Study of the LHCb pile-up trigger and the BsJ/ decay
Zaitsev, N.Y.

Citation for published version (APA):

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CHAPTER 2

The LHC and LHCb

4 Introduction

This chapter describes the LHCb setup and its experimental environment. It starts with the description of the Large Hadron Collider (LHC), which is the source of B-mesons. Then the LHCb detector is reviewed indicating why a particular choice for individual detector components was made and how data from particular detectors are analyzed. At the end, the trigger and DAQ architecture are given in some detail.

5 Large Hadron Collider

The LHC [18] is CERN’s next accelerator facility. It is a collider with two proton beams rotating in opposite directions and colliding with a c.m. energy of $\sqrt{s} = 14$ TeV. The main experimental topics of this machine are the searches for Higgs particles (Atlas and CMS), the quark-gluon plasma (Alice), the study of CP-violation effects (mainly by LHCb, but also Atlas and CMS) and effects of possible physics outside the Standard Model (SM).

In order to be sensitive to these phenomena, which are characterized by very small signal to background ratios, high luminosities are required. The luminosity proposed for the LHC is $10^{34}$ s$^{-1}$ cm$^{-2}$. This can be achieved by filling the ring with a large number of very dense bunches. The density foreseen is $10^{11}$ particles per bunch. At such densities one has to cope with disturbances due to the bunch crossings. While only a tiny fraction of the particles interact, all the others are deflected by the strong electromagnetic field of the opposing bunch. These deflections, which are stronger for denser bunches, accumulate turn after turn and may eventually lead to particle loss. This beam-beam effect was studied in previous colliders. It was found that one cannot increase the bunch density beyond a certain beam-beam limit in order to preserve a sufficiently long beam lifetime. In order to reach the desired luminosity the LHC has to operate as close as possible to this limit. Its injectors, the old PS and SPS, are refurbished to provide the required beam density.

The bunches traveling in the vacuum pipe leave behind an electromagnetic wake-field which perturbs the succeeding bunches. These perturbations accumulate and lead to large collective instabilities, which if not suppressed may cause the loss of the beam.
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Compensation systems to counteract these effects include special elements to compensate for imperfections, special coating of the beam pipe to reduce the resistance to beam induced wall currents and complex feedback systems.

The luminosity is given by:

\[ L = \frac{N_1 N_2 k_b f \gamma}{4 \pi \varepsilon_n \beta^y} F \]  

(18)

where \( N_{1,2} \) are the number of protons per bunch, \( k_b \) the number of bunches, \( f \) the revolution frequency, \( \gamma \) the relativistic factor, \( \varepsilon_n \) the normalized transverse emittance, \( \beta^y \) the value of the betatron function at the interaction point, and \( F \) a reduction factor of about 0.9 which takes into account the fact that the beams cross at an angle [18]. From this formula it follows that to achieve a high luminosity one has to make the number of particles \( (N_1, N_2) \) and the bunch crossing frequency as high as possible, while keeping \( \varepsilon_n \) and \( \beta^y \) small. The transverse emittance, \( \varepsilon_n \), characterizes compactness and divergence of the bunch and depends on beam-beam effects, while the amplitude function, \( \beta^y \), is a measure of the ability of the magnet optics to focus the beam at the interaction point. The nominal values of these parameters are presented in the Table 2.

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<tr>
<td>( \beta )</td>
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**Table 2:** LHC performance parameters [18]. Numbers give the design luminosity of \( 10^{34} \text{ s}^{-1} \text{ cm}^{-2} \).

The Radio Frequency (RF) of the LHC is 400 MHz. However, only every tenth RF bucket can be filled corresponding to a minimum bunch distance of 25 ns and a total number of 3564 bunches along the circumference of the ring. The bunch crossing structure is given by:

\[ 3564 = 11[3(81b + 8e) + 30e] + 2(81b + 8e) + 119e \]  

(19)

where \( b \) is a bunch crossing (BC) and \( e \) is an empty crossing (0BC). This bunch structure is due to the filling scheme of the injectors: PS (81 bunches with 25 ns space = PS-train) and SPS (3 PS-trains). Empty bunches (or beam gaps) arise due to a non-integer ratio of the PS, SPS and LHC revolution frequencies. This results in 2835 actually filled bunches.

The LHCb detector will be located at Intersection Point 8. The size of the experimental area does not allow the detector to be positioned in the middle of the hall. The interaction region is shifted 11.5 m off the center. This and the demand of a relatively low luminosity of \( <5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) requires a modification of the LHC optics at the interaction point. As a consequence the existing cavern can be used maximally giving 19.7 m of free space for the LHCb detector. The lower luminosity with an average interaction rate of \( \leq 1.5 \) per bunch
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crossing allows its reliable operation because of the lower counting rate in the detector components. Because of the shift of the interaction point from its nominal position a fraction of the bunches misses each other and the BC structure now will be:

\[
3564 = 8[3(78b + 11e) + 30e] + 2(78b + 11e) + 119e
+ 2[3(78b + 11e) + 30e] + 2(78b + 11e) + 119e
\]

This gives 2652 bunch crossings, i.e. only 74.4% of all non-empty BC’s are expected to have an interaction.

The bunch size at the interaction point is given by Gaussians. The longitudinal and transverse dimensions are given by \(\sigma=7.5\) cm and \(\sigma=75\) μm respectively. The interaction volume is due to the crossing of two bunches and has a \(\sigma=5.3\) cm longitudinally \(\sigma=53\) μm transversally.

6 LHCb detectors

For the studies described in this thesis, we base ourselves on the layout and the technologies given in the Technical Proposal of LHCb [19], even though the development and design of the detector technology is still on-going. The analysis presented in Chapter 6 however, is not sensitive to the detailed design. In the following we give a brief description of the detector components.

