We give an outline of the LHCb trigger strategy and performance. The first and second levels (called L0 and L1) are discussed in some detail, while the subsequent Higher Level Trigger (HLT), which is currently under development, is only briefly described.

1 Introduction

Precise measurements of CP-violating asymmetries, oscillation parameters and branching ratios on numerous B-decay channels will allow an overdetermination of CKM parameters, with possible inconsistencies pointing to physics beyond the Standard Model. In order to achieve this, an experiment capable of triggering on the various decay modes of B-mesons (in particular hadronic modes) is desirable. LHCb is an experiment dedicated to such precision studies at the large hadron collider (LHC). It is designed as a forward spectrometer, because B\(\overline{B}\) pairs are expected to be predominantly produced at small polar angles. An overview of the LHCb detector and trigger scheme is shown in Figure 1.

The trigger contains three levels, called Level-0 (L0), Level-1 (L1) and Higher Level Trigger (HLT).

**L0** uses information from the Pile-up Veto, the calorimeters and the muon chambers. All electronics are implemented in full custom boards, however only commercial components are used. Part of the functionality of the calorimeter triggers is placed in an environment which is expected to receive a few hundred rad per year, all other hardware is housed in a radiation-free region. L0 is fully synchronous, i.e. its latency does not depend upon occupancy nor on history. The front-end electronics allow a maximum latency of 4 \(\mu\)s, and the maximum output rate is limited to 1.1 MHz due to the multiplexing of the FE electronics of the other sub-systems.

**L1** is based on two silicon tracker systems (the vertex locator, VELO, and the trigger tracker, TT) and on the summary information of L0. The trigger algorithm is implemented on a commodity CPU farm. Its maximum output rate is 40 kHz, at which rate full event building is performed.

**HLT** has access to the full event data, and is executed on the same commodity CPU farm. The algorithm first confirms the L0 and L1 triggers with better precision, and then will mimic the off-line selection algorithms for the various channels to reduce the rate to 200 Hz, at which rate events will be written to storage. The HLT algorithms are under development, and will be described in more detail in the forthcoming LHCb trigger technical design report.

The L0 and L1 triggers have been simulated in the standard LHCb software framework, which includes an event generator tuned to the LHCb phase-space (Pythia 6.205), a detailed material description of the detector (in Geant3) and a realistic description of the digitization stage with various sources of background (electronics noise, cross-talk, machine background, etc.).
2 Level-0 trigger

The L0 trigger has two distinct components: on the one hand B-meson decay products, such as large $E_T$ leptons and hadrons, are reconstructed, while on the other hand global event variables such as the number of interactions and multiplicities are collected. The former are used to distinguish interactions with interesting B-meson decays from the minimum-bias background, while the latter are used to assure that the events are selected based on the B signature rather than because of large combinatorics. Thus, it is avoided that these events occupy a disproportional fraction of the data-flow bandwidth or available processing power.

The muon chambers allow stand-alone muon reconstruction with a $p_T$ resolution of $\sim 20\%$ [3]. The chambers are subdivided into 120k pads and strips. Pads and strips are combined to form 26k so-called logical pads, which range in size from $1.0 \times 2.5 \text{cm}^2$ near the beam to $25 \times 31 \text{cm}^2$ for the pads in M5 furthest away from the beam. All pads are projective in the non-bending plane. One crate per quarter houses the trigger boards which reconstruct the two muons with the largest $p_T$. There are no cross connections between the crates, and hence muons crossing the quarter boundaries are not reconstructed.

The calorimeter system [5] provides the following information for the L0 trigger:

1. The electromagnetic calorimeter (ECAL) is of the shashlik type, 25 radiation lengths thick, contains 5952 cells, and provides 8-bit $E_T$ information per cell.

2. The preshower (PS) collects the light after 2.5 radiation lengths of lead, is also subdivided in 5952 cells, and provides one bit per cell for $e/\pi$ separation by setting a threshold that depends on the radial position of the cell.

3. The scintillating pad detector (SPD) distinguishes between charged and neutral particles which produce a shower in the ECAL, and consists of 5952 cells, providing one bit per cell.

4. The hadronic calorimeter (HCAL) is constructed of iron/scintillating tiles subdivided into 1468 cells and also provides 8-bit $E_T$ information per cell.

The implementation of the calorimeter trigger is based on forming clusters by adding the $E_T$ of $2 \times 2$ cells, and selecting the clusters with the largest $E_T$. Clusters found in the ECAL are identified as e, $\gamma$ or hadron depending on the information from the PS and SPD. The largest HCAL clusters have the energy of the corresponding ECAL cluster added to them if this ECAL cluster is the largest cluster in an area of $4 \times 8$ cells and matches the HCAL cluster position. By summing all transverse energy in $4 \times 8$ cells in the ECAL so-called local-$\pi^0$ candidates are formed. Largest $E_T$ clusters on neighbouring groups of $4 \times 8$ cells in the ECAL are combined to form so-called global-$\pi^0$ candidates. The $E_T$ of all HCAL cells is summed to provide global event information to allow an interaction trigger. The total number of SPD cells with a hit are counted to provide a measure of the charged track multiplicity in the crossing, a parameter that is used to reduce the data size and processing time in the L1/HLT CPU farm while preserving the signal efficiencies [3].

