LHCb Note 2006-065
TRIGGER

The LHCb Trigger System

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December 2006, revised January 2007

Abstract

The LHCb detector has been conceived to study with high precision CP violation and rare decays of b-flavoured hadrons produced at the LHC. The LHCb trigger is of crucial importance in selecting the collisions of interest for b-physics studies. The trigger is based on a two-level system. The first level, Level-0, is implemented in hardware and uses information from the calorimeter, muon and pile-up systems to select events containing particles with relatively large transverse momentum, typically above 1-2 GeV. The Level-0 trigger accepts events at a rate of 1 MHz. All the detector information is then read out and fed into the High Level Trigger. This software trigger runs in the event-filter farm composed of about 1800 CPU nodes. Events are selected at a rate of 2 kHz and sent for mass storage and subsequent offline reconstruction and analysis. The current status and expected performance of the trigger system are described.

[1]Presented at Beauty 2006, 11^{th} International Conference on B-Physics at Hadron Machines Keble College, University of Oxford (UK), 25-29 September 2006

1 TRIGGER STRATEGY

Bottom quarks will be copiously produced at the Large Hadron Collider (LHC). The LHCb experiment is a single-arm spectrometer [1] and is designed to study with high precision CP violation phenomena and rare decays of b-flavoured hadrons produced at the LHC.

LHCb will operate at a luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, about fifty times less than the LHC design luminosity. The LHC bunches cross at a rate of 40 MHz. At the lower operating luminosity, the LHCb spectrometer will have only 10 MHz of crossings with "visible interactions", defined as interactions that produce at least two charged particles with sufficient hits to be reconstructed in the spectrometer. Of the 10 MHz of visible interactions, about 100 kHz of $b\bar{b}$ pairs are expected given that the $b\bar{b}$-production cross section is less than 1% of the total inelastic pp cross section, expected to be ~100 mb at a centre-of-mass energy of 14 TeV. Furthermore, the b decays of interest have branching ratios that are typically below 10^{-4}.

The LHCb trigger [2] is of crucial importance in selecting amongst the collisions those that are of interest for b-physics studies. The trigger is based on a two-level system and exploits the fact that b-flavoured hadrons are heavy and long-lived. The first level, Level-0, is implemented in hardware. Its main goal is to select high transverse energy, E_T, particles using partial detector information. The Level-0 trigger reduces a rate of 10 MHz of crossings with at least one visible interaction to an output rate of 1 MHz.

After a Level-0 accept, all the detector information is then read out and fed into the High Level Trigger (HLT). This software trigger runs in the event-filter farm composed of about 1800 CPU nodes. Algorithms separated in dedicated trigger selections exploit the Level-0 triggering information and refine the selection using both the high transverse momenta and large impact parameters characteristic of B-decay products. From the HLT, events are selected at a rate of 2 kHz and sent for mass storage and subsequent offline reconstruction and analysis.

2 THE LEVEL-0 TRIGGER

The main goal of the Level-0 is three-fold:

- to select high E_T particles: hadrons, electrons, photons, neutral pions and muons;
- to reject complex/busy events which are more difficult, and take longer, to reconstruct;
- to reject beam-halo events.

The Level-0 is a hardware trigger which uses information from the calorimeter system, the muon chambers and the so-called "pile-up" system. The Level-0 decision unit (L0DU) combines the output from these three components and issues the final trigger decision. The sub-systems which provide the Level-0 trigger candidates for the L0DU will be described briefly below.

The rejection of uninteresting events for B-physics analyses is achieved with a series of cuts on global event variables, also presented below. Dedicated thresholds are applied to the particle candidates of the various categories to select those with a high transverse momentum.

2.1 The pile-up veto system

The pile-up veto system is a component of the Vertex Locator (VELO) [3] and is made of two silicon planes, positioned upstream (with respect to the spectrometer) of the nominal interaction point. The pile-up veto provides rejection by identifying bunch crossings with multiple primary vertices. Two-interaction crossings are identified with an efficiency of 60% and a purity of about 95%.

The output of the pile-up system to the L0DU consists of two global event variables: the number of tracks from the second vertex and the pile-up system hit multiplicity.

