The LHCb Trigger System: Performance and Outlook

Albert Puig Navarro, *on behalf of the LHCb Trigger Project*

***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. The design and performance of these selection algorithms will be discussed in the context of the 2012 data taking. 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.**

I. 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. Its 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 $4\,\mathrm{Tm}$, 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 $5\,\mathrm{GeV}/c$ to 0.6% at $100\,\mathrm{GeV}/c$, and impact parameter (IP) resolution of $20\,\mu\mathrm{m}$ for tracks with large transverse momentum (p_{T}). 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 designed to be operated at an instantaneous luminosity of $\mathcal{L} = 2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at center-of-mass energy $\sqrt{s} = 14\,\mathrm{TeV}$. However, during the running period of 2011 and 2012 data were taken at twice the luminosity design value, $\mathcal{L} = 4\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with center-of-mass energies of $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$, respectively, which corresponds to an average number of visible interactions per bunch crossing of $\mu = 1.6$. This was possible thanks to the excellent performance of both the detector hardware and the reconstruction software.

Manuscript received November 15, 2013.

A. P. Author is with the Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland (e-mail: albert.puig@epfl.ch).

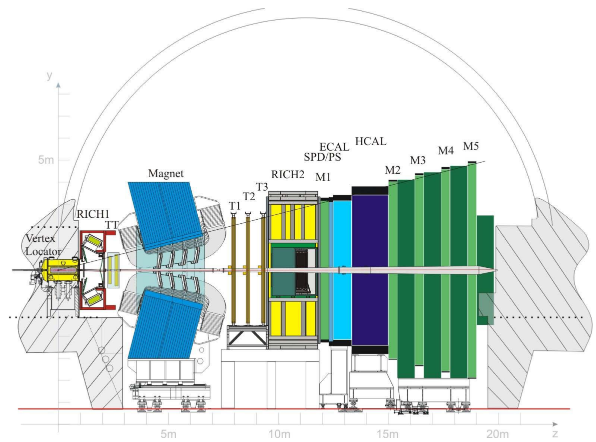


Fig. 1: Layout of the LHCb detector.

Data taking after the current shutdown (LS1) is expected to restart in 2015, with an increased center-of-mass energy of $\sqrt{s} \sim 13\,\mathrm{TeV}$ and keeping the 2012 instantaneous luminosity, and to extend up to 2018. After a second shutdown (LS2), starting in 2019, is is planned to run at a higher luminosity of $\mathcal{L} \sim 2\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with the upgraded LHCb detector.

Key signatures for the selection of heavy flavor (b and c) decays will be discussed first. Afterwards, the design of the LHCb trigger, as well as its performance during 2011 and 2012, will be presented. Finally, future developments of the trigger system, both for the time after LS1 and for the LHCb upgrade, will be summarized.

II. Heavy flavor decay signatures

The LHCb experiment performs precision measurements of heavy flavor decays, which are produced in sizeable quantities at the LHC thanks to large production cross sections for $b\bar{b}$ and $c\bar{c}$ quark pairs of $\sigma_{b\bar{b}} = (75.3 \pm 14.1)$ µb [2] and $\sigma_{c\bar{c}} = (1419 \pm 134)$ µb [3] in the LHCb acceptance. The efficient selection of these type of decays, as well as the rejection of low-p_{T} QCD background from the pp interaction, is performed by exploiting some of their key signatures:

- Hadrons containing b and c quarks have large lifetimes, *i.e.*, $\tau(B) \sim 1.6$ ps and $\tau(D^0) \sim 0.4$ ps [4], resulting in flight distances much larger, $\mathcal{O}(1\text{ cm})$ and $\mathcal{O}(4\text{ mm})$ respectively, than the LHCb IP resolution of $20\ \mu\mathrm{m}$.

- Due to the large mass of b and c hadrons, well above 1 GeV/c^2, the child particles of heavy flavor decays carry a significant p_{T}.
- Several key channels for the LHCb experiment, such as $B_s^0 \to \mu^+\mu^-$, $B_s^0 \to J/\psi\,\phi$ and $B^0 \to K^{*0}\mu^+\mu^-$, contain muons in the final state, which can be identified with the help of the LHCb muon system.

