PROCEEDINGS OF SCIENCE

The LHCb trigger system: performance and outlook

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The LHCb experiment is dedicated to the study of heavy flavour at the LHC. The LHCb trigger system plays a key role in selecting signal events and rejecting background. The bulk of the LHCb trigger is implemented in software and deployed on a farm of 29,000 processor cores. This system, called the high level trigger, is responsible for reducing the event rate from 1 MHz, at which the LHCb detector can be read out, to 5 kHz, which can be written to disk. 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 and 2012 and planned improvements for data taking in 2015 and beyond are discussed.

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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 Fig. 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 detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting 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 $\mathscr{L} = 2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. During the running period of 2011 and 2012 data was taken with twice the design value, $\mathscr{L} = 4\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which was possible thanks to the excellent performance of both the detector hardware and the reconstruction software. These chosen 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 $\sqrt{s} \approx 13\,\mathrm{TeV}$. For the LHCb upgrade it is planned to run at a higher luminosity of $\sim 2\times10^{33}\,\mathrm{cm}^{2}\,\mathrm{s}^{-1}$ with the upgraded LHCb detector [2].

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 future developements of the trigger system for the time after LS1 and the LHCb upgrade will be discussed.

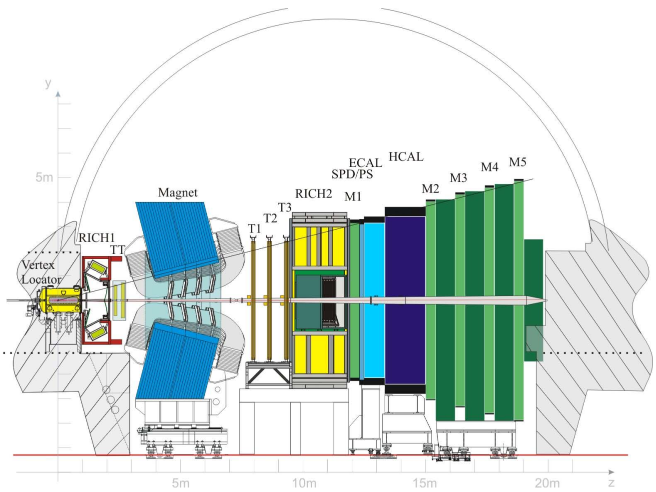

Figure 1: Layout of the LHCb detector.

2. Heavy flavour decays

The LHCb experiment performs precision measurements of heavy flavour decays exploiting the large cross sections for $b\bar{b}$ and $c\bar{c}$ quark production at the LHC: $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\text{b}$ [3] and $\sigma_{c\bar{c}} = (1419 \pm 134)\,\mu\text{b}$ [4] in the LHCb acceptance. Hadrons containing b or c quarks have comparably large lifetimes, *e.g.* $\tau(B^+) = (1.641 \pm 0.008)\,\text{ps}$ and $\tau(D^0) = (0.410 \pm 0.002)\,\text{ps}$ [6]. This results in significant flight distances of $\mathcal{O}(1\,\text{cm})$, much larger than LHCb's IP resolution of $20\,\mu\text{m}$. Because b and c hadrons have masses of $\mathcal{O}(1\,\text{GeV}/c^2)$, the daughter particles of heavy flavour decays additionally carry significant transverse momentum (p_T). Several key channels for the LHCb experiment contain muons in the final state. Examples are the decays $B_s^0 \to \mu^+\mu^-$, $B_s^0 \to J/\psi\,\phi$ and $B^0 \to K^{*0}\mu^+\mu^-$. For the selection of these decays LHCb's muon system is used to provide muon identification.

The trigger system exploits these key signatures to efficiently select heavy flavour decays while suppressing low p_T QCD background from the pp interaction. In this endeavour, it needs to respect the limits of the available computing resources and output bandwidth as will be detailed below.

3. The LHCb Trigger system and its performance

The LHCb trigger is designed as a two stage system comprised of the level 0 trigger (L0) which is implemented in hardware and the high level trigger (HLT). The HLT is implemented in software and runs on a dedicated computing farm consisting of 29,000 cores. A more detailed discussion of the trigger system is given in [5].

