ATLAS Calorimetry: Hadronic Calibration Studies

KARL-JOHAN GRAHN

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Cover photo: The ATLAS experiment under construction at CERN, LHC Point 1, January 2006.
Abstract

The ATLAS experiment – situated at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) in Geneva – is on schedule to take its first collision data in 2009. Physics topics include finding the Higgs boson, heavy quark physics, and looking for extensions of the standard model such as supersymmetry.

Upon acceptance of an event by the level 1 trigger, data is read out from the liquid argon calorimeter using multi-mode optical fibers. In total, 58 cables were installed, corresponding to 232 12-fiber ribbons or 2784 individual fibers. The cables, about one hundred meters in length, were installed between the main ATLAS cavern and the counting room in the USA15 cavern. Patch cables were spliced onto the ribbons and the fiber attenuation was measured. For 1296 fiber pairs in 54 cables, the average attenuation was $0.69 \text{ dB}$. Only five fibers were found to have losses exceeding 4 dB, resulting in a failure rate of less than 2 per mill.

In the ATLAS liquid argon barrel presampler, short circuits consisting of small pieces of dust, metal, etc. can be burned away in situ by discharging a capacitor over the high voltage lines. In a burning campaign in November 2006, seventeen existing short circuits were successfully removed.

An investigation on how to implement saturation effects in liquid argon due to high ionization densities resulted into the implementation of the effect in the ATLAS Monte Carlo code, improving agreement with beam test data.

The timing structure of hadronic showers was investigated using a Geant4 Monte Carlo. The expected behavior as described in the literature was reproduced, with the exception that some sets of physics models gave unphysical gamma energies from nuclear neutron capture.

An ATLAS Combined Beam Test was conducted in the summer/fall of 2004 in the CERN H8 area, containing a whole slice of the ATLAS detectors in the central barrel region. The controlled single-particle environment allows the validation of Monte Carlo code and calibration.

A method for calibrating the response of a segmented calorimeter to hadrons was developed. The ansatz is that information on longitudinal shower fluctuations gained from a principal component analysis of the layer energy depositions can improve energy resolution by correcting for hadronic invisible energy and dead material losses: projections along the eigenvectors of the correlation matrix are used as input for the calibration. The technique was used to reconstruct the energy of pions impinging on the ATLAS calorimeters during the 2004 Combined Beam Test. Simulated Monte Carlo events were used to derive corrections for invisible energy lost in nuclear reactions and in dead material in front and in between the calorimeters. For pion beams with energies between 20 and 180 GeV, the particle energy was reconstructed within 3% and the resolution was improved by about 20%.

As a comparison, a simple iterative scheme with a single $e/\pi$ factor and dead material corrections was devised, giving similar performance.
# Contents

## 1 Introduction
1.1 Introduction and physics motivation ........................................ 1
1.2 Outline .................................................................................. 2
1.3 Author’s contribution ............................................................... 2

## 2 The LHC and the ATLAS experiment ........................................ 5
2.1 The LHC .............................................................................. 5
2.2 A tour of ATLAS ................................................................. 6

## 3 The ATLAS barrel calorimeters ............................................... 13
3.1 Interaction of radiation and matter ............................................. 13
3.2 Calorimetry .......................................................................... 16
3.3 ATLAS calorimeters .............................................................. 19

## 4 Installation and testing of LAr optical cables ............................ 29
4.1 Introduction ............................................................................ 29
4.2 Properties of fibers and cables ................................................ 29
4.3 Installation procedure ............................................................ 31
4.4 Measurements ....................................................................... 34
4.5 Results .................................................................................. 34

## 5 Presampler short-circuit evaporation ...................................... 37
5.1 Introduction ............................................................................ 37
5.2 The ATLAS Barrel Presampler ............................................... 38
5.3 Method .................................................................................. 40
5.4 Results .................................................................................. 41

## 6 Simulation studies of effects from saturation in liquid argon and
timing of hadronic showers ......................................................... 45
6.1 Introduction ............................................................................ 45
6.2 Monte Carlo simulation – Geant4 ............................................ 46
Chapter 1

Introduction

1.1 Introduction and physics motivation

The ATLAS experiment is one of the largest scientific collaborations in the world. Located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, and involving more than 2000 physicists, it is set to explore the high-energy frontier of physics, using data from colliding 7 TeV protons at the Large Hadron Collider (LHC). The first collision data is expected in 2009. The almost ten times higher collision energy that presently available opens up a region where new physics is thought to appear. Some of the outstanding questions are: Is the Higgs mechanism the correct explanation for the particle masses, i.e. does the Higgs boson exist? Do supersymmetric particles exist and is the lightest supersymmetric particle the explanation to dark matter? Does the standard model give a correct description at the higher collision energy? The answers to these and other important questions often involve physics signatures that contain particle jets consisting of hadrons as well as leptons. In some cases the physics signature involves heavy neutral particles that will not interact with the detector material and thus result in missing transverse energy.

In all of these cases, calorimeters are important. As the energy frontier is pushed forward, they have the inherent advantage of improved energy resolution with higher energy, as opposed to trackers, where a larger bending radius worsens resolution.

Crucial for the correct reconstruction of jets and missing transverse energy will then be correctly calibrated calorimeters. The ATLAS calorimeters are intrinsically non-compensating – i.e. the response to hadrons is lower that the response to electrons and photons – meaning off-line compensation methods are needed to restore measurement linearity.

Monte Carlo simulations are important for understanding calorimeter physics. They need to be able to reproduce beam test data to a reasonable accuracy.
1.2 Outline

The outline of this thesis is as follows:

Chapter 2 gives a general overview of the ATLAS experiment and the Large Hadron Collider, while chapter 3 describes the general principles of calorimetry and the ATLAS calorimeters, with emphasis on the central barrel parts.

The chapters thereafter detail detector hardware preparations and tests that the author has contributed to. Chapter 4 explains the procedure for installation and testing of the liquid argon calorimeter optical readout cables, while chapter 5 explains a procedure for evaporating short circuits in the liquid argon barrel presampler.

Chapter 6 describes studies involving the ATLAS Monte Carlo simulation: an investigation on how to implement ionization-density-dependent saturation effects in liquid argon and a study of how well the Geant4 simulation can reproduces the expected time structure of hadronic showers.

Attention is then turned to the 2004 ATLAS Barrel Combined Beam Test, which is described in detail in chapter 7.

Finally, a novel approach to hadronic calibration exploiting the correlations between the different calorimeter layers is presented and applied to Combined Beam Test data in chapter 8.

1.3 Author’s contribution

I was the main responsible for splicing and testing the optical readout cables for all the liquid argon calorimeters, as described in chapter 4, a work lasting several months in total. It was performed together with Stefan Rydstöm and Per Hansson. The result of the cable measurements has been published in [Buc08].

I took active part in the presampler burning campaign of chapter 5 and presented the results to the collaboration.

The Monte Carlo timing study in section 6.4 was done in collaboration with Tancredi Carli. I personally wrote the code and made all the plots and performed the literature search.

The investigation on Birks’ law in liquiad argon in section 6.3 was done in collaboration with Tancredi Carli and Peter Speckmayer. I performed the literature search and added the first implementation of the model to the ATLAS Monte Carlo code.

An ATLAS note on the results of chapter 6 is in preparation.

The calibration method of chapter 8 was developed in collaboration with Tancredi Carli, Francesco Spanò, and Peter Speckmayer. I took over an existing analysis and extended it considerably, adding e.g. dead material corrections and iteration and performed studies on improving the method. The results of the Layer Correlation hadronic calibration method are in ATLAS note ATL-COM-CAL-2008-004,
1.3. AUTHOR’S CONTRIBUTION

currently under review. The simple comparison method of section 8.8 was entirely implemented by me.

Forthcoming is a note on the calorimeter response of pions in the 2004 Barrel Combined Beam Test, of which I am a co-author.
Chapter 2

The LHC and the ATLAS experiment

2.1 The LHC

The Large Hadron Collider (LHC) [Eva08], currently under final construction at CERN, will be the largest accelerator complex in the world. Proton–proton collisions with a center-of-mass energy of $\sqrt{s} = 14$ TeV will bring experimental high energy physics to previously uncharted territories. In addition to protons, there will also be collisions of lead ions.

In the LHC, bunches of up to $10^{11}$ protons will collide at a rate of 40 MHz and a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, although in initial runs, the luminosity will be orders of magnitude lower.

Proton energies are increased by a series of accelerators before reaching the main LHC ring, which straddles the French–Swiss border west of Geneva. Protons coming from an ion source and are accelerated by a linear accelerator, the Proton Synchrotron Booster, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) before reaching the main LHC machine.

The LHC uses the same 27 km circular tunnel as the now dismantled LEP electron–positron collider. Particle beams are bent by 1232 superconducting NbTi dipole magnets cooled by superfluid helium to below 2 K, carrying a current of several kiloamps and generating a peak 8.33 T magnetic field. Each proton beam will consist of 2808 bunches, separated in time by 25 ns. The design uses twin bore magnets due to space constraints.

Located around the LHC ring are several different experiments/detectors:

- CMS (Compact Muon Solenoid) [Cha08] and ATLAS [Aad08] are general-purpose physics experiments investigating primarily proton–proton collisions, but also heavy ion collisions. Physics topics include searching for the Higgs boson, top quark and b physics and looking physics beyond the standard model, such as supersymmetry.
ALICE [Aam08] is specifically geared toward the study of the strong interaction sector of the standard model (QCD), primarily in collisions of lead ions.

LHCb [Alv08] is optimized for heavy-flavor physics. The primary goal is to look for indirect evidence of new physics in CP violation and rare decays of bottom and charm hadrons. CP violation beyond the standard model is thought to be needed to explain the prevalence of matter over antimatter in the universe.

TOTEM [Ane08] will measure the total cross-section of proton-proton collisions based on the optical theorem. It is an independent experiment, technically integrated with CMS. ATLAS also has instrumentation to do similar measurements.

LHCf [Adr08] will measure the production spectrum of neutral particles in the very forward region of LHC collisions. The aim is to get data to calibrate Monte Carlo models of the showers induced by Extremely High-Energy Cosmic Rays.

### 2.2 A tour of ATLAS

This section gives a general overview of ATLAS and its subdetectors.

The ATLAS coordinate system is laid out so that the $z$ axis is parallel to the beam pipe, while the $x$ axis points upwards, and the $y$ axis towards the center of the LHC ring. Coordinates are usually expressed in a non-Cartesian system $(r, \phi, \eta)$ where $r$ is the distance from the interaction point, $\phi$ is the polar angle in the $xy$ plane and

$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right),$$

(2.1)

where $\theta$ is the angle relative to the beam axis. The pseudorapidity $\eta$ approximates rapidity for relativistic particles. It is more convenient to use than the angle $\theta$, since particle production can be shown to be approximately flatly distributed in $\eta$.

In general, the detector has a cylindrical symmetry with several layers centered on the interaction point. From the beam pipe and outward, ATLAS consists of an inner tracking detector, electromagnetic and hadronic calorimeters, and a muon spectrometer. ATLAS is thoroughly described in [Aad08].

In general, the ATLAS electronics is designed so that the signal read out from the detectors is digitized by front end electronics situated on the experiment itself. This is to make the analog signal path as short as possible, and thereby reduce noise.

Figure 2.1 shows a cross section of the detector and its various subsystems. In the very center of the experiment, closest to the interaction point, is the inner detector. It consists of three subdetector systems:
2.2. A TOUR OF ATLAS

The pixel detector, the semiconductor tracker (SCT), and the transition radiation tracker (TRT).

2.2.1 Inner detector

The task of the inner detector is to measure the angles, momenta, and life-times of particles emerging from the interaction point down to sub-GeV transverse momenta $p_T$. That is done by observing the curvature of their trajectory in a magnetic field. It should provide so-called b-tagging of particles coming from a secondary vertex where a b quark decayed. It should also provide discrimination between electrons and hadrons. About 1000 particles will emerge from the interaction point in each interaction, resulting in a very large track density.

Situated close to the beam pipe and the interaction point, the inner detector is exposed to an immense radiation environment. It is located in a solenoidal magnetic field of 2 T, generated by a superconducting solenoid electromagnet located in the same cryostat as the liquid argon barrel calorimeter (see below).

Figure 2.2 shows an overview of the inner detector, which consists of three sub-systems: The pixel detector, the semiconductor tracker (SCT), and the transition
radiation tracker (TRT). It is located within a cylindrical envelope 7 m long and with a radius of slightly more than one meter.

**Pixel detector**

The pixel detector is the part of ATLAS located closest to the beam pipe and the interaction point. It consists of three radial barrel layers approximately 5, 9 and 12 cm away from the interaction point and six discs, three on each side of the interaction point, perpendicular to the beampipe, at the approximate distances of 50, 58, and 65 cm. In the immense radiation environment it is expected to need replacement after three years of running at design luminosity. All pixel sensors are identical and have a minimum pixel size of $40 \times 400 \mu m^2$. In total, there are 80.4 million readout channels. The pixel detector contains 1744 pixel sensors, each having 47232 pixels. The sensors are 250 $\mu$m thick. The layers are segmented in $R - \phi$ and $z$. The intrinsic accuracy in the barrel (discs) is $10 \mu m$ in $R - \phi$ ($R - \phi$) and $115 \mu m$ in $z$ ($R$).

**Semiconductor tracker**

The semiconductor tracker (SCT) uses sets of stereo strips for tracking. There are four stereo layers in the barrel region, at radial distances from the interaction
2.2. A TOUR OF ATLAS

point of 30–51 cm, and nine disc stereo layers in each end-cap, 85–272 cm from the interaction point in $z$. The intrinsic accuracy in the barrel (discs) is 17 $\mu$m in $R - \phi$ ($R - \phi$) and 580 $\mu$m in $z$ ($R$).

The SCT has 15912 sensors, each $285 \pm 15 \mu$m thick. The number of channels is about 6.3 million.

Transition radiation tracker

The TRT forms the outermost tracking system in ATLAS, located between the SCT and the calorimeters. It consists of a collection of 4 mm diameter polyimide straw tubes filled with a mixture of xenon, carbon dioxide and oxygen.

Transition radiation is emitted when a charged particle passes the interface between two media having different index of refraction. The amount of emitted radiation depends on the Lorentz $\gamma$ factor of the particle. Since $\gamma = E/(mc^2)$, the lower mass of electrons compared to hadrons gives them a much higher gamma factor for a given momentum, making it possible to discriminate between the two.

The TRT barrel (end-cap) only provides $R - \phi (\phi - z)$ information, with an intrinsic accuracy of 130 $\mu$m per straw. In the barrel region, the straws are parallel to the beam direction, and in the end-cap they are arranged radially in wheels. In total there is about 351000 readout channels.

2.2.2 Calorimeters

Calorimeters measure particle energy by sampling the particle showers they induce. ATLAS has a range of different electromagnetic and hadronic calorimeters: the liquid argon barrel electromagnetic calorimeter (EMB), the Tile barrel and extended barrel hadronic calorimeters, the liquid argon electromagnetic end-cap calorimeters (EMEC), the liquid argon hadronic end-cap calorimeters (HEC), and the forward calorimeters (FCal). They are described in chapter 3.

2.2.3 Muon spectrometer

Due to their considerably higher mass than electrons, muons at the energies at hand in ATLAS don’t loose energy radiatively and thus remain minimum ionizing particles (MIPs). Consequently they don’t develop showers in the calorimeter systems, loosing only a negligible part of their energy.

The task of the muon spectrometer system is to measure the momentum of those muons by observing the curvature of their trajectory in the magnetic field created by the large air-wound barrel and end-cap toroid magnets.

The length needed to observe a sufficient deviation from a straight path (sagitta) is what determines the overall dimensions of the whole experiment.

There are vastly different demands put on the muon system: Radiation levels differ greatly depending on $\eta$. The muon level 1 trigger requires fast readout,
while the full readout requires high precision. Due to this, muon chambers of four different technologies are used in ATLAS:

For precision measurements:

- MDTs, monitored drift tubes, are used in most regions. The drift tubes are about 3 cm in diameter and are filled with a mixture of argon and carbon dioxide.

- CSCs, cathode strip chambers, are used in the more intense radiation environment in the end-caps, at high pseudorapidity. They are multiwire proportional chambers, with both cathodes segmented, perpendicular to each other, each providing one coordinate for the track.

For fast triggering:

- RPCs, resistive plate chambers are used in the barrel. They consist of two resistive plates, kept parallel at a distance of 2 mm. Avalanches form along the ionizing tracks and the signal is read out through capacitive coupling to metallic strips located on the outside of the strips.

- TGCs, thin gap chambers, are used in the end-caps. They are also in the form of multiwire proportional chambers.

The general geometry of the muon system is shown in figure 2.3. The muon chambers can be physically installed with sub-centimeter precision. However, meeting the design requirements requires their position to be known to a much higher precision, less than 30 $\mu$m. To achieve this a combination of an optical alignment system and track reconstruction is used.

2.2.4 Magnet system

The ATLAS magnet system consists of the central solenoid, providing the magnetic field for the inner detector, and the barrel and end-cap toroids, providing the field for the muon spectrometer.

2.2.5 Trigger

Reconstructing and storing events at the LHC bunch crossing rate every 25 ns would be impossible. In addition, in the vast majority of cases, events are so-called minimum-bias QCD events, containing no new physics. A multi-leveled trigger system is used to bring the 40 MHz event rate down to a practical few hundred hertz.

Level 1 trigger

The largest reduction in event rate is due to the level 1 trigger. It brings the event rate from the bunch crossing frequency of 40 MHz to a more manageable 70 kHz\(^1\).

\(^{1}\)The system is upgradeable to 100 kHz
Figure 2.3: A general overview of the ATLAS muon spectrometer.

The level one trigger has a 2.5 $\mu$s window to make its decision whether to accept or reject an event, before instructing the front-end electronics to accept an event. It uses analog signal sums collected at the detectors before A/D conversion. Input comes from the calorimeters and the muon spectrometer – the inner detector does not provide a signal for the level 1 trigger. The experimental signatures used by the level 1 trigger are particles and jets with high transverse energy $E_t = E \sin \theta$, where $\theta$ is the angle to the beam axis, and missing transverse energy due to uncharged particles escaping the experiment undetected. As mentioned, the latter is an important experimental signal for supersymmetry. Precision is limited to a modest 5 per cent. If the rate of events passing a certain trigger condition is high enough to saturate the 70 kHz maximum level 1 rate, a pre-scaling factor $P$ can be applied, where only every $P$th event is kept.

**High Level Trigger**

The high level trigger consists of the level 2 trigger and a third level, called the Event Filter. Both operate on events fully reconstructed by the readout drivers,
although the level 2 trigger limits its scope to regions of interest (ROIs) determined by the level 1 trigger.

2.2.6 Computing, software

The amount of experimental data collected in a year in ATLAS will amount to petabytes. This puts unprecedented demands on the computing and distribution infrastructure.

The ATLAS computing model follows a tiered structure, where the Tier 0 computing center – located at CERN – distributes data to Tier 1 and Tier 2 centers located around the world [ATL05].

ATLAS software is divided into on-line and offline-parts. The off-line reconstruction software is called Athena. Written in object-oriented C++, it is based on the GAUDI [Bar00] framework, shared with the LHCb experiment. Event data are stored in the format of the ROOT framework [Bru96].

Python is used as a glue language to bind different modules together. Package and version management is done by CMT and CVS. Work is done in objects of a class called algorithms. They can communicate by storing and retrieving objects from services.

The data analysis in the present work was done using the ROOT software framework. It is a continuation of the old FORTRAN77-based PAW/HBOOK [PAW] software package, with which it has authors in common. ROOT is written in C++, and is aiming to be object-oriented. It is today the de-facto standard analysis framework in high energy physics.

The output of the ATLAS reconstruction is stored in the form of event summary data (ESD), which can be condensed into analysis object data (AOD). Then, depending on the different requirements of different physics analyses, derived physics data (DPD) is produced. For the purposes of Combined Beam Test analysis, a simpler approach is followed, where reconstruction algorithm output dumped into a so-called Combined Ntuple (CBNT), which is a plain ROOT ntuple.
Chapter 3

The ATLAS barrel calorimeters

This chapter will first give a short introduction to the interaction of radiation and matter and calorimeter physics. Then the calorimeter systems in ATLAS will be described, with emphasis on the barrel calorimeters: the liquid argon barrel electromagnetic calorimeter and the Tile hadronic calorimeter.

3.1 Interaction of radiation and matter

3.1.1 Charged particles

Nuclear interactions aside, charged particles heavier than electrons and positrons (such as pions or muons) primarily lose energy due to ionization of the material through which they pass. The mean energy loss per unit length and material density is given by the Bethe–Bloch formula [PDG08]

\[ \frac{dE}{dx} = K z^2 Z \frac{1}{A} \beta^2 \left( \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\beta \gamma}{2} \right), \quad (3.1) \]

where \( K = 4\pi N_A r_e^2 m_e c^2 \), \( N_A \) is Avogadro’s number, \( r_e \) is the classical electron radius, \( z e \) is the charge of the incident particle, \( Z \) is the atomic number of the absorber material, \( A \) is the atomic mass of the absorber material, \( \beta c \) and \( \gamma \) are the speed and Lorentz gamma of the particle, respectively, and \( m_e \) is the electron mass. \( T_{\text{max}} \) is the maximum kinetic energy that can be transferred to a free electron in a single collision. It is given by [PDG08]

\[ T_{\text{max}} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2 \gamma m_e / M + (m_e / M)^2}, \quad (3.2) \]
where $M$ is the mass of the particle. The $\delta(\beta\gamma)$ term describes the so-called density effect, which is due to polarization of the material, comes into effect at high energies. $\delta/2$ is then proportional to a constant plus $\ln \beta\gamma$.

With small deviations, the Bethe–Bloch $dE/dx$ depends on the particle speed $\beta$ only. At low energies it goes as $1/\beta^2$. At high energies, the density effect term makes the whole Bethe–Bloch formula rise logarithmically as $\ln \beta\gamma$ instead of $\ln \beta^2\gamma^2$ until the point where radiative losses must be taken into account. For a broad range of energies, relativistic pions and muons can be considered to be minimum-ionizing particles (MIPs). Yet higher-mass particles, such as protons and alpha particles, will have a lower $\beta$ at a given energy, and the low energy rise will thus be more important.

Ionization usually occurs in an almost smooth and continuous way. However, electrons are sometimes knocked out with rather high energy, propagating away from the ionization region. These are sometimes called delta rays.

Just like heavy particles, electrons and positrons lose energy by ionization, in a way similar to the Bethe–Bloch equation. However, due to their low mass mass, radiative effects start to dominate already at low energies. So-called Bremsstrahlung occurs when an electron or positron emits a photon when it interacts with an atomic nucleus.

