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Data Reconstruction with the LHCb VELO: hit processing, tracking, vertexing and luminosity monitoring

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Abstract

The LHCb experiment is dedicated to performing a detailed study of CP symmetry violation and rare decays of B and D mesons. In order to reach these physics goals the LHCb spectrometer must provide excellent vertexing and tracking performance both off-line and on-line in the trigger. The LHCb VELO (VErtex LOcator) is the silicon microstrip detector which surrounds the collision point and hence is critical to these aims. Its hit processing and zero suppression is performed in a series of algorithms implemented on FPGAs. The tuning of the parameters of these algorithms is performed using a bit-perfect emulation of these algorithms integrated in to the full off-line software of the experiment. Tracking and vertexing is then performed using the clusters produced. These algorithms are described and the results for primary and secondary vertex resolutions are given. Finally, a novel technique for measuring the absolute luminosity using gas injection in the VELO is described.

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1 Introduction.

The main purpose of the LHCb [1] experiment at the LHC [2] is to study indirect evidence of new physics in the beauty and charm sector. This is performed through the precise measurement of CP violation and rare decays. The LHCb detector is a single-arm spectrometer, since at high energies $B^0 - B^0$ pairs are produced in the same (forward or backward) direction. For this type of studies a precise silicon vertex detector is needed to reconstruct both primary and secondary vertices. For LHCb this is provided by the VELO detector. This detector is also an important part of the overall tracking system and provides vital information for the trigger.

The LHCb detector and its tracking system [3] are introduced in section 2.

This is followed by the tracking performance description using simulated data samples. The section 3 is devoted to the description of the off-line software - VETRA. Section 5 gives short description of the new method proposed to measure the absolute luminosity and to monitor the LHC proton beams. Final remarks and conclusions are given in section 6.

2 The LHCb detector.

The single-arm forward geometry of the LHCb detector covers the angular region from approximately 10 mrad to 300 mrad corresponding to the pseudo-rapidity interval $1.9 < \eta < 4.9$. The layout of the detector is depicted schematically in Fig. 1.