The dominant production mechanism of \(b\overline{b}\)-quarks in proton-proton collisions is the fusion of two (or more) gluons radiated from the quark-constituents of the colliding protons. This leads to a flat distribution in rapidity of produced particles and accordingly to an enhanced production rate at small polar angles. This dictates the choice of a forward spectrometer at the LHC. The enhancement of the production rate and the correlation between the production angles of \(b\) and \(\overline{b}\)-quarks is illustrated by Figure 3, where the polar angle (with respect to the beam axis) of the

![Figure 3](image)

**Figure 3:** Correlation of angle of \(b\)-quark and angle of \(\overline{b}\)-quark produced in the same \(pp\)-interaction.
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hadron containing a b-quark in b\bar{b}-event is plotted versus the polar angle of the other hadron containing the \bar{b}-quark.

The LHCb detector covers the forward region around the direction of one of the proton beams from 10 to 300 mrad in polar angle, see Figure 4. Since B-particles are produced in the forward direction the design leads to a large acceptance for the two B-particles in a b\bar{b} production event. One of these has to be fully reconstructed while the other should be sufficiently well reconstructed to provide a flavour tag. The forward geometry of LHCb makes it possible to measure the B-decay distance for a large range of momenta of the B-particles. Since the average momentum of the forwardly produced B-particles are large, the decay lengths are equally large. This provides better conditions for the study of systematics than in case of a central geometry detector, like ATLAS or CMS, where there is an upper limit on the measured momentum.

6.1 Detector components

In the LHCb detector one can distinguish the following five principal detector systems (see Figure 4):

1. The vertex detector system. It contains a silicon vertex detector telescope and a pileup veto counter. These are used in the event trigger and for the reconstruction of vertices. The vertex detector itself is enclosed by a vacuum tank and the beam pipe.

Figure 4: LHCb detector.

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2. Aerogel and gas Ring Imaging CHERENKOV (RICH) counters. They are used for particle identification.
3. A spectrometer consisting of a tracking system and a dipole magnet. It measures the track momenta and provides information on the trajectories of charged particles (measured in the other detector components of the LHCb).
4. Electromagnetic and hadron calorimeters. They are used to trigger on b-b events. The electromagnetic calorimeter is optimized for efficient $\pi^0$ reconstruction.
5. A muon detector composed of iron filters, interleaved with tracking chambers. It is used in the off-line analysis, to tag the $b$-flavour and to identify muons for the trigger.

A right-handed coordinate system is used with its origin at the center of the interaction volume, with the $z$-axis along the beam direction and $y$-axis pointing upwards. Charged particles are bent in the horizontal $x\varphi$-plane.

6.2 Vertex detector

The vertex detector provides precise information about charged particle trajectories near to the interaction point. This allows for the reconstruction of the primary vertex and possible secondary decay vertices and provides input for the Level-0 pile-up and Level-1 topology trigger. Final states of $B$-mesons have to be detected with branching ratios $\ll 10^{-5}$. The detection of background and the demand of a minimum dilution in the measurement of CP-asymmetry requires the $B$-meson decay time to be measured with a resolution of the order of 50 fs or better. This roughly corresponds to a resolution of 300 $\mu$m in determining the decay vertex position. The forward detector geometry allows this goal to be achieved by placing vertex detectors as close to the interaction region as possible.

For this reason, all the detectors including the readout electronics are located inside a special vacuum vessel which includes a roman pot system for moving the detectors away from the beam during the beam filling. The vessel has a thin forward window which extends over the full LHCb detector acceptance. It is connected to a specially designed part of the beam pipe which passes through all detectors downstream of the vacuum tank. This part is about 20 meters long and is made of two conical parts: the first is 1.5 m long and has a 25 mrad opening angle, and the second is 16 m long and has a 10 mrad opening angle. The pipe has an aluminium wall with thickness ranging from 1 to 6 mm.

The individual elements of the vertex detector are silicon semiconductor strip detectors. The detectors have $n$-strip readout and individual $p$-isolation between the strips, see Figure 5. The $n$-implants are capacitively coupled to aluminium strips. The aluminium strip resistivity is about 20 $\Omega/$cm and its capacitance to the implant is about 12 pF/cm. These values were chosen to provide low heating of the strip and a fast collection of the charge left in the detector by ionizing particles.

The vertex detector consists of 17 stations of silicon strip detectors around the interaction point (IP) between $z= -18$ cm and +80 cm. Each station has two discs separated by 2 mm with circular ($r$) and radial ($\varphi$) strips. The distance between the first 12 stations is 4 cm. The remaining five stations are positioned at $z=35, 50, 60, 70, 80$ cm. All discs are made of two halves. The upper half is shifted by 2 cm with respect to the lower one. This is done in order to avoid mechanical interference, provide better coverage of acceptance and improve detector alignment. The two halves are retracted by 3 cm during LHC beam injection.

The detector provides high precision measurements of tracks and vertices around the IP. The
required precision and the high radiation conditions in the region close to the beam demand a small strip pitch of a few tens of microns. Geometry details are given in Figure 6. The strip size

- is optimized to achieve small hit occupancy, minimize the amount of material due to detectors (multiple scattering) and provide a reliable measurement of all accepted tracks. The strip pitch in the inner part of the detector (radius<2.56cm) is 40 µm yielding a single hit precision of 6-9 µm, whereas at large radii a pitch of 80 µm is foreseen corresponding to a single hit.

Figure 5: Schematic cross-section of the silicon detectors showing the depletion region after irradiation.

Figure 6: Layout of vertex detectors.

61° silicon vertex detector elements

φ-d detector

256 + 640
= 896 strips

r-d detector

2 384 + 256 + 241
= 1265 strips

40 - 105 µm

40 - 104 µm

1.0 2.5 [cm] 6.0 1.0 2.5 4.1 [cm] 6.0

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resolution of 10-18 μm.

