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Vertex Reconstruction and Tracking in the Trigger in LHCb

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A brief overview of the LHCb Trigger is given with details particular to the vertex reconstruction and tracking identified. The use of the silicon VETO detectors to exclude events with multiple primary vertices is described.

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[1] Speaker

1. Introduction

Below we provide a brief summary of the LHCb trigger with special reference to vertex finding and tracking [1]. Much more complete descriptions are available elsewhere[2-5]. First we note that experiment is fundamentally different from ATLAS or CMS (see these proceedings) in that it is not a General Purpose Detector (GPD) The LHCb experiment is dedicated to the study of CP violation from B-decays from pp interactions at the LHC[6]. This means the experiment concentrates on precision vertexing, tracking and the identification of charged pions, kaons and protons. These enable the high quality determination of decay positions and the high signal/noise reconstruction resonances. Before describing the trigger it is important to review some of the features of LHCb that provide its unique capabilities.

2. LHCb interaction environment

The LHC is designed to provide pp collisions at a centre of mass energy of 14TeV/c^2. It is capable of delivering luminosities of > 10^{33} $cm^{-2}s^{-1}$ which provides a sufficient number of interaction per second to enable the GPDs to fulfil their physics programme. The probability of the number of interactions per crossing as a function of luminosity is shown in Figure 1. At luminosities < 10^{31} $cm^{-2}s^{-1}$ almost every beam crossing is "empty" i.e. there is a probability > 95% that no interaction occurs. At luminosities > 10^{33} $cm^{-2}s^{-1}$ the probability of having two or more interactions per crossing rises above 25%. The original LHCb concept required that the number of interactions per crossing ~1. This retains a high number events/s (40MHz) whilst ensuring that those containing of multiple interactions are minimized. This is to provide a "clean" sample of events containing only a pairs of forward produced B hadrons [7]. Multiple events can give rise to ambiguities in the tagging of B flavours and a resultant dilution of the CP signals compared to noise. The actual operation luminosity of the LHCb experiment is chosen to be 2×10^{32} $cm^{-2}s^{-1}$ which corresponds to an average number of interactions per crossing of ~1.2 and is approximately an order of magnitude lower than that chosen for the GPDs.

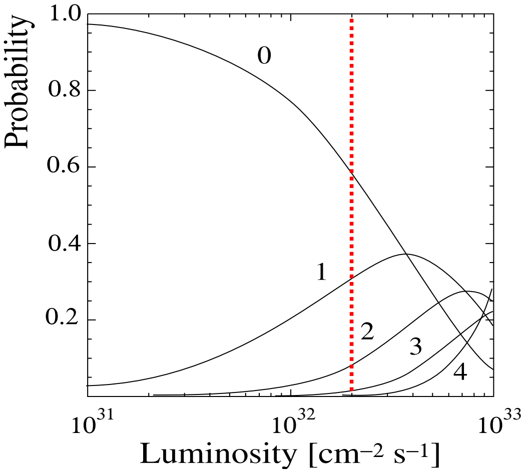

Figure 1: Number of interactions per pp crossing at the LHC as a function of luminosity.

3. LHCb detector

As the majority of B hadron pairs are produced in the forwards or backwards directions, the LHCb experiment is designed as a single arm spectrometer, see Figure 2. Key elements [8] used in the trigger are described below.

