Studies of Single Hadron Calibration of the CMS Calorimeter

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Diplomarbeit

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2. Gutachter: JProf. Dr. Johannes Haller
Abstract
The CMS detector at the LHC accelerator is an experiment for the search of the missing Standard Model particle, the higgs boson, as well as for the search for new physics beyond the Standard Model. For a promising search, a precise understanding of the detector and its subcomponents as a basis for a precise calibration is essential. This thesis investigates, on the basis of Monte Carlo datasets, what the responses of the calorimeters for single pions are and how the shower energy distributes radially around the shower center. Based on these measurements we will then investigate how such a dataset with isolated pions can be obtained for calibration purposes and what the neutral background in the investigated detector area looks like.

Kurzfassung
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Chapter 1

Introduction

Nowadays the Standard Model of particle physics presents a theory that describes all known particles and their interactions, except gravity. This approach led to a number of predictions which could be experimentally verified, but one major prediction still is unproven, the existence of the Higgs-boson, through which all other particles are believed to gather their masses.

Finding this particle is one of the main goals of the CMS experiment at the new Large Hadron Collider (LHC) at CERN, the biggest particle accelerator ever built. Other goals of this machine are the investigation of possible new physics which is believed to manifest at the energies of the LHC. An example is supersymmetries, which would result in an additional superpartner for every supersymmetry for all of the Standard Model particles.

Obviously, signatures from new physics are very rare as they have not been found in previous accelerator experiments. To gather a reasonable amount of interesting events, the luminosity of the LHC has been increased by a factor of 100 compared to the last high-energy-accelerator, the Tevatron. This provides significant new challenges for the reconstruction of an event, as the number of particles per single event rises to several hundreds. For a precise reconstruction of this number of particles in an event, the detectors for these particles have to be well calibrated.

In this thesis, we will investigate the feasibility of single charged particle calibration for the CMS detector, where the momentum of the track, measured by the CMS tracker, is used to calibrate the energy deposit in those CMS calorimeter parts where the single particle initiated a shower in. First, the theoretical framework consisting of the Standard Model and the interaction of particles with matter. This is followed by a description of the CMS detector, with focus on the tracker and the calorimeters, especially the barrel region calorimeters. We will then continue with the actual analysis, consisting of studies of the calorimeter response of a Monte Carlo single pion dataset and how a single pion dataset can be obtained for calibration purposes. The studies include the comparison of positively and negatively charged pions, the comparison of the responses of our dataset to testbeam data, and investigations of
the radial shower profiles for both barrel calorimeters. We will also show, that it is advantageous to distinguish between particles that start in the electromagnetic calorimeter and particles that do not start showering until reaching the hadron calorimeter.

We will then show how a dataset with particles isolated from other charged tracks can be obtained from fully simulated events, and show how the responses differ from those of the single pion dataset. We will show, that the differences are due to neutral particles showering in the same calorimeter region as the single particle we want to calibrate with and investigate this neutral particle background.
Chapter 2

Theory

This chapter provides the theoretical framework necessary to understand this thesis. This covers the Standard Model as well as the interaction of particles with matter.

2.1 Notation and Conventions

Some of the variables that will be frequently used in this thesis are summarized in table 2.1. Also used are the dirac matrices $\gamma^\mu$ and the Einstein notation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Energy</td>
</tr>
<tr>
<td>P</td>
<td>Momentum</td>
</tr>
<tr>
<td>Z</td>
<td>Atomic number of absorber</td>
</tr>
<tr>
<td>A</td>
<td>Atomic mass of absorber</td>
</tr>
<tr>
<td>$N_A$</td>
<td>Avogadro’s number</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Electron mass</td>
</tr>
<tr>
<td>$r_e$</td>
<td>Classical electron radius</td>
</tr>
<tr>
<td>$z$</td>
<td>Charge of incident particle</td>
</tr>
<tr>
<td>I</td>
<td>Mean excitation energy</td>
</tr>
<tr>
<td>$K$</td>
<td>$4\pi N_A r_e^2 m_e c^2$</td>
</tr>
<tr>
<td>$\delta(\beta\gamma)$</td>
<td>Density effect correction to ionization loss</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of variables used in this thesis.

2.2 The Standard Model

As we are dealing with particle physics, we should at least get a brief overview over the generally accepted concepts of which particles this world consists and how they interact with each other. The theories and discoveries of numerous physicists
over the past century have resulted into a remarkable insight into the fundamental structure of matter: everything found until today is made up of twelve objects called fundamental particles and four forces governing interactions between these fundamental particles. Our best understanding how these particles and three of the four forces are related to each other is encapsulated in a theory called “Standard Model” [1][2]. Most of the theory was developed in the 1970’s and until today it has successfully explained many experimental results and predicted a wide variety of phenomena.

The twelve fundamental fermions (spin-$\frac{1}{2}$-particles) and three interactions of the Standard Model are introduced in the following sections. For quantum electrodynamics we will show how an interaction “arises” from a local symmetry and we will also give a brief overview of the underlying symmetries and gauge bosons of the other interactions.

2.3 The fundamental fermions

Generally all matter that we encounter in our daily life is built up of only three different particles: the electrons ($e^-$), the protons (p) and the neutrons (n). But we know today, that only the electron is a “fundamental” particle (fundamental particle mean, that is has no substructure). The protons and neutrons are built up by quarks, more precisely, they consist of up- (u) and down-quarks (d) and the gluons which bind them together. In addition to these three particles, there is the non electromagnetically charged neutrino. The electron and the neutrino are called leptons. These four particles form the first generation of the Standard Model fermions. Up to the present day, two additional generations of fermions have been found, each one also consisting of two quarks and a “heavy electron” and a neutrino, all having a spin of $\frac{1}{2}$. All these particles are listed in table 2.2

2.3.1 Particles of the Standard Model

We now give a summary of the fundamental particles of the Standard Model, the twelve fundamental fermions and the gauge bosons of the electromagnetic, the weak and the strong force (table 2.2). Each of the fermions listed below has according to the laws of quantum field theory an antiparticle with the same quantum numbers, just with opposite sign. Also not shown is the Higgs, which has not yet been found, hypothetical super-partners (supersymmetry) and the hypothetical graviton of a theory of quantum gravity, as such a theory could not be proven up to the present day.

2.3.2 Quantum electrodynamics

In quantum field theories particles are described by fields. Particles of spin 0 are described by scalar fields ($\phi$), particles with spin $\frac{1}{2}$ by spinor fields ($\Psi$), and particles
### Fermions (Spin 1/2)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quantum numbers</th>
<th>Y</th>
<th>Q</th>
<th>I3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_L$</td>
<td>$\nu_e$</td>
<td>-1</td>
<td>-1</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$\mu_L$</td>
<td>$\nu_\mu$</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>$\tau_L$</td>
<td>$\nu_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_R$</td>
<td>$\mu_R$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_R$</td>
<td>$\nu_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Quarks (Spin 1)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quantum numbers</th>
<th>Y</th>
<th>Q</th>
<th>I3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_L$</td>
<td>$\nu_e$</td>
<td>-1</td>
<td>-1</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$\mu_L$</td>
<td>$\nu_\mu$</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>$\tau_L$</td>
<td>$\nu_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_R$</td>
<td>$\mu_R$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_R$</td>
<td>$\nu_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Gauge Bosons (Spin 1)

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Gauge boson</th>
<th>Y</th>
<th>Q</th>
<th>I3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>$\gamma$ (Photon)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>$Z^0$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm$</td>
<td>0</td>
<td>±1</td>
<td>±1</td>
</tr>
<tr>
<td>Strong</td>
<td>$g_{1,8}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.2: Fundamental particles of the Standard Model [3].
with spin 1 are described by vectorfields \((A_\mu, B_\mu)\). The Lagrangian of a free particle with mass \(m\) and wavefunction \(\Psi\) is given by the appropriate Dirac equation:

\[
L_{\text{Dirac, free}} = \bar{\Psi} \gamma^\mu \partial_\mu \Psi - m \bar{\Psi} \Psi. \tag{2.1}
\]

The first term describes the kinetic energy of the particle, whereas the second one corresponds to its mass. It’s easy to show, that this Lagrangian is invariant under Lorentz transformations as well as global phase transformations

\[
\Psi \rightarrow \Psi e^{i\alpha}, \tag{2.2}
\]

but it is not invariant under local phase transformations

\[
\Psi \rightarrow \Psi e^{-i\alpha(x)}, \tag{2.3}
\]

because of the derivative operator in the kinetic term. These local phase transformations are also called local U(1)-(phase)-transformation, because the symmetry group is U(1), the unitary group in 1 dimension. \(L_{\text{Dirac, free}}\) changes like

\[
L_{\text{Dirac, free}}(\Psi) \rightarrow L'_{\text{Dirac, free}}(\Psi) = L_{\text{Dirac, free}}(\Psi) + \bar{\Psi} \gamma^\mu \partial_\mu \alpha(x'). \tag{2.4}
\]

The solution to this invariance problem will be shown below for the interacting theory. To get to a theory with interactions, we need to add interaction terms to the free Lagrangian from equation 2.1 plus terms for the new fields (kinetic and mass terms). For a theory of electrodynamics we have have only one additional vector field \(A^\mu\). The kinetic term \(L_{\text{EM}}\) for the electromagnetic field is:

\[
L_{\text{EM}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \tag{2.5}
\]

where

\[
F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \tag{2.6}
\]

As interaction we use the minimal coupling:

\[
L_{\text{INT}} = e \bar{\Psi} \gamma^\mu \Psi A_\mu = J^\mu A_\mu, \tag{2.7}
\]

with \(J^\mu = e \bar{\Psi} \gamma^\mu \Psi\) as vector current. The resulting Lagrangian

\[
L = \bar{\Psi} \gamma^\mu \partial_\mu \Psi - m \bar{\Psi} \Psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + e \bar{\Psi} \gamma^\mu \Psi A_\mu \tag{2.8}
\]

is invariant to Lorentz transformation and to global phase transformations, but still not to local phase transformation for the same reason as for the free Dirac Lagrangian (see equation 2.4). However, the term introduced by the local phase transformation has a similar structure as the interaction term \(L_{\text{EM}}\) as both are proportional to \(e \bar{\Psi} \gamma^\mu \Psi\) and therefore we write these terms together:

\[
L(\Psi', A_\mu) = L_{\text{Dirac, free}}(\Psi) + L_{\text{EM}}(A_\mu) + e \bar{\Psi} \gamma^\mu \Psi \left( A_\mu + \frac{1}{e} \partial_\mu (\alpha(x')) \right). \tag{2.9}
\]
If we now shift the field $A_\mu$ by a gauge transformation $A_\mu \rightarrow A'_\mu + \partial_\mu \xi$ with $\xi = -(1/e)\alpha(x^\nu)$:

$$A_\mu \rightarrow A'_\mu = A_\mu - \frac{1}{e} \partial_\mu \alpha(x^\nu)$$ (2.10)

If we now replace $A_\mu$ in equation 2.9 by $A'_\mu$ we see that the terms generated by the local phase transformation cancel those of the gauge transformation. Thus we needed a gauge field $A_\mu$ to achieve invariance under local transformations. We now have a gauge theory that is invariant under local U(1)-transformations or a local $U(1)$ gauge theory. By usage of the covariant derivative $D_\mu = \partial_\mu - ieA_\mu$, this can be written down in a more convenient way:

$$L_{QED} = \bar{\Psi}i\gamma^\mu D_\mu \Psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - m\bar{\Psi}\Psi,$$ (2.11)

which is indeed the true Lagrangian for quantum electrodynamics (QED). The one thing left to obtain a full theory of QED is to quantize the field $A_\mu$ which is shown in various books, e.g [4].

In terms of *Feynman graphs*, which describe the interaction of fundamental particles in a graphical way with lines (propagators) and dots (vertices), nevertheless containing all the physical information, there is just one fundamental diagram in QED: the absorption/emission of a photon by a charged particle. Quantum field theory tells us that it is possible to derive the scatter-matrix element $M$ for a given interaction from these diagramms in a straightforward way. And from the matrix-element we can easily derive the cross section, which describes the likelihood for an interaction, via Fermis golden rule if the phase factor $\rho$ is known:

$$\sigma \sim |M|^2 \rho.$$ (2.12)

2.3.3 Quantum chromodynamics

In the 1970s there was a mismatch of experimental data and the predictions from pure QED for the ratio $R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$ by a factor of 3. Other measurements showed the same mismatch by a factor of 3 or sometimes 9. A solution to this problem was found by the introduction of a new degree of freedom for the quarks - color - which also proved to be a solution to the problem, that quarks seemed to violate the Pauli-principle [5] [6].

There are three different states called red, green, and blue. The names were chosen because the new quantum number shows the same additive properties as normal color (red, green, and blue add to “neutral” white). The gauge group of this theory called *quantum chromodynamics* (QCD) is SU(3)$_C$, the index “C” stands for color (we will skip the index in the following). The adjoint representation of the SU(3) shows us that there are eight different gauge bosons called gluons. As the SU(3) is in contrast to the U(1) from QED a non-abelian group, we will encounter a very
different behavior of QCD compared to QED.

The quanta of the QCD, the gluons, carry color and anticolor themselves, which induces self-interaction between the gluons and translates in the formalism of Feynman graphs to the existence of 3- and 4-gluon vertices. There is also the *confinement* of quarks, meaning that up to the present day only color neutral states have been observed: the mesons, composed of a quark carrying color and an antiquark carrying the corresponding anticolor, or baryons consisting of three quarks or three antiquarks, each carrying one of the three states red, green, or blue. Newer measurements of the quarks show, that this simple model must be modified, as e.g. the baryons do not only consist of three quarks. In fact the current models predict that baryons are made up of three *valence quarks* and in addition to this numerous *sea-quarks* and gluons.

Another important feature of the QCD is called “asymptotic” freedom: the strength of the coupling of gluons to the colored particles becomes arbitrarily weak at ever shorter distances. This makes it possible to treat the scattering of quarks inside a meson or baryon as scattering of quasi-free and non-interacting particles. But it also prohibits us to treat low-energetic scattering of quarks with pertubative techniques.

### 2.3.4 Electroweak unification

The first hints for weak interactions was found at the beginning of the 20th century in $\beta$-decays like:

$$
\begin{align*}
7N^{12} & \rightarrow 6C^{12} + \beta^+ \\
5B^{12} & \rightarrow 6C^{12} + \beta^-.
\end{align*}
$$

However at that time these reactions seemed to violate the conservation laws for energy, momentum and angular momentum. After two decades of confusion about this violation, Wolfgang Pauli proposed a new neutral, massless particle, the *neutrino* $\nu$, in order to solve problems with energy conservation. In fact, this particle must have spin $\frac{1}{2}$, to also conserve the angular momentum:

$$
7N^{12} \rightarrow 6 C^{12} + e^+ + \nu_e.
$$

Of course there is also the associated *anti-neutrino* $\overline{\nu}$:

$$
5B^{12} \rightarrow 6 C^{12} + e^- + \overline{\nu}_e.
$$

This was the first time a particle was predicted before it was measured, and it was only measured many years later with great experimental effort ([7]), because the neutrino was found out to be only subject to the weak force.
2.3. THE FUNDAMENTAL FERMIONS

The next big step in building a theory of weak interactions (which is needed for an Electroweak theory) was the famous experiment of C.S. Wu et al. with polarized Co\textsuperscript{60} nuclei ([8]). Wu found out, that electrons were mostly emitted into the opposite direction to that of the nuclei’s spin. In fact, this violation of parity is maximal, i.e. the weak force in this process only couples to left-handed particles and right-handed anti-particles, where right-handed means, that the projection of the spin onto the momentum has the sign +1 (both vectors point in the same direction) and left-handed means that spin and momentum point in opposite directions. Similar to the interaction term in the QED, there is a term of the form:

$$J_{\text{weak}}^\mu W_\mu,$$  

with

$$J_{\text{weak}}^\mu = \overline{\Psi}_L \gamma^\mu \Psi_L = \frac{1}{2} \overline{\Psi} (\gamma^\mu - \gamma^\mu \gamma^5) \Psi$$  

As the product $\gamma^\mu \gamma^5$ is an axial-vector, the term in brackets has the form of an vector - axial vector coupling, which actually gave name to the theory: $(V-A)$-Theory. This term is also “responsible” for the parity-violation.

In the weak reactions mentioned above, the electric charge changes by one (proton changes into neutron and vice versa). Therefore the involved intermediate gauge bosons have to carry this charge, which brought up the idea, that the weak force is related to the electromagnetic one and both theories may be part of a bigger electroweak theory, which was first formulated by Glashow, Salam, and Weinberg [9].

The gauge group of the weak interaction is the $SU(2)_L$, which has three generators resulting in three different weak gauge bosons denoted by $W_{1-3}$. To include QED, we need a bigger group and the most simple one meeting all requirements is $SU(2)_L \times U(1)_Y$, where the $Y$ denotes the hypercharge:

$$Y = 2Q - I_3$$  

with $I_3$ being the third component of the weak isospin

$$I_i = \frac{1}{2} \tau_i$$  

and with $\tau_i$ as Pauli-matrices. Here $Y$ is the generator of the $U(1)_Y$ instead of the electric charge in $U(1)_{EM}$. Since the Pauli-matrices do not commute, they form a non-abelian group similar to $SU(3)_C$ in QCD, which results also in 3- and 4-boson-vertices for the electroweak theory.

The covariant derivative of the electroweak theory is

$$D_\mu = \partial_\mu - ig \frac{Y}{2} B_\mu - ig \frac{T_i}{2} W_{i,\mu}$$  

with $T_i = \tau_i$ for left handed particles and $T_i = 0$ for right-handed ones. There are four fields $(B, W_{1-3})$ in the covariant derivative above, which are in fact not the
fields one can measure, but linear combinations of them form the physical fields: $W_1$ and $W_2$ mix to form the two charged gauge bosons $W^+$ and $W^-:

$$W^\pm = \frac{W_1 \pm iW_2}{\sqrt{2}},$$

while the photon ($A_\mu$-field) and the $Z^0$ boson are linear combinations of the fields $W_3$ and B:

$$A = \cos \theta_W B + \sin \theta_W W_3$$
$$Z = -\sin \theta_W B + \cos \theta_W W_3.$$ 

The *electroweak mixing angle* $\theta_W$ can be used to express the relation between the electroweak coupling constants $g$ and $g'$ and the electric charge $e$:

$$g = \frac{e}{\sin \theta_W}$$
$$g' = \frac{e}{\cos \theta_W}.$$ 

The coupling constant $g$ is also related to the coupling constant $G_F$ of the first theory of weak interactions by Fermi via the W-boson mass $M_W$:

$$\frac{g^2}{M_W^2} = \frac{8G_F}{\sqrt{2}}$$  \hspace{1cm} (2.18)

Also, the electroweak mixing angle is proportional to the ratio of the boson masses

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$  \hspace{1cm} (2.19)

which has been measured with the result that $\sin^2 \theta_W \approx 0.2231$ at the energy of the restmass of the Z-boson $M_Z$ [3].