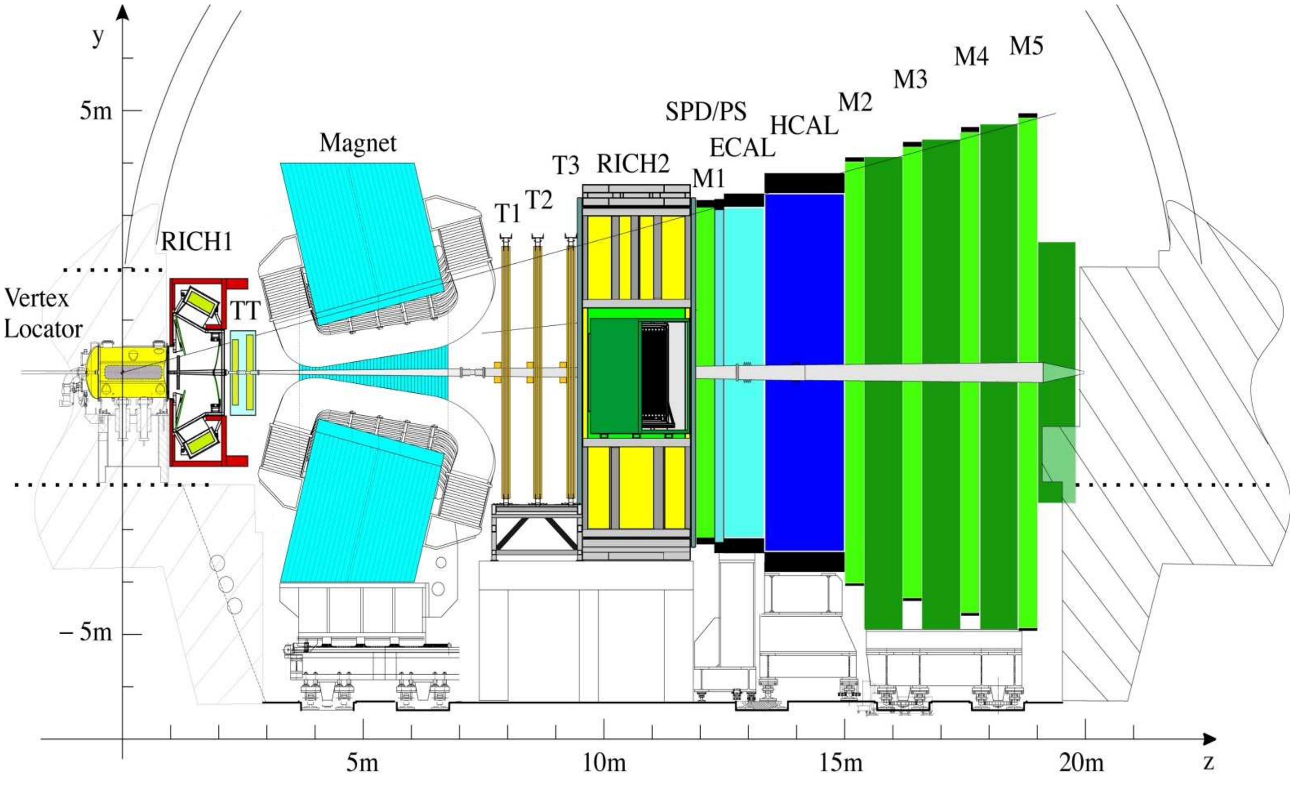

Figure 1: Cross-section of the LHCb detector.

A right-handed coordinate system is used with the Z axis along the beam and the Y axis pointing up. The origin of the Z axis corresponds to the interaction point.

The spectrometer consists of (starting from the interaction point):

- the vertex locator (VELO) system (including the pile-up veto stations)
- Ring Imaging Cherenkov counter (RICH1)
- silicon trigger tracker (TT)
- dipole magnet
- tracking stations (T1-T3)

- RICH2
- electromagnetic calorimeter (ECAL)
- hadronic calorimeter (HCAL)
- muon stations (M1-M5)

The VELO detector's primary task is to provide precise measurements of track coordinates close to the interaction point. This is essential for efficient displaced (secondary) vertices reconstruction that are the main feature of b and c-hadron decays. The VELO is a silicon microstrip technology based detector. It consists of a number of modules each of which contains one R (with concentric strips) and one Φ (with inner and outer radial strips with stereo angle) silicon sensor. The geometry of the VELO sensors is shown in Fig. 2. The modules are arranged along the beam with the sensor planes perpendicular to it. The sensors are $\mathrm{n}^+ - \mathrm{on} - \mathrm{n}$ type and are 300 μm thick. The radial coverage of each sensor is from approximately 8 mm to approximately 42 mm. Both R and Phi sensors have 2048 strips with varying pitch from 40 μm to 100 μm.