The radiation length, $X_0$, is both the average distance after which a high-energy electron has lost all but $1/e$ of its energy due to Bremsstrahlung and $7/9$ of the mean free path for pair production by a high-energy photon. Naturally it is material-dependent. Approximately (within a few per cent), it is given by [PDG08]

$$X_0 = \frac{716.4 \text{ g/cm}^2 A}{Z(Z + 1) \ln(287/\sqrt{Z})}.$$  

As an example, this gives $X_0 = 19.9 \text{ g/cm}^2$ for argon and $X_0 = 6.3 \text{ g/cm}^2$ for lead, or, removing the density normalization $X_0/\rho = 14 \text{ cm}$ for argon and $X_0/\rho = 0.56 \text{ cm}$ for lead.

The critical energy, $E_c$, is usually defined as the energy where ionization and radiative effects for electrons and positrons are equal in magnitude. An approximate expression is [PDG08]

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24}$$  

for solids and liquids and

$$E_c = \frac{710 \text{ MeV}}{Z + 0.92}$$  

for gases. Again as an example, this gives $E_c = 31.7 \text{ MeV}$ for liquid argon and $E_c = 7.3 \text{ MeV}$ for lead. An alternative definition (after Rossi) is to set $E_c$ as the

$^1 E \gg 1 \text{ GeV}$

$^2$Using $\rho_{\text{LAr}} = 1.396 \text{ g/cm}^3$ and $\rho_{\text{Pb}} = 11.34 \text{ g/cm}^3$
3.1. INTERACTION OF RADIATION AND MATTER

energy where the ionization losses per radiation length equals the electron energy. Both definitions are roughly equivalent.

Multiple scattering is the result of many small-angle deflections due to Coulomb scattering against the nuclei of the material as the particle traverses it. Strong interactions may also contribute for hadrons. The scattering angle distribution after a length $x$ is approximately Gaussian, with the width \[\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0}\] (3.6)

Finally, inelastic nuclear interactions naturally play a large role for all hadrons.

3.1.2 Photons
Photons interact with matter through the photoelectric effect, Compton scattering and pair production, while Rayleigh scattering is important only at very low energies. Photonuclear reactions may play a small role at high energies. The photoelectric effect dominates at low energies, Compton scattering in an intermediate range, and pair production at higher energies.

The photoelectric effect amounts to the energy of a photon being completely absorbed by an atom, thereby knocking out an electron from its atomic shell. It is strongly dependent on the number of available electrons, and thus the atomic number $Z$ of the material. The cross-section scales as $Z^n$, with $n$ between 4 and 5. With energy, it scales as $E^{-3}$, making it dominant only at energies well under 1 MeV for all practical materials [Wig00].

In Compton scattering only a fraction of the photon energy is transfered to an atomic electron. The cross section is almost proportional to $Z$. The effect dominates in an intermediate region up a few tens of MeV [Wig00].

Pair production occurs when the photon is converted into an electron–positron pair by interacting with an atomic nucleus. This can only occur above a photon energy equal to twice the electron mass of 511 keV. The cross section rises with energy until it hits a plateau related to the radiation length $X_0$ at above-GeV energies. For high-$Z$ materials, pair production starts to dominate earlier than for low-$Z$ materials, meaning that the energy range in which Compton scattering dominates is smaller for the former [Wig00].

3.1.3 Material response
Materials may respond to ionizing radiation in a number of ways that are useful for signal readout. In addition to an electric ionization signal – occurring in for example semiconductor, liquid or gas detectors – various forms of light may be produced: Some inorganic crystals and polymers produce scintillation light that may be picked up and amplified by photo multiplier tubes (PMTs).

Čerenkov radiation is an optical shock wave phenomenon occurring when a charged particle passes through a material at a speed higher than the local phase
velocity of light \((c/n, \text{ where } n \text{ is the index of refraction})\). Emission depends only on the speed of the particle \(v = \beta c\) and is directed along a circular cone at an angle of \(\theta_c = 1/(n\beta)\) with respect to the particle track [PDG08].

Transition radiation (TR) occurs when a charged particle passes the interface between two materials with different index of refraction. The radiation intensity is proportional to the Lorentz gamma, \(\gamma\), of the particle [PDG08].

Both Čerenkov and transition radiation are useful for particle identification. The ATLAS inner detector has a transition radiation tracker as its outermost layer (chapter 2) and the beamline of the Barrel Combined Beam Test has a Čerenkov detector (chapter 7).

### 3.2 Calorimetry

Calorimeters aim to exploit particle showers in the detector material to measure particle energies and angles. Based on the types of interactions of the particles they are designed for, they can be divided into electromagnetic calorimeters (electrons, positrons, photons) and hadronic calorimeters (pions, protons, neutrons, jets). Usually, collider experiments will have both electromagnetic and hadronic calorimeters in sequence.

If they are divided into several compartments with independent signal readout, either laterally or longitudinally, calorimeters are said to be segmented.

There are homogeneous calorimeters and sampling calorimeters: In a homogeneous calorimeter all detector material will give a contribution to the read out signal, while in a sampling calorimeter only a part of the material is used for signal readout. The ratio of energy deposited in the active material to the total energy deposited is called the sampling fraction, \(f_{\text{sampl}}\).

A sampling calorimeter allows an optimum choice of detector and absorber material. A dense absorber material makes it possible to construct a compact, cheap calorimeter that is easy to segment. On the other hand the amount of charge created in the active detector material will be lower, meaning that the stochastic resolution term (see below) will be larger.

Homogeneous calorimeters can be made of for example high-\(Z\) inorganic scintillators or Čerenkov-emitting lead glass. The active detector material of sampling calorimeters can be organic scintillators or liquid noble gas (mostly argon) ionization chambers.

#### 3.2.1 Electromagnetic calorimetry

Particle showers can be classified into two different categories depending on the interactions of the impinging particle: electromagnetic and hadronic showers.
3.2. CALORIMETRY

Electromagnetic (EM) showers occur for high-energy particles that are subject to electromagnetic interactions, but not to strong interactions. For practical purposes, those particles are electrons, positrons and photons\(^3\).

The fundamental length scale for electromagnetic showers is the so-called \textit{radiation length}, \(X_0\), defined above.

The basic processes in electromagnetic shower development are Bremsstrahlung and pair production. Consider a high-energy electron reaching the calorimeter. It will deposit energy by ionizing the atoms or molecules of the detector material, but will predominantly lose energy by emitting Bremsstrahlung photons. Those photons will in turn be converted into electron–positrons pairs, which again emit Bremsstrahlung photons (figure 3.1). This process will continue until the average electron energy is below the critical energy and ionization losses start to dominate.

From this tree-like model one can expect an exponential-like start of the shower, followed by a rapid decay. The longitudinal extent of the shower should depend logarithmically on the incident particle energy.

The average longitudinal profile is reasonably described [PDG08] by a \(\Gamma\) distribution:

\[
\frac{dE}{dt} = E_0 b (bt)^{a-1} e^{-bt} \over \Gamma(a) ,
\]

\[\tag{3.7}\]

\(^3\)Muons, due to their higher mass, do not emit bremsstrahlung photons until reaching very high energies, and thus usually do not form EM showers at the energies at hand in collider experiments. Instead, they pass through the calorimeter system as minimum-ionizing particles.

Figure 3.1: The principles of an electromagnetic shower. An incident electron emits Bremsstrahlung photons, which in turn convert into electron–positrons pairs. The fundamental length scale is the radiation length \(X_0\).
where \( t = x/X_0 \) is the distance normalized to radiation lengths. The shower maximum occurs at

\[
t_{\text{max}} = (a - 1)/b = 1.0 \cdot (\ln \frac{E}{E_c} + C),
\]

(3.8)

where \( b \approx 0.5 \) and \( C = -0.5 \) for electron-induced showers and \( C = +0.5 \) for photon-induced showers. The logarithmic dependence on the incident particle energy is consistent with exponential shower growth model outlined above.

The lateral scale of the shower extent is given by the Molière radius:

\[
R_m = \frac{\sqrt{4\pi/\alpha \ m_e c^2}}{E_c} \approx 21.2 \text{ MeV},
\]

(3.9)

where \( \alpha \) is the fine structure constant and \( E_c \) follows Rossi’s definition.

The resolution of an electromagnetic calorimeter is usually parameterized as follows:

\[
\frac{\sigma_E}{E} = a \oplus \frac{b}{E} \oplus c,
\]

(3.10)

where \( \oplus \) denotes adding the terms in quadrature and taking the square root. The three terms are called the stochastic, noise, and constant terms respectively. The stochastic term is due to the Poisson-like statistics of shower development, giving an energy error of \( \sqrt{E} \). Since the electronic noise is independent of energy, the noise term will be a constant in terms of absolute resolution and thus go as \( 1/E \) in terms of relative resolution. The final constant term is due to inhomogeneities between different parts of the calorimeter. One sees that relative resolution improves with increasing energy, contrary to momentum measurements in trackers, where resolution instead degrades as energy increases.

### 3.2.2 Hadronic calorimetry

Hadronic showers follow a similar pattern to electromagnetic ones, with one particle giving rise to several others when interacting with the detector material, in this case mainly through nuclear interactions. However, due to the complexities of the strong interaction and a much larger number of possible final states, shower fluctuations are much larger.

This complexity comes from inelastic reactions between a hadronic particle and atomic nuclei. Such reactions result in both prompt new hadrons and later gammas and evaporation neutrons.

The hadronic analog to the electromagnetic radiation length \( X_0 \) is the nuclear interaction length \( \lambda \).

Hadronic showers carry both a hadronic component and an electromagnetic component. This is due to the fact that \( \pi^0 \) mesons may be produced in nuclear reactions. Since they decay into two gamma photons, the resultant shower will behave exactly like an electromagnetic shower.
3.3. ATLAS CALORIMETERS

In the general case a calorimeter will have a different response to the electromagnetic and hadronic components of the shower. This is due to the hadronic component having energy deposits not showing up as ionization in the detector, due mostly to energy lost in nuclear break-up.

The differing response to the electromagnetic and hadronic components of a shower is characterized by the $e/h$ ratio, giving the ratio of the electromagnetic to hadronic response. This is an intrinsic property of the calorimeter in question. If $e/h = 1$, the calorimeter is said to be compensating, if $e/h > 1$ it is under-compensating, and if $e/h < 1$ it is over-compensating. Due to invisible energy, most calorimeters – including those in ATLAS – have $e/h < 1$.

With increasing incident particle energy, the number of nuclear interactions increases and thus also the number of $\pi^0$ particles produced. This in turn increases the electromagnetic component of the shower, giving rise to a non-linear response if $e/h \neq 1$. The ratio of the of the signals read out for an incident electron and an incident pion of the same energy is called the $e/\pi$ ratio, which thus is beam energy dependent. If $f_{em}$ is the electromagnetic fraction of the shower, the pion response can then be written [Wig00]

$$\pi = f_{em}e + (1 - f_{em})h,$$  \hspace{1cm} (3.11)

from which follows

$$\frac{e}{\pi} = \frac{e/h}{1 - f_{em}(1 - e/h)}$$  \hspace{1cm} (3.12)

$f_{em}$ has a power-law behavior [Gab94, Wig00]

$$f_{em} = 1 - \left(\frac{E}{E_0}\right)^{k-1}.$$  \hspace{1cm} (3.13)

The parameters $E_0$ and $k$ are somewhat material dependent, but are approximately $E_0 \approx 1$ GeV and $k \approx 0.8$ [Wig00].

Various methods exist to achieve compensation, either boosting the hadronic response or reducing the electromagnetic response. For example, the former can be achieved by using detector materials rich in protons, which recoil from the elastic scattering of soft neutrons in the shower and the latter by using high-Z materials such as uranium as absorbers [Wig00]. As mentioned, the ATLAS calorimeters are intrinsically non-compensating.

3.3 ATLAS calorimeters

The calorimeters measure particle and jet energies by sampling the ionization signal from the particle showers that develop when the incoming particles interact with the detector material. They also measure the direction of particles and jets. Signs of interesting physics in ATLAS will be missing (unbalanced) transverse energy –
which is a signature of particles not interacting with the detector – and high-energy leptons and photons. Calorimeters play a crucial role for measuring both.

The demands on the calorimeters are high. To measure missing transverse energy, they must have an angular coverage as large as possible, minimizing gaps (hermeticity). This is achieved by the arrangement of barrel and end-cap calorimeters described below. Common to all ATLAS is that the intense radiation environment requires radiation-hard detectors. The short time between collisions means that detectors will need to have a fast response time to avoid event pile-up. Due to the spatial constraints on how large the calorimeter system can be, sampling calorimeters are used. Leptons and photons need to be clearly distinguished from hadrons. This together with general background rejection requires a fine detector granularity, meaning a large number of channels that need to be processed. Cell energies in the range of MeV s (electronic noise) to TeV need to be measured. This requires a high dynamic range.

In terms of resolution, the ATLAS electromagnetic calorimeters were designed for a sampling term constant of $10\% \sqrt{\text{GeV}}$ and a constant term of $0.7\%$. The requirement of the hadronic calorimetry is a sampling term constant of $10\% \sqrt{\text{GeV}}$ and a constant term of $3\%$.

The ATLAS calorimeters employ a range of different technologies, optimized for their different use. They are either based on liquid argon or scintillating tiles. All are segmented, sampling calorimeters. Figure 3.2 shows an overview of the different calorimeter subsystems.

### 3.3.1 Liquid argon calorimeters

All the electromagnetic calorimeters in ATLAS utilize liquid argon technology. Liquid argon was chosen as the active calorimeter medium due to its well-known linear response to ionization, and its inherent radiation hardness.

The liquid argon calorimeters are the electromagnetic barrel calorimeter (EMB), the electromagnetic end-cap (EMEC), the hadronic end-cap (HEC), and the forward calorimeter (FCal). They are thoroughly described in [ATL96a].

**LAr–barrel calorimeter**

Since modules from it are present in the Combined Beam Test (chapter 7), the LAr–barrel calorimeter will be described here in more detail than the other LAr calorimeters, serving as an example.

The electromagnetic barrel calorimeter has an accordion geometry, chosen both for its ability to provide coverage without gaps in $\phi$ and for the possibility of extracting the signal with a short rise time.

The liquid argon has to be located inside a cryostat cooled to 89.3 K. In ATLAS, this extends from an inner radius of $\sim 1.2$ m to an outer radius of $\sim 2.3$ m. It is made of aluminum – to reduce the amount of radiation lengths traversed by the particles – and consists of a warm vessel and a cold vessel separated by vacuum insulation. On
3.3. ATLAS CALORIMETERS

the inner warm vessel, the superconducting solenoid coil that provides the magnetic field for the inner detector is mounted.

The high demands of performance and radiation hardness put on the inner detector unavoidably leads to a large amount of material being present between the interaction point and the calorimeter system. Electromagnetically interacting particles will start showering already before reaching the calorimeter, due to this material in the inner detector and cryostat wall, degrading energy resolution. To compensate for this effect presampler detectors are present just in front of the EMB and EMEC detectors. Their principle of operation is to sample the shower early in its development, giving a signal that is well correlated to the energy lost upstream of it. The LAr–barrel presampler was developed in collaboration between KTH and LPSC Grenoble. It has a thin (11 mm) active layer of liquid argon, located between alternating anodes and cathodes made of glass-epoxy circuit boards. The cathodes are double-sided, while the anodes have three conducting layers. For the latter, high voltage is applied to the outer electrodes, while the inner ones at ground potential are used for signal readout. Both kinds of electrodes are a few hundred micrometers thick.

The granularity of the presampler readout cells is $\Delta \eta = 0.025$ in the $\eta$ direction and $\Delta \phi \approx 0.1$ in the $\phi$ direction.
The presampler modules are enclosed in a glass-epoxy shell.

The calorimeter proper is made up of interspersed electrodes and absorbers, folded in an accordion pattern. In total, there are 1024 each of electrodes and absorbers, giving a spacing of $\Delta \phi = 2\pi/1024$.

For manufacturing, the calorimeter is divided into 16 modules for each half-barrel ($\eta > 0$ and $\eta < 0$). However, once in place, there is no discontinuity between the modules.

The electrodes, a few hundred micrometers thick, are copper-polyimide printed circuit boards and have three conducting layers. The two outer layers are connected to the high voltage supply, while the central one is used for signal readout, coupled capacitively to the circuit formed by the liquid argon gap and the applied high voltage.

The absorbers are made of lead sheets sandwiched between two stainless steel plates. The lead sheets are 1.5 mm thick for $\eta < 0.8$. Combined with the steel plates this gives a total thickness of 2.2 mm. For $\eta > 0.8$ the lead thickness is reduced to 1.1 mm, taking advantage of the increasing length available in the calorimeter to increase the sampling fraction – the relative amount of energy deposited in the active material – and thereby improve resolution.

The electrodes and absorbers are folded into an accordion shape in order to achieve a geometry with no gaps in the $\phi$ (azimuth) direction. The folding angle decreases with increasing radius to ensure an approximately constant gap between absorber and electrodes.

Electrodes and absorbers are separated by insulating honeycomb spacers made of paper impregnated with phenolic resin.

In the radial direction, the electrodes are divided into three so called layers (also called samplings or compartments$^4$): the strips, the middle sampling, and the back sampling. The division in $\eta$ comes from etched pads on the electrodes. All cells are aligned to point towards the interaction point.

- The strips have a very fine spacing in $\eta$, $\Delta \eta = 0.003125$.
- Most of the energy is deposited in the middle section. Here the cells have an $\eta$ spacing of $\Delta \eta = 0.025$, each middle cell corresponding to eight strips.
- The back sampling has an $\eta$ spacing of $\Delta \eta = 0.050$, corresponding to two middle cells or sixteen strips.

At $\eta = 0$ there is 1.7 $X_0$ before the calorimeter, 4.3 $X_0$ in the strip layers, 16 $X_0$ in middle sampling, and 2 $X_0$ in the back sampling.

To achieve the sought-after granularity in the $\phi$ direction, the signal from a number of electrodes are summed together. This is done differently for each sampling.

$^4$The terms will be used interchangeably.
3.3. ATLAS CALORIMETERS

![Diagram of ATLAS calorimeters]

Figure 3.3: From [ATL96b, figure 1-2]. The accordion structure of the calorimeter and the granularity of the different samplings. Also the radiation lengths of the layers.

- In the strips, sixteen electrodes are summed together to give a granularity of $\Delta \phi = 2\pi/64 \approx 0.1$.
- In the middle and back samplings, four electrode signals are summed, giving a granularity of $\Delta \phi = 2\pi/256 \approx 0.025$

This is all illustrated in figure 3.3.

From the presampler and the strips the signal is taken out from the inner radius of the calorimeter, while for the middle and back samplings, it is brought out from the outer radius.

End-Cap calorimeters

In the end-caps, both the electromagnetic and hadronic calorimeters utilize liquid argon technology. The electromagnetic end-cap (EMEC) calorimeter used lead as absorbing material just like the electromagnetic barrel calorimeter, while the hadronic end-cap calorimeter uses copper. Both are housed in the same cryostat together with the forward calorimeter (FCal).

The electromagnetic end-cap calorimeter has an accordion geometry similar to the liquid argon barrel calorimeter. In each end-cap it consists of two coaxial wheels,
CHAPTER 3. THE ATLAS BARREL CALORIMETERS

with a border at $\eta = 2.5$. There are mostly three longitudinal samplings, although some regions have only two.

The hadronic end-cap calorimeter is located behind the EMEC as seen from the interaction point. It consists of copper plates in planes perpendicular to the beampipe. The 8.5 mm liquid argon gaps between the plates are divided into four separate drift zones by electrodes. An electrostatic transformer (EST) structure reduces the needed high voltage. There are four samplings.

Finally, the forward calorimeter is situated in the high-radiation environment at high $\eta$, closest to the beampipe. It has been designed with the very high particle fluxes at high $\eta$ in mind. The calorimeter has three modules in depth: one electromagnetic module and two hadronic modules. The electromagnetic module uses copper as absorbing material, while the hadronic ones use tungsten. The electrode structure used has small-diameter rods, centered in tubes which are oriented parallel to the beam direction. The narrow liquid argon gaps are between the tubes and the rods. This arrangement avoids ion build-up and ensures a high density.

Signal treatment

The liquid argon gaps of the calorimeters work as ionization chambers: Ionizing particles pass through the liquid argon gaps of the detector, creating electron–ion pairs. The electrons and ions drift towards the electrodes in the applied electric field – 10 kV/cm in the LAr–barrel. The field results from a voltage of about 2 kV applied over the liquid argon gaps between absorbers and readout electrodes. The high-voltage lines have their own feedthroughs in the cryostat walls.

The ionization creates a triangular current signal as the electrons successively reach the electrode. The ions have a much longer drift time, making their contribution to the current negligible.

The anodes have three conducting layers and the signal couples capacitively to the central one, where it is read out.

Analog summing boards and motherboards are located inside the cryostat. The summing boards are responsible for adding together the currents from a number of electrodes so as to achieve the desired detector granularity. The signals then go to the motherboards, where they are collected before they pass through the feedthrough of the cryostat.

The front end boards (FEBs) are located in the front end crates (FECs), which are situated on the outer edge of the cryostat in the gap between the barrel and end-cap tile calorimeters. The crate works as an extension of the Faraday cage formed by the cryostat, shielding the sensitive electronics inside.

On the FEB, the signal first reaches the current-sensitive pre-amplifier. It amplifies the signal above the noise level of downstream stages, so as to be the only contributor to electronics noise.

Next come the shaping amplifiers, which are bi-polar $CR-(RC)^2$ filters. The electrons have a drift time in the order of several hundred nanoseconds, much longer than the LHC bunch crossing frequency of 40 MHz. Therefore, only the beginning
of the ionization signal can be utilized for signal readout. This is accomplished by shaping electronics in preamplifier situated on the FEBs. There is a trade-off between the reduction of electronic noise – favoring a slow shaping time – and the reduction of pile-up noise from overlapping events – favoring a fast shaping time.

The ionization signal has a triangular shape: a short rise time of a few nanoseconds, and then a linear decay as the ionization electrons drift towards the electrodes. This current pulse – with an amplitude of a few milliamperes – is transformed by the shaping electronics to a bipolar voltage pulse of a few volts and around 100 ns long, suitable for digitization. The bipolar shape ensures a time integral of zero, leading to a zero integrated charge transport and therefore a constant DC level.

After the shaper there are switched capacitor arrays (SCAs) that store the analog samples awaiting digitization in a subsequent analog to digital converter (ADC). Digitization is only done if the event is accepted by the trigger system. Acceptance by the trigger occurs on a timescale of $2^{15}$ s, a hundred times longer than the bunch-crossing and sampling period.

In fact there are three different shapers and SCAs for each channel, with each amplifier having a gain different by a factor of about ten. These are called low, medium and high gain. This is done to optimize the total noise and achieve a 16-bit dynamic range in a cost-effective way, using 12-bit ADCs instead of 16-bit ones.