3.1 The L0 trigger

The L0 trigger reduces the 40 MHz bunch crossing rate of the LHC to a rate of 1 MHz with which the LHCb detector can be read out. The hardware implementation reaches a decision inside $4\,\mu\text{s}$. It triggers on high p_T muons and large deposited transverse energy (E_T) in the calorimeters. Using only the muon chambers for a reconstruction of the muon momentum, a relative momentum resolution of 20% can be reached. Events containing a single muon with $p_\text{T} > 1.76\,\text{GeV}/c$ or a dimuon object with $p_{\text{T},1}p_{\text{T},2} > (1.6\,\text{GeV}/c)^2$ are selected. The resulting L0 muon rate is 400 kHz. Hadrons are selected if they deposit large E_T in the hadronic calorimeter ($E_\text{T} > 3.68\,\text{GeV}$). Electrons and photons are triggered by significant energy deposition in the electromagnetic calorimeter ($E_\text{T} > 3.0\,\text{GeV}$). The L0 output rates are 450 kHz and 150 kHz for hadrons and electromagnetic objects, respectively. The L0 thresholds are given for data taking in 2012, the values for 2011 are given in [5]. The efficiency of the L0 requirements described above strongly depend on the decay channel.

- For B decays containing two muons in the final state, the L0 muon requirements are typically more than 90% efficient.
- The efficiency of the L0 hadron requirements on fully hadronic decay modes varies from $\sim 60\%$ for $B^0 \to h^+h^-$ decays to $20-30\%$ for charm decays. This is mainly due to the lower mass of charmed hadrons.

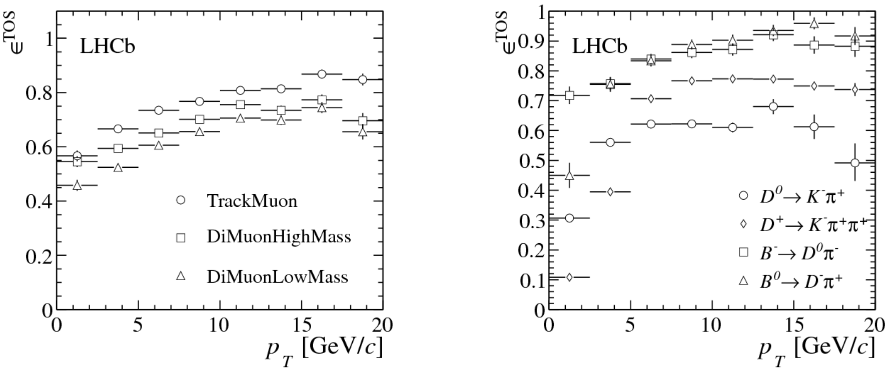

Figure 2: (Left) Efficiency of the HLT1 muon lines for $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ events as a function of p_T. (Right) Efficiency of the HLT1 lines selecting displaced tracks for several purely hadronic decays as a function of p_T. Figure from [5].

- For radiative B decays like $B^0 \to K^{*0}\gamma$ the L0 photon/electron requirement is more than 80% efficient.

3.2 HLT1

The HLT consists of two stages, the HLT1 and the HLT2. The HLT1 performs a partial event reconstruction and reduces the event rate from 1 MHz to $\sim$ 70 kHz (43 kHz in 2011). To this end, the HLT1 reconstructs track segments in LHCb's vertex detector (VELO). High IP track segments and track segments that can be matched with hits in the muon chambers are then extrapolated into the main tracker. If a good quality track with a minimum p_T of $1.6\,\mathrm{GeV}/c$ ($1.0\,\mathrm{GeV}/c$ for muon tracks, $0.5\,\mathrm{GeV}/c$ for dimuon candidates) can be reconstructed, the event is accepted by HLT1. Fig. 2 shows the efficiency of the HLT1 selection criteria, depending on p_T, for both decays containing muons in the final state and purely hadronic decays.

The efficiencies are determined on data using the TISTOS method. The efficiency of the trigger on signal (TOS) can be calculated according to $\varepsilon_\mathrm{TOS} = N_\mathrm{TIS\&TOS}/N_\mathrm{TIS}$, where N_TIS denotes the number of signal events triggered independently of the signal decay (TIS) and $N_\mathrm{TIS\&TOS}$ denotes the events triggered by both the signal decay and independently of the signal decay.

