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The LHCb trigger system

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ABSTRACT: The LHCb experiment is dedicated to the study of particles containing *b* or *c* quarks at the LHC. The LHCb trigger system plays a key role in selecting signal events and rejecting background. It consists of two stages: a hardware trigger followed by a high-level trigger implemented in software. The majority of the work is performed by the high level trigger. With its flexible design, the LHCb trigger can quickly adapt to changing running conditions and has performed far beyond its design in terms of signal efficiencies. The trigger system showcases a number of pioneering concepts, among them the use of multivariate classifiers to identify b-hadrons and the buffering of events to local disks and their processing at a later time, when the LHC is not producing collisions. The design of the trigger system, its performance during 2011/2012 and improvements for data taking in 2015 are discussed. The redesign of the trigger system for the upgrade of the LHCb experiment in 2018 is outlined.

KEYWORDS: Trigger concepts and systems (hardware and software); Online farms and online filtering; Data acquisition concepts

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Contents

1 Introduction

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector layout is shown in figure 1. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter (IP) resolution of 20 µm for tracks with large transverse momentum. Different types of charged hadrons are distinguished by information from two ring-imaging Cherenkov (RICH) detectors. Photon, electron and hadron candidates are identified by a calorimeter system consist- ing of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The LHCb detector was originally designed to be operated at an instantaneous luminosity of $L = 2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. During the running period of 2011 and 2012 data were taken with twice the design value, $L = 4\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which was possible thanks to the excellent performance of both the detector hardware and the reconstruction software. These running conditions correspond to an average number of visible interactions per bunch crossing of $\mu = 1.6$. Data taking after the current shutdown (LS1) is expected to restart in 2015 with an increased beam energy of $\sqrt{s} = 13\,\mathrm{TeV}$. For the LHCb upgrade it is planned to run at a higher luminosity of $1-2\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with an upgraded detector [2–4].

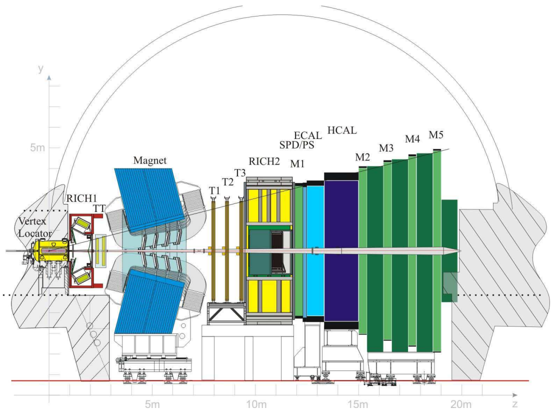

Figure 1: Layout of the LHCb detector.

Key signatures for the selection of heavy flavour decays will be discussed first. The design of the LHCb trigger system and its performance during the years 2011 and 2012 will be presented afterwards. Finally, the plans for the trigger system for the time after LS1 and the LHCb upgrade will be discussed.

2 Heavy flavour decay signatures

The LHCb experiment performs precision measurements of heavy flavour decays. These are copiously produced at the LHC, the production cross sections in the LHCb acceptance for $b\bar{b}$ and $c\bar{c}$ quark pairs are $\sigma_{b\bar{b}} = (75.3 \pm 14.1)$ µb [5] and $\sigma_{c\bar{c}} = (1419 \pm 134)$ µb [6], respectively. Hadrons containing b or c quarks have:

- large lifetimes: $\tau(B^+) = (1.641 \pm 0.008)$ ps and $\tau\left(D^0\right) = (0.410 \pm 0.002)$ ps [7]. This results in flight distances much larger than the IP resolution of the LHCb experiment;
- a large mass of above $1\,\mathrm{GeV}/\mathrm{c}^2$. As a result the daughter particles carry significant transverse momentum (p_T); and
- several key channels contain muons in their final state, which can be identified with LHCb's muon system.

