The LHCb trigger system

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(ricevuto il 3 Giugno 2008; pubblicato online il 4 Agosto 2008)

Summary. — The LHCb experiment intends to perform highly accurate measurements on CP-violating processes and rare decays of B-mesons at the Large Hadron Collider. The ratio between the expected p-p inelastic cross-section (about 100 mb) and the b-b cross-section (0.5 mb) demands for a very robust and efficient trigger system. In this paper the two trigger levels (Level-0 and High Level Trigger) foreseen for the experiment are described and their main performance analysed. The expected annual yields of some of the most interesting B-decay channels are also summarised.

PACS 29.40.Cs – Gas-filled counters: ionization chambers, proportional, and avalanche counters.
PACS 29.40.Vj – Calorimeters.
PACS 29.40.Wk – Solid-state detectors.
PACS 29.85.Ca – Data acquisition and sorting.

1. – Introduction

The LHCb experiment [1] will operate at an average luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, much lower than the maximum design luminosity of the LHC. The number of interactions per bunch crossing is dominated by single interactions (fig. 1 (left)), which facilitates triggering and reconstruction by assuring low channel occupancy. In order to enhance the signal over the background, two main characteristics of B-decay events can be exploited: the high mass of the B-mesons and its long lifetime as shown in fig. 1 (right). Due to the LHC bunch structure and to the low luminosity, the crossing frequency with visible interactions(1) by the spectrometer is about 10 MHz, which has to be reduced by the trigger to about 2 kHZ, at which rate the events are written to storage for the off-line analysis. This reduction is achieved in two trigger levels [2]: the Level-0 (L0) and the High Level Trigger (HLT). The L0 is implemented using custom made electronics, operates synchronously with the 40 MHz bunch crossing frequency, while the HLT is

(*) On behalf of the LHCb Collaboration.
(1) An interaction is defined to be visible if it produces at least two charged particles with sufficient hits in the detector to allow them to be reconstructible.
executed asynchronously on a processor farm, using commercially available equipment. The bunch crossings with visible p-p interactions are expected to contain a rate of about 100 kHz of B-meson pairs. However, only about 15% of these events will include at least one B-meson with all its decay products contained in the spectrometer acceptance. Furthermore the branching ratios of interesting B-meson decays used to study for instance CP violation are typically less than $10^{-3}$.

2. – The Level-0 Trigger

The purpose of the L0 trigger is to reduce the LHC beam crossing rate of 40 MHz to the rate of 1 MHz with which the entire detector can be read out. A Level-0 Decision Unit (L0DU), as shown on the left in fig. 3, collects information from three sub-systems: the VELO [3], the calorimeter [4] system and the muon detector [5] and derives the final Level-0 trigger decision for each bunch crossing.

2'1. The pile-up veto system. – The pile-up system aims at individuating events with more than one visible p-p interaction. It is based on four silicon detectors of the same type as those of the VELO to measure the radial position of the tracks. It is placed upstream of the interaction point with respect to the LHCb apparatus and thus looks for tracks that do not enter in the LHCb detector. Because of its position, it is not sensitive to secondary vertices due to B-meson decays. It is able to detect secondary interaction point with an efficiency of 65% and a purity of 95%.

2'2. The calorimeter system. – The calorimeter trigger is based on the information provided by the calorimeter system shown on the left of fig. 2. It looks for high–transverse-energy ($E_T$) electrons, $\gamma$, $\pi^0$ or hadrons. It forms clusters by adding the $E_T$ of $2 \times 2$ cells and selecting the clusters with the largest $E_T$. The clusters are identified as electrons, photons or hadrons exploiting the information of a Scintillator Pad Detector (SPD), of a 2.5 $X_0$ Pre-Shower and of the electromagnetic (ECAL) and hadronic calorimeter (HCAL). The total $E_T$ measured by the HCAL is sent to the L0DU to reject crossings without visible interactions and to reject trigger from the beam halo. The calorimeters calculate the total observed energy and estimate the number of tracks, based on the number of hits in the SPD. With the help of these global quantities events may be rejected, which would otherwise be triggered due to large combinatorial background.
2.3. The muon detector. – The muon chambers provide a stand-alone muon reconstruction with a transverse-momentum \( (p_T) \) resolution of about 20%. Muon track finding is performed by processing elements which combine the data from the five stations to form tracks pointing towards the interaction region as shown on the right of fig. 2. The muon L0 selects the two muons with highest \( p_T \) in each quadrant in the muon detector.