3.3 HLT2

The HLT2 performs a full event reconstruction of all tracks with a minimum p_T of $300\,\mathrm{MeV}/c$ and reduces the rate to 5 kHz (3 kHz in 2011) which is written to disk. Several exclusive selections are performed in the HLT2. In particular prompt charm decays require, due to their high rate, an exclusive trigger selection with tight cuts on the invariant masses. Another example of an exclusive selection in the HLT2 is the lifetime unbiased trigger for $B_s^0 \to K^+K^-$ decays.

In addition to the exclusive lines, inclusive selections are performed to identify heavy flavour decays. Several trigger lines select events containing dimuon signatures, both with and without requiring separation from the primary interaction vertex [7]. Without the requirement of a detached secondary vertex, the dimuon object needs to have significant p_T or large invariant mass. Fig. 3 shows the efficiency of two HLT2 dimuon lines for the decay $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$. The

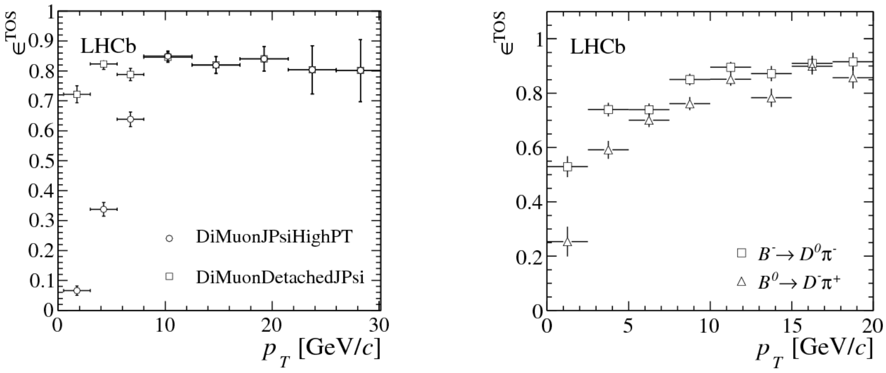

Figure 3: (Left) Efficiency of two HLT2 muon lines for $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ events as a function of p_{T}. (Right) Efficiency of the HLT2 topological trigger lines selecting purely hadronic B decays as a function of p_{T}. Figure from [5].

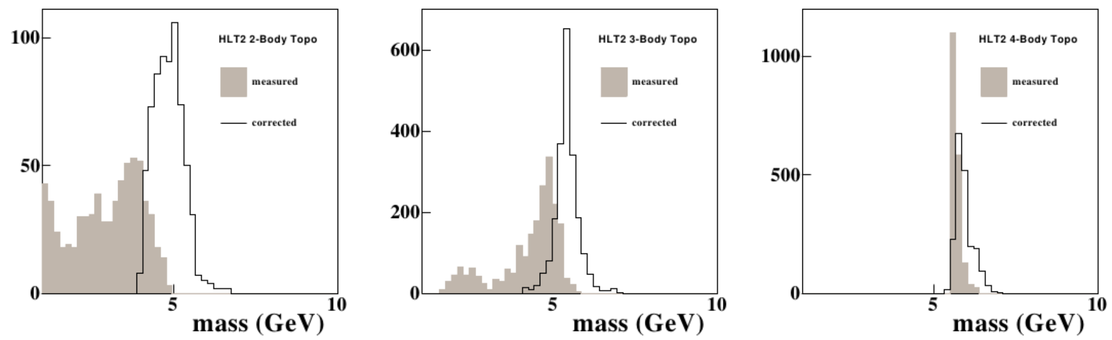

Figure 4: Reconstructed and corrected mass for (left) two, (middle) three and (right) four reconstructed tracks using $B^0 \to K^{*0}\mu^+\mu^-$ decays.

integrated efficiency of the HLT2 for B decays with two muons in the final state is generally larger than 90%. The total output rate of the muon lines in 2012 is 1 kHz.

