

Measuring Hadronic Jets at the ILC

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From Particle Flow Calorimetry
to the Higgs Self-Coupling

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Zusammenfassung

Diese Arbeit behandelt die Entwicklung eines technischen Prototypen eines hochsegmentierten Hadronkalorimeters für Präzisionsmessungen am zukünftigen International Linear Collider (ILC). Die Präzisionsmessungen am ILC stellen besondere Herausforderungen sowohl für die Detektortechnologie als auch für die Rekonstruktionsmethoden dar. In dieser Arbeit werden zwei Aspekte zu hadronischen Endzuständen untersucht. Der erste Teil behandelt einen Prototypen eines hoch segmentierten hadronischen Kalorimeters und der zweite Teil kinematische Fits zur Bestimmung der Higgs-Selbstkopplung in Zerfällen des Higgs Boson in b quarks.

Die Herausforderung für den untersuchten Prototypen des hadronischen Kalorimeters liegt in der Demonstration der technischen Machbarkeit eines realen Detektors. Der ILC verfolgt das Particle Flow Konzept, als Konsequenz daraus folgt für das Kalorimetersystem eine hohe Granularität und eine integrierte Ausleseelektronik. Zwei wichtige Aspekte des Kalorimeter-Prototypen sind die kanalweise einstellbare Triggerschwelle und die Power-Pulsing-Funktionalität, um den Energieverbrauch zu minimieren.

In dieser Arbeit konnte gezeigt werden, dass bei der derzeitigen Auslesechipgeneration der Einsatz der kanalweisen Schwellenanpassung zu einer Verschiebung der globalen Triggerschwelle führt. Trotz Funktionalität des Power-Pulsing liegt der Gesamtstromverbrauch 30-mal über dem angestrebten Verbrauch von $25\mu\text{W}/\text{Kanal}$. In den Daten einer Teststrahl Kampagne am CERN 2012 wurde das Pedestal bestimmt, die Stabilität untersucht sowie Besonderheiten des Pedestals identifiziert.

Um die Genauigkeit für die Messung der Higgs Selbst-Kopplung zu verbessern, untersucht diese Arbeit die Verwendbarkeit kinematischer Fits im Rahmen des Higgs-Selbstkopplung. Grundlage der Analyse ist der Leptonenkanal $ZHH \rightarrow \ell\bar{\ell}b\bar{b}b\bar{b}$. Es konnte gezeigt werden, dass die Verwendung kinematischer Fits die Massenauflösung verbessert und so die Unsicherheit des Wirkungsquerschnitts um 18% reduziert. Die Verwendung eines modifizierten Fit Prozessors verbessert die richtige Zuordnung von Jets zu Bosonen um $\sim 13\%$.

Abstract

This work deals with the development of a technical prototype of a highly segmented hadron calorimeter for precision measurements at the future International Linear Collider (ILC). The precision measurements at the ILC pose special challenges for both the detector technology as well as for the reconstruction methods. In this thesis two aspects to hadronic final states are examined. The first part deals with a prototype of a highly segmented hadronic calorimeter and the second part with kinematic Fits for the determination of the Higgs self-coupling in decays of the Higgs boson into b quarks.

The challenge for the examined prototype of the hadronic calorimeter is the demonstration of the technical feasibility of a real detector. The ILC is pursuing the Particle Flow concept, as a consequence, it follows for the calorimeter a high granularity and an integrated readout electronics. Two important aspects of the calorimeter prototype are the channel-wise adjustable trigger threshold and the power-pulsing functionality to minimize the power consumption.

In this work it could be shown that with the current readout chip generation, the use of the channel-wise threshold adjustment leads to a shift of the global trigger threshold. Despite of the functionality of the power pulsing, the total current consumption is 30 times above the desired power consumption of $25\mu\text{W}/\text{channel}$. In the data of a test beam campaign at CERN 2012 the pedestal was determined, the stability analyzed and specific features of the pedestal identified.

In order to achieve the accuracy for the measurement of the Higgs self-coupling, this work examines the applicability of kinematic fits within the framework of the Higgs self-coupling analysis. Basis of the analysis is the lepton channel $ZHH \rightarrow l\bar{l}b\bar{b}b\bar{b}$. It could be shown that the use of kinematic fits improves the mass resolution, thus the uncertainty of the cross section is reduced by 18%. The use of a modified fit processor improves the correct assignment of jets to bosons by $\sim 13\%$.

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1 Introduction

Typical for mankind is a natural interest in the fundamental principles of the universe. Here, the systematic approach of physics has proven to be of great help in understanding these principles. The *Standard Model of particle physics* is one of those examples. It is based on gauge invariance, which requires massless gauge bosons. While this is true for photons and gluons, the gauge bosons of the electromagnetic and strong interaction, the gauge bosons of the weak interaction, W and Z boson are two of the heaviest known elementary particles. Therefore, the electroweak gauge symmetry must be broken. An important cornerstone of the model is the Higgs mechanism that explains the generation of mass through electroweak symmetry breaking. Nevertheless, the reasons for electroweak symmetry breaking are still unknown and the Higgs mechanism is assumed in the simplest form in the Standard Model. One of the current challenges in particle physics lies in the exploration of the Higgs Sector. To explain electroweak symmetry breaking, it is necessary that the Higgs field interacts with itself. Therefore, to explore the Higgs sector the Higgs self-coupling is an important quantity. Besides the great success of the Standard Model, there are still certain inadequacies like the Hierarchy Problem, the origin of neutrino masses or the composition of dark matter which have to be solved.

One major step in exploring the electroweak symmetry breaking has been made on the 4th of July in 2012 when the ATLAS [1] and CMS [2] experiments published the discovery of a Higgs-like particle at the Large Hadron Collider (LHC). The collision of protons with a center-of-mass energy of up to $\sqrt{s} = 14$ TeV makes the LHC a perfect discovery machine. Nevertheless, protons are composite particles consisting of quarks and gluons, which means that the colliding objects carry an unknown fraction of the overall proton momentum. Additionally, the strong force is the dominating interaction and responsible for a lot of background in the detector, which in turn makes a measurement of the total cross section of Higgs production almost impossible. As a result, only the ratios of branching ratios can be measured at the LHC. Altogether, these effects complicate precise measurements at the LHC.

An ideal addition to the results of the LHC is the proposed **I**nternational **L**inear **C**ollider (ILC) [3]. The collision of electrons and positrons at a center-of-mass energy of $\sqrt{s} = 500$ GeV ensures a clean environment and serves as an access point to all possible decay modes of the Higgs. The clean environment with less radiation and less background in

the detectors is the basis for precise measurements at the ILC. Furthermore, the use of leptons provides exact knowledge of the initial state of the colliding particles.

Besides the accelerator, a new generation of detectors is also necessary to exploit the full potential of the ILC. The underlying design concept of the detectors at the ILC is driven by the Particle Flow Concept (PFC) [4], which demands a high resolution tracking system combined with a highly granular calorimeter system. The PFC measures the particles with the sub-detector with the best resolution corresponding to the respective particle type. The PFC is the only fully demonstrated way to reach a jet energy resolution of 3 - 4%, which is required to reach the physics goals of the ILC. The derived detector requirements from this concept are a strong magnetic field, a large radius and length to reach a clear jet separation and a small Molière radius in the calorimeter system to minimize a shower overlapping. This demands a high granularity of the calorimeter system in both longitudinal and transverse direction.

The engineering prototype [5] for a highly segmented hadron calorimeter will be part of the discussion of this thesis. The challenges for this prototype are a compact detector design with a minimum of dead regions in the detector, no space between the layers and a minimized gap between the barrel and the endcap. All these issues lead to a calorimeter system with integrated readout electronics. The hadron calorimeter system incorporates 8 million calorimeter cells (the ATLAS detector counts ~ 7800 hadron calorimeter cells). Such a multi-channel design with integrated readout electronics requires an auto-triggering of the channels operated in a power pulsed mode to reduce the power consumption and to avoid an extra cooling system in the detector. For instance, the additional material from an extra cooling system would worsen the jet energy resolution. Issues of the usability of an auto-triggered and power pulsed detector are part of the discussion in this thesis. The readout electronics are tested and evaluated for its applicability at the ILC. Particular attention is paid to a channel-wise auto trigger function which enables setting the threshold for each channel individually. Herein, the analysis of the performance and applicability of this function will be discussed.

A power pulsed operated detector take advantage of the specific spill structure at the ILC. Between the colliding bunches not necessarily needed electronic parts of the readout electronics can be switched off between the collisions in order to reduce the power consumption. The power pulsing function of the readout electronics is tested and evaluated for its performance and usability at the ILC. The study has been done in the laboratory. Additionally, the engineering prototype was tested in a test beam environment which showed that such a detector fulfills the needs for a LC detector. With the data obtained from the test beam relevant parameters could be studied. Questions concerning the pedestal and pedestal stability are part of this thesis. The pedestal determines the basis of each measurement in the detector, since it determines the zero point of the measuring scale for the deposited energy.

Besides state of the art detector technologies analysis tools are also needed to exploit the full potential. Probing the Higgs self-coupling is one of the most important tasks at the ILC. The measurement of the Higgs self-coupling with a detector which pursues the PFC is a sophisticated task. This analysis considers Higgs decays of $H \rightarrow b\bar{b}$. This decay has a large branching ratio, but an efficient and correct reconstruction of the b jets and the Higgs mass from the jets is necessary for the analysis. Therefore, the jet energy resolution plays a key role for this analysis. Simulations are essential to estimate what is expected for the measurement at the ILC. The final performance can only be gained in the interplay of the detector and analysis.

To perform the Higgs self-coupling measurement at the ILC two production modes exist: the double Higgs-strahlung ZHH and the WW fusion. A full simulation of the Higgs self-coupling measurement [6] for both decay modes has been performed previously and an update [7] with a Higgs boson mass of 125 GeV for the double Higgs-strahlung ZHH at $\sqrt{s} = 500$ GeV is ongoing. The precision of the measurement can be improved with corresponding analysis tools. This thesis discusses the applicability of kinematic fitting to improve the precision of the measurement. Object of this analysis is the leptonic decay of the Z boson of double Higgs-strahlung events ($ZHH \rightarrow e^+e^-b\bar{b}b\bar{b}$). The impact of kinematic fitting on the mass resolution, the assignment of primary quarks to reconstructed jets (jet pairing) and the separation between signal and background will be discussed. Additionally, the impact of initial state radiation on kinematic fitting and consequences for the implementation into the simulation are part of discussion.

This thesis discusses the topics as follows: *Chapter 2* presents the fundamentals of the Standard Model with special attention to the Higgs sector. Also, some of the shortcomings and possible extensions of the Standard Model will be introduced. *Chapter 3* discusses the experimental basis for this thesis, the ILC: The ILC machine parameters, the physics program, the luminosity and finally one of the detector concepts for the ILC, the ILD. *Chapter 4* covers the basics for calorimetry, in which a key role is played by the PFC. *Chapter 5* introduces the engineering prototype of the hadronic calorimeter, while *Chapter 6* subsequently discusses the above mentioned channel-wise auto trigger system and the power pulsing function of this detector. *Chapter 7* presents the test beam campaign and the study of the pedestal.

In the second part of this thesis, the focus lies on kinematic fitting in the framework of the Higgs self-coupling study. *Chapter 8* introduces kinematic fitting and describes the parametrization of the jet energy resolution for kinematic fitting. In *Chapter 9* kinematic fitting is applied on ZHH events with a leptonic decay of the Z boson to answer questions concerning the mass resolution, jet pairing and the separation of signal and background. Finally, this thesis is concluded in *Chapter 10*.

2 Elementary Particle Physics

The theoretical foundations for this thesis are presented in this chapter. Herein a short introduction to the Standard Model of particle physics (SM) is given. This includes a brief review on the basics of the Standard Model in sec. 2.1.1- 2.1.3 (this part follows [8] and [9]), a short discussion about the mechanism of electroweak symmetry breaking in sec. 2.1.4 and the Higgs particle itself in sec. 2.1.5. Subsequently, the Higgs potential in sec. 2.1.6 and the measurement of the Higgs self-coupling in sec. 2.2 are introduced. Finally, in sec. 2.3, some of the shortcomings of the Standard Model and in this context the relevance of the Higgs self-coupling (sec.2.4) will be discussed.

2.1 The Standard Model of Particle Physics

Modern particle physics has its origin in the famous scattering experiments made by Rutherford [10] at the beginning of the 20th century. Until then one of the most important knowledge was John Daltons nuclear hypothesis [11], which describes matter as a construction of small indivisible atoms. The intention of particle physics is related to the fundamental constituents which are composing our Universe. These constituents are the actually *elementary particles*. All attempts to categorize and describe the particles concluded in the 1960's and 1970's in the *Standard Model of particle physics*. It describes all known elementary particles and their interactions (strong, weak and electromagnetic interaction), only gravity is not included.

In the current view, the Standard Model distinguishes between two classes of elementary matter particles: the quarks and the leptons. To describe their interactions it is based on gauge theories and includes quantum chromodynamics (QCD) and quantum electrodynamics (QED), which is incorporated in the Glashow-Salam-Weinberg theory of electroweak interactions [12–14].

The interactions between matter particles are mediated by a third class of particles, the gauge bosons. Finally, breaking the electroweak interaction into the electromagnetic and weak interaction is caused by the Higgs field, which manifests itself as Higgs boson. The interaction of the particles with the Higgs field and the properties of the Higgs field are responsible for the mass generation of the particles. This will be discussed in more detail in sec. 2.1.4.

Particle	Flavour			el. charge ($Q/ e $)	Color	weak Isospin (I, I_3)		
						left-handed	right-handed	
quarks	u	c	t	+2/3	r, g, b	1/2	+1/2	0
	d	s	b	-1/3		1/2	-1/2	
leptons	ν_e	ν_μ	ν_τ	0	-	1/2	+1/2	-
	e^-	μ^-	τ^-	-1		1/2	-1/2	0

Table 2.1 – Quarks and Leptons of the Standard Model.

2.1.1 Elementary Matter Particles

In the Standard Model there are six leptons and six flavors of quarks (see tab. 2.1) separated into three generations. Both particle types are fermions with spin $1/2$. The quarks are divided into up- and down-type quarks, while the leptons are divided into charged leptons and neutrinos. The Dirac equation describes the propagation of the particles in vacuum. One result of the Dirac equation is that every particle has a corresponding counterpart, which is called antiparticle. The antiparticle has the same mass as the particle but the electrical charge and all charge related quantum numbers have the opposite sign. The quarks and leptons carry charges corresponding to the interactions they undergo. For instance, electrical charge is responsible for electromagnetic interactions, the color charge for strong interactions (the interactions will be discussed in sec. 2.1.2). Quarks are the only matter particles, which carry a color charge. A special feature of the color charge is that there are three different color charges, often called red, green and blue (to be exact, there is also for any color the corresponding anticolor). Particles with color charges underly the *confinement*, which determines that matter is only visible in color neutral states. Therefore, quarks only exist in colorless combinations, which are called hadrons. States of three quarks are called baryons and states of quark - antiquark are called mesons. Leptons do not carry any color charge, therefore they do not participate on strong interactions. The neutrinos taking a special role, since they carry neither any electrical charge nor color charge, so they are taking part only in weak interactions.

2.1.2 Fundamental Forces

The constituents appeal forces to each other with several interactions and these forces might lead to bindings. At this time three types of interactions are known:

- Gravity describes interactions due to the mass.
- Strong force is in charge for the binding of quarks and therefore responsible for the stability of matter.

- Electroweak force plays a role for the force between charged particles and also for the radioactive decay. The electromagnetic and weak force are unified to the electroweak force and separated by electroweak symmetry breaking.

One goal of modern particle physics is to simplify pictures of nature. From an aesthetic point of view it is unclear why our world is held together by three fundamental forces, therefore physics is aimed to unify all forces to one overall force, like the unification of the electromagnetic and the weak force to the electroweak force. This principle is called *Grand Unified Theory* and it is still unclear if it will ever be possible to unify the description of nature in such that way. A simplified picture for bindings to bigger units of matter can be given with the three fundamental forces. The strong force binds quarks to nucleons and nucleons to nuclei. The weak force is in charge for the radioactive decay of the nuclei. The electromagnetic force binds electrons and nuclei to atoms and atoms to molecules. Big and massive bodies will be built in the interplay of all three fundamental forces, but for interactions at very large ranges and between very massive objects, like stars just gravity is relevant.

The Standard Model is based on *local gauge invariance*. Herein, the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ represents the strong, weak and electromagnetic interaction. The symmetry group $SU(3)_C$ represents the gauge group of quantum chromodynamics (QCD). QCD is a field theory to describe the strong force. It was developed in the 1970's by Gell-Mann, Fritzsch and Leutwyler [15]. The gauge group $SU(2)_L \times U(1)_Y$ depicts the electroweak interaction, in which the quantum electrodynamic (QED) is included in the $U(1)$ gauge symmetry. $U(1)$ is a Abelian gauge group with the consequence that the photon field is a non self-interacting field, whereas $SU(2)$ and $SU(3)$ are non Abelian gauge groups with the property of self-interaction. These gauge groups are described by the Yang-Mills theory [16].

2.1.3 Mediators

The effect of each force on particles can be described by the exchange of mediator particles. Relevant mediators for particle physics are spin-1 force-carrying particles. The mediators for the strong force are the gluons. Each gluon carries one color and one anticolor to interact. This leads to a color octet and a color singlet in $SU(3)_C$ with eight possible combinations for gluons. The color singlet could exist as a free particle and it would be like a strongly interacting "photon" with infinite range. Such a strongly interacting long-range particle would have far-reaching consequences for our universe. It would be a photon with a long-range force of strong coupling, but it is well known that the strong force is of very short range. Thus, the strong interaction is mediated by 8 gluons.

The mediator for the electromagnetic force is the photon, which couples to electric charge.

Interaction	Boson		Mass/GeV	Strength	Q/ e
Strong	8 gluons	g	0	1	0
Electromagnetic	Photon	γ	0	10^{-3}	0
Weak	W boson	$W^\pm$	$80.385^{[17]}$	10^{-8}	± 1
	Z boson	Z	$91.1876^{[17]}$		0

Table 2.2 – Gauge bosons of the Standard Model.

The $W^\pm$ and Z -boson are the mediators for the weak interaction and couples to the weak isospin. The gauge bosons are incorporated in the Standard Model and listed in tab. 2.2. For instance for the electroweak interaction, the Standard Model incorporates four gauge bosons for $SU(2)_L \times U(1)_Y$: the triplet W_μ^1 , W_μ^2 and W_μ^3 for the generators of $SU(2)$ and a neutral B_μ for $U(1)$. The charged weak gauge bosons $W_\mu^\pm$ are a linear combination of W_μ^1 and W_μ^2 :

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm W_\mu^2). \quad (2.1)$$

W_μ^3 and B_μ mix to the massless photon A and the massive Z^0 with

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos(\Theta_W) & \sin(\Theta_W) \\ -\sin(\Theta_W) & \cos(\Theta_W) \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}, \quad (2.2)$$

where Θ_W denotes the *Weinberg angle*. It is the mixing angle for weak interactions and is defined as:

$$\tan \Theta_W = \frac{g'}{g}. \quad (2.3)$$

g and g' are the coupling constants of $SU(2)_L$ and $U(1)_Y$. The coupling constant of $U(1)_Y$ can be expressed as:

$$e \equiv g \sin \Theta_W = g' \cos \Theta_W. \quad (2.4)$$

2.1.4 Electroweak Symmetry Breaking

The Standard Model of particle physics requires renormalization, because in quantum field theory higher order effects can cause divergencies in the propagators and these divergencies can lead to infinite masses and charges. A renormalizable theory can absorb these divergencies, but a basic requirement for renormalization is local gauge invariance for the theory [18]. The principle of gauge invariance in turn requires that the gauge

bosons are massless. This is fulfilled for photons and gluons, but the $W^\pm$ - and Z - bosons are very heavy particles and an insertion of the masses by hand violates the renormalizability. Since the electromagnetic and the weak interaction can be interpreted as one electroweak interaction, the gauge symmetry of the electroweak interaction has to be broken to generate mass for the gauge bosons for small energies compared to their masses. To preserve renormalizability in case of massive gauge bosons, the adoption of an additional field, which is called the "*Higgs field*", is a possibility to create masses in a dynamical way. The interaction with the Higgs field is responsible for the (spontaneous) symmetry breaking of the electroweak interaction and the creation of masses. This means the electroweak $SU(2)_L \times U(1)_Y$ is broken and only the electromagnetic $U(1)_{em}$ symmetry will remain unbroken. This process is usually referred to as "*Higgs mechanism*". While in 1964 three groups proposed independently from each other a theory of spontaneous symmetry breaking (P.W. Higgs [19, 20], F. Englert and R. Brout (who is now deceased) [21] and G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble [22]), P. W. Higgs was the first to postulate an additional boson. In 2013 P. W. Higgs and F. Englert were awarded with the Nobel prize in Physics for their explanation for the origin of mass for subatomic particles.

2.1.4.1 Higgs Mechanism

In case of the Higgs mechanism gauge bosons should gain mass by the breaking of local gauge symmetry. The easiest way to generate mass for Z^0 and $W^\pm$ while keeping the photon massless in a dynamical way, is to use a complex $SU(2)$ doublet of scalar fields (eq. 2.5) in the Lagrange density ¹. One scalar field assigns one complex value of a function at each point in the universe. Since the Higgs field is required to generate masses of the $W^\pm$ - and Z - bosons, one of the scalar fields has to be charged (ϕ^+) and the other one has to be neutral (ϕ^0). Since the ϕ^+ and ϕ^0 can be complex, the doublet has four degrees of freedom illustrated with ϕ_1, ϕ_2, ϕ_3 and ϕ_4 .

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.5)$$

The scalar product is defined by $\phi^* \phi = |\phi|^2 = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2)$. To obtain symmetry breaking the vacuum expectation value v of the field has to be $\neq 0$. This constraint is not trivial, hence a self interaction with the field itself is needed to achieve this. The

¹The Lagrangian density describes fields by their equations of motion, thereby it describes the density of the Lagrange function in a volume element $L = \int \mathcal{L} d^3r$. It was named after the mathematician Joseph Louis Lagrange.

Lagrangian for a complex scalar field is

$$\mathcal{L} = (\partial_\mu \phi)^* (\partial^\mu \phi) - V(\phi). \quad (2.6)$$

A potential with a minimum of $\phi_0 \neq 0$ is known from the magnetization (M) of ferromagnets below the Curie temperature, where the potential can be described with $V = -\alpha^2 M^2 + \beta^2 M^4$ with the two parameters α and β [23]. This concept can be adopted and a potential for the Higgs field like

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \quad (2.7)$$

$$= \mu^2 |\phi|^2 + \lambda |\phi|^4 \quad (2.8)$$

can be set. To limit the potential from below, λ is set to be $\lambda > 0$. In case of $\mu^2 > 0$, the minimum occurs if the fields are zero and therefore v is $v = 0$, the symmetry of the Lagrangian is depicted in fig. 2.1(a). In case of $\mu^2 < 0$, the minimum of the potential differs from zero and lies on a circle defined by $\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2$, depicted by a 2d illustration of the potential in fig. 2.1(b). The value of v can be calculated as:

$$\frac{\partial V}{\partial \phi} = |\phi| (2\mu^2 + 4\lambda |\phi|^2) = 0 \quad (2.9)$$

$$\Rightarrow |\phi|^2 = \frac{-\mu^2}{2\lambda} = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = \frac{v^2}{2} \quad (2.10)$$

$$\Rightarrow v = \sqrt{\frac{-\mu^2}{\lambda}}. \quad (2.11)$$

In case of $\mu^2 < 0$ the theory is not gauge invariant and in particular the symmetry of

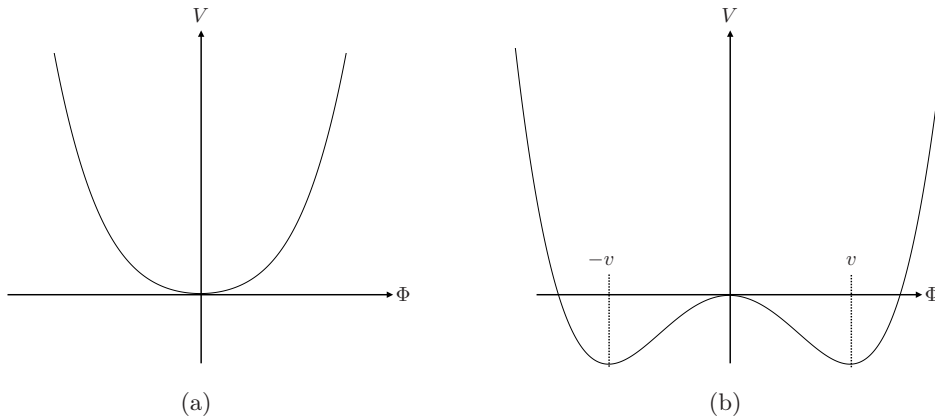


Figure 2.1 – 1d illustration of the potential $V(\phi)$ for $\lambda > 0$ with a) $\mu^2 > 0$ and b) $\mu^2 < 0$.

$SU(2)_L \times U(1)_Y$ is broken and the electromagnetic $U(1)_{em}$ is conserved. From the four gauge bosons the photon has to remain massless after the symmetry breaking. To let the

vacuum be uncharged, the non-zero expectation value corresponds to ϕ^0 [24].

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.12)$$

The gauge bosons and fermions gain masses due to the interaction with the Higgs field. This becomes clear, if ϕ is developed around the minimum of the potential, therefore a state $\phi(x)$ is considered in the vicinity of the ground state.

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.13)$$

The term $h(x)$ includes the dependency on the space time coordinates x .

Toy Model

To illustrate the Higgs mechanism a toy model is used with one gauge field A_μ and the covariant derivative $D_\mu \equiv \partial_\mu - igA_\mu$ and a scalar Higgs field. The Lagrangian then looks like:

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 \quad (2.14)$$

Using $\phi(x) = 1/\sqrt{2}(v + h(x))$ in eq. 2.14 offers a look into the properties of the system. The Lagrangian takes the form:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu - igA_\mu)(v + h)(\partial^\mu + igA^\mu)(v + h) - \frac{1}{2}\mu^2(v + h)^2 - \frac{1}{4}\lambda(v + h)^4 \quad (2.15)$$

$\mu^2 = -\lambda v^2$ transforms eq. 2.15 into

$$\mathcal{L} = \underbrace{\frac{1}{2}\partial_\mu h \partial^\mu h}_{\text{free Higgs particle}} + \underbrace{\frac{h^2}{2}g^2 A_\mu A^\mu}_{\text{gauge-Higgs interaction}} + \underbrace{\frac{v^2}{2}g^2 A_\mu A^\mu}_{\text{mass term for } A_\mu} + \underbrace{vhg^2 A_\mu A^\mu}_{\text{gauge-Higgs interaction}} \quad (2.16)$$

$$\underbrace{-\frac{1}{4}\lambda h^4 - \lambda v h^3}_{\text{Higgs self-interaction}} - \underbrace{\lambda v^2 h^2}_{\text{Higgs mass}} + \text{const.} \quad (2.17)$$

Even in this toy model the terms in eq. 2.16 can be assorted to terms describing masses of gauge bosons and interactions of a Higgs boson. Here and in the Standard Model the Higgs mass term is $-\lambda v^2 h^2$. The λ parameter is unknown, therefore no direct predictions for the Higgs mass can be gained from the Standard Model. The terms $\frac{h^2}{2}g^2 A_\mu A^\mu$ and $vhg^2 A_\mu A^\mu$ are interaction terms between Higgs and the gauge boson of A_μ . By the choice of the expectation value of the Higgs potential, the Higgs interacts with itself, which is

demonstrated by the terms $-\frac{1}{4}\lambda h^4 - \lambda v h^3$. The issue of self-interaction is discussed in more detail in sec. 2.1.6. The term $\frac{1}{2}g^2 v^2 A_\mu A^\mu$ is the mass term for a gauge boson with $M^2 \propto \frac{1}{2}g^2 v^2$.

Interpretation in the Standard Model

Similarly in the Standard Model, one can obtain the mass terms of the gauge bosons by replacing the derivative in eq. 2.6 with the according covariant derivatives which respect the $SU(2)_L \times U(1)_Y$ local gauge symmetry and using a doublet for the Higgs field, since three mass terms are acquired for the W^+ , W^- and Z boson.

With the coupling constants g , g' and the vacuum expectation value v , the masses for the W 's, Z and the photon in the Standard Model are:

$$M_W = \frac{1}{2}gv \quad (2.18)$$

$$M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2} \quad (2.19)$$

$$M_A = 0, \quad (2.20)$$

where M_A can be identified as the mass of the photon. From $M_W = \frac{1}{2}gv$ and the values for M_W and g , the vacuum expectation value v can be determined as:

$$v \approx 246 \text{ GeV}. \quad (2.21)$$

Masses for fermions and gauge bosons (except the neutrino masses) are included in the Standard Model. The gauge bosons gain their masses via the Higgs mechanism, as explained above. Also the fermions get their masses in a dynamical way via the Higgs mechanism. Consequently, gauge invariant interaction terms between the Higgs field and the fermions are appearing in the Standard Model Lagrangian, since due to the electroweak symmetry breaking the Higgs generates dynamical mass terms for the fermions. The mass of the fermions are depending on the couplings of the Higgs to fermions and these couplings are called Yukawa couplings. The Yukawa couplings are not predicted but inserted as free parameters in the Lagrangian. The full Standard Model Lagrangian can be found e.g. in [25].

2.1.5 The Standard Model Higgs Boson

In July 2012, the ATLAS and CMS collaborations discovered a Higgs-like particle [1, 2]. A combined analysis of the data from both collaborations determined a Higgs mass of

$$m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (sys.) GeV [26]} \quad (2.22)$$

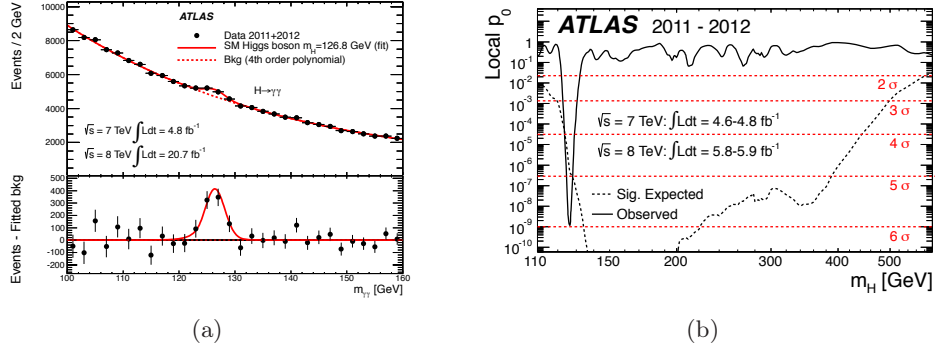


Figure 2.2 – a) In the invariant mass distribution determined by the ATLAS collaboration for the diphoton channel, a Higgs-like particle appears at 126.5 GeV [27] and b) the local p_0 as a function of the mass m_H and the expectation for a SM Higgs boson [1]. The local p_0 is the probability, that the data matches with the null hypothesis. Where the null hypothesis assumes that there is no expectation for a Higgs boson. This explains the small values for p_0 at 126.5 GeV.

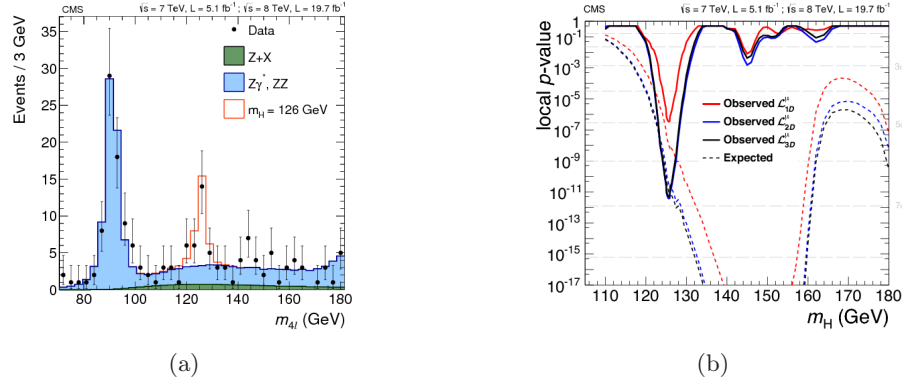


Figure 2.3 – a) Invariant mass distribution determined by the CMS collaboration for the four lepton channel [28], b) shows the significance of the local excess with respect to the Standard Model background in dependence of the Higgs mass [28].

with an integrated luminosity of about $\int \mathcal{L} dt = 5 \text{ fb}^{-1}$ for $\sqrt{s} = 7 \text{ TeV}$ and 20 fb^{-1} for $\sqrt{s} = 8 \text{ TeV}$ for each experiment [26]. To illustrate the discovery, fig. 2.2 shows ATLAS results of the diphoton channel from two studies, [1] and [27], and fig. 2.3 results from the CMS detector for four leptons [28]. It should be noted that $H \rightarrow \gamma\gamma$ is a loop mediated process, which has a very small Branching Ratio. But nevertheless it offers a clear signature at LHC. To fully understand the nature of electroweak symmetry breaking, a full profile of the Higgs boson is needed. To characterize the Higgs boson the Higgs mass, the spin, the width, the Higgs self-coupling, the coupling between the gauge bosons and the Higgs boson, the Yukawa couplings of the Higgs to fermions and the CP properties of the Higgs are important properties [6].

2.1.6 The Higgs Self-coupling

The focus in this thesis lies on the measurement of the Higgs self-coupling. As mentioned in sec. 2.1.4 the Higgs potential after electroweak symmetry breaking is given as

$$V(\phi^*, \phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \quad (2.23)$$

$$= \frac{1}{2} \mu^2 (v + h)^2 + \frac{1}{4} \lambda (v + h)^4 \quad (2.24)$$

$$= \underbrace{\lambda v^2 h^2}_{\text{Higgs mass term}} + \underbrace{\lambda v h^3}_{\text{trilinear Higgs self coupling}} + \underbrace{\frac{1}{4} \lambda h^4}_{\text{quartic Higgs self interaction}} \quad (2.25)$$

Insertion of $M_h^2 = 2\lambda v^2$ and $\mu^2 = -\lambda v^2$ results in a Higgs potential of:

$$V(h) = \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4, \quad (2.26)$$

where h represents the physical Higgs field, M_h the Higgs mass and λ the Higgs self-coupling. The potential (eq. 2.26) consists of three terms: the Higgs mass term, the trilinear Higgs self-coupling and the quartic Higgs self-coupling. In principle, each term must be measured in order to determine the shape of the potential. The Higgs mass term can already be measured at the LHC and can be improved further at an e^+e^- -collider. The quartic self-coupling term is very difficult to measure due to the small cross section. So in the end the trilinear self-coupling term becomes important to be measured as precisely as possible, in order to describe the potential as good as possible. From the measurement at the LHC the determined mass of the Higgs boson offers the opportunity to estimate the expected value of the Higgs self-coupling λ as

$$\lambda = \frac{M_h^2}{2v^2} \sim 0.13. \quad (2.27)$$

But if this is the Standard Model expected value has to be verified in a measurement. The influence of different values of λ on the shape of the Higgs potential is visible in fig. 2.4. Larger values of λ causes a higher slope, while the points of the minimum and the intersections with the θ -axis remain the same. Only the depth of the minimum increases and the overall shape of the potential gets more compact. It is the same story for smaller values of λ , but the potential shows a smaller slope, which results in a broader distribution of the potential and the depth of the minimum decreases. The black curve is the Standard Model expected shape of the Higgs potential.

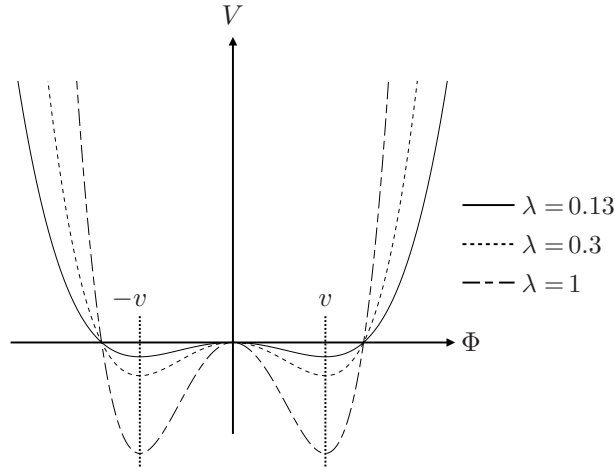


Figure 2.4 – Sketch of the Higgs potential for different values of λ . Larger values of λ increase the slope and make the width of the overall distribution more compact, while smaller values of λ lead to a broadening of the distribution with a smaller slope. Increasing of λ leads to an increased depth of the minimum, but the positioning of the minimum and the intersections with the Φ -axis remain the same.

2.2 Measurement of the Higgs Self-coupling in e^+e^- -collisions

To determine the trilinear Higgs self-coupling, two processes can be used in e^+e^- -collisions. Depending on the center of mass energy, the double Higgs production in Higgs-strahlung [29–31] and the WW -fusion [32, 33] are appropriate processes for this measurement. Fig. 2.5(a) and fig. 2.5(b) show the corresponding Feynman diagrams for the double Higgs production in Higgs-strahlung and WW -fusion. From a theoretical point of view, the ZZ -fusion process of double Higgs production is also possible, but this process is suppressed by an order of magnitude compared to WW -fusion, due to the small coupling of the Z boson to electrons [30]. The center of mass energy is a crucial criterion,

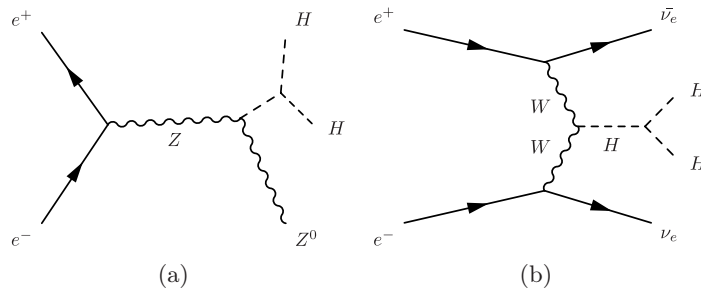


Figure 2.5 – Feynman diagrams for double Higgs production in a) the Higgs-strahlung and b) the WW -fusion.

because the cross-section for both processes depends on $\sqrt{s}$, as depicted in fig. 2.6. At 500 GeV, the Higgs-strahlung is dominant and for higher energies the WW -fusion process becomes important. The maximum of the cross-section for the Higgs-strahlung is reached in the vicinity of the threshold $\sqrt{s} \sim 2m_H + m_Z + 200$ GeV [34]. The maximum of the cross-section at $\sqrt{s} \approx 540$ GeV is reached because the propagator which connects the intermediate virtual Higgs boson to the two real Higgs bosons gets maximal for this value of $\sqrt{s}$ [34].

On the other hand the WW -fusion process is a t-channel fusion process where the e^+e^- -beams radiate two virtual W -bosons, which collide. The logarithmic increase of the cross-section of the t-channel fusion process with $\sqrt{s}$ makes the WW -fusion process above 1 TeV the most relevant process, since the ZHH cross-section drops with $\sqrt{s}$ [34]. Also visible in fig. 2.6 is the distinction for two polarizations. For example the default baseline design setup of the ILC foresees a polarization of $P(e^+, e^-) = (0.3, -0.8)$ with an 80 % longitudinal polarized electron beam and a 30 % longitudinal polarized positron beam with a possible upgrade to $P(e^+, e^-) = (0.6, -0.8)$, depicted as dashed lines in fig. 2.6. Polarization offers precision tests on the Standard Model as well as the search for new particles [35]. By steering the polarizations of the incoming beams it is possible to enhance or suppress specific signals and backgrounds. For instance, in the Standard Model particles with opposite helicity couple for the s-channel annihilation process of e^+e^- into a vector boson. Using polarized beams with opposite signs of the incoming beams allows to enhance the collision cross-section for double Higgs-strahlung. The analysis here in this thesis is just focussed on $P(e^+, e^-) = (0.3, -0.8)$. Important for both

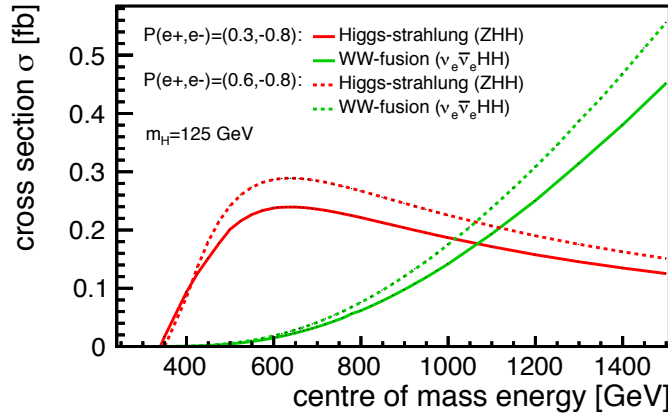


Figure 2.6 – Cross-section for the Higgs-strahlung and WW -fusion for different center of mass energies [36].

processes is that at tree-level additional processes can superimpose the measurement. These processes have the same final states but are not related to the Higgs self-coupling. The Feynman diagrams for Higgs-strahlung as well as WW -fusion are shown in fig. 2.7 and in fig. 2.8. The additional diagrams make the determination of the Higgs self-

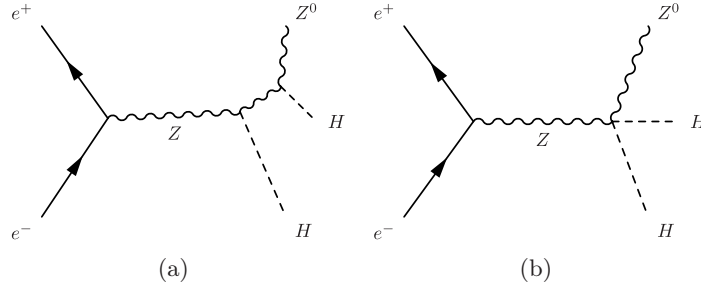


Figure 2.7 – a) and b) show the Feynman diagrams, which have the same final states as the double Higgs production in the Higgs-strahlung process.

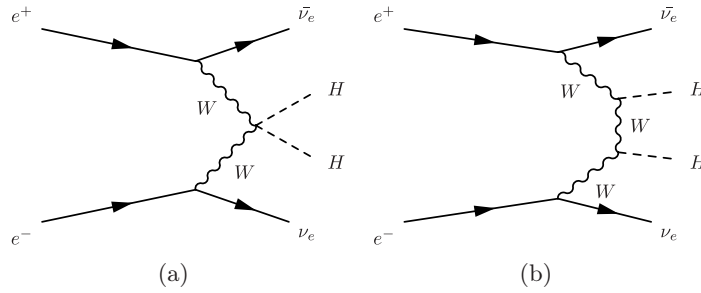


Figure 2.8 – a) and b) show the Feynman diagrams, which have the same final states as the double Higgs production in the WW -fusion process.

coupling more complicated, because they interfere with the related Higgs self-coupling diagram. As a result, the cross-section σ is not just proportional to λ^2 . Instead, σ can be formulated as:

$$\sigma = a\lambda^2 + b\lambda + c. \quad (2.28)$$

a is a constant from the Higgs self-coupling diagram, b represents the interference between the diagrams and c gives the contribution from the additional diagrams [36]. The precision of the Higgs self-coupling for a Higgs mass of $M_H = 125$ GeV at $\sqrt{s} = 500$ GeV relates to the precision of the cross-section measurement [36] as:

$$\frac{\delta\lambda}{\lambda} = 1.74 \cdot \frac{\delta\sigma}{\sigma}. \quad (2.29)$$

Herein, the conversion factor of 1.74 is called the sensitivity factor and correspond to a Standard Model-like Higgs self-coupling.

Without the additional diagrams, eq. 2.28 reduces to $\sigma = a\lambda^2$ which would lead to $\delta\lambda/\lambda = 0.5\delta\sigma/\sigma$. Fig. 2.9 shows the sensitivity factor in dependency of the center of mass energy for the Higgs-Strahlung process (red line) and the WW -fusion process (blue line). For smaller values of the sensitivity factor the precision gets more sensitive on λ and vice versa for larger values of the sensitivity factor the precision gets less sensitive on λ . The sensitivity of WW -fusion is in general bigger compared to the Higgs-strahlung.

Decay Mode	$Z \rightarrow$	$H_1 \rightarrow$	$H_2 \rightarrow$	Branching Ratio
1	$l\bar{l}$	$b\bar{b}$	$b\bar{b}$	3 %
2	$\nu\bar{\nu}$	$b\bar{b}$	$b\bar{b}$	9 %
3	$q\bar{q}$	$b\bar{b}$	$b\bar{b}$	31 %

Table 2.3 – Branching ratios for $H \rightarrow ZZ$ and different Z decays [6].

Due to the cross-section and the precision of the WW -fusion process, an analysis of the Higgs self-coupling with WW -fusion at higher energies gets important. However, a 1 TeV upgrade of the ILC lies in the very far future. Thus, the more challenging case of $\sqrt{s} = 500$ GeV with a Higgs mass of $M_H = 125$ GeV is studied. In the Higgs-strahlung

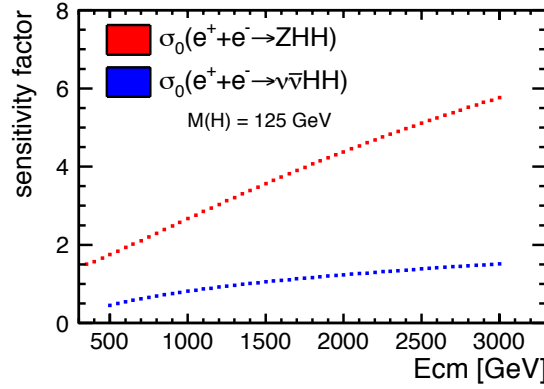


Figure 2.9 – The "sensitivity factor", which relates $\delta\sigma/\sigma$ to $\delta\lambda/\lambda$ as function of the center of mass energy for a Higgs mass of $M_H = 125$ GeV [6]. The red line displays the sensitivity factor for the Higgs-Strahlung and the blue line the sensitivity factor for the WW -fusion.

scenario, $e^+e^- \rightarrow ZHH$ undergoes several decay modes for the Z and H . Concerning the Z , $e^+e^- \rightarrow ZHH$ can be separated in three 3 decay scenarios: 1) the lepton channel ($e^+e^- \rightarrow l\bar{l}HH$), 2) the neutrino channel ($e^+e^- \rightarrow \nu\bar{\nu}HH$) and 3) the hadronic channel ($e^+e^- \rightarrow q\bar{q}HH$). The most frequent decay of the Higgs is $H \rightarrow b\bar{b}$. The branching ratios for the decay modes with $H \rightarrow 4b$ are shown in tab.2.3. Each channel provides advantages and disadvantages. The lepton channel offers a clear signature in the detector due to the two leptons and the 4 jets, but this channel has a small branching ratio. The neutrino channel gives clean events for the H 's, but the missing energy from the two neutrinos makes the reconstruction more difficult. The statistical dominance of the quark channel has the disadvantage that due to the 6 jets the identification of the correct jet pairing is sophisticated and misleading combinations have to be taken into account.

2.3 Shortcomings of the Standard Model

The Standard Model of particle physics in its current form is very successful. It is a self-consistent theory about elementary particles and their interactions. But nevertheless the Standard Model has some inadequacies. It relies on more than 20 parameters like the fermion masses or the Weinberg angle. All these values have to be determined experimentally and inserted by hand. From a theoretical point of view a complete Standard Model of particle physics should consist out of a few parameters and a relatively simple equation. Additionally, it should also incorporate the fourth fundamental force, the gravity, and solve some other issues. Just to name a few, current drawbacks of the Standard Model are:

- The Standard Model predicts three different neutrinos, which are per definition massless. From studies on neutrino oscillations it has been proven that at least two of the three neutrinos are massive particles. However, the masses of the neutrinos are not incorporated in the Standard Model and therefore the Standard Model needs a corresponding mass term in the Lagrangian.
- It is well established that the Universe is dominated by matter compared to antimatter. This misbalance is called baryon asymmetry and cannot be explained with the Standard Model. While the Universe started to expand the temperature decreased and at a given point the baryons started to freeze out. Without CP violation the amount of baryons and anti-baryons should be equal. Rather than a balance, the asymmetry has the value [37]

$$\eta = \frac{\eta_B - \eta_{\bar{B}}}{s} \sim 10^{-10}. \quad (2.30)$$

η_B is the number density of baryons, $\eta_{\bar{B}}$ the number density of anti-baryons and s the entropy density. CP violation might in principle explain the asymmetry but to explain the full matter-antimatter asymmetry further conditions are needed. These conditions were defined by Sakharov [38]. 1) the conservation of the baryon number must be broken, 2) departure from the thermal equilibrium, because in thermal equilibrium the baryon number will be balanced by the inverse reaction and 3) a symmetry breaking via CP violation is needed. CP violation is incorporated in the Standard Model due to the three generations of fermions (quarks/leptons), but until now CP violation has been observed only in weak interactions of the quark sector. This effect is not sufficient to explain the asymmetry in the universe. A thorough discussion can be found e.g. in [39, 40].

- Observations in the mid 1930's showed that a significant fraction of matter in the universe is not visible [41]. Otherwise the rotational speed of galaxies or gravitational lensing effects cannot be explained [42]. For example in the milky way, the

major amount of visible matter is centered in the central region. Matter which is outside of the central region is accelerated given by the centripetal acceleration. Assuming the major amount of matter is centered in the central bulge, the rotational speed of the stars should decrease for outer regions. But the observed rotational speed of the milky way is much higher than the expected one which is explainable if a non-visible component of matter exists. A recent review can be found in [43].