We saw that the coupling constant of the weak interaction is in fact bigger than the electromagnetic coupling constant. Yet the cross sections for weak processes are much smaller than electromagnetic ones, which is due to the short range of weak interactions because of the high gauge boson mass. A simple mass term in the electroweak Lagrangian would not be gauge invariant and the mechanism of the *electroweak symmetry breaking* is yet not fully understood. It is widely believed, that the presumed *Higgs field* [10] [11] is responsible for this and it is one of the main purposes of the LHC (see section 3.1) to find out.

### 2.4 Pions

Historically the pions were first described by H. Yukawa in 1935 who predicted a meson with a mass of $\approx 100$ MeV as interaction particle of the strong nuclear force.
2.5. INTERACTION WITH MATTER

[12]. Just one year later, the muon was experimentally discovered and the muon was thought to be that meson because of its mass ($m_\mu \approx 106$ GeV). The first real pions were found in 1947 by a collaboration under C. Powell from the University of Bristol [13]. The prediction as well as the experimental discovery were awarded with a Nobel Prize.

The pions are the lightest mesons, that can be composed of the Standard Model fundamental particles. They consist of up- and down-quarks and form a spin-0-triplet with two charged mesons, $\pi^+$ and $\pi^-$, and one neutral mesons, the $\pi^0$. The quark combinations for the pions are

\begin{align*}
\pi^+ & : \quad |ud\rangle \\
\pi^- & : \quad |d\bar{u}\rangle \\
\pi^0 & : \quad \frac{1}{\sqrt{2}}(|u\bar{u}⟩ - |d\bar{d}\rangle)
\end{align*}

The masses, lifetimes and main decay modes for pions are shown in table 2.3.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass [MeV]</th>
<th>Mean Lifetime [s]</th>
<th>Main decay modes (Fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>139.57018 $\pm$ 0.00035</td>
<td>$(2.6033 \pm 0.0005) \times 10^{-8}$</td>
<td>$\mu^+\nu_\mu$ $(99.9877 \pm 0.00004 \ %)$ $e^+\nu_e$ $(1.230 \pm 0.004 \times 10^{-4} \ %)$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>139.57018 $\pm$ 0.00035</td>
<td>$(2.6033 \pm 0.0005) \times 10^{-8}$</td>
<td>$\mu^-\bar{\nu}_\mu$ $(99.9877 \pm 0.00004 \ %)$ $e^-\bar{\nu}_e$ $(1.230 \pm 0.004 \times 10^{-4} \ %)$</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>134.9766 $\pm$ 0.0006</td>
<td>$(8.4 \pm 0.6) \times 10^{-17}$</td>
<td>$\gamma\gamma$ $(98.798 \pm 0.032 \ %)$ $e^+e^-\gamma$ $(1.198 \pm 0.032 \ %)$</td>
</tr>
</tbody>
</table>

Table 2.3: Masses, lifetimes and main decay modes for Pions(Values from [3]).

2.5 Interaction with matter

When a particle traverses matter it will generally interact with that matter and lose (at least a fraction of) its energy. Due to energy conservation, the traversed medium will be heated up in this process or more precisely, the constituents of the medium are excited into a higher energy state. The actual interaction process that occurs depends strongly on the energy and the nature of the traversing particle. They are the results of the electromagnetic, the strong, and more rarely the weak forces reigning in between the particle and the medium’s constituents.

2.5.1 Photon interactions

The quantum of the electromagnetic force, the photon, is mainly affected by three different processes when traversing matter: the photoelectric effect, incoherent (Compton) scattering and electron-positron pair production. Smaller contributions arise from photonuclear reactions and coherent (Rayleigh) scattering. Figure 2.1 shows
the total cross section, which describes the likelihood of an interaction between particles, and the contributions from different effects, which are described below, as a function of the energy for photons transversing lead. The energy dependence of the photon total cross section is approximately flat for at least two orders of magnitude beyond the energy range shown[3].

Figure 2.1: Photon total cross section as a function of energy for lead showing the contributions for different processes [3]: $\sigma_{\text{p.e.}} = \text{Atomic photoelectric effect}$; $\sigma_{\text{Raleigh}} = \text{Rayleigh scattering}$; $\sigma_{\text{Compton}} = \text{Compton scattering}$; $\kappa_{\text{nuc}} = \text{Pair production, nuclear field}$, $\kappa_{\text{e}} = \text{Pair production, electron field}$; $\sigma_{\text{g.d.r}} = \text{Photonnuclear reactions, most notably the giant dipole resonance.}$
2.5. Interaction with Matter

**Photoelectric effect**

At low energies, the *photoelectric effect* (or photoeffect) is the most likely one to occur, although other effects also contribute to the total cross section. It describes the phenomenon where an atom absorbs the photon, emits an electron and is left in an excited state. This only takes place beyond an energy threshold which is dependent on the material. The atom returns to the ground state by the emission of Auger electrons or X-rays.

The cross section for the photoelectric effect depends strongly on the number of available electrons and therefore on the *Z*-value of the absorber medium. Fits to data imply that the cross section scales with the atomic number *Z* of the absorber with *Z*\(^n\) where *n* is between four and five and with energy *E* as *E*\(^{-3}\) [14]. Therefore the photoeffect drastically loses importance at higher energies as shown in figure 2.1 (for materials with lower *Z* the cross section of photoeffect decreases even more). Also visible are discontinuities in the cross section (absorption edges). They arise when the photons have enough energy to ionize electrons from deeper shells.

**Compton scattering**

The *Compton scattering* describes the scattering of photons and electrons with energy and momentum transfer. Applying the conservation laws for energy and momentum gives insight on the relations between the different kinematic variables in a very straightforward way, e.g. if the photon energy is defined in terms of electron restmass (*ξ* = *E*\(γ\)/\(m_e c^2\)), one can derive the formula for the relation of the scattering angles of the electron (ω) and the photon (ρ) as shown in figure 2.3 [14]:

\[
\cot \omega = (1 + \xi) \tan \frac{\rho}{2}
\]

The cross section for Compton scattering was one of the first to be derived by QED as only contributions from two Feynman diagrams have to be calculated at lowest order and is known as *Klein-Nishima* formula

\[
\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \left[ \frac{1 + \xi(1 - \cos \rho)}{(1 + \cos^2 \rho/)(1 + \xi(1 - \cos \rho))} \right] \left[ 1 + \frac{\xi^2(1 - \cos \rho)^2}{(1 + \cos^2 \rho/)(1 + \xi(1 - \cos \rho))} \right]
\]

which reduces to \(\frac{r_e^2}{2(1+\cos^2 \rho)}\), the classical expression for Thompson scattering, in the limit of zero energy. The cross section is much less dependent on the *Z* value of the absorber material (σ ∼ *Z*) and the energy dependence is also less distinctive (σ ∼ 1/*E*) [14]. This process is dominating at the intermediate energy region and may take place multiple times before the energy of the photon is low enough for it to be absorbed via the photoeffect.

**Pair production**

At high energies and in an electromagnetic field of an atom or its electrons, a photon may decay into a particle and its antiparticle, most likely an electron-positron pair.
Figure 2.2: The two Feynman graphs, which contribute to Compton scattering in lowest order.

Figure 2.3: The Compton scattering process.
2.5. INTERACTION WITH MATTER

For this process, called pair production, the energy of the photon needs to exceed the double restmass of the produced particles \(E > 2 \times 511\) keV for electron-positron pair production). The total cross section for \(e^+e^-\) pair-production in the high energy limit is\[14][3]:

\[
\sigma = \frac{7}{9} \frac{A}{X_0 N_A} \tag{2.23}
\]

with \(X_0\) as material constant (see section 2.6.1).

Rayleigh scattering

In this process, important at low energies, the photon is deflected by the atomic electrons. However, the photon does not lose energy in this elastic scattering, called Rayleigh scattering. Therefore this process does not contribute to the energy deposition process itself, but it affects the spatial distribution of the energy deposition.

Photonuclear reactions

At energies between 5-20 MeV a modest role may also be played by photonuclear reactions like \(\gamma n\) and \(\gamma p\) or photo-induced nuclear fission. Usually the cross section of these processes do not exceed 1% of the total photon cross section\[14].

2.5.2 Energy loss of charged particles

Electrons traversing dense matter

The way an electron (or positron) loses its energy when traversing a medium is fundamentally different to those of photons. Photons lose their energy in a number of discrete steps, whereas electrons (and positrons) lose their energy in a continuous stream of events. The two main mechanisms through which electrons deposit their energy when traversing matter are ionization and bremsstrahlung.

Which one is the dominating source for energy loss depends on the energy of the transversing electron. The energy where both processes contribute equally to the energy loss may be defined as the critical energy \(\epsilon_c\)[14]. However, the PDG [3] prefers a slightly different definition of the critical energy, originally formulated by B.Rossi, who defines the critical energy \(\epsilon_c\) as the energy at which the ionization loss per radiation length (see chapter 2.6.1 for definition) is equal to the electron energy. This form has been found to describe transverse electromagnetic shower development more accurately. Both definitions are equivalent with the approximation \(|dE/dx|_{\text{brems}} \approx E/X_0\) (see fig. 2.4).

As figure 2.5 shows, low energy electrons lose their energy mainly via ionization, although other processes like Bhabha scattering, Møller scattering or positron annihilation contribute. The loss rates of ionization rise logarithmically with energy (see figure 2.4), whereas the loss from bremsstrahlung rises nearly linearly. Therefore,
the fractional loss is nearly independent of energy for bremsstrahlung and starts dominating above a few tens of MeV in most materials.

Figure 2.4: Two definitions of the critical energy $\epsilon_c$. [3]

Charged heavy particles transversing dense matter

The way muons (and other charged heavy particles like pions, protons, etc) lose their energy at given particle energy is substantially different from the way electrons lose their energy due to their much greater restmass ($m_e \ll m_\mu$), although the mechanisms are the same (ionization, bremsstrahlung). The muons lose their energy primarily through ionization. Bremsstrahlung occurs only at very high energies ($E_\mu > 1$ TeV). A typical muon loses only 1-2 MeV g$^{-1}$ cm$^2$ while transversing an absorber. This is much less than an electron of the same energy and therefore it takes very substantial amount of matter to absorb high energetic muons. The mean energy loss per unit path length of muons and charged hadrons is well described by the Bethe-Bloch formula:

$$-\left<\frac{dE}{dx}\right> = K \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right],$$

with $T_{\text{max}}$ as maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in table 2.1.

This function as computed for pions on various materials is shown in figure 2.6. A minor dependence on the restmass of the incident particles is introduced through $T_{\text{max}}$ at highest energies, but for all practical purposes in high-energy physics, $dE/dx$ in a given material is depending on the $\beta$ of the incident particle. In this form, the Bethe-Bloch equation describes the energy loss of pions in a material such as copper to about 1 % accuracy for momenta between about 6 MeV/c and 6 GeV/c. At
lower energies various corrections have to be made, e.g. corrections for the atomic binding. At higher energies, radiative effect become more important, especially for muons and pions (with increasing rest mass, the radiative effects start to become only significant at even higher energies). Also corrections for the density effect $\delta(\beta\gamma)$ have to be made. This is shown in detail in [3].

All other stable heavy particles except the muon which is a lepton are made of quarks. So these particles may also interact via the strong force. Here pretty much every strong process might occur as long as the conservation laws (energy, momentum, baryon number, etc.) are adhered to.

### 2.5.3 The interactions of neutrons with matter

This section will give a brief overview over the mechanism through which neutrons deposit their energy in an absorber medium: elastic and inelastic scattering, production of $\alpha$-particles and neutron decay and capture. The neutrons, e.g. may originate from reactions induced by hadrons as discussed in section 2.6.2.

**Elastic neutron scattering**

The *elastic scattering* of neutrons is the overwhelmingly dominant process for neutrons with low kinetic energy (few eV up to 1 MeV) when transversing a medium. The energy fraction $f$ lost by neutrons in these collisions with an absorber nucleus with atomic number $A$ varies between 0 (for glancing collision) and $4A/(A + 1)^2$, the kinematic limit for central collisions. Therefore hydrogen-rich compounds are the material of choice for neutron-shielding purposes, e.g. in nuclear reactors.
Figure 2.6: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma > 1000$, and at lower momenta for muons in higher Z-absorbers. [3]
2.5. INTERACTION WITH MATTER

Inelastic neutron scattering

The fact that the energy loss by transversing neutrons is extremely dependent on subtleties of the nuclear structure of the absorber can be understood if we examine the role of **inelastic scattering**. Inelastic scattering means that a fraction of the neutron’s kinetic energy is used to bring the nucleus in an excited state. The nucleus re-emits this excitation energy in the form of one or several photons. The contribution of elastic scattering to the overall neutron energy loss depends completely on the details of the nucleus’ structure. In e.g. lead ($^{208}$Pb) this process is insignificant at energies below 2.6 MeV, as this is the energy needed, to get from the ground state to the first excited state. But if iron ($^{56}$Fe) is used as absorber material, this process is significant down to energies of 0.85 MeV, as this is the difference between ground state and first excited state in $^{56}$Fe. This, in fact, is the reason why steel-reinforced concrete is a good shielding versus neutrons in the MeV-region.

Production of $\alpha$ particles

At energies between 3 and 20 GeV neutrons frequently release $\alpha$ particles from the nucleus, they interact with, e.g. through ($n,\alpha$) reactions. But in high-$Z$ materials like copper or iron, $\alpha$ production takes only place in $\sim 3\%$ of the inelastic reactions.

Neutron capture

When a neutron transversing an absorber has lost (almost) all its kinetic energy one of two things may happen:

- the free neutron decays through
  \[ n \rightarrow p + e^- + \overline{\nu}_e. \]  
  \[ (2.25) \]
  But the timescale for this process is very long ($\tau \approx 15$ min).

- the neutron gets captured by a nucleus. As the cross section for this process is usually large, neutron capture is much more likely to occur than decay.

When a neutron is captured, the nucleus is excited into a more energetic state, because of the additional nuclear binding energy. The nucleus then loses this energy via X-ray emission. This way some of the energy lost during release of the neutron (nuclear binding energy) is gained back.

The neutron capture is distinctly different from the processes through which protons and electrons are absorbed, as they simply become part of the absorber structure. In contrast to this, the captured neutron transforms an absorber nucleus into another one, thus transforming the absorber.
2.6 Particle showers

2.6.1 Electromagnetic showers

When a high energetic electron (positron) or photon transverses an absorber medium its loses its energy through a combination of the processes mentioned in sections 2.5.1 and 2.5.2. Thus a multi GeV electron would emit Bremsstrahlung on its way through the medium. Some of the photons emitted in this process with the appropriate energy do pair production. The produced electrons and positron are doing Bremsstrahlung again and so on until the energy of the photon is no longer sufficient to produce particle-antiparticle pairs. The photons with too less energy for pair production are scattered (in most cases multiple times) via Compton scattering until the energy is low enough for the photons to be absorbed via the photoelectric effect. The scattered compton electrons and photoelectrons then deposit their remaining energy via ionization. This is the basic structure of an electromagnetic shower.

An important feature of multi GeV electromagnetic showers is particle multiplication, as multi GeV electrons (and positrons) emit numerous Bremsstrahlung photons, which in turn transform into electron-positron pairs. This shower particle multiplication continues until the emitted photons are no longer energetic enough to do pair production, because the average energy of the individual shower particles decreases with every multiplication step. The depth at which the maximum number of shower particles occurs is called the shower maximum. Beyond the shower maximum, the number of shower particles and thus the amount of energy deposited in a slice of given thickness decreases[14].

Electromagnetic shower profiles

Since the shower development is primarily determined by the electron density of the absorber material, it is to some extent possible to describe the shower profiles in a material independent way. The units that we will use to do this are the radiation length for the longitudinal shower profile, while the Moliere radius is used to describe the lateral profile[14].

The radiation length $X_0$ is defined as the distance over which a high-energy ($\gg 1$ GeV) electron or positron loses, on average, 62.3 % (i.e. $1 - e^{-1}$) of its energy to bremsstrahlung. By this definition material effects are eliminated in first approximation. For approximate calculations, which are accurate within 3 %, the Particle Data Group [3] recommends the following expression:

$$X_0 = \frac{716.4 \ A}{Z(Z+1)\ln(287/\sqrt{Z})} \ g \ cm^{-2} \quad (2.26)$$

It can be shown that the asymmetric cross section for photon interactions is related
2.6. PARTICLE SHOWERS

to $X_0$ as:

$$\sigma(E \rightarrow \infty) = \frac{7}{9} \frac{A}{N_A X_0}$$  \hspace{1cm} (2.27)

This implies that the mean free path of very-high-energy photons equals $\frac{9}{7}X_0$. Expressed in $g/cm^2$ the radiation length scales with $A/Z^2$.

The radiation length for a mixture of different materials can be calculated when the fraction of the volume $V_i$ and the radiation lengths $X_i$ of the different materials are known:

$$\frac{1}{X_0} = \sum_i \frac{V_i}{X_{0i}}$$  \hspace{1cm} (2.28)

The same accounts for a compound when the fraction of mass for the $i$th component of the compound is known:

$$\frac{1}{X_0} = \sum_i \frac{m_i}{X_{0i}}$$  \hspace{1cm} (2.29)

The Moliere radius $\rho_M$ is defined to describe the lateral shower profile, although it does not have physics meaning equal in precision to that of the radiation length. It is defined via radiation length $X_0$, critical energy $\epsilon_c$ (see section 2.5.2) and the scale energy $E_s = m_ec^2\sqrt{4\pi/\alpha}$ which equals 21.2 MeV:

$$\rho_M = \frac{E_s X_0}{\epsilon_c}$$  \hspace{1cm} (2.30)

On average 90% of the shower energy is contained within a cylinder of radius $\rho_M$. The Moliere radius of mixtures and compounds can be calculated in the same way as equations 2.28 and 2.29 for the radiation length, just the $X_i$ have to be replaced with the corresponding $\rho_M$ for the $i$th component. Expressed in $g/cm^2$, $\rho_M$ scales as $A/Z$ and is therefore much less material independent than $X_0$.

2.6.2 Hadron showers

Hadron showers describe the process when a hadron transverses sufficient amounts of matter. A hadron that transverses matter will first do ionization (when its charged), in the same way a muon would do when transversing matter. However, in general, that hadron will interact strongly with an atomic nucleus of the absorber at some depth. In this reaction, called spallation process, the hadron will change dramatically (for neutral hadrons, this is the only way to lose energy and therefore their showers behave totally different from those of charged hadrons).

In contrast to the relatively simple electromagnetic showers, which are quite well understood due to the good understanding of the QED and its processes, hadron showers are much more complicated due to the complex nature of the strong force and are accordingly less well understood. Despite similarities like particle multiplication up to shower maximum, there are vast differences in both shower developments.
Every hadron shower has an underlying electromagnetic shower, as some particles interact or decay electromagnetically, but in addition to this there is a vast number of strong interactions, that can happen in the hadronic component of the shower. The fraction of energy that is deposited in the electromagnetic shower component, the electromagnetic fraction $f_{em}$, varies strongly from event to event, but on average increases with energy. Also the scales of the hadron showers are much greater than those of the electromagnetic ones.

One of the most important consequences of the involvement of the strong interactions for calorimetry is the "invisible-energy" phenomenon. In electromagnetic showers, the whole energy is carried by particles which can be measured. However, as we will see, the situation is different for hadron showers as a certain fraction of the energy is fundamentally undetectable. And since the invisible and the electromagnetic fraction is energy dependent, calorimeters are non-linear for hadron detection.

