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# Real time analysis with the upgraded LHCb trigger in Run III

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**Abstract**. The current LHCb trigger system consists of a hardware level, which reduces the LHC bunch-crossing rate of 40 MHz to 1.1 MHz, a rate at which the entire detector is read out. A second level, implemented in a farm of around 20k parallel processing CPUs, the event rate is reduced to around 12.5 kHz. The LHCb experiment plans a major upgrade of the detector and DAQ system in the LHC long shutdown II (2018-2019). In this upgrade, a purely software based trigger system is being developed and it will have to process the full 30 MHz of bunch crossings with inelastic collisions. LHCb will also receive a factor of 5 increase in the instantaneous luminosity, which further contributes to the challenge of reconstructing and selecting events in real time with the CPU farm. We discuss the plans and progress towards achieving efficient reconstruction and selection with a 30 MHz throughput. Another challenge is to exploit the increased signal rate that results from removing the 1.1 MHz readout bottleneck, combined with the higher instantaneous luminosity. Many charm hadron signals can be recorded at up to 50 times higher rate. LHCb is implementing a new paradigm in the form of real time data analysis, in which abundant signals are recorded in a reduced event format that can be fed directly to the physics analyses. These data do not need any further offline event reconstruction, which allows a larger fraction of the grid computing resources to be devoted to Monte Carlo productions. We discuss how this real-time analysis model is absolutely critical to the LHCb upgrade, and how it will evolve during Run-II.

## 1. Introduction

LHCb (Large Hadron Collider beauty) is a dedicated experiment [1] for studying CP violation phenomena and rare decays in heavy flavour quark sector at LHC (Large Hadron Collider). The majority of the physics results published so far by LHCb Collaboration is based on the collision data taken during Run I (2010 – 2012). This was followed by the first long shutdown period (LS1), which was devoted to various fixes and enhancements for the machine to enable it to operate at the nominal luminosity and energy. No hardware changes to the LHCb spectrometer were introduced during the LS1, however, the second, software part of the trigger system[1] was almost completely rebuilt and commissioned for the Run-II data taking (2015 – 2018). The HLT is an application comprising of a set of algorithms implemented in the official LHCb software framework. It runs on the, so called, event filter farm (EFF) built of approximately 52 000 logical CPU cores (during Run-I the farm operated 29 000 cores). This processing cluster is located in the LHCb cavern near the detector. Accepted events are persisted and used in the subsequent physics analyses.

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[1] The overall trigger architecture of LHCb comprises of two layers. The hardware one, called Level 0 (L0), using mainly information provided by the muon chambers and calorimeters to reduce the events rate to 1.1 MHz. This allows then to read the full detector and run the software High Level Trigger (HLT).

In 2019 another long shutdown period (LS2) is going to commence where a major hardware upgrade of the LHCb experiment is foreseen [2]. The trigger system will also be changed and will feature the trigger-less readout system and comprise with a single fully software layer. The modernized detector is expected to collect up to 50 fb$^{-1}$ of data in Run-III and Run-IV. A short introduction to the upgraded LHCb spectrometer is presented in Section 2. The evolution of the current trigger towards the Run-III system is given in Section 3 which is followed by discussion of selected results obtained using Run-II data collected with the revised trigger. The paper is concluded with a short summary.