In the FECs, there are also tower builder boards that perform the final analog summing of the level 1 trigger signal before it is lead off to the trigger system. For the level 1 trigger, calorimeter cells are added into so-called trigger towers of the size $\Delta \eta = 0.1$ and $\Delta \phi = 2\pi/32 \approx 0.1$. This analog summation is done on the signals coming out of the shapers, and is done in two steps. First, signals from the same layer are added up on the front end board. Signals from different layers belonging to the same trigger tower are then summed on special Tower Builder Boards, which are also located in the Front End Crates. The signal – still analog – is then transmitted to the USA15 cavern.

Upon level 1 trigger accept, typically five ADC samples are transmitted (on optical cables, see chapter 4) from the FEBs on the experiment to the readout drivers (RODs), which are also located in the adjacent USA15 cavern.

Final energy reconstruction is performed in the RODs, using a digital filtering method [Cle94]. The ADC samples are multiplied with a set of Optimal Filtering Coefficients (OFCs) in order to determine the signal amplitude

$$ A = \sum a_i (s_i - P),$$

(3.14)

where $a_i$ are the OFCs, $s_i$ are the signal samples and $P$ is the pedestal level, corresponding to no signal present. Usually five ADC samples are used. Another set of OFC determine the timing of the signal

$$ A\tau = \sum b_i s_i.$$    

(3.15)
To determine the OFCs, knowledge of the pulse shape is required, as well as its derivative and the autocorrelation matrix

\[ V_{ij} = < s_i s_j > \]  

between the different ADC samples. The latter is determined in so-called pedestal runs, where there is no signal.

There is also a system for calibrating the electronics chain, equalizing the different detector cells for the effects of different electronics response and different capacitance of the detector cells. For this, there are dedicated calibration boards in the Front End Crates from which calibration pulses of a known amplitude can be injected. In the electromagnetic barrel and end-cap calorimeters, these pulses are injected inside the cryostat on the motherboard through special calibration lines. The signal can then be read out in the same way as a physics signal. Each calibration line pulses a number of cells, arranged in a pattern so as to be able to estimate and avoid effects of crosstalk between different pulsed cells. The pulses are exponentially decaying, mimicking the triangular shape of the real ionization signal.

### 3.3.2 Scintillating Tile Calorimeter

The Tile hadronic calorimeter is a sampling calorimeter using organic scintillating tiles as the active signal-collecting medium and steel plates as the absorbing medium. It consists of the Tile barrel calorimeter located outside the liquid argon barrel calorimeter and the Tile extended barrel calorimeters located outside the liquid argon end-caps. The readout granularity is \( \Delta \eta = 0.1 \) and \( \Delta \phi = 0.1 \).

The scintillators consist of 3 mm thick tiles, sandwiched between 4 and 5 mm thick iron plates. Scintillator tiles and absorber plates are stacked stacked perpendicularly to the incident particles. Figure 3.4 shows the geometry.

The Tile Calorimeter has three longitudinal samplings, named A, BC and D. The geometry of the cells is roughly projective with respect to the interaction point. The cell geometry is shown in figure 3.5. Tiles are in groups of 3, 6, and 2 radially for samplings A, BC, and D, respectively. The depths of the samplings in terms of nuclear interaction lengths are 1.5, 4.1 and 1.9 \( \lambda \), respectively, at \( \eta = 0 \).

#### Signal treatment

The scintillation light emitted by the tiles when traversed by ionizing particles is passed to wavelength-shifting fibers located on the sides of the models. It then reaches photomultiplier tubes (PMTs), which are located with other front end electronics in a drawer on the calorimeter (figure 3.4). Fibers are grouped together to form the suitable calorimeter cell size. Light is collected independently on each side of each tile, meaning that each calorimeter cell is read out by two different PMTs. The PMTs are fed with high voltage, on average 680 V, for a nominal gain of \( 10^5 \).
3.3. ATLAS CALORIMETERS

Photomultiplier

Wavelength-shifting fibre

Scintillator Steel

Source tubes

Figure 3.4: Geometry and readout principle of a Tile calorimeter module. From [Aad08].

Figure 3.5: Cell geometry in the Tile calorimeter. From [Aad08].
Analog electronics is placed on so-called 3-in-1 cards. These cards output a unipolar signal with a pulse width of 50 ns. There are two outputs for each channel, with a relative gain difference of 64. Each output is connected to a 10-bit ADC, giving a combined dynamic range of 16 bits. Contrary to the liquid argon calorimeters, the Tile calorimeter uses a digital pipeline to store samples awaiting level 1 trigger accept, after which normally seven samples are read out.

The 3-in-1 boards also provide output to adder boards, which form analog signal sums for the level 1 trigger.

Just as for the liquid argon calorimeters, cell energy is reconstructed using optimal filtering in RODs, located in the USA15 cavern.

Calibration systems exist to independently calibrate the optical part of the readout (scintillators and fibers), the PMTs, and the front end electronics.

- **Cesium calibration.** A $^{137}$Cs source can be moved hydraulically through holes in the modules. This system sees the scintillators, fibers, and PMTs and allows inter-calibration of the scintillators and the optical system. The PMT high voltage is adjusted to equalize the response. This system is read out with current-integrating electronics on the 3-in-1 cards, different from the one used for normal readout, meaning that it can only be used for inter-calibration and not for setting the absolute electromagnetic scale. The cesium calibration is performed in dedicated runs, with the source traversing each of the hundreds of thousands of tiles in the detector.

- There is a *laser calibration* system, which is primarily used to calibrate the PMTs. The system sees both the PMTs and the front end electronics. Laser pulses with a wavelength of 532 nm are generated in the USA15 cavern and sent via clear plastic fibers and several splits to each photocathode. This system can also be used to set the calorimeter timing.

- The *charge injection (CIS)* is used to calibrate the front end electronics. Calibration pulses are inserted before the shaping electronics using a precision DAC on the 3-in-1 cards.
Chapter 4

Installation and testing of LAr optical cables

4.1 Introduction

Upon level 1 trigger accept, full digital readout data of the event is transmitted from the front end electronics located on the experiment itself, to the back end electronics, situated in the counting room in the USA15 cavern about one hundred meters away. The transmission is done using fiber-optic cables.

For the all the liquid argon calorimeters (Barrel, Electromagnetic End-cap, Hadronic End-Cap and Forward calorimeters) the data consists of digitized samples (40 MHz) of calorimeter cell signals. It is transmitted from the front end boards (FEBs) sitting in the front end crates (FECs), located just outside the barrel and end-cap cryostat feedthroughs, to the readout drivers (RODs) in USA15.

4.2 Properties of fibers and cables

The fibers naturally need to traverse the experiment, and the cables carrying them must be sufficiently protected against damage both during installation and later handling of nearby detector components. In addition, the end-caps need to be able to retract from their data-taking position to allow access to the calorimeter front end electronics and the inner detector. This movement must not damage the fibers, thus, the cables and fibers must allow bending on flexible cable trays.

Furthermore, the fibers need to tolerate the radiation environment near the front end electronics, where the first few meters of fibers pass. This has been shown [Mha00] to be the case, with an attenuation of less than 0.1 dB/m.

The fibers are multi-mode Draka (previously Plasma Optical Fibers) HiCap 50 μm core with graded refractive index, operated at a wavelength of 850 nm. To assure simple installation and robustness, they are assembled into twelve-fiber color-coded encapsulated-type ribbons with a thin outer layer. Each cable consists of
CHAPTER 4. OPTICAL CABLES

four fiber ribbons each containing twelve fibers. Three of the ribbons in each cable normally carry signal, while the fourth one is used as a spare. There is one cable serving each FEC. Each half-barrel (side A and side C) has 16 FECs, while each end-cap has 13, giving a total of 58 cables, 232 ribbons, or 2784 individual fibers.

Figure 4.1 shows the optical readout cable, with the sheath peeled off to reveal its structure. The green sheath is made of a halogen-free flame-retardant (HFFR) thermoplastic compound. The sheath has an outer diameter of 9.5 mm and has a 4 × 5 mm² rectangular hole for the ribbons. Two glass-fiber reinforced polyester (GRP) rods are included in the sheath to ensure that bending only occurs in the plane of the ribs.

The cables were developed for use at LHC by the Ericsson Network Technology company. Details are described in [Arv00]. The cable is specified for a pulling force of 800 N, while tests have shown no significant attenuation up to 2 kN. The maximum fiber strain is 1.1 kN. Crush tests using a 100 mm diameter plate showed attenuation above 2 kN force. Bending the cable 360° showed no loss for radii above 100 mm, while losses were noted for smaller radii. For bends below 180° no attenuation was observed down to 80 mm bending radius.

The cables run from 76 × 245 × 153 mm³ non-magnetic stainless steel boxes (figure 4.2) attached between two tile fingers, adjacent to the LAr FEC, at which point they are split into individual fibers connected to the FEBs. The boxes provide strain relief for the cable sheath as well as the split fibers, and also provide storage for the twelve spare fibers, which are rolled up inside them.

On the USA15 side, the cables emerge into the racks housing the ROD crates from below the floor, terminating in 19-inch metal boxes at the bottom of the racks (figure 4.3). In the boxes, each cable is attached to a vertical plate, again providing
4.3 INSTALLATION PROCEDURE

Cables were delivered from Ericsson in pairs, with one stainless steel front end box with spliced-on patch cables in each end. In that way testing of the cables was possible before installation. These cables were cut in half into their final configuration and routed from the remaining metal box at the experiment to the rack boxes in USA15.
Figure 4.3: Lower part of one ROD rack in the USA15 cavern. Serving one end-cap, it receives 13 cables. The green optical cables can be seen arriving through the floor. They are attached to plates on which the four 12-fiber ribbons on each cables are split into individual fibers, which are to be connected to the readout driver boards (RODs). Picture taken with an 8 mm fisheye lens.

On delivery, the cables were laid in number eight figures to ease installation. Unfortunately, due to prolonged storage, tension along the turns had deformed the sheaths of some cables. Rolling the cables up on cable drums and treating them overnight in an oven at a temperature of about 50 °C proved to be sufficient to straighten the cables out.

Patch cables were spliced on to the cables at the USA15 end. This was performed on a workbench adjacent to the racks housing the ROD crates. Cables were cut to their final length and stripped to reveal the fiber ribbons. They were then attached to the vertical plates, and so were the patch cables splitting up the ribbons into individual fibers. The four ribbons of each cable were then spliced onto the patch cable ribbons. Surplus ribbons (about one meter on each side of the splicing) were rolled up on the plates.

Splicing (figures 4.4 and 4.5) was performed using an Ericsson RSU12 Ribbon
4.3. INSTALLATION PROCEDURE

Figure 4.4: Splicing cables in the USA15 cavern. In the foreground is the vertical plate to which the ribbons and cables are attached, and the fiber cleaver. In the background is the ribbon splicing unit.

Figure 4.5: Close-up of the Ericsson RSU12 ribbon splicing unit during splicing. The progress can be monitored using two cameras inside the unit. The ultrasound fiber cleaner is to the right of the main unit.
CHAPTER 4. OPTICAL CABLES

Splicing Unit. The procedure is as follows: First, ribbons are thermally stripped to reveal the bare fibers. Then, fibers are cleaned in ethanol using ultrasound, to remove any dirt or dust. Subsequently the fibers are cleaved to achieve a straight end-surface suitable for splicing. Finally, the fibers are spliced together by striking an electric arc between two electrodes inside the unit. Alignment between the two fiber cores is critical. To the aid of the operator, there are two cameras mounted inside the unit, showing the alignment from two different angles. As a last step, the fragile splicing is protected by a thermally shrinking sheath, which is attached to the plate as well.

The plates were then slid down to their final positions in the rack boxes. The patch cords were tied to cable ladders located between the racks, and lead to the proper ROD crates.

4.4 Measurements

After splicing, the fiber signal attenuation was measured. The metal boxes adjacent to the FECs were accessed through scaffolding, and the fiber ribbons were verified against mix-up or inversion. The fibers were then connected in pairs at the experiment side, allowing the whole measurement to be carried out by one operator, freeing up the experiment-side operator to locate the next cable to be tested. If a fiber pair with an unacceptable high attenuation was found, the single fiber responsible was identified.

The measurements was carried out using a Fluke SimpliFiber instrument, consisting of one transmitter, set to 850 nm, and one receiver. Attached to the transmitter was a short patch cable including a few small-diameter turns to eliminate higher-order modes. The system was calibrated by connecting the patch cable directly to the receiver, defining the reference power level relative to which attenuation was measured. When doing the actual measurements, the transmitter patch cable was connected to one of the fibers joined. There are thus two additional fiber-fiber connectors compared to normal operation, and these effect of these will be included in the measured attenuation.

Cleaning each fiber before measurement was found to beneficial for a consistent result. Measurements were downloaded to a PC laptop via the serial port.

4.5 Results

Figure 4.6 shows a histogram of the measured transmission loss for 1296 fiber pairs in 54 cables. The average attenuation is 0.69 dB. Only five fibers were found to have losses exceeding 4 dB, resulting in a failure rate of less than 2 per mil. This can be compared to the 33% redundant spare fibers available. For the faulty fibers, spares were substituted. Two fibers were broken at the USA15 side during installation, and were also replaced by spares.
4.5. RESULTS

Figure 4.6: Histogram of the measured fiber pair transmission loss for 1296 fiber pairs, corresponding to 54 cables. The mean attenuation is 0.69 dB.

Figure 4.7: ROD racks with all fibers connected.
After testing, the final connection of the fibers to the RODs and FEBs could be made. Figure 4.7 shows the ROD racks with all fibers connected.
Chapter 5

Presampler short-circuit evaporation

5.1 Introduction

As described in chapter 3, the purpose of the barrel and end-cap presamplers is to correct for energy lost upstream of the main calorimeter, thereby improving the measured energy resolution. The presamplers use liquid argon technology where ionization electrons drift across a 2 mm gap between two electrodes.

The applied electric field (2 kV potential difference in the barrel presampler and calorimeter) is essential for the operation for the ATLAS liquid argon calorimeters. If there is no electric field, no charge can be collected.

Unavoidably, some contamination of small pieces of dust, metal, etc. may be present inside the liquid argon cryostat. In some cases, they will give rise to short circuits between the electrodes. This risks a current overload, “tripping”, of the high voltage supplies, causing a loss of signal for the part of the presampler served by that high voltage line.

To prevent such a loss of signal, a number of techniques are employed: In each part of the presampler, high voltage feeding of the liquid argon gaps alternates between two different high voltage channels (section 5.2), meaning that only half the signal will be lost in the event of a short circuit in one of the high voltage channels, although this will lead to an increase in measurement noise. In addition, some power supplies can be run in a special high-current mode, allowing them to still operate in the presence of short circuits.\footnote{While not used for the presampler, this approach is used extensively in the Barrel calorimeter, where short circuits have been seen to be harder to evaporate than in the presampler.}

Despite this, it is of course preferable if the short circuits can be removed. Access to the inside of the cryostat is not possible once it is installed in the ATLAS pit. Thus, the short circuits must be removed \textit{in situ}. In the lab it has been
CHAPTER 5. PRESAMPLER SHORT-CIRCUIT EVAPORATION

High voltage sectors

\( \eta = 1.51 \)

\( \eta = 0 \)

Figure 5.1: Drawing of one presampler sector, extending from \(|\eta| = 0\) to \(|\eta| = 1.51\). Each sector consists of eight presampler modules. Two modules form one high voltage sector, fed by two high voltage lines.

shown possible [Ber05] to do this, burning the short circuits away by discharging a capacitor over the high voltage lines.

5.2 The ATLAS Barrel Presampler

The barrel presampler [ATL96a, Aad08] consists of two half-barrels (\( \eta < 0 \) and \( \eta > 0 \)).

For each half-barrel, there are 32 sectors in \( \phi \), each corresponding to a cryostat signal feedthrough, and each consisting of eight presampler modules in \( \eta \). Figure 5.1 shows a drawing of one presampler sector.

The modules in turn consist of individual electrodes. Anodes and cathodes alternate, with a \( \sim 2 \) mm gap between them.

The electrodes consist of conductive layers made of copper glued on to glass-fiber composite layers. The anodes and cathodes have a separate design. The cathodes are double-sided and serve as high voltage ground. The anodes have three sides, where the outer ones are fed with high voltage and the middle one is used for signal readout, coupling capacitively to the outer layers. The electrodes forming a module are glued between FR4 plates.

All modules have a length of \( \Delta \eta = 0.2 \), except the last one, which has \( \Delta \eta = 0.12 \). This is achieved by the modules having a varying number of electrodes, while maintaining a constant liquid argon gap between the electrodes.

The readout granularity is \( \Delta \eta \times \Delta \phi = 0.025 \times 2\pi/64 \). This is accomplished by dividing each electrode in two in \( \phi \) and summing up the signal from an appropriate
5.2. THE ATLAS BARREL PRESAMPLER

For high voltage purposes, $\eta$ adjacent presampler modules are connected in pairs, forming high voltage sectors. There are thus four high voltage sectors in one presampler sector. Each high voltage sector thus extends over an area of $\Delta\eta \times \Delta \phi = 0.4 \times 2\pi/32$ (sector 1–3) or $\Delta\eta \times \Delta \phi = 0.32 \times 2\pi/32$ (sector 4). In sectors 1–3, this corresponds to $160 \times 2$ readout cells.

Each high voltage sector has two high voltage buses, each feeding the high-$\eta$ or low-$\eta$ side of the anodes, respectively. A schematic diagram of this arrangement is in figure 5.2. 2 kV applied over a liquid argon gap of $\sim 2$ mm gives an electric field of $\sim 10$ kV/cm.

As mentioned, due to this arrangement, if one high voltage line fail in a high voltage sector, readout will still be available from half of the cells.

Figure 5.3 shows an anode electrode in detail. The outer copper layer is divided in two, creating two different signal readout regions, giving the desired $\Delta \eta = 2\pi/64$ granularity. The height of the electrode is 13 mm, of which 11 mm form the con-
Figure 5.3: Close-up on a presampler anode. The two high voltage lines are visible near the top, as are 1 MΩ surface mounted resistors connected in series with the conducting layers. The thin copper strips between the resistors and the electrodes proper can act as fuses.

The two high voltage lines, supplying each side of the electrode, are clearly visible. The high voltage is supplied in series with surface-mounted 1 MΩ resistors.

5.3 Method

The thin copper strips between the resistor and the electrode proper can act as a fuse and be burned away using a larger capacitance, if the short circuit itself cannot be disintegrated.

The high voltage lines are accessed through the high voltage feedthrough at the top of the barrel cryostat (figure 5.4). To protect the electronics, the corresponding front end boards (FECs) are removed from their respective crates.

The resistance to ground for the short-circuited high voltage line is measured. A typical resistance is 1 MΩ due to the injection resistor.

A 7 μF capacitance is charged to 2 kV and discharged over the high voltage line. The voltage over the line is monitored with an oscilloscope (figure 5.5). A relay closes the circuit at $t = 20$ ms. In the beginning the voltage decays weakly exponentially as the main voltage drop in the circuit is over the 1 MΩ resistor on the electrode. Meanwhile, corona effects start forming a plasma parallel to the
5.4 Results

A burning campaign was carried out between November 22 and November 24 2006. In total, 17 short circuits (figure 5.6) were successfully burned away, although, since 2006, five of the short circuits have reappeared.

To confirm that the short circuit was burned away, and not the 1 MΩ resistor, a sinusoidal signal can be injected on the high-voltage lines and read out on the regular signal lines, to which the signal couples capacitively. The signal can be read out either through the regular ATLAS DAQ system, or thought a dedicated KTH-developed oscilloscope-based system. The latter is labor-intensive, since it involved completely removing the FEBs to access the FEC backplanes.

During the burning campaign in the fall of 2006, the full ATLAS DAQ was not yet available. In the June of the same year, a small number of short circuits were evaporated in a test session. Afterwards, the KTH signal injection system was run. A 10 kHz signal was injected on the high voltage lines. Figure 5.7 shows the amplitude of the signal seen on the signal lines for the one presampler sectors.
corresponding to feedthroughs 23 and 24, side A. With rising \( \eta \), the capacitance increases due to the increased number of electrodes in each presampler module. For one cell (channel 81 in feedthrough 24, first high voltage line) has a signal response higher than the others in the same module. The corresponding high voltage line was burned with a larger capacitance than the usual 7 \( \mu \)F. The anomalous response indicated that a 1 M\( \Omega \) resistor had been damaged. This does not affect normal presampler operation.
Figure 5.6: Overview of the high voltage sectors that had short circuits before the 2006 campaign. All were successfully burned away. Since 2006, five of the short circuits have reappeared.
Figure 5.7: Measured peak-to-peak signal level when injecting a 10 kHz sinusoidal signal on the high voltage lines. Shown are measurements for the presampler sectors corresponding to feedthroughs 23 (a) and 24 (b), side A. $\eta$ increases with channel number. HV1 and HV2 are the two different high voltage lines that are connected to pairs of presampler modules. The steps in response occurs at module boundaries.
Chapter 6

Simulation studies of effects from saturation in liquid argon and timing of hadronic showers

6.1 Introduction

Monte Carlo simulations are an important tool for the understanding and calibration of a calorimeter system, allowing microscopic interaction models to be used to describe macroscopic observables. They make it possible to follow the shower development in detail, extracting information that is not available from beam test data. For instance, invisible energy depositions that do not give rise to a signal in the real calorimeter can be tracked.

The simulations are an important in most physics analyses. They allow the developing and testing of analysis code even before real physics data is available and make it possible to study how final states from expected new physics interact with the detector. They make it possible to develop off-line hadronic compensation and calibration schemes for the calorimeters, including dead-material corrections.

Essential then is that the simulation is able to reproduce real beam test data. All known physics processes and effects that may affect the result must be included.

This chapter will detail two investigations into improving the ATLAS Monte Carlo code. Both concern hadronic showers in the calorimeters. The first one concerns the implementation of saturation effects depending on the ionization density in the liquid argon barrel calorimeter and the second one is a study on how the code reproduces the timing profile of hadronic showers. First, there is a brief explanation of the ATLAS Geant4-based simulation code and the Geant physics models.
6.2 Monte Carlo simulation – Geant4

The general principle of a particle Monte Carlo\textsuperscript{1} simulation is to track individual particles as they traverse the detector geometry and interact with matter, possibly creating new secondary particles. It has knowledge of interaction cross-sections and models for the production of secondary particles. Interactions can be continuous, e.g. the ionization caused by a charged particle, or discrete e.g. the photoelectric effect.

The primary simulation code used for the LHC experiments is Geant4 [Ago03, All06]. Developed by an international collaboration using modern software design principles [G4c], it is a flexible and extensible framework written in object-oriented C++. It replaces the FORTRAN-based GEANT version 3.21 [Apo05], and is distributed under an open-source software license.

Geant4 has classes [G4b] to handle all aspects of simulation, including definition of detector geometry and materials, tracking of particles traversing material and magnetic fields, and physics models for the generation of secondary particles.