The time between bunch crossings determines the choice of electronics. Full charge collection requires that the peaking time of the readout must not exceed 25 ns. In order to minimize signal overlap (from different bunch crossings) the FWHM of the signal shape must not exceed 25 ns. As not all the signals can be transferred every bunch crossing, pipeline buffers with a length of 168 bunch crossings are included. The readout chip contains preamplifiers, signal comparators and buffer logic. Since the data are used both in the trigger and the off-line analysis, the chip has two buffers of equal length: one is dedicated to the data acquisition and another to the triggering.

The circulation of the proton bunches with high frequency causes pick-up in the readout system. RF-shielding is foreseen in order to minimize this effect.

6.3 Tracking system

Downstream of the vertex detector the tracking system provides a momentum measurement of charged particles and an appropriate reference for all information obtained with other detector components. In particular it allows the propagation of tracks between the vertex detector and the RICH and the extrapolation of tracks to the electromagnetic and hadron calorimeters. The system consists of 11 stations of tracking chambers (T1-T11) located between the vertex detector and the calorimeters. Each station contains several planes with wire orientation at 0, ±5° (y,z,y) with respect to the vertical. This provides efficient rejection of ghost tracks. Stations adjacent to the RICH detectors have additional detector planes, which provide precision measurements in the non-bending plane.

The system is split into two parts: Inner and Outer Trackers. This is done because of the large occupancies expected near the beam. In the outer tracker region the particle flux is less than $1.4\times10^5 \text{ cm}^{-2} \text{ s}^{-1}$ and allows the use of wire drift chambers. The Inner Tracker covers a region of 60×40 cm² around the beam pipe. The particle fluxes here can reach up to $3.5\times10^6 \text{ cm}^{-2} \text{ s}^{-1}$. This requires a different technology. Due to its small size, the separation of station T1 into an inner and an outer region was deemed inappropriate so that the Inner Tracker here is extended to cover the full acceptance.

The dipole magnet provides a total field length of 4 T·m over a short effective length. The field is oriented along the y-axis and has a maximum value of 1.1 T. The yoke aperture is 4.3 m horizontally and 3.6 m vertically. This results in nearly 100% acceptance for charged particles with a momentum above 2 GeV. The iron shield upstream of the magnet reduces the stray field in the vicinity of the vertex detector and the RICH1 detector (see Figure 4). During operation it is foreseen to reverse regularly the polarity of the magnet field to reduce systematic errors in the asymmetry measurement expected from CP-violations.

A momentum resolution of 0.3% is expected for particles with a momentum in the range from 5 to 200 GeV/c. For momenta under 100 GeV/c it is mainly limited by multiple scattering.

6.3.1 Outer Tracker

The technology foreseen for the outer tracking is gas drift chambers. An Outer region only exists in 10 of the tracking stations. The first one (T1) downstream of the vacuum tank uses only Inner tracker technology. A single station consists of 6-8 layers with y,u,v,x orientations, which provides measurements for three dimensional track reconstruction. Each layer has 5 mm drift cells. The material in a single layer of the detector is equivalent to 0.4% of radiation length ($X_0$). Stations 2, 10 and 11, around the RICH counters, contain two additional λ modules. The total

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number of channels foreseen in the outer tracking system is 110,000.

The chamber dimensions follow the LHCb acceptance and increase from 75×75 cm² (T2, at z=217 cm) to 360×297 cm² (T11, at z=1165 cm) in the x and y directions, respectively. Chambers are split into modules in order to have no wires longer than ~3 m.

Using a fast CF₄-based drift gas, the maximum signal latency covers two bunch-crossing intervals. The estimated single cell resolution is <200 μm. An expected maximum cell occupancy of less than 10% determines the inner boundary of the Outer Tracker.

The tracker will be read out by 8-channel preamplifier/discriminator chips. The on-board TDC will be driven by the bunch-crossing clock. Each individual channel is designed to have a Level-0 pipeline. Time measurement within 25 ns and 5-bit precision will be sufficient.

Usage of the tracker for triggering is foreseen. This is, however, still under investigation and is not considered in this thesis.

6.3.2 Inner Tracker

The inside dimensions of the Inner Tracker are determined by the diameter of the beam pipe (from 3.6 to 13 cm). The outside dimensions are 60×40 cm² (in x,y) everywhere except T1 (70×70 cm²) and T2 (60×60 cm²). This results in a total detector area of 14 m².

Three technologies are currently under investigation for the inner tracker. They are:

- MicroStrip Gas Chamber with Gaseous Electron Multiplier (MSGC + GEM).
- Recent studies have demonstrated stable operation of MSGC+3GEM layers (so-called triple GEM).
- Micro Cathode Strip Chambers (MCSC).
- Silicon Strip Detectors, as a back-up option in case neither of the previous two performs adequately.

These technologies have similar over-all properties:

- Readout pitch of 220 μm with a single hit resolution of better than 65 μm.
- Signal latency less than the bunch-crossing interval.
- A total number of channels of about 220,000.

In the simulation we have used these properties without specification of the technique employed.

6.4 RICH detectors

The RICH detectors allow the identification of pions and kaons over a wide momentum range. This is crucial information to increase the signal to background ratio for b-decays and provides a kaon tag for CP asymmetry measurements.

Charged particles traversing the material with a velocity exceeding the phase velocity in that material emit electromagnetic (Cherenkov) radiation around an angle proportional to inverse velocity of this particle: \( \cos \Theta_v = 1/(\beta c) \), where \( \Theta_v \) is the angle of the Cherenkov radiation with respect to the flight path of the particle. The Cherenkov radiation is a threshold phenomenon, i.e. the light is produced only above the critical speed of the particle: \( v_c = \beta_c c = c/n \), where \( n \) is the refractive index of a radiator. The number of emitted photons depends on the

\(^{(*)}\)Cherenkov has discovered this phenomenon during his Ph.D. work in the experiment done under supervision and close collaboration with S.Vavilov. In Russia both are appreciated and it is named “Vavilov-Cherenkov radiation”. The story is memorized by V.Ginzburg [20].

