The LHCb Trigger

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Abstract

LHCb will study CP violation and other rare phenomena in B-decays with a forward spectrometer at the LHC. The LHCb trigger has to efficiently select a few Hz of interesting B-decays from a non-elastic pp interaction cross-section of 80 mb, which corresponds to 16 MHz of interactions at the preferred LHCb luminosity of $2{\times}10^{32}\mathrm{cm}^{-1}\mathrm{s}^{-1}$. The first trigger level reduces the rate to 1 MHz using large E_t triggers. At 1 MHz all data is digitised, and a subset of tracking information is used to reduce the rate to 40kHz, at which rate the full event building is performed. Having access to all detector information the rate is subsequently reduced to around 200 Hz and written to storage. This paper emphasises the data available at the various trigger stages and the algorithms employed to select B-decay candidates, rather than describing the implementation of the trigger.

1 Introduction

In pp interactions at 14 TeV in the centre of mass both the b and $\overline{b}$-hadrons are predominantly produced in the same forward cone. This consideration has led to the design of the LHCb single-arm spectrometer [1], which is depicted in Fig. 1. The LHC bunch crossing rate is 40.08 MHz, however due to the bunch structure of the LHC machine only 2622 out of 3564 bunch crossings can have collisions in the LHCb interaction point. LHCb has optimised its detector and trigger for crossings with single interactions. The PYTHIA (v6.2) generator [2] predicts a non-elastic cross section of 80 mb, however only about 60 mb of this cross-section is detected by the spectrometer which covers an η range of $1.9 < \eta < 4.9$. LHCb will be provided with a low-beta insertions which will allow LHCb to tune its luminosity up to $5{\times}10^{32}\text{cm}^{-1}\text{s}^{-1}$ when the LHC maximum luminosity will be $10^{33}\text{cm}^{-1}\text{s}^{-1}$ at start-up, and down to $2{\times}10^{32}\text{cm}^{-1}\text{s}^{-1}$ when the LHC will reach its maximum luminosity of $10^{34}\text{cm}^{-1}\text{s}^{-1}$. The first level trigger (L0) identifies crossings with multiple "visible" interactions using the Silicon Pileup Veto stations located upstream of the interaction envelope, which contains 95% of the interactions within a 20-30 cm region