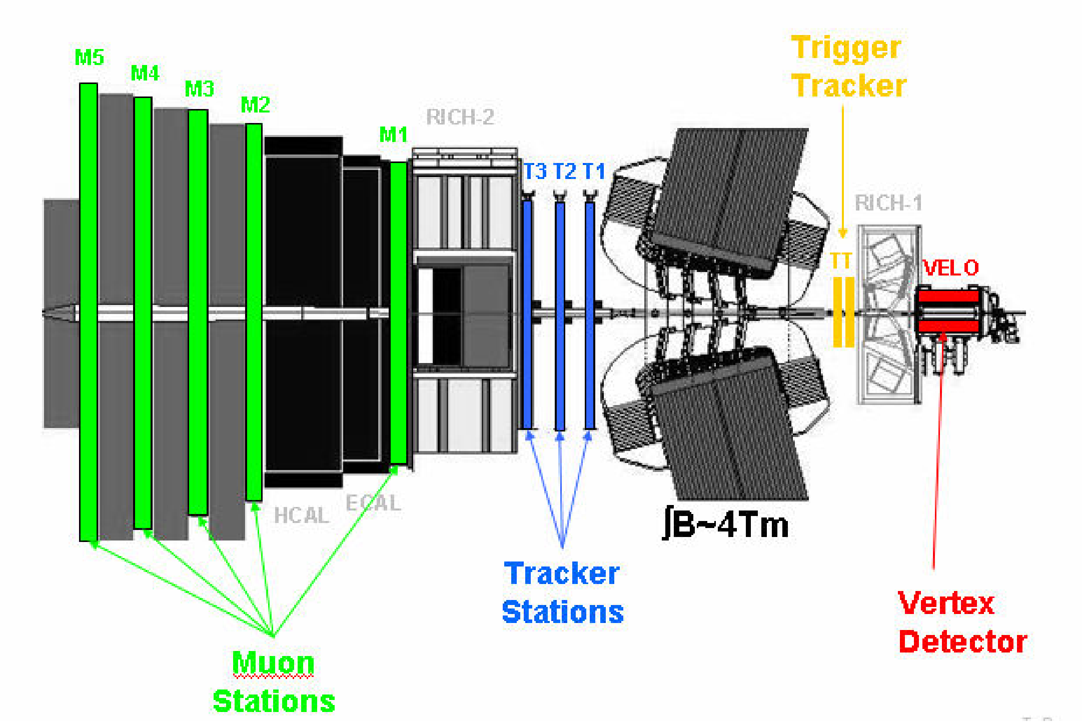

Figure 2: A schematic of the LHCb detector at CERN. The interaction occur within the Vertex Detector (VELO). The experiment is approximately 20m long.

The pp collisions occur within the vertex detector (VELO) which is composed of 21 silicon “disks” placed along ~1m (see these proceedings). Subsequently B hadrons from the interactions pass through a ring imaging Çerenkov (RICH1)[9] to an analysing magnet and from there to a series of tracker stations. From there additional particle identification is provided by RICH2. Absorption of electromagnetic particles is performed by the electromagnetic calorimeters (ECAL) and hadron calorimeters (HCAL) respectively whilst a series of chambers, using the Hadron Calorimeter as a filter, detect muons [10].

4. Overall Trigger Scheme

As with the other LHC experiments it is impossible to record and analyze all the events produced at the LHCb interaction point. At a beam crossing rate of 40MHz an operational year of 10^7s implies a total $>10^{14}$ events are produced within LHCb. In order to limit the number of events to a “feasible” number, i.e. one that does not saturate the bandwidth limit of the detector data acquisition or reconstructions system it is necessary to deploy a trigger.

The LHCb trigger has an identical function to those of the GPDs inasmuch as it must reduce the number of events passed from both to the DAQ and to the "offline" reconstruction. However it must maximize the physics content by retaining the highest possible "signal/noise" ratio of interesting events to background. For example for the LHCb experiment this means that B hadrons decays with specific signatures (e.g. $B\rightarrow\mu\mu$) must be kept whilst minimum bias should be rejected.

