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The LHCb Vertex Locator and Level-1 trigger

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Abstract

LHCb will study CP violation and other rare phenomena in B-decays with a forward detector at the LHC. One of the challenges is to design a fast and efficient trigger. The design of the silicon Vertex Locator (VELO) has been driven by the requirements of one of the most selective triggers of the experiment. The VELO trigger is designed to work at an input rate of 1 MHz. The requirements and implementation of the VELO and the associated trigger are summarised, followed by a description of an upgrade which improves the trigger performance significantly.

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1 Introduction

In pp interactions at LHC energies 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 covers only particles produced below 300 mrad. Apart from the silicon Vertex Locator (VELO) described in this paper the spectrometer consists of a tracking system, a 4 Tm dipole magnet, aerogel and gas RICHes, electron and hadron-calorimeters and muon detectors. The trigger has to be highly selective to reduce the event rate from the LHC bunch crossing frequency of 40 MHz to a rate of 200 Hz, with which events can be written to storage. The trigger strategy is graphically explained in figure 1. Due to the LHC bunch structure the average bunch crossing rate at LHCb is 30 MHz. LHCb has chosen to operate at a luminosity of 2×10^{32} cm^{-2}s^{-1} to reduce the number of events with multiple pp interaction, which are more difficult to reconstruct. This results in 9.3 MHz of single pp interactions and 3 MHz of crossings with more than one interaction, assuming a 80 mb pp cross-section. A multiple interaction veto reduces these rates to 8.92 MHz and 0.6 MHz respectively. The Level-0 trigger makes use of the information from the calorimeters and muon chambers to select particles with relatively high E_T and reduces the rate to 1 MHz. The Level-1 trigger is based on the VELO and will be described in this paper. After Level-1 the event rate is 40 kHz, making it possible to do full event building with an average event size below 100 kbytes. The Level 2 and 3 triggers perform partial and full event reconstruction respectively to reduce the final rate to about 200 Hz. The efficiency of this trigger chain as measured relative to events which pass the off-line selection criteria is typically between 20-40% depending on the B-meson decay mode. This paper summarises the requirements and constraints which drove the chosen layout of the detector in sections 2- 5. Section 6 describes a new development in the Level-1 trigger algorithm called Super-Level-1.

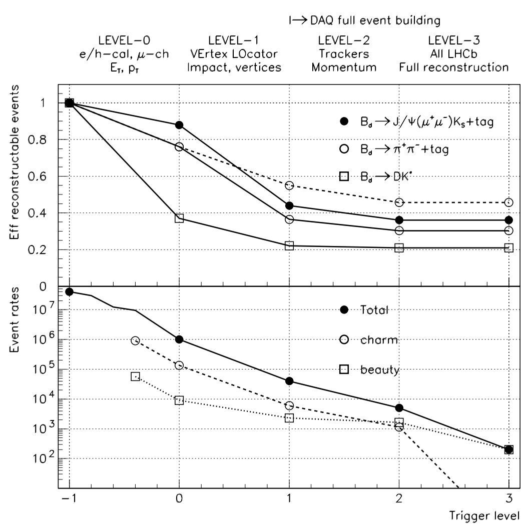

Fig. 1. Illustration of the LHCb trigger strategy. The trigger efficiencies are shown for events which pass the off-line selections. The efficiency expected after the upgrade described in section 6 is indicated with a dashed line for $B_d \to \pi^+\pi^-$.

2 Acceptance

The LHCb spectrometer has an acceptance of 15 mrad< θ <300 mrad. To measure at least three points per track the VELO consists of 17 stations, each station is composed of 2 silicon discs which are positioned perpendicular to the LHC beams, and have a radial coverage of 1 cm to 6 cm. Twelve stations have a 4 cm spacing along the beam to cover the whole beam-spot (σ_{xy} =70μm, σ_z =5.3 cm), while the remaining stations are positioned up to 80 cm down-stream of the beam-spot to cover angles down to 15 mrad. This arrangement assures that a typical track traverses between 5-6 stations.

3 LHC Machine Constraints

During LHC filling and ramping a clearance to the beam of 30 mm is required, hence the whole VELO is mounted in two parts in Roman Pots, allowing the detector to be retracted. The clearance to the beam during stable physics runs is 4 mm. The 6 mm gap between the sensitive area of the silicon detectors and the beam clearance accommodates a guard ring structure which allows large depletion voltages, a 100 μm thick Al RF-shield to separate the primary vacuum of the LHC-machine from the Roman Pots vacuum and prevent pick-up, and a wake field suppressor to suppress the coherent RF-coupling due to the cavity like structure of the RF-shield. Studies are ongoing to merge the RF-shield and the wake field suppressor in a single shield to reduce the amount of material and possibly allow the sensitive area of the silicon to approach the beam even closer.