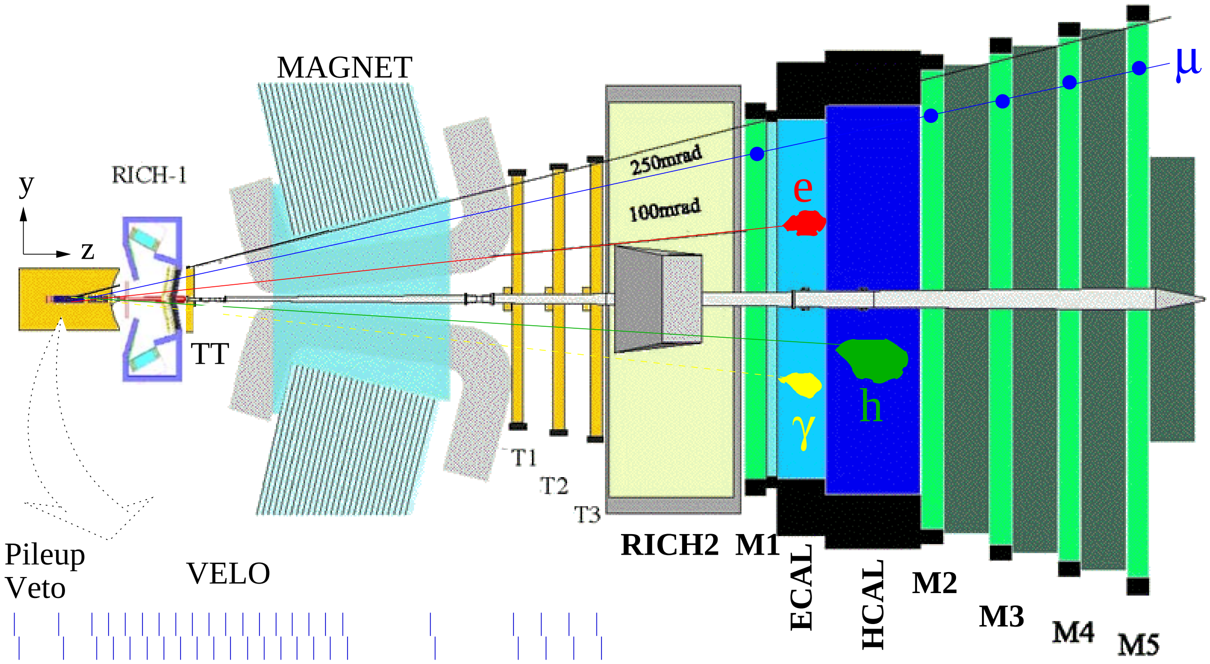

Figure 1: A side view of the LHCb spectrometer, showing the Pileup Veto, the vertex detector (VELO), two RICHes for particle identification, four tracking stations (TT, T1, T2 and T3), the di-pole magnet, five muon stations (M1-M5) and the electromagnetic (ECAL) and hadronic (HCAL) calorimeters.

along the beam depending on the time into a fill. The best yield of events containing interesting B-decays in crossings with single interactions is obtained for luminosities in the range of 2-3$\times10^{32}$cm^{-1}s^{-1}, and throughout this paper a luminosity of 2×10^{32}cm^{-1}s^{-1} will be assumed. At that luminosity the 10 MHz of crossings with visible interactions contain 8 MHz of single interactions, which is reduced to the maximum rate at which all data can be digitised, which is 1.1 MHz, using the ECAL and HCAL calorimeters and the muon chambers to reconstruct the transverse momenta of leptons, photons and hadrons. Subsequently the second level trigger (L1) makes use of the VELO and TT detectors in addition to reduce the rate to 40 kHz, at which rate the event building is performed for all LHCb data. The data is written to permanent storage at a rate of about 200 Hz, which is achieved by performing full pattern recognition using all spectrometer information to select the interesting B decays. The L0 trigger will be described in the following section, L1 will be described in section 3, and section 4 will give an overview of higher trigger level algorithms.

2 The L0-Trigger

The L0 trigger is based on the information provided by the Pileup Veto, the calorimeters and the muon stations. The implementations of all L0 triggers is fully pipelined and synchronous, making use only of non-custom components. Its input rate is 40.08 MHz, while its maximum output rate is 1.1 MHz. The relatively large B-meson mass results in decay products which have a transverse momentum significantly larger than the particles produced in interactions with only light quarks. The L0-Trigger aims at providing a large acceptance for a wide range of B-meson decays, i.e. hadronic decays like $\mathrm{B}_d \rightarrow \pi^+\pi^-$ or $\mathrm{D}^+_{\hookrightarrow K^-\pi^+\pi^+}\mathrm{D}^-_{\hookrightarrow K^+\pi^-\pi^-}$, leptonic decays like $\mathrm{B}_d \rightarrow \psi_{\hookrightarrow \mu^+\mu^-, e^+e^-}\mathrm{K}^0_S$ or channels containing a large p_T π^0 or γ like $\mathrm{B}_d \rightarrow \pi^+\pi^-\pi^0$ or $\mathrm{K}^\star\gamma$.

2.1 L0 Pileup Veto Trigger

The aim of this trigger is to distinguish between crossings with single and multiple visible interactions. It uses two Si-sensors of the same type as the VELO uses to measure the radial position of tracks, and which are described elsewhere in these proceedings [3]. The two sensors are located upstream of the interaction point, covering $-4.2 < \eta < -2.9$ in solid angle. For tracks coming from the beam-line the radial position r of a track passing the two sensors at z_A and z_B is related to their origin by z_{vertex}=($\mathrm{r}_B\mathrm{z}_A$-$\mathrm{r}_A\mathrm{z}_B$/(r_B-r_A). The two Silicon sensors provide 2048 binary channels using the Beetle FE-chip [4]. The radial hits are projected into appropriately binned histograms according to the above relation using FPGAs[5]. The highest peak is looked for in this histogram. All hits contributing to this peak, which is usually the vertex with the largest charged track multiplicity in the crossing, are removed. This cleaning step proved to be necessary to improve the sensitivity for recognising vertices which are masked by larger multiplicity vertices due to combinatorics. The height of the second peak found is shown in Fig. 2 for events which contain a $B_d \to \pi^+\pi^-$ decay in the acceptance of the spectrometer. For 95% of the single interactions the height of the second peak is $\leq$2. Multiple visible interactions per crossing will trigger the L0 at a fraction of 1-(1-ϵ)^n, where ϵ is the fraction of single interactions triggered, and n is the number of such interactions, and hence would take a large fraction of the L0 bandwidth. Typically L0 would have triggered 26% of the vetoed minimum bias events, while events considered by the Pileup Veto to have only one interaction trigger 14% of the events.

