The LHCb Trigger System: performance and outlook

Abstract

The trigger of the LHCb experiment consists of two stages : an initial hardware trigger, and a high-level trigger implemented in a farm of CPUs. It reduces the event rate from an input of 15 MHz to around 5 kHz. To maximize efficiencies and minimize biases, the trigger is designed around inclusive selection algorithms, culminating in a novel boosted decision tree which enables the efficient selection of beauty hadron decays based on a robust partial reconstruction of their decay products. In order to improve performance, the LHCb upgrade aims to significantly increase the rate at which the detector will be read out, and hence shift more of the workload onto the high-level trigger. It is demonstrated that the current high-level trigger architecture will be able to meet this challenge, and the expected efficiencies in several key channels are discussed in context of the LHCb upgrade.

Key words: Trigger systems, Multivariate Selections, Flavour Physics, LHC
PACS: 07.05.Hd, 02.50.Sk, 13.20.He, 13.20.Fc

1. Introduction

The LHCb detector [1] is a single-arm forward spectrometer designed for studing beauty and charm (heavy flavour) hadrons produced in proton-proton collisions at the Large Hadron Collider (LHC) at CERN.

Although designed for a luminosity of $2{\cdot}10^{32}$ cm^{-2}s^{-1}, LHCb took data at an average luminosity of $2.8{\cdot}10^{32}$ cm^{-2}s^{-1} throughout 2011 and at $4 \cdot 10^{32}$ cm^{-2}s^{-1} during 2012. The latter corresponds to an average of 1.7 proton-proton collisions per bunch crossing. The LHCb upgrade is planned to run at a luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} but with a 25 ns LHC bunch spacing instead of the current 50 ns. This implies an increase in the average number of proton-proton collisions per bunch crossing to around 7. Furthermore the centre-of-mass energy will increase from the current 8 TeV to 14 TeV, but this is expected to have only a modest effect on the particle multiplicity. As a result the current running conditions can be extrapolated to predict the performance of an upgraded detector.

2. The LHC environment

As the goal of a trigger is to accept interesting events, and reject others, it is important to understand the properties and production cross-sections of various kinds of processes at the LHC. The mass of beauty and charm hadrons is transformed into transverse momentum of their decay products, and the O(ps) lifetimes of beauty and charm hadrons ensure that their decay products form vertices detached from the proton-proton interaction. A beauty or charm hadron produced at the LHC has a decay length of around 1 cm per mean lifetime, greater than the impact parameter resolution of 20 μm.

The most important consideration is the ratio of prompt charm to prompt beauty production, which is measured to be around 20 at 7 TeV. This is critical, as even though charm hadrons are lighter and shorter-lived than beauty hadrons, they nevertheless produced detached vertices and decay products with substantial transverse momentum. and are thus the most challenging backgrounds for beauty hadron triggers. Just as importantly, charm hadrons are interesting to study in their own right, and should be triggered as efficiently as possible within the available output bandwidth. It follows that good separation between charm and beauty hadron decays is mandatory, whilst maintaining high efficiency for dimuon final states, and generic heavy, long-lived objects to allow the discovery of potential new particles produced at the LHC.

3. Performance of the current LHCb trigger

The LHC proton-proton collision rate of 15 MHz must be reduced by the data acquisition system (trigger) to a few kHz. The trigger consists of a hardware (L0) and a software (HLT) stage [2]. The L0 must reduce the interaction rate to at most 1 MHz, the rate at which LHCb's detectors can be read out. L0 is implemented in hardware and has a fixed latency of 4 μs. It makes decisions based on energy deposits in the calorimeter system and track stubs in the muon detectors. The HLT is implemented in a software farm of around 30000 (logical) cores, giving it, on average, 30 ms in which to process an event.

The L0 performance varies according to the nature of the event. For decays involving multiple muons in the final state, whether of beauty or charm hadrons, L0 is > 90% efficient with respect to offline selected events. This is mainly because muons are rarely produced directly, so just identifying a muon is already a powerful discriminant. For beauty decays involving a single muon, L0 maintains > 70% efficiency. For decays involving photons, typically a high transverse energy photon is required. This requirement can be imposed within L0, maintaining > 90% efficiency. Finally, for purely hadronic decays, L0 has efficiencies of O(10%) for charm decays and O(20%) for beauty meson decays. This is mainly because of the higher

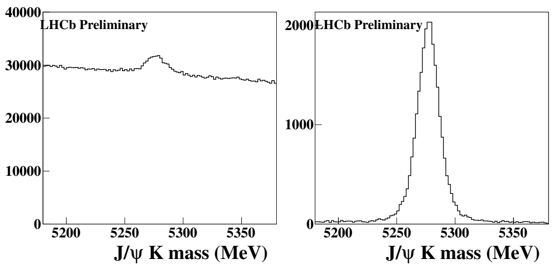

Figure 1: Candidate $B^+ \to J/\psi K^+$ decays from data collected in 2011 by LHCb. On the left, selected using dimuon triggers only. On the right, the subset of the same events which fire the topological trigger. Reproduced from [6].

backgrounds which require tighter transverse energy requirements.