The life-span of a single particle is associated with a \textit{track}, which is pushed by a stepping manager through the geometry in many \textit{steps}. The step length is determined by querying the physics processes associated with the particle in question, choosing the shortest one [G4c, chapter 2.4]. In ATLAS, particles with a range larger than 1 mm are tracked.

The geometry can either be defined as hard-coded C++ code or loaded at runtime. ATLAS uses its own geometry description package called GeoModel [Geo]. Geant4 is completely integrated with the ATLAS Athena software, from which it is run.

6.2.1 Hadronic physics models

Physics models are implemented to simulate purely electromagnetic interactions, photonuclear interactions and hadronic interactions. For hadronic physics, Geant4 offers a range of different models, valid in different energy ranges and for different particles and materials. A specific choice of physics models and cross-sections, and their respective energy ranges of validity, are collected into a \textit{physics list}. Different ranges may apply for different kinds of particles. To make the transition between different models smooth, there may be energy ranges where several models apply. The decision which one to use is then made stochastically, using a continuous probability distribution that in the transition interval goes from exclusively using the lower-energy model to exclusively using the higher-energy one. Both data/parameterization-driven models and theory-driven models are available.

Parameterization-driven models are used by the LHEP physics list. It is a C++ reimplementation of the GHEISHA model in GEANT 3.21. LHEP uses a Low Energy Parameterized (LEP) and a High Energy Parameterized (HEP) model [G4a, \textsuperscript{1}Named after the casino, since it is based on random numbers and probabilities.]
chapter 21]. LEP is used below 25 GeV, while HEP is used above 55 GeV [G4P]. In the intermediate range, a linear probability function is used in deciding which model to employ. Both models use measured and extrapolated cross-sections, particle spectra, and multiplicities for the final state. Several parameters have been tuned in a global fit to describe hadron–hadron scattering data. LHEP provides fast simulation, but baryon and meson resonances are not produced. In addition, secondary angular distributions for low-energy reactions of the order 100 MeV cannot be described in detail.

QGSP [Fol03] (Quark–Gluon String Precompound) is a commonly used parton–string model. It uses a phenomenological model describing the hadron-nucleus interaction by the formation and fragmentation of excited strings together with the de-excitation of an excited nucleus. At energies below 12 GeV, QGSP is not applicable and LEP is used instead, with an overlap between QGSP and LEP extending up to 25 GeV [G4P]. An alternative to QGSP is the Fritiof model (FTF) [Nil87].

Both the QGSP and LHEP models can be used in conjunction with the Bertini cascade model [G4a, chapter 25]². Added is then the Bertini description of the in-nuclear hadronic cascade [Gut68, Ber71, Ste88]. Since the de Broglie wavelength of incident particles is shorter than the in-nucleon distance, the cascade inside the nucleon can be treated as consisting of classical particles. The cascade particles are propagated in a nuclear density model consisting of three concentric spheres, while excited states are collected. Cross-sections and angular distributions are the free-particle ones, although the Pauli principle is obeyed. After this fast in-nuclear cascade, a slower phase follows with decay of the resulting nucleus.

The Bertini model is applied up to 9.9 GeV, which gives a small overlap with LEP starting at 9.5 GeV [G4P]. QGSP in combination with the Bertini model has been adopted as standard for ATLAS, based on it providing the best match to beam test data.

The Bertini cascade may be replaced by the Binary cascade [G4a, chapter 26]. High-precision neutron tracking [G4a, chapter 37] – at the cost of higher CPU usage – is available³. The neutron tracking is then used up to 20 MeV [G4P].

6.2.2 Monte Carlo in the ATLAS calorimeters

In ATLAS Monte Carlo simulation is made in three steps, that are explained in the following:

Simulation

In the first one, simulation, the passages of particles through the detector, and the resulting showers are simulated using the Geant4 toolkit. The resulting cell energy deposits, hits, are recorded.

²The corresponding physics lists are called QGSP_BERT and LHEP_BERT.
³The corresponding physics list have the suffix “HP“, e.g. QGSP_BERT_HP.
Various charge collection and detector efficiency effects are implemented at this stage. In the liquid argon calorimeters, this includes charge collection in the ionization gaps.

The simulation of the Tile calorimeter scintillators includes saturation effects modeled according to Birks' law [Bir51, Bir64]. However, no attempt is made to describe the detailed optical properties of the scintillating tiles and the readout fibers.

Through a callback mechanism, a user supplied class can be called whenever energy depositions occur in the sensitive detector material. This creates hits, which are collections of energy deposits with a certain granularity in time and space.

There are two kinds of hits, regular hits and calibration hits:

- **Regular hits** are used in digitization (see below) when simulating the whole electronics chain response. Here physical detector effects, such as saturation, drift time and recombination are included. They only exist for active material in the detector.

- **Calibration hits** reflect the true energy deposited in the calorimeter and are used for calibration purposes and estimating the shower development and energy loss in dead and passive material.

Calibration hits are put into different hit collections depending on the role of the material where the deposition was made in the calorimeter:

- **Active** hits occur in the active material in the calorimeters, from which signal is read out, i.e. liquid argon or scintillator tiles in the LAr or Tile calorimeters, respectively. This corresponds to the same energy depositions as the regular hits, although detector effects are not included.

- **Passive** hits occur in the passive material of the sampling calorimeters, e.g. lead absorbers in LAr-barrel and steel in the Tile calorimeter.

- Finally, **dead material** hits occur for depositions in material which isn’t regarded as either active or passive calorimeter material. Examples of this category are the whole inner detector, the walls of the liquid argon cryostats, the liquid argon and electronics between the barrel presampler and the barrel calorimeter, and leakage beyond the Tile calorimeter.

The hits in each of the three categories above are divided into four different components, corresponding to the physics of the deposition:

- **Electromagnetic** energy comes from ionization of the active calorimeter material from the purely electromagnetic part of a shower, i.e. electrons, positrons, and photons.

- **Non-electromagnetic** energy is other depositions from ionization than those included in the last point, e.g. ionizing charged pions and protons.
• *Invisible* energy is not showing up as measurable in the calorimeter, e.g. breakup energy in nuclear interactions.

• Finally *escaped* energy is the energy of particles leaving the world volume of the simulation, e.g. neutrinos and high-energy muons, and, possibly, neutrons and low energy photons escaping the calorimeters. It is accounted for at the point of creation of the escaping particle.

The first two components collectively form the *visible* energy component.

### Digitization

The aim of the *digitization* step is to convert the (regular) simulation hits into a simulated signal (measurable in ADC counts) that is suitable for use as input to the reconstruction algorithms. Here, various effects due to electronic readout are implemented.

Hits in 1 ns bins are convoluted with the electronics pulse shape. The output is a collection of *digits*, i.e simulated ADC samples, which are then fed to the regular reconstruction algorithms.

In the liquid argon calorimeters [Lam07], this includes simulating electronic noise and pile-up noise, if present. Also, cross-talk between adjacent cells in the first sampling (strips) and between the second (middle) and third (back) samplings is taken into account.

In the Tile calorimeter, the effect of photo statistics in the PMTs is included. The electronic noise was extracted from experimental data using randomly triggered events and added incoherently to the energy of each PMT in the MC samples. Coherent noise is not simulated, but known to be relatively small.

### Reconstruction

Finally, in the third step, *reconstruction*, the simulated ADC samples are fed to the same Athena energy reconstruction algorithms as for real data.

### 6.3 Saturation effects in liquid argon – Birks’ law

#### 6.3.1 Introduction

When charged particles pass through the drift gaps in the liquid argon calorimeters, they ionize the medium. The resulting electrons and ions drift in the \( \sim 10 \text{ kV/cm} \) electric field between the electrodes. The resulting ionization current comes primarily from drifting electrons, since the ion drift is much slower, and the resulting current can be neglected.

Ideally, the signal being read out should be proportional to the amount of initial ionization created. The connection between the amount of charge created and the energy lost by the ionizing particles is in turn well-understood [Miy74].
One of the compelling reasons to use liquid argon as the active medium of a 
calorimeter is its extraordinarily linear response in converting energy deposited as 
ionization to electric charge. This is especially true for electromagnetic showers, 
where the particles depositing energy can be assumed to be relativistic and thereby 
minimum-ionizing [Wig00]. However, small deviations from linear behavior do exist. 
These are due to the fact that ions and ionization electrons may recombine before 
giving rise to a signal. This effect may potentially depend on two things, namely:

1. The strength of the applied electric field, where a weaker field can be expected 
to lead to more recombination of ion–electron pairs, and thus less signal. In 
the LAr–barrel calorimeter a voltage of 2 kV is applied over electrode gaps of 
2.1 mm, resulting in an electric field of about 10 kV/cm. However, close to 
the folds of the accordion structure the field will be weaker.

2. The linear ionization density $dE/dx$. The track from a strongly ionizing 
particle can be expected to have a higher probability of recombination due 
to the higher spatial density of ionization electrons and ions. This effect is 
naturally more important in hadronic showers compared to electromagnetic 
one, since the former contain more strongly ionizing particles such as low-
energy protons and charged pions.

6.3.2 Review of literature – theory

Jaffé theory

The first theory of the recombination of ions and electrons created by the passage 
of an ionizing particle through a fluid was published by Jaffé in 1913 [Jaf13]. This 
so-called “columnar theory” considers the columns of ionization created close to 
the track of the charged particle, which is assumed to be a straight line.

Assuming the density of negative and positive charges initially having a Gaussian 
distribution transverse to the ionization track with a characteristic width $b$, the 
charge density is modeled using a pair of partial differential equations each having 
a drift term, a diffusion term, and a recombination term:

$$\frac{\partial n_\pm}{\partial t} = \mp u (\nabla \cdot \mathbf{F}) + D \nabla^2 n_\pm - \alpha n_+ n_-,$$

where $n_+$ ($n_-$) is the density of positive (negative) charges, $\mathbf{F}$ is the applied electric 
field, $u$ is the mobility constant of the charge carriers in the electric field, $D$ is the 
diffusion constant, and $\alpha$ is the recombination constant. The diffusion and mobility 
constants are assumed to be equal for positive and negative charges.

Due to the recombination term being proportional to the product of the positive 
and negative charge densities, the equations are non-linear and cannot be solved 
analytically. Instead, recombination is neglected and the familiar solution to the 
diffusion equation as a spreading Gaussian function is found. Recombination is
then accounted for by substituting this solution back into the original equation, while making the normalization factor of the Gaussian function time dependent.

This gives for the fraction of surviving charge carrier pairs at infinite time,

$$R(F) = \frac{2uF \cos(\varphi)}{d} \int_0^T \frac{dt}{1 + \frac{\alpha N_0}{2\pi} \int_0^t e^{-\frac{2u^2 F^2 \sin^2(\varphi) t^2}{4Dt + b^2}} dt}$$  \hspace{1cm} (6.2)$$

Making the further assumption of the electric field $F$ and the angle $\varphi$ between the ionization column and the electric field being not too small, the following expression is derived for the fraction of surviving charge carriers at infinite time:

$$R(F) = \frac{1}{1 + \frac{\alpha N_0}{8\pi D} \sqrt{\frac{\pi}{2z}} S(z')}, \quad z' = \frac{b^2 u^2 F^2 \sin^2(\varphi)}{2D^2}.$$  \hspace{1cm} (6.3)$$

where $N_0$ is the initial ionization density per unit length, $b$ is the characteristic width of the initial Gaussian distribution of charge carriers, with $b \to 0$ representing the case of an initial delta function distribution. The function $S(x)$ is defined as

$$S(x) = \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{e^{-s} ds}{\sqrt{s (1 + \frac{z}{x})}}.$$  \hspace{1cm} (6.4)$$

At large enough electric field, $S(z')$ will be proportional to $1/F$ and equation (6.4) reduces to

$$R(F) = \frac{1}{1 + \frac{k' N_0}{F}},$$  \hspace{1cm} (6.5)$$

with $k'$ being a constant, or, since $N_0$ is proportional to $dE/dx$,

$$R(F) = \frac{1}{1 + k \frac{dE/dx}{F}}.$$  \hspace{1cm} (6.6)$$

This relation is often referred to as “Birks’ law” in analogy to Birks’ law for scintillators [Bir51, Bir64]. At fixed electric field, one can define

$$k_Q(F) = \frac{k}{F}.$$  \hspace{1cm} (6.7)$$

**Onsager theory**

Onsager [Ons38], on the other hand, considers “initial recombination”, in which the original electron–ion pair recombines. The one-particle equation of Brownian motion is considered, with a two-term potential consisting of an external applied field and the Coulomb attraction between the electron and the ion.
The theory takes into account the dependence on an external electric field, but has no dependence on the ionization density, since only a single electron–ion pair is considered, and thus cannot account for increased recombination due to a high ionization density.

The predicted recombination factor at low electric field is

\[ R = e^{-r_{kT}/r_0}(1 + E/E_{kT}), \]  

valid when the electric field \( E < E_{kT} \). \( r_{kT} = e^2/(\varepsilon kT) \) is the Onsager length, \( r_0 \) is the thermalization length, and \( E_{kT} = 2e k^2 T^2/\varepsilon^3 \). In liquid argon \( E_{kT} \approx 1.3 \text{kV/cm} \) [Sca82, Amo04].

**Kramers theory**

Kramers [Kra52] developed a modification of Jaffé’s theory. Starting from the same equations as Jaffé (6.1) and the same initial assumption of a cylindrically symmetric Gaussian distribution of ions, it is argued that the recombination term will dominate over the other two, thus bringing Jaffé’s solution into doubt. Instead, the equation is solved in a manner complementary to Jaffé’s approach, keeping only the drift and recombination terms, while neglecting the diffusion term. Diffusion is then accounted for though an approximation.

The resulting recombination factor is

\[ R(F) = f \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{\sqrt{\xi} d\xi}{f^* e^\xi + 1}, \]  

(6.9)

where

\[ f^* = f \sqrt{\frac{e^2}{\pi}} \int_0^{c f} e^{-\xi^2} d\xi; \quad f = F/\sqrt{4\pi e N_0 b}; \quad c = 8\theta \sqrt{\pi e^2 N_0 b}, \]

and \( \theta \) is a numerical factor of order unity.

A drawback of the Kramers theory is that it offers no analytic form for the result. At high electric fields it has the same \( 1 - kN_0/F \) behavior as the Jaffé theory.

**Thomas and Imel box model**

Thomas and Imel [Tho87] again start from the same equations as Jaffé, but note that in liquid argon and liquid xenon, the diffusion term is very small. Also, the ion drift velocity is three to five orders of magnitude smaller than the electron drift velocity. Consequently, the diffusion terms and ion drift terms can be dropped, reducing the Jaffé equations (6.1) to

\[ \frac{\partial n_+}{\partial t} = -\alpha n_+ n_- \]  

(6.10)

\[ \frac{\partial n_-}{\partial t} = u (\nabla \cdot \mathbf{F}) - \alpha n_+ n_- \]  

(6.11)
6.3. SATURATION EFFECTS IN LIQUID ARGON – BIRKS’ LAW

Using the initial condition that the charges are uniformly distributed inside a box of side $a$, the fraction of charge collected is calculated to be

$$\frac{Q}{Q_0} = \frac{1}{\xi} \ln(1 + \xi),$$  \hspace{1cm} (6.12)

with

$$\xi = \frac{N_0 \alpha}{4 a^2 u F}.$$

Taylor expanding as a function of $\xi$, one sees that the box model again has the same $1 - k N_0 / F$ high-field behavior as the Jaffé and Kramers models.

6.3.3 Review of literature – experiment

Only a few experiments have measured the $dE/dx$ dependence of recombination have been found.

The ICARUS project has made an extensive review [Amo04] of theory and experiment and also their own measurements.

Using a liquid argon TPC (Time Projection Chamber), it was possible for ICARUS to study how the recombination depends on both the applied electric field and the ionization density, since the TPC makes it possible to measure $dE/dx$ along individual particle tracks. This experiment was able to verify the functional form of Birks’ law for the first time. Data was taken using stopping cosmic muons and protons at electric fields of 200, 350, and 500 V/cm.

A Birks’ law fit using an overall normalization constant

$$R(F) = \frac{A}{1 + k \frac{dE/dx}{F}},$$  \hspace{1cm} (6.13)

gave the result

$$A = 0.800 \pm 0.003 \quad \text{and} \quad k = (0.0486 \pm 0.0006) \text{ kV/cm g/cm}^2 \text{MeV}$$

The authors do not expect that the fit can be extended to higher fields. Nevertheless, the ICARUS data is significant, since it is the only recombination experiment found that actually measures $dE/dx$.

The RD-4 project at CERN [Cen92, Vui93] investigated in the early nineties the feasibility of making a partly-compensating calorimeter using liquid argon doped with ethylene. The photo-sensitive ethylene would convert UV scintillation light to detectable charge. The larger recombination of hadronic shower particles would then push up the hadronic response.

Charge collection from both an $^{241}$Am $\alpha$ source and a $^{207}$Bi $\beta$ source was measured in electric fields ranging from about 0.5 kV/cm to about 8.0 kV/cm for a variety of ethylene concentrations, and also for pure liquid argon. The collected charge was found to be heavily dependent on ethylene concentration.
Figure 6.1: Power-law \( (k = p_0 \cdot F^{p_1}) \) fit of RD-4 Birks parameter data, digitized from [Cen92, figure 4]. The Birks parameter measurement errors have been estimated to 0.0002 g MeV\(^{-1}\) cm\(^{-2}\). Using the fit parameters and errors thus obtained, an extrapolation of the Birks parameter value at 10 kV/cm gives a Birks parameter of \( (0.0057 \pm 0.0001) \) g MeV\(^{-1}\) cm\(^{-2}\).

Calculating \( dE/dx \) from the energy of the particles emitted by each of the sources, one can determine the Birks parameter, *assuming* that Birks’ law holds. A major disadvantage with these measurements are of course that there are only two data points in \( dE/dx \).

Figure 6.1 shows the Birks parameter in pure liquid argon as a function of the electric field. Fitting the values with a power-law and extrapolating to an electric field of 10 kV/cm, the Birks parameter is \( k_Q = (0.0057 \pm 0.0001) \) g MeV\(^{-1}\) cm\(^{-2}\).

### 6.3.4 Complications

\( \delta \) rays

As the authors of the ICARUS paper [Amo04] point out, there is a difference in how delta rays are handled in Monte Carlo simulations and in real experiments. In the latter the delta rays are part of the measured ionization track and contribute to the measured \( dE/dx \). In the simulation, however, there is a cut energy under which ionization is treated as continuous and above which \( \delta \) electrons are individually
6.3. SATURATION EFFECTS IN LIQUID ARGON — BIRKS’ LAW

Measuring current, not charge

All measurements cited above concern the total charge collected on the electrodes towards which the electrons and ions drift. But the ATLAS liquid argon calorimeters effectively measure current, and not charge, in order to accommodate for the short time between collisions at the LHC. However, an electron drift velocity in the order thousands of meters per second and an ionization column width in the order of 10 nm [Amo04, Jaf13, Kra52] gives a timescale for recombination to occur in the order of picoseconds. This is much faster than the electronics shaping time, which in the order of ten nanoseconds. Current and charge measurements should therefore yield the same results.

6.3.5 Implementation in ATLAS

It can be considered a well-established experimental fact that ionization-density-dependent recombination effects exist in liquid argon, which should be implemented in the ATLAS Monte Carlo code. However, as has been seen from literature there exists some uncertainty on how the effect should best be modeled. All models depend on more or less realistic approximations, as no model offers completely realistic assumptions. Accuracy in the simulation is limited by this model uncertainty and the goal must be to use the current best knowledge.

Amoruso et al [Amo04] point out that all models are based on the assumption that drift velocity is proportional to the applied electric field, an assumption that fails in liquid argon above a few hundred volts per centimeter. The Onsager model can be ruled out, since it doesn’t take ionization density into account. The Kramers model is hard to implement, since it doesn’t offer an analytic formula. The box model – although being based on more realistic assumptions than the Jaffé model – has not had its $dE/dx$ dependence fitted to experimental data.

Remaining is the Birks formula (6.13) stemming from the Jaffé model. Although it is based on some unrealistic assumptions, it is the only model found having some experimental verification, in the form of the ICARUS and RD-4 data. It was thus chosen.

The ICARUS data is the only measurement with access to more than two data points in $dE/dx$. On the other hand, data was taken at a much lower electric field ($\leq 500$ V/cm) that the case of ATLAS LAr-barrel (10 kV/cm). However, the Birks parameter calculated from the RD-4 data is of a similar magnitude.

The H1 experiment at the HERA collider at DESY [And93] used a Birks constant of 0.005 g MeV$^{-1}$ cm$^{-2}$, quoting Fabjan et al. [Fab77] and Brau et al. [Bra83]. Reference [Bra83], a Monte Carlo study, uses $k = 0.0045$ g MeV$^{-1}$ cm$^{-2}$ on the basis that a 5 MeV alpha particle gives the same signal as a 1.25 MeV electron. This is based on [Fab77] quoting an alpha-to-electron ratio of 0.25 to 0.05 depending on

tracked.
the electric field. This in turn is based on an earlier paper by some of the same authors, [Wil74].

The Birks parameter was chosen to be

$$k = 0.0486 \text{kV/cm} \frac{\text{g/cm}^2}{\text{MeV}}$$  \hspace{1cm} (6.14)

from the ICARUS data. This gives

$$k_Q = 0.00486 \frac{\text{g/cm}^2}{\text{MeV}}$$  \hspace{1cm} (6.15)

for the 10 kV/cm electric field in LAr-barrel, which was assumed to be constant.

The overall normalization factor $A$ was adjusted to that the calorimeter response for electromagnetic showers remains unchanged. In liquid argon, $dE/dx$ for a minimum-ionizing particle is [PDG08] 1.51 MeV/g cm$^2$. For the energy to be unchanged, $A$ should then be chosen as

$$A = 1 + k \frac{dE/dx}{F} = 1.0072,$$  \hspace{1cm} (6.16)

which is in a per mil-level agreement with the value $A = 1.0085$ found by running the simulation ensuring that the response to electron showers is unchanged.

Recombination dependent on the electric fields occur due to diminished electric fields in the accordion fold of the calorimeter. It is implemented through current maps, which gives the fraction of charge reaching the electrodes as a function of the position of the energy deposition, and also takes the drift time into account. Factorizing these two effects (electric field and ionization density) is thought to be reasonable, since the former is expected to dominate for electromagnetic showers and the latter for hadronic showers. Electromagnetic showers primarily have relativistic minimum-ionizing particles, for which recombination effects due to ionization density will be small. $dE/dx$ effects on recombination will therefore be small. For hadronic showers, those effect will instead dominate. Since they are much wider, a detailed modeling of the charge collection due to the electric field is less important.