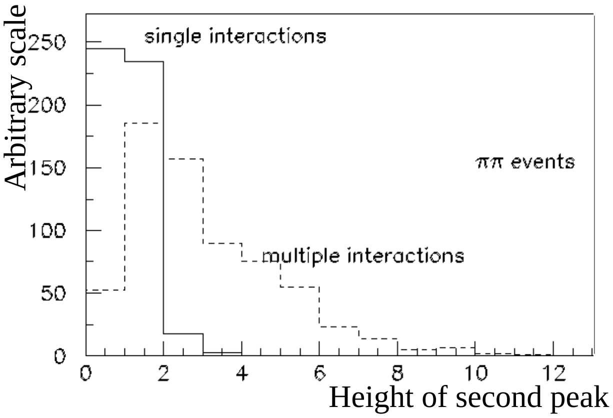

Figure 2: The height of the second peak for single interactions per crossing (solid line) and multiple interactions (dashed line) per crossing.

2.2 L0 Muon trigger

The LHCb muon chambers allow stand-alone muon reconstruction with a p_T resolution of around 20% [6]. The chambers are subdivided in 120k pads and strips, and the requirement is that each chamber has a > 99% efficiency, which is obtained by or-ing two layers per station. Pads and strips are combined to form 26k so-called logical pads, which range in size from 1.×2.5 cm^2 near the beam to 25×31 cm^2 for the pads in M5 furthest away from the beam. All pads are projective in the non-bending plane. The muon system is treated in four separate quarters. One VME crate per quarter houses the trigger boards which reconstruct the two muons with the largest p_T [7]. Fig. 3 compares the p_T distribution of the muon with the largest p_T in the events for minimum bias events, semi-leptonic B-decays and $B_d \to \psi_{\hookrightarrow\mu^+\mu^-} K^0_S$ decays, where for the signal events only those events are shown where the muon has a hit in M3. For a p_T cut of around 1 GeV/c a rate of around 200kHz for minimum bias events is obtained, while the efficiency to select $B_d \to \psi_{\hookrightarrow\mu^+\mu^-} K^0_S$ decays is around 90%. The efficiency to trigger on the semi-leptonic decay of a B-meson is around 50%. The sensitivity to background has been checked taking into account the expected μ-halo of the LHC machine, and larger background in the muon chambers, both of which constitute a negligible loss in efficiency.

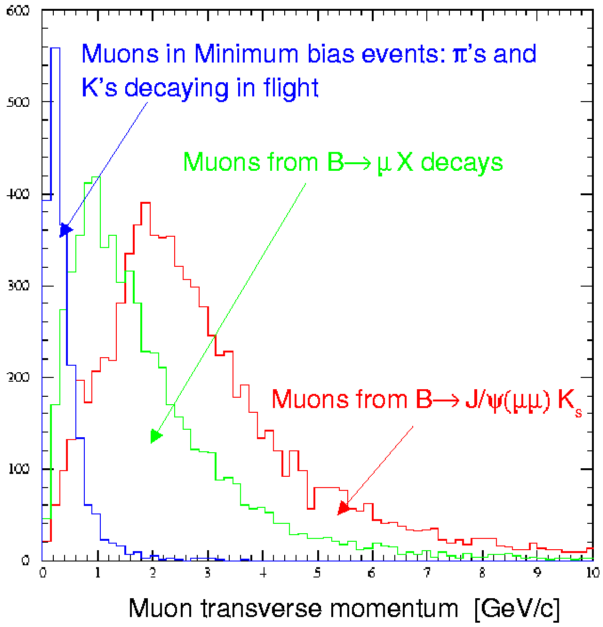

Figure 3: The p_T distributions of the muon with the largest p_T in the event for different data samples as indicated in the figure.