- The Higgs boson with a mass of ~ 125 GeV raises a theoretical challenge, which is known as the hierarchy problem. At higher energies, the Higgs mass receives large corrections from loops with fermions, gauge bosons and the Higgs itself. If the Standard Model should be valid up to the Planck scale $\Lambda_P \sim 10^{19}$ GeV, these quantum corrections become very large. Usually the gauge bosons are protected by local gauge symmetries from these corrections, but the Higgs boson is a scalar particle with spin 0, which can't be protected from these corrections and therefore for very high energies it is difficult to keep the Higgs mass at the electroweak scale ($\sim 10^2$ GeV). Basically, this can be renormalized, but this requires an unnatural amount of fine-tuning. Generally the Hierarchy problem is not a problem of the Standard Model itself, but it might be a hint that there is new physics at higher energies and the Standard Model is just a "low energy" approximation.

There are three ways to handle the hierarchy problem:

- Cancellation of the quantum loop corrections.
- Consideration of the Higgs particle as a non-fundamental scalar particle.
- Avoidance of the hierarchy problem with an extended structure of the metric of the universe.

These ideas are pursued by various approaches and these concepts lead to extended Higgs theories, since the Standard Model Higgs mechanism is just one of the simplest choices to generate spontaneous symmetry breaking.

2.4 New Physics & Higgs self-coupling

As mentioned above, the inadequacies of the Standard Model indicate a need for new physics. There are several concepts, which follow the above mentioned ideas to solve the inadequacies. A lot of them differ slightly from each other, therefore only the main concepts will be presented in this section. For instance, *Supersymmetry* solves the hierarchy problem in natural way by canceling the loop contributions, *Technicolor* bypasses the hierarchy problem by considering the Higgs boson as non-fundamental particle and generates electroweak symmetry breaking in a dynamical way and the *Extra Dimension*

Model avoids the hierarchy problem with an extended structure of the metric of the universe.

In addition to these concepts the relevance of the Higgs self-coupling in this context will be discussed, because especially the Higgs self-coupling can have very large deviations in these extended Higgs theories compared to the Standard Model value. Herein, the trilinear Higgs self-coupling is one of the most discriminative quantities to reveal new physics [44]. [45] has shown that a precision of better than 20% is needed for the Higgs self-coupling measurement in order to discover new physics. Furthermore it must be mentioned, that a large deviation of the trilinear Higgs self-coupling from the Standard Model is required to describe a successful scenario of electroweak baryogenesis [46–49], because this can indicate a common signature of a strong first order electroweak phase transition [50–53]. Summarized, the trilinear Higgs self-coupling plays a key role for the understanding of our universe.

2.4.1 Supersymmetry (SUSY)

Supersymmetry emerged in the 1970's and is a concept which connects particles with a super-partner. There are several concepts of SUSY theories available, the most common theories are the so called Minimal Supersymmetric Standard Model (MSSM), [54] and [55] and the Next-to Minimal Supersymmetric Standard Model (NMSSM). Here, just the basic concept of SUSY will be presented.

In general, two classes of particles are known, fermions and bosons. In SUSY each fermion has an equivalent bosonic super-partner and every Standard Model boson a fermionic super-partner. A super-partner of a particle is a so called "sparticle", for example the super-partner of an electron is the selectron. The super-partners have the same quantum numbers as their partners except of the spin. The spin differs by a 1/2 integer. The symmetry is described by a generator G with:

$$G|F\rangle = |B\rangle \quad (2.31)$$

$$G|B\rangle = |F\rangle \quad (2.32)$$

where $|F\rangle$ ($|B\rangle$) describes the fermionic (bosonic) state of a particle. One feature of SUSY is that for every loop of a particle the corresponding loop of a sparticle provides a contribution with the opposite sign and the loop corrections are canceled pairwise. This solves the hierarchy problem in a natural way. But SUSY has to be a broken symmetry, otherwise the masses of the super partner would be equal to the masses of the particles and in this case the sparticles would have been already discovered. More informations can be found in [56]. The physics of the electroweak symmetry breaking differs in the MSSM compared to the Standard Model, because the MSSM postulates five Higgs bosons instead of one Higgs boson. This will have an influence on the value of the trilinear Higgs

self-coupling. It has been estimated that the deviation of the triple Higgs boson coupling will be up to 15% [45].

2.4.2 Technicolor

The concept of Technicolor introduces the electroweak symmetry breaking in a dynamical way by replacing the scalar field with strongly interacting gauge systems others than QCD [57]. Then the Higgs particle itself is not a fundamental particle, it is composed out of fermions which are so called Techniquarks. At very high energies the new strong interaction becomes asymptotically free and for energies at the electroweak scale the interaction becomes confining, which means that the chiral symmetry of the Technifermions gets broken and the gauge bosons gain mass, similar to the electroweak symmetry breaking of the Standard Model. This dynamical approach also prevents from the hierarchy problem of the Standard Model. This is a completely different approach compared to the Standard Model and predicts large deviations in the Higgs self-coupling. If nature follows the picture of Technicolor than the deviation of the trilinear Higgs self-coupling compared to the Standard Model value will be in the order of tens of % [45].

2.4.3 Extra Dimension Models

Most models in physics incorporate 3 space dimensions and one time dimension. Nevertheless there are attempts which involve additional dimensions [58–61]. In these theories the weakness of the fourth fundamental force, the gravitation, compared to the other forces is due to the existence of one or more extra dimensions, because in these theories, gravity is the only interaction that propagates in these additional dimensions. In conclusion, the Planck scale is more a consequence due to the large size of these extra dimension [62]. Thus, the hierarchy problem is an effect of the metric itself. Such a universe can have a substantial effect on the properties of the Higgs boson [63]. Furthermore, these theories allow to describe gravity in a different way. But until now no experiment gave a hint that extra dimensions exist.

3 The International Linear Collider

The focus in this chapter lies on the **I**nternational **L**inear **C**ollider (ILC), which is the experimental basis of the analysis performed in this thesis. At first in sec. 3.1 the general concept of the ILC and some general aspects on linear accelerators will be given. Subsequently in sec. 3.2 the ILC accelerator will be introduced. Herein, some key parameters and the most important components will be discussed. In sec. 3.3 the physics program at the ILC is summarized. Special attention will be paid to the Higgs boson measurements, since this thesis studies kinematic fits in the context of the Higgs self-coupling measurement. Finally, sec. 3.4 presents the International Large Detector (ILD) concept for the ILC, since the studies of this thesis are based on simulated data of the ILD. Herein also the performance requirements of ILD will be discussed. The description is oriented on [64].

3.1 The ILC Concept

The ILC is a concept of a future linear e^+e^- collider. It is foreseen as a high luminosity machine with center-of-mass energies of 200 - 500 GeV¹, based on superconducting radio-frequency accelerating technology (SCRF). The purpose of the ILC is to offer a variety of measurements which address the most important questions in particle physics. Therefore the ILC will use polarized electron and positron beams in order to realize its full potential.

3.1.1 ILC Historical Context

The ILC concept results from three independent competing projects, namely TESLA² [65], JLC³ [66] and NLC⁴ [67]. TESLA was based on superconducting cavities, while the JLC and NLC were based on room-temperature acceleration technology. In 2004 the International Committee for Future Accelerators (ICFA) made a preference in [68] for the technology of a future linear collider in favor for the TESLA technology. In 2005 and under the mandate of the ICFA, the Global Design Effort intended to bring together the concepts of the various proposals in a detailed technical design for the ILC with the result of the Reference Design Report of the ILC [69–72] in 2007 and recently in the Technical

¹Also a possible upgrade to 1 TeV is considered.

²TeV Energy Superconducting Linear Accelerator

³Japanese Linear Collider

⁴Next Linear Collider

Design Report [3, 74–76].

The development of the ILC is currently conducted under the auspices of the Linear Collider Collaboration (LCC), which also includes the CLIC⁵ project [77]. The main difference between both projects is the acceleration technology. CLIC is based on a low energy, high intensity drive beam, which is used for the excitation of the actual normal conducting accelerating cavities, while the ILC is set on superconducting radio frequency cavities, driven by conventional clystrons.

3.1.2 Linear vs. Ring Collider

There are two general concepts for accelerators for collision experiments established in particle physics. These are the concepts of a circular collider and a linear collider. Circular colliders are designed as storage rings, where the particles are accelerated on closed rings. The main advantage for such colliders are that the particles pass the same accelerating structure many times and the main disadvantage is the energy loss of the particles due to the transverse acceleration of the particles, which they experience on a circular path. The energy loss in the form of light is called synchrotron radiation and its power can be calculated as:

$$P_{sync} = \frac{4\pi \alpha \hbar c}{3} \frac{E^4}{m_0^4 c^8 R} \propto \frac{E^4}{R \cdot m^4} \quad (3.1)$$

The energy loss due to synchrotron radiation scales with the inverse of the radius R , the fourth power of the particle energy E^4 and the inverse of the fourth power of the particle mass m . Due to the m^4 dependence, electrons are used for synchrotron sources, but for a ring collider heavy particles are preferred to be used to minimize the energy loss by synchrotron radiation. To reduce the energy loss of the particles the accelerator radius has to be enlarged, but this option is a cost driver.

A possible way to avoid the circular collider dilemma is the concept of a linear collider. This concept was suggested by M. Tigner in 1964 [78]. In a linear collider the particles do not lose their energy via synchrotron radiation. But the beam passes each accelerator module once, therefore many acceleration modules have to be installed to reach the desired beam energy.

Comparing both approaches a cost optimization shows that the expenditure of a circular collider grows quadratically with the desired beam energy [79], while in case of a linear collider, it grows linearly with accelerator length. As a result, a linear collider for electrons is preferred for beam energies beyond 200 GeV [79]. Therefore, this clarifies the linear collider design of the proposed ILC.

⁵Compact Linear Collider

3.1.3 Advantages of Lepton Colliders

Basically, it can be distinguished between hadron and lepton colliders. Both types have their advantages and disadvantages, but especially in the past it has been shown that the interplay between both types showed a successful way to address questions of modern particle physics. Here, the emphasis lies on lepton colliders, since the ILC is an e^+e^- collider. Already in the past, lepton colliders have indicated their great potential. For instance, at PETRA⁶ at DESY⁷, the gluon was discovered in 1979 [80] and LEP⁸ and SLAC⁹ helped with its precise measurements of the Z boson [81] to underline the success of the Standard Model of particle physics.

Hadron colliders benefit from large center-of-mass energy ranges and a large diversity of interactions which a hadron can undergo, since a hadron is a composite particle made of quarks and gluons. While all this makes hadron colliders perfect discovery machines, lepton colliders complement the discoveries with precise measurements. The advantages that come into play for the ILC in contrast to a hadron collider, like the Large Hadron Collider (LHC), are **cleanliness**, **democracy**, **calculability** and **detail**, all documented in [73]. Here, just a very brief overview about these points will be given:

- **Cleanliness:** Cleanliness means that at the ILC the collision environment is usually much more favorable compared to the LHC. The interaction rate at the LHC is very high, which causes a high occupancy in the detectors with hundreds of high energetic particles. The background at the ILC is dominated by $\gamma\gamma$ collisions, which have a cross-section, which is six orders of magnitude lower than the background at the LHC. Moreover, the collision of elementary particles avoids multi-parton interactions and even the foreseen high luminosity at the ILC will not make pile-up an issue.
- **Democracy:** Democracy summarizes that at the ILC, and in general at lepton colliders, the coupling of the photon and the Z boson to all particles is almost equal, while the collisions at a hadron collider are dominated by soft QCD processes. Furthermore, the proton is a composite particle and the parton distributions cause a suppressed production of heavy particles. The consequence is that the cross-section, that is needed for the relevant high momentum transfer to produce heavy flavor particles accounts for only a small fraction of the total cross-section. To study processes which involve e.g. top quarks, sophisticated trigger systems are needed, to filter out these events. On the other hand, the chosen trigger can cause a bias on the recorded data set, while becoming insensible for new physics. Despite of smaller production cross-sections compared to strong interactions, the ILC does

⁶Positron-Elektron-Tandem-Ring-Anlage

⁷Deutsches Elektronen-Synchrotron

⁸Large Electron Positron Collider

⁹Stanford Linear Accelerator Center

not need a sophisticated trigger system and a continuous readout can be used. But the biggest advantage is that at the ILC the recognition of hadronic decays of W and Z bosons is much easier, which is an enormous advantage in the study of heavy particles, since the QCD background is rather small.

- **Calculability:** The calculability of the processes at the ILC is favored, due to the point-like e^+e^- particles, which couple to electroweak interactions. The electroweak processes at the ILC are, in contrast to the QCD processes at the LHC, fully perturbative and only very small theoretical uncertainties have to be taken into account. This gives an improved precision, while at the LHC, in turn, the Next-Leading-Order QCD corrections are in the order of 30 – 50% [73, 82].
- **Detail:** Detail means that the use of leptons has the advantage that the interactions of elementary particles offers an access to the complete topology for the reconstruction of the events. Herein, the full kinematic information from the events can be used for kinematic fitting to improve the reconstruction of the events. Furthermore, the beams of the electrons/positrons are highly polarized which gives the opportunity to study spin-dependent production and decay processes. Additional information on polarization at the ILC can be found in [83].

3.1.4 Luminosity at a Lepton Collider

One of the most important parameters of a collider is the luminosity $\mathcal{L}$. It describes the number of collisions in a detector per cm^2 and per second. To evaluate the collected data size over the time rather the integrated luminosity $\int \mathcal{L} dt$ is used. This value is used to characterize the performance of an accelerator. The introduction here is oriented on [84]. In order to determine the luminosity the number of bunches n_b and the number of particles N carried by each bunch is needed. At the ILC, the so called bunch trains collide with a repetition rate of $f_{rep} = 5 \text{ Hz}$. With these ingredients the luminosity can be expressed as

$$\mathcal{L} = \frac{n_b N^2 f_{rep}}{A} H_D. \quad (3.2)$$

Herein, H_D is the "beam-beam enhancement factor" and usually in the order of two. H_D is caused by additional focusing effects due to the electromagnetic fields of the colliding bunches [71]. The beam cross-section at the interaction point (IP) is represented by " A ". In case of gaussian beam profiles $A = 4\pi\sigma_x\sigma_y$ with the horizontal and vertical bunch size $\sigma_{x,y}$. Furthermore, the bunch sizes can be expressed by the emittance $\epsilon_{x,y}$ and the $\beta_{x,y}$ function at the IP.

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}}. \quad (3.3)$$

Implementing the center-of-mass energy $\sqrt{s}$ into eq. 3.2 gives

$$\mathcal{L} = \frac{\sqrt{s} n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y\sqrt{s}} H_D, \quad (3.4)$$

while $\sqrt{s} n_b N f_{rep}$ is the beam power P_{beam} . P_{beam} is proportional to the provided RF power P_{RF} with $P_{beam} \propto \eta_{RF} P_{RF}$. η_{RF} is the proportionality factor of transferring RF power into beam power. Following [85] η_{RF} is in the order of 20 - 60%. With P_{beam} and the neglect of H_D , eq. 3.4 can be transformed into

$$\mathcal{L} \propto \frac{\eta_{RF} P_{RF} N}{4\pi\sigma_x\sigma_y\sqrt{s}}. \quad (3.5)$$

Especially right before the collision, the particles experience an energy loss due to the strong focusing of the beams at the IP. This energy loss δ_{BS} depends on the longitudinal expansion of the bunches σ_z [85] and is proportional to

$$\delta_{BS} \propto \frac{\sqrt{s} N^2}{\sigma_z(\sigma_x + \sigma_y)^2}. \quad (3.6)$$

For most linear collider designs δ_{BS} is in the order of 3 - 10%. In [86] it has been shown that for high luminosity operation, while keeping the energy loss small, flat beams are the preferred beams with $\sigma_x \gg \sigma_y$. Combining all together, eq. 3.5 can be re-expressed as

$$\mathcal{L} \propto \frac{\eta_{RF} P_{RF}}{\sqrt{s}} \sqrt{\frac{\delta_{BS}}{\epsilon_y}} \sqrt{\frac{\sigma_z}{\beta_y}}. \quad (3.7)$$

From eq. 3.7 the demands for a high luminosity linear collider can be gained directly. The acceleration technique has to be able to handle a large acceleration gradient, here displayed in the RF power, which is transferred to the beam. The beam has to have a small vertical emittance, while it needs to be strongly focused at the Interaction point. In order to reach the required luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, the vertical bunch size has to be in the nanometer range.

For the ILC, the luminosity will in the order of $\mathcal{L} = 0.75 - 1.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for the baseline design¹⁰ [3]. The recommended integrated luminosity for the ILC after a running time of 20.2 years for the 250 GeV run period is $\int \mathcal{L} dt = 2 \text{ ab}^{-1}$, for the 350 GeV run period $\int \mathcal{L} dt = 0.2 \text{ ab}^{-1}$ and for the 500 GeV run period $\int \mathcal{L} dt = 4 \text{ ab}^{-1}$ [87].

3.2 The ILC Accelerator

The overall performance of the ILC depends on the used technology of all sub-systems. Here, the major sub-systems of the ILC will be presented. These are the electron/positron

¹⁰In case of the upgrade, the luminosity will be $\mathcal{L} = 3.6 - 4.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

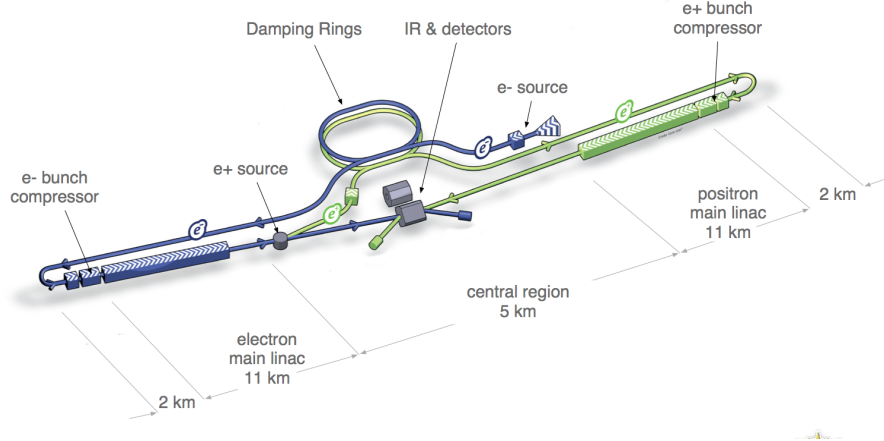


Figure 3.1 – Layout of the *International Linear Collider* with the major subsystems. [3].

sources, two 5 GeV damping rings, two main linacs¹¹ and two beam delivery systems. These components are depicted in a schematic overview of the ILC in fig. 3.1. All these main sub-systems are described in detail in [75].

3.2.1 The ILC Bunch Structure and the Concept of Power Pulsing

The ILC foresees a specific beam structure. As mentioned before the repetition rate of the bunches at the ILC takes 5 Hz. A bunch train contains 1312 bunches (for 1 TeV operation 2450 bunches per train are foreseen) [75]. The bunch population accounts $2 \cdot 10^{10}$ particles (for the 1 TeV operation $1.74 \cdot 10^{10}$ particles) [75].

The length of a typical bunch train is 1 ms. Compared with the repetition rate of 5 Hz, most of the time the detector components are running idle. In addition, for ILD a minimum of material in front of the calorimeter system is required (which will be discussed in more detail in sec. 4.4), which minimize the need for an extra cooling system. The specific bunch structure of the ILC is adopted by the detector and many hardware components follow the concept of power pulsing, where not necessarily needed detector components are switched off between the bunch trains. A cooling system would add additional unmonitored material in the detector, which would worsen the performance of the detector. The concept of power pulsing will be discussed in more detail on hand of a engineering prototype for a hadronic calorimeter in sec. 6.5.

3.2.2 Particle Sources

The electron source is based on a photocathode direct current (DC) gun, herein a laser system illuminates a strained GaAs target. In order to match the band gap of the

¹¹main linear accelerator

target, the laser system uses a wavelength of 790 nm. The baseline design of the ILC foresees 80% electron polarization. This is fulfilled by the composition of the target, which allows a natural emission of 85% polarized electrons. After the generation of the electrons, normal-conducting structures pre-accelerate the electrons to 76 MeV. After this pre-acceleration a superconducting linac accelerates the electrons to 5 GeV. Additionally, before they enter the damping ring a superconducting solenoid rotates the spin vector into the vertical direction.

The generation of the polarized positrons is a more sophisticated procedure compared to the generation of polarized electrons. To acquire the needed intensity the fully accelerated electrons beam enters a ~ 150 m long helical undulator. The undulator produces photons, which are shot on a target, where they produce electron-positron pairs. The produced photons are circularly polarized, while the generated electrons and positrons are longitudinally polarized. After focussing, a dipole chicane separates the electrons and positrons from each other. The electrons are guided into a dump and the positrons are further accelerated. The baseline design foresees a polarization of 30% for the positrons (after an optional upgrade a polarization of 60% is possible).

One of the biggest challenges is the design of the photon target of the positron source, because it has to be very thin (1.4 cm) and it has to withstand an enormous heat. The current design foresees a spinning wheel with a diameter of 1 m and the foreseen material is titanium alloy.

Both, the electrons and the positrons are pre-accelerated, so they leave the sources with an energy of 5 GeV.

3.2.3 Damping Rings

After the generation of the electrons and positrons, the particles enter the damping rings (DR). The ILC is hosting one damping ring per particle type in the same tunnel. The DRs have a circumference of 3.2 km and they are optimized to operate at beam energies of 5 GeV. After the production of the electrons and positrons, the particle beams have a large transverse and longitudinal emittance. In order to acquire the needed luminosity, the DRs have to reduce the emittance to $5.5 \mu\text{m}$ horizontal emittance and 20 nm vertical emittance. In particular, the DRs have to be capable to store a full bunch train (which incorporates 1312 bunches), while reducing the emittance to the required level within a 200 ms interval between the bunch trains. To store a full train, the pulses have to be compressed by a factor nine. Therefore a superferric wiggler¹² per beam is installed with a length of 100 m. The wigglers reach a peak-field of 1.51 T ¹³. There are some limitations for the beam emittance at the DRs, here only the most important ones

¹²the alternating magnetic field of a "wiggler" causes the generation of synchrotron radiation, which reduces the beam emittance.

¹³For a planned 10 Hz operation a peak field of 2.16 T is foreseen [75].

will be named: the electron cloud effect for the positrons and the fast ion instability for the electrons. In case of the electron cloud effect, synchrotron radiated photons hit electrons out of the vacuum pipe walls. These electrons cause disturbances in the electromagnetic field of the bunches. Special coatings of the vacuum pipe walls can reduce this effect [88]. In case of the fast ion instability rest gas molecules in the beam pipe can collide with the bunches. The created ions can influence the following bunches. In order to minimize this effect a very low vacuum pressure of 1×10^{-7} Pa is needed. The generated damped beams with low emittance are transferred to the main linacs. The beams still have an energy of 5 GeV.

3.2.4 Main Linacs

The electrons and positrons experience on their way to the main linacs another pre-acceleration from 5 GeV to 15 GeV in a two-stage bunch compressor. After entering the main linacs the actual acceleration takes place, where the electrons and positrons are accelerated to their final beam energy of up to 250 GeV. The two main linacs incorporate 7400 so called nine-cell niobium cavities, each operating at a radio frequency of 1.3 GHz. Fig. 3.2 shows one cavity, where the nine cells are particularly evident.

The cells are able to generate a very large effective electric field gradient of 31.5 MV/m. This performance is only possible if niobium becomes superconducting, therefore the cavities have to be cooled down to 2 K. To do this, the cavities must be embedded into a cryomodule. These modules are 12.65 m long and include liquid helium II as cooling substance. At this temperature helium becomes suprafluid and provides a very large heat conductivity.



Figure 3.2 – Picture of a nine-cell cavity. One main linac incorporates 7400 of these cavities to accelerate the electrons or positrons up to 250 GeV with an electric field gradient of 31.5 MV/m. [74].

3.2.5 Beam Delivery System

After the acceleration of the electrons and positrons, the particles pass a 3.5 km long way to the IP, which is called the beam delivery system (BDS). The main task of the BDS is focusing of the beams to ensure the required luminosity, collision of the beams and transporting the spent beams into the beam extraction line. Therefore, along the BDS a lot of quadrupole and dipole magnets for adjustment and stabilization of the

beams are installed. To monitor the performance of the BDS, the BDS is equipped with tools for measuring the beam position, emittance and polarization. A four laser beam setup in horizontal and vertical direction is planned to measure the beam size with a precision of $1\,\mu\text{m}$. Herein, the photons of the lasers interact with the electrons. The Compton-scattered photons can be detected downstream and give information about the size of the beam. Afterwards a Compton polarimeter is planned, which measures the beam polarization. Detailed information on the measurement principle can be found in [89].

The last 500 m of the BDS are used for the final focussing. The beam size is required to be in the order of a few nanometers. For focussing of the beam quadrupoles are used. For correction of chromatic aberrations, caused by the system of electromagnetic lenses, sextupoles are used. At the IP the beams collide with a crossing angle of 14 mrad. The crossing angle is used to generate enough space for the spent beams. In order to compensate this angle and to ensure head-on collisions crab cavities are used. They rotate the bunches by 7 mrad for each bunch. After the collision the bunches are highly disrupted. A corresponding beam optics guides the bunches to the beam dumps. The beam dumps are 11 m long high pressure water tanks and are already designed for 1 TeV operation.

3.3 The Physics case

The physics program of the ILC focusses on precision measurements. A detailed summary on the physics cases of the ILC can be found in [73]. The main part of this thesis deals with the Higgs self-coupling measurement at the ILC, therefore in this section the measurements of the properties of the Higgs at the ILC will be discussed. Since the top quark takes a special role in the Standard Model, due to the strongest coupling to the Higgs boson, the physics of the top quark at the ILC will be treated here as well.

An overview on the most relevant processes at the ILC, depending on the center-of-mass energy $\sqrt{s}$ is displayed in tab. 3.1.

3.3.1 Higgs Physics

In order to achieve a complete picture of the electroweak symmetry breaking, the properties of the Higgs boson play a key role. To determine the properties of the Higgs boson there are two production channels available at the ILC. Below 450 GeV center-of-mass energy the Higgs-strahlung $e^+e^- \rightarrow ZH$ and for higher energies, the WW fusion process $e^+e^- \rightarrow \nu\bar{\nu}H$ is the dominating production channel. A thorough discussion about the Higgs can be found in [90] and an overview in [35].

To determine the Higgs mass, the recoil mass offers a model-independent analysis. In case of the Higgs-strahlung the decay products of the Z boson together with the precise knowl-

$\sqrt{s}$ [GeV]	Reaction	Physics goal
91	$e^+e^- \rightarrow Z$	ultra-precision electroweak
160	$e^+e^- \rightarrow WW$	ultra-precision W boson mass
250	$e^+e^- \rightarrow ZH$	precision Higgs-coupling

	$e^+e^- \rightarrow t\bar{t}$	top quark mass/width
350-400	$e^+e^- \rightarrow WW$	precision W boson couplings
	$e^+e^- \rightarrow \nu\bar{\nu}H$	precision Higgs couplings

	$e^+e^- \rightarrow f\bar{f}$	precision search for Z'
	$e^+e^- \rightarrow t\bar{t}$	top quark couplings
500	$e^+e^- \rightarrow t\bar{t}H$	Higgs couplings to top
	$e^+e^- \rightarrow ZHH$	Higgs self-coupling
	$e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}$	search for Supersymmetry/Dark Matter
	$e^+e^- \rightarrow AH, H^+H^-$	search for extended Higgs states

	$e^+e^- \rightarrow \nu\bar{\nu}HH$	Higgs self-coupling
700-1000	$e^+e^- \rightarrow \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \rightarrow \nu\bar{\nu}t\bar{t}$	composite Higgs & top
	$e^+e^- \rightarrow \tilde{t}\tilde{t}^*$	search for Supersymmetry

Table 3.1 – Overview of the most relevant processes at the ILC at different center-of-mass energies. Independently of the precise measurements, the ILC is also suitable for discoveries of physics beyond the Standard Model. The table is taken from [73].

edge of the initial state can be used to reconstruct the Higgs mass. Herein, the leptonic decay of the Z boson provides the highest precision for the reconstruction, as discussed in [91]. The approach of the recoil mass additionally offers the possibility to measure directly invisible decays of the Higgs boson, which opens the door to searches for physics beyond the Standard Model. But the biggest advantage of this model-independent analysis is the fact that this method doesn't need further assumptions on the couplings and decays of the Higgs.

The requirements for the ILC on the precision of the measurement of the Higgs boson couplings to Standard Model particles are on the percent level or even below to distinguish between the Standard Model and theories beyond the Standard Model, like the Minimal Supersymmetric Standard Model (MSSM) [92]. The ILC will be capable to reach an accuracy for the total width of the Higgs boson of 1.1% [90] by considering all possible measurements at the ILC.

As mentioned earlier, the measurement of the Higgs self-coupling plays a key role in the understanding of the electroweak symmetry breaking mechanism. Also, here the precision of the measurement is a crucial parameter, since the value of the Higgs self-coupling might indicate new physics. This was discussed in more detail in sec. 2.4. But even in the clean environment of the ILC this measurement is very sophisticated, since the cross sections of the processes $e^+e^- \rightarrow ZHH$ and $e^+e^- \rightarrow \nu\bar{\nu}HH$ are very small.

3.3.2 Top Physics

The top quark is the heaviest known elementary particle. Since it couples strongest to the Higgs boson, the top mass becomes a very important parameter for the understanding of the electroweak symmetry breaking, because the loop contributions from the top quark in the Higgs sector have the greatest impact. To measure the couplings of the top quark to the Higgs boson, the process $e^+e^- \rightarrow t\bar{t}H$ can be studied, for $\sqrt{s} \geq 500$ GeV. The determination of the top mass is more challenging, because the theoretically well defined quantity, the pole mass, cannot be related directly to the measurement of the top mass. Therefore theoretical uncertainties have to be taken into account and these uncertainties influence the precision of the measurement. Anyhow, in case of the ILC a precision of $\delta m_t = 100$ MeV can be achieved for a threshold scan of $t\bar{t}$ at $\sqrt{s} \sim 350$ GeV [93], which includes theoretical and systematic uncertainties. Moreover, the ILC offers an environment, which makes it possible to study the left-right asymmetry and forward-backward asymmetry of $t\bar{t}$ production [94].

3.4 The Detector concepts

Nowadays, modern collider experiments are working according to the four-eyes principle, which means that the physics community only speaks about a new discovery when

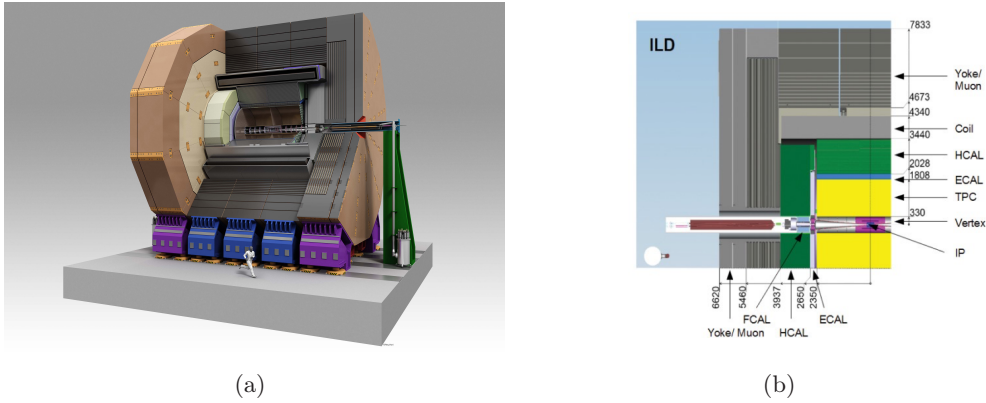


Figure 3.3 – a) 3d illustration of ILD, b) profile of ILD, where the interaction point is placed in the lower right corner. The dimensions are displayed in mm. Pictures are taken from [3].

at least two detectors confirm the discovery. For the ILC, there are two detector concepts foreseen, the **Silicon Detector** (SID) [76] and the **International Large Detector** (ILD) [76], both working at the same interaction point in a push-pull concept. Here, only the ILD will be discussed, since both parts of this thesis are related to the ILD.

3.4.1 The International Large Detector (ILD)

The ILD concept study is a fusion of the LDC¹⁴ and the GLD¹⁵[95, 96] concepts. The structure of ILD is typical for collider experiments. A technical sketch of ILD is depicted in fig. 3.3.

A detailed description can be found in [3]. Starting from the IP the single sub-detectors of ILD can be divided into:

Vertex Detector (VTX): The IP is surrounded by a multi-layer pixel vertex detector (VTX), realized in pure barrel geometry. The vertex detector provides a high impact parameter resolution with an optimized point resolution, which is better than $3\mu\text{m}$ and a minimized material thickness (0.15% of a radiation length per layer).

The VTX is enclosed by the Tracking System.

Tracking System: The tracking concept of ILD is based on a hybrid system. The main part of the tracking system is a Time Projection Chamber (TPC), which is surrounded by a so called silicon envelope (layers of silicon detectors). The silicon tracking is based on the concept of the SiLC Collaboration [97].

The **Time Projection Chamber (TPC)** is a large volume TPC with up to 224

¹⁴Large Detector Concept

¹⁵Global Linear Collider Detector

points per track. Besides an optimized 3d point resolution, the material inside the field cage and in the end-plate is minimized. This system is enclosed by a system of silicon detectors. First to improve the tracking performance with additional space points and second to provide additional redundancy between the TPC and the calorimeters.

In the barrel region between the VTX and the TPC, the **Silicon Inner Tracker (SIT)** is placed, and to bridge the gap between the TPC and the electromagnetic calorimeter, the **Silicon External Tracker (SET)** is placed. The overall detector system is based on silicon strip sensors. For occupancy reasons, the first two layers, which are closest to the interaction point are instrumented with pixel detectors.

Calorimeter: The calorimeter system follows after the TPC and can be distinguished into the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). The overall calorimeter system contains a cylindrical barrel system closed by two end caps. Herein, the ECAL is enclosed by the HCAL. Both calorimeters are designed as highly segmented sampling calorimeters. The high segmentation results in a unprecedented 10^8 readout channel system for the HCAL and a 10^{10} readout channel system for the ECAL [76]. Due to the large number of readout channels, the calorimeter system is optimized for an integration of the readout electronics into the sensitive layers.

The ECAL provides 30 samples in depth with a small transverse cell size of $0.5 \times 0.5 \text{ cm}^2$. The absorber material of the ECAL is tungsten and for the sensitive area different prototypes testing silicon diodes, scintillator strips or a combination of both are studied.

For the HCAL steel is used as absorber material. There are two readout technologies under consideration. The first option for the HCAL bases on an analogue readout system with $3 \times 3 \text{ cm}^2$ scintillating tiles, which is called the Analogue Hadron Calorimeter (AHCAL). The AHCAL is basis of the hardware studies of this thesis and will be presented in more detail in the next section.

The other option uses a gas-based readout with a $1 \times 1 \text{ cm}^2$ cell geometry in either a semi-digital or binary readout. For the active layers, two concepts are in development. The main development foresees the use of Glass Resistive Plate Chambers (GRPC) and the alternative technology considers the use of Micro Mesh Gaseous Structures (Micromegas).

Coil & Yoke: After the calorimeter system a superconducting coil is foreseen, which generates an axial B -field of 3.5 T and subsequently the final part of the ILD is given by an iron yoke, which returns the magnetic flux and operates as a muon detector/filter and as a tail-catcher to cover leakage from the HCAL.

3.4.2 Performance Requirements of ILD

The physics program of the ILC require an excellent performance of the detector systems. Determined by the physics need, the vertex detector provides an excellent flavor tagging, the trackers are essential for the recoil mass measurements and the calorimeter system have to separate W and Z boson di-jet final states. These goals are quantified in the optimization studies of ILD. Here, just a short overview will be given:

Jet energy resolution: Many measurements need the reconstruction of invariant masses from jets. Herein, the jet energy resolution takes a special place. Taking decays of W and Z bosons as benchmark criteria, ILD should be able to distinguish between W and Z di-jet final states with a precision of the reconstructed jets of

$$\frac{\sigma_E}{E} = 3 - 4\% \quad (3.8)$$

In comparison, the required jet energy resolution of ILD has to be improved by a factor of 2 compared to the jet energy resolution of the last lepton collider LEP¹⁶ at CERN. For instance, the jet energy resolution at the ATLAS experiment accounts $\sim 10\%$ [98] and better than 10% for a 100 GeV jet at the CMS experiment [99]. In order to reach such an excellent jet energy resolution, ILD pursues the Particle Flow Algorithm (PFA), which will be introduced in sec. 4.3.

Momentum resolution: Another crucial criterion for the measurements at ILD relies on a very precise tracking system. Herein, ILD demands a tracking system with a momentum resolution of

$$\sigma_{1/p_t} = 2 \times 10^{-5} \text{ GeV}^{-1} \oplus \frac{1 \times 10^{-3}}{p_t \sin(\theta)}. \quad (3.9)$$

p_t represents the transverse momentum.

Heavy flavor tagging: The performance of flavor tagging is a crucial criterion for ILD. Many measurements, like measurements of the Higgs couplings to Standard Model fermions, are dependent on an excellent b -tagging performance. For instance, the separation between $H \rightarrow b\bar{b}$, $H \rightarrow c\bar{c}$ and $H \rightarrow \tau^+\tau^-$ is needed for these measurements. But also the top quark measurements are a point of interest in the ILC physics program, because top quarks are decaying predominately into b quarks and W bosons. In order to meet the requirements, the performance of an excellent flavor tagging depends on the precision in the reconstruction of secondary vertices. This requirement can be formulated in the design goal of the impact parameter resolution as

$$\sigma_{r,\phi} = 5 \mu\text{m} \oplus \frac{10}{p(\text{GeV}) \sin^{3/2}(\phi)} \mu\text{m} \quad (3.10)$$

¹⁶Large Electron Positron Collider, operated from 1989 - 2000 with a center-of-mass energy of up to 209 GeV

4 Calorimetry & Particle Flow

Since the hardware part of this thesis discusses a highly segmented hadronic calorimeter prototype for ILD, this chapter emphasises the basics of calorimetry. In sec. 4.1 the basic physics of interactions of particles with matter will be discussed and subsequently the detection methods to measure the interaction products. In sec. 4.2 different calorimeter concepts and some key parameters for calorimeters will conclude this chapter. The approach of particle flow calorimetry will be discussed in sec. 4.3 and the requirements for particle flow in sec. 4.4.

4.1 Interaction of Particles with Matter

After the collisions of the beams, the created particles are passing through the detector. These particles can be detected in the sub-detector systems of the detector. For the detection the sub-detector systems can advantage of the interactions that a particle can undergo. The different processes can be used to measure the properties of the particles, like the energy and momentum. In general, these processes can be distinguished into ionization, bremsstrahlung, photon scattering, nuclear reactions and weak interactions. The following sections will discuss these processes. Herein, a distinction is made between electromagnetic and hadronic interactions. The description is oriented on [100–102].

4.1.1 Electromagnetic Interactions in Matter

Electromagnetic interactions describe interactions of charged particles. The charged particles are separated in two classes, the electrons/positrons and heavier particles, like muons and charged hadrons. Heavy particles lose their energy primarily by ionization processes, while electrons and positrons are losing their energy primarily by bremsstrahlung.

4.1.1.1 Ionization

Inelastic scattering of heavy particles with shell electrons is the dominant contribution for the ionization process. Herein, energy is transferred from the incoming particles to the electrons of the material. In certain circumstances the transferred energy is bigger than the binding energy of the atom and the electron can escape, with the result of an

ionized atom and a free electron. The energy transfer through ionization is described as mean energy loss dE per path length dx for a particle by the *Bethe-Bloch* equation [103]:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \quad (4.1)$$

K is $\approx 0.307 \text{ MeV cm}^2 \text{ mol}^{-1}$. It is a constant term containing Avogadro's number. Z and A are the atomic number and atomic mass of the material, T_{max} is the maximum kinetic energy transferred in a collision, I the ionization constant of the material, m_e the electron mass and δ a term for density correction at higher energies. In fig. 4.1 the average energy loss of positively charged muons in copper is depicted. At low energies the $1/\beta^2$ term is dominating, while at higher energies the $\ln \gamma^2$ term gets dominant. The increase of the energy loss at higher energies is a relativistic effect. In case of a further increasing to higher energies, besides a relativistic effect the electric field of the charged particles experiences a flattening which results in the polarization of the material [101]. This effect is considered by the density correction term δ . A minimum at $\beta\gamma \approx 3 - 4$ is visible between the decrease of the energy loss, described by $1/\beta^2$ and the relativistic increase. Particles in this range are depositing a minimum amount of energy in the material and therefore they can penetrate deep into the material. They are called *minimum ionizing particles* (MIP). In general, MIPs are a very good candidate for calibration measurements, due to their predictable energy deposition and their high penetration range. Herein, muons are often taken, because their high penetration range allows them to pass a whole detector. At very high energies (above $\beta\gamma \approx 1000$) radiation processes become dominant, while below $\beta\gamma \approx 0.1$ additional corrections have to be considered.

Different particles with the same momentum can be identified by their dE/dx , due to its $\beta\gamma$ dependency. Their masses cause a shift of the curve in fig. 4.1, because different masses cause different $\beta\gamma$ values. Since

$$\beta\gamma = \vec{p}/m \cdot c \quad (4.2)$$

considers the relativistic momentum $\vec{p}$, the mass m of the particle and the velocity of light c .

4.1.1.2 Bremsstrahlung

As mentioned above, electrons and positrons take a special role in the interaction with matter, because they lose their energy primarily by bremsstrahlung. The electrons and positrons emit electromagnetic radiation from the interaction with the electric fields of the material. In a classical description this process can be understood as an acceleration of the particles in the Coulomb field of a nucleus, and accelerated particles emit photons. For energies typically below 10 MeV, the overall contribution of bremsstrahlung to the

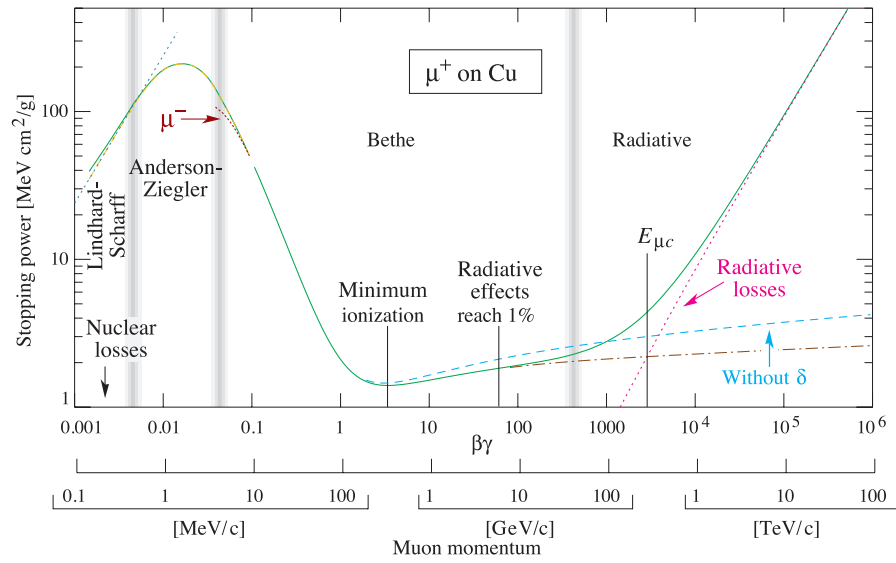


Figure 4.1 – Transferred energy, here displayed as stopping power ($\langle dE/dx \cdot 1/\rho \rangle$), from positive muons to the penetrated material, in this case copper, as function of the muon momentum. The vertical lines indicate boundaries between different approximations. The solid curve displays the total energy loss. For energies in the range $\approx 6 \text{ MeV} - 60 \text{ GeV}$, dE/dx is dominated by the ionization process, described by the Bethe-Bloch equation. The dashed lines indicate an idealistic behavior of the energy loss under certain assumptions, see text. Figure is taken from [101].

energy loss in material is small compared to the ionization process, but above 10 MeV this process gets relevant. The energy at which the energy loss via bremsstrahlung is equal to the energy loss via ionization is defined as critical energy E_C (in fig. 4.1 E_C is displayed for muons as $E_{\mu c}$):

$$\left(\frac{dE}{dx}(E_C)\right)_{rad.} = \left(\frac{dE}{dx}(E_C)\right)_{ion.} . \quad (4.3)$$

For energies above E_C the bremsstrahlung process is dominating. Both processes depend on the atomic number Z of the material:

$$\text{ionization : } \sim Z \cdot \ln E/m \quad (4.4)$$

$$\text{bremsstrahlung : } \sim Z^2 \cdot E/m^2 \quad (4.5)$$

therefore E_C is different for different materials. For instance, for electrons in iron E_C is at 21.04 MeV [102].

4.1.1.3 Photon Scattering

The term photon scattering includes all interactions of photons in matter. Depending on the energy it can be distinguished between the electron-positron pair production, the photo-electric effect and the Compton effect.

Most important in particle physics is the electron-positron pair production. For the pair production it is necessary that the photon energy is above twice the rest mass of the electron. Here, the interaction of a photon with the electric field of an atomic nucleus or a shell electron is responsible for the conversion into e^+e^- .

At lower energies photons lose their energy primarily via the photo-electric effect, where the photon will be absorbed by a shell electron. If the energy of the photon is large enough, the shell electron becomes free and the kinetic energy of the electron is the energy of the photon subtracted by the binding energy.

In case of the Compton effect, the photon scatters on quasi-free electrons, only loosely bound in the outer shells of an atom. If the energy of the photon is high enough, the shell electrons of the material are considered as quasi free particles, where the binding energy gets negligible. The photon transfers a fraction of its energy in an elastic scattering with the shell electron. The cross-section for this process is proportional to the atomic number Z of the material.

4.1.1.4 Electromagnetic Shower

The process of bremsstrahlung and the process of pair production are causing, in combination, the generation of an electromagnetic shower. In this case both processes are alternating, so that in the end the whole energy of the incoming particle is deposited

by ionization in the material. For example, to start a shower either a high energetic incoming photon converts into an electron-positron pair or an incoming electron/positron radiates a photon. Independent of the shower start, basically for the shower development is that the photons convert into electron-positron pairs, which in turn emit photons via bremsstrahlung. Therefore, high energetic electrons lose their energy in matter by bremsstrahlung and high energetic photons by electron-positron pair production. This process repeats until the energy of the electrons and positrons are below the critical energy. The whole development of such a cascade is a statistical process, in which a common scale for the description of an electromagnetic shower has shown to be very helpful. The radiation length X_0 describes the distance after which a high energetic electron has lost all but $1/e \approx 63.2\%$ of its energy by traversing through matter. In an approximation it can be expressed as

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1) \ln(287/\sqrt{Z})}. \quad (4.6)$$

Starting with a photon with the energy E_0 entering matter, the generation of a pair of e^+e^- is reached after a mean free path of λ_{pair} , which relates to the radiation length as

$$\lambda_{pair} \simeq \frac{9}{7} \cdot X_0 \quad (4.7)$$

and the electron, respectively the positron, get an energy of $E_0/2$. Besides the mean free path of a photon to convert into an e^+e^- pair, the electrons or positrons starts immediately by traversing matter to emit photons via bremsstrahlung.

The shower develops a broadening along the beam axis, caused by the angle between the electron and positron due to the pair production. Multiple scattering and the emission of bremsstrahlung photons are causing a further deflection from the beam axis. To describe the transversal development of an electromagnetic shower the *Molière radius* R_M is used [100]:

$$R_M \approx \frac{21 \text{ MeV} \cdot X_0}{E_C}. \quad (4.8)$$

E_C is the critical energy (see eq. 4.3). Below E_C the development of the cascade is stopped. In general, with E_C , X_0 and R_M an electromagnetic cascade can be described very well.

4.1.2 Hadronic Interactions in Matter

Besides the electromagnetic processes for charged particles and photons, also hadronic processes can take place, if the particle participates in strong interactions. This is the case for all charged and neutral hadrons, because they consist of quarks and gluons. Hadrons that pass through matter can either scatter elastically or inelastically with

the nuclei of the material. In case of elastic processes the hadron transfers a part of its momentum to the nucleus, while changing its direction. But more important are the inelastic scattering processes. Herein, the incoming hadron hits the nucleus in a way that one or both particles change their identity, while generating several secondary particles. Just as in case of electromagnetically interacting particles, also a strongly interacting particle can produce a shower in matter. Hadronic showers behave similarly to electromagnetic showers (in which the length and density vary greatly), except that they are subject to bigger statistical fluctuations, due to the fluctuations in the particle content and the interactions, which they undergo. The diversity of interactions in case of hadronic showers is much bigger than in case of electromagnetic showers.

Analog to the radiation length for electromagnetic showers a nuclear interaction length λ_{had} can be defined [100]:

$$\lambda_{had} = \frac{A}{N_A} \cdot \frac{1}{\sigma_{inelas.} \cdot \rho} \quad (4.9)$$

The interaction length is given by the atomic mass A , the Avogadro number N_A , the cross-section for inelastic scattering $\sigma_{inelas.}$ and the density of the medium ρ . λ_{had} describes the average distance for a hadron traversing through matter, before it undergoes a strong interaction.