## 2. LHCb Detector Upgrade

The LHCb detector is built as a single-arm forward spectrometer that is fully instrumented within the pseudorapidity range $2 < \eta < 5$ units. The setup contains a high-precision and robust tracking system that includes: a silicon micro-strip vertex detector (VELO) that is located closest to the proton-proton interaction region, a large area silicon micro-strip detector (TT) placed upstream to the LHCb magnet and a three hybrid tracking stations, placed downstream the magnet, comprising the silicon micro-strip based inner part (IT) and the outer part built with gas straw tubes (OT). The tracking system includes also a warm dipole magnet with a total bending power of approximately $4\,\mathrm{Tm}$. The momentum resolution, $\delta p/p$, of particles that are registered by all sub-detectors of the tracking system varies from $0.4\%$ at $5\,\mathrm{GeV}/c$ to $0.6\%$ at $100\,\mathrm{GeV}/c$. The impact parameter resolution amounts to approximately $20\,\mu\mathrm{m}$ for high transverse momentum particles. Two Cherenkov RICH detectors are used to identify charged hadrons. Electromagnetic and hadronic calorimeter systems are used to identify photons, electrons and hadrons. Muons are measured using multiwire proportional gas chambers.

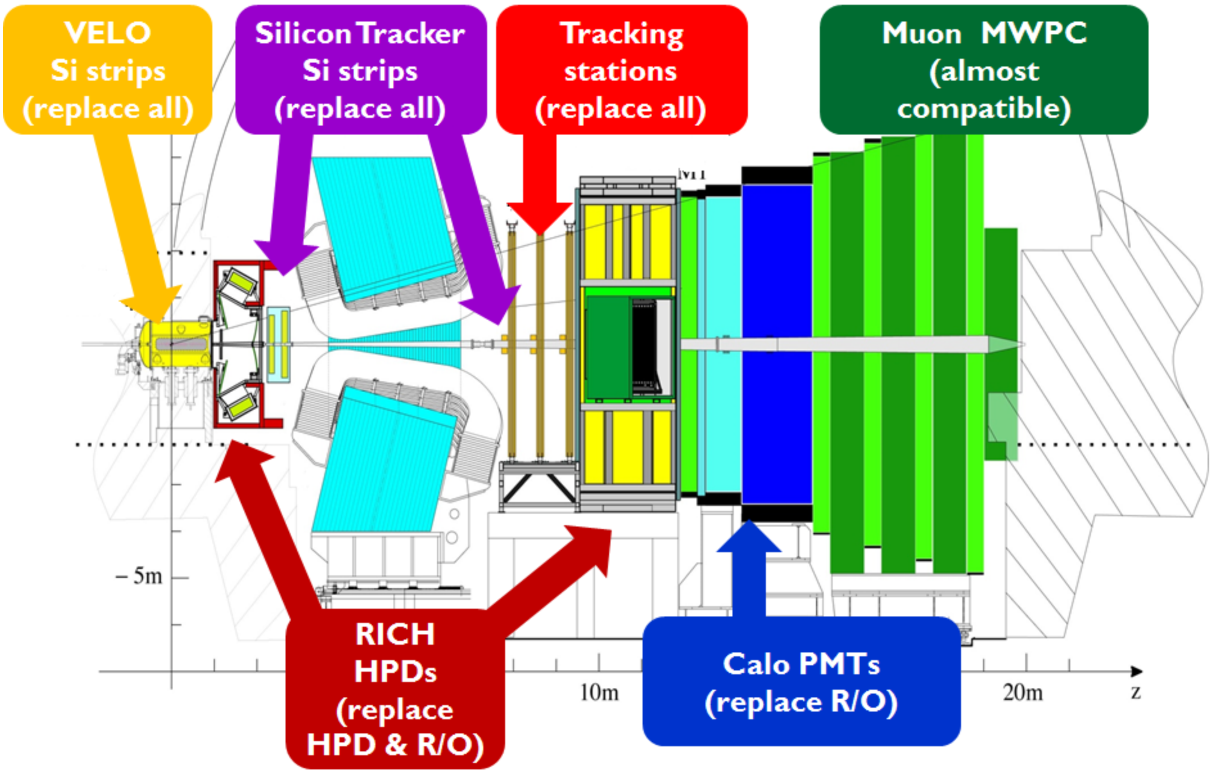

**Figure 1.** Schematic view of the upgraded LHCb spectrometer. Respective subdetectors are indicated along with information on the scope of modification with respect to the current setup. VELO, silicon tracker (TT + IT) and both RICH detectors will be completely replaced.