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length of the radiator: \( N = 2\pi \alpha L \sin^2 \theta \left( 1/\lambda_2 - 1/\lambda_1 \right) \), where \( \lambda_1 \) and \( \lambda_2 \) determine the wavelength range of detected photons and \( \alpha \) is the fine-structure constant. A 1 m thick radiator produces \( \sim 120 \) photons in the range \( 400 < \lambda < 700 \) nm. Assuming the photodetectors to have a quantum efficiency of \( \sim 0.3 \) we can detect 40 photoelectrons.

RICH (Ring Imaging CHERenkov counter) detectors detect ring images formed by Cherenkov photons that are emitted by charged particles crossing the radiator (see Figure 7). Given the momentum of the particle the measurement of the radius of the produced ring allows the separation of particles of different mass. In particular it allows the separation of kaons and pions. The momentum and entry point of the particle are provided by the tracking system. A system of focusing mirrors (not shown on the picture) focuses the ring onto a compact array of photodetectors, reducing the size of the whole detector, and reflects the image outside the detection acceptance allowing the use of non-radiation hard electronics.

The RICH detectors at LHCb have to identify charged particles over the momentum range 1-150 GeV/c and within the large acceptance of 10-330 mrad. Particle identification is crucial to reduce background in selected final states and to provide an efficient kaon tag. The angle-momentum correlation of particles generated in proton-proton interactions at high energy (as \( \theta \sim 1/p \)) requires the use of two RICH detectors in order to provide particle ID over the full momentum range.

**The upstream, RICH1, detector** has both, a silica aerogel and a \( \text{C}_2\text{F}_{10} \) gas radiator, and is designed to identify low-momentum tracks. It has an acceptance from 25 to 330 mrad in both \( x \) and \( y \) projections and is situated upstream of the magnet, between chambers T1 and T2. The estimated resolution for the emission angle of a photoelectron is 1.1 (1.45) mrad for \( \text{C}_2\text{F}_{10} \) (Silica) radiators. This corresponds to a 0.15 (0.37) mrad angular resolution per track.

**The downstream, RICH2, detector** uses \( \text{CF}_4 \) gas as radiator. It has an angular acceptance of 10-120 mrad in \( x \) and 10-100 mrad in \( y \). It is positioned between chambers T10 and T11. The resolution of the emission angle is estimated to be 0.06 (0.35) mrad per track (photoelectron).

From a maximum likelihood analysis it is concluded that tracks from \( b \)-events can be identified with efficiencies and purities above 90\%. A 3\( \sigma \) separation of pions and kaons is achieved over the momentum range 1-150 GeV/c, where RICH1 provides coverage from 1 to 40 GeV/c and RICH2 from 5 to 150 GeV/c.

### 6.5 Calorimeters

The calorimetry system of LHCb consist of an electromagnetic calorimeter with preshower detector and a hadron calorimeter. It identifies photons, electrons and hadrons and measures their position and energy. The information will be used in the trigger and in the off-line analysis. The chosen detector segmentation is a compromise between a small number of readout channels and a low occupancy with reasonable position and energy resolutions. The cell sizes and

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positions match in all three sub-systems (preshower, electromagnetic and hadron calorimeters) in order to facilitate their use in the trigger.

Inclusion of the calorimeter information in the Level-0 trigger requires the signal collection time in all three detectors to be below 25 ns.

6.5.1 Electromagnetic calorimeter and Preshower detector

The interaction of photons/electrons with matter leads to a cascade of $e^+/e^-$ pairs and bremsstrahlung photons, which continues till the energy of the secondary particles in the cascade falls below the critical energy, $E_c$, or till particles leave the detector volume (leakage). $E_c$ is determined by the mass of a positron-electron pair ($\sim$1 MeV) and the ability of an electron to emit a bremsstrahlung photon, with energy losses due to ionization starting to dominate at electron energies below a few MeV for heavy and dense materials with $Z \geq 30$. The energy of electrons and positrons below $E_c$ dissipates in the material through the ionization and excitation of atoms. The preshower and the electromagnetic calorimeter are located between $z=1230$ and $1319$ cm and have a total radiation length of 25 $X_0$.

The preshower detector is positioned in front of the electromagnetic calorimeter at $z=1230$ cm. It consists of 1.4 cm of lead ($2.5 X_0$) followed by 1 cm of scintillators. The difference in the development of the electromagnetic shower induced by a photon or an electron allows their separation. This information is used in the Level-0 high-$p_t$ triggers and in the offline-analysis.

The signals from the scintillator are readout with Photo Multiplier Tubes (PMT) and digitized with 8-bit ADC’s.

Electromagnetic calorimeter. The efficient reconstruction of $\pi^0$’s and their discrimination from electrons and charged hadrons with overlapping photons requires a fine transverse segmentation. In order to reduce the complexity of the detectors while maintaining a decent position/energy resolution three different cell sizes in three radial regions $(x \times y)$ are foreseen: $4 \times 4$ cm$^2$ in the region up to $192 \times 320$ cm$^2$, $8 \times 8$ cm$^2$ in the subsequent region up to $384 \times 512$ cm$^2$ and $16 \times 16$ cm$^2$ finally up to $640 \times 832$ cm$^2$. The detectors use Schashlik technology with lead as the absorber material. The energy resolution is $\sigma(E)/E = 10%/\sqrt{E} \oplus 1.5%$ ($E$ in GeV).

