Performance of the LHCb High Level Trigger in 2012

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Abstract. The trigger system of the LHCb experiment is discussed in this paper and its performance is evaluated on a dataset recorded during the 2012 run of the LHC. The main purpose of the LHCb trigger system is to separate heavy flavour signals from the light quark background. The trigger reduces the roughly 11 MHz of bunch-bunch crossings with inelastic collisions to a rate of 5 kHz, which is written to storage.

1. Introduction

The LHCb detector, discussed in detail in Ref. [1], is a single arm forward spectrometer that covers a pseudo-rapidity range of $2 < \eta < 5$, with the primary purpose of performing precision measurements at the LHC. The trigger system of the LHCb experiment consists of two levels: the first level, implemented in hardware (L0), and the High Level Trigger (HLT), implemented in a CPU farm of about 29 000 logical cores. The LHCb trigger system and its performance during 2011 data taking has been described in detail in Ref. [2]. This paper describes the adjustments of the system for 2012 running and evaluates the performance on 2012 data.

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. 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 pre-shower 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 for an instantaneous luminosity of $\mathcal{L} = 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. During the running period of 2012, this design luminosity was doubled to $\mathcal{L} = 4 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which was possible thanks to the excellent performance of both the detector hardware and the trigger system. In these conditions, the average number of visible interactions per bunch crossing is $\mu = 1.6$.

The LHCb trigger system and its performance during the 2012 run will be discussed first. Afterwards, future developments of the trigger system for the time after long shutdown 1 (LS1) and the LHCb upgrade are presented.

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2. Data-driven performance evaluation

The trigger efficiency is evaluated using events that are reconstructed using the full offline software and selected with the final analysis selection for the respective channel. Thus, the trigger efficiency contains only the additional inefficiency due to simplifications used in the trigger, possible alignment inaccuracies, worse resolution than the offline reconstruction or harder cuts imposed by rate and/or processing time limitations. The following channels are chosen to show the performance of the trigger:

- $B^+ \to J/\psi K^+$, where the $J/\psi \to \mu^+\mu^-$ channel is selected. This decay allows the evaluation of the muon trigger efficiency and serves as excellent proxy for the CP violation and rare decay channels containing a dimuon final state.
- $B^0 \to K^+\pi^-$ as a typical two-body beauty decay.
- $B^0 \to D^0\pi^-$, followed by the decay $D^0 \to K^-\pi^+$ as a typical three-body beauty decay.
- $D^0 \to K^-\pi^+$ as a two-body charm decay.
- $D^+ \to K^-\pi^+\pi^+$ as a three-body charm decay.
- $D^{*+} \to D^0\pi^+$, followed by the four body charm decay $D^0 \to K^-\pi^+\pi^-\pi^+$.

These channels and their selections are representative for those used in most analyses. The selected charm modes cover the topologies most sensitive to CP violating effects. In all off-line selected signal samples the level of background is significantly lower than the signal. Substantial differences in trigger efficiency, however, are observed for true signal and background. The trigger performance on each channel is measured by determining the signal component using fits to the invariant mass distributions, hence avoiding any background contamination.

In what follows, the term signal refers to a combination of tracks that form the off-line reconstructed and selected b or c-hadron candidate. To determine the trigger efficiency, trigger objects are associated to signal tracks. The trigger records all the information needed for such an association. All measurements of the sub-detectors have a unique identifier, and these identifiers are written in a trigger report in the data stream for every trigger line that accepts an event. The criteria used to associate a trigger object with a signal track are as follows: An event is classified as TOS (Trigger on Signal) if the trigger objects that are associated with the signal are sufficient to trigger the event. An event is classified as TIS (Trigger Independent of Signal) if it could have been triggered by those trigger objects that are not associated to the signal. A number of events can be classified as TIS and TOS simultaneously ($N^{TIS\&TOS}$), which allows the extraction of the trigger efficiency relative to the off-line reconstructed events from data alone. The efficiency to trigger an event independently of the signal, ϵ^{TIS}, is given by $\epsilon^{TIS} = N^{TIS\&TOS}/N^{TOS}$, where N^{TOS} is the number of events classified as TOS. The efficiency to trigger an event on the signal alone, ϵ^{TOS}, is given by $\epsilon^{TOS} = N^{TIS\&TOS}/N^{TIS}$, where N^{TIS} is the number of events classified as TIS.