The most severe limitation of the current detector is the fixed-latency hardware L0 part of the trigger system. In order to increase the physics, reach and discovery potential of the LHCb experiment this bottleneck must be removed. This will make the full detector readout at 30 MHz possible, however, must also be followed by a major upgrade in detector sub-systems in order to cope with the increased throughput. The upgraded LHCb detector is diagrammatically shown in Figure 1. The whole detector system, apart from the magnet, will be replaced. The micro-strip vertex detector will be replaced with a pixel silicon detector, the silicon micro-strip Upstream Tracker (UT) will replace the current TT and finally downstream tracking stations will be changed to scintillating fibers detector. Also, the RICH detectors will be completely new. Calorimeters and muon chambers readout electronic will be modernized accordingly.

## 3. Evolution of the Trigger System

The modernised LHCb trigger that is meant for Run-III and beyond, is pushing the envelope by introducing a completely new approach which is meant to remove the boundaries between the online and offline data processing. The most innovative features of the upgraded LHCb trigger are: offline quality tracking performed in the real time, run-by-run quasi online calibration and alignment as well as the trigger level physics selections. There are very interesting implications of having such a trigger system on the physics performance of the experiment. Firstly, any subsequent offline data analysis would be using the very same tracks and vertices that were used to select the events in the first place. This should assert the consistency between online and offline selections and improve time stability of the physics results in the course of data taking. Secondly, with the calibration runs performed in quasi online mode there will be no need for the frequent re-processing, which makes it possible to discard the redundant raw data completely and store only high level objects like tracks or vertices.

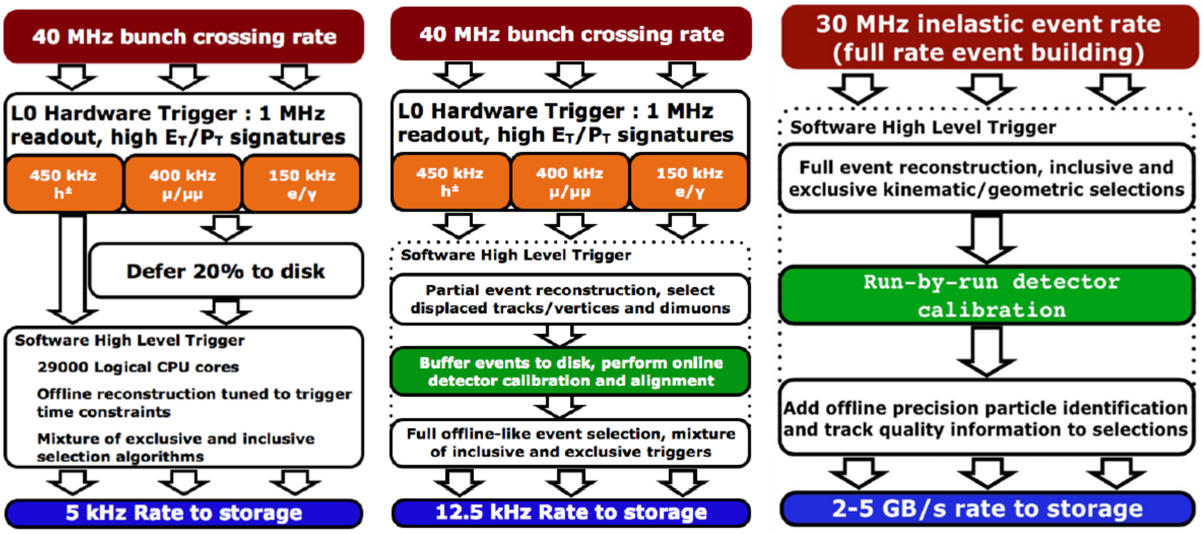

**Figure 2.** Schematic representation of the HLT trigger architectures. Run-I/2012 with 20% of L0 accepted events being deferred for offline processing (left plot), Run-II trigger with asynchronous Hlt1 and Hlt2 stages – all Hlt1 accepted events are deferred (middle plot), Run-III/2020 trigger with one fully software layer of processing.