The LHCb strategy is to use two "levels" of trigger. A Level 0 trigger [8] allows for rapid identification of events of interest that contains muons, high momentum photons or hadrons and rejects multiple interactions. Events having a high probability of containing a highly energetic muon or hadron but a low probability of being a multiple interaction are passed to the high level trigger (HLT) [11]. This is shown graphically in Figure 3

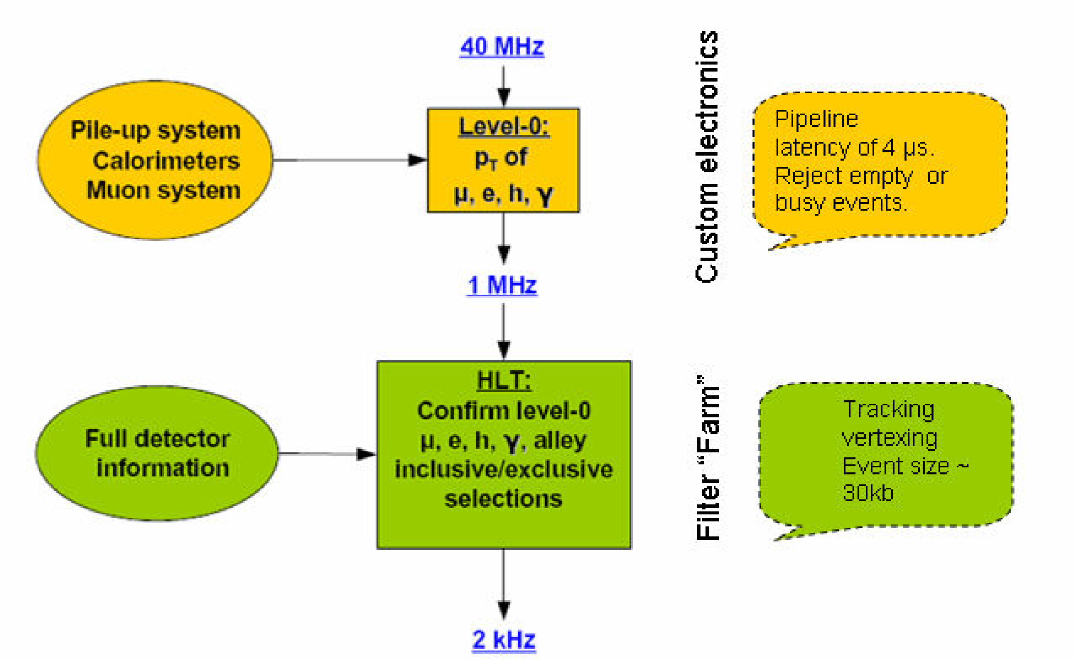

Figure 3: Schematic of the LHCb trigger scheme.

The Level 0 trigger outputs events at ~1MHz. However there is pipeline latency of only 4μs in which a decision can be made and as such it only uses relatively crude information. No displaced vertex information, to select B events, or tracking is available at Level 0. Much more refined data is available in the HLT where the full detector information is used. The output of the HLT is ~2kHz of events which correspond to a modest 60Mb/s assuming an LHCb event ~30kb. Below we discuss the functions of the Level 0 and HLT in more detail.

4.1 L0 trigger

In order to make decisions at the necessary rate for the HLT the L0 trigger utilizes custom electronics and firmware to process the outputs of three detectors systems: the Pile-Up (VETO) system which is located next to the VELO, the calorimeters and the Muon system, (see Figure 4). A single decision as to whether to keep an event or not is made by the L0 decision unit in < 1.2μs [12]. The L0 operates using > 2000 optical links with a bandwidth of 1.6 Gb/s.

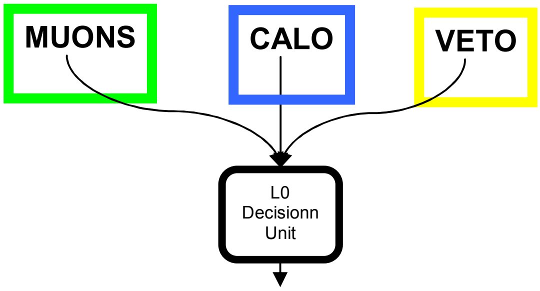

Figure 4: Schematic of the L0 trigger scheme. Data from the calorimeters, muons and VETO are fed to a L0 decision unit.