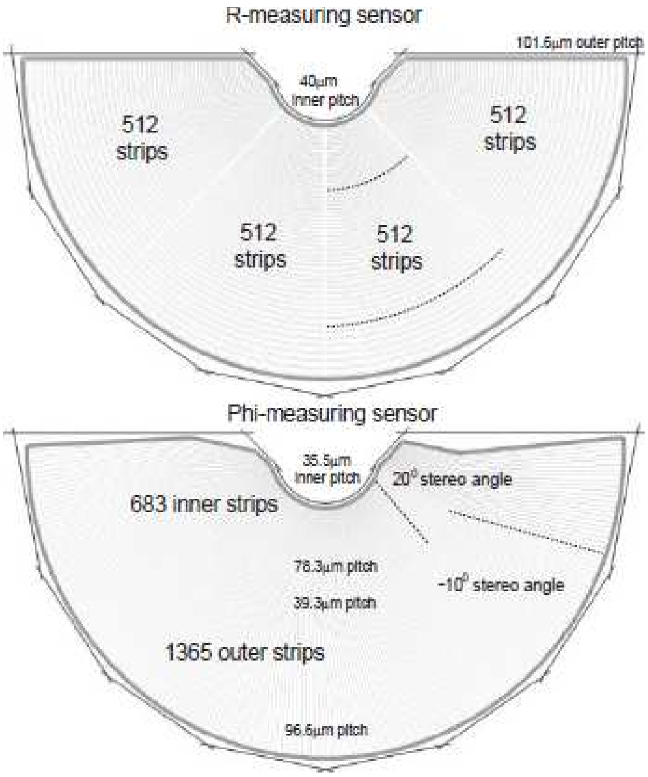

Figure 2: The RΦ geometry of the VELO sensors (for the sake of clarity only a portion of the strips are presented).

The $\mathrm{R} - \Phi$ sensor design was chosen to optimize reconstruction of tracks originating from the interaction region. The VELO tracking is split up into two steps: first fast 2D $\mathrm{R} - \mathrm{Z}$ tracking is performed; and then the extra ϕ hits information is added to form 3D tracks.

The silicon tracker (ST) consists of: the Tracker Turicensis [1] (TT) and the Inner Tracker (IT). Both detectors use $\mathrm{p}^+ - \mathrm{on} - \mathrm{n}$ silicon micro-strips sensors with a fixed pitch of about 200 μm. The thickness of the sensor is 500 μm and 320 μm for the TT and IT respectively. The TT is located upstream of the LHCb magnet and covers the full geometrical acceptance of the experiment. The IT covers a cross shaped area of the innermost part of the three tracking stations downstream of the magnet. Each of the ST tracking stations has four detection planes. The first and the last planes have vertical strips and the second and the third have strips rotated by a stereo angle of -5° and $+5^{\circ}$ respectively.

The outer tracker (OT) constitutes the outer part of the downstream tracking stations. The OT is made from 5mm radius Kapton/Al straw tubes and uses drift-time measurements to improve its resolution.

A detailed description of the LHCb spectrometer's sub-detectors can be found in [1].

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[1] Former Trigger Tracker.

3 VELO hit processing

The analogue pulse-height signals from the front-end chips of the VELO detector are processed in the FPGA based TELL1 [7] data processing board. The algorithms implemented in this board process the full (non-zero suppressed) data from the detector to produce clusters. A bit-perfect emulation of the performance of these algorithms has been developed and integrated into the standard reconstruction software of the LHCb experiment. This is performed in the VETRA [4] project. This project facilitates the optimization of the performance of these algorithms and to tune the over one million parameters of these algorithms for optimal data reconstruction.

The emulator is implemented as a sequence of algorithms (coded in C/C++) that are designed to model the VHDL code that is run within the TELL1's FPGA processing units. The emulator is fed with non-zero suppressed data, which is taken as special calibration data for the detector. By rerunning the emulator with a range of parameters the response for different sets of processing parameters can be studied and the parameters automatically optimized for each strip of the detector.

The baseline emulation sequence is shown in Fig 3. The algorithms correspond directly to the processing steps that are performed within the processing units of the TELL1 board.