The proposed physics measurements at LHCb are best done with events that contain only 1 or 2 primary vertices. For this reason the luminosity at LHCb will be tuned in the range $2\sim5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$. To further increase the event fraction with a single interaction, the Pile-up Veto detector is incorporated in L0. It uses four silicon sensors of the same type as those used in the VELO to measure the radial position of tracks and distinguish between crossings with single and multiple visible interactions. The sensors are subdivided in two stations located upstream of the interaction point, covering $-4.2 < \eta < -2.9$. For tracks coming from the beam-line the radial position $r$ of a track passing the two stations at $z_A$ and $z_B$ is related to their origin by $z_{\text{vertex}} = (r_B z_A - r_A z_B)/(r_B - r_A)$. The sensors provide 2048 binary channels using the Beetle front-end chip [7]. The radial hits are projected into an appropriately binned histogram according to the above relation using FPGAs. All hits contributing to the highest peak in this histogram are masked, after which the height of the second peak is a measure of the number of tracks coming from a second interaction in the crossing. Apart from the backward track multiplicity in the first and second vertex found, the Pile-up Veto provides the position of these vertex candidates along the beam-line and the total hit multiplicity in the two stations. The Pile-up Veto information allows a relative luminosity measurement [8].

The L0 decision unit (LODU) collects all information from L0 components to form the L0 trigger, i.e. the largest $E_T$ e, $\gamma$, $\pi^0_{\text{local}}$, $\pi^0_{\text{global}}$, and the two largest $E_T$ hadron clusters. Global event variables are also collected: the SPD multiplicity, and the sum of the transverse energy of the HCAL of the actual crossing, and of the two preceding and following crossings. From the possible eight muons provided by the four quadrants of the muon trigger the three largest in $p_T$ are selected. Finally the Pile-up Veto information is also used. The LODU is able to perform simple arithmetic to combine all signatures into one decision per crossing. The algorithm employed at the moment accepts events where at least one of the largest $E_T$ e, $\gamma$, $\pi^0_{\text{local}}$, $\pi^0_{\text{global}}$, hadrons or muons is above the trigger threshold for the corresponding particle type (about 2.6, 3, 4.8, 4.9, 3.5 and 1.3 GeV, respectively), providing the Pile-up Veto detects less than three tracks coming from a second primary vertex. Events are also accepted if the sum of the $p_T$ of the two muons with the largest transverse momentum are above a thresh-
old, irrespective of the Pile-up Veto result. Other global event variables like hit multiplicities of the Pile-up Veto and SPD are not yet used in the results presented below, but instead are considered as contingency.

The above mentioned thresholds have to be set such that the output rate of L0 is 1.1 MHz. The L0 hadron trigger plays a central role in LHCb, occupying approximately 60% of the total L0 bandwidth while the muon/di-muon and $e/\gamma/\pi^0$ triggers fill each about 20%. Note also that, of the 40 million nominal LHC bunch crossings per second, only 75% occur with oppositely moving bunches, and in only about 1/3 of these cases is a collision expected which produces at least 2 tracks in the LHCb detector. Hence, the “visible” event rate is about 10 MHz. Therefore, the LHCb L0 trigger reduces the visible rate by only a factor of 9, by applying relatively soft $E_T$ and $p_T$ cuts. After this modest rate reduction, a full software trigger is used to further filter the events.

3 Level-1 trigger

The L1 trigger exploits the finite life time of the B-mesons in addition to the large B-meson mass as a further signature to improve the purity of the selected events. The following information is used by L1:

1. The L0DU summary information as described in the previous section.

2. The VELO measurements of the radial and angular position of the tracks, in silicon planes perpendicular to the beam-line between radii of 8 mm and 42 mm. The angular position is measured with quasi-radial strips with a stereo angle between 10–20°. A cluster search algorithm is performed in the 170k channels using FPGAs to find roughly 1000 clusters per event.

3. The TT measurements from its four silicon planes, two with vertical strips and two with a ±5° stereo angle. About 400 clusters are found in 144k channels using the same implementation as the VELO and a similar algorithm.

The L1 trigger algorithm will be executed on ~500 commodity CPUs, and requires event building at 4 kbytes/event to be performed at a L0 output rate ≤ 1 MHz.