The performance of the L0 depends strongly on the instantaneous luminosity. Whereas the signal yield for muons, where L0 is best able to discriminate between signal and background, increases linearly with luminosity, it plateaus for other kinds of decays, due to the requirement that the L0 output rate can not exceed 1 MHz.

The L0 output of 1 MHz of events, of which around 10% actually contain a charm or beauty hadron, is processed by the HLT. It starts with the reconstruction of tracks and primary vertices in the vertex detector. Next, two types of tracks are identified : those detached from the primary interaction, and those matched to segments in the muon detectors. These tracks are extrapolated to the main tracking system, enabling the determination of their (transverse) momentum. Event are selected if they contains either a high p_T detached track, a single detached muon track, a detached dimuon candidate, or a dimuon candidate near or above the J/ψ meson mass. This reduces the rate to around 50 kHz, and takes around half the time available, almost independent of the number of interactions per event. It is $> 80\%$ efficient on any beauty hadron decay involving multiple charged particles, and around 50% efficient on key charm hadron decay modes[3, 4].

The second HLT stage performs three major kinds of selections : firstly, it searches for charmed hadrons produced in the primary interaction decaying into a variety of exclusive modes; secondly, it searches for inclusive di- and multi-muon signals; thirdly, it performs an inclusive search for two-, three-, and four-charged particle detached vertices consistent with the decay of a beauty hadron [5, 6]. The inclusive selection of these vertices is based around a seven-variable bagged boosted decision tree [7] algorithm known as the "topological trigger", whose input variables are discretized according to their resolution. This discretization protects against overtraining, and makes the algorithm sufficiently fast for use in a trigger . The topological trigger is $> 75\%$ efficient on generic B decays into charged particles, while suppressing almost all events not containing a B hadron. This is illustrated in Fig. 1.

4. The LHCb trigger upgrade

The current LHCb running conditions closely resemble the nominal upgrade running conditions in terms of the detector occupancy. Since the trigger timing is relatively insensitive to the average number of interactions, the current HLT design is expected to perform its job in the upgrade era, provided the available computing power scales to the higher input rate. As the LHC upgrade is scheduled to begin taking data in 2018, Moore's law implies than an input rate ten times higher than the current one should be achievable [8]. A rate of 10 MHz into the HLT is therefore taken as the working point.

Table 1: HLT signal efficiency for some key channels in two upgrade scenarios.

HLT input/output rate	5 MHz / 16 kHz	10 MHz / 26 kHz
$B_s^0 \to \phi\phi$	29%	50%
$B_s^0 \to \phi\gamma$	43%	53%
$B_d^0 \to K^{*0}\mu\mu$	75%	85%

Performance studies for the upgrade have been performed with simulated events generated in the LHCb simulation, assuming 14 TeV centre-of-mass energy and an instantaneous luminosity of $2 \cdot 10^{32}$ cm^{2}s^{-1}. Table 1 shows the expected rate and signal efficiency of the upgraded detector in some key modes, both for the nominal configuration and a more pessimistic scenario in which the HLT input rate is 5 MHz. The later will collect almost ten times more signal events per second of LHC running because of the twice higher cross section for producing B hadrons and 5 times higher instantaneous luminosity compared to 2012 datataking. In the former, hadronic modes gain almost another factor two.

5. Conclusions

The LHCb experiment is currently taking data at twice its nominal instantaneous luminosity at the LHC. The maximum instantanous luminosity at which the detector can be usefully operated is largely limited by the performance of the hardware trigger, which becomes inefficient for hadronic decay modes at high luminosities owing to limited background discriminants available to it. For this reason the LHCb upgrade aims to increase the detector readout rate from 1 MHz to 40 MHz, allowing more of the work to be performed within the software trigger.

References

[1] LHCb Collaboration (A. Alves et al.), The LHCb Detector at the LHC, JINST, 3:S08005 (2008).

[2] R. Aaij et al., The LHCb trigger and its performance in 2011, JINST, 8:P04022 (2013).

[3] V. V. Gligorov, A Single Track HLT1 Trigger, LHCb-PUB-2011-003 (2011).

[4] J. Albrecht and R. Aaij, Muon triggers in the High Level Trigger of LHCb, LHCb-PUB-2011-017 (2011).

[5] M. Williams et al., The HLT2 Topological Lines, LHCb-PUB-2011-002 (2011).

[6] V. V. Gligorov, C. Thomas, and M. Williams, The HLT inclusive B triggers, LHCb-PUB-2011-016 (2011).

[7] L. Breiman, Bagging Predictors, Machine Learning 24, 123-140 (1996); 553-568 (1997).

[8] LHCb Collaboration (R. Aaij et al.), Letter of Intent for the LHCb Upgrade, CERN-LHCC-2011-001 (2011).