4.2 Higher Level Trigger

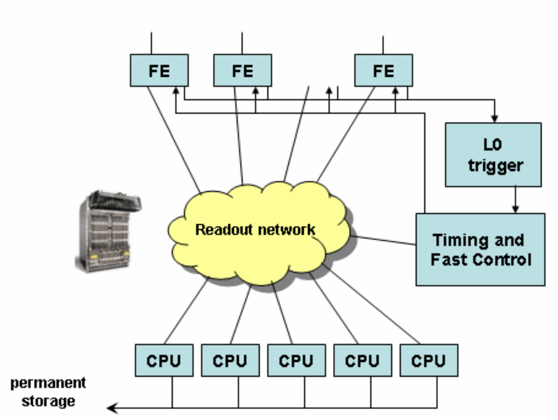

Figure 5: Schematic of the HLT/DAQ network.

Alley	Rate (kHz)
Muon	160
Muon and Hadron	10
Hadron	600
Ecal	280

Table 1 Rates into each of the 4 basic HLT alleys

The HLT is conceptually and physically very different from the L0. It is built using commercial components [11, 13]. Indeed its configuration would not be unfamiliar to any large scale computing project world wide, and to all intents and purposes is simply a High Performance Computing cluster. A detailed description of the HLT/DAQ architecture is given in these proceedings. Data from the front ends (FEs) of the detector elements is extracted from the detector into the HLT cluster provided a L0 trigger is present. The data is routed via a high performance Force10 switch to the HLT processing elements that are highly performant PCs – see Figure 5. The HLT farm is O(2000) CPUs and can be upgraded or extended if necessary.

The data flow within the HLT architecture follows a series of paths or "alleys". Each alley has a specific function. For example the first alley determines if there is a high quality muon trigger and is called the muon alley[14]. Others are: the "muon+hadron" alley, the hadron alley, the ECAL alley and finally an alley designed to trigger on exclusive and inclusive hadron decays. All data moves through these alleys in a ordered fashion, and the output of each alley is recorded to allow detailed study of efficiencies. The path through the alleys is shown in Figure 6. The first, and very important alley is the muon alley. Should a muon have been identified as L0 muon candidate the information event is processed through the muon alley. After following the muon alley the event will then be examined to see if the HLT confirmed a muon. In the case that it was the muon and hadron alley is entered.

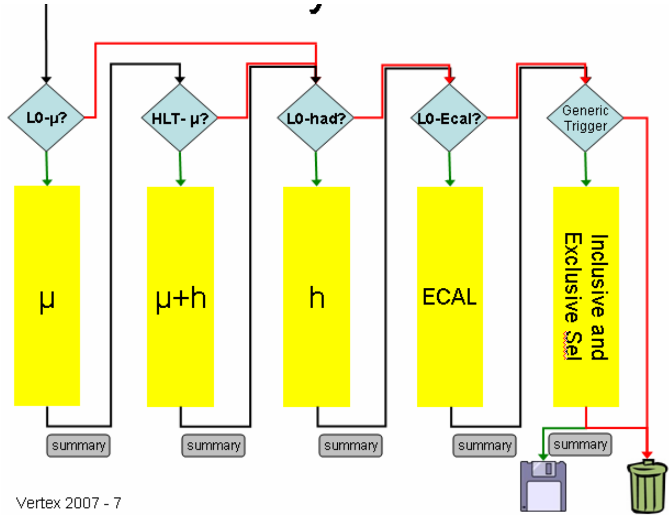

Figure 6: HLT Alleys

For the case no muon was confirmed the muon and hadron alley is skipped and the logical data flow rejoins the path of events that were not identified as muon L0 candidates. From there on each event traverses the hadron and ECAL alleys subject to a L0 trigger. Finally a choice is made whether to keep or reject the event and severe cuts placed to reduce the overall event rate to a few kHz. The rates of events into the alleys is shown in Table 1. The sum of rates from the first four HLT alleys matches approximately the total output rate of the L0 trigger (1MHz). The final alley allows the "throttling" of the output to a suitable level for storage and offline processing.