These properties allow for an efficient selection of heavy flavour decays with excellent suppression of the otherwise overwhelming QCD background from pp interactions. A further constraint for the trigger system arises from the available computing resources for further processing of selected events, this will be detailed below.

3 The LHCb trigger system and its performance

The LHCb trigger system is structured as a two stage system. The level 0 trigger (L0) implemented in hardware, followed by the high level trigger (HLT) implemented in software which runs on a dedicated computing farm consisting of 29 000 cores. A detailed discussion of the trigger system can be found in ref. [8, 9].

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3.1 The L0 trigger

The task of the L0 trigger is to reduce the rate of visible interactions of $\sim 13\,\mathrm{MHz}$ to $1\,\mathrm{MHz}$ at which the LHCb detector can be read out. To achieve this goal a decision has to be reached by the hardware implementation in under $4\,\mu\mathrm{s}$. The L0 decisions are based exclusively on information from the muon system and calorimeters, as these are the only pieces of information available at such a high rate. Events with either high p_{T} muons or large transverse energy deposits in the calorimeter are selected by L0.

The muon trigger selects events containing either a single muon with $p_{\mathrm{T}} > 1.76\,\mathrm{GeV/c}$ or a pair of muons with $p_{\mathrm{T},1} \times p_{\mathrm{T},2} > (1.6\,\mathrm{GeV/c})^2$. The relative momentum resolution for muons reconstructed using exclusively information from the muon chambers is 20%. The output rate of the L0 muon triggers is about 400 kHz.

The hadron trigger selects events in which a significant amount of transverse energy ($E_{\mathrm{T}} > 3.68\,\mathrm{GeV}$) is deposited in the hadronic calorimeter. Electrons and photons trigger the event selection by a deposit of $E_{\mathrm{T}} > 3\,\mathrm{GeV}$ in the electromagnetic calorimeter. The output rates of the hadron and electromagnetic triggers are 450 kHz and 150 kHz, respectively.

The efficiency of the L0 requirements described above strongly depend on the decay channel:

- For B decays to two muons, the L0 muon requirements are typically more than 90% efficient.
- The efficiency of the L0 hadron trigger for fully hadronic decay modes varies from $\sim 60\%$ for $B^0 \to h^+h^-$ decays to $20-30\%$ for charm decays. Charm decays typically have lower efficiencies due to the lower mass of the charmed hadrons compared to a B hadron.
- The L0 photon/electron requirements are more than 80% efficient for radiative decays B decays, such as $B \to K^{*0}\gamma$.

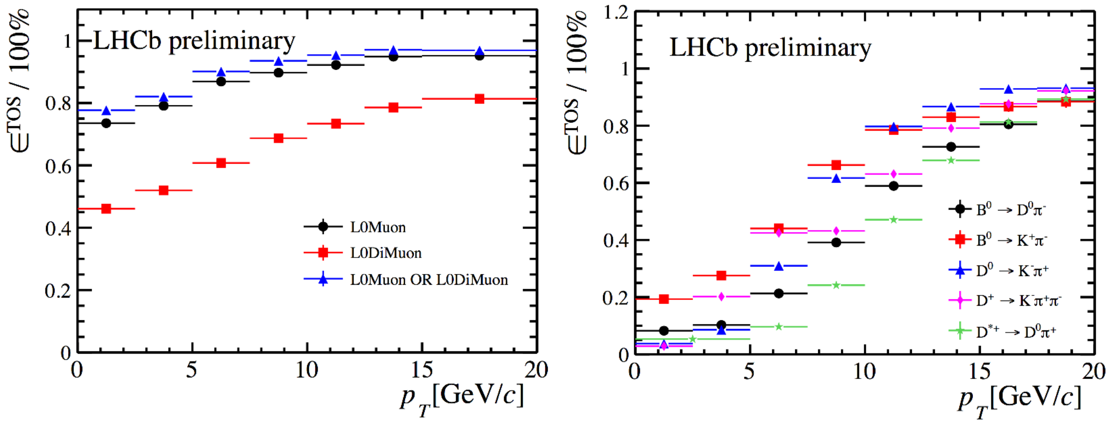
The L0 hadron and muon efficiencies are shown in figure 2.