Although, these ideas were initially meant for the upgraded trigger system (Run-III) many of them, to large extent, have already been implemented and exploited during both Run-I and Run-II data taking periods. For instance, the software component of the trigger system had been logically divided into two parts, called Hlt1 and Hlt2 respectively, for the entire Run-I. Hlt1 accepts events triggered by the L0 and performs partial reconstruction of charged particle trajectories using the full information from the tracking system. If at least one track is detected that fulfil tight quality and transverse momentum criteria the whole event is accepted and passed to the second level of the software trigger[2]. The output event rate of Hlt1 can be tuned by changing the respective thresholds, in the end of Run-I the output rate was approximately 150 kHz. At the end of Run-I (2012) about 20% of L0 accepted events were deferred to local hard drives and they were subsequently processed asynchronously in the inter-fill periods (see Figure 2 left plot).

In Run-II the two parts of the HLT trigger have been completely split and are working asynchronously (see Figure 2 middle plot). The L0 candidates are processed by the Hlt1 part which attempts the partial event reconstruction and selection of displaced tracks and vertices (similarly to Run-I operation also di-muon candidates are selected). The Hlt1 output is then stored on disks and full calibration and alignment of the LHCb detector is performed. Subsequently, the data cached in the disk buffer are processed by the Hlt2 using the updated calibration and alignment constants that are determined on run-by-run basis. During the data taking the Hlt2 has always lower priority to Hlt1 instance in order not to interfere with its performance – events not triggered by Hlt1 are lost permanently. The Hlt2 trigger runs the full event reconstruction, using the Kalman filter algorithm to fit particle trajectories, starting from the Hlt1 tracks and vertices and on top of this performs the particle identification. The results obtained by studying the performance of the online executed tracking (no offline reprocessing) showed that this approach is viable with respect to results obtained offline. Moreover, the quality of tracks reconstructed at trigger level allowed to run successfully the offline like event selections which resulted in data samples of high purity. For instance, the real-time physics selections have been performed for various charm decay channels, which allowed a rapid cross-section measurements to be performed and published as the first results with 13 TeV collision data (see also Section 4).

First experiences gained in Run-II with the revised trigger system proved that offline quality tracking and physics selections can be run online. A combination of new computing resources and improvement of Hlt1 code (introduction of multivariate algorithms) allowed to reconstruct tracks with transverse momentum down to $500\ \mathrm{MeV}/c$. In turn, Hlt2 performs the full event reconstruction without any up-front cuts on transverse momenta (in Run-I a cut of $300\ \mathrm{MeV}/c$ was applied).

For Run-III the overall architecture of the trigger system will be similar to that used so far. The first part, so called, Low Level Trigger (LLT) will select events containing high transverse energy or momentum objects using information from the calorimeters and muon chambers respectively. The high level software part will be divided into two parts, Hlt1 and Hlt2, and executed asynchronously. The whole output stream of Hlt1 will be saved on local disks whilst the full calibration procedure will be performed on the run-by-run basis. Similarly, to the present Run-II trigger Hlt1 will perform partial reconstruction while Hlt2 will run inclusive and exclusive physics selections. The operational instantaneous luminosity will be $\mathcal{L} = 2\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. This impose a very big challenge on the upgrade trigger since majority of events are expected to have more than one primary vertex. The particle multiplicity will of course increase accordingly. Also, each event will contain heavy meson with beauty or charm quark. This will bring an important shift to the operation paradigm of the trigger system – we will no longer be interested in simple signal background discrimination but rather in signal categorisation.