In general λ_{had} is bigger than X_0 , which extends the length of hadronic showers compared to electromagnetic showers.

Most of the generated secondary particles in inelastic interactions are η mesons or pions ($\pi^\pm, \pi^0$). The dominant decay of π^0 is $\pi^0 \rightarrow 2\gamma$ and is almost instantaneous, due to its electromagnetic nature. Therefore, as sub-component of a hadronic shower nearly always an electromagnetic shower is generated. Besides the generation of mesons, protons and neutrons are released from the hit nucleus. The dominant processes to de-excite the hit nucleus are spallation, fission and the radiation of high energetic photons.

Spallation: A highly energetic, strongly interacting particle causes a transformation of the nucleus. In this process several other elementary particles, α particles and bigger nucleus fragments will be emitted. After the spallation, the nucleus is in an excited state and will be turned back into the ground state with secondary processes like nucleus evaporation. The excited nucleus emits fragments as long as the excitation energy is bigger than the binding energy of the nucleus fragments. These secondary particles can have enough energy to start a new nuclear interaction.

Fission: After spallation or capturing of a neutron the fission process is possible. The nucleus decays into two almost equal nuclear fragments. Coincidentally photons and neutrons will be emitted. The fission process depends on the used element of the material, e.g. uranium has a high ability for fission.

Radiation of high energetic photons: If the energy of the nuclei drops below the bind-

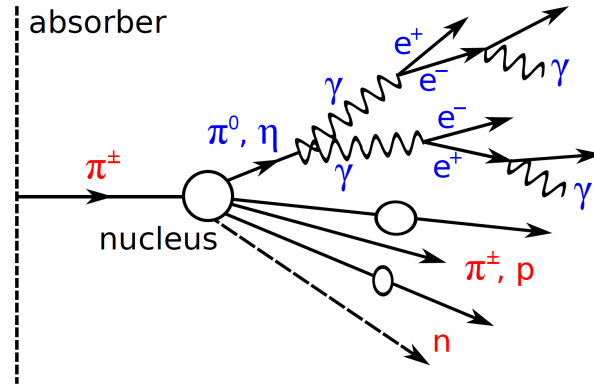


Figure 4.2 – Schematic of a hadronic cascade. The inelastic scattering of a hadron with a nucleus produces a variety of secondary particles. The generated neutral mesons (e.g. π^0) contribute to the electromagnetic fraction, due to their decay into 2 γ 's. The generated hadrons traverse the material until they interact strongly and generate further secondary particles. Picture is taken from [104].

ing energy of the nucleons, the residual excitation is released by gamma radiation.

Most of the deposited energy from hard interactions is released on a time scale of $\sim 10^{-18}$ s. Between the hard interactions charged particles will lose their energy additionally by ionization. Since hadrons are much heavier than electrons, the ionization density can be much larger. For illustration, fig. 4.2 shows the scenario of a hadronic interaction, where a charged pion enters matter and hits a nucleus. The blue marked particles indicate the generated electromagnetically shower fraction and the red marked particles the hadronic shower fraction.

4.1.3 Invisible Energy and Neutral Hadrons

In nuclear processes, a part of the energy is deposited in a way that cannot be measured in a calorimeter, so called invisible energy. Primarily, invisible energy means the deposition of energy as nuclear binding energy or target recoil, but also other things are often referred as invisible energy.

For instance, neutrinos can be generated in hard interactions. These particles are non-detectable and often also referred as escaped energy. Nevertheless, generated neutrinos make the prediction of a hadronic shower even more difficult.

A special case is represented by neutrons and K^0 s, which are neutral hadrons. Also π^0 are neutral hadrons, but they decay immediately decay into photons, which leads to electromagnetic cascades. Therefore π^0 s are not discussed here.

Neutrons and K^0 s have to be treated separately, since their cross-section is very small. Due to their neutral charge they don't participate in the electromagnetic interaction, so

they have to get very close to the atoms of the absorber material to interact with the strong force with the nucleus. As a result, the particles can travel long distances through the detector before they participate in interactions. Due to their long travelled distances, these particles can generate clusters in the detector, which are far away from the point where they were produced. These clusters are potential candidates for the confusion term of the particle flow approach (cluster splitting), which will be discussed in sec. 4.3.

4.2 Calorimeters

After the introduction of the electromagnetic and strong interactions with matter, it will be discussed how the energy of the incoming particles in the calorimeter can be measured. At first, it should be mentioned that for present detectors, the detection principles are based on the electromagnetic interactions of the ionization. The basic idea for a calorimeter is that in case of an interaction with the detector material, the original particle loses energy and in the ideal case it is absorbed completely, which makes dense materials for calorimeters necessary to cover the whole particle shower. To determine the energy it is used that parts of the energy deposited in the material can be transformed into electrical signals, which are proportional to the original energy loss.

To measure the energy, typically two calorimeter systems are used in one detector, due to the different behavior of electromagnetic and hadronic showers. The electromagnetic calorimeter is optimized for electromagnetic showers, caused by electrons, positrons or photons, while the hadronic calorimeter is optimized for hadronic showers. Here, the shower-producing particles are charged or neutral hadrons.

Calorimeters in general use that the generated number of particles N in a shower is proportional to the energy of the incoming particle $E_{incoming}$ and the statistical error of N is determined by the poisson statistic with $\sqrt{N}$. From statistical considerations it is expected that

$$\sigma_E \propto \sqrt{N} \propto \sqrt{E} \quad (4.10)$$

Calorimeters are classified into homogenous and sampling calorimeters according to the choice of materials to perform the two tasks of absorption and signal creation.

Homogeneous calorimeters: Homogeneous calorimeters are built of a single material, which performs both tasks: It absorbs the energy of the particle and generates a signal which is proportional to the energy loss of the particle. Thus homogeneous calorimeters offer the possibility to restore the whole energy of a particle in the medium (if it is stopped completely in the material). One possible material which performs both tasks is lead glass. One homogeneous detector, for instance, is the electromagnetic calorimeter of the CMS detector with lead tungstate crystals (PbWO_4).

Sampling calorimeters: Sampling calorimeters fulfill the tasks of absorbing and detecting in alternating structures of material. Thus, the determination of the energy loss is sampled by the active parts in between the absorbers, hence the name of *sampling* calorimeter. For the absorber very dense materials with a high atomic number are preferred, which are mainly responsible for the shower development. Herein predominantly iron, tungsten, lead or copper are used, while for the energy measurement of the incoming particle so called active components are responsible. Different geometries for the active components are possible, like fibers or tiles, but the typical structure are active layers between layers of absorber. These active layers should provide a high ability to generate a signal from traversing particles. The thickness of the active layers is usually given in units of radiation length (for electromagnetic calorimeters) or interaction length (for hadronic calorimeters). The active layers are realized with organic or inorganic scintillators, RPCs or silicon or many other options. The choice for the active material depends on the needed quality, complexity and radiation resistance.

The sampling structure allows a much more compact construction of the calorimeter which is often preferred in high energy physics. Additionally, the alternating structure of the absorber and active layers offers practically a better space resolution of the showers and a better particle identification compared to homogeneous calorimeters. But the calorimeter can only detect energy that is deposited in the active layers, which result in a much better energy resolution for homogenous calorimeter¹. This follows directly from the higher number of detected particles and eq. 4.10. The deposited energy in a sampling calorimeter varies between absorber and active layer from event to event, which causes fluctuations in the measurement and therefore influences the energy resolution of the calorimeter. These fluctuations are called *sampling fluctuations* and also worsen the energy resolution.

Due to the fact that in general, the nuclear interaction length is much bigger than the radiation length in most materials, the size of hadronic calorimeters is significant bigger than electromagnetic calorimeters. Therefore hadronic calorimeters are normally build as sampling calorimeters.

4.2.1 Calorimeter Response to Electrons and Hadrons

The calorimeter response is usually proportional to the energy of the incoming particle. This assumption can be very well confirmed in the case of an electromagnetic calorimeter, since electrons and photons are visible particles and can be detected. The calorimeter response for hadronic showers is more complex, since fluctuations in the electromagnetic fraction, the hadronic fraction and the invisible energy of the shower content lead to a

¹The much better energy resolution of homogenous calorimeters is often used in electromagnetic calorimeters.

different scaling between the detectable deposited energy and the shower energy.

The different deposited invisible energy in a hadronic shower and the fluctuations from event to event of the electromagnetic fraction of the shower yield to a different response of the calorimeter for a purely hadronic shower (h) compared to a purely electromagnetic shower (e) originating from a particle of the same energy. To evaluate the response of a calorimeter, the ratio

$$h/e = \frac{\epsilon_{vis}(h)}{\epsilon_{vis}(e)} \quad (4.11)$$

is used, with the measurable energies $\epsilon_{vis}(h)$ and $\epsilon_{vis}(e)$ for h and e of the energy of the incoming particle. This ratio is an intrinsic energy independent property of the calorimeter. Hence the signal for an electron differs from the signal of a hadron at the same energy. But h is a theoretical value which can not be determined directly, since hadronic showers include also electromagnetic showers.

To evaluate the response of the calorimeter, the ratio of π/e can be used, which is the ratio of the response of the calorimeter for a pion and an electron of the same energy. The π/e ratio is a function of the energy. To characterize hadron calorimeters independently of the energy, the h/e ratio can be inferred from π/e . The ratio is defined as

$$\langle \pi/e \rangle = \langle f_{em} \rangle + \langle f_h \rangle (h/e) = 1 - (1 - (h/e)) \langle f_h \rangle \quad (4.12)$$

$$\langle f_h \rangle = 1 - \langle f_{em} \rangle \approx (E/E_0)^{m-1}. \quad (4.13)$$

f_h and f_{em} are the fraction of hadronic and electromagnetic deposited energy compared to the whole shower energy. E is the energy of the incoming particle, E_0 is roughly the needed energy for inelastic collisions (for π 's E_0 is typically in the order of ≈ 1 GeV) and m a multiplicity factor for the production of π^0 in single collisions². Measuring $\langle \pi/e \rangle$ as a function of the energy E gives in principle $(1 - \langle h/e \rangle)E_0^{1-m}$. Since $1 - m$ is small and $E_0 \approx 1$ GeV, the ratio $\langle h/e \rangle$ can be determined directly.

If a ratio of $e/h = 1$ is reached, the calorimeter is called compensating, else the calorimeter is called non-compensating. A non-compensating calorimeter ($h/e \neq 1$) has a worse energy resolution than a compensating calorimeter, since the fluctuations in e.g. f_{em} from event to event are very big, which worsen the resolution. Therefore, it is the goal to reach a compensating calorimeter. A well-considered choice of absorber and active material allows an increase of the hadronic response, where in most cases the fraction of invisible detectable energy is decreased, e.g. with depleted uranium in the absorber material or increasing of the hydrogen content of the active material in form of organic scintillators. Uranium is appropriate to catch neutrons and therefore the decay products can be detected. Increasing the hydrogen content offers a higher momentum transfer between the particles. With a higher momentum transfer, particles can ionize

²Usually in the order of 0.80 - 0.87

the material more easily.

The ratio can also be tuned offline with software compensation, where an adequate weighting of the data will adjust the ratio.

4.2.2 Energy Resolution of Calorimeters

As mentioned above the number of generated particles N in a shower is proportional to the energy of the incoming particle, the statistical error of N follows the poisson statistic with $\sqrt{N}$, it can be assumed

$$N \propto E \Rightarrow \sigma_E \propto \sqrt{E} \Rightarrow \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \quad (4.14)$$

Therefore, the relative energy resolution gets better for higher energies.

Additionally, there are also losses of the shower, due to not-instrumented areas of the detector, where no detection can happen. This fraction is considered as a constant term in the relative energy resolution. Also electronic noise effects influence the overall energy resolution, these effects are independent of E , therefore they scale in the relative energy resolution with $\sim 1/E$. Summarized, the relative energy resolution for a calorimeter σ_E/E can be parametrized as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (4.15)$$

$$= \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2} \quad (4.16)$$

where $a/\sqrt{E}$ is the stochastic term, which describes e.g. sampling fluctuations, b/E represents electronic noise and background signals and is called the noise term, c is a constant term and represents inter calibration errors. The stochastic and noise terms become smaller for higher energies. Therefore, the resolution is limited at high energies by the constant term. On the other hand at low energies the resolution of the calorimeter is limited by the noise term and detection statistics.

4.3 Particle Flow and Jet Energy

In order to meet the physics goals for the ILC, the desired measurement resolutions, especially for the jet energy resolution require the use of a Particle Flow Algorithm (PFA). The design of ILD is based on this approach.

Particle Flow Algorithm bases on the idea, that instead of measuring the jet energy exclusively in the ECAL and HCAL, each particle is reconstructed by the detector component which gives the best resolution for the particle by employing pattern recognition algorithms [4, 105, 106]. The starting point for particle flow is the composition of jets [4].

On average, a jet consists of $\approx 62\%$ charged particles, $\approx 27\%$ photons, $\approx 10\%$ neutral hadrons and $\approx 1.5\%$ neutrinos. As mentioned before, in typical calorimetry all hadrons are reconstructed in the hadronic calorimeter. But the intrinsic poor energy resolution of the hadronic calorimeter limits the overall resolution, since the typical energy resolution for hadronic calorimeters is in the order of $> 55\%/\sqrt{E(\text{GeV})}$ [4]. The PFA exploits that all charged particles can be reconstructed by the tracking system. Therefore, the already mentioned highly segmented calorimeter system is needed to distinguish between the individual calorimeter clusters to sort the clusters from charged and neutral particles (charged particles can be assigned to corresponding tracks). A simplified working principle of the PFA is depicted in fig. 4.3. Due to the tracking system only the neutral hadrons of the jet (on average 10% of the energy) have to be reconstructed in the hadron calorimeter, since the charged particles are reconstructed in the tracker system and the electrons and photons are measured in the electromagnetic calorimeter. To demonstrate

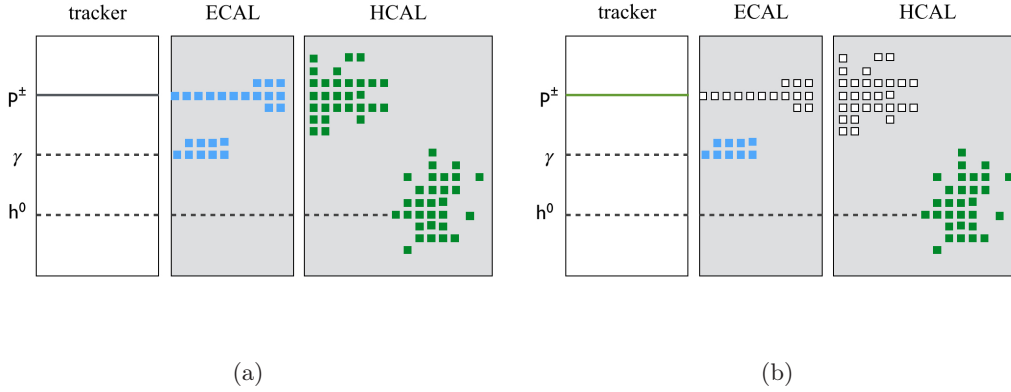


Figure 4.3 – Reconstruction principles: a) conventional calorimetry: charged particles $p^\pm$ and neutral hadrons h^0 are measured in the ECAL and HCAL (indicated by the blue and red colored clusters). Photons are exclusively measured in the ECAL (blue clusters in the ECAL). b) Particle Flow approach: $p^\pm$ is measured by the tracker (indicated by the green colored line), while only h^0 is measured in the HCAL.

the effect of PFA, an idealized example from [4] will be discussed, where no mismatching of the clusters is considered. Taking a hadronic calorimeter with an energy resolution of $55\%/\sqrt{E(\text{GeV})}$ in combination with an electromagnetic calorimeter with a resolution of $15\%/\sqrt{E(\text{GeV})}$ the overall jet energy resolution results to $19\%/\sqrt{E(\text{GeV})}$. The performance of the PFA depends on the so-called confusion, which summarizes mismatching of the calorimeter clusters. The confusion can be separated into:

- **Cluster Splitting:** Only a fraction of the energy deposition in the calorimeter is associated with the track of a charged particle. The remaining part of the cluster is recognized as a cluster of a neutral hadron. Both parts, the track energy and the energy fraction of the wrongly assigned neutral cluster goes into the energy

balance. This causes a double counting of the energy. The effect of cluster splitting is illustrated in fig. 4.4(a).

- **Cluster Merging:** Cluster merging refers to the case if the cluster of a neutral particle is so close to a charged particle cluster that it cannot be resolved. In the reconstruction then both clusters are merged and since the energy from the charged particle is determined by the track information, the energy of the neutral cluster is missed. This causes loss of energy. The effect of cluster merging is illustrated in fig. 4.4(b).

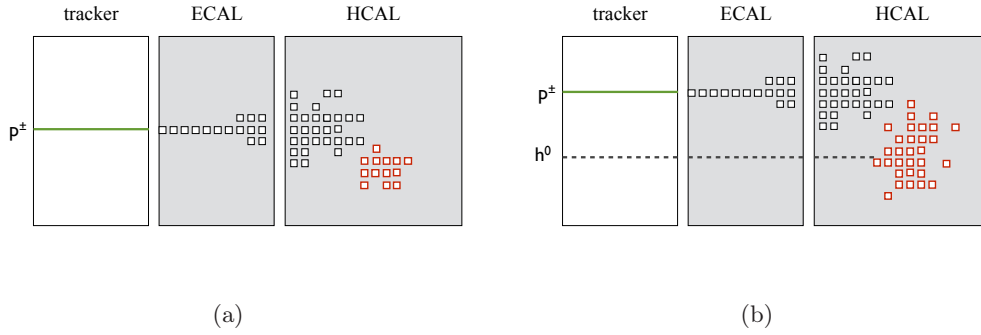


Figure 4.4 – Illustration of the PFA confusion. a) cluster splitting, if a fraction of a charged particle cluster is reconstructed as a neutral particle cluster (red marked cluster). This results in a double counting of the energy. b) cluster merging, if a neutral particle cluster (red marked cluster) is too close to a charged particle cluster and both clusters are merged together. This leads to a loss of energy in the reconstruction.

Since the PFA considers additional information from the sub-detectors for the reconstruction, the energy resolution of the tracker system, the electromagnetic calorimeter and the hadron calorimeter contribute to the total jet energy resolution according to the fractions of particles, measured in each sub-detector. But also wrong assignments from the confusion have to be considered. To improve the performance of a particle flow detector the confusion term σ_{conf} has to be minimized with a high segmentation of the calorimeter cells, as proposed for ILD. Additional other effects like the energy loss through leakage (σ_{loss}) or the effects of a detector threshold σ_{thr} have to be minimized [107]. Therefore, the overall jet energy resolution can then be decomposed as:

$$\sigma_{jet}^2 = \sigma_{h^\pm, l^\pm}^2 + \sigma_\gamma^2 + \sigma_{h^0}^2 + \sigma_{conf}^2 + \sigma_{thr}^2 + \sigma_{loss}^2 \quad (4.17)$$

$\sigma_{h^\pm, l^\pm}^2$ denotes the energy resolution for all charged hadrons and leptons, σ_γ^2 is the energy resolution for photons, $\sigma_{h^0}^2$ the energy resolution for neutral hadrons, the mixing of the deposited energy between neutral and charged hadrons is presented by σ_{conf}^2 and

imperfect reconstruction and geometric inefficiencies by σ_{loss}^2 . The confusion term limits the resolution in particle flow calorimetry at least for very high energies. At low energies the limiting factor is the intrinsic resolution of the hadron calorimeter, fig. 4.5 illustrates this. In addition, leakage effects play a role at higher energies, which are not included in the $60\%/\sqrt{E} \oplus 2.0\%$ curve.

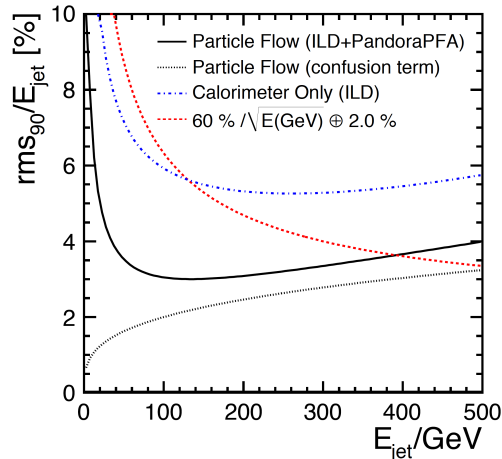


Figure 4.5 – The jet energy resolution obtained from Particle low Calorimetry. The confusion term is displayed as dotted line. The dashed curve indicates the jet energy resolution achieved with traditional calorimetry ($60\%/\sqrt{E(\text{GeV})} \oplus 2.0\%$). Figure is taken from [4].

4.4 Requirements for Particle Flow

The Particle Flow Approach has far-reaching consequences for the detector and in particular for the calorimeter system of the ILD. Crucial for the performance of the PFA is the fraction of the confusion σ_{conf} within the calorimeter system between the single particle contributions. In order to minimize σ_{conf} an unprecedented granularity of the calorimeter system is needed. Based on test beam data and detailed simulations, the needed granularity for the calorimeter system has been optimized. For the ECAL a segmentation of $1 \times 1 \text{ cm}^2$ or less for the cell size is necessary in order to meet the requirement of a jet energy resolution of less than 4% for jet energies between 45 and 250 GeV, see fig. 4.6(a). For the HCAL it is sufficient, especially for higher jet energies to choose a $3 \times 3 \text{ cm}^2$ segmentation for the scintillator tile size, see fig. 4.6(b). This high segmentation result in an electromagnetic calorimeter system with 10^8 readout channels and a hadronic calorimeter system with 10^7 readout channels. The unprecedented large number of readout channels sets requirements to the readout electronics.

The amount of readout channels results in a high data volume, therefore in order to reduce the data volume the calorimeter system is planned to operate in auto-trigger mode

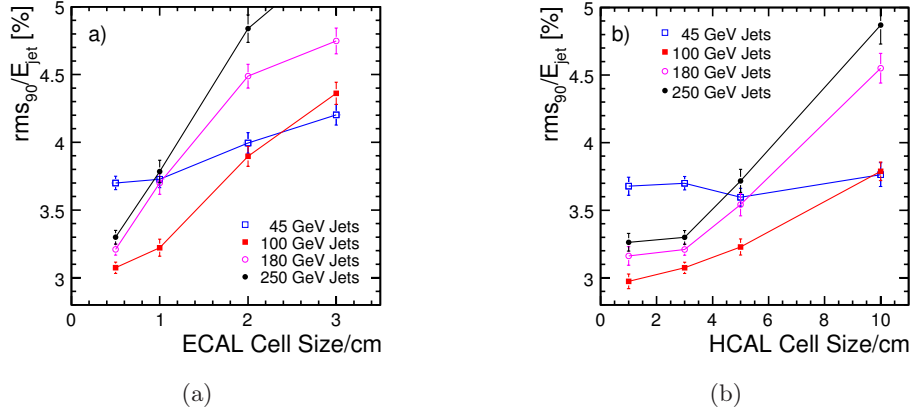


Figure 4.6 – a) the dependence of the jet energy resolution (rms_{90}) on the segmentation for the ECAL. b) the dependence of the jet energy resolution (rms_{90}) on the HCAL segmentation. Pictures are taken from [107].

with zero suppression.

Another aspect is that the large number of readout channels will have an impact on the calibration strategies of the calorimeter system. Herein, a homogenous response of the channels is required in terms of a fast and efficient calibration.

The amount of readout channels also requires an integration of the readout electronics inside of the calorimeter system, as a calorimeter system with external readout electronics and 10^8 readout channels is not feasible.

Important for the performance of the PFA and in particular for the jet energy resolution is a minimum of material in front of the calorimeter. This requires the avoidance of an extra cooling system in the detector. A calorimeter system with integrated read-out electronics without an extra cooling system can only work if it is operated in power pulsed mode. The use of a power pulsed detector is feasible due to the specific design of the ILC bunch train structure (see sec. 3.2.1). Whereas a power pulsed detector at the LHC is not possible. The concept of power pulsing prevents a heating of the detector and reduces the power consumption about a factor 100.

Especially the auto-trigger mode and the concept of power pulsing will be discussed in more detail in sec. 6 in the context of an engineering prototype of a hadronic calorimeter system.

5 The Analogue Hadronic Calorimeter Engineering Prototype

After the introduction of ILD and within the presentation of the Particle Flow approach, the importance of the calorimeter system was underlined. The CALICE collaboration develops calorimeter prototypes, which meet the requirements of the Particle Flow Approach (sec. 4.4). One of these prototypes is the analogue hadronic calorimeter prototype (AHCAL), this prototype is the main focus of the hardware part of this thesis. After an introduction of the CALICE collaboration (sec. 5.1), the AHCAL prototype will be introduced in sec. 5.2. Subsequently, the signal chain for the detection of deposited energy in the calorimeter will be subject in sec. 5.3. Of particular note is the auto trigger and powerpulsing function of the detector, since these functions will be focus of the hardware analysis in the following chapter. Finally, the calibration procedure for the prototype in sec. 5.5 concludes the chapter.

5.1 The CALICE Collaboration

The CALICE collaboration develops highly granular calorimeter systems optimized for particle flow algorithm. The CALICE collaboration consists out of 39 institutes from 12 countries. The aim is to develop calorimeters with high granularity in both longitudinal and transversal direction. Thus for both, the electromagnetic and the hadronic calorimeter, physics prototypes have been developed to operate in test beam environments and to prove the feasibility and capabilities of the concepts. For the hadron calorimeter besides the development of the AHCAL, the CALICE collaboration also spends efforts in the development of a digital hadronic calorimeter and a semi-digital calorimeter:

The Digital Hadron Calorimeter (DHCAL): The DHCAL is a concept for the planned SiD, the second detector concept for the ILC [108, 109]. The DHCAL realizes a calorimeter based on resistive plate chambers (RPC). The RPC generates an avalanche due to high voltage at the electrodes. The linear relation between number of hits and tracks in the calorimeter is used. To reach the needed performance the calorimeter cell size has to be less than $1 \times 1 \text{ cm}^2$. Due to the small size for the calorimeter cells the digital hadronic calorimeter will take around 40 million channels.

The Semi-Digital Hadron Calorimeter (SDHCAL): The SDHCAL is a prototype based on gaseous sensors. Even two concepts are in development, one based on Glass Resistive Plate Chambers (GRPC) and a second one on Micro mesh gaseous structure (Micromegas) [110]. The prototype with GRPCs is similar to the DHCAL, it contains 48 active layers and 48 GRPCs. Each GRPC has a size of 1 m^2 . The signal is read out by pads, each with a size of 1 cm^2 .

Alternatively for a gaseous detector a micro-pattern technology (Micromegas) can be used. The Micromegas consists out of a conductive mesh which is held a few micrometers on top of an anode plate (amplification gap) and surmounted by a cathode (drift gap). The gas in the drift gap will be ionized by an incident charged particle. The released electrons create an avalanche in the amplification field region in the amplification gap. This structure guarantees a full efficiency for MIPs [110, 111].

5.2 The AHCAL Engineering Prototype

The development of a sophisticated detector like the AHCAL requires several development steps. In a first step, a physics prototype [112] has demonstrated the successful performance of the PFA in a scintillator readout technology implemented in a steel sandwich calorimeter. The successful operation of the physics prototype of the AHCAL is documented in [113–115].

In a second step, the technical challenges of such a detector as part of a collider detector have to be solved, therefore an engineering prototype is part of the development process to demonstrate the feasibility for ILD. This prototype is based on a full integration of the readout and calibration electronics into the active layers of the calorimeter and is described in detail here.

5.2.1 Layout of the AHCAL

The concept of the AHCAL is based on a steel-sandwich structure where two different materials are used to absorb and detect incident particles. The active material are $3 \times 3\text{ cm}^2$ scintillator cells, which are read out by silicon photomultipliers (SiPM). To fulfill the needs for a calorimeter based on PFA, the AHCAL for ILD will include 8 million calorimeter cells/readout channels. In most calorimeters of existing detectors the readout electronics is placed outside of the detector and each calorimeter cell is linked to the readout electronics via cables. 8 million readout cells can't be read out via single cables and a readout via cables will worsen the resolution of the detector due to the additional non-instrumented material caused by the cables. To reach the technical requirements a full integration of the readout electronics inside of the detector is needed. The main structure of the AHCAL for ILD is a segmentation of the hadronic calorimeter

into 2×16 sections in the barrel region, two segments along the beam axis and a 16 field segmentation in ϕ . Two endcaps enclose the hadronic calorimeter of ILD. Each section of the barrel contains up to 48 layers, each with a thickness of 3 mm scintillating material and 2.4 mm of readout electronics. Each layer incorporates ≈ 2600 scintillating tiles with a single cell geometry of $3 \times 3 \times 0.3 \text{ cm}^3$ including a silicon photomultipliers (SiPM) as readout device. The layers are supported by 16 mm stainless steel plates as absorber material. Within the layers no cooling system is foreseen to keep the calorimeter compact while minimizing the necessary size of the magnet coil. The drawing in fig. 5.1 illustrates the inner structure of the calorimeter system, which is surrounded by the magnet. The blue area depicts the ECAL and the green the HCAL. The alternating structure with the integrated readout electronics is displayed in the zoomed area.

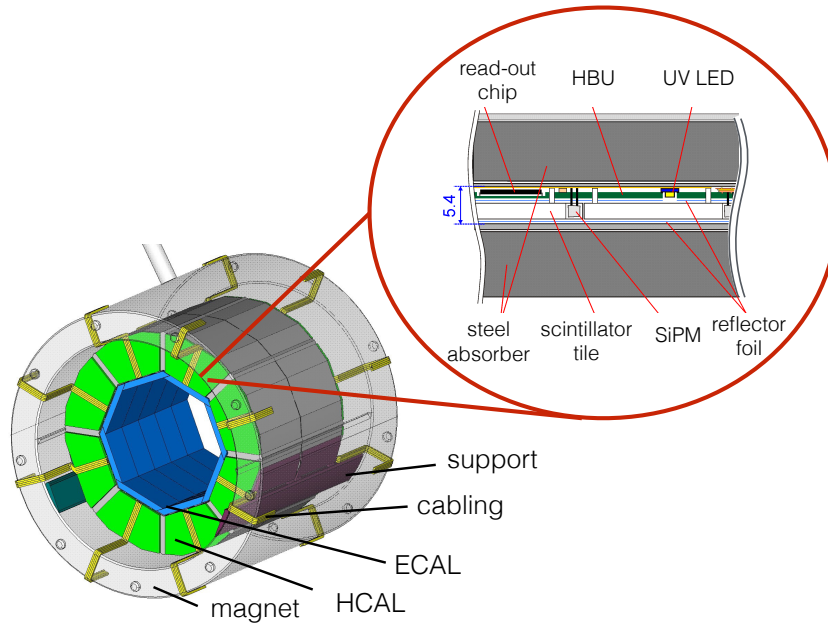


Figure 5.1 – Layout of the barrel calorimeter of ILD. The HCAL is shown in green, while the ECAL is displayed in blue. The whole calorimeter is surrounded by the magnet. The sampling structure with the absorber material is zoomed out to point out the integrated readout electronics with the scintillating tiles.

5.2.2 The Engineering Prototype for the CERN Test Beam 2012

The engineering prototype for the CERN test beam campaign in November 2012 consist of a one layer structure, depicted in fig. 5.2. Herein, the scintillator layer is subdivided into 576 calorimeter scintillator cells. The readout electronics of the layer of the engineering prototype provided 4 printed circuit boards, so called Hadron Calorimeter Base Unit (HBU), which will be discussed in sec. 5.3.3. Each HBU hosts 4 readout chips and has a size of $36 \times 36 \text{ cm}^2$. The four HBU's are subdivided into two slabs. An overview

on the engineering prototype can be found in [5, 116–118].

Fig. 5.2(b) shows a picture of the engineering prototype. Altogether the layer setup has a size of $72 \times 72 \text{ cm}^2$. In order to fit into current test beam absorber structures the readout electronic is placed on a $1 \times 1 \text{ m}^2$ big and 16 mm thick stainless steel absorber plate. Test beam extender boards have to be installed to have both the Detector Interface (DIF) board located outside and the HBUs centered. The first slab hosts the Central Interface board (CIB). The second slab is connected with the Side Interface Board (SIB) to the CIB. The CIB hosts units for the power supply, the calibration and the data transfer of the detector. The CIB and DIF will be discussed in sec. 5.3.3.

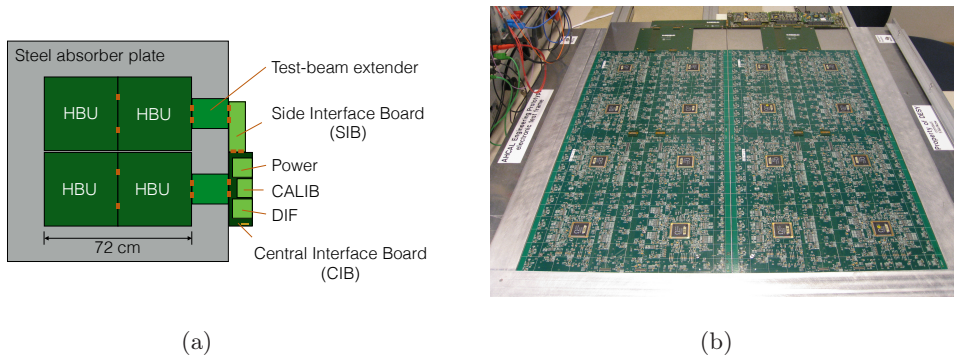


Figure 5.2 – a) technical sketch of the engineering prototype. In order to fit into current test beam absorber structures, the test beam extender board and SIB connects the HBUs with the CIB, which is the interface between inner-detector and the DAQ (see sec. 5.3.3). b) Photo of the engineering prototype.

5.3 Detection of Deposited Energy in the AHCAL

The signal chain of the detector to detect deposited energy is sketched in fig. 5.3. If a charged particle passes through the active layer it deposits energy, which leads to the emission of ultraviolet (UV) light in the scintillating tiles. The emitted UV light in the scintillator will be collected by a wavelength shifting fiber (WLS) and guided to a SiPM, which generates a proportional electronic signal. The signal will be registered by an ASIC (SPIROC2b) where storing, signal processing and digitization happens. The Data Interface Board (DIF) reads out the chip from where the data are passed on to an external PC. In the following the major components for the signal detection, as depicted in fig. 5.3, will be discussed.

5.3.1 Scintillator and Wavelength Shifting Fiber

The plastic scintillator tiles are the active medium of the AHCAL. If a particle (e.g. hadron) crosses the tile and deposits energy in the scintillator, it produces ultraviolet

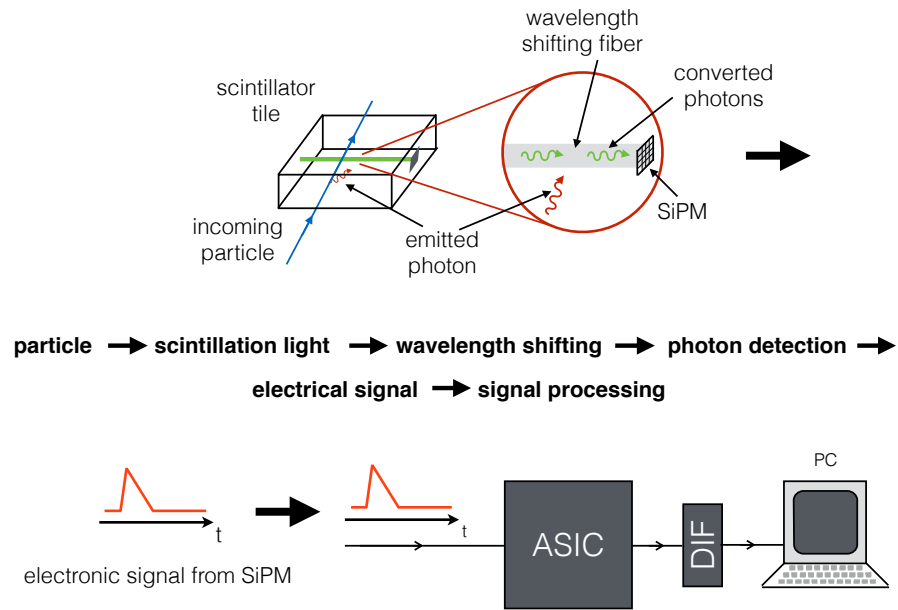


Figure 5.3 – Illustration of the signal chain in the AHCAL to measure deposited energy. A particle deposits energy in the scintillating tile. The generated photons are collected by a wavelength-shifting fiber. The shifted photons are guided to a SiPM, where photodiodes are generating an electrical signal. The signal is transferred to a readout chip. There, signal processing, storing and digitization happen. Via the DIF the data is lead to an external PC, where further data processing can be done.

light. The number of produced photons is proportional to the deposited energy. Scintillators can be distinguished into organic and inorganic. Since the scintillator used in the AHCAL is an organic scintillator, only organic scintillators will be discussed here. Plastic scintillator tiles are made out of polystyrene with additional scintillating additives. The working principle is that a charged particle excites the material, which results in the emission of photons. In plastic scintillators, the photon production is a molecular process, where the deposited energy (either by a charged particle or a photon) causes an excited state. The excess energy of this excited state is dissipated in the form of photons. The scintillator itself is transparent for the generated light from the excited state, since the probability for re-absorption of the photons is small. The emission spectrum of a typical scintillator shows a maximum at around 400 nm with a full width at half maximum of around 50 nm. In order to fit into the efficient spectral range of early SiPMs a green wavelength shifting fiber was inserted into the tile, which shifts the collected photons into the green spectral range. In addition, the WLS fiber can improve the uniformity of the light collection within the tile. Several setups for the WLS have been tested, because the collection efficiency of the photons depends on the integration of the fiber into the tile. Fig. 5.4 shows the different setups. The AHCAL engineering prototype uses the scintillator setup from fig. 5.4(c) for three reasons. First for longer WLS fibers attenuation effects become an issue, second also bending of the fibers causes light losses and third the alignment between SiPMs and fibers gets more sophisticated for bended fibers [119]. The current design of the AHCAL engineering prototype tile is depicted in fig. 5.4(c). The concept foresees that on one side of the fiber the silicon photomultiplier

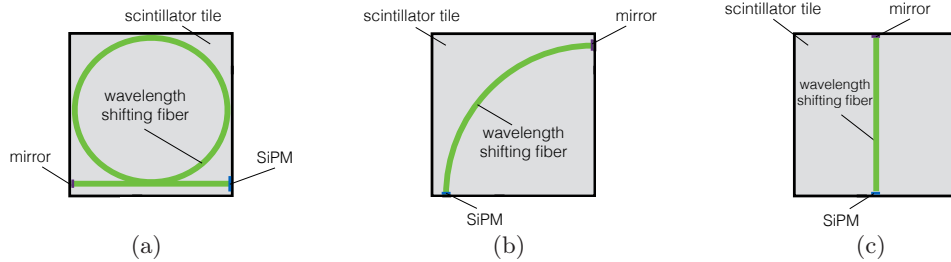


Figure 5.4 – Schematic of different scintillator/wavelength shifting fiber setups. a) with a circular placed fiber, b) with a quarter of WLS fiber and c) with straight aligned WLS fiber. All setups incorporate the scintillating tile, the WLS fiber, the SiPM and a mirror, to increase the photon efficiency.

(SiPM) is coupled and on the other end a small mirror is placed to increase the photon detection efficiency. Additionally, the edges of the tiles are chemically matted to reduce crosstalk effects with neighboring tiles, with the result that the edges diffusely reflect light back into the tile. In addition, a reflector foil is placed above and below the tiles. In order to minimize crosstalk effects, a new alternative development from the University of Hamburg foresees a complete wrapping of the tiles with a reflector foil, see fig. 5.5(b).

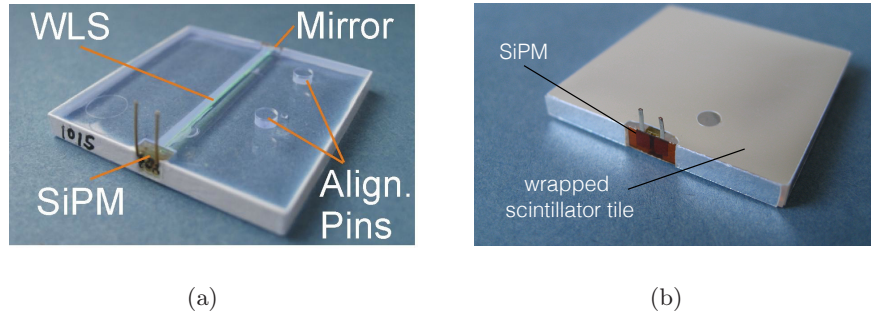


Figure 5.5 – a) picture of the scintillating tile used in the AHCAL. In the tile, the WLS fiber is inserted and a SiPM is incorporated in the matted sides. Picture is taken from [120]. b) a new version, where the tiles are wrapped completely with reflector foil in order to minimize optical crosstalk effects and to increase the photon detection efficiency.

This hasn't been used for the prototype studies discussed in this thesis, but for later versions of the AHCAL engineering prototype this will be an option.

For the tiles of the engineering prototype a material is used, which is doped with 1 % p-terphylene as scintillating material. Here, P-terphylene emits light in the range of 340 nm. For the optimization of the photon efficiency, the tile is additionally doped with 0.03 % POPOP¹. The absorption spectrum fits closely with the emission spectrum of p-terphylene and the wavelength of the photons is shifted to 410 nm. Into the tile a Kuraray Y-11 wavelength shifting fiber is inserted, which shifts the collected photons into the green spectral range. Several studies on the optimization of the scintillator-fiber system are explained in detail in [119].

Since development of the SiPM technology is ongoing, UV sensitive SiPMs have become available recently, these new devices are an attractive option for the AHCAL engineering prototype. Because with this option, the use of a WLS fiber in the tile can be avoided. A picture of this new tile type is shown in fig. 5.6. This offers a cost efficient design for the AHCAL and a reduced mechanical complexity, since otherwise the SiPMs have to be aligned very precisely to the fiber.

5.3.2 SiPM

Silicon photomultipliers are a matrix of several photodiodes operated in Geiger mode. The overall concept of Geiger mode operation for silicon photodetectors is reviewed in [121, 122]. Each photodiode works as a p-n-junction. Fig. 5.7 sketches such a diode with an external reverse bias voltage (U_{bias}), while fig. 5.7(b) depicts a full SiPM. If a photon enters the depletion region of the diode, it can be absorbed and an electron hole

¹POPOP is also known as $C_{24}H_{16}N_2O_2$.

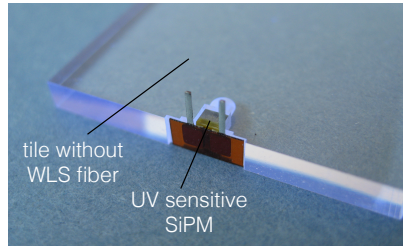


Figure 5.6 – Picture of a new tile prototype. A SiPM, which is sensitive in the UV range makes a WLS fiber unnecessary. It serves a special geometry of cutout for SiPM to improve the signal uniformity within the tile. These tile are an option for later versions of the engineering prototype.

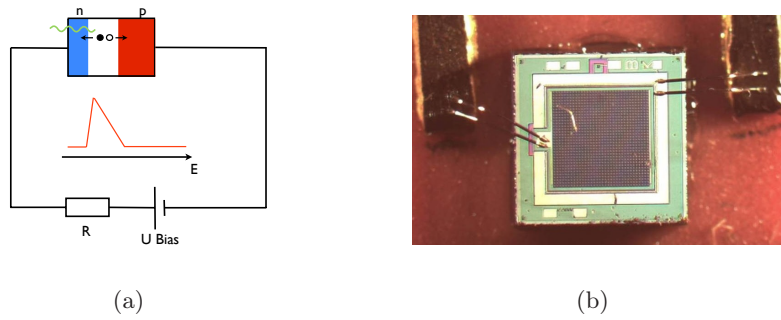


Figure 5.7 – a) Scheme of a SiPM diode: p-n-junction. A photon enters the depletion region of the SiPM, creating an electron-hole pair. The electric field drifts the electron-hole pair apart. The electron, due to the kinematic energy gained in the acceleration, creates further electron-hole pairs via collisions, which are accelerated too. The initiated avalanche of the electrons can be measured as an electrical signal. b) picture of a full SiPM. Picture is taken from [120].

pair will be created. The electric field drifts the electron and hole apart, and the electron and hole accelerate towards the respective electrodes. The fast drift offers enough energy to the electron to collide with lattice atoms of the crystal and create another electron hole pair. This process repeats and creates a lot of free charge carriers resulting in an *avalanche*. Depending on the voltage U_{bias} the population of free charge carriers can be steered: if the voltage exceeds a breakdown voltage, the population leads to an exponential growth of the current. The gain is defined as the avalanche multiplicity. The functionality is called *Geiger Mode*. The Geiger avalanche is stopped passively by a resistor which is connected in series to the diode. A SiPM is the parallel sum of all diode-resistor components.

The silicon photomultipliers used here have a size of $1.27 \times 1.27 \text{ mm}^2$. Each SiPM comprises 796 pixels (avalanche photodiodes), see picture 5.7(b).

Some characteristics of SiPMs are listed in the following:

Photon Detection efficiency: One of the most important parameters of the SiPM is the photon detection efficiency ϵ . ϵ is determined by the geometrical efficiency ϵ_A , the quantum efficiency ϵ_Q and the Geiger efficiency ϵ_G . ϵ_A is defined as the ratio of the active area of the SiPM and the total surface of the SiPM. ϵ_Q is defined as the probability of a photon to create an electron hole pair in the depletion region and ϵ_G gives the probability of an electron to generate a Geiger avalanche. ϵ_Q is usually in the order of 70%. ϵ_A depends strongly on the size of the surface and the number of pixels, while ϵ_G is strongly correlated with the voltage difference between the bias voltage (U_{bias}) and the breakdown voltage U_{BD} , $U_{bias} - U_{BD}$. The total efficiency ϵ is a product of these three efficiencies:

$$\epsilon = \epsilon_A \cdot \epsilon_Q \cdot \epsilon_G \quad (5.1)$$

Dark Rate: The random generation of an electron-hole pair in the depletion region of a SiPM can initiate an avalanche and generate large signals. So by using such a device for counting photons these events can inflate the count. In general, these events are called *dark events* and the number of dark events per second is the *dark event rate*. Dark events are caused mainly by two mechanism: the thermal excitation and the tunnel effect. The electric pulses generated from these events are indistinguishable from the signal of a photon detection.

The effect of thermal excitation of an electron can be minimized by cooling of the device, because in case of thermal excitation the electron is able to bridge the potential barrier between the conduction band and the valence band.

In case of the tunneling effect, high electric fields in the device can assist electrons to tunnel through the potential barrier and cause an electric pulse. Both mechanisms are depicted in fig. 5.8. Improved quality of the material or cooling of the SiPM will reduce the contribution of the dark current to the measuring signal. This behavior and the influence of the dark rate for the engineering prototype is discussed in sec. 7.1.2.

Gain: The SiPM gain G is given by the electric pulse, which is generated if one photon hits a pixel of the SiPM. Each SiPM has its own gain (intrinsic gain). It is defined as:

$$G = \frac{Q_{pixel}}{e}. \quad (5.2)$$

The gain is the ratio of the generated charge Q_{pixel} of one fired pixel and the electron charge e (released from the incident photon), which initiated the avalanche in the pixel. The generated signal (A) of the overall SiPM is the sum of the produced

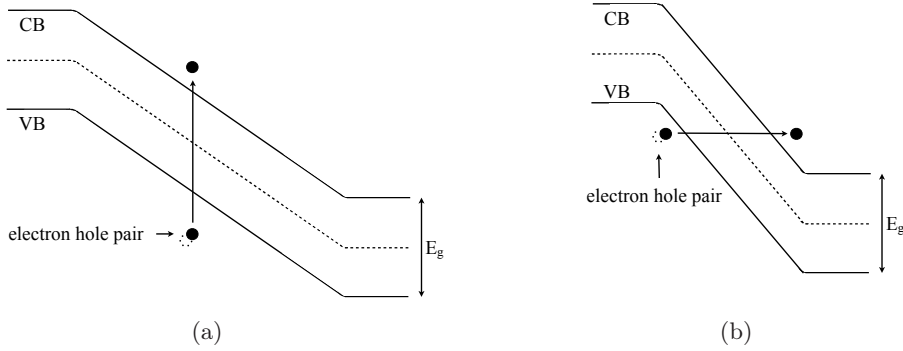


Figure 5.8 – Sketch of the two main mechanism which generate an electron hole pair in a silicon device. a) thermal excitation and b) tunnel effect. E_g is the energy gap, VB the energy level of the valence band and CB the energy level of the conduction band. The slope between the bands appears through the depletion region of the SiPM. The depletion region develops through the different fermi energies in both materials.

charge for all fired pixels (N_{pixel}):

$$A = N_{pixel} \cdot Q_{pixel}. \quad (5.3)$$

The SiPMs in the engineering prototype operate with a gain of $\sim 0.5 \cdot 10^6 - 2.0 \cdot 10^6$ [120].

Light Yield: The number of responding pixels of the SiPM for a minimal ionizing particle traversing a tile is defined as the light yield. It is a quantity of the tile and the SiPM. The light yield can be adjusted with the high voltage of the SiPM. Typical values for the light yield of the engineering prototype are in the order of 15 pixels/MIP.