In addition, this selection needs to respect the constraints of the available computing resources and output bandwidth, which will be discussed in the following section.

III. The LHCb Trigger and its Performance

The LHCb trigger system [5] is composed of two stages: the Level 0 trigger (L0), which is implemented in hardware, and the High Level Trigger (HLT), which is implemented in software and runs on a dedicated computing farm made up by 29,000 cores. This software trigger is subdivided in two stages (HLT1 and HLT2), designed to be very flexible and to be able to rapidly adapt to changing running conditions.

The three stages of the LHCb trigger and their performances will be discussed in detail in the following subsections. L0 thresholds, HLT cut values, rates and efficiencies are given for the 2012 data taking period. Values for the 2011 data taking can be found in [5].

A. The L0 trigger

The goal of the L0 trigger is to reduce the 40 MHz bunch crossing rate in the LHC—corresponding to $\sim$ 15 MHz of visible interactions— to 1 MHz, the rate at which the LHCb detector can be read out, in less than 4 µs.

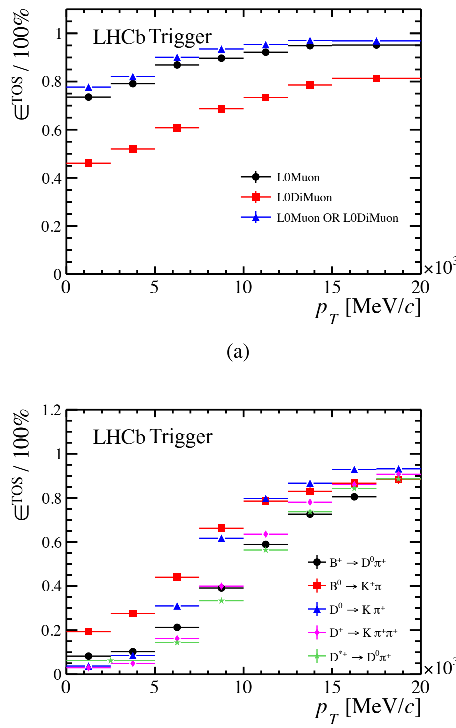
Reconstruction of the muon momentum using only the muon chambers affords a momentum resolution of $\sim$ 20%. Events containing a single muon with $p_{\mathrm{T}} > 1.76$ GeV/c or a muon pair with $p_{\mathrm{T},1} \times p_{\mathrm{T},2} > (1.6\ \mathrm{GeV}/c)^2$ are selected, resulting in a L0 muon rate of 400 kHz.

Hadrons are selected if they deposit a significant amount of transverse energy (E_{T}) in the hadronic calorimeter, $E_{\mathrm{T}} >$ 3.68 GeV, while electrons and photons are triggered by a E_{T} deposition in the electromagnetic calorimeter above 3.0 GeV. The output rates of hadrons and electromagnetic particles are 450 kHz and 150 kHz, respectively.

The efficiency of the L0 requirements outlined above strongly depends on the particular physics channel under study, but as a general guideline one can state that[1]:

- for B decays containing two muons in the final state, the efficiency of the L0 muon requirements is typically above 90% (see Fig. 2a);
- the efficiency of the L0 hadron requirement on fully hadronic decay modes ranges from $\sim$ 60% to 30%, depending on the channel, as shown in Fig. 2b. Charm decays have typically lower efficiencies due to the lower mass of the charmed hadrons;
- radiative B decays, such as $B^0 \to K^{*0}\gamma$, have efficiencies above 80% when triggering on the photon in the L0.

[1] All efficiencies given throughout this document are computed with respect to offline-selected events, *i.e.*, with the final selection for physics analysis. They are determined on data using the TISTOS method [6]. The efficiency of the trigger on signal (TOS) is calculated as $\epsilon^{\mathrm{TOS}} = N_{\mathrm{TIS\&TOS}}/N_{\mathrm{TIS}}$, where N_{TIS} denotes the number of signal events triggered independently of the signal decay (TIS) and $N_{\mathrm{TIS\&TOS}}$ denotes events triggered both by the signal and independently of the signal.



(a)

(b)

Fig. 2: 2012 L0 efficiencies 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}.