## 4. Quasi-online Calibration and Alignment

Additional computing resources installation in the LHCb EFF allowed to store all of Hlt1 selected candidates in a disk buffer and perform calibration and alignment on the fly. This in turn provides information to Hlt2 part of the software trigger and effectively makes any further data reprocessing not necessary. Dedicated calibration and alignment tasks are run on selected EFF nodes using data samples from Hlt1 and usually take about several minutes to complete. Results of the calibration tasks are used for both Hlt1 and Hlt2 to get the optimal results during subsequent processing. The frequency of calibration tasks varies depending on the parameters being calculated. Some of them need to be

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[2] A di-muon combination also can fire the Hlt1.

evaluated each time a new fill is prepared and other, more stable, can be determined less frequently. New calibration constants are compared to the ones used at a given time and if a significant change is detected the old calibration is updated. The new set of parameters is stored in a specialised data base as a function of time. One of the most critical issue that has a direct impact on the physics performance (momentum and mass resolution) of the whole LHCb spectrometer is misalignment of the tracking system. The alignment constants are calculated using an algorithm that performs the residuals minimisation of Hlt1 tracks reconstructed with a Kalman fitter. The improvement in mass resolution obtained with properly align tracking detectors is shown in Figure 3.

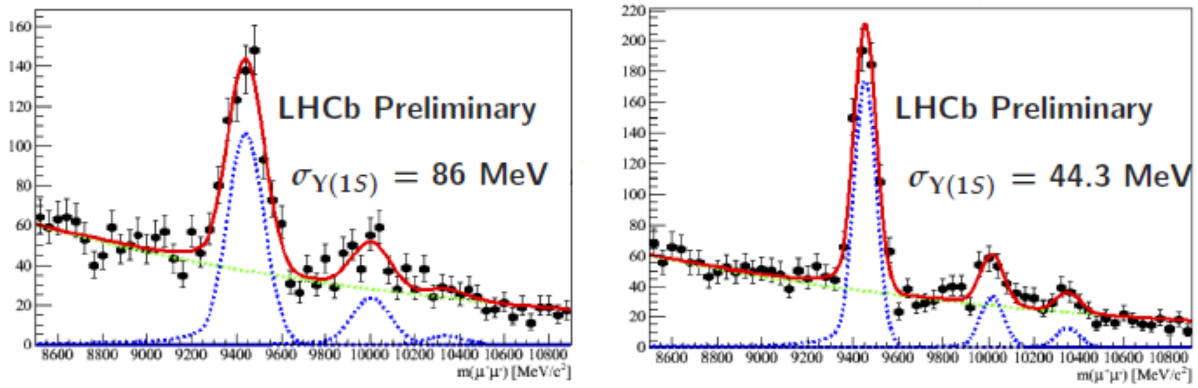

**Figure 3.** Invariant mass distribution of the $\Upsilon \to \mu^+\mu^-$ decays measured by the LHCb experiment. The three peaks correspond (from left to right) to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3)$. The left-hand side plot shows the mass spectrum obtained without optimized alignment constants, whilst the right-hand side one shows the same distribution after the final alignment was evaluated.

Alignment constants are also determined for RICH detectors for each mirror individually. For misaligned RICH the Cherenkov rings are distorted which results in strong dependence of the projected track position with respect to the ring centre on the azimuthal angle. Again, the appropriate alignment constants are evaluated using well reconstructed Hlt1 tracks. Remaining calibration tasks are related with: RICH radiators refractive index measurements as a function of temperature and pressure, determination of the global drift time offset for the straw tubes in the OT stations and calibration of the gains for calorimeters. Calibration of the full spectrometer in quasi real time is extremely complex and challenging task. Providing an automatic procedure that is fast, robust and reliable is a significant achievement that is necessary for running Hlt2 part of the trigger.