3. L0 Hardware Trigger

The bunch crossing frequency of the LHC is 40 MHz. This rate is reduced by the L0 trigger to a rate of 1 MHz, at which the full detector is read out. The L0 trigger is implemented in custom hardware and has a latency of 4 μs. It triggers on high transverse momentum (p_T) muons and on large transverse energy (E_T) deposition in the calorimeter. A relative momentum resolution of about 20% can be reached in the L0 muon reconstruction. The thresholds applied in L0 are given in Tab. 1.

The trigger efficiencies are measured on offline selected events, using the techniques described in Section 2. For L0 muon decisions, evaluated on $B^+ \to J/\psi K^+$ events, they are shown in

Table 1. L0 thresholds in 2011 and 2012.

	2011	2012
single muon	1.48 GeV	1.76 GeV
dimuon $p_{T1} \times p_{T2}$	$(1.296\,\text{GeV})^2$	$(1.6\,\text{GeV})^2$
hadron	3.5 GeV	3.7 GeV
electron	2.5 GeV	3 GeV
photon	2.5 GeV	3 GeV

Fig. 1. The single muon trigger contributes the dominant part to the efficiency. The largest inefficiency originates in the tight muon identification requirements inside the L0 reconstruction algorithm. The L0 dimuon trigger selects a small fraction of additional candidates at lower transverse momenta. The integrated efficiency for both L0 muon triggers combined is evaluated to be 89%.

The L0 hadron efficiency is shown in Fig. 2 for the two and three prong beauty decays $B^0 \to K^+\pi^-$ and $B^0 \to D^0\pi^-$ and the two, three and four prong charm decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^0\pi^+$. The two prong beauty decay is most efficiently triggered by the L0 hadron E_T criterion ($\epsilon^{TOS} = 40\%$) and the four prong charm decay $D^{*+} \to D^0\pi^+$ is selected with the lowest efficiency ($\epsilon^{TOS} = 22\%$). The other modes lie in between, see Fig. 2. Allowing also TIS triggers, the integrated efficiencies increases significantly, (e.g. to ϵ^{TRIG} =53% for $B^0 \to K^+\pi^-$).

The total output rate of the L0 trigger is limited to 1 MHz, the maximum rate at which the LHCb detector can be read out. This output rate is composed of approximately 400 kHz of muon triggers (`L0Muon` and `L0DiMuon`), 490 kHz `L0Hadron` triggers and 150 kHz `L0Photon` and `L0Electron` triggers.

4. High Level Trigger

The High Level Trigger consists of two stages, HLT1 and HLT2. The first stage, HLT1, performs a partial event reconstruction and an inclusive selection of signal candidates. At the reduced rate of 80 kHz, HLT2 performs a full event reconstruction with only minor adjustments to the offline reconstruction sequence. After this reconstruction, a set of inclusive and exclusive selections

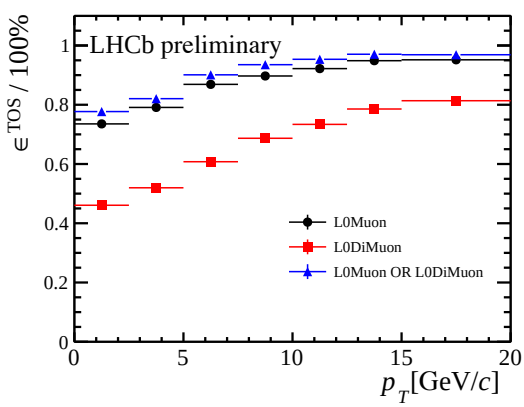

Figure 1. L0 muon trigger performance: TOS trigger efficiency for selected $B^+ \to J/\psi K^+$ candidates.