**The underlying electromagnetic component**

As mentioned some of the particles produced in a hadronic cascade like $\pi^0$ or $\eta$ decay through electromagnetic interactions, e.g. $\pi^0 \rightarrow \gamma \gamma$, which leads to a electromagnetically propagating component in a hadron shower. The fraction of the energy from the shower initiating hadron which is converted into $\pi^0$- and $\eta$-mesons varies strongly from shower to shower and depends on the individual initial processes in a shower, i.e. the time when production of these particles is energetically possible. Approximately one third of the mesons produced in the first generation of particle multiplication are on average $\pi^0$-mesons. The same amounts for the second and subsequent generations as long as the remaining energy is sufficient for $\pi^0$ production. The number of generations $n$ is a function of the energy $E$ of the shower initiating particle. And since the production of $\pi^0$’s is irreversible, the fraction of the initial shower energy which is converted into $\pi^0$ increases with energy and amounts after $n$ generations to

$$f_{em} = 1 - \left(1 - \frac{1}{3}\right)^n$$

(2.31)

under the assumption, that the average number of mesons produced per interaction is independent of $E$. Or in a more general form

$$f_{em} = 1 - (1 - f_{\pi^0})^n$$

(2.32)

where $f_{\pi^0}$ denotes the fraction of energy that is transformed into $\pi^0$’s per generation. In reality $f_{\pi^0}$ is not exactly 1/3, but this can be considered as the upper limit for $f_{\pi^0}$, because:

- not all of the produced particles are charged or neutral pions ($\approx 90\%$ are pions [15]).
2.6. PARTICLE SHOWERS

- Energy loss by nuclear excitations and ionization have been neglected, which are strongly absorber dependent and thus lead to an absorber dependency of the electromagnetic shower component.

- Other small effects play a role in shower development, e.g. baryon number conservation, which leads to smaller electromagnetic shower fractions in proton induced showers, than in pion induced ones (15% at \( P = 100 \text{ GeV} \)) or simply the nature of the shower initiating particle.

All these effects have been studied in great detail elsewhere [16].

The nuclear sector When a hadron interacts strongly with a "hit" nucleus, the most likely process to occur is spallation. It is mostly described as a two stage process.

- the first step is a fast intra-nuclear cascade when the incoming hadron makes a quasi-free collision with nucleons inside the "hit" absorber nucleus. The struck nucleons now travel through the nucleus colliding with the remaining nucleons, and thus developing a cascade of fast nucleons. In this cascade pions and other unstable particles may be created if the energy is sufficiently high. Some of the cascade particles will reach the nucleons boundary and escape, while the other ones remain inside and distribute their kinetic energy among the remaining nucleons of the nucleus.

- The second step is a slower evaporation stage where the intermediate nucleus is de-excitated. This is achieved by evaporating some particles, mostly free neutrons and protons, but sometimes also \( \alpha \)-particles or even heavier nucleon aggregates, until the remaining excitation energy is less than the binding energy of one nucleon. The rest, typically a few MeV, is radiated in the form of \( \gamma \)-rays.

Much experimental data on spallation processes have been acquired in the past and Rudstam gives an empirical formula [17] for spallation cross sections, which is valid within a broad range \( (E > 50 \text{ MeV} \) and \( A > 20) \)). When a particle with energy \( E \) (in MeV) hits a nucleus with atomic mass \( A_T \), the relative cross sections \( \sigma \) for the production of spallation products \((Z_f, A_f)\) is given by:

\[
\sigma(Z_f, A_f) \sim \exp[-a(A_T - A_f)] \times \exp[-b|Z_f - cA_f + dA_f^2|^{3/2}]. \tag{2.33}
\]

The parameters \( a, b, c \) and \( d \) have the values: \( a = 20E^{-0.77} \) for \( E < 2100 \text{ MeV} \), \( a = 0.056 \) for \( E > 2100 \text{ MeV} \), \( b = 11.8A_f^{-0.45} \), \( c = 0.486 \) and \( d = 0.00038 \).

There are normally tens to hundreds of different spallation processes with equal cross sections thus explaining the enormous variety of processes that may occur. The average number of involved protons, neutrons, etc is strongly absorber-material dependent, but in general there are not more than 3 generations of spallation processes
in hadron showers (much less generations than in electromagnetic showers). When
the released nucleons do no more spallation, they lose their remaining energy via ion-
ization (charged particles) or by the mechanisms shown in section 2.5.3 for neutrons.

In these spallation reactions, considerable amounts of nucleons may be released
from the target nuclei. However, this energy, i.e. the nuclear binding energy,
does not contribute to the calorimeter signals: it is **invisible**. But as mentioned
in section 2.5.3, a fraction of this energy is gained back when the neutrons are
captured. Due to to enormous variety of processes, that may occur, there are also
large event-to-event fluctuations in the invisible energy. These fluctuations have no
equivalent in electromagnetic showers with the result, that the energy resolution
of hadron calorimeters is usually considerably worse than those of electromagnetic
calorimeters.

**Hadron shower profiles**

Hadron shower development is dominated by nuclear interactions, and therefore the
shower size can be described by the **nuclear interaction length** $\lambda_I$. The nuclear
interaction length of an absorber medium is defined as the average distance a high
energy hadron has to pass inside that medium before a nuclear interaction occurs.
Thus, the probability that a particle traverses a distance $z$ in a given medium without
causing a nuclear reaction is given by:

$$W = \exp\left(-\frac{z}{\lambda_I}\right).$$  \hfill (2.34)

This definition is equivalent to the one for the mean free path of high energy photons
(see section 2.6.1). The mean free path of photons is inversely proportional to the
total cross section $\sigma_{tot}$ for photon-induced reaction, and the same holds for $\lambda_I$:

$$\sigma_{tot} = \frac{A}{N_A \lambda_I}.$$ \hfill (2.35)

The cross section is determined by the size of the projectiles and the size of the
target nuclei. The cross section is determined by their radius squared, and since
the volume of these nuclei (and thus $r^3$) scales with the atomic weight $A$, this cross
section scales with $A^{2/3}$ and therefore $\lambda_I$ scales with $A^{1/3}$ when expressed in $g\ cm^{-2}$.
The shortest nuclear interactions lengths $\lambda_I$ are found for high-density, high-$Z$ ma-
terials, such as tungsten, gold, platinum or uranium and are approximately 10 cm.
For frequently used absorber materials as iron or copper, the nuclear interaction
length is twice as long. This is in contrast to the radiation length where there is an
increase by a factor of five when going from uranium to iron.

The nuclear interaction length for a mixture or compound is calculated in the same
way as for the radiation length (see equations 2.28 and 2.29).

The values given normally for $\lambda_I$ are for interactions caused by protons. The
interaction probability, and therefore the mean free path also depends on the size
2.7 Calorimeters

A calorimeter is a device for energy measurement. If it consists of sufficient amounts of matter, a traversing particle will deposit all of its energy in it, through the mechanisms listed in the last sections. Calorimeters are built up of absorber material, where the traversing particles initiate their showers in, as well as active material, which sample the deposited energy. In general, there are two different design types of calorimeters:

- **Homogeneous calorimeter**, where the same material is used for absorption and sampling. An example for this type of calorimeter is the CMS Ecal (see chapter 3.6).

- **Sampling calorimeters**, in which two different kinds of material are used for absorption and sampling, e.g. the CMS hadron calorimeters. In this type of calorimeter, only a fraction of the shower energy is sampled by the active layer. This fraction is called *sampling fraction* and is it usually defined on the basis e/mip, which means the signal an traversing electron generates divided by the signal a traversing minimum ionizing particle has. The difference in the sampling of these two signals emerges from the fact, that electromagnetic showers are dominated by very soft shower particles, as the majority of these soft γ’s is absorbed in the absorber layers, due to the huge Z-dependance of the cross section of the photoeffect. The difference decreases with decreasing absorber layer depth.

Because of the energy dependence of the electromagnetic shower fraction $f_{em}$ in hadron showers, the electron/pion response ratio $e/\pi$, i.e. the ratio of the electron and pions are sampled with, is inherently energy dependent. Because of the invisible energy in hadron showers, this ratio is usually $> 1$. To characterize the degree of non-compensation in an energy independent way, the $e/h$ ratio has been introduced, which relates the response of the calorimeter to the electromagnetic and non-electromagnetic components. However, this ratio can not be measured directly, but it can be derived from the $e/\pi$ ratios at various energies. The response of pions
can be written as
\[ \pi = f_{em} \cdot e + (1 - f_{em}) \cdot h. \] (2.36)

From this we get:
\[ \frac{e}{\pi} = \frac{e/h}{1 - f_{em}(1 - e/h)}. \] (2.37)

Assuming linearity for electromagnetic shower detection, it follows that the ratio of pions responses at energies \( E_1 \) and \( E_2 \) is related to the \( e/h \) value as
\[ \frac{\pi(E_1)}{\pi(E_2)} = \frac{f_{em}(E_1) + [1 - f_{em}(E_2)](e/h)^{-1}}{f_{em}(E_2) + [1 - f_{em}(E_1)](e/h)^{-1}} \] (2.38)

or
\[ \frac{e}{h} = 1 + \frac{\pi(E_1) - \pi(E_2)}{\pi(E_2) \cdot f_{em}(E_1) - \pi(E_1) \cdot f_{em}(E_2)}. \] (2.39)
Chapter 3

The CMS Experiment

This chapter will describe the LHC accelerator and one of its experiments the CMS detector with most of its subsystems.

3.1 The LHC accelerator

The Large Hadron Collider (LHC) is a proton-proton collider located inside the 27-km tunnel of the former Large Electron-Positron collider at CERN near Geneva. It will yield head-on collisions of two protons (ions) beams of 7 TeV each (2.75 TeV per nucleon), with a design luminosity of $10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$ ($10^{27}\ \text{cm}^{-2}\ \text{s}^{-1}$).

The prime motivation for the LHC is to elucidate the nature of the electroweak symmetry breaking for which the Higgs mechanism is presumed to be responsible. The experimental study of the Standard Model at energy scales above 1 TeV gives room for potential new discoveries, like new symmetries (e.g. supersymmetry). The associated new particles or extra dimensions could pave the way towards a unified theory and provide compelling reasons to investigate the TeV scale.

The LHC will also provide heavy-ion beams at energies over 30 times higher than in previous experiments that allows the extension of studies of QCD matter under extreme conditions of temperature, density and parton momentum fraction.

To achieve these goals, four different detectors have been build in four collision halls where the two beams cross. These detectors are the two specialized experiments ALICE and LHCb and two complementary multipurpose detectors ATLAS and CMS.

The beam energy of the LHC is limited by the strength of the magnetic dipole field, which is produced by superconducting niobium-titanium magnets to keep the protons on their circular track. The high beam energy is needed since the protons are no fundamental particles but composed of quarks and gluons. The actual
interaction takes place between these particles which carry only a fraction of the respective proton momenta.

3.2 The CMS detector

![Figure 3.1: Layout of the CMS Detector](image)

The CMS (Compact Muon Solenoid) experiment is a multipurpose apparatus located at the CERN LHC. The name of the detector refers to its compact design in comparison to other detectors, its superconducting solenoid magnet and its sophisticated muon system. The CMS-subdetectors cover an area of nearly $4\pi$ using a cylindric geometry. This results in the division of the subdetectors into barrel- and endcap-parts.

The requirements on the CMS detector were the following:

- Efficient muon identification and good muon momentum resolution over a wide kinematic range and geometric coverage.
- The best possible electromagnetic calorimeter providing an accurate diphoton and dielectron invariant mass resolution and efficient $\pi^0$ rejection.
3.2. THE CMS DETECTOR

- An inner tracking detector with good momentum resolution and reconstruction efficiency of charged particles which provides efficient triggering and offline vertex reconstruction.

- A hadron calorimeter with almost hermetic coverage to allow an accurate determination of missing transverse energy, which is a signature of unknown particles, and a fine lateral segmentation for a good dijet mass resolution.

The components of the detector (see Figure 3.1) in order from the innermost to outermost subdetector part are the tracking-system, the electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL), the superconducting solenoid magnet, the hadron outer calorimeter and as outermost subdetector the muon chambers which are built into the returnyoke for the magnetic field. These subdetectors are described in detail in the following sections.

3.2.1 CMS coordinate system conventions

The coordinate system used by CMS [18] has its origin at the nominal collision point inside the detector, the \(x\)-axis is pointing radially inwards towards the center of the LHC, the \(y\)-axis is pointing vertically upwards and the \(z\)-axis is along the beampipe towards the Jura mountains from LHC Point 5. The azimuthal angle \(\phi\) is measured from the \(x\)-axis in the \(x-y\) plane. The polar angle \(\theta\) is measured from the \(z\)-axis. It is often more convenient to use the pseudorapidity \(\eta\) defined as

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

instead of \(\theta\). For massless particles this quantity is equal to the rapidity defined as

\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)
\]

The angular distance between two point objects, as observed from the origin of the CMS coordinate system, is expressed as the size

\[
dR = \sqrt{ (\Delta \eta)^2 + (\Delta \phi)^2 }
\]

The momentum and energy measured transverse to the \(z\)-axis, denoted by \(P_t\) and \(E_t\), respectively, are computed from the \(x\) and \(y\) components. The transverse momentum \(P_t\) is the projection of the momentum \(P\) onto the \(x-y\) plane

\[
P_t = \sqrt{ P_x^2 + P_y^2 },
\]

while the transverse energy \(E_t\) is the fraction of the energy perpendicular to the \(z\)-axis

\[
E_t = \sqrt{ E^2 \frac{P_t^2}{P^2} }.
\]
Figure 3.2: The muon momentum resolution versus $p$ using the muon system only, the inner tracking system only and both systems together [18]

### 3.3 Magnet and return yoke

The magnet used by the CMS experiment is a superconducting solenoid (see table 3.1) with a weight of 220 t, a length of 13 m, a bore of 6 m, and a field strength of 4 T which stores an energy of 2.6 GJ at full current. An important feature in the design of the solenoid was to provide a large bending power (12 Tm) before the muon bending angle is measured by the muon system. (The expected muon momentum resolution using only the muon system, only the inner tracker and using both systems is shown in figure 3.2.) The field is returned through an iron return yoke outside the solenoid. This return field is strong enough to saturate 1.5 m of iron, thereby allowing four muon stations to be integrated (see section 3.4). The inner diameter of the solenoid provides sufficient space to accommodate the inner tracking system (see section 3.5) and most of the calorimetry (see sections 3.6 and 3.7).

The yoke is compounded of eleven large elements, five barrel wheels and six endcap disks. The lightest of the parts has a weight of only 400 t, whereas the central barrel ring, including also the coil and its cryostat has a weight of 1920 t.

### 3.4 Muon system

As already implied by the middle name of the CMS detector and mentioned above, muon identification and precise muon measurement is of central importance to the experiment. This is because muon detection provides a very powerful tool for filtering out the events of interest over the high background when LHC runs with full luminosity. A good example is the predicted decay of a Standard Model Higgs into ZZ, which in turn decays into four leptons. When all these four leptons are muons
### General parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic length</td>
<td>12.5 m</td>
</tr>
<tr>
<td>Free bore diameter</td>
<td>6.3 m</td>
</tr>
<tr>
<td>Central magnetic induction</td>
<td>4 T</td>
</tr>
<tr>
<td>Total Ampere-turns</td>
<td>41.7 MA-turns</td>
</tr>
<tr>
<td>Nominal current</td>
<td>19.41 kA</td>
</tr>
<tr>
<td>Inductance</td>
<td>14.2 H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.6 GJ</td>
</tr>
</tbody>
</table>

### Cold mass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial thickness of cold mass</td>
<td>312 mm</td>
</tr>
<tr>
<td>Radiation thickness of cold mass</td>
<td>3.9 $X_0$</td>
</tr>
<tr>
<td>Radial thickness in interaction lengths</td>
<td>$1.4 \lambda_l$</td>
</tr>
<tr>
<td>Weight of cold mass</td>
<td>220 t</td>
</tr>
<tr>
<td>Maximum induction on conductor</td>
<td>4.6 T</td>
</tr>
<tr>
<td>Temperature margin wrt operating temp</td>
<td>1.8 K</td>
</tr>
<tr>
<td>Stored energy per unit cold mass</td>
<td>11.6 kJ/kg</td>
</tr>
</tbody>
</table>

### Iron yoke

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of the iron flats</td>
<td>14 m</td>
</tr>
<tr>
<td>Length of barrel</td>
<td>13 m</td>
</tr>
<tr>
<td>Thickness of the iron layers in barrel</td>
<td>300, 630 and 630 mm</td>
</tr>
<tr>
<td>Mass of the iron in barrel</td>
<td>6000 t</td>
</tr>
<tr>
<td>Thickness of iron disks in endcap</td>
<td>250, 600 and 600 mm</td>
</tr>
<tr>
<td>Mass of iron in each endcap</td>
<td>2000 t</td>
</tr>
<tr>
<td>Total mass of iron in return yoke</td>
<td>10000 t</td>
</tr>
</tbody>
</table>

Table 3.1: Main parameters of the CMS solenoid magnet and of the iron return yoke
they can be detected and measured with high precision due to the sophisticated muon system of the CMS detector.

The muon system is designed to reconstruct the momentum and charge of muons over the whole kinematic range of the LHC and to provide as much solid angle coverage as possible. Constrained by the shape of the solenoid it was easiest to give the muon system also a cylindrical geometry with a barrel region and two endcap regions. The muon system utilizes three different types of gasouses particle detectors: drift tube chamber (DTs) cover the pseudorapidity region of $|\eta| < 1.2$, cathode strip chambers (CSCs) in the pseudorapidity region $0.9 < |\eta| < 2.4$ and resistive plate chambers which cover the pseudorapidity region $|\eta| < 1.6$.

3.4.1 Muon barrel

As the parts of the barrel muon system are intergrated into the return yoke, the muon barrel geometry follows that of the return yoke. In the barrel part of the muon system, there are 4 layers called muon stations in the radial direction which are divided into 12 $\phi$ sectors which can be seen in figure 3.3. The segmentation in $\eta$ follows the one of the return yoke, therefore there are five different rings. The three inner cylinders consist 60 DTs each, the outermost station has 70, which gives about 172000 sensitive wires in total. The possibility to use drift chambers as tracking system for the muon barrel is given through the low expected rate of muons in this region and the relatively low local magnetic field strength.

The muon stations of the first three layers are made of three superlayers (SL) each consisting of 4 layers of DTs In two of the SLs the DTs are oriented along the beam direction to provide track measurement in the magnetic bending plane ($r-\phi$) and in the remaining SL, the wires are oriented perpendicular to the beam line to
provide z-measurement. This third SL is not present in the fourth cylinder layer.

### 3.4.2 Muon endcaps

In the pseudorapidity region above $|\eta| > 1.2$ particle flux is too high to use DTs. Therefore the four layers, each muon endcap system is made of CSCs which are placed around the iron disks of the return yoke. At the time of LHC start-up both the Muon endcaps together will consist 468 CSCs.

The CSCs are multiwire proportional chambers made of six anode wire planes placed in between seven cathode panels. Wires running azimuthally define a radial coordinate of traversing particle while an azimuthal coordinate can be obtained by interpolating charges which are induced on the strips milled on the cathode panels.