4 Radiation environment

Despite the relative low luminosity at LHCb of 2×10^{32} cm^{-2}s^{-1} the radiation dose which is received by the silicon at 1 cm from the beam still amounts to 0.8-1.2$\times$ 10^{14} particles/cm^2 per year, the uncertainty coming from the type of generator which is being used: DTUJET93 or PYTHIA. The particle flux is dominated by charged particles from the primary interaction. The thermal neutron background contributes less than 0.2% to this flux, and hence the large uncertainty in the modelling of this contribution plays no role in the determination of the total dose. To be able to sustain this dose n-side silicon devices of 150 μm thickness have been chosen. Thin detectors have the advantage of low depletion voltage for full charge collection, low multiple scattering and low power dissipation, thus avoiding extra material in the fiducial area for cooling the detectors. Analogue read-out has been chosen, since it allows for better monitoring and control of the effects due to the very non-uniform radiation damage, and gives a better spatial precision for a given strip pitch. A double metal layer is used to rout the signals from the strips to the read-out electronics.

5 L1-trigger

The Level-0 trigger accepts events at a rate of 1 MHz, hence the whole VELO has to be read-out within 1 μs. To achieve this the channels are multiplexed in groups of 32 and read-out with a 40MHz clock. The latency of Level-1 is 1024 μs, which allows the execution of the trigger algorithm to be performed in a small CPU-farm [3]. Typically there are about a thousand clusters per event which have to be transferred to the farm. For the trigger algorithm only binary information is used, which requires a switch with a capacity of around 3 Gbytes/s. The Level-1 trigger algorithm [2] consists of the following steps:

- B-mesons with all their decay products within the acceptance of the spectrometer are typically produced at polar angles below 200 mrad. Hence, the projection of the impact parameter of the decay product to the primary vertex in the rz-plane is large, while in the plane perpendicular to the beam-axis it is similar to tracks originating from the primary vertex. Level-1 exploits this by requiring one of the two discs in a station to have strips at constant radius. These detectors are then used to reconstruct all tracks in the rz-view. The strips below a radius of 25 mm have a pitch of 40μm, and a circle is subdivided in 12 strips with a length of 5.3-13 mm. At larger radii the circles are subdivided in 6 separate strips and have pitches between 60-80μm. This keeps the occupancy below 0.5% for all channels and assures a precise measurement of the hits closest to the vertex.
- All tracks are required to have at least one hit at a radius smaller than 25 mm. The rz-tracks contain ϕ information due to the segmentation in ϕ of the r-strips, which allows the reconstruction of the primary vertex with a resolution of σ_{xy} =20μm and σ_z =80μm per event.
- Tracks with a significant impact (typically 100μm) are selected for full 3D track reconstruction, typically 5 tracks per minimum bias event. The other disc in a station contains radial strips, with a $\pm5^0$ stereo angle in alternating stations to allow the two views to be combined. Figure 2 show the strips hit in a typical event for a 60^0 slice in three consecutive stations. Note that all tracks have at least one hit in the 30^0 slice below a radius of 25 mm. This area contains on average one cluster per minimum bias event.
- No momentum information is available since there is no magnetic field around the VELO. However, due to multiple scattering the reconstruction efficiency of tracks below 2 GeV drops significantly. To reject background tracks with a large impact parameter, tracks are required to form a secondary vertex significantly separated from the primary. The impact parameter information from those tracks is used to form a total event probability, which gives the efficiencies as shown in figure 1.

Coulomb scatters, and a further 15% are ghost tracks. The requirement that these tracks form a good vertex with at least one other track reduces their contribution significantly, but they remain a dominant source of background. Super-Level-1 combines the information obtained during the Level-0 trigger with that of Level-1 on a track to track basis. Figure 3 shows a top view of the components of the LHCb spectrometer which are being used for the Level-0 and Super-Level-1 trigger. The Level-0 trigger recon-

