Performance and robustness studies of the trigger for the ATLAS experiment

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Declaration

I declare that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis. Details of my original research are given in the preface.

Andrew John Lowe
Abstract

The ATLAS detector is one of two general-purpose particle detectors that will soon begin taking data at the Large Hadron Collider (LHC) at CERN. It is designed to explore a new energy frontier and answer fundamental questions about the nature of matter and the forces that shape the universe. The ATLAS trigger system is designed to select rare physics processes of interest from an extremely high rate of proton-proton collisions produced by the LHC. It is comprised of three levels. The first level is hardware-based. The second- and third-level triggers are software-based and are collectively known as the High-Level Trigger (HLT). The first part of this thesis is a study of the time overhead of the data navigation mechanism used by the HLT. The results of this study highlighted key areas for improvement within the design of the navigation mechanism. The second part of this thesis is a study of the impact of unresponsive Electromagnetic Calorimeter (ECAL) cells and Front-End Boards (FEBs) on electron trigger efficiencies. The performance of the single electron trigger “e25i” was calculated for single electrons and for the standard physics channels $W \rightarrow e\nu$, $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$. The effect of unresponsive cells and FEBs was simulated during the reconstruction of these types of events. The results obtained with single electron events demonstrate that the trigger efficiency decreases linearly by a little over 1% per 1% increase in the fraction of unresponsive cells or FEBs. The results for the physics channels are of the same order of magnitude.
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To

Nóra & Rebecca
This thesis presents the results of two separate studies of the ATLAS trigger. In the first study, detailed time profiling of the data navigation mechanism used by the ATLAS High-Level Trigger was performed. The navigation provides the means for trigger algorithms to access the data they need to work on. The performance bottlenecks in the design of the navigation were identified and improvements were devised for making the navigation faster.

The second study examines the effect of dead Electromagnetic Calorimeter (ECAL) cells and dead Front-End Boards (FEBs) on the performance of the single electron trigger, which is one of the major selection signatures needed to guarantee the physics coverage for the initial running of the Large Hadron Collider. Of the electron-based selections, this particular trigger provides the largest contribution to the final output rate. The results of this study demonstrate that the electron trigger is robust against the effects of both dead cells and dead FEBs.

This thesis is organised in the following way:

- Chapter 1 provides a short overview of the Standard Model of particle physics and outlines in brief the reasons for undertaking the work presented in this thesis.

- Chapter 2 describes the ATLAS detector, with particular focus on the ECAL. A short summary of the ECAL electronics is provided, and the FEB is introduced. This provides the background for the studies presented in Chapter 8.

- Chapter 3 provides a global view of the ATLAS trigger and data acquisition system.

- Chapter 4 builds on the previous chapter with a detailed discussion of the High-Level Trigger Selection Software. The data navigation mechanism is described. This provides the background for the studies presented in Chapter 5.
• Chapter 5 presents the results of the navigation timing study. Improvements to the design of the navigation mechanism are discussed.

• Chapter 6 details the selection cuts for the single electron trigger. The cuts themselves were devised, tuned and implemented in analysis software by the ATLAS Physics and Event Selection Architecture e/\gamma group. However, the software implementation of the cuts was significantly improved by the present author to achieve more accurate results.

• Chapter 7 presents the performance of the single electron trigger with an optimal ECAL. The performance was evaluated for single electrons and for the standard physics channels $W \rightarrow ev$, $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$. The results presented in this chapter are the benchmark against which the performance obtained with an ECAL affected by dead cells or dead FEBs is to be compared.

• Chapter 8 presents the results of the electron trigger robustness study. The impact of dead cells and dead FEBs on the performance of the single electron trigger with respect to the aforementioned processes was investigated. The relationship between trigger efficiency and the percentage of dead cells or dead FEBs was found to be linear up to at least 5%. For each of the processes studied, the trigger efficiency is shown to decrease by no more than 1% per 1% increase in dead cells or dead FEBs.

*Chapters 5, 7 and 8 (also Appendices B and C) are the result of the author’s original research.*
Chapter 1

Theory and motivation

1.1 Particles and interactions

Particle physics is the study of subatomic particles and the fundamental forces that act between them. The current theoretical description of elementary particles and their interactions is known as the Standard Model (SM) \[1-3\]. Only a brief account of the SM will be given as it has been described in detail elsewhere \[4-8\]. The SM describes matter and interactions in terms of elementary point-like particles. They have no spatial extension, but nevertheless can carry spin angular momentum. This is parameterised by a spin quantum number, which can only take integer or half-integer values.

In the SM the fundamental particles of matter are quarks and leptons, which are fermions. Fermions are particles with half-integer spin that obey Fermi-Dirac statistics, which require that two or more identical particles cannot occupy the same quantum state simultaneously. For every matter particle there exists a corresponding antimatter particle with the same mass but opposite electric charge; these are denoted with a bar or with a superscript that indicates the opposite charge.

1.1.1 Quarks

There are six known types, or *flavours*, of quarks. The quarks are organised in three families, or *generations*, as shown in Table 1.1 on the facing page. Quarks are always bound together in groups of three, called *baryons*\(^1\), or in quark-antiquark pairs, called *mesons*\(^2\). Isolated free quarks are not observed in nature. Baryons and mesons are collectively known

\(^1\) From the Greek βαρύς (barys), meaning “heavy”.
\(^2\) From the Greek μέσος (mesos), meaning “in the middle”.
1.1 Particles and interactions

as *hadrons*\(^3\). Examples of baryons are the ubiquitous proton and neutron of ordinary matter.

<table>
<thead>
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<th>Name</th>
<th>Symbol</th>
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<th>Mass</th>
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<tr>
<td>1(^{st})</td>
<td>Up</td>
<td>u</td>
<td>(\frac{2}{3})</td>
<td>(\sim 1.5 - 3.0 \text{ MeV}/c^2)</td>
</tr>
<tr>
<td></td>
<td>Down</td>
<td>d</td>
<td>(-\frac{1}{3})</td>
<td>(\sim 3 - 7 \text{ MeV}/c^2)</td>
</tr>
<tr>
<td>2(^{nd})</td>
<td>Charm</td>
<td>c</td>
<td>(\frac{2}{3})</td>
<td>(1.25 \pm 0.09 \text{ GeV}/c^2)</td>
</tr>
<tr>
<td></td>
<td>Strange</td>
<td>s</td>
<td>(-\frac{1}{3})</td>
<td>(95 \pm 25 \text{ MeV}/c^2)</td>
</tr>
<tr>
<td>3(^{rd})</td>
<td>Top</td>
<td>t</td>
<td>(\frac{2}{3})</td>
<td>(174.2 \pm 3.3 \text{ GeV}/c^2)</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>b</td>
<td>(-\frac{1}{3})</td>
<td>(4.20 \pm 0.07 \text{ GeV}/c^2)</td>
</tr>
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Table 1.1: Quarks and their properties. Electric charge is given in units of the magnitude of the charge on an electron. From [9].

Quarks possess an attribute whimsically called *colour*, which has no relation to colour in the everyday sense of the word. There are three quark colours: red (R), green (G) and blue (B). Antiquarks carry the complementary colours: anti-red (\(\bar{R}\)), anti-green (\(\bar{G}\)) and anti-blue (\(\bar{B}\)). All quark bound states are colourless. A phenomenon known as *colour confinement* exists which requires that hadrons can only exist as colour-neutral states. Therefore free quarks are prohibited.

There are three possible ways of constructing colourless bound states from coloured quarks. Firstly, a red, green and blue quark can form a baryon. Secondly, an anti-red, anti-green and anti-blue antiquark can form an antibaryon. Finally, a quark with any colour and an antiquark with the complementary colour can form a colourless bound state. Mesons are \(q\bar{q}\) states. Although \(R\bar{R}, G\bar{G}\) and \(B\bar{B}\) are colourless, it is in fact only the combination of these, \(R\bar{R}+G\bar{G}+B\bar{B}\), that is observed in nature [4]. Because the quarks within baryons are coloured differently, states such as the \(\Omega^-\) (sss) or the \(\Delta^{++}\) (uuu) are allowed to exist that would otherwise be forbidden by the rules of Fermi-Dirac statistics. These quarks are the basic components of hadrons and are known as *valence quarks*. Instead of empty space, they are surrounded by a foaming sea of virtual quark-antiquark pairs of different flavours that spontaneously pop into, and out of, existence. (A *virtual* particle is one that temporarily violates the relativistic energy-momentum relationship \(E^2 = p^2 + m^2\), where \(E\) is the total energy, \(p\) is the 3-momentum, and \(m\) is the rest mass. The equation is given in natural units, in which \(\hbar = c = 1\).)

\(^3\) From the Greek \(\delta\hat{x}\nu\zeta\) (hadros), meaning “bulky”.
However, this description of hadron substructure is rather naive. Hadron substructure is more properly described by the mathematical machinery of *quantum chromodynamics*, which will be discussed later.

### 1.1.2 Leptons

There are six known leptons\(^4\). Leptons, like quarks, are also organised in three families. The leptons are shown in Table 1.2. The muon and tau can be thought of as heavier versions of the electron\(^5\), which is the most familiar example of a lepton.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Name</th>
<th>Symbol</th>
<th>Charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st})</td>
<td>Electron</td>
<td>e(^-)</td>
<td>−1</td>
<td>0.511 MeV/c(^2)</td>
</tr>
<tr>
<td></td>
<td>Electron neutrino</td>
<td>(\nu_e)</td>
<td>0</td>
<td>&lt; 3 eV/c(^2)</td>
</tr>
<tr>
<td>2(^{nd})</td>
<td>Muon</td>
<td>(\mu^-)</td>
<td>−1</td>
<td>105.7 MeV/c(^2)</td>
</tr>
<tr>
<td></td>
<td>Muon neutrino</td>
<td>(\nu_\mu)</td>
<td>0</td>
<td>&lt; 0.19 MeV/c(^2)</td>
</tr>
<tr>
<td>3(^{rd})</td>
<td>Tau</td>
<td>(\tau^-)</td>
<td>−1</td>
<td>1777 MeV/c(^2)</td>
</tr>
<tr>
<td></td>
<td>Tau neutrino</td>
<td>(\nu_\tau)</td>
<td>0</td>
<td>&lt; 18.2 MeV/c(^2)</td>
</tr>
</tbody>
</table>

Table 1.2: Leptons and their properties. Electric charge is given in units of the magnitude of the charge on an electron. From [10].

Neutrinos are weakly interacting neutral particles that travel essentially at the speed of light. This could be inferred from the measured arrival times of photons and neutrinos from supernova SN1987A in the Large Magellanic Cloud, about 170 thousand light-years from Earth. The approximate equality of arrival times of the first photons and neutrinos from SN1987A implies that the speed of photons and neutrinos cannot differ by more than 1 part in \(10^8\) [11, 12]. There is strong evidence, namely, from studies of Z boson production in \(e^+e^-\) collisions at the Large Electron-Positron collider (LEP), that only three *light* neutrino types exist [9, 13]. Light neutrinos are those with a mass less than half the Z boson mass. (The Z boson will be introduced in the next section.) Results from several experiments have shown that neutrinos possess a small, but nevertheless nonzero, mass [14–17].

---

\(^4\) From the Greek \(\lambda\epsilon\pi\omicron\upsilon\varsigma\) (leptos), meaning “light”.

\(^5\) The antimatter counterpart of the electron has its own name: the positron. Often “electrons” is used to refer to both electrons and positrons. It should be understood from the context in which this word appears when this generalisation applies.
1.1 Particles and interactions

1.1.3 Gauge bosons

There are four fundamental forces of nature: the electromagnetic interaction, the weak interaction, the strong interaction and gravity. The latter of these, gravity, is neglected in the SM because there does not exist an accepted theory describing the physics of gravitational interactions at the quantum mechanical level. However, a number of theoretical frameworks have been proposed that might eventually provide this. Examples include string theory, supergravity and loop quantum gravity. The gravitational force between elementary particles is extremely weak compared to the other three forces.

The fundamental forces arise from the exchange of gauge bosons between the fermions. For this reason they are called exchange forces. The gauge bosons act as force carriers. Bosons are particles with zero or integer spin that obey Bose-Einstein statistics, which allows two or more identical particles to occupy the same quantum state simultaneously. The gauge bosons that mediate the electromagnetic, weak, and strong interactions are all vector (spin-1) particles.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Boson</th>
<th>Charge</th>
<th>Mass (GeV/c²)</th>
<th>Typical coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>γ (photon)</td>
<td>0</td>
<td>0</td>
<td>~1/137</td>
</tr>
<tr>
<td>Weak</td>
<td>W⁺⁻</td>
<td>±1</td>
<td>80.403±0.029</td>
<td>~10⁻⁶</td>
</tr>
<tr>
<td>Weak</td>
<td>Z⁰</td>
<td>0</td>
<td>91.1876±0.0021</td>
<td></td>
</tr>
<tr>
<td>Strong</td>
<td>g (gluon)</td>
<td>0</td>
<td>0</td>
<td>~1</td>
</tr>
</tbody>
</table>

Table 1.3: Gauge bosons and their properties. Electric charge is given in units of the magnitude of the charge on an electron. Usually the W⁺⁻ and Z⁰ are written without superscripts. From [4, 9].

The electromagnetic interaction is associated with the exchange of virtual photons between charged particles, and for this reason photons are said to couple to electric charge. The strength of the interaction is proportional to the electric charge on a particle and is characterised by the fine structure constant \( \alpha \), given by

\[
\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137}\]

(1.1)

where \( e \) is the electron charge magnitude, \( \varepsilon_0 \) is the permittivity of free space, \( \hbar \) is the reduced Planck constant \( (h/2\pi) \) and \( c \) is the speed of light in vacuum. The electromagnetic interaction has an infinite range. The long-range nature of the force is related to the fact that the photon is massless.
The weak force is mediated by the W and Z bosons and is felt by both quarks and leptons. They are very massive, and the resultant force is short range. The mass of the W and Z accounts for the low rates observed for weak decays. The mass of the Z is almost one hundred times that of the proton. The weak and electromagnetic interactions can be regarded as two different aspects of a unified electroweak interaction, in the same way that electrostatic and magnetic forces are two different aspects of electromagnetism. It is theorised that at high energies the weak and electromagnetic coupling constants converge to a single value. This has been confirmed experimentally. Interactions involving W bosons are called charged current processes because they change by one unit the charge of the quarks or leptons they couple to. Interactions involving the Z are known as neutral current processes.

The strong force is mediated by gluons — of which there are eight types — and is felt by quarks. Gluons couple to colour, but also carry colour. Consequently, they interact not only with the quarks but also with each other. Gluons are massless, but due to the nature of their self-interactions this does not lead to a force of infinite range. In fact, the strength of the force between quarks increases as the distance between them increases. This aspect of gluon interactions is responsible for the short-range nature of the strong force. Quarks and gluons are collectively known as partons when in a hadron.

1.1.4 The origin of mass

The SM does not explain the observed masses for quarks and leptons, or the large differences in mass between the quark and lepton generations. It does not explain the masses of the W and Z. The particle masses are all free parameters of the theory. The SM falls short of being a complete theory of fundamental interactions, partly because it lacks a quantum description of gravity, but also because of the large number of numerical parameters that must be determined empirically rather than derived from first principles. Naively one might ask why the SM cannot be formulated entirely in terms of massless particles, and then add mass terms afterwards. However, the resulting theory is fundamentally defective.

1.2 Basic theoretical concepts

The SM is an example of a quantum field theory. These are theories in which particles are treated as fields. One of the fundamental tenets of quantum field theory is the principle that for every reaction (such as a scattering or a decay) there is an associated amplitude,
and that if a reaction can proceed by more than one path, the total amplitude is the sum of the amplitudes for each path. There are, in fact, an infinite number of different paths by which a particle physics interaction may proceed. The simplest of these might, for example, correspond to the exchange of a single gauge boson between fermions. The paths become progressively more complex as those that involve a greater number of intermediate particles or gauge boson couplings are considered. The different paths correspond to terms in a perturbation series. Progressively complex paths are associated with higher-order terms in the series. These higher-order terms act as small corrections to the total amplitude, if the perturbation expansion is valid. The probability for a reaction to occur is proportional to the absolute square of the total amplitude. These probabilities are expressed as scattering cross-sections or as decay rates.

The cross-section is a measure of the probability for a given final state to be produced. It depends only on the nature of the interaction, and corresponds to an idealised area through which an incident particle must pass for the interaction to occur. It is a quantity that can both be predicted by theory and measured experimentally. As such, it provides an interface between theory and experiment. Cross-sections are measured in units of area, typically the barn or decimal sub-multiples thereof. One barn (symbol: b) is equal to $10^{-24}$ cm$^2$. Because they are related to the probability of a process occurring, it is said that cross sections are bounded to lie below the unitarity limit. The prescription for computing cross sections is known as perturbation theory. Usually the terms in perturbation theory are depicted pictorially by Feynman diagrams, which are schematic representations of particle reactions.

The parts of the SM which describe electromagnetic and strong interactions are known as quantum electrodynamics (QED) and quantum chromodynamics (QCD), respectively. Before perturbation theory can be used with QED and QCD to compute cross sections, an additional mathematical technique is needed, because it is found that without it the cross-sections exceed the unitarity limit; the amplitudes corresponding to higher-order terms in the perturbation series give rise to infinities. These infinities are eliminated using a mathematical technique called renormalisation, developed by the architects of QED. This ensures that the cross-sections do not exceed the unitarity limit.
1.3 Symmetries

The concept of symmetry has a special place in particle physics. The SM explains particle physics phenomena in terms of symmetries and the breaking of symmetries. The form of the theory is determined by the symmetries respected by nature.

There is a fundamental connection between symmetries and conservation laws. In general, the existence of a symmetry implies the existence of an associated conservation law. For example, the law of conservation of energy is a consequence of the fact that all laws of physics are invariant with respect to time translation \([4]\). If a physical system is invariant with respect to a transformation \(U\), it is said that \(U\) is a symmetry of the system. A corollary is that \(U\) is a symmetry if it leaves the Hamiltonian \(H\) of the system invariant, or equivalently, if \(U\) commutes with the Hamiltonian.

Local gauge symmetry plays a crucial role in particle physics. Its existence in a theory implies that globally-conserved physical quantities, such as charge or colour, are conserved in local regions of spacetime also. In particle physics, invariance of the Lagrangian density under gauge transformations is treated as a fundamental requirement of quantum field theories. This is called the gauge principle. Quantum field theories based on this principle are called gauge theories. QED and QCD are both gauge theories. The gauge principle forces the introduction of vector fields to the QED and QCD Lagrangian densities. The quanta of these fields are the gauge bosons. Moreover, demanding that the QED and QCD Lagrangian densities are locally gauge invariant requires that the photon and gluon are massless. It turns out that all renormalisable quantum field theories must be gauge theories involving the exchange of gauge bosons \([18]\).

Adding mass terms to the Lagrangian densities of gauge theories destroys the gauge symmetry. This is the reason for requiring that the photon and gluon are massless. However, the W and Z bosons that mediate the weak interaction are massive. This is a serious problem, because the addition of mass terms to the Lagrangian density breaks the gauge symmetry, and the resulting theory is unrenormalisable. Infinities appear that cannot be eliminated. No predictions are possible, and the theory is meaningless. Therefore the need arises for some mechanism that allows for massive particles without breaking the local gauge symmetry. The Higgs mechanism provides a solution to this problem \([19]\).
1.4 The Higgs mechanism

In the Higgs mechanism, the particle masses are not introduced directly into the theory. Instead, the Lagrangian density includes a term corresponding to the Higgs field. It is the Higgs field that is responsible for imparting mass to the particles. This field is unusual in that its state of lowest energy — its vacuum expectation value (VEV) — is non-zero. Recall that in quantum field theory particles are treated as fields. The state of lowest energy for the usual SM fields corresponds to there being no particles present. It is the part of the Higgs field that remains even in the state of lowest energy that imparts mass to particles. The resulting theory is renormalisable because the Higgs mechanism respects the gauge symmetry of the Lagrangian density. In the same way that photons are quanta of the electromagnetic field, Higgs bosons are quanta of the Higgs field. The simplest version of the Higgs mechanism predicts the existence of one electrically-neutral scalar (that is, spin-0) SM Higgs boson, denoted $H$.

Other versions of the Higgs mechanism posit the existence of more Higgs bosons. Supersymmetry (SUSY) is a theory that hypothesises that every fermion has a bosonic counterpart, and vice versa. If SUSY is a correct description of nature, then SUSY must be a broken symmetry allowing the “superpartners” to be heavy. This would explain why SUSY particles have not been observed yet; they are too heavy to be produced in accelerators that have been built so far. The Minimal Supersymmetric Standard Model (MSSM) is the SUSY extension of the SM with minimal new particle content, and one of the best studied candidates for physics beyond the SM. The Higgs sector of the MSSM contains two charged ($H^\pm$) and three neutral (h, H, A) physical states [9]. This topic is presented as an aside: from now on, only SM Higgs bosons will be considered.

1.5 Higgs boson searches

The branching ratio (the probability for a given decay mode) of the Higgs boson into various final states as a function of the Higgs mass is shown in Figure 1.1 on the following page.

The mass of the Higgs boson itself is not predicted by theory, but is believed to be less than 1 TeV/$c^2$ because the Higgs boson is self-interacting and the couplings are required to be sufficiently weak such that perturbation theory is applicable [20]. Experimental searches at LEP have excluded a large range of Higgs boson masses. The existence of a Higgs boson with a mass less than 114.4 GeV/$c^2$ has been excluded at the 95% confidence level [21].
Tantalising signs of a Higgs boson with a mass of 115 GeV/c^2 were found at LEP during the summer of 2000 [22]. LEP was scheduled to close at the end of September that year, but a five-week extension of running was granted by CERN in an attempt to confirm or rule out the signal. Unfortunately, the new data was not sufficiently conclusive to announce a discovery. LEP finally closed on 2 November 2000 to make way for construction of the Large Hadron Collider.

If the mass of the Higgs boson (m_H) is indeed 115 GeV/c^2, then it will decay with greatest probability into a b\bar{b} pair, as shown in Figure 1.1. However, it will be extremely difficult to extract a signal from these decays at the Large Hadron Collider [23]. The decay channel H → WW(+) → l\ell\nu\nu has a higher branching ratio for Higgs boson masses above 140 GeV/c^2, but it is not possible to reconstruct the Higgs boson mass peak from these events. In this case, evidence for a Higgs boson signal can be extracted from an excess of events above the expected background from SM processes [24].

At the other end of the scale, the decay channel H → WW → l\ell\j\j provides the best discovery potential for a heavy SM Higgs boson with a mass between 400 GeV/c^2 and about 1 TeV/c^2 [24]. A Higgs boson search in this mass range would be complemented by the decay channels H → ZZ → l\ell\j\j and H → ZZ → l\ell\nu\nu [24].

The decay channel H → ZZ^* → 4l provides a particularly clean signature for a Higgs boson with a mass between about 120 GeV/c^2 and twice the mass of the Z boson (2m_Z ≈ 180 GeV/c^2), above which the so-called “gold-plated” channel with two real Z bosons opens up. Indeed, the H → ZZ → 4l channel will be the most reliable channel for the
discovery of a SM Higgs boson for masses between 180 GeV/c^2 and about 700 GeV/c^2 [24].
Possible final states are $e^+e^-$, $e^+e^-$ and $\mu^+\mu^-$. A peak in the distribution of the invariant mass of the particles in these final states would indicate the presence of the Higgs boson. Each of these channels is promising in its own right. With respect to the decay channel $H \to ZZ^{(*)} \to 4e$, the ATLAS experiment at the Large Hadron Collider should be able to detect the signal of a 150 GeV/c^2 Higgs boson with a significance of over 7 standard deviations using data from only the first three years of running (30 fb^{-1}) [25].

1.6 Motivation

Detection of a Higgs boson via the $H \to ZZ^{(*)} \to 4e$ decay channel will rely heavily on Electromagnetic Calorimeter information. Indeed, the Electromagnetic Calorimeter will be the leading detector in many measurements for the reconstruction of physics channels of prime interest. This raises the important question: given the tidal wave of data that will be produced by the Large Hadron Collider, how will the ATLAS detector’s ability to select interesting events be affected by imperfections in the Electromagnetic Calorimeter? This question is addressed in this thesis, with respect to the robustness of the electron trigger selection against the effects of both dead (unresponsive) Electromagnetic Calorimeter cells and dead on-detector electronics boards. Details can be found in Chapters 7 and 8.

The high rate of collisions at the Large Hadron Collider imposes severe constraints on the amount of time available for the ATLAS detector to decide whether an event is interesting, and therefore worth recording for later offline analysis. In this thesis, a study in presented of the time overhead of a key part of the event selection software, namely, the mechanism whereby trigger algorithms are guided to the data they need to work on. This is described in Chapter 5.
The ATLAS experiment at the Large Hadron Collider

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a next-generation particle accelerator that is currently under construction at CERN (Organisation Européenne pour la Recherche Nucléaire) [26]. It is scheduled to begin operation in May 2008. The LHC is being installed in a near-circular underground tunnel almost 27 km in circumference, approximately 100 m beneath the Franco-Swiss border, between Lake Geneva and the Jura mountains [27, 28]. When completed, the LHC will be the world’s largest and most powerful particle accelerator [9]. It will accelerate two counter-rotating beams of protons or heavy ions and bring them into head-on collisions at one of four points around the LHC ring [27].

The LHC physics programme is mainly based on proton-proton collisions. However, for a few weeks of each year, the LHC will run with heavy ions. Collisions between fully stripped lead (\(^{208}{\text{Pb}}^{82+}\)) ions are scheduled for one year after collisions with protons [27]. The ions will have a beam energy of 2.76 TeV per nucleon, yielding a total centre-of-mass energy (total energy in the rest frame of the system of particles) of 1148 TeV [27, 29].

In proton-proton collider mode the beam energy will be 7 TeV, resulting in a centre-of-mass energy of 14 TeV. The protons in each beam are divided into discrete portions, or “bunches”. Each beam consists of a train of proton bunches following each other at 24.95 ns intervals [30]. The bunch-crossing frequency is 40 MHz [30]. This implies a bunch spacing of 7.48 m [30]. About 20% of the bunches will be empty due to proton injection and extraction requirements. Table 2.1 shows a selection of important LHC parameters.

<table>
<thead>
<tr>
<th>Table 2.1: Important LHC Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Beam Energy</td>
</tr>
<tr>
<td>Total Centre-of-Mass Energy</td>
</tr>
<tr>
<td>Proton Bunch Separation</td>
</tr>
<tr>
<td>Bunch-Crossing Frequency</td>
</tr>
<tr>
<td>Bunch Spacing</td>
</tr>
</tbody>
</table>
### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating beam energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Relativistic $\gamma$</td>
<td>7461</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>24.95 ns / 7.48 m</td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td>334 MJ</td>
</tr>
<tr>
<td>Number of all/full bunches</td>
<td>3564/2835</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$1.05 \times 10^{11}$</td>
</tr>
<tr>
<td>Average beam current</td>
<td>536 mA</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$2 \times 10^{33}$ to $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Dipole magnetic field</td>
<td>8.4 T</td>
</tr>
<tr>
<td>Cryostat temperature</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>22 h</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>10 h</td>
</tr>
<tr>
<td>Number of interactions per beam crossing</td>
<td>23$^a$</td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>RMS bunch radius $\sigma_x = \sigma_y$</td>
<td>16 $\mu$m</td>
</tr>
<tr>
<td>RMS length of luminous region</td>
<td>56 mm</td>
</tr>
<tr>
<td>Total crossing angle</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>Power consumption</td>
<td>125.75 MW</td>
</tr>
<tr>
<td>Cost</td>
<td>~3 billion CHF</td>
</tr>
</tbody>
</table>

$^a$ Assuming 70 mb for the inelastic proton-proton cross-section and $L = 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

Table 2.1: Parameters of the LHC. From [26, 30].
A single set of particle interactions resulting from a proton-proton collision is known as an event. The number of events of a given type per unit time is called the event rate. The event rate is proportional to the LHC luminosity. The constant of proportionality between the event rate $R$ and the luminosity is the cross-section $\sigma$ for the given final state to be produced. Luminosity is a figure of merit for an accelerator that quantifies the intensity of the beams. It is equal to the number of particles per unit area per unit time, and is usual expressed in units of cm$^{-2}$s$^{-1}$. It is a measure of the collision rate between the particles in the beams. The initial luminosity at the LHC will be about $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ and will scale-up to the full design luminosity of $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ [31].

The majority of collisions at the LHC will be "soft" elastic collisions in which the momentum transfer between partons in the interacting protons is small. The cross-section for inelastic proton-proton interactions at the LHC is expected to be about 70 mb [32]. The estimated uncertainty on this figure is about 30% [30, 33]. Based on this assumption for the inelastic proton-proton cross-section, and taking into account the average filling factor of 2835 active bunches over 3564 clock cycles, one finds on average 23 inelastic events per "active" bunch-crossing at design luminosity [34]. This implies that 23 proton-proton interactions on average will be superposed in each bunch-crossing at design luminosity. These events are referred to as pile-up.

Six detectors are being constructed at the LHC:

- ALICE (A Large Ion Collider Experiment),
- ATLAS (A Toroidal LHC ApparatuS),
- CMS (Compact Muon Solenoid),
- LHCb (Large Hadron Collider beauty),
- LHCf (Large Hadron Collider forward) and
- TOTEM (TOTal and Elastic Measurement)

[ALICE, ATLAS, CMS] and [LHCb] are located in large underground caverns excavated at each of the LHC's four collision points, as shown in Figure 2.1 on the facing page. LHCf and TOTEM are smaller, more specialised, experiments to be installed near the interaction points of ATLAS and CMS respectively. ATLAS and CMS are both large general-purpose detectors with extensive physics programmes. ALICE is a heavy-ion experiment that will study the physics of strongly-interacting matter at extreme energy densities. LHCb aims
to measure the parameters of charge-parity (CP) violation using the decays of B-hadrons. LHCf will study photons and neutral pions emitted in the very forward region of collisions at the LHC at very small angles from the beam axis, to provide information for the understanding of cosmic ray phenomena. TOTEM will measure the total proton-proton cross-section and will study elastic scattering and diffractive dissociation processes at the LHC.

![Figure 2.1: The Large Hadron Collider.](image)

### 2.2 The ATLAS Detector

In common with other detectors at colliders, the ATLAS detector consists of several highly granular and hermetic subdetectors arranged in concentric layers oriented coaxially with respect to the beamline and centred around the nominal interaction point. In general terms, the ATLAS detector resembles a cylinder with a total length of 42 m and a radius of 11 m. The ATLAS detector is divided into a barrel section and two endcaps. Most of the ATLAS subdetectors exist in both areas. The overall weight of the ATLAS detector is approximately 7000 tonnes [32]. Figure 2.2 on the next page shows the ATLAS detector.
The ATLAS experiment at the Large Hadron Collider

layout with the major components labelled. A portion of the detector has been cut away to reveal the interior.

![ATLAS Detector Diagram](image)

Figure 2.2: The ATLAS Detector. Adapted from [32].

The different subdetector systems are discussed in the subsequent sections, starting with the innermost subdetector and moving radially outwards, after a brief introduction to the nomenclature that is relevant to the ATLAS experiment.

### 2.2.1 Nomenclature

The ATLAS coordinate system is a right-handed system with the $x$-axis pointing towards the centre of the LHC ring, the $y$-axis pointing upwards, and the $z$-axis pointing along the beam axis, as shown in Figure 2.3 on the facing page. The azimuthal angle $\phi$ is measured around the beam axis. $\phi = 0$ corresponds to the positive $x$-axis. $\phi$ increases clockwise looking in the positive $z$ direction. The polar angle $\theta$ is measured from the positive $z$-axis.
2.2 The ATLAS Detector

The transverse momentum ($p_T$) and transverse energy ($E_T$) of a particle are defined in the $x - y$ plane as follows:

\[ p_T = \sqrt{p_x^2 + p_y^2}, \]  
\[ E_T = \sqrt{E^2 - p_z^2}, \]

where $E$ is the total energy of the particle and $p_x$, $p_y$ are the $x$, $y$ and $z$ components of the particle’s 3-momentum vector, respectively. Here and henceforth, units are used in which $\hbar = c = 1$.

The pseudorapidity $\eta$ of a particle is defined as

\[ \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right). \]

Pseudorapidity is a dimensionless quantity. The ATLAS coordinate system uses pseudorapidity and azimuthal angle as generic spatial coordinates. The distance $\Delta R$ in the pseudorapidity-azimuthal angle space is defined as

\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}. \]
2.2.2 The Inner Detector

The Inner Detector (ID) performs precision measurements of charged particle tracks. Specifically, the ID’s tasks include pattern recognition, momentum and vertex measurements, and electron identification. The detector is contained within a cylinder 7 m in length with a radius of 1.15 m and covers the angular region corresponding to $|\eta| < 2.5$. The ID consists of a barrel part, extending over ±80 cm from the nominal interaction point, and two identical endcaps each 2.7 m long. The detector layers are arranged on concentric cylinders around the beam axis in the barrel region, while the endcap detectors are mounted on disks perpendicular to the beam axis. Three subdetector systems constitute the ID: the Pixel Detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT) [37].

The Pixel Detector and the SCT are both high-resolution solid state detectors, while the TRT is a combined straw drift-tube tracker and transition radiation detector. These detectors are immersed in a 2 T axial magnetic field generated by a superconducting solenoid magnet outside the TRT. Each track typically crosses three pixel layers, four double layers of silicon microstrips in the SCT, and about 36 layers of straw tubes in the TRT [37]. Longitudinal and transverse views of the ID are shown in Figure 2.4 and Figure 2.5 on the facing page, respectively.