### 3.4.3 Resitive plate chambers

There are resistive plate chambers placed in addition to the DTs and CSCs. They cover the pseudorapidity range $|\eta| < 1.6$ at the time of LHC start-up. It is planned to enhance the coverage up to $|\eta| < 2.1$ in a later upgrade. The RPCs are gaseous parallel-plate detectors, that combine adequate spatial resolution with a time resolution comparable to that of scintillators. This provides a fast dedicated muon trigger which allows the association of muons to the correct bunch crossing even at the high rates and huge backgrounds expected at LHC.

### 3.5 Tracker

The CMS inner tracking system was designed to provide a precise measurement of the trajectories of charged particles and also a precise reconstruction of secondary interaction vertices. It encases the nominal interaction vertex and has a total length of 5.8 m and a diameter of 2.5 m. The inner tracking system consists of ten layers of silicon strip detector for the precise track reconstruction and in addition three layer of pixel detectors for the precise reconstruction of the vertices in the barrel part and two pixel layer and three plus nine strip layers in each endcap section (see figure 3.5). At the LHC design luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$, one expects more than 1000 particles from 20 overlapping proton-proton interactions expected per bunch crossing (25 ns). For the identification of this number of trajectories and to attribute them to the correct bunch crossing, a high granularity and a fast responding detector technology is needed. Also the initial rate of events is reduced from 40 MHz down to a storable amount of 100 Hz due to the use of tracking information in the high level triggers. But due to the high power density required for the fast responding detector, an efficient cooling system has to be built in between the active detector region, undermining the aim to keep the non-active material to a minimum in order to limit multiple scattering, bremsstrahlung, photon conversion, and
nuclear interactions. The amount of material in the tracker can be seen in figure 3.7.

The intense radiation due to the high particle flux in the tracking system will also cause severe damage to this detector. Thus one of the main challenges for the design of the tracker was to develop detector components which are able to operate in this radiation-dense environment for the expected lifetime of ten years. With a design fully based on silicon detector technology these requirements on granularity, speed and radiation hardness were fulfilled.

Its acceptance covers a pseudorapidity range of $|\eta| < 2.5$ and with an active silicon area of 200 m$^2$ the CMS tracker is the largest silicon tracker ever built. Over 500 physicists and engineers of 51 institutes worked for over 12 years to design, development and construction for the completion of this subdetector. The estimated pion momentum resolution is shown in figure 3.6 and in figure 3.2 for muons.

According to the the charged particle flux at various radii at high luminosity (Table 3.2) three different regions are proclaimed, each one with a unique design:

### 3.5.1 Pixel detector

Closest to the nominal interaction vertex pixel detectors with a size of $\approx 100 \times 150$ $\mu$m$^2$ and an occupancy of $10^{-4}$ per Pixel per LHC-crossing are used, because of the extreme high particle flux and also to provide excellent spatial resolution for secondary vertex fitting. The non-quadratic cell sizes are chosen to achieve a similar

Figure 3.5: Schematic cross section through the CMS Tracker. Each line represents a detector module. Double lines indicate back-to-back modules, which deliver stereo hits [19].
3.5. TRACKER

resolution in both the $r$-$\phi$ and $z$-directions. The pixel tracking system is divided into a pixel barrel and a pixel forward detector and covers the pseudorapidity region of $|\eta| < 2.5$ (see figure 3.8).

The pixel barrel detector is composed of three 53-cm long layers at mean radii of 4.4, 7.3 and 10.2 cm, each subdivided into two half-cylinders which are composed of ladders and half-ladders, providing the support structure and the cooling. Each ladder contains 8 pixel modules. There is a small overlap between the sensitive detector area to provide hermetic coverage in the $r$-$\phi$-plane.

The pixel forward consists of four disks, two at each side of the vertex. The disks extend radially from $\approx$ 6 to 15 cm and are placed at $z = \pm 34.5$ cm and $z = \pm 46.5$ cm. Every disk is composed of 24 blades with seven modules of different size on each blade. The blades are tilted by $20^\circ$ resulting in a turbine-like geometry and providing enough overlap between the modules for hermetic coverage.

3.5.2 Inner Tracker

Next to the pixel subdetector is the inner tracker ($20 < r < 55$ cm), consisting of the Tracker Inner Barrel (TIB) and of the Tracker Inner Disk (TID). Silicon microstrip detectors with a minimum cell size of $10 \text{cm} \times 80 \text{\(\mu\text{m)}}$, leading to an occupancy $\approx 2-3$ % per LHC-crossing are used in this intermediate region.

The Tracker Inner Barrel is composed of four layers located at radii of 25.5, 33.9, 41.85 and 49.8 cm. Each layer, extending in the $z$-direction from $-70$ cm to $+70$ cm, is divided into four parts, an upper and a lower part on every side of the vertex. In these parts, the silicon strips are arranged in “strings”, each strip carrying three modules or double-sided modules (first two layers). The structure of the strings varies among the different layers.

The TID comprises six identical disk structures, three on each side of the interaction point located at distances from the interaction point between $\pm 80$ cm and $\pm 90$ cm. On each disk the modules are placed in three rings alternatively in the forward and backward parts of the disk. The inner two rings on every disk have double sided modules and there is a small overlap between the active modules to provide hermetic coverage.

3.5.3 Outer Tracker

The outer tracker is subdivided into three parts, the Tracker Outer Barrel (TOB) and two Tracker EndCaps (TEC) called TEC+ and TEC- according to their position in the CMS coordinate system. The Outer Tracker uses larger and thicker silicon
Table 3.2: Hadron fluence and radiation dose in different radial layers of the CMS tracker (barrel part) for an integrated luminosity of 500 $fb^{-1}$ ($\approx$ 10 years)

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Fluence of fast hadrons ($10^{14}$ cm$^{-2}$)</th>
<th>Dose (kGy)</th>
<th>Charged Particle Flux (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>32</td>
<td>840</td>
<td>$10^8$</td>
</tr>
<tr>
<td>11</td>
<td>4.6</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.6</td>
<td>70</td>
<td>$6 \times 10^6$</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>115</td>
<td>0.2</td>
<td>1.8</td>
<td>$3 \times 10^5$</td>
</tr>
</tbody>
</table>

strips than the Inner Tracker to limit the number of individual readout channels.

The Tracker Outer Barrel is made of a single mechanical structure (wheel) which contains six layers of in total 688 “rods”, self-contained sub assemblies with six modules inside a rod as active detector. Only the two innermost layers are made of rods carrying double-sided modules. The wheel has a length of 218 cm or 236 cm with cabling attached to the wheel and an inner and outer radii of 55 cm and 116 cm, respectively. The rods itself are self-contained assemblies providing support and cooling for 6 or 12 silicon detector modules.

The Tracker Endcaps extend in the z-direction from ±124 cm to ±280 cm and radially from 22 cm to 113.5 cm (diameter 227 cm). Each endcap contains nine disks made of a “Carbon Fiber Composite”-honeycomb-structure. A total of 16 petals are mounted on each disk, eight petals on the frontface of the disk and the same number on the backside.

The active modules are mounted on the petals and are arranged in rings around the beampipe. Disks one to three carry seven modules on every petal, disks four to six lack ring 1, on disks seven and eight ring 1,2 are missing and disk nine has only rings 4-7. Rings 1,2 and 5 made of up of double sided modules, providing even better space information.

The modules belonging to rings 1,3,5,7 are mounted to the frontsides of the petals, whereas the modules of rings 2,4 and 6 are mounted on the backsides of each petal. The front petals overlap with the back petals on a given disk. There is also overlap between the modules within a given ring and between the rings themselves.

### 3.6 Electromagnetic Calorimeter

As electromagnetic calorimeter (ECAL) for the CMS-Experiment a hermetic, homogeneous lead-tungstate scintillating crystal calorimeter was chosen. The ECAL
3.6. ELECTROMAGNETIC CALORIMETER

is subdivided into a barrel part (EB) comprised by 61200 PbWO$_4$ crystals which is closed by two endcaps (EE) each made of 7324 crystals. PbWO$_4$ crystals are used because of their high density (8.82 g/cm$^3$), short radiation length ($X_0 = 0.89$ cm) and small Moliere radius (2.2 cm), which results in a fine granularity and a compact calorimeter. These requirements are needed for the calorimeters to be placed inside the solenoid magnet. The fine granularity allows the precise energy reconstruction of electrons and photons, and in conjunction with the hadron calorimeter also for jets.

The read out of the PbWO$_4$ crystal responses is also fast enough for the LHC bunch crossing times (80% of the light is emitted within 25 ns) and show also good radiation hardness (up to 10 Mrad), which is needed because of the high particle flux close to the tracker. Although the crystals will get a fair amount of radiation damage during the lifetime of the CMS experiment, the effect of this damage can be corrected by monitoring their optical transparency with injected laser light.

3.6.1 Electron Barrel

The barrel part of the ECAL, which starts at a radius of 1.29 m, covers the pseudorapidity range $|\eta| < 1.479$. The granularity of the barrel region is 360-fold in $\phi$ and $(2\times85)$-fold in $\eta$, which gives in total 61200 crystals in the EB. It has an e/h value of roughly 2.6 [20]. The shape of the crystals itself is that of a truncated-pyramid and they are mounted so that their axis is slightly rotated (3$^\circ$) against the vector pointing at the nominal interaction vertex, both in $\phi$- and in $\eta$-direction, resulting in a quasi-projective geometry with overlap.

The crystal surface perpendicular to the vector pointing at the nominal interaction vertex is $0.0174 \times 0.0174^\circ$ in $\Delta \eta \times \Delta \phi$ or $22 \times 22$ mm$^2$ at the front of the crystal and $26 \times 26$ mm$^2$ in the rear end. All crystals have a length of 230 mm corresponding to 25.8 $X_0$. This gives a total crystal volume of 8.14 m$^3$ and a weight of 67.4 t for the EB.

The crystals themselves are organized in a supermodule structure (see figure 3.11): They are contained in a thin walled alveolar structure called submodule which contains ten crystals each. The nominal crystal to crystal distance is 0.35 mm inside a submodule and 0.5 mm between the submodules. To reduce the number of different types of crystals, every submodule consists of pairs of shapes, left and right reflections of a single shape, giving in total only 17 such pairs of shape along the $z^-$- and the $z^+$-axis. These submodules are assembled into modules, each containing 400 crystals or 500 in case of the module at $|\eta| = 0$ position. Four of these modules form a supermodule containing 1700 crystals, which covers an area of $\Delta \phi \times \Delta \eta = 20^\circ \times 1.479$, so 18 of these supermodules form a half-barrel.

All services, cooling manifolds and cables converge to a patch panel at the ex-
ternal end of the supermodule. For more details see [18][19].

### 3.6.2 Electron Endcap

The two endcaps (EE) cover the pseudorapidity range of $1.479 < |\eta| < 3.0$. The longitudinal distance from the interaction point to the endcaps envelope is 315.5 cm taking already into account, that the interaction points position will change when the magnet is switched on. Each of the endcaps is divided into two half-disks, also called *Dees*. Every Dee holds 3662 identical shaped crystals which are organized into mechanical units of $5 \times 5$ crystals, called supercrystals (SC) and positioned in a rectangular x-y grid (see figure 3.10).

There are 138 standard SCs and 28 special partial ones at the inner and outer circumference. The crystal axes focus a point 130 cm beyond the interaction point, giving off-pointing angles of $2^\circ$ to $8^\circ$ and preventing that charged particles escape through cracks in the geometry. The endcap crystals have a front face area of $28.62 \times 28.62 \text{ mm}^2$, a rear face cross section of $30 \times 30 \text{ mm}^2$ and a length of 220 mm, corresponding to $24.7 X_0$. This gives a total crystal volume of $\approx 2.90 \text{ m}^3$ and a weight of 24.0 t for the two EEs. For more details see [18][19].

### 3.7 Hadron Calorimeter

The design of the Hadron Calorimeter (HCAL) is strongly influenced by the given magnet since most of the HCAL is located inside the magnet coil and surrounds the ECAL. It is an important requirement of the HCAL to minimize the non-Gaussian tail in the energy resolution and to provide good containment and hermeticity for the $E_T^{\text{Miss}}$ measurement ($E_T^{\text{Miss}}$ means the missing traverse energy). Therefore, the HCAL was designed to maximize the material inside the magnet coil in terms of interaction lengths. The HCAL is divided into four subsystems, each covering a certain area of the CMS detector.

#### 3.7.1 Hadron Barrel

The Hadron Barrel (HB) consist of two half-barrels (HB+ and HB-, depending on their z-position), formed by 36 identical azimuthal wedges, which are constructed of flat brass absorber plates aligned parallel to the beampipe (see table 3.4 for brass details). It covers a pseudorapidity range up to $|\eta| < 1.4$ and expands radially from 1.77 m to 2.95 m. The plates are bolted together in a staggered geometry, so that the assembly contains no projective dead material for the full radial extend of a wedge. The wedges themselves are bolted together in a way that the cracks between adjacent wedges become smaller than 0.2 cm.

There are 16 layers of absorber material in the radial direction interleaved with scintillator plates. The first and the last layer are made of stainless steel for struc-
3.7. HADRON CALORIMETER

<table>
<thead>
<tr>
<th>layer</th>
<th>material</th>
<th>thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Bicron BC408</td>
<td>9 mm</td>
</tr>
<tr>
<td>1-15</td>
<td>Kuraray SCSN81</td>
<td>3.7 mm</td>
</tr>
<tr>
<td>16</td>
<td>Kuraray SCSN81</td>
<td>9 mm</td>
</tr>
</tbody>
</table>

Table 3.3: Thickness of the different scintillator layers in the HB. [19]

atural strength and have a thickness of 40 mm respectively 75 mm. The first eight brass plates beyond the steel frontplate measure 50.5 mm in diameter, followed by six 56.5 mm thick brass plates. This results in a total radial diameter for the HB in terms of interaction lengths $\lambda_I$ of 5.82 at 90° and increasing with $1/\sin \theta$.

There are 16 layers of scintillator placed in between the absorber layers with properties shown in table 3.3 which transport their light via wavelength shifting fibres (WLS) to the photo detectors. A special layer 0 was placed in front of the absorber plates, to sample hadron showers developing in the inert material between EB and HB. The last layer (16) has a differing thickness to correct for late developing showers the leak out of the back of the HB. To limit the number of individual scintillator pieces that have to be mechanically handled separately and also provide easy maintenance, the scintillator is grouped in megatiles. The wedges of the HB have four sectors in $\phi$ indexed 1 to 4, and in everyone is one megatile inserted per layer, giving in total 72 $\Delta \phi$ segments. The segmentation along the $z$-axis is such the the towers are quadratic in $\Delta \eta - \Delta \phi$. A megatile consists of individual scintillators with edges painted white and wrapped in Tyvek 1073D and mounted on a 0.5-mm-thick plastic substrate with plastic rivets. Light from each tile is collected with a 0.94-mm-diameter green double-cladded WLS (Kuranay Y-11) placed in a groove in the scintillator. After exiting the scintillator the WLS are spliced to clear fibres (Kuranay double-clad) which go to an optical connector at the end of a tray. The connector transfers the light to a optical decoding unit (ODU) where the individual fibres are arranged into read-out towers and the light is finally read-out by a hybrid photodiode (HPD). The read-out towers have a $\Delta \eta \times \Delta \phi$ segmentation of 0.087 $\times$ 0.087. This gives in total 2304 read-out towers for the HB (numbering scheme shown in figure 3.13).

The $\eta$ towers -14 to 14 have a single longitudinal readout, but the $\eta$ towers closest to the endcap region (-16,-15,15,16) have two segments in depth. The front segment of towers -15 and 15 consist of scintillator layers 0-11 for the middle two $\phi$ sector, respectively layers 0-12 for the two outer $\phi$ sectors due to the placement of the read-out box. The front segment of towers -16 and 16 has only five scintillator layers and no layer 0. The rear segments of all four $\eta$ towergroups have three scintillator layers. The e/h value of the calorimeter is roughly 1.4 [20]. For more details see [21][18][22][19].
TABLE 3.4: Physical properties of the HB brass absorber, known as C26000/cartridge brass. [19]

<table>
<thead>
<tr>
<th>chemical composition</th>
<th>70% Cu, 30% Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>8.53 g/cm³</td>
</tr>
<tr>
<td>radiation length</td>
<td>1.49 cm</td>
</tr>
<tr>
<td>interaction length</td>
<td>16.42 cm</td>
</tr>
</tbody>
</table>

Table 3.5: Tower data for HB. The given thicknesses correspond to the center of the tower.
3.7. HADRON CALORIMETER

3.7.2 Hadron Endcap

The Hadron Endcap (HE) is a sampling calorimeter similar to the HB and covers a solid angle of 13.2%, which corresponds to a pseudorapidity range of $1.3 < |\eta| < 3.0$, a region containing about 34% of the particles produced in the final state. Due to the high luminosity of the LHC ($10^{34}$ cm$^{-2}$ s$^{-1}$), the HE has to handle high counting rates (MHz) and has to resist significant amounts of radiation ($\approx 10$ Mrad after 10 years of operation at design luminosity). Since the HE is inserted into the ends of a 4 T magnet, the absorber has to be made from a non-magnetic material. It must also provide a maximization of interaction lengths to fully contain hadron showers, must have good mechanical properties, and this at a reasonable cost, leading to the choice of C26000 cartridge brass, the same used for the HB (see table 3.4).

The design of the absorber was driven by the need to minimize cracks (which have been made non-projective) between HB and HE, rather than single particle energy resolution, since the resolution of jets is limited by pileup, parton fragmentation and effects from the non-homogeneity of the magnetic field. The absorber plates are bolted together in a staggered geometry to achieve a configuration that contains no projective uninstrumented material and thus providing a self-supporting hermetic construction. The brass plates are 79 mm thick with 9 mm gaps for the scintillator tiles, which are inserted after the assembly of the absorber. The outer layers of the HE have a cutout region for the installation of the photodetectors and front-end electronics. To compensate this loss of absorber material, an extra layer (-1) has been attached to the front of tower 18. The outer layers of the absorber are fixed to a 10-cm-thick stainless steel support plate.

The scintillator tiles for the HE have a trapezoidal-shape and are made of 4-mm-thick SCSN81 or 9-mm-thick Bicron BC408 for layer 0. The light of the scintillator is collected by wavelength shifting fibres (WLS), which are embedded into grooves in the scintillator. This design minimizes “dead” zones because the absorber can be made as a solid piece without supporting structures, while the light can be easily routed to the multipixel hybrid photodiodes (HPDs) which are used as photodetectors in the HE calorimeter due to their low sensitivity to magnetic fields and their large dynamical range. The total number of tiles for both HE calorimeters is 20916, put together to 1368 trays, resulting in a granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for $|\eta| < 1.6$ and $\Delta\eta \times \Delta\phi \approx 0.17 \times 0.17$ for $|\eta| \geq 1.6$.