2.3 L0 Calorimeter Trigger

The calorimeter system [8] provides the following information for the L0 trigger:

- The Scintillating Pad Detector (SPD) measures the charge of particles producing a shower in the electromagnetic calorimeter, and consists of 5952 cells, providing one bit per cell.
- The Pre-Shower(PS) collects the light after 2.5 radiation length of lead, is also subdivided in 5952 cells, and provides one bit per cell for e/π separation by setting a threshold that depends on the radial position of the cell.
- The Electromagnetic Calorimeter (ECAL) is of the shaslik type, 25 radiation length thick, contains 5952 cells, and provides 8-bit E_T information per cell.
- The Hadronic Calorimeter (HCAL) is constructed of iron/scintillating tiles subdivided in 1468 cells and also provides 8-bit E_T information per cell.

The fully synchronous implementation of the trigger [9] is based on forming clusters by adding the E_T of 2×2 cells, and selecting the clusters with the largest E_T. Clusters found in the ECAL are identified as e,γ 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 4×8 cells in front of it. By summing all transverse energy in 4×8 cells so-called Local-π^0 candidates are formed. Largest E_T clusters on neighbouring groups of 4×8 cells are combined to form so-called Global-π^0 candidates. The E_T of all HCAL cells is summed to provide an interaction trigger, and the total number of SPD cells with a hit are counted to provide a measure of the charged track multiplicity in the crossing. Fig. 4 shows the performance for the electron and hadron triggers. At trigger rates of 100 kHz and 600 kHz for the electron and hadron trigger rates for minimum bias events respectively, the efficiencies for retaining signal events which pass the off-line selection criteria is typically 40-70% depending on the channel.

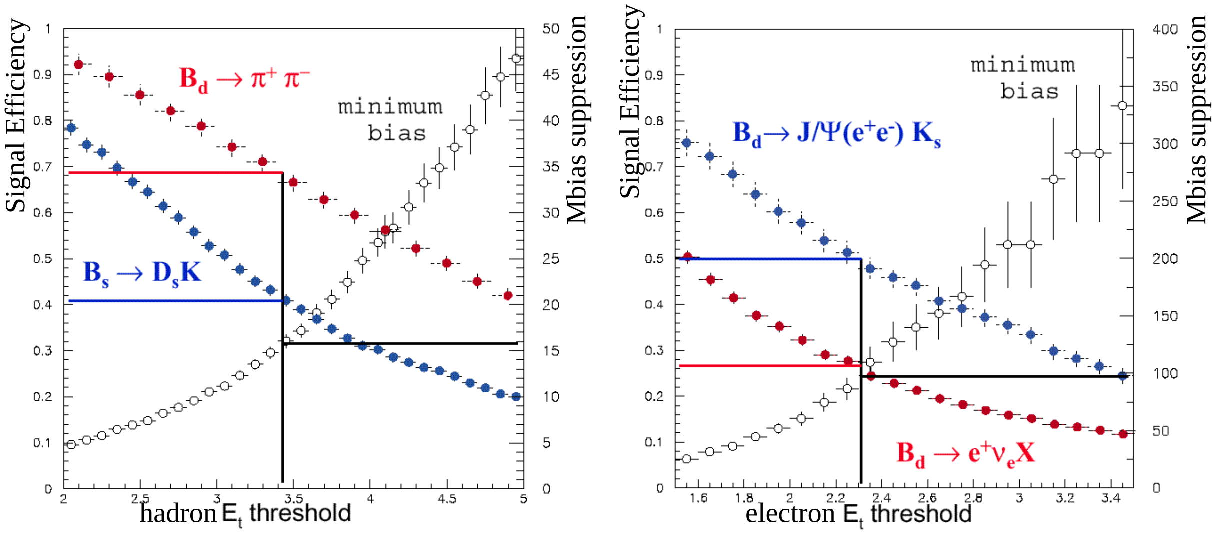

Figure 4: The E_T distributions for signal and minimum bias events for the largest HCAL (left plots) and ECAL (right plot) clusters in the event. For signal events the efficiency is determined relative to the events which pass the off-line selection. The suppression factor for minimum bias events is relative to a single interaction rate of 10 MHz, which also includes the invisible interactions.

An example of the use of the charge multiplicity as measured by the SPD is illustrated in Fig. 5, which shows the CPU time necessary to reconstruct all tracks as a function of the SPD multiplicity. By rejecting only a small fraction of events at the earliest stage of the trigger the average processing time can be reduced significantly, and events which might run into a time-out in the L1-Trigger can be rejected. The loss in efficiency is even lower than the fraction of events rejected, since the L0-thresholds can be lowered to still fill the total allowed L0-bandwidth.