Figure 2.4: Longitudinal cross-section of the Inner Detector. From [32].
2.2 The ATLAS Detector

2.2.2.1 The Pixel Detector

The innermost tracking detector, the Pixel Detector, provides the most accurate track position measurements. It is composed of a central barrel region and two identical endcaps. The barrel consists of three cylindrical layers with radii of 50.5 mm, 88.5 mm and 122.5 mm arranged coaxially around the beam axis [38]. Each barrel layer is made of identical staves inclined at an azimuthal angle of 20°. There are 22, 38 and 52 staves in each of these layers, respectively. The endcaps each contain three disk layers mounted perpendicular to the beam axis [39]. The number of pixel layers in the detector must be limited because of the material they introduce and their high cost. The layout of the Pixel Detector is shown in Figure 2.6 on the next page.

Each pixel sensor is a wafer of silicon approximately 6 cm by 2 cm with 46080 pixels, each measuring 50 μm × 400 μm [39]. All sensors are identical. Each stave is composed of 13 pixel sensors. Each disk consists of 8 sectors, with 6 pixel sensors in each sector. Hence, there are about 80 million pixel elements in the detector. In the barrel, the typical spatial resolution of the pixel sensors is predicted to be 12 μm in the transverse direction and 66 μm in the direction parallel to the beam axis; in the endcaps, 12 μm in the transverse direction.
direction and 77 \( \mu m \) in the radial direction (the actual resolution depends on the impact angle) \[32\].

The lifetime of the innermost layer (the B-layer) of the Pixel Detector will be limited by radiation damage. The mechanical design of the Pixel Detector allows the possibility of replacing the B-layer \[32\]. This enables the performance of the Pixel Detector to be maintained throughout the lifetime of the experiment. This is especially important for B-physics studies, Higgs boson searches and SUSY searches, which rely on good b-tagging performance. b-tagging is a method used to identify jets that have originated from b-quarks by means of precision measurements of the position of decay vertices. A jet is a narrow cone of hadrons produced by the hadronisation of partons produced in the proton-proton collision. To a great extent, the Pixel Detector’s performance determines the impact parameter\(^1\) resolution and the ability of the ID to find short-lived particles such as B-hadrons and \( \tau \) leptons \[32\].

### 2.2.2.2 Semiconductor Tracker

The SCT is contained within a cylinder 5.6 m long with a diameter of 112 cm and covers the pseudorapidity range \( |\eta| < 2.5 \). The detector is divided into a barrel section comprised of four nested cylindrical layers 1.5 m long with radii ranging from 299 to 514 mm, and two endcaps of nine disks each at distances between \( \pm 872 \) and \( \pm 2705 \) mm from the nominal interaction point with radial dimensions of 267 to 560 mm \[40\]. The SCT is shown in simplified form in Figure 2.7 and in transverse cross-section in Figure 2.8.

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\(^1\) The transverse impact parameter and longitudinal impact parameter are defined as the transverse distance of the closest approach of the track to the beam axis, and the \( z \) position of the track at this point, respectively.
2.2 The ATLAS Detector

Figure 2.7: Layout of the Semiconductor Tracker. From [40].

Figure 2.8: Transverse cross-section of the Semiconductor Tracker.
The SCT contains 4088 silicon microstrip modules. The barrel contains 2112 modules, while the endcaps contain 1976 modules in total. Each module is composed of one or two pairs of single-sided silicon microstrip sensors glued back-to-back with a 40 mrad stereo rotation to enable two-dimensional track reconstruction. Between the sensors is a thermally-conductive support plate. Each sensor consists of 768 $p$-type strips implanted in an 285 $\mu$m thick $n$-type substrate wafer [41]. Barrel modules are constructed from two pairs of rectangular sensors. Each barrel sensor has an area of $63.56 \times 63.96 \text{ mm}^2$ and a strip pitch of 80 $\mu$m. On each side of the module, two sensors are wire-bonded together to form 12.6 cm strips [42].

Due to the circular geometry of the disks, endcap modules use wedge-shaped sensors of different dimensions with radial strips. Their strip pitch varies from 57 to 94 $\mu$m [41]. The endcap modules are arranged in three rings on each disk and are of four different types: “inner” and “short middle” modules with one sensor on each side, and “long middle” and “outer” with two wire-bonded sensors per side [40, 42]. Wire-bonding doubles the effective strip length in the latter two types of modules to about 12 cm [32, 40]. In total, the SCT has 6.3 million readout channels [43].

The SCT is designed to provide four precision space points per track in the intermediate radial range with a spatial resolution of 16 $\mu$m in $r\phi$ (perpendicular to the strips) and 580 $\mu$m in the second coordinate ($z$ for the barrel, $r$ for the endcaps). It is expected that tracks can be distinguished if separated by more than about 200 $\mu$m [32, 40, 42].

2.2.2.3 Transition Radiation Detector

The TRT is the outermost component of the ID. It is both a straw drift-tube tracker and transition radiation detector. The TRT consists of 372032 gas-filled straws. The straws are 4 mm in diameter and made of Kapton$^2$ with an electrically-conductive coating. Each straw contains a 30 $\mu$m diameter gold-plated tungsten-rhenium wire at its centre. The straws are filled with a gas mixture of 70% xenon, 27% CO$_2$ and 3% O$_2$. A negative high voltage of about 1530 V is applied to the straws, while the wires are kept at ground potential [44, 45].

The TRT is divided into a barrel section and two endcaps. The TRT barrel is 1.5 m long and consists of three nested cylindrical layers of 32 modules each. There are three different types of module, one for each barrel layer. All three types of module differ both in size and in the number of straws that they contain. Table 2.2 on the facing page shows

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$^2$ Kapton is a polyimide film developed by DuPont.
2.2 The ATLAS Detector

the main parameters relevant to the modules in each layer. The straws in the barrel are 144 cm long, corresponding to the pseudorapidity range $|\eta| < 0.7$, and oriented parallel to the beam axis. The anode wires are electrically split in the centre and read out at both ends of the straws. The space between the straws is filled with randomly-distributed 15 μm diameter polypropylene fibres [44–46]. The layout of the TRT barrel is shown in Figure 2.9. The endcaps consists of three different types of modules called wheels. Each wheel contains eight planes of radially-oriented straws, interleaved with stacks of 15 μm thick polypropylene foils [46]. The endcap wheel parameters are shown in Table 2.3 on the following page.

<table>
<thead>
<tr>
<th>Barrel layer</th>
<th>Inner</th>
<th>Middle</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of straws per module</td>
<td>329</td>
<td>520</td>
<td>793</td>
</tr>
<tr>
<td>Number of straw layers per module</td>
<td>19</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>Module inner radius (mm)</td>
<td>560</td>
<td>697</td>
<td>864</td>
</tr>
<tr>
<td>Module outer radius (mm)</td>
<td>695</td>
<td>862</td>
<td>1070</td>
</tr>
</tbody>
</table>

Table 2.2: TRT barrel module parameters. From [44].

Charged particles traversing a straw leave a trail of electron-ion pairs in their wake. As the liberated electrons drift towards the anode wire, they gain energy and create further electron-ions pairs. This leads to an avalanche process in which a cascade of electron-ion pairs is created. The gas gain for the chosen gas mixture and operating voltage is $2.5 \times 10^4$ [44]. The drift time for each straw is used to determine the distance of closest approach of each particle to the anode wire (the maximum drift time is 48 ns with
The ATLAS experiment at the Large Hadron Collider

### Endcap wheel type

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels per endcap</td>
<td>12</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Straws per layer</td>
<td>768</td>
<td>768</td>
<td>576</td>
</tr>
<tr>
<td>Straws per wheel</td>
<td>6144</td>
<td>6144</td>
<td>4608</td>
</tr>
<tr>
<td>Gap between straws (mm)</td>
<td>4</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Length of straws (mm)</td>
<td>370</td>
<td>370</td>
<td>550</td>
</tr>
<tr>
<td>Longitudinal coverage (mm)</td>
<td>827 &lt;</td>
<td>z</td>
<td>&lt; 1715</td>
</tr>
</tbody>
</table>

<sup>a</sup> The construction of the type-C wheels has been staged, therefore they will not be part of the initial detector configuration.

Table 2.3: TRT endcap wheel parameters. Data from [44, 46-48].

The present gas mixture). The TRT uses several such measurements to track the paths of charged particles traversing the detector. The large number of position measurements provided by the TRT contributes significantly to the measurement of particle momenta [32].

At the time of the publication of the ID Technical Design Report (TDR) in 1997, the spatial resolution per straw was estimated to be about 170 μm. The large number of straws per track was estimated to result in a combined measurement accuracy of better than 50 μm, averaged over all straws and including a systematic error of about 30 μm from alignment [32, 37]. More recent beam-test results have demonstrated that that a single-straw resolution of about 130 μm is feasible [45, 49, 50].

The electron identification capabilities of the whole experiment are enhanced by the TRT’s sensitivity to transition radiation. Transition radiation is produced by relativistic charged particles when they cross the interface between two media of different dielectric constants: polypropylene and the Xe/CF<sub>4</sub>/CO<sub>2</sub> gas mixture for the TRT [46]. The intensity of the radiation is roughly proportional to the particle’s relativistic γ. This means that, for a given energy, the TRT is able to discriminate between electrons (which have a high γ) and hadrons (which are heavier and consequently have a low γ). The transition radiation photons are absorbed by the xenon-rich gas. The signal generated in the TRT is

<sup>3</sup> The original TRT gas mixture was 70% xenon, 20% CF<sub>4</sub>, 10% CO<sub>2</sub>. A new gas mixture was adopted after studies of the original gas mixture demonstrated that HF and other reactive fluorine-base species, which degrade materials used in the construction of the detector, are created when moisture levels in the gas exceed about 1000 ppm [49].
of the superposition of the energy deposition due to the absorption of the transition-radiation photons (≈8–10 keV) and the ionisation energy loss of the particle (≈2 keV on average).

2.2.3 Calorimetry

The calorimeters are responsible for measuring the energy and position of electrons, positrons, photons, hadrons and jets. The ATLAS calorimetry system is contained within a cylinder 13.3 m long with a radius of 4.23 m. The physical components that constitute the calorimetry system are:

- For electromagnetic calorimetry:
  - The Electromagnetic Accordion Calorimeter
  - The Electromagnetic Forward Calorimeter (×2)

- For hadronic calorimetry:
  - The Hadronic Tile Calorimeter
  - The Hadronic Endcap Calorimeter (×2)
  - The Hadronic Forward Calorimeter (×2)

The layout of the various calorimeters is shown in Figure 2.10 on the next page. ATLAS calorimetry covers the angular region corresponding to |η| < 4.9. The total weight of the calorimetry system, including the central solenoid flux-return iron yoke which is integrated into the Tile Calorimeter support structure, is about 4000 tonnes [32, 51].

The electromagnetic (EM) calorimeters measure the energy and direction of EM showers initiated by incoming electrons, positrons and photons in the calorimeter material. An EM shower occurs when a high-energy electron, positron or photon enters a medium and initiates a cascade of secondary electrons, photons and positrons via alternating pair-production (γ → e⁺e⁻) and bremsstrahlung (e± → e±γ) processes. Bremsstrahlung is radiation emitted by charged particles under acceleration. In particular, the term is used to refer to the radiation emitted by charged particles moving through the electric field of atomic nuclei [52].

An appropriate length scale for describing EM showers is the radiation length (X₀). It is both the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and 7/9 of the mean free path for pair-production by a high-energy photon [9]. X₀ is usually given in units of g cm⁻² (but one can convert to cm by dividing by the material’s density). The transverse size of an EM shower can be described by the Molière radius R_M, which is a characteristic constant of a material.
Figure 2.10: Three-dimensional view of the ATLAS calorimeters. Adapted from [32].
cylinder of radius $1 R_M$ contains 90% of the shower energy. About 99% of the energy of a shower is contained within a cylinder of radius $3.5 R_M$ [9].

The hadronic Tile, Endcap and Forward calorimeters constitute the Hadronic Calorimeter (HCAL). The HCAL measures the energy and direction of hadronic showers, thereby providing information about incident hadrons. A hadronic shower is a cascade of secondary particles (consisting of pions, nuclear fragments and many photons) that is produced when a high-energy hadron enters a dense medium and initiates a succession of strong interactions with atomic nuclei. This process continues until the energy of the incident particle has been dissipated. The mean free path of a hadron before undergoing an inelastic nuclear interaction is called the *interaction length* ($\lambda_I$) [52].

ATLAS uses sampling calorimeters for both EM and hadronic calorimetry. In a sampling calorimeter, layers of dense absorber material alternate with layers of a material that is sensitive to incoming shower particles. As the name suggests, calorimeters of this type periodically “sample” the charged particle density of particle showers. The calorimetry system of the ATLAS detector is based on two different technologies: the EM Accordion Calorimeter, the Forward Calorimeters and the Hadronic Endcap Calorimeter are noble liquid ionisation calorimeters that use liquid argon (LAr) as the sensitive medium, while the barrel region of the HCAL is a scintillating tile calorimeter.

The LAr calorimeters use a variety of materials as absorbers: lead in the EM Accordion Calorimeter, copper in the Hadronic Endcap Calorimeter and EM Forward Calorimeter, and tungsten in the hadronic Forward Calorimeter. These are dense materials with small values of $X_0$ (0.56 cm, 1.43 cm and 0.35 cm respectively [9]) that cause showers to evolve quickly. The shower particles create ionisation in the LAr-filled gaps between the absorber material. The ionisation charge is collected by copper electrodes located in the middle of the gaps. On average, the total amount of ionisation collected on the electrodes is proportional to the energy of the incident particle. Using liquid argon, rather than gaseous argon, increases the amount of ionisation generated per incoming particle. The LAr calorimeters require cryostats and cooling services. There are three cryostats that house the barrel and endcaps sections of the LAr calorimeters. They are constructed from aluminium alloy and are vacuum insulated. The LAr within them is kept at a constant temperature of 89.3 K [34].

The calorimeters are segmented longitudinally and transversally. The longitudinal segments, or *samplings*, provide information about the shapes of particle showers as they develop. Each sampling is segmented transversally into multiple individual *cells* to provide
information about the direction of incoming particles. Cells are the smallest units of calorimeter information to be read out and digitised. Typically, the transverse granularity of the calorimeters is different among samplings. The pseudorapidity coverage, transverse granularity and longitudinal segmentation of the calorimeters is shown in Table 2.4 on the facing page.

For purpose of triggering, the calorimeters are partitioned into about 7200 projective trigger towers that point to the nominal interaction point [53]. Trigger towers are groupings of cells whose signals are summed to form the trigger signal used by the first level of triggering [34, 51]. In the central pseudorapidity region, trigger towers have an approximate size of $0.1 \times 0.1$ rad in $\Delta \eta \times \Delta \phi$. The transverse trigger granularity becomes coarser beyond $|\eta| = 2.5$. There are separate sets of trigger towers for the EM and hadronic calorimeters [32, 54]. Figure 2.11 shows the detector granularity inside a typical EM trigger tower in the pseudorapidity region $|\eta| < 1.4$.

$$\text{Trigger tower } \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \text{ rad}$$

![Granularity of an EM trigger tower in the pseudorapidity region $|\eta| < 1.4$. There are 64 such towers in $\phi$ and $2 \times 14$ towers in $\eta$. Typically 60 cells are summed to form pointing trigger towers with a size of $0.1 \times 0.1$ rad in $\Delta \eta \times \Delta \phi$. Adapted from [34].](image)

The energy resolution of a calorimeter can be parameterised as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c. \quad (2.5)$$

The first term is the sampling term, which accounts for statistical fluctuations in the shower development. The second term accounts for electronic and pile-up noise. The final term is the constant term, which accounts for both non-uniformities in the calorimeter response and calibration uncertainties. The energy $E$ is expressed in GeV and $\oplus$ denotes addition in quadrature. The target energy resolutions of the HCAL are

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%. \quad (2.6)$$
2.2 The ATLAS Detector

<table>
<thead>
<tr>
<th>EM ACCORDION CALORIMETER</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Longitudinal segmentation</td>
<td>3 samplings</td>
<td>3 samplings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 samplings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Granularity ($\Delta \eta \times \Delta \phi$)

| Sampling 1               | $0.003 \times 0.1$ | $0.025 \times 0.1$ | $1.375 < |\eta| < 1.5$ |
|                         | $0.003 \times 0.1$ | $1.5 < |\eta| < 1.8$ |
|                         | $0.004 \times 0.1$ | $1.8 < |\eta| < 2.0$ |
|                         | $0.006 \times 0.1$ | $2.0 < |\eta| < 2.5$ |
|                         | $0.1 \times 0.1$    | $2.5 < |\eta| < 3.2$ |

| Sampling 2               | $0.025 \times 0.025$ | $0.025 \times 0.025$ | $1.375 < |\eta| < 2.5$ |
|                         | $0.1 \times 0.1$    | $2.5 < |\eta| < 3.2$ |

| Sampling 3               | $0.05 \times 0.025$ | $0.05 \times 0.025$ | $1.5 < |\eta| < 2.5$ |

PRESAMPLER

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
</tr>
<tr>
<td>Longitudinal segmentation</td>
<td>1 sampling</td>
</tr>
<tr>
<td>Granularity ($\Delta \eta \times \Delta \phi$)</td>
<td>$0.025 \times 0.1$</td>
</tr>
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HADRONIC TILE

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</thead>
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<td>$</td>
</tr>
<tr>
<td>Longitudinal segmentation</td>
<td>3 samplings</td>
</tr>
<tr>
<td>Granularity ($\Delta \eta \times \Delta \phi$)</td>
<td>$0.1 \times 0.1$</td>
</tr>
<tr>
<td>Samplings 1 and 2</td>
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HADRONIC LAr

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<tr>
<td>Coverage</td>
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<tr>
<td>Longitudinal segmentation</td>
</tr>
<tr>
<td>Granularity ($\Delta \eta \times \Delta \phi$)</td>
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FORWARD CALORIMETER

<table>
<thead>
<tr>
<th>Forward</th>
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<tbody>
<tr>
<td>Coverage</td>
</tr>
<tr>
<td>Longitudinal segmentation</td>
</tr>
<tr>
<td>Granularity ($\Delta \eta \times \Delta \phi$)</td>
</tr>
</tbody>
</table>

Table 2.4: Pseudorapidity coverage, transverse granularity and longitudinal segmentation of the ATLAS calorimeters. $\Delta \phi$ is given in radians. From [32].
in the central pseudorapidity region ($|\eta| < 3$) and

$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 7\%. \quad (2.7)$$

in the forward region ($3 < |\eta| < 4.9$) [32].

The search for a low-mass Higgs boson ($m_H = 90-180$ GeV/$c^2$) using the decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ sets severe requirements on both the energy resolution and the angular resolution of the EM Accordion Calorimeter. In order to measure the Higgs boson mass with 1% precision using the calorimeter system alone, the target energy resolution is required to be better than

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \quad (2.8)$$

and the angular resolution needs to be less than $50 \text{ mrad}/\sqrt{E}$ [55-57]. The total depth of the EM Accordion Calorimeter is required to be at least $24 \text{X}_0$ to minimise the effect of longitudinal shower leakage on the energy resolution above 500 GeV [58].

2.2.3.1 The Electromagnetic Calorimeter

Electromagnetic calorimetry in the pseudorapidity region $|\eta| < 3.2$ is provided by a lead-LAr calorimeter with accordion-shaped Kapton electrodes and lead absorber plates. This detector is sometimes called the Accordion Calorimeter [32, 34, 51, 54], but is more commonly known simply as the Electromagnetic Calorimeter (ECAL). Consequently, one might read in relevant literature that the Electromagnetic Calorimeter covers the pseudorapidity region $|\eta| < 3.2$ [32], whereas in fact electromagnetic calorimetry covers the pseudorapidity region $|\eta| < 4.9$ (albeit with lower precision for $|\eta| > 2.5$) [34, 55, 56, 59, 60]. Therefore, to avoid any possible confusion, it should be understood that henceforth the term “Electromagnetic Calorimeter” (or ECAL) refers to the LAr EM Accordion Calorimeter only; the EM module in the Forward Calorimeter (described in Section 2.2.3.4 on page 58) is not included in this definition. This is in keeping with popular convention. The reason for this convention stems from the fact that the Accordion Calorimeter is the main part of the ATLAS EM calorimetry system [60]. The layout of the ECAL and the pseudorapidity coverage of the various detector components is shown in Figure 2.12 on the next page.

The ECAL is divided into a barrel section and two endcaps. Each of these is housed in a different cryostat. The Electromagnetic Barrel Calorimeter (EMB) consists of two identical half-barrels, separated by a 6 mm gap at $z = 0$ [32]. Each half-barrel is 3.2 m
Figure 2.12: Longitudinal view of a quadrant of the ECAL. From [32].
long with inner and outer radii of about 1.4 m and 2 m respectively. Each half-barrel is composed of 1024 accordion-shaped absorbers, interleaved with readout electrodes [61]. The EMB is housed in a barrel cryostat ~6.8 m long with an outer radius of 2.25 m and an inner cavity radius of 1.15 m [34]. A perspective view of one half of the barrel cryostat and EMB is shown in Figure 2.13.

![Figure 2.13: Perspective view of one half of the barrel cryostat. The barrel cryostat encloses the two 3.2 m long half-barrels of the EMB. Adapted from [34].](image.png)

Each Electromagnetic Endcap Calorimeter (EMEC) is divided into two coaxial wheels: an outer wheel covering the region $1.375 < |\eta| < 2.5$, and an inner wheel covering the region $2.5 < |\eta| < 3.2$ [32]. The boundary between these wheels is projective (see Figure 2.12 on the page before). The corresponding crack is 3 mm wide [62]. Each wheel is divided into eight wedge-shaped modules. The absorber plates are mounted in a radial arrangement like the spokes of a bicycle wheel, as shown in Figure 2.14 on the facing page. There are 768 plates in the outer wheel and 256 in the inner wheel [62]. Each endcap cryostat is 3.17 m long. The outer radius of the endcap cryostat warm shell is 2.25 m [34]. Figure 2.15 shows
2.2 The ATLAS Detector

a perspective view of an endcap cryostat, containing the EMEC, the Hadronic Endcap Calorimeter and the Forward Calorimeter.

Figure 2.14: View of one wheel of the EMEC. Only a few absorbers are shown. The diameter is about 4.5 m and the thickness is about 1 m [58]. From [34].

The accordion geometry of the absorbers and electrodes enables the ECAL to be built without any cracks in $\phi$ [34]. The absorbers are made from lead plates glued between thin (0.2 mm) sheets of stainless steel. The electrodes are made of three layers of copper insulated by two layers of Kapton. The outer two layers are connected to high voltage (HV) sources. These layers create the electric field in the LAr gap. The absorbers are grounded.

Figure 2.15: Perspective view of one endcap cryostat. From [34].
The signal induced by the ionisation electrons drifting in the LAr gaps is read out from the central copper layer via capacitive coupling [63, 64]. Figure 2.16 shows the structure of the electrodes in the EMB. The ECAL is segmented into 173312 cells which vary in size according to sampling and pseudorapidity. The cells point to the nominal interaction point over the complete pseudorapidity coverage [32]. The cells are defined in $\eta$ by etched divisions in the copper readout layer, and in $\phi$ by summing signals from a number of adjacent readout layers (see Figure 2.17 on the facing page) [64]. The electrode signal layer in the EMB is shown in Figure 2.18.

![Figure 2.16: Structure of the electrodes in the EMB. From [56].](image)

The survivability of the ID to radiation limits the useful region of the ECAL for precision physics involving electrons to $|\eta| < 2.5$ [56]. Consequently, there is a change at $|\eta| = 2.5$ in the transverse granularity of the ECAL. The finest granularity of the ECAL is in the region $|\eta| < 2.5$. Over this region, the ECAL is segmented into three longitudinal samplings. For the EMEC inner wheel ($|\eta| > 2.5$), there are two longitudinal samplings with coarse transverse granularity [56].

The first sampling, which has a constant thickness of $6 \times X_0$ (upstream material included, that is, including material closer to the nominal interaction point), has narrow strips with a pitch of about 4 mm in the $\eta$ direction. This sampling acts as a “preshower” detector. In addition to providing a precise position measurement in $\eta$, this geometry enables the first sampling to look for substructure within a shower. This information is
2.2 The ATLAS Detector

Figure 2.17: Sketch of the three samplings of the EMB at $\eta = 0$. The presampler is not shown. From [34].

Figure 2.18: Electrode signal layer in the EMB. A longitudinal section of a single quadrant is shown. $\eta$ increases from left to right, $\rho$ from bottom to top. From [34].
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used to provide discrimination against pions and jets. The energy depositions in the first sampling are analysed to be consistent with the deposition expected from an electron or a single photon. The decay angle of the photons from the decay of a neutral pion with $p_T \approx 20\mathrm{GeV}/c$ is so small that the photons are typically separated by 1–2 cm in the first sampling.

The second sampling is transversally segmented into square towers of approximate size 0.025 × 0.025 rad in $\Delta\eta \times \Delta\phi$. This is about 4 × 4 cm$^2$ at $\eta = 0$. The adopted transverse granularity of the second sampling is derived from the Molière radius of the calorimeter, which is about 2.5 cm in the barrel. (However, it is important to note that the transverse shower profile will be elliptical rather than circular because the magnetic field in the central solenoid will broaden showers in $\phi$ somewhat.) This granularity enables clusters (of cells) to be defined that are an optimum compromise between the lateral shower containment and the contribution of the electronic plus pile-up noise to the energy resolution. Furthermore, this granularity enables EM showers to be distinguished from showers produced by pions or jets. Typically more than 70% of the energy of an EM shower will be deposited in the second sampling. The total calorimeter thickness up to the end of the second sampling, including upstream material, is about 24 $X_0$.

Since the thickness of the second sampling is sufficient to contain most of the EM shower energy, information from the third sampling is not needed to measure the shower point. Therefore the third sampling has a coarser transverse granularity in $\eta$. The thickness of the third sampling varies with $\eta$ between 2 $X_0$ and 12 $X_0$. The total thickness of the ECAL is at least 24 $X_0$ in the EMB and more than 26 $X_0$ in the EMEC.

Both the EMB and EMEC are complemented with presampler detectors, installed immediately behind the cryostat cold wall, that cover the pseudorapidity region $|\eta| < 1.8$ (see Figure 2.12 on page 47). Their purpose is to correct for the energy lost by electrons and photons in the material (ID, cryostat, solenoid coil) upstream of the calorimeter. Each presampler is essentially a single thin layer of LAr equipped with readout electronics but no absorber. The total material seen by an incident particle before the calorimeter front face is about 2.3 $X_0$ at $\eta = 0$, and increases with pseudorapidity because of the particle angle.

In the transition region between the EMB and EMEC, the amount of material reaches a localised maximum of about 7 $X_0$. In this region, the presampler is complemented by a scintillator slab inserted in the crack between the barrel and endcap cryostats (see Figure 2.12 on page 47). This scintillator is part of the Tile Calorimeter described in...
2.2 The ATLAS Detector

Section 2.2.3.2 on page 56. The region $1.37 < |\eta| < 1.52$ is not used for precision physics measurements because of the large amount of material situated in front of the ECAL [32].

Beam tests with full-size final module prototypes ("module 0’s") have demonstrated that the energy resolutions of the EMB and EMEC are expected to be better than

$$\frac{\sigma_E}{E} = \frac{9.5\%}{\sqrt{E}} \oplus 0.3\% \quad (2.9)$$

and

$$\frac{\sigma_E}{E} = \frac{12.5\%}{\sqrt{E}} \oplus 0.5\% \quad (2.10)$$

respectively [61, 62, 64]. The angular resolution was measured to be about $50\,\text{mrad}/\sqrt{E}$, which is within the ATLAS specifications [63, 66].

The following section briefly describes the calorimeter readout electronics and introduces the Front-End Board, thereby providing the background for the work presented in Chapter 8. In addition, the strategy behind the mapping of the calorimeter onto Front-End Boards is reviewed.

2.2.3.1.1 Calorimeter electronics

Signals from 182468 electronic channels$^4$ from the LAr calorimeters leave the cryostats through cold-to-warm feedthroughs located between the barrel and extended barrels of the Tile Calorimeter, and at the back of each endcap cryostat (see Figures 2.13 on page 48 and 2.15 on page 49) [32]. To minimise the cost and complexity associated with the cables for so many channels, and to reduce the effect of signal degradation that increases with cable length, the analogue readout electronics are located on the detector inside electronics boxes called Front-End Crates (FECs) attached to the cold-to-warm feedthroughs [34, 55]. Most of the digital electronics are located off the detector, in a control room.

The FECs are mounted on the rims of the barrel and endcap cryostats in the gap between the barrel and endcap calorimeters, and at the rear of the endcaps. This arrangement restricts access to the FECs for long periods of time. To access the FECs, the endcaps will have to be recessed by a couple of metres [34]. This is expected to happen once per year during the operation of the ATLAS experiment [67]. Thus, high reliability is a concern. The electronics need to be radiation tolerant. The calorimeter electronics in the barrel-endcap gap will be exposed to radiation levels of about $20\,\text{Gy}$ and $10^{12}\,\text{n/cm}^2$ of neutron flux during a standard one-year run at high luminosity [34, 68].

$^4$ 173312 + 5632 + 3524 cells in the EM, hadronic, and forward calorimeters, respectively.
The main purpose of each [FEC] is to form a Faraday cage that shields the calorimeter electronics from external radio frequency (RF) noise [67, 69]. In addition, the FECs provide mechanical support, cooling, power distribution, and data communication among the circuit boards [34]. The FECs are attached to mechanical structures called pedestals, which enable the flat-bottomed FECs to be mounted on the cryostat cylindrical walls. Inside the pedestals, signals are routed to baseplane boards from the feedthroughs via strip-line cables (warm cables). Each FEC has a baseplane board into which circuit boards are plugged [67]. Figure 2.19 shows a FEC in exploded view.

![Figure 2.19: Conceptual drawing of a Front-End Crate in exploded view. Adapted from [67].](image-url)
FECs contain the following types of boards:

- Calibration boards with precision pulsers, which reproduce the timing and dynamic range of physics signals and thereby simulate energy deposits in the calorimeters.

- Front-End Boards (FEBs), which:
  - amplify and shape the analogue signals from the calorimeter cells
  - sum the calorimeter cells by trigger tower within each sampling and prepare the input signals for the Tower Builder Board
  - store the signals in an analogue memory waiting for the event accept/reject decision by the first level of triggering (Level-1)
  - digitise the selected pulses
  - transmit on optical fibres the multiplexed digital results to read-out driver modules located off-detector

- Tower Builder Boards (TBBs), which perform the final level of analogue summation to form trigger tower signals and transmit the analogue signals to the Level-1 cavern for digitisation and processing by the Level-1 trigger processor.

- Control boards, which receive and distribute the 40 MHz clock signal, the event accept signal from Level-1, and information to configure and control the various boards in the FEC.

- Monitoring boards

FEBs will be inserted in the FECs from the top, as shown in Figure 2.19 on the preceding page. The FEBs are produced from an identical set of printed circuit boards (PCBs), which are subsequently customised according to the calorimeter they read out. The external dimensions of the FEBs are $490 \times 409.5 \text{ mm}^2$. The board thickness is limited to a maximum of $2.54 \text{ mm}$ [67]. Each FEB reads out signals from up to 128 calorimeter cells [34]. These signals should arrive at the same time to minimise the number of sampling clocks on the FEBs and to allow for a simple analogue summation of the calorimeter cell signals for the formation of the Level-1 signal. In the ECAL, signals from different samplings have different shapes and the peaks of the pulses are not aligned. There is not much space to store cable loops in the cryostat, and in most cases cables are cut to length. Therefore, to satisfy the equal timing requirement, cells close to each other that
have similar cable lengths are brought to the same FEB [34]. Consequently, each FEB corresponds to a region of contiguous cells in a single sampling.

The ECAL requires 1448 FEBs. The FEB production plan requires that 1522 FEBs are produced for the ECAL. Of these, 74 FEBs are to be fully tested and kept at CERN ready as spares for installation in the ATLAS detector during maintenance periods. This implies that the capacity exists to replace up to about 5% of the ECAL FEBs if required.

### 2.2.3.2 The Tile Calorimeter

The Tile Calorimeter is located behind the EM Accordion Calorimeter. It is roughly cylindrical in shape with an inner radius of 2.28 m and an outer radius of 4.23 m. The Tile Calorimeter is divided into a central barrel and two shorter extended barrels. The central barrel is 5.64 m long and covers the pseudorapidity region $|\eta| < 1.0$. The two extended barrels are each 2.91 m long and cover the pseudorapidity region $0.8 < |\eta| < 1.7$. There is a 60 cm gap between the central barrel and each of the two extended barrels to allow space for cables, pipes and on-detector electronics [32, 51, 70]. The Tile Calorimeter is shown in Figure 2.20.

![Figure 2.20: Three-dimensional view of the Tile Calorimeter barrel and extended barrels. Each section of the detector is built from 64 wedge-shaped modules. From [51].](image)

The Tile Calorimeter is constructed from steel absorber tiles interleaved with tiles of scintillating plastic. The tiles are placed in planes perpendicular to the beam axis and are
staggered in depth. Hadrons entering the Tile Calorimeter initiate hadronic showers in
the steel absorber tiles. The shower particles induce the production of ultra-violet light
in the base material of the scintillator tiles. Fluorescent scintillator dyes convert this to
visible light. Both sides of the scintillator tiles are read out by wavelength-shifting (WLS)
fibres into two separate photomultiplier tubes (PMTs). The WLS fibres absorb the light
from the scintillators and re-emit it at a longer wavelength where it reaches the PMTs via
total internal reflection. The longer wavelength is chosen to match the sensitive region of
the PMT photo-cathode \cite{51}.

