. With the LHCb upgrade, it will be possible a result that would measure this branching ratio to 35%, guarantee an observation and approach theoretical error expectations (5%).

Another interesting topic for the LHCb upgrade is the measurement of *CP* violation in the B_s^0 sector. This measurement is of special interest for penguin dominated diagrams, such as $B_s^0 \to \phi\phi$, where the cancellation between decay and mixing phases results in *CP* violating phase of value 0. Physics beyond the SM, such as new particles in the penguin loop, could produce a deviation from 0 at the percent level. LHCb recently measured this phase with a large error [11]. The upgraded detector would be able to perform the same measurement with an error similar to the theoretical one (2%).

Charm Physics will also benefit from the LHCb upgrade. Theoretical expectations for *CP* violation in the Charm sector are difficult to make, but it is a widely shared opinion that the effects in the SM should be of the order of 1×10^{-3}. LHCb is already performing searches with a sensitivity of $\approx 2 \times 10^{-3}$. Reaching the sensitivity of 10^{-4} is in the potential of the LHCb upgrade, that should be able to measure SM *CP* violation if any, and effects beyond the SM that may enhance it.

The LHCb upgrade would not be devoted to Flavor Physics only. The forward geometry of the LHCb detector, covering the pseudo-rapidity range $2 < \eta < 5$, allows it to perform measurements complementary to ATLAS and CMS, such as the effective Electroweak mixing angle, and QCD studies in jet forward region. Moreover, its excellent tracking capabilities provide high sensitivity in searching exotic long lived particles.

3. Trigger Upgrade

In Sec. 1 it has already been mentioned that the Physics target of the LHCb upgrade places some requirements on the upgraded trigger. The muon trigger efficiency needs to remain constant with the increase in luminosity, while the hadron trigger efficiency should double [12].

Those requirements cannot be met by the present infrastructure due to hardware limitations. The readout of the LHCb detector is now 1 MHz, while the LHC clock is 40 MHz, that means the LHCb detector cannot be read out for each collision produced by the accelerator. Furthermore, the output of the trigger farm to tape is 5 kHz, which is not enough to fulfill the linear increase in the trigger output required by a constant or increased efficiency with increased luminosity.

Studies have been made which demonstrate that the present trigger is not capable of matching the aforementioned requirements. Especially the L0 hardware trigger that LHCb employs to lower the interactions rate to 1 MHz places hard constraints on the capability of the current layout. It has been shown that with the increase of luminosity, the cuts should be tightened so much to keep the rate under control that the efficiency would lower, yielding at best a constant yield of triggered events even with increased luminosity. Furthermore, doubling the efficiency of the hadronic trigger