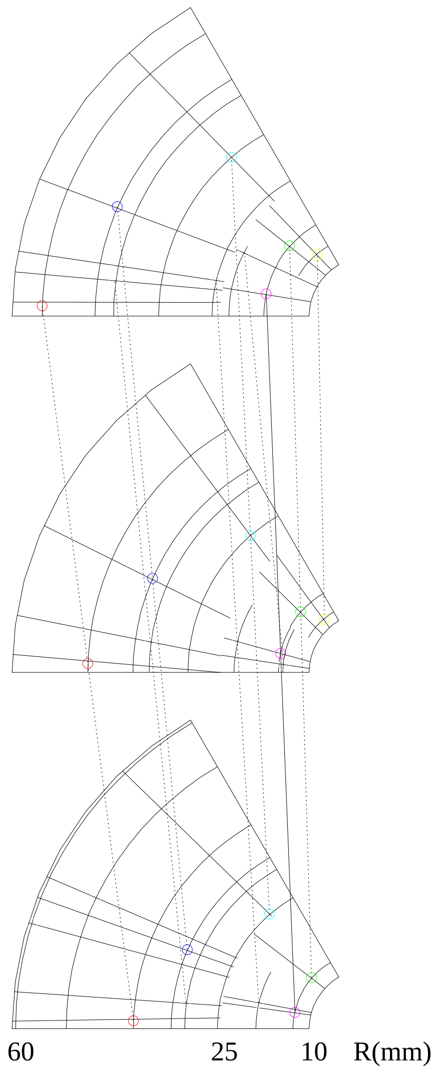

Fig. 2. Event display of a 60^0 slice for three stations. The lines between the stations indicate the positions of the true tracks.

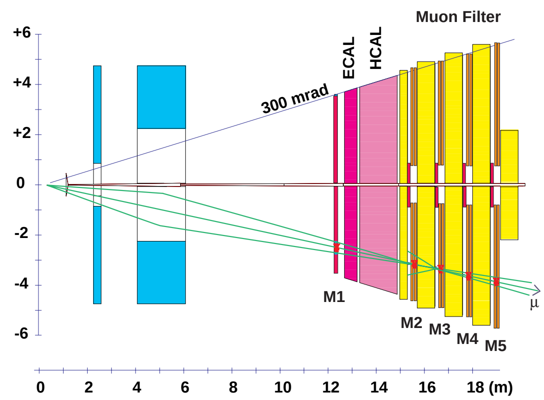

Fig. 3. Top-view (bending plane) of the components of the LHCb spectrometer which are used in the Super-Level-1 trigger. Shown are the magnet shielding plate and its coils, the muon stations M1-5 and the two calorimeters.

6 Super-Level-1

The Level-1 trigger achieves efficiencies between 45-60% depending on the channel as shown in figure 1. The major source of erroneously accepting events without a B-decay is the lack of momentum information. About 50% of the tracks with a significant impact parameter are due to large

structs on average one lepton candidate per event, and in the order of 15 hadron clusters with a cluster energy larger than 5 GeV, which is the threshold for particles to stay within the 300 mrad aperture of LHCb after the 4 Tm magnet. The Level-0 trigger is then obtained by applying a p_T-threshold to the reconstruced particles. To transfer these lepton-candidates and hadron clusters to the Level-1 CPU-farm constitutes about

5% of the VELO data. The 3D tracks are matched to Level-0 lepton-candidates or hadron-clusters by extrapolating the tracks in the non-bending plane to the position of the lepton-candidatess or hadron-clusters, and by taking the measured energy for electrons and hadrons or the measured angle for muons into account in the bending plane. The error in the extrapolation in the (non-)bending plane is dominated by the energy (position) resolution of the leptons and hadrons as measured in Level-0, the VELO contribution being negligible. The resolution in the non-bending plane varies between 2.5 cm for muons to 8 cm for low momentum hadrons. Roughly 50% of the low momentum tracks, which do not have a corresponding cluster in the HCAL, are matched erroneously to a cluster anyway. However, they are usually matched to low momentum, and low p_T clusters. Figure 4 compares the assigned momentum of VELO tracks in minimum bias events which passed the Level-0 trigger and have an impact parameter larger than 100μm, with those from tracks originating from a $B_d \rightarrow \pi^+\pi^-$ decays. The dashed line in figure 1 shows the improvement in the $B_d \rightarrow \pi^+\pi^-$ channel when this momentum signature is combined with the algorithm described in the previous section. Combining the tracks as measured by the VELO with the Level-0 leptons or hadron-clusters yields a momentum resolution δp/p=10-15%, hence for certain channels invariant mass distributions could provide an extra signature. This is shown in figure 5 for the channels $B_d \rightarrow \psi(\mu^+\mu^-)K^0_S$ and $B_d \rightarrow \pi^+\pi^-$. For the HCAL clusters the un-calibrated energy has been used, which is systematically to low,

