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THE LHCb EXPERIMENT*

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The LHCb experiment is dedicated to performing a detailed study of CP symmetry violation and rare decays of B and D mesons at the Large Hadron Collider (LHC) at CERN. In order to achieve these physics goals the LHCb spectrometer must provide excellent vertexing and tracking performance both off-line and on-line. The LHCb VELO (VErtex LOcator) is the silicon micro-strip detector which surrounds the collision point and hence is critical to these aims. During routine operation the VELO detector will be located 7 mm from the LHC beam.

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1. Introduction

The main purpose of the LHCb [1] experiment at the Large Hadron Collider (LHC) [2] is to study indirect evidence of New Physics (beyond the Standard Model) in the beauty and charm sector. This is performed through the precise measurement of CP violation and rare decays. Due to the high relativistic boost at a nominal LHC collision energy B^0–$\overline{B^0}$ pairs are produced in the same (forward or backward) direction, thus, the LHCb detector is a single arm spectrometer. For this type of studies a precise silicon vertex detector is needed to reconstruct both primary and secondary (displaced) vertices. For LHCb this is provided by the VELO detector. This detector is also an essential part of the overall tracking system and provides critical information for the LHCb trigger.

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The LHCb detector and its tracking system [3] are described in Section 2. This is followed by the description of tracking performance obtained using simulated data samples.

A short account for the LHCb performance with the early collision data taken at the end of 2009 at centre-of-mass energies of 900 GeV and 2.32 TeV is given in Section 3. Final remarks and conclusions are given in Section 4.

2. The LHCb detector

The single-arm forward geometry of the LHCb detector covers the angular region from approximately 10 mrad to 300 (250) mrad in bending (non-bending) plane corresponding to the pseudo-rapidity interval $1.9 < \eta < 4.9$.

A right-handed coordinate system is used with the Z axis along the beam and the Y axis pointing up. The origin of the coordinate system 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 reconstruction of displaced (secondary) vertices that are the main feature of b- and c-hadron decays. The VELO is a silicon detector based on micro-strip technology. It consists of a number of modules, each containing 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. 1. The modules are arranged along the beam with the sensor planes perpendicular to it. The sensors are "n^+ on n" type and are 300 μm thick. The radial coverage of each sensor is from approximately 8 mm to approximately 42 mm. Each R-type and each Φ-type sensor has 2048 strips with varying pitch from 40 μm to 100 μm.

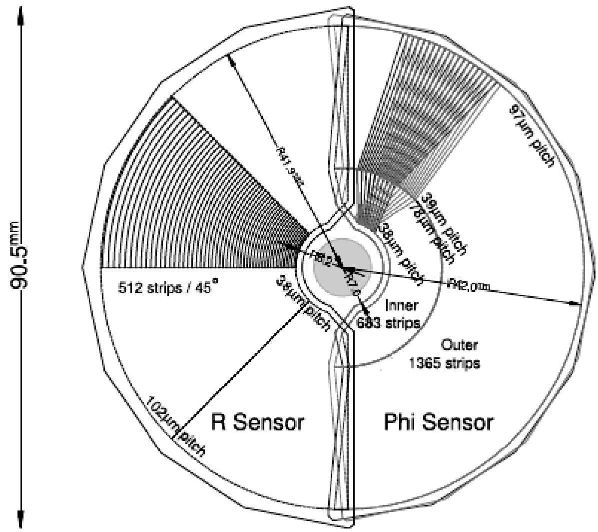

Fig. 1. The R–Φ geometry of the VELO sensors (for the sake of clarity only a portion of the strips is presented).

The R–Φ sensor design was chosen to optimize the reconstruction of tracks originating from the interaction region. The VELO tracking is split up into two steps: first fast 2D R–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 "p^+ on 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 in 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 $+5°$, respectively.

The outer tracker (OT) constitutes the outer part of the downstream tracking stations. The OT is made from 5 mm 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].

[1] Former Trigger Tracker.