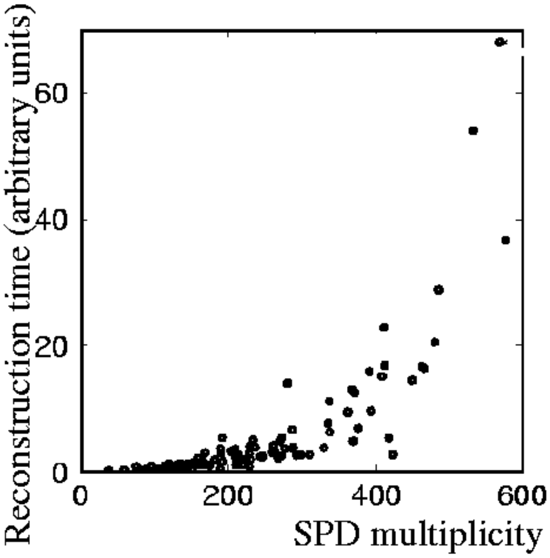

Figure 5: The time to reconstruct an event as a function of the charged track multiplicity observed in the SPD.

3 The L1-Trigger

The L1-Trigger exploits the finite lifetime 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 the L1-Trigger:

- The L0-Decision-Unit (L0DU) collects all information from L0 components to form the L0-Trigger. The L0DU provides the L1-Trigger with a summary of the information from L0, which contains the largest E_T e,γ, π^0_{Local} and π^0_{Global}. Also the two largest E_T hadron clusters and the sum of the transverse energy of the HCAL of the actual crossing, and of the preceding and following two crossings. From the possible eight muons provided by the four quadrants of the muon trigger the three largest in p_T are selected. And finally also the position of the primary vertex along the beam-line as determined by the Pileup Veto is provided.

- The VELO [10] consists of 220 μm thick Si-sensors which measure the radial and angular position of the tracks in planes perpendicular to the beam-line, starting at a radius of 8 mm from the beam-line. 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 the roughly 1000 clusters per event.

- The Trigger Tracker (TT) consists of four layers of Si-planes, two with vertical strips and two planes with a ±5° stereo angle, which measure the bending of tracks in the fringe field of the magnet between the VELO and TT. As for the VELO about 400 clusters are found in 150k channels.

The L1-Trigger algorithm is executed on commodity CPUs, which requires to perform event building of the about 3-4 kbytes/event at the L0-output rate of maximum 1.1 MHz. To achieve this the roughly 300-400 CPUs necessary are arranged in a 2D-torus, interconnected with Scalable Coherent Interfaces [11]. 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 first tracks using only the VELO sensors which measure the radial position. These so-called 2D tracks are also sufficient to measure the position of the primary vertex since the strips at constant radius are segmented in phi. Fig. 6 shows the resolution which can be obtained this way on the position of the primary vertex per event, which should be compared to the mean B-meson decay length of 7 mm. Hence halve the clusters of the VELO are used to already measure the impact parameter of tracks, and make a pre-selection on B-decay candidates. The B-decay candidates are then matched to the electron and hadron clusters from the L0 calorimeter trigger, and the L0-muon candidates for more refined B-decay candidate selection. Using the sensors with radial strips the candidate tracks are then converted to 3D tracks, and matched to hits in TT to measure their momenta. The $\int$Bdl between the VELO and TT is 0.12 Tm, which allows a momentum resolution as shown in Fig. 7, which is sufficient to use the p_T of tracks as a B-signature [12], and also allows to calculate the error on the impact parameter due to multiple scattering,