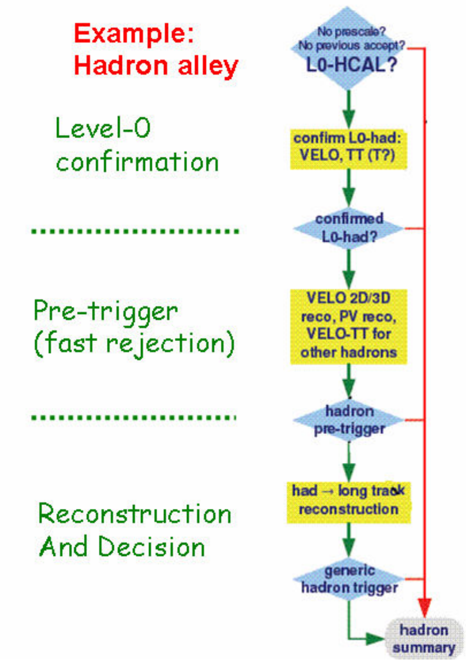

Figure 7: Detail of hadron alley

It is instructive to look at the structure of one of the alleys in a little more detail. We choose the hadron alley because of its importance but also because it utilizes the tracking. The format is similar in the other alleys. The traverse of the alley happens in three phases. First the L0 trigger, which is a pre-requisite for the event, is confirmed. For the hadron alley this means that a track from the VELO must be consistent with the calorimeter trigger. Failing confirmation the event leaves the alley after having written to the hadron summary for the event. In the second phase code is run that enables the fast rejection of unsuitable candidates. This forms an effective software pre-trigger. For the hadron alley this entails more detailed 3D reconstruction of the VELO tracks, primary vertex reconstructions and a match of track from the VELO to the trigger tracker (See Figure 2). Once again failure to satisfy the pre-trigger results in the event exiting the alley after having written to the hadron summary. If both the first two phases are passed an event is able to pass onto the third phase. This entails a detailed reconstruction of the event, very similar to the offline reconstruction. For the hadron trigger this involves fully reconstructing the track and matching it, after the magnetic field, to the main LHCb tracker elements. The long tracks give detailed information about the charge and momentum of particles. Based on the full information that now includes primary vertex as well as momentum information tracks can be selection in a generic hadron trigger.

5. Trigger Instantiation: Vertexing and Tracking

Below we provide a few more details of the trigger of particular interest to the participants of this conference. In particular we concentrate on the vertex and tracking information. There exist of course many other details that we have omitted which are equally, if not more, important. Here we will look at the vertexing in L0 and provide some information on the tracking in the HLT.

5.1 L0 Pileup VETO

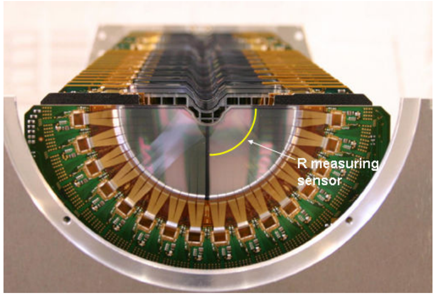

Figure 8: End-on view of the ½ disks of the VELO and VETO detectors. The two VETO counters are nearest.