The Tile Calorimeter is longitudinally segmented into three samplings, approximately
1.4, 4.0 and 1.8 interaction lengths (\(\lambda_I\)) thick at \(\eta = 0\). The material in front of the calor-
imeter is about 1.2 \(\lambda_I\) \cite{60}. The total thickness of the Tile Calorimeter is approximately
11 \(\lambda_I\) at \(\eta = 0\), including about 1.5 \(\lambda_I\) from the outer support, which is sufficient to pro-
vide good containment for hadronic showers and reduce “punch-through” into the Muon
Spectrometer to a minimum. Close to 10 \(\lambda_I\) of active calorimeter are adequate to pro-
vide good resolution for high-energy jets \cite{32}. Results with test beams have demonstrated
an energy resolution for pions of about 40\%\(\sqrt{E}\) with a linearity better than 2\% up to
300 GeV \cite{60, 71}. The total number of channels is about 10000 \cite{32}.

2.2.3.3 The Hadronic Endcap Calorimeter

The Hadronic Endcap Calorimeter (HEC) is a LAr sampling calorimeter which provides
hadronic coverage for the pseudorapidity range \(1.5 < |\eta| < 3.2\). The HEC is housed in the
LAr endcap cryostat behind the EMEC. The HEC consists of two independent wheels,
both with an outer radius of 2.03 m. Each wheel consists of several parallel copper plates
orthogonal to the beam axis and is divided into two longitudinal segments. The upstream
wheel is built from 25 mm thick plates, while the downstream one has plates twice as thick
(as a cost-saving measure). There is an 8.5 mm LAr-filled gap between consecutive copper
plates which is equipped with three parallel electrodes that split the gap into four drift
spaces each about 1.8 mm thick. The readout electrode is the central one. The upstream
and downstream wheels weigh 67 and 90 tonnes respectively \cite{32}. The active part of the
HEC is about 12 \(\lambda_I\) thick. Test beam results have shown that an energy resolution of
56\%\(\sqrt{E}\) \(\oplus\) 2\% can be expected \cite{60}. 
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2.2.3.4 The Forward Calorimeter

The Forward Calorimeter (FCAL) provides EM and hadronic calorimetry coverage in the pseudorapidity region \(3.1 < \eta < 4.9\) \[34\]. The FCAL is chiefly responsible for jet reconstruction and \(E^\text{miss}_T\) measurements \[72\]. The FCAL increases the angular coverage of the detector, enabling the reconstruction of jets that would otherwise escape detection. These jets can be used as “tags” to enhance the signal significance of physics processes of interest, such as the heavy Higgs boson decay channels \(H \rightarrow WW \rightarrow l\nu jj\), \(H \rightarrow ZZ \rightarrow l\nu jj\) and \(H \rightarrow ZZ \rightarrow l\nu l\nu\). These processes are accompanied by forward-backward jets coming from the WW/ZZ-fusion production process \[24\]. \(E^\text{miss}_T\) measurements are important for several physics channels and, in particular, for SUSY particle searches \[56\].

The front face of the FCAL is about 4.7 m from the nominal interaction point and is integrated into the LAr endcap cryostat \[34\]. The FCAL is a LAr calorimeter containing three modules; an EM module (FCAL1) and two hadronic modules (FCAL2 and FCAL3). All three modules are 450 mm long and have an outer radius of 455 mm. Each module consists of a metal matrix with regularly-spaced longitudinal channels filled with concentric rods and tubes \[34\]. The FCAL is shown in longitudinal cross-section in Figure 2.21.

\[\text{Figure 2.21: Longitudinal section of the Forward Calorimeter modules housed in their support tube. The light grey module on the left is the EM Forward Calorimeter. It is followed by the two hadronic modules (in dark grey). The light grey module on the right is a passive copper “plug” which provides extra shielding for the Muon Spectrometer. From \[72\].}]

The EM module, the Electromagnetic Forward Calorimeter, consists of copper rods parallel to the beam axis inside an outer tube with a 250 \(\mu\)m LAr-filled gap in between. The active depth of the EM module is about 28 \(X_0\). Test beam results have demonstrated an energy resolution of

\[
\frac{\sigma_E}{E} = 34\% \pm 2\%,
\]

(2.11)
with a linearity better than 1% [60].

The two modules that comprise the Hadronic Forward Calorimeter are located behind the EM module, which contributes $2.6 \lambda_I$ of material. The total active length of the FCAL is $9.5 \lambda_I$. The main structural differences between the hadronic and EM modules are the choice of absorber material and the width of the LAr-filled gap between the tubes and the rods within them. The hadronic modules are composed of tungsten and sintered tungsten alloy, and the LAr-gap thickness in FCAL2 and FCAL3 is 375 µm and 500 µm respectively [60]. Test beam results with the EM and only the first hadronic module have yielded an energy resolution of

$$\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}} \oplus 2.7\%,$$

which is better than target resolution for hadronic physics in this region [60].

### 2.2.4 The Magnet System

The [ATLAS] superconducting magnet system consists of a thin central solenoid (CS) surrounding the ID cavity and three large air-core toroids outside the calorimeters. The CS provides an axial magnetic field for the ID, while the air-core toroids provide a tangential magnetic field for the Muon Spectrometer. The open structure of the toroid magnet system minimises the contribution of multiple scattering to the momentum resolution of the Muon Spectrometer. Overall, the magnet system is 26 m long and 20 m in diameter [73].

The CS is 5.3 m long and has a bore of 2.44 m [73]. The bare solenoid is 44 mm thick and contributes 0.63 $X_0$ to the material in front of the ECAL [34]. In order to minimise the amount of material upstream of the ECAL, the CS shares the barrel cryostat with the EMB. This eliminates two vacuum walls [32]. The CS provides a field of 2 T in the central tracking volume with a peak field of 2.6 T at the superconductor itself [73].

The air-core toroid system is comprised of a large barrel toroid (BT) and two smaller endcap toroids (ECTs). The ECTs have a length of 5 m, an outer diameter of 10.7 m, and an inner bore of 1.65 m [73]. Each of the three toroids consists of eight coils assembled radially and symmetrically around the beam axis. The BT coils are housed in separate cryostats, while each ECT is housed in a single cryostat. The BT coil system is 25.3 m long, with an outer diameter of 20.1 m and a bore of 9.4 m [73]. The two ECTs are inserted in the BT either side of the CS. The ECTs are rotated $22.5^\circ$ with respect to the BT coil system in order to provide radial overlap and to optimise the bending power in the interface regions of both coil systems [73]. The toroid magnet system creates a field of
typically 0.5 to 2 T in the air \cite{74}. The peak magnetic fields on the superconductors in the BT and ECTs are 3.9 T and 4.1 T respectively \cite{73}.

The conductor used in all the coils is a composite that consists of flat niobium-titanium (NbTi) superconducting cable in an aluminium stabiliser \cite{73}. The magnets are indirectly cooled by liquid helium to 4.5 K \cite{73}. Figure 2.22 shows a three-dimensional view of the bare windings of the magnet system.

![Figure 2.22: Three-dimensional view of the bare windings of the superconducting magnet system: the central solenoid, the eight coils of the air-core barrel toroid and the 16 coils of the air-core endcap toroids. From \cite{73}.](image)

\section{2.2.5 The Muon Spectrometer}

The Muon Spectrometer identifies muons and measures their deflections in the magnetic field produced by the air-core toroid magnet system. It has been designed to provide both high-resolution momentum measurements and stand-alone triggering capability \cite{75}. The Muon Spectrometer covers the pseudorapidity region $|\eta| < 2.7$ for precision track measurements and $|\eta| < 2.4$ for triggering \cite{74}.

Using information from both the ID and the Muon Spectrometer, the reconstruction efficiency for muons with $p_T$ from 6 GeV/c to 2 TeV/c is better than 85% \cite{32}. The momentum resolution is typically 2–3% over most of the kinematic range, except at very high momenta where it increases to about 10% at $p_T = 1$ TeV/c \cite{74}. The invariant mass resolution for the decay of a heavy particle into two muons\footnote{Such as the decay of a heavy MSSM Higgs boson $A^0 \rightarrow \mu^+\mu^-$ or a heavy Z decay $Z' \rightarrow \mu^+\mu^-$.} is 2–4% for masses up to
1 TeV/c\(^2\), increasing to 15% for a 5 TeV/c\(^2\) particle. For a heavy particle that decays into four muons\(^6\), the mass resolution is 2–3% for masses up to 1 TeV/c\(^2\) [74]. The time resolution of the Muon Spectrometer is sufficient for muons to be unambiguously associated with their parent bunch-crossings [74].

The Muon Spectrometer defines the overall dimensions of the ATLAS detector. The outer chambers of the barrel are at a radius of about 11 m. The outer chambers of the endcaps, mounted on the cavern walls, are about 23 m from the nominal interaction point [32].

Four different chamber technologies are employed by the Muon Spectrometer: Monitored Drift Tubes (MDTs), Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs). The overall layout of the Muon Spectrometer is shown in Figure 2.23, which indicates the different regions in which the four chamber technologies are used.

---

\(^6\) Such as the Higgs boson decay H → ZZ\(^(*)\) → 4\(\mu\).
The endcap chambers are arranged in four large vertical disks located 7, 10, 14 and 21–23 m from the nominal interaction point. These chambers cover the pseudorapidity region \(1.0 < |\eta| < 2.7\). The endcap chambers are trapezoidal with tapering angles of 8.5° and 14° for the small and large chambers, respectively. They have individual areas of 1–10 m². There is a vertical crack at \(\eta = 0\) for the passage of cables and services to the detectors located within the Muon Spectrometer [74].

Precision measurements are provided by the MDTs over most of the pseudorapidity region covered by the Muon Spectrometer, except for the innermost ring \((2.0 < |\eta| < 2.7)\) of the inner station of the endcaps: the high particle fluxes in this region require the more radiation-tolerant CSC technology. The MDTs and CSCs are collectively known as precision chambers. They provide a precise single-coordinate measurement, made in the \(R - z\) projection, in the direction parallel to the bending direction of the magnetic field. The axial coordinate \((z)\) is measured in the barrel and the radial coordinate \((R)\) is measured in the endcaps.

The trigger function in the barrel is provided by three stations of RPCs on both sides of the middle MDT station, and on the inside of the outer MDT station. In the endcaps, three stations of TGCs located near the middle MDT station are used for triggering. The RPCs and TGCs are collectively known as trigger chambers. In addition to providing bunch-crossing identification, the trigger chambers provide a measurement of the coordinate orthogonal to that measured by the precision chambers. Resolutions of 5–10 mm are typical for the second coordinate measurement [74]. Table 2.5 summarises the number of chambers, the area covered, and the number of readout channels for each of the four different chamber technologies.

<table>
<thead>
<tr>
<th>Precision chambers</th>
<th>Trigger chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSC</td>
<td>MDT</td>
</tr>
<tr>
<td>Number of chambers</td>
<td>32</td>
</tr>
<tr>
<td>Number of readout channels</td>
<td>67000</td>
</tr>
<tr>
<td>Area covered (m²)</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 2.5: Summary of muon chamber instrumentation. From [74].
2.2.5.1 Precision chambers

2.2.5.1.1 Monitored Drift Tubes

The MDTs consist of layers of gas-filled aluminium tubes, each with a 50 \( \mu \text{m} \) diameter tungsten-rhenium (WRe) wire running through the centre. The tubes are 30 mm in diameter with a wall thickness of 400 \( \mu \text{m} \). The tube lengths vary from 70 to 630 cm \(^{[74]}\). The tubes are operated with a non-flammable mixture of 93\% argon and 7\% carbon dioxide at 3 bar absolute pressure, and have a total volume of 800 m\(^3\) \(^{[32]}\). The maximum drift time is about 700 ns. The single-wire resolution is about 80 \( \mu \text{m} \) \(^{[32]}\). To improve the spatial resolution of a chamber beyond the single-wire limit, the MDTs are constructed from two “multilayers” each containing three or four single layers of tubes \(^{[74]}\). These multilayers are arranged either side of a rigid support structure, as shown in Figure 2.24. An in-plane optical alignment system monitors the mechanical deformations of the MDT chambers after they have been installed in the Muon Spectrometer (hence the name Monitored Drift Tube). This enables offline corrections to be applied to track measurements in order to compensate for the effects of gravitational sagging and thermal distortion \(^{[32]}\).

![Figure 2.24: Schematic drawing of a rectangular MDT chamber constructed from multilayers of three single layers of tubes each, for installation in the barrel spectrometer. The chambers for the endcap are of trapezoidal shape, but are of similar design otherwise. From \(^{[74]}\).](image-url)


2.2.5.1.2 Cathode Strip Chambers

CSCs are Multi-Wire Proportional Chambers (MWPCs) with cathode strip readout. They consist of arrays of closely-spaced anode wires in a narrow gas enclosure with cathode strips orthogonal to the wires, as shown in Figure 2.25. The CSC gas is a non-flammable mixture of 30% Ar, 50% CO\textsubscript{2} and 20% CF\textsubscript{4}, with a total volume of 1.1 m\textsuperscript{3} [32]. The precision coordinate is obtained by measuring the charge induced on the segmented cathode by the avalanche formed on the anode wire. The electron drift time is about 30 ns. The time resolution is about 7 ns. Good spatial resolution is achieved by interpolating the charge collected between neighbouring strips. Position resolutions of better than 60 \(\mu\)m are expected [32].

![Schematic diagram showing two views of a CSC](image)

Figure 2.25: Schematic diagram showing two views of a CSC. The anode-cathode distance \(d\) is equal to the anode wire spacing \(S\), which is 2.54 mm. The cathode readout pitch \(W\) is 5.08 mm. The cathode readout strips are 1.07 mm wide and separated from each other by a distance of 0.25 mm. From [74].

2.2.5.2 Trigger chambers

2.2.5.2.1 Resistive Plate Chambers

The RPC is a gaseous detector; the basic unit is a narrow gas gap formed by two 2 mm thick parallel resistive Bakelite\textsuperscript{7} plates, separated by 2 mm thick polycarbonate insulating spacers glued on at 10 cm intervals. A 7 mm wide polycarbonate frame is used to seal the gas gap at all four edges. The gas mixture is based on tetrafluoroethane (C\textsubscript{2}H\textsubscript{2}F\textsubscript{4}) with some small admixture of sulphur hexafluoride (SF\textsubscript{6}). The primary ionisation electrons are multiplied into avalanches by a uniform electric field of typically 4.5 kV/mm. Amplification in avalanche mode produce pulses of typically 0.5 pC. The signal is read out on metal strips

\textsuperscript{7} Bakelite (polyoxybenzylmethylenglycolanhydride) is chemically-stable thermosetting phenol formaldehyde resin, otherwise known as the first artificial plastic.
on both sides of the chamber via capacitive coupling. A trigger chamber consists of two rectangular detector layers, each read out by two orthogonal series of pick-up strips. The resistive plates are coated with thin layers of graphite paint which are connected to a high-voltage power supply. A 200 μm thick insulating film glued on both graphite layers separates the graphite electrodes from the pick-up strips. The readout strips are arranged with a pitch varying from 30.0 to 39.5 mm. The RPCs have typical spatial and time resolutions of 1 cm and 1.5 ns respectively [32, 74].

2.2.5.2.2 Thin Gap Chambers

The TGCs are similar in design to MWPCs, but with an anode wire pitch (1.8 mm) that is larger than the cathode-anode distance (1.4 mm). The anode wires are 50 μm in diameter. The operating HV is foreseen to be 3.1 kV. The anode wires are sandwiched between two cathode planes made of 1.6 mm thick plates of G-10 (a glass-epoxy laminate and composite) on which the graphite cathode is deposited. Behind the cathode planes are copper readout strips arranged orthogonal to the anode wires. Signals are read out from both the anode wires and the readout strips [32]. To form a trigger signal, several anode wires are grouped together and fed to a common readout. The number of wires per group varies, as a function of η, between 4 and 20. The signals from the strips are used to measure the φ coordinate of muon tracks [74]. The TGCs have a typical time resolution of about 5 ns [55]. Figure 2.26 shows the structure of a TGC.

Figure 2.26: TGC structure. The readout strips are orthogonal to the anode wires. From [74].

TGCs are constructed in doublets and triplets of chambers. The TGC layers are separated by 20 mm thick paper honeycomb panels. These provide the mechanical support
for the chambers. The outside TGC layers are supported by 5 mm thick paper honeycomb panels. These are covered by 0.5 mm G-10 plates [74]. The gas mixture is based on 50% CO2 and 45% \( n \)-pentane \((n - C_5H_{12})\), with a total volume of 16 m\(^3\). This gas mixture is highly flammable and requires adequate safety precautions [74]. Figure 2.27 shows a schematic cross-section of a triplet and a doublet of TGCs.

Figure 2.27: Schematic cross-section of a triplet (left) and a doublet (right) of TGCs. The width of the gas gap is shown enlarged. From [74].
The ATLAS Trigger/DAQ System

3.1 Overview

The trigger and data acquisition (TDAQ) system is responsible for selecting interesting events from the ATLAS detector and moving the data corresponding to these events to permanent storage for later off-line analysis. Triggering is the process whereby the detector’s read-out system is triggered to record the data for an event that has been identified as interesting. It involves using simple criteria to select interesting events as efficiently as possible, while rejecting high-rate background events.

Based on the assumption for the inelastic proton-proton cross-section at the LHC (70 mb), the total interaction rate at high luminosity (1 x 10^{34} cm^{-2} s^{-1}) will be on the order of 10^9 Hz [32]. The TDAQ system must reduce this rate by a factor of 10^7 to yield a manageable event rate that can be written to permanent storage. As shown in Figure 3.1 on the next page, the physics processes of interest have cross-sections that are several orders of magnitude smaller than the inelastic proton-proton cross-section. For example, the decay of a SM Higgs boson with a mass of 120 MeV/c^2 via the channel H → γγ is expected to occur at a rate of 10^{-13} of the interaction rate [76]. Trigger rates are dominated by QCD jets, semileptonic decays of b and c quarks, and π/K → μν decays [30]. Thus, the ATLAS trigger system must provide a very efficient, unbiased and robust selection. It is highly desirable to reject background processes as early as possible to optimise the usage of the available resources.

The average event size is 1–2 MB [80–82]. It is estimated that, during running, 200–400 MB of data per second will be transferred to permanent media for subsequent off-line analysis. At this rate, ATLAS expects to store a few petabytes of data per year.
Figure 3.1: Proton-(anti)proton cross-sections and event rates at \( \mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) as a function of centre-of-mass energy (left), and as a function of the produced particle mass or the highest jet transverse energy for a centre-of-mass energy (\( \sqrt{s} \)) of 14 TeV (right). From \([77-79]\).
The ATLAS trigger is organised in three levels as shown in Figure 3.2. The first-level trigger (Level-1) is hardware-based. The second-level trigger (Level-2) and the third-level trigger (the Event Filter) collectively form the High-Level Trigger (HLT). The HLT runs on farms of commercially-available personal computers (PCs) executing an offline-like software suite. Level-1 (LVL1) uses special-purpose processors to act on reduced-granularity data from a subset of the detectors. Level-2 (LVL2) uses full-granularity, full-precision data from most of the detectors, but only examines those regions of the detector that have been identified by LVL1 as containing interesting information. The Event Filter (EF) uses the full event data to decide which events are to be recorded for off-line analysis. The ATLAS trigger is programmable and trigger criteria will be chosen according to experience gained from initial running of the LHC.

Figure 3.2: The ATLAS three-level trigger/DAQ architecture. From [81].

The variety of physics signatures requires that ATLAS is able to trigger on final states involving: charged leptons, high-\(p_T\) quark and gluon jets, photons, weak gauge bosons (W’s and Z’s), and missing transverse-energy that can be attributed to weakly-interacting neutral particles such as neutrinos.

The tidal wave of data that will be produced by the LHC places an unprecedented challenge on the ATLAS TDAQ system, and it is the need to select rare physics processes
with high efficiency while rejecting high-rate background processes that drives the TDAQ architectural decisions and technology choices.

3.2 The LVL1 Trigger

3.2.1 LVL1 overview

The LVL1 trigger is a hardware system based on dedicated electronics and pipelined memories. The primary task of the LVL1 trigger is to perform a preliminary rejection of background events. LVL1 operates at the LHC bunch-crossing frequency of 40 MHz and must unambiguously identify and provide a decision for each bunch-crossing using only coarse-granularity information from the calorimeters and a subset of the muon detectors.

The time taken to form and distribute a trigger decision is known as the latency. The LVL1 latency is about 2 μs, which is longer than the 25 ns bunch-crossing time. The maximum allowed latency is 2.5 μs, leaving a 500 ns safety margin. The LVL1 latency is mainly due to cable propagation delays between systems, and trigger processing time [55]. The former is minimised by mounting the electronics for the trigger processors on, or near, the detector. During the LVL1 trigger processing, the data from multiple bunch-crossings are held in pipeline memories. The maximum accept rate of LVL1 is limited to 75 kHz (upgradeable to 100 kHz) by the capabilities of the subdetector read-out systems and the LVL2 trigger [32].

The LVL1 trigger comprises the muon trigger, the calorimeter trigger, the Central Trigger Processor (CTP), and the Timing, Trigger and Control (TTC) system. The LVL1 trigger architecture is shown schematically in Figure 3.3 on the next page.

3.2.2 The Muon Trigger

The LVL1 muon trigger is based on the measurement of muon trajectories using only the RPCs and TGCs in the Muon Spectrometer. RPCs and TGCs are used because they have a very fast response time and enable the bunch-crossing of interest to be uniquely identified. The muon trigger uses two stations of chambers for the low-$p_T$ triggers and three stations for the high-$p_T$ triggers. The muon trigger looks for a coincidence of hits in the different chamber layers within a geometric road, the width of which depends on the $p_T$ threshold to be applied. Six independently programmable $p_T$ thresholds are available;
3.2 The LVL1 Trigger

Calorimeters

Muon Detectors

![Diagram of Level-1 trigger architecture](image)

Figure 3.3: The Level-1 trigger architecture. From [55].

three for the low-$p_T$ trigger and three for the high-$p_T$ trigger. The LVL1 processors forward information on the multiplicity of muons satisfying these thresholds to the CTP [54].

3.2.3 The Calorimeter Trigger

The calorimeter trigger uses information from the EM and hadronic calorimeters in the barrel, endcap and forward regions, but with reduced granularity. The calorimeter trigger searches for $e/\gamma$ clusters, jets, and large missing and total $E_T$. It uses trigger towers of size $0.1 \times 0.1 \, \text{rad}$ in $\Delta\eta \times \Delta\phi$ with a single depth compartment (that is, all samplings are summed) in each of the EM and hadronic calorimeter. Analogue signals from the trigger towers are sent to the front-end pre-processor, which digitises them using fast analogue to digital converters (ADCs) and calculates the $E_T$ of the pulses in units of 1 GeV [55]. Any event in which an ADC overflows (at $E_T \approx 250 \, \text{GeV}$) will be accepted by the LVL1 trigger. To reduce the effect of electronic noise and pile-up, pulses with $E_T < 1 \, \text{GeV}$ are ignored [55].

The subsequent processing in the calorimeter trigger is divided into three sub-triggers (see Figure 3.3) which process information, independently and in parallel, on high-$p_T$ EM clusters, hadron/\tau clusters, and high-$E_T$ jets. Regions of the detector containing jets and EM clusters are flagged for analysis by LVL2. Eight programmable sets of thresholds
are provided for each calorimeter sub-trigger. For each bunch-crossing, the calorimeter processor informs the CTP of the multiplicity of EM clusters, hadron/τ clusters, and jet candidates for each threshold [55].

3.2.4 The CTP and TTC system

Muon trigger processor and calorimeter trigger processor decisions are passed to the CTP. The CTP correlates the results from the calorimeter trigger processor and the muon trigger processor, and makes the overall LVL1 trigger decision which is passed on to the TTC system. The CTP is also responsible for the control of dead-time. Dead-time can be triggered by an external “busy” signal or by internal algorithms that predict overflow conditions in the front-end system, for example if the buffers in the read-out system become full [54]. The TTC system distributes the CTP trigger decision, the 40 MHz LHC clock signal, and other signals to the front-end system [54].

3.3 The High-Level Trigger

The ATLAS HLT consists of a software-based framework in which guided algorithms validate or invalidate specific trigger hypotheses. The HLT consists of two stages: the LVL2 trigger and the EF. The boundary between these two stages is flexible in order to profit from the complementary features of both trigger steps.

3.3.1 The LVL2 Trigger

3.3.1.1 LVL2 overview

When the LVL1 trigger has accepted an event, the data stored in pipeline memories are sent to the read-out drivers (RODs). The high instantaneous data rate at the output of the pipeline memories is averaged out to match the available input bandwidth of the RODs by intermediate buffers, labelled “derandomisers” in Figure 3.2 on page 69. The data are then sent to the readout buffer input cards (ROBINs). There the data are kept until LVL2 rejects the event or until the Event Builder (EB), which combines the data fragments into a complete event record, has read the data.

The LVL2 trigger uses full-precision information from the ID and full-granularity data from the calorimeters and muon detectors, but only inspects the geometrical regions of the detector that the LVL1 trigger has identified as containing interesting activity; these
are known as Regions of Interest (RoIs). This means only a fraction (about 2%) of the full event data stored in the ROBINs are transferred to the LVL2 processors, which reduces the LVL2 latency [31].

RoIs can be of two types: primary and secondary. Primary RoIs are those that have passed the trigger threshold. Secondary RoIs are those that have been flagged by LVL1 but played no direct role in event selection at that trigger level. They are passed to LVL2 purely as additional information about the event [33]. There are typically 1–2 primary RoIs and about 3 secondary RoIs per event [83]. RoIs may contain high-\(p_T\) muons, EM clusters, hadron/\(\tau\) clusters, or jets. For each RoI, the data are combined from all the subdetectors. This enables better particle identification and more precise measurements than LVL1. RoI information is used to decide which ROBINs contain data to be transferred to the LVL2 processors.

The LVL2 trigger is provided with data from LVL1 that it has collected on \(p_T\) thresholds (six \(p_T\) thresholds for the muon trigger, eight \(p_T\) thresholds for the calorimeter trigger), multiplicities of objects in each \(p_T\) threshold, and RoI locations in the detector, plus event and bunch-crossing identifier numbers and any error flags [54]. Different sets of algorithms will be executed at LVL2 according to the type of RoIs found at LVL1 [81].

The LVL2 trigger reduces the acceptance rate from 75 kHz to about 2 kHz, which is a rate that can be sustained by the EB [76]. The average LVL2 latency is 10 ms [76]. It should be noted that this is not a hard limit. Instead, it is an estimated time based on the expected number of processors running on the LVL2 central processing unit (CPU) farm [84].

The LVL2 trigger has four principle blocks: the readout buffer (ROB) complex, the Supervisor and RoI Builder, the networks, and the processing farms. Figure 3.4 on the following page shows the main features of the LVL2 trigger.

### 3.3.1.2 The ROB complex

Data corresponding to events accepted by LVL1 are stored temporarily in ROBINs. The ROB complex serves both the LVL2 trigger and the EB. The main function of the ROB complex is to store raw data fragments during LVL2 processing. The LVL2 trigger can access the ROBINs to request data, and can also clear data for events which it has rejected [59].
3.3.1.3 The Supervisor and RoI Builder

The task of the RoI Builder is receive data from LVL1 at the LVL1 accept rate and build an RoI record. The record contains a list of RoIs, their type and their positions within the ATLAS detector. The Supervisor is responsible for assigning LVL2 processors and forwarding the RoI record to the appropriate part of the LVL2 trigger, so that the LVL2 processor receives the corresponding data from the ROB complex. The Supervisor also receives LVL2 decisions and broadcasts them to the ROB complex so that data can be cleared for events that have been rejected.

3.3.1.4 The networks

There are two logically distinct networks in the LVL2 trigger: the data collection network and the control network. The data collection network transmits the RoI information from the ROB complex to the LVL2 processors. The control network carries the LVL1 accept, LVL1 RoI request, and LVL2 decision messages to the ROB complex.
3.3.1.5 The processing farms

Three main tasks are performed in the processing farms: feature extraction (FEX), object building, and trigger-type selection.

- In feature extraction, data from one RoI in a single subdetector are collated and processed to give a compact description of the data. Example features are calorimeter clusters and tracks.

- Object building combines the features from one RoI from all relevant subdetectors, and returns the particle parameters and possible type.

- Trigger-type selection combines all objects from an event and compares the result to a menu of physics selections, called a trigger menu. The LVL2 decision is based on the outcome of this comparison.

3.3.1.5.1 Feature extraction

The muon FEX

The muon FEX algorithm uses full-granularity data to calculate track parameters, reduce the background, and sharpen $p_T$ thresholds, which reduces the LVL1 muon rate by a factor of two [59].

The calorimeter FEX

The calorimeter FEX algorithm uses full-granularity data to search for clusters in the EM and HCAL. The $E_T$ thresholds are sharpened, and shapes and properties of showers are calculated. The calorimeter FEX helps identify $\tau$’s and distinguish electrons and photons from $\pi^0$ showers.

The jet FEX

The jet FEX algorithm improves the energy and position measurements of LVL1 jet candidates. The jet RoI covers a large volume in the detector, therefore there are a lot of data to transfer from the ROBINs to the LVL2 processors.

The Inner Detector FEX

The Inner Detector FEX algorithm searches for tracks in the TRT and precision layers (Pixel and SCT) of the ID. A high-$p_T$ trigger searches, with guidance from RoIs, for
high-$p_T$ tracks ($p_T > 5$ GeV/c). A low-$p_T$ trigger searches, without guidance from RoIs, in the TRT for low-$p_T$ tracks ($p_T > 0.5$ GeV/c). The former is useful for finding high-$p_T$ muons and electrons, the latter is designed for B-physics studies. Searches in the TRT and in the precision layers of the ID are performed independently \[59\].

### 3.3.1.5.2 Object building

#### Muon object building

The muon object building matches muon chamber and ID features for muons and tests for track isolation using the calorimeter. The muon trigger suffers from a high background rate from charged pions and kaons decaying in flight ($\pi/K \rightarrow \mu\nu$). The combination of the features of tracks measured in the Muon Spectrometer and the ID provides rejection power against muons from these decays \[31\].

#### $e/\gamma$ object building

The $e/\gamma$ object building matches calorimeter and ID features for electrons. In addition to requiring the presence of a track with a minimum $p_T$ in the EM RoI, this association requires position and energy-momentum matching between the cluster and the track. The $e/\gamma$ trigger rate is dominated by isolated pions, narrow hadronic showers, and neutral pions decaying to photons; shower shape analysis using the EM and hadronic calorimeters can be used to reject these \[59\].

#### $\tau$ object building

The $\tau$ object building matches narrow isolated jets in the calorimeters with tracks in the ID.

### 3.3.2 The Event Filter

The EF reduces the event rate by an additional factor of ten, and performs the final event selection and data reduction before permanent storage. The EF latency is on the order of 1 s \[59\]. The enables more sophisticated algorithms to run at the EF than is possible at LVL2. The EF will also apply quick calibration and alignment corrections. It may also perform some data preparation steps before mass storage of accepted events; for example, zero suppression\(^1\) of data in inactive regions of the LAr calorimeters \[85\].

\(^1\) Compression of data by removal of values equal to zero.
3.3 The High-Level Trigger

After an event is accepted by the LVL2 trigger, the data for the event are moved from the ROBInS to the EF processors via the EB. The EB reconstructs events from data fragments. Vertex reconstruction and track fitting are performed at this level. The EB will process data at a rate of about 1–10 GB of data per second [59].
The High-Level Trigger Selection Software

The High-Level Trigger Selection Software (HLTSSW) is responsible for the selection and classification of events at LVL2 and the EF. Abstract physics objects\(^1\) representing candidates such as electrons, jets, muons, and photons are reconstructed from event data by using a particular set of HLT Algorithms and applying appropriate cuts. An event is selected if the reconstructed objects satisfy at least one of the specified selection criteria [31, 85]. Figure 4.1 on the next page shows a simplified package diagram of the HLTSSW.

The HLTSSW has four main components: the HLT Algorithms which process the event data, the Steering which guides and steers the algorithmic processing of events and is responsible for event selection, the Data Manager which handles the event data during the trigger processing, and the Event Data Model which specifies the objectified representation of the event data to be used by the HLT Algorithms [76, 80]. This chapter describes how these four components work together. The Navigation mechanism is introduced and its role within the HLTSSW is described. This provides the context for the results presented in Chapter 5.

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\(^1\) Objects are the basic building blocks of a C++ program. An object is a self-contained runtime entity that consists of data and functions that operate on that data.
4.1 The Data Manager

The purpose of the Data Manager is to encapsulate and abstract the raw event data access for HLT Algorithms. The Data Manager provides the infrastructure to retrieve the raw event data, store and access the intermediate results, and save the final results. It is used to receive and transmit the results of each stage of the trigger processing. Therefore, it enables the information about each event to be built up as it is processed. It provides the HLT Algorithms with the event data they request and the Steering with the algorithmic results needed for obtaining the trigger decision [85–87].

The raw data from the ATLAS detector will be delivered in terms of a so-called “bytestream” of data consisting of hierarchically arranged fragments formatted in a subdetector-dependant way. The bytestream data must be converted into objects which can then be used by HLT Algorithms. The Data Manager provides the infrastructure to perform this task [82].