5.3.3 Signal Processing

After the generation of an electrical signal from the SiPMs, the signal is transferred to a readout chip, where further signal processing takes place. A DAQ system prepares and monitors the data transfer to an external PC. All the components for the signal processing will be discussed in the following:

HCAL Base Unit (HBU): The HBU plays a key role in the readout chain of the integrated readout electronics. It is a printed circuit board (PCB) with a size of $36 \times 36 \text{ cm}^2$, it connects the scintillating tiles with the readout electronics and therefore ensures the transmission of the signals from the SiPMs to the readout chip. Further, it also provides the connection from the readout chip to the Data Acquisition (DAQ), which transfers the data from the detector to an external PC. The tiles are placed beneath the HBU, the readout chips and resistors, capacitors et cetera are integrated on top of the HBU. A picture of the HBU is shown in

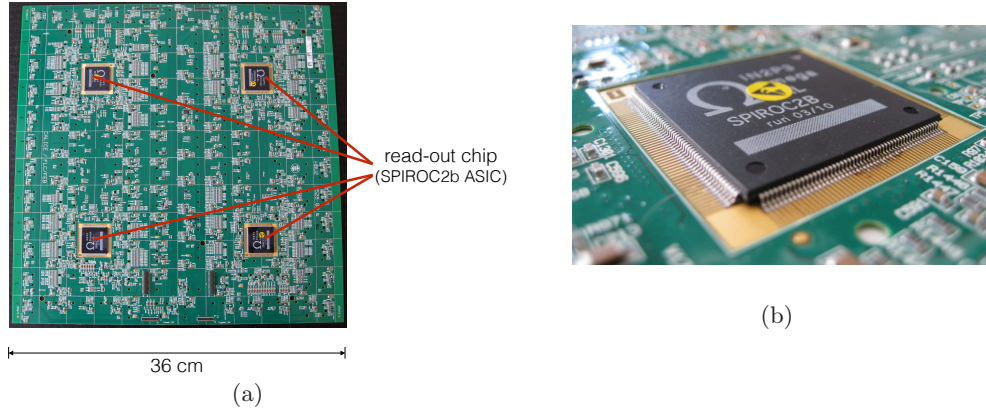


Figure 5.9 – a) top view of the HBU, each HBU hosts 4 read-out chips. Beneath the HBU the scintillator tiles are mounted. Each HBU hosts 144 scintillator tiles. b) the read-out chip is lowered into the circuit board to save space of the overall electronic thickness.

fig. 5.9(a). The tiles are held and placed by alignment pins. A gap of ~ 0.1 mm is foreseen between the tiles to compensate size fluctuations. Each HBU hosts 4 readout chips, each with 36 channels, therefore 144 scintillating tiles are connected to one HBU.

In order to minimize the thickness of the electronics, the readout chips are lowered into the PCB (see fig. 5.9(b)). The development of an engineering prototype is an ongoing progress, up to now four versions of the HBU have been developed. The used version is a revision of HBU2 and the actual version is named HBU3.

The SPIROC2b Chip: The SPIROC chip is especially designed for a SiPM calorimeter at the ILC. The readout chip offers a lot of features, specified on the needs of the ILC. The chip itself is a 36-channel ASIC, called SPIROC2b (depicted in fig. 5.9(b)). It is designed for low power consumption, in order to avoid an extra cooling system. Therefore besides a continuous powering the chip offers a power pulsing mode in order to reach a power consumption of less than $25 \mu\text{W}$ ($40 \mu\text{W}$) per channel (including the power consumption of the SiPMs) [126]. In power pulsing mode always only those components are switched on that are needed between ILC bunch trains. Everything that is not needed will be switched off. Further details will be discussed in sec. 6.5.

The chip offers features, which will be discussed in more detail in chapter 6. Here, only an overview will be given. The SPIROC does bias voltage adjustment, triggering, amplification and digitization of the signals: Each readout channel is able to adjust the bias voltage individually for each SiPM with a 5 V Digital to Analog Converter (DAC).

In order to reduce the data amount, the chip must be able to operate in self-

triggering mode (auto trigger mode). Herein, besides of a global threshold per chip, also a channel-wise tuning of the threshold is possible [5, 116–118]. Additionally, an external trigger mode is implemented to operate in test beam environments and laboratory setups, where auto triggering is not sufficient. In external trigger mode the chip is triggered from an external signal, e.g. pulse generator. Chapter 6 will discuss the auto trigger mode of the SPIROC2b in more detail.

The chip hosts an amplification setup to equalize gain fluctuations of the SiPMs, which is necessary to unify the response of all channels (see sec. 5.5). In order to reach a high dynamic range for data taking the chip supports two gain modes, a low gain and a high gain mode. With both modes 1 to 2000 photoelectrons can be detected. The amplification ratio between both modes is roughly 1:10. Both modes can be either used in external or auto trigger mode. The low gain mode is preliminary used for data taking for signals with higher amplitudes and the high gain mode is primarily used to take calibration data. The chip can operate in auto gain mode where it switches automatically between low and high gain mode.

Each hit is stored with a time information. Therefore, the chip uses a dual-ramp Time-to-Digital-Converter (TDC), which gives a time resolution for individual hits of about 1 ns [5, 116, 117]. The events are stored in analog form in memory cells. To store an event the signal passes a preamplifier and is processed in two signal chains. One signal passes a fast shaper, where subsequently a discriminator decides according to the amplitude of the signal if there is a hit or not. Additionally, the fast shaper determines the time information given by the TDC. In case of a hit a trigger is sent to a slow shaper. The highest amplitude from the second signal which passes the slow shaper and the time information given by the first signal is stored in the memory cells. For storing, the chip has 16 memory cells per channel.

Data Acquisition Interface (DAQ): At the end of each layer, the HBUs are connected to the DAQ system [123, 124]. Herein, the HBUs are connected to one Central Interface Board (CIB)². The CIB is an important interface for the Data Acquisition System by fulfilling several tasks. The CIB hosts three modules, the Power Board, the Calibration Board (Calib) and the Detector Interface Board (DIF). **The Power Board** provides all needed voltages in the active layers. It operates with a 6 V, 12 V and a "high voltage" input to generate the needed voltages. The high voltage (40-100 V) serves the bias voltages of the SiPMs. With voltage dividers the bias voltage for the SiPMs can be reduced in order to fit to the operating voltage of the SiPMs. Also the power pulsing function is enabled with the power board to avoid a cooling system inside of the detector. The power pulsing function is discussed in more detail in sec. 6.5. **The Calib Board** is the steering board for the calibration

²The middle slab of HBUs is connected directly to the CIB, while the neighboring slabs are connected via the Side Interface Boards (SIB) to the CIB, as shown in fig. 5.2(a).

system. That also includes the steering of an LED system to calibrate and monitor the gain of each SiPM, which is necessary since the SiPMs show a variation with temperature and bias voltage in their gain. **The DIF Board** fulfills monitoring and controlling of the communication between the SPIROCs, the power board, the calibration board and further data processing. Furthermore, it serves as interface between the inner-detector and the DAQ.

For the DAQ of the engineering prototype as used in the CERN test beam in 2012 a USB interface is used, which connects the DIF directly to a PC and for the measurements a Labview based user interface. For a larger detector with several layers a more sophisticated DAQ system is needed. There, a Link/Data Aggregator (XLDA) collects the data from the DIFs of several layers. Via TCP connection the data is sent to a DAQ PC. The Clock and Control Card (CCC) provides a common clock for the system [125].

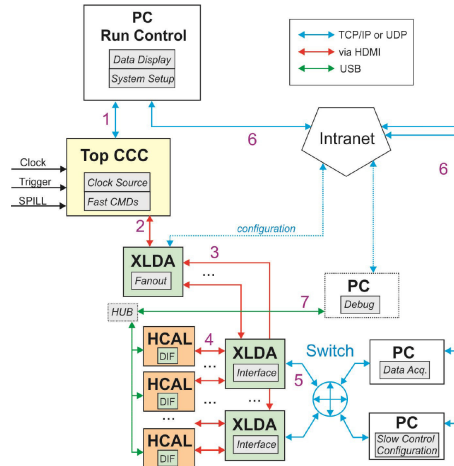


Figure 5.10 – Sketch of the DAQ system of the AHCAL. The DIF transfers the data to the XLDA, which sends the data to DAQ PCs. The CCC (here it is called Top CCC) serves the clock for all components.

5.4 Trigger Modes & Power pulsing

The auto trigger mode and the power pulsing are focal points in this thesis, therefore the trigger modes and the power pulsing mode of the engineering prototype will be introduced here, while detailed discussions will take place in chapter 6.

As mentioned before, the readout chip (SPIROC2b) offers two trigger modes to take data: external trigger and auto trigger mode. In an ILC environment both options are needed to run the detector. It also has an external validation mode, which is a combination of auto trigger and an external trigger.

5.4.1 Auto Trigger Mode

In auto trigger mode, the ASIC decides for each channel whether there is a signal or not to be stored by comparing the SiPM output to a trigger threshold. Typically, the threshold is chosen to correspond to 0.5 MIP. For the auto trigger a global threshold per chip can be set. The threshold can be set in a 10 bit range. In addition to the global threshold each channel allows some fine tuning in a 4 bit range with the channel-wise auto trigger in order to optimize the threshold. The auto trigger mode allows a self-determined running of the detector and the fine tuning option allows an optimizing of the signal to noise ratio for each channel. The channel-wise auto trigger mode is studied in further detail in sec. 6.3.

5.4.2 External Trigger Mode

In external trigger mode an external signal is fed into the SPIROC2b directly and all channels set a hit bit. In an ILC environment the external trigger mode will be used for calibration runs (runs without physics events to determine detector parameters) and the auto trigger mode for event detection.

5.4.3 External Validation Mode

To optimize the event efficiency of data taking and to minimize the fraction of dark events (generated pulses from SiPMs due to thermal excitation and tunnel effects) in the recorded data an external event validation can be used in a test beam campaign. The general concept for external detector triggering is that only events are stored in the chip which are coincident with an external signal. Therefore, the external event validation adapted this concept and uses the advantages of the external and auto trigger mode. In auto trigger mode, if one channel triggers, the hit information is stored in a memory cell, and the ASIC will store the next hit in the next memory cell. In external validation mode, the hit will only be stored if there is an external validation signal at the same time. Otherwise, the same memory cell is overwritten by the next hit. With the information of external scintillators the influence of noise and dark events in the recorded data can be reduced dramatically. Fig. 5.11 shows a measurement of a MIP taken with external validation and without external validation. Especially the left side of both distributions shows a difference. Without an external event validation, fig. 5.11(a) shows a trigger threshold at ~ 300 ADC units and a noise tail above trigger threshold extending to about 370 ADC units. With external event validation the impact of noise events can be minimized (fig. 5.11(b)) and the MIP distribution is clear visible, while the entries from noise events are negligible. Both measurements were taken with roughly the same measurement time.

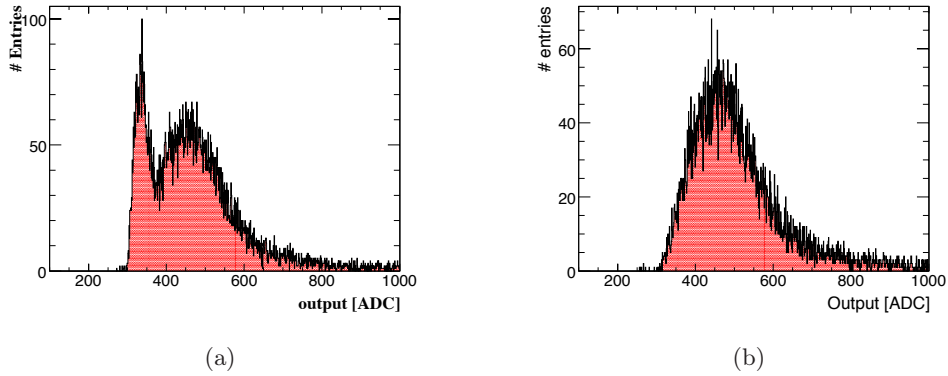


Figure 5.11 – a) example of a MIP measurement, taken in auto-trigger mode without external validation. Besides the MIP distribution a large peak from noise events occurs at 300-350 ADC units. b) the corresponding measurement with external validation. The entries caused by noise events are negligible and the MIP distribution is clearly visible.

5.4.4 Power Pulsing

In order to meet the low power consumption requirements for the calorimeter at the ILC in order to avoid a cooling system, the power dissipation of the SPIROC2b has to be rather small ($25 \mu\text{W}$ per channel, respectively $40 \mu\text{W}$ per channel including SiPM power consumption). Therefore a continuous operation of all electronics is not possible. The bunch train structure of the ILC (sec. 3.2.1) allows to switch off not just needed electronic parts between the bunch trains. The chip operates with separate voltages for the analog and digital parts of the chip, such that parts of the chip can be switched off while others are still running. A detailed characterization of the power pulsing functionality will be presented in chapter 6.

5.5 Calibration

One challenge in a multi-channel setup, such as the AHCAL is the identification and characterization of relevant parameters that are needed to ensure a uniform detector response in each channel for the signal detection. These parameters determine the required calibration procedure of the detector, in order to ensure an equal response in each channel, not only for the AHCAL prototype also for the HCAL of ILD with 8 million readout channels. Basically, a calibration is thereby desirable that needs to be done only once for the whole detector. Therefore, the calibration procedure can be split into a long part to characterize the detector fully, and a short part to be repeated regularly during detector operation to monitor variations with time. Such a characterization procedure has been developed in [120] and has been used for the detector during test beam campaigns. In principle, there are two possibilities to equalize the response of the detector. First, all

channels respond in the same way and second the differences between the channels are corrected in the reconstruction. The second option makes individual threshold settings for every channel necessary. This is not practicable with the current prototype, due to the individual setting of the threshold and even more unpractical for ILD, due to the huge number of channels. Hence, the calibration procedure is based on an equalized response of all channels. Since this is an important procedure, a short overview will be given here and detailed information can be found in [120].

5.5.1 Commissioning of the Engineering Prototype

The main task for the commissioning is the equalization of the SiPM parameter fluctuations. To equalize the response of each channel, the parameters for the detected signal have to be adjusted. The equalization gets more complicated, because besides the fluctuations from SiPM to SiPM and tile to tile, also fluctuations from SPIROC to SPIROC and channel to channel has to be considered.

The measured signal is influenced by the light yield, the intrinsic SiPM gain and the gain of the electronics. If a MIP passes through a tile, a certain amount of photons will be produced and guided to a SiPM. By adjusting the operating voltage (high voltage) of the SiPM the efficiency of detecting these photons can be steered. In order to adjust an equalized response for each channel, the calibration procedure for the prototype can be sorted after the installation of all components into several steps:

1. Testing of a reliable USB connectivity between chip and PC. Here, it will be checked if the board and the PC communicates with each other.
2. To adjust for each SiPM the optimal bias voltage, the InputDAC setting is used to fine tune the voltage at each SiPM with a foreseen light yield of 15 pixels/MIP. With 15 pixels/MIP, 0.5 MIP threshold corresponds to ~ 7 pixels, which ensures that the influence from noise is low enough. A scan utility is used to scan the full range of DAC settings to show the dependence between InputDAC voltage and InputDAC in DAC units. The optimal value of the bias voltage is given by the SiPM/tile manufacturer for a light yield of 15 pixels/MIP. The corresponding DAC unit is written to the control files.
3. Testing of the readout chain to check if every tile gives a signal.
4. Setting the preamplifier to equalize the SiPMs on the ADC scale, in order to equalize the ADC response to an incident MIP. To equalize the ADC response in each channel, a so called cell gain C is defined. C is a product of $N \cdot G$, where N is a preamplifier conversion factor, while G represents the intrinsic gain of the SiPM. For each channel the cell gain is determined with a fixed reference preamplifier

setting. By measuring N in dependence of different preamplifier settings³ and defining a target cell gain (which can be matched by all cells), the preamplifier settings for all channels can be calculated. For all boards and channels a target cell gain of 22 ADC tics/pixel is chosen [120], which could be met by all boards.

5. Noise measurements for trigger setup.
6. MIP measurements are needed to convert the electronic ADC output to the MIP scale. This is necessary to determine the deposited energy in the scintillator material and to cross check that the light yield and gain calibration are correct.

5.5.2 MIP Calibration

After the equalization of all channels and in order to do later fundamental physics with the engineering prototype the output of the electronics (ADC) should give information to the deposited energy in the scintillator material. Therefore, the ADC output has to be converted to the MIP scale. In the DESY test beam facility each tile was exposed to a 3 GeV electron beam without absorber structures. In one layer of scintillating material electrons deposit about the same amount of energy as muons. So with the DESY test beam a MIP-like measurement was made for each tile in auto trigger mode. An example of a measured spectrum is shown in fig. 5.12. On the left side a fast rising edge is caused by the threshold where the auto trigger accepts an event (indicated by the dashed line in fig. 5.12). The defined value for the MIP is the most probable value of the distribution. The distribution can be fitted with a Landau function convoluted with a Gaussian. The Landau function describes the deposited energy and the Gaussian considers the detector noise, which smears the distribution. The noise will be discussed in detail in chapter 7. Using the pedestal information a rescaling from ADC to MIP is possible.

5.5.2.1 Setup in the DESY test beam

The HBU was mounted in the DESY II test beam facility perpendicular to the beam axis on a movable stage. To protect the tiles from stray light the whole HBU was covered into aluminum cassettes. Additionally the setup was covered by light tight cloth to minimize incident light.

To generate MIP-like signals 2.4 GeV positrons are used [127]. The positrons are hitting a thin carbon fiber which is placed inside of the halo of the DESY-II positron beam. By hitting the fiber the positrons generate bremsstrahlung photons. These photons hit a metal target and are converted into an e^+e^- pair. With a dipole magnet the particles can be sorted by their energy with their angles. By steering the dipole current the energy of the selected particles can be adjusted. A final collimator cuts out the final beam.

³The preamplifier conversion factor is measured as a function of the preamplifier capacitance.

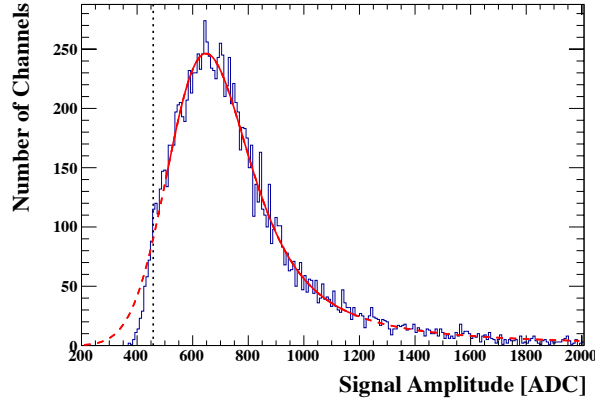


Figure 5.12 – Spectrum of a MIP measurement with a convolution of a Landau-Gauss fit function in one channel. The black dash line shows the threshold of the auto trigger. Picture is taken from [120].

The data of the measurements were taken in auto trigger mode. At the beginning each tile on the HBU was measured on its own by switching off all other preamplifiers of all other channels, later this was not necessary when the event validation was used. With the stage the detector was adjusted to be hit by the beam nearly at the center of each tile. Since the exact positioning and energy was not relevant for this measurement, the collimator was left open for maximum rate, resulting in a wide beam of several cm width.

5.5.2.2 MIP Spectrum & Lightyield

For each MIP measurement 15000 events were taken in each channel with the cell gain equalized preamplifier setup. It was expected that one trigger threshold can be set for all channels, because after the cell gain equalization the MIP position fluctuates less, but the tiles show considerably different noise rates, which makes some fine tunings of the threshold necessary. The resulting spectrum for each channel can be fitted with a Landau function convoluted with a Gaussian. The MIP most probable value is obtained from the fit. Conversion of the fitted MIP positions to the pixel scale for each channel gives the light yield distribution of each SiPM in each tile. With the cell equalized preamplifier setup a mean light yield of 13.6 ± 1.44 pixels/MIP is reached which is around 10% less compared to the target light yield of 15 pixels/MIP [120]. Nevertheless, this value was suitable for further test beam campaigns.

6 Test of SPIROC2b

The main parts of this work focussed on the characterization and the evaluation of key components of the readout chip SPIROC2b, which are needed for the commissioning and operation of the AHCAL engineering prototype. As already mentioned, the calorimeter system of ILD requires a compact detector which incorporates a minimum of dead material in the detector region and an optimum of monitored area. The needed highly segmented calorimeter system makes an integration of the readout electronics essential. The performance of the properties of the readout electronics derived from the requirements were tested extensively in the laboratory. Especially the channel-wise adjustable auto-trigger threshold and the power pulsing mode are important for the use in a calorimeter with fully integrated electronics in ILD. The characterization of the channel-wise auto-trigger and power pulsing mode and evaluation for the use at ILD with the current chip design will be presented in this chapter. After a short introduction of the requirements for the use at ILD and the chip design in sec. 6.1 and 6.2, the test of the channel-wise auto-trigger mode will be presented in sec. 6.3, followed by a discussion of the influence of the preamplifiers on the performance of the chip in sec. 6.4. Finally, in sec. 6.5 the power pulsing function is tested.

6.1 Requirements of the Electronics for the Use at ILD

The requirements for a calorimeter system for ILD have already been discussed in sec. 4.4. This section focuses on the derived requirements for the electronics of the hadronic calorimeter for ILD. One main goal for ILD is the measurement of all energy deposits for all physics events. One possible solution would be the storage of the complete detector information for every bunch crossing for all readout channels, but due to eight million readout channels for AHCAL alone the data volume for an external triggered detector would be immense and impractical. Therefore only sufficiently large energy depositions in one detector cell will be stored and read out. "Sufficiently large" will be defined by the auto-trigger threshold. Due to the fluctuations of the gains of the SiPMs, the response of each channel to the same amount of charge has to be balanced out. In order to reach a uniform response for eight million readout channels (as it was emphasized in sec. 4.4) it is necessary to set the threshold as similar as possible on the MIP scale. Therefore, a relation of MIP to the trigger threshold (DAC trigger threshold,

see sec. 6.3) needs to be calibrated for each channel. One possibility is to equalize the gain of the SiPMs with preamplifiers, or the threshold in each channel has to be suitably adjusted with a channel-wise auto-trigger adjustment.

Due to the compact design of the calorimeter system with minimized space and minimized non-instrumented areas in the detector it is foreseen to avoid an extra cooling system inside of the detector. The performance of the SiPMs is correlated with the temperature of the environment, the higher the temperature the greater the noise and the smaller the gain and the light yield of the SiPMs. An increased power consumption leads to a higher temperature inside of the detector. In order to balance the temperature inside of the detector while avoiding of an extra cooling system, the overall power consumption of each channel should be limited to $25\mu\text{W}/\text{channel}$ [126].

6.2 Chip Design

The engineering prototype and the overall signal chain of the readout electronics has been presented in sec. 5. Besides all other components the readout chip SPIROC2b plays a key role for the performance of the calorimeter system. The channel-wise auto trigger adjustment as well as the power pulsing functionality are features of the chip, therefore the overall chip design will be discussed in more detail in this section. A technical sketch of the chip design is depicted in fig. 6.1. In the first green area the signal enters the chip and passes the preamplifiers (shown as triangles). Here, the amplification of the signal takes place. For every channel a different amplification can be chosen in order to equalize gain fluctuations from the SiPMs. In the second green region the signal is splitted in two signals. One passes a fast shaper (beige triangle) which transforms the signal into a peak-like signal. The amplitude of the peak-like signal is compared with a threshold of a discriminator (big beige triangle). If the signal from the fast shaper exhibits a sufficiently large amplitude, the amplitude information of the second signal is recorded which is transformed into a Gaussian-like signal by a slow shaper (blue triangles). Besides a global threshold which is set per chip, each channel incorporates a 4-bit threshold adjustment in order to fine tune the trigger threshold at the discriminator. The recorded signal information is stored in the third green area by the memory cells which have a depth of 16. In the fourth green region, the electric charge stored in the memory cells is digitized with a 12-bit analog to digital converter into a digital ADC unit. This unit is read out. The fifth orange marked region incorporates the time measurement of the signals. A time to digital converter is triggered by the discriminator and allows a time-resolved measurement of the signals. The time information is not used in the analysis presented here.

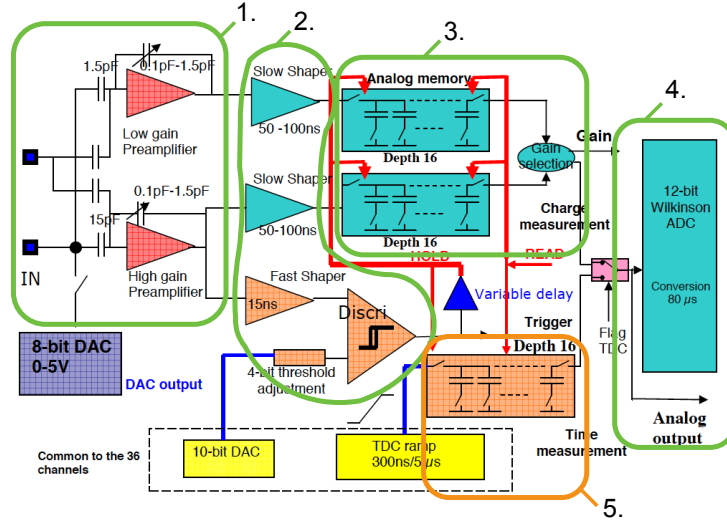


Figure 6.1 – Schematic of one channel of the readout chip SPIROC2b. The relevant parts of the chip are marked in green areas. The first green area shows the preamplifier stage, the second marked area the auto trigger stage, the third marked area the signal storage and the fourth marked area the digitization stage. The fifth orange marked area was not relevant for this analysis and shows the time measurement of the signals.

6.3 Characterization of the Channel Wise Adjustable Auto Trigger Threshold

The auto-trigger mode is one of two options of the SPIROC2b to take data. But only the auto-trigger mode is appropriate to take data in the ILC environment. For the auto-trigger mode a global threshold for one chip in a range of 10 bit can be set. The global threshold of the SPIROC2b is defined as a DAC value, which will be set in the slow control files of the readout software. To optimize the signal to noise ratio in each channel and to compensate fluctuations between the channels each channel can be fine tuned in a 4 bit range. The DAC threshold is a combination of the 10 bit global threshold and the 4 bit channel wise adjustment. If a signal enters the discriminator, the discriminator compares the signal amplitude with the set DAC threshold. The characterization of the channel-wise auto trigger adjustment incorporates studies of the tuning range of the 4-bit channel-wise adjustment, the influence on the global threshold and crosstalk effects to neighboring channels.

6.3.1 Experimental Setup

To study the channel-wise auto trigger threshold the charge injection method is used. A pulse generator is connected to one channel of the SPIROC2b and injects a well

defined charge into the channel. This approach uses a fixed injected charge and varies the threshold settings (DAC value) to scan the threshold, since the resolution of the threshold setting is better than the resolution of the pulse generator. The charge varied between 0.3 and 1.5 MIP. To characterize the response of the auto trigger, the numbers of injected and detected triggers are compared with each other. Above the threshold all injected triggers should be detected and below the threshold no trigger should be detected. Fig. 6.2 shows the detection efficiency of the auto trigger response as function of the DAC trigger threshold value. The threshold is shown in units of the set DAC value and in MIP units (the conversion will be discussed below).

Theoretically a threshold at the position t_0 will be described by the Heaviside function [128],

$$u(t - t_0) = \begin{cases} 1 & \text{if } t - t_0 > 0, \\ 0 & \text{if } t - t_0 < 0. \end{cases} \quad (6.1)$$

Due to inefficiencies of the discriminator a smeared step function of the threshold will be seen in a real environment. This function will be called *s-curve* in the following. To describe the s-curve the integral of the gaussian function [128] can be used:

$$F(x) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^x e^{-\frac{1}{2}\left(\frac{t-t_0}{\sigma}\right)^2} dt. \quad (6.2)$$

The function $F(x)$ depends on the expectation value t_0 and the standard deviation σ . If a measured s-curve is fitted with eq. 6.2 the expectation value would correspond to the most probable threshold and σ would describe the width of the s-curve.

Using the substitution $u = \frac{t-t_0}{\sigma}$ and $du = \frac{1}{\sigma}dt$ and set $t_0=0$ and $\sigma=1$ eq. 6.2 is splitted into ϕ and ϕ_0 and transformed into the following definition with the corresponding relation:

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{u^2}{2}} du, \quad (6.3)$$

$$\phi_0(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{u^2}{2}} du = \phi(x) - \frac{1}{2}. \quad (6.4)$$

Eq. 6.3 is called integral of the standardized normal distribution. To fit the s-curve the *error function* is used, which is a special form of eq. 6.4 [128]:

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\tau^2} d\tau = 2 \cdot \phi_0(\sqrt{2}x). \quad (6.5)$$

For scaling reasons $0.5 \cdot \text{erf}(x) + 0.5$ is computed to fit the s-curve. Therefore with eq. 6.5 the threshold value t_0 and the width σ of the s-curve can be determined, as shown in fig. 6.2.

The y axis displays the ratio of the detected trigger to the injected trigger. The s-curve

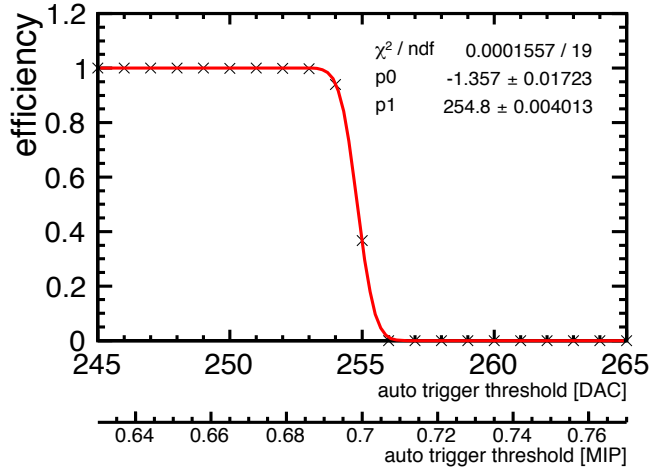


Figure 6.2 – Typical s-curve. Determination of the auto trigger threshold by variation of the threshold in DAC units. The conversion to MIP units is explained in the text.

is fitted with the error function. The parameter $p0$ corresponds to the width of the error function and $p1$ to the 50% value of the fit, which corresponds to the threshold expectation value t_0 and is defined as the threshold. As it is suggested in fig. 6.2, the width of the fit function varies within $\sim \pm 1.4$ DAC units, which is rather small. The x axis displays the threshold value, which is displayed in DAC and MIP units.

DAC to MIP Conversion

To calculate the relation between the trigger threshold, set in DAC units and the corresponding signal size in MIPs, the preamplifier gain and the light yield are needed. The whole electronics like the capacitors and in particular the preamplifier gain underlies strong channel to channel fluctuations. In addition, also the light yield and the gain of the SiPM-tile units are underlying fluctuations. In order to make concrete statements for every channel, each channel has to be analyzed individually. The fluctuations of the electronics and the tiles cause a shift of the MIP on the ADC scale even if the channels have the same settings. In the following, an average value for the channel will be used. In [120] it has been shown that the preamplifier gain for a preamplifier capacitance of 100 fF varies between 15 and 40, therefore here a mean preamplifier gain of 30 will be assumed. For the light yield, the SiPM-tile units were optimized for 15 pixels/MIP. The product of both, preamplifier gain and light yield gives an average ADC value for one MIP, which accounts to 450 ADC units. Adding the pedestal value (the pedestal will be discussed in sec. 7.1), which was determined for the electronics on average to ~ 240 ADC units gives the total ADC value for one MIP, 690 ADC units. This is in good agreement

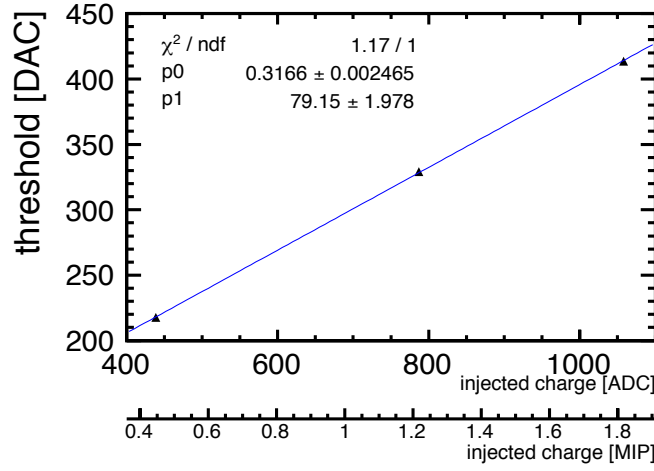


Figure 6.3 – Auto trigger threshold as function of the injected charge. Each trigger threshold is determined by variation of the threshold and measuring an s-curve.

with fig. 5.12 and allows to calculate the MIP to ADC relation with

$$MIP = \frac{ADC - 240}{450}$$

$$\Leftrightarrow ADC = MIP \cdot 450 + 240. \quad (6.6)$$

To convert DAC into MIP units, it is necessary to determine the ADC to DAC relation. Fig. 6.3 shows the DAC trigger threshold for different amounts of injected charge in one channel by measuring a s-curve and using the 50% value of the fit as DAC trigger threshold. A clear linear dependence between DAC and ADC conversion is visible. This allows to convert and fit the DAC to ADC response, respectively MIP response with a linear relation. The fit in fig. 6.3 gives

$$DAC = (0.317 \pm 0.002) \cdot ADC + (79 \pm 2). \quad (6.7)$$

By inserting eq. 6.6 into eq. 6.7 the DAC to MIP conversion results to

$$DAC = (0.317 \cdot (MIP \cdot 450 + 240)) + 79$$

$$\Leftrightarrow MIP = \frac{DAC - 79}{143} - 0.53. \quad (6.8)$$

This gives an average DAC to MIP conversion. For detailed studies this conversion needs to be considered for each channel individually, but for an average consideration it is sufficient and in this analysis it will be used to convert the effects of the electronics into corresponding typical signal sizes in MIPs.

6.3.2 Dynamic Range

An important parameter is the dynamic range of the 4 bit channel wise auto trigger adjustment. The dynamic range has to be large enough to balance all channels. Additionally to the global threshold each channel can fine tune the threshold within the 4 bit channel-wise adjustment. To analyze the dynamic range of the channel-wise adjustment the shift of the threshold in the channel in which a charge is injected is determined. The 4 bit range of the channel-wise auto trigger adjustment allows values between 0 and 15 (these values will be named bit values in the following). To determine the dynamic range the channel-wise auto trigger adjustment is set to 8 as default. This allows a variation of $+7$ units in up direction (from 8 to 15) and -8 in down direction (from 8 to 0), which guarantees in a real beam environment good conditions to optimize the threshold and to compensate fluctuations in both directions. At first a charge is injected into one channel and the s-curve is determined, as explained in sec. 6.3.1. The injected charge is chosen to correspond to ~ 0.5 MIP, but the dynamic range is independent from the injected charge, because the 4 bit channel-wise adjustment works independently from the 10 bit global threshold. Next the channel wise adjustment is set to 0 and 15, while in both cases the s-curve is determined again to analyze the shift of the threshold for both directions. The result is the threshold shift in DAC units of the global threshold. This determines the dynamic range of the channel wise auto trigger adjustment. In fig. 6.4 the shift in both directions and their correlation is displayed. The measurement was made for five channels. For each direction, around 20 DAC units can be obtained, altogether 40 DAC units, which corresponds to $\sim 1/4$ MIP. In fig. 6.4(c), the correlation between both directions is displayed and an asymmetric behavior can be seen, due to the asymmetric tuning range (7 units in up direction and 8 in down direction).

From fig. 6.4(a) and fig. 6.4(b) an average value for the tuning range in the up (18.61 ± 4.75 DAC units) and down direction (14.93 ± 3.92 DAC units) can be gained from the 5 channels. In both cases (up and down direction) a histogram is filled. The mean and the RMS of the histograms can be used to determine a linear fit function for the tuning range, see fig. 6.5. The big uncertainties are due to the large spread between the measured channels, but probably also due to the small statistics. The linear fit function (eq. 6.9) can be used to determine the shift of the threshold by adjusting the 4 bit range:

$$\Delta\text{threshold}_{\text{MIP}} = \frac{x_{4\text{bitrange}} - (8 \pm 1)}{(64 \pm 12)}. \quad (6.9)$$

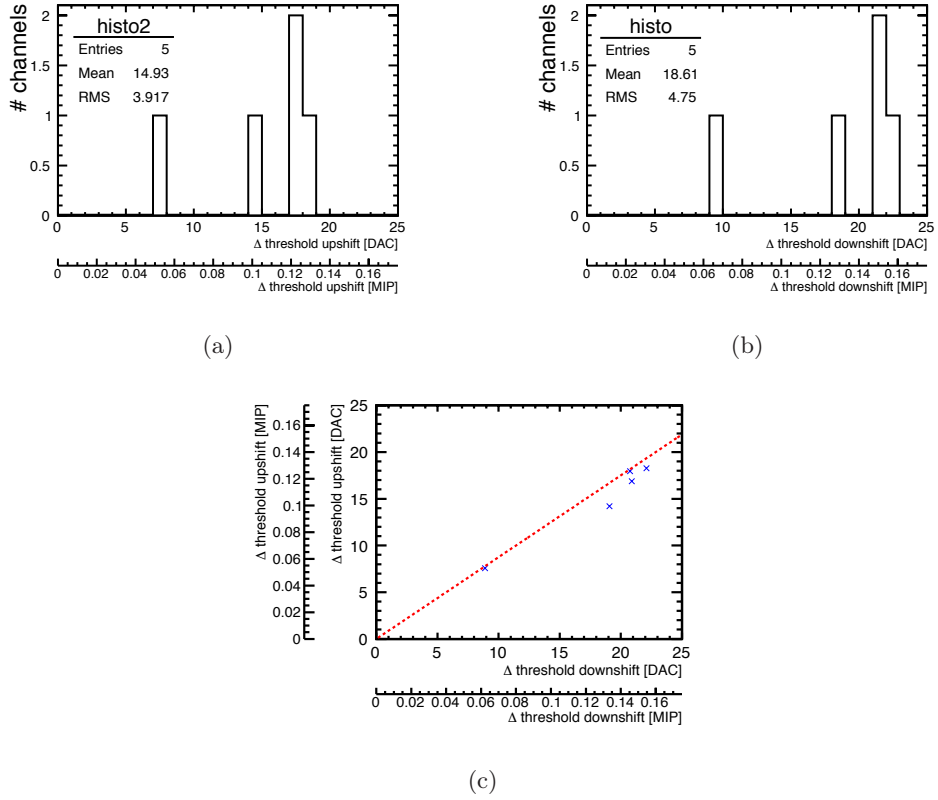


Figure 6.4 – Determination of the dynamic range for the channel-wise auto trigger threshold adjustment in both directions (down- and up-shift) and the correlation between both directions. The dotted line in c) shows the correlation between both directions with respect to the asymmetric tuning range.

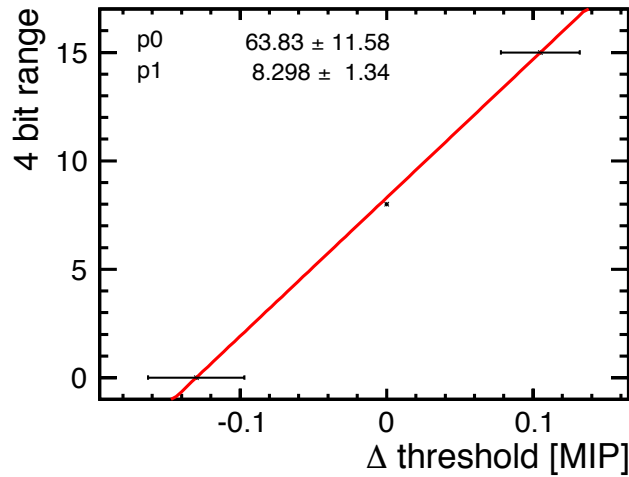


Figure 6.5 – Linear fit to determine the shift of the threshold depending on the use of the 4 bit tuning range.

6.3.3 Shift of the Global Threshold

It is important to know the usability of the channel-wise threshold, therefore it is tested if the use of the channel-wise adjustment has an impact on the global threshold of the chip. To study this, the threshold in one channel is measured while several neighboring channels use the channel-wise auto trigger adjustment. Channel 2 is used to determine the threshold by measuring an s-curve, neighboring channels are using the full 4 bit range of the channel wise adjustment (the channel-wise adjustment is set to 15). These channels will be called "active" in the following. Fig. 6.6 shows the result for 0, 2, 3, 5, 10 and 20 active neighboring channels and for three different injected charges. The error bars are given as width of the fit function, which were smaller as the point size and therefore not visible in fig. 6.6. Fig. 6.7 shows the physical position of the signal lines of the channels to the chip.

The threshold responses for different injected charges show a linear behavior and can be fitted with a straight line. Additional activated neighboring channels lead to an offset of the line. The shift of the threshold is independent of the injected charge. From fig. 6.6 the shift of the threshold depending on the number of activated neighboring channels is determined and displayed in fig. 6.8. The measurement of the shift was made for three channels. On the x axis the number of active channels are shown. The y axis shows the shift of the threshold. A linear behavior of the shift between the additional channels as function of the number of active channels is visible. Fluctuations in the slope of the different channels are expected, due to slight differences of the electronics at each channel, like e.g. fluctuations in the capacity of the preamplifiers. The error bars are determined via error propagation from fig. 6.6, because each point in fig. 6.6 takes a variance from the width of the fit function to the threshold. Fig. 6.9 shows a histogram of the shift of the threshold for 10 active channels and on average a shift of the threshold of 0.08 ± 0.01 MIP can be observed.

One reason for the shift of the threshold could be that in auto trigger mode the discriminator consumes power and so does the 4 bit channel-wise auto trigger adjustment. This additional power consumption can cause a ground shift which results in a shift of the threshold.

Also crucial is, if the shift of the global threshold is counterbalanced. All 36 channels of one chip have been set to the default setup (position 8) and the s-curve has been measured in one channel. The measured channel is left in the default setup and half of the other channels have been set to position 15 while the other half are set to position 1. Measuring the s-curve in the channel with the default setup allows a comparison of the threshold position. Several combinations with a different quantity of active channels have been tested, which offers conclusions about the net shift and the shift of the global threshold. The net shift is defined as the difference in bit values to the default value of 8, summed over all channels. Always combinations with a net shift of zero were chosen.

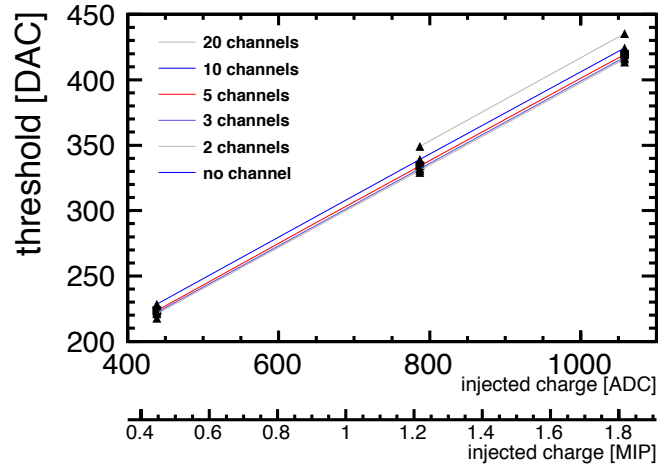


Figure 6.6 – The picture shows the auto trigger threshold for three different injected charges. The different curves are displaying setups with different numbers of active neighboring channels, which use the full 4bit range of the channel wise auto trigger adjustment.

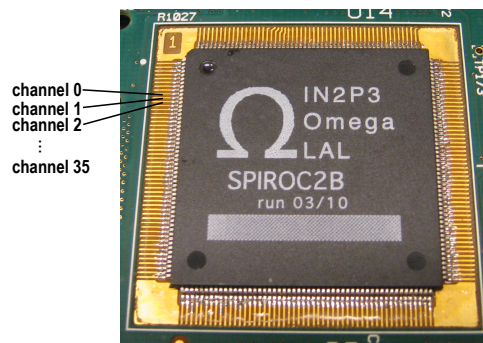


Figure 6.7 – The picture shows the physical connection of the channels to the SPIROC2b.

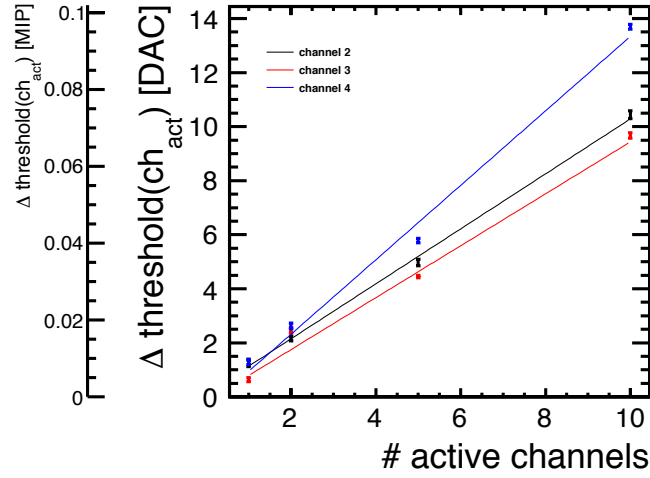


Figure 6.8 – Shift of the threshold by using different numbers of active channels.

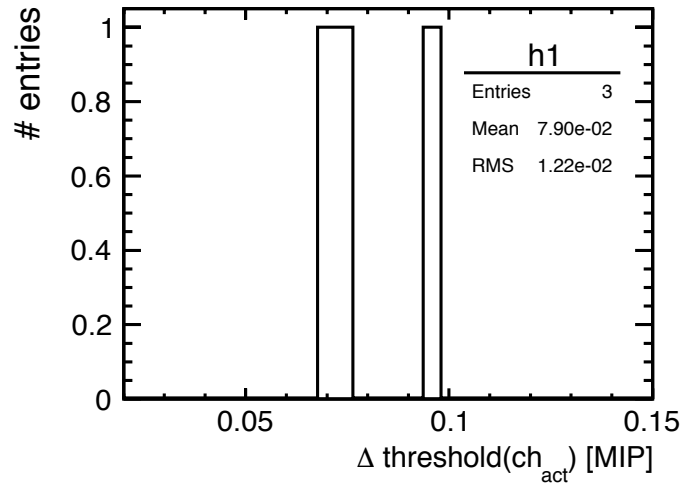


Figure 6.9 – Histogram of the threshold shift in MIP for 10 active channels.

It turned out that, if the net shift of the channel wise auto trigger adjustment is around zero, the shift of the global threshold is negligible. For the use of the channel-wise auto trigger adjustment only the net shift has to be regarded to determine the shift of the global threshold. Due to the negligible shift of the global threshold no histograms were taken.

6.3.4 Crosstalk

Another important information is, whether the influence of the use of the channel wise auto trigger adjustment on channels on the same chip is related to their position

on the HBU or not. To study a possible relation, one channel uses the channel-wise auto trigger adjustment and the influence on the global threshold of another channel depending on the position of the channel on the HBU is analyzed. Therefore, a well defined charge (~ 0.5 MIP) is injected in one channel (channel 2) and the s-curve is determined while another channel on the same chip uses the channel-wise adjustment (bit value 15). The determination of the s-curve in channel 2 allows to check if the position of the channels relative to each other has an influence on the shift of the threshold. The results are presented in fig. 6.10. Each point represents the threshold and RMS of the s-curve in channel 2, while on the x-axis the active channel number is displayed. Channel 2 shows a slightly higher threshold when channel 3 or 7 are using the channel-wise adjustment compared to channels 12, 17, 22, 27, 32 and 35. Therefore, it seems that close channels influence each other due to their geometrical position. Electromagnetic effects are suspected, but due to the rather small effect (< 1 DAC unit) this was not analyzed in more detail. In practice, an effect of less than 1 DAC unit is negligible even for the smallest measurable signals of 0.5 MIP.

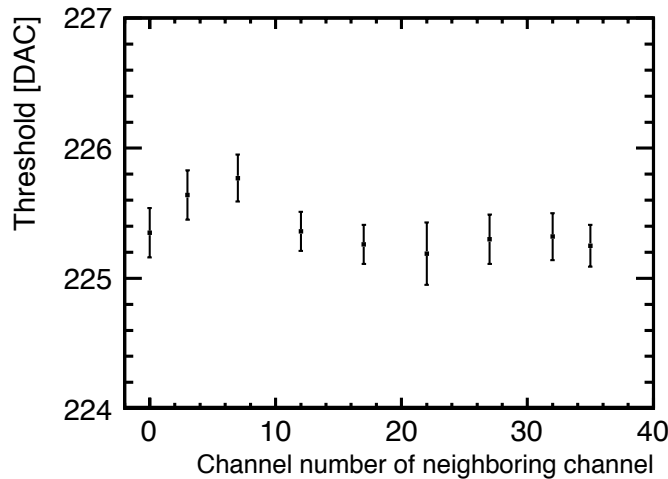


Figure 6.10 – Shift of the auto trigger threshold in channel 2 as a function of the number of the next active channel.

6.3.5 Summary

The channel-wise auto trigger threshold adjustment of the SPIROC2b covers a tuning range of ~ 0.25 MIP. Using the channel-wise auto trigger threshold leads to a shift of the global trigger threshold, which depends on the number of active channels and their actual value. The shift of the global threshold in a counterbalanced setup with a net shift of $\sim$ zero is negligible, therefore the tuning directions are compensating each others shift of the global threshold. For 10 channels, using the full 4 bit range in the same

direction, the shift of the threshold in a neighboring channel is about 11 DAC tics or ~ 0.08 MIP. From the measurements follows that the channel-wise adjustment is useable when the signals in the channels do not vary by more than ± 0.125 MIP. But even then a counterbalanced threshold matching is needed, because the shift of the global threshold is not small compared to the channel-wise tuning range.