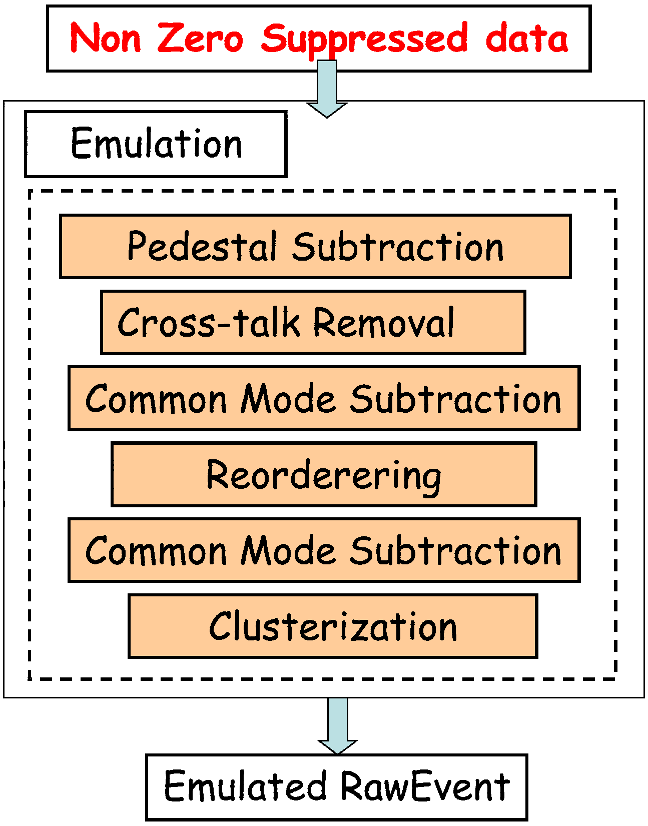

Figure 3: The emulation sequence implemented in VETRA project.

The data processing procedure starts with pedestal following that uses a number (a tunable parameter) of events to determine the pedestal noise for each channel. The next processing step removes any distortion that may have been introduced during the analogue signal transfer off the detector over the long (approximately 60 m) copper cables. This is followed by the first common mode subtraction algorithm (only a mean correction is applied at this point). The reordering algorithm is a VELO specific feature of the processing and is needed in order to translate the electronic chip channel readout order into the geometric strip order of the sensors. After this data rearrangement the second common mode correction is applied (this time allowing a linear slope as well as a mean correction). The last step of the processing is the cauterization which produces the raw bank with encoded clusters.

Correctly optimized processing parameters are vital for the quality of the output data produced by the VELO, as they reduce the noise fake rate, increase the efficiency and improve the resolution of the detector. An example of the tuning procedure for one algorithm is presented in the following section.

This emulation procedure for the TELL1 algorithms is also used for optimizing the performance of the silicon tracker.

3.1 Example parameter tuning study: Cauterization Thresholds

The cauterization algorithm used by the VELO detector (performed as the last step of the raw data zero-suppression procedure) needs three sets of thresholds to be specified:

- seeding (high) - to find the initial hits which are the seeds of the clusters
- inclusion (low) - used to determine which strips to add to the cluster seed
- spill over (sum) - to indicate whether a given cluster could have resulted from charge remaining in a strip from the previous bunch crossing

Here a short description of the seeding threshold tuning procedure is given.

The value of the seeding threshold should be chosen to push the probability of accepting the noise cluster as a signal one down to about 10^{-5}.This procedure provides a lower bound on the seeding threshold of the cluster. The initial procedure to determine the lower value of the seed for each detector channel is as follow:

- after the pedestal and common mode subtraction the noise value is calculated in the emulation for each channel. We call this value the noise σ in a given channel. A non-zero suppressed data sample from the detector without any beam collisions or test pulses present is used.
- for each channel the seeding threshold is calculated as 3.5σ
- the noise cluster rate is then calculated using another data sample, running with the calculated seeding threshold
- Once the seeding threshold is determined in the emulation for each strip of the detector these parameters are uploaded to the FPGAs and used in the hardware for optimal detector performance.

4 Tracking and vertexing at LHCb.

The VELO detector is a crucial part of the LHCb tracking system. Its performance has the paramount impact on both track reconstruction and the high level trigger (HLT)[1] performance. The LHCb reconstruction software is grouped within the Brunel [5] project that is based on the GAUDI framework [6].