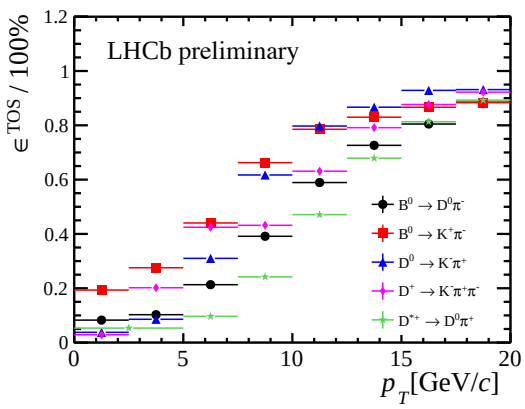

Figure 2. L0 hadron trigger performance: TOS trigger efficiency for different beauty and charm decay modes.

reduces the trigger rate to 5 kHz, which are saved for later offline analysis. The rates discussed above are average rates from the 2012 run of the LHC, in 2011 the HLT1 output rate was approximately 40 kHz and the HLT2 output rate was 3 kHz.

4.1. First level software trigger

The partial reconstruction in HLT1 starts by reconstructing track segments in the 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. This extrapolation is done using the identical forward tracking algorithm [3] as used in offline processing, however, with reduced search window sizes corresponding to a minimum p_T requirement.

The inclusive beauty and charm trigger line `Hlt1TrackAllL0` selects good quality track candidates based on their p_T ($p_T > 1.6$ GeV) and displacement from the primary vertex. This trigger line gets the dominant part of the HLT1 bandwidth allocated, about 58 kHz. It is the dominant trigger line for most physics channels that do not contain leptons in the final state. The performance of HLT1 for hadronic signatures is shown in Fig. 3 as a function of resonance p_T.

A similar line exists if the track is matched with hits in the muon chambers [4], `Hlt1TrackMuon`. This single muon trigger line selects good quality muon candidates with a $p_T > 1$ GeV that are not coming from the primary vertex. Single muon candidates which satisfy a p_T requirement of $p_T > 4.8$ GeV are selected by the line `Hlt1SingleMuonHighPT` without any vertex separation requirements.

Dimuon candidates are either selected based on their mass ($m_{\mu\mu} > 2.5$ GeV) without any kind of displacement requirement (`Hlt1DiMuonHighMass`), or based on the distance between primary and secondary vertex, but without the mass restriction (`Hlt1DiMuonLowMass`). The dominant inefficiency for these lines originates in the online muon identification algorithms. The performance of HLT1 at selecting muonic signatures is shown in Fig. 4 as a function of p_T of the B^+ candidate. The integrated efficiency is summarised in Tab. 2.

The trigger efficiency for events that are triggered by the `L0Photon` or `L0Electron` triggers are enhanced by the `Hlt1TrackPhoton` trigger line, which has relaxed track quality and p_T requirements with respect to `Hlt1TrackAllL0`.

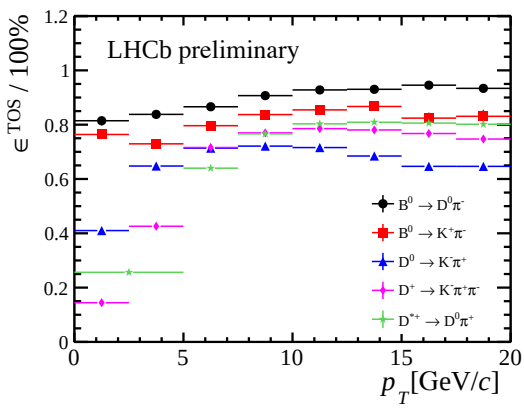

Figure 3. `Hlt1TrackAllL0` performance: TOS efficiency for various channels as a function of B or D p_T.

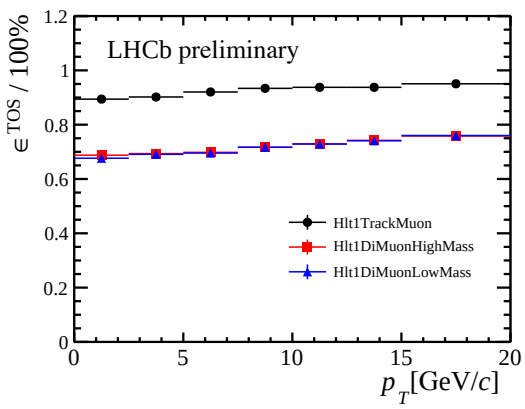

Figure 4. HLT1 muon trigger performance: TOS efficiency for $B^+ \to J/\psi K^+$ candidates as function of B^+ p_T.