In contrast to the HB, the HE towers have a longitudinal segmentation. This is motivated by the radiation environment, thus offering the possibility to correct the calibration coefficients after scintillator degradation. The towers nearest to the beam line (27, 28 and guard ring 29) have three readout segments in depth, while the other towers (except for towers 16, 17 which are overlapping with the HB) have two longitudinal readouts. For more details see [22][18][23][19].
3.7.3 Hadron Outer

In the central pseudorapidity region $|\eta| < 1.26$ the combined material of EB and HB is not enough to provide sufficient containment for hadron showers. Therefore, the hadron calorimeter is extended outside the solenoid with an additional calorimeter, the hadron outer (HO), serving as a “tail catcher”. The HO utilizes the solenoid coil as supplementary absorber with a thickness of $1.4/\sin \theta$ interaction lengths. In addition to this there is a 19.5-cm-thick iron layer in the middle of the HO where the HB has the minimal absorber depth. Since the HO is physically located inside the muon system, it is strongly constrained by its geometry. The muon system is subdivided into 5 rings along the z-axis. Each of these rings is 2.536 m wide in z-direction and the HO is placed as first sensitive layer in these rings, with a scintillator thickness of 10 mm. Bicron BC408 has been used as scintillator material. Ring 0 carries two scintillator layers, one placed at each side of the above mentioned additional iron plate. The scintillator is placed at a radial distance of 4.07 m, respectively at 3.82 m and 4.07 m is case of ring 0. The sizes and positions of the individual scintillator tiles are supposed to roughly map the layers of the HB to make towers of granularity $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$. The light of the scintillator is transported by Y11 Kurenai wavelength shifting fibres (WLS) to the photodetectors. For more details see [22][18][19].

3.7.4 Hadron Forward

To increase the sensitive solid angle of the calorimeter system up to a pseudorapidity range of $|\eta| < 5.2$, hadron forward calorimeters (HF) have been placed on each “cap” side of the CMS detector. The longitudinal diameters of the HF are 165.0 cm ($\approx 10 \lambda_I$) and frontfaces of the HF have a distance to the interaction point of 11.2 m. On average, 760 GeV per proton-proton collision is deposited into the two forward calorimeters, compared to only 100 GeV for the rest of the detector. Moreover, this energy is not uniformly distributed, but has a pronounced maximum at highest pseudorapidities. As the HF will experience unprecedented particle fluxes, the main challenge in its design was to create a calorimetry system which is able to survive under these harsh conditions for at least a decade. To guarantee for the functioning of the calorimeter for this period, quartz fibres which have good radiation hardness have been chosen as active medium.

The HF is essentially a cylindrical steel structure with an outer radius of 130.0 cm and a cylindrical hole for the beampipe with a diameter of 25.0 cm. Its made of 5 mm thick grooved steel plates which have quartz fibres inserted into the grooves. These fibres run parallel to the beamline providing a non-projective geometry and are bundled to form $\Delta \eta \times \Delta \phi = 0.175 \times 0.175$ towers. The detector is functionally subdivided into 2 longitudinal segments with half of the fibres running over the full depth of the absorber and the other half starting at a distance of 22.0 cm away
from the frontface of the calorimeter. Each set of fibres is read out separately, which makes it possible to distinguish between showers initiated by photons and electrons and those initiated by traversing hadrons, as the former deposit most of their energy in the first 22 cm of steel, whereas the latter produce equal signals in both calorimeter segments. The signal is produced when charged shower particles above the Cherenkov threshold ($E \leq 190$ keV for electrons) generate Cherenkov light, thereby rendering the HF mostly sensitive to the electromagnetic component of the shower. For more details see [22][18][19].

3.8 The Calotower concept

The standard readout cell of the CMS calorimeters for the barrel region is the calotower. It consist of an EB-, a HB- and a HO-segment. The Ecal segment, called Ecal-tower is an array of $5 \times 5$ Ecal crystals, the Hcal segment is an Hcal-tower, and the HO segment is the corresponding HO-tower. All have the same $\Delta \eta \times \Delta \phi$-size and can be read out individually. A schematic view of a calotower is shown in figure 3.14.

3.9 Triggers

As mentioned in the beginning of this chapter, there is a bunch crossing every 25 ns at LHC, which corresponds to a frequency of 40 MHz. Even with a event size of only 250 kb this would result in a data stream of 1 TB/s. This is far too much data to be processed in real time and even far too much to store, but also a fraction of the total events has interesting signatures. Therefore triggers are used to reduce the datastream to a moderate level.

This is done in a two-step process. The Level 1 (L1) trigger is used to get a brief glimpse of the event. Only the fast-responding detector components are read out and very basic reconstruction techniques are used. The trigger looks for interesting signatures like high $P_T$ jets and leptons, high jet multiplicities or a large $E_{miss}^\gamma$. In this step, the datastream is decreased to approximately 30 kHz, but this is still to much to be stored.

Therefore High Level Triggers (HLT) are utilized for further filtering of the events. The usey more sophisticated reconstruction algorithms with higher tresholds. This decreases the datastream down to a bearable amount of approximately 100 Hz which is stored. Copies of the data will be distributed to processing centers throughout the world, where most of the actual analysis can be done locally.
Figure 3.6: Global track reconstruction efficiency for pions of transverse momenta of 1, 10, 100 GeV [19]
3.9. TRIGGERS

Figure 3.7: Material budget in units of radiation length as a function of pseudo-rapidity $\eta$ for the different subdetectors (left) and broken down into the functional contributions (right panel) [19]

Figure 3.8: Layout of the Pixel detector in the CMS Tracker [18]
Figure 3.9: Transverse section through the ECAL showing geometrical configuration. [18]

Figure 3.10: Layout of the CMS ECAL showing the arrangement of crystal modules, supermodules, supercrystals and endcaps with preshower in front. [18]
3.9. TRIGGERS

Figure 3.11: Layout of the EB supermodule mechanics. [19]

Figure 3.12: Isometric view of a HB wedge, showing the hermetic design. [19]
Figure 3.13: The HCAL tower segmentation in the r-z-plane for one-fourth of the HB, HO and HE detectors. The numbers on the edge indicate the scintillator layer. The different colours represent the different longitudinal readouts. [18]
Figure 3.14: Schematic view of a calotower, consisting of $5 \times 5$ Ecal-crystals, a HB-tower and a HO-tower. (modified from [19])
Chapter 4

Analysis

In this chapter, we will study the responses of isolated pions depositing their energy in the calorimeter to improve our understanding of the CMS barrel calorimeters. We will first study the responses of charged pions and then also investigate the radial shower distributions. With this knowledge we will then try to achieve a dataset of isolated particles that can be used for calibration purposes, a technique which was first officially proposed for CMS in [24]. With this technique, the calibration constants for the towers are simply the ratio of the isolated particle momenta and the calorimeter-measured energy deposit that can be contributed to this particle. This method has some advantages to the jet calibration technique proposed in [25], as it does not utilize jets and therefore avoids numerous problems. We will then finish with a study of the background induced by neutral particles.

4.1 Studies of CMS HB-calorimeter

To study the properties of the CMS HCAL, two Monte-Carlo datasets of pions have been produced with a particle gun from the CMS-software version 1.6.11. One with single $\pi^-$ containing 495000 events and one with single $\pi^+$ containing 500000 events. The $P$- and $P_t$-spectra of the tracks of both datasets as well as their $\eta$- and $\phi$-distributions can be seen in figure 4.1. As visible in the figure, the datasets have been produced for $|\eta| < 1.392$ for the whole $\phi$-range with transverse momentum of $1 \text{ GeV} < P_t^{\text{pion}} < 100 \text{ GeV}$ with equal statistics over the whole eta-, phi- and transverse momentum range. The shift from transverse momenta with slightly below 100 GeV to transverse momenta higher than 100 GeV is due to the track reconstruction resolution. The accumulation for very low $P_t$ tracks is due to pions which already interact in the tracker, thus producing more than just one track per pion. Of course the tracks have only a fraction of the original transverse momentum and therefore we may have many low $P_t$ tracks.
CHAPTER 4. ANALYSIS

Figure 4.1: The momentum (a), the transverse momentum (b), the $\eta$ (c) and $\phi$ (d) distributions for all tracks in both pion datasets.

4.1.1 Track isolation

We now look for isolated tracks in the datasets. Our minimum requirements for a track are a transverse momentum $P_t > 5 \text{ GeV}$ and a minimum of 9 hits in the tracker, $N_{\text{Hits}} \geq 9$, (a tracker hit means a measurement in one of the tracker layers) to ensure a reasonable track reconstruction. As mentioned before, a small number of pions decay or interact on their way to the calorimeters. To guarantee that no other charged particle deposits energy in the examined cluster, we demand that the sum of the transverse momentum of all other tracks in a dR-cone with radius 0.5 around our track does not exceed 1 GeV.

$$\sum_{dR=0.5} P_t < 1 \text{ GeV} \quad (4.1)$$

The number of tracks which fulfill this criteria are shown in table 4.1. The momentum- and transverse momentum- spectra for all tracks in the $\pi^\pm$-datasets, for the “good” tracks ($P_t > 5 \text{ GeV}$ and $N_{\text{Hits}} \geq 9$) and for the “good” isolated tracks are also shown in figure 4.2. One can see, that the cuts remove the low momentum tracks.

We then calculate the trajectory of this track up to Hcal with a software module called PropagateToCal[26]. Then we use the detector geometry to find the nearest
Table 4.1: The total number of events, the total number of tracks, the number of good tracks and the number of isolated tracks for both pion-datasets.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Total number of events in dataset</th>
<th>Total number of tracks in dataset</th>
<th>Number of &quot;good&quot; tracks in dataset</th>
<th>Number of &quot;good&quot; isolated tracks in dataset</th>
<th>good isolated tracks in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>500000</td>
<td>528078</td>
<td>454366</td>
<td>440086</td>
<td>88.02</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>495000</td>
<td>521827</td>
<td>450240</td>
<td>436149</td>
<td>88.11</td>
</tr>
</tbody>
</table>

calotower to the intersection point of the track trajectory and the Hcal. We call this calotower the hit tower and store all the information of a $7 \times 7$-calotower cluster centered in the hit tower and all the energy content of all according Ecal crystals. To calculate the intersection with the Hcal is somewhat optimistic as a fair amount of particles starts showering already in the Ecal, but it works out rather sufficiently as shown in section 4.1.5.
Figure 4.2: The momentum- and transverse momentum-spectra for the $\pi^+$- (a), (c) and $\pi^-$-dataset (b), (d) for all tracks in the dataset, the "good" tracks and the "good" isolated tracks.
4.1. STUDIES OF CMS HB-CALORIMETER

4.1.2 The Response

As already mentioned in the beginning of this chapter, the inverse of the calibration constant is the **response**. The response distribution of a calorimeter shows, how much of the track momentum is measured by the calorimeter in the form of energy deposit. We now have to define the response of the calorimeter and its subcalorimeters as:

\[
\text{Response} = \frac{E_{\text{Calo-Cluster}}}{P_{\text{Track}}}.
\]  

The next thing to do is to choose a form and a size for the cluster we want to match against the momentum of the track. As form we chose a quadratical calorimeter-tower cluster as we follow the segmentation of the calorimeter and not the physical form of the shower (circle-like). Figure 4.3 shows the energy-contents of the hit and its surrounding calo-towers in percent. We chose the 3 \times 3-cluster as it on average already contains approximately 95\% of the measurable energy (see invisible energy, section 2.6.2), whereas a single tower contains on average only 50\%. Bigger clusters contain on average only small extra amounts of the shower energy, something that can be easily corrected for, while it is more difficult to find bigger isolated clusters than smaller ones. There are also thresholds for the calotowers as shown in figure 4.5. The reconstruction threshold for a Ecal-tower is 0.2 GeV respectively 0.9 GeV for a Hcal-tower.

![Average fraction of the track momentum that is deposited per calotower for 7 \times 7 calotower cluster, in the left for π⁺ and in the right for π⁻. On average nearly all of the energy is deposited in a 3 \times 3-calotower cluster around the hit tower.](image)

We define three different responses

\[
\text{Ecal Response} = \frac{E_{\text{EB-3x3}}}{P_{\text{Track}}},
\]

\[
\text{Hcal Response} = \frac{E_{\text{HB-3x3}}}{P_{\text{Track}}}
\]

\[
\text{Combined Response} = \frac{E_{\text{EB-3x3}} + E_{\text{HB-3x3}} + E_{\text{HO-3x3}}}{P_{\text{Track}}}
\]
where $E_{cal\ Response}$ is the energy deposited in a $3 \times 3$-Ecal-tower cluster centered in the hit calotower divided by track momentum, the $H_{cal\ Response}$ is the same, just for the HB-towers and the $Combined\ Response$ is the energy of a $3 \times 3$-calotower cluster. As shown in figure 4.4, the Combined Response varies only slightly, if the clustersize is increased beyond $3 \times 3$, whereas it varies significantly between a single tower and a $3 \times 3$-cluster.

![Combined Response distribution](image)

Figure 4.4: The Combined Response distribution for a single tower (pink), a $3 \times 3$- (red), $5 \times 5$- (green) and $7 \times 7$-calotower clusters (blue) for the $\pi^+$- (a) and the $\pi^-$- dataset (b).
Figure 4.5: Energy deposits in a given Ecal-tower (left) and Hcal-tower (right). Apparently there are thresholds of 0.2 GeV for Ecal-tower and 0.9 GeV for Hcal-tower.
4.1.3 Responses of the pions

We will now examine the Ecal, Hcal, and Combined Response-functions of these isolated tracks for different track momentum intervals and compare the Responses for positive and negative pions. The individual Response distributions for particles in the momentum ranges of $9 - 11$ GeV, $45 - 55$ GeV, and $95 - 105$ GeV are shown in figure 4.6 (the response comparisons for the other energy intervals can be found in the appendix). The track momentum intervals have a size of $2$ GeV for $5$ GeV $< P_{\text{Track}} < 25$ GeV and $10$ GeV for $25$ GeV $< P_{\text{Track}} < 105$ GeV. The Ecal Response shape is more or less independent of the track momentum, but with increasing track momentum a double peak structure in the Hcal Response becomes perceptible. The origin of these double-peak structure of the Ecal and Hcal Responses will be explained in section 4.1.4. The Combined Responses have the anticipated Gaussian shape and therefore it can be approximated with a Gaussian fit, although there are deviations from the Gaussian shape at low track momenta. The result of this fit is again Gauss-fitted in a range of $2\sigma$ around the mean of the first fit. This second Gauss approximation is then also displayed in the Combined Response histogram. The Ecal and Hcal Response distributions do not have such a simple shape as the Combined Response, and are therefore not approximated. All means of the response distributions as well as the means of the Gaussian fits and the medians are listed in table 4.2 and 4.3.

To determine the energy dependency of the response distributions, the means and medians are displayed as a function of the track momentum in figure 4.7. Plot (a) shows the means of the Ecal Response, which has an abnormal and not fully understood shape at lower track momenta. But the decrease of the Ecal Response for higher track momenta can be satisfactorily explained, because, on average, the pions deposit a greater fraction of the total shower energy in the Hcal as the track momenta increases. The mean Hcal Response (b) shows a sharp rise as the momentum increases up to about $30$ GeV, but for larger momenta, the response increment is smaller. The plot (c) shows the means of the Combined Response, as well as the means of the Gaussian fits and the medians of the Combined Response. The Combined Response also becomes larger as the track momentum increases. This is because, on average, the Hcal Response dominates the Combined Response and therefore the mean Ecal Response shape has only a minor influence on the shape of the Combined Response. The means of the fits and the medians are especially at low energies systematically smaller than the means of the distributions, which is due to the deviations from the gaussian form of the Combined Response at low track momenta. The difference of the means, the means of the fits, and the medians vanishes as the track momentum increases, respectively the Combined Response becomes more Gaussian.

The responses for energies above $20$ GeV are equal for negative and positive pions. Below this threshold we see a difference in the Ecal Response of $\pi^+$ and
\( \pi^- \) which results in different Combined Responses for both pions in the low-energy region. The Ecal Response for \( \pi^- \) is larger than \( \pi^+ \). The opposing effect (Ecal Response\( \pi^+ \) > Ecal Response\( \pi^- \)) was reported from testbeam data [20]. We have to wait for real data, to see if this effect is observed again. From this point we put both datasets together to double the statistics as the differences are rather small. We also need to know, which resolutions in the energy measurement can be achieved. This is shown in figure 4.8 as a function of the track momentum. As expected, the resolution improves drastically with increasing track momentum to approximately 20% at 100 GeV. The better resolutions which are obtained from a Gaussian fit can be explained with the deviations from the Gaussian from of the Combined Response at low track momenta, as the resolution difference becomes also smaller as track momenta increase. This resolution less than reported from testbeam measurements [20], but this can be (at least to a fraction) accounted to the size of our track momentum intervals. Our Combined Response is actually the sum of the distributions, of different momenta, which increases the width of our Combined Response, whereas the testbeam had a well defined beam energy. Also our Hcal is in contrast to the testbeam Hcal not calibrated. As shown in the next section, it is also the sum of responses of those particles, which shower only in the Hcal and those, which start showering already in the Ecal. Both have significantly differing responses, which also increases the width of our Combined Response distribution.
Figure 4.6: The Ecal (a), Hcal (b), and Combined Responses (c) for 9 GeV \leq P_{\text{Track}} < 11 GeV, 45 GeV \leq P_{\text{Track}} < 55 GeV, and 95 GeV \leq P_{\text{Track}} < 105 GeV. For the Combined Response the result of the Gaussian fit is also shown. The $\pi^+$ are displayed in red, $\pi^-$ in blue.
4.1. STUDIES OF CMS HB-CALORIMETER