The baseline pattern recognition algorithm used for the formation of tracks from the VELO clusters assumes that the tracks originate from the interaction region. In that case the tracks are linear in an $\mathrm{R-Z}$ projection and almost constant in ϕ. As mentioned in section 2, that optimized track reconstruction in VELO is divided into two steps: $\mathrm{R-Z}$ tracking; and 3D tracking where the ϕ information is added to the raw 2D tracks formed in the first step. The pattern recognition algorithm starts from the most downstream detection plane. Each hit found in this plane is paired with each one found in the third most downstream layer. Each pair of hits that is created defines a straight line segment. Each segment in turn is required to originate from the interaction region. Subsequently a best matching hit from the middle layer is added to the pair and a triplet is formed. Next, for each good triplet, the line segment is extrapolated to the remaining layers and all the best matched hits from each layer are included to create raw 2D tracks. Once all the hits from the most downstream layer have been checked the algorithm moves to the next layer and the process is repeated.

The 3D pattern recognition uses the $\mathrm{R-Z}$ tracks found in the first step and attempts to add the ϕ information to them. The algorithm uses all clusters from the planes compatible with the 2D tracks. It starts from the most downstream sensor and works towards the crossing point. The ϕ coordinate of a cluster is calculated by using the R estimate from the 2D track, this is needed as the ϕ sensors have a stereo angle. It is possible to create more than one 3D track for each $\mathrm{R-Z}$ track. In that case at the finalization step a decision is made based on a track quality χ^2 as to which track to pick-up as a 3D VELO seed.

The VELO tracks can then be used as the seeds with which to reconstruct tracks passing through other components of the detector. Long tracks are produced using hits from the TT and tracking stations. The reconstruction of the long tracks can be done via two methods.

First, a forward tracking algorithm is applied to match a VELO 3D tracks seed with a hit in one of the T1-T3 stations. Each combination of a VELO linear track segment and a hit from one of the T1-T3 stations is used to determine a momentum estimate of the track candidate. Subsequently the algorithm searches for hits in other tracking stations (including the TT). Using the standard LHCb simulated events about 90% of all long tracks found are reconstructed through the forward tracking algorithm.

In the second method, an additional refinement is run after the forward tracking algorithm. All hits from the T1-T3 stations that have been used by the forward tracking are removed. T1-T3 station seeds are then formed and downstream tracking is performed where the track state of the created T1-T3 seeds are extrapolated to the VELO region.

About 30% of all tracks are reconstructed as long tracks. In addition apart from the long tracks the LHCb reconstruction software can also form other track types that do not have associated hits in all tracking detectors. A large fraction of tracks (about 30%) have hits only in the VELO detector. These, so called, VELO tracks have no momentum information but are used in primary vertex reconstruction. If a T1-T3 station seed does not have any associated seeds in the VELO region a downstream track can be formed by matching this T1-T3 track with a hit in one of the TT stations. These downstream tracks have good momentum information and are used in the reconstruction of $\mathrm{K_s}$ and Λs particles that often decay outside of the VELO. It can also happen that the VELO 3D seeds can be matched only with hits in TT stations. These are in general low momentum tracks that do not traverse the magnet and thus their momentum resolution is poor. However, such tracks can help in the identification of background hits in RICH1 and hence increase the performance of its particle identification. If a track is measured only in the T1-T3 stations it is designated as a T-track. These are usually particles that come from secondary interactions. While they are not interesting from the point of view of physics analysis they can be very useful for improving the RICH2 performance.

After the pattern recognition step has been completed all the tracks found are fitted using a bi-direction Kalman filter. This fitting procedure also makes use of the alignment constants of each detector to improve the quality of the tracks produced. The final relative momentum resolution for long tracks that come from the B decays varies from 0.35% to 0.5%. The average reconstruction efficiency for these tracks entirely inside the LHCb acceptance is 95%. One of the quantities that is most effective to cut on in identifying B events is the impact parameter of the tracks with respect to the primary vertex. The impact parameter resolution for high $\mathrm{p_T}$ tracks ($\mathrm{p_T} > 1.5$ GeV) is about 14 μm. This performance in turn can be translated into B mass resolution for typical signal decays of about 14 MeV.