B. HLT1

The first stage of the HLT, denoted as HLT1, performs a partial event reconstruction in order to reduce the event rate from the L0 output of 1 MHz to $\sim$ 70 kHz (43 kHz in 2011). This partial reconstruction works as follows

1. Track segments are reconstructed in the vertex detector (VELO).
2. Track segments that either have high IP or can be matched to hits in the muon chambers are extrapolated into the main tracker.
3. Tracking is then performed in search windows defined by the track type.

If a good quality track with a minimum p_{T} of 1.6 GeV/c (or 1.0 GeV/c and 0.5 GeV/c for muon and dimuon tracks, respectively) can be reconstructed, the event is accepted. Figure 3 shows the efficiency of the HLT1 selections, as a function of p_{T}, for decays with muons in the final state and for purely hadronic decays.

C. HLT2

At the HLT2 stage, full event reconstruction is performed for all tracks with p_{T} above 300 MeV/c (500 MeV/c in 2011)

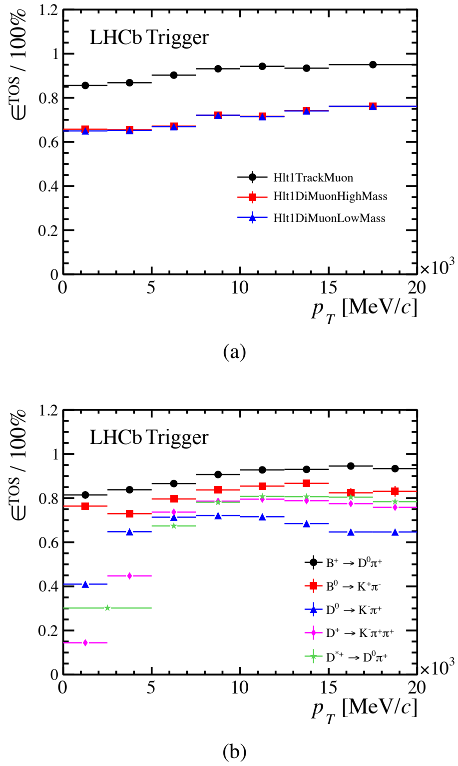


Fig. 3: 2012 efficiencies of (a) the HLT1 muon lines for $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ and (b) L0 hadron requirements on several fully hadronic decay modes as a function of the parent p_{T}.

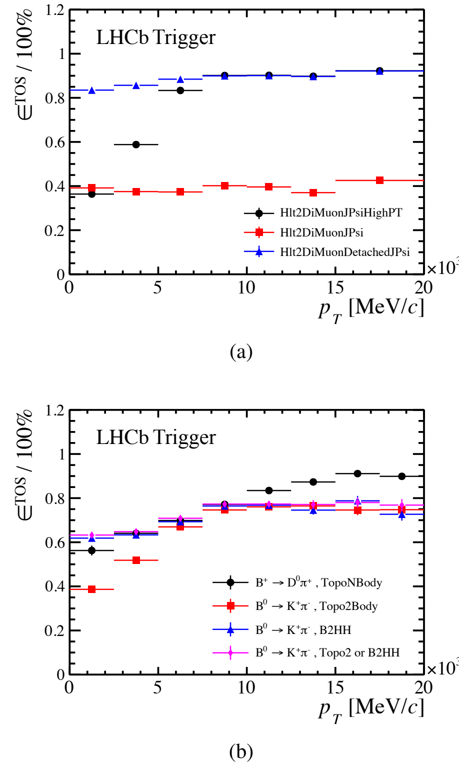


Fig. 4: 2012 efficiencies of (a) the HLT2 muon lines for $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ and (b) the topological and exclusive $B \to hh$ HLT2 lines as a function of the parent p_{T}.

and the event rate is reduced to the final 5 kHz (3 kHz in 2011) that are written to disk. The HLT, and especially HLT2, is run within a powerful and flexible software environment which allows fast adaptation of selection thresholds and line prescales to varying running conditions, as well as the use of complex selection criteria such as multivariate tools.

The trigger strategy in HLT2 is twofold: on one hand, several exclusive selections are applied, for example for high-rate prompt charm decays or for lifetime-unbiased B decays; on the other hand, inclusive selections are performed taking advantage of the heavy flavor decay signatures outlined in Sec. II.