Table 2. Integrated efficiencies of the HLT1 triggers, normalised to events that are offline selected (see Sec.2) and have passed the previous trigger level.

channel	trigger line	ϵ^{TOS}
$B^+ \to J/\psi K^+$	single muon (dimuon)	90% (69%)
$B^0 \to K^+\pi^-$	1Track	86%
$B^0 \to D^0\pi^-$	1Track	89%
$D^0 \to K^-\pi^+$	1Track	67%
$D^+ \to K^-\pi^+\pi^+$	1Track	59%
$D^{*+} \to D^0\pi^+$	1Track	60%

Additionally to the trigger lines discussed above, special lines are implemented to enhance the trigger performance for events containing candidates for high p_T electrons, di-protons, displaced vertices or high E_T jets. A set of technical lines including selections for luminosity and beam gas measurements complete the list of HLT1 triggers.

4.2. Second level software trigger

The second software trigger level, HLT2, performs a full event reconstruction for all tracks with a minimum p_T of 300 MeV. It reduces the event rate to 5 kHz, which is written to permanent storage. Several exclusive and inclusive selections are performed in this trigger level, the most important ones are discussed in this section.

Generic beauty trigger

A multivariate selection is used to trigger B decays into charged hadrons in an inclusive selection based on two- three- and four-prong vertices [5]. These trigger lines, named `Hlt2Topo(N)Body`, are based on a BDT classifier that uses discretized input variables [6] which ensures a fast and robust implementation. A crucial input to the BDT is the corrected mass, defined as

$$m_{corr} = \sqrt{m^2 + |p_T^{miss}|^2} + p_T^{miss}\,, \tag{1}$$

where p_T^{miss} denotes the missing momentum transverse to the direction of flight. This allows the topological trigger to select heavy flavour decays even in case not all final state particles are reconstructed. Fig. 5 shows the reconstructed 2-body mass for $B^0 \to K^{*0}\mu^+\mu^-$ events, and superimposed, the corrected mass. Fig. 6 shows the efficiency for the topological trigger lines for $B^0 \to K^+\pi^-$ and $B^0 \to D^0\pi^-$ events as well as the additional efficiency that can be gained by an exclusive selection for $B^0 \to K^+\pi^-$ in the low p_T regime. The output rate of the topological trigger is 2 kHz.

Muon triggers

Several trigger lines select events with one or two identified muons. The muon identification procedure in HLT2 is identical to the one used in offline analysis [7]. Single muon candidate events are selected if the muon passes a tight p_T requirement ($p_T > 10$ GeV) or if candidates not consistent with the primary vertex as their origin and pass moderate p_T ($p_T > 1.3$ GeV) and tight track quality requirements. Additionally, the latter line is pre-scaled by a factor of two.

Dimuon candidate events are selected without a mass requirement if the dimuon vertex is separated from the primary vertex. If the mass of the muon pair is consistent with a J/ψ resonance mass, three trigger selection are applied

- `Hlt2DiMuonJPsi`: All candidates in a mass range of 100 MeV ($\approx 8\sigma$) around the J/ψ mass are accepted. In a part of the dataset, this prompt J/ψ trigger was pre-scaled.
- `Hlt2DiMuonJPsiHighPT`: If the J/ψ resonance p_T is above 2 GeV, the event is selected.

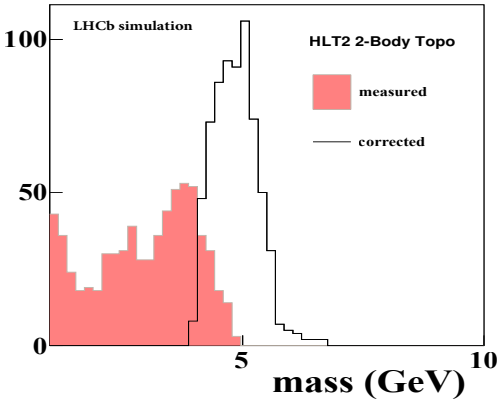

Figure 5. Simulated $B^0 \to K^{*0}\mu^+\mu^-$ events: reconstructed 2-body mass in red and corrected mass (see text for definition) in black.