The primary vertex can be reconstructed both on-line and off-line. For this purpose three separate algorithms exist. Two of them are run during on-line reconstruction used by the HLT trigger. The first one is based on 2D VELO tracks and is used to reconstruct the primary vertices at the beginning of the high level trigger. The second one produces the primary vertices for use in the detailed selections of the second stage of the high level trigger using 3D VELO tracks. The third algorithm is used for the off-line physics analysis and can use full information available after the off-line tracking. For a typical simulated signal event the primary vertex (off-line) resolution is about 9 μm in the X and Y projections and about 50 μm along the Z (beam) direction. Studies conducted on simulated samples indicate that the LHCb can measure the B proper time with a resolution of about 40 fs.

5 Luminosity measurement.

Luminosity measurements are required for the determination of cross-sections at LHCb. They are also of great importance for the monitoring and tuning of the LHC beam. Both relative and absolute luminosity measurements are planned at LHCb.

Two independent techniques are being developed for the relative luminosity determination. The first one uses CdTe sensors to determine the rate of neutrons and photons generated in beam-beam collisions. This flux is proportional to the luminosity. The second method uses the forward stations (Pile-up stations) of the VELO detector to determine the number of primary vertices in the event, this is dependent on the luminosity.

Recently a new method for determining the absolute luminosity using the VELO detector has been proposed [8]. This novel technique is based on imaging the profile of the proton beam by reconstructing beam-gas interaction vertices. The key quantity that must be obtained experimentally is the overlap between the beams. The absolute bunch charge normalization is also needed, which is a parameter of the accelerator.

Moreover, this method also allows the monitoring with the VELO of the position of both beams, their shape and angles as a function of time. This technique can either use interactions with the residual gas in the accelerator, or if the rate is too low, additional gas can be injected. Residual gas (Xe) would be injected in the VELO region at a pressure of about 10^{-7} Torr. Accuracy on the absolute luminosity at the level of a few percent is then possible within a few days of data taking.

The main requirements for this method are:

- vertex resolution in X/Y projections needs to be better than the beam sizes. The resolution from the VELO is about a factor three smaller than the 70 μm beam size.
- any dependency of the gas pressure or reconstruction efficiency on the X/Y coordinates must be very well known

- an ability to distinguish beam1-gas, beam2-gas and beam-beam interactions is essential. This is readily with the event reconstruction in the VELO.

6 Conclusions.

The hit processing algorithms of the silicon detectors of LHCb are implemented in an FPGA based board. A bit perfect emulation of these algorithms has been implemented in the off-line C++ software framework of the experiment. This technique has allowed the algorithms to be optimized and allows their tunable parameters to be determined. This emulation procedure, using special calibration non-zero suppressed events, will be used during the normal data taking of the experiment to monitor the detector performance.

The LHCb experiment tracking system consists of the following detectors: VErtex LOcator (VELO), Trigger Turicensis (TT) and Tracking Stations. The system is capable of measuring tracks with a momentum resolution of about 0.35%-0.55% for tracks with high p_T. The experiment relies on topological identification of B meson decays through displaced secondary vertices and high impact parameter values to select the most interesting events. Studies of simulation events show that the impact parameter resolution for the tracks with high momentum is about 14 μm. The primary vertex resolution is approximately 8 μm and 47 μm for the X/Y projections and along the Z direction respectively. Resolution of the secondary B vertex is about 169 μm along the beam direction for the typical simulated signal sample.

A novel absolute luminosity measurement technique using the VELO detector has been proposed and initial studies performed. It is based on beam profile imaging via beam-gas interactions inside the VELO region. The method can potentially give an absolute luminosity measurement with a precision on the level of a few percent.

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