Birks’ law was first implemented in the LAr-barrel subsystem. It was then compared with 2004 Combined Beam Test data, and was found to improve the match between data and Monte Carlo. The effect was also studied in the context of an hadronic end-cap beam test, also with encouraging results in improving the match between data and Monte Carlo in terms of calorimeter response and resolution. Following these initial investigations, the effect was implemented in a consistent way in all LAr subsystems, starting from Athena release 14.

6.3.6 Results

Figure 6.2 shows how the response in the liquid argon calorimeter changes with the Birks parameter. This is looking at this effect separately, by applying the Birks
6.4. MC TIMING STUDIES

6.4.1 Introduction

As noted in chapter 3, the ATLAS calorimeters use shaping electronics in order to provide a fast enough readout to match the $f_{\text{bunch}} = 40$ MHz LHC bunch crossing frequency. The shaping time is selected such that contributions from electronic noise and pile-up events are equal.
CHAPTER 6. SATURATION IN LAR AND SHOWER TIMING

Figure 6.3: Effect of applying Birks’ law for 20 and 50 GeV pions.
In the digitization step of the simulation, the timing of the energy deposits in the calorimeters is convoluted with the electronics pulse shape. In order to achieve a good match between data and Monte Carlo for beam tests and collision data, it is thus important to verify that the Geant4 Monte Carlo code is able to reproduce the correct time development of hadronic showers.

A hadronic shower [Wig00, Brü88] can be expected to consist of a prompt delta-function-like energy deposition and one or several delayed ones. The former consists of the electromagnetic part of the shower, and the fast components of the hadronic part, such as ionization from pions.

The delayed energy depositions will essentially be due to neutrons created in the nuclear interactions of the initial shower. Those neutrons will be created in the MeV range. At those energies, the neutron absorption cross section is low for most materials, and the neutrons will scatter elastically against the nuclei of the calorimeter material. In hydrogen-rich materials, such as organic scintillators, protons will recoil and contribute to the visible signal. This effect can thus be expected to be seen in the ATLAS Tile calorimeter.

In some materials, neutrons may also induce fission of nuclei.

Eventually, the neutrons will have lost enough energy for the capture cross section to be non-negligible. In \((n, \gamma)\) processes, excited nuclei may emit gamma rays after neutron capture, giving rise to a late electromagnetic component of the shower.

### 6.4.2 Review of literature

Most of the studies found in the literature were done in the context of using depleted uranium calorimeters in order to achieve compensation, i.e. an equal response to electromagnetic and hadronic showers.

The general physics of hadronic showers in Monte Carlo simulation was studied by Brückmann et al. [Brü88] in 1988. They used the HERMES Monte Carlo framework which incorporated several Monte Carlo codes available at the time. Time-dependent energy spectra for particles were calculated on an average basis, with event-by-event fluctuations only being taken into account when coupled to a three-dimensional geometry in a final step.

The time structure of visible energy depositions were studied for two depleted uranium calorimeters: one using scintillators as the active material and another using liquid argon. The scintillator calorimeter shows three different late components corresponding to three different physics effects:

- The dominating component is recoil protons from the scintillator material, stemming from elastic interactions with neutrons, peaking at a time of \( \sim 9\ \text{ns} \).

- Gammas from secondary nuclear fission deposit energy on a similar timescale, but the effect is much smaller in magnitude.
• Gammas emitted after nuclear neutron capture is the second-largest effect. The effect is much slower than the other components, peaking at a time between 200 and 300 ns.

The liquid argon calorimeter shows similar effects, timescales and magnitudes for the secondary fission and neutron capture components. However, the proton recoil component is absent, consistent with the absence of the proton-rich scintillator material.

Caldwell et al [Cal93] used the compensating depleted uranium–scintillator calorimeter of the ZEUS experiment to measure the time development of hadronic showers in real experimental data. During a beam test using a secondary negatively charged hadron beam at Fermilab, charge-integrating electronics was used to record the time development. Scintillator and electronics effects were de-convoluted from the physical shower development using an electron-induced electromagnetic shower as reference. The time response was modeled as the sum of a delta-function component – corresponding to the prompt component of the showers – and three exponentially decaying components with different time constants:

$$ h(t) = A_0 \delta(t) + \sum_{i=1}^{3} \frac{A_i}{\tau_i} e^{-t/\tau_i}. \tag{6.17} $$

In a combined fit at beam momenta of 20, 50, and 100 GeV/c, the values $\tau_1 = 9 \pm 1$ ns, $\tau_2 = 120 \pm 20$ ns, and $\tau_3 = 1160 \pm 100$ ns were found. The relative contribution to the total deposited energy were $A_0 = 57.5\%$, $A_1 = 35.4\%$, $A_2 = 1.6\%$, and $A_3 = 4.5\%$ at a beam momentum of 50 GeV/c, giving a total non-instantaneous contribution in the order of 40%.

When the beam energy momentum increases from 20 GeV/c to 100 GeV/c, $A_0$ increases from 50.0% to 59.6%, consistent with the expectation that the electromagnetic fraction of the shower increases with increasing beam energy.

The degree of compensation as a function of integration time was measured, with the conclusion that an integration time of 100 ns was needed to achieve compensation on a per cent level. Larger integration times resulted in over-compensation.

Borer et al [Bor94] did time-of-flight measurements with hodoscope scintillator layers inside a ZEUS calorimeter prototype. They found an exponentially decaying delayed shower component with a time constant of 3.5 ns or 6 ns, depending on cuts.

In the uranium calorimeters studies above, the late contributions from fission fragments and neutron capture gammas can be expected to be large. In ATLAS, there is no fissile material or material prone to neutron capture in the calorimeters. However, some of the effects, such as protons from the elastic scattering of neutrons should be visible. In, addition, the general timescales should be similar.

Experimental measurements in calorimeters using other absorber materials than uranium are rarer. The SPACAL collaboration [Aco91] used a lead–scintillating fiber calorimeter. Data was taken in the H2 beam of the CERN SPS accelerator.
in 1989-1990. The main purpose of the study was to discriminate between pions and electrons using lateral shower information. The pulse shapes for pions and protons were studied. The electron pulse shape showed the typical scintillator response, while the pions pulses showed evidence of delayed components, both in terms of double peaks and as longer tails. An analog filter was designed with the purpose of deconvoluting detector effects. The output of the filter was fitted on an event-by-event basis. The filter output for 150 GeV electrons was well fitted with a gaussian function, having an average full width at half maximum (FWHM) of 4.03 ns with a standard deviation of 0.09 ns. For pions, the gaussian component was considerably wider, with a FWHM of 6.4 ns and a standard deviation of 0.8 ns, reflecting the larger longitudinal fluctuations in hadronic showers. The pion showers also contained an exponentially decaying signal component, having an average time constant of 9.9 ns, with a standard deviation of 1.7 ns.

The expectation from theory and experiment is thus a prompt component from the initial shower, followed by a neutron-related delayed component on a timescale in the order of 10 ns. Finally there may be a component resulting from neutron capture gammas. The question is now whether the Geant4-based ATLAS Monte Carlo can reproduce these general features.

6.4.3 Method

Since \( \frac{c}{f_{\text{bunch}}} = 7.5 \text{ m} \), new collisions will already have occurred before a signal traveling at the speed of light has reached even the outer parts of the detector. To correlate the read out signal with the right bunch crossing, the local timing used for readout at a certain detector cell is shifted with respect to the global time:

\[
t_{\text{local}} = t_{\text{global}} - \frac{R}{c},
\]

where \( R \) is the distance from the point in question to the interaction point\(^4\).

As explained in section 6.2, Geant4 tracks simulation particles through the concepts of tracks and steps. A track is associated with the whole life of a particle, while a step corresponds to a single iteration of the simulation, possible making an energy deposit.

By saving information about every simulation step depositing energy in the active part of the calorimeter, the time structure and genealogy of the particles making the deposits can be traced.

In parallel a Geant4 tracking action stores information about each track created. Events were simulated using the ATLAS 2004 combined beam test geometry. 50 GeV pions and protons were simulated using each of the physics lists QGSP, QGSP_BERT, and QGSP_BERT_HP (see section 6.2.1). 100 events were used for the Tile calorimeter and about 80 for the liquid argon calorimeter. The simulations were run using Athena 12.0.5 patched to use Geant version 4.9.

\(^4\)In the CBT geometry, the same formula can be used if care is taken to set up the simulation so that the initial particle passes the origin of the coordinate system when \( t_{\text{global}} = 0 \)
6.4.4 Results

All the following plots shows visible ionization energy deposited in the active material of the calimeters (liquid argon and tile organic scintillators, in the LAr and Tile calorimeters respectively).

Figures 6.4 and 6.5 shows cumulative and non-cumulative plots of the timing of the energy deposits in LAr and Tile and for the different physics models. For the LAr calorimeter, the onset of deposits occurs at a time several orders of magnitude smaller than one nanosecond, meaning that the timing as defined in equation 6.18 is correct. The slightly higher time of flight of protons compared to pions – due to their higher mass – can be seen.

For the Tile calorimeter, the onset is slightly later, peaking at about 2 ns. For practical purposes, this is of no importance, since it is of the same order as the 1 ns time bins used when convoluting with the electronics pulse shape.

All the models have a similar time profile. QGSP_BERT has the largest fraction of late deposits, with more than ten per cent of the total energy not deposited after the first few tens of nanoseconds.

For the non-HP physics lists, neutrons are tracked for 10 ns, after which time their energy is accounted for as a point-like deposition. This can be seen in figures 6.4(a) and 6.5(a) for LAr and Tile, respectively, where deposits are seen to abruptly stop at a time of approximately 10 ns.

Energy deposition separated by particle type

Figures 6.6–6.11 again show the cumulative energy deposition, but now separated according to the kind of particle making the deposition: pions, electrons/positrons, neutrons, or protons. The “others” category includes deuterons, alphas, and heavier nuclei.

The shower development shows three periods

1. First nanoseconds. The initial shower develops with hadronic and electromagnetic components. Close to all the energy from electrons and charged pions is deposited now.

2. Up to about 100 ns. Deposition is mainly by protons. This component is largest for the Tile calorimeter and for the physics lists using the Bertini cascade.

3. After about 1 µs there is a third component, with energy deposited by electrons. This effect is largest for the Tile calorimeter and the QGSP_BERT physics list.

The fact that neutrons are seen depositing energy directly in the non-HP physics lists is due to elastic scattering of neutrons off protons in the organic scintillators. If the energy of the recoil proton is too low for it to be tracked individually, the energy deposition is assigned to the neutron. That this effect is more prevalent with
6.4. MC TIMING STUDIES

Figure 6.4: Time structure of energy deposits, liquid argon calorimeter. Only energy deposits made in the active material are considered.
Figure 6.5: Time structure of energy deposits, Tile calorimeter. Only energy deposits made in the active material are considered.
6.4. MC TIMING STUDIES

Figure 6.6: Cumulative energy distribution separated by particle type in the LAr-barrel calorimeter. QGSP physics list.

Figure 6.7: Cumulative energy distribution separated by particle type in the LAr-barrel calorimeter. QGSP_BERT physics list.
CHAPTER 6. SATURATION IN LAR AND SHOWER TIMING

Figure 6.8: Cumulative energy distribution separated by particle type in the LAr–barrel calorimeter. QGSP_BERT_HP physics list.

Figure 6.9: Cumulative energy distribution separated by particle type in the Tile–Barrel calorimeter. QGSP physics list.
Figure 6.10: Cumulative energy distribution separated by particle type in the Tile–Barrel calorimeter. QGSP_BERT physics list.

Figure 6.11: Cumulative energy distribution separated by particle type in the Tile–Barrel calorimeter. QGSP_BERT_HP physics list.
QGSP_BERT compared to QGSP can be explained by the fact that the QGSP with the Bertini cascade is known to produce more neutrons compared to plain QGSP. The corresponding plots for protons as projectiles look very similar, although with a slightly higher fraction of the energy deposited by protons.

**Origin of late protons**

Figures 6.12–6.14 trace the origin of the late protons in the Tile calorimeter. Specifically, figure 6.12 shows the process that created the protons. Three different regions can be observed:

1. First, protons created in the inelastic nuclear reactions of \( \pi^+ \), \( \pi^- \), protons and neutrons in the prompt shower deposit their energy within the first couple of nanoseconds.

2. Secondly, protons produced in inelastic nuclear reactions of neutrons deposit their energy in an intermediate region, approximately \( 2 \text{ ns} < t < 10 \text{ ns} \).

3. Finally, protons stemming from elastic hadronic reactions deposit energy up to a time of about 100 ns.

Figure 6.13 shows the parent particles of the protons making deposits in the Tile calorimeter. The parents of the prompt protons are seen to be pions, protons, and neutrons. The parents of later protons are neutrons, consistent with the processes seen in figure 6.12.

Additionally, figure 6.14 shows the material where the protons making deposits were created, also for the Tile calorimeter. It can be seen that the prompt protons are created in the iron absorber. For the intermediate time region, both the iron absorbers and the organic scintillator contribute protons, while for the final region, only the scintillators contribute. Elastic scattering of neutrons in the proton-rich organic scintillators explain why protons are much more numerous in the Tile calorimeter compared to the liquid argon calorimeter. That the effect is much more visible for QGSP_BERT compared to QGSP is due to the fact that the Bertini cascade is known to produce neutrons in larger numbers.

**Origin of very late electrons**

The origin of the very late (> 100 ns) electrons seen primarily in the Tile calorimeter for the QGSP_BERT physics list can also be traced. Figure 6.15 shows the parent particles of the electrons making deposits. The parents of the very late electrons are photons. Figure 6.16 shows the process in which these parent photons were created, which is hadron capture by nuclei. Figure 6.17 shows the material in which the parent particles were created. For the photon parents of the very late electrons, the material is the iron absorber plates. Finally, figure 6.18 shows electron grandparents. The grandparents of the very late electrons are seen to be neutrons, confirming their origin in nuclear neutron capture.
6.4. MC TIMING STUDIES

Figure 6.12: Cumulative energy plots of creation process of protons making depositions in the Tile calorimeter. 50 GeV $\pi^+$ simulated with the QGSP_BERT physics list.

Figure 6.13: Cumulative energy plots of the parent particles of protons making depositions in the Tile calorimeter. 50 GeV $\pi^+$ simulated with the QGSP_BERT physics list.
CHAPTER 6. SATURATION IN LAR AND SHOWER TIMING

The physics lists without the high-precision neutron tracking are known [Har] to have an inaccurate neutron absorption model. Cross-sections are extrapolated from hydrogen nuclei and gamma energies are not accurately modeled. Thus, the very late depositions seen for QGSP.BERT are just an artifact of an inaccurate physics model. Again, the effect is much more visible for QGSP.BERT due to the larger number of neutrons produced.

6.4.5 Conclusions

In conclusion, the Geant4 simulation is capable of reproducing the expected time structure of hadronic showers. Care must be taken not to count unphysical neutron capture gammas produced when using the QGSP.BERT physics list.
6.4. MC TIMING STUDIES

Figure 6.15: Cumulative energy plots of the parent particles of electrons making depositions in the Tile calorimeter. 50 GeV π⁺ simulated with the QGSP_BERT physics list.

Figure 6.16: Cumulative energy plots of the creation process of the parent particles of electrons making depositions in the Tile calorimeter. 50 GeV π⁺ simulated with the QGSP_BERT physics list.
CHAPTER 6. SATURATION IN LAR AND SHOWER TIMING

Figure 6.17: Cumulative energy plots of the creation material of electrons making depositions in the Tile calorimeter. 50 GeV $\pi^+$ simulated with the QGSP_BERT physics list.

Figure 6.18: Cumulative energy plots of the grandparent particles of electrons making depositions in the Tile calorimeter. 50 GeV $\pi^+$ simulated with the QGSP_BERT physics list.
Chapter 7

ATLAS 2004 Barrel Combined Beam Test

7.1 General

The ATLAS Barrel Combined Beam Test (CBT) was performed from May 5 to November 11. It took place in the the H8 beamline of the SPS accelerator in the North Area of CERN. The controlled single-particle environment allows the validation of calibration and Monte Carlo code.

For the present analysis, data from the fully combined data-taking period has been used, where all the different subdetectors in the barrel region of ATLAS were present and online in a configuration close to the full ATLAS experiment. The beam passes a system of detectors that monitor the beam position and identify the particle type. It then reaches the inner detector, with the Pixel detector, the Semiconductor tracker (SCT) and the Transition Radiation Tracker (TRT). Finally, it reaches the calorimeters, with the liquid argon (LAr) electromagnetic calorimeter and the Tile hadronic calorimeter. At the end of the beamline was the muon spectrometer, not used in this analysis. Figure 7.1 shows the setup.

In total, around 90 million events were registered. Beam particles included electrons, photons, pions, protons and muons with momenta ranging from 1 GeV/c to 350 GeV/c.

7.2 Primary and secondary beam

The primary beam consisting of $p = 400$ GeV/c protons from the SPS accelerator impinges on an up to 30 cm thick primary target made of beryllium. In the target, various secondary particles such as protons, pions, electrons and kaons – and their anti-particles – are produced. Beryllium is used as target material due to it having a ratio of the hadronic interaction length $\lambda_h$ to the electromagnetic interaction length.
$X_0$ close to one (0.87), producing a mixture of electrons and hadrons as secondary particles.

Through a system of magnets and collimators, outgoing secondary beams can be selected in the momentum range $10^{-300}$ GeV/c. Electrons can be separated from the hadrons of the beam through synchrotron radiation in the magnetic field. The beam momentum spread is estimated to be 1%.

The beams used were electrons, positrons, photons and pions. Energies ranged from a few GeVs up to more than 250 GeV. Beams with energies below 20 GeV are tertiary beams in a special VLE (Very Low Energy) beamline configuration. Positive pion beams will be contaminated by protons and by muons, which have to be removed by veto scintillators behind the detectors.

### 7.3 Beamline and beam instrumentation

The general beam test geometry is described in [Di 05b]. The beamline instrumentation is described in detail in [Di 05a].
There are a number of special detectors installed in the H8 beamline to monitor the beam position and reject background events. This is shown in figure 7.2. The lower branch right after the secondary target is the VLE beamline, which is not used in this study. The main trigger used the scintillators S1, S2, and S3. SMH is the muon halo scintillator, which has a hole of diameter 3.4 cm centered on the beam, allowing it to be used for vetoing halo muons and other particles. The muon tag scintillator SMT is used to veto muons, which are able to pass through all the detectors. BC0 and BC1 are wire chambers measuring the transverse $x$ and $y$ position of the beam particles. The Čerenkov counters CHRV2 and other scintillators are not used in this study. Neither is the BC-1 beam chamber and the MDT muon chambers.

As explained in chapter 2, the inner detector consists of the pixel detector, the silicon tracker (SCT) and the transition radiation tracker (TRT). Modules of each were present in the beamline. The pixel and SCT modules were inside located inside a magnet, although the magnetic field was not turned on for the runs used in this analysis.

The calorimeter system is mounted behind the inner detector on a table that is able to turn and slide to let the particle beam be incident on different values of $\eta$ and $\phi$ relative to an imagined ATLAS interaction point. Figure 7.3 illustrates this.
Figure 7.3: From [Di 05a], this illustration shows the beam test detector set-up. The beam encounters, in order, the inner detector with pixel, SCT and TRT detectors, the liquid argon electromagnetic calorimeter inside its cryostat and the tile hadronic calorimeter. Further downstream, there are several types of muon chambers.

Figures 7.4 and 7.5 are photographs of the calorimeter assembly from two different angles.

The electromagnetic calorimeter used in the beam test is only one φ module inside a smaller cryostat than in ATLAS. The φ coverage is 2π/16. For the Tile calorimeter, three modules were used, with a φ coverage of 3/64 · 2π.

For a beam impinging at a pseudorapidity of η = 0.45 the expected amount of material in front of the LAr is about 0.44 λ_I. The LAr modules extend to 1.3 λ_I. The dead material between the Tile and liquid argon calorimeters spans about 0.6 λ_I. Finally the Tile calorimeter covers about 8.2 λ_I.

7.4 Calorimeter electromagnetic calibration

Calibrating the calorimeters to the electromagnetic scale aims to allow the reconstruction of the ionization energy deposited by electromagnetic showers in the active and passive material of the calorimeter. This involves both physical effects of shower development (sampling fraction) and calibration of the readout electronics.
Figure 7.4: Photo of the inner detector and calorimeter setup. To the far left is the magnet which houses the pixel and SCT detectors. Further to the right – before the calorimeters – is the TRT. The calorimeter table is turned to a high-$\eta$ configuration. Visible are the liquid argon cryostat – housing the electromagnetic calorimeter – and some tile extended barrel hadronic calorimeter modules. The tile barrel calorimeter modules would be hidden behind the liquid argon cryostat.

7.4.1 LAr

In ATLAS, as noted in chapter 3, final cell energy reconstruction from the ADC samples is performed in the Read Out Drivers (RODs), located in the USA15 cavern, through the method of optimal filtering. For the 2004 Combined Beam Test, six individual ADC samples were stored, and the ROD function was performed offline. This enabled the calibration to change as the analysis of the data progressed. The pedestal level – corresponding to no signal present – that is subtracted from the ADC samples can be determined either through dedicated calibration runs, or through random triggers between the physics events. In the Combined Beam Test, due to the pedestal level being sensitive to the varying temperature of the front end boards, random triggers had to be used.

In ATLAS, detector pulses will have a constant timing with respect to the 40 MHz LHC bunch crossing frequency, and only one set of OFCs is needed. However, in the beam test environment, particles arrive asynchronously with respect to
Figure 7.5: The calorimeter set-up with only one of the three Tile calorimeter modules present. The empty electromagnetic calorimeter front end crates (FECs) can be seen, as well as the cryostat feedthroughs. In the bottom one can discern the rails used to turn the cryostat table.

The electronic calibration in the context of the 2004 Combined Beam Test is described fully in [Ale06], and a short summary will be given here.

The reconstructed cell energy can be written

\[
E = F_{DAC \rightarrow \mu A} \cdot F_{\mu A \rightarrow \text{MeV}} \cdot \frac{M_{\text{phys}}}{M_{\text{cali}}} \cdot \sum_{j=1,2} R_j A^j
\]  

(7.1)

- \( F_{DAC \rightarrow \mu A} \) is the conversion from DAC setting in the calibration board to actual injected current at the motherboard. Is equal to

\[
F_{DAC \rightarrow \mu A} = \frac{76.295 \, \mu V}{R_{\text{inj}}},
\]  

(7.2)

where \( R_{\text{inj}} \) is the resistance of the precision injection resistor (about 1 M\(\Omega\)). Since the injection resistors were at a slightly different value than what is used in the reconstruction code, a correction factor of 0.9907 is applied to all cell energies in the first compartment (strips).
7.4. CALORIMETER ELECTROMAGNETIC CALIBRATION

- $F_{\mu A \rightarrow \text{MeV}}$ converts the ionization current to the actual energy deposited in the calorimeter cell, setting the absolute electromagnetic energy scale. It can be written

$$F_{\mu A \rightarrow \text{MeV}} = \frac{1}{I/E \cdot f_{\text{sampl}}}, \quad (7.3)$$

where $I/E$ is the conversion from energy deposited in the liquid argon gaps to ionization current, and $f_{\text{sampl}}$ is the sampling fraction accounting for energy deposited in the lead absorbers. In reality, the sampling fraction will vary with shower depth, a fact that will have to be accounted for at a later stage in the calibration, if high precision is required. The $F_{\mu A \rightarrow \text{MeV}}$ value used here is from a beam test analysis of 2002 [Aha06]. The value depends on the liquid argon temperature, which was precisely known in 2002, while no precise measurement was made in 2004. The absolute scale was therefore determined empirically using electrons. In this analysis an extra overall factor of 1.03 is applied to all cells. The expected systematic uncertainty on the absolute electromagnetic scale is about 0.8%.