This is difficult in practice and another approach is more appropriate to calibrate the detector. The cell gain equalization from sec. 5.5 can be used to reach the same signal in ADC units for a MIP in all channels, allowing the use of the global auto-trigger threshold without channel-wise fine tuning for all channels on one chip, since the cell gain equalization doesn't influence the global threshold. This approach will be discussed in more detail in sec. 6.4. Nevertheless, the channel-wise auto trigger threshold adjustment can be used to do some fine tuning in the electronics. Finally, it should be noted, that the consideration of an average MIP is a simplified assumption, due to the fluctuations in the preamplifier gain and in the light yield. The results here may deviate significantly for individual channels.

In conclusion, the tuning width is basically sufficient, but the effect of the shift of the global threshold is a surprise and in detector operation a counterbalanced setup is unlikely. Therefore, the SPIROC2b needs to be improved in this regard, if the channel-wise fine-tuning is still needed and no other methods may be used.

6.4 Influence of the Preamplifier Capacitance on the Threshold

Since it was shown in sec. 6.3 that the channel-wise auto-trigger adjustment is not the optimal way to ensure a uniform response, the equalization of the preamplifier gains is crucial for the physics performance. To calibrate the engineering prototype the preamplifiers are adjusted according to the SiPM gains to guarantee an equalized output for all channels [120]. Due to the uncertainties of the electronic components like the capacity of the preamplifiers or other components, a small broadening of the ADC output distribution is expected, when the same amount of charge is injected in every channel. But this effect should be rather small.

In order to test the influence of the preamplifier on the trigger threshold, three fixed charges are injected into one channel by varying the preamplifier setup between 100 fF, 225 fF, 400 fF and 800 fF. For every preamplifier capacitor and every injected charge the DAC trigger threshold is measured by a s-curve (like in sec. 6.3). The results are depicted in fig. 6.11. The ADC output of the chip is different for every capacitor by injecting the same amount of charge. This was expected since the preamplifiers are used in order to fine tune the ADC output and to equalize gain fluctuations from the SiPMs. But it was unexpected that the preamplifier of the circuit has an influence on the DAC trigger

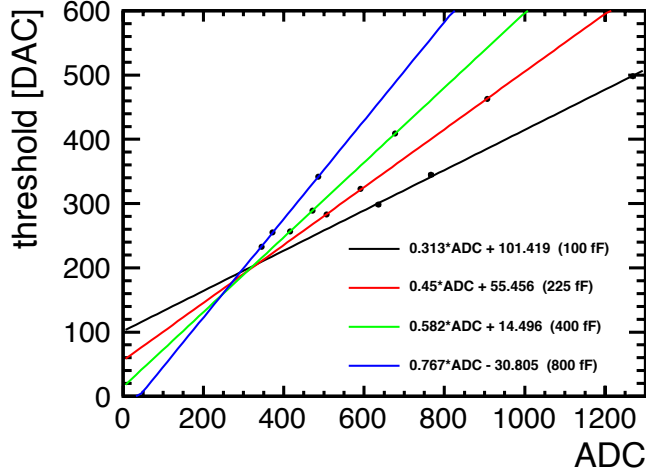


Figure 6.11 – DAC threshold versus ADC output of one channel by injecting three fixed charges and varying the preamplifier capacity. Linear fits to the measurements with the same preamplifier setup are also shown. The uncertainties are smaller than the marker size.

threshold of each channel. Usually, for a multi-channel detector it is preferable that the DAC trigger threshold of every channel for the same amount of charge is the same, independent of the preamplifier setting. Therefore, changing the preamplifiers shouldn't have an influence on the DAC to ADC behavior. In consequence for the SPIROC2b, changing the preamplifier setting also changes the DAC trigger threshold for 0.5 MIP. Therefore, an appropriate description must be found in order to calculate the DAC trigger threshold, depending on the preamplifier setting of each channel. A linear fit is used for every preamplifier capacitor in order to determine the DAC to ADC behavior in dependence of the preamplifier capacity.

From fig. 6.11 the intersection points with the y axis and the slopes from the fits can be used to describe a dependency of both with the preamplifier. Fig. 6.12(a) shows the intersection points with the y axis and fig. 6.12(b) the slopes from the fits in fig. 6.11. Both are fitted with a second order polynomial. The intersection with the y axis $Y_{intersec.}$ and the slope of the fit Y_{slope} in dependence of the preamplifier setting X_{preamp} can be given as:

$$Y_{intersec.} = (139.6 \pm 5.5) - (0.42 \pm 0.03) \cdot X_{preamp} + (0.26 \cdot 10^{-3} \pm 0.03 \cdot 10^{-3}) \cdot X_{preamp}^2 \quad (6.10)$$

$$Y_{slope} = (0.201 \pm 0.015) + (12.2 \pm 0.09 \cdot 10^{-3}) \cdot X_{preamp} - (6.42 \cdot 10^{-7} \pm 0.9 \cdot 10^{-7}) \cdot X_{preamp}^2. \quad (6.11)$$

A second order polynomial describes the influence of the capacitor relatively well as a first shot, but further investigations are needed to understand the functional dependence.

With the two quantities $Y_{intersection}$ and Y_{slope} , the DAC to ADC behavior for every preamplifier setting can be determined with

$$DAC = Y_{slope} \cdot ADC + Y_{intersec.} \quad (6.12)$$

The value for one MIP on the ADC scale is known from the test beam measurements. And after the gain equalization this value is, apart from fluctuations, the same for every channel. Therefore, it is straight forward to determine the DAC trigger threshold for 0.5 MIP for every preamplifier setting, respectively for every channel. In fig. 6.11 the region where the lines cross each other at ~ 270 ADC units (~ 200 DAC units) corresponds to the pedestal (see sec. 7.1).

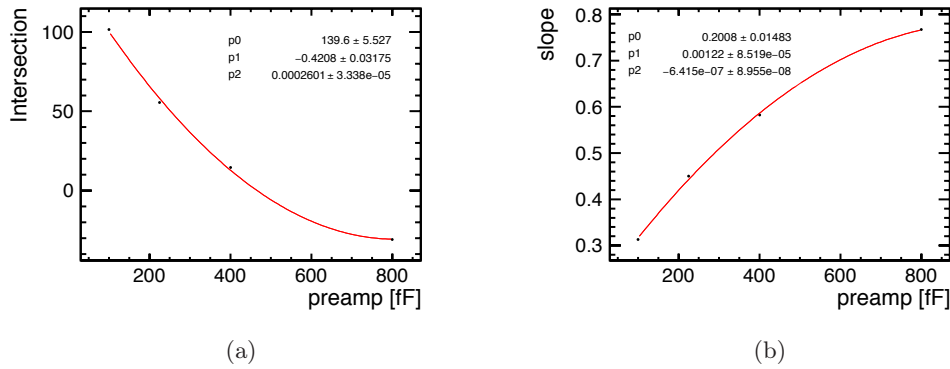


Figure 6.12 – a) Fit of the intersection graph and b) fit of the slope that can be used to calculate new preamplifier capacities.

After data taking at the DESY test beam, the MIP spectra of each channel can be analyzed (fig. 5.12) and the 0.5 MIP threshold in ADC units can be determined. With the ADC information for 0.5 MIP from the MIP spectra in each channel and the according fit function, the 0.5 MIP threshold in DAC units can be determined and a histogram with the distribution for 0.5 MIP in DAC units can be filled. Fig. 6.13 shows the 0.5 MIP DAC threshold distribution of one ASIC. The width and mean of the distribution shows the influence of the different preamplifier values after the gain equalization. Since the impact of others uncertainties can be neglected, it can be assumed that the influence of the preamplifiers has an impact on the width of the distribution in fig. 6.13. The channel-wise auto trigger adjustment can be used to narrow the distribution after the channel gain equalization. With the channel-wise auto trigger adjustment, the threshold in each channel can be shifted of up to 20 DAC units in both directions. As seen in fig. 6.13 the spread can be compensated with a shift of ~ 16 DAC units. So this will guarantee a very

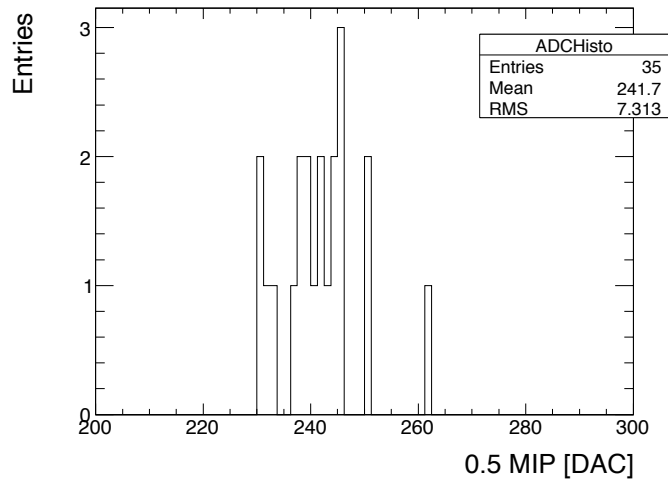


Figure 6.13 – Distribution of the 0.5 MIP threshold for one chip.

narrow distribution. Due to the influence of the channel-wise trigger threshold on the global threshold this procedure was not used for the test beam at CERN, but was also developed as backup solution for the test beam. For the measurements at the CERN test beam campaign it was essentially important to set the threshold below 0.5 MIP to ensure a good data quality for the MIP calibration. In the reconstruction it is afterwards always possible to set a cut at 0.5 MIP. Therefore, for fig. 6.13 a threshold of 230 DAC units seems to be appropriate if the noise rate is tolerable.

6.5 Characterization of the Power Pulsing Mode of the SPIROC2b

In order to build a dense, compact and highly granular calorimeter with a minimum of unmonitored material in between, the calorimeter system foresees no cooling system inside of the active layers. In order to avoid a cooling system, the power consumption of the electronics is limited to $25 \mu\text{W}/\text{channel}$ [126]. If the power consumption from the SiPMs is also considered, the total power consumption results to $40 \mu\text{W}/\text{channel}$. Keeping the power consumption below $25 \mu\text{W}/\text{channel}$ offers the possibility to just conduct the heat by the material of the absorber plates. This results in a heating difference between the inner detector and the outer detector of $\Delta T \sim 0.35 \text{ K}$ [126]. Fig. 6.14 shows the heating process inside of the detector depending on the position parallel to the beam axis. The temperature difference of 0.35 K is related to the fact that at the end of the barrel a cooling pipe will be installed and the temperature of the cooling water will drive the temperature gradient inside of the detector.

In order to realize a low power consumption, the duty cycle of the ILC can be used. The

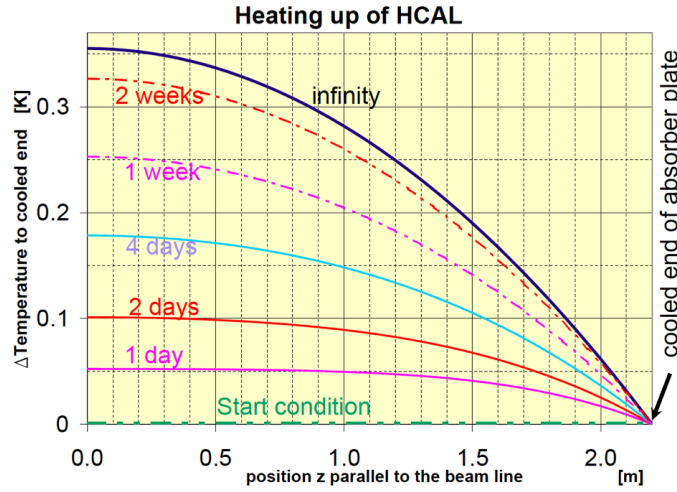


Figure 6.14 – Temperature development of the hadron calorimeter as a function of the position on the z axis. The calculated temperature along the z axis shown for various heating periods, assuming that the absorber plate is heated homogenous with $40 \mu\text{W}/(3\text{cm})^2$. The service ends are cooled in order to stabilize the temperature. The picture is taken from [126].

duty cycle of the accelerator offers 1 ms bunch trains every 200 ms, therefore the fast analog electronics of the ASIC can be switched off between the bunch trains (the current sources can be synchronized with the bunch structure). This means that the current sources of the readout ASIC can be switched off for 99% of the time. But the analog part has to be switched on soon enough for the first bunch in a train, the analog signal handling and the digitization. The low amount of data keeps the power consumption for the digital electronics low. To evaluate the power cycling of the SPIROC2b, the performance and the power consumption of the ASIC has been tested. In particular, it has been studied if the ASIC fulfills the requirements for the power consumption for a detector operation at ILD and the performance of the chip in dependence of the switching on time has been measured.

6.5.1 Power Pulsing Mode of the SPIROC2b

The power for the SPIROC2b will be delivered by the power board. The power board steers the power for the required working processes with corresponding steering signals (Fig. 6.15) from the DIF board. Different control signals (e.g. `pw_a` or `pw_d`) steer the power supplies for the different electronic parts of the chip. The same names for the control signals and the corresponding power supplies are used. The `pw_a` delivers the power for the analog parts of the ASIC. Analog parts are for example the preamplifiers, the shapers or the memory cells and they are switched on during the data acquisition

(1 ms) plus an extra short activation time (T_{on}) for the electronics parts to be ready for data taking. The SiPM bias voltage is also an analog signal, but this voltage is switched on all the time. Directly after the bunch train the data are converted from analog into digital data with the A/D converter. In the digitization process all 16 ADC and 16 TDC memory cells have to be digitized. The digitization process for one memory cell is calculated with $\sim 100 \mu\text{s}$. In total, the digitization process will roughly take 3.2 ms. The converter will be supplied with power by pwr_adc . As the pwr_a , the pwr_adc needs also some extra time ($100 \mu\text{s}$) to start up. The pwr_d supplies the power for the data digitization and also the readout of the 24 ASICs (6 HBUs/slab $\cdot$ 4 ASICS/HBU). For the measurements described here, the pwr_d is switched on for $\sim 150 \text{ ms}$ plus an additional activation time (T_{on}). The readout chips will be read out subsequently and only chips with stored events will be read out. The POD module (see section 6.5.4) couldn't be used for this measurement, therefore each readout chip is switched on for 150 ms. Additional analog and digital parts are supplied by the pwr_dac , which is e.g. the DAC threshold. The 1 ms bunch train length is a fixed value for the ILC. T_{on} is for every power part the same. The necessary activation time T_{on} has been estimated to be $20 \mu\text{s}$ by the manufacturer of the readout chip.

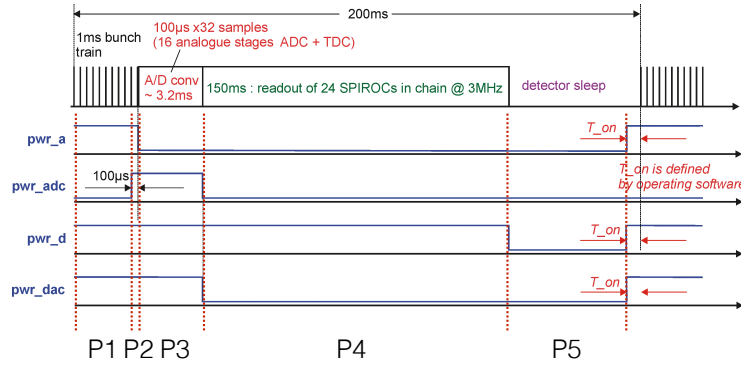


Figure 6.15 – Sketch of the power cycling scheme and the time structure, subdivided into time periods with different power consumption. The total power consumption for pwr_a , pwr_adc , pwr_d and pwr_dac is subdivided in the periods P1, P2, P3, P4 and P5 according to the power cycling scheme when the supplies are switched on.

6.5.2 Determination and Evaluation of the Activation Time T_{on}

The activation time T_{on} is an important quantity which ensures an optimal performance of the electronic components during power cycling. In this analysis the performance of

the electronics in dependence of the activation time is tested in order to optimize and evaluate the activation time. If T_{on} is too small than the measured signal is not correct and if T_{on} is too large than the power consumption is higher than necessary.

6.5.2.1 Setup

To analyze T_{on} , the measured signal as function of time which corresponds to a switch-on of voltages will be studied. The chronological order of operation of the different power components are controlled within the Detector Interface (DIF). Just the activation time can be adjusted with a PC. By varying T_{on} and analyzing the output signals from different memory cells conclusions on the electronics can be drawn. For the experimental setup one channel is connected to a pulse generator, which injects 16 triggers with a well defined amount of charge and which can be triggered by the DIF. For these measurements a charge of 3pC was chosen, which corresponds to ~ 1.8 MIP. A technical sketch of the setup is depicted in fig. 6.16(a). The memory cells are operating like a register. With 16 triggers the 16 memory cells of one channel can be filled. Due to the time dependent injection of the triggers into the channel each entry in the memory cell is linked to an activation time T_{on} , since the measured signal in the memory cell depends on T_{on} . By analyzing the memory cells, information on the time dependence of the performance of the electronics can be gained. The DAQ program offers two possibilities to vary the time. The first is to steer the activation time T_{on} itself and the other is to vary the time between the injected triggers that are measured. Both ways have been used in the measurements performed here. Fig. 6.16(b) illustrates the activation time and triggers respectively the trigger distance in the setup.

6.5.2.2 Measurement

The distance between the starting point of the measurement (start_acq) and the first trigger is set in the DIF-firmware and has a constant value of $8\mu s$, see fig. 6.16(b). The ASIC always interprets the ADC read out values of the first trigger as a zero, which is a well known bug of the SPIROC2b. Therefore for the measurement, the first memory cell and the first trigger is not taken into account. Therefore in the following instead of T_{on} , T_{eff} (effective activation time) is used, which also contains the constant value of $8\mu s$ and the time distance between the first two triggers, $T_{eff} = T_{on} + 8\mu s + \text{trigger time distance}$. In addition, if it is spoken from the first memory cell, actually the second memory cell is meant, which is the first filled memory cell. Every measurement is made with and without power cycling. To compare the output of the memory cells (with and without power cycling), histograms for every memory cell are filled.

In fig. 6.17 the red histograms represent the recorded signal in ADC units of four memory cells without power pulsing and the black histograms represent the output of the memory

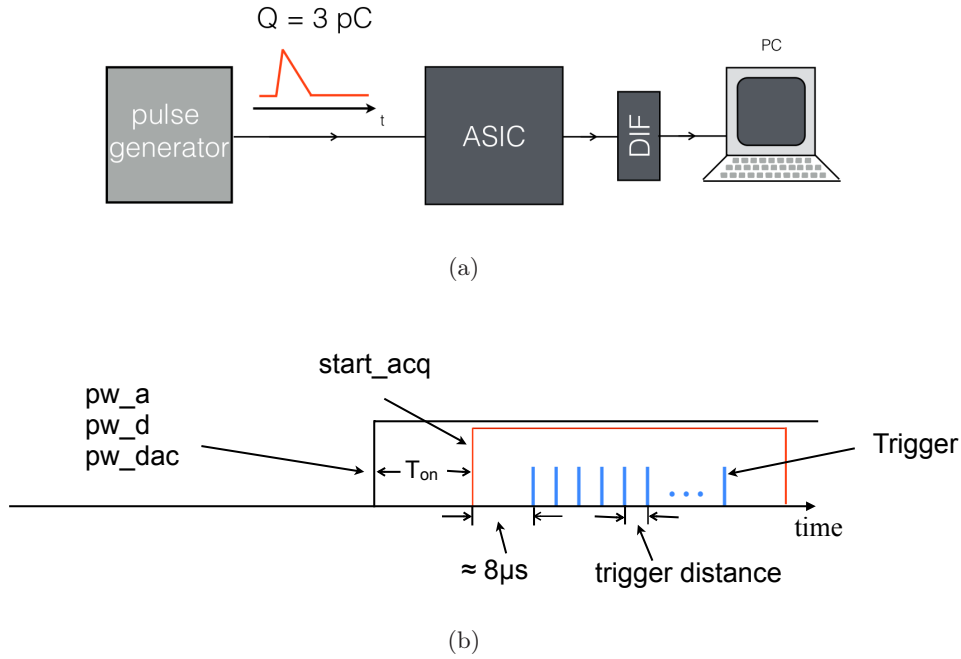


Figure 6.16 – a) shows a sketch of the experimental setup for the measurement of the activation time. A pulse generator generates an electrical signal, which is injected into one channel of the engineering prototype. The trigger settings are steered with the ASIC via the DIF and the data is read out and analyzed with an external PC. b) shows a detailed sketch of the timing of the signals used for the measurement. For the measurement, T_{on} or the trigger distance can be varied. The rising edges for e.g. pw_a or start_acq indicate the starting point for their operation.

cells with power pulsing. Comparing the output of the memory cells with and without power pulsing, it can be seen that the measured ADC output for the injected charge in power pulsing mode, especially for the first memory cells, is significantly lower than without power pulsing. The first memory cell gives the information of the shortest time and the last memory cell gives the information of the longest time. For shorter times of T_{eff} (e.g. fig. 6.17(a)) the ADC output in power pulsing mode is much less than the reference value without power pulsing. For longer times (e.g. fig. 6.17(d)) the ADC output gets close to the reference value. It should be noted that for longer times the distribution of the ADC output gets narrower than the reference distribution, which is visible in the higher peak of the histograms, since the number of entries in both cases are the same. The mean of a gaussian fit of the histograms is used in the following as the mean ADC value of the memory cells. To get information on the performance of the electronics depending on T_{eff} the ratios of the means with and without power pulsing for each memory cell are analyzed. Fig. 6.18 shows the ADC output of four different memory cells and therefore a direct impact of T_{eff} . Fig. 6.18(a) represents

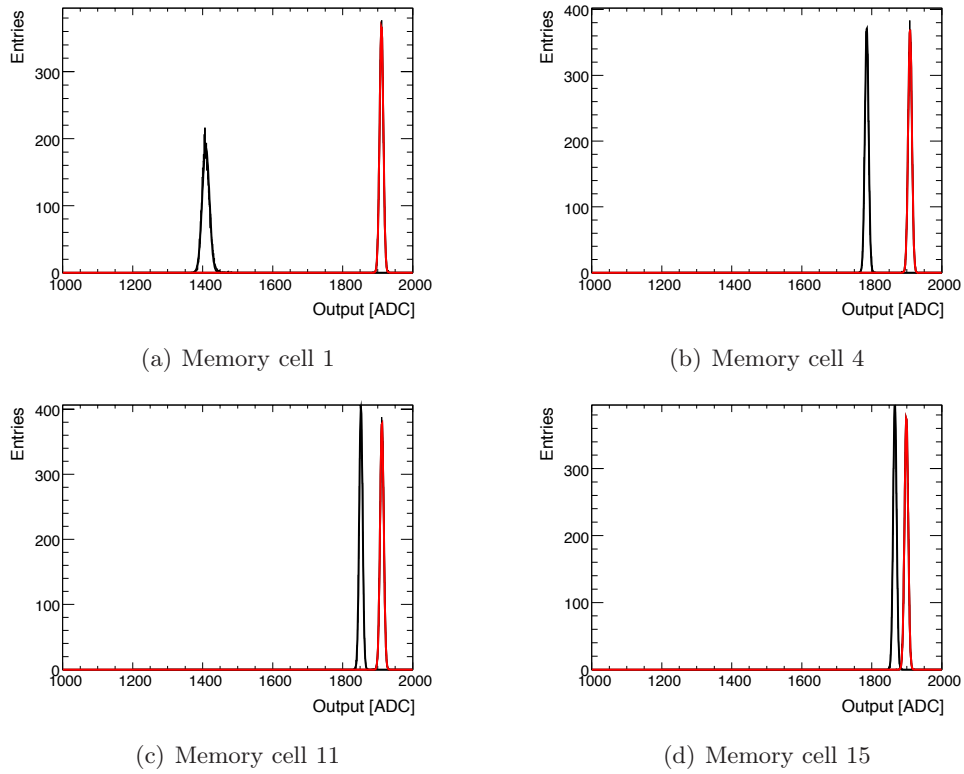


Figure 6.17 – Signal in different memory cells. The red curves are gaussian fits of the entries in the different memory cells measured without power cycling and the black curves are gaussian fits of the entries in the different memory cells measured with power cycling. This measurement was made for different time settings always with the similar result.

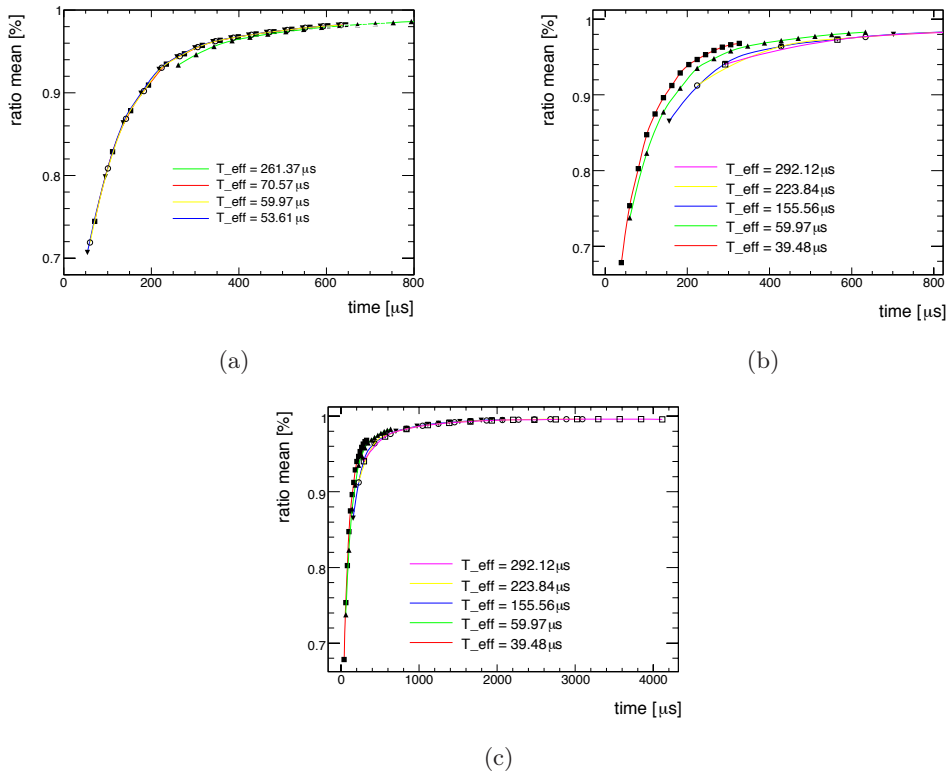


Figure 6.18 – Measurement of the performance of the electronics in dependence of T_{eff} . Each curve represents one measurement with one T_{eff} , every mark corresponds to one memory cell. Picture a) has a constant trigger time distance of $40.97 \mu s$ with different activation times T_{on} . Picture b) has a constant activation time of $11 \mu s$ with different trigger time distances. Picture c) shows the same as b) but for longer times.

the time behavior of the ratio for different activation times (time between triggers is set to $40.97 \mu\text{s}$). Each curve represents one T_{eff} . The curves always starts with memory cell 1. For instance, the first entry in fig. 6.18(a) for $T_{on} = 4.64 \mu\text{s}$ corresponds to $T_{eff} = 53.61 \mu\text{s}$, because the first memory cell is filled after $T_{eff} = T_{on} + 8 \mu\text{s} + 40.97 \mu\text{s}$. Fig 6.18(b) and Fig. 6.18(c) show the measurement with a constant activation time of $T_{on} = 11 \mu\text{s}$ by varying the time distance between the injected triggers. $11 \mu\text{s}$ was chosen in order to start below the dedicated $20 \mu\text{s}$, estimated by the manufacturer of the chip. Fig 6.18(a) and Fig. 6.18(b) show a similar time development, meaning that the output of the memory cells mainly depends on the time when the electronics is switched on. It is noticed that the ratio approaches 1 (98%) after about 1 ms, so the output of the electronics with power cycling needs a long time to reach the same output as without power cycling. The $20 \mu\text{s}$ estimated by the manufacturer of the chip for the activation time T_{on} would lead to a strong reduction of the measured signal.

6.5.2.3 Influence of the R-C element of the Preamplifier

One possible reason for the reduced efficiency is the preamplifier of each channel. In power pulsing mode the preamplifier is switched on and off. Between the connection of the preamplifier power supply (VDDA_PA) and the preamplifier an R-C element is installed to reduce the common mode noise (noise correlated between the channels). Fig. 6.19 shows a technical sketch of the R-C element and the preamplifier. The common mode attenuation has the disadvantage that every time when the power supply is switched on or off, the capacitor is charging or discharging. So the voltage at the preamplifier depends on the time constant of the R-C element ($\tau = R \cdot C$). The default setup for the R-C element is $R = 10 \Omega$ and $C = 33 \mu\text{F}$ with a τ of $330 \mu\text{s}$. A measurement in the laboratory shows that the voltage at the preamplifier drops $\sim 0.2 \text{ V}$ due to the voltage drop at the resistor of the R-C element after switching on. The impact of the R-C element on the noise in two channels is shown in fig. 6.20. The correlation of the noise between two channels with an R-C element and without an R-C element is shown. The x-axis shows the pedestal entries for one channel and the y-axis shows the pedestal entries for another channel measured in one pedestal run. Without an R-C element a strong correlation between them is observed and with this R-C element the dependence is suppressed.

Looking at fig. 6.18 the default setup with a time constant of $\tau = 330 \mu\text{s}$ seems too large to be the main responsible for the slow rising of the efficiency. An efficiency of 95% is reached around $300 \mu\text{s}$, therefore rather a time constant of $\tau \approx 100 \mu\text{s}$ seems to be responsible for the slow rising of the efficiency. Nevertheless, the preamplifier R-C element might have a relevant influence on the reduced signal size after a few hundred μs . Therefore, the impact of the R-C element is studied in the following.

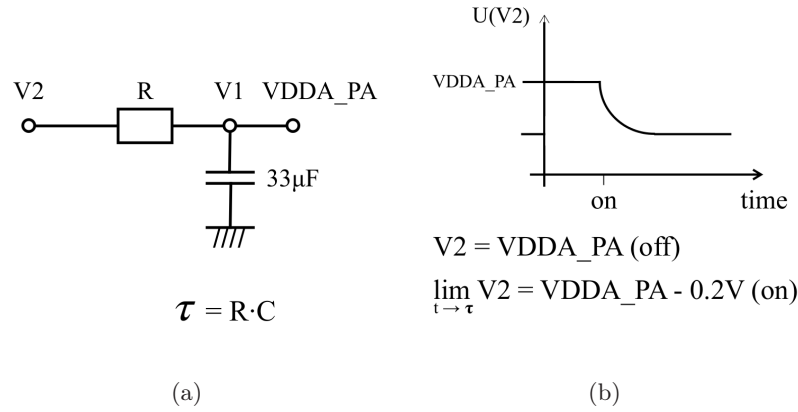


Figure 6.19 – a) scheme of the R-C element of the preamplifier. The preamplifier will be supplied by the VDDA_PA. Between the preamplifier (V2) and the VDDA_PA the R-C element is installed. b) technical sketch for the voltage drop at the preamplifier. The voltage at the preamplifier (V2) is determined by the R-C element. The voltage at V2 drops -0.2 V after switching on. In switched off mode the VDDA_PA supplies 3.3 V only the current supply is switched off.

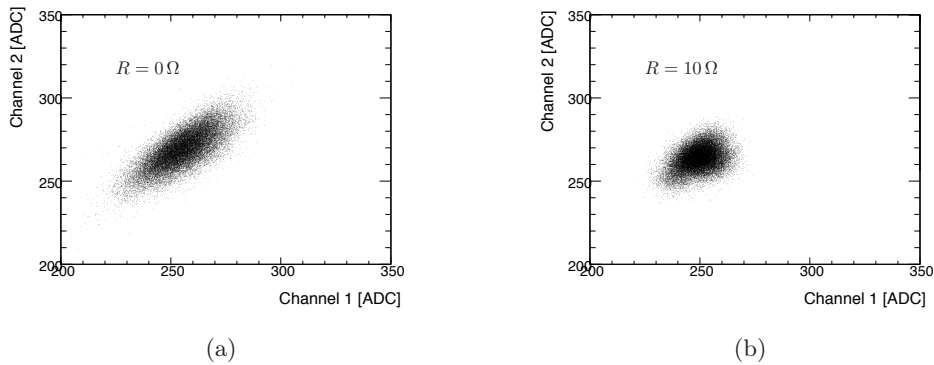


Figure 6.20 – Correlation of the pedestal behavior between the channels. a) without preamplifier R-C element a big component of correlated noise can be seen b) with R-C element the correlated noise component is much reduced.

Pedestal

The R-C element is needed to suppress the common mode noise. So it is interesting to investigate the influence of the R-C element and the power cycling on the pedestal. An example for one memory cell is displayed in fig. 6.21. The pedestal distribution looks like gaussian signals and can be fitted. From the fit, the mean and width can be determined. The width for the fits of 10 Ω and 5 Ω in fig. 6.21(a) and 6.21(b) are comparable, but in fig. 6.21(c) the width of the pedestal of the 0 Ω setup is considerably larger. The influence of the common mode noise is observable. As a next step the width of the pedestals with the 5 Ω, 10 Ω and 0 Ω setup with power pulsing is analyzed as function of

the time. Fig. 6.22 shows the comparison of the width of the pedestals of the memory cells on dependence of T_{eff} for one channel with the different setups. The common mode noise leads to an increased width of the pedestal distribution for the setup without R-C element and it is stable over the time. In the $R = 0\ \Omega$ setup, the width of the pedestal is about a factor 2 bigger compared to the other setups. Astonishingly the width of the pedestal with power pulsing mode for 10 and 5 Ω is as small as for the 10 Ω setup without power pulsing, also here the width is stable over the time.

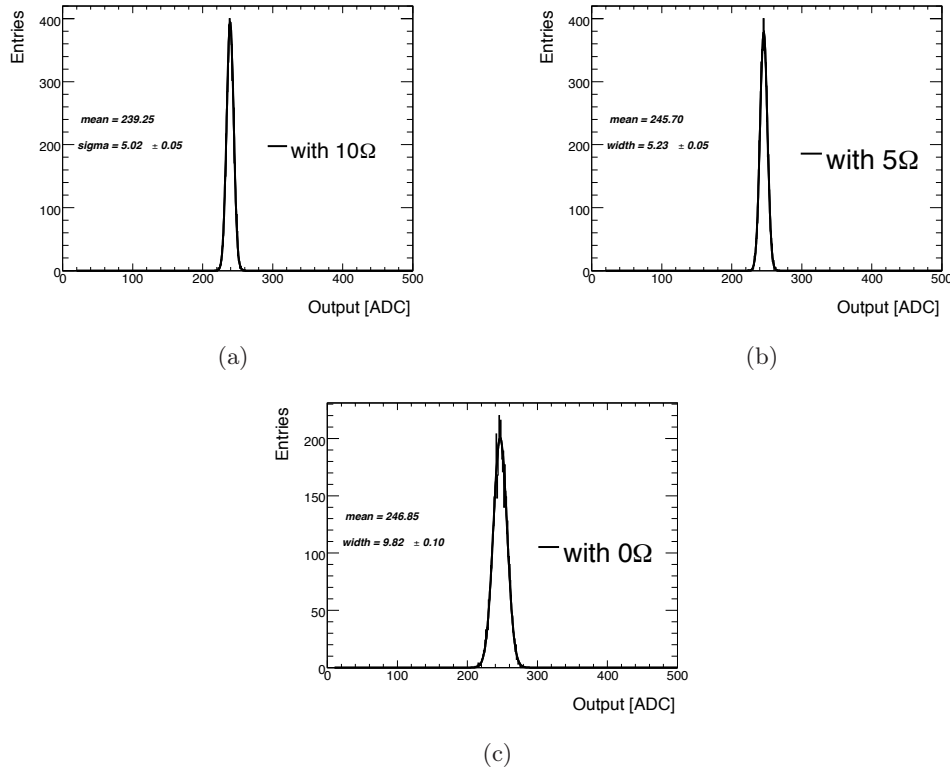


Figure 6.21 – Measurement of the pedestals of the same channel for different R-C elements (10 Ω , 5 Ω , 0 Ω).

Signal Measurements with changed R-C Element

To study and analyze the influence of the R-C-element on the time dependence of a signal in power pulsing mode, first a measurement without an R-C-element is used. Analyzing the histograms of the memory cells taken with power pulsing shows that the entries of the histograms do not follow a Gaussian distribution and the distributions are very broad (fig. 6.23). One possible reason could be the common mode noise, because without an R-C element the common mode noise gets the full impact on the electronics. Therefore, this setup is not useable for physics measurements.

But to analyze the influence of the R-C element, the resistor R can be reduced. In

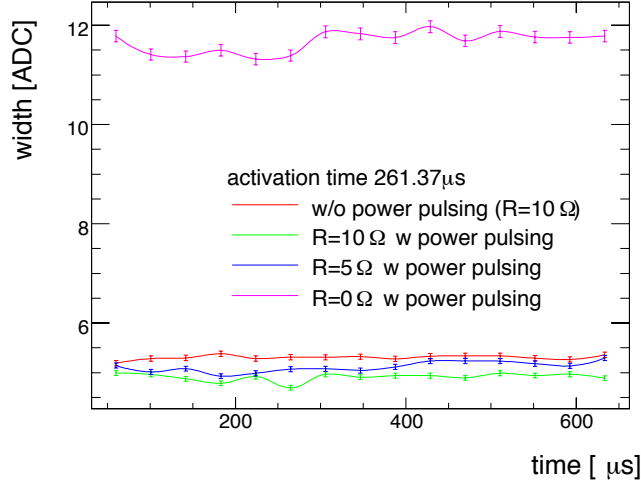


Figure 6.22 – Comparison of the width of the pedestals of the memory cells of one channel for different R-C elements for the preamplifiers, with and without power pulsing in dependence of the time after the electronics is switched on.

order to test the influence of the R-C element on the needed activation time the default setup is changed from $10\ \Omega$ and $33\ \mu\text{F}$ ($\tau = 0.33\ \text{ms}$) to $5\ \Omega$ and $33\ \mu\text{F}$ ($\tau = 0.165\ \text{ms}$). By halving the time constant the measured signal size should approach the value without power pulsing much faster. The measurement is made for different T_{eff} s (varying the activation time and the time between the injected triggers). Fig. 6.24 represents the results for the $5\ \Omega$ setup, which show a similar chronological development as the default setup. To see the influence of the changed setup, the measurement for the default setup and the $5\ \Omega$ setup are compared directly for an effective activation time of $T_{eff} = 59.97\ \mu\text{s}$ and a trigger distance time of $40.97\ \mu\text{s}$. The ratios as function of time can be seen in fig. 6.25. A comparable rising of the ratios with a slightly higher plateau in the $5\ \Omega$ setup is visible. But due to halving the time constant of the $10\ \Omega$ setup a much faster rising in the ratios with the $5\ \Omega$ setup is expected. In agreement with the discussion about the time constant of the R-C element at the beginning of sec. 6.5.2.3, the impact of the R-C element for the long activation time as the main reason can be excluded. But the R-C element has an impact for the signal size at intermediate times of $\sim 400 - 600\ \mu\text{s}$. It is still unclear what causes this behavior. In order to disentangle effects of the SPIROC from effects of the HBU, measurements with a SPIROC on a test board would be needed, as it is planned in the future.

6.5.3 Power Consumption

In ILC mode, the power cycling is linked to the ILC bunch train structure to reduce the power consumption and avoid too much heating within the detector. To achieve this, the power consumption should be limited to $25\ \mu\text{W}/\text{channel}$ (without the power

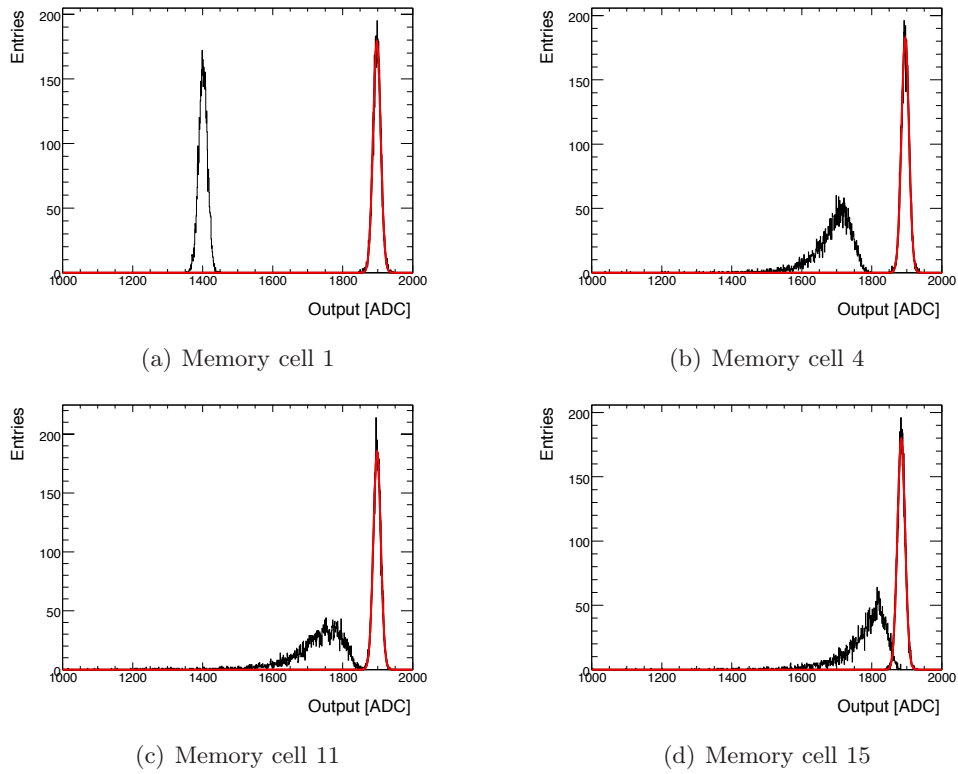


Figure 6.23 – Signal in different memory cells measured without an R-C element in the preamplifier power supply. The black curves are the fits of the entries in the different memory cells measured with power cycling and the red curves are the fits of the entries in the different memory cells measured without power cycling.

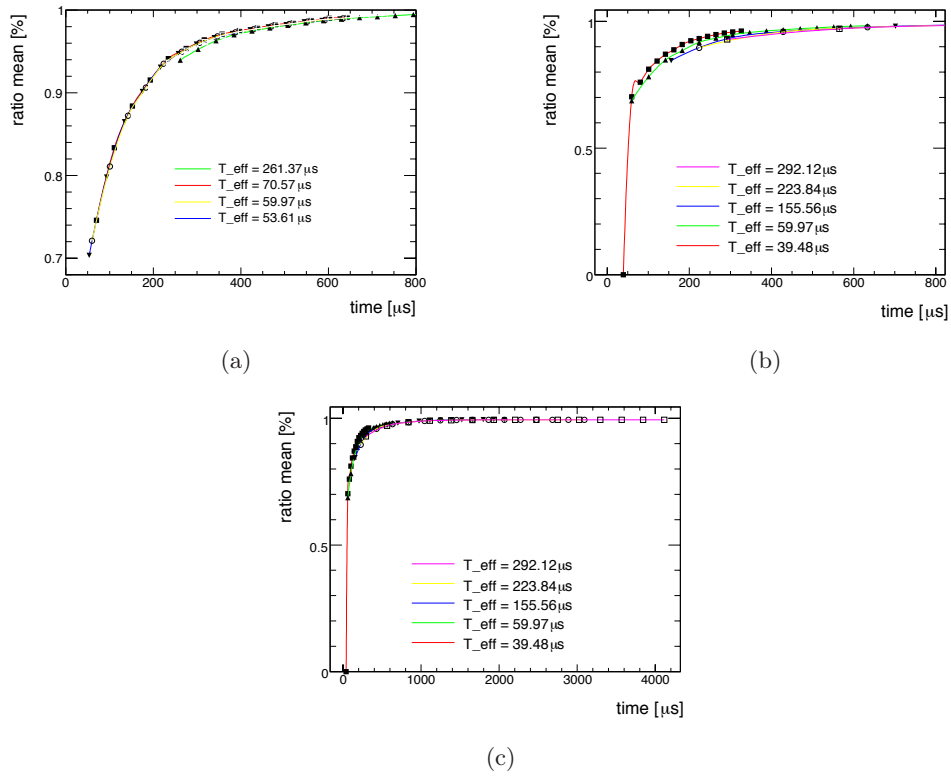


Figure 6.24 – Measurement with a 5Ω preamplifier R-C element, which corresponds to a time constant of 0.165 ms. Each curve represents one measurement with T_{eff} , every mark corresponds to one memory cell. Picture a) has a constant trigger time distance of $40.97\mu s$. Pictures b) and c) have a constant activation time of $T_{on} = 11\mu s$.

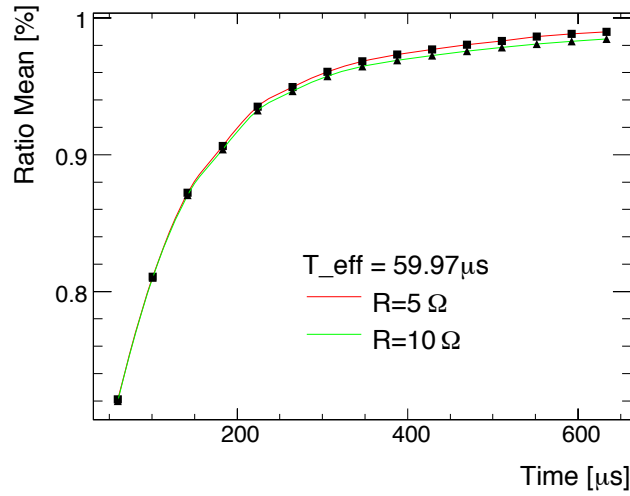


Figure 6.25 – Comparison of the 5 Ω and 10 Ω setup. Both curves have the same specific adjustment (activation time and trigger time distance) with different resistors for the R-C element.

consumption of the SiPMs) as explained in sec. 6.5. This section studies the total power consumption of the electronics, in order to evaluate the performance and to give indications for improvement. A time sketch for the power supplies is displayed in fig. 6.15. The power consumption is determined for time windows with constant conditions. In every time window several power supplies work together. With

$$E_i = U_i \cdot I_i \cdot \Delta t_i \quad (6.13)$$

the electrical energy E_i for every time window can be determined. Δt_i is the length of the time window i . Δt_i is separated from t_1 to t_5 according to the power supplies which are switched on during that time (as displayed in fig. 6.15). So the total power consumption P_{all} is:

$$P_{all} = \frac{\sum_{i=1}^5 E_i}{T}. \quad (6.14)$$

T is the distance between one bunch train to the next ($T = 200$ ms). E_1 to E_5 are the electrical energies for the time windows t_1 to t_5 . E_5 is driven by the $VDAC$ and $VRef$ which are not displayed in fig. 6.15, but are switched on during the whole power cycle. $VRef$ is a reference voltage for all analog components. It supplies constant voltages for analog components. The $VDAC$ is the power supply for the DAC threshold.

The ASIC generates all voltages from two powers supplies, $VDDA$ (voltage drain drain analog) and $VDDD$ (voltage drain drain digital) which are provided by the power board. On these supplies the different currents (I_{VDDA} and I_{VDDD}) of the board can be measured. These supplies have a voltage of 3.3 V. Every single E_i has fractions of the $VDDA$

and $VDDD$ supply :

$$E_i = E_{i_{VDDA}} + E_{i_{VDDD}} \quad (6.15)$$

Table 6.1 shows the measured currents in the corresponding time windows. With the currents, the time table and the according voltage, a calculation of the electrical energy is possible. In addition, during the whole power cycling, the ASIC is supplied by the $VDAC$ and the $VRef$ power supply. The $VDAC$ power supply delivers 0.01 mA at 5 V and the $VRef$ supplies 0.42 mA with 4.5 V. This power has also to be taken into account, see Tab. 6.1. The total power consumption for all four chips on one HBU is $P_{all} = 100.2$ mW. In this setup one channel consumes ~ 700 μ W. This magnitude is much higher than the desired 25 μ W/channel. To reach the goal of 25 μ W/channel, a factor 30 has to be improved. The dominant part is the electrical energy in the readout phase t_4 by E_{VDDD} , which result in a power consumption of 72.5 mW. In this calculation, the activation time is not taken into account. If an appropriate activation time is fixed this time has to be added to time window t_1 and subtracted in time window t_5 . For ~ 1 ms activation time for ILD, the contribution in t_1 to the total power would be roughly doubled, even the power consumption of the VDDA will exceed 50 μ W/channel. To reach the desired power consumption of 25 μ W/channel, the duration and the power consumption of the activation time have to be reduced. The decreasing of T_{on} is a challenge of the electronics and new chip generations should optimize this issue. To reduce the overall power consumption a new strategy in the readout process of the chips seems to be very promising to reduce the power consumption of P_{VDDD} during t_4 and is described in the next section.