2.1. Track and vertex reconstruction at LHCb

The VELO detector is a crucial part of the LHCb tracking system. Its performance is of paramount impact on both track reconstruction and the high level trigger (HLT) [1] performance. The LHCb reconstruction software is grouped within the Brunel [4] project that is based on the GAUDI framework [5].

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 R–Z projection and almost constant in azimuthal angle ϕ. As mentioned in Section 2, that optimized track reconstruction in VELO is divided into two steps: 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 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-type sensors have a stereo angle. It is possible to create more than one 3D track for each 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.

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 K_s and Λ particles that often decay outside 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 improve the performance of its particle identification.

After the pattern recognition 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 p_{T} tracks ($p_{\mathrm{T}} > 1.5$ 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 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.

3. LHCb performance with the early collision data

The first data samples collected at LHC in summer 2008 came from proton collision with a beam absorber facility. The data taking was a part of the LHC synchronisation test and helped to identify a number of areas that are critical for the proper detector performance and the data quality. The further description will be focused mainly on the VELO detector since it is the critical component for the physics performance of the LHCb spectrometer.

It has been shown that the VELO data quality is mostly affected by the hit processing algorithms tuning and the time alignment.

After a positive trigger decision is obtained, the data from the VELO detector is read out for pre-processing by the TELL1 acquisition electronic boards [6]. The pre-processing sequence is performed by programmable FPGA processors and its purpose is to produce the raw bank (VELO clusters). This processing sequence consists of a number of algorithms that perform pedestal subtraction, cross-talk correction, common mode removal and clusterisation. Each such pre-processing step is implemented as a separate algorithm. The suite of algorithms are executed by the processing units of the TELL1 and are implemented in the low level VHDL language as a part of the TELL1 firmware. The algorithms are controlled by over one million processing parameters that need to be determined and tuned for each channel separately. In order to extract the processing parameters a novel approach was taken where the raw data were processed by the bit perfect emulation of the TELL1 board [7]. The emulation has been implemented within the experiment software framework and can handle the standard data stream produced by the detector read-out electronics. The appropriate automatic procedure for the processing parameters determination and tuning has been developed and tested before the 2009 collision data taking.

The time alignment procedure is based on the optimisation of the front-end chip sampling time with respect to the central LHC clock. The signal in the analogue front-end has rise and fall times similar to the LHC clock (around 25 ns). In order to determine the pulse shape of the chip data was taken for different sampling times for the whole VELO. This has allowed to tune the sampling time for all sensors to within 2 ns of the optimal point.

The reconstruction of both primary vertices and 3D impact parameter (the distance of closest approach of tracks to the primary vertex) is essential for the physics performance of the LHCb experiment and depends directly on the single hit resolution of the VELO. The resolution measured by the R-type sensor is shown in Fig. 2 as a function of the pitch. This result was obtained

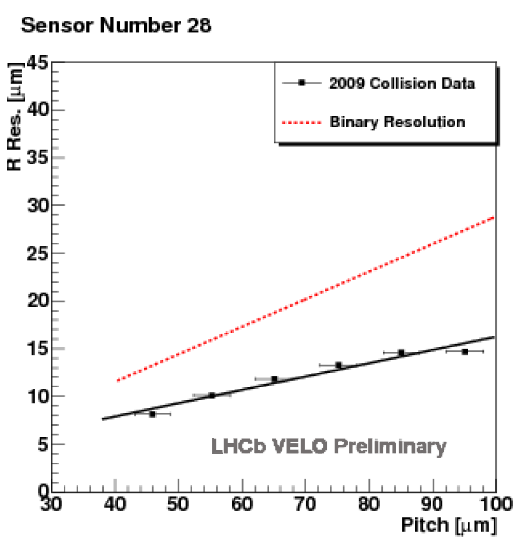

Fig. 2. Resolution of a representative R-type sensor as a function of the inter-strip pitch on the sensor.

for tracks that had polar angles with respect to the beam in the range 6°–12°. The best resolution that was obtained for the minimal pitch (40 μm) and track angle around 10° was 4 μm. The pitch is an increasing function of radius. The single hit resolution has been measured using the space alignment information obtained during the synchronisation tests described above. The alignment method is based on a non-iterative matrix inversion algorithm. The precision of this method has been measured to be 4 μm in the plane perpendicular to the beam.