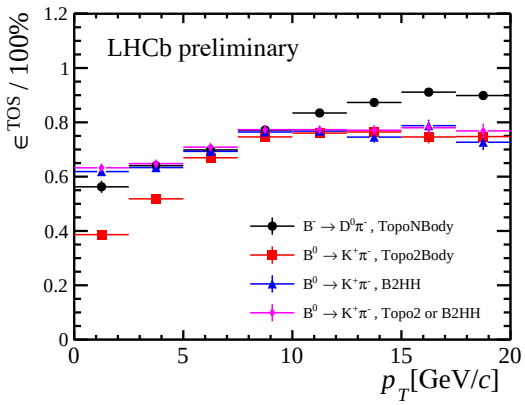

Figure 6. HLT2 inclusive beauty trigger performance as a function of B p_T. The efficiency for the exclusive $B^0 \to K^+\pi^-$ trigger line is also given.

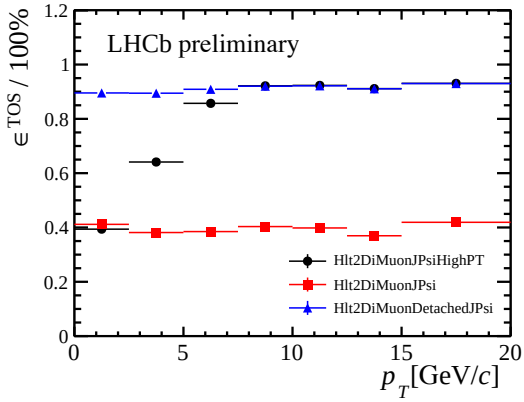

Figure 7. HLT2 muon trigger performance for the J/ψ trigger lines.

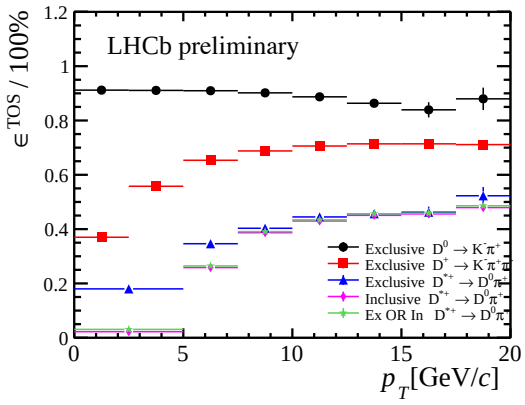

Figure 8. HLT2 charm trigger performance for inclusive and exclusive selections.

- `Hlt2DiMuonDetachedJPsi`: If the J/ψ candidate vertex is separated from the primary vertex, the event is triggered.

This set of lines is optimised to fully exploit the large physics potential in both prompt J/ψ and $B \to J/\psi X$ decays. Fig. 7 shows the performance of the J/ψ triggers. The effective pre-scale of about a factor two on the prompt J/ψ line `Hlt2DiMuonJPsi` is visible, as well as the p_T turn on of the `Hlt2DiMuonJPsiHighPT` line. The total output rate of all single and dimuon trigger lines is about 1 kHz.

Charm triggers

In the 2012 running, about 600 kHz of $c\bar{c}$-events are produced in the acceptance of the LHCb spectrometer. This high rate implies tight cuts on the invariant mass in exclusive trigger selections. Only the decay chain $D^{*+} \to D^0\pi^+$ can be selected inclusively, i.e. only reconstructing two charged tracks from the D^0 decay matched to a slow pion from the D^{*+} decay. The mass difference between the D^{*+} and D^0 candidates remains a good discriminating variable because of the small q-value of the decay, enabling the rate to be sufficiently reduced. The D^0 is partially reconstructed in all different combinations of $\pi^\pm$, $K^\pm$, p, $\mu^\pm$, K^0_S or Λ^0

allowing both rare decay and CP violation measurements. The dominant exclusive selections for prompt charm are the hadronic two body selection `Hlt2CharmHadD02HH` and three body selection `Hlt2CharmHadD2HHH`. The efficiency of these trigger lines is summarised in Fig. 8. Further selections for hadronic, leptonic and semi-leptonic D and Λ_c decays are implemented. The total output rate of all charm selections is about 2 kHz.