Figure 9: Side view of the two VETO modules in a ½ disks in LHCb

Unlike the proposed BTeV [15] experiment, which had similar physics objectives, the LHCb experiment is not equipped with a low level, high speed vertex finder. The reconstruction of primary (and secondary) vertices for physics happens in the HLT. However there does exist one part of the detector that is designed to reject multiple interactions at L0 through the identification multiple vertices. To the 21 disks (or planes) of Si in the VELO [16] an additional two specialized Si planes have been added in the upstream direction (Figure 8 and Figure 9). These Si planes detect particles emanating from the nominal interaction point but traveling in the opposite direction (upstream) to the magnet. The VETO counter planes are composed of R-measuring sensors i.e. in each plane only the radial distance of a particle from the beam line is measured. However this enables 2D trajectories to be reconstructed in the rZ plane i.e. with no azimuthal information except the 45° segmentation of the radial strips. It should also be remembered that there is effectively no magnetic field in the region of the VELO thus all tracks, barring multiple scattering, follow straight trajectories. The purpose of the VETO counters is to use “backwards” moving tracks from interactions to identify, and allow rejection of, events that contain more than one primary vertex. This is made possible at high speed using the comparators built into the Beetle[17] ASIC used by the LHCb experiment. As well as amplifiers, pipelines and output drivers the Beetle chips can operate in a mode in which the fast binary output of groups of strips that exceed a specific threshold are provided. Using specially constructed hybrids and readout cables these signals can be sent to a special board whose sole purpose is the identification of the number of “primary” vertices formed by tracks in the VETO counters. The entire process is fast deliver a decision within 1μs thus is compatible with L0 trigger times. Differntial signals are taken off the special VETO hybrids using 1000 copper cables. This is converted within a few metres of the VELO to optical signals and transmitted over 60 meters on 95 fibres towards the 5 vertex finder boards. These vertex finder boards utilize field programmable gate arrays to perform the processing.

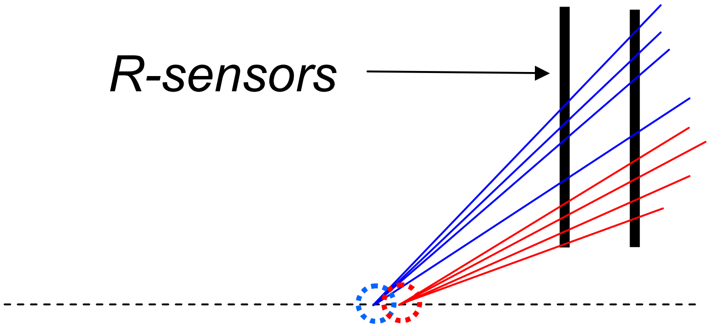

Figure 10: Schematic of the 2 planes of VETO Si used in LHCb.

The process for finding the pile-up events in the VETO counters is relatively simple. All pairs of “hits” from the two planes of VETO Si (read out into the processor board from the comparators) are combined to construct 2D tracks. These tracks are extrapolated back to the line formed by the nominal beam position. All pairs of tracks are used to form “vertices” close to the beam line, see Figure 10. The z-distributions of these vertices are “histogrammed” . A highest peak is identified and all the “hits” associated with the primary vertex candidate are removed. The process is then repeated and a second highest peak identified. If a secondary peak with sufficient significance is reconstructed the event is classified as multiple interaction and may be rejected by the L0 processor unit.

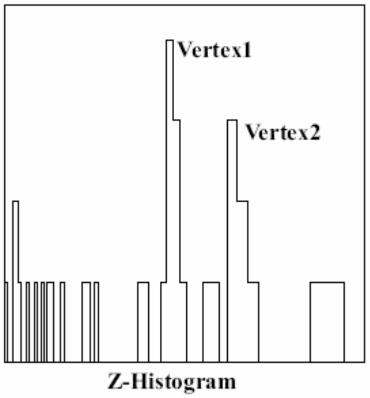

Figure 11: Histogram of Vertices from VETO processor.

A typical histogram for the output of the L0 VETO process is shown in Figure 11. The use of the trigger VETO allows a refinement of the number of pure B-events collected. For LHCb two interaction crossings are identified, using the technique, with an efficiency ~60% and a purity of approximately 95%. This increases the purity of the "pure" B events by more than 10%.