3.2 First stage of the HLT

The first stage of the HLT (HLT1) performs a partial event reconstruction in order to reduce the event rate from 1 MHz to $\sim 70\,\mathrm{kHz}$ in 2012. Only a partial event reconstruction is possible due to the available computing power. The partial reconstruction performs the following steps:

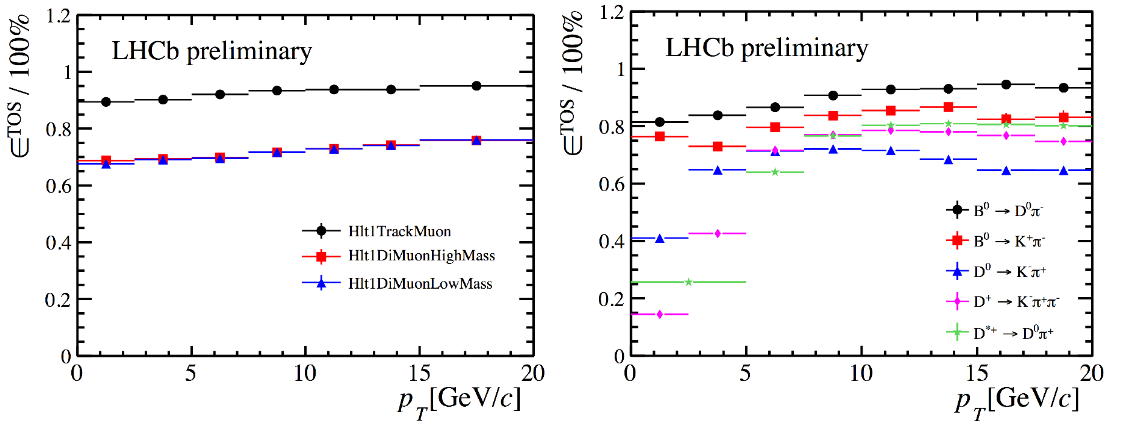
1. Track segments are reconstructed in the vertex locator (VELO),
2. track segments that either have a large IP or can be matched to hits in the muon chambers are extrapolated into the main tracker,
3. the selected track segments are extended in the tracking stations, by searching for hits consistent with a high p_{T} track.

If a good quality track with a $p_{\mathrm{T}} > 1.6\,\mathrm{GeV/c}$ ($1\,\mathrm{GeV/c}$ for muon and $0.5\,\mathrm{GeV/c}$ for dimuon tracks [10]) can be reconstructed the event is accepted and processing continues in the next stage. Figure 3 shows the efficiency of the HLT1 selection criteria as a function of p_{T} for both decays containing muons in the final state and purely hadronic decays.



(a) (b)

Figure 2: L0 efficiencies for data taken during 2012 of (a) L0 muon requirements for $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ and (b) L0 hadron requirements for several fully hadronic decay modes as a function of the parent p_{T}.



(a) (b)

Figure 3: HLT1 efficiencies for data taken during 2012 (a) for the HLT1 muon lines for $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ and (b) the HLT1 lines selecting displaced tracks for several purely hadronic decays.

3.3 Second stage of the HLT

Events selected by HLT1 are passed on to the second stage of the HLT (HLT2). Here all tracks with a minimum p_{T} of 300 MeV/c are reconstructed, independent of their IP or matching hits in the muon chambers. In 2012 HLT2 reduced the event rate further to 5 kHz (3 kHz in 2011) which is written to disk. Several exclusive selections are performed in the HLT. In particular high rate, prompt charm decays require exclusive trigger selections using a narrow invariant mass window. The charm selections accept events at a rate of about 2 kHz. A further example of an exclusive selection in HLT2 is the lifetime unbiased trigger for $B_s \to K^+K^-$ decays.