The central part of the Data Manager is the Transient Event Store (TES). The TES is responsible for holding the objectified representations of the event data during the trigger processing. Each object is recorded in the TES with a key. The key is like a cloakroom ticket. The same key is required to retrieve the object. This enables the objectified representation of event data that was produced and stored by one HLT Algorithm to be retrieved and analysed by another HLT Algorithm later in the trigger processing.
4.2 The HLT Algorithms

The HLT Algorithms are used by the Steering to process the event information and obtain the data on the basis of which the event decision is taken. They are the building blocks of the reconstruction. The Algorithms that run at LVL2 are custom-written to comply with the stringent latency requirements and only have access to the data in LVL1 RoIs. Latency imposes less of a burden on EF Algorithms than LVL2 Algorithms. Consequently, the Algorithms that run at the EF are generally adapted from offline reconstruction code and have access to the whole event data. The sequencing of Algorithms is driven by a static configuration that informs the Steering which Algorithm must be executed in the case that a particular (dynamic) trigger condition is active. There are two types of HLT Algorithm:

- **FEX** Algorithms process the event data and produce abstract physics objects (“features”) that represent candidates for electrons, muons, jets, and so on. FEX Algorithms operate on features and produce new ones, thereby refining the event information.

- **Hypothesis** Algorithms perform a task similar to particle identification. A Hypothesis Algorithm tests whether a previously created feature agrees with the hypothesis of an assumed physics object by applying selection cuts on the feature’s properties. It can then flag the hypothesis as valid or invalid.

4.3 The Event Data Model

The Event Data Model (EDM) is the common language within and between Algorithms defining the objectified representation of event data. It is the “language spoken” by the HLTSSW to communicate information about each event. The EDM covers all data entities in each event and the relationships between them. The data entities span from the raw data in bytestream format, the reconstructed features produced by HLT Algorithms, and trigger-related data. Henceforth, all objects covered by the EDM will be referred to as Event Data Objects (EDOs) to distinguish them from other C++ objects.

The raw data includes the LVL1 Result, LVL2 Result and EF Result. The LVL1 Result contains the LVL1 RoI information. The LVL2 Result and the EF Result contain information about the abstract physics objects that pass the selection at LVL2 and the EF, respectively. The trigger-related data includes RoI Objects, RoI Descriptors, and
Trigger Elements. An RoI Object is the objectified representation of a LVL1 RoI. An RoI Descriptor is a special EDO in which the position of an RoI is stored. An Algorithm may update this for the benefit of downstream Algorithms [31, 76, 80].

Contrary to canonical object-oriented programming, EDOs contain minimal algorithmic content. For example, the objectified representation of a track left by a charged particle does not contain any Algorithms for finding tracks [82].

4.3.1 Trigger Elements

*Trigger Elements (TEs)* enable communication between the HLT Algorithms and the Steering. A TE represents a *hypothesis* for a physical feature. TEs do not have any properties or states of their own other than a label that denotes the abstract physics objects they represent and a boolean flag that indicates whether the TE is active or not. The boolean flag is used by the Steering to check whether the hypothesis represented by the TE is valid. An active TE represents a valid hypothesis. The task of the HLT Algorithms is to confirm or reject this hypothesis and signal the result to the Steering by activating or deactivating the TE.

TE labels are written in the form "oXXi", where “o" denotes the final state physics object represented by the TE ("e" for electrons, “μ” for muons, “τ” for tau leptons, “γ” for photons, “j” for jets and “xET” for missing $E_T$), “XX” denotes a minimum $p_T$ threshold that must be passed, and “i” refers to any isolation criteria. For example, a TE with the label “e25i” represents a hypothesis that the physical feature associated with the TE is an isolated electron with $p_T \geq 25$ GeV/c. The thresholds are generally given at the point where the LVL1 and LVL2 algorithms are 95% and 90% efficient, respectively [31, 33].

TEs are used by the Steering as handles to steer the event processing. They do not hold any data themselves, but are related to EDOs and to each other in a navigable way. A TE functions like a hook on which to hang data EDOs. Hence, a TE can be thought of as the entry point for an Algorithm into an event.

4.3.2 Relations, navigability and the seeding mechanism

An important aspect of the EDM is the concept of navigability between data EDOs. Navigability is essential for the Algorithm processing. The algorithmic processing of events is divided into a number of sequential parts. Each part is allotted by the Steering to
a specific [HLT] Algorithm which refines the event information. The Navigation is the mechanism that links the EDOs produced at each stage of the RoI reconstruction so that HLT Algorithms can find EDOs created by previous Algorithms. This enables the outcome of one Algorithm to be used as the “seed” for the next.

The navigable links are logical relations represented in the implementation by Standard Template Library (STL) strings. The role names of the relations indicate the nature of the association. The “seeded by” relation would be used to link EDO $A$ to EDO $B$ if EDO $A$ is reconstructed by an Algorithm that in turn has been seeded by EDO $B$. The “uses” relation is used to associate EDOs to the EDOs they use. The “excludes” relation between two EDOs indicates that they are conflicting. For example, the “excludes” relation would be used between two TEs labelled “electron” and “photon” that are both seeded by the same EM RoI Object from LVL1. Figure 4.2 shows how the Navigation relates TEs to each other and to the reconstructed features used and produced by [HLT] Algorithms.

![Diagram showing navigable links](image)

Figure 4.2: Schematic showing how navigable links are used to structure the event data. The example shows the reconstruction of an electron at LVL2. The reconstruction is initiated by an EM RoI from LVL1. HLT Algorithms run sequentially to incrementally refine the event information. The outcome of each Algorithm is used as the seed for the next Algorithm. The navigable links between EDOs enable the Algorithms to find the data they must work on.

The seeding mechanism uses the Navigation to guide the reconstruction to the event fragments that the [HLT] Algorithms must work on in order to derive the trigger decision. The seeded reconstruction allows the Algorithms to focus only on the promising regions of the event and on EDOs already signalled as interesting at a previous stage in the triggering process [85]. Figure 4.3 on the facing page shows an example illustrating how the seeding mechanism works.

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3 Ordered sequences of consecutive alphanumeric characters.
4.3 The Event Data Model

Figure 4.3: Diagram illustrating the basic concept of the seeding mechanism. Figure (a) shows the flow of actions relevant to the Steering that takes place during Algorithm execution. Figure (b) shows an example of the fragment of the event information that is built up as a result of those actions. Adapted from [81].

As shown in the example, the HLT Algorithm is seeded by the output TE (not the input TE; as one might expect; the reason for this will be explained later). The Algorithm needs to access the event information. In this case, it requires the EM RoI Object from LVL1. Therefore it navigates via the “seeded by” and “uses” relations to the EM RoI Object and the does its reconstruction and analysis work. The result of the algorithmic work is a calorimeter cluster that is linked to the output TE by the “uses” relation so that a subsequent Algorithm can access the feature found for this RoI. The algorithmic work done by a Hypothesis Algorithm involves applying selection cuts to validate the hypothesis represented by the output TE. If the hypothesis is validated, the Algorithm signals this to the Steering by activating the output TE.

4.3.2.1 History Objects

All navigational relations between TEs and EDOs are encoded in History Objects. A History Object is essentially a list of relationship-EDO pairs. That is, each item on the list associates a relation with the EDO it refers to. Every TE has a History Object that stores its links to other EDOs.

A History Object can be thought of as a list of event features that can be queried by an Algorithm in order to test the hypothesis represented by a TE. For example, the History Object belonging to an e25i TE might contain a link to a calorimeter cluster and a track. Given this TE, an Algorithm could navigate to these features and use them to validate
or invalidate the TE hypothesis. The Algorithm could, for example, perform position and energy-momentum matching between the calorimeter cluster and the track. In this case, a close match would indicate that this TE is good electron candidate. In essence, History Objects allow Algorithms to ask questions about event features so that they can decide if a TE hypothesis is valid.

History Objects are instances of the class\textsuperscript{4} \texttt{key2keyStore}, which is based on the STL class \texttt{hash_multimap}. (The name “\texttt{key2keyStore}” is a misnomer. It is a legacy of an old implementation of the Navigation in which keys labelling the nature of the navigational relation mapped to keys used to tag EDOs in the TES \cite{88}.)

\texttt{Hash}\texttt{\_multimaps} are unsorted containers that map keys to data. There is no limit on the number of elements whose keys may be the same. In the case of \texttt{key2keyStore}, the keys are STL strings that contain the role names of the relations. (The decision to use strings for keys was taken early in the design process because of constraints imposed by the TES technology at the time, namely that specific instances of EDOs in the TES are accessed via string keys.) Given a key, the \texttt{hash\_multimap} will find the corresponding data. This kind of operation is called a “lookup”. It works by transforming the key using a \textit{hash function} into a number that is used to index the position in an array where the data should be. This is called “hashing”.

The data stored in the \texttt{hash\_multimap} are not the EDOs themselves, but are pointers\textsuperscript{5} to special “Holder Objects” that each contain a pointer to an EDO. The decision to use \texttt{hash\_multimaps} to record the Navigation links between EDOs was taken at a very early stage in the design process. Although only three type of Navigation link are in use, the design allowed for more if they were needed.

\subsection{Reading and writing Navigation links}

Instances of the class \texttt{key2keyStore} are \textit{polymorphic} containers. In this context, “polymorphic” means that the same container can be used to store objects of different types. C++ is a statically-typed programming language, which means that the data-type of every variable, parameter and function return value is known at compile-time. It is the programmer’s responsibility to provide the type information. This implies that a programmer writing a container class must know in advance what type of objects could be stored

\textsuperscript{4} In C++, a class is a compile-time blueprint for creating (“instantiating”) an object.

\textsuperscript{5} In C++, a pointer is a variable that holds the memory address of an object. The address may be expressed in hexadecimal with the prefix “0x”, for example: “0x131d0f7b”.
4.3 The Event Data Model

in it. Polymorphism is a language mechanism that allows a single definition to be used with different types of data. It allows a container class to be written without consideration of the data-type with which it will eventually be used.

All objects stored in a `hash_multimap` are constrained to be instances of the same class. `Key2keyStore` uses polymorphism to enable its `hash_multimap` to contain any type of object. Objects are given a generic “wrapper” that hides their true type before they are stored in the `hash_multimap`. This is done by creating an instance of a class derived from the class template `Holder<T>`. (In C++, a class template is a way to fabricate many similar classes from one piece of code. The parameter `T` is a placeholder in the class definition for a data-type. When the compiler encounters an instance of the template, it automatically generates a version of the class where `T` is replaced by the actual type supplied by the template parameter.) The instance of the class derived from the `Holder<T>` template (a `Holder Object`) contains the pointer to the EDO.

In object-oriented programming, inheritance is a way to form new classes using classes that have already been defined. The new classes derive (“inherit”) attributes and behaviour from the pre-existing classes. At a more fundamental level, inheritance is a way of arranging type hierarchies. `Holder<T>` inherits from the class `BaseHolder`. This means that all instances of classes generated from `Holder<T` “are a kind of” `BaseHolder`. Instances of classes `Holder<TriggerElement*>`, `Holder<Cluster*>`, `Holder<Track*>`, and so on are all specialisations of `BaseHolder`. Therefore, a `hash_multimap` will treat them as if they were all as instances of a single class: `BaseHolder`. As such, they can all be inserted directly into a `hash_multimap`. This is how instances of `key2keyStore` can store any type of object. The `hash_multimap` used by `key2keyStore` actually associates string keys with `BaseHolder` pointers. Consequently, the implementation of `key2keyStore` allows History Objects to record the relationships between TEs and any type of EDO.

`Key2keyStore` also provides a means to map TEs to the History Objects that belong to them, via the special `key2keyStore` named `TE2history`. Rather than impose a requirement that each TE must contain a pointer to their History Object, each TE’s History Object is stored in `TE2history`. The string key is generated from the TE’s pointer address, which is guaranteed to be unique. This is done by the `key2keyStore` static member function `getKey`, which takes the TE’s pointer as an argument and returns a string containing the pointer address expressed as a hexadecimal number. The actual content of

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6 In C++, a `datatype*` is a pointer to data of type `datatype`; “*” is the pointer declarator.
a History Object in the case of a TE linked to three different EDOs with three different relations is shown in Figure 4.4.

Figure 4.4: Example contents of a History Object. Adapted from [81].

The steps required to retrieve an object from an instance of key2keyStore (either TE2history or any History Object) are as follows:

1. Find the BaseHolder in the hash_multimap associated with the search key,
2. “Unwrap” the BaseHolder to reveal the Holder Object,
3. Retrieve the stored object from the Holder Object.

The second step involves converting the BaseHolder to the specific type of Holder Object that contains the stored object. For example, a conversion from BaseHolder to Holder<TriggerElement*> is required to retrieve a stored TE. This is done using the C++ operator dynamic_cast. The statement dynamic_cast<target>(x) will attempt to convert the type of the operand to the requested target type. This kind of operation is called “casting”. The process of writing and reading Navigation links between TEs and EDOs is illustrated in Figure 4.5 on the facing page and Figure 4.6 on the next page.

4.4 The Steering

The Steering controls the selection software. It is responsible for arranging the algorithmic processing in the correct order and obtaining the trigger decision. The Steering uses the
4.4 The Steering

Figure 4.5: Writing a Navigation link in a History Object. The TE’s pointer is used as a key to find the BaseHolder in “TE2history” that contains the TE’s History Object. The BaseHolder is converted (via dynamic_cast) to a Holder Object, from which the History Object is retrieved. The EDO is put into a new Holder Object, and this is inserted into the TE’s History Object with a key describing the Navigation relationship.

Figure 4.6: Reading a Navigation link in a History Object. The TE’s History Object is retrieved as described in Figure 4.5. The Navigation relation is used as a key to find the BaseHolder in the TE’s History Object that contains the EDO. The BaseHolder is converted (via dynamic_cast) to a Holder Object, from which the EDO is retrieved.
seeding mechanism described in the previous section to restrict the reconstruction to the parts of the event corresponding to a given LVL1 RoI. The HLT processing flow is disaggregated into sequential Steps. A Step consists of a set of Algorithms followed by a trigger decision. Events can be rejected at any Step. Therefore, stepwise reconstruction enables events to be rejected as early as possible, saving processing time and network resources. Algorithms functioning in the context of the HLT must validate or reject TE hypotheses formed at a previous stage in the triggering process. Therefore, the reconstruction of an event in the trigger can be viewed as the process of refining TE hypotheses.

4.4.1 Trigger Configuration

At initialisation time the HLTSSW is configured to execute the LVL2 or EF selection, depending on the sub-system the software is running in. The configuration is responsible for providing the information, in terms of TEs and HLT Algorithms, that the Steering needs in order to control the data-driven trigger processing. The input to the configuration are two Extensible Markup Language (XML) files that are parsed into C++ objects. These files encode the Sequences and Signatures that instruct the Steering when to run an Algorithm and if a physics signatures is fulfilled.

4.4.1.1 Signatures

Signatures represent particular physical criteria that must be satisfied in order for an event to be accepted. They are described in terms of required TEs. A Trigger Menu consists of the list of Signatures that could be validated at a given stage in the triggering process. Therefore, a Trigger Menu can be thought of as a “shopping list” used by the Steering to decide if an event is interesting. An example Signature is “2e15i”. This Signature would be satisfied if two active TEs with the label “e15i” are found in the TES. Each Signature has an associated pre-scale and forced-accept factor. If the rate for a particular Signature is very high the pre-scale factor can be used to inform the trigger that only a percentage of the events satisfying that Signature should be accepted, thereby reducing the rate. The forced-accept factor is used to force the trigger to accept events that satisfy a Signature, regardless of further selection, to some percentage. This is useful for randomly sampling events rejected by the trigger for cross checks and efficiency/bias studies.

Table 4.1 on the facing page gives an overview of the HLT Trigger Menu with rates for a luminosity of $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. The single electron trigger e25i is responsible for
the largest single contribution from the EM selections to the HLT output rate. For this reason, the e25i trigger was chosen for the studies presented in this thesis.

<table>
<thead>
<tr>
<th>Signature</th>
<th>Example physics coverage</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e25i</td>
<td>$W \rightarrow e\nu, Z \rightarrow ee, t$ production, $H \rightarrow WW^{(<em>)}/ZZ^{(</em>)}$, $W'$, $Z'$</td>
<td>40</td>
</tr>
<tr>
<td>2e15i</td>
<td>$Z \rightarrow ee, H \rightarrow WW^{(<em>)}/ZZ^{(</em>)}$</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>γ60i</td>
<td>direct photon production, $H \rightarrow \gamma\gamma$</td>
<td>25</td>
</tr>
<tr>
<td>2γ20i</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>2</td>
</tr>
<tr>
<td>μ20i</td>
<td>$W \rightarrow \mu\nu, Z \rightarrow \mu\mu, t$ production, $H \rightarrow WW^{(<em>)}/ZZ^{(</em>)}$, $W'$, $Z'$</td>
<td>40</td>
</tr>
<tr>
<td>2μ10</td>
<td>$Z \rightarrow \mu\mu, H \rightarrow WW^{(<em>)}/ZZ^{(</em>)}$</td>
<td>10</td>
</tr>
<tr>
<td>j400</td>
<td>QCD, SUSY, new resonances</td>
<td>10</td>
</tr>
<tr>
<td>3j165</td>
<td>QCD, SUSY</td>
<td>10</td>
</tr>
<tr>
<td>4j110</td>
<td>QCD, SUSY</td>
<td>10</td>
</tr>
<tr>
<td>j70+xE70</td>
<td>SUSY</td>
<td>20</td>
</tr>
<tr>
<td>τ35i+xE45</td>
<td>qqH ($\tau\tau$), $W \rightarrow \tau\nu, Z \rightarrow \tau\tau$, SUSY at large $\tan\beta$</td>
<td>5</td>
</tr>
<tr>
<td>2μ6$^a$</td>
<td>rare b-hadron decays ($B \rightarrow \mu\mu X$), $B \rightarrow J/\psi(\psi') X$</td>
<td>10</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>~200</td>
</tr>
</tbody>
</table>

$^a$ With vertex, decay-length and mass cuts.

Table 4.1: HLT trigger menu with rates for each Signature for a luminosity of $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. From [31].

4.4.1.2 Sequences

A Sequence is defined as a transformation of one or more TEs, via a set of HLT Algorithms, into a new TE. A typical Sequence consists of a FEX Algorithm which reconstructs physical quantities, and a Hypothesis Algorithm which tests whether a previously created feature agrees with the TE hypothesis. A simple example Sequence is:

\[ \text{inputTE AlgName outputTE} \]

This Sequence would direct the Steering to look for active TEs in the Transient Event Store (TES) with the label inputTE. If any are found, the Steering creates a TE with the label outputTE and then executes the Algorithm with the name AlgName. The pointer to the
outputTE is passed as an argument to the Algorithm that in turn can set up navigational links to reconstructed features. A Sequence Table consists of a set of Sequences. An example set of Sequences is:

\[
\begin{align*}
\text{LVL2:} & \quad \text{TE1 Alg1 TE2} \\
\text{LVL2:} & \quad \text{TE2 Alg2 TE3} \\
\text{LVL2:} & \quad \text{TE3 Alg3 TE4} \\
\text{EF:} & \quad \text{TE4 Alg4 TE5}
\end{align*}
\]

where the \text{LVL2} and \text{EF} tags have been added since it is possible to select the trigger level at which the Algorithm runs. In this scheme, each \text{TE} is the seed for the next Algorithm through another Sequence.

### 4.4.2 Implementation of the Steering

The Steering consists of several components, which are implemented as separate C++ classes. A class diagram for the Steering software is shown in Figure 4.7 on the next page. The \text{StepController} presides over the event selection at \text{LVL2} and the \text{EF}. The \text{Trigger-Configuration} provides the Sequence Table and Trigger Menu for the Step processing. The Steering uses one Sequence Table and one Trigger Menu per step [81]. The \text{Step-Handler} is responsible for the stepwise processing of each event. The \text{StepSequencer} executes the HLT Algorithms in the Sequences. The \text{StepDecision} compares the results of the Algorithmic processing, given in terms of active \text{TE}s, with the Signatures to reach a trigger decision. The \text{LVL1Conversion} and \text{LVL2Conversion} convert the raw data from the previous trigger level into the RoI Objects that seed the selection at \text{LVL2} and the \text{EF}, respectively. The \text{ResultBuilder} produces the \text{LVL2 Result} at \text{LVL2} and the \text{EF Result} at the \text{EF}. The \text{SteeringMonitoring} collects summary information at the end of event processing for monitoring purposes.

### 4.4.3 Event processing

Before an event is processed, seed EDOs are created in the TES. Reconstruction is initiated at \text{LVL2} by the \text{LVL1 Result}, which contains the \text{LVL1 RoIs} [85]. The \text{StepController} uses the \text{LVL1Conversion} to unpack the \text{LVL1 Result} and recreate the \text{LVL1 RoI Objects} in the TES. The Steering is responsible for the creation of \text{TE}s and the links between them. For every RoI Object, the \text{LVL1Conversion} creates a corresponding input \text{TE} in the TES and establishes the “uses” relation between the input \text{TE} and the RoI Object.
In the case of the EF, the corresponding LVL2Conversion decodes the LVL2 Result and prepares the TEs needed for the EF selection. After preparing the seeds for the event selection, the StepController executes the StepHandler. A sequence diagram for the event processing during the execution of the StepHandler is shown in Figure 4.8 on the following page. The diagram presents a simplified view of the sequence of actions that occur. No interactions with the TES are shown.

The StepHandler loops over all the Steps. For each Step, the StepHandler executes the StepSequencer and the StepDecision. The StepSequencer performs the reconstruction part of each Step. The StepSequencer loops over all the Sequences in the Sequence Table for that Step. For each Sequence, the StepSequencer looks for active TEs in the TES. Having found the input TEs, the StepSequencer creates the expected output TEs as specified in the Sequence. The newly-created output TEs are linked to the corresponding input TEs with the “seeded by” relation. The StepSequencer executes the HLT Algorithms in the Sequence. The seed for each HLT Algorithm is the expected output TE, which is passed as an argument to the Algorithm. Creating the expected output TEs of an Algorithm before the Algorithm runs is not aesthetically pleasing, but enables the Steering and Algorithm realms to be kept as separate as possible. Starting with the output TE simplifies the way in which the relations between the EDOs and the TEs are established.
Figure 4.8: A sequence diagram for the StepHandler processing an event. From [31].

This is a diagram which shows the interaction between objects over the progression of time. The top boxes represent objects. The vertical lines represent the life of each object. Time flows from top to bottom. The solid horizontal arrows represent function calls. The tall rectangles show the period of time during which a given object has control and is active. Nested tall rectangles represent recursion. After a function call, control returns to the object calling the function. This is optionally shown by a dashed arrow for emphasis.
Each Algorithm begins by accessing the event fragment it must work on. For example, the first FEX Algorithm at LVL2 must retrieve the LVL1 RoI Object in the TES. Therefore, the Algorithm navigates from the output TE via the “seeded by” and “uses” relations to access the LVL1 RoI Object. The Algorithm then does its reconstruction and analysis work. The result of the reconstruction is linked to the output TE via the “uses” relation. Thus, a subsequent Algorithm can access the feature found for this RoI. In general, the next Algorithm to run may be another FEX Algorithm which produces a new feature. Sequences end with execution of a Hypothesis Algorithm. The Hypothesis Algorithm applies selection cuts on the properties of reconstructed features to test the validity of the hypothesis represented by the output TE. The Hypothesis Algorithm signals the hypothesis as valid or invalid by activating or deactivating the output TE respectively.

After all the Sequences have been run, the StepHandler executes the StepDecision. The StepDecision loops over all the Signatures listed in the Trigger Menu and checks to see if any match the active TEs in the TES. The event is rejected if none of the Signatures are satisfied. This concludes the processing of a Step. The next Step is processed only if the present data still allow for the event to be triggered, or until all the Steps have been done. Only the data necessary for the next Step are gathered and processed. Since an event can be rejected after any of the Steps, the amount of time invested in rejected events is comparatively small on average. Events that pass all the Steps in a trigger level pass the selection and are either sent to the next trigger level for processing or to mass storage for offline analysis. A fraction of the events is accepted forcibly to provide the offline analysis with an unbiased sample of events.
Chapter 5

Navigation timing studies

The purpose of this study was to investigate the time overhead of the Navigation using a test HLT Algorithm. The Navigation is part of the mechanism whereby the reconstruction is guided to the event fragments needed for preparing the trigger decision. It is a requirement of the HLTSSW that the total amount of time spent performing the Navigation should be less than 1% of the allowed latency at LVL2 and the EF [89]. However, it should be noted that this value was set rather arbitrarily before any software was written and should be considered to be more of a goal than a hard requirement. The spirit of the requirement is that most of the processing time should be available for algorithmic work and that the time spent performing the Navigation should be as small as possible. There are other functional requirements, but these are not addressed in this study. The performance of the Navigation will be judged in terms of SPECint2000 seconds, rather than latency, to avoid the complications of different CPU speeds and types. This amounts to nothing more than a change of units. SPECint2000 is an industry-standard computing benchmark for rating the processing power of a CPU.

5.1 Introduction

A software package was developed that provided an example of a LVL2 calorimeter-based electron trigger with two HLT Algorithms running consecutively. The package contained only dummy Algorithms. That is, the software performed no real algorithmic work. The purpose of the Algorithms was to exercise the functionality of the Steering and the TES, and show Algorithm developers how to integrate their code with the HLT software framework. It was a contrived example. Nevertheless, it adequately demonstrated the Navigation mechanism.
Once a working prototype had been developed, modifications were made to simplify the Navigation. All HLT Algorithms inherit from a common HLT Algorithm base class \[90\]. Consequently, all HLT Algorithms may access functions and attributes defined in that base class. New member functions (“methods”) were added to the Algorithm base class to facilitate interactions with the TES. These helper methods were designed to hide the complexity of the Navigation mechanism behind a simple interface. The most important of these were:

- **writeHistoryOfTE(TE, label, EDO)**
  This method records that an EDO is related to a TE in a navigable way. The method inserts the EDO into the TE’s History Object and attaches a label describing the relationship between the EDO and the TE. More accurately, the EDO’s pointer is stored in the TE’s History Object using the relationship label as a key.

- **getVectorOfObjects(EDO, label, TE)**
  This method retrieves all the EDOs (or rather, their pointers) that match a specific relationship label from the TE’s History Object.

After a working example of the Navigation mechanism had been developed and refined, the next logical step was to time it. The Navigation time is determined primarily by the time spent in the aforementioned two methods, so it was these methods that were timed. A single test Algorithm was prepared that used both of these methods. It was hypothesised that the time spent in these methods depends on factors that relate to the performance characteristics of hash multimap’s methods for storing and retrieving data.

An algorithm’s computing time can be characterised in terms of the worst-case time or the average-case time. The worst-case time is defined as the maximum time taken by a given operation in the worst-case scenario. The average-case time is defined as the average time taken by a given operation, calculated by assuming all possible scenarios occur with equal probability. The average-case time for finding all the elements of a hash multimap associated with a given key is proportional to the number of elements with that key, but is independent of the size of the hash multimap \[91\]. However, if the hash function is poor (that is, if many different keys hash to the same storage location) then this will hurt performance. The worst-case time for finding all the elements in a hash multimap associated with a given key grows linearly with the size of the hash multimap \[91\]. Therefore, the time taken by the getVectorOfObjects method was expected to be proportional to the number of EDOs retrieved. It was also conjectured that the time
taken by the `getVectorOfObjects` method might be proportional to the size of the TE's History Object.

Hash multimaps are unordered containers, so it was expected that the time taken to retrieve an EDO from a TE's History Object using the `getVectorOfObjects` method would be independent of the EDO's entry order. That is, the retrieval time was expected to be independent of the sequence in which the EDOs were originally recorded. The time taken to insert an EDO into the TE's History Object was not expected to depend on the number of EDOs already stored, because no re-ordering of elements occurs. To test these assumptions, four separate studies were devised:

1. A fixed number of EDOs were inserted into a TE's History Object. One EDO was stored with a unique relationship label ("excludes"), whereas the remaining EDOs were stored with a common relationship label ("uses"). The total number of EDOs stored in the TE's History Object was kept constant, but the entry order of the uniquely-labelled EDO was varied. The time taken to retrieve the uniquely-labelled EDO from the TE's History Object was measured.

2. As in the previous study, the time taken to retrieve a uniquely-labelled EDO was measured. However, the entry order of this EDO was kept constant and the total number of EDOs stored in the TE's History Object was varied instead.

3. The effect of the number of EDOs retrieved on the retrieval time was investigated. The time taken to retrieve all the EDOs stored with the common relationship label was measured. By adjusting the total number of EDOs stored, the number of EDOs retrieved was varied.

4. The time taken to insert an EDO into the TE's History Object was measured. The entry order of the EDO was varied.

The timing measurements were performed using the software package TrigTimeAlgs. This package contains a utility that uses the CPU system clock to measure and log timing information. The utility provides timers that can be embedded in the code of interest and controlled by means of `start` and `stop` statements. The measurements were made on a dedicated PC with an Intel Xeon single-core 2.40 GHz CPU with a 512 KB cache. The CPU had a 0.42 ns clock cycle. The precision of the timers on such a machine is expected to be on the order of microseconds. The package uses the C++ function `gettimeofday` which determines the maximum precision of the measurements. The precision
5.1 Introduction

of \texttt{gettimeofday} is in the optimal case microseconds but depends on the machine where running \cite{92}.

It is known that \textit{time-slicing} can cause temporary perturbations that can affect timing measurements. Time-slicing is a method by which common processing resources on a PC such as the CPU are shared between multiple tasks. Each task is interrupted after some time and control of the CPU is given to another task. This allows several programs to run on the same PC concurrently. Hence, time-slicing can temporarily slow the execution of the program making the timing measurements. This introduces deviations in the timing measurements that are always in the direction of longer times. Measurements that are taken while the PC is in a disturbed state tend to cluster and form a distinct small second peak in the distribution of timing measurements \cite{92}. The timing measurements in this second peak were discarded. To further minimise the effect of these temporary perturbations, measurements were taken from about 100 events and averaged. The period of time required to run 100 events was considered to be sufficiently long to mitigate the effect of any temporary disturbances to the PC. Access to the PC was limited. At most, perhaps only one or two other users were running programs on this PC at the same time as the timing measurements were made. Text output (used for debugging and testing) would have contributed significantly to the time taken for the test Algorithm to run. Therefore, all text output from the test Algorithm was switched off. Additionally, the code was compiled in optimised mode; that is, in the same way as the code that will run in the real online system.

Before the execution of each HLT Algorithm, the Steering creates the output TE and writes a link in its History Object to the input TE. The label "seeded by" describes the relationship between the input TE and the output TE. For the timing studies described, it is preferable to start with a History Object that is initially empty. Therefore, the test Algorithm was modified to create both a new TE and an empty History Object for use in the timing studies. For the sake of simplicity, all the EDOs stored and retrieved were chosen to be instances of the same class: \texttt{TriggerElement}. This choice was not expected to affect the results, because the methods being timed store and retrieve the EDOs pointers and not the EDOs themselves. The upper limit on the number of TEs stored in the History Object was set at 25. It is highly unlikely that a TE would have this many links to EDOs in its History Object. However, this number was chosen because it was considered large enough for any trends in the data to be spotted.

The statistical errors were taken to be equal to the standard error on the mean. The
systematic errors are on the order of 10%. This is the degree to which TrigTimeAlgs’s results obtained with different PCs but with identical CPUs can vary, and is the principle constraint for timing measurements [92]. This figure comes from a study of the TrigTimeAlgs package [92]. The same PC was used throughout for all timing studies.

5.2 Results

5.2.1 Computation time of methods in the first event

It was observed that HLT Algorithm methods generally take 10 times longer to execute when called for the first time (in the first event) than when they are called again later. This is true regardless of whether the subsequent function call occurs in the same event or in any that follow. This behaviour is illustrated by Figure 5.1 on the next page, which shows the time spent in the getVectorOfObjects method. The figure shows timing measurements obtained from 25 samples of 98 events each. The smaller of the two peaks corresponds to the computation time for the first call to the getVectorOfObjects method in each of the 25 samples. On average, getVectorOfObjects takes 14 times longer to run when called for the first time than when called again later.

This behaviour is manifested even in very simple methods. A method that does nothing more than return a pointer to an Algorithm data member was timed. This method is called once per event. On average, this method took 10 times longer to execute in the first event than in subsequent events. This behaviour was found to be typical among all the methods that were timed.

These observations strongly suggest that some kind of caching is taking place somewhere. A cache is a temporary storage area where frequently accessed data can be stored for rapid access. Once the data is stored in the cache, future accesses to the data can be made by accessing the cached copy rather than re-fetching or recomputing the original data. This lowers the average access time for the data. None of the methods that were timed have caching implemented in their code. Therefore, the caching is happening in the PC’s hardware rather than in the software.

PCs typically have a cache on the motherboard (the level 2 cache) and a cache built directly into the processor (the level 1 cache). The level 1 cache caches the level 2 cache that, in turn, caches the main memory. When a function is called for the first time, the data it acts upon is buffered from the main memory into a cache. When the function is called again later, the data is accessed from the cache instead of from memory.
5.2 Results

Figure 5.1: Comparison of the EDO retrieval time between the first event and subsequent events. The smaller peak corresponds to the first use of the `getVectorOfObjects` method in the first event in each of the 25 samples used.

For all the studies, the timing measurements obtained from the first event in each sample were excluded from the calculation of the results presented in the following sections. This was done because the addition of these anomalous measurements expands the size of the errors bars to such an extent that it is impossible to discern the underlying trend in any of the data. The justification for doing this is that the first event is only one of many that will be processed in a single run; it is not representative of the typical pattern of behaviour.