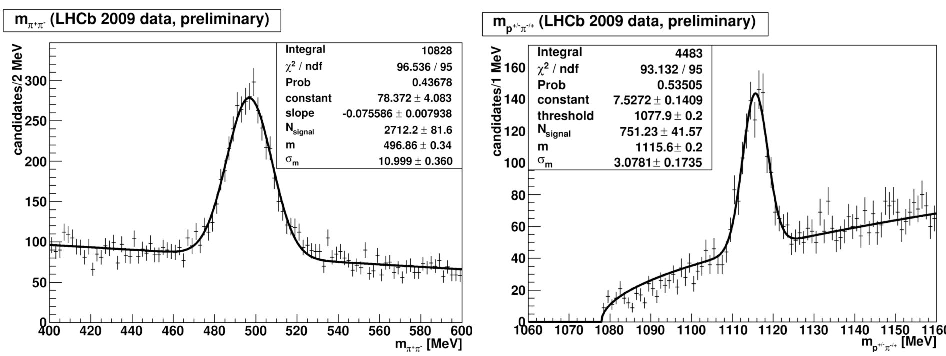

Fig. 3. Reconstructed invariant mass for decays $K_s \to \pi^+\pi^-$ (left-hand plot) and $\overset{(-)}{\Lambda} \to p^\pm\pi^\mp$ using the LHCb tracking system without the VELO detector.

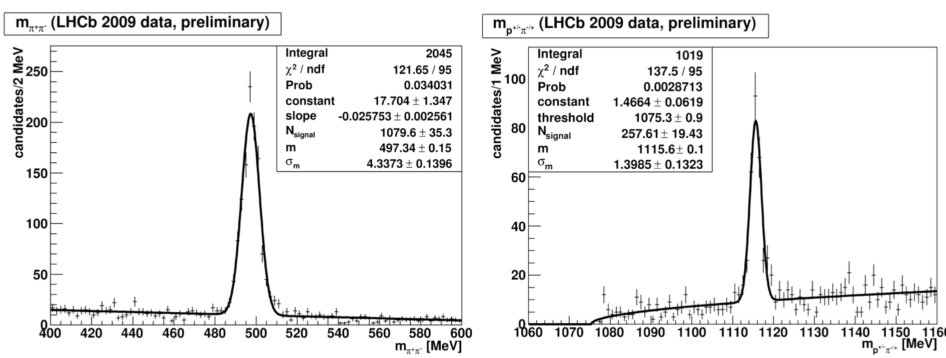

Fig. 4. Reconstructed invariant mass for decays $K_s \to \pi^+\pi^-$ (left-hand plot) and $\overset{(-)}{\Lambda} \to p^\pm\pi^\mp$ using the full LHCb tracking system including the VELO detector (partially inserted at ± 15 mm).

The full insertion of the VELO detector can be performed safely once the beam energy rises above 2 TeV. During the early data taking in 2009 the VELO was only partially inserted (the separation between the VELO halves was 30 mm). Nevertheless, it was showed that the mass resolution improves more than twice when the VELO hits are included in the track fit. This has been demonstrated (see Fig. 3 and Fig. 4) in reconstructing the mass distributions for $K_s \to \pi^+\pi^-$ and $\overset{(-)}{\Lambda} \to p^\pm\pi^\mp$ decays.

4. Conclusions.

The LHCb detector has been successfully commissioned and operated during the first period of data taking. The essential part of the LHCb spectrometer is the VErtex LOcator (VELO) that is placed around the interaction region. The high quality of the data produced by the VELO is critical for both off-line and on-line (trigger) analysis. 3D impact parameter is essential for all physics selections and its precision depends directly on the single hit resolution measured by the VELO. For the 2009 collision data the best hit precision has been measured. It has been shown that VELO improves considerably the mass resolution of the reconstructed particles.

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