WILL LHCb RUN IN THE HL-LHC ERA?

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Abstract

The LHCb collaboration presented a Letter of Intent (LOI) to the LHCC in March 2011 for upgrading the detector during LS2 (2018) and intends to collect a data sample of 50 fb^{-1} in the LHC and HL-LHC eras. The physics case and the strategy for the upgrade have been endorsed by the LHCC.

This paper presents briefly the physics motivations for the LHCb upgrade and the proposed changes to the detector and trigger. In the following part machine related issues for the LHCb upgrade are discussed, in particular issues in relation to the Target Absorber for Secondaries (TAS), Radiation to Electronics (R2E), β* and crossing angle in IP8.

INTRODUCTION

The LHCb experiment has been designed to study rare decays and to perform precision measurements of the violation of the combined charge-conjugation and parity symmetries (*CP).* Its aim is to investigate potential effects of physics beyond the Standard Model (SM). Results obtained from data collected in 2010 and 2011 show that the detector is robust and functioning well. While LHCb will be able to measure a host of interesting channels in heavy flavour decays in the coming years, a limit of about 1-2 fb^{-1} of data per year can only be overcome by upgrading the detector. With a detector read out at 40 MHz, a much more flexible software-based triggering strategy will allow a large increase not only in the data rate, as the detector will collect at least 5 fb^{-1} per year, but also in the ability to increase trigger efficiencies especially in decays to hadronic final states. In addition, it will be possible to modify trigger algorithms in order to explore different physics as LHC discoveries point to the most interesting channels.

PHYSICS MOTIVATION

The evidence for CP violation in the charm sector [1] is one of the most important and unexpected results to have come from the LHC so far, and illustrates the potential of probing for new physics in the flavour sector. This is a powerful approach because decays of beauty and charm quarks can probe large mass scales, beyond that reachable by direct new particle searches, via virtual production in loop diagrams. The *indirect searches* for physics beyond the SM are therefore a complementary approach to the *direct searches* of ATLAS and CMS. Therefore, LHCb contributes to the diversity of the CERN physics program.

The LHCb searches for new physics are also complementary to those of the Super-B factories operating at e^+e^- colliders. At such machines the B_s system, about which very little is known and where new physics effects may be apparent, cannot be explored in depth. Therefore, LHCb and its upgrade offer unique possibilities to enhance our knowledge of flavour physics and to measure *CP*-violating asymmetries to unprecedented levels.

Two phases of the LHCb physics program

The LHCb physics program will be executed in two phases. In the first phase of the experiment, i.e. with data collected up to 2017 with the current detector, LHCb will obtain results that will severely test the SM. It will be possible to extend significantly the precision of many key parameters in beauty and charm meson systems beyond what was possible at the B-factories, and make the first exploration of the B_s system. The hope is to observe clear signs of non SM effects. Whatever the outcome of this initial exploration, however, precision measurements of key parameters will be required. They will be carried out in the second phase of the experiment with the upgraded detector. An improved knowledge of the key parameters and observables will be essential to understand the physics beyond the SM, which hopefully will be uncovered at the LHC.

The scope of the LHCb physics program

The scientific goals of LHCb extend also beyond quark-flavour physics. Important studies are possible in the lepton sector, including the search for lepton-flavour violating tau decays and for low mass Majorana neutrinos. Furthermore, LHC has unique and exciting possibilities in the areas as diverse as electroweak physics, the search for long-lived new particles, and QCD. In all cases great benefit will come both from the increased sample sizes that will be made available with the upgrade, and the flexible software trigger. Therefore, the upgraded LHCb experiment can be regarded as a general-purpose detector in the forward direction.

THE LHCb SPECTROMETER

Since pairs of beauty quarks are predominantly produced in the forward or backward direction, the LHCb detector [2] was designed as a forward spectrometer, covering the angular range between 10 and 300 mrad. The detector elements are placed along the beamline of the LHC, as shown in Figure 1. The Vertex Locator (VELO), a silicon strip device, surrounds the proton-proton interaction region and provides excellent impact parameter and proper time resolutions. In conjunction with the VELO, the main devices used to measure track momenta comprise a large area silicon strip detector (TT) located in front of a 4 Tm dipole magnet, and a combination of silicon strip detectors and straw drift chambers (T1-T3)

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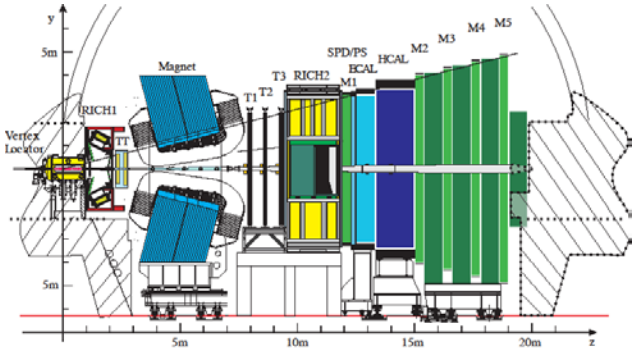

Figure 1: Layout of the present LHCb detector

placed behind.