5.2.2 Effect of EDO entry order on retrieval time

The time taken to retrieve the uniquely-labelled TE from the test TE’s History Object using the `getVectorOfObjects` method was measured. The total number of TEs stored in the History Object was kept constant, but the entry order of the uniquely-labelled TE was varied. Figure 5.2 on the following page shows the mean retrieval time versus the entry order of the uniquely-labelled TE. The data suggests that, as expected, the time taken to retrieve an EDO from a TE’s History Object is approximately independent of the entry order of the EDO. In the general case, the average time taken to retrieve an EDO was $22.4 \pm 0.2\text{(stat.)} \pm 2.2\text{(syst.)} \mu s$. 
5.2.3 Effect of History Object size on retrieval time

As in the previous study, the retrieval time for the uniquely-labelled TE was measured. However, the entry order of the uniquely-labelled TE in the test TE’s History Object was kept constant and the total number of TEs stored was varied instead. The mean retrieval time versus the total number of TEs stored is shown in Figure 5.3 on the next page. The results suggest that the retrieval time is not strongly dependent on the total number of TEs stored. This is the best performance that can be expected with a hash_multimap and implies that the hash function is satisfactory. The average retrieval time measured in this study was 22.6 ± 0.2(stat.) ± 2.3(syst.) μs.

5.2.4 Effect of number of EDOs retrieved on retrieval time

In this study, the number of TEs retrieved from the test TE’s History Object was varied and the time taken for their retrieval was measured. In practice, this involved varying the total number of TEs stored in the test TE’s History Object and timing the retrieval of all the TEs except the uniquely-labelled one. Figure 5.4 on the facing page shows the mean retrieval time versus the number of TEs retrieved. A linear fit to the data is shown. It was expected that the retrieval time is proportional to the number of EDOs retrieved. This is exactly what is seen in the data. The measured retrieval time for a single TE is consistent with the results from the previous two studies. The gradient of the linear fit is 0.27μs per number of EDOs retrieved. The intercept on the ordinate is 23.14 ± 0.04μs. The meaning of the intercept is the overhead for retrieval.
5.2 Results

Figure 5.3: Mean time taken to retrieve a single TE versus the total number of TEs stored in the test TE’s History Object.

Figure 5.4: Mean retrieval time versus the number of TEs retrieved from the test TE’s History Object.
5.2.5 Effect of EDO entry order on insertion time

The time taken to insert a TE into the test TE’s History Object using the writeHistoryOfTE method was measured. The entry order of the TE was varied. This is equivalent to varying the number of TEs already stored in the test TE’s History Object. The mean insertion time versus the TE’s entry order is shown in Figure 5.5. The first write to the test TE’s History Object takes significantly longer than subsequent writes. This is true in every event. After the first EDO is stored, the time taken to write further EDOs into the test TE’s History Object is nominally constant. The first write takes 23.8 ± 0.1(stat) ± 2.4(syst) ms. Subsequent writes take 20.8 ± 0.1(stat) ± 2.1(syst) ms. The difference is 3.0 ± 0.1(stat) ± 0.3(syst) ms.

![Mean insertion time vs entry order](image)

Figure 5.5: Mean time taken to insert a TE into the test TE’s History Object versus the TE’s entry order.

The reason for the first write taking longer than subsequent writes was investigated. By a process of trial and elimination, the source of this behaviour was ultimately traced to a section of code in key2keyStore that performs the dynamic_cast from BaseHolder to Holder<key2keyStore*>, when retrieving the TE’s History Object to be written to. This is demonstrated by Figure 5.6 on the facing page.

The time taken to dynamic_cast a BaseHolder pointer to a Holder<key2keyStore*> pointer is longer for the first cast than for subsequent casts. This is because dynamic_cast is not a constant time operation. Dynamic_cast does a runtime check to make sure the cast is safe before actually performing the cast. This is called runtime type identification (RTTI). It has to transverse the object’s class derivation tree at runtime until it has found the target object in it. Only then can dynamic_cast decide whether
5.2 Results

Figure 5.6: Mean time taken to dynamic_cast a pointer from type BaseHolder to type Holder<key2keyStore*>.

the requested cast can be done [93, 94]. The time taken to check the validity of the cast depends on the complexity of the class hierarchy of the object and its proximity to the target type. The performance penalty for this check may be noticeable if the operand is a deeply derived object or the target is an unrelated class type.

The RTTI information is stored in an object of type type_info. Any object with virtual methods (that is, methods whose functionality can be over-ridden in derived classes) contains a hidden internal pointer to a lookup table of functions. This lookup table is known as a virtual table, or vtable. There is usually only one vtable per class. The vtable also contains the type_info object for the class corresponding to that vtable. A dynamic_cast conceptually involves getting to the vtable, finding the most derived class object that the object in question belongs to, extracting the type_info pointer from that object’s vtable to determine whether the cast is valid, and then performing the cast [95]. It is likely that this vtable lookup is cached. Figure 5.6 provides compelling evidence that this is what is happening.

The getVectorOfObjects method performs a dynamic_cast from BaseHolder to an instance of a class derived from Holder<T> when retrieving all the EDOs from the TE’s History Object that match the relationship label passed as an argument to getVectorOfObjects. In the timing studies, the EDOs retrieved were all instances of the class TriggerElement. Therefore the dynamic_cast was always from BaseHolder to Holder<TriggerElement*>. The Steering performs exactly the same kind of cast before each HLT Algorithm runs, when retrieving the input TE. This means this kind of cast was never
performed for the first time in the `getVectorOfObjects` method. This is a consequence of the design of the timing studies. The `getVectorOfObjects` method can, of course, retrieve other types of EDOs besides `TEs`. For each different class, 3 µs must be added to the computation time of the `getVectorOfObjects` method per event.

The `getVectorOfObjects` and `writeHistoryOfTE` methods both perform a `dynamic_cast` from `BaseHolder` to `Holder<key2keyStore*>`, as shown in Figure 4.5 on page 87 and Figure 4.6 on page 87. The cast is done during the retrieval of the `TE`'s History Object from the `key2keyStore` named `TE2history`. In the test HLT Algorithm that was used for the timing studies, the `writeHistoryOfTE` method is called first. The requirement that the test `TE`'s History Object is initially empty sets the order in which the `writeHistoryOfTE` and `getVectorOfObjects` methods are called. Therefore, the first cast from `BaseHolder` to `Holder<key2keyStore*>` happens in the `writeHistoryOfTE` method. This is the reason why `writeHistoryOfTE` — and not `getVectorOfObjects` — takes longer to run when called for the first time than when called again.

### 5.2.6 Navigation time

An order of magnitude estimate of the Navigation time was calculated using the results presented in the previous sections. The calculation focuses on the Navigation's performance at LVL2. It is axiomatic that if the Navigation is fast enough for LVL2, then it is also fast enough for the EF. The calculation is subject to assumptions set forth below. All the assumptions are reasonable and are based on knowledge of the Steering mechanism.

For a 75 kHz LVL1 rate at low luminosity, there are typically 1–2 primary RoIs per event [83]. For the purpose of this calculation, it was assumed that there are always exactly 2 RoIs per event. It was assumed that there are 3 Steps and 5 trigger thresholds per RoI. For each trigger threshold, there is one Sequence per Step. Therefore, there are 15 Sequences per RoI. Each Sequence contains one FEX Algorithm and one Hypothesis Algorithm. This is shown schematically in Figure 5.7 on the facing page.

It was assumed that each of the 5 Sequences per Step are run with the same FEX Algorithm but a different Hypothesis Algorithm. In reality, the Steering runs each FEX Algorithm only once per Step and caches the result. This difference does not matter from the point of view of the Navigation, because the links between EDOs set by the FEX Algorithm must be copied when validating the next trigger threshold; hence the number of reads and writes is the same. Therefore, it was assumed that 30 FEX Algorithms and 30 Hypothesis Algorithms run per event. This is the worst-case scenario because the
5.2 Results

Figure 5.7: A simplified schematic showing how the Steering performs the stepwise reconstruction starting from an initial RoI.

calculation does not account for the effect of early rejection by the Hypothesis Algorithms, which reduce the number of times later Algorithms are run. It was assumed that each FEX Algorithm retrieves a TE and an RoI Descriptor, and writes an RoI Descriptor and a feature (for example, a track or a calorimeter cluster). Each Hypothesis Algorithm was assumed to retrieve a TE and two features, but not write anything.

The Steering itself also performs some Navigation before a Sequence is run. This must be accounted for in the calculation. At the start of each event, the Steering creates a TE for each trigger threshold. Therefore it was assumed that 5 TEs per RoI are created by the Steering. The Steering creates an RoI Descriptor for each RoI, and writes links between the TEs and RoI Descriptors. For each Sequence, the Steering retrieves the active input TE, creates the expected output TE, and writes the “seeded by” relation in the output TE’s History Object. Therefore, the Steering performs 2 writes per TE and 1 retrieval per Sequence. Hence, it was assumed that the Steering performs 40 writes and 15 retrievals per RoI.

The class that runs the Sequences (the StepSequencer) does not derive from the HLT Algorithm base class, so cannot use the getVectorOfObjects and writeHistory-OfTE methods for Navigation. Nevertheless, the Steering performs the same tasks as these methods whenever an EDO is retrieved or written. The only difference is that the Step-
Sequencer runs code that would otherwise be hidden behind calls to the Navigation helper methods. It is therefore reasonable to assume that the time taken by the Steering to read and write links is the same as if it had used the `getVectorOfObjects` and `writeHistoryOfTE` methods.

The `writeHistoryOfTE` method takes $20.8 \pm 0.1\text{(stat.)} \pm 2.1\text{(syst.)}\,\mu s$ to execute. The average time to retrieve an EDO with the `getVectorOfObjects` method was taken to be $22.5 \pm 0.1\text{(stat.)} \pm 2.3\text{(syst.)}\,\mu s$, which is the average of the results presented in Sections 5.2.2 and 5.2.3. For the first call of either the `getVectorOfObjects` method or the `writeHistoryOfTE` method, and for each call to `getVectorOfObjects` that requests the retrieval of an EDO type not previously encountered in the same event, $3.0 \pm 0.1\text{(stat.)} \pm 0.3\text{(syst.)}\,\mu s$ must be added. It was assumed that 6 different types of EDOs are retrieved by the `getVectorOfObjects` method: TEs, RoI Objects, RoI Descriptors and 3 different types of features. Therefore $21.0 \pm 1.0\text{(stat.)} \pm 2.1\text{(syst.)}\,\mu s$ must be added.

The Navigation was estimated to perform 180 retrievals (calls to `getVectorOfObjects`) and 140 writes (calls to `writeHistoryOfTE`) in total per event. Hence, the time spent performing the Navigation was calculated to be

$$6.98 \pm 0.03\text{(stat.)} \pm 0.70\text{(syst.)}\,ms.$$  

This seems to be 70% of the allowed latency at LVL2, but this result needs to be put in the context of the actual LVL2 system. The HLT processor racks being purchased and built at the moment contain Intel “Woodcrest” dual-core 3 GHz CPUsootnote{Intel Xeon Processor 5160, sSpec number SL9RT, product code 80556.}. Nowadays, clock speed does not give a good indication of the performance of a CPU. This is because processor manufacturers have in recent years focused on increasing processing power by placing multiple processors (cores) on a single chip rather than increasing clock speeds. A better measure of the performance of a CPU is the SPEC Cint2000 Base rating, also known as the SPECint2000 (SI2k) rating.

SPECint2000 is a common industry-standard computing benchmark, maintained by the Standard Performance Evaluation Corporation (SPEC), that rates the processing power of a CPU by running a number of standard tests and trials against it. The tests are designed to mimic a particular type of workload on a component or system. The SPECint2000 rating is the normalised mean of the scores for 12 benchmark programs. The benchmark programs are written in a standard programming language, which is then
5.3 Conclusions

compiled for each particular CPU architecture and operating system. The score for each
test is the ratio of its computation time to a reference time defined by SPEC. The perfor-
mance measured is that of the CPU, memory, and compiler.

With the funds currently available, the estimated initial processing power that can be
afforded for LVL2 is 0.3 MSI2k. At present, figures for the final system are not available
and depend on budgetary constraints. For the system that will operate during the LHC
initial data-taking at reduced luminosity, it has been estimated that an HLT input rate
of 10 kHz can be sustained. Therefore, 30 SI2ks of processing power will be available per
event.

The SPECint2000 rating for the system on which the timing measurements were made
is 792 SI2k. On this PC, the 7 ms spent performing the Navigation is equivalent to 5.5 SI2ks
of processing power per event. Therefore, the Navigation uses 18.4% of the total processing
power per event that will be available to the initial LVL2 system. The results of the timing
measurements are summarised in Table 5.1.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time (µs)</th>
<th>Processing power (mSI2k s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>getVectorOfObjects</td>
<td>22.5 ± 0.1 ± 2.3</td>
<td>17.8 ± 0.1 ± 1.8</td>
</tr>
<tr>
<td>writeHistoryOfTE</td>
<td>20.8 ± 0.1 ± 2.1</td>
<td>16.5 ± 0.1 ± 1.6</td>
</tr>
<tr>
<td>Navigation</td>
<td>6983.0 ± 30.0 ± 698.3</td>
<td>5530.5 ± 23.8 ± 553.1</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of timing measurements. Statistical and systematic errors are given.
The Navigation is estimated to use 18.4% of the total processing power that will be avail-
able to the initial LVL2 system.

5.3 Conclusions

This work highlighted a number of obvious improvements that could make the Navigation
faster:

- Use of C++ enumerations instead of strings to express EDO relationships. Enum-
  erations are treated like integers at runtime. Integer comparison can be done in
  constant time, whereas the average-case time for string comparisons is proportional
to the length of the strings. Using enumerations for relationship labels would reduce
the time spent finding the EDOs whose keys match a specific label. It would also
reduce the time spent in the hash function translating keys to numbers that index the storage locations in hash_multimaps.

- Use of integers instead of strings as unique identifiers for TEs. This would reduce the time spent retrieving each TE’s History Object from TE2history.

- Replacement of the use of string key generation with integer key generation. Clearly this is necessary if integers are used as keys to identify TEs.

Using strings as keys to identify the location of data stored in a container is notoriously inefficient whenever the time spent inserting and retrieving data is important. This is because the process of string comparison requires a character-by-character check for equality. It had been conjectured that the aforementioned changes could increase the speed of the Navigation. The results of this study support this. These are minimal changes that could easily be made with very little impact on the Navigation’s interface.

The Navigation was subsequently given a tune-up by another developer. The foremost change was the replacement of the use of strings with enumerations and integers. In addition, some more intrusive and fundamental modifications were made that go beyond the scope of the recommendations previously stated. They break from the original design of the Navigation, but this is acceptable given what has been learnt since the development of the Steering prototype [88]. The hash_multimap in key2keyStore was replaced with a statically allocated array to eliminate the overhead for dynamic memory allocation. This approach is a sure-fire way to improve performance, provided care is taken not to write beyond the end of the array. A two-dimensional array of pointers to objects of class Holder is used. Holder objects perform a similar function to instances of classes derived from the Holder<T> class template described earlier, but in a different way. An instance of a class derived from Holder<T> holds a pointer to an EDO, whereas a Holder object holds the integral conversion of the EDO’s pointer. To store an EDO in a Holder object, the EDO’s pointer is cast to an unsigned integer and stored. To retrieve an EDO from a Holder object, the integral representation of the EDO’s pointer is cast back to its original data-type and returned. Although the format in which the integer value represents the pointer is platform-specific, a pointer cast to an integer of sufficient size and back to the same pointer type will have its original value [93]. C-style casts were used.

Using objects instantiated from the class Holder instead of classes derived from the class template Holder<T> removed the need for the BaseHolder class. Consequently, the dynamic_cast operator was no longer needed. The TriggerElement class was modified so
that each TE owns a pointer to its History Object. This eliminates the need for a lookup in TE2\textit{history} to retrieve the TE’s History Object. The collective result of these changes was reported to reduce the Navigation time to about 0.85 ms. The timing measurement was made on a PC with an Intel Xeon single-core 2.40 GHz CPU.

The time spent performing the tuned-up Navigation is equivalent to 0.7 SI2k s of processing power per event. Given that the processing power that will be available to initial LVL2 system is 30 SI2k s per event, the changes previously stated reduce the Navigation’s overhead to just 2.2% of the processing power available per event. This is very close to being acceptable, and certainly the right order of magnitude.

Development of the trigger software is an ongoing process. At the same time as this thesis was being written, developers were busy rewriting the Navigation software. The focus of this work was not so much on improving the speed of the Navigation, but rather on addressing various functional requirements not covered here. Knowledge and experience gained from the previous version of the Navigation was vital in guiding the design of the new version of the Navigation. In that sense, the Navigation examined in this thesis represents an important step in the evolution of the software.
Chapter 6

Trigger selection cuts

6.1 Level-1

6.1.1 The LVL1 electron/photon trigger

The LVL1 electron/photon trigger algorithm is illustrated in Figure 6.1 on the facing page. The algorithm uses reduced granularity information from the EM and Hadronic Calorimeters. For the purposes of algorithmic processing, the EM and Hadronic Calorimeters are partitioned into about 7200 trigger towers with dimensions of $0.1 \times 0.1 \text{ rad}$ in $\Delta \eta \times \Delta \phi$ [30].

A trigger tower is an element of calorimeter information formed in the front-end electronics from the analogue summation of calorimeter cells. The analogue trigger tower signals are the inputs to the calorimeter trigger system. The number of calorimeter cells that must be summed to form a trigger tower varies with depth and $\eta$. There are separate sets of trigger towers from the EM and Hadronic Calorimeters [54].

The electron/photon trigger algorithm uses a $4 \times 4$ trigger tower window which slides in steps of one trigger tower in both $\eta$ and $\phi$ [96]. The window is considered to contain an electron/photon candidate if certain criteria imposed on five elements contained within the algorithm window are satisfied [53]. The algorithm window contains the following elements:

- Four 2-tower EM clusters $1 \times 2$- or $2 \times 1$-tower EM clusters) formed from the summation of pairs of adjacent EM trigger towers in the centre of the algorithm window.

- A $2 \times 2$-tower hadronic core isolation region centred in the algorithm window behind the 2-tower EM clusters.

- An EM isolation ring of 12 EM trigger towers surrounding the 2-tower EM clusters.
6.1 Level-1

- A hadronic isolation ring of 12 hadronic trigger towers surrounding the hadronic core.

- A $2 \times 2$-tower RoI cluster, formed from the sum of the central four EM and hadronic trigger towers, which is used to identify RoI candidates.

![Diagram of the LVL1 electron/photon algorithm. Adapted from [96].](image)

The conditions for identifying an RoI include the requirement that the RoI cluster must be a local $E_T$ maximum. The term “local $E_T$ maximum” has a specific meaning within the context of the LVL1 calorimeter trigger, and is best explained by example. An EM shower contained entirely within one trigger tower will result in four RoI clusters of equal $E_T$. Similarly, an EM shower contained entirely within two trigger towers will result in two RoI clusters of equal $E_T$. Some additional logic is required in order to resolve this ambiguity and assign a unique RoI to each EM shower. For this reason, the RoI cluster is required to be more energetic than its neighbours along two connected edges and at least as energetic as its neighbours along the opposite two edges. This condition is what is meant when it is said that an RoI cluster must be a local $E_T$ maximum. The algorithm for testing an RoI cluster for this condition is shown schematically in Figure 6.2 on the next page.

The two types of inequalities ensure no multiple-counting of electron/photon candidates occurs. The inequalities are arranged opposite each other so that when any pair of
Figure 6.2: Local $E_T$ maximum test for an RoI candidate. The $2 \times 2$-tower cluster “R” is defined to be a local maximum if it is more energetic than the clusters marked “>” and as least as energetic as those marked “≥”. The $\eta$ axis runs from left to right, and the $\phi$ axis from bottom to top. From [53].

of equal RoI clusters are compared, whatever their relative positions, one will be required to be more energetic than the other (and so fail) while the other will be required to be at least as energetic as the first (and so pass). The process of producing a single RoI per trigger candidate is often referred to as “declustering”. The declustering algorithm finds the window of $4 \times 4$ towers in which the RoI cluster is a local $E_T$ maximum. The number of electron/photon candidates is simply the number of algorithm windows accepted by the trigger. The algorithm window is accepted if the EM and hadronic isolation criteria are satisfied and the window contains a 2-tower EM cluster with $E_T$ above threshold [30].

Note that pairs of electrons or photons separated by less than 0.3 in $\eta$ or 0.3 rad in $\phi$ cannot be resolved efficiently as separate entities by the electron/photon algorithm because the $2 \times 2$-tower clusters will overlap. Pairs of electrons or photons separated by less than 0.2 in $\eta$ and 0.2 rad in $\phi$ will appear to the algorithm as a single entity [30].

6.1.2 Trigger selection

The requirements for an electron candidate to pass the e25i selection at LVL1 depend on quantities reconstructed by the LVL1 electron/photon trigger algorithm [30]. The following cuts were applied:

- The most energetic of the four 2-tower clusters must have $E_T > 19$ GeV.
- The EM isolation ring must have total $E_T \leq 3$ GeV.
- The hadronic isolation ring must have total $E_T \leq 2$ GeV.
- The $2 \times 2$ hadronic core isolation region must have total $E_T \leq 2$ GeV.
6.2 Level-2

6.2.1 Calibration

The LVL2 electron/photon trigger corrects the $E_T$ of each LVL2 reconstructed cluster for the energy lost laterally outside the cluster \cite{30, 98}. This was not done within the reconstruction software. Therefore, before applying cuts, the $E_T$ of each LVL2 cluster was multiplied by an $\eta$-dependent calibration constant to account for lateral energy leakage. The same calibration constants were used for all processes studied. The calibration constants were obtained by the Physics and Event Selection Architecture (PESA) e/$\gamma$ group using simulated events containing single 25 GeV electrons and are given by

$$\frac{25 \text{ GeV}}{\langle E_T^{\text{rec}} \rangle_i},$$

where $\langle E_T^{\text{rec}} \rangle_i$ is the mean $E_T$ of LVL2 clusters located in the $i^{th}$ $|\eta|$ interval.

6.2.2 LVL2 calorimetry

The inputs to the LVL2 calorimeter trigger are the EM RoIs that have passed LVL1. The LVL2 trigger examines clusters within an RoI of size $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ rad \cite{82}. Accordingly, the e25i trigger selection implemented in this study only inspects LVL2 clusters that are within $0.2 \times 0.2$ rad of the LVL1 RoI; all other LVL2 clusters are immediately rejected. The following cuts were applied:

- $R_{\eta}^{\text{shape}} \geq 0.9$

$R_{\eta}^{\text{shape}}$ is equal to $E_3 \times \gamma / E_\gamma \times \gamma$ calculated in the second sampling in ECAL, where $E_n \times m$ is the energy deposited in a window of $n \times m$ cells in $\Delta \eta \times \Delta \phi$ around the position $(\eta_1, \phi_1)$ of the cell with the highest energy in the second sampling of the ECAL \cite{31}. The second sampling of the ECAL is used because most of the energy of the shower (typically more than 70\%) is deposited in this layer \cite{30}. A window of $3 \times 7$ cells in the second sampling of the ECAL barrel has been found to be optimal for containing the shower from an electron \cite{32}. More cells in $\phi$ than in $\eta$ are needed because the presence of the solenoidal magnetic field causes showers that start in the ID to widen in $\phi$ \cite{32}. The cells in the second sampling, which are typically of size $0.025 \times 0.025$ rad in $\Delta \eta \times \Delta \phi$, are used as a reference for window definitions. Hadronic showers are typically broader than EM showers. For this reason, $R_{\eta}^{\text{shape}}$ is useful for distinguishing between EM clusters and jets. $R_{\eta}^{\text{shape}}$ is typically larger than
0.9 for electrons with large tails at lower values for jets, as shown in Figure 6.3. No cluster corrections are applied to the $E_T$ values used in the calculation of $R_\eta^{\text{shape}}$ [30].

**Figure 6.3:** Distribution of $R_\eta^{\text{shape}}$ for $E_T = 30$ GeV electrons and jets at high luminosity. No other cuts have been applied. From [30].

- $R_\eta^{\text{strip}} \geq 0.72$

  $R_\eta^{\text{strip}}$ is equal to $(E_1 - E_2)/(E_1 + E_2)$ calculated in the first sampling in ECAL, where $E_1$ and $E_2$ are the energies of the highest and second-highest strip maxima, respectively. Strips are defined to be a local maximum if they have energy greater than their two adjacent strips [30]. The cut on $R_\eta^{\text{strip}}$ exploits the fine granularity in $\eta$ of the first sampling of the ECAL to detect substructure in clusters, the presence of which is used to discriminate against neutral pions and jets. Showers from electrons or photons are evinced by a high first maximum. Neutral pions (or $\gamma$’s) decaying to pairs of photons exhibit two peaks separated by a few millimetres, and jets manifest several small peaks [59]. Figure 6.4 on the next page shows some examples of how jet and photon showers look in the first sampling. Figure 6.5 on page 116 shows the distribution $R_\eta^{\text{strip}}$ for 30 GeV electrons and jets at high luminosity after the LVL1 trigger. Since the strips are parallel to the $\phi$-direction, $R_\eta^{\text{strip}}$ is not affected by photon conversions or bremsstrahlung off electrons [30].

- If $E_T^{\text{EM}} \leq 90$ GeV: $E_T^{\text{had}} < 1$ GeV

1 $\gamma \rightarrow e^+ e^-$. About 30% of $\gamma$’s convert before the ECAL; 75% of these conversions occur in the ID [59].
Figure 6.4: Lateral shower distribution with respect to the centre of gravity of the shower in the first sampling of the ECAL for (a) to (c) jets and for (d) a photon. These distributions are for single events at low luminosity. From [30].
$E_T^{had}$ is equal to the $E_T$ deposited in the first sampling of the HCAL in a window of size $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ rad around the energy-weighted barycentre of the cluster $(\eta_c, \phi_c)$. $E_T^{EM}$ is equal to the $E_T$ deposited in the ECAL in a window of $3 \times 7$ cells around $(\eta_1, \phi_1)$, summing over all samplings. Typically, EM showers are almost entirely contained within the ECAL and deposit very little energy into the HCAL.

- If $E_T^{EM} > 90$ GeV: $E_T^{had} < 999.0$ GeV

The energy leakage into the HCAL from an EM shower becomes significant as the energy of the incident electrons and photons increases [30]; this is the reason for the 90 GeV threshold. Raising the value of the cut on $E_T^{had}$ to 999.0 GeV is comparable to applying no hadronic isolation.

- $E_T^{EM} > 22.5$ GeV

$E_T^{EM}$ is calculated in a window of $3 \times 7$ cells around $(\eta_1, \phi_1)$. Note that this cut was applied after LVL2 tracking-cluster matching cuts (described in 6.2.4 on the next page) were applied.

### 6.2.3 LVL2 tracking

For the event to be selected at this trigger step, at least one track reconstructed by the LVL2 track-finding algorithm IDScan must be found in the event with $p_T > 8$ GeV/c. The
6.2 Level-2
c25i selection implemented in this study applies this cut to all IDScan tracks in the event. This cut discriminates against jets, in which the $p_T$ of individual tracks tends to be low [99].

6.2.4 LVL2 track-cluster matching

In this trigger step, LVL2 tracks surviving the $p_T$ cut in the previous trigger step are matched to LVL2 clusters that have survived the LVL2 calorimeter cuts. This is a two-stage process. In the first stage, for each cluster, at least one track must satisfy the following cuts that depend on the $\eta$ of the track at perigee$^2$ ($\eta_0^{\text{track}}$):

- If $0.0 \leq |\eta_0^{\text{track}}| < 2.0$: $0.2 < E_\text{cluster}^{\text{track}} / p_T^{\text{track}} < 3.0$
- If $2.0 \leq |\eta_0^{\text{track}}| < 10.0^3$: $0.2 < E_\text{cluster}^{\text{track}} / p_T^{\text{track}} < 3.5$

The cuts were optimised in separate $|\eta|$ regions to account for the differences in tracking and calorimetry between the central and forward regions of the detector. The ratio $E_T / p_T$ of the transverse energy of the cluster to the transverse momentum of the track is used to reject jets. The $E_T / p_T$ distribution has a peak at $E_T / p_T = 1$ for electrons. For jets, the $E_T / p_T$ distribution has a tail toward large values which is more pronounced than that for electrons because the cluster $E_T$ is likely to be larger than the $p_T$ of any individual track within the jet. Mismeasurement of track parameters is likely to result in tails toward low values of $E_T / p_T$ because the SCT and Pixel Detector track-finding algorithm preferentially selects the track candidate with the highest $p_T$ [99], but this effect is more significant for jets than electrons. Hence, cuts to reject small and large values of $E_T / p_T$ provides discrimination against jets [99].

In the second stage, surviving tracks are extrapolated to the nominal inner face of the ECAL using the approximation of a homogeneous magnetic field in the solenoid. The track closest to the cluster was found by minimising $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, where $\Delta \eta$ and $\Delta \phi$ are the differences in $\eta$ and $\phi$ between the cluster and the track, respectively. The following cuts, that depend on the $\eta$ of the track at perigee, were applied on this track only:

- If $0.0 \leq |\eta_0^{\text{track}}| < 1.0$: $|\Delta \eta| < 0.07$ and $|\Delta \phi| < 0.035$
- If $1.0 \leq |\eta_0^{\text{track}}| < 1.5$: $|\Delta \eta| < 0.06$ and $|\Delta \phi| < 0.035$
- If $1.5 \leq |\eta_0^{\text{track}}| < 2.0$: $|\Delta \eta| < 0.05$ and $|\Delta \phi| < 0.030$
- If $2.0 \leq |\eta_0^{\text{track}}| < 10.0$: $|\Delta \eta| < 0.05$ and $|\Delta \phi| < 0.025$

$^2$ The point of closest approach to the beam axis.

$^3$ This figure has no special significance. It is simply an arbitrarily large number.
In jet events, clusters are often due to the energy deposition from more than one particle. These clusters do not match well with the position of any track. Electrons, conversely, have significantly narrower $\Delta \eta$ and $\Delta \phi$ distributions. Therefore, cuts on $\Delta \eta$ and $\Delta \phi$ discriminate against jets [99].

The LVL2 cluster $E_T$ cut is applied at the end of this trigger step (see 6.2.2 on page 116). The number of electron candidates selected by the LVL2 track-cluster matching cuts is equal to the number of surviving LVL2 clusters.

### 6.3 Event Filter

#### 6.3.1 Calibration

The calorimeter reconstruction used cluster corrections that were obtained using simulated events containing single unconverted photons [100]. These corrections are applied to account for energy lost in the ID and cryostat. The interaction probability in the material upstream of the ECAL is larger for electrons than for photons [32]. Therefore, the cluster energies were underestimated. To account for this, the $E_T$ of each EF cluster was multiplied by an $\eta$-dependent (re)calibration constant. The calibration constants were obtained using simulated events containing single 25 GeV electrons.

#### 6.3.2 EF calorimetry

The e25i trigger selection implemented in this study only inspects EF clusters that are within $0.2 \times 0.2$ rad of the LVL2 clusters that have passed the previous trigger step. On these EF clusters, the following cuts are applied:

- In the ECAL cluster $E_T > 22.0$ GeV.
- Uncorrected energy in a $7 \times 7$ cell window in the second sampling of the ECAL must not be zero. EM showers typically deposit most of their energy in the second sampling of the ECAL [30].
- $isEM = 0$.

The $isEM$ flag contains information about which cuts the electron/photon candidate has passed. The EF selects candidates using a combination of cuts based on calorimeter and ID information. A bit is set in the $isEM$ flag for every cut not passed; hence $isEM = 0$ indicates a good electron/photon candidate.
6.3.3 EF tracking

The following track quality cuts are applied on tracks reconstructed by the EF track-finding algorithm xKalman++ [31] that are associated with EF clusters that had passed the previous trigger step:

- Number of precision (SCT and pixel) hits \( \geq 7 \)
- Number of pixel hits \( \geq 1 \)
- Number of B-layer (innermost pixel layer) hits \( \geq 1 \)
- \( |d_0| \leq 2 \text{ mm} \), where \( d_0 \) is the transverse impact parameter. The transverse impact parameter is defined as the transverse distance of closest approach of the track to the nominal interaction point.

These cuts are useful in discriminating against electrons from photon conversions and “fake tracks” consisting of hits from more than one particle and/or noise hits [32, 99].

6.3.3.1 TRT cuts

The TRT detector information was not digitised correctly in some of the Data Challenge 1 data sets. There was a fault in the software that affected the digitisation of the TRT’s response to electrons in the endcaps. Therefore, as in other electron trigger studies\(^4\), no cuts on reconstructed TRT variables were applied.

6.3.3.2 Track-cluster misassociation

The EF algorithm egammaRec uses both calorimeter and tracking information to distinguish electrons and photons from jets [31]. Track-cluster association is performed within egammaRec by the algorithm tool EMTrackMatchBuilder. During this study it was observed that egammaRec sometimes fails to provide a unique track for every EF cluster that has passed the previous trigger step. It was found that a single track can be associated to more than one cluster if they are very close. Also, it was found that some EF clusters that have passed the previous trigger step have no associated track. If egammaRec fails to match a track to a cluster it assigns the value -1 to the index of the best matched track in the event and fills the track-cluster matching data with nonphysical values. The responsibility of recognising these unreal tracks and dealing with them accordingly is delegated to the

\(^4\) For example, studies for the HLT TDR [31, 101].
user. There is a danger that the contribution of these tracks might yield erroneous results. For this study, improvements were made to the code to recognise and reject these tracks.

Tests with events containing single electrons, and with events containing \( W \rightarrow e\nu \), showed that approximately 3.5\% of the clusters accepted by the previous trigger step (EF calorimetry cuts) do not have an associated track. Consequently, approximately 3.5\% of the events accepted by the previous trigger step in these data have no tracks on which to apply cuts. Clearly, these events are immediately rejected by the EF tracking cuts.