These inclusive selections contain several lines that trigger on dimuon signatures, both with and without the requirement of separation from the interaction vertex [7]; in the latter case, significant p_{T} or large invariant mass is required. These lines have a total output rate in 2012 of 1 kHz, yielding an integrated efficiency of the HLT2 for B decays in the final state typically above 90%.

Final states containing hadrons are selected using a multivariate classifier that identifies B decays by constructing two-, three- and four-track vertices [8], [9], reaching efficiencies well above 60% (see Fig. 4b). This algorithm, known as *topological trigger*, is based on a modified Boosted Decision Tree (BDT) with discretized input variables [10]. The topological trigger is able to select heavy flavor decays even when not all child tracks are reconstructed by taking advantage of the missing momentum transverse to the direction of flight, $p_{\mathrm{T,miss}}$, through the corrected mass variable, defined as $m_{\mathrm{corrected}} = \sqrt{m^2 + |p_{\mathrm{T,miss}}|^2} + |p_{\mathrm{T,miss}}|$. The distribution of the corrected mass for two, three and four reconstructed tracks is shown in Fig. 5 in the case of the $B^0 \to K^{*0}\mu^+\mu^-$ decay.

D. Deferred trigger

During LHC interfill gaps, the large computing resources of the HLT farm remain unused, since there is no trigger to process. In 2012, the *deferred trigger* method was introduced in LHCb in order to make use of these otherwise idling farm nodes: 20% of all L0-accepted events are stored in the local disks of the nodes, waiting to be reprocessed at a later time during the interfill gaps.

Thanks to this better usage of resources, it was possible to reduce the minimum p_{T} requirement in the HLT2 track reconstruction from 500 MeV/c to 300 MeV/c, as well as to add downstream tracking for long-lived particles. A failsafe trigger configuration, with tighter p_{T} requirements in HLT1, was prepared in case the disks of the nodes filled up; however, the peak disk usage never exceeded 90%, and this configuration was never needed.

IV. Future Developments

A. After LS1

In 2015, after the LHC LS1, the deferral of events will take place after HLT1; thus, HLT1 and HLT2 will be split. This will allow to perform an online calibration of the particle identification provided by the RICH detectors, allowing for

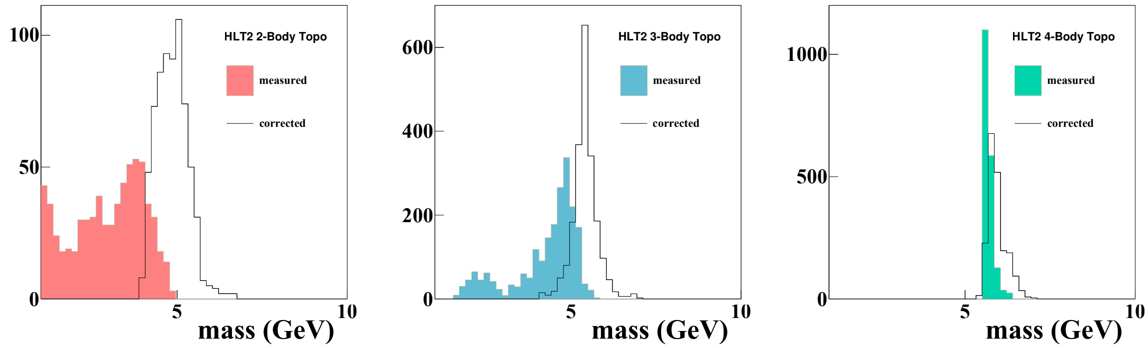


Fig. 5: Reconstructed and corrected mass for (left) two, (middle) three, and (right) four reconstructed tracks in $B^0 \to K^{*0}\mu^+\mu^-$.