Two ring-imaging Cherenkov (RICH) detectors are used to identify charged hadrons. These detectors have been of particular importance for the first observation of *CP*-violation in the charm sector [1], and provide kaon-pion discrimination for the full range of track momenta. Figure 2 shows the invariant mass distributions of the 1.4×10^6 K^-K^+ and 0.4×10^6 $\pi^-\pi^+$ pairs used in this analysis. The distributions are centered at the D meson mass of 1865 MeV/c^2.

Further downstream an Electromagnetic Calorimeter (ECAL) is used for photon detection and electron identification, followed by a Hadron Calorimeter (HCAL), and a Muon system consisting of five stations interleaved with iron shields to distinguish muons from hadrons. The ECAL, HCAL and Muon System provide the capability of first-level hardware triggering.

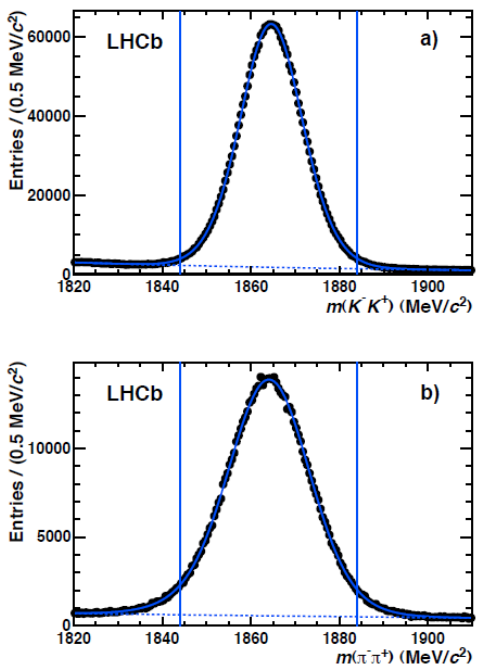

Figure 2: Fits to the (a) m(K^-K^+) and (b) m($\pi^-\pi^+$) spectra of D^{*+} candidates passing the selection. The dashed line corresponds to the background component in the fit, and the vertical lines indicate the signal window of 1844–1884 MeV/c^2.

THE LHCb UPGRADE

Trigger and readout architecture

In the present LHCb experiment trigger selections with the first level trigger (L0) are made at the 40 MHz beam crossing rate, using either the Calorimeters or the Muon System. The detector is read out at a maximum rate of 1 MHz. To trigger at an increased event rate requires a substantial change in the LHCb read-out architecture.

The criteria for the present L0-triggers are based on the deposit of several GeV of transverse energy, E_T. While this provides high efficiencies on dimuon events, fully hadronic signal decays typically have an efficiency less than 50%. In these hadronic decays the E_T threshold required to reduce the rate of triggered events to an acceptable level is already a substantial fraction of the *B*-meson mass. Any further increase in the rate requires an increase of this threshold, which then removes a substantial fraction of signal decays. The trigger yield therefore saturates for hadronic channels with increasing luminosity.

To overcome this situation it is essential to remove the 1 MHz L0 limitation and to introduce information in the trigger that is more discriminating than E_T, e.g. displaced vertex information. The most effective way of achieving this is to supply the full event information at the 40 MHz beam crossing frequency and to analyze each event in a trigger system implemented in software. A detector upgraded in this way would allow the yield of hadronic *B* decays to be increased by a factor 10 for the same LHC machine run-time.

The above shows that the physics program of LHCb is limited by the detector, not by the LHC. As a consequence, the detector upgrade allows LHCb to better utilise the LHC capabilities.

Detector upgrade

Many of the challenges of the 40 MHz readout scheme can be met using modern technologies adapted for high energy physics. In order to minimise cost, development time and installation effort, parts the existing electronics that satisfies the upgrade requirements will be re-used and common devices and modules will be developed. A detailed overview of the upgraded detector is given in reference [3].

The physics program for the LHCb upgrade requires an extremely performant vertex detector with fast pattern recognition capabilities, very good vertex resolution and two track separation. Sufficient radiation hardness is important to guarantee excellent performance throughout the upgrade data-taking period. Moreover, because the trigger performance of the upgrade relies heavily on vertex detector data, its use in the trigger must be fast and flexible enough to adapt to the evolving physics needs of the experiment.