### 6.3.4 EF track-cluster matching

The following cuts were applied on the track-cluster matching data associated with each EF cluster that had survived the previous trigger step:

- \(|\Delta \eta| < 0.01\)
  
  \(\Delta \eta\) is the difference between the \(\eta\) of the cluster and the \(\eta\) of the track extrapolated to the first sampling of the ECAL. The first sampling, which has the finest granularity in \(\eta\) of the ECAL samplings, is used because it enables \(\Delta \eta\) to be measured with the best possible resolution.

- \(|\Delta \phi| < 0.02\)
  
  \(\Delta \phi\) is the difference between the \(\phi\) of the cluster and the \(\phi\) of the track extrapolated to the second sampling of the ECAL. The second sampling is used because it has finer granularity in \(\phi\) than the first sampling, and the second sampling is where most of the energy of an EM shower is deposited.

- If \(\eta_{\text{cluster}} < 1.37\): \(0.7 < E_{\text{cluster}}/p_{\text{track}} < 1.7\)

- If \(\eta_{\text{cluster}} \geq 1.37\): \(0.7 < E_{\text{cluster}}/p_{\text{track}} < 2.7\)

The track-finding algorithm xKalman++ uses the position of clusters in the ECAL to improve its estimate of the \(p_T\) of electrons that have lost energy due to bremsstrahlung in the Inner Detector. xKalman++ searches for tracks in a cone of size \(0.2 \times 0.2\) rad in \(\Delta \eta \times \Delta \phi\) around clusters centres. xKalman++ uses the principle that the centre of each cluster is coincident with the energy-weighted barycentre of the impact points in the calorimeter of the electron and the bremsstrahlung photon that both formed the cluster, and that this energy-weighted barycentre lies on the extrapolation of the initial electron trajectory. The track \(p_T\) is improved by minimising a \(\chi^2\) containing the fitted track information and the cluster position \( \)\( \). The track
momentum is likely to be overestimated if photons from, for example, neutral pions are deposited in the cluster \[^{[32]}\]. This can cause \( E/p \) to be lower. As discussed in Section 6.2.4, tails at low values of \( E/p \) are more pronounced for jets than for electrons.
Chapter 7

Electron Trigger Performance

7.1 Data sets

7.1.1 ATLAS Data Challenges

In preparation for data-taking and analysis at the LHC, the ATLAS collaboration has run a series of so-called Data Challenges to validate its computing and data models, software suite and technical choices. This involved the production of several large event samples. All data used in this study originated from Data Challenge 1 (DC1) [102]. This means that, with the exception of the single electron events that will be discussed later, all data used in this study was generated in the same way and comparisons among results obtained with the different data are valid. The data was obtained from a central repository. Bookkeeping for DC1 was done by the ATLAS Metadata Interface (AMI), which is a database application that is used to store information about the data.

7.1.2 Production of Monte Carlo data

The production of Monte Carlo (MC) generated events typically includes the following steps: event generation, detector simulation, digitisation, and reconstruction. These stages are illustrated in Figure 7.1 on the next page. With the exception of one sample, the data used in this study was obtained after the digitisation stage and then reconstructed with code tailored for this study.

Event generation refers to the simulation of particle physics processes using programs based on theory and phenomenology. Simulation of particle physics processes using a hadronic event generator usually starts with two beams of particles travelling towards
Figure 7.1: Schematic representation of MC data production. The fast simulation package ATLFAST can be used to replace the detector simulation, digitisation, and reconstruction stages of the data production chain. Fast simulation is performed by smearing the truth information from event generation. It is possible to generate single particle events during the detector simulation stage without an event generator. Pile-up is simulated by adding hits from a large number of background events and digitising the combined set of hits.
each other. In simulations of the LHC, these particles are protons. The protons are characterised by parton distribution functions that describe their partonic substructure. In a typical event with high transverse momentum exchange between protons, partons from each beam emerge and seed initial-state showers. A parton from each of these two showers then interact in the hard process. This is the part of the event with high momentum exchange between the protons. The resultant outgoing particles can then decay or produce final-state showers. Phenomenological methods are implemented within event generators to deal with the hadronisation of partons. The data produced from event generation contains a record of the particles generated in each event, their four-vectors, charge and other properties. This MC-generated information is often called “truth”.

Detector simulation is the process whereby the passage of the generated particles through the matter of the virtual detector is simulated. The data produced from detector simulation contains a record (called “hits”) of where particles traversed the detector and how much energy they deposited.

Digitisation is the process whereby the electronic response of the detector is simulated; the data from the detector simulation (hits) are transformed into the format of the digitised raw data (called “digits”) from the real detector electronics.

Reconstruction is the process of turning the digitised data in each event into tracks and clusters. With the exception of one data set that will be discussed in the next section, the data used to investigate the electron trigger performance was reconstructed specifically for this study. The reconstruction software and options used were the same for all samples. All data was reconstructed in the Athena framework and included the simulation of electronic noise in the LAr and Tile Calorimeters.

7.1.3 The single electron events sample

To evaluate the trigger efficiency of the e25i selection, events that each contain a single electron were used. In contrast to the physics samples (W→eν, Z→ee and H→ZZ(*)→4e) that will be described later, the single electron events were produced without an event generator. More accurately, the data production chain started at the detector simulation stage without using data from an event generator as input. The detector simulation was done in the atlsim framework. A single particle generator was used to dynamically generate the events while the detector simulation was running. The electrons were distributed uniformly in η, in the range -2.5 < η < 2.5. Three separate samples were generated, each with different p_T distributions:
7.1 Data sets

- All electrons have $p_T = 25 \text{ GeV/c}$,
- The electron $p_T$ distribution is uniform between 7 and 32 GeV/c,
- The electron $p_T$ distribution is uniform between 30 and 80 GeV/c.

The second and third samples listed above were combined to yield a sample with electrons with $p_T$ in the range 7–80 GeV/c. Details of the samples are summarised in Table 7.1 and the $p_T$ and $|\eta|$ distributions of the [MC] truth electrons from the single particle generator are shown in Figures 7.2, 7.3 and 7.4 on the next page.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Electron $p_T$ (GeV/c)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>002026</td>
<td>25</td>
<td>5000</td>
</tr>
<tr>
<td>002564</td>
<td>7–32</td>
<td>48956</td>
</tr>
<tr>
<td>002565</td>
<td>30–80</td>
<td>49500</td>
</tr>
</tbody>
</table>

Table 7.1: Details of the single electron events.

The ATLAS detector simulation was done using GEANT3 [103] in the ATLSIM framework [102]. The effect of bremsstrahlung occurring in the matter of the detector was simulated. Synchrotron radiation ($e^+ \rightarrow e^+\gamma$) emitted by electrons passing through the magnetic field in the solenoid was not simulated.

The 25 GeV single electron events sample was reconstructed by the ATLAS HLT $e/\gamma$ group for use in a preliminary study prepared for the HLT TDR [31]; this is the only sample that was not reconstructed specifically for this study. The reconstruction software and options used were identical to those used for the other samples.

7.1.4 The QCD dijet events sample

A sample consisting overwhelmingly of QCD dijet events was used to evaluate the trigger rate for the e25i selection. The sample was produced such that it contains only events that have a reasonable chance of triggering, in order to make economical use of memory and CPU resources. The dijet events were generated with PYTHIA 6.203. On the parton level each jet was required to have $p_T$ of at least 17 GeV. Initial and final state radiation was simulated [100]. The sample contains a small admixture of physics processes such as $W$, $Z$ and top production [104]. Table 7.2 on page 127 shows that the cross sections for the physics processes included in the QCD dijet events sample are on the order of $10^{-4}$ mb or
Figure 7.2: $p_T$ and $|\eta|$ of the electrons in the 25 GeV/c single electrons sample. The $p_T$ and $|\eta|$ are that of the electrons from the single particle generator.

Figure 7.3: $p_T$ and $|\eta|$ of the electrons in the 7–32 GeV/c single electrons sample. The $p_T$ and $|\eta|$ are that of the electrons from the single particle generator.

Figure 7.4: $p_T$ and $|\eta|$ of the electrons in the 30–80 GeV/c single electrons sample. The $p_T$ and $|\eta|$ are that of the electrons from the single particle generator.
7.1 Data sets

smaller. The QCD dijet cross section is poorly known and the corresponding uncertainty in the trigger rates could be as high as a factor of two to three [84].

<table>
<thead>
<tr>
<th>Hard process</th>
<th>PYTHIA subprocess</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_i q_j \rightarrow q_i q_j ) ( q_i q_i \rightarrow q_i q_i ), ( q_i q_i \rightarrow gg )</td>
<td>11, 12, 13</td>
<td>( 1.5 )</td>
</tr>
<tr>
<td>( q_i g \rightarrow q_i g, gg \rightarrow q_i q_i, gg \rightarrow gg )</td>
<td>28, 53, 68</td>
<td>( 3.0 \times 10^{-4} )</td>
</tr>
<tr>
<td>( q_i q_i \rightarrow g \gamma, q_i g \rightarrow q_i \gamma )</td>
<td>14, 29</td>
<td>( 4.4 \times 10^{-5} )</td>
</tr>
<tr>
<td>( q_i q_j \rightarrow W )</td>
<td>2</td>
<td>( 4.8 \times 10^{-7} )</td>
</tr>
<tr>
<td>( q_i q_i \rightarrow t \overline{t}, gg \rightarrow t \overline{t} )</td>
<td>81, 82</td>
<td>( 4.8 \times 10^{-7} )</td>
</tr>
</tbody>
</table>

Table 7.2: Cross-sections for processes included in the QCD dijet sample. Flavours appearing already in the initial state are denoted by indices \( i \) and \( j \), whereas a new flavour in the final state is denoted by \( k \). Also shown are the PYTHIA subprocess numbers which are used to select the type of events to be generated. From [104].

Particles with \( |\eta| > 2.7 \) were not processed by GEANT3 to conserve memory and CPU processing. A particle-level filter was applied at generator level before detector simulation to reject events that would not pass the LVL1 trigger [100]. 2862334 events were generated to obtain the 241916 events contained in the data. Therefore, only one out of every 11.8 events was fully simulated.

7.1.5 The physics events samples

The following physics processes were considered in this study:

- \( W \rightarrow e\nu \),
- \( Z \rightarrow e e \),
- \( H \rightarrow ZZ^{(*)} \rightarrow 4e \).

The final states of these processes all contain at least one high-\( p_T \) electron. These are processes that the e25i trigger has been designed to select with high efficiency [31]. The data were generated using PYTHIA 6.203. Initial and final state radiation was simulated. A particle-level filter was applied before detector simulation. The \( W \rightarrow e\nu \) events were filtered such that all events contained at least one electron with \( |\eta| \leq 2.7 \) in the final state. The \( Z \rightarrow ee \) events were filtered such that all events contained at least two electrons with
$|\eta| \leq 2.7$ in the final state. Note that the particle-level filter imposed no requirement that the electrons that caused the $W \rightarrow e\nu$ and $Z \rightarrow ee$ events to be accepted must come from the decay of a $W$ or $Z$. Consequently, some $W \rightarrow e\nu$ and $Z \rightarrow ee$ events contain electrons from $W$ or $Z$ decay with $|\eta| > 2.7$. These events were accepted because they contain other electrons with $|\eta| \leq 2.7$.

The Higgs events were filtered such that all events contained at least four electrons with $p_T > 4 \text{ GeV}/c$ and $|\eta| \leq 2.7$ in the final state. Detector simulation was done by GEANT3. Synchrotron radiation was not simulated. Details of the samples are summarised in Table 7.3 and the $p_T$ and $|\eta|$ distributions of the MC truth electrons are shown in Figures 7.5 to 7.9 on pages [129-130].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>002510</td>
<td>$W \rightarrow e\nu$</td>
<td>12500</td>
</tr>
<tr>
<td>002513</td>
<td>$Z \rightarrow ee$</td>
<td>8000</td>
</tr>
<tr>
<td>002505</td>
<td>$H \rightarrow ZZ^* \rightarrow 4e$, $m_H = 130 \text{ GeV}/c^2$</td>
<td>9248</td>
</tr>
<tr>
<td>002507</td>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 180 \text{ GeV}/c^2$</td>
<td>5389</td>
</tr>
<tr>
<td>002542</td>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 300 \text{ GeV}/c^2$</td>
<td>5441</td>
</tr>
</tbody>
</table>

Table 7.3: Details of the physics samples.

### 7.1.6 Pile-up

In general there will be more than one proton-proton (pp) collision per bunch crossing at the LHC. The readout from the ATLAS detector will include information from these multiple collisions superposed. This phenomenon is called "pile-up". Most of these collisions will be "soft" with little $p_T$ transferred among interacting partons. These collisions are representative of the sample of events observed by ATLAS when the trigger makes no requirement on the type of events to be selected. They are called "minimum-bias" events for this reason. At design luminosity ($\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) each event that triggered the readout will contain a superposition of an average of 23 minimum-bias pp collisions. At start-up luminosity ($\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) an average of 4.6 minimum-bias pp collisions are superposed for every triggered event [100]. The actual number of minimum-bias pp collisions per bunch-crossing follows a Poisson distribution [105].
7.1 Data sets

Figure 7.5: $p_T$ and $|\eta|$ of the electrons in the $W \rightarrow e\nu$ sample. The $p_T$ and $|\eta|$ are that of the electrons from the W.

Figure 7.6: $p_T$ and $|\eta|$ of the electrons in the $Z \rightarrow ee$ sample. The $p_T$ and $|\eta|$ are that of the electrons from the Z.
Figure 7.7: $p_T$ and $|\eta|$ of the electrons in the $H \rightarrow ZZ^* \rightarrow 4e$ ($m_H = 130 \text{GeV}/c^2$) sample. The $p_T$ and $|\eta|$ are that of the electrons from the Z.

Figure 7.8: $p_T$ and $|\eta|$ of the electrons in the $H \rightarrow ZZ \rightarrow 4e$ ($m_H = 180 \text{GeV}/c^2$) sample. The $p_T$ and $|\eta|$ are that of the electrons from the Z.

Figure 7.9: $p_T$ and $|\eta|$ of the electrons in the $H \rightarrow ZZ \rightarrow 4e$ ($m_H = 300 \text{GeV}/c^2$) sample. The $p_T$ and $|\eta|$ are that of the electrons from the Z.
7.2 Analysis

All the data used in this study contains the effect of pile-up. Pile-up was simulated at start-up luminosity. This is because the process $H \rightarrow ZZ^{(*)} \rightarrow 4e$, which is a channel particularly suited for Higgs boson searches at start-up luminosity, is expected to be sensitive to the calorimeter effects that were investigated in this study. It has been shown that a 150 GeV Higgs boson can be observed with the ATLAS detector with a significance of over 7 standard deviations in the channel $H \rightarrow ZZ^{*} \rightarrow 4e$ with an integrated luminosity of $30 \text{ fb}^{-1}$, which is expected to be achieved in the first three years of running the LHC at start-up luminosity [25].

To simulate the effect of pile-up in the events, hits (data from detector simulation) in each event were merged with hits from a Poisson-distributed number of minimum-bias pp collisions selected from pre-prepared samples stored in a central repository. The combined sets of hits were then digitised together [105]. An average of 4.6 minimum-bias pp collisions were added per bunch-crossing to simulate conditions at start-up luminosity [100].

7.2 Analysis

7.2.1 Quantifying the performance of the single electron trigger

The performance of a trigger is evaluated in terms of the efficiency to trigger on signal events and the rate expected from background events. Triggers are optimised to maximise the trigger efficiency for an acceptable trigger rate. The current rate budget for the e25i trigger allows a final rate of 40 Hz at start-up luminosity [31]. The total output rate for the HLT is limited to 200 Hz.

In addition to the trigger efficiency and the trigger rate, another quantity that is useful for analysing the performance of the single electron trigger is the electron selection efficiency. The trigger efficiency quantifies the effectiveness of the trigger to select events. In contrast, the electron selection efficiency quantifies the effectiveness of the trigger to select electrons. If single electron events are used to evaluate the e25i selection, the distinction between trigger efficiency and electron selection efficiency is subtle; the overwhelming majority of events that have been accepted by the trigger contain only a single electron candidate, so the trigger efficiency and the electron selection efficiency are equal (within statistical errors).
However, the trigger efficiency and the electron selection efficiency are not equal if the sample used to evaluate the e25i selection contains events in which more than one electron is available to cause triggering. This is because the single electron trigger requires only one electron to trigger the event, but more than one electron could be selected. Therefore, the trigger efficiency and electron selection efficiency will not be equal when evaluated using the physics events samples $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$.

Moreover, the trigger efficiency and electron selection efficiency will typically not be equal when evaluated using the $W \rightarrow e\nu$ sample because a fraction of the events will contain additional electrons that can trigger the event. These electrons come from, for example, converted photons from $\pi^0$ decays and semileptonic decays of hadrons. The events contain both the electrons from the signal processes and the electrons from accompanying processes not exclusively targeted by the trigger.

Trigger efficiencies are given with respect to well-defined samples of events, and are taken to be equal to the fraction of events input to the trigger that are accepted. Similarly, the electron selection efficiencies are taken to be equal to the fraction of electrons input to the trigger that are selected. Unless indicated otherwise, the terms “trigger efficiency” and “electron selection efficiency” refer to the final values obtained after the EF.

### 7.2.1.1 Calculation of efficiencies and their errors

The e25i trigger selection can be considered to be a binomial process with a probability for success $\varepsilon$. Given the true trigger efficiency $\varepsilon$ and sample size $N$, the expectation value $E[n]$ and variance $V[n]$ of the number of events $n$ passing the trigger selection are

$$E[n] = N \varepsilon$$

and

$$V[n] = N \varepsilon (1 - \varepsilon).$$

Therefore the standard deviation of $n$ is

$$\sigma_n = \sqrt{N \varepsilon (1 - \varepsilon)}.\quad (7.3)$$

A standard unbiased estimator $\hat{\varepsilon}$ for the true and unknown efficiency $\varepsilon$ is

$$\hat{\varepsilon} = \frac{n}{N}.\quad (7.4)$$
The estimator $\hat{\sigma}_\varepsilon$ for the error of $\hat{\varepsilon}$ was obtained by replacing $\varepsilon$ in Equation (7.3) with $\hat{\varepsilon}$ and then dividing through by $N$, yielding the result

$$\hat{\sigma}_\varepsilon = \frac{1}{N} \sqrt{n \left(1 - \frac{n}{N}\right)}$$  \hspace{1cm} (7.5)

$$= \sqrt{\frac{\hat{\varepsilon} (1 - \hat{\varepsilon})}{N}}.$$  \hspace{1cm} (7.6)

This prescription was repeated for the calculation of errors on electron selection efficiencies, where $n$ is the number of selected electron candidates and $N$ the total number of [MC] truth electrons in the sample. This treatment of errors has the advantage that error ranges are bounded to lie within zero and unity.

### 7.2.1.2 Calculation of trigger rates and their errors

The trigger rate $R$ is given by

$$R = \sigma \mathcal{L} f_r \frac{n}{N}$$  \hspace{1cm} (7.7)

where $R$ is the trigger rate, $\sigma$ is the [QCD] dijet production cross section, $\mathcal{L}$ is the nominal instantaneous luminosity, $f_r$ is the rejection factor corresponding to the fraction of events generated that are contained in the data, $n$ is the number of events in the data that were selected by the e25i trigger and $N$ is the total number of events in the data [99]. The trigger rates at start-up luminosity are

$$R = (1.5 \text{ mb}) \times (2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}) \times \left(\frac{1}{11.8}\right) \times \left(\frac{n}{N}\right) \hspace{1cm} (7.8)$$

$$= 254 \text{ kHz} \times \left(\frac{n}{N}\right) \hspace{1cm} (7.9)$$

The error $\sigma_R$ on the trigger rate is

$$\sigma_R = 254 \text{ kHz} \times \sqrt{\frac{\varepsilon (1 - \varepsilon)}{N}} \hspace{1cm} (7.10)$$

where $\varepsilon = n/N$ and denotes the fraction of [QCD] dijet events selected. The quoted errors on the trigger rates are purely statistical; as discussed previously, there is a large systematic uncertainty in the trigger rate estimates.

### 7.2.2 The analysis software

The trigger efficiencies and trigger rates presented in this study were calculated using a modified version of the TrigEgammaAnalysis software package. This package was formally
called “The $e/\gamma$ Analysis Framework”. The original version was written by the PESA $e/\gamma$ group. Many significant improvements were made to the software for this study by the present author, including several changes that were made to improve the accuracy of the results. The source code is available from the ATLAS Concurrent Versions System (CVS) repository.

The inputs to the analysis software were reconstructed events. The outputs were either trigger efficiencies or trigger rates. Trigger efficiencies were obtained by running on a sample of signal events (single electrons, $W \rightarrow e\nu$, $Z \rightarrow ee$ or $H \rightarrow ZZ^{(*)} \rightarrow 4e$). Trigger rates were obtained by running on the QCD dijet events sample. Modifications were made to the analysis software specifically for this study that enable the electron selection efficiency to be plotted in a histogram against the $p_T$ or $|\eta|$ of the MC truth electrons.

The first stage in the analysis of the e25i trigger was the exclusion of electrons from the signal events sample that have a negligible probability of being selected. For example, electrons with $\eta$ outside the region covered by ID tracking and high-granularity EM calorimetry will not be selected. The process of defining a fiducial sample is called preselection. The trigger efficiencies are given with respect to these fiducial samples. Only events that satisfied the preselection criteria were used in the calculation of trigger efficiency. Events were preselected according to cuts applied on MC truth quantities. No preselection was applied to the QCD dijet events sample because they had already been filtered at generator level. The preselection criteria are discussed in more detail in Section 7.2.3.

After preselection, the events were passed to the e25i selection. The trigger steps in the selection are factorised by detector to show the trigger efficiency and trigger rate after each of the major selection steps. Each trigger step in the sequence was executed only if at least one electron candidate passed the previous trigger step. This means that the event was rejected at the earliest opportunity. The e25i trigger selection was described in Chapter 6. After all the events in the sample had been processed, the electron candidates and events passing each trigger step were counted and trigger efficiencies or trigger rates were calculated.

### 7.2.3 Preselection criteria

The efficiencies were calculated with respect to samples that satisfied the following preselection criteria, which depend on the events used:

- Single electrons: at least one electron with $p_T > 15$ GeV/c,
7.2 Analysis

- \( W \rightarrow e\nu \): at least one electron with \( p_T > 25 \text{ GeV/c} \),
- \( Z \rightarrow ee \): at least two electrons with \( p_T > 15 \text{ GeV/c} \),
- \( H \rightarrow ZZ^{(*)} \rightarrow 4e \): at least two electrons with \( p_T > 20 \text{ GeV/c} \) and two additional electrons with \( p_T > 7 \text{ GeV/c} \).

These cuts closely resemble offline analysis cuts. Electrons were required to be within the region \( |\eta| \leq 2.47 \) but not in the transition regions in the ECAL between the barrel and endcaps:

- \( |\eta| \leq 2.47 \) (but not in \( 1.37 \leq |\eta| \leq 1.52 \))

(There was one exception to this rule: to investigate how the electron selection efficiency varies as a function of the \( \eta \) of the electrons, no cuts on \( \eta \) were applied.) ID tracking and high-granularity EM calorimetry covers the region \( |\eta| < 2.5 \), but precision physics measurements are limited to the region \( |\eta| \leq 2.47 \) [30, 32]. Electrons outside this region were excluded from the calculations for this reason. The crack regions between the barrel and endcaps are not used for precision physics measurements because of the large amount of passive material in front of the ECAL, where a large fraction of the energy of an EM shower could be lost [32]. Electrons in the crack regions were excluded from the calculations, as in other analyses [32, 37, 84, 107, 108]. Finally, two cuts that were common to all preselection criteria are:

- Electrons must not be duplicates of electrons appearing earlier in the event record,
- Electrons must not come from photons that have converted.

These cuts exist to account for the way in which the MC truth data are recorded and prevent multiple-counting of electrons. The event record contains the history of each event and includes information about the particles that were present, including those that have decayed, converted or hadronised and are not present in the final state. The record for each event can contain entries representing the particles produced by the physics generator plus duplicate entries representing some of the same particles that were copied to the detector simulation. Also, some (but not all) of the electrons and photons that were involved in the evolution of an electromagnetic shower are recorded. The first cut ensures that if two or more electrons exist with identical properties, the one that appeared first in the event record is the one that is counted. The second cut ensures that if an electron generates an EM shower in the detector, the electron that is counted is the electron that seeds the shower.
7.2.4 Level-2 tracking technical issues

The LVL2 tracking algorithm IDScan failed to find a track in 6.7% of all 25 GeV/c single electron events that were accepted by the preselection cuts. The EF tracking algorithm xKalman++ would have found at least one track in these events, had they not been rejected at LVL2. About 50% of these events would have passed the EF selection criteria. These “missing track” events lower the trigger efficiency and are caused by a fault in the algorithm that reconstructs space points in the ID and passes them to the tracking algorithms [100, 109].

This problem can be accounted for by excluding from the calculation of trigger efficiency the events in which xKalman++ finds at least one track but IDScan does not [109]. These kind of prescriptions are known to have been used in the past, but were phased-out as IDScan improved in efficiency [110]. Unless stated otherwise, the results that are shown in this thesis were obtained without using any special treatment or corrections to account for missing IDScan tracks. This is because the variation (and not the absolute values) of trigger efficiencies are of chief importance in this study. IDScan failed to find a track in less than 0.3% of the $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events. The events in these samples offer IDScan with at least four opportunities to find a track. The problems in the LVL2 tracking code in the software used for this study will have little effect on the efficiency to trigger on events in these samples. The LVL2 tracking improved in more recent versions of the software [111]. The performance of IDScan is now well within the requirements for reconstruction efficiency [112].

7.3 Performance with an optimal ECAL

This section presents the results obtained with data which was reconstructed without simulating the effect of dead ECAL cells or dead FEBs. As such, these results can be regarded as the benchmark against which the performance obtained with a less than optimal ECAL is to be compared.

7.3.1 Comparison with results from a previous study

The performance of the e25i trigger used in this study was compared against the results of a previous study done by the ATLAS HLT group [107], which was itself based on a study done for the ATLAS HLT TDR [31]. The purpose of this comparison was to demonstrate
agreement between the benchmark results and canonical results. Both sets of results are presented in Table 7.4. The results of the previous study were given with respect to LVL1. The HLT group often presented the results of trigger performance studies in this way. This was done so that the performance of the HLT could be analysed independently of the LVL1 trigger. The results of this study have been presented accordingly for means of comparison. Furthermore, a prescription known to be in common usage at the time of the previous study was used to account for the problem with the LVL2 tracking as discussed in Section 7.2.4 on the facing page. The LVL2 tracking problem results in a drop in efficiency of about 5% at the end of the trigger selection. The use of the prescription is permissible because these events will be recovered in the future.

<table>
<thead>
<tr>
<th>Trigger step</th>
<th>Post-TDR HLT study [107]</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency w.r.t. LVL1 (%)</td>
<td>Rate (Hz)</td>
</tr>
<tr>
<td>LVL2 calorimetry</td>
<td>95.6 ± 0.3</td>
<td>1948 ± 46</td>
</tr>
<tr>
<td>LVL2 tracking</td>
<td>89.4 ± 0.5</td>
<td>364 ± 21</td>
</tr>
<tr>
<td>LVL2 matching</td>
<td>87.7 ± 0.6</td>
<td>143 ± 12</td>
</tr>
<tr>
<td>EF calorimetry</td>
<td>86.1 ± 0.6</td>
<td>101 ± 15</td>
</tr>
<tr>
<td>EF tracking</td>
<td>82.0 ± 0.6</td>
<td>71 ± 10</td>
</tr>
<tr>
<td>EF matching</td>
<td>79.7 ± 0.7</td>
<td>34 ± 6</td>
</tr>
</tbody>
</table>

\(^a\) The sample used to calculate these figures does not include events in which xKalman++ finds at least one track but IDScan does not.

Table 7.4: Performance of the single electron HLT at start-up luminosity compared with a previous study. The efficiencies are given for single electrons with \(p_T = 25\) GeV/c and are shown with respect to LVL1. In both sets of results, the efficiency of the LVL1 selection is 95%. Matching refers to position and energy-momentum matching between calorimeter clusters and reconstructed tracks. The quoted errors are statistical, as discussed in the text.

The designated goal of the HLT is to accept electrons with an efficiency of about 80% with respect to LVL1 (so to not cut too hard on physics) and reduce the final rate to about 40 Hz at start-up luminosity [31]. The results shown in Table 7.4 demonstrate that this can be achieved with the e25i trigger used for this study. The results are comparable
with those obtained in earlier studies. The e25i trigger selection is sufficient for use in this study. The differences between the results obtained from this study and the results obtained in the previous study are caused by two effects:

- Small differences in the e25i cuts, or their implementation in the analysis software.
- Differences in the reconstruction software used to produce the data. This study used a more recent version of the reconstruction software to produce the data than the previous study.

The data used for the previous study was obtained and processed using the new analysis software. The trigger efficiency with respect to [LVL1] was found to be $81.0 \pm 0.4\%$ for a final rate of $48 \pm 7\text{ Hz}$. *The results that follow include the performance of the electron trigger at [LVL1] and were calculated without using any prescription or corrections to account for the problems with the [LVL2] tracking.*

### 7.3.2 Performance evaluated with single electron events

Table 7.5 restates the results of this study including the performance of [LVL1] and without the use of corrections for the inefficiencies encountered with IDScan.

<table>
<thead>
<tr>
<th>Trigger step</th>
<th>Trigger efficiency (%)</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[LVL1]</td>
<td>95.2 ± 0.3</td>
<td>7085 ± 85</td>
</tr>
<tr>
<td>[LVL2] calorimetry</td>
<td>92.7 ± 0.4</td>
<td>1915 ± 45</td>
</tr>
<tr>
<td>[LVL2] tracking</td>
<td>83.3 ± 0.5</td>
<td>369 ± 20</td>
</tr>
<tr>
<td>[LVL2] matching</td>
<td>81.0 ± 0.6</td>
<td>147 ± 12</td>
</tr>
<tr>
<td>[EF] calorimetry</td>
<td>79.1 ± 0.6</td>
<td>106 ± 11</td>
</tr>
<tr>
<td>[EF] tracking</td>
<td>72.0 ± 0.7</td>
<td>55 ± 8</td>
</tr>
<tr>
<td>[EF] matching</td>
<td>69.6 ± 0.7</td>
<td>47 ± 7</td>
</tr>
</tbody>
</table>

Table 7.5: Performance of the single electron trigger. The efficiencies were evaluated with single electrons with $p_T = 25\text{ GeV/c}$. The quoted errors are statistical.

The efficiency of the single electron trigger reported in Table 7.5 is more modest than that shown in Table 7.4 on the preceding page; this is the most obvious difference between the results. This is a direct consequence of using a different approach to report the performance of the trigger. For reference, the trigger efficiency output from the e25i
trigger used in this study was $74.6 \pm 0.7\%$ when events in which IDScan did not find a track are excluded from the calculation.

Figure 7.10 shows the electron selection efficiency as a function of the $p_T$ of the MC truth electrons. The results show that there is an effective $p_T$ threshold for triggering at about 22 GeV/c. Events that do not contain electrons with $p_T$ above this threshold have a negligible chance of triggering. Above this threshold, electrons are selected with a probability that does not change significantly with further increases in electron $p_T$.

![Figure 7.10: Electron selection efficiency as a function of electron $p_T$. The efficiencies were evaluated with electrons with $p_T$ in the range 7–80 GeV/c. A zeroth-order polynomial fit to the data in the region 30–80 GeV/c is shown.](image)

The electron selection efficiency as a function of electron $p_T$ is not quite asymptotically flat above the effective threshold for triggering. A linear fit to the data with $p_T$ in the range 30–80 GeV/c has a gradient of $-0.03 \pm 0.01\%$ per GeV/c. (The lower-bound on this interval was chosen because it was judged to be an appropriate distance away from the effective threshold for triggering.) It is plausible that the very small downward trend in the electron selection efficiency is due to the effect of isolation cuts, such as cuts on shower leakage into the HCAL. The gradient is rather small and was neglected in this
study. The electron selection efficiency above the effective threshold for triggering was considered to be constant.

The trigger efficiency obtained at the end of the selection in Table 7.5 on page 138 (69.6 ± 0.7%) corresponds to the value of the electron selection efficiency at $p_T = 25$ GeV/c in Figure 7.10 on the page before. This connection is possible because the trigger requires a single electron to pass the selection criteria, and both the sets of results were evaluated with single electron events. For reference, the electron selection efficiency extracted from Figure 7.10 on the preceding page for electrons with $25$ GeV/c < $p_T$ < $26$ GeV/c is 69.4 ± 1.1%.

Figure 7.10 on the page before shows that electron selection efficiency is a strong function of electron $p_T$. This is also supported by the discovery of a function with electron $p_T$ as the only independent variable that fits the data remarkably well over the whole range of electron $p_T$ and reproduces the key features of the data with a high degree of accuracy. The details of this function can be found in Appendix B. For this study, the key piece of information to be gained from Figure 7.10 on the preceding page is the average value of the electron selection efficiency. The average value of the electron selection efficiency, denoted by $\bar{e}$, is defined as the value obtained from the zeroth-order polynomial fit to the data above the effective $p_T$ threshold for triggering\(^1\). The fit was obtained by minimising the $\chi^2$ between the zeroth-order polynomial and the data. The value of the electron selection efficiency obtained from the fit is 72.7 ± 0.2%. $\bar{e}$ for single electron events can also be interpreted as the trigger efficiency for single electrons with $p_T$ ≥ 30 GeV/c.