2.2 The Level-0 calorimeter trigger

The calorimeter system [4] comprises a Scintillating Pad Detector (SPD), a Pre-shower (Prs), followed by Electromagnetic (ECAL) and Hadronic (HCAL) Calorimeters. The calorimeter elements are based on scintillating tiles, read out to photomultipliers via wavelength-shifting fibres. The scintillator is interleaved with lead for the ECAL in a Shashlik construction, and interleaved with iron tiles for the HCAL.

The calorimeter system provides candidate hadrons, electrons, photons and neutral pions. The (transverse) energy is measured in the ECAL and HCAL from the energy deposits in 2x2 (cluster) cells. The SPD and Prs help, respectively, in identifying the charged and electromagnetic nature of the clusters.

The calorimeter system outputs to the L0DU the highest-E_T hadron, electron, photon and π^0 candidates, and the total HCAL E_T and SPD multiplicity.

2.3 The level-0 muon trigger

The muon system [5] consists of five measuring stations equipped with Multi-Wire Proportional Chambers (MWPCs) separated by iron filters. For the innermost region of the first muon station, where the rate will be higher, triple-GEM detectors are used.

Muon candidates are searched for in each of the four quadrants of the stations. A momentum precision of $\sigma_p/p \approx 20\%$ is achieved by the Level-0 processor, assuming all muons originate from the primary vertex. The two highest-p_T muon candidates from each quadrant are sent to the L0DU.

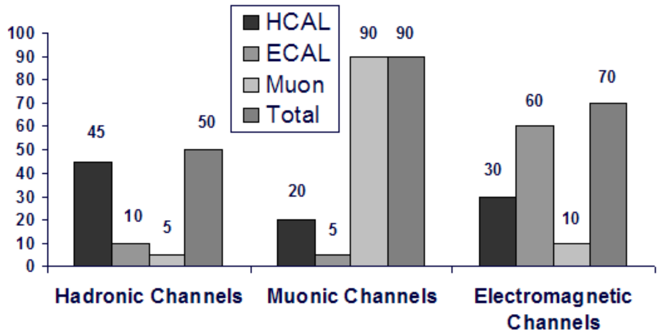

Figure 1: Typical Level-0 efficiencies for hadronic, muonic and electromagnetic B-decay channels (see the text for details).

2.4 The Level-0 performance

The performance of the Level-0 trigger is summarised in Fig. 1 in terms of Level-0 efficiencies for so-called "offline-selected events". These efficiencies are defined with respect to "reconstructable" B-events, $i.e.$ those that would in principle pass the offline B-selection algorithm used for physics analyses. Figure 1 shows typical Level-0 efficiencies (denoted by "Total") for hadronic B-decay channels such as $B^0 \to \pi^+\pi^-$ and $B_s^0 \to D_s^-\pi^+$, muonic B-decay channels such as $B_s^0 \to J/\psi(\mu^+\mu^-)K_S^0$ and $B^0 \to K^*\mu^+\mu^-$, and electromagnetic B-decay channels such as $B^0 \to K^*\gamma$ and $B_s^0 \to J/\psi(e^+e^-)K_S^0$, respectively. The Level-0 efficiencies for the hadronic, muonic and electromagnetic channels are typically of the order of 50%, 90% and 70%, respectively. Figure 1 also presents the inclusive efficiencies when one triggers solely with information from either the hadronic calorimeter ("HCAL"), the electromagnetic calorimeter ("CAL") or the muon chambers ("MUON").

2.5 Hardware status

The commissioning of individual components of the Level-0 will start in early 2007. The first partial system tests are foreseen for February 2007. The total system is planned to be installed before the LHC pilot run at the end of 2007.

3 THE HIGH LEVEL TRIGGER

All Level-0 accepted events are passed on to the HLT at a maximum average rate of 1 MHz. The full detector information is read out into an "event-filter farm" comprising of order 1800 nodes divided in sub-farms. The event-filter farm involves a large network with a data throughput of about 50 GBytes/s [6]. The design is scalable, allowing for a straightforward upgrade. The present size estimate comes from a real-time trigger challenge that took place in 2005 to test under realistic data-taking conditions the online environment.