PoS(Beauty 2013)058

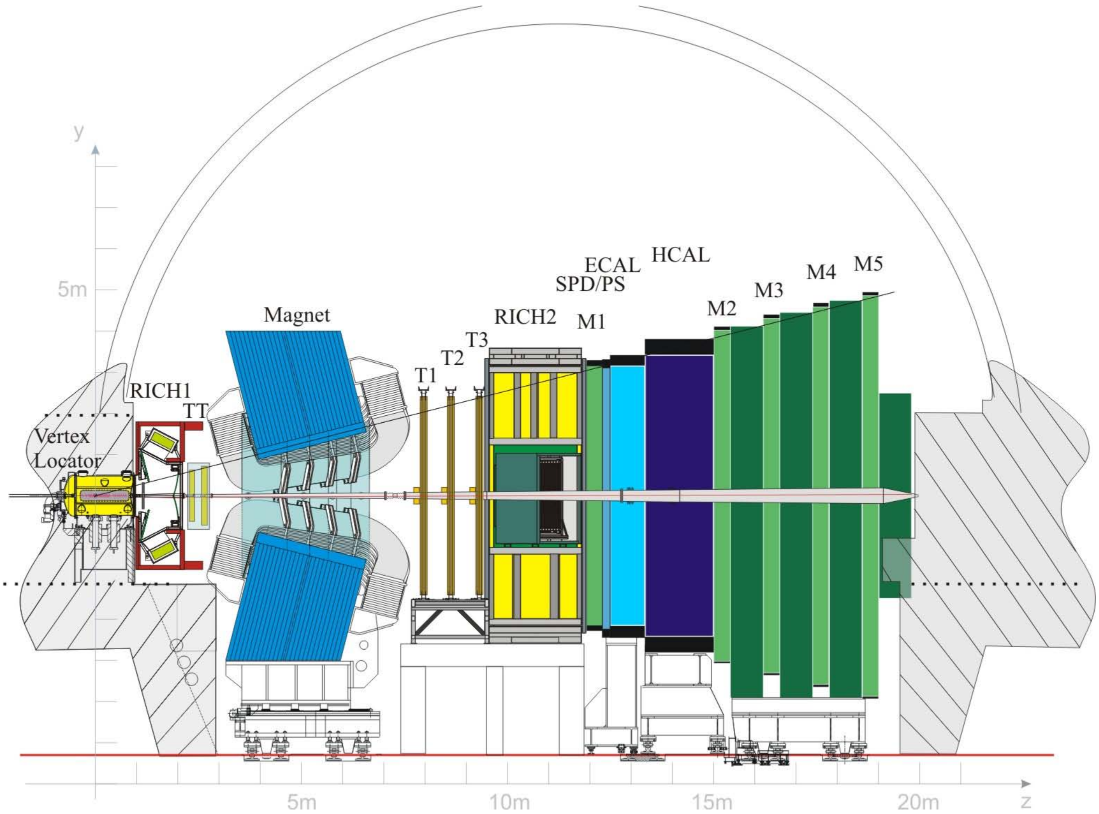

Figure 1: A schematic view of the LHCb detector.

lines can be pursued only by loosening the selection cuts. This implies that the event reconstruction at trigger level needs to be more accurate, such that the rates can be kept under control.

The proposed solution is to read out the detector at 40 MHz and remove the hardware trigger layer. A complete software trigger would indeed allow the detector to benefit from the increasing luminosity. The costs of this choice are more CPU computing power for the trigger farm, a redesign of the trigger itself, and a modification of the read out of all subdetectors. The amount of data to be registered to tape also needs to increase. The plan is to run the trigger with an output rate of 20 kHz.

4. Upgrade of the sub-detectors

The eighteen months shutdown in 2018 allows to replace the sub-detectors that suffered most from irradiation, such as the silicon ones. Other sub-detectors need to be upgraded to cope with the higher occupancies expected at 2×10^{33}. For all, the readout must be modified. Technology improved in the last few years, and new solutions have been tested to gain in terms of efficiency and resolution. The LHCb spectrometer is schematically shown in Fig. 1. Almost all the sub-detectors are planned to go towards an upgrade [12]. In the following, the main changes are briefly reviewed.

The Vertex Locator (VELO) modules need to be redesigned to cope with the 40 MHz readout and with the higher irradiation environment [13]. Furthermore, the chance of redesigning them has been taken to improve the Impact Parameter (IP) resolution. There are two ways to achieve

PoS(Beauty 2013)058

this target: move the first measured point closer to the interaction region, and reduce the material budget. Both the two aspects have been taken into account in the design of the upgraded detector. Two solutions have been found to satisfy the requirements. One is a direct upgrade of the current detector, that is a silicon strip detectors with channels that describe radial and polar coordinates on the two sides of each module, respectively. In the upgrade more channels are required to reduce occupancy, a smaller inner radius to improve IP resolution, and a diamond plane to drain the heat away of the silicon, therefore improving radiation hardness. The alternative solution is based on a full redesign of the detector that changes the sensors technology turning to the Timepix [14] pixel readout chips that have 256×256 channels with a pitch of $55\mu\text{m} \times 55\mu\text{m}$. The main advantages of this configuration are the radiation hardness and the lower material budget, the latter is guaranteed by the pixel resolution allowing for a single-sided module. Since this meeting, the decision has been taken on the solution to be adopted in the upgrade, favoring the pixel configuration.