Figure 4.7: The means for the Ecal- (a), Hcal- (b), and the Combined Response as a function of the track momentum. Figure (c) shows in addition to the mean also the mean of a Gaussian fit as well as the median. The $\pi^+$ are displayed in red, $\pi^-$ in blue.
<table>
<thead>
<tr>
<th>Track momentum [GeV]</th>
<th>Ecal-Response mean value</th>
<th>Hcal-Response mean value</th>
<th>Combined Response mean value (RMS)</th>
<th>Combined Response gaussian fit mean value (σ)</th>
<th>Combined Response median value (0.9 quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7</td>
<td>0.27</td>
<td>0.28</td>
<td>0.544 ± 0.006 (0.30)</td>
<td>0.490 ± 0.005 (0.25)</td>
<td>0.488 (0.92)</td>
</tr>
<tr>
<td>7-9</td>
<td>0.25</td>
<td>0.31</td>
<td>0.562 ± 0.004 (0.29)</td>
<td>0.512 ± 0.004 (0.24)</td>
<td>0.501 (0.94)</td>
</tr>
<tr>
<td>9-11</td>
<td>0.25</td>
<td>0.32</td>
<td>0.559 ± 0.004 (0.28)</td>
<td>0.520 ± 0.004 (0.23)</td>
<td>0.513 (0.91)</td>
</tr>
<tr>
<td>11-13</td>
<td>0.25</td>
<td>0.34</td>
<td>0.581 ± 0.003 (0.27)</td>
<td>0.545 ± 0.003 (0.23)</td>
<td>0.530 (0.93)</td>
</tr>
<tr>
<td>13-15</td>
<td>0.25</td>
<td>0.36</td>
<td>0.608 ± 0.003 (0.27)</td>
<td>0.575 ± 0.003 (0.23)</td>
<td>0.564 (0.95)</td>
</tr>
<tr>
<td>15-25</td>
<td>0.28</td>
<td>0.41</td>
<td>0.672 ± 0.001 (0.26)</td>
<td>0.643 ± 0.001 (0.23)</td>
<td>0.639 (0.99)</td>
</tr>
<tr>
<td>25-35</td>
<td>0.29</td>
<td>0.46</td>
<td>0.737 ± 0.001 (0.24)</td>
<td>0.712 ± 0.001 (0.21)</td>
<td>0.708 (1.03)</td>
</tr>
<tr>
<td>35-45</td>
<td>0.29</td>
<td>0.49</td>
<td>0.765 ± 0.001 (0.23)</td>
<td>0.741 ± 0.001 (0.19)</td>
<td>0.738 (1.03)</td>
</tr>
<tr>
<td>45-55</td>
<td>0.28</td>
<td>0.50</td>
<td>0.777 ± 0.001 (0.22)</td>
<td>0.757 ± 0.001 (0.19)</td>
<td>0.756 (1.03)</td>
</tr>
<tr>
<td>55-65</td>
<td>0.27</td>
<td>0.52</td>
<td>0.787 ± 0.001 (0.20)</td>
<td>0.771 ± 0.001 (0.18)</td>
<td>0.769 (1.03)</td>
</tr>
<tr>
<td>65-75</td>
<td>0.26</td>
<td>0.53</td>
<td>0.794 ± 0.001 (0.19)</td>
<td>0.785 ± 0.001 (0.17)</td>
<td>0.781 (1.03)</td>
</tr>
<tr>
<td>75-85</td>
<td>0.25</td>
<td>0.55</td>
<td>0.800 ± 0.001 (0.18)</td>
<td>0.793 ± 0.001 (0.17)</td>
<td>0.790 (1.03)</td>
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<tr>
<td>85-95</td>
<td>0.24</td>
<td>0.56</td>
<td>0.801 ± 0.001 (0.17)</td>
<td>0.800 ± 0.001 (0.16)</td>
<td>0.797 (1.03)</td>
</tr>
<tr>
<td>95-105</td>
<td>0.24</td>
<td>0.55</td>
<td>0.798 ± 0.001 (0.16)</td>
<td>0.794 ± 0.001 (0.16)</td>
<td>0.791 (1.01)</td>
</tr>
</tbody>
</table>

Table 4.2: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the $\pi^+$-dataset. For the Combined Response also the means of the fits and the medians as well as the RMS, the $\sigma$ and the 0.5-quantile are listed. The given errors are simply statistical.
### 4.1. STUDIES OF CMS HB-CALORIMETER

<table>
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<tr>
<th>Track momentum [GeV]</th>
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<th>Hcal-Response mean value</th>
<th>Combined Response mean value (RMS)</th>
<th>Combined Response gaussian fit mean value ($\sigma$)</th>
<th>Combined Response median value (0.9 quantile)</th>
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<td>0.505 (0.95)</td>
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<td>0.575 ± 0.004 (0.30)</td>
<td>0.525 ± 0.004 (0.25)</td>
<td>0.517 (0.96)</td>
</tr>
<tr>
<td>9-11</td>
<td>0.26</td>
<td>0.32</td>
<td>0.574 ± 0.004 (0.28)</td>
<td>0.532 ± 0.003 (0.24)</td>
<td>0.519 (0.93)</td>
</tr>
<tr>
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<td>0.593 ± 0.003 (0.28)</td>
<td>0.560 ± 0.003 (0.24)</td>
<td>0.550 (0.94)</td>
</tr>
<tr>
<td>13-15</td>
<td>0.26</td>
<td>0.37</td>
<td>0.608 ± 0.003 (0.27)</td>
<td>0.583 ± 0.003 (0.23)</td>
<td>0.572 (0.96)</td>
</tr>
<tr>
<td>15-25</td>
<td>0.28</td>
<td>0.41</td>
<td>0.674 ± 0.001 (0.26)</td>
<td>0.644 ± 0.001 (0.22)</td>
<td>0.644 (0.99)</td>
</tr>
<tr>
<td>25-35</td>
<td>0.29</td>
<td>0.45</td>
<td>0.736 ± 0.001 (0.24)</td>
<td>0.712 ± 0.001 (0.20)</td>
<td>0.710 (1.02)</td>
</tr>
<tr>
<td>35-45</td>
<td>0.29</td>
<td>0.49</td>
<td>0.766 ± 0.001 (0.24)</td>
<td>0.742 ± 0.001 (0.20)</td>
<td>0.738 (1.05)</td>
</tr>
<tr>
<td>45-55</td>
<td>0.28</td>
<td>0.51</td>
<td>0.780 ± 0.001 (0.22)</td>
<td>0.759 ± 0.001 (0.18)</td>
<td>0.757 (1.04)</td>
</tr>
<tr>
<td>55-65</td>
<td>0.27</td>
<td>0.52</td>
<td>0.788 ± 0.001 (0.20)</td>
<td>0.773 ± 0.001 (0.18)</td>
<td>0.771 (1.03)</td>
</tr>
<tr>
<td>65-75</td>
<td>0.26</td>
<td>0.54</td>
<td>0.796 ± 0.001 (0.19)</td>
<td>0.785 ± 0.001 (0.17)</td>
<td>0.784 (1.03)</td>
</tr>
<tr>
<td>75-85</td>
<td>0.25</td>
<td>0.55</td>
<td>0.801 ± 0.001 (0.18)</td>
<td>0.794 ± 0.001 (0.16)</td>
<td>0.791 (1.02)</td>
</tr>
<tr>
<td>85-95</td>
<td>0.25</td>
<td>0.55</td>
<td>0.804 ± 0.001 (0.17)</td>
<td>0.799 ± 0.001 (0.16)</td>
<td>0.798 (1.02)</td>
</tr>
<tr>
<td>95-105</td>
<td>0.24</td>
<td>0.55</td>
<td>0.800 ± 0.001 (0.16)</td>
<td>0.798 ± 0.001 (0.16)</td>
<td>0.795 (1.01)</td>
</tr>
</tbody>
</table>

Table 4.3: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the $\pi^-$-dataset. For the Combined Response also the means of the fits and the medians as well as the RMS, the $\sigma$ and the 0.5-quantile are listed. The given errors are simply statistical.
Figure 4.8: Shown is the resolution of the CMS barrel calorimeters for uncalibrated, isolated pions, calculated from the rms of the Combined Response and its mean, respectively from the $\sigma$ of the Gaussian fit and the according mean of the fit. The resolution calculated from the Combined Response are displayed in red, the resolution calculated from the Gauss-fitted Combined Response is displayed in green.
4.1.4 Late and early showering pions

The large difference of the $e/h$-values of the Ecal and Hcal has some severe consequences for the energy measurement at CMS. Figure 4.9 shows the absolute response of the Ecal for tracks with momenta beyond 20 GeV. The second peak in the histogram proves, that a significant amount of particles traverse the Ecal without causing any or at least nearly no signal (the first peak at zero originates from the calotower reconstruction thresholds), as if they were minimum ionizing particles (mips) like muons. We call these pions from now on late-showering (LS) and call all particles that have an Ecal Response $< 1.2$ GeV late-showering particles, the others are called early-showering (ES). The name refers to the starting point of shower, that a traversing particle induces. One might argue to set the cut at a lower Ecal-deposit, but we will set the cut according to definitions from previous studies [20] to ensure good comparability.

Figure 4.9: Shown is the absolute Ecal energy for tracks with $P_{\text{Track}} > 20$ GeV. A significant amount of pions traverse the Ecal with almost no energy loss ($E_{\text{Ecal loss}} < 1.2$ GeV). The LS pions are displayed in green, whereas the ES pions are displayed in pink.

Figure 4.10 to 4.14 show the Ecal, the Hcal, and the Combined Response for different energy intervals. The intervals have a size of 2 GeV for $5 \leq P_{\text{Track}} < 15$ GeV and 10 GeV size for $15 \leq P_{\text{Track}} < 105$ GeV. The mean responses for the different track momentum intervals of the LS pions are listed in table 4.4 and in table 4.5 for
the ES pions. For the Combined Response, also the mean of the Gaussian fits as well as the medians with the according rms, $\sigma$, and 0.5-quantiles are listed.

For the Ecal and Hcal Response the amount of LS and ES pions are stacked on top of each other, which gives us the possibility to understand the double peak structure of both responses. The first peak in the Ecal-Response is simply the amount of particles, that traverse the Ecal with (nearly) no energy loss. The second peak can be contributed to the ES particles as visible in the figures.

The first Hcal Response peak at zero (especially visible for low track momenta) originates from calotower reconstruction thresholds. At low momenta, there is only one other peak visible which originates from those particles, that transversed the Ecal without energy loss, the LS pions. As track momentum increases, a third peak becomes visible in between the read out threshold peak and the LS peak, which is due to the fact, that the ES pions deposit on average larger fractions of their total energy in the Hcal with increasing track momentum, because of the fixed ES-LS threshold of 1.2 GeV.

When examining the Combined Responses one notices on first sight that the means of the LS and ES pions differ significantly. This is due to the large difference of the $e/h$-values of the EB and the HB. If we do not distinguish between the LS and ES pions and simply sum over all pions for the Combined Response, we get a much broader distribution. If we compare the raw energy resolutions ($\text{rms/mean}$, respectively $\sigma/\text{mean}$ for the gaussian fit) without any further calibration applied, we see that for high track momenta (95-105 GeV) we get an improvement of 3% (5% for the gaussian fit) for the LS pions and an improvement of 1% (4%) for the ES pions. At low momenta, we also get an improvement for the ES pions.

Some of the figures also show available testbeam data. The testbeam data was acquired at the H2 testbeamline at CERN. For the exact setup of the beamline see [20]. The data was taken with the final HB which was calibrated with 50 GeV pions, and the final Ecal design, but the read out cluster consisted of only an $9 \times 9$-crystal array. Also, no read out thresholds were applied to the calotowers. When we compare the individual Ecal distributions, we observe a fairly good matching, although much less Ecal Response above one have been measured at testbeam. This might well be due to the limited size of the Ecal read out array. We will see in section 4.1.6 that the whole energy that is deposited in the Ecal is on average deposited in an $10 \times 10$-cell array. Individual showers distribute their energy in an even bigger array. The situation is different for the HB, as the recording of the data was done with a whole HB wedge. But here we see, that the HCAL-Response from the testbeam is systematically larger than the Hcal-Response from our pion dataset. This originates from the 50-GeV pion calibration. Therefore the Combined Responses are also systematically larger. We will account for this point when we look at the means of the distributions.
4.1. STUDIES OF CMS HB-CALORIMETER

Figure 4.15 shows the means of the individual distributions as a function of the track momentum. The decreasing Ecal-Response (a) of the LS pions is trivial, due to the fixed LS-ES threshold. The Ecal-Response for the ES pions shows an interesting behavior at low track momenta which is not seen in the testbeam data. This dropdown to a local minimum, followed by a rise until it decreases again is not understood at the moment. It might be an artifact of the simulation software and we have to wait for real data for further investigations. Other explanations, based on the idea, that the starting points of showers move on average further into the material as the track momentum increases are speculative as we lack the information about the longitudinal shower development. For high track momenta, the response decreases almost linear, as an increasing fraction of the shower energy is deposited in the Hcal.

The mean Hcal-Responses (b) increase with increasing track momentum for both, the LS and the ES pions. At low track momenta the increment is for both much larger than for high track momenta. The testbeam pions have a significantly higher response, due to the calibration of the testbeam Hcal with 50 GeV pions. We will come back to this point in the end of this section, when we scale the Hcal and Combined Responses to account the 50-GeV calibration for a better comparison.

Figure (c) shows the Combined Response as a function of the track momentum. It is obvious that the LS and ES pions should be treated separately as their Combined Responses differ significantly. The Response of the LS pions rises fast up to track momenta of 40 GeV, than it becomes almost constant, with a maximum of approximately 0.9. The same holds for to the ES pions, but they show a different low track momentum behaviour, in particular the Response is constant between momenta of 5-10 GeV and the maximum is lower (approximately 0.74). Fitted Responses and medians basically follow the shape of the Combined Responses, thus they show a different behavior for LS and ES pions. For the ES pions the fitted mean and the median basically equal each other but they converge to the mean at much higher track momenta (80 GeV). For the LS pions, the fit and the median converge to the mean already at 20 GeV, but they do not equal each other below this energy.

For a better comparison, the means of the Hcal- and Combined Response of the LS and ES testbeam pions have been scaled by such a factor, that the means of LS pions of our dataset and of the testbeam dataset equal at a track momentum of 50 GeV (see figure 4.16). We see perfect match for the LS pions in the Hcal at high momenta, but differences at low momenta, which is most probably due to the fact, that no read out thresholds have been applied to the calorimeter towers in the testbeam setup (see figure 4.17). The ES pions are hard to compare because of the different Ecal setup.
Figure 4.10: The Ecal (a)) and Hcal Responses (b) for late- (green) and early-showering (pink) pions stacked on top of each other. The Combined Response for late- and early showering as well as the double gaussian fit for each distribution is shown in c). Available testbeam data is shown in red (LS) and blue (ES). The testbeam data in a) and b) has been scaled that is has the same integral as the stacked late- and early-showering distributions. The Combined Response for the early showering and the Combined Responses for testbeam data have been scaled to have the same integral as the late-showering distribution. This is shown for different track momentum intervals.
4.1. STUDIES OF CMS HB-CALORIMETER

![Graphs showing Ecal and Hcal responses for different momentum intervals.](image)

Figure 4.11: The Ecal (a)) and Heal Responses (b) for late- (green) and early-showering (pink) pions stacked on top of each other. The Combined Response for late- and early showering as well as the double gaussian fit for each distribution is shown in c). Available testbeam data is shown in red (LS) and blue (ES). The testbeam data in a) and b) has been scaled that is has the same integral as the stacked late- and early-showering distributions. The Combined Response for the early showering and the Combined Responses for testbeam data have been scaled to have the same integral as the late-showering distribution. This is shown for different track momentum intervals.
Figure 4.12: The Ecal (a)) and Hcal Responses (b) for late- (green) and early- showering (pink) pions stacked on top of each other. The Combined Response for late- and early showering as well as the double gaussian fit for each distribution is shown in c). Available testbeam data is shown in red (LS) and blue (ES). The testbeam data in a) and b) has been scaled that is has the same integral as the stacked late- and early-showering distributions. The Combined Response for the early showering and the Combined Responses for testbeam data have been scaled to have the same integral as the late-showering distribution. This is shown for different track momentum intervals.
Figure 4.13: The Ecal (a)) and Heal Responses (b) for late- (green) and early-showering (pink) pions stacked on top of each other. The Combined Response for late- and early showering as well as the double gaussian fit for each distribution is shown in c). Available testbeam data is shown in red (LS) and blue (ES). The testbeam data in a) and b) has been scaled that is has the same integral as the stacked late- and early-showering distributions. The Combined Response for the early showering and the Combined Responses for testbeam data have been scaled to have the same integral as the late-showering distribution. This is shown for different track momentum intervals.
Figure 4.14: The Ecal (a) and Hcal Responses (b) for late- (green) and early-showering (pink) pions stacked on top of each other. The Combined Response for late- and early showering as well as the double gaussian fit for each distribution is shown in (c). Available testbeam data is shown in red (LS) and blue (ES). The testbeam data in a) and b) has been scaled that is has the same integral as the stacked late- and early-showering distributions. The Combined Response for the early showering and the Combined Responses for testbeam data have been scaled to have the same integral as the late-showering distribution. This is shown for different track momentum intervals.
Figure 4.15: The mean values for the Ecal (a), the Hcal (b), and the Combined Response (c) for late- and early-showering pions in comparison to testbeam data as a function of the track momentum. In (c) are also shown the mean values for the gauss fits as well as the medians.
CHAPTER 4. ANALYSIS

Figure 4.16: The plots show the means of the Hcal Response and the Combined Response for the pion dataset and the shifted testbeam data broken down into LS and ES pions. The shift factor is explained in the text.

Figure 4.17: Shown are the energy deposits of a $7 \times 7$-Ecal-crystal array (left) and of a $3 \times 3$-Hcal-tower cluster (right) of the testbeam setup. Apparently there are no read out thresholds. The negative entries are noise fluctuations.
### 4.1. STUDIES OF CMS HB-CALORIMETER

Table 4.4: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the LS pions. For the Combined Response also the means of the fits and the medians as well as the RMS, the $\sigma$ and the 0.5-quantile are listed. The errors are statistical errors.

<table>
<thead>
<tr>
<th>Track momentum [GeV]</th>
<th>Ecal-Response mean value</th>
<th>Hcal-Response mean value</th>
<th>Combined Response mean value (RMS)</th>
<th>Combined Response gaussian fit mean value ($\sigma$)</th>
<th>Combined Response median value (0.9 quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7</td>
<td>0.06</td>
<td>0.57</td>
<td>0.620 ± 0.008 (0.37)</td>
<td>0.520 ± 0.012 (0.41)</td>
<td>0.569 (1.13)</td>
</tr>
<tr>
<td>7-9</td>
<td>0.04</td>
<td>0.61</td>
<td>0.655 ± 0.005 (0.36)</td>
<td>0.591 ± 0.007 (0.35)</td>
<td>0.611 (1.14)</td>
</tr>
<tr>
<td>9-11</td>
<td>0.03</td>
<td>0.63</td>
<td>0.664 ± 0.005 (0.33)</td>
<td>0.624 ± 0.005 (0.32)</td>
<td>0.637 (1.09)</td>
</tr>
<tr>
<td>11-13</td>
<td>0.03</td>
<td>0.66</td>
<td>0.689 ± 0.004 (0.31)</td>
<td>0.662 ± 0.005 (0.30)</td>
<td>0.674 (1.09)</td>
</tr>
<tr>
<td>13-15</td>
<td>0.02</td>
<td>0.70</td>
<td>0.723 ± 0.004 (0.30)</td>
<td>0.701 ± 0.004 (0.28)</td>
<td>0.704 (1.10)</td>
</tr>
<tr>
<td>15-25</td>
<td>0.02</td>
<td>0.77</td>
<td>0.783 ± 0.002 (0.27)</td>
<td>0.775 ± 0.002 (0.25)</td>
<td>0.777 (1.11)</td>
</tr>
<tr>
<td>25-35</td>
<td>0.01</td>
<td>0.83</td>
<td>0.841 ± 0.001 (0.23)</td>
<td>0.839 ± 0.001 (0.21)</td>
<td>0.839 (1.12)</td>
</tr>
<tr>
<td>35-45</td>
<td>0.01</td>
<td>0.85</td>
<td>0.865 ± 0.001 (0.20)</td>
<td>0.866 ± 0.001 (0.19)</td>
<td>0.867 (1.11)</td>
</tr>
<tr>
<td>45-55</td>
<td>0.01</td>
<td>0.87</td>
<td>0.877 ± 0.001 (0.19)</td>
<td>0.882 ± 0.001 (0.17)</td>
<td>0.881 (1.10)</td>
</tr>
<tr>
<td>55-65</td>
<td>&lt; 0.01</td>
<td>0.88</td>
<td>0.887 ± 0.001 (0.18)</td>
<td>0.891 ± 0.001 (0.16)</td>
<td>0.893 (1.10)</td>
</tr>
<tr>
<td>65-75</td>
<td>&lt; 0.01</td>
<td>0.88</td>
<td>0.895 ± 0.001 (0.17)</td>
<td>0.903 ± 0.001 (0.15)</td>
<td>0.902 (1.10)</td>
</tr>
<tr>
<td>75-85</td>
<td>&lt; 0.01</td>
<td>0.89</td>
<td>0.902 ± 0.001 (0.16)</td>
<td>0.907 ± 0.001 (0.15)</td>
<td>0.908 (1.10)</td>
</tr>
<tr>
<td>85-95</td>
<td>&lt; 0.01</td>
<td>0.89</td>
<td>0.905 ± 0.001 (0.16)</td>
<td>0.913 ± 0.001 (0.14)</td>
<td>0.912 (1.10)</td>
</tr>
<tr>
<td>95-105</td>
<td>&lt; 0.01</td>
<td>0.89</td>
<td>0.901 ± 0.001 (0.16)</td>
<td>0.909 ± 0.001 (0.14)</td>
<td>0.910 (1.09)</td>
</tr>
</tbody>
</table>
Table 4.5: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the ES pions. For the Combined Response also the means of the fits and the medians as well as the RMS, the $\sigma$ and the 0.5-quantile are listed. The errors are statistical errors.
4.1.5 Weighted means

Originally developed to validate our track-propagation to the Hcal, we will present another technique to visualize the lateral energy distribution within a given shower, the weighted mean $\text{mean}_W$. This method only works under the assumption, that the lateral shower profiles are mirror-symmetric with a maximum at the point where the traversing particle hits the calorimeter. We will show this separately for a tower row in $\eta$ and $\phi$, which is centered in the hit tower. Therefore, we calculate the weighted sum of the energies of the towers next to the hit tower in $\eta$- or $\phi$-direction and normalize this with the total energy deposited in these three towers:

$$\text{mean}_W = \frac{\sum_{i=-1}^{1} i \cdot \text{TowEn}_i}{\sum_{i=-1}^{1} \text{TowEn}_i},$$

(4.6)

where $\text{TowEn}_i$ means the energy of the $i$th calotower. Also we calculate the according rms:

$$\text{rms}_W = \sqrt{\frac{\sum_{i=-1}^{1} \text{TowEn}_i (\text{mean}_W - i)^2}{\sum_{i=-1}^{1} \text{TowEn}_i}}.$$  

(4.7)

The weighted means $\text{mean}_W^\eta$ and $\text{mean}_W^\phi$ and the rms’ are shown in figures 4.18 for different track momentum intervals with a size of 25 GeV for tracks with momenta from 5GeV to 105 GeV. Those events, where the difference of the adjacent towers equals zero are skipped in this analysis as it is extremely unlikely that both towers have exactly the same energy. In most cases, these towers have zero energy deposit because of the noise cuts.