- The $M_{\text{phys}}/M_{\text{cali}}$ factor accounts for the fact that physics and calibration pulses differ slightly, since the former are triangular pulses decaying linearly, while the latter decay exponentially.

- $R_i$ – so called “ramps” – close the calibration chain by giving the conversion from ADC values to DAC values. Included is a second-order term to account for non-linearities. The values are determined in so-called ramp runs, where the different DAC values are scanned through, and the amplitude of the resulting pulse is determined for each DAC setting from the ADC samples.

- Finally, $A$ is the amplitude of the signal, as determined by optimal filtering.

Some additional scaling factors have been applied to the simulated samples due to some peculiarities of the Monte Carlo samples used: Energies up to 100 GeV were simulated with an erroneous overall Birks law factor in the liquid argon calorimeter, pushing down the response in the LAr calorimeter by a few per cent. To compensate for this, and additional overall factor of 1.0176 is applied to the simulated samples. To compensate for an inadequate description in the simulation of the electric field in the presampler, the energy in this sampling has been multiplied by 0.96.

7.4.2 Tile

In this beam test, the charge injection and cesium calibrations were used, while the laser calibration system was not employed.

Although optimal filtering is intended to be used for the Tile calorimeter as well, for the Combined Beam Test a simpler method was used, where a parameterized waveform $g(t)$ was fitted to the ADC samples:

$$S(t) = A_{\text{fit}} \cdot g(t - \tau_{\text{fit}}) + P_{\text{fit}}. \quad (7.4)$$
$A_{\text{fit}}$ gives the signal amplitude and $P_{\text{fit}}$ the pedestal (baseline). $\tau_{\text{fit}}$ is the timing offset of the pulse. The pulse shape was extracted from data taking advantage of the asynchronous arrival time of particles compared to the 40 MHz clock. One pulse shape is used for each gain.

The reconstructed channel energy can be written

$$E = F_{\text{pC} \to \text{MeV}} \cdot F_{\text{ADC} \to \text{pC}} \cdot F_{\text{Cs}} \cdot (A_{\text{fit}} - P_{\text{fit}})$$  \hspace{1cm} (7.5)

- $F_{\text{pC} \to \text{MeV}}$ gives the absolute electromagnetic scale, converting measured charge to deposited energy in active and passive material. The value used in the reconstruction, 1.05 pC/MeV, is derived from electron beam tests in 2002 and 2003.

Since an electromagnetic shower from an electron test-beam will be mostly contained in the first sampling, only this layer can be calibrated this way. The cesium calibration system is then used to equalize the BC and D sampling with the A sampling. However, there are also geometric effects to take into account, since light attenuation increases in the deeper samplings, due to a larger tile size. This can be measured in beam test by exposing the calorimeter from the side with muons, which then only traverse one tile row. The resulting correction factors are 1.00 for the A sampling, 0.977 for the BC sampling, and 0.919 for the D sampling.

- $F_{\text{ADC} \to \text{pC}}$ gives the calibration of the front end electronics. First a linear calibration factor unique for each channel and gain is applied. To correct for non-linearities in low gain due to cross-talk from the saturated high gain branch, a correction factor is then taken from a lookup table.

- $F_{\text{Cs}}$ corrects for cell non-uniformities due to differing optical properties of tiles and fibers. It is derived from cesium calibration runs.

The reconstructed cell energy is then the average of two channels each read out by one PMT.

A re-analysis of Tile calorimeter 2002 beam test data results in scaling each energy deposition by a factor 1.018 to correct the $F_{\text{pC} \to \text{MeV}}$ factor. This additional factor is thus applied to the data.

### 7.5 Event selection

Events are selected if they meet the following requirements:

A signal in the trigger scintillators and a measurement in adjacent beam chambers that is compatible with one particle passing close to the nominal beamline are required. Beam halo muons are cut out using the SMH scintillator. Some events close to the LAr 25 ns wrap-around time are rejected due to problems choosing the right set of OFCs. Events with coherent noise in the presampler are removed by a cut on the energy deposited outside the beam spot area ($\pm 0.1$ in $\eta$).
In addition, at least one global track with at least 6 hits in the Pixel or the SCT and at least 20 hits in the TRT is asked for. The track in the TRT must be compatible with a pion track, i.e. no more than 2 higher level hits must be present. Events with a second track in the TRT are rejected: this ensures that the pion does not interact strongly before the TRT.

There must be at least one cluster with at least 5 GeV in the calorimeters. This cut rejects muons contained in the beam, together with a cut using the SMT muon scintillator downstream of the beamline. To reject some residual electron background events with more than 99% of their energy in the LAr calorimeter are rejected.

The same selection is applied on simulated Monte Carlo events and on data with the exception of cuts related to beam chambers and scintillators.

### 7.6 Runs used

Table 7.1 shows the runs and energies used for the present analysis. All are taken at $\eta = 0.45$ and $\phi = 0.1$, and consist of single positive pions and protons impinging on the calorimeters.

Positive pion beams in the H8 beamline are known to have a sizable proton contamination, see section 7.7.

All data was collected without magnetic field around the pixel and silicon detectors. Data samples were reconstructed using Athena release 12.0.7.

Measured beam momenta – as opposed to nominal ones – come from Hall probe measurements in 2002, where the relationship between the measured current in the bending magnets and the produced magnetic was established to high accuracy. The precision of the knowledge of the beam momenta is about 0.3%. For the runs at 20, 50, and 100 GeV the magnet currents were not recorded and the beam momenta of runs that are near-by in time have been used.

<table>
<thead>
<tr>
<th>Run</th>
<th>$E_{\text{beam}}^{\text{nom}}$ (GeV)</th>
<th>$E_{\text{beam}}^{\text{meas}}$ (GeV)</th>
<th>Before cuts</th>
<th>After cuts</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>2102396</td>
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<td>20.19</td>
<td>49871</td>
<td>7812</td>
<td>$\pi^+$</td>
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<td>179.68</td>
<td>85967</td>
<td>4318</td>
<td>$\pi^+$ ($e^+$)</td>
</tr>
</tbody>
</table>

---

1i.e. on the center of the calorimeter modules.
7.7 Proton contamination

The positive pion beams are known to have a sizable proton contamination. As noted above, several different types of particles are produced as the primary SPS beam strikes the beryllium target, including positrons, pions, and protons. Positrons are easily distinguished using synchrotron radiation in a magnetic field, while pions and protons are harder to separate. Thus the positive pion beams are known to have a sizable proton contamination, $f_{prot}$, defined as the fraction of the events in a sample that result from protons impinging on the calorimeters.

This gives rise to two potential problems in a calorimeter analysis:

1. Since test beam particles are selected using beam momentum, particles with different total energy will be selected.

2. The calorimeter response is different for pions and protons [Wig00].

These two points will be addressed below.

Since the beam is selected based on momentum, this results in a beam with particles having a different total energy, due to their differing mass. The relative difference in energy compared to the beam momentum can be written

$$\frac{E_{p}(p) - E_{\pi}(p)}{p} = \sqrt{1 + \frac{m_{p}^{2}}{p^{2}}} - \sqrt{1 + \frac{m_{\pi}^{2}}{p^{2}}} = \frac{m_{p}^{2}}{2p^{2}} - \frac{m_{\pi}^{2}}{2p^{2}} + O\left(\frac{m_{p}^{4}}{p^{4}}\right)$$

which is less than two per mil for beam energies above 15 GeV.

The second problem – the different response of pions and protons – is more serious. To achieve a good match between data and Monte Carlo simulation the right ratio of pions to protons must be used in the simulation.

Of course, this requires the beam proton fraction $f_{p}$, defined as the fraction of the events in a sample that result from protons impinging on the calorimeters, to be known to a reasonable accuracy. With the instrumentation at hand in the CBT, it is not possible to discriminate on an event-by-event basis between pions and protons. However, the TRT (Transition Radiation Tracker) can be used to measure the proton contamination on average. Each hit in the tracker produces either normal or high-threshold (HT) hits, depending on the amount of transition radiation emitted. This is normally used to identify electrons, which can be distinguished from hadrons on an event-by-event basis. However, the probability of a high-level hit is different for pions and protons, making it possible to distinguish between them on a statistical level, for beam energies above 30 GeV.

This measurement has been carried out [Pet]: First, the shape of the transition radiation onset as a function of $\gamma$ was determined using electron and muon beams. Then, the high-level hit probability $p$ was measured in the $\pi^{\pm} - p$ beam. This was compared with the theoretical expectation for a pure pion or proton beam: $p_{\pi}^{\pm}$ and $p_{p}$, respectively, shown in figure 7.6.
Table 7.2: Expected high-level hit probability for pions and protons, measured high-level hit probability, and calculated proton fraction as a function of beam energy, including combined systematic and statistical errors.

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>$p_{\pi^+}$ (%)</th>
<th>$p_\pi$ (%)</th>
<th>$p_{\text{meas}}$</th>
<th>$f_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.40</td>
<td>2.98</td>
<td>3.46 ± 0.09</td>
<td>-15 ± 32</td>
</tr>
<tr>
<td>50</td>
<td>4.19</td>
<td>3.12</td>
<td>3.71 ± 0.08</td>
<td>45 ± 12</td>
</tr>
<tr>
<td>80</td>
<td>5.15</td>
<td>3.22</td>
<td>4.07 ± 0.09</td>
<td>56 ± 7</td>
</tr>
<tr>
<td>100</td>
<td>5.83</td>
<td>3.28</td>
<td>4.28 ± 0.08</td>
<td>61 ± 6</td>
</tr>
<tr>
<td>180</td>
<td>8.49</td>
<td>3.56</td>
<td>4.74 ± 0.07</td>
<td>76 ± 4</td>
</tr>
</tbody>
</table>

The beam proton fraction was then calculated as:

$$f_p = \frac{p_{\pi^+} - p_{\text{meas}}}{p_{\pi^+} - p_\pi}$$

The results are given in table 7.2, with both systematic and statistical errors. The systematic errors on the proton contamination are due to the uncertainty on the shape of the onset function, and an overall scale uncertainty due to variations between runs, particle types, selections, etc. The former is estimated to 2.5% on the proton contamination from using several different parameterizations of the onset function. The latter is estimated to 0.1% in the high-level hit probability.

Table 7.3 compares the present analysis with figures obtained in analyses done on earlier beam tests conducted in the same beamline. While no TRT was available then, there were Čerenkov counters calibrated to separate pions and protons.

“Čerenkov 2001” numbers are from figure 3 in [Con01]. Since the beam muon fraction is plotted separately there, the sum of the beam pion and proton fractions does not add up to one. Here the beam proton fractions have been renormalized to $f_p/(f_p + f_{\pi^+})$.

“Čerenkov 2002” numbers are from [Sim07] and [Hak07]. There the number of events in a pion and proton sample are given, together with the expected contamination in each. The beam proton fractions are calculated as $N_p \cdot (1 - C_\pi^+)/(N_p + N_{\pi^+})$, where $N_p$ ($N_{\pi^+}$) are the number of events in the proton (pion) sample and $C_\pi^+$ is the estimated level of pion contamination in the proton sample.

The proton fractions estimated from the TRT analysis are in good agreement with measurements done with a dedicated Čerenkov counter in 2001 and 2002. However, at 180 GeV the TRT measurement gives a markedly higher proton fraction than the Čerenkov-based ones.

### 7.8 Monte Carlo simulation

The Monte Carlo simulation uses a dedicated beam test geometry. For the present analysis Geant 4.7 and Athena release 12.0.5 were used. In total, about four million
Figure 7.6: Measured TRT high-level hit probability compared to expected probabilities for pions and protons.

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>$f_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cerenkov 2001</td>
</tr>
<tr>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>80</td>
<td>49</td>
</tr>
<tr>
<td>100</td>
<td>59</td>
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</table>

Table 7.3: Comparison of measured proton fractions in analyses of different SPS H8 beam tests. The “Čerenkov 2001” numbers are from figure 3 in [Con01]. The “Čerenkov 2002” numbers are from [Sim07]. The errors of the Čerenkov measurements are in the order of one per cent.
events were simulated. The interaction of the particles in the detector was simulated with GEANT4.7 using the QGSP_BERT physics list, which is the ATLAS default. For details on Geant4 and physics models, see chapter 6.

7.8.1 Samples definition

The simulated data set was divided into two approximately equal parts, forming statistically independent samples:

- the ”correction” sample, which was used for deriving weights and dead material corrections, and
- the ”signal” sample, which was used as simulated data to test the expected performance of the corrections.

The exact number of event available for each of the two samples above are in tables 7.4 and 7.5.
Table 7.4: Fully simulated Monte Carlo samples used for the present analysis. The “correction” sample used to derive the corrections.

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$\pi^+$ Bef. cuts</th>
<th>$\pi^+$ Aft. cuts</th>
<th>$p$ Bef. cuts</th>
<th>$p$ Aft. cuts</th>
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<td>1032336</td>
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Table 7.5: Fully simulated Monte Carlo samples used for the present analysis. The "signal" sample is used to compare to the data.

<table>
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<th>Energy (GeV)</th>
<th>( \pi^+ ) Bef. cuts</th>
<th>( \pi^+ ) Aft. cuts</th>
<th>( p ) Bef. cuts</th>
<th>( p ) Aft. cuts</th>
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</tbody>
</table>
Chapter 8

Hadronic calibration of the ATLAS Barrel calorimeters

8.1 Introduction

Hadronic calibration means bringing the response of the calorimeter system to hadrons from the electromagnetic scale, directly related to the visible energy deposited in the calorimeters, to the true energy of the incoming particles. In the case of ATLAS, hadronic particles will mostly be present in the form of jets, and a calibration should reach the whole way to the level of the initial partons giving rise to the jet. This can be done according to different schemes. Either the whole calibration can be done in a global fashion, accounting for jet physics and detector effects at the same time, or in a more local manner, correcting for each effect separately.

In order to measure the energy of a hadron impinging on a calorimeter one has to overcome the fact that part of the energy is deposited in a non measurable (invisible) form, i.e. nuclear break-up and excitation, out-of-time delayed photons, soft neutrons, etc. All of these effects are absent in the case of particles interacting only electromagnetically [Ler00, Fab03, Wig00]. All secondary particle showers generated by hadrons will have a component of such particles. Depending on the materials and geometry used in a calorimeter, this lost ”invisible” energy can be more or less well compensated by other effects. As the average size of this hadronic shower component increases with the energy of the impinging hadron [Gro07], the ratio of visible and invisible energy increases, resulting in a non-linear response of the calorimeter, described by the $e/h$ ratio (chapter 3).

Compared to electromagnetic showers, hadronic showers fluctuate wildly from event to event, both in their transversal and longitudinal dimensions. This is due to large number of possible final states for hadronic interactions in matter. The distribution of energy between the LAr and Tile calorimeters – with different intrinsic $e/h$ ratios – varies greatly.
The detector material and size are not always aimed at (or capable of) equalizing the hadronic and electromagnetic energy response (compensation). Such is the case for both of the main calorimeter systems in ATLAS – the electromagnetic liquid argon (LAr) calorimeter and the tile hadronic calorimeter. Both are intrinsically non-compensating, meaning their response to showers induced by electromagnetically showering particles – e.g. electrons or photons – and hadronically interacting particles – e.g. pions or protons – are different.

In these cases offline calibration techniques are developed that use the properties of the visible deposited energy to derive energy corrections aimed at restoring linearity in the response and improving the resolution. Average corrections can restore the linearity of the response, but they cannot compensate the calorimeter on an event-by-event basis and thus hardly improve the resolution. Techniques that are spatially sensitive to the difference between electromagnetic and hadronic energy deposits and their fluctuations are therefore more suited to produce event-by-event corrections that will also affect the resolution.

The standard ATLAS local hadronic calibration scheme [Ber07, Spe08] picks weights from two-dimensional look-up tables in cell energy density and cluster energy. Here an alternative to the standard method: the Layer Correlation (LC) method will be described and applied to beam test data. As a comparison, a simple $e/\pi$ weighting scheme is also considered.

8.2 Clustering

The building blocks of the following calibration are topological calorimeter clusters found by the following algorithm:

For each event cell clusters are derived by adding up the energy in neighboring cells with a dynamical topological algorithm in three dimensions into topological clusters, “topoclusters”. The algorithm is described in [top]. It starts by finding seed cells, having an energy above a certain seed threshold and not already being part of a cluster. Then the cluster is grown by recursively adding all neighboring cells that have an energy above a neighbor threshold. Finally, when no further adjacent cells with energies above the neighbor threshold can be found, all cells surrounding the cluster are added if their energy exceeds the perimeter threshold. The values used for the seed, neighbor and boundary thresholds are, respectively, four, two and zero times the expected noise in the given cell.

For this analysis, the reconstructed energy in layer $L$ is obtained by building all the 3D topoclusters in the event and summing only the energy of the cells in layer $L$ that belong to a topocluster. The total reconstructed energy is then derived by
8.3. THE LAYER CORRELATION METHOD

summing over the $N_{lay}$ longitudinal layer in the calorimeter:

$$E_{rec}^L = \sum_{cell_{t3D}} E_{cell_{t3D},L}^{rec}$$ (8.1)

$$E_{tot}^{rec} = \sum_{L} E_{L}^{rec}$$ (8.2)

The topocluster parameters are a trade-off between large energy containment, and increased noise. The 4-2-0 cluster configuration has been shown [Spe08] to be optimal in terms of resolution and energy containment.

8.3 The Layer Correlation method

8.3.1 Introduction

The correlations between the energy deposits in the longitudinal development of the shower is shown [Nak05] to have information on the electromagnetic and hadronic nature of shower. An improvement in resolution is expected to result from capturing more of the properties of the different fluctuations.

In this study a technique for energy compensation is developed that uses the properties of such correlations to derive a Monte-Carlo based event-by-event compensation technique. The application is quite specific to ATLAS, but the framework is rather general and it can be tested on any segmented calorimeter. Layer weighting has already been explored in ATLAS in a different fashion for jet energy calibration [Gup06].

The weighting is applied to ATLAS 2004 Barrel Combined Beam Test data. The experimental setup was presented in chapter 7, including basic selection and reconstruction of the events and properties of the data and Monte Carlo samples used.

The Layer Correlation method (LC in the following) is based on the ansatz that different longitudinal fluctuation properties characterize events with different invisible energy content: variables that can describe the various possible fluctuations should discriminate the different corrections to be applied to recover invisible losses due to hadronic interactions. In addition dead material losses will vary depending on the shower development: fluctuation-sensitive variables should then also help to recover dead material losses while capturing their correlation with invisible energy fluctuations.

The aim of the LC technique is to derive an event-by-event correction to the energy deposited in each longitudinal calorimeter layer on the basis of Monte Carlo simulated events. A unified treatment for compensation and dead material correction is obtained by deriving both corrections from the same set of variables.
The energy in each layer is then corrected by a weight and an additive correction to account for compensation and dead material effects, respectively:

\[ w_L = \langle \frac{E_{L}^{\text{true}}}{E_{L}^{\text{rec}}} \rangle \]  \hspace{1cm} (8.3)

\[ E_{L}^{\text{weighted}} = w_L E_{L}^{\text{rec}} \]  \hspace{1cm} (8.4)

\[ E_{\text{weighted}}^{\text{tot}} = \sum_{L} E_{L}^{\text{weighted}} \]  \hspace{1cm} (8.5)

\[ E_{\text{corr}}^{\text{tot}} = E_{\text{weighted}}^{\text{tot}} + E_{\text{DM}} \]  \hspace{1cm} (8.6)

where \( w_L \) is the weight correcting for invisible energy in layer \( L \) and \( E_{\text{DM}} \) is the dead material correction. The \( N_{\text{lay}} \) weighting functions and the additive correction are derived in the steps outlined below.

The events in a fully simulated Monte Carlo sample are usually generated at a fixed beam energy in order to test the calorimeter response. The corrections derived from a fixed beam energy sample are, in principle, dependent on that information i.e. they depend on the same quantity (pion energy) for the reconstruction of which they should be used. Sample mixing and iteration techniques are used to overcome such dependence and properly define a procedure for converging towards the appropriate corrections using only the visible energy in the calorimeter. The description of the weighting technique and the dead material corrections in the following sections (8.3.2 and 8.3.4) assumes that simulated events have a fixed beam energy. Section 8.3.5 deals with overcoming the beam energy dependence when deriving the corrections.

### 8.3.2 Compensation weights

Each event is associated to

- a set of \( N \) energy deposits \( (E_1, ..., E_N) \), one per calorimeter layer, representing a point in an \( N \) dimensional vector space. In principle, it is not necessary to consider all the layers, so \( N \) can be any positive integer that is smaller than the total number of layers \( N_{\text{lay}} \).

- the corresponding \( N_{\text{lay}} \) coefficients necessary to re-weight each reconstructed layer energy deposit to the true deposited energy known is in Monte Carlo i.e.

\[ w(L, i) = \frac{E_{L, i}^{\text{true}}}{E_{L, i}^{\text{rec}}} \]  \hspace{1cm} (8.7)

where, for the \( L^{th} \) layer in the \( i^{th} \) event, the \( w(L, i) \) is the weight, \( E_{L, i}^{\text{true}} \) is the true total deposited energy, as given by summing the active and passive material calibration hits for visible, invisible, and escaped energy (see section 6.2.2), and \( E_{L, i}^{\text{rec}} \) is the reconstructed energy as defined in equation 8.2.
8.3. THE LAYER CORRELATION METHOD

An average weight $w_{av,k}(L)$ for each layer $L$ can then be defined for any bin $k$ of the $N$-dimensional subspace of the layer energy deposits:

$$w_{av,k}(L) = \langle w_k(L, i) \rangle = \frac{\sum_i w_k(L, i)}{N_{ev,k}}, \quad (8.8)$$

where the weights $w_k(L, i)$ are those derived for the $N_{ev,k}$ events in the $k^{th}$ bin.