6.5.4 Power On Digital Module

The Power on Digital module (POD) has been developed to meet the power budget of the ILC. With the POD module only the chip that is read out, is switched on. The POD module is an integrated part of the ASIC but is not configured to be used in the current setup. In the current setup all chips are switched on during the whole readout phase. With the POD, each chip is switched on for 6.25 ms instead of 150 ms, since one slab contains 24 chips. If a POD module is used, the power should be changed in time window 4 and 5 (t_4, t_5). In case of the use of a POD module, the power consumption is estimated to 7.63 mW per chip or 200 μ W per channel, which improves the power consumption by a factor 3.5 compared to 700 μ W/channel. In the setup, this value would still be 8 times too big for the desired 25 μ W per channel. Even if the power consumption is still too large, this concept looks very promising. Future chip generations must improve the total power consumption.

Power	Time window	I_{VDDA} [mA]	I_{VDD} [mA]	t_i [ms]	E_{iVDDA} [mJ]	E_{iVDD} [mJ]	E [mJ]
E_1	t_1	498.47	30.33	0.9	1.48	0.09	-
E_2	t_2	519.47	37.56	0.1	0.17	0.01	-
E_3	t_3	245.20	36.79	3.2	2.59	0.38	-
E_4	t_4	0.71	29.31	150	0.35	14.5	-
E_5	t_5	0.56	0.01	45.8	0.08	$1.5 \cdot 10^{-3}$	-
$VDAC$	-	-	-	-	-	-	0.01
$VRef$	-	-	-	-	-	-	0.38
ΣE	20.04 mJ						
ΣP	100.2 mW						

Table 6.1 – Table with the different currents, electrical energies and times for one HBU operated in power pulsing mode.

6.5.5 Summary of the Characterization of the Power Pulsing Mode

The power cycling mode is mandatorily needed for a high granularity calorimeter with integrated readout electronics in order to avoid an extra cooling system. In the setup used for these measurements the output of the chip in power pulsing mode is worse than the output of the chip without power pulsing. The measured signal is lower for ~ 1 ms after switch on of the electronics and the activation time is not influenced by an R-C-filter on the preamplifier supply voltage.

The measured power consumption in power pulsing mode is a factor ~ 30 too high, even with a POD module. Therefore, the power consumption itself during all phases needs to be reduced. An improved behavior is expected in the next chip generation of the SPIROC chip and will be tested then. The next generation of the chip should be improved like in aspects of the activation time and the power consumption.

7 Noise and Pedestal

One layer of the CALICE AHCAL engineering prototype has been operated together with the DHCAL prototype in a test beam campaign at the CERN SPS test beam facility in November 2012. The H8 beam line provides particles with energies in the range from 10-300 GeV. Beams of muons and pions were used with energies of 50 GeV and 180 GeV. This chapter describes studies of the pedestal during the test beam campaign. After common considerations of the noise, the experimental configurations at the test beam campaign and the determination of the pedestal will be presented here. In this context also a measurement of the dark rate will be discussed that was performed before the test beam campaign to estimate the rate of dark events expected during the test beam.

7.1 Pedestal

The parameter *pedestal* is an important parameter for studying data in many high energy physics experiments. In principle, the pedestal is a value which defines a starting point of a measurement scale. "Noise" in turn is a feature of every electronic device and the noise broadens the pedestal. Therefore, the noise can be measured by the width of the pedestal. For example, if the detector is switched on and running idle, than the ADC output will fluctuate around a certain ADC value (for instance 250 ADC units). This ADC value determines the starting point of your measurement, the pedestal, and the fluctuations correspond to the noise. Measuring the starting point will give usually a gaussian distribution. The mean value of this gaussian corresponds to the pedestal and the width to the noise. In an ideal world the noise would be negligible and the pedestal would be visible as a δ - distribution. The offset from zero is usually set intentionally in order to measure very small signals also in presence of noise, which can shift them to values below the pedestal. If the pedestal would be set to zero these signals wouldn't be measurable.

To describe and understand the pedestal and noise for the AHCAL engineering prototype, the electronic noise will be introduced in the first place before the pedestal will be described. The description follows [100, 129].

7.1.1 Characterization of the Electronic Noise

Generally, a minimum size for an electronic signal is not expected for a measurement device. Theoretically a random number of amplifiers can be installed to amplify and measure any small signals, but in an experimental environment such a circuit shows a detection limit [129], which is called *noise*. Every electronic device has this feature. The noise itself can be separated in different parts, so the total noise gets influenced by many noise sources. In general these noise sources can be distinguished into intrinsic, internal or external noise sources [100]. Intrinsic noise characterizes the minimal noise of an electronic circuit, internal noise describes internal disturbance sources like local oscillations or switch flanks, which increase the noise. External noise sources inject noise from the environment like supply circuits. The external noise can be minimized with appropriate grounding or shielding.

Fluctuations in the electric current cause noise by the discrete nature of the electrons. In general, the current can be described with the number of electrons n with the electron charge e which move with the velocity v between two electrodes. The induced current i depends on the spacing l between the electrodes [100]:

$$i = \frac{n e v}{l}. \quad (7.1)$$

The fluctuation of the current is described by the total differential

$$\langle di \rangle^2 = \left(\frac{n e}{l} \langle dv \rangle \right)^2 + \left(\frac{e v}{l} \langle dn \rangle \right)^2. \quad (7.2)$$

The two terms added in quadrature are statistically uncorrelated. The number of charge carriers and the fluctuations in the velocity drive the total noise. The noise can be separated in several components. The *Shot Noise* considers fluctuations in the number of charge carriers and the *Thermal Noise* regards fluctuations of the velocity. Additionally, the *Contact Noise* contributes to the total noise:

1. **Shot Noise:** Electrical current is associated with the movement of charge carriers across a potential barrier. Considering currents where electrons flow independent from each other, then their contribution to the current is just statistically distributed [129]. Therefore, the current will fluctuate around an average value. This is called Shot Noise. The Shot Noise occurs in semiconductors or vacuum tubes [100].
2. **Thermal noise:** Velocity fluctuations are described by random thermally excited disordered movements of charge carriers. This causes thermal motion. The charge carriers have a mean free path until they scatter at lattice atoms, so the charge carriers cause statistically independent current pulses. Therefore, thermal noise

has a random signal and can be described in a normal distribution of amplitude and frequency. It is also called *white noise* [100].

3. **Contact or flicker noise:** Contact or flicker noise is caused by fluctuating conductivity due to imperfect contact between two materials. Statistically fluctuating conductivity between single crystallites of the material are responsible for this noise contribution. The contact noise occurs in switches, relays and transistors. It is also called $1/f$ noise, due to its frequency characteristic. For low frequencies these effects become more important [100].

For the detector, the noise performance is very important. All these kinds of noise occur in the detector. Even the components which are needed to connect the SiPMs with the readout chip add some noise. Noise contributions are usually expressed as a voltage (e.g. contact noise) or current (e.g. noise due to the detector dark current) fluctuation to characterize the complete noise in the detector. The quality of the noise can be expressed in the signal to noise ratio.

Noise fluctuations are also superimposed on the measured signal. The amplitude distribution of the noise is gaussian, therefore the measured signal is also smeared with a gaussian distribution.

7.1.2 Influence of the SiPMs on the Noise (Dark Rate)

The pedestal and the noise in the engineering prototype determines a minimum level for detectable signals. For a good quality of the analyzed data a detailed study of the noise is necessary. Fig. 7.1 shows a typical pedestal distribution of one channel of the detector. It is expected that the broadening of the distribution due to the electronic noise should follow a gaussian distribution. Fig. 7.1 shows an asymmetric behavior. Especially the right tail of the distribution differs from the gaussian distribution. The histogram gets additional entries from the SiPMs. The SiPMs are working in Geiger mode, the random generation of an electron hole pair can initiate an avalanche which will be detected as an electric pulse (dark events). As mentioned in sec. 5.3.2, the dark events are indistinguishable from the signal of a photon detection, and the main mechanism for the random generation of dark events are the thermal excitation and the tunnel effect (as depicted in fig. 5.8). The determination of the dark rate of the AHCAL engineering prototype is discussed in sec. 7.3.

7.2 Pedestal Determination on the Basis of the CERN Test Beam Campaign

This section presents the beam setup for the engineering prototype and the determination and study of the pedestal from the CERN test beam data. In principle, the pedestal

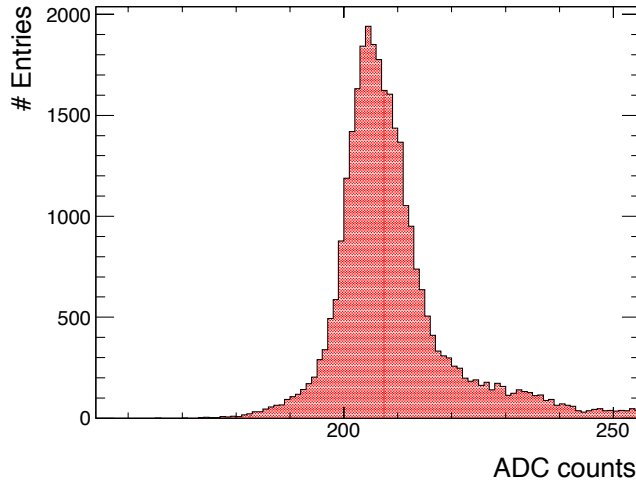


Figure 7.1 – Typical histogram of the noise in one channel of the AHCAL engineering prototype. The RMS of the histogram is defined as the value of the noise.

can be determined in the laboratory. But it has to be verified in a test beam to prove that the setup has no influence on the pedestal in a test beam environment.

7.2.1 Beam Setup at the CERN Test Beam Campaign

For the beam generation, the primary proton beam from the SPS hit a target. To transport the beam, a momentum-selection and focussing system is used. The components of the beam depend on the momentum selection but also on the inserted target and/or absorbers in the beam line. In front of the detector system a trigger and tracking telescope is installed which is set up with three delay wire chambers plus two $10 \times 10 \text{ cm}^2$ trigger scintillators. Before the beam hits the detector the secondary beam passes a delay wire chamber and two Cerenkov counters, which can be filled either with Helium or Nitrogen for particle identification. These three components are always in the beam line. To tag muons two $30 \times 30 \text{ cm}^2$ scintillators were installed to scan over the detector area. For the CERN test beam a setup of the beam was chosen which delivers mainly pions. For the muon runs, additional dumps or collimators were used to block the beam line. Since the information from the Cerenkov detectors could not be implemented directly into the DAQ system of the AHCAL engineering prototype, the information from the Cerenkov detectors could not be used.

7.2.2 Experimental Setup

The AHCAL engineering prototype from sec. 5.2.2 was placed behind the Digital Hadron Calorimeter (DHCAL) prototype downstream $\sim 600 \text{ m}$ from the first target of



Figure 7.2 – Pictures of the engineering prototype in the test beam facility. a) the AHCAL engineering prototype is installed as 40th layer behind the DHCAL followed by a tail catcher. For temperature stability reasons the prototype was placed in a climate tent, in b) the deinstallation of the climate tent is visible.

the primary proton beam. The DHCAL contains a 39 layer structure, based on Resistive Plate Chambers (RPCs), with 1 cm thick tungsten absorber plates. The layers of the DHCAL were contained in cassettes with a 2 mm copper front plate and a 2 mm thick steel plate [108]. Additionally a tail catcher based on RPCs with a 8 layer structure with 2 cm thick steel plates followed by six 10 cm steel plates was used to identify muons. For efficiency of the RPCs of the DHCAL, the detector setup (except the tail catcher) was in a climate tent which was filled with fans to stabilize the temperature inside of the tent. The AHCAL was installed inside the tent as 40th layer with 4 HBUs on a 1×1 m² absorber structure. The experimental setup is shown in fig. 7.2.

7.2.3 Trigger System

To guarantee a good data quality and to minimize the amount of dark events in the data, a validation trigger setup (external validation trigger mode, see chapter 5.4.3) was installed. The DHCAL took data by external triggering, it used the trigger and tracking system which was installed in front of the detector. The AHCAL engineering prototype took data in fully self-triggered operation. The trigger threshold was mainly determined by the dark event rate of the detector. The data of the AHCAL were read out during the spill signal if the memory cells were full.

For detailed data studies a comparison and combination with the data which were taken with the DHCAL would be desirable. Unfortunately, a synchronization of both prototypes wasn't possible due to the completely different trigger and data acquisition setups. During the read out phase, the AHCAL electronics was not able to record the missed triggers and therefore also an offline synchronization with the DHCAL data is not possible.

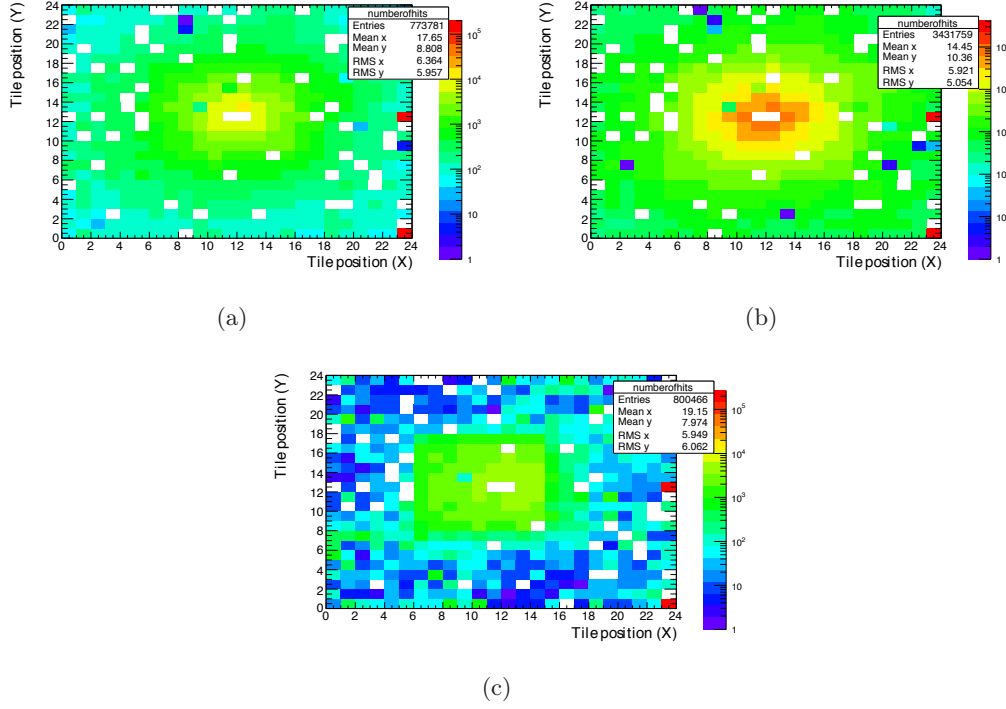


Figure 7.3 – Number of hits for the AHCAL layer. a) for all 50 GeV pion runs, b) for all 180 GeV pion runs, c) for all 180 GeV muon runs with a central scintillator.

7.2.4 Collected Data Samples

The main focus of the test beam was a system test of one layer and a first look into the hit time measurement capabilities of the AHCAL. The CERN test beam campaign took 10 days of beam time, where the AHCAL ran parasitically with the DHCAL low rate (a few 10 Hz) due to the RPC rate limitations. One day of the beam time was dedicated for the AHCAL with high rate runs. During these days muons at 180 GeV with central, upper and lower position of the $30 \times 30 \text{ cm}^2$ scintillator and pions at 50 and 180 GeV with a central $10 \times 10 \text{ cm}^2$ scintillator were recorded. In this thesis only a first look into the data will be presented to demonstrate the quality of the collected data. Fig. 7.3(a)-7.3(c) shows the number of hits collected for pions at the two different energies and for muons with central trigger position. For the pion, the shower profile is visible, since the whole layer records hits, while for muons almost only hits in the central trigger scintillator region are detected.

7.2.5 Pedestal Determination

As mentioned in chapter 7.1.2, the broadening of the pedestal distribution due to noise of one channel is strongly correlated with the dark rate of the SiPMs. For further analysis it is important to characterize the pedestal of the engineering prototype in an

appropriate way. The dark events are not just influencing the pedestal distribution, they also influence the detected signals. The pedestal distribution is smeared by dark events in one direction and this bias should not be ignored. In the following, the mean value of the pedestal histogram will be used and this value is defined as the *pedestal*, vice versa the width of the pedestal distribution will be named *noise* in the following. To analyze the pedestal in detail, dedicated pedestal runs were taken in external trigger mode during the CERN test beam campaign. In addition, physics runs which were taken in auto trigger mode can be used. In auto trigger mode all channels of one chip will be read out if only one channel of the chip has a signal that passes the threshold. To analyze the pedestal only information from channels without a hit bit are used. This excludes channels with large signals from a beam event. Physics runs have the advantage that all possible variations during a measurement are taken into account. The main disadvantage is that additional real signals that were below the auto trigger threshold can appear in the histogram.

To determine the pedestal it is important to cover as much as possible of the right tail of the distribution to include most of the dark events. For that purpose the setting of the range of the histogram is difficult, because a good compromise is needed between the inclusion of dark events and the exclusion of real hits (for physics runs). In the approach taken here, in a first step the most probable value (MPV) and the RMS (which is the noise of the pedestal) are determined by filling a histogram in the range from 100 to 400 ADC tics with signals, because from operating experience the pedestal will be in that range. Using the noise, a new range for the histogram can be set. Fig. 7.4 shows the histogram with ranges of 2, 3 and 5 times of the noise. For 3 and 5 times of the noise a second peak at 300 ADC tics can be seen. These entries are suspected to originate from energy depositions of particles, either in the tile directly or due to cross talk from neighboring tiles, so these entries should be excluded.

From that point of view a range which is set to 2 times the noise covers appropriately the dark events and excludes additional entries. The noise of the pedestal determines the range of the histogram and the mean value of the histogram determines the value of the pedestal.

7.2.5.1 External and Auto Trigger Mode

The pedestal distribution in external trigger mode (fig. 7.5(a)) looks quite different from the pedestal distribution in auto trigger mode in the same channel (fig. 7.4). The difference is shown in fig. 7.5(b) with a direct comparison, especially the smeared right tail of the pedestal distribution caused by dark events for a physics run is visible and a shift of the pedestal distribution itself. In particular, also the left tail of the pedestal distribution is shifted to the right. It is suspected that the use of the auto trigger mode causes a shift of the ground, because the use of the auto trigger needs some additional

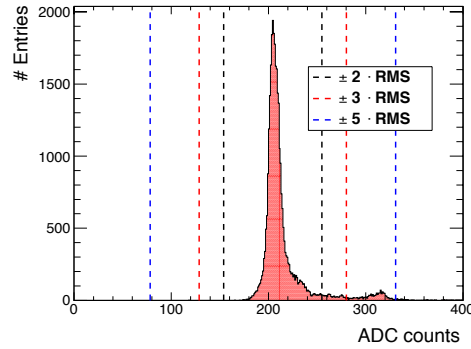


Figure 7.4 – Digitized detector response for a pedestal run with vertical lines to indicate ranges of the histogram, with a ranges of 2,3 and 5 times the noise (here declared as RMS).

power, which could explain the shift of the pedestal distribution, but this is very difficult to test. Also the second peak at 300 ADC units is not visible in external trigger mode, which supports the hypothesis that the additional entries in auto-trigger mode are physics events that should be excluded in the pedestal determination

To do a crosscheck it is useful that during a test beam campaign the pedestal should

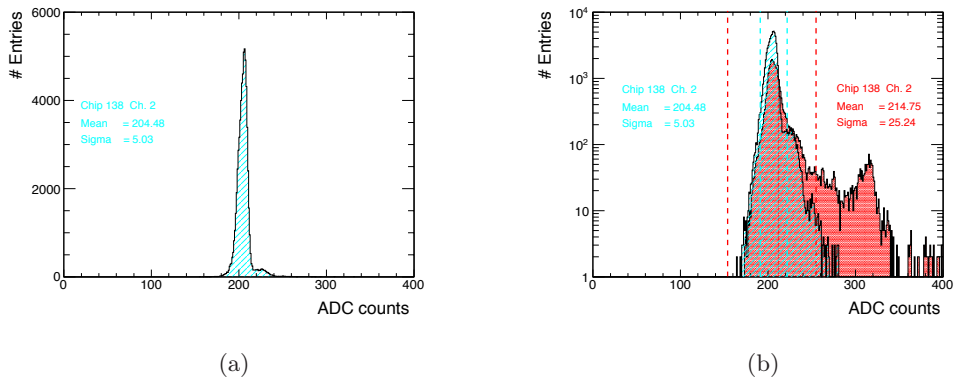


Figure 7.5 – a) noise distribution taken in external trigger mode for channel 2 and b) comparison of the noise distribution between external (blue marked distribution) and auto trigger mode (red marked distribution) for the same channel.

be stable in one channel. If this approach is appropriate the fluctuations of the pedestal and the noise should be around a few ADC tics, because the temperature in the tent was stable. The noise and pedestal respectively should depend on the temperature, this is expected based on the experience with the AHCAL physics prototype [113–115]. Fig. 7.6(a) shows the pedestal in one channel for each run taken at the CERN test beam campaign and fig. 7.6(b) shows the according distribution. All runs except a few outliers agree with a value of 266 ADC units within ± 5 ADC units. Outliers are runs which were taken in external trigger mode at 242 ADC units and a short run with low statistics at

Run number	0 - 12	13 - 26	27 - 32	33 - 45	46 - 53	54 - 61	62 - 70	71 - 76
Energy [GeV]	180	180	50	180	50	180	50	180
Particle type	μ	pion	pion	pion	pion	pion	pion	pion

Table 7.1 – Table of the sections of run numbers with corresponding energies and particle type, which were used. Runs were taken in auto-trigger mode, except run 6 and 17, which were taken in external trigger mode.

290 ADC units. A step between run 12 and 13 is visible, which corresponds to a switch of the particle type from muons to pions. But this shouldn't have an impact, despite the detector occupancy plays a role for the electronics, which is very difficult to test. Also between run 26 and 27 a slight step is visible, here the energy was changed from 180 GeV to 50 GeV. But the energy was changed several times and not all energy changes lead to slight steps in the pedestal value. Tab. 7.1 shows the run number, the energy and the particle type.

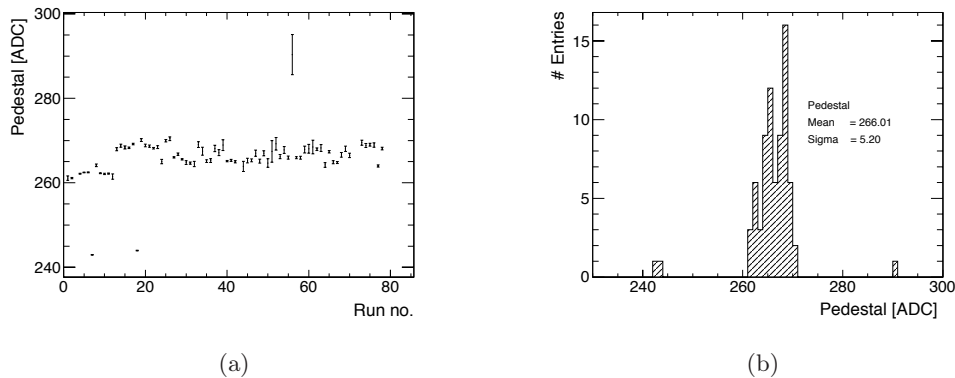


Figure 7.6 – a) shows the pedestal for channel 19 as a function of the run number at the CERN test beam campaign and b) shows the corresponding distribution of the pedestal.

Fig. 7.7(a) represents the noise of the same channel at each run of the test beam campaign. The noise is an important value because here fluctuations of the dark events can be seen. The dark events are strongly correlated to the temperature, due to the tunnel effect and the thermal excitation. If the fluctuations in the noise are quite high then it indicates fluctuations in the temperature during the test beam. Also the noise was quite stable during the test beam (see fig. 7.7(b)). The outliers at 7 ADC units are the noise of two runs which were taken in external trigger mode (calibration runs) and the outlier at 37 ADC units is a run with very low statistics. This means in particular that the fluctuations of the temperature were small enough not to influence the dark event rate of the SiPMs too much, as it is indicated in fig. 7.12(c). Fig. 7.12(c) and the influence of

the temperature will be discussed in more detail in sec. 7.2.5.3.

A detailed look at fig. 7.6(a) and fig. 7.7(a) supposes that there is a correlation between the pedestal and the noise. In fig. 7.8 a correlation between the pedestal and the noise is shown. The two entries at 7-9 ADC units on the x axis are the external trigger runs and the entry at 38 ADC units on the x axis is a low statistics run. A clear correlation between the noise and the pedestal is visible. The correlation suggests that the variation of both values (pedestal and noise) is influenced by a common cause, which is still unclear. One potential reason for a correlation between pedestal and noise could be the temperature. The dark events are determined by thermal excitation and tunnel effects. Both effects are correlated to the temperature.

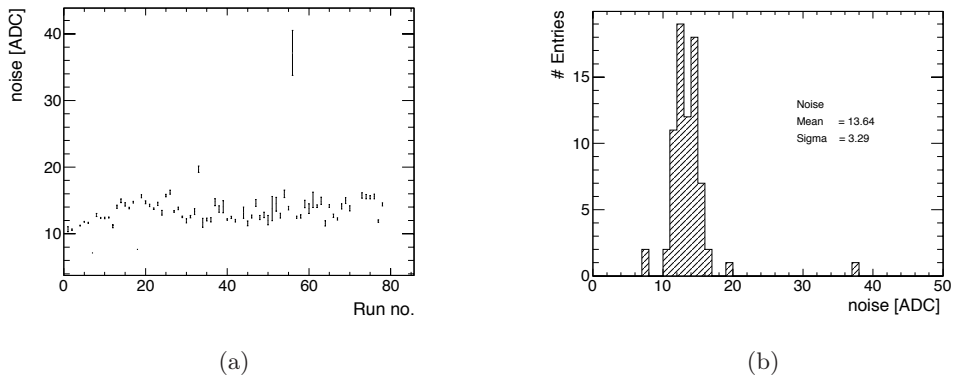


Figure 7.7 – a) width of the noise histogram for one channel in each run at the CERN test beam campaign and b) distribution of the width.

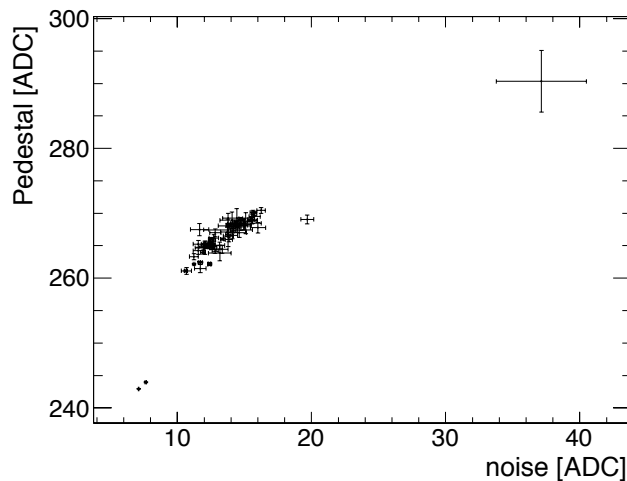


Figure 7.8 – Correlation of the noise and the pedestal for one channel in each run at the CERN test beam campaign.

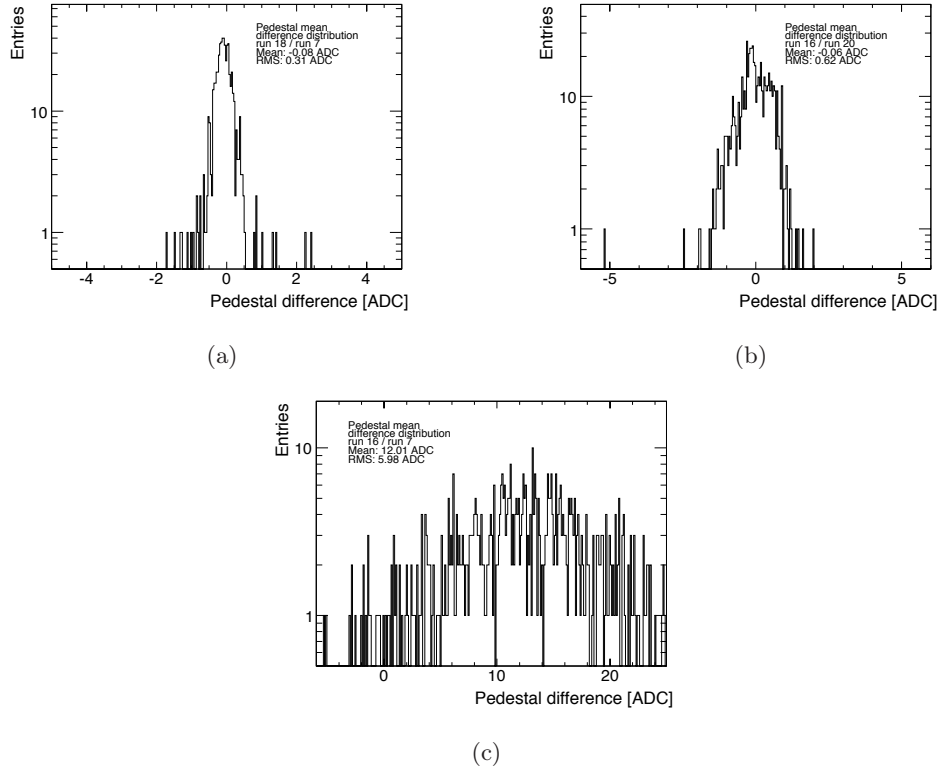


Figure 7.9 – Channel-wise comparison of the pedestal a) in two runs taken in external trigger b) in two runs taken in auto trigger mode and c) in runs of auto trigger and external trigger mode.

Both measurements, pedestal and the noise, show an offset in using the external trigger mode compared to the auto trigger mode. In order to check the difference between the trigger modes, the pedestal values for the same channel in two different runs are compared. For both runs and every channel the pedestal value is determined and a channel-wise comparison between the runs is possible. The offset of the pedestal between the different runs for every channel is shown in fig. 7.9(a) with two runs which were taken in external trigger mode. Fig. 7.9(b) shows the difference of the pedestal for two runs which were taken in auto trigger mode and fig. 7.9(c) the offset of the pedestal for two runs which were taken in auto and external trigger mode. From the comparison two main conclusions can be drawn:

1. differences between runs in the same trigger mode are much smaller than between different trigger modes. This is a common feature for all channels.
2. the average difference between trigger modes is ~ 12 ADC, this is too large to use externally triggered runs to determine pedestals that will be used for data taking with auto trigger mode.

7.2.5.2 Influence of the Memory Cells

In section 7.1.2 it was mentioned that the SiPMs add additional entries to the noise distribution. To exclude other effects which might cause the right tail in fig. 7.4 the influence of the memory cells of one channel is analyzed. Each channel contains 16 memory cells and the noise distribution of one channel is the sum of all 16 memory cells. If fluctuations in the signal of the memory cells are influencing the overall noise distribution then it should be visible by analyzing each memory cell itself. To cross-check the memory cells, a dedicated pedestal run from the CERN test beam data was analyzed because pedestal runs provide high statistics for all memory cells. In particular the pedestal distributions of the memory cells for one channel of one chip are analyzed. Fig. 7.10(a) shows the typical noise of one memory cell. The mean and the width of the histogram are determined as described in section 7.2.5. The red dashed lines indicate the ranges for the determination of the mean and the width. Both values are determined for each memory cell and displayed in fig. 7.10(b). The first memory cell (cell no. 0) is excluded, because the SPIROC2b stores the first event always as a zero. It should be noted that no structure can be seen in the fluctuations. The histogram of the mean and the width are shown in fig. 7.11(a) and fig. 7.11(b). The spread of the mean in fig. 7.11(a) is around a few ADC units. Compared to the average pedestal width of ~ 13 ADC units (fig. 7.7(b)) during the test beam this effect is small. Therefore, the contribution of the memory cells to the width of the overall pedestal distribution for one channel is rather small. Even the width of the pedestals of the memory cells (fig. 7.11(b)) are quite equal.

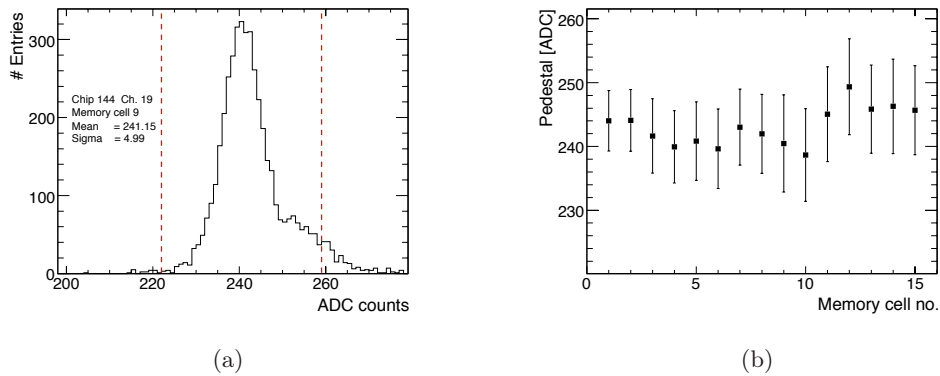


Figure 7.10 – a) noise of one memory cell of one channel of one chip b) mean and RMS of the pedestal for all memory cells of one channel of one chip.

7.2.5.3 Temperature

The engineering prototype was placed as an additional layer of the DHCAL prototype. Due to the conditions of the DHCAL a cooling system was installed which minimized

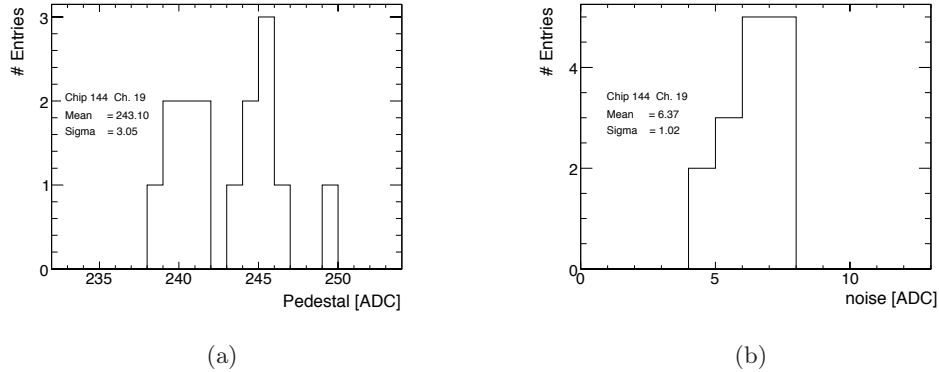


Figure 7.11 – a) mean and b) width values of the pedestal stored in different memory cells of one channel.

the temperature fluctuations. Extracting the temperature information from the run data allows a direct comparison of the pedestal distribution measured at different temperatures. The temperatures were recorded by 6 integrated temperature sensors placed on the readout board. The average temperature of the 6 sensors is taken for each run for this analysis. Fig. 7.12(a) shows the temperature distribution of all sensors for one run. It should be noted, that the temperature was measured several times during one run. Taking one run from each day and using the run with the highest temperature as reference value, a shift of the pedestal and the noise depending on the temperature difference is studied. Herein, two runs are compared with each other like it was done for the comparison distributions in fig. 7.9(b).

From these comparisons the mean and the RMS for the shift of the pedestal and noise are used. Fig. 7.12(b) shows the shift of the noise by comparing two runs with each other. The temperature fluctuations between the runs were around 3 degrees during the test beam campaign. Fig. 7.12(c) and fig. 7.12(d) show that the influence of temperature fluctuations on the pedestal and the noise is negligible.

7.2.5.4 Pedestal Distribution

To study the distribution of the pedestal values of all channels one random run can be used, due to the negligible differences between the channels in two physics runs. The pedestal value for all chips and all channels for one run (random physics run) shows a broad pedestal distribution (fig. 7.13(a)). A detailed look reveals that each chip has its own narrow area in the pedestal distribution (fig. 7.13(b)). Compared to 1 MIP (~ 180 ADC units [130]) the variation between the chips is not negligible which underlines that a channel-wise pedestal calibration is needed.

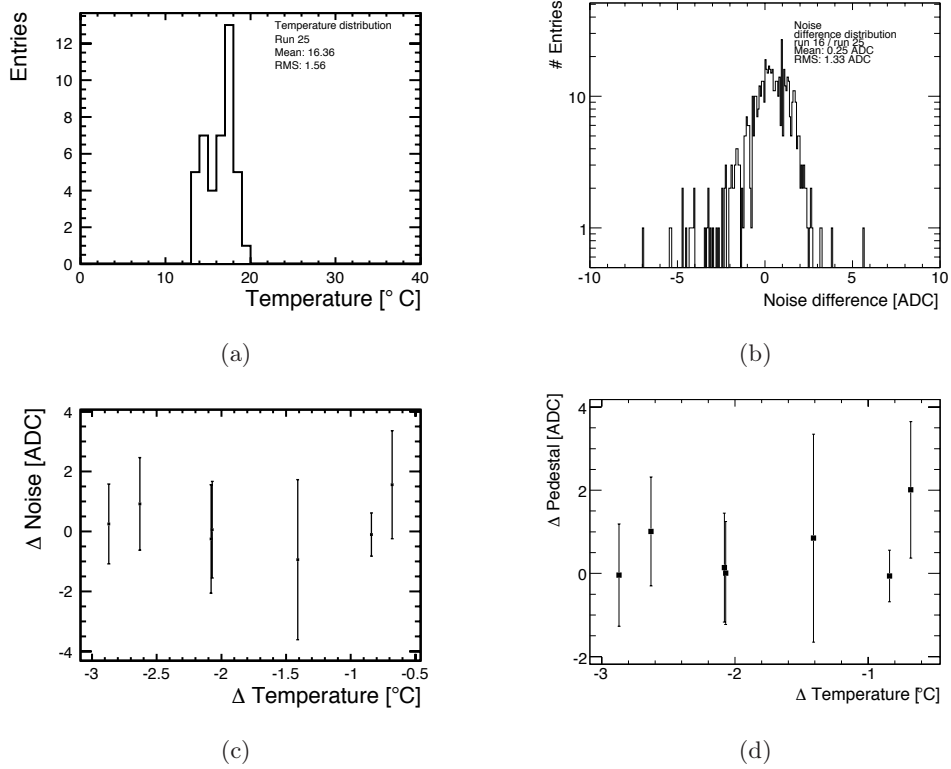


Figure 7.12 – a) distribution of the temperature given by all sensors for one run. b) channel-wise comparison of the noise in two runs taken in auto-trigger mode. c) fluctuations of the noise for all channels depending on the temperature, determined by the comparison of two runs, whereby one run was set as reference value. The mean and the RMS bars are taken from the comparison distribution, e.g. fig. 7.12(b). d) fluctuations of the pedestal as in c).

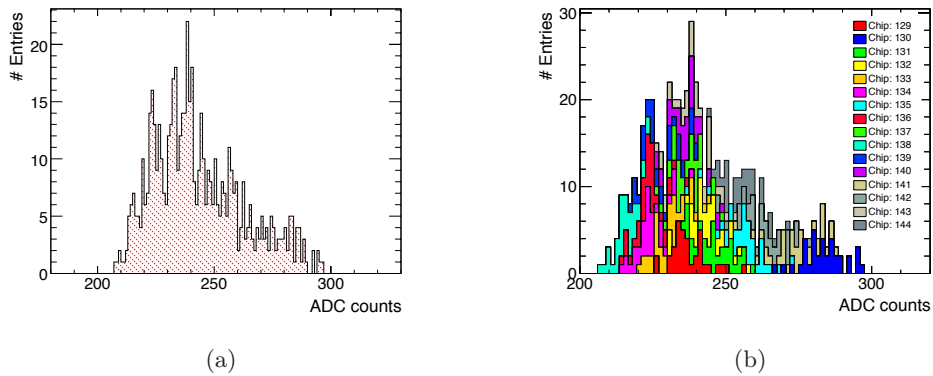


Figure 7.13 – a) distribution of the pedestal values of the whole engineering prototype, b) distribution of the pedestal values of the whole engineering prototype with marked chips.

7.2.6 Correlations

To classify the noise in a multi channel setup the noise is separated into *coherent* and *incoherent noise*. Coherent noise results in a common fluctuation of several or all channels. Especially during the studies with the AHCAL physics prototype, several chips had to be changed, because the data was strongly influenced by coherent noise [131]. Incoherent noise is an independent fluctuation from channel to channel. Fig. 7.14 shows a simulation how a coherent and incoherent noise between two neighboring channels could look like for the pedestal. Analyzing data from the CERN test beam campaign

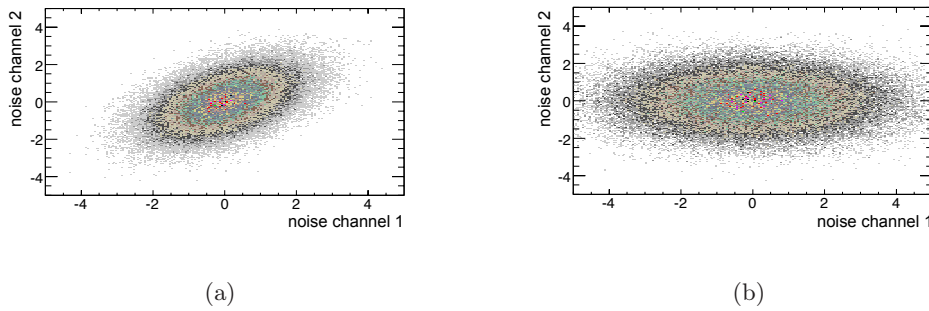


Figure 7.14 – a) simulation of noise with coherent and incoherent component between two channels and b) simulation for fully incoherent noise for two channels. Both were simulated with 10000 events.

for two channels of the engineering prototype, fig. 7.15 shows that the contribution of coherent noise is rather small. In a next step information for all chips and all channels is collected. To quantify the two contributions for all 36 read out channels of one SPIROC the following formula from [132] is applied:

$$AV_{incoherent} \equiv AV_{alt.sum} / \sqrt{n_{channels}} \quad (7.3)$$

$$AV_{coherent} \equiv \sqrt{AV_{dir.sum}^2 - AV_{alt.sum}^2} / n_{channels}. \quad (7.4)$$

Generally, AV stands for average. The $AV_{dir.sum}$ describes the sum of amplitudes of all 36 channels of 1 ASIC and the alternating sum $AV_{alt.sum}$ describes the sum of the amplitudes of even channels minus the sum of amplitudes of odd channels. The idea is that the coherent contributions are cancelled in the alternating sum. Fig. 7.16 shows the average contribution of coherent and incoherent noise for each chip. To gain this information one pedestal run was analyzed to exclude influences from real signals. As indicated in fig. 7.15 the coherent noise for each chip is considerably smaller than the incoherent noise. Chip 13 and 14 are noisier compared to the other chips.

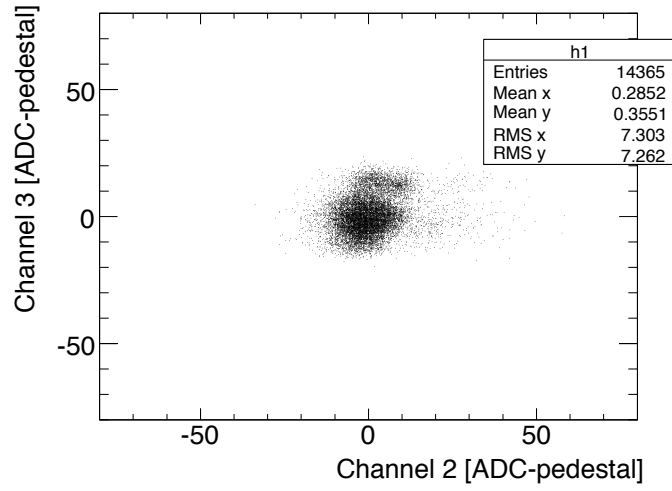


Figure 7.15 – Correlation between channel 2 and channel 3 of the prototype. The entries are pedestal subtracted.

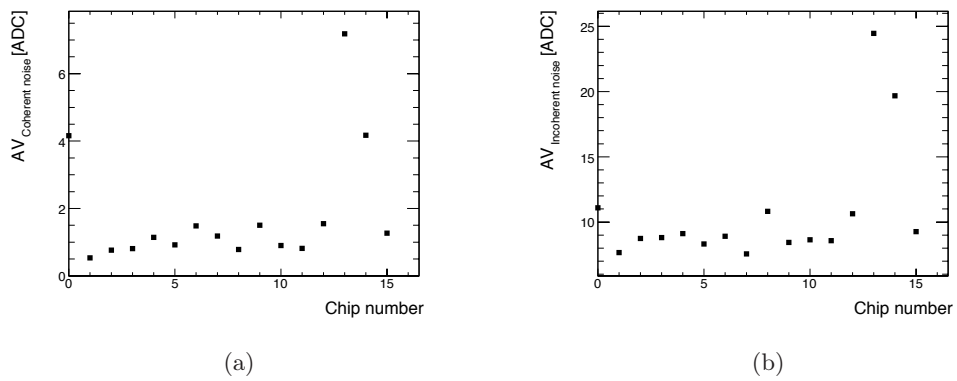


Figure 7.16 – Picture a) shows the coherent part of the pedestal width for each chip and b) the incoherent part of the pedestal.

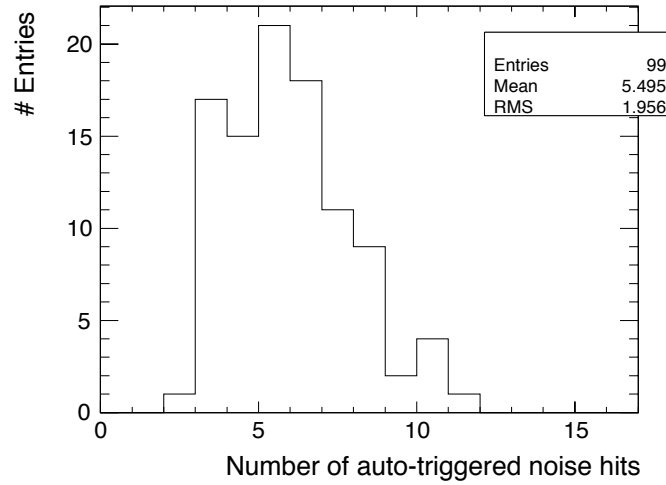


Figure 7.17 – Typical histogram filled with triggered noise hits. The number of auto-triggered noise events were analyzed with the number of memory cells which were filled.

7.3 Dark Rate Measurement

To determine the dark rate of the SiPMs, each of the four electronic boards of the engineering prototype fully equipped with SiPMs were adjusted with the correct bias voltage for the SiPMs and covered light tight in the laboratory. The measurement was done without event validation. By generating a spill signal with a frequency generator and setting a threshold for the auto trigger mode the rate of hits from the SiPMs which reached the threshold can be determined. By varying the threshold the dependency of the noise rate can be determined. Depending on the threshold and the measuring time, a histogram can be filled with the number of auto-triggered noise events. Fig. 7.17 shows such a measurement. The noise rate is not directly measurable with an HBU since the measurement stops after 16 events. So depending on the rate that should be measured, the measurement time has to be adjusted such that the probability for more than 16 events during the measurement interval is negligible. This guarantees that the 16 memory cells are not completely filled and additional events are not detected. This is the case for a mean number of 7-8 events per interval. Out of the histograms, the noise rate for the corresponding threshold can be calculated. To get the rate, the mean of the distribution was taken and divided by the corresponding measuring time.

7.3.1 Result

Fig. 7.18 shows the rate dependency on the threshold for one chip on one electronic board. The 0.5 MIP threshold is around 250 DAC tics. So a rate of ~ 1000 Hz is detected

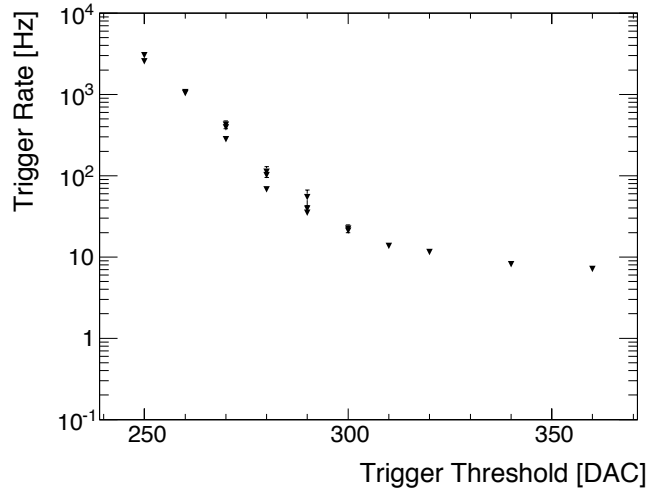


Figure 7.18 – Rate of dark hits depending on the auto trigger threshold for one chip on one electronic board. The other boards look roughly the same. Multiple measurement points belong to different measurements with different measuring times.

per chip with 36 channels. This corresponds to an average rate of ~ 30 Hz per channel, in agreement with the values given by ITEP (suppliers of the SiPM & tile). Above a threshold of 310 DAC a saturation rate of slightly below 10 Hz can be seen. These 10 Hz were probably caused by cosmic rays which can't be avoided. The influence of the cosmic rays depends on the angle and follows a $\sim \cos^2$ distribution. Placing the HBU perpendicular to the ground would minimize the cosmic ray events. Due to the low rate of the cosmic ray events compared to the dark rate for trigger thresholds corresponding to 0.5 MIP, this was not investigated in more detail.