6.5.2 Hadron calorimeter

The purpose of the hadron calorimeter is identification of hadronic particles. The main process used in this detector is the inelastic interaction of hadrons with the detector material. The products of the primary interaction are mainly pions: $\pi^+$ and $\pi^-$. Charged pions are detected in the sensitive material of the detector (scintillators), while neutral pions decay to gammas and generate electromagnetic showers. The scintillator response to the electromagnetic shower is larger than that to charged pions because of the cut-off ($m_{\pi} \approx 140$ MeV/$c^2$) in the cascade development for the latter. Therefore, fluctuations in the $\pi^0$ component of the shower directly contribute to a deterioration of the energy resolution. Part of the energy in inelastic interactions of hadrons goes into the excitation of nuclei with the subsequent emission of low energetic gammas and neutrons. A small fraction (~1%) of the shower particles, such as muons and neutrinos, are leaving the detector without interaction. Sampling fluctuations due to the inactive material of the detectors (of “sandwich” type) are twice as large as for electromagnetic calorimeters. The above three sources of uncertainties add-up to an energy resolution for the hadron calorimeter of 70-90%/$\sqrt{E}$(GeV).

The shower length is proportional to the nuclear interaction length ($\lambda_n$). In order to have full energy absorption over short distances calorimeters are made from heavy inactive material
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interspaced with active scintillator material. In the LHCb detector the absorber material is iron, which has advantages in cost and constructional stability over, for example, lead (Pb).

The hadron calorimeter (HCAL) cells are embedded in an iron support structure. They are 1.5 m long corresponding to $7.3 \lambda$. Each of the cells matches 4 ECAL cells ($1 \times 2 \times 2$). As in the case of the ECAL this results in three regions with different cell size. The expected energy resolution is $\sigma(E)/E = 80\% / \sqrt{E} \oplus 5\%$. The outer dimension of the HCAL is $8.96 \times 7.04$ m with a square hole of $0.64 \times 0.64$ m to let the beam pass through. Material between the beam pipe and the inner surface of the HCAL absorbs the products of interactions of particles with the pipe.

The scintillators are read out by PMT’s. The signals are digitized and inserted into the data stream at the bunch crossing rate of 40 MHz. The 12-bit dynamic range of the digitized signal implies an energy range dependent on the polar angle: $50 \text{ MeV} \rightarrow 200 \text{ GeV}$ for the inner region, $25 \text{ MeV} \rightarrow 100 \text{ GeV}$ for the middle region and $12.5 \text{ MeV} \rightarrow 50 \text{ GeV}$ for the outer region. The contribution to the resolution due to this digitalization scheme is negligible with respect to other contributions to the energy resolution of the calorimeters.

6.6 Muon detector

The muon detector allows the identification of muons. This information is used in the Level-0 trigger, the offline reconstruction and the flavour tagging. The detector consists of a muon shield and a set of chambers. The shield is composed of the ECAL, the HCAL and four layers of steel. Five muon tracking stations, M1-M5, are interspaced with the steel layers. The total radiation (interaction) length in front of muon station M2 is 112.5 $X_0$ (10.4 $\lambda$). Each station of M3-M5 is shielded with an additional 39.3 $X_0$ (4.2 $\lambda$). The full detector can be penetrated by a muon with an energy of 6 GeV or higher. Other particles than muons (except neutrinos) have a small chance to survive. The station M1 is not shielded. It is positioned in front of the ECAL calorimeter and is used in the photon and electron triggers. Positions of stations M1-M5 are $z = 1195, 1500, 1620, 1740$ and 1860 cm respectively.

Most of the outer acceptance is covered with Multigap Resistive Plate Chambers (MRPC) while the inner part is filled with Cathode Pad Chambers (CPC). The higher occupancy around the beam pipe is the reason for their division. The upstream M1 station is using CPC technology.

A total number of 236k channels will be read out by electronics mounted on the edge of the detectors. The signals are pipelined in on-board buffers. Logical combinations of channels reduce this number to 45164 for use in the Level-0 trigger.

7 Event trigger and selection

7.1 Introduction

LHCb should effectively select useful (signal) events and store them onto tape. The main physics objective of the LHCb is the study of CP-violation in decays of neutral B-mesons. For this reason, we want to detect particular B-decay channels and have the possibility to tag the flavour of the decaying B-meson. Storage devices can not record all events produced in proton-proton interactions and even not all potentially reconstructible B-mesons. This demands the reduction of data to an acceptable level using the trigger system, while enhancing the fraction of B-events in the remaining data sample.

The expected rate of signal events is proportional to the cross section for $b\bar{b}$-production.
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($\sigma_{bb}=0.5 \text{ mb}$). This corresponds to a 100 kHz rate of B-events at a luminosity of $2 \times 10^{32} \text{ s}^{-1} \text{ cm}^{-2}$. Since we cannot store all B-mesons we must optimize the trigger selection for the few (pilot) channels in which we want to study CP-violation. Some of these interesting channels are given in Table 3. The decay channels listed in the table allow the measurement of all angles of the

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</tr>
<tr>
<td>$B_s \rightarrow D_s K$</td>
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</tr>
<tr>
<td>$B_s \rightarrow J/\psi \phi$</td>
<td>$\delta\gamma, \lambda$</td>
</tr>
<tr>
<td>$B_s \rightarrow D^* \pi$</td>
<td>$\lambda$</td>
</tr>
</tbody>
</table>

Table 3: Pilot channels and parameters of interest.

CKM unitarity triangle (see Chapter 1). They also give access to the CP parameters with small theoretical uncertainties. Their visible branching ratios are all of the order of $10^{-5}$ or lower. Features of B-events in the LHCb detectors used for the selection are the following:

1. Due to the large mass of b-hadrons and their relatively large transverse momentum with respect to the beam direction their decay products have on average a large transverse momentum ($p_T$) too.

2. The lifetime of the b-quark is about 1.5 ps. B-particles accepted by the spectrometer have typically a momentum of about 80 GeV. A b-event will, therefore, contain decay vertices which are separated from the interaction point by ~1 cm on average. Tracks associated with these vertices have large impact parameters with respect to the primary interaction point.

3. The small decay width of B-hadrons, the large mass difference between $c$ and $b$-quarks and the excellent mass-resolution of the LHCb spectrometer allow an efficient background rejection and preselection of signal events.

The backgrounds, which must be rejected by the trigger system fall into two distinct categories. The first consists of minimum bias events, which do not contain any B-hadron. The particles in these events have typically a lower $p_T$ than the particles associated with a B-hadron.