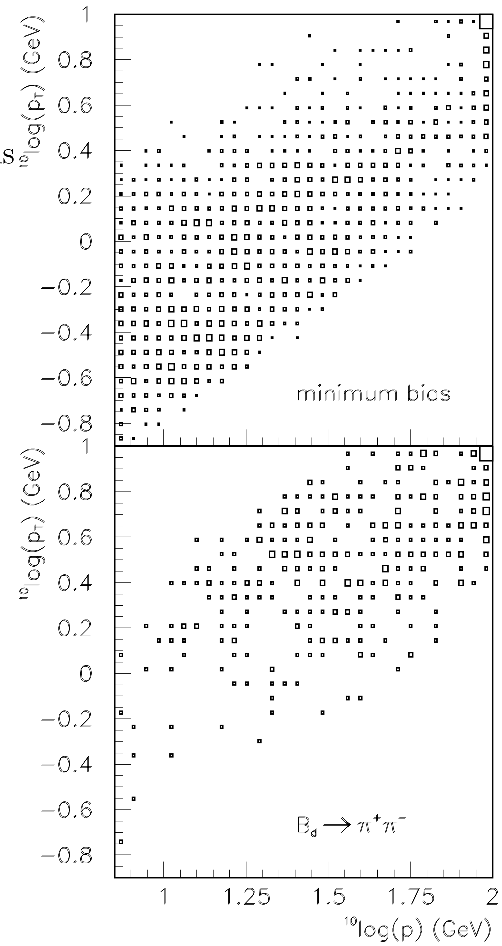

Fig. 4. Distribution of momentum versus transverse momentum of the VELO tracks which have been matched to clusters in the HCAL.

hence the lower invariant mass. To generate the shape of the background, the relative normalisation is arbitrary, no impact parameter cut was imposed for the muon-candidates, while for the pion-candidates the impact parameter is larger than 100μm, but no good vertex is required. The way in which these invariant mass signatures could improve the trigger efficiency for a few "golden" channels is under study.

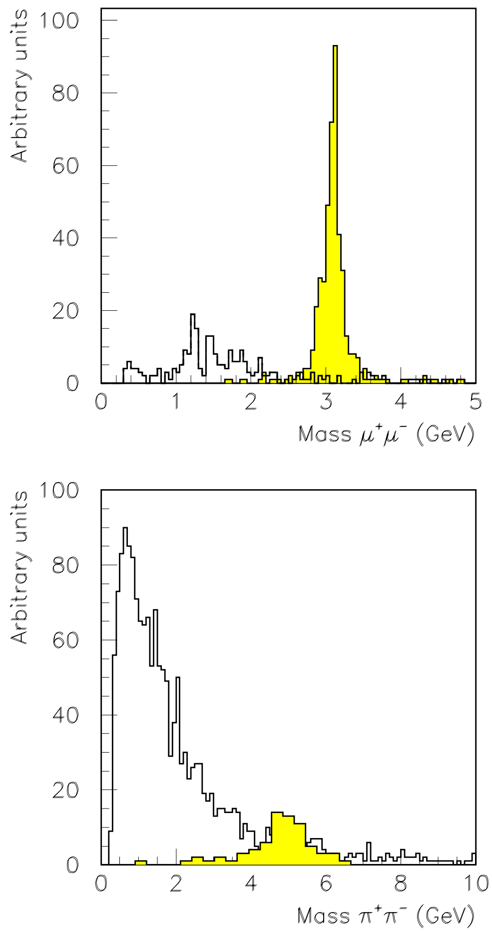

Fig. 5. Invariant mass of the muon and hadron pairs reconstructed by the Super-Level-1 trigger.

7 Conclusions

The design of the VELO is mainly driven by the trigger requirements. The radiation environment will require the detector to be replaced every few years, but this is a small investment since the total surface area is less than 0.4 m^2. The trigger based on the VELO data has to operate at 1 MHz input rate, however the 3kbyte event size allows it to be implemented in a CPU-farm. As a consequence the trigger algorithm is very flexible, and this paper shows one of the improvements which increases the event yield in the $B_d \rightarrow \pi^+\pi^-$ by 50% compared to the expectations quoted in the LHCb Technical Proposal [1].

8 Acknowledgements

The work described in this paper is the result of the contributions from many LHCb collaborators. I would like to single out Mike Koratzinos for converting the new Super-Level-1 B-signatures into efficiencies.

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