Due to the reduced efficiency of the DHCAL at larger event rates, the beam rate at the CERN test beam campaign was limited to around 20 Hz. A noise rate of ~ 1000 Hz compared to a beam rate of ~ 20 Hz is much too high. In order to guarantee that the memory cells are not filled completely with noise events, due to the low beam rate and to optimize the event efficiency, it was decided to perform the measurement at CERN with event validation.

7.4 Summary

The AHCAL engineering prototype layer consisting of 4 HBUs run robust during the CERN test beam in November 2012. The pedestal was quite stable during the test beam campaign. The influence of the temperature and therefore fluctuations due to thermal excitation and tunnel effects are negligible. For ongoing analyzing studies one pedestal value for all runs can be used for each channel. With the actual prototype it is not

appropriate to extract the pedestal from calibration runs where the external trigger is used, due to an offset of the pedestal. Therefore, the pedestals have to be extracted from data runs.

The test beam campaign was a success all along the line. The noise rate measurement showed that a noise rate of 1000 Hz was too high compared to the low beam rate of 20 Hz. In consequence, an event validation was necessary for beam rates below 1 kHz, which worked quite well during the test beam.

The detector seems to be understood and the parameters are reliable. First steps for analyzing the data were done and paved the way to analyze the data in more detail. This test beam campaign lies the fundament for a further development of the engineering prototype to a multi layer setup.

8 Kinematic Fitting and Jet Error Parametrization

In the previous chapter new detector technologies for a high precision detector like ILD have been presented. In particular, key requirements for realizing a highly granular and very compact calorimeter for the particle flow concept have been studied. Herein, the goal is to reach a jet energy resolution to separate hadronic W and Z decays. Together with the physics prototype it could be shown that the needed energy resolution for single hadrons for particle flow can be reached. However, in a real physics analysis many more issues for the jet energy reconstruction enter, like e.g. fragmentation and hadronisation of quarks. Therefore, it has to be considered how does jets arise from e.g. a Higgs, Z or W boson. This opens the question which analysis tools can be exploited to improve beyond the intrinsic calorimeter energy resolution.

Kinematic fitting is one of these analysis tools which can be used to improve the jet energy resolution. Therefore, the second part of this thesis concentrates on kinematic fitting, discussed in the framework of the Higgs self-coupling measurement. As mentioned in section 2.2, the measurement of the Higgs self-coupling is an important task. The main focus in this thesis lies on the feasibility of kinematic fitting in the lepton channel of the Higgs self-coupling measurement ($e^+e^- \rightarrow ZHH \rightarrow e^+e^-b\bar{b}b\bar{b}$), because this channel offers a clear signature in the detector and a complete set of constraints, like energy conservation and momentum conservation. Here, issues such as the influence of kinematic fitting on the mass resolution, the correct assignment of jets to bosons and the influence on the separation from background processes, especially ZZH are discussed. In this chapter jets and their reconstruction, the formalism of kinematic fitting, the data samples and software tools, the preselection for the jet energy resolution studies, the jet energy resolution on basis of WW events decaying into 4 jets and the jet energy resolution for ZHH events decaying into 2 leptons and 4 jets will be presented. Finally, the performance of the jet energy resolution of this analysis is compared with the performance of the particle flow algorithm.

8.1 Hadronic Jets

In collision experiments at sufficiently high energies bosons like the Higgs, Z or W boson arise. These bosons in turn decay into pairs of quarks or leptons. The quarks

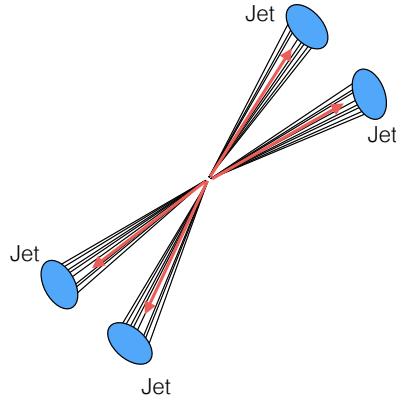


Figure 8.1 – Sketch of an event with 4 jets. The black lines indicate the sub-particles of one jet and the red arrows indicate the gathered information of one jet as used in the reconstruction.

underly the strong interaction, which ensures that the quarks are subject of the *confinement*. After their generation the quarks are flying apart from each other and undergo parton showering. The quarks are emitting gluons, and the emitted gluons generate again quark- antiquark pairs. The field energy increases with the distance between the quarks and at a certain field energy threshold a new pair of quarks is generated. This fragmentation process repeats several times and generates a lot of particles. As the energy of the produced particles decreases, they start to form hadrons (mesons or baryons). Thus, a primary quark turns into a bundle of hadrons. The directions of the particles are similar to the first quark, these particles form a jet. A sketch of an event with 4 jets is displayed in fig. 8.1. Several particles forming a jet are displayed as black lines. It is characteristic for a jet, that the particles have a small transversal momentum with respect to the jet axis. The sum of the momentum and energy of all particles of one jet offers information about the primary partons. In the reconstruction, algorithms are used which gather particles into jets and reconstruct the jets from the energy and momentum sum of the sub particles, in fig. 8.1 displayed as red jet axes. In the analysis, it is assumed that the jet four-momenta reconstructs the primary quarks, thus a jet pair reconstructs a weak boson. For the reconstruction and in particular for kinematic fitting, the information of the energy and momentum direction can be used to parametrize jets in a sufficient way. This will be discussed in more detail in sec. 8.2.1.

8.2 Kinematic Fitting

The mass resolution of jet pairs has a big impact on the significance on the analysis of the Higgs-self coupling. Kinematic fits can help to improve the mass resolution and

therefore kinematic fitting will have an impact on the precision of the measurement. Kinematic fits were already established at LEP [133] to determine the W mass with a higher precision, since the hadronic calorimeters had an energy resolution of $60\%/\sqrt{E}$, which made kinematic fitting very important. The width of the invariant mass distribution of 8 - 10 GeV could be improved to 3 - 4 GeV¹, by imposing constraints of the energy and momentum conservation ($E, \vec{p} = \sqrt{s}, 0$). The particle flow concept foresees a jet energy resolution of 3 - 4%. A jet energy resolution of 3 - 4% at 100 GeV corresponds to the natural width of the W boson. In consequence, the particle flow concept allows the ILC to distinguish between W and Z boson. The development of the Particle Flow Algorithm and kinematic fitting in turn offers the ILC to benefit from the interplay of both.

8.2.1 Formalism & Principle

In this section, the formalism for kinematic fitting is described following [135]. The precise initial states at the ILC allow to use additional redundant information in the reconstruction, like the conservation of the energy or momentum. The general idea of kinematic fitting is to do a correction of the measured parameters within their measurement uncertainties. The kinematic parameters are varied to fulfill specific constraints, like energy conservation with respect to the initial state. Sources of uncertainty during a jet measurement could be:

- fragmentation and hadronization
- the limited detector resolution.
- detectable particles, which could escape through dead areas of the detector.
- undetectable particles like neutrinos from semi-leptonic decays.
- jet mis-clustering caused by parton showers and gluon radiation

The first three points are considered in the canonical definition of the particle flow performance, while the last two points are also considered in this analysis. The consequence for the performance of the particle flow approach and this analysis will be discussed in sec. 8.6.2. A kinematic fit tries to fit the data with a so called *fit hypothesis*. The fit hypothesis contains the constraints and so called *fit objects*. Fit objects can be distinguished between visible and invisible objects in the detector. For instance visible objects are hadronic jets or charged leptons and invisible objects are neutrinos. In general, fit objects are handled as four vectors with E and $\vec{p}$, which in turn need to be expressed in terms of the measured quantities. Examples of possible parametrisations are given in

¹This is comparable to the natural width $\Gamma_W = 2.085 \pm 0.042$ GeV [17]

Objects	Parameters	measured
Hadronic jets	E, θ, ϕ	measured
$\nu_{e,\mu,\tau}$	p_x, p_y, p_z	unmeasured
electrons	E, θ, ϕ	measured
	$1/p_t, \theta, \phi$	

Table 8.1 – Table of possible parametrisations for different fit objects. For hadronic jets it is sufficient to choose a parametrisation with E, θ, ϕ . Neutrinos are not directly detectable in the detector. Usually they are parametrized with the momentum, which correspond to the missing momentum in the detector. Electrons can be parametrized with E, θ, ϕ or $1/p_t, \theta, \phi$. The momentum of charged particles is given by the tracking system with $1/p_t$, but final state radiation and bremsstrahlung photons allows to parametrize them with the energy given by the calorimeter system.

tab. 8.1. For hadronic jets it is sufficient to parametrize them with the energy E and the two angles θ and ϕ . For electrons, two parametrisations are possible, due to their electrical charge, the momentum is determined very precisely by the tracking system which is given in units of $1/p_t$. Bremsstrahlung generates additional photons, the photons and the electrons are detected in the calorimeter system and joined with the track momentum. Hence, the same type of parametrisation for electrons as for hadronic jets can be used. Neutrinos which can't be measured in the detector are usually parametrized with the momentum in the x, y and z plane. In general, the momentum should correspond to the missing momentum which is needed to ensure momentum conservation in the detector. The kinematic fit connects the fit hypothesis (e.g. $ZHH \rightarrow \bar{l}l q\bar{q}q\bar{q}$) with the constraints (e.g. momentum conservation) and the measured values (e.g. hadronic jets). The basis for the correction of the measured values is the additional information from the constraints, therefore to find the best results, the fit varies the parameters in order to fulfill the constraints with respect to the allowed uncertainties. If the fit hypothesis is bad or even wrong, the deviations to the measured values get very big [135]. To evaluate the fitted parameters the χ^2 is used as degree of deviation between the fitted parameters $\boldsymbol{\eta}$ and the measured values $\boldsymbol{a}$:

$$\chi^2 = (\boldsymbol{\eta} - \boldsymbol{a})^T C^{-1} (\boldsymbol{\eta} - \boldsymbol{a}) \quad (8.1)$$

C^{-1} is the covariance matrix which includes the uncertainties of the parameters. These deviations should be minimized while fulfilling the constraints. This is ensured by mini-

mizing:

$$\chi_T^2 = \chi^2(\boldsymbol{\eta}, \mathbf{a}) + \sum_{k=1}^K \lambda_k \cdot G_k(\boldsymbol{\eta}, \boldsymbol{\xi}) + \sum_{l=1}^L \chi_l^2(\boldsymbol{\eta}, \boldsymbol{\xi}). \quad (8.2)$$

Here λ_k are the langrange multipliers and $G_k(\boldsymbol{\eta}, \boldsymbol{\xi})$ are so called hard constraints. These hard constraints have to be fulfilled exactly, like the energy conservation. The energy sum of the incoming particles has to be equal of the energy sum of the outgoing particles:

$$G_k(\boldsymbol{\eta}, \boldsymbol{\xi}) = \sum_i E_i^{in}(\boldsymbol{\eta}, \boldsymbol{\xi}) - \sum_j E_j^{out}(\boldsymbol{\eta}, \boldsymbol{\xi}) = 0 \quad (8.3)$$

$\boldsymbol{\xi}$ are the parameters of unmeasured fit objects like neutrinos. $\chi_l^2(\boldsymbol{\eta}, \boldsymbol{\xi})$ in eq. 8.2 are so called soft constraints. Soft constraints don't have to be fulfilled exactly and allow for instance the consideration of a natural width of a particle, if it is not negligible compared to the detector resolution.

$$\chi_l^2(\boldsymbol{\eta}, \boldsymbol{\xi}) = \frac{H_l^2(\boldsymbol{\eta}, \boldsymbol{\xi})}{\delta H_l^2} \quad (8.4)$$

H_l^2 is a function which vanishes if the constraint is exactly fulfilled. δH_l^2 is the corresponding resolution for this constraint.

The required condition for the minimum of χ^2 is $\nabla \chi_T^2 = 0$. This guarantees that G_K is always fulfilled, because

$$\frac{\partial \chi_T^2}{\partial \lambda_k} = G_k = 0 \quad (8.5)$$

ensures the fulfilling of the hard constraint. The solving of this system of equations is time intense and performed by a so called "fitter", which solves the system of equations stepwise. Fig. 8.2 sketches the functioning of a fitter with one hard constraint with two parameters. Further literature can be found in [134].

In practice, instead of the χ^2 the probability of the χ^2 ($P(\chi^2, N)$) can be used to evaluate the quality of the fit. $P(\chi^2, N)$ is defined as [136]:

$$P(\chi^2, N) = \frac{1}{\sqrt{2^N \Gamma(\frac{N}{2})}} \int_X^\infty e^{-\frac{1}{2}t} t^{\frac{N}{2}-1} dt. \quad (8.6)$$

where N is the dimension of the χ^2 distribution. The fit probability is defined such that a uniform distribution between 0 and 1 is expected in case of a correct fit hypothesis and correctly estimated and gaussian uncertainties.

In the simulation, the jet uncertainties are caused by the fragmentation of the initial quarks followed by hadronisation into a jet. In addition, semi-leptonic decays lead to the generation of undetectable neutrinos and the intrinsic resolution of the calorimeter system limits the overall resolution for jets. All this leads to the uncertainties for the reconstructed jets. Therefore, a method for an adequate estimation of the measurement

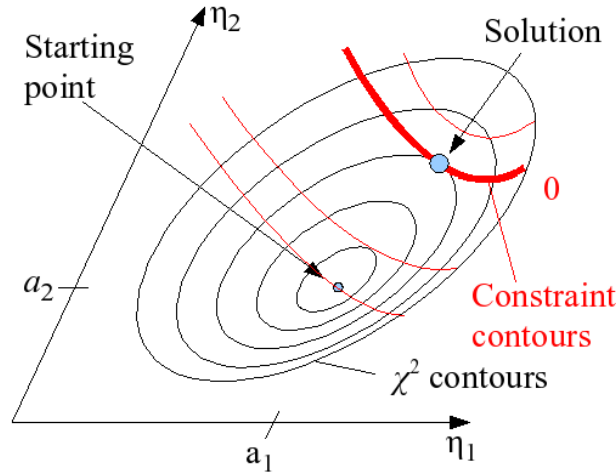


Figure 8.2 – Illustration of the mechanism of a kinematic fit. The parameters start at the measured value a_1, a_2 . Here it is $\chi^2 = 0$. To fulfill the constraint the fitter gets closer to the solution stepwise by varying the parameters. The solution for the smallest χ^2 and a fulfilled constraint is the point where the contours intersect. Figure is taken from [135].

uncertainties is important and this will be part of discussion in sec. 8.5.

8.3 Software Tools and Data Samples

In this section, the data samples and software tools which were needed for Monte-Carlo simulations and the reconstruction of physics events in order to study kinematic fitting in the framework of the Higgs self-coupling analysis are presented following [64]. This incorporates the data samples of WW , ZHH and ZZH events for the analysis, the event generation, the detector simulation and the reconstruction. All of this is part of the ILD software framework [137] and will be presented briefly. The software framework is elaborated in high level of detail in order to fulfill the needs of the Particle Flow concept and to allow a detector optimisation which is based on physics goals.

8.3.1 Samples

For the analysis three data samples have been used, each are generated with **Whizard**. **Whizard** will be introduced later in this section:

WW sample: In order to develop a jet error parametrisation approach, a data set of hadronic decaying W^+W^- s has been used. The data set incorporates $e^+e^- \rightarrow u, \bar{d}, s, \bar{c}$ decays which are required to originate from W^+W^- decays. Additionally, the data set offers a simple and clear signature in the detector, which simplifies the

Data set	Events	$ZHH \rightarrow e^+e^-HH$	$e^+e^- \rightarrow e^+e^-b\bar{b}b\bar{b}$
ZHH	159200 (100%)	126108 (79.2%)	40396 (25.4%)
ZZH	96500 (100%)	82996 (86%)	47122 (48.8%)

Table 8.2 – Statistics before and after an event selection of $Z \rightarrow e^+e^-$ and $H \rightarrow b\bar{b}$. In case of ZZH events, one Z boson decays into u, d, s, c , or b quarks.

analysis. The data set ² incorporates 3857107 events with an integrated luminosity of $\int \mathcal{L} dt = 500 \text{ fb}^{-1}$ and has been generated with **Whizard 1.95**. From the data set only a subsample of 159200 events have been analyzed.

ZHH sample: To study kinematic fitting in the framework of the Higgs self-coupling, the data set from the analysis has been used. It incorporates all possible decay modes and correspond to an integrated luminosity of $\int \mathcal{L} dt = 2000 \text{ fb}^{-1}$ with a polarization of 100% for electrons, positrons respectively. The data set has been generated with **Whizard 1.97**. For kinematic fitting, the data set from the lepton channel has been used, which includes all possible leptonic decay modes of the Z boson. For the study 40396 events have been analyzed.

ZZH Data Sample: The data set for the Higgs self-coupling analysis also incorporates data for background, like ZZH events. The ZZH background has also been studied and here 47122 events have been used.

For technical reasons, the ZHH and ZZH samples comprise all final states of the Z 's and H 's, assuming Standard Model branching ratios for the Higgs boson. Since the analysis discussed here targets only the $e^+e^-b\bar{b}b\bar{b}$ final state, the corresponding events are singled out based on generator-level information. Out of 159200 (96500) ZHH (ZZH) events generated, 40396 (47122) fall into the $e^+e^-b\bar{b}b\bar{b}$ category, see tab. 8.2. All further studies refer to these subsamples. It has to be considered that all processes have different cross-sections for the incoming electron and positron depending on the polarization. Therefore, the signals have to be weighted corresponding to their cross-sections σ_b with the integrated luminosity $\int \mathcal{L} dt$ and the polarization. The overall weighting factor w_{tot} is given as:

$$w_{tot} = w_{lumi} \cdot w_h^{pol}. \quad (8.7)$$

With the weighting for the luminosity w_{lumi} and the weighting for the polarization w_h^{pol} . h corresponds to the helicity states of the signal, which can be RR, RL, LR or LL . The

²The data set has the name 4f_ww_hadronic with the process IDs 250006 and 250008 and can be found in the ILC MC database.

w_h^{pol}	$P(e^-, e^+) = P(-0.8, 0.3)$
w_{RR}^{pol}	0.315
w_{RL}^{pol}	0.035
w_{LR}^{pol}	0.585
w_{LL}^{pol}	0.065

Table 8.3 – Table of possible weighting factors for beam polarisations of the incoming electron and positron. The first index corresponds to helicity states of the electron and the second to the positron.

first index corresponds to the helicity state of the electron and the second to the positron. The weighting of the luminosity is performed as

$$w_{lumi} = \frac{\sigma_b \cdot \int \mathcal{L} dt}{N_{gen}^S} \quad (8.8)$$

where σ_b corresponds to the cross section of the signal (ZHH or ZZH) and N_{gen}^S to the number of generated events. For the analysis a polarization of $P(e^-; e^+) = P(-0.8; 0.3)$ is used. The polarization weights can be calculated with the corresponding fractions of the number of the electrons/positrons with left-handed/right-handed polarizations (N_L/N_R):

$$P = \frac{N_R - N_L}{N_R + N_L} \quad (8.9)$$

For a polarization of -0.8 for the electrons 10% right-handed and 90% left-handed electrons are needed. For a polarization of 0.3 for the positrons 65% right-handed and 35% left-handed positrons are needed. To generate a corresponding data sample with $P(e^-; e^+) = P(-0.8, 0.3)$ the weighting factor for the polarisation w_h^{pol} for the data sample are given in tab. 9.10.

These factors have been used to scale the events of the study.

8.3.2 Event Generation

In order to study physics events in a simulation, the software package **Whizard** [138] is used, which generates Monte-Carlo events. **Wizard** is an event generator optimized for the specific needs for physics at a future linear collider. Hence, **Whizard** also includes the simulation of initial state radiation or beam polarization.

In order to compute helicity amplitudes for a given model, **Whizard** is using **O'Mega** [139].

In the simulation, **Whizard** is used for the hard interactions. But subsequently for the fragmentation and hadronisation of the initial simulated quarks **PYTHIA 6.4.22** is used. In addition, the hadronisation tune to LEP data, as provided by the OPAL experiment [140] has been used.

The output format for the event generation is **stdhep** [141]. The default event data format at the ILC is the **LCIO** format, therefore there are converting tools to change the **stdhep** data format into the **LCIO** format. The **LCIO** format is defined in the **LCIO** package [142], which also defines the data structure of the events. Herein, it provides classes for different kinds of data, like calorimeter clusters, tracks or detector hits.

For instance, the data from the Monte-Carlo simulation is stored as **MCParticles** in the data model. The history of **MCParticle** is always structured in the same way, the first two lines are used for the hard interaction, followed by two lines with photons in order to simulate initial state radiation (ISR). In case that the event doesn't include ISR these photons are carrying no energy. The subsequent lines are written by final states or products generated from hadronisation and fragmentation processes. This list is given to the **Mokka** program for the simulation of the ILD detector response.

In detail, each particle in the simulation is stored per event in the collection of one object class.

8.3.3 Detector Simulation

The software package **Mokka** [143] is in charge for the detector simulation. It is based on the **GEANT4** framework [144]. **Mokka** incorporates a very realistic model of the ILD detector. This covers sub detectors, dead material, mechanical support structures, gaps, cabling and electronics in high detail. Also different types of technology for the electromagnetic and hadronic calorimeter are considered in the model, since different technologies are under discussion for ILD. Besides a silicon-tungsten electromagnetic and an analog hadronic calorimeter also a scintillator-strip electromagnetic and a semi-digital hadronic calorimeter is available in the model. For the study of kinematic fitting, the option **ILD_o1-v05** has been used, which implements an analog HCAL with a silicon-tungsten ECAL [76].

The **MCParticle** list is used by **Mokka** in order to simulate the events in the detector. The **Mokka** algorithm translates the list into the **GEANT4** object structure.

8.3.4 Reconstruction

The **Marlin** framework is used for the event reconstruction [145]. It is part of the ILC software package and includes analysis tools. **Marlin** covers digitization of simulated data, the event reconstruction and analysis with different modules [137, 145]. **Marlin** is

based on the **LCIO** data model [146]. The main program provides the event loop as well as the algorithms for analyzing. The tasks of the algorithms range from simple filling of histograms towards a complete reconstruction of the events. In the processing chain, the framework reads the data event by event and creates an **LCEvent** to hand the data from algorithm to algorithm. The algorithms themselves only have the permission to read and add information to the data. The algorithms are configured with input parameters in a steering file. The steering file also arranges the sequence of the algorithm execution. In order to simplify the data analysis, an algorithm called **LCTuple** is used, which stores the **LCIO** events in **Root** trees [147]. The standard event reconstruction covers the following:

For the reconstruction the **Marlin** framework incorporates algorithms for forward tracking (**FwdTracking**), pattern recognition in the TPC (**Clupatra**) and a track fitter, which is based on a Kalman filter (**KalTest**). An algorithm for combining single track segments to final output tracks (**FullLDCTracking**) is also incorporated.

The **PandoraPFANew** package contains the Particle Flow Algorithm (PFA). The package provides more than 60 algorithms for calorimeter track-cluster-matching, re-clustering and cell clustering [4]. Herein, **MarlinPandora** generates a list of Particle Flow Objects (PFO) which can be used for further advanced analysis.

The **LCFIVertex** and **LCFIPlus** package are used for secondary vertex finding, jet clustering and a flavour tagging [148].

8.3.4.1 Background Overlay

Due to the strong electromagnetic fields at the bunch collisions, a lot of photons are generated during the collisions. The interaction of these photons can generate hadrons which causes an hadronic background in the detector. These events are acting as pile-up and cause the necessity to consider the background $\gamma\gamma \rightarrow \text{hadrons}$ in the simulation [149]. The simulation of $\gamma\gamma \rightarrow \text{hadrons}$ is performed by **PYTHIA**, while the detector response is simulated by **Mokka**. In consequence, any hard process in the simulation is overlaid with $\gamma\gamma \rightarrow \text{hadrons}$ events. The number of $\gamma\gamma \rightarrow \text{hadrons}$ events is distributed poissonian with a mean of $\langle N \rangle = 1.2$ events.

In order to analyze a clear event topology the impact of $\gamma\gamma \rightarrow \text{hadrons}$ should be excluded in the analysis. Characteristic for the generated hadrons is a very low transversal momentum p_t , since these hadrons (beam jets) are directed very forward. In order to exclude the background, the use of *exclusive* jet algorithms is common at colliders in the analysis. These jet algorithms reject the beam jets from $\gamma\gamma \rightarrow \text{hadrons}$ events and cluster the remaining reconstructed particles into jets.

In this analysis, an exclusive k_T jet clustering algorithm [150, 151] with a clustering pa-

parameter of $R = 1.3$ has been used, which has been studied to be an optimized value [152]. The algorithm determines two distances for each particle. The closest distance to the neighboring particle and the transverse distance to the beam axis. If the distance to the beam axis is smaller than the distance to a neighboring particle, then the algorithm identifies this particle as a particle from a $\gamma\gamma$ interaction which is considered as background and removes it. It should be noted that the ZHH and ZZH sample doesn't include a $\gamma\gamma$ overlay and only in case of the WW sample, the $\gamma\gamma$ overlay has to be removed. After the removal of $\gamma\gamma \rightarrow \text{hadrons}$ events, the identified and generated jets are decomposed in the next step into Particle Flow Objects for further analyses.

8.3.4.2 Jet Clustering

The Durham jet clustering algorithm [153] has been used for the jet clustering of the events, since the Durham jet clustering algorithm combines all PFOs into final jets, while the exclusive k_T jet clustering algorithm also forms beam jets. The algorithm calculates for all PFOs the distance between two particles k and l :

$$y_{k,l} = 2(1 - \cos(\theta_{k,l})) \frac{\min(E_k^2, E_l^2)}{E_{CM}^2}, \quad (8.10)$$

$E_{k,l}$ is the energy for the individual particle, E_{CM} is the center-of-mass energy and $\theta_{k,l}$ the angle between both particles. The particles with the smallest $y_{k,l}$ are merged to so called pseudo particles. This process of merging continues until the targeted number of jets for the analysis is reached. The Durham algorithm forms all particles remaining after the overlay removal into final jets.

8.4 Preselection for Jet Energy Resolution Studies

For technical studies, a special subsample is used which features a simple and clear event topology for the analysis. This includes a reduction of the impact of ISR, a small angle deviation α between reconstructed jets and initial primary MC quarks and a detector range determined by θ where jets and Monte-Carlo (MC) quarks are inside of the detector acceptance. The remaining data after this preselection will be called in the following the *golden sample*.

8.4.1 Initial State Radiation

The experience at LEP showed that one of the most important constraints for kinematic fits is the conservation of the energy [133]. In a lepton collider additional effects can occur, which reduce the center-of-mass energy $\sqrt{s}$. In the following two processes will be presented which affect $\sqrt{s}$: The initial state radiation (ISR) and the beam-strahlung.

Initial State Radiation: In case of the Initial state radiation (ISR) real photons are emitted before the actual interaction, see fig. 8.3. The other way around, it can happen

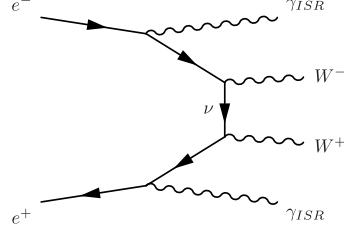


Figure 8.3 – One example of a feynman graphs with ISR in the production of WW pairs.

that photons are emitted after the actual interaction. This is called final state radiation (FSR). The radiation of a photon before the actual interaction reduces the center-of-mass energy $\sqrt{s}$ at the interaction point. With the four momentum vectors $\mathbf{p}_1$ and $\mathbf{p}_2$ of the incoming particles and the energy E_γ of the emitted photon with the unit vector $\vec{e}_\gamma$, the reduction of $\sqrt{s}$ to $\sqrt{s'}$ in laboratory system is given by

$$s' = (\mathbf{p}_1 + \mathbf{p}_2)^2 = \begin{pmatrix} \sqrt{s} - E_\gamma \\ -E_\gamma \cdot \vec{e}_\gamma \end{pmatrix}^2 = (\sqrt{s} - E_\gamma)^2 - E_\gamma^2 = s - 2\sqrt{s}E_\gamma. \quad (8.11)$$

Beam Strahlung: In a collider like the ILC the electrons are colliding in bunches. Due to the high energy and the strong focussing, the bunches interact with the electric field of the incoming bunch. In case of head-on collisions both bunches are focussed transversally. This is called pinch effect. This deflection causes the emission of photons, which is called beam-strahlung (BS). The average energy loss at the ILC will be in the order of $\delta_{BS} = 2.4\%$ [154] at a center-of-mass energy of $\sqrt{s} = 500$ GeV.

In both cases of ISR and BS the precise initial states are not known, if the photons escape the detector through the beam pipe. The energies and momenta of these photons are missing for the constraints of the kinematic fit. If they are not properly taken into account in the kinematic fit, the deviation of the fitted energy and momenta compared to the true values are getting quite big and this introduces a bias in the reconstructed mass. It has been shown that in principle missing energy caused by an ISR photon can be considered in a kinematic fit by adding an additional ISR photon as a fit object [135], resulting in the same mass resolution. In the following, events without ISR will be taken, since the focus here lies on the parametrization of the jet energy resolution.

The main data sets for the analysis are the WW and ZHH data set. In the following, the impact of ISR is studied in fig. 8.4 for both data sets. Fig. 8.4(a) shows the distribution of the energy sum for all MC quarks in case of $e^+e^- \rightarrow WW$ and fig. 8.4(b) in case of

Data set	Events	$\sqrt{s'} > 495 \text{ GeV}$	$\alpha < 1 \text{ rad}$	$8^\circ < \theta < 172^\circ$
WW	159200 (100%)	55388 (34.8%)	46704 (29.3%)	43861 (27.5%)
ZHH	40396 (100%)	17641 (43.7%)	13419 (33.2%)	13043 (32.3%)
ZZH	47122 (100%)	19648 (41.7%)	15366 (32.6%)	11566 (24.5%)

Table 8.4 – Statistics before and after cuts of $\sqrt{s'} > 495 \text{ GeV}$, $\alpha < 1 \text{ rad}$ and $8^\circ < \theta < 172^\circ$ on the primary quarks for the different data set of the analysis.

$e^+e^- \rightarrow ZHH \rightarrow e^+e^-b\bar{b}b\bar{b}$. In fig. 8.4(a), a bump at $\sim 280 \text{ GeV}$ is visible. The energy spectrum of $\sqrt{s'}$ is a convolution of the cross section, the beam spectrum and ISR. The maximum of the cross section for WW production is $< 200 \text{ GeV}$. Therefore the bump at $\sim 280 \text{ GeV}$ is mainly caused by the beam spectrum and ISR photons.

In both cases the peak at 500 GeV is expected due to $\sqrt{s} = 500 \text{ GeV}$. The tail on the left side is caused by ISR photons which reduce $\sqrt{s}$ to $\sqrt{s'}$. To ensure energy conservation and to minimize the effect of ISR, just events are considered in the following which fulfill an energy sum of the quarks $\sum_i^4 E_{qi} = \sqrt{s'} > 495 \text{ GeV}$. The energy spectrum of both data will be discussed in more detail in sec. 8.6. This cut has an influence on the number

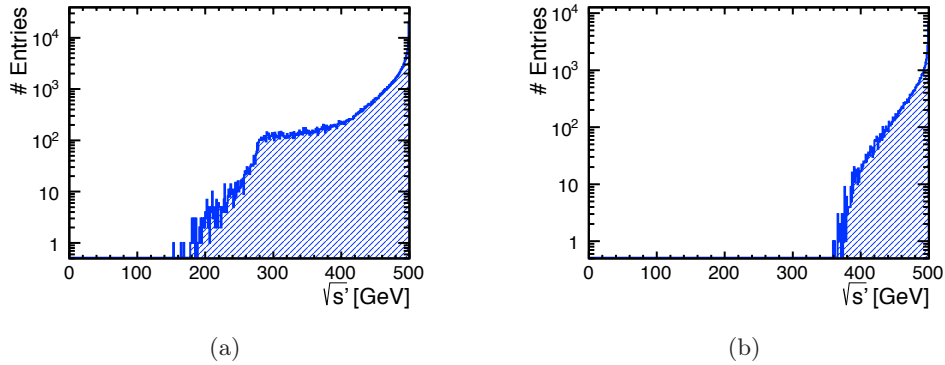


Figure 8.4 – a) $\sqrt{s'}$ of the energy sum of the primary quarks $\sum_i^4 E_{qi}$ for $e^+e^- \rightarrow WW \rightarrow 4 \text{ jets}$. The long left tail is caused by ISR photons. The left tail of the distribution shows a bump at $\sim 280 \text{ GeV}$, caused by the beam spectrum and ISR photons, b) $\sqrt{s'}$ obtained as sum of the energies of the patrons from the primary hard interaction after the selection of $Z \rightarrow e^+e^-$ and $H \rightarrow b\bar{b}$.

of remaining events. Tab. 8.4 shows the influence of the energy cut on the different data sets of the analysis. About 35% of the events from the WW data set are left for the analysis. This is in a good agreement with [135]. For ZHH events, 43.7% remain.

8.4.2 Angle Deviation α between Jets and initial Quarks

In the simulation, the parton shower, the fragmentation, the hadronisation, the detector simulation and also decays of c and s quarks ³ leads to a deviation of the information of the reconstructed jets compared to the informations of MC quarks. For instance, the detector simulation adds a deviation to the reconstructed jets compared to the MC quarks, due to the different sub-detector resolutions, calibrations, energy scaling factors (e.g. scaling factors for electromagnetic showers) or the confusion term from the PFA. The deviation is for example visible in the momenta of the reconstructed jets compared to the momenta of the MC quarks. Since the momentum is a vector, this difference is visible in the angle between MC quarks and reconstructed jets. Fig. 8.5 shows a sketch of 4 MC quarks and 4 reconstructed jet axes in order to display the deviation. The

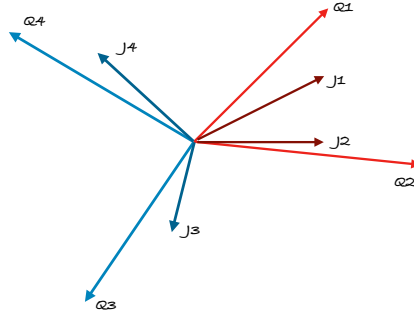


Figure 8.5 – Sketch of the jet/quark assignment.

angle between MC quarks and reconstructed jet axes can be determined with the scalar product

$$\alpha_i = \frac{\vec{p}_j \cdot \vec{p}_q}{|\vec{p}_j| \cdot |\vec{p}_q|}. \quad (8.12)$$

The index i represents one of the four pairings between jet and quark. $\vec{p}_j$ and $\vec{p}_q$ are the momentum of the jet and quark, respectively. For 4 quarks and 4 jets it is possible to combine 4 angles between quarks and jets in 24 combinations. For example, the first jet can combine with 4 quarks, the second jet can combine with three quarks, the third jet has two possibilities to combine with quarks and the last jet has one option to combine with a quark, with the result of $4 \cdot 3 \cdot 2 \cdot 1 = 24 = n!$ combinations. For each combination the 4 angles can be summed. The combination with the smallest angle sum is defined as the right permutation. Fig. 8.6 shows the angle sum for all permutations. The red curve is the angle sum for the best permutations. It shows a peak at ~ 100 mrad which is an indication of the jet direction resolution. In order to keep an accurate and clean data set without large deviations between MC quarks and reconstructed jets, an α constraint of

³One of the decay products from c and s quarks can be neutrinos, which will be missed in the reconstruction.

$\sum_{i=1}^4 \alpha_i < 1 \text{ rad}$ between MC quarks and reconstructed jets is applied. Additionally, the defined right permutation can be used as reference value in the analysis. This will be relevant in sec. 9.5. The resulting impact of the α constraint on the data sets is displayed in tab. 8.4.

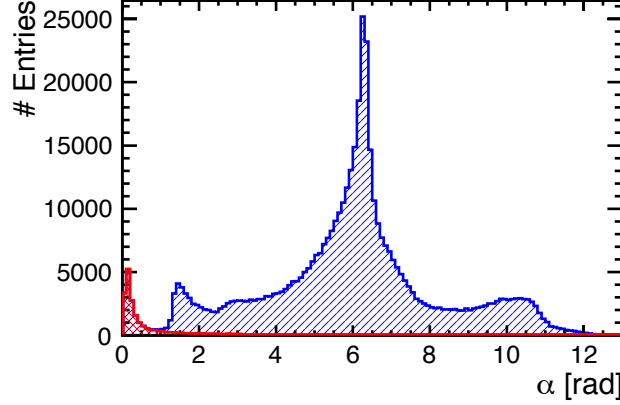


Figure 8.6 – Angle sum for all possible quark/jet combinations in blue and in red for the best quark/jet combination.

8.4.3 Detector Ranges

In order to ensure a data set where the events are contained inside of the detector, it is sufficient to apply a θ constraint on the MC quarks and reconstructed jets for the analysis. To guarantee that MC quarks and jets are within the detector acceptance, they should be in the θ range of $8^\circ < \theta < 172^\circ$. Applying the θ constraint on the data sets, the reduction of the data set is displayed in tab. 8.4.

The remaining sample after all cuts is defined as the "golden sample" on which further studies are based.

8.4.4 Invariant Mass of a Dijet System

One important parameter for the reconstruction and to analyze the data sets is the invariant mass of the dijet systems. Therefore, in this section the invariant mass of dijets will be introduced. To calculate the invariant mass of the dijets $m^2 = \mathbf{p}^2 = E^2 - \vec{p}^2$ can be used. The invariant mass m_{jj} is a sum of the four momenta of both jets $\mathbf{p}_1$ and $\mathbf{p}_2$.

$$\begin{aligned}
 m_{jj}^2 &= (\mathbf{p}_1 + \mathbf{p}_2)^2 = \mathbf{p}_1^2 + \mathbf{p}_2^2 + 2 \cdot \mathbf{p}_1 \mathbf{p}_2 \\
 &= m_1^2 + m_2^2 + 2 \cdot (E_1 \cdot E_2 - \vec{p}_1 \cdot \vec{p}_2) \\
 &= m_1^2 + m_2^2 + 2 \cdot (E_1 \cdot E_2 - \sqrt{E_1^2 - m_1^2} \cdot \sqrt{E_2^2 - m_2^2} \cdot \cos \alpha),
 \end{aligned} \tag{8.13}$$

with the opening angle α between the 2 jets. Since the masses of the quarks m_1 and m_2 are small compared to the jet energies E_1 and E_2 , eq. 8.13 can be approximated with

$$m_{jj}^2 = m_1^2 + m_2^2 + 2 \cdot E_1 \cdot E_2 \cdot (1 - \cos \alpha). \quad (8.14)$$

Eq. 8.14 will be used very often in the following, e.g. in order to study the influence of kinematic fitting on the mass resolution.

8.5 Jet Energy Resolution in $WW \rightarrow 4$ Jets Events

Before applying a kinematic fit to the Higgs self-coupling measurement a method is needed in order to estimate the measurement uncertainties in a sufficient way. Therefore, in this section the main focus lies on the development of a jet error parametrization approach.

To develop a jet error parametrisation approach, the golden sample of the WW data has been analyzed, in order to apply the developed jet error parametrisation approach afterwards on the lepton channel of the Higgs self-coupling. Similar to the Higgs self-coupling analysis, the W^+W^- data set offers two bosons, which decay into 2 jets each. Therefore, the impact of kinematic fitting on the mass resolution and the assignment of Monte Carlo quarks to reconstructed jets can be studied on this data sample. In particular, two approaches will be presented. First with a simplified assumption of the covariance matrix C^{-1} and second a more sophisticated approach, where the Monte Carlo quarks are compared with the reconstructed jets.

8.5.1 Parametrisation

As mentioned in sec. 8.2.1, the χ^2 depends on the parameters, the measured values and the covariance matrix C^{-1} . Since C^{-1} contains the measurement uncertainties of the parameters, C^{-1} needs to be determined before a kinematic fitting is applied. For the parameterization, it is assumed that the parameters do not correlate with each other in a measurement. This means that the uncertainties must be estimated, which are caused as already mentioned, by the fragmentation of the initial quarks, the hadronisation into a jet, additional semi-leptonic decays and the intrinsic resolution of the calorimeter system. Summed, the first main task is to determine the resolution parameters of C^{-1} from $e^+e^- \rightarrow WW \rightarrow u, \bar{d}, s, \bar{c}$.

In this thesis the jets are parametrized as a four-vector with the jet energy E , the polar angle θ , the azimuth angle ϕ and the invariant mass m .

Since the ILD is planned to be an isotropic detector, it is assumed that the jet resolution is dominated rather by the energy than the angular dependency, therefore in a basic

approach C^{-1} can be set as

$$C^{-1} : \Delta E = \sqrt{E} \cdot \sigma_E \quad (8.15)$$

$$\Delta\theta = x [\text{mrad}] \quad (8.16)$$

$$\Delta\phi = y [\text{mrad}]. \quad (8.17)$$

Where it is assumed that the angular uncertainties $\Delta\theta$ and $\Delta\phi$ are constants and the jet energy resolution ΔE is depending on the jet energy. This seems to be sufficient, since these parameters are uncorrelated, directly measurable quantities. In addition, it may be assumed that the uncertainties are gaussian distributed, since the effects of fragmentation, hadronisation and the detector resolution influences are uncorrelated effects. To optimize the parameters of C^{-1} , the parameters are varied in a simple first attempt to find the best performance of the fit.

8.5.2 Effect of ΔE on Convergence Rate, Jet Pairing and Invariant Mass

In the simulation from the WW data set 4 jets have been generated, which have to be combined into two dijets in order to correspond to the W -bosons. In case of 4 jets, there are three possible combinations to generate two dijets. The kinematic fits tries each of these three permutations and evaluates each with the fit probability from eq. 8.6. The combination with the highest fit probability is defined as the best permutation. The fit is a so called 5C fit, because 5 constraints are imposed: energy conservation for the energy sum of the jets $\sum_1^4 E_{ji} = \sqrt{s'}$, momentum conservation for p_x, p_y and p_z with $\sum \vec{p} = 0$ and an equal mass constraint for the invariant mass of the dijets determined by eq. 8.13. Equal mass constraint means that the fit forces the invariant masses of the two dijets to be equal with $M_{j_1 j_2} = M_{j_3 j_4}$.

To evaluate the performance of the fit, the convergence rate can be used, which is defined by the number of the events which offer the correct invariant mass ($M_W < 100 \text{ GeV}$) for the jet combination with the highest fit probability ($P(\chi^2)$) divided by the number of all events. It should be noted, that in case of an incorrect invariant mass, the mass will be most likely $M_W > 100 \text{ GeV}$. Fig. 8.7 shows the invariant mass distribution after kinematic fitting for the WW data set. The entries with $M_W > 100 \text{ GeV}$ show the events where the wrong dijet combination is chosen. The wrong dijet combination causes a higher invariant mass, because these combinations tend to large opening angles between the two jets, see eq. 8.13.

From fig. 8.7 it can be concluded that a criterion of $M_W < 100 \text{ GeV}$ is a proper constraint in order to identify correct invariant masses of the dijet systems.

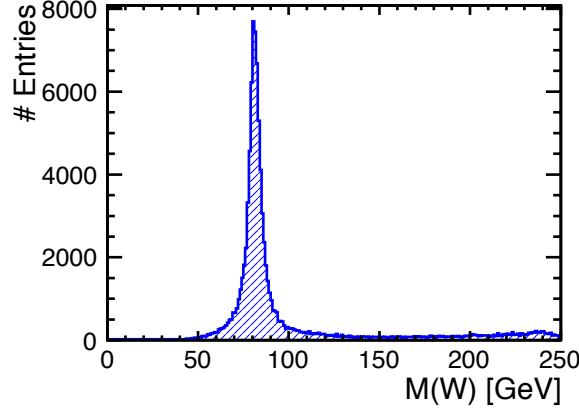


Figure 8.7 – Invariant mass distribution of W^+W^- events. Besides the main peak at ~ 80 GeV additional entries up to 250 GeV are visible. Here, the fit chooses a wrong dijet combination to reconstruct the WW s.

Starting point to determine an optimal configuration of C^{-1} in a first attempt is a setup of C^{-1} for ΔE , $\Delta\theta$ and $\Delta\phi$ with $100\%/\sqrt{E}$, 10 mrad and 10 mrad, since this setup was preferred in other simulation studies.

Starting from this setup, $\Delta\phi$ is varied in order to determine the best convergence rate for $\Delta\phi$. Fig. 8.8(a) shows the convergence rate for $\Delta\phi$ and at 100 mrad a saturation of the convergence rate is visible.

Subsequently, with an optimized setting of $\Delta\phi$, $\Delta\theta$ is varied in order to determine the best convergence rate for $\Delta\theta$ (displayed in fig. 8.8(b)). Also here a saturation at 100 mrad is visible.

The uncertainties of both, $\Delta\phi$ and $\Delta\theta$ show a saturation at 100 mrad. Both values are embedded in a broader plateau, shifting the uncertainty to e.g. 50 mrad would have a minor influence on the convergence rate. This agrees with the peak at $\alpha \approx 100$ mrad in fig. 8.6, where deviations in ϕ and θ direction are considered by the used scalar product (eq. 8.12). Finally with the best setting for $\Delta\phi$ and $\Delta\theta$, the best convergence rate for ΔE is determined. Fig. 8.8(c) shows that at $120\%/\sqrt{E}$ the best convergence rate for ΔE is reached.

For ILD a jet energy resolution of $30\%/\sqrt{E}$ for 100 GeV jets is desired. This considers an ideal case, where no jet-clustering, fragmentation or semi-leptonic decays are considered. The deviation originates from these additional uncertainty sources and worsen the resolution. Additionally it should be mentioned, that looking at fig. 8.8(c), the $120\%/\sqrt{E}$ displays the maximum of the curve, which is also embedded in a broader plateau. Also a jet energy resolution of $\sim 75\%/\sqrt{E}$ provides a comparable convergence rate. The energy resolution of $75\%/\sqrt{E}$ is compared with an ideal energy resolution of $30\%/\sqrt{E}$ in sec. 8.6.2.

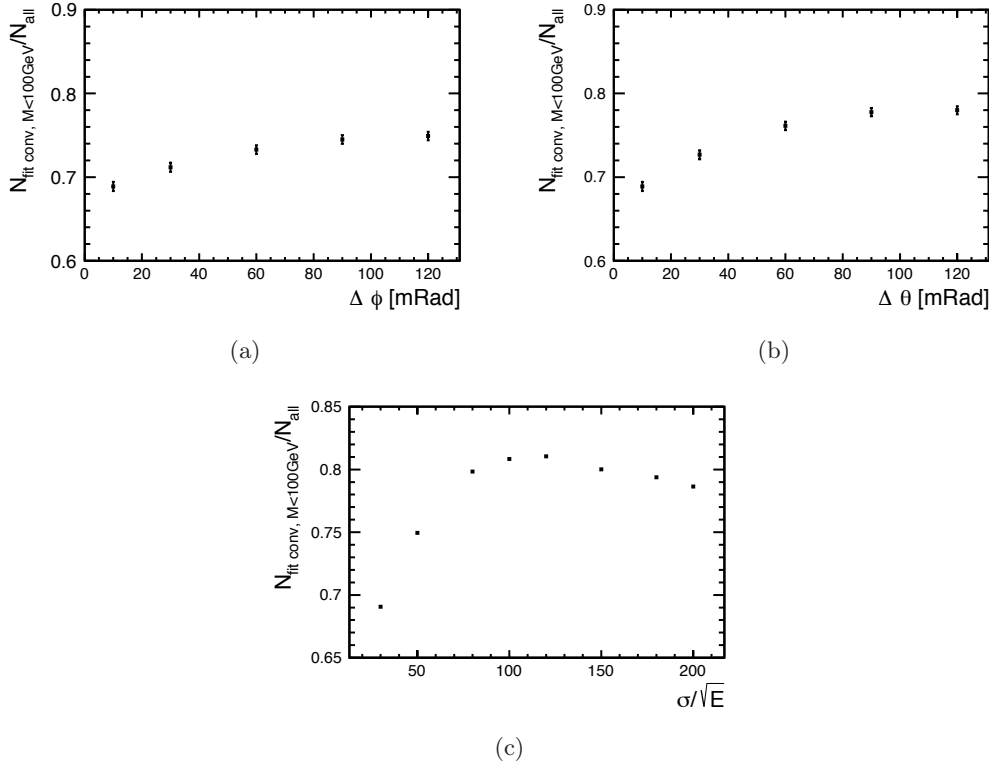


Figure 8.8 – Determination of the uncertainties for the best convergence rate of the fit. The plots show the fraction of the fits converging to the correct jet pairing as a function of the resolution for a) ϕ , b) θ and c) the energy resolution.

Implementing this parameterization into the kinematic fit processor and running the processor on the data set $P(\chi^2)$ can be studied. $P(\chi^2)$ in fig. 8.9 shows an almost uniform distribution with peaks at 0 and 1 and is determined with the optimized setting for $\Delta\phi$, $\Delta\theta$ and ΔE . If the errors follow a gaussian distribution, the fit probability would show a uniform distribution. Deviations from the expected to the determined χ^2 -distribution will be visible in $P(\chi^2)$ in form of peaks at 0 and 1, as it is the case in fig. 8.9. A peak at 0 indicates that for some events the assumed errors are too small or even the fit hypothesis is wrong, which means that the deviation from the expected χ^2 -distribution was too big to find any compliance with the result of very small fit probabilities. Vice versa a peak at 1 indicates that for some events the assumed errors are too big which causes a bias to higher fit probabilities.

8.5.2.1 Invariant Mass of WW -events

With the optimized setting for $\Delta\phi$, $\Delta\theta$ and ΔE , the invariant masses before and after kinematic fitting can be studied. Herein, eq. 8.13 has been used.