---

*Visible branching ratio is defined as the product of branching ratios of decays leading to a detected final state.
The LHC and LHCb

The rate is proportional to the total inelastic cross-section which is estimated to be $\sigma_{mb}=80$ mb. The second category consists of events with multiple primary interactions. Since events with multiple interactions confuse the standard Level-0 trigger and reconstruction algorithms, it is imperative to recognize and remove these events at an early stage. The rate of these events depends on the luminosity and follows Poisson statistics. For example, at a luminosity of $2\cdot10^{32}$ s$^{-1}$ cm$^{-2}$ events with multiple interactions represent 41% of the total number of bunch crossings with at least one inelastic interaction.

The required data reduction level depends on the capacity of the off-line storage devices and on the data flow obtained from the entire LHCb detector. The LHCb has 950k readout channels, which at a bunch crossing frequency of 40 MHz corresponds to a data flow of 40 TB/s whereas only 20 MB/s can be stored on tapes. Therefore, the data reduction must be at least a factor 200000. Sophisticated on-line analysis is slow and will cause a loss of statistics due to the deadtime of the detection system. The classical solution to this problem is a multi-level trigger scheme with simple and fast selection at the beginning to create more comfortable conditions for the operation of more sophisticated and slow algorithms at the end. Temporary data storage in pipeline buffers reduces the deadtime effect due to the limited latency of corresponding triggers.

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The LHCb has a 4-level (from Level-0 to Level-3) trigger system. Logically they can be split into two groups. The first group of triggers, Level-0 and Level-1, uses local information from individual detectors. At Level-0 we consider only raw data. The Level-1 uses data after zero subtraction and clustering of hits. The levels 2 and 3 employ more sophisticated algorithms using combinations of data from several (Level-2) or all (Level-3) detector and analyze global event information.

7.2 Level-0

The Level-0 triggers exploit the relatively high transverse momentum of B-decay products compared to that of particles from minimum bias events. There will be four “high-$p_t$ triggers” running in parallel. They are specialized to detect electrons, photons, hadrons and muons respectively. The first three share a common algorithm although with different selection cuts and use raw calorimetry information, while the last one uses data from the muon detectors. The $p_t$ resolution at Level-0 is limited since the total number of channels used in the algorithms is smaller than in the off-line analysis and because of simplifications in the algorithms.

Another type of trigger is the “pileup” trigger, which identifies and vetoes events with multiple interactions.

The Level-0 bandwidth is fixed at 1 MHz. At the average LHCb luminosity the data rate should therefore be reduced by a factor of about 16.

7.2.1 Calorimeter triggers

Any charged particle depositing more energy than that of a minimum ionizing particle in the calorimeter is either an electron, a hadron or a photon. The transverse calorimeter segmentation allows the estimation of the center of gravity of isolated clusters and provides a rough measurement of transverse momentum. A projective geometry with respect to the mean interaction point is used for the cell sizes and their positions in order to simplify the algorithms.
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**Electron trigger**

The electron trigger uses data from the pad chamber, M1, in front of the calorimeters, preshower and the ECAL. The projectivity of pads and cells is exploited in the algorithm by matching signals in corresponding detector elements. First, a signal above the threshold of 3 GeV in a 3×3 cell window is searched for in the calorimeter. The signal in the central cell is required to be above any of its eight neighbors (isolation cut). The center of gravity is calculated and is taken as the position of the isolated cluster. Predictions are made for the position of the pad chamber using two hypotheses, one for positive and one for negative charge, using in addition an estimate of the electron energy. Comparison with the measured pad chamber position then allows the rejection of background from gamma which is converted in the material between the interaction point and the calorimeter. The addition of the pad chamber measurement improves the p_t resolution for particles with momentum below ~20 GeV. An energy above 3 MIP is demanded in the preshower in order to remove gammas, which induce similar electromagnetic showers as electrons. The central cluster energy (E_c) is required to be at least 40% of the total energy seen in the 3×3 window (E_0). Finally the transverse energy (E_t) is calculated from E_c and the position of the cluster.

The E_t cut is tuned to achieve a suppression of ~100 for inelastic single pp interactions. The electron trigger selects with high efficiency and purity B-events with electrons in the final state, such as semileptonic decays (tagging) and decays containing J/ψ → ee in the decay chain.

**Photon trigger algorithm**

This trigger follows the electron trigger algorithm with two exceptions. Firstly, the pad chamber should have no hits within the search window. Secondly, the E_t cut is significantly higher with a rejection factor of about 150 of single minimum bias events.

**Hadron trigger algorithm**

Events with a hadron in the final state of a B-decay are accepted by the high E_t signature in the hadron calorimeter. Clusters in 3×3 cell windows are searched for with E_t>5 GeV. Cluster position and particle trajectory are calculated in the same manner as for the electron trigger, using the pad chamber. The energy in the ECAL 3×3 clusters along the trajectory is added to give the total energy of the candidate (E_0t). The E_t is calculated using the total energy and position of the cluster.

With a minimum bias rejection factor of ~17 the trigger retains 60% of B_d→ππ decays. As expected the higher multiplicity decays, such as B_c→D^*⁺π, have a smaller retention of 30%. This trigger has no particular background source. However, its performance is influenced by the energy resolution in the HCAL and the large cell granularity that determines the resolution of the cluster position.