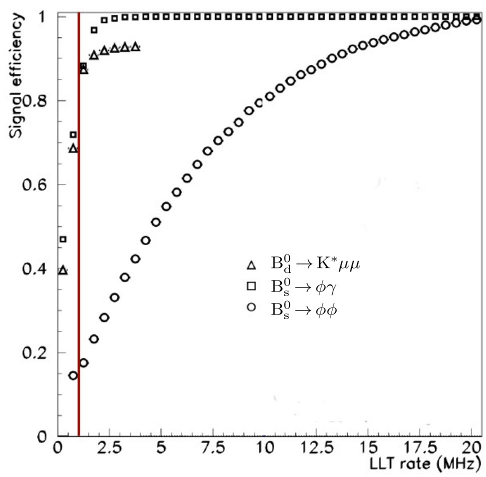


Fig. 6: LHCb upgrade trigger efficiency depending on the hardware trigger rate for $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\gamma$ and the purely hadronic $B_s^0 \to \phi\phi$.

an optimal —more "offline"-like— use in the HLT2. This is especially important for studies in the charm sector, which has a large cross section and for which one wishes to select the more suppressed channels, *e.g.*, the doubly Cabbibo suppressed $D^0 \to K^+\pi^-$ against the more abundant $D^0 \to K^-\pi^+$. In addition, after LS1 LHCb will be able to store up to $\sim 12.5\,\mathrm{kHz}$ of events to disk, thanks to its increased computing resources.

B. After LS2: the LHCb upgrade

The upgraded LHCb detector, which is scheduled to start operation in 2019 with a luminosity of $\mathcal{L} = 2\times10^{33}\ \mathrm{cm}^{-1}\,\mathrm{s}^{-1}$, will allow a readout at $40\ \mathrm{MHz}$. Under these conditions, the L0 trigger rate becomes a bottle neck, in particular for channels with a fully hadronic final state, as demonstrated in Fig. 6. To mitigate this effect, it is planned to gradually 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 computing resources available in the HLT farm.

V. Conclusions

During the LHC run period between 2011 and 2012, the LHCb trigger has performed very successfully. Its flexible software implementation has allowed the HLT to rapidly adapt to the varying running conditions and to cover a very wide physics range —including decay signatures not initially considered— while achieving very high trigger efficiencies: modes with muon pairs in the final state have been triggered with an efficiency close to 80%, whereas hadronic modes, including those with photons in their final state, have typical efficiencies larger than 60%.

During 2011-2012, several improvements have been introduced to reach this impressive performance: deferred triggering allows to optimize the trigger for mean instead of peak performance of the computing resources, while the introduction of multivariate techniques has allowed to trigger heavy flavor decays even in the case in which not all the final state particles have been reconstructed.

In the near future, the splitting of HLT1 and HLT2 will allow an optimal utilization of particle identification in trigger selections, moving them closer to what is done offline. For the LHCb upgrade, the fraction of the trigger implemented in software will be increased and a variable-rate hardware trigger level will be introduced, leading to even higher signal efficiencies and an even wider physics reach.

References

[1] A. A. Alves Jr. *et al.*, "The LHCb detector at the LHC," *JINST*, vol. 3, p. S08005, 2008.

[2] R. Aaij *et al.*, "Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s} = 7\ TeV$ in the forward region," *Phys. Lett.*, vol. B694, p. 209, 2010.

[3] ——, "Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV," *Nucl. Phys.*, vol. B871, p. 1, 2013.

[4] J. Beringer *et al.*, "Review of particle physics," *Phys. Rev.*, vol. D86, p. 010001, 2012.

[5] R. Aaij *et al.*, "The LHCb trigger and its performance in 2011," *JINST*, vol. 8, p. P04022, 2013.

[6] J. A. Hernando Morata, E. Lopez Asamar, D. Martinez Santos, H. Ruiz-Pérez, and F. Teubert, "Measurement of trigger efficiencies and biases," CERN, Geneva, LHCb Public Note CERN-LHCb-2008-073, 2010.

[7] R. Aaij and J. Albrecht, "Muon triggers in the High Level Trigger of LHCb," LHCb Public Note LHCb-PUB-2011-003, 2011.

[8] M. Williams, V. Gligorov, C. Thomas, H. Dijkstra, J. Nardulli, and P. Spradlin, "The HLT2 Topological Lines," LHCb Public Note LHCb-PUB-2011-002, 2011.

[9] V. Gligorov, C. Thomas, and M. Williams, "The HLT inclusive B triggers," LHCb Public Note LHCb-PUB-2011-016, 2011.

[10] V. V. Gligorov and M. Williams, "Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree," *JINST*, vol. 8, p. P02013, 2013.