Another main challenge of the LHCb upgrade lies in the redesign of the tracking system, which should be able to sustain luminosities of $2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$. The new tracking systems which will replace the TT and parts of tracking

stations T1-T3, are based on two possible options: one relies on fibers readout by silicon photo-multipliers, and the other on silicon strips. As for the VELO, the tracking detectors must ensure radiation resistance, good granularity, low material budget and fast response to minimize spillover events. In order to avoid occupancy problems at luminosities of 2×10^{33} cm^{-2}s^{-1}, 25 ns bunch spacing is an important requirement for the LHCb upgrade.

The particle identification (PID) system is also a vital component of the upgraded detector. As mentioned earlier, several key physics channels which involve kaons rely on the RICH PID to reject copious backgrounds from multiple track combinatorics and events with similar decay topologies. The current RICH system employs custom-built Hybrid Photon Detectors (HPD), the Pixel HPDs, which operate very successfully. However these cannot be reused in the upgraded RICH detector since the HPD readout electronics are limited to a 1 MHz event readout rate, incompatible with the upgrade rate of 40 MHz. It is therefore proposed to replace the HPDs with Multi-anode Photomultipliers (MaPMTs) with external 40 MHz readout electronics. A further particle ID device based on time of flight that uses Cherenkov light in quartz, called the TORCH, is foreseen, complementing the RICH detectors in the low momentum particle ID. The TORCH is a challenging project, and its installation could come later, without compromising the initial operation of the upgraded detector.

Coping with luminosities of 10^{33} cm^{-2}s^{-1} does not require substantial rebuilds of the Calorimeter and Muon systems. Only small modifications are needed to have the system fully integrated with the rest of the upgraded DAQ.

A bigger CPU farm, more disk storage and more computing power will be needed to cope with a factor 10 more events at the output of the HLT. The upgraded detector will be able to collect at least 5 fb^{-1} per year, running at a luminosity of $1\text{-}2\times10^{33}$ cm^{-2}s^{-1}. If one considers the increase in trigger efficiency for the hadronic channels, this will result in a yield of events at least ten times greater than the present experiment.

MACHINE RELATED ISSUES

Target Absorber for Secondaries (TAS)

The high luminosity insertions at IP1 and IP5 are equipped with a TAS and a TAN to protect the triplet quadrupole magnets and other machine elements from charged and neutral particles leaving the IP. This raises the question whether the envisaged luminosity increase to 2×10^{33} cm^{-2}s^{-1} would require a TAS and a TAN also in IP8. In order to answer this question a good knowledge of beam loss monitor (BLM) thresholds around IP8 is important and detailed FLUKA simulations are needed.

To get a first estimation for the expected background at higher luminosities, the beam losses up- and down-stream of IP8 have been monitored for fill 2242, taken on October 23 and 24, 2011, with beams colliding at center-of-mass energy of 7 TeV. For several hours during this fill

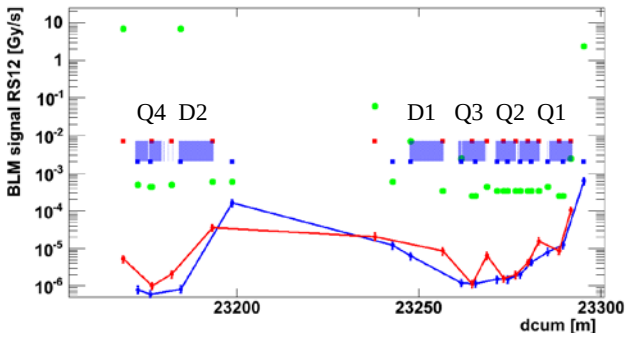

Figure 3: Average loss rate during 5 hours of fill 2242. Shown are the BLM signals for beam 1 (blue) and beam 2 (red) over 150m left of IP8, together with the dump threshold (green).

the luminosity in LHCb was 4×10^{32} cm^{-2}s^{-1}. The losses measured with the BLMs follow precisely the delivered luminosity, as expected. Figure 3 shows the average Running Sum 12 (RS12, taken over 84s) for 15 BLMs left of IR8. The signal has been averaged over the 5 hours when the luminosity in LHCb has been 4×10^{32} cm^{-2}s^{-1}. The figure shows that the measured BLM signals are in general about 100 times below the dump threshold*, which is at present at about 30% of the quench limit [4]. In order to compare this with the situation expected at the time of the LHCb upgrade, the following factors have to be taken into account:

- The beam energy has been a factor 2 less than the LHC design energy of 7 TeV. A first (conservative) approximation sows that the deposited energy per proton scales with the beam energy [5];
- Going from 3.5 to 7 TeV beam energy, the quench limit will decrease by a factor of 4.5 due to the larger current in the magnets [6];
- The luminosity has been a factor 5 below the maximum luminosity for the LHCb upgrade;
- A factor 4 is needed to take into account the difference between $\mathcal{L}_{peak}$ and $\mathcal{L}_{Level}$ [7]. This is mainly for machine protection.