## 5. Trigger Level Event Selections in Run-II

The quasi real-time calibration and alignment procedure described in Section 4 allows to achieve the offline quality of the track reconstruction and event selections performed in Hlt2. Exploiting this fact a part of the trigger output bandwidth has been dedicated to, so called, Turbo Stream [3]. The candidates from the Turbo Stream are ready for the final physics analyses without necessity for any reprocessing in just a few hours after the data were taken. Turbo events are prepared using a specialised Tesla application [4] that is a part of the official LHCb framework. These events contain only the objects (e.g., track, vertices, etc.) that were used to trigger them by Hlt2, thus, their size is more than one order of magnitude smaller comparing to events from the full stream. The Turbo Stream performance was tested at the beginning of Run-II using first proton-proton collisions. The LHCb Collaboration was able to perform successfully a series of “early measurements”, based on the Turbo events, including various cross-sections for quarkonia, beauty and charm production.

The Turbo events were used for the first time to measure the production cross-section of the $J/\psi$ meson. The Turbo candidates were used directly to extract the number of prompt $J/\psi$ and $J/\psi$-from-b using the pseudo-decay time variable [5]. Invariant mass distribution was, in turn, used to distinguish between the real meson production and the background events. In Figure 4 fits to the invariant mass distribution of both $J/\psi$ fractions and the pseudo-decay time, coming directly form the Turbo Stream and processed by Tesla, are presented. This results were presented publicly just one week after the sample was collected.

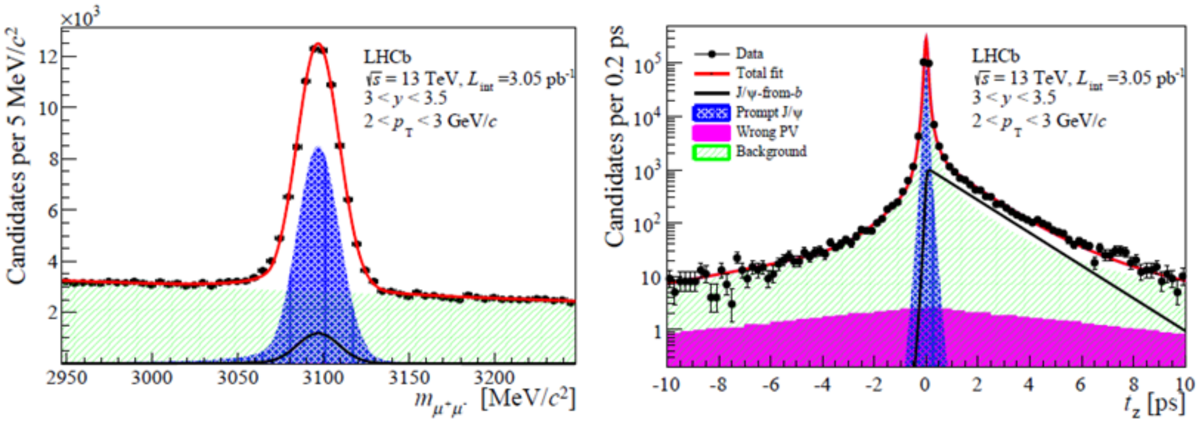

**Figure 4.** Invariant mass (left-hand side plot) and pseudo-decay time (right-hand side plot) distributions plotted for one selected $(p_T, y)$ bin. Fit results are superimposed as well (solid line), the shaded area corresponds to the background events. Prompt and secondary $J/\psi$ are represented by cross-hatched area and solid black line respectively.

## 6. Summary

The LHCb Collaboration is preparing a truly novel approach for the trigger system that is will be operational in Run-III. The full detector will be read out for each beam crossing and processed by a fully software trigger. The reconstruction, particle identification and event selections will be run online with offline quality thanks to quasi real-time calibration and alignment that will be performed on run-by-run basis. A number of ideas related to this scheme of operation has already been implemented for Run-II trigger and successfully tested. LHCb Collaboration proved that it is possible to achieve offline quality physics results in online system.

## Acknowledgements

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