If the events themselves have a weight $^1$, the functions are modified accordingly:

$$w_{av,k}^{we}(L) = \langle w_k(L, i)^{we} \rangle = \frac{\sum_i w^{we}_i w_k(L, i)}{\sum_i w^{we}_i}, \quad (8.9)$$

where $w^{we}_i$ is the weight assigned to the $i^{th}$ event.

The choice of the $N$-dimensional subspace of layer energy deposits and of a suitable base for it are critical to achieve the best performance i.e.

- good separation of events with different content of invisible energy
- maximal information capture without having to resort to the full $N_{lay}$ dimensions.

The choice used here is as follows:

A new basis for the energy deposit vector space is derived. The $N_{lay}$-dimensional covariance matrix of the layer energy deposits is calculated as:

$$Cov(M, L) = \langle E_{L}^{\text{rec}} E_{M}^{\text{rec}} \rangle - \langle E_{L}^{\text{rec}} \rangle \langle E_{M}^{\text{rec}} \rangle, \quad (8.10)$$

where

$$\langle E_{L}^{\text{rec}} E_{M}^{\text{rec}} \rangle = \sum_{i} \frac{E_{M,i}^{\text{rec}} E_{L,i}^{\text{rec}}}{N_{ev}} \quad \text{and} \quad \langle E_{M}^{\text{rec}} \rangle = \sum_{i} \frac{E_{M,i}^{\text{rec}}}{N_{ev}}, \quad (8.11)$$

where the sums are performed over all the $N_{ev}$ events in the sample and $E_{M,i}^{\text{rec}}$ is the energy deposited in the $M^{th}$ layer in the $i^{th}$ event. The coordinates of each event can then be expressed in the new eigenvector basis as follows:

$$E_{M}^{\text{rec}} = \sum_{\text{eig}} \alpha_{M, \text{eig}}^{\text{rec}} E_{\text{eig}}^{\text{rec}} \quad (8.12)$$

where $\alpha_{M, \text{eig}}$ is the matrix that performs the rotation to the new orthogonal basis of the eigenvector in the $N_{lay}$-dimensional vector space.

The eigenvectors are ordered according to the size of their eigenvalues and their directions are those of the independent fluctuations in the $N_{lay}$-dimensional space. The eigenvectors with the largest eigenvalues determine the directions along which most of the fluctuations of the total energy take place. Thus a lower-dimensional space can be used to determine $w_{av,k}$. This is done by choosing $N$-dimensional bins (with $N \leq N_{lay}$) in the new eigenvector basis.

\(^1\text{For instance, to equalize the number of events for all data sets.}\)
CHAPTER 8. HADRONIC CALIBRATION

8.3.3 Calculation of covariance matrix and eigenvectors

The layer energy covariance matrix \( \text{Cov}(M,L) \) (equations 8.10 and 8.11) is calculated by using events from an appropriate mix of pions and protons. The full seven-dimensional covariance matrix is used i.e. \( N = N_{\text{lay}} = 7 \) (see section 8.3.2.)

In any given event a symmetric energy cut is applied on each layer energy such that the energy for that layer is re-defined as \( E_{\text{rec}}^M \), if \( |E_{\text{rec}}^M| > E_{\text{thr}}^M \), zero otherwise.

In this way the contribution to the covariance from a layer only containing noise is set to zero. The energy threshold vector is

\[
\vec{E}_{\text{thr}} \text{(GeV)} = (\sigma(1), \sigma(2), \sigma(3), \sigma(4), \sigma(5), \sigma(6), \sigma(7)) \quad (8.13)
\]

where \( \vec{\sigma} \text{(GeV)} = (0.032, 0.108, 0.03, 0.150, 0.039, 0.070, 0.042) \). The cuts were optimized to obtain the best expected compensation performance on fully simulated Monte Carlo samples at 50 GeV.

The covariance matrix \( \text{Cov}(M,L) \) is then diagonalized: the normalized eigenvectors and corresponding eigenvalues are calculated for all the samples.

The eigenvectors’ directions are observed to be stable with beam energy and choice of physics list.

A physical interpretation of the eigenvalues and normalized eigenvectors can be obtained by looking at figures 8.1 and 8.2 where the the individual eigenvector components are plotted.

We find that:

- \( \vec{E}_{\text{rec}}^{\text{eig}}_0 \approx \frac{1}{\sqrt{6}} (-2 \vec{E}_{\text{LAr,middle}} + \vec{E}_{\text{Tile,A}} + \vec{E}_{\text{Tile,BC}}) \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_1 \approx \frac{1}{\sqrt{2}} (-\vec{E}_{\text{Tile,A}} + \vec{E}_{\text{Tile,BC}}) \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_2 \approx \frac{1}{\sqrt{3}} (\vec{E}_{\text{LAr,middle}} + \vec{E}_{\text{Tile,A}} + \vec{E}_{\text{Tile,BC}}) \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_3 \approx \vec{E}_{\text{Tile,D}} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_4 \approx \vec{E}_{\text{LAr,strips}} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_5 \approx \vec{E}_{\text{LAr,presampler}} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_6 \approx -\vec{E}_{\text{LAr,back}} \)

So in a more qualitative, but suggestive way we can maintain that:

- \( \vec{E}_{\text{rec}}^{\text{eig}}_0 \approx \text{“Difference between Tile and LAr”} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_1 \approx \text{“Difference between Tile second (middle) layer and Tile first layer”} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_2 \approx \text{“Total Energy”} \)
- \( \vec{E}_{\text{rec}}^{\text{eig}}_3 \) to \( \vec{E}_{\text{rec}}^{\text{eig}}_6 \approx \text{“Individual layers”} \)
Figure 8.1: Eigenvector components for the seven layers of the ATLAS combined beam test for simulated pions. Each plots shows an eigenvector, ordered left–right, top–down, starting with the zeroth one in the top left. In each plot the eigenvector is expressed in the basis of the seven ATLAS calorimeter layers: LAr presampler, strips, middle, and back, and Tile A, BC and D.

8.3.4 Dead Material corrections

The energy loss in non-instrumented (dead) material between the LAr and the Tile calorimeters is expected to be the largest dead material effect [Mas] in the reconstruction of pion energy. The LC technique is used for correcting this loss.

Additional dead material losses give rise to smaller corrections. For these a parametrization of the energy loss as a function of the best estimate of the pion energy is used.

Dead material between LAr and Tile

A similar technique as for the compensation is developed for the LAr-Tile energy loss.

Each event is associated to
Figure 8.2: Eigenvector components for the seven layers of the ATLAS combined beam test for a simulated mix of protons and pions with 45% proton contamination. Each plot shows an eigenvector, ordered left–right, top–down, starting with the zeroth one in the top left. In each plot the eigenvector is expressed in the basis of the seven ATLAS calorimeter layers: LAr presampler, strips, middle, and back, and Tile A, BC and D.

- its $N$ energy deposits in the active calorimeter layers (as illustrated in the previous section)
- the true total energy lost in the dead material between LAr and Tile in that event i.e. $E_{\text{DM}}^i$, the loss in the $i^{\text{th}}$ event.

An average dead material correction, $E_{\text{av},k}^{\text{DM}}$, is defined in any given bin $k$ of a given subspace of the energy deposits:

$$E_{\text{av},k}^{\text{DM}} = < E_{\text{DM}}^i > = \frac{\sum_i E_{\text{DM}}^i (i)}{N_{\text{ev},k}},$$  \hspace{1cm} (8.14)

where $E_{\text{DM}}^i (i)$ is the dead material loss for the $i^{\text{th}}$ event present in $k^{\text{th}}$ bin.

The $E_{\text{av},k}^{\text{DM}}$ can be obtained using any $T$-dimensional subspace of the energy layer deposits. The same change of base is performed for the dead material corrections.
as the one performed for the compensation weights as illustrated in formula 8.12. In general, the subspace chosen for deriving the dead material correction and its dimension $T$ can be different from the one chosen for compensation, both in content (spanned by different eigenvectors) and in dimension ($T$ can be different from $N$).

**Other dead material corrections**

While the losses between the calorimeters dominate, there is are still other regions where dead material losses can occur. These are losses located in the cryostat upstream of the LAr calorimeter, between the LAr presampler and strips and leakage beyond the Tile Calorimeter.

To compensate for these losses the mean energy loss was determined as a function of beam energy, and the resulting data points were fitted using a suitable functional form, not using the eigenvector projections.

$$DM(E_{\text{beam}}) = \begin{cases} C_1 + C_2 \sqrt{E_{\text{beam}}} & \text{if } E_{\text{beam}} < 30 \text{GeV} \\ C_3 + C_4 E_{\text{beam}} & \text{otherwise.} \end{cases}$$ (8.15)

The fit can be seen in figure 8.3. The resulting fitted parameters are

- $C_1 = (-75 \pm 31) \text{MeV}$ (8.16)
- $C_2 = (5.78 \pm 0.22) \sqrt{\text{MeV}}$ (8.17)
- $C_3 = (931 \pm 5) \text{MeV}$ (8.18)
- $C_4 = 0.01435 \pm 0.0001$ (8.19)

**Total dead material correction**

The total dead material correction is derived from summing two contributions:

$$E_{k}^{DM}(E) = E_{\text{av},k}^{DM} + E_{\text{other}}^{DM}(E)$$ (8.20)

where $k$ is the bin in the $T$-dimensional appropriate subspace of layer energy depositions and $E$ is the best estimate for the total deposited pion energy.

**8.3.5 Beam energy dependence**

The average weight function defined in equation 8.8, the dead material correction obtained in equation 8.14 and the associated eigenvectors are in principle different, if calculated from simulated pion samples generated at different beam energies.

In order to overcome such dependence a unique set of look up tables (seven for weighting, one per calorimeter layer, and one for dead material corrections) is filled with all the simulated events. The associated eigenvectors are derived. This set is used to derive the corrections to any data or Monte Carlo sample under study.

Improvements to this procedure are obtained by using an iteration technique: the weighted estimate of the energy is used to make a new choice of the correction
Figure 8.3: Dead material losses other than those between the liquid argon and Tile calorimeters. Statistical errors are smaller than the markers.

tables until the returned value is stable. This can be coupled (or not) to the iteration on the dead material corrections (see below) so as to obtain the best energy estimate. The iteration cut-off is a tunable parameter.

For the LAr-Tile dead material corrections the three dimensions of the look up table are all shown to scale with beam energy i.e. a table determined at a given beam energy can be turned into one at a different beam energy by scaling all the dimensions with the ratio of the two energies (see section 8.4.3).

The look up table for LAr-Tile dead material corrections can then be obtained as a function of the beam energy normalized components of the eigenvectors i.e. each event coordinates are expressed as

$$E_M^\text{rec,norm} = E_M^\text{rec} / E = \sum_{\text{eig}} \alpha_{M,\text{eig}}^\text{rec} E_{\text{eig}}^\text{rec} / E,$$

(8.21)

where the variables have the same meaning as in equation 8.12 and $E$ is the best estimate of the beam energy of the simulated pion in that event (see below). The unique dead material look-up table is filled by using the events of all the simulated events i.e. including all the beam energies.

An iteration technique is used for determining all the dead material corrections. At each step the best estimate of the reconstructed energy, $E_{\text{tot}}^\text{corr}$, after all corrections, is used to set

- the scaling factor $1/E$ (equation 8.21) for LAr-Tile corrections
- the best pion energy estimate in the parametrization for the other dead material corrections.
8.3.6 Using the corrections

The weights can be applied to any data set by taking the following steps:

- Associate each event to a bin in both the $N$ and $T$-dimensional subspaces defined in sections 8.3.2 and 8.3.4 by expressing its energy deposition vector in the eigenvector basis derived from the simulated events.

- Extract the corrections for the energy of each given layer from the look-up tables defined for compensation weights and dead material estimates. Apply them according to formulas 8.6 and 8.20.

- Use the iteration for dead material corrections as discussed in section 8.3.5.

8.4 Layer Correlation method: Implementation

Five steps are necessary to derive the compensation weights and dead material correction from simulated Monte Carlo samples:

- define the samples for weights generation and performance study
- provide the energy deposited in each layer at the electromagnetic scale
- calculate the covariance matrix
- extract the eigenvectors and eigenvalues
- build the compensation weights and dead material corrections look-up tables

8.4.1 Samples definition

All the available “correction” Monte Carlo samples are used to build a “mixed” sample which is input to constructing the corresponding weight and dead material tables. In order to account for the beam content mentioned in section 7.1, at each energy of the interval, a pion and a proton sample generated at that energy, are considered. If the samples have different number of events a sample-dependent weight is applied to equalize them. Equalization weights are determined initially so that all pions and protons samples in the interval are normalized to the same size before selection cuts. Given the proton contamination $f_{\text{prot}}$ at a given energy, pions and protons events for each same-energy pair of samples are assigned a weight of...
$f_{\text{prot}}$ and $1 - f_{\text{prot}}$, respectively. The resulting samples constitute the global “mixed” sample.

A different choice of the pion-proton mix will result in a different “mixed” sample: weights can then be derived for each available data set taking into account the measured values reported in table 7.2.

The pion and proton “signal” samples of table 7.5 are also paired in energy, normalized and mixed with the same proportions as in the data as above to obtain a “mixed signal” sample on which to apply calibration corrections and to compare with data.

8.4.2 EM scale energy determination

The estimate of the energy deposited in each calorimeter layer derived in equation 8.2 is expected to provide the correct reconstruction of the energy electromagnetically deposited in the calorimeters. The weights are defined in formula 8.7 with this assumption.

8.4.3 Preparation of look-up tables for compensation weights and dead material corrections

Look-up tables for compensation weights and dead material are derived using the information from the covariance matrix.

A set of eight tables is built for each energy interval: one for each layer of the calorimeter and one to derive the dead material correction between Tile and LAr.

For compensation weights, the $w_{av,k}$ functions defined in equation 8.9 are calculated in bins of the two-dimensional space spanned by the eigenvectors corresponding to the two highest eigenvalues i.e. $N = 2$ (see section 8.3.2). Thus, each layer is associated with a two-dimensional look-up table. For a given layer the average weights in each bin are calculated using only the energy values that passed the cuts defined in section 8.3.3. The table has the same number of equally spaced bins along the two dimensions: $128 \times 128$. Weights for the presampler layer of the LAr are not calculated, even if the presampler is kept in the covariance matrix. No weights are applied to the energy deposited in the presampler layer, since energy deposited in the presampler itself is taken as part of the upstream dead material losses.

For LAr-Tile dead material corrections, the $E_{av,k}^{\text{DM}}$ functions defined in equation 8.14 are calculated in bins of the two-dimensional space spanned by the eigenvectors corresponding to the first and third eigenvalues i.e. $T = 2$ (see section 8.3.4.) Correction tables are derived from a same-size $128 \times 128$ bins look-up table. In addition the proton weights are corrected by the factor $\frac{E_{\text{beam}}}{E_{\text{beam}} - m_{\text{proton}}}$ for the fact that, for a proton, the sum of the total true deposited energy in the calorimeter is $E_{\text{beam}} - m_{\text{proton}}$.

For both look-up tables, the coordinates of the vector of energy deposits in the chosen eigenvector basis are obtained according to equation 8.12.
8.5 Layer Correlation: Method Validation on Monte Carlo

The weights and dead material corrections are derived from the “correction samples” and applied and validated on the statistically independent “signal samples”.

This validation is made in separate steps:

The weighting technique is validated on Monte Carlo samples in separate steps:

- Apply compensation weights to reconstruct the deposited energy in the calorimeters (compensation validation).
- Reconstruct the full energy of the incoming particles, including dead material corrections, and quantify the performance in terms of linearity and resolution.

The performance is evaluated in terms of bias and resolution.

The results in this section are derived for pions only.

8.5.1 Compensation

The event-by-event difference $E_{\text{weighted}}^{\text{tot}} - E_{\text{true}}^{\text{tot}}(\text{calo})$ is considered where $E_{\text{true}}^{\text{tot}}(\text{calo})$ is the true total energy deposited in the calorimeter. The bias is defined as the average value $< E_{\text{tot}}^{\text{weighted}} - E_{\text{true}}^{\text{tot}}(\text{calo}) >$ and the resolution is obtained by calculating the standard deviation $\sigma(E_{\text{tot}}^{\text{weighted}} - E_{\text{tot}}^{\text{true}}(\text{calo}))$.

The performance of the LC technique is compared to a simple calibration scheme (called $e/\pi$ in the following) which uses beam energy information: each event in the sample is weighted with the same factor $e/\pi = < E_{\text{true}}^{\text{tot}} > / < E_{\text{tot}}^{\text{reco}} >$ where $< E_{\text{true}}^{\text{true}} > ( < E_{\text{reco}}^{\text{true}} > )$ is the average true total (reconstructed) energy deposited in the given sample in the whole calorimeter, but not in the dead material. The $e/\pi$ calibration scheme provides a reference/scale to which the improvement in resolution of the LC weighting can be compared.
Figure 8.4: Weight table for simulated pion-proton mixed events (45% proton contamination) in the LAr middle layer (top) and Tile first layer (bottom).
The results of the validation procedure are shown in figure 8.7. The bias is zero by construction for the $e/\pi$ weighting. The LC weighting mostly gives a slight positive bias of about 0.6%. At the edges of the energy range studied the bias instead turns slightly negative. At high energies, this is due to the eigenvector projections being outside the weight tables. In this case, the code returns a weight of one, leading to an under-estimation of the energy. At low energies, the weights required to reconstruct the right energy start to increase, since the electromagnetic fraction in the shower is lower. This again leading to an under-estimation of the energy as one gets close to the lowest beam energy used to make the table.

The resolution improvement increases with beam energy. It is 10% at 50 GeV and 20% at 230 GeV.

### 8.5.2 Dead material corrections

Figure 8.8 again shows the bias of the weighted energy, and also the bias of the dead material corrections. Contrary to the weighted energy, the LAr–Tile dead material correction mostly has a slight negative bias, with a positive bias at low energy. This cancels out most of the bias from the weighting.
8.5.3 Linearity and Resolution

The performance for the fully corrected energy reconstruction is finally assessed in terms of linearity with respect to the beam energy and relative resolution.

The reconstructed energy distribution is fitted with a Gaussian distribution in the interval \((\mu - 2\sigma, \mu + 2\sigma)\), where \(\mu\) and \(\sigma\) are the mean value and the standard deviation, respectively.

The mean value \(E_{\text{fit}}\) and the standard deviation \(\sigma_{\text{fit}}\) of the fitted Gaussian are used together with the beam energy \(E_{\text{beam}}\) to define the linearity and the relative resolution:

- the linearity is \(E_{\text{fit}}/E_{\text{beam}}\) as a function of \(E_{\text{beam}}\)
- the relative resolution is \(\sigma_{\text{fit}}/E_{\text{fit}}\) as a function of \(E_{\text{beam}}\).

Both linearity and relative resolution are derived for the energy distribution at four stages:

- at the electromagnetic scale
- at the compensated scale i.e. after applying the compensation weights
Figure 8.7: Bias and resolution of weighted energy minus true deposited energy for energy deposited in the calorimeters in simulated samples for $e/\pi$ weighting and LC weighting.
Figure 8.8: Bias (reconstructed energy minus true deposited energy, divided by beam energy) for the three individual corrections: Weighted calorimeter energy, correction for dead material between the liquid argon and Tile calorimeters, and other dead material corrections. Last, the bias of the final reconstructed energy, which is the sum of the three.

- after compensating weighting and application of dead material correction for losses between LAr and Tile

- after compensation weighting and all dead material corrections

The evolution of the energy distributions after applying the subsequent corrections are shown in figures 8.9 and 8.10.

Figure 8.11 shows linearity and relative resolution for the (20 GeV, 180 GeV) interval for fully simulated pions.

The linearity plot shows that the electromagnetic scale is reconstructing only two-thirds of the beam energy. The compensation weights push the recovery to about 90% of the beam energy. Finally the dead material corrections allow beam energy to be recovered within 1% for pion energies above 40 GeV and within 3% for lower energies. The apparent discontinuity between the results at energies below 150 GeV and those above might be due to a geometry change in the description of
Figure 8.9: Evolution of reconstructed energy distribution at the different correction stages mentioned in the text: from electromagnetic scale to full dead material and compensation correction. The upper plot shows the simulation of 20 GeV GeV pions, while the lower plots features 50 GeV GeV pions. In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
Figure 8.10: Evolution of reconstructed energy distribution at the different correction stages mentioned in the text: from electromagnetic scale to full dead material and compensation correction. The upper plot shows the simulation of 100 GeV GeV pions while the lower plot features 180 GeV GeV pions. In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
the test-beam set-up: three cm of aluminium were included in the Inner Detector system for energies larger or equal than 150 GeV.

The relative resolution improves when applying the different correction steps. At high beam energies (above $E_{\text{beam}} = 100$ GeV) compensation weights’ contribution to resolution improvement has the same magnitude as that of also applying LAr-Tile dead material corrections. At lower beam energies dead material corrections account for about 70% of the relative resolution improvement down to about $E_{\text{beam}} \approx 30$ GeV. Below $E_{\text{beam}} \approx 30$ GeV all the corrections account for a similar fraction of the improvement: other dead material corrections than those for LAr-Tile account for about 20% of the resolution improvement, they are marginal above that threshold.

8.6 Layer Correlation method: Results

The distributions of the fundamental inputs to the calibration corrections are compared in data and Monte Carlo. The weights and dead material corrections derived from Monte Carlo “mixed correction” samples are finally applied on both data and “mixed signal” Monte Carlo samples.

8.6.1 Data to Monte Carlo comparisons

The pion-proton “mixed signal” samples are used to compare data and Monte Carlo for the distribution for the first three components of the layer energy vector along the basis of covariance matrix eigenvectors as defined in section 8.3.3. Figure 8.12 shows such comparison for a proton contamination of 45%. The agreement between data and simulated events is reasonable.

The normalized energy distributions (in unit bins of energy and events) for data and Monte Carlo are compared for all energies in figures 8.13 and 8.14. The four stages of corrections are shown. The quality of the initial description of data by Monte Carlo is not modified by the application of the compensation weights and dead material corrections (also see section 8.6.2).
Figure 8.11: Linearity (upper plot) and relative resolution (lower plot) for fully simulated pure pion samples. In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
Figure 8.12: Distribution of the first three eigenvector projections for data (filled circles) and Monte Carlo pion-proton “mixed signal” with a proton contamination of 45% 7.2.
Figure 8.13: Normalized energy distribution for $E_{\text{beam}} = 20$ GeV (upper plot) and $E_{\text{beam}} = 50$ GeV (lower plot) after applying subsequent corrections for compensation and dead material effect. Data (filled circles) are compared with Monte Carlo simulation (solid lines). In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
8.6. LAYER CORRELATION METHOD: RESULTS

Figure 8.14: Normalized energy distribution for $E_{\text{beam}} = 100$ GeV (upper plot) and $E_{\text{beam}} = 180$ GeV (lower plot) after applying subsequent corrections for compensation and dead material effects. Data (filled circles) are compared with Monte Carlo simulation (solid lines). In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
8.6.2 Linearity and Resolution

Linearity and relative resolution are extracted at all energies for both data and “mixed signal” Monte Carlo samples.