We see that our track propagation does not only work on average, but also for the individual events of the dataset. The peak at 0.5 for both rms’ might originate from those events where the hit tower and an adjacent tower have the same energy deposit, i.e. the particle hits pretty much the middle between two towers and therefore deposits same amounts of energy in both towers.

This method also provides the possibility to cut on these distributions at a later stage, because those events with $\text{mean}_W > 0.5$ are most likely events where another (neutral) particle has deposited energy in the same $3 \times 3$-calotower cluster as this would of course shift the center of the energy distribution for the event. But contributions also come from the fact, that in some ES events, especially in the low track momentum region, our calculation, that derives the hit tower from the Hcal intersection point, is not perfectly suited.

4.1.6 Shower profiles

We now take a closer look at the showerprofiles. The Hcal has no finer segmentation than the towers, but at least for the Ecal we can make use of its fine granularity. Each of the figures 4.19 to 4.22 shows the average fraction of the total track momentum that is deposited in each HB-tower (left two pictures) for a $3 \times 3$-HB-tower
Figure 4.18: The weighted means $\langle W \rangle$ and the according rms in $\eta$- (upper) and $\phi$-direction (below) for different energy intervals.
4.1. STUDIES OF CMS HB-CALORIMETER

Figure 4.19: The left two pictures show the average fraction of the track momentum that is deposited in each Ecal-crystal for a 35 cell × 35 cell-cluster. The right two pictures show the average energy fraction, that is deposited in each Hcal-tower. This is shown for late-showering (upper) and early-showering (below) pions with momentum 5 Gev ≤ P_{Track} < 30 GeV.

For LS as well as ES pions the energy deposited in the Ecal is on average contained within a 10 × 10-cell cluster (or even a circular cluster with a radius of 5 cells). For the LS pions, the area where the energy is contained is even slightly smaller. For the Hcal we see that the energy from ES pions is deposited with greater lateral spread, especially at low track momenta, which can most probably be attributed to the fact, that we calculate the middle of the showers from the intersection point of the calculated particle trajectory and the inner Hcal surface, although some particles start their showers before reaching the Hcal. This can possibly be improved, as this would result in lower responses, as a fraction of the shower energy is not deposited in our 3 × 3-calotower cluster.
Figure 4.20: The left two pictures show the average fraction of the track momentum that is deposited in each Ecal-crystal for a 35 cell $\times$ 35 cell-cluster. The right two pictures show the average energy fraction, that is deposited in each Hcal-tower. This is show for late-showering (upper) and early-showering (below) pions with momentum $30 \text{ Gev} \leq P_{\text{Track}} < 55 \text{ GeV}$.

Figure 4.21: The left two pictures show the average fraction of the track momentum that is deposited in each Ecal-crystal for a 35 cell $\times$ 35 cell-cluster. The right two pictures show the average energy fraction, that is deposited in each Hcal-tower. This is show for late-showering (upper) and early-showering (below) pions with momentum $55 \text{ Gev} \leq P_{\text{Track}} < 80 \text{ GeV}$. 
4.1. STUDIES OF CMS HB-CALORIMETER

Figure 4.22: The left two pictures show the average fraction of the track momentum that is deposited in each Ecal-crystal for a 35 cell \( \times \) 35 cell-cluster. The right two pictures show the average energy fraction, that is deposited in each Hcal-tower. This is show for late-showering (upper) and early-showering (below) pions with momentum \( 80 \text{ GeV} \leq p^{Track} < 105 \text{ GeV} \).
4.2 Calibration

In this section it is shown how a dataset of isolated tracks can be acquired for calibration purposes. For testing we used a dataset called Gumbo soup with has a $P_t$-spectrum normalized to an integrated luminosity of 100 pb$^{-1}$ [27].

4.2.1 The Gumbo soup

The Gumbo Soup is one of three datasets from the official CSA07 production. It contains various files with QCD, photon+jets, and minBias events. These events have been weighted to represent a realistic spectrum for an integrated luminosity of 100 pb$^{-1}$ [27]. The momentum, transverse momentum, $\phi$ and $\eta$ distributions for all tracks in the Gumbo soup can be seen in figure 4.23.

4.2.2 Isolated Tracks

We search the Gumbo soup for the same kind of tracks we used for the single pion dataset, i.e. we are looking for tracks with $P_t > 5$ GeV and $N_{Hits} \geq 9$, which do not have any other tracks with $\sum P_t \geq 1$ GeV in a $dR$-cone of 0.5. The $P$- and $P_t$-spectra for all, the good, and the isolated tracks are shown in figure 4.24. We find about $2.3 \times 10^9$ isolated tracks in the Gumbo soup (which has in total $3.5 \times 10^{12}$ tracks) with a spectrum which is falling accordingly to a power law. Approximately 0.66 % of all tracks in the Gumbo Soup are isolated track with above mentioned properties.
4.2. CALIBRATION

We can not assume, the all those isolated tracks correspond to charged pions. For this resason we will no longer speak of isolated pions, but of isolated tracks. To investigate this, we accessed the MC-event-generation information and tried to match the isolated tracks to MC particles, to obtain their particle species. The results are shown in figure 4.25. Obviously, the majority of isolated tracks are indeed pions, but there is also a considerable fraction of charged K-mesons and protons (antiprotons). Isolated particles such as electrons (positrons), muons and others (most dominantly strange baryons) are rather rare.

4.2.3 Responses for late- and early-showering tracks

We will now compare the different responses of the isolated tracks from the Gumbo Soup for LS and ES particles to the responses of the LS and ES particles from the pion-datasets. The response distributions of the pion-dataset have been scaled to have the same integral as the distributions of the Gumbo Soup. We first show the Combined Response for tracks with momenta between $15\text{ GeV} \leq P_{\text{Track}} < 25\text{ GeV}$ with no event weights applied (figure 4.26). One can clearly distinguish between the responses of muons (first small peak at low momenta), electrons, respectively positrons (peak at 1) and the broad distribution of the responses hadron cause. But again, the broad hadron distribution with also lots of very high responses gives us evidence, that there is severe background from neutral particles. When the event weights are applied, the muon and the electron peaks in the response distributions vanish.
Figure 4.25: Shown are the particle species, our isolated tracks dataset consists of. This is derived from the matching of isolated tracks to MC-event-generation information.
Again the Combined Response is approximated with a Gaussian fit in the same way as before (see figure 4.27 and appendix). Tables 4.6 and 4.7 show the means, the means of the fits, the medians and the according rms’ and 0.9-quantiles and figure 4.28 shows the means as a function of the track momentum. We see at all energies major differences between the responses of the pion dataset and the isolated tracks from the Gumbo Soup. Cleaning cuts like Ecal vs Hcal brought no improvement. This is not due to the fact, that not all tracks are pions, but this can be attributed to the fact, that neutral particles also deposit (at least a fraction of) their shower energy in the investigated 3 × 3-calotower cluster. With this knowledge it seems to be promising to use the full Ecal granularity and define a dR-cut with a radius similar to the radius of the energy distribution in the Ecal of the pion-induced showers (see section 4.1.6). But presently this can not be done as the official CSA07-datasets (like Gumbo Soup) do not contain the information of the energy content of individual Ecal-crystals.
Figure 4.27: The Ecal-, Hcal-, and Combined Response for late- (red) and early-showering (blue) isolated tracks from the gumbo soup. The Ecal and Hcal distributions are stacked on top of each other. Shown are also the distributions for the late- (pink) and early-showering (cyan) pions from the pion-data set. The pion Ecal and Hcal distributions are scaled to have the same integral as the distributions from the Gumbo dataset. The Combined Response for the early-showering isolated tracks from the Gumbo soup and the pions are scaled to have the same integral as the late-showering Gumbo tracks. This is shown for $15 \text{ GeV} \leq P^{\text{Track}} < 25 \text{ GeV}$. 
Figure 4.28: The mean responses for the late- and early-showering isolated tracks for the Gumbo Soup in comparison to the mean responses from the pion-dataset. For the Combined Response, the gauss fit as well as the medians are also shown.
<table>
<thead>
<tr>
<th>Track momentum [GeV]</th>
<th>Ecal-Response mean value</th>
<th>Hcal-Response mean value</th>
<th>Combined Response mean value (RMS)</th>
<th>Combined Response gaussian fit mean value (σ)</th>
<th>Combined Response median value (0.9 quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7</td>
<td>0.06</td>
<td>0.68</td>
<td>0.730 ± 0.013 (0.47)</td>
<td>0.440 ± &lt; 0.001 (0.68)</td>
<td>0.631 (1.48)</td>
</tr>
<tr>
<td>7-9</td>
<td>0.05</td>
<td>0.75</td>
<td>0.797 ± 0.014 (0.48)</td>
<td>0.692 ± &lt; 0.001 (0.69)</td>
<td>0.712 (1.53)</td>
</tr>
<tr>
<td>9-11</td>
<td>0.04</td>
<td>0.80</td>
<td>0.842 ± 0.017 (0.46)</td>
<td>0.751 ± &lt; 0.001 (0.58)</td>
<td>0.767 (1.51)</td>
</tr>
<tr>
<td>11-13</td>
<td>0.03</td>
<td>0.87</td>
<td>0.899 ± 0.023 (0.41)</td>
<td>0.880 ± &lt; 0.001 (0.42)</td>
<td>0.887 (1.44)</td>
</tr>
<tr>
<td>13-15</td>
<td>0.03</td>
<td>0.97</td>
<td>1.002 ± 0.031 (0.40)</td>
<td>0.956 ± &lt; 0.001 (0.38)</td>
<td>0.946 (1.61)</td>
</tr>
<tr>
<td>15-25</td>
<td>0.02</td>
<td>0.92</td>
<td>0.939 ± 0.017 (0.31)</td>
<td>0.935 ± &lt; 0.001 (0.29)</td>
<td>0.928 (1.35)</td>
</tr>
<tr>
<td>25-35</td>
<td>0.01</td>
<td>0.86</td>
<td>0.874 ± 0.031 (0.48)</td>
<td>0.855 ± &lt; 0.001 (0.69)</td>
<td>0.867 (1.55)</td>
</tr>
<tr>
<td>35-45</td>
<td>0.01</td>
<td>0.97</td>
<td>0.931 ± 0.032 (0.46)</td>
<td>0.938 ± &lt; 0.001 (0.58)</td>
<td>0.930 (1.51)</td>
</tr>
<tr>
<td>45-55</td>
<td>0.01</td>
<td>0.85</td>
<td>0.855 ± 0.051 (0.41)</td>
<td>0.813 ± &lt; 0.001 (0.42)</td>
<td>0.796 (1.44)</td>
</tr>
<tr>
<td>55-65</td>
<td>0.01</td>
<td>1.03</td>
<td>1.039 ± 0.116 (0.40)</td>
<td>1.084 ± 0.001 (0.38)</td>
<td>1.048 (1.61)</td>
</tr>
<tr>
<td>65-75</td>
<td>0.01</td>
<td>0.87</td>
<td>0.882 ± 0.087 (0.31)</td>
<td>0.841 ± 0.001 (0.29)</td>
<td>0.849 (1.35)</td>
</tr>
<tr>
<td>75-85</td>
<td>0.01</td>
<td>1.02</td>
<td>1.026 ± 0.112 (0.26)</td>
<td>1.002 ± 0.002 (0.24)</td>
<td>1.060 (1.21)</td>
</tr>
<tr>
<td>85-95</td>
<td>&lt; 0.001</td>
<td>1.04</td>
<td>1.045 ± 0.094 (0.25)</td>
<td>1.130 ± 0.010 (0.25)</td>
<td>1.030 (1.27)</td>
</tr>
<tr>
<td>95-105</td>
<td>&lt; 0.001</td>
<td>1.03</td>
<td>1.037 ± 0.096 (0.25)</td>
<td>0.623 ± 0.114 (0.17)</td>
<td>0.947 (1.17)</td>
</tr>
</tbody>
</table>

Table 4.6: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the LS pions from the Gumbo Soup. For the Combined Response also the means of the fits and the medians as well as the RMS, the σ and the 0.5-quantile are listed. The errors are statistical errors.
### Table 4.7: The table shows the means of the Ecal-, Hcal-, and the Combined Response for different track momenta for the ES pions from the Gumbo Soup. For the Combined Response also the means of the fits and the medians as well as the RMS, the σ and the 0.5-quantile are listed. The given errors are statistical.

<table>
<thead>
<tr>
<th>Track momentum [GeV]</th>
<th>Ecal-Response mean value</th>
<th>Hcal-Response mean value</th>
<th>Combined Response mean value (RMS)</th>
<th>Combined Response gaussian fit mean value (σ)</th>
<th>Combined Response median value (0.9 quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7</td>
<td>0.52</td>
<td>0.20</td>
<td>0.673 ± 0.008 (0.38)</td>
<td>0.587 ± &lt; 0.001 (0.28)</td>
<td>0.566 (1.23)</td>
</tr>
<tr>
<td>7-9</td>
<td>0.51</td>
<td>0.25</td>
<td>0.713 ± 0.009 (0.41)</td>
<td>0.613 ± &lt; 0.001 (0.38)</td>
<td>0.591 (1.37)</td>
</tr>
<tr>
<td>9-11</td>
<td>0.48</td>
<td>0.28</td>
<td>0.722 ± 0.010 (0.41)</td>
<td>0.623 ± &lt; 0.001 (0.39)</td>
<td>0.607 (1.37)</td>
</tr>
<tr>
<td>11-13</td>
<td>0.50</td>
<td>0.34</td>
<td>0.814 ± 0.015 (0.42)</td>
<td>0.752 ± &lt; 0.001 (0.47)</td>
<td>0.731 (1.45)</td>
</tr>
<tr>
<td>13-15</td>
<td>0.52</td>
<td>0.33</td>
<td>0.837 ± 0.017 (0.38)</td>
<td>0.802 ± &lt; 0.001 (0.38)</td>
<td>0.773 (1.40)</td>
</tr>
<tr>
<td>15-25</td>
<td>0.49</td>
<td>0.41</td>
<td>0.881 ± 0.011 (0.35)</td>
<td>0.826 ± &lt; 0.001 (0.36)</td>
<td>0.837 (1.38)</td>
</tr>
<tr>
<td>25-35</td>
<td>0.45</td>
<td>0.37</td>
<td>0.814 ± 0.017 (0.41)</td>
<td>0.772 ± &lt; 0.001 (0.38)</td>
<td>0.757 (1.37)</td>
</tr>
<tr>
<td>35-45</td>
<td>0.43</td>
<td>0.37</td>
<td>0.789 ± 0.027 (0.41)</td>
<td>0.754 ± &lt; 0.001 (0.39)</td>
<td>0.740 (1.37)</td>
</tr>
<tr>
<td>45-55</td>
<td>0.47</td>
<td>0.36</td>
<td>0.818 ± 0.034 (0.42)</td>
<td>0.787 ± &lt; 0.001 (0.47)</td>
<td>0.778 (1.45)</td>
</tr>
<tr>
<td>55-65</td>
<td>0.35</td>
<td>0.48</td>
<td>0.826 ± 0.049 (0.38)</td>
<td>0.753 ± &lt; 0.001 (0.375)</td>
<td>0.741 (1.40)</td>
</tr>
<tr>
<td>65-75</td>
<td>0.38</td>
<td>0.41</td>
<td>0.792 ± 0.055 (0.35)</td>
<td>0.750 ± &lt; 0.001 (0.36)</td>
<td>0.736 (1.38)</td>
</tr>
<tr>
<td>75-85</td>
<td>0.37</td>
<td>0.50</td>
<td>0.866 ± 0.060 (0.30)</td>
<td>0.823 ± &lt; 0.001 (0.25)</td>
<td>0.849 (1.26)</td>
</tr>
<tr>
<td>85-95</td>
<td>0.30</td>
<td>0.59</td>
<td>0.894 ± 0.060 (0.28)</td>
<td>0.869 ± &lt; 0.001 (0.23)</td>
<td>0.867 (1.18)</td>
</tr>
<tr>
<td>95-105</td>
<td>0.31</td>
<td>0.64</td>
<td>0.948 ± 0.070 (0.28)</td>
<td>0.916 ± &lt; 0.001 (0.22)</td>
<td>0.905 (1.22)</td>
</tr>
</tbody>
</table>
4.2.4 The neutral particle Background

As already mentioned in the last section, the Responses we measure from the isolated tracks from the Gumbo Soup are significantly higher than those of the pion dataset. Although the track isolation works against charged particles, it does not isolate against neutral particles as those leave no signal in the tracker. We tried several cleaning cuts which used the energy content of the calotower which surround the investigated $3 \times 3$-calotower cluster, but this brought no improvement (the full granularity can not be used, as the energy content of the individual crystals was not stored in the dataset). Therefore, we will now investigate what particles cause the additional energy deposit in the $3 \times 3$-calotower cluster.