Figure 7.11 on the next page shows the electron selection efficiency as a function of the $|\eta|$ of the MC truth electrons. The effect of the transition regions in the ECAL between the barrel and endcaps is clearly visible as a pronounced drop in electron selection efficiency in the region 1.37 ≤ $|\eta|$ ≤ 1.52, as expected. The electron selection efficiency falls sharply to zero for electrons with $|\eta|$ > 2.47; this is the effective $|\eta|$ threshold above which precision physics measurements cannot be made.

\(^1\) In addition to its usual mathematical meaning, the bar atop $\varepsilon$ serves as a reminder that the value is obtained from a horizontal-line fit.
7.3 Performance with an optimal Electromagnetic Calorimeter

7.3.3 Estimated trigger efficiencies for physics processes

7.3.3.1 Introduction

A simple model was constructed to estimate the efficiency to trigger on $W \rightarrow e\nu$, $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events, thereby providing a cross-check of the results obtained by applying the $e25i$ selection on these physics events. The model estimates the trigger efficiencies based on the assumption that both of the following are independent of the type of events:

- The relationship between electron selection efficiency and $|\eta|$ for triggering, $\epsilon_{\text{r}}$.
- The average value of the electron selection efficiency above the effective $p_T$ threshold for triggering, $\overline{\epsilon}$. 

The calculation uses only $\text{MC}$ truth information in the physics events. The model is not intended to be a substitute for full detector simulation and reconstruction, but does provide insight into the behaviour of the single electron trigger and the differences in performance obtained with the various samples of events.

Figure 7.11: Electron selection efficiency as a function of electron $|\eta|$. No cuts on $\text{MC}$ truth electron $|\eta|$ were applied during preselection, but their values are shown for reference.
7.3.3.2 Hypothesis

Figure 7.10 on page 139 demonstrates that electron selection efficiency depends on the $p_T$ of the electrons. At least one electron from each event must satisfy the $e_{25i}$ selection criteria in order for the event to trigger. The trigger efficiency depends on how many electrons are in each event that have $p_T$ above the effective threshold for triggering. This threshold is not well-defined because the relationship between electron selection efficiency and electron $p_T$ is not strictly a step function.

Based on the assumption that the electron selection efficiency depends only on the $p_T$ of the electrons in each event, a simple model was constructed to estimate the trigger efficiencies for various physics processes.

7.3.3.3 Model

The starting point in the series of logical steps that led to this model was to consider the case in which all events contain at least one electron above the $p_T$ threshold for selection. In this case, the trigger efficiency $\varepsilon_E$ (where the subscript indicates that this is the efficiency to select events) is equal to the electron selection efficiency $\varepsilon_e$ (where the subscript indicates that this is the efficiency to select individual electrons).

If two electrons are present in each event, both with the same electron selection efficiency, the trigger efficiency is equal to unity minus the inefficiency to trigger the event. This is equivalent to the statement that the probability to trigger an event is equal to unity minus the probability to not trigger the event. In the frequentist interpretation of probability, the definition of the probability to trigger an event is identical to the definition of the trigger efficiency and the two may be used interchangeably. It is reasonable to assume that the selection of the two electrons are independent processes. Therefore, the probability to select neither electron in the event is simply the product of the probability to not select the first electron and the probability to not select the second electron. This yields

$$\varepsilon_E = 1 - (1 - \varepsilon_e)^2. \quad (7.11)$$

Extending to the case in which each event contains $n$ electrons potentially capable of triggering the event, the trigger efficiency is given by

$$\varepsilon_E = 1 - (1 - \varepsilon_e)^n. \quad (7.12)$$

Suppose that in the previous case, in which each event contains two electrons, the probability to select the electrons depends on the $p_T$ of the electrons and that the $p_T$ of
7.3 Performance with an optimal Electromagnetic Calorimeter

the two electrons are different. The trigger efficiency is given by

\[ \varepsilon_E = 1 - (1 - \varepsilon_{e1}) (1 - \varepsilon_{e2}). \]  (7.13)

Extending to the case in which each event contains \( n \) electrons, each with different \( p_T \), the trigger efficiency is

\[ \varepsilon_E = 1 - \prod_{i=1}^{n} (1 - \varepsilon_{ei}). \]  (7.14)

The goal of the simple model was to construct a function of the observed measurements — the \( p_T \) of the electrons in the physics events — to estimate the true value of the parameter \( \varepsilon_E \). The estimator \( \hat{\varepsilon}_E \) for the true and unknown probability for an event containing \( n \) electrons to trigger is given by

\[ \hat{\varepsilon}_E (p_{T1}, \ldots, p_{Tn}) = 1 - \prod_{i=1}^{n} (1 - \hat{\varepsilon} (p_{Ti})) \]  (7.15)

where \( \hat{\varepsilon} (p_T) \) is the estimator for the true and unknown probability to select in an event an electron with a particular \( p_T \). The maximum likelihood estimator of \( \varepsilon (p_{Ti}) \) is given by

\[ \hat{\varepsilon} (p_{Ti}) = \frac{n_i}{N_i} \]  (7.16)

where \( n_i \) and \( N_i \) are the number of electrons selected with transverse momentum \( p_{Ti} \), and the total number of electrons with transverse momentum \( p_{Ti} \), respectively.

The value of \( \hat{\varepsilon} (p_{Ti}) \) used was obtained from the midpoint of the \( i \)th bin in the histogram of electron selection efficiency as a function of electron \( p_T \), shown in Figure 7.10 on page 139 and obtained using a sample of events containing single electrons with \( p_T \) distributed uniformly in the range 7–80 GeV. This enabled the electrons in each (1 GeV wide) \( p_T \) bin to be mapped to a selection efficiency. For \( p_T \) greater than 80 GeV, the final bin in the histogram was used. This is reasonable because the electron selection efficiency can be considered to be constant after 30 GeV, and the \( p_T \) distribution of the electrons in the physics samples is such that only a small fraction have \( p_T \) above 80 GeV. The process of discretising the continuum of electron \( p_T \) results in a subtle change in the definition of \( i \), which previously referred to the \( i \)th electron in an event with a particular \( p_T \); \( i \) now labels the bin that contains the electron with that \( p_T \).

In the limit of large sample size, the mean of the estimates will converge to the true value of the trigger efficiency \( \varepsilon_E \). The next step is to propagate the errors from the \( \hat{\varepsilon} (p_{Ti}) \) to the estimator \( \hat{\varepsilon}_E \). Using the method of propagation of errors, the estimator for the variance of \( \hat{\varepsilon}_E \) is

\[ \sigma_{\hat{\varepsilon}_E}^2 \approx \sum_{i=1}^{n} \left( \frac{\partial \hat{\varepsilon}_E}{\partial \hat{\varepsilon} (p_{Ti})} \right)^2 \sigma_{\hat{\varepsilon} (p_{Ti})}^2 \]  (7.17)
where $\hat{\sigma}_{\hat{\varepsilon}(p_T_i)}$ is the estimator of the error of $\hat{\varepsilon}(p_T_i)$. From Equation (7.15) on the preceding page, the partial derivative is

$$\frac{\partial \hat{\varepsilon}}{\partial \hat{\varepsilon}(p_T_i)} = \prod_{i \neq j}^{n} (1 - \hat{\varepsilon}(p_T_j)).$$  \hspace{1cm} (7.18)

Therefore the estimator for the variance of $\hat{\varepsilon}$ is

$$\hat{\sigma}_{\hat{\varepsilon}}^2 = \sum_{i=1}^{n} \left( \prod_{i \neq j}^{n} (1 - \hat{\varepsilon}(p_T_j)) \right) \frac{2 \hat{\sigma}_{\hat{\varepsilon}(p_T_i)}}{\hat{\sigma}_{\hat{\varepsilon}(p_T_i)}}.$$  \hspace{1cm} (7.19)

and the estimator for the error of $\hat{\varepsilon}$ is taken to be the square root. The number of electrons selected, $n_i$, out of the total number of electrons, $N_i$, in each $p_T$ bin individually follow the binomial distribution. The errors $\hat{\sigma}_{\hat{\varepsilon}(p_T_i)}$ were taken to be

$$\hat{\sigma}_{\hat{\varepsilon}(p_T_i)} = \sqrt{\frac{\hat{\varepsilon}(p_T_i) (1 - \hat{\varepsilon}(p_T_i))}{N_i}}.$$  \hspace{1cm} (7.20)

The final step is to include the uncertainties $\hat{\sigma}_{\hat{\varepsilon}(p_T_i)}$ in the estimates of the electron selection efficiencies in the estimate of the uncertainty of the estimated trigger efficiency. The estimated probability to trigger the event $\varepsilon_{E}^{obs}$ is the observed value of the estimator $\hat{\varepsilon}$ evaluated with the data. This is taken to be

$$\varepsilon_{E}^{obs} = \hat{\varepsilon} (1 + r \hat{\sigma}_{\hat{\varepsilon}})$$  \hspace{1cm} (7.21)

where $r$ is a Gaussian-distributed random number, with mean equal to zero and standard deviation equal to unity, generated for each event. The events used in the calculation were required to satisfy the preselection criteria listed in Section 7.2.3 on page 134. The estimators $\hat{\varepsilon}$ and $\hat{\sigma}_{\hat{\varepsilon}}$ were evaluated with the data for each event, and the value of $\varepsilon_{E}^{obs}$ was calculated. This procedure ensures that the resultant standard deviation of the $\varepsilon_{E}^{obs}$ distribution will include the statistical error of $\hat{\varepsilon}(p_T)$. The estimate of the trigger efficiency was obtained from the mean value of $\varepsilon_{E}^{obs}$. The error $\sigma_{\varepsilon_{E}^{obs}}$ on the estimate of the trigger efficiency was obtained from

$$\sigma_{\varepsilon_{E}^{obs}} = \frac{\sigma}{\sqrt{N}}$$  \hspace{1cm} (7.22)

where $\sigma$ is the standard deviation of the $\varepsilon_{E}^{obs}$ distribution and $N$ is the number of events.

The model described so far provides an estimate of the trigger efficiency after the $\text{EF}$. A trivial extension to the model enables the trigger efficiency for any of the preceding trigger steps to be estimated also. The histogram of electron selection efficiency after the $\text{EF}$ as a function of electron $p_T$, shown in Figure 7.10 on page 139, is used as input data to estimate the trigger efficiency after the $\text{EF}$. To estimate the trigger efficiency after any other trigger step, the equivalent histogram for that trigger step is used instead.
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7.3.3.4 Results

The trigger efficiency after each trigger step was estimated for various physics processes using this model. The validity of the model was checked by estimating the trigger efficiency after each trigger step for 25 GeV/c single electron events; the estimates agree with the results reported in Table 7.5 on page 138. The estimated trigger efficiencies for the physics events samples are shown in Table 7.6. The estimated errors are all smaller than 0.1%. This is because the errors on the electron selection efficiencies used in the calculation that were extracted from the histogram in Figure 7.10 on page 139 are small.

<table>
<thead>
<tr>
<th>Trigger step</th>
<th>Estimated trigger efficiency (%)</th>
<th>W→eν</th>
<th>Z→ee</th>
<th>H→ZZ(+)→4e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>130 GeV/c²</td>
<td>180 GeV/c²</td>
<td>300 GeV/c²</td>
</tr>
<tr>
<td>LVL1</td>
<td>97.6</td>
<td>99.4</td>
<td>99.9</td>
<td>100.0</td>
</tr>
<tr>
<td>LVL2 calorimetry</td>
<td>95.6</td>
<td>99.1</td>
<td>99.8</td>
<td>100.0</td>
</tr>
<tr>
<td>LVL2 tracking</td>
<td>87.2</td>
<td>97.4</td>
<td>99.0</td>
<td>99.8</td>
</tr>
<tr>
<td>LVL2 matching</td>
<td>84.9</td>
<td>95.5</td>
<td>97.6</td>
<td>99.6</td>
</tr>
<tr>
<td>EF calorimetry</td>
<td>84.0</td>
<td>95.1</td>
<td>97.4</td>
<td>99.5</td>
</tr>
<tr>
<td>EF tracking</td>
<td>76.6</td>
<td>92.0</td>
<td>95.2</td>
<td>98.9</td>
</tr>
<tr>
<td>EF matching</td>
<td>72.8</td>
<td>89.8</td>
<td>93.6</td>
<td>98.4</td>
</tr>
</tbody>
</table>

Table 7.6: Estimated trigger efficiencies for various physics processes. The results correspond to the initial luminosity scenario of $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. Efficiencies for the $H→ZZ(+)→4e$ channel are given for Higgs bosons with three different masses: $m_H < 2m_Z$ (130 GeV/c²), $m_H = 2m_Z$ (180 GeV/c²) and $m_H > 2m_Z$ (300 GeV/c²). The statistical errors are all smaller than 0.1%.

7.3.4 Performance evaluated with physics events

Table 7.7 on the following page shows the electron trigger performance that can expected for the physics channels $W→e\nu$, $Z→ee$ and $H→ZZ(+)→4e$ at start-up luminosity.

The results indicate that the trigger efficiencies for each physics events sample depend on the number of electrons in each event with $p_T$ above the effective threshold for triggering. The trigger efficiencies obtained with $Z→ee$ and $H→ZZ(+)→4e$ events are
<table>
<thead>
<tr>
<th>Trigger step</th>
<th>W → eν</th>
<th>Z → ee</th>
<th>H → ZZ(*) → 4e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVL1</td>
<td>95.8 ± 0.2</td>
<td>99.1 ± 0.1</td>
<td>99.4 ± 0.1</td>
</tr>
<tr>
<td>LVL2 calorimetry</td>
<td>91.7 ± 0.3</td>
<td>98.3 ± 0.2</td>
<td>98.9 ± 0.1</td>
</tr>
<tr>
<td>LVL2 tracking</td>
<td>80.1 ± 0.4</td>
<td>96.3 ± 0.3</td>
<td>98.5 ± 0.2</td>
</tr>
<tr>
<td>LVL2 matching</td>
<td>77.1 ± 0.5</td>
<td>92.0 ± 0.4</td>
<td>91.9 ± 0.4</td>
</tr>
<tr>
<td>EF calorimetry</td>
<td>75.9 ± 0.5</td>
<td>91.0 ± 0.4</td>
<td>90.6 ± 0.4</td>
</tr>
<tr>
<td>EF tracking</td>
<td>69.6 ± 0.5</td>
<td>85.9 ± 0.5</td>
<td>86.6 ± 0.5</td>
</tr>
<tr>
<td>EF matching</td>
<td>65.5 ± 0.5</td>
<td>83.3 ± 0.5</td>
<td>84.4 ± 0.5</td>
</tr>
<tr>
<td>Estimated</td>
<td>72.8</td>
<td>89.8</td>
<td>93.6</td>
</tr>
</tbody>
</table>

Table 7.7: Trigger efficiencies for various physics channels. The results correspond to the initial luminosity scenario of $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. Efficiencies for the $H \rightarrow ZZ(\ast) \rightarrow 4e$ channel are given for Higgs bosons with three different masses: $m_H < 2m_Z$ (130 GeV/c$^2$), $m_H = 2m_Z$ (180 GeV/c$^2$) and $m_H > 2m_Z$ (300 GeV/c$^2$). Efficiencies are given with respect to kinematical and geometrical cuts described in the text. The estimated trigger efficiencies after the EF for each physics process (taken from Table 7.6 on the preceding page) are also given. The statistical errors on the estimated trigger efficiencies are all smaller than 0.1%.
significantly higher than the trigger efficiencies obtained with $W\rightarrow e\nu$ events. The events in the $Z\rightarrow ee$ and $H\rightarrow ZZ^{(*)} \rightarrow 4e$ samples each contain more than one high-$p_T$ electron; consequently, the single electron trigger has more than one opportunity to find an electron that satisfies the selection criteria.

Figure 7.12 shows the dependency of the trigger efficiency on the mass of the Higgs boson. The efficiency to trigger on this channel increases with the Higgs boson mass. This is because a more massive Higgs boson is able to impart more energy to the decay electrons than a less massive one, therefore the number of events that contain electrons with $p_T$ above the effective threshold for triggering increases with the Higgs boson mass.

Figure 7.12: Trigger efficiency as a function of the Higgs boson mass for the $H\rightarrow ZZ^{(*)} \rightarrow 4e$ channel. The results correspond to the initial luminosity scenario of $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

There is a significant difference in the trigger efficiencies obtained with $W\rightarrow e\nu$ events ($65.5 \pm 0.5\%$) and $25 \text{ GeV/c}$ single electron events ($69.6 \pm 0.7\%$). Both samples contain a single high-$p_T$ electron in each event. If no other factors are taken into consideration, it would be reasonable to expect agreement between the results obtained with the two samples. The difference in the results is not caused by the different electron $p_T$ thresholds used during preselection. This was confirmed by checking that the trigger efficiency evaluated with $25 \text{ GeV/c}$ single electron events is the same irrespective of whether the preselection used is the one for $W\rightarrow e\nu$ events or the one for single electrons.

The trigger efficiencies obtained do not agree with the predictions of the simple model. The simple model overestimates the trigger efficiencies for the physics events samples. This means that at least one of the assumptions on which the simple model is built is false. The assumptions were that $\varepsilon_e$ is the same irrespective of the type of events and that the
electron selection efficiency depends only on the $p_T$ of the electrons in each event. The electron selection efficiency as a function of electron $p_T$ is shown in Figure 7.13 on the facing page for each physics events sample. The size of the error bars is a reflection of the $p_T$ distribution of the electrons in each sample.

\( \varepsilon_e \) for each sample is shown in Figure 7.14 on page 150. The values of \( \varepsilon_e \) obtained with the physics events samples agree with each other but are significantly lower than the value of \( \varepsilon_e \) obtained with single electron events.

In summary, the discrepancies in the results are as follows:

- The trigger efficiencies for $W \rightarrow e\nu$ events and single electron events are significantly different. One would expect there to be better agreement between the results, given that both samples contain a single high-$p_T$ electron in each event.

- The trigger efficiencies obtained with the physics events samples and the estimates from the simple model are significantly different. The simple model works by assuming that the estimated values can be inferred from the observed trend between electron selection efficiency and electron $p_T$ for single electron events. The simple model is able to accurately reconstitute the trigger efficiencies for the single electron events. Based on this information, one can conclude that the discrepancy must be due to differences between the physics events samples and the single electron events.

- \( \varepsilon_e \) for the physics events samples and the single electron events are significantly different. This confirms the previous point.

These discrepancies do not constitute a problem for the studies presented in this thesis, but they do provide insight into the differences between the physics events samples and the single electron events.

### 7.3.4.1 Differences in physics content between the samples

The percentage of events in which the LVL2 tracking algorithm IDScan fails to find a track varies between samples. Putting the samples on the same footing with regard to IDScan performance, by excluding from all the samples the events in which IDScan fails to find at least one track, does not make the values of \( \varepsilon_e \) obtained with the physics events samples equal to the value of \( \varepsilon_e \) obtained with the single electron events sample. Nor does it result in equality between the trigger efficiencies obtained with the physics events samples and the estimates from the simple model. Therefore, IDScan’s performance is not responsible for the observed discrepancies.
7.3 Performance with an optimal Electromagnetic Calorimeter

Figure 7.13: Electron selection efficiency as a function of electron $p_T$ for various physics processes. The results obtained with single electron events (Figure 7.10 on page 139) are shown in Figure (a) for comparison. In each figure, a zeroth-order polynomial has been fitted to the data with $p_T$ in the range 30–80 GeV/c.
Figure 7.14: $\varepsilon^-$ for each sample. The figures in the parentheses are the values of the Higgs boson mass. A zeroth-order polynomial fit to the data corresponding to the physics events samples is shown. This yields the average value of $\varepsilon^-$ for the physics events samples.
Three effects related to the physics content of the events were identified as possible causes for the differences in the values of $\xi_{T}$ between the physics events and the single electron events. These effects were also expected to be the reason for the simple model’s overestimation of the trigger efficiencies for the physics events samples. These effects pertain to features present at event generation in the physics events samples that are not present in the single electron events:

- The physics events contain photons from final state radiation emitted by electrons. These photons are present in the physics events at the event generation stage; they are not to be confused with photons from synchrotron radiation or bremsstrahlung. Initial and final state radiation was simulated in all the physics events samples. In contrast, bremsstrahlung is the only source of photons in the single electron events.

- The physics events contain photons from the decay of hadrons such as $\pi^0$’s and $\eta$’s. The physics events contain these particles in abundance. They are produced in hadronic processes in the events not exclusively targeted by the trigger. These photons are absent from the single electron events.

- The $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events have multiple high-$p_T$ electrons in the final state. It was conjectured that electrons that are narrowly separated might have a lower probability for selection, thereby decreasing the trigger efficiency. However, this is not expected to be a big effect because the final state electrons in these events will overwhelmingly be emitted back-to-back. Nevertheless, this was checked.

### 7.3.4.1.1 Photons from final state radiation

Figure [7.15](#) on the following page shows the relative location of particles from event generation in a region of size $0.2 \times 0.2 \text{rad}$ centred on the electrons in each physics event that have passed the preselection criteria. The particles close to the centre of the plot are correlated with the direction of the electrons.

The types of these particles are shown in Figure [7.16](#) on the next page. As expected, most of these particles are photons. The correlation between the location of the photons relative to the direction of the electrons demonstrates that the photons were radiated from the electrons. These photons are present in the samples before detector simulation. Hence, this is clear evidence that the photons are from final state radiation. A filter was added after the preselection to remove events that contain photons from final state radiation.
Figure 7.15: Relative location of particles near preselected electrons in physics events. The sample used was $H \rightarrow ZZ^* \rightarrow 4e$ with $m_H = 130\text{ GeV}/c^2$.

Figure 7.16: Type of particles near preselected electrons in physics events.
7.3 Performance with an optimal Electromagnetic Calorimeter

7.3.4.1.2 Photons from hadron decays

Figure 7.17 shows the relative location of particles from event generation in a region of size 0.2 × 0.2 rad centred on the electrons in each physics event that have passed the preselection criteria after events containing photons from final state radiation have been removed. The particles that remain form an isotropic background.

The type of these particles and their mothers are shown in Figures 7.18 on the next page and 7.19 on page 155, respectively. These figures show that particles forming the isotropic background in Figure 7.17 are mostly photons from the decay of hadrons, primarily \( \pi^0 \)'s and \( \eta \)'s.

To put the physics events samples on a more equal footing with the single electron events samples, a particle veto was added after the preselection; events that contain photons from hadron decays within 0.2 in \( \eta \) or 0.2 rad in \( \phi \) of preselected electrons were removed. The LVL2 calorimeter trigger examines clusters within an RoI of size 0.2 × 0.2 rad in \( \Delta \eta \times \Delta \phi \) [82]. Photons from final state radiation or hadron decays could potentially cause a LVL2 cluster to fail cuts on shower-shape quantities. LVL2 clusters are rejected if they are too broad or if the first sampling of the ECAL finds evidence of shower substructure. At the EF, the tracking algorithm \( x\text{Kalman}++ \) searches for tracks in a cone of size 0.2 × 0.2 around clusters centres. \( x\text{Kalman}++ \) uses the position of clusters in the ECAL to improve its estimate of the \( p_T \) of electrons that have lost energy because of bremsstrahlung in the ID. The track momentum is likely to be overestimated if photons from hadron de-
Figure 7.18: Type of particles near preselected electrons in physics events without photons from final state radiation.

cays are deposited in the cluster [32]. This can result in $E/p$ being too low for the electron candidate to be accepted.

7.3.4.1.3 Electron separation in multi-electron events

The effect of electron separation in $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events was investigated. The LVL1 electron/photon trigger algorithm identifies RoI of size $0.2 \times 0.2$ rad in $\Delta \eta \times \Delta \phi$. Consequently, pairs of electrons or photons separated by less than 0.2 in $\eta$ and 0.2 rad in $\phi$ will appear to the algorithm as a single entity [30]. For a multi-electron event such as $H \rightarrow ZZ^{(*)} \rightarrow 4e$, failure to resolve a pair of electrons as separate entities will result in a decrement in the number of opportunities available for the event to be selected by the single electron trigger. For this reason, it was expected that events in which the preselected electrons are closer than 0.2 in $\eta$ and 0.2 rad in $\phi$ would contribute negatively to the trigger efficiencies. Therefore, these events were excluded from the calculation of trigger efficiencies. As stated previously, this was not expected to have a noticeable effect but was checked nevertheless.
Figure 7.19: Type of mother of particles near preselected electrons in physics events without photons from final state radiation. (A “string” is an artifact of the phenomenological model of hadronisation used by PYTHIA. Particle mothers that were not saved in the event record are labelled “other”.)
7.3.4.1.4 Results of additional preselection criteria

The incremental and cumulative effect of the exclusion of events with photons from final state radiation, events with photons from hadron decays, and events with narrowly-separated electrons is shown in Figure 7.20 and Table 7.8 on the next page.

![Diagram](image)

Figure 7.20: Cumulative effect of additional filtering criteria on $\varepsilon_e^e$ for various physics channels. Additional filters were added after the preselection of events to exclude events with photons from final state radiation, events with photons from hadron decays, and events with narrowly-separated electrons. The additional filters were applied successively; see text for details. The figures in the parentheses are the values of the Higgs boson mass.

Figure 7.20 shows that the difference in $\varepsilon_e^e$ between the physics events samples and the single electron events sample can be narrowed, but cannot be completely accounted for, by the removal of the features that were identified as being unique to the physics events samples. The removal of events containing narrowly-separated electrons was found to have a negligible effect on the electron selection efficiencies, as expected.

Table 7.9 on page 158 shows that the discrepancy between the trigger efficiencies obtained for the physics events samples and the predictions of the simple model can be resolved if the LVL2 tracking and LVL2 matching steps are omitted from the the e25i selection. The estimates for the trigger efficiencies that would be expected from the e25i
### 7.3 Performance with an optimal Electromagnetic Calorimeter

#### Trigger efficiency (%)

<table>
<thead>
<tr>
<th>Preselection</th>
<th>Trigger efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W→eν</td>
<td>Z→ee</td>
</tr>
<tr>
<td>H→ZZ(µ→e)→4e, m_H (in GeV/c²):</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>180</td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Standard(^a)</td>
<td>65.5 ± 0.5</td>
</tr>
<tr>
<td>No FSR γ's(^b)</td>
<td>68.7 ± 0.6</td>
</tr>
<tr>
<td>No hadron decay γ's(^c)</td>
<td>69.7 ± 0.6</td>
</tr>
<tr>
<td>No non-isolated e±(^d)</td>
<td>69.7 ± 0.6</td>
</tr>
<tr>
<td>Estimated</td>
<td>72.8</td>
</tr>
</tbody>
</table>

- **Estimated**

The samples used to calculate these figures include events that contain:

- a Electrons that must satisfy preselection criteria that depend on p_T, \(\eta\), and multiplicity,
- b No photons from final state radiation,
- c No photons from hadron decay within 0.2 in \(\eta\) or 0.2 rad in \(\phi\) from preselected electrons,
- d No preselected electrons that are separated by less than 0.2 in \(\eta\) or 0.2 rad in \(\phi\).

Table 7.8: Cumulative effect of additional preselection criteria on trigger efficiencies for various physics channels. Additional requirements were added to the preselection of events to exclude events with photons from final state radiation, events with photons from hadron decays, and events with narrowly-separated electrons. The statistical errors on the estimated trigger efficiencies are all smaller than 0.1%.
selection without the \textit{LVL2} tracking and \textit{LVL2} matching steps were obtained from the simple model by using as input data a histogram of electron selection efficiency versus electron $p_T$ generated with these two trigger steps omitted from the selection.

The simple model was based on two assumptions: that $\varepsilon_e$ is the same irrespective of the type of events, and that the electron selection efficiency depends only on the $p_T$ of the electrons in each event. The first assumption has been proved false. The results in Table 7.9 seem to indicate that second assumption is reasonable only if the \textit{LVL2} tracking and \textit{LVL2} matching steps are omitted from the selection.

<table>
<thead>
<tr>
<th>Result</th>
<th>$W^{\rightarrow e\nu}$</th>
<th>$Z^{\rightarrow ee}$</th>
<th>$H^{\rightarrow ZZ^{(*)}\rightarrow 4\ell}$, $m_H$ (in GeV/$c^2$):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual$^{a,b,c,d}$</td>
<td>$76.7 \pm 0.5$</td>
<td>$92.5 \pm 0.5$</td>
<td>$95.3 \pm 0.5$</td>
</tr>
<tr>
<td></td>
<td>$98.9 \pm 0.3$</td>
<td>$99.4 \pm 0.2$</td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>$77.4$</td>
<td>$92.6$</td>
<td>$95.7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$99.1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$99.4$</td>
</tr>
</tbody>
</table>

The samples used to calculate these figures include events that contain:

- Electrons that must satisfy preselection criteria that depend on $p_T$, $\eta$, and multiplicity,
- No photons from final state radiation,
- No photons from hadron decay within 0.2 in $\eta$ or 0.2 rad in $\phi$ from preselected electrons,
- No preselected electrons that are separated by less than 0.2 in $\eta$ or 0.2 rad in $\phi$.

The statistical errors on the estimated trigger efficiencies are all smaller than 0.1%.

### 7.3.4.2 Overall trigger efficiencies

The trigger efficiencies that appear in this thesis are calculated with events that must satisfy geometrical and kinematical cuts, as described previously. The cuts were applied before detector simulation (to make economical use of memory and CPU resources) and during preselection (to reject events that have a negligible chance of triggering). These cuts were applied for the sake of convenience. The \textit{overall trigger efficiency} is defined to be equal to the trigger efficiency normalised with respect to the events accepted in the
The overall trigger efficiencies for the physics events samples are shown in Table 7.10. For each sample, the overall trigger efficiency was taken to be equal to the product of the (geometrical and kinematical) acceptance and the trigger efficiency evaluated with events that had not been preselected. The acceptance was taken to be equal to the number of fully-simulated events divided by the number of generated events. Appendix C contains a note about how the overall trigger efficiency relates to the true efficiency to trigger on the events as they occur in nature.

<table>
<thead>
<tr>
<th>Process</th>
<th>Acceptance (%)</th>
<th>Overall trigger efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>64.2 ± 0.4</td>
<td>30.0 ± 0.3</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>53.3 ± 0.4</td>
<td>39.9 ± 0.4</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4e$, $m_H = 130 \text{ GeV}/c^2$</td>
<td>63.9 ± 0.4</td>
<td>50.9 ± 0.4</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 180 \text{ GeV}/c^2$</td>
<td>71.9 ± 0.5</td>
<td>64.6 ± 0.6</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 300 \text{ GeV}/c^2$</td>
<td>77.9 ± 0.5</td>
<td>71.6 ± 0.5</td>
</tr>
</tbody>
</table>

Table 7.10: Overall trigger efficiencies for the physics samples. No preselection of events was applied.

7.4 Conclusions

The results obtained with single electron events demonstrate that the e25i trigger selection meets the requirements of the HLT and is sufficient for use in this study. The performance is comparable with that obtained in a previous study undertaken by the ATLAS HLT group. The performance of the selection for various physics processes was examined and the efficiencies were found to be smaller than expected. This is attributable to features that are present in the physics events. These features contribute negatively to the trigger efficiencies. The single electron events are distinct from the physics events and were produced in a unique way. Therefore, it should not be too surprising that the performance obtained with single electron events is different from the performance obtained with physics events. This highlights the importance of cross-checking the performance of the single electron trigger with fully-simulated physics events to test the robustness of the selection under realistic conditions expected at the LHC.
Chapter 8

Electron trigger robustness

The purpose of this study was to investigate the effects of unresponsive LAr ECAL cells and LAr ECAL FEBs (hereafter referred to as dead cells and dead FEBs, respectively) on the single electron trigger. Initially the investigation focuses on the effects of dead cells and dead FEBs on the efficiency to trigger on single electron events. This is followed by an investigation of the effects of dead cells and dead FEBs on the trigger efficiency for $W \rightarrow \ell\nu$, $Z \rightarrow e^+e^-$ and $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ events. During operation of the real detector, the proportion of dead cells and dead FEBs will be measurable. Therefore, the results of this study will enable the loss in trigger efficiency for these important physics channels to be estimated for a given proportion of dead cells or dead FEBs.

8.1 Introduction

The effects of dead cells and dead FEBs were studied independently of each other. For each event, a list of cells or FEBs to be “killed” was randomly generated. The generated list for a given proportion of cells or FEBs to be killed was different for every data production run. This was done to avoid any systematic bias in the results. There may be particular configurations of dead cells that are more critical than others. Changing the configuration of dead cells every event has the effect that the results of this study correspond to the average of all possible configurations of dead cells. This approach is more efficient at converging to a result than choosing a particular configuration for each data production run, and it does not depend on any assumptions about the patterns of failure of cells or FEBs that could occur.

FEBs do not exist as entities in the simulation code. It is only possible to request the unique identification number of the FEB to which a particular cell belongs. The effect of
dead FEBs was simulated by killing all the cells that are associated with the identification number of the FEBs listed as dead.

The list of dead cells was consulted during the simulation of the LVL1 trigger tower readout and the HLT cell readout, thereby guaranteeing that each dead cell will appear dead in both electronics chains. The cells themselves were killed by zeroing their energy. They were killed randomly, independent of their size, location, sampling or energy content. Similarly, all FEBs were treated equally. There is no reason to believe that any single FEB is more susceptible to failure than any other.

The LVL1 calorimeter simulation used in this study built trigger towers directly from calorimeter cells instead of using simulations of the actual analogue trigger tower signals. The difference is that the former method builds trigger towers from digitised data which is not part of the real signal path, whereas the latter method builds trigger towers from the analogue sums of the hits in the cells. This is an approach that has been used for many other trigger studies and is judged to have a negligible impact on the results.