Figure 8.15 shows that weighting recovers from 80% to 90% of the incoming beam energy. The dead material between LAr and Tile accounts for an additional 5% to 8%. The remaining dead material corrections allow linearity to be recovered within 3% (within 1% above 20 GeV). Weighting is more important at high energies. Dead material effects play a more significant role at low energies particularly at 20 GeV where other corrections than LAr-Tile dead material are important to get to within 3% of the beam energy.

Figure 8.16 shows that the relative resolution is improved by about 17% to 22% in data when evolving from the electromagnetic scale to the fully corrected energy scale. A similar relative improvement is obtained in the Monte Carlo expectations: from 17% to 29%. The relative resolution is however smaller in Monte Carlo than in data: the discrepancies, at each correction stage, vary between 6% an 24% depending on the energy. The discrepancies in the shape of the total energy distribution are more pronounced at lower energies and they are already present at the electromagnetic scale (see figures 8.13 and 8.14).

The effect on how the calibration technique distorts data-Monte Carlo agreement can be explored by considering the following double ratios:

\[
D_{\text{Ratio}}^{\text{Lin}} = \frac{(E_{\text{fit,MC}}/E_{\text{fit,MC}})_{\text{rec}}}{(E_{\text{fit,MC}}/E_{\text{fit,MC}})_{\text{corr}}} \quad (8.22)
\]

\[
D_{\text{Ratio}}^{\text{Res}} = \frac{(\sigma_{\text{fit}}/E_{\text{fit}})_{\text{MC}}}{(\sigma_{\text{fit}}/E_{\text{fit}})_{\text{MC}}} \quad (8.23)
\]

They represent the variation in the data to Monte Carlo ratio when corrections are applied to bring the reconstructed energy from the electromagnetic (rec) scale to the fully corrected hadronic (corr) scale. The ratio is considered both for the linearity and for the relative resolution as defined in section 8.5.3. The deviation of the double ratio from unity is a measure of the effect of the weighting technique on the description of the data by the simulation.

Figure 8.17 shows the evolution of the double ratio at three different stages of energy correction. The double ratio for linearity and resolution are consistent with unity within 0.7% and 5% respectively.

For linearity such changes are of the same order of magnitude of the discrepancies between data and Monte Carlo at the electromagnetic scale: the agreement between data and Monte Carlo simulation is the same for all corrections stages. This means that the Monte Carlo is able to predict the corrections that should be applied on the data. The ability of the Monte Carlo to reproduce the data at the electromagnetic scale (i.e. before any correction) seems to be the most critical limiting factor.
Figure 8.15: Data and Monte Carlo “mixed” pion-proton samples are compared for linearity at all stages of the corrections. The upper plots shows the superposed absolute values, the lower plot shows the evolution of the Data to Monte-Carlo ratio. See text for details. In the upper plot, data is shown by markers and Monte Carlo by horizontal lines. In both plots, black is the calorimeter energy reconstructed at the electromagnetic scale. Red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr-Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
Figure 8.16: Data and Monte Carlo “mixed” pion–proton samples are compared for relative resolution at all stages of the corrections. The upper plots shows the superposed absolute values, the lower plot shows the evolution of the Data to Monte-Carlo ratio. See text for details. In the upper plot, data is shown by markers and Monte Carlo by horizontal lines. In both plots, black is the calorimeter energy reconstructed at the electromagnetic scale. Red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
For the relative resolution the changes are small, if compared with the discrepancies at the \((\text{rec})\) scale: the discrepancies do not get worse when the corrections are applied to the data. From preliminary studies the new GEANT4 version (4.9) is able to provide a better description of the resolution in the data and it should be used for future analyses.

### 8.7 Layer Correlation method: Conclusions

An energy calibration technique was developed to deal in a coherent manner with both compensating the response to hadrons and their most significant dead material losses in a segmented calorimeter. The technique is based on the sensitivity to hadronic and electromagnetic deposits of the correlation between the deposited energies in the different calorimeter layers.

The calibration technique was applied to the energy reconstruction of pions impinging on a subset of the central calorimeters during the ATLAS combined beam test in 2004. When taking into account the beam composition, linearity is recovered within 2% for \(E_{\text{beam}} > 30\) GeV (3% overall) and the relative resolution is improved by 17 to 22%. Consistency with the expectation from Monte Carlo studies is good for both the linearity and the percentage improvement in the relative resolution. The absolute value of the relative resolution is larger in data compared to Monte Carlo by 10% to 20% already at the electromagnetic scale, before any corrections have been applied. This discrepancy is not altered significantly by the corrections. Additional improvement in the data description by Monte Carlo simulation can help to fulfill the expected absolute value for relative resolution.

Naturally, hadronic final states in ATLAS will mostly consist of jets rather than single pions, so an obvious next step will be to try the layer correlation method on jets.

### 8.8 Simple \(e/\pi\) model

As a comparison to the layer correlation weighting method, a simple \(e/\pi\) weighting method was devised with dead material corrections. All correction constants were parameterized as a function of beam energy.

#### 8.8.1 \(e/\pi\) weights

The \(e/\pi\) weight is defined as the ratio of the sum of all calibration hits, i.e. all true deposited energy in active and passive calorimeter material, to the sum of all topoclusters reconstructed at EM scale. It is beam energy dependent.

\[
\frac{e}{\pi}(E_{\text{beam}}) = \frac{\langle \sum L E_{L}^{\text{true}} \rangle}{\langle \sum L E_{L}^{\text{rec}} \rangle},
\]

\((8.24)\)
Figure 8.17: Double ratios of data to Monte Carlo as defined in equations 8.22 and 8.22 at three different correction stages as a function of beam energy. The uncertainties on the electromagnetic and corrected ratios are assumed to be fully correlated. Red is the weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
where $L$ signify the calorimeter layers and $E^{true}_L$ is the true total deposited energy in the $L^{th}$ layer and $E^{rec}_L$ is the reconstructed energy in layer $L$ as defined in equation 8.2.

It thus includes out-of-cluster effects, in the same way as the LC weights do. It can be seen as a zero-dimensional weight table.

### 8.8.2 Dead material corrections

Individual dead material corrections were derived for the four different regions of the beam test geometry where dead material losses can occur. The individual dead material corrections presented here (upstream, presampler–strips, and leakage) were found to not improve resolution when used together with the Layer Correlation method based weighting and dead material corrections for the LAr–Tile losses. For the LC method, they were thus replaced with the simpler scheme presented in section 8.3.4. For the $e/\pi$ method, however, individual corrections are used.

#### Upstream losses

This category includes losses in the inner detector and in the inner liquid argon cryostat, up to and including the presampler. Losses in the inner detector, though, were found to be poorly correlated with the presampler signal and are not included in the correction. These very early interactions create a long tail in the total reconstructed energy distribution, without affecting the peak much, and can thus be neglected.

It can be noted that the Monte Carlo simulation geometry lacks the trigger scintillator that exists in the real beamline. The secondaries of pions interacting very early before the calorimeters will not hit this scintillator and will be naturally excluded in the real data.

The upstream correction is

$$E_{DM,\text{upstream}} = C_{\text{upstream}}(E_{\text{beam}}) \cdot E_{\text{presampler}}. \quad (8.25)$$

#### Presampler–strips

This correction is for losses in the liquid argon between the presampler and the calorimeter proper. It uses the geometric mean of the presampler and strip signals:

$$E_{DM,\text{presampler–strips}} = C_{\text{presampler–strips}}(E_{\text{beam}}) \cdot \sqrt{E_{\text{presampler}} E_{\text{strips}}}. \quad (8.26)$$

#### LAr–Tile

This correction is for losses between the liquid argon and Tile calorimeters, mainly the liquid argon cryostat wall. It uses the geometric mean of the liquid argon back sampling and the first sampling in the Tile calorimeter:

$$E_{DM,\text{LAr–Tile}} = C_{\text{LAr–Tile}}(E_{\text{beam}}) \cdot \sqrt{E_{\text{LAr–back}} E_{\text{Tile–A}}}. \quad (8.27)$$
Leakage losses

The final correction accounts for energy leakage beyond the Tile calorimeter. It has no dependence on the calorimeter sampling signals.

\[ E_{\text{DM,leakage}} = C_{\text{leakage}}(E_{\text{beam}}) \]  

(8.28)

8.8.3 Fits

All the dead material correction parameters \( C_i \) were fitted as a function of beam energy using a suitable parametrization. For the upstream correction:

\[
C_{\text{upstream}}(E_{\text{beam}}) = \begin{cases} 
C_{A1} + C_{A2} E_{\text{rel}} + C_{A3} E_{\text{rel}}^2 & \text{if } E_{\text{rel}} < 0 \\
C_{A4} + C_{A5} \exp (-C_{A6} E_{\text{rel}}) & \text{otherwise},
\end{cases}
\]

(8.29)

where \( E_{\text{rel}} = E_{\text{beam}} - 27 \times 10^3 \text{ MeV} \). For the presampler–strips correction

\[
C_{\text{presampler–strips}}(E_{\text{rel}}) = \begin{cases} 
C_{B1} + C_{B2} E_{\text{rel}} + C_{B3} E_{\text{rel}}^2 & \text{if } E_{\text{rel}} < 0 \\
C_{B4} + C_{B5} \exp (-C_{B6} E_{\text{rel}}) & \text{otherwise},
\end{cases}
\]

(8.30)

where \( E_{\text{rel}} = E_{\text{beam}} - 27 \times 10^3 \text{ MeV} \). For the LAr–Tile correction

\[
C_{\text{LAr–Tile}}(E_{\text{rel}}) = \begin{cases} 
C_{C1} + C_{C2} \exp (-C_{C3} E_{\text{rel}}) & \text{if } E_{\text{rel}} < 0 \\
C_{C4} + C_{C5} E_{\text{rel}} & \text{otherwise},
\end{cases}
\]

(8.31)

where \( E_{\text{rel}} = E_{\text{beam}} - 125 \times 10^3 \text{ MeV} \). Finally, for the leakage correction,

\[
C_{\text{leakage}}(E_{\text{beam}}) = C_{D1} + C_{D2} E_{\text{beam}} + C_{D3} E_{\text{beam}}^2.
\]

(8.32)

The \( e/\pi \) weights are parameterized as

\[
\frac{e}{\pi}(E_{\text{beam}}) = \begin{cases} 
C_{E1} + C_{E2} E_{\text{beam}} + C_{E3} E_{\text{beam}}^2 & \text{if } E_{\text{beam}} < 27 \times 10^3 \text{ MeV} \\
C_{E4} + C_{E5} \exp (-C_{E6} E_{\text{beam}}) & \text{otherwise}.
\end{cases}
\]

(8.33)

All energies are assumed to be measured in MeV. The resulting fitted parameters for pure pions are listed in tables 8.1–8.3. Similar fits were done for the beam proton fractions present in the data. Figure 8.18 shows data points and fits.

8.8.4 Iteration method

The full reconstructed energy is thus

\[
E_{\text{rec}}(E_{\text{beam}}) = \frac{e}{\pi}(E_{\text{beam}}) \cdot \sum_{L} E_{L}^{\text{rec}} + \sum_{i} E_{\text{DM},i}(E_{\text{beam}})
\]

(8.34)

where \( i \) stands for the each of the four dead material categories. The reconstruction parameters depend (weakly) on the beam energy, which is what should be reconstructed in the end. To remove this dependence, just as for the LC method, an iterative procedure is used. Starting with an initial assumption of the EM scale energy, the energy of one reconstruction step is fed into the next, unit convergence is reached.
### 8.8. SIMPLE \( E/\pi \) MODEL

<table>
<thead>
<tr>
<th>Parameter no.</th>
<th>Upstream ((A))</th>
<th>Presampler-Strips ((B))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.163 ± 0.041</td>
<td>0.5501 ± 0.0079</td>
</tr>
<tr>
<td>2</td>
<td>((-5.4 ± 1.4) \times 10^{-5})</td>
<td>((-7.8 ± 2.7) \times 10^{-6})</td>
</tr>
<tr>
<td>3</td>
<td>((-2.53 ± 0.98) \times 10^{-9})</td>
<td>((1.7 ± 1.9) \times 10^{-10})</td>
</tr>
<tr>
<td>4</td>
<td>1.758 ± 0.013</td>
<td>0.4054 ± 0.0026</td>
</tr>
<tr>
<td>5</td>
<td>0.492 ± 0.011</td>
<td>0.1459 ± 0.0023</td>
</tr>
<tr>
<td>6</td>
<td>((1.40 ± 0.12) \times 10^{-5})</td>
<td>((1.426 ± 0.085) \times 10^{-5})</td>
</tr>
</tbody>
</table>

Table 8.1: Fitted correction parameters for pure pions. Energy unit MeV assumed.

<table>
<thead>
<tr>
<th>Parameter no.</th>
<th>LAr-Tile ((C))</th>
<th>Leakage ((D))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6670 ± 0.0064</td>
<td>(-10.3 ± 2.4) \times 10</td>
</tr>
<tr>
<td>2</td>
<td>0.0420 ± 0.0033</td>
<td>0.00447 ± 0.00012</td>
</tr>
<tr>
<td>3</td>
<td>((2.44 ± 0.068) \times 10^{-5})</td>
<td>((2.678 ± 0.080) \times 10^{-8})</td>
</tr>
<tr>
<td>4</td>
<td>((1.7428 ± 0.0025) \times 10)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>((-1.018 ± 0.043) \times 10^{-6})</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2: Fitted correction parameters for pure pions. Energy unit MeV assumed.

<table>
<thead>
<tr>
<th>Parameter no.</th>
<th>(\varepsilon/\pi) ((E))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2186 ± 0.0020</td>
</tr>
<tr>
<td>2</td>
<td>((-4.38 ± 0.65) \times 10^{-6})</td>
</tr>
<tr>
<td>3</td>
<td>((9.6 ± 4.5) \times 10^{-11})</td>
</tr>
<tr>
<td>4</td>
<td>1.1551 ± 0.0010</td>
</tr>
<tr>
<td>5</td>
<td>0.0626 ± 0.0009</td>
</tr>
<tr>
<td>6</td>
<td>((1.422 ± 0.071) \times 10^{-5})</td>
</tr>
</tbody>
</table>

Table 8.3: Fitted correction parameters for pure pions. Energy unit MeV assumed.

#### 8.8.5 Results

Linearity and resolution as a function of beam energy for pure pion Monte Carlo simulations are shown in figure 8.19. Linearity and resolution comparing data and Monte Carlo and using the appropriate pion–proton mix can be found in figure 8.20. The same 2\(\sigma\) fit as for the layer correlation method is used. Figures 8.21 and 8.22 show histograms of the reconstructed energy at beam energies of 20, 50, 100, and 180 GeV.
Figure 8.18: Correction parameters fitted as a function of beam energy. Pure pions. The discontinuity at 125 GeV for the LAr–Tile correction is due slightly different run conditions.

8.8.6 Conclusion, comparison with LC weighting

Although the layer correlation weighting is able to improve the resolution of $E_{\text{weighted}} - E_{\text{true}}$, when coupled to dead material corrections it performs similarly in terms of linearity and resolution to the simple $e/\pi$ scheme. The performance of the layer correlation weighting is in turn comparable to the standard ATLAS local hadronic calibration [Spe08]. All models have to be studied with simulated jets in order to compare their final performance. This is however beyond the scope of this thesis.
8.8. SIMPLE $E/\pi$ MODEL

Figure 8.19: Linearity (top) and resolution (bottom) as a function of beam energy with the simple $e/\pi$ model. Pure pion simulation. Black is the calorimeter energy reconstructed at the electromagnetic scale. Red is the $e/\pi$ weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
Figure 8.20: Linearity (top) and resolution (bottom) as a function of beam energy with the simple $e/\pi$ model. Pion–proton mix, data (markers) and simulation (horizontal lines). Black is the calorimeter energy reconstructed at the electromagnetic scale. Red is the $e/\pi$ weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
8.8. **SIMPLE $E/\pi$ MODEL**

Figure 8.21: Histograms reconstructed energy at the different reconstruction stages with the simple $e/\pi$ model. Data (markers) and Monte Carlo (solid line). In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the $e/\pi$ weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
Figure 8.22: Histograms reconstructed energy at the different reconstruction stages with the simple $e/\pi$ model. In black is the calorimeter energy reconstructed at the electromagnetic scale. In red is the $e/\pi$ weighted calorimeter energy. Green shows the weighted calorimeter energy plus the LAr–Tile dead material correction. Finally, in blue is the final reconstructed energy with all dead material corrections.
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List of Figures

2.1 A general overview of the ATLAS experiment. .................... 7
2.2 A general overview of the ATLAS inner detector. ................. 8
2.3 A general overview of the ATLAS muon spectrometer. ............ 11

3.1 The principles of an electromagnetic shower. .................... 17
3.2 A general overview of the ATLAS calorimeters. .................. 21
3.3 The accordion structure and granularity of the calorimeter. ..... 23
3.4 Geometry and readout principle of a Tile calorimeter module ... 27
3.5 Cell geometry in the Tile calorimeter. ......................... 27

4.1 Photograph of LAr optical readout cable. ....................... 30
4.2 LAr Front End Crate ........................................... 31
4.3 Inside ROD rack .................................................. 32
4.4 Splicing cables. .................................................. 33
4.5 Ericsson RSU12 ................................................... 33
4.6 Measured fiber pair transmission loss. ......................... 35
4.7 ROD racks with all fibers connected. ......................... 35

5.1 Drawing of one presampler sector. .............................. 38
5.2 High-voltage feeding arrangement in the barrel presampler. .. 39
5.3 Close-up on a presampler ....................................... 40
5.4 Accessing the high-voltage feedthrough. ....................... 41
5.5 Time evolution of voltage on high voltage line. ............... 42
5.6 Sectors with evaporated short circuits. ....................... 43
5.7 Signal response in the presampler when injecting a 10 kHz sine wave. 44

6.1 Power-law fit of RD-4 Birks parameter data. .................... 54
6.2 Response as a function of Birks parameter ...................... 57
6.3 Effect of applying Birks’ law for 20 and 50 GeV pions. ........ 58
6.4 Time structure of energy deposits, liquid argon calorimeter. .. 63
6.5 Time structure of energy deposits, Tile calorimeter. .......... 64
6.6 Time-cumulative distribution by particle type in LAr. QGSP .... 65
6.7 Time-cumulative distribution by particle type in LAr. QGSP_BERT... 65
List of Figures

6.8 Time-cumulative distribution by particle type in LAr. QGSP_BERT_HP. 66
6.9 Time-cumulative plot by particle type in Tile. QGSP. . . . . . . . . . . 66
6.10 Time-cumulative plot by particle type in Tile. QGSP_BERT. . . . . . 67
6.11 Time-cumulative plot by particle type in Tile. QGSP_BERT_HP. . . . 67
6.12 Time-cumulative plot of the creation process of protons in Tile. . . . 69
6.13 Time-cumulative plot of the parent particles of protons in Tile. . . . 69
6.14 Time-cumulative plot of the creation material of protons in Tile. . . 70
6.15 Time-cumulative plot of the parent particles of electrons in Tile. . . . 71
6.16 Time-cumulative plot of the creation process parents of electrons in Tile. 71
6.17 Time-cumulative plot of the creation material of electrons in Tile. . . 72
6.18 Time-cumulative plot of the grandparent particles of electrons in Tile. . 72

7.1 The Combined Beam Test setup. . . . . . . . . . . . . . . . . . . . . . . 74
7.2 Schematic drawing of the CBT beamline. . . . . . . . . . . . . . . . . . 75
7.3 Beam test detector set-up. . . . . . . . . . . . . . . . . . . . . . . . . . . 76
7.4 Photo of the inner detector and calorimeter setup. . . . . . . . . . . . 77
7.5 Calorimeter set-up photograph . . . . . . . . . . . . . . . . . . . . . . . 78
7.6 TRT high-level hit probabilities: measured and expected . . . . . . . . 84

8.1 Eigenvector components for simulated pions. . . . . . . . . . . . . . . . 95
8.2 Eigenvector components for a simulated mix of protons and pions. . . 96
8.3 Dead material losses other than those between LAr and Tile. . . . . . 98
8.4 Weight table for LAr middle layer and Tile first layer. . . . . . . . . . 102
8.5 Weight table for Tile second layer. . . . . . . . . . . . . . . . . . . . . 103
8.6 Look-up table for LAr–Tile dead material corrections. . . . . . . . 104
8.7 Bias and resolution for $e/\pi$ weighting and LC weighting . . . . . . . 105
8.8 Bias for weighted calorimeter energy and dead material corrections. . 106
8.9 The different correction stages. 20 and 50 GeV simulated pions. . . . 107
8.10 The different correction stages. 100 and 180 GeV simulated pions. . 108
8.11 Linearity and relative resolution for simulated pions . . . . . . . . . . 110
8.12 Distribution of three eigenvector projections for data and Monte Carlo . 111
8.13 Correction stages. 20 / 50 GeV pions–protons in data and simulation . 112
8.14 Correction stages. 100 / 180 GeV pions–protons in data and simulation 113
8.15 Linearity for data and simulation. Pions–proton mix. . . . . . . . . . 115
8.16 Relative resolution for data and simulation. Pions–proton mix. . . . . 116
8.17 Double ratios of data to Monte Carlo for linearity and resolution . . . 118
8.18 Correction parameters fitted as a function of beam energy. . . . . . . 122
8.19 Linearity/res.with the simple $e/\pi$ model. Pure pion simulation. . . 123
8.20 Linearity/res. with the simple $e/\pi$ model. Pure pion simulation. . . 124
8.21 Correction stages. 20 / 50 GeV pions–protons in data and simulation . 125
8.22 Correction stages. 100 / 180 GeV pions–protons in data and simulation 126
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Data samples in the CBT04 used in the present analysis.</td>
<td>81</td>
</tr>
<tr>
<td>7.2</td>
<td>TRT high-level hit probabilities. Calculated proton fractions.</td>
<td>83</td>
</tr>
<tr>
<td>7.3</td>
<td>Measured proton fractions in analyses of different SPS H8 beam tests.</td>
<td>84</td>
</tr>
<tr>
<td>7.4</td>
<td>Monte Carlo samples used for the present analysis. “correction” sample</td>
<td>86</td>
</tr>
<tr>
<td>7.5</td>
<td>Monte Carlo samples used for the present analysis. ”signal” sample</td>
<td>87</td>
</tr>
<tr>
<td>8.1</td>
<td>Fitted correction parameters.</td>
<td>121</td>
</tr>
<tr>
<td>8.2</td>
<td>Fitted correction parameters.</td>
<td>121</td>
</tr>
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<td>Fitted correction parameters.</td>
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