The system is fully synchronous with the 40 MHz bunch crossing signal of the LHC. The latencies are fixed and depend neither on the occupancy nor on the bunch crossing history. All L0 electronics is implemented in fully custom designed boards, which make use of parallelism and pipelining to do the necessary calculations fast enough. Typical L0 efficiencies are shown in fig. 3 (right).

3. – The High Level Trigger

In order to be able to reduce the event rate from 1 MHz down to 2 kHz, the HLT makes use of the full event data available and in particular of the tracker measurements [6]. It makes use of the concept of alleys [7]. On the left of fig. 4 the alley structure is sketched. Four alleys are foreseen: muons, muons and hadrons close to each other, hadrons and electromagnetic particles (i.e. electrons, \( \gamma \) and \( \pi^0 \)). The alley to be followed is selected...
from the Level-0 decision. The generic alley selection strategy proceeds in two main steps:

1) **Refine candidates found by the Level-0.** The $p_T$ of the candidate muon tracks is measured with a resolution of the level of 1% by using the information of the tracking stations. The tracks pointing to the calorimeter candidate clusters are fully reconstructed in the VELO and with the help of the TT their $p_T$ are measured with a resolution of about 30%.

2) **Search for other $B$ decay products.** If the L0 object is confirmed, other tracks with high IP are searched for in the VELO. A rate of 30 kHz of events with secondary high-IP tracks is expected and thus the information of the tracking system can be used to evaluate the $p_T$ with an accuracy of the order of 1%.

The combined output rate of events accepted by the alleys is sufficiently low to allow to reconstruct the remaining tracks in the event. Prior to the final selection a set of tracks is selected with very loose cuts on their momentum and impact parameter. These tracks are used to form composite particles, like $\phi \to K^+K^-$, $D^0 \to \pi^+\pi^-$ or $J/\psi \to \mu^+\mu^-$ which are subsequently used for all selections. An example of the resolution obtained on-line in reconstructing the $J/\psi \to \mu^+\mu^-$ decay is shown on the right of fig. 4. Previous trigger stages do not use cuts either on invariant mass or on precise pointing to a primary vertex. After the alley algorithms, inclusive and exclusive selections aim to use these cuts to reduce the rate down to around 2 kHz, the rate at which the data is written to storage for further analysis. The exclusive triggers are sensitive to tracking performance, while the inclusive triggers select partial $B$-decays to $\phi X$, $J/\psi X$, $DX$, $\mu X$ and $\mu h X$ and therefore are less dependent on having to reconstruct all particles on-line. However, the exclusive selections of these channels produce a smaller rate, allowing for a more relaxed set of cuts. The final trigger is a logical OR of the inclusive and exclusive selections. The 2 kHz output rate is subdivided into four different streams as shown in table I. For the most interesting channels the following annual yields are expected [8]:

- $10^5$ events for $B_d \to J/\psi K_s$, $B_d \to D^+\pi$, $B_s \to J/\psi \phi$, $B_s \to D_s \pi$;
- $10^4$–$10^5$ events for $B_s \to kk$, $B_d \to \pi\pi$, $B_d \to \pi\pi\pi$;
- 20 events of $B_s \to \mu\mu$. 

Fig. 4. – Left: sketch of the High-Level-Trigger system of alleys. Right: invariant mass of a $J/\psi$ as reconstructed with the HLT algorithm.
Table I. – Output streams of the High Level Trigger.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Output rate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-Muon</td>
<td>600 Hz</td>
<td>Muon pairs with invariant mass higher than 2.5 GeV mainly due to resonance decays. Useful for evaluating the uncertainties on the lifetime measurements.</td>
</tr>
<tr>
<td>Inclusive B</td>
<td>900 Hz</td>
<td>High-(p_T) and IP muons with high-(p_T) and IP hadrons produced in heavy hadron decays. They allow studies about the performance of the trigger and tagging.</td>
</tr>
<tr>
<td>Exclusive B</td>
<td>200 Hz</td>
<td>The B-decay channels for the main physics studies.</td>
</tr>
<tr>
<td>Inclusive D</td>
<td>300 Hz</td>
<td>D-meson decays used to evaluate the PID performance.</td>
</tr>
</tbody>
</table>

4. – Conclusion

The structure and strategies of the LHCb trigger system were presented. The Level-0 trigger, completely based on custom electronics, is flexible and robust and shows good performance for the LHCb physics program. The High Level Trigger is a software one and will run on a farm of several hundred nodes. Algorithms separated in dedicated trigger selections exploit the Level-0 triggering information and refine the selection. The HLT selects events sent for subsequent offline, with a rate of 2 kHz.

REFERENCES