During operation of the real detector, dead cells and dead FEBs will be easily detectable by unusually low electronic noise. If a significant number of cells are discovered to be dead, the calibration of the affected cells or trigger towers might be adjusted to partially compensate for the EM shower energy that is lost. However, energy resolution would still be severely degraded because the fraction of the EM shower energy that is lost is subject to statistical fluctuations [97]. In this study, no corrections to cluster or trigger tower energies were applied to account for the effects of dead cells or dead FEBs.

8.2 Results with single electron events

The location in $\eta$-$\phi$ space of calorimeter cells that are unresponsive because the cells themselves, or the FEBs they are connected to, are dead is shown in Figure 8.1 on the following page. Figure 8.1(a) shows the result of killing individual cells; the cells that are dead are distributed throughout the whole calorimeter. Figure 8.1(b) shows the result of killing FEBs; the cells that are dead are aggregated and form regions of contiguous dead cells. The latter plot demonstrates that the failure of an FEB results in a rectangular “hole” or “blind spot” in a sampling. The affected regions vary in size according to the granularity of the cells in each sampling. In the calorimeter endcaps, where the granularity of cells is coarse, these regions can be large.
Figure 8.1: Location in $\eta$-$\phi$ space of dead calorimeter cells. Figure (a) shows the location of the cells that are dead when 0.1% of the cells are killed individually. Figure (b) shows the location of the cells that are rendered unresponsive when 0.1% of FEBs are killed. Data from 100 events was superposed to exaggerate the effect of killing cells and FEBs, for the sake of visual clarity. All calorimeter samplings are shown.
The effect of dead cells and dead FEBs on electron selection efficiency is shown in Figure 8.2 on the next page. Electron selection efficiency versus MC truth electron $p_T$ is plotted for samples of reconstructed single electron events in which various proportions of dead cells or dead FEBs have been simulated. The two sets of samples that were used to obtain the results shown in Figure 8.2(a) and Figure 8.2(b) differed only in the way in which the dead cells were distributed in the calorimeter. Irrespective of whether the effect simulated was that of dead cells or dead FEBs, the proportion of dead cells was the same.

In the data used to obtain the results shown in Figure 8.2 on the following page, the proportion of dead cells and the proportion of dead FEBs both range from 0 to 50%. It is generally assumed that a scenario in which more than 1% of the calorimeter cells are dead, whether as a result of attrition of individual cells or FEB failure, will never occur. The investigation of what happens if the proportion of dead cells is larger than this is essentially academic. The results corresponding to this scenario are shown to exaggerate the effect of dead cells or dead FEBs, for the sake of visual clarity.

The results show that $\varepsilon_e$ for single electron events decreases as the proportion of dead cells or dead FEBs increases. In addition, the effective $p_T$ threshold for triggering is smeared towards higher values of electron $p_T$. This has the effect that, as the proportion of dead cells or dead FEBs increases, more electrons will have $p_T$ below this threshold and will be rejected.

Even if the calorimeter is unaffected by dead cells or dead FEBs, electrons with $p_T$ below the effective threshold for triggering have a negligible chance of being accepted. Electrons with $p_T$ very close to this threshold have a triflingly small probability for selection only because the relationship between electron selection efficiency and electron $p_T$ is not strictly a step function. Generally, electrons with $p_T$ below the effective threshold for triggering are not accepted. The trigger’s response to these electrons is not affected by the effect of dead cells or dead FEBs because, even with an optimal calorimeter, they have a negligible chance of being accepted.

However, the same is not true of electrons that have $p_T$ just above the effective threshold for triggering; the efficiency to select these electrons is particularly susceptible to increases in the proportion of dead cells or dead FEBs. To demonstrate this, the bin-by-bin difference in electron selection efficiency for single electron events between the 10% dead cell scenario and the optimal calorimeter scenario is shown in Figure 8.3(a). Similarly, the bin-by-bin difference in electron selection efficiency for single electron events between the 10% dead FEB scenario and the optimal calorimeter scenario is shown in Figure 8.3(b).
Electron selection efficiency versus MC truth electron $p_T$ for various proportions of dead cells and dead FEBs.

(a) Dead cells.

(b) Dead FEBs.
8.2 Results with single electron events

(The value 10% has no special significance; it was chosen merely so that the systematic effect would be large enough to be plainly visible.) When comparing the 10% dead cell scenario and the optimal calorimeter scenario, the bin-by-bin difference \( \Delta \varepsilon_e \) is given by

\[
\Delta \varepsilon_e = \varepsilon_e^{10\% \text{ dead cells}} - \varepsilon_e^{\text{Optimal calorimeter}}.
\]  

(8.1)

When comparing the 10% dead FEB scenario and the optimal calorimeter scenario, \( \Delta \varepsilon_e \) is given by

\[
\Delta \varepsilon_e = \varepsilon_e^{10\% \text{ dead FEBs}} - \varepsilon_e^{\text{Optimal calorimeter}}.
\]  

(8.2)

Figure 8.3 on the next page demonstrates that the severity of the effect of dead cells or dead FEBs on the single electron trigger depends on the \( p_T \) of the electrons in the events. It also shows that dead cells have a more pronounced effect on the effective \( p_T \) threshold for triggering than dead FEBs; there is a marked qualitative difference in \( \Delta \varepsilon_e \) between Figure 8.3(a) and Figure 8.3(b) for electrons with \( p_T \approx 23 \text{ GeV}/c \).

On average, 10% of the cells that EM showers deposit their energy into will be dead if 10% of the cells in the calorimeter are dead. This is a direct consequence of the dead cells being distributed uniformly throughout the calorimeter. The loss of active cells degrades the calorimeter’s ability to resolve the true energy and transverse barycentre of an EM shower. As a result, the reconstructed \( p_T, \eta \) and \( \phi \) of electron candidates is smeared. This can cause electron candidates to fail cuts on, for example, quantities like cluster energy, shower-shape variables and \( E_T/p_T \). This effect is eventually manifested in the apparent smearing of the effective \( p_T \) threshold for triggering.

For the scenario in which 10% of FEBs are dead, it is not true that 10% of the cells that EM showers deposit their energy into will be dead. The extent to which EM showers are affected by dead FEBs depends on the probability that an EM shower will overlap with a region of contiguous dead cells. The probability for this to happen depends only in part on the proportion of FEBs that are dead. It also depends on the relative transverse sizes of EM showers and regions of contiguous dead cells. Figure 8.4 on page 167 shows the transverse dimensions of both an EM shower and a region of contiguous dead cells resulting from the failure of a single FEB. It can be seen from the figure that the EM shower and the region of contiguous dead cells are comparable in size. The region in question is of size 0.2 \( \times \) 0.4 rad in \( \Delta \eta \times \Delta \phi \) and corresponds to 32 \( \times \) 4 cells, each of size 0.006 \( \times \) 0.1 rad, in the first sampling of the EMEC.

The second sampling has coarser transverse granularity than the first sampling. Consequently, the regions affected by dead FEBs are larger in the second sampling than in
Figure 8.3: Bin-by-bin difference in electron selection efficiency for single electron events for two different dead cell and dead FEB scenarios (0 and 10% dead cells, and 0 and 10% dead FEBs).
Figure 8.4: Typical transverse dimensions of both an EM shower and a region of contiguous dead cells resulting from the failure of a single FEB. A single event is shown. Figure (a) shows the cells in the calorimeter with energy less than or equal to zero in a typical single electron event. This is the “negative” of the image produced by plotting the cells that have energy remaining after pedestal subtraction to remove noise. The negative of the image is shown for aesthetic reasons and for the sake of clarity. All calorimeter samplings are shown. An EM shower is clearly visible in the lower left-hand corner of the figure. Figure (b) shows the cells rendered unresponsive by the failure of a single FEB. These dead cells are located in a single sampling and form a rectangular “hole”. The position of the MC truth electron is shown with an asterisk.
the first. Likewise, those in the third sampling are larger still. The cells in the second sampling are of size $3.75 \times 3.68 \text{ cm}^2$ at $\eta = 0$. One possible configuration of dead cells in this sampling resulting from the failure of an FEB might be a region of $8 \times 16$ cells. At $\eta = 0$, this region is about $30 \times 60 \text{ cm}^2$ in size. Therefore, regions affected by dead FEBs vary from being comparable in size to the transverse profile of an EM shower to a few times larger.

In each event, the locations of both the EM showers and the regions rendered unresponsive by FEB failure are determined by independent random processes. An EM shower is more likely to be affected by one or more dead cells if all the dead cells are individually distributed in the calorimeter, rather than if they are concentrated within a number of regions. However, an overlap between an EM shower and a region of contiguous dead cells affects the energy of reconstructed electron candidates more severely than an overlap between an EM shower and a few individually distributed dead cells.

To demonstrate this, the event-by-event difference in the $E_T$ of clusters reconstructed at LVL1, LVL2 and the EF between the 10% dead cell scenario and the optimal calorimeter scenario are shown in Figure 8.5 to 8.7 on pages 169–170. The event-by-event cluster $E_T$ differences between the 10% dead FEB scenario and the optimal calorimeter scenario are superposed. For a given event with a given cluster at a given trigger level, the cluster $E_T$ difference $\Delta E_T$ is given by

$$\Delta E_T = E_{T\text{10% dead cells}} - E_{T\text{Optimal calorimeter}}$$

when comparing the 10% dead cell and the optimal calorimeter scenarios, and by

$$\Delta E_T = E_{T\text{10% dead FEBs}} - E_{T\text{Optimal calorimeter}}$$

when comparing the 10% dead FEBs and the optimal calorimeter scenarios.

The results show that dead cells are more likely to be responsible for small cluster $E_T$ losses than dead FEBs. If an EM shower is coincident with a single dead cell, the measured $E_T$ of the EM shower will differ only slightly from the $E_T$ that would be measured if that cell was active. The measured $E_T$ of the EM shower is gradually reduced as the number of dead cells coincident with the EM shower increases. This is evident in Figure 8.5 to 8.7 on pages 169–170; the distribution of $\Delta E_T$ varies smoothly for clusters that have lost energy as a result of dead cells that are individually distributed throughout the calorimeter. This figure also shows that dead FEBs are more likely to cause large cluster $E_T$ losses than dead cells. There are conspicuous steps in the distribution of $\Delta E_T$ for clusters that have lost energy as a result of dead FEBs. It is likely that these steps are the result of
8.2 Results with single electron events

Figure 8.5: Difference in cluster $E_T$ at LVL1 between the 10% dead cell scenario and the optimal calorimeter scenario, and also between the 10% dead FEB scenario and the optimal calorimeter scenario. The events contain single electrons with $p_T$ between 30 and 80 GeV/c.

Figure 8.6: Difference in cluster $E_T$ at LVL2 between the 10% dead cell scenario and the optimal calorimeter scenario, and also between the 10% dead FEB scenario and the optimal calorimeter scenario. The events contain single electrons with $p_T$ between 30 and 80 GeV/c.
Figure 8.7: Difference in cluster $E_T$ at the EF between the 10% dead cell scenario and the optimal calorimeter scenario, and also between the 10% dead FEB scenario and the optimal calorimeter scenario. The events contain single electrons with $p_T$ between 30 and 80 GeV/c.

Overlaps between EM showers and regions of contiguous dead cells in successive calorimeter samplings. The smooth transition between each step is most probably due to various degrees of overlap in each sampling between EM showers and regions affected by dead FEBs. The small number of entries in the histograms bins corresponding to positive $\Delta E_T$ are likely due to pedestal subtraction to account for electronic noise in the ECAL [114].

The effect of dead cells on $\varepsilon_e$ and trigger rates is shown in Figure 8.8 on the next page. Figure 8.9 on page 172 shows the effect of dead FEBs on $\varepsilon_e$ and trigger rates. The results show that relationship between $\varepsilon_e$ for single electron events and the proportion of dead cells or dead FEBs in the calorimeter is linear up to at least 5% dead cells or dead FEBs. The value of $\varepsilon_e$ for single electron events decreases by $1.25 \pm 0.05\%$ for every 1% increase in dead cells, and by $1.15 \pm 0.05\%$ for every 1% increase in dead FEBs. The difference in behaviour arises solely from the difference in the distribution of the dead cells in the calorimeter.

It is not possible to discern from the results that dead cells or dead FEBs have any effect on trigger rates. There are no obvious trends. There are two random elements that affect the production of the data used for each data point:

- The sequence of random numbers that was used to determine which cells or FEBs are to be killed in each event was different for each data point. (The seed value for
8.2 Results with single electron events

Figure 8.8: $\varepsilon_e$ and trigger rate versus proportion of dead cells. A linear fit and zeroth-order polynomial fit to the data are shown in (a) and (b), respectively. The errors are correlated.
Figure 8.9: $\sigma_e$ and trigger rate versus proportion of dead FEBs. A linear fit and zeroth-order polynomial fit to the data are shown in [a] and [b], respectively. The errors are correlated.
8.3 Results with physics events

the random number generator was different for each data production run.)

- Some data production runs did not complete successfully and returned no data. Consequently, some events are missing in each sample. Therefore, the samples used to generate each data point are not identical. Each event is given a unique identification number during event generation. A comparison of these numbers was used to determine that 76% of the events in each sample are identical in all respects, other than in the percentage of cells or FEBs killed, to the events in the other samples.

These effects are responsible for the variation in the estimates of the trigger rates. Many more dijet events would need to be produced to decrease the size of the statistical errors. This might reveal an underlying trend.

The signal to background ratio \( S/B \) is defined as

\[
\frac{S}{B} = \frac{\varepsilon_E}{R}.
\] (8.5)

The number of single electron events \( S \) is proportional to \( \varepsilon_E \), which is taken to be the trigger efficiency for single electrons with \( p_T \geq 30 \text{ GeV/c} \). That is, \( \varepsilon_E = \varepsilon_e \). The number of dijet events \( B \) is proportional to the trigger rate \( R \). Figure 8.10(a) and 8.10(b) on the next page show \( S/B \) versus the proportion of cells or FEBs that are dead, respectively. The dark grey bands in each plot illustrate the extent of the variation in the values of \( S/B \). The maximum relative deviation from the average value of \( S/B \) defines the upper and lower bounds of these bands. The signal to background ratio \( S/B \) varies no more than \( \pm 5.6\% \) and \( \pm 11.5\% \) for dead cell fractions and dead FEBs fractions up to 5%, respectively.

8.3 Results with physics events

Values of \( \varepsilon_e \) for various physics samples versus the proportion of dead cells or dead FEBs are shown in Figure 8.11 on page 175. The gradient of \( \varepsilon_e \) is approximately the same for all the physics samples. The results show that, for all samples, the relationship between \( \varepsilon_e \) and the proportion of dead cells or dead FEBs is linear up to at least 5% dead cells or dead FEBs for all samples. On average, \( \varepsilon_e \) for physics samples decreases by \( 1.15 \pm 0.05\% \) for every 1% increase in dead cells, and by \( 1.03 \pm 0.05\% \) for every 1% increase in dead FEBs. These figures confirm the earlier finding, obtained with single electron events, that dead cells have a larger effect on electron selection efficiencies than dead FEBs. Moreover,
Figure 8.10: Signal to background ratio $S/B$ versus proportion of dead cells or dead FEBs. A zeroth-order polynomial fit to the data is shown. The dark grey band in each plot represents the largest deviation from the average value of $S/B$. The light grey band in each plot represent the typical size of the statistical errors on $S/B$. 
the size of the effect of dead cells and the size of the effect of dead FEBs both agree with the results presented earlier that were obtained with single electron events.

Figure 8.11: \( \sigma_T \) for physics events versus proportion of dead cells or dead FEBs. Linear fits to the data are shown.

The trigger efficiency for various physics samples versus the proportion of dead cells or dead FEBs is shown in Figure 8.12 on the next page. The relationship between trigger efficiency and the proportion of dead cells or dead FEBs is linear up to at least 5% dead
cells or dead FEBs for all physics samples. Table 8.1 on the facing page shows the gradients of the linear fits to the data.

Figure 8.12: Trigger efficiency for physics events versus proportion of dead cells or dead FEBs. Linear fits to the data are shown.

The results show that dead cells have a greater effect on trigger efficiency than dead FEBs. Among the physics samples, there is a noticeable variation in the severity of the effect of dead cells and dead FEBs on trigger efficiency. The severity of the effect of dead cells or dead FEBs decreases as the number of final-state electrons from each signal process increases.
Table 8.1: Gradients of linear fits to trigger efficiency versus dead cell and dead FEB data. The figures are applicable for proportions of dead cells and dead FEBs up to at least 5% increases. The trigger efficiency for $W\to e\nu$ events, which have one final-state electron from the signal process, is affected most by dead cells and dead FEBs. The trigger efficiency for $H\to ZZ^{(*)}\to 4e$ events, which have four final-state electrons from the signal process, is affected least by dead cells and dead FEBs.

For the $H\to ZZ^{(*)}\to 4e$ events, the trigger efficiency is affected by dead cells and dead FEBs less severely as the Higgs boson mass increases. This is because the average $p_T$ of the four electrons from the Higgs decay increases with the Higgs boson mass. As a result, more electrons have $p_T$ above the effective threshold for triggering. The region near the effective threshold for triggering is particularly susceptible to increases in the proportion of dead cells or FEBs. Therefore, as the Higgs boson mass increases, the efficiency to select $H\to ZZ^{(*)}\to 4e$ events is affected less severely by dead cells and dead FEBs. The effects of dead cells and dead FEBs on the trigger efficiency for $H\to ZZ^{(*)}\to 4e$ events are never completely mitigated. A heavier Higgs boson results in more electrons per event that have $p_T$ in the range where the effect of dead cells and dead FEBs on electron selection efficiency is somewhat constant with respect to electron $p_T$, as illustrated in Figure 8.3 on page 166.

The gradients of the linear fits to the data for $H\to ZZ^{(*)}\to 4e$ events in Figure 8.12 on the facing page are plotted against the mass of the Higgs boson in Figure 8.13 on the next page, which demonstrates that the severity of the effect of dead cells and dead FEBs on the trigger efficiency for $H\to ZZ^{(*)}\to 4e$ events is reduced — but not entirely mitigated — as the Higgs boson mass increases.

No obvious trends were observed in the signal to background ratios for the physics
events samples. It is not possible to discern from the results that dead cells or dead FEBs have any effect on the signal to background ratios. This might be because the dijet event samples are too small. The errors on the trigger rates are large and are propagated to the errors on $S/B$. The maximum relative deviation from the average value of the signal to background ratio for dead cell fractions and dead FEBs fractions up to 5%, $\delta(S/B)$, is shown in Table 8.2 for the physics events samples.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\delta(S/B)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>Dead cells: 5.7, Dead FEBs: 11.5</td>
</tr>
<tr>
<td>$Z \rightarrow e e$</td>
<td>Dead cells: 5.4, Dead FEBs: 11.3</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4e$, $m_H = 130\text{ GeV}/c^2$</td>
<td>Dead cells: 5.5, Dead FEBs: 11.8</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 180\text{ GeV}/c^2$</td>
<td>Dead cells: 7.2, Dead FEBs: 11.5</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 300\text{ GeV}/c^2$</td>
<td>Dead cells: 8.2, Dead FEBs: 11.4</td>
</tr>
</tbody>
</table>

Table 8.2: Maximum relative deviation from the average signal to background ratio, for dead cell fractions and dead FEBs fractions up to 5%, for physics events samples.

The effects of dead cells and dead FEBs on overall trigger efficiency are shown in Figure 8.14 on page 180 and summarised in Table 8.3 on the facing page. The table shows...
8.4 Conclusions

the rate at which dead cells and dead FEBs affect overall trigger efficiency. The figures in the table show that, in general, overall trigger efficiencies for physics events are affected less severely by dead cells and dead FEBs than trigger efficiencies. This is because the effect of dead cells or dead FEBs on overall trigger efficiency is diluted by events that contain electrons that have only a small chance of triggering, even with the best possible calorimeter. These events are absent from the samples that have been preselected. For example, the preselection of the $W \rightarrow e\nu$ sample only accepted events that contain at least one electron with $p_T > 25$ GeV/c. The remaining 34.4% of events that were rejected by the preselection had a trigger efficiency of only $11.0 \pm 0.5\%$ with an optimal calorimeter.

The variation in the figures in Table 8.3, or lack thereof, is due to the $p_T$ distribution of the electrons in the physics samples. The results are consistent with the trends that are apparent in Table 8.1 on page 177: dead cells have more of an effect on trigger performance than dead FEBs, and the severity of both effects decreases as the multiplicity and $p_T$ of electrons in each event increases.

<table>
<thead>
<tr>
<th>Process</th>
<th>Dead cells</th>
<th>Dead FEBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$-0.6 \pm 0.1$</td>
<td>$-0.5 \pm 0.1$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$-0.5 \pm 0.1$</td>
<td>$-0.4 \pm 0.1$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4e$, $m_H = 130$ GeV/$c^2$</td>
<td>$-0.6 \pm 0.1$</td>
<td>$-0.4 \pm 0.1$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 180$ GeV/$c^2$</td>
<td>$-0.5 \pm 0.1$</td>
<td>$-0.3 \pm 0.1$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4e$, $m_H = 300$ GeV/$c^2$</td>
<td>$-0.4 \pm 0.1$</td>
<td>$-0.3 \pm 0.1$</td>
</tr>
</tbody>
</table>

Table 8.3: Gradients of linear fits to overall trigger efficiency versus dead cell and dead FEB data. The figures are applicable for proportions of dead cells and dead FEBs up to at least 5%.

8.4 Conclusions

The results show that dead cells and dead FEBs reduce the efficiency of the single electron trigger. The severity of the effect depends on the multiplicity and $p_T$ of electrons in the events; the trigger efficiency is less affected as the multiplicity and $p_T$ of electrons in each event increases. Although dead FEBs can potentially reduce the energy of an EM shower
Figure 8.14: Overall trigger efficiency for physics events versus proportion of dead cells or dead FEBs. (The meaning of overall trigger efficiency was described in Section 7.3.4.2.)
to a greater degree than dead cells, it is the effect of dead cells that has the greater impact on trigger efficiency.

Single electron events are a staple for benchmarking the single electron trigger. From these events, a rough but easily remembered result was obtained: the trigger efficiency for single electrons with $p_T \geq 30\, \text{GeV}/c$ decreases by a little over 1% for every 1% increase in dead cells or dead FEBs. The search for a Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4e$ decay channel will rely heavily on the ECAL information. The results of this study demonstrated that, depending on the mass of the Higgs boson, the trigger efficiency for $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events decreases by between 0.3 and 0.9% for every 1% increase in dead cells or dead FEBs. Correspondingly, the overall trigger efficiency decreases by between 0.3 and 0.6%. These trends are applicable for proportions of dead cells or dead FEBs up to at least 5%.
Appendix A

Acronyms

ADC  analogue to digital converter
ALICE A Large Ion Collider Experiment
AMI ATLAS Metadata Interface
ATLAS A Toroidal LHC ApparatuS
BT  barrel toroid
CERN Organisation Européenne pour la Recherche Nucléaire
CMS Compact Muon Solenoid
CP  charge-parity
CPU central processing unit
CSC Cathode Strip Chamber
CS  central solenoid
CTP Central Trigger Processor
CVS Concurrent Versions System
DC1 Data Challenge 1
EB  Event Builder
ECAL Electromagnetic Calorimeter
ECT endcap toroid
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM</td>
<td>Event Data Model</td>
</tr>
<tr>
<td>EDO</td>
<td>Event Data Object</td>
</tr>
<tr>
<td>EF</td>
<td>Event Filter</td>
</tr>
<tr>
<td>EMB</td>
<td>Electromagnetic Barrel Calorimeter</td>
</tr>
<tr>
<td>EMEC</td>
<td>Electromagnetic Endcap Calorimeter</td>
</tr>
<tr>
<td>EM</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>FCAL</td>
<td>Forward Calorimeter</td>
</tr>
<tr>
<td>FEB</td>
<td>Front-End Board</td>
</tr>
<tr>
<td>FEC</td>
<td>Front-End Crate</td>
</tr>
<tr>
<td>FEX</td>
<td>feature extraction</td>
</tr>
<tr>
<td>HCAL</td>
<td>Hadronic Calorimeter</td>
</tr>
<tr>
<td>HEC</td>
<td>Hadronic Endcap Calorimeter</td>
</tr>
<tr>
<td>HLT</td>
<td>High-Level Trigger</td>
</tr>
<tr>
<td>HLTSSW</td>
<td>High-Level Trigger Selection Software</td>
</tr>
<tr>
<td>HV</td>
<td>high voltage</td>
</tr>
<tr>
<td>ID</td>
<td>Inner Detector</td>
</tr>
<tr>
<td>LAr</td>
<td>liquid argon</td>
</tr>
<tr>
<td>LEP</td>
<td>Large Electron-Positron collider</td>
</tr>
<tr>
<td>LHCb</td>
<td>Large Hadron Collider beauty</td>
</tr>
<tr>
<td>LHCf</td>
<td>Large Hadron Collider forward</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>LVL1</td>
<td>Level-1</td>
</tr>
<tr>
<td>LVL2</td>
<td>Level-2</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>MDT</td>
<td>Monitored Drift Tube</td>
</tr>
<tr>
<td>MSSM</td>
<td>Minimal Supersymmetric Standard Model</td>
</tr>
<tr>
<td>MWPC</td>
<td>Multi-Wire Proportional Chamber</td>
</tr>
<tr>
<td>NbTi</td>
<td>niobium-titanium</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
</tr>
<tr>
<td>PC</td>
<td>personal computer</td>
</tr>
<tr>
<td>PESA</td>
<td>Physics and Event Selection Architecture</td>
</tr>
<tr>
<td>PMT</td>
<td>photomultiplier tube</td>
</tr>
<tr>
<td>QCD</td>
<td>quantum chromodynamics</td>
</tr>
<tr>
<td>QED</td>
<td>quantum electrodynamics</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>ROB</td>
<td>readout buffer</td>
</tr>
<tr>
<td>ROBIN</td>
<td>readout buffer input card</td>
</tr>
<tr>
<td>ROD</td>
<td>read-out driver</td>
</tr>
<tr>
<td>RoI</td>
<td>Region of Interest</td>
</tr>
<tr>
<td>RPC</td>
<td>Resistive Plate Chamber</td>
</tr>
<tr>
<td>RTTI</td>
<td>runtime type identification</td>
</tr>
<tr>
<td>SCT</td>
<td>Semiconductor Tracker</td>
</tr>
<tr>
<td>SM</td>
<td>Standard Model</td>
</tr>
<tr>
<td>SPEC</td>
<td>Standard Performance Evaluation Corporation</td>
</tr>
<tr>
<td>STL</td>
<td>Standard Template Library</td>
</tr>
<tr>
<td>TES</td>
<td>Transient Event Store</td>
</tr>
<tr>
<td>SUSY</td>
<td>Supersymmetry</td>
</tr>
<tr>
<td>TBB</td>
<td>Tower Builder Board</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>TDAQ</td>
<td>trigger and data acquisition</td>
</tr>
<tr>
<td>TDR</td>
<td>Technical Design Report</td>
</tr>
<tr>
<td>TE</td>
<td>Trigger Element</td>
</tr>
<tr>
<td>TGC</td>
<td>Thin Gap Chamber</td>
</tr>
<tr>
<td>TOTEM</td>
<td>TOTal and Elastic Measurement</td>
</tr>
<tr>
<td>TRT</td>
<td>Transition Radiation Tracker</td>
</tr>
<tr>
<td>TTC</td>
<td>Timing, Trigger and Control</td>
</tr>
<tr>
<td>VEV</td>
<td>vacuum expectation value</td>
</tr>
<tr>
<td>WLS</td>
<td>wavelength-shifting</td>
</tr>
<tr>
<td>WRe</td>
<td>tungsten-rhenium</td>
</tr>
<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
</tr>
</tbody>
</table>
A function for modelling the $p_T$-dependence of the e25i trigger

The average value of the electron selection efficiency above the effective $p_T$ threshold for triggering is of prime interest in this thesis. A zeroth-order polynomial fit to the data with $p_T$ in the range 30–80 GeV/c is sufficient for estimating the average value of the electron selection efficiency above the effective $p_T$ threshold for triggering. However, it is interesting to examine other models that could fit the data better; a desirable property would be that the model is applicable over the full range of electron $p_T$. (Note that the following was not used in the studies presented earlier in this thesis.)

The data appears to exhibit S-shaped growth. Curves of this type are often well modelled by a logistic growth function [115]. Logistic growth functions have been used extensively for modelling biological processes and population dynamics [116]. Models based on logistic growth functions assume that the system being modelled grows exponentially until an upper limit is reached, at which point the growth rate slows and eventually saturates. In the simple logistic growth model, it is assumed that a single growth process operates in isolation.

A reasonable fit to the data was obtained using a “bilogistic” growth function. Bilogistic growth functions are useful in modelling systems in cases when growth is controlled by dual processes which operate either sequentially or simultaneously, or a mixture of the two. It was expected that a bilogistic growth function would fit the data better than a simple logistic function because the e25i selection contains several cuts, and therefore it is unlikely that a single growth process is at work. The function to be fitted to the data was

$$
\varepsilon(p_T) = \frac{\kappa_1}{1 + e^{-\alpha_1(p_T - \beta_1)}} + \frac{\kappa_2}{1 + e^{-\alpha_2(p_T - \beta_2)}} \quad (B.1)
$$
A function for modelling the $p_T$-dependence of the e25i trigger

where $\kappa_1$ and $\kappa_2$ specify the levels at which the two growth processes saturate, $\alpha_1$ and $\alpha_2$ are the growth rates, and $\beta_1$ and $\beta_2$ are the $p_T$ at which maximum growth occurs in the two growth processes. The sum of $\kappa_1$ and $\kappa_2$ is the value of the electron selection efficiency at the horizontal asymptote, and $\alpha_1$ and $\alpha_2$ account for the “lop-sidedness” of the data about the effective $p_T$ threshold for triggering. The use of this model was motivated purely by the observed distribution of the data points. Figure B.1 shows the fit to the data.

![Figure B.1: Bilogistic fit to electron selection efficiency data. The fit was obtained by minimising the $\chi^2$ between the bilogistic function and the data.](image)

The fitted value of the electron selection efficiency obtained from the zeroth-order polynomial fit is equal to the sum of $\kappa_1$ and $\kappa_2$ (within statistical errors). This function can be used in place of the electron selection efficiency histogram used to estimate trigger efficiencies for various physics processes, described in Section 7.3.3.
Calculating overall trigger efficiencies

The efficiency to trigger on events as they occur in nature is given by

\[
P (t \cap (p \cup \bar{p}) \cap (s \cup \bar{s})) = P ((t \cap p \cap s) \cup (t \cap p \cap \bar{s}) \cup (t \cap \bar{p} \cap s) \cup (t \cap \bar{p} \cap \bar{s}))
= P (t \cap p \cap s) + P (t \cap p \cap \bar{s}) + P (t \cap \bar{p} \cap s)
+ P (t \cap \bar{p} \cap \bar{s})
= P (s) P (p|s) P (t|p \cap s) + P (s) P (\bar{p}|s) P (t|\bar{p} \cap s)
+ P (\bar{s}) P (\bar{p}|\bar{s}) P (t|\bar{p} \cap \bar{s})
\]

where \( t \) denotes that the event is accepted by the trigger, \( p \) denotes that the event is accepted by the preselection, and \( s \) denotes that the (generated) event is accepted for full-simulation. \( \bar{p} \) and \( \bar{s} \) are the complements of \( p \) and \( s \), respectively. The acceptance \( P (s) \) is taken to be equal to the number of fully-simulated events divided by the number of generated events, \( P (p|s) \) is taken to be equal to the fraction of fully-simulated events that are accepted by the preselection, and \( P (t|p \cap s) \) is taken to be equal to the trigger efficiency that is obtained with preselected events.

The derivation is simplified by the fact that \( P (t \cap p \cap \bar{s}) \) is equal to zero, because the requirements imposed by the preselection on each event are more restrictive than those imposed by the particle level filter before detector simulation (\( p \cap \bar{s} = \emptyset \)). Corollaries of this are that \( \bar{p} \cap \bar{s} = \bar{s} \) and \( P(\bar{p}|\bar{s}) = 1 \). Therefore

\[
P (t \cap \bar{p} \cap \bar{s}) = P(\bar{s}) P(\bar{p}|\bar{s}) P (t|\bar{p} \cap \bar{s})
= P(\bar{s}) P (t|\bar{s}).
\]
This is the probability to select an event that has failed both the particle level filter and the preselection. Both the particle level filter and the preselection require that a minimum number of electrons satisfy cuts on $p_T$ and $\eta$ in each event: at least one electron for $W \rightarrow e\nu$, at least two electrons for $Z \rightarrow ee$ and at least four electrons for $H \rightarrow ZZ^{(*)} \rightarrow 4e$. It is possible that some events that do not contain enough electrons to pass the particle level filter and preselection might nevertheless contain at least one electron with the potential to be accepted by the single electron trigger. Therefore, $P(s)P(t|s)$ might provide a contribution to the efficiency to trigger on $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events as they occur in nature. For $W \rightarrow e\nu$ events, $P(s)P(t|s)$ is equal to zero because there is no possibility of triggering events that have failed to pass the particle level filter and the preselection. It was not possible to determine the value of $P(t|s)$ for $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events. This would require access to the events that had not been simulated.

The overall trigger efficiency is defined to be equal to the trigger efficiency normalised with respect to the events accepted in the whole phase space region. In the case of $Z \rightarrow ee$ and $H \rightarrow ZZ^{(*)} \rightarrow 4e$ events, $P(t|s)$ was taken to be equal to zero and the overall trigger efficiency is therefore understood to be the lower limit on the efficiency to trigger on these events as they occur in nature. If no preselection is applied, the overall trigger efficiency is

$$P(s)P(t|s).$$  \hfill (C.1)
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