The product of these correction factors (180) is nearly two times higher than above the ratio of 100 between the measured losses and the dump threshold. This is a first indication that some additional protection for the triplets and the superconducting magnet D1 in IP8 would be needed. A careful study of BLM thresholds and the quench limit, which is strongly dependent on the duration of the beam loss process, is important to arrive at a firm conclusion on this issue.

Radiation to Electronics (R2E)

Higher luminosity implies higher radiation levels. The relocation of some equipment has therefore been foreseen already in LS1 [8]. More simulations are ongoing to

* The BLM at 23200m is installed very close to the beam-line to protect the TCTH from beam 1 losses and gives a signal less than 10 below the dump threshold.

determine whether other equipment needs to be mitigated for the proposed upgrade scenario. Should this become necessary, the cable length needs to be checked and, if needed, corrective measures have to be taken. In this context the safe room for electronics needs also to be reviewed as the presently installed shielding might become insufficient. The latter is especially important once the EN/EL equipment inside the safe room is going to be changed for a more recent technology (thus likely to be more radiation sensitive).

β in IP8 for the upgrade*

The beam parameters foreseen for the HL-LHC with 25ns bunch spacing operation are as follows [7]:

- bunch intensity: $N_{b,max} = 2.2 \times 10^{11}$;
- transverse beam emittance: $\varepsilon_{n,col} \geq 2.4$ μm ;
- fill length: about 8 hours.

In order to maintain luminosities of 2×10^{33} $cm^{-2}s^{-1}$ at IP8 throughout the fill, the virtual luminosity at the beginning of the fill has to be 4 times larger. Such luminosities can only be obtained if the β* in IP8 would be about 3.5m. In the context of the ATS (Achromatic-Telescopic Squeezing) optics [9], the matching quadrupoles of IR8 are strongly sollicitated to get to β* values as low as 0.1m at IP1. Studies are ongoing to find ATS optics compatible with the LHCb upgrade requirement.

Crossing angle in IP8

The measurement of *CP* asymmetries done with LHCb requires a very good control of systematic uncertainties. It is therefore of particular importance that equal amounts of data are taken with the two spectrometer polarities. In case of 25 ns bunch spacing, as required for the upgrade, this is only possible if the *external* crossing angle is in the vertical plane [10]. Moreover, since the *internal* crossing angle due to the LHCb spectrometer magnet is in the horizontal plane, a configuration with the external crossing angle in the vertical plane has the advantage that the external crossing angle would be decoupled from the dipole polarity. As a consequence the *effective* crossing angle for both magnet polarities would have the same absolute value and would be in a tilted plane.

With an external crossing angle in the horizontal plane and a beam energy of 3.5 TeV, as was the case during 2011, the effective crossing angle for one polarity (down, +) has been 1040 μrad, while it was only 40 μrad for the other polarity (up, -). The very small crossing angle leads sometimes to parasitic encounters, which should be avoided.

The implementation of the external vertical crossing has therefore been suggested already for this year. However, due to the orientation of the beam screen in the inner triplet, an external vertical crossing angle already at injection has very little aperture. It has therefore been suggested to change the crossing plane only at the end of squeeze. In order to simplify this for the long term future it would be important that the beam screen in the inner triplet is rotated.

SUMMARY

LHCb submitted a Letter of Intent to the LHCC in March 2011 and has a firm plan to upgrade the detector by 2018. The LHCC considers the physics case compelling and the 40 MHz readout as the right upgrade strategy. Therefore the LHCC encouraged LHCb to prepare a TDR as soon as possible.

Given its forward geometry, its excellent tracking and PID capabilities and the foreseen flexible software trigger, the upgraded LHCb detector is an ideal detector for the next generation of flavour physics experiments and provides unique and complementary possibilities for New Physics studies. LHCb intends to run for about 10 years after the upgrade and relies on 25 ns LHC operation, luminosity levelling and equal amounts of data for the two spectrometer magnet polarities.

First discussions with the machine in relation to the upgrade have taken place and we intend to continue them in view of the TDRs under preparation.

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