**7.2.2 Muon trigger**

The muon trigger operates in a relatively easy environment where all other than muon high energy particles have been absorbed in the muon filters. Its purpose is to select semileptonic B-decays with a muon in the final state. The trigger algorithm uses all five pad chambers, M1 to M5, of the muon detector. It proceeds in several steps. All active pads in the M3 chamber are considered as candidate seeds. If hits are found within a search window in the M2, M4 and M5...
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chambers, then the active pad of M2 closest to the center of the search window is taken. The x-intercept coordinate in M1 is predicted by the M2 and M3 pad coordinates and the closest pad hit to this x-coordinate is chosen. The y-slope (angle with respect to the beam in zy-plane) is determined from the M1 and M2 pad coordinates. A rough y-intercept is calculated with respect to the nominal position of the interaction point. A successful candidate must have a value of the y-intercept below a certain limit, which is determined by the pad sizes of the muon chambers. The x-slope (angle with respect to the beam in zx-plane: i.e. the bending plane) is determined from the M1 and M2 pad coordinates. The y-slope is recalculated using the M1 pad hit and the coordinate of the nominal interaction point. The p_th cut of the muon candidate is calculated from the x- and y-slopes and the nominal magnetic field. The p_th cut is tuned to reject minimum bias events.

Simulations suggest that the main background comes from interactions of low angle, mainly very energetic, particles with the beam pipe and from muons from π/K decays. Contributions from other sources, like punch-through or overlap with background muons, are found to be small.

7.2.3 Pileup Veto

At the nominal luminosity of LHCb (2·10^{32} s^{-1} cm^{-2}) a large fraction (40%) of the bunch crossings contains more than one pp interaction. These events are preferably accepted by the high-p_threshold triggers, thus usurping the LO-bandwidth (1MHz). Therefore, some fraction of the B-events potentially accepted by Level-0 is lost. In order to keep these events bunch crossings with multiple interactions must be detected and removed from the data stream.

To this aim a special purpose trigger is built, which can do a fast reconstruction of primary vertices and give an estimate of their number, to be implemented at Level-0. Because of the long interaction region (σ=5.3 cm) the primary vertices created in multiple interactions are widely spread along the beam axis and only a modest vertex resolution (≤3 mm) is necessary to achieve good detection efficiency (≥90%) for multiple interactions.

The algorithm uses linear correlations of track hits measured in two planes of the vertex detector with azimuthal strips giving a vertex resolution of the order of 1 mm. By tuning the trigger to select 95% of single interaction events the efficiency to detect double and higher multiplicity events is greater then 70%. As a result, 30-40% more B-events can be collected.

The pileup algorithm is a topic of this thesis and is described in greater detail in Chapter 4.

7.2.4 Level-0 Decision Unit

The Level-0 decision unit combines all relevant information collected at Level-0 in order to allow or deny the further processing of event data. The maximal time to establish the usefulness of an event is fixed to 4.2 μs. This presumes a 168 long buffer (168×25 ns) in which the data are waiting for a decision in a pipeline queue.

The event production rate at the nominal luminosity is about 16 MHz. With assumed efficiency of the pileup veto the input data flow is reduced to ~13 MHz. This eases the load of the high-p_threshold triggers, which can use more relaxed cuts in order to achieve an output rate of 1 MHz.

The output rate is optimized to select events of particular interest for the CP-violation study. About 90% of the events are selected with the high-p_threshold, muon (20%), electron (10%) and hadron (60%) triggers. The remaining 10% correspond to single events with high-p_threshold, photon and multi-leptons triggers. The p_thresholds are adjusted in accordance to the physics needs. The corresponding trigger efficiencies are given in Table 4. Examples of channels that can be
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<table>
<thead>
<tr>
<th>Reaction</th>
<th>high-(p_t) (\mu)</th>
<th>high-(p_t) (e)</th>
<th>high-(p_t) (h)</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_d \rightarrow J/\Psi(\mu\mu)K_S+\text{tag})</td>
<td>17</td>
<td>63</td>
<td>17</td>
<td>72</td>
</tr>
<tr>
<td>(B_s \rightarrow J/\Psi(\mu\mu)K_S+\text{tag})</td>
<td>87</td>
<td>6</td>
<td>16</td>
<td>88</td>
</tr>
<tr>
<td>(B_d \rightarrow \pi\pi)</td>
<td>14</td>
<td>8</td>
<td>70</td>
<td>76</td>
</tr>
</tbody>
</table>

**Table 4:** Level-0 high-\(p_t\) trigger efficiencies for some selected channels. Bold numbers indicate correspondent correlations. [21]

selected with the above high-\(p_t\) triggers are:

- \(e\): \(b \rightarrow e+X\) (flavour tag). Typical example: \(B \rightarrow J/\Psi(e^+e^-)+X\);
- \(\mu\): \(b \rightarrow \mu+X\) (flavour tag). Typical example: \(B \rightarrow J/\Psi(\mu^+\mu^-)+X\);
- \(h\): \(B^0 \rightarrow \pi^0\pi^+\). \(B_s^0 \rightarrow D^+,\ K^+\);
- \(\gamma\): \(B_s^0 \rightarrow K^{+0}\gamma\).

The Level-0 decision unit is programmable so that the selection criteria can be easily changed to reflect physics interests. An event selected by the Level-0 trigger proceeds to the next level.

### 7.3 Level-1

The Level-1 trigger uses data from the vertex detector and tracking system. It analyses topological information represented by relative positions of primary vertex, tracks and secondary vertices. Decay vertices of B-particles are well separated from the interaction point due to the long lifetime of the \(b\)-quark (see Section 7.1, "Introduction"). This leads to high impact parameters of B-decay products. The high momentum of the tracks can also be used in the selection criteria for B-events. The selection cuts are tuned so that the input data rate of 1 MHz is reduced to 40 kHz at the output.

#### 7.3.1 Topology trigger

The Level-1 topology trigger uses data from the silicon vertex detector to select events on the basis of topology information. In order to do this the algorithm should be able to reconstruct tracks and vertices. This is done in a few consecutive steps (see Figure 8). These are described extensively in the Technical Proposal and are summarized below:

- The algorithm first starts to select 2D-tracks in the \(r\)-plane using all possible 3-hit combinations in 3 consecutive stations, then combines these 2D-tracks to build vertices.
- These vertices are used to determine, in combination with the information on the \(\phi\)-coordinates of the \(r\)-sectors, a 3D primary vertex.
- The impact parameter of each track is calculated with respect to the primary vertex and a probability that the track belongs to the primary vertex is determined from a look up table. Tracks with a low probability are selected and the information from the \(\phi\)-detector is added to give a 3D-track after which the impact parameter is recalculated.
- From these 3D tracks those combinations are taken for which the track to track distance at the point of closest approach is less than 200 \(\mu m\). For each combination
a secondary vertex is determined. A vertex probability is assigned to each of these vertices.