5. Deferred trigger

The LHC machine delivers stable beams only for about 30% of the time. In order to use the idle time of the Event Filter Farm, the local hard discs of the Event Filter Farm nodes are used. In this approach, called deferred triggering, about 20% of the L0 accepted events are temporarily saved. They are analysed at a later time during the inter-fill gaps. The scheme of deferred triggering is discussed in more detail in Ref. [8]. This more optimal usage of CPU resources allowed to improve the track reconstruction in HLT2 in two ways:

- it allowed to decrease the p_T requirement inside the forward tracking algorithm from 500 MeV to 300 MeV, and
- allowed the implementation of a specialised track reconstruction for long lived particles (e.g. K_S^0), which reconstructs tracks also if no hits are found in the Velo detector.

These modifications of the trigger configuration enhanced the performance to select charm decays significantly.

6. Future developments beyond LS1

The restart of the LHC accelerator after LS1 is planned for 2015. The HLT1 and HLT2 will then be decoupled from each other and the deferral of events will occur after they are accepted by HLT1. This deferral at a reduced rate allows to buffer the data significantly longer and thus allows to perform an online calibration of the detector. The most important part here is the run-by-run calibration of the refractive index and the mirror alignment of the RICH detectors. This will allow PID selections in HLT2 which are very close in performance to the currently used offline selections. This enables to specifically select Cabibbo suppressed charm decays and suppress the dominant Cabibbo favoured decays with pre-scales. Details of the planned splitting between HLT1 and HLT2 are given in Ref. [9]. In addition, LHCb will be able to profit from a larger trigger farm. Increased computing resources available in 2015 will allow to record about 12.5 kHz of events to disk.

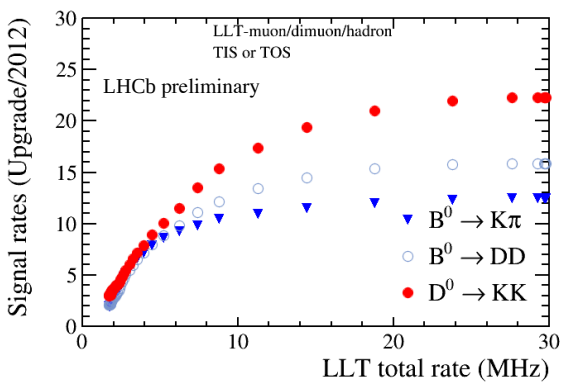

Figure 9. Expected increase in signal yield per unit luminosity dependent on the LLT output rate for three benchmark channels.

The upgraded LHCb detector following long shutdown 2 will allow a detector readout at the full bunch crossing rate of 40 MHz. A Low Level Trigger (LLT) with variable output rate between 1 and 40 MHz will initially reduce the HLT input rate until the full DAQ network and CPU farm are installed. Fig. 9 shows the factor in signal yield for hadronic channels that can be gained if the 1 MHz L0 trigger bottleneck is removed by a a flexible LLT. From LLT rates of 10 MHz onwards, factors between 10 and 20 can be gained, depending on the particular decay channel.

7. Summary

The LHCb trigger system has been performing extraordinarily well in the first running phase of the LHC. It is designed to select charm and beauty hadrons in a large range of decay modes and permits the measurement of its efficiency directly on data. The flexible design of the HLT, fully deployed in software, allows to quickly adjust to changes in running conditions and physics goals. Inclusive selections in the full trigger chain allow an efficient trigger for basically any beauty decay to charged tracks. Several innovative concepts have enabled this performance: the deferred triggering allows to optimise the trigger usage for mean instead of peak usage of the available computing resources. Multivariate selections allow the inclusive selection of beauty decays into charged tracks with high efficiency.

For the future, several improvements of the trigger system are planned: the two software trigger levels will be decoupled which allows calibrations between them and thus a performance much closer to the one achieved offline. LHCb is preparing to upgrade the detector in 2018. It will feature a fully software based trigger system that will allow to explore the physics goals of the experiment at significantly increased luminosities.

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