In the farm the subsequent trigger decisions are taken by software, to reduce the rate of events sent for mass storage to 2 kHz. The average event size has been estimated to be about 30 kBytes.

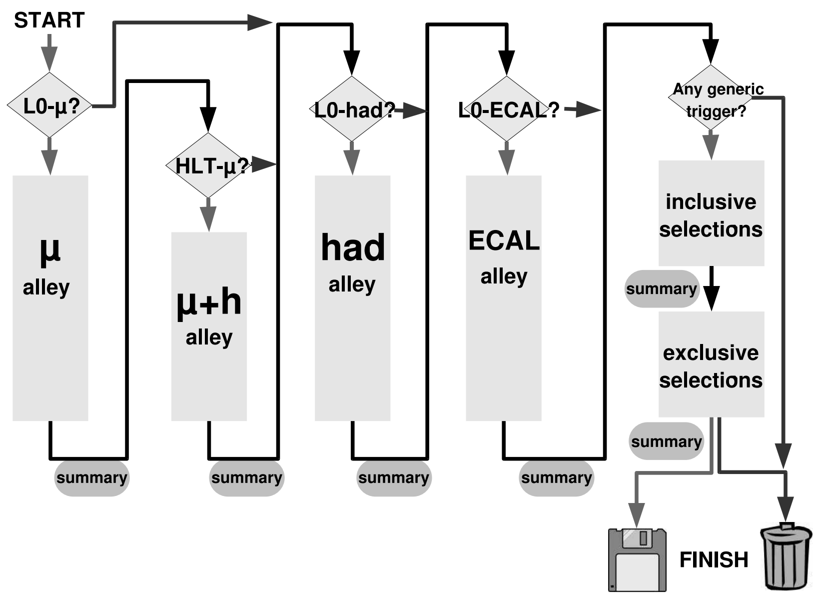

Figure 2: The High Level Trigger flow-chart.

3.1 The concept of trigger alleys

The HLT is based on the concept of independent "trigger alleys", a set of dedicated streams that exploit and refine the Level-0 triggering information. The HLT features a muon stream, a muon and hadron stream, and hadronic and electromagnetic streams. Each of these can be triggered to run depending on the Level-0 trigger decision and the Level-0 selected candidates. The sequence also includes both inclusive and exclusive selections, and a classification of interesting physics events. A pictorial representation of the alleys is given in Fig. 2.

In the trigger alleys, a partial event reconstruction is first performed. During this partial reconstruction, a few tracks are selected per alley based on their transverse momentum and impact parameter (with respect to the primary vertex). The full reconstruction is done solely at the end of the streams, after a significant decrease of the event rate. A large fraction of the time budget is spent on the track and vertex reconstruction.

Both the tracking and the vertexing achieve a precision comparable to what is later obtained offline. As an example, a momentum precision close to $\sigma_p/p \approx 1\%$ is obtained for "long" tracks traversing the whole tracking system; for comparison the offline precision is $\sigma_p/p \approx 0.4\%$.

3.2 The hadron alley

The hadron alley is executed if a Level-0 hadron candidate triggered Level-0. In a first "pre-trigger" stage, straight-line tracks from the vertex detector ("VELO tracks") are reconstructed and selected if their impact parameter satisfies $IP > 150\,\mu\mathrm{m}$. The primary vertex is reconstructed with a precision of $\sigma_z \sim 60\,\mu\mathrm{m}$ along the beam direction and of $\sigma_{x,y} \sim 20\,\mu\mathrm{m}$ perpendicular to the beam direction. A rough estimate of the momentum of these tracks is obtained with the addition of hits from the first downstream tracking station, the Trigger Tracker (TT) [7]. For a single hadron, a cut on the transverse momentum of $p_T > 2.5$ GeV is applied; this cut is somewhat relaxed in presence of two hadrons. These cuts ensure a b purity of $\sim 14\%$ for a hadronic B-decay efficiency of around 80%.