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The real power of the software based HLT comes to light with the inclusive selections for heavy flavour decays. These inclusive selections contain several lines that trigger on dimoun signatures, both with and without the requirement of separation from the interaction vertex. In 2012 data taking conditions these lines have a total output rate of 1 kHz, yielding an integrated efficiency of the HLT2 for B decays with muons in the final state of above 90 %.

Heavy flavour decays with hadrons in the final state are selected using a multivariate classifier that identifies B decays by constructing two-, three- and four-track vertices [11, 12] achieving efficiencies of over 60 %. This algorithm, known as the "topological trigger", is based on a modified Boosted Decision Tree with discretised input variables [13]. The output rate of the topological trigger is about 2 kHz.

3.4 Deferred trigger

In 2012 the trigger system was improved further by introducing the so-called "deferred trigger". This trigger stores about 20 % of all L0 accepted events on the local disks of the HLT farm nodes. These events are then processed by the HLT during the interfill gaps of the LHC. Using computing resources which would otherwise be idle. This increase in effective computing power means the minimum p_{T} requirement in the HLT2 track reconstruction could be lowered from 500 MeV/c to 300 MeV/c. A more restrictive configuration of HLT1 can be used when the available disk space is exceeded. However, this configuration was never used during data taking in 2012.

4 Developments beyond LS1 and the LHCb upgrade

In 2015, after LS1, the two stages of the HLT will be run asynchronously. This allows the deferral of events after they have been accepted by HLT1. It also gives time to perform a calibration of the particle identification provided by the RICH detectors as well as the tracking detectors. So far the calibration is performed before the offline reconstruction.With calibrated particle identification information already available in the HLT2 it can be used more aggressively, as it is off the same quality and precision as achieved in the offline reconstruction. This new feature will be particularly beneficial for the selection of charmed hadrons as it allows a preferential selection of the doubly Cabbibo suppressed decay $D^0 \to K^+\pi^-$ over the otherwise indistinguishable and more numerous $D^0 \to K^-\pi^+$ decay.

In addition LHCb will be able to profit from a larger trigger farm. This increase in computing resources makes it possible to record ~ 12.5 kHz of events to disk.

The upgraded LHCb detector will be installed by 2019 and data taking will start at an instantaneous luminosity of $L = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Under these conditions the maximum rate at which the current detector can be readout becomes a bottleneck. In particular for channels with a fully hadronic final state the efficiency is limited to less than 20 %. A major goal of the upgrade is to enable full detector readout at 40 MHz. This constitutes a trigger-less readout and every event will be processed by a fully software based trigger. The first step of the software trigger will be reconstructing all tracks above a minimum p_{T} threshold regardless of IP. Being able to reconstruct all tracks for every event in software maximises the flexibility of the trigger system, allowing for a fast response to changing demands dictated by an ambitious physics programme. The details of the proposed trigger system can be found in recently published TDR [14].

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5 Conclusions

During the data taking periods of 2011 and 2012 the LHCb trigger system has been performing extremely well. The flexible design of the software HLT allowed LHCb to quickly adapt to different running conditions and to trigger on signatures that had originally not been considered.

The total trigger efficiency for B decays is high: dimuon modes can be triggered with around 90 % efficiency, and typical trigger efficiencies for hadronic modes are larger than 60 %. Innovative concepts like the deferred trigger and use of multivariate classifiers in the trigger have play a large role in achieving this outstanding performance.

When data taking resumes in 2015 the trigger will have access to offline quality particle identification information, further reducing differences between trigger and analysis selections as well as separating otherwise indistinguishable final states.

For the LHCb upgrade the experiment will operate in a trigger-less mode. Every event will be readout and processed by a HLT implemented fully in software. This approach, pioneered by LHCb, guarantees maximum flexibility and power in delivering a highly efficient trigger for the LHCb physics programme.

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