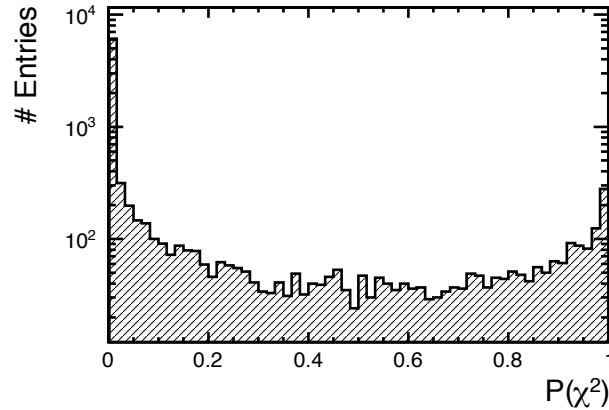


Figure 8.9 – The fit probability for the best jet combination in $WW \rightarrow u\bar{d}s\bar{c}$ events with an optimized setting for $\Delta\phi$, $\Delta\theta$ and ΔE with $\Delta\phi = 100$ mrad, $\Delta\theta = 100$ mrad and $\Delta E = 120\%/\sqrt{E}$.

Fig. 8.10 shows the data before and after the fitting. The invariant mass distribution after the fitting shows an improved mass resolution compared to the mass distribution before the fit. Especially the long tail on the left of the red histogram shows that after the fit, the mass resolution is improved.

The fit evaluates all three permutations with the fit probability. The slightly extended tails on the right of the blue histogram (entries in the range of 100-150 GeV) is caused by events where the fit chooses the wrong permutation. This can happen if the fit probabilities of the best and second best permutation are very close. The correlation

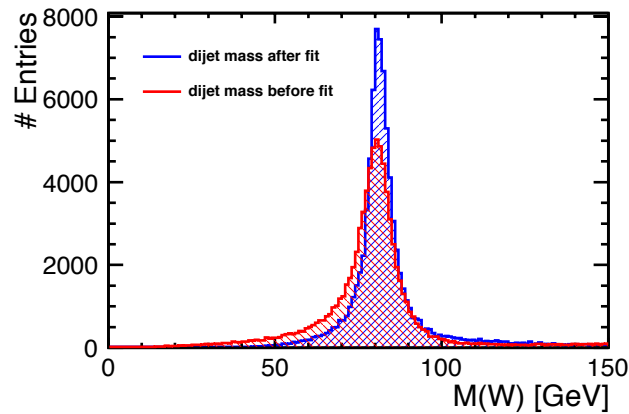


Figure 8.10 – Reconstructed invariant mass of WW 's events. The red curve shows the mass distribution before the fit and the blue curve the mass distribution after fit.

between the best and second best fit probability is shown in fig. 8.11(a). Entries on the diagonal are entries where the fit probabilities are very close. Especially for small

fit probabilities there are a lot of events where the two best fit probabilities are very similar. The probability to choose the wrong jet combination for different fit probability differences is shown in fig. 8.11(b). For very small differences the probability to pick the wrong jet permutation is rather high ($\sim 50\%$) and for small fit probabilities this can happen quite often. For the wrong jet permutation a tendency to wrong invariant masses is expected as it is visible in fig. 8.10 in the right tail of the blue histogram.

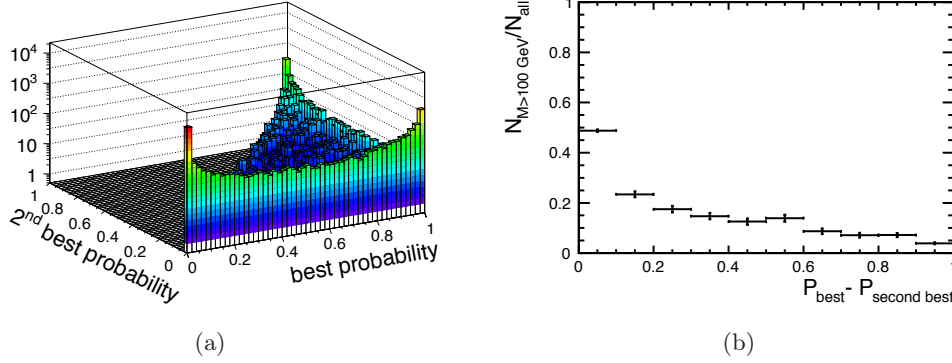


Figure 8.11 – a) correlation between the two best fit probabilities and b) probability to pick the wrong jet combination for certain probability differences between the best and second best jet combination.

8.5.3 Determining ΔE from Quark - Jet Comparison

In the previous section, a first simple approach has been used to determine C^{-1} such that the fit gives the best resolution. In this section, a more sophisticated approach will be presented.

The information from the Monte Carlo particles (quarks) can be compared with the information from the reconstructed jets. Also for the comparison of MC particles and reconstructed jets, it is assumed that the errors for ϕ and θ can be set as constants like in sec. 8.5.2. In order to determine C^{-1} in this approach, the following steps are taken:

- Analysis of the angle between the Monte Carlo (MC) quarks and the reconstructed jets.
- Study of the energy deviation between Monte Carlo quarks and reconstructed jets.
- Determination of the energy resolution.

A comparison of the MC quarks and reconstructed jets allows to study the energy deviation between quarks and jets. Fig. 8.12(a) shows $\Delta E_{jets-quarks}/E_{quarks}$ in dependence of the quark energy (E_{quark}). Especially for low quark energies the spread between the energy of the jets and the quarks is visible.

The histogram in fig. 8.12(a) can be split in 25 slices on the x -axis. For each slice the projection on the y -axis can be analyzed. Fig. 8.12(b) shows the mean of the projection of each slice and the uncertainty of the mean in y -direction. The shift of the mean is caused by the non-gaussian tails, although the peak of the gaussian is relative stable at 0. All 25 projections are shown in fig. 8.13 and each slice can be analyzed individually.

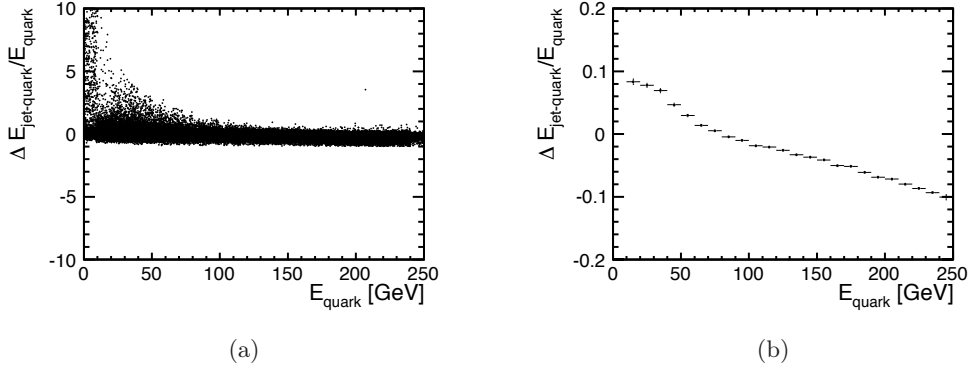
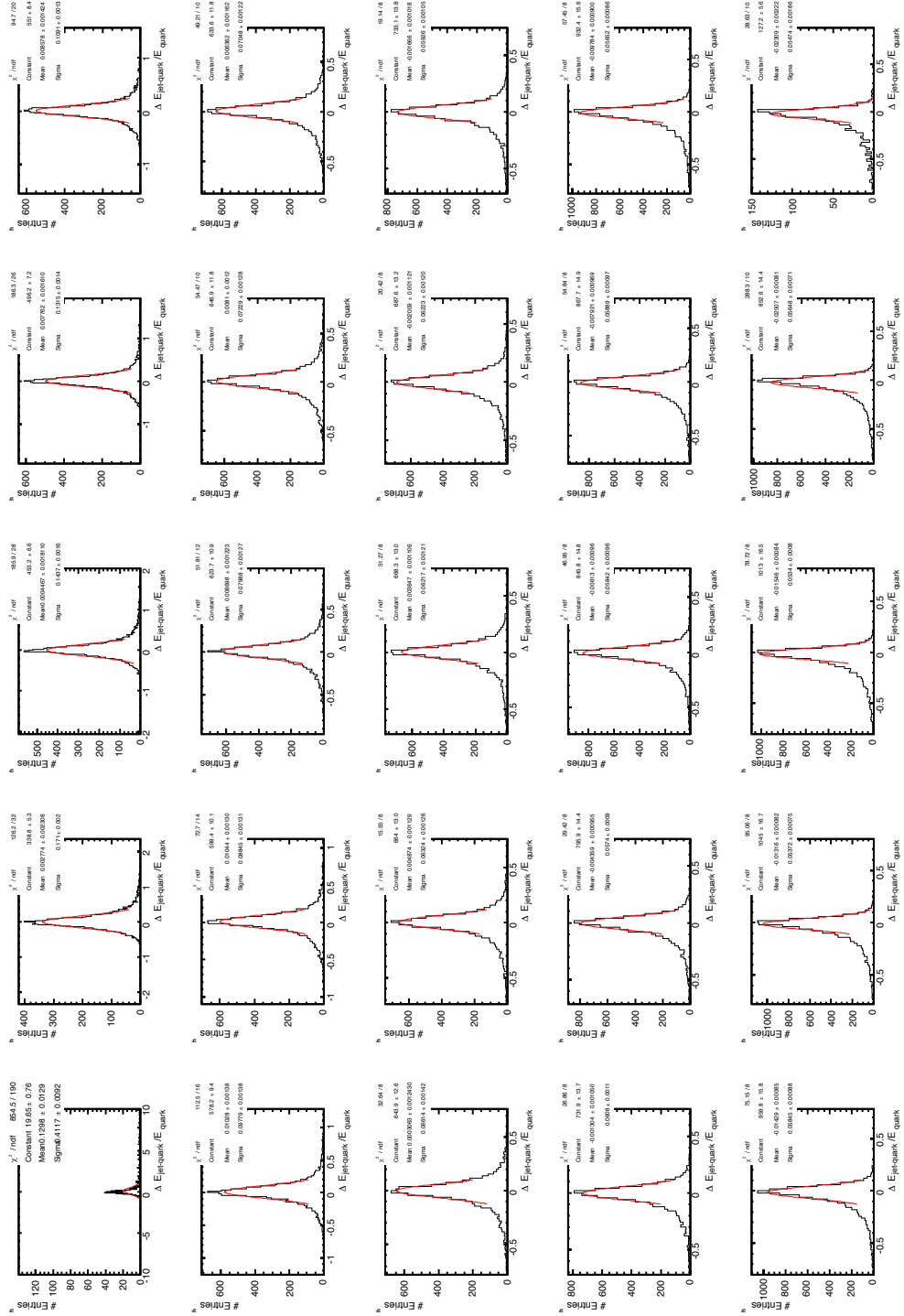


Figure 8.12 – a) Spread of the energy between the initial quarks and the reconstructed jets in dependence of the quark energy. b) the mean and uncertainty of the mean if a) is split in 25 slices.

Fig. 8.14 shows the projection of slice 7. By fitting each projection with a gaussian, the width of the gaussian (σ) and the uncertainty of the width ($\Delta\sigma$) can be determined from the fit function. The distribution itself doesn't show a gaussian behavior due to the non-gaussian tails, but the core in the range of $\pm 0.75 \cdot \text{RMS}$ can be fitted with a gaussian which gives an optimistic estimate of the resolution, since it neglects the tails.

Determination of the Energy Resolution

The determined σ and $\Delta\sigma$ from the fit function of each projection can be used as an estimate of the energy resolution and its uncertainty for the reconstruction of a quark of the data set. Fig. 8.15 shows the quark energy resolution determined in this way for $e^+e^- \rightarrow WW \rightarrow 4f$. For comparison, the parametrization of the energy resolution with $120\%/\sqrt{E}$ used in the previous section is also shown. The new points indicate a much better resolution than $120\%/\sqrt{E}$ which is expected since only the gaussian core of the distributions has been fitted. Fitting the new points with eq. 8.18 ($\sigma/E = \sqrt{(a/\sqrt{E})^2 + (b/E)^2 + c^2}$) gives a new parametrization for the energy resolution, displayed as red curve. The new points can be described with $\sigma/E = a/\sqrt{E}$, since the b and c term can be neglected. Especially compared to the $120\%/E$, the core resolution is smaller and steeper, which follows from the fact that 120% is a measure for the average RMS of the entire data. The new fit function leads to an energy resolution of:


 Figure 8.13 – y-projections of all 25 slices of $\frac{\Delta E}{E}$ in bins of E .

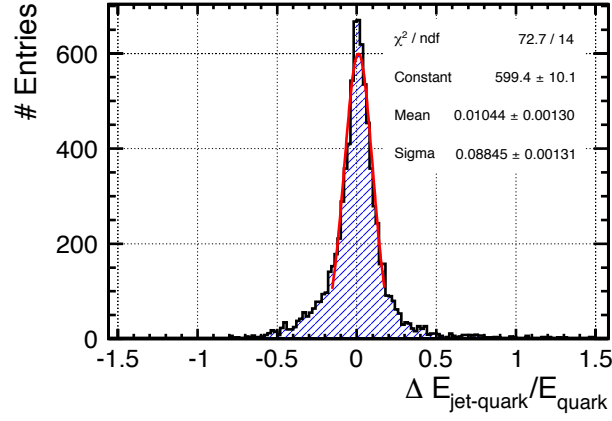


Figure 8.14 – Projection of the energy range 60 - 70 GeV (slice number 7) The distribution is fitted in the range of $\pm 0.75 \cdot \text{RMS}$ with a gaussian.

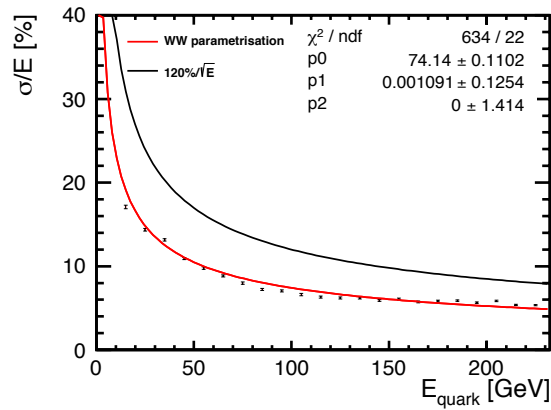


Figure 8.15 – The jet energy resolution function (curve) for $e^+e^- \rightarrow WW$ events determined by the σ from the slices in fig. 8.13 (dots). The fit function describes the energy resolution for the comparison of MC quarks and jets, displayed as red curve.

$$\frac{\sigma}{E} = \sqrt{\left(\frac{(74.1 \pm 0.1)\% [\sqrt{GeV}]}{\sqrt{E}} \right)^2} \quad (8.18)$$

As it was mentioned in sec. 8.5.2, a jet energy resolution of $75\%/\sqrt{E}$ gives almost the same performance on the convergence rate as $120\%/\sqrt{E}$ with stronger restrictions for the energy uncertainty. Considering only the core resolution of the slices is in principle the same restriction. Therefore, both results fit very well together. In order to improve this consideration it would be necessary to consider the non-gaussian tails.

The energy resolution (eq. 8.18) can be implemented into the covariance matrix of the kinematic fit.

Detector ranges

Since ILD is a typical collider detector, it will consist of a barrel enclosed by two endcaps (illustrated in fig. 3.3). The particles produced in the interactions are recorded in the barrel, the endcap or the transition region between barrel and endcap. In this case the angle of incidence, the thickness and the construction of the detector differ for the particles in the three regions of the detector. Therefore the energy resolution for the different detector regions (barrel, endcap and transition region) should be analyzed. This has been done for each detector region in the ranges as depicted in fig. 8.16(a). The resulting energy resolutions are depicted in fig. 8.16(b). The difference between all

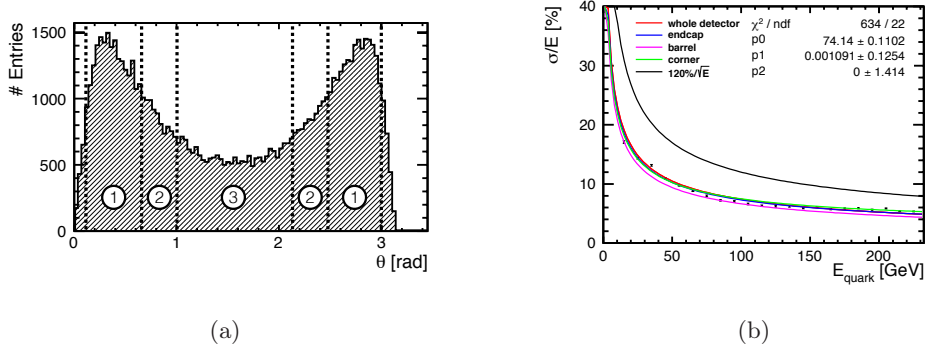


Figure 8.16 – a) θ distribution of the jets for $e^+e^- \rightarrow u\bar{d}s\bar{c}$ events. The vertical dashed lines indicate different detector ranges: range 1 covers the endcaps, range 2 the transition region between endcaps and barrel and range 3 displays the barrel region. b) energy resolution for $e^+e^- \rightarrow WW$ events in different detector regions. The fit function describes the energy resolution of the whole detector.

energy resolutions in fig. 8.16(b) is very small. Looking at the θ distribution of the jets (fig. 8.16(a)) of $e^+e^- \rightarrow WW$ -events most of the events will be detected in the endcaps of ILD and therefore a tendency that the resolution of the endcaps will dominate the

overall energy resolution is expected. But due to the small differences between the energy resolutions of the different detector regions this effect is almost not visible and can be neglected. Therefore an averaged energy resolution for the whole detector can be applied as given in eq. 8.18 and one energy resolution for the whole detector can be implemented in the kinematic fit. This shows that the differences between the quark and jet energy is not dominated by the detector resolution, but rather by fragmentation, hadronisation and semi-leptonic decays.

8.5.4 Implementation into the Kinematic Fit

If the energy resolution of eq. 8.18 is implemented in the kinematic fit, $P(\chi^2)$ can be studied. Fig. 8.17(a) shows an almost uniform distribution of $P(\chi^2)$ with peaks at 0 and 1. The distribution is slightly improved compared to the fit probability of the parametrization from sec. 8.5.2 with a reduced peak at 1. The high peak at 0 is caused by the small setting of $\pm 0.75 \cdot \text{RMS}$ of range in which the resolution is determined, which is owed to the non-gaussian tails in fig. 8.13 and fig. 8.14 and the remaining ISR photons in the data. These tails are not considered in the parametrization of the energy resolution. Alternatively a variable transformation to a gaussian distribution can improve the error estimation, which would include the non-gaussian tails in the error estimation, but this is not applied in this thesis. Fig. 8.17(b) is the counterpart to fig. 8.11(a) and shows the correlation between the first two best permutations. In comparison to the jet error parametrization from sec. 8.5.2 hardly any improvement can be seen. Also the number of events where the difference between both fit probabilities is ≈ 0 couldn't be reduced. In both cases the mass resolution is improved and the convergence rates are in the same

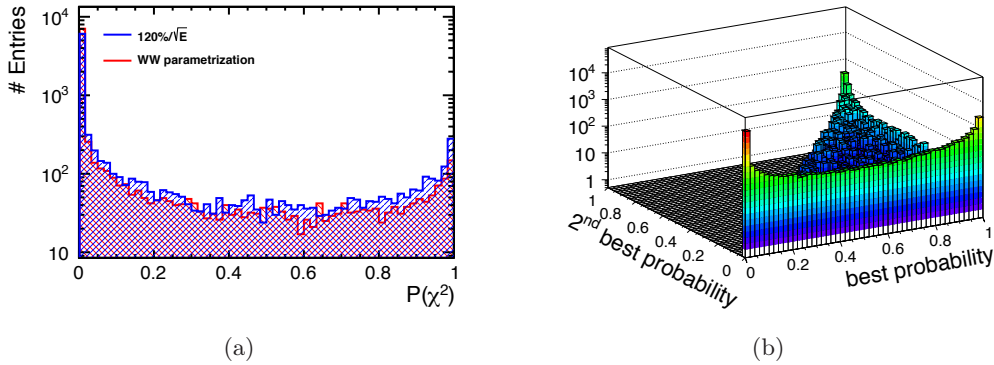


Figure 8.17 – a) Fit probability for both energy resolutions b) Comparison of the best and second best fit probability with the new energy resolution.

order. Despite the fact that the energy resolution determined by the comparison of MC quarks with reconstructed jets offers a big potential for further improvements, like e.g. a variable transformation to a gaussian distribution, the energy resolution of the lepton

channel of the Higgs self-coupling is studied in the next chapter with this method.

8.6 Jet Energy Resolution in $ZHH \rightarrow e^+e^- 4 \text{ Jets}$

To study the lepton channel of the Higgs self-coupling measurement, the developed method from sec. 8.5.3 is used to determine the inverse covariance matrix C^{-1} with the goal to apply kinematic fitting to the lepton channel. In general, it has to be considered that a decay of the Higgs bosons into b quarks will cause much more semi-leptonic decays and in particular for the lepton channel it has to be considered that besides the decay of the two Higgs bosons into 2 b -quarks each, the Z -boson decays into two leptons. This will have an impact on the constraints of the kinematic fit and on the error parametrization, since the leptons have to be parametrized as well as explained later.

Additionally, it has to be considered that the remaining energy after the generation of the particles is different for both data sets. For ZHH data, the generation of the particles requires a minimum of energy of $M_Z + 2M_H \sim 90 + 125 + 125 \text{ GeV} = 340 \text{ GeV}$ from $\sqrt{s'}$. Fig. 8.4(b) shows that the energy spectrum starts at $\sim 340 \text{ GeV}$. While for the WW data $2M_W \sim 80 + 80 \text{ GeV} = 160 \text{ GeV}$ is needed, which also agrees with fig. 8.4(a). It is expected, that this will have an impact on the energy resolution:

Impact of ISR: The less remaining energy for the ZHH data set causes that the "cut off" energy for ISR photons is higher compared for the WW data set. Fig. 8.4 shows the energy spectrum for both data sets. As expected, fig. 8.4(a) shows a longer tail due to the lower cut off energy for the WW 's compared ZHH events.

Angular distribution: The ZHH events are generated in s -channel processes, the WW events are generated either in s - or t -channel processes. The t -channel processes causes an angular dependence, which leads to a stronger forward direction of the generated jets. In result, most of the events are recorded in the endcap region of the detector for WW events (see fig. 8.16(a)). In addition, the additional boson in ZHH events causes less momentum for the Higgs bosons compared to WW events. As result, for ZHH events it is expected that the jets will be recorded more likely in the inner region of the detector, due to the smaller momentum fraction of the jets and the s -channel dependence. Fig. 8.18 shows the angle distribution of the jets for ZHH events. Here, it can be confirmed that most jets were detected in the central region of the detector. Since the jet energy resolution does not seem to depend significantly on θ , only a minimal impact is expected.

b quarks: The ZHH data set only considers decays of the Higgs bosons into b quarks. b quarks are heavier than the generated light quarks in WW events. In case of

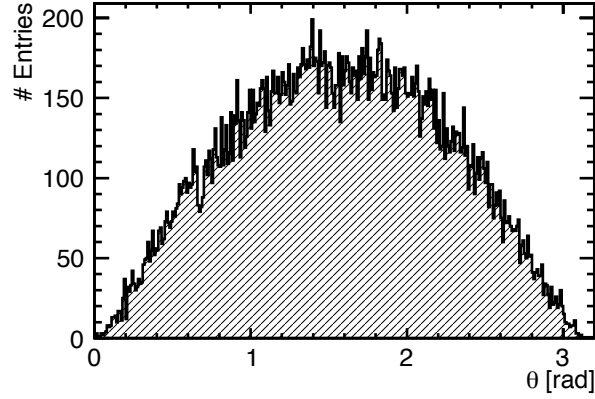


Figure 8.18 – θ -distribution of the jets of the lepton channel of $e^+e^- \rightarrow ZHH$. Most of the jets are recorded in the central region of the detector.

b quarks it is expected, that more undetected energy is generated, due to semi-leptonic decays of b quarks into neutrinos, e.g. $b \rightarrow c\ell\nu_\ell$. In addition, the needed energy for the generation of the particles in both data sets is different. The energy and momentum is distributed to two bosons in case of the WW data, compared to ZHH events where the energy is distributed to three bosons gives $\sim 1/3$ more momentum to the WW bosons. The additional momentum causes a stronger boosting of the jets.

The higher mass together with the smaller amount of remaining energy and momentum makes it more likely that the jets are less collimated compared to WW events. These effects could result in stronger deviations of the MC quarks to the reconstructed jets. But looking at the energy deviation between primary quarks and assigned jets in fig. 8.19(a), it could be seen that the energy deviation between quarks and jets is smaller compared to WW -events. But also the energy range is smaller, since instead of four jets, the energy is distributed to six jets, because at the same $\sqrt{s'}$ additionally a Z boson is produced. Comparing fig. 8.12(a) with fig. 8.19(a) underlines this statement. Fig. 8.19(a) will be explained in the following.

Energy Resolution

Fig. 8.19(a) shows analog to fig. 8.12(a) for WW processes, the energy deviation of the primary quarks to the reconstructed jets in dependence of the quark energy for ZHH processes. Separating fig. 8.19(a) into 25 slices and determining the mean and the uncertainty of the mean of each projection shows that the mean has an average offset of around -6% in fig. 8.19(b). The offset is caused to the non-gaussian distribution of the tails of the slices and the mean is the mean of the whole histogram. Each slice is shown

in fig. 8.20. Comparing fig. 8.19(b) with fig. 8.12(b) it can be seen that the distributions are quite different. Here, the impact of b quarks becomes relevant. b quarks can decay into a c quarks and a lepton plus the corresponding neutrino. And the neutrinos result in undetectable energy. The undetectable energy causes the tails to lower measured energies, clearly visible in fig. 8.20. Comparing fig. 8.20 and fig. 8.19(b), it is clear that the shift of $\sim 6\%$ in the overall mean is due to the tails, while the actual peak of the gaussian core is centered at 0.

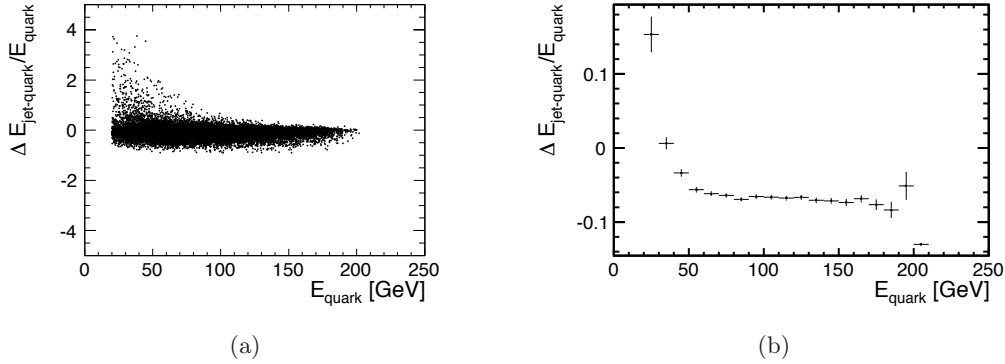


Figure 8.19 – a) Spread of the energy between the initial quarks and the reconstructed jets in dependence of the quark energy for ZHH events. b) shows the mean and the uncertainty of the mean if a) is splitted in 25 slices.

Fitting the distributions of each slice, like before with a gaussian in the range of $0.75 \cdot \text{RMS}$, σ and $\Delta\sigma$ can be determined. Fig. 8.21 shows the jet energy resolution for the data of the lepton channel of the Higgs self-coupling simulation. Also here the impact of the different detector regions on the jet energy resolutions is negligible and an overall energy resolution can be used. In addition to the different detector ranges in fig. 8.21, the $120\%/\sqrt{E}$ parametrization and the fit parameters for the overall detector resolution are shown. The assumed parametrization corresponds to $\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$, which results in an energy parametrization of

$$\frac{\sigma}{E} = \sqrt{\left(\frac{(56.8 \pm 0.4)\% [\sqrt{GeV}]}{\sqrt{E}}\right)^2 + \left(\frac{(330 \pm 1)\% [GeV]}{E}\right)^2}. \quad (8.19)$$

The steeper rising of the parametrization for lower energies makes the b term necessary compared to eq. 8.18, while the c term can be neglected.

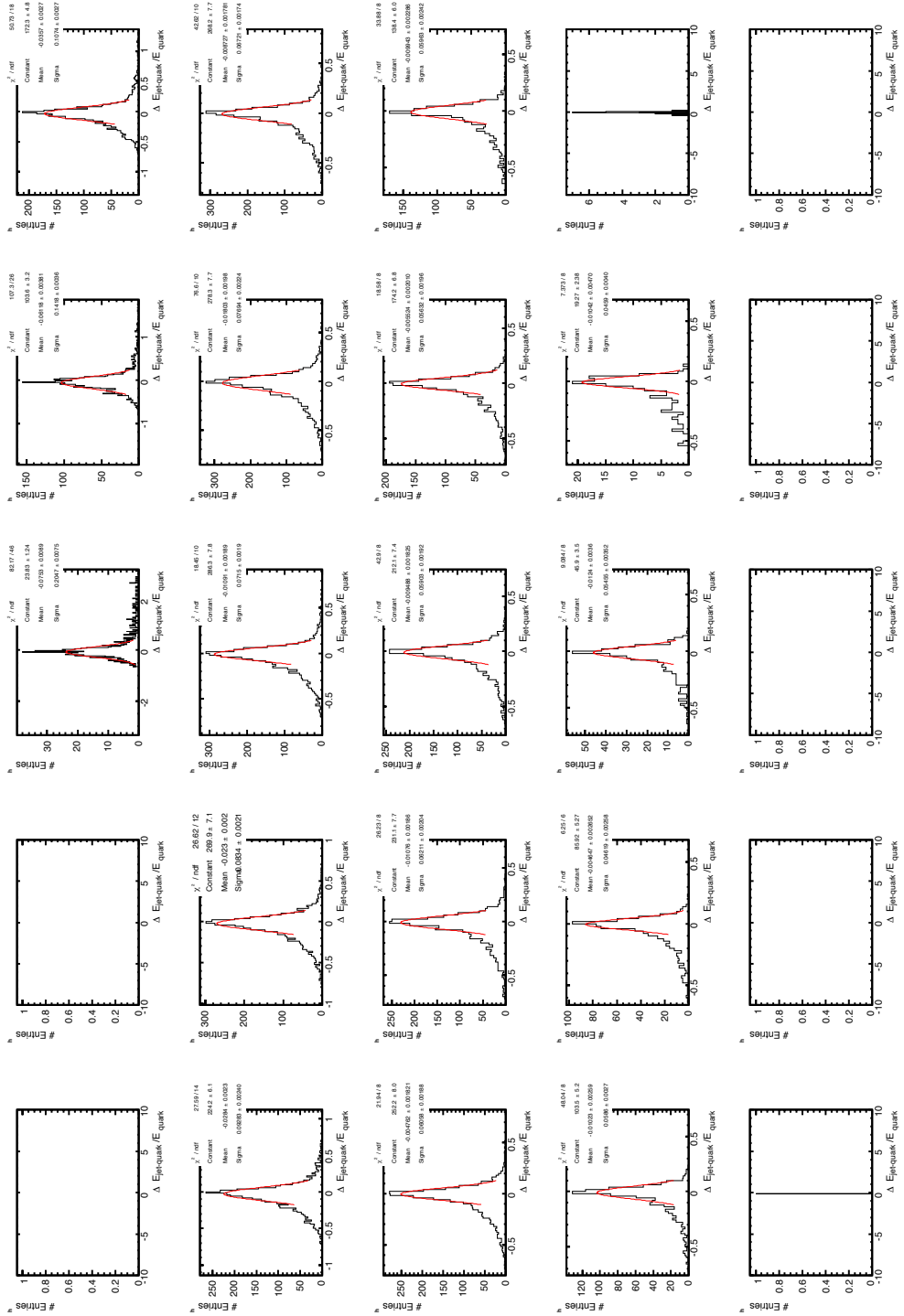


Figure 8.20 – σ_E/E in bins of E for the lepton channel of ZHH events. $\langle E \rangle$ for each bin accounts 25 GeV.

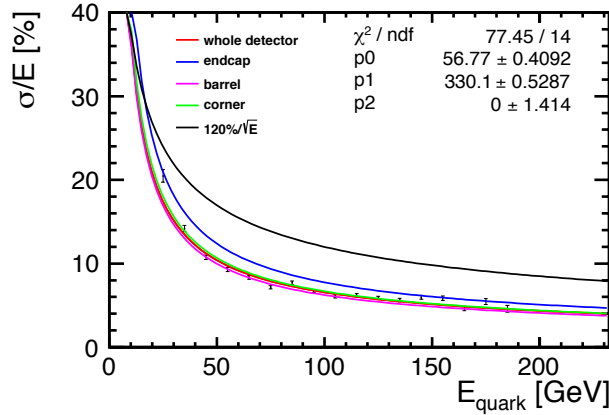


Figure 8.21 – Jet energy resolution for $e^+e^- \rightarrow ZHH$ events.

8.6.1 Comparison with the WW Parametrisation

In the previous section the differences for both data sets and the impact on the energy resolution has been discussed. Comparing both energy resolutions in fig. 8.22, it can be seen that in case of ZHH events a steeper increasing of the jet energy resolution in the lower energy range (0 - 80 GeV) is visible, but the overall energy resolutions are quite similar. This is caused by the fitting of the slices. The energy resolutions are determined by fitting the peak in each slice. The peaks in the slices are very similar for both data sets. The mean difference for both data sets is visible in the tails, as it was mentioned before. Here, an improved method should be developed in the future in order to consider the whole distribution in each slice, then a major difference between both energy resolutions should be visible. One possibility could be a variable transformations in order to reach a gaussian distribution for each slice. Nevertheless, the parametrisation of eq. 8.19 will be used in the following in a kinematic fit processor in order to study the impact of kinematic fitting on the lepton channel of the Higgs self-coupling. Also ZZH events will be studied with this energy resolution.

8.6.2 Comparison with Particle Flow Performance

For ILD an overall jet energy resolution of $\sigma/E = 3 - 4\%$ is needed, which can be reached with the particle flow approach [4]. The analysis of the particle flow approach considers only light quarks in the simulation with $e^+e^- \rightarrow u, d, s$ quarks. In addition, the energy of the whole event is taken and divided by a factor 2, which avoids the necessity of jet finding. For the determination of the resolution the RMS90 has been used.

The main difference to the quoted performance of the particle flow algorithm compared to this analysis is that the determination in [4] does not consider jet mis-clustering and heavy quarks and the RMS90 excludes long tails in the energy distribution from e.g.

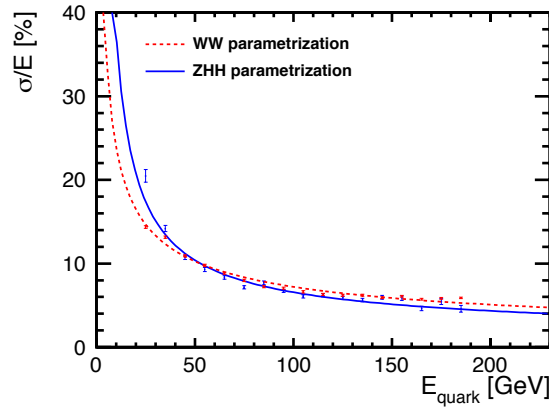


Figure 8.22 – The jet energy resolution function for both $e^+e^- \rightarrow WW$ and $e^+e^- \rightarrow ZHH$ events.

fig. 8.20. The RMS is $\sim 20\%$ smaller for a gaussian compared to the used σ of this analysis. All this lead to a different performance of the jet energy parametrisation. At high energies the jets are strong collimated. The strong collimation causes a small error in the jet clustering, and here the energy resolution determined in this analysis is close to 4%. At lower energies the collimation of the jets is less. Due to the less collimation the error caused by jet mis-clustering gets dominant. In addition to that, the heavy quarks which are included in this analysis cause a significant amount of semi-leptonic decays. And the resulting invisible particles lead to larger errors in the jet energy resolution. The impact of semi-leptonic decays on this analysis is discussed in more detail in sec. 9.5. The determination of the jet energy resolution will improve further when a proper consideration of the tails from fig. 8.20 will be done.

9 Kinematic Fitting in the Context of the Higgs Self-Coupling Measurement

As emphasized in sec. 2.1.6 and sec. 2.4, the determination of the Higgs self-coupling is essential to cover a full profile of the Higgs sector and to possibly reveal a door to new physics. In this chapter, the application of kinematic fits in the framework of the Higgs self-coupling analysis is studied and discussed. Using the leptonic channel $\bar{l}lh h$ of the double Higgs-strahlung process for the kinematic fit is investigated in this analysis. This channel offers a complete set of constraints for the kinematic fit, as well as a clear signature in the detector due to the leptonic decay of the Z boson. After a short introduction, the Higgs self-coupling analysis will be presented briefly in sec. 9.1. In sec. 9.2, the application of the kinematic fitting procedure to double Higgs-strahlung events is investigated and its consequences are discussed. In sec. 9.3, the mass resolution and separation from certain background process is discussed, while subsequently the impact of ISR photons on the fitting procedure is presented in sec. 9.4. The impact of the kinematic fit on the assignment of jets to bosons is studied in sec. 9.5. The conclusions are drawn in sec. 9.6 and an outlook will be given in sec. 9.7.

9.1 Overview on the Higgs Self-coupling Analysis

In order to understand electroweak symmetry breaking, the trilinear Higgs self-coupling (eq. 2.26) has to be measured at the ILC. Thus, the achievable precision for this measurement is an important criterion to gauge the performance of the accelerator and the detector. The preliminary results of the most recent, and still ongoing Higgs self-coupling study [7] of the double Higgs-strahlung process ZHH give a precision of $\frac{\delta\lambda}{\lambda} = 52\%$, assuming an integrated luminosity of $\int \mathcal{L} dt = 2000 \text{ fb}^{-1}$ at a center-of-mass-energy of $\sqrt{s} = 500 \text{ GeV}$ and a polarization of $P(e^+, e^-) = (0.3, -0.8)$. There are several additional strategic ideas which have the potential to improve the precision of the measurement to approximately 40%. One of these methods is the application of kinematic fits to improve the invariant mass resolution and the assignment of jets to bosons, which can result in a better separation between signal and backgrounds.

The goal is to study the impact of the kinematic fits on the leptonic channel of the Higgs self-coupling measurement, focussing on

- the improvement of the mass resolution,
- an improved identification of the correct jet pairing due to an improved jet-boson assignment,
- the signal and background separation by using the fit probability as a selection variable.

In order to understand the use of kinematic fits in the analysis, a brief overview of the analysis is given in the following, with a focus on the lepton channel.

The Higgs Self-coupling Analysis

The Higgs self-coupling analysis is a complex study with several analysis steps and a large simulation framework. In the analysis, the signal process ZHH is divided into three search channels, corresponding to the decay mode of the Z boson: the lepton channel ($Z \rightarrow \ell\bar{\ell}$), hadron channel ($Z \rightarrow q\bar{q}$) and neutrino channel ($Z \rightarrow \nu\bar{\nu}$). Here, both Higgs bosons are assumed to decay to $b\bar{b}$, which covers $\sim 25.4\%$ of all ZHH events for a analysis with $Z \rightarrow e^+e^-$, see tab. 8.2. In another analysis, the Higgs self-coupling for $ZHH \rightarrow b\bar{b}WW^*$ is investigated [155]. In the analysis, four types of backgrounds are considered: the *full hadronic background* which does not contain leptons in the final state, the *few jet background* where only two jets with two leptons are in the final state, the *semi-leptonic background* with four jets, one missing neutrino and one charged lepton in the final state and the *same final states background* which contain four jets and two leptons in the final state. A detailed description of the backgrounds can be found in [6, 36]. In every channel, there is a pre- and final selection to identify signal and background from the data. Additionally, flavour tag information are used to suppress the background further. After the event selection, the combined ZHH significance is calculated which gives an indication of how well ZHH processes can be observed. In addition, a ZHH cross section measurement is performed from which it is possible to extract the precision of the Higgs self-coupling measurement.

The focus of this thesis lies on the lepton channel $ZHH \rightarrow \ell\bar{\ell}HH \rightarrow \ell\bar{\ell}b\bar{b}b\bar{b}$ of the double Higgs-strahlung process. Therefore, the pre- and final selection and the flavour tagging of this channel is presented in more detail. The description follows [6, 7, 36].

Preselection

The preselection of the lepton channel considers a decay of the Z boson into e^+e^- or $\mu^+\mu^-$. Although, in the analysis of this thesis only the Z boson decay into e^+e^- pairs is investigated, the preselection of $Z \rightarrow \mu^+\mu^-$ will be presented for the sake of completeness.

The signal final states contain four b jets, and two isolated charged leptons. First of all,

events are selected with two oppositely charged isolated leptons. Then all other PFOs are combined to four jets which are then paired to form the two Higgs bosons. Therefore, the preselection is structured in two main components: the *isolated lepton selection* and the *jet clustering/pairing*.

1. **Isolated lepton selection:** In order to identify events originating from $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$, a neural net based isolated lepton identification is used. Herein, signal samples with two isolated leptons in the final state, as well as full hadronic background samples are used for the neural net training. Two separate neural nets are trained for electrons and muons events using information from calorimeter energy distributions, deposited in the ECAL and HCAL, as well as additional quantities. The main difference between both particle types is, that electrons deposit almost all of their energy in the ECAL, while muons deposit only a small fraction of their energy in the ECAL and HCAL.

An example for another quantity is the cone energy E_{cone} . A cone with an angle θ is defined around the momentum of each particle and the energy of the PFOs inside the cone is summed up. Misidentified isolated electrons come mainly from charged pions, which interact in the ECAL, and from semi-leptonic decays of b and c quarks. Both, charged pions and electrons from weak decays usually have a smaller momentum and more particles around them, which are a consequence from parton showers and fragmentation. However, in case of prompt electrons the effect of bremsstrahlung leads to a larger cone energy. A complete list of input variables can be found in [156]. A further improvement for the lepton identification could be the use of the energy loss dE/dx of the particles in the detector, as discussed in [155].

The resulting training weights are used to test the event samples and the corresponding neural net outputs are then used to identify isolated leptons. These outputs represent the likeliness of an event to have an isolated electron or muon. Leptons with a larger likeliness than a certain threshold value of the neural net output are identified as isolated. Events are selected when at least one electron or muon pair, formed by two leptons of opposite charge, survived this isolation selection. Additionally, since the leptons in the signal come from the Z boson decay, the isolated lepton pair has to be consistent with the Z mass within

$$|M(l^+l^-) - M(Z)| < 32 \text{ GeV}. \quad (9.1)$$

The efficiency of the isolated lepton identification accounts to $\sim 87\%$ [156].

2. **Jet clustering/pairing:** After selecting events with two isolated charged leptons, all other PFOs are clustered into four jets. Herein, the Durham jet algorithm (sec. 8.3.4.2) is used. The four jets correspond to the signal bosons. Herein, the

smallest χ^2 defines the correct combination of the jets:

$$\chi^2 = \frac{(M(j_1, j_2) - M(H))^2}{\sigma_H^2} + \frac{(M(j_3, j_4) - M(H))^2}{\sigma_H^2}, \quad (9.2)$$

where $M(j_1 j_2)$ and $M(j_3 j_4)$ are the invariant masses for the jets j_1, j_2 and j_3, j_4 respectively. $M(H) = 125 \text{ GeV}$ represents the nominal Higgs mass and $\sigma_H = 7.2 \text{ GeV}$ the resolution on the reconstructed Higgs mass. The natural width of the Higgs boson is not known yet and is expected to be in the order of a few MeV [45]. Thus, the natural width of the Higgs boson is negligible with respect to the detector resolution. Additionally, the invariant masses $M(j_1, j_2)$ and $M(j_3, j_4)$ should satisfy

$$|M(j_1, j_2) - M(H)| < 80 \text{ GeV}; \quad |M(j_3, j_4) - M(H)| < 80 \text{ GeV}. \quad (9.3)$$

Final selection

The *fully hadronic background* is well suppressed by the preselection. However, the three remaining backgrounds are still dominant. The main idea to suppress these backgrounds is to apply neural nets. For the three background types, separate neural nets are trained with specific quantities as input variables. For the neural nets the TVMA package [157] is used. It should be mentioned that for training and testing, statistically independent signal and background samples are used. The output from the neural nets are used in the analysis as selection variables to identify events and suppress the corresponding backgrounds. With this method the suppression of the *few jets background* and the *semi-leptonic background* works very well (combined $< 1\%$ background signals remain [161]). Therefore, these backgrounds will not be discussed in detail in this section. Further information can be found in [36]. However, the suppression of backgrounds which have the same final states particles as the signal is much more challenging. Improving the event selection, which leads to an improvement of the Higgs self-coupling precision, is directly related to an enhanced suppression of this background type which makes it the most important background.

The *same final state background* originates from ZZZ and ZZH events. The quantities which can be used as input variables to train a neural net are invariant mass and angular distributions. The input variables for the neural net are:

Reconstructed two Higgs boson masses: When the dijet system is reconstructed as two Higgs bosons then these distributions are the most discriminative to separate the background.

Invariant masses of ZH and ZZ signals: When the dijet system is reconstructed as ZH or ZZ events then these masses can offer an additional discriminative in order

to suppress the background.

Polar angles: These backgrounds are dominated by t -channel processes, which provide an angular dependence characterized by a Z boson emitted in the very forward direction. Here, the momentum and the polar angle can be used to describe the t -channel characteristics.

The key observables in the selection are the invariant masses of the Higgs candidates. In case of the double Higgs boson signal, these should peak at 125 GeV, while in case of the background processes, they peak at the Z mass or at both masses. Fig. 9.1 shows the reconstructed mass of the most energetic Higgs boson $M(H1)$ of ZHH , as well as ZZH and ZZZ processes, when these events are reconstructed as ZHH events. The two isolated leptons come from a Z boson, whereas the other two bosons decay into $q\bar{q}$. It can be seen clearly that an improved resolution on the reconstructed boson masses will improve the separation between signal and background.

As result from the neural net training, the cutting variable $MLP_{lbbb} > 0.25$ [7] is used in order to suppress the background. In fig. 9.1(b) the neural net output is shown. The output distribution of background and signal is optimized with the values of the quantities. On hand of this distribution the cut value of < 0.25 of the neural net for the events is determined.

In order to achieve a even better suppression, flavour tag information can be used to eliminate backgrounds with less than two b quarks in the parton level. The b likeness of each jet is ordered from the smallest to the largest. The b likeness values are denoted as **Bmax1**, **Bmax2**, **Bmax3** and **Bmax4**. For the lepton channel, **Bmax3** has the most discriminative power and is used as cutting variable to separate background and signal with **Bmax3** > 0.18 [7].

The selection strategy of ZZH and ZZZ background events emphasizes the use of kinematic fits in the Higgs self-coupling analysis in order to improve the mass resolution. In addition, improving the jet-boson assignment could enhance a correct jet pairing as well which could also improve the mass resolution. As result, an improved mass resolution could lead to a better suppression of the background. Additionally, information which can be obtained from the fit as the fit probability, could represent possible discriminative variables for the neural net training.

9.2 Applying Kinematic Fitting

In order to isolate the impact of kinematic fitting, it is advantageous to consider a simplified benchmark. For this purpose, the preselection of the lepton channel is performed

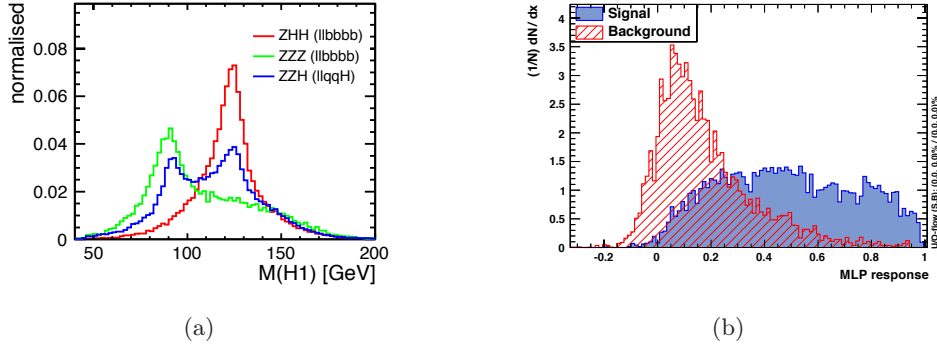


Figure 9.1 – a) invariant mass distribution of the Higgs-strahlung events with two main backgrounds ZZH and ZZZ at the ILC at $\sqrt{s} = 500$ GeV. In case of ZZH events the decay of the Higgs boson is considered in all possible decay modes. b) output distribution from the neural net which is used to separate signal from background[156].

as described in sec. 9.1. Then, the kinematic fit is applied, and the improvement on the separation between ZHH and ZZH is assessed by a criterion which will be defined in sec. 9.3.2. First, the studies of the kinematic fits are performed for events without ISR, with the golden sample of ZHH processes as defined in sec. 8.4.3. Subsequently, the impact of ISR on kinematic fitting is studied. It is also discussed if ISR needs to be considered like in [135].

The specific needs of the lepton channel makes it necessary to distinguish between the electrons and the hadronic jets of the data for kinematic fitting. As presented in the previous chapter, the jet error parametrisation from eq. 8.19 can be used for the ZHH processes for kinematic fitting of hadronic jets. This is fulfilled with the corresponding error parametrisation