Moving away from the interaction region, LHCb has one tracking detector (Tracker Turicensis - TT) ahead of the magnet and three tracking stations (Inner/Outer Tracker - IT/OT) behind it. The TT and IT are silicon detectors, while the OT is made of straw tubes. The main issue in the tracking stations is the larger occupancy caused by the higher luminosity, that favors the production of fake tracks in the tracking reconstruction algorithms. Studies have demonstrated that the tracking algorithms are still able to remove a large quantity of fake tracks, assuming a larger coverage at high pseudo-rapidity η. One more desired feature of the upgraded tracking detectors is less material budget, to reduce the error on the momentum estimate. The TT should remain more or less the same in the upgrade, but there is an effort to redesign it to improve tracks reconstruction and coverage at high η. For the tracking station behind the magnet, two options are under study. An enlarged, thinner and lighter IT would reduce the occupancy in the OT. This is needed to obtain an high tracking efficiency in the high irradiation environment. The downside of this solution is the material budget introduced by the IT supports and electronics. A second option is replacing the IT and part of the OT with a central tracker made of 0.25 mm diameter scintillating fibers to be read out with silicon photo-multipliers. The main advantage in this case is represented by the lower material budget in the central region, that would significantly reduce the error on the momentum estimate.

The hadron identification in LHCb is currently achieved by two ring imaging Cherenkov detectors, RICH1 and RICH2, placed ahead and after the tracking stations, respectively. The main issue for the RICH in the upgrade is the readout currently limited to 1 MHz by the Pixel HPDs [15] used in the existing detector. An upgrade of the readout to meet the 40 MHz requirement is therefore mandatory. Since the HPD readout is integrated within the vacuum envelope of the detectors, the problem cannot be solved by simply changing it. Both the tubes and their readout need to be replaced, and multi-anode photo-multiplier tubes with external 40 MHz readout have been identified as the perfect solution to this problem [16, 17]. One more limitation of the current RICH detectors is the aerogel in RICH1. The high occupancy of the upgraded detector does not allow aerogel to be used, since this radiator produces relatively few photoelectrons for Cherenkov ring which prevents a problem for pattern recognition. Removing the aerogel decreases the material budget and allows for a reduction in the number of photo-multiplier tubes in RICH1.

The electronic and hadronic calorimeters will not change much in the upgrade. Both detector modules and photo-multiplier tubes can withstand the increased irradiation. The only modification

PoS(Beauty 2013)058

is the reduction of the photo-multiplier tubes gain to keep the anode current constant with the higher occupancy. This will be compensated with an increased front end amplification. The readout electronics will be modified to match the 40 MHz requirement. Other components of the LHCb calorimetry are the scintillating pad detector and the pre-shower. Both of them will not be present in the upgrade because they have been used mainly for triggering purposes at hardware level. Since the upgrade trigger will be fully software based, there is no need for them, and they will be removed to reduce the material budget. The effect of their absence on electrons and photons identification is under study.

The multi-wire proportional chambers used for muons identification almost meet the upgrade requirements. The plan is then to keep all the chambers except the first station, that is before the calorimeter and is used mainly for hardware triggering purpose, and modify the electronics to read out at 40 MHz. Studies are ongoing on the performance in a high occupancy environment, and on their aging. There is also a research and development study ongoing on the feasibility of replacing the high pseudo rapidity region of the chambers with Gas Electron Multiplication detectors.

5. Conclusions

The LHCb detector is performing very well in difficult conditions. The luminosity per bunch crossing is 4 times the design parameter, nonetheless the sub-detectors have been over 99% operational and the vertex and momentum resolution behaves as expected.

The collaboration has already taken advantage of the efficient operations to produce outstanding physics results, such as the evidence for the $B_s^0 \to \mu^+\mu^-$ decay, the measurement of ϕ_s in $B_s^0 \to J\psi\phi$, the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$, and the mixing and *CP* violation measurements in charm decays.

The years ahead of the LHCb collaboration look fruitful, assuming that we do not stop at this point. One step further is needed to record unprecedented amounts of beauty and charm decays and reach the target of 50 fb^{-1} of pp data. This target can be met only with new data-taking conditions, but those require the detector to be subjected to an upgrade to match the requirements. A 40 MHz readout is needed from all the detectors, such that a full software trigger could allow the experiment to record data with the same or higher efficiency at higher luminosity. Nonetheless it's important to retain the key LHCb performance parameters, the vertex and momentum resolution, the particle identification and the tracking reconstruction efficiencies. The studies performed by the LHCb collaboration showed that an upgrade of the detector that fulfills these requirements is possible. The project is fully endorsed by the LHCC and has been already approved by the CERN Research Board.

After the installation starting at the beginning of 2018, the LHCb upgrade will allow the LHCb collaboration to search for effects beyond the Standard Model in the flavor sector with unprecedented precision.

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PoS(Beauty 2013)058

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PoS(Beauty 2013)058