We accessed the MC generation event information and compare the trajectory of these truth particles to the investigated calotower cluster. If the particle lies inside, we consider it as a particle that gives us additional energy in our calotower cluster. This is somewhat optimistic, as of course tracks that lie slightly outside of our calotower cluster might as well deposit energy inside, but for more sophisticated criteria additional investigations on the shower profiles of the neutral particles would be needed. We will do this separately for the LS and ES isolated tracks.

The background for the LS tracks

At first we will investigate how many neutral particles deposit energy in our examined calotower cluster. This is shown in figure 4.29 on the left side. The mean of the distribution is approximately 7 particles. The right side of this figure shows the fractions of the total background for the dominant particles species. All other particles than photons, neutrons, $K^0$-mesons, and $\Lambda$-mesons are stated as rest. These are the pure numbers, which explains, that although we examine this for LS tracks, which do not have more than 1.2 GeV in the $3 \times 3$-Ecal-tower cluster, the majority of the background particles are photons (which deposit their complete energy in the Ecal). But the majority of this photons is very soft, so a fair amount will not be seen in the calorimeters because of the reconstruction thresholds. This becomes more clear when we weight every background particle with a factor equal to the ratio of the background particle momentum and the momentum of the isolated LS track (figure 4.30).

In addition, figure 4.31 shows the momentum spectra of the dominant background particle species. We see that in fact the majority of the photons is very soft, but it extends also up to high energies. The momentum spectrum of all other particle species is more flat. Cuts on a minimum background particle momentum also decrease the photon fraction of the total background.

In figure 4.32 the ratio of the momentum sum of all background particles in an event and the isolated tracks momentum is shown (left). This gives an impression if there are events with isolated particles, that have (nearly) no background particles depositing energy in the investigated calotower cluster at all. Obviously there is a
4.2. CALIBRATION

Figure 4.29: The average background multiplicity (right) and the fraction of the total background for different particle species. This is shown for LS tracks.

fair amount of events without neutral particle background. Also shown (right) is the sum of the MC momenta of all neutral hadron in our investigated calotower cluster. Again, there is a fair amount of events, that have (nearly) no background, but at the moment have no chance to distinguish between those isolated tracks which have no neutral hadron background and those tracks with neutral hadron background.

The background for the ES tracks

We will now do the same investigations for the ES tracks. We see that the mean number of background particles of approximately 8 is larger than for the LS tracks (figure 4.33, left side). This is because the background of the ES tracks is even more photon dominated than the background of the LS tracks. This is not well-visible in the right side of figure 4.33, but in figure 4.34. The momentum spectra (figure 4.35) show again, that the overwhelming majority of the photons are very soft. The spectra of the other particle species are approximately the same as for the LS tracks. Once again, we investigate if there are events with isolated tracks, but without (or only with negligible) neutral particle background. This is shown in figure 4.36 (left), and again there is a fair amount of particles with (nearly) no background, which could be used for calibration purposes. We also take a separate look at the neutral hadron background (right) and observe, that it is even worse for ES tracks than for LS tracks.
Figure 4.30: The weighted fraction of the total background of the LS tracks for different particles. The weightfactor is explained in the text.
4.2. CALIBRATION

Figure 4.31: The momentum spectra of the neutral particles that have track coordinates that lie inside the $3 \times 3$-calotower cluster for those events that have LS tracks.

Figure 4.32: Shown is the ratio of total background momentum and the isolated tracks momentum (left) and the sum of the MC momenta of the neutral hadrons in the investigated calotower cluster per event (right) for LS Gumbo tracks.
CHAPTER 4. ANALYSIS

Figure 4.33: The average background multiplicity (right) and the fraction of the total background for different particle species. This is shown for ES tracks.

Figure 4.34: The weighted fraction of the total background of the ES tracks for different particles. The weight factor is explained in the text.
Figure 4.35: The momentum spectra of the neutral particles that have track coordinates that lie inside the $3 \times 3$-calotower cluster for those events that have ES tracks.

Figure 4.36: Shown is the ratio of total background momentum and the isolated tracks momentum (left) and the sum of the MC momenta of the neutral hadrons in the investigated calotower cluster per event (right) for ES Gumbo tracks.
4.3 Calibration of the Hcal

Based on the knowledge about the background particles, we decided to concentrate on the LS tracks from Gumbo Soup, and tried to obtain a calibration dataset of LS tracks for the Hcal. We reduced the number of track momentum intervals to four (5-10 GeV, 10-20 GeV, 20-40 GeV, 40-100 GeV). Due to the size of the intervals, we expect the responses from Gumbo Soup to be slightly smaller than the responses from the pion dataset, because most of the LS Gumbo tracks are at the lower border of the interval, as the momentum spectrum is sharply falling, as track momentum increases. Whereas the momentum spectrum of the pion dataset is explicitly flat. We also show the errors of every bin entry (to account for the applied weights).

Table 4.8 shows the number of LS tracks per track momentum interval. The first entry gives the number of events with an LS track in the Gumbo Soup. The second entry gives the weighted number of LS tracks in the Gumbo Soup, i.e. the number of LS tracks in 100 pb$^{-1}$. The means, the means of the Gaussian fits and the medians are also listed in table 4.9.

When we compare the distributions of the Combined Response for LS Gumbo Soup tracks and LS pions from our pion dataset (see figure 4.37), we see a fair agreement for tracks with momenta above 40 GeV, which becomes worse as track momenta decrease. At 20-40 GeV, the Combined Response for LS Gumbo tracks is slightly larger than the Combined Response distribution of the LS pions. At lower track momenta, the differences between the distributions is even more significant, as the 10-20 GeV Combined Response is not only shifted to higher energies, but also significantly broader. At lowest track momenta there is not even a clear peak visible. Therefore the results of the Gauss fit can not be taken too serious.

To improve this, we lowered the cut for the distinction of LS and ES tracks from 1.2 GeV to 0.5 GeV. The number of tracks, which still fulfill the LS criteria are shown in table 4.10 and their Combined Response distribution are shown in figure 4.38. The mean values of the Combined Response, the mean of the fit and the medians are listed in table 4.11. Obviously, the lowering of this cut, does not have a great effect on the response distribution, but it slightly improves our result as mostly events with very high responses are cut off. At the same time the cut affects our statistics only in a minor way.

Further we propose a cut, to limit the energy deposit in the two calotower rings next to our $3 \times 3$-calotower cluster (energy in $7 \times 7$-cluster - energy in $3 \times 3$-cluster). The motivation for this cut is given by figure 4.39, which shown the absolute energy deposit in the surrounding ring versus the absolute Ecal energy deposit in a $3 \times 3$- Ecaltower cluster. We can distinguish different populations in this plot: the LS tracks, which have nearly no Ecal energy deposit, and which can be found along the $x$-axis. We also see the ES tracks along the $y$-axis. But can further distinguish between those LS and ES tracks, that have (nearly) no energy deposit in the sur-
rounding towers, and those with energy in those tower. We decided to set the \textit{Ring cut} \((E_{7x7}-E_{3x3})\) to 0.1. This has an perceptible effect on our statistics as shown in table 4.12, but we still have more than enough LS tracks in every track momentum interval to calibrate a single tower. The cut intensifies the peak structure of the Combined Response at low track momenta and the number of high responses decreases as shown in figure 4.40.

But we still have significant differences between the Combined Responses from the LS Gumbo tracks and the LS pions. For a further improvement we propose an improved track isolation, as still other charged, low momentum tracks might curl into our calotower cluster, as the isolation is calculated from the starting pion of the tracks, and not by the coordinates they have when reaching the calorimeters. In addition, the full Ecal granularity should be used as proposed before. But as shown in section 4.2.4 many of our LS tracks are biased with neutral hadrons, which prohibits us to make an absolute calibration of single towers at low track momenta.

Nevertheless, we can still use the single hadron calibration for a relative calibration of the towers in \(\phi\), as it can be assumed that the neutral hadron background has no \(\phi\)-dependence. If we use tracks with momenta between 20 GeV and 40 GeV (the first momentum bin with a clear peak), where we have approximately 6.5 million tracks in 100 \(\text{pb}^{-1}\) for 2304 towers, we can calibrate with an accuracy of approximately 0.5 \%.

<table>
<thead>
<tr>
<th>(p_{\text{track}})</th>
<th>Number of LS tracks in dataset</th>
<th>Weighted number of tracks in dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10 GeV</td>
<td>60319</td>
<td>(6.09 \times 10^8)</td>
</tr>
<tr>
<td>10-20 GeV</td>
<td>17944</td>
<td>(1.89 \times 10^8)</td>
</tr>
<tr>
<td>20-40 GeV</td>
<td>4121</td>
<td>(2.92 \times 10^7)</td>
</tr>
<tr>
<td>40-100 GeV</td>
<td>2350</td>
<td>(1.07 \times 10^6)</td>
</tr>
</tbody>
</table>

Table 4.8: Shown are the number of LS tracks in the Gumbo soup per track momentum interval and the weighted number of events per interval. The LS cut is set to 1.2 GeV.
Table 4.9: Shows the means, the means of the fit, the medians, and the according rms, $\sigma$ and 0.9-quantile for LS tracks.

<table>
<thead>
<tr>
<th>$P_{\text{track}}$ [GeV]</th>
<th>mean Combined Response (RMS)</th>
<th>mean of fitted Combined Response (sigma)</th>
<th>median of Combined Response (0.9-quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>0.766 ± 0.009 (0.47)</td>
<td>0.549 ± &lt; 0.001 (0.66)</td>
<td>0.669 (1.50)</td>
</tr>
<tr>
<td>10-20</td>
<td>0.924 ± 0.013 (0.41)</td>
<td>0.899 ± &lt; 0.001 (0.43)</td>
<td>0.907 (1.49)</td>
</tr>
<tr>
<td>20-40</td>
<td>0.922 ± 0.020 (0.26)</td>
<td>0.899 ± &lt; 0.001 (0.24)</td>
<td>0.909 (1.25)</td>
</tr>
<tr>
<td>40-100</td>
<td>0.887 ± 0.036 (0.26)</td>
<td>0.884 ± &lt; 0.001 (0.23)</td>
<td>0.869 (1.22)</td>
</tr>
</tbody>
</table>

Table 4.10: Shown are the number of LS tracks in the Gumbo soup per track momentum interval and the weighted number of events per interval. The LS cut is lowered to 0.5 GeV.

<table>
<thead>
<tr>
<th>$P_{\text{track}}$ [GeV]</th>
<th>Number of LS tracks in dataset</th>
<th>Weighted number of LS tracks in dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10 GeV</td>
<td>40878</td>
<td>4.26 · 10^8</td>
</tr>
<tr>
<td>10-20 GeV</td>
<td>12223</td>
<td>1.39 · 10^8</td>
</tr>
<tr>
<td>20-40 GeV</td>
<td>3225</td>
<td>2.23 · 10^7</td>
</tr>
<tr>
<td>40-100 GeV</td>
<td>1903</td>
<td>829032</td>
</tr>
</tbody>
</table>

Table 4.11: Shows the means, the means of the fit, the medians, and the according rms, $\sigma$ and 0.9-quantile for LS tracks with the LS cut lowered to 0.5.
4.3. CALIBRATION OF THE HCAL

Figure 4.37: The comparison of the Combined Response distribution of LS gumbo tracks (red) and LS pions (blue). This is shown for four different track momentum intervals: (upper left) $5 \text{ GeV} \leq P_{\text{Track}} < 10 \text{ GeV}$, (upper right) $10 \text{ GeV} \leq P_{\text{Track}} < 20 \text{ GeV}$, (lower left) $20 \text{ GeV} \leq P_{\text{Track}} < 40 \text{ GeV}$, (lower right) $40 \text{ GeV} \leq P_{\text{Track}} < 100 \text{ GeV}$.

<table>
<thead>
<tr>
<th>$P_{\text{Track}}$</th>
<th>Number of LS tracks in dataset</th>
<th>Weighted number of LS tracks in dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10 GeV</td>
<td>9313</td>
<td>$9.89 \cdot 10^6$</td>
</tr>
<tr>
<td>10-20 GeV</td>
<td>2618</td>
<td>$3.19 \cdot 10^7$</td>
</tr>
<tr>
<td>20-40 GeV</td>
<td>1335</td>
<td>$6.47 \cdot 10^8$</td>
</tr>
<tr>
<td>40-100 GeV</td>
<td>1088</td>
<td>138813</td>
</tr>
</tbody>
</table>

Table 4.12: Shown are the number of LS tracks in the Gumbo soup per track momentum interval and the weighted number of events per interval. The LS cut is lowered to 0.5 GeV and an additional Ring cut of 0.1 is used.
Figure 4.38: The comparison of the Combined Response distribution of LS gumbo tracks (red) and LS pions (blue) with the LS cut lowered from 1.2 GeV to 0.5 GeV. This is shown for four different track momentum intervals: (upper left) $5 \text{ GeV} \leq P_{\text{Track}} < 10 \text{ GeV}$, (upper right) $10 \text{ GeV} \leq P_{\text{Track}} < 20 \text{ GeV}$, (lower left) $20 \text{ GeV} \leq P_{\text{Track}} < 40 \text{ GeV}$, (lower right) $40 \text{ GeV} \leq P_{\text{Track}} < 100 \text{ GeV}$.

<table>
<thead>
<tr>
<th>$P_{\text{Track}}$ [GeV]</th>
<th>mean Combined Response (RMS)</th>
<th>mean of fitted Combined Response (sigma)</th>
<th>median of Combined Response (0.9-quantile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>$0.805 \pm 0.023$ (0.48)</td>
<td>$0.619 \pm 0.001$ (0.69)</td>
<td>0.713 (1.53)</td>
</tr>
<tr>
<td>10-20</td>
<td>$1.117 \pm 0.036$ (0.42)</td>
<td>$1.136 \pm 0.001$ (0.49)</td>
<td>1.117 (1.70)</td>
</tr>
<tr>
<td>20-40</td>
<td>$0.963 \pm 0.046$ (0.26)</td>
<td>$0.944 \pm 0.001$ (0.26)</td>
<td>0.947 (1.41)</td>
</tr>
<tr>
<td>40-100</td>
<td>$1.040 \pm 0.088$ (0.27)</td>
<td>$0.986 \pm 0.001$ (0.20)</td>
<td>0.992 (1.28)</td>
</tr>
</tbody>
</table>

Table 4.13: Shows the means, the means of the fit, the medians, and the according rms, $\sigma$ and 0.9-quantile for LS tracks with the LS cut lowered to 0.5 and an additional Ring cut of 0.1.
Figure 4.39: Shown is the distribution of the energy deposit in the calotower ring, that surround our $3 \times 3$-calotower cluster against the absolute Ecal energy deposit.
Figure 4.40: The comparison of the Combined Response distribution of LS gumbo tracks (red) and LS pions (blue) with the LS cut lowered from 1.2 GeV to 0.5 GeV and an additional Ring cut (see text) of 0.1. This is shown for four different track momentum intervals: (upper left) $5 \text{ GeV} \leq p_{\text{Track}} < 10 \text{ GeV}$, (upper right) $10 \text{ GeV} \leq p_{\text{Track}} < 20 \text{ GeV}$, (lower left) $20 \text{ GeV} \leq p_{\text{Track}} < 40 \text{ GeV}$, (lower right) $40 \text{ GeV} \leq p_{\text{Track}} < 100 \text{ GeV}$. 
Chapter 5

Summary and Outlook

In this thesis, the responses of two simulated single pion datasets have been studied and compared testbeam data. A significant energy dependence of the responses is observed: the Combined Response (Ecal + Hcal + HO) increases with increasing energy up to a maximum of about 0.8 at 70 GeV; but we found no significant dependence of the responses on $\phi$ and $\eta$ for the barrel region. Also, we observed a minor difference in the Ecal Response for positive and negative pions, which needs further investigation as soon as real data are available.

We also showed that it is reasonable to distinguish between those particles who deposit a significant amount of their shower energy in the Ecal (ES) and those particles which traverse the Ecal with nearly no energy loss (LS). We have demonstrated that the responses of these two have major differences (the responses of the ES pions are significantly lower) which can be explained by the large differences of the $e/h$-values of Ecal and Hcal. In addition, both distributions have different energy resolutions, and the overall resolution can be improved when both are treated individually.

The comparison of our pion dataset to testbeam data from the 2007 testbeam run showed a perfect match between testbeam data and our single pion datasets for high momentum pions. In the low momentum region we found minor differences which can most probably be attributed to the missing of readout (reconstruction) thresholds in the testbeam setup and the different size of the readout Ecal cluster.

Studies of the average radial shower profiles brought the result, that most of the energy is distributed within a $3 \times 3$-calotower cluster around the particles estimated impact point on the Hcal. For the Ecal, the energy distribution takes place in an even smaller area, which has approximately the radius of five Ecal cells around the estimated impact point. But we also addressed some inaccuracies of the method for low momentum ES pions. This can probably be further improved.

Equipped with this knowledge, we then tried to obtain a dataset of isolated
tracks for calibration purposes from the Gumbo Soup, an official MC dataset, which when the appropriate event weights are applied, represents an integrated luminosity of $100 \text{ pb}^{-1}$. We found that a track isolation alone is rather pointless, due to the neutral particle background. We investigated an additional Ecal cut based on the results of the radial shower distributions, which utilizes the full granularity of the Ecal. This can be done as soon as datasets with the full Ecal information are available (either new MC datasets or recorded data from CMS).

Motivated by these results, we investigated which neutral particles also deposit energy in the $3 \times 3$-calotower cluster, and are therefore responsible for the strikingly increased responses from the Gumbo Soup with respect to single pion events. We showed that the background for LS- as well as ES-tracks is mostly due to low energy photons. Smaller contributions come from neutrons, $K^0$-mesons, and other neutral particles. We then showed that there is actually a fair amount of isolated tracks for both, LS and ES tracks, which have (nearly) no additional energy deposit in the calorimeters from neutral particles. The same holds for just the neutral hadron background, but we have presently no chance to distinguish between isolated tracks that are accompanied by neutral hadrons and those isolated tracks without.

Finally, we presented how far we can push the single hadron calibration at the moment. We observed a severe difference between the responses from the isolated Gumbo tracks and those of the single pion dataset. The lowering of the LS cut and an additional cut on the energy deposit of the surrounding calotowers brought no significant improvement. Therefore, the single hadron calibration can not be utilized for an absolute calibration (to get rid of the track momentum dependence), but for an intercalibration in $\phi$. This can be done with an accuracy of 0.5 % for an integrated luminosity of $100 \text{ pb}^{-1}$.
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Bibliography


[26] Private communications with C. Autermann. Software can be found in CMS repository under: UserCode/Bromo/Calibration.

[27] https://twiki.cern.ch.
Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und nur unter zur Hilfenahme der angegebenen Quellen und Hilfsmittel angefertigt habe.

Mit einer späteren Ausleihe meiner Diplomarbeit bin ich einverstanden.

Clemens Günter,
Hamburg, 4.9.2008