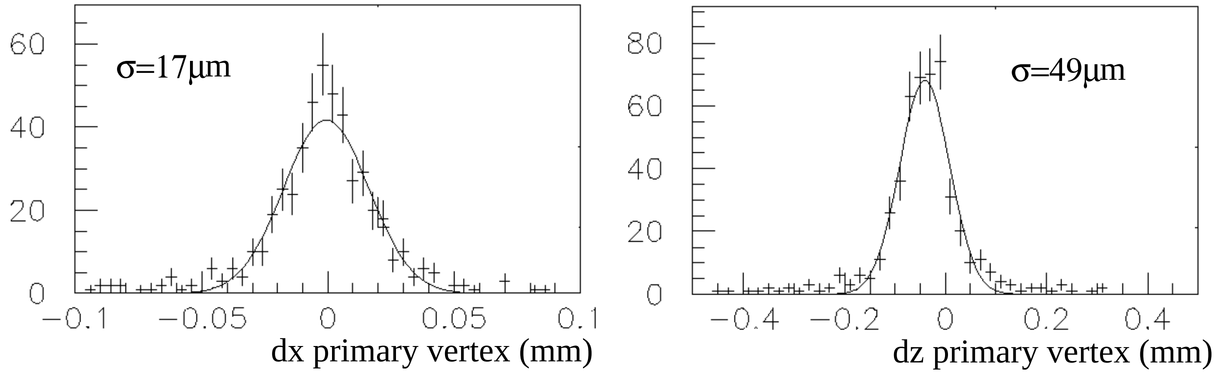

Figure 6: The primary vertex resolution per event obtained from the 2D tracks reconstructed in the r-measuring sensors only.

The final L1-Trigger decision is made by combining the information for tracks with significant impact parameters, larger p_T and possibly being matched to leptons and hadrons

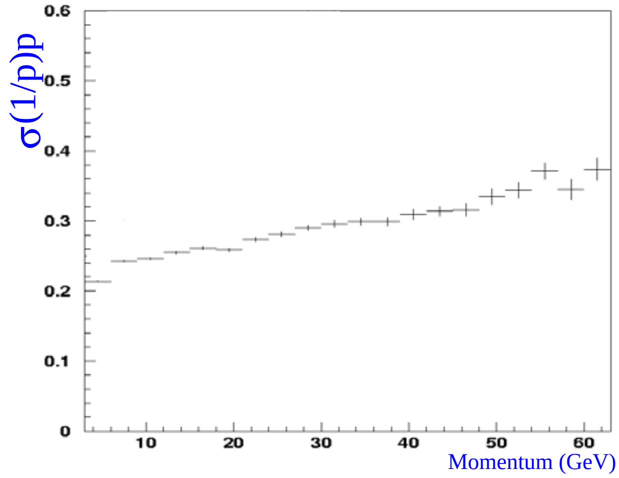

Figure 7: The momentum resolution measured for VELO-TT tracks.

from L0. For a L1-output rate of around 40 kHz efficiencies in the order of 60-90% can be obtained for channels which are accepted by the off-line reconstruction. Especially channels with leptons in the final state profit from the matching between VELO tracks and L0-lepton candidates, while the VELO-TT matching boosts the efficiency for hadronic final states compared to just exploiting the impact parameter information from the VELO.

4 Higher Level Triggers

At the L1-output rate of 40 kHz all data is readout, and the complete events are distributed over a CPU-farm which will contain around 900 units. To reduce the rate to the required 200 Hz at which the events will be written to permanent storage, the following algorithms will be employed:

- First essentially the algorithm used in L1 is repeated, but now with relaxed criteria on selecting B-decay candidates, but measuring their momenta using the tracking stations T1, T2 and T3 with a precision around 1%. With the use of T1-3 the lepton matching can also be improved. Then B-candidate events are selected using generic cuts, rather than full reconstruction as will be used in the next step, since the dominant background at this stage is still light quark events. This algorithm will reduce the rate to a few kHz, of which the $b\bar{b}$ events constitute a sizeable fraction.

- At a rate of a few kHz all tracks in an event can be reconstructed using all tracking information, i.e. VELO, TT and T1-3. Leptons can be identified, and for selected tracks the RICH information can be used for K/π separation. It is part of an ongoing study to judge if it will be possible to reach the required output rate of 200 Hz with generic cuts, or for each final state a separate selection will have to be made.

5 Summary

The LHCb L0-Trigger aims at being able to select leptons, photons and hadrons originating from B-decays down to p_T values around 1 GeV/c. In addition extra information is collected on the number of interactions per crossing, the total hadronic energy and charged multiplicity, which are aimed at selecting events which are easier to reconstruct either in the subsequent trigger levels or off-line. The L1-Trigger combines the impact parameter information obtained with the VELO detector with p_T information using either TT or the L0 clusters and tracks to reduce the rate to a level where the full event can be read out. When all data is available on the on-line farm, all tracking stations are used to get the nearly off-line momentum resolution to select the events which will be used to study CP-violation.

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