Furthermore, a multivariate classifier is used to identify B decays by selecting detached two-, three- or four-track vertices [8, 9]. This algorithm, known as "topological trigger", is based on a BDT using discretized input variables [10] which allows for a fast implementation and protects against overtraining. A crucial input for the multivariate selection is the corrected mass $m_{\mathrm{corr}} = \sqrt{m^2 + |p_{\mathrm{T,miss}}|^2} + |p_{\mathrm{T,miss}}|$, where $|p_{\mathrm{T,miss}}|$ denotes the missing momentum transverse to the direction of flight. This allows the topological trigger to select heavy flavour decays even when not all daughter tracks are reconstructed. Fig. 4 shows the resolution that is reached for the corrected mass with two, three and four reconstructed tracks for the decay $B^0 \to K^{*0}\mu^+\mu^-$. Fig. 3 shows the efficiency of the topological trigger lines for the purely hadronic decays $B^- \to D^0\pi^-$ and $B^0 \to D^-\pi^+$. The output rate of the topological trigger in 2012 is 2 kHz, while the remaining 2 kHz of the total HLT2 output rate of 5 kHz are taken up by the charm selections.

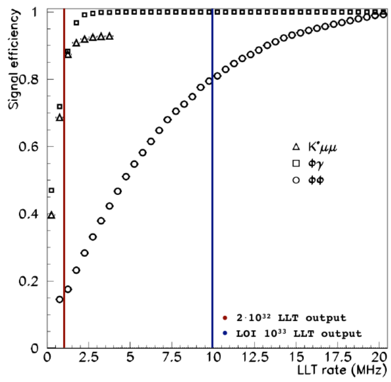

Figure 5: Trigger efficiency depending on the LLT rate for the decays $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\gamma$ and the purely hadronic mode $B_s^0 \to \phi\phi$.

3.4 Deferred trigger

An important improvement of the trigger system in 2012 was the introduction of the so-called "deferred trigger", which allows to store a fraction of 20% of all L0 accepted events on the local disks of the HLT farm nodes. These events are analysed at a later time during the interfill gaps, using computing resources that would otherwise be idling. This more optimal usage of resources allowed to reduce the transverse moment requirement in the HLT2 track reconstruction from $500\,\mathrm{MeV}/c$ to $300\,\mathrm{MeV}/c$. A trigger configuration with tighter p_T requirements in the HLT1 was prepared for the case that the disks of the farm node were running full. However, this configuration did not have to be used in 2012.

4. Future developements beyond LS1 and the LHCb upgrade

In 2015, after LS1, the HLT will be split and the deferral of events will occur after they are accepted by HLT1. This allows to perform an online calibration of the particle identification provided by the RICH detectors. With the calibrated particle identification information available in the HLT2, more efficient and "offline-like" trigger selections will be possible. With the large charm cross section it is particularly important to preferentially select the doubly Cabbibo suppressed decay $D^0 \to K^+\pi^-$ compared to the much more numerous $D^0 \to K^-\pi^+$ decays which can be prescaled. This distinction will only be possible due to the available calibrated particle identification information. In addition, LHCb will be able to profit from a larger trigger farm. Increased computing resources available in 2015 will allow to record $\sim 12.5\,\mathrm{kHz}$ of events to disk.

The upgraded LHCb detector following LS2 will allow a readout with 40 MHz. Fig. 5 shows that the L0 trigger rate becomes a bottleneck under the upgrade conditions, in particular for fully hadronic channels. It is therefore planned to further increase the fraction of the trigger system implemented in software. A hardware based low level trigger (LLT) will be operated with a variable $1-40\,\mathrm{MHz}$ output rate, depending on the available computing resources for the HLT farm.

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5. Conclusions

During the running period of 2011 and 2012 the LHCb trigger system has been performing extraordinarily 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 very high: modes with a dimuon in the final state can be triggered with around 90% efficiency, while typical trigger efficiencies for hadronic modes are larger than 60%. Several innovative concepts have helped to reach this impressive performance: The deferred triggering allows to optimise the trigger for mean instead of peak performance of the available computing resources. Another example is the usage of multivariate classifiers in the trigger which allows to select heavy flavour decays even if not all daughter tracks of the decay are reconstructed.

For the future several further improvements of the trigger system are planned. The splitting of HLT1 and HLT2 will allow the usage of particle identification information in the trigger and therefore more "offline-like" trigger selections. For the LHCb upgrade the fraction of the trigger system implemented in software will be further increased. This will lead to higher signal efficiencies, in particular for fully hadronic decays.

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