B-mesons with their decay products in the LHCb acceptance move predominantly forward along the beam-line, which implies that the projection of the impact parameter in the plane defined by the beam-line and the track is large, while in the plane perpendicular to the beam it is almost indistinguishable from primary tracks. The L1 algorithm exploits this by reconstructing so-called 2D tracks using only the VELO sensors which measure the radial position.

The 2D track finding efficiency for charged tracks originating from a B-meson decay and inside the acceptance of the spectrometer is ~98%. The 2D tracks are also sufficient to measure the position of the primary vertex since the strips at constant radius are segmented in 45° φ-slices. The RMS of the primary vertex resolution obtained is 170 $\mu$m and 50 $\mu$m in the directions along and transverse to the beam respectively. Figure 2 shows an event display of the result of the 2D track search in a 45° slice of the VELO. In this event 72 forward tracks are found in total, while the mean number of forward tracks in L1 events is 58.

Half of the clusters in the VELO are used to measure the impact parameter of tracks, and make a preselection on B-decay candidates. Using the sensors measuring the angular position, the candidate tracks with an impact parameter between 200 $\mu$m and 3 mm are then converted to tracks in three dimensions (3D tracks). The B-decay can-
The final L1 trigger decision is made by combining the information from tracks with significant impact parameter significance for (a) off-line selected $B^0 \rightarrow D_s^+ K^-$ events, and (b) minimum-bias events which have been accepted by L0. Indicated is the cut which selects 4% of the minimum-bias events.

Candidates are also matched to the electron and hadron clusters from the L0-calorimeter trigger, and the L0-muon candidates. In Fig. 3 the invariant mass formed from all oppositely-charged pairs of L0-muon candidates that have been matched to 3D VELO tracks is shown. A clear $J/\psi$ signal can be seen, while in minimum bias events only a small fraction of the events have a $\mu\mu$-candidate with an invariant mass above 2 GeV.

About eight 3D tracks per event are selected based on their impact parameter and matched to hits in TT to measure their momenta. The 3D VELO tracks are considered matched if at least three hits are found in the four TT planes. The magnetic field distribution allows a momentum resolution of about 20–40% depending on the momentum, which is sufficient to use the $p_T$ of tracks as a B signature, and also allows the error on the impact parameter to be calculated including multiple scattering. The field in between the VELO and TT is parametrized to take its non-uniformity into account.

The final L1 trigger decision is made by combining the information for tracks with significant impact parameter, large $p_T$ and possibly being matched to leptons and hadrons from L0. Figure 4 shows how the $p_T$ and impact parameter significance are used to distinguish between the minimum-bias background events and, in this example, the channel $B^0_s \rightarrow D_s^- K^-$. Events are selected according to the logarithmic sum of the $p_T$ of the two VELO–TT tracks with the largest $p_T$ in the event, and the logarithmic sum of their impact parameter significance. Events are also accepted if the invariant mass formed from two oppositely-charged pairs of L0-muon candidates exceeds 2 GeV/$c^2$. Channels with leptons in the final state especially profit from the matching between VELO tracks and L0-lepton candidates, while the VELO–TT and VELO–L0-hadron matching boosts the efficiency for hadronic final states compared to just exploiting the impact parameter information from the VELO.

### Table 1

| Channel                  | $\epsilon_{L0}$ | $\epsilon_{L1}$ | $\epsilon_{L0L1}$ | Yield |
|--------------------------|------------------|------------------|-------------------|-------|
| $B^0_d \rightarrow \pi^+ \pi^-$ | 61%              | 51%              | 31%               | 27 k  |
| $B^0_d \rightarrow K^+ \pi^-$  | 60%              | 49%              | 29%               | 115 k |
| $B^0_s \rightarrow K^+ K^-$    | 57%              | 48%              | 27%               | 35 k  |
| $B^0_s \rightarrow D_s^- \pi^+$ | 46%              | 53%              | 24%               | 72 k  |
| $B^0_s \rightarrow D_s^- K^-$   | 44%              | 65%              | 29%               | 8 k   |
| $B^0_s \rightarrow J/\psi(\mu^+ \mu^-)\phi$ | 93%              | 73%              | 68%               | 109 k |
| $B^0_s \rightarrow J/\psi(e^+ e^-)\phi$   | 52%              | 43%              | 22%               | 19 k  |
| $B^0_s \rightarrow J/\psi(\mu^+ \mu^-)K_s^0$ | 91%              | 71%              | 65%               | 119 k |
| $B^0_s \rightarrow K^+ \gamma$       | 82%              | 33%              | 27%               | 20 k  |

### 4 Summary

We have presented the LHCb trigger strategy and performance. Table 1 shows the efficiency of the L0, L1 and combined L0×L1 triggers relative to off-line selected and untagged events for a sample of physics channels. The last column gives the expected annual yield of untagged B decays useful for physics analysis. Studies are now concentrating on developing the HLT with efficiencies in excess of 90% and on optimising the trigger chain with respect to flavour-tagged physics events.

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