In a second stage, two-track vertices are formed from track pairs with a distance of closest approach of less than $200\,\mu$m. The selection of those vertices compatible with the decay of a (secondary) particle coming from the primary vertex enriches the b-sample to a purity of about 50%.

The hadron alley triggers events at a rate of ~ 4 kHz.

3.3 The muon alley

As described in Section 2.3, the stand-alone muon reconstruction in the muon stations gives only a coarse momentum estimate at Level-0, $\sigma_p/p \approx 20\%$. At the pre-trigger stage of the muon alley, the matching of the VELO tracks with these muon seeds improves the momentum resolution by a factor four. Those selected muons pass on to the second stage. Here further inclusion of hits from the most downstream tracking stations improves the momentum resolution to $\sigma_p/p \approx 1\%$, also refining the quality of the muon identification by matching these long tracks with the muon seeds.

If two muon candidates are found with an invariant mass above 2.5 GeV (no impact parameter cut applied) the event passes the HLT and is sent to storage. If the invariant mass is above 0.5 GeV and the impact parameter satisfies $|IP| > 100\,\mu\mathrm{m}$, the event also triggers the HLT. Events with a single muon can also pass the muon alley if $p_T > 3.0$ GeV and the impact parameter significance $IP/\sigma_{IP} > 3\sigma$.

Overall the muon alley triggers events at a rate of ~ 1.5 kHz.

3.4 The muon and hadron alley

The muon and hadron alley is run when the Level-0 has been triggered by a muon (or di-muon) candidate but the HLT muon did not pass the HLT muon alley. The strategy is here to select events with a muon and a hadron track with a high impact parameter and relatively high p_T, when the muon does not have enough p_T and impact parameter to trigger the muon alley by itself. It is hoped to achieve a b purity around $50 - 60\%$ for a HLT rate of the order of $2 - 5$ kHz.

3.5 The electromagnetic alley

Level-0 provides of order 200 kHz of events triggered by candidates from the electromagnetic calorimeter trigger. These Level-0 electron and photon candidates are first confirmed in the pre-trigger stage of the electromagnetic alley. For the electron, a track with impact parameter is also required to match the Level-0 candidate. For the photon candidate, it is foreseen to demand in addition the existence in the event of a high-p_T hadron with a large impact parameter with respect to the primary vertex.

This electromagnetic alley is designed to boost the efficiency of decay channels such as $B^0 \to K^*\gamma$. The complete strategy is currently being finalized.

3.6 The inclusive selections

A full tracking reconstruction is performed for all inclusive selections at a few kHz. Common inclusive selections are the D_s, D^*, ϕ and muon selections.

The D^* inclusive selection, for example, provides a very high statistics sample of $D^{*+} \to D^0(K^-\pi^+)\pi^+$ events. It is foreseen that this hadronic selection will trigger at a rate of a few hundred Hz.

The muon inclusive selection exploits the presence of either a single muon or a pair of muons. In the di-muon case, J/ψ's from a $B \to J/\psi(\mu^+\mu^-)K_s$ decay are reconstructed in the HLT with an invariant mass resolution of 17 MeV [8]. Avoiding a cut on the impact parameter, this selection allows the selection of di-muons with no bias on the lifetime of the parent B meson.

The single-muon inclusive selection provides a high purity (around 70%) $B \to \mu X$ sample that can serve to study the LHCb tagging performance.

3.7 The exclusive selections

At the end of the HLT sequence, a few exclusive B-decay selections are also run, exploiting selected particles (e.g. D_s, D^0, K^*, etc.) made available previously by the other alleys. Wide mass-window cuts ∼500 MeV are typically applied. These exclusive selections obtain efficiencies of approximately 90% for an output rate of order 200 Hz.

4 OUTLOOK

The current status and expected performance of the LHCb trigger system has been presented. The strategy for the Level-0 trigger is well defined and is flexible and robust, with a built-in redundancy. It shows good performance for the LHCb B-physics program. The production, installation and commissioning of the hardware components is underway. The commissioning of the trigger system will start in early 2007.

The details of the strategy of the High Level Trigger is being finalized. This software trigger is flexible and robust, and highly efficient.

References

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