- Subsequently, using the product of all vertex probabilities an event probability is calculated which determines whether the event is likely to be a minimum bias event or not.

The algorithm is difficult to optimize for events with more than one primary interaction. Firstly, twice larger average occupancy will lead to a quadratic increase of computing time. Secondly, the assignment of tracks to a primary vertex is highly ambiguous in the presence of other vertices.

7.4 Level-2

To better select b-events more complete information from different detectors is necessary. Slow tracks with large multiple scattering are the main source of fake secondary vertices in the Level-1 topology trigger. The momentum measured in the spectrometer helps to improve the primary vertex estimate and the resolution of the impact parameter. This results in a more efficient rejection of events with light quark hadrons while very few B-events are lost.

The track reconstruction algorithm proceeds along the following steps:

- Reconstruction of 3D-tracks in the forward and backward directions with respect to the primary vertex. The same algorithm is used as in Level-1. Tracks which share common hits are rejected.

- The momentum of the track is evaluated using the fact that it is proportional to the inverse of the polar angle. This allows an estimate of the effect of multiple scattering due to material between the primary vertex and the first silicon detector traversed by the track. The resolution of the impact parameter is estimated from the detector resolution and the multiple scattering.

- For each track with impact parameter IP and resolution $\delta$(IP) a significance IP/$\delta$(IP) is determined. The sum of these significances is minimized and the position of the primary vertex is found with a resolution of $(\delta x, \delta y, \delta z)_v = (9, 9.38) \mu m$. 

Figure 8: Illustration of the Level-1 topology trigger algorithm.
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- Forward tracks with large impact parameter significance (IP/\delta(IP)>2) are extrapolated to the first tracking station. The Kalman technique is used (fit and pattern recognition) to propagate the track up to the 5th station, which is in the middle of the magnet.
- After selecting tracks with a predetermined number of hits in the tracker (at least 4 in all stations and at least one in stations T3-T5, see Figure 4 on page 13) about 90% of high momentum (p>2 GeV/c) tracks remain. The impact parameter resolution of these tracks is recalculated. The relative momentum resolution of selected tracks is about 1%.

An event is accepted if there are at least 3 tracks with IP/\delta(IP)>3. Background from K_\pi and \Lambda decays is reduced by requiring IP<2 mm. The efficiency to recognize the two and three body decays and the decay channel B→J/\Psi X is about 80%. For B→DX decays, which have typically a higher multiplicity, the efficiency is about 90%. At the same time only 6.5% of udsc-events entering the Level-2 are accepted.

After the Level-2 the selected sample contains only 8-10% minimum bias events. The average output rate is 5 kHz.

### 7.5 Level-3

The Level-3 trigger (also called Event Filter) has almost the complexity of the off-line analysis. It uses particle identification information to select particular decays of the B-mesons. Four topological classes are considered:

- **Two body decays**: charged two-body combinations compatible with the mass of the B-meson (e.g. B→π\pi, B→KK, B→K\pi, B→µµ);
- **Dilepton decays**: pair of leptons from a displaced decay vertex compatible with the J/\Psi mass (e.g. B→J/\Psi K_\pi, B_d→J/\Psi K^+ \cdot B_s→J/\Psi \phi);
- **Low multiplicity decays with neutrals**: two charged tracks and a \pi^0 or photon which, combined, correspond to the B-meson mass (e.g. B_d→\rho^π, \rho^0\pi^0 and B_{d,s}→K\gamma);
- **Decays with D-mesons**: any of the above categories with a combination compatible with the D-meson mass.
- **Non B-physics channels**: those including charm particles, tau lepton etc.

Due to the limited time available for the decision, the selection algorithms are simplified compared with those used in the off-line analysis. This results in a slightly worse vertex and momentum resolution and particle identification than can be obtained in the off-line analysis. The output rate at this level is about 200 events per second. These are stored on tape. The contribution from minimum bias events to this sample is estimated to be less than 1%.

### 7.6 Data acquisition

The philosophy of the Data Acquisition (DAQ) system is rather standard. It is implemented as a multi-level system. The data are stored in pipeline buffers while waiting for a positive decision from the corresponding trigger level. The buffer length depends on the complexity of the algorithm and the available computing power. The pipeline lengths at Level-0 and Level-1 are proportional to the latency of these triggers.

The data and decision flow can be summarized in the following steps (see Figure 9):

**Event trigger and selection**
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![Diagram of LHC and LHCb](image)

Figure 9: Data Acquisition and Trigger scheme.

- Data obtained at 40 MHz are stored in on-board pipeline buffers waiting for the receipt of the Level-0 decision from the decision unit (L0DU). The data is shifted synchronously through the pipeline buffers under supervision of the “Timing and Fast Control” unit. An asynchronous solution would in principle also be possible, however, for the moment is disfavored. After receiving the Level-0 “OK” the data will be transferred to off-detector Level-1 buffers at a rate of 1 MHz.

- The data is in the Level-1 buffer is waiting for the Level-1 decision, in a similar way as in the Level-0.

- A positive Level-1 decision starts the process of event building. It uses the individual Readout Units, a Readout Network (RU) and Sub-Farm Controllers (SFC). The RU collects data from one or more front-end links, the network redistributes all the parts of a given event to one destination and the SFC assembles all data from different detectors into a full event data block. The assembled event information is used by the Level-2 and Level-3 trigger algorithms which decide either to keep an event or not.

The functionality of the data acquisition system is continuously monitored at the different levels.

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