5.2 Tracking in the HLT

As one might expect HLT relies heavily on the tracking information from the detector to make its final decisions. Two slightly different approaches are used in the muon alley compared with the hadron alley and we summarize both.

5.2.1 Muon Alley

The first stage in the muon alley depend on verifying the output of the L0 muon trigger[10]. The L0 muon trigger follows a simple methodology. First straight lines are reconstructed using hits in M2-M5 and then matching hits in M1 are found. Knowing this information only the momentum of the muons can be estimated to within 20%. The L0 decision unit (another special processor) selects the two highest p_T candidates per quadrant. The efficiency of $B \rightarrow J/\psi(\mu\mu)X$ ~88% at this stage and the system has a latency ~1µs. The L0 muon trigger is delivers triggers ~200kHz.

To "verify" or confirm the L0 unit the HLT matches the muon station hits to the tracker stations. This improves the momentum resolution to approximately dp/p~3%. (Figure 12). Dimuon candidates are found and $J/\psi(\mu\mu)$ are reconstructed.

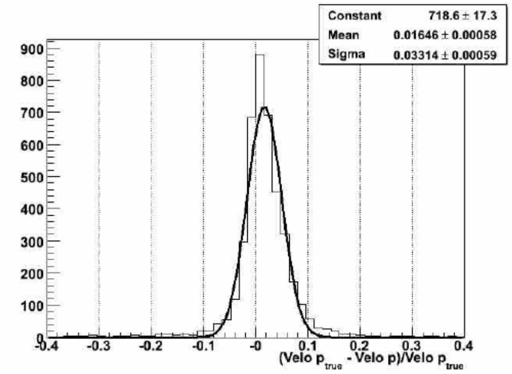

Figure 12: Momentum resolution of muons after the tracking stations is added is approximately 3%.

The next step is to to add the information from the upstream VELO, which is before the magnet. The process of 2D matching and fitting improves the momentum resolution to 1%. The matching of the muons tracks is then improved using a 3D fit. The total rate of events identified as containing muons of interest (p_T>1GeV/c) is finally approximately 80kHz of which approximately 10kHz are $J/\psi(\mu\mu)$ with displaced vertices. The muon trigger is almost fully efficient. at p_T>1GeV/c.

5.2.2 Hadron Alley

The hadron alley starts with a much higher input from L0 Calorimeter of about 600kHz. The first step, as discussed above, is to perform VELO tracking in 2D. This is similar to the VETO tracking in that only the rZ information is used. The VELO 2D tracking is performed by processors (rather than FPGA) and uses more planes (~6) than the VETO tracking that only uses two. The VELO tracks are then matched to hadron calorimeter candidates of which there about 5/event. For the matches full VELO 3D tracking is performed, using the azimuthal information from the phi-measuring VELO sensors, and the matching to the calorimeters confirmed.

For the majority of hadronic tracks of interest to LHCb are from particles with high impact parameters. Thus an impact parameter cut is applied. This reduces the rate to approximately 300kHz. Further refinement of the hadronic triggers come through performing a full match to the other tracking detectors of the VELO tracks. This yields a momentum performance of dp/p~1%. Hadronic tracks which are displaced from the primary vertex, have a $p_T > 2.5$GeV/c are reconstructed at about 30kHz.

6. Summary

The LHCb trigger is designed for the study of CP violation and B decays at the LHC. It permits the reduction of the interaction rate from ~ 40MHz to approximately 2kHz of pure B's of interest to tape. This represents an expected statistical sample of $> 10^{10}$ B/year. The trigger provides a robust way to trigger on high p_T muons and hadrons with displaced vertices with a low rate of fakes. The hardware is a combination of custom electronics and firmware at L0 combined with standard processing farms in the HLT.

Interestingly LHCb does not possess a L0 displaced vertex trigger. Substantial development to the hardware of the vertex detector and the trigger will be required if this were to be implemented. High luminosity running[18] could require a rethink of the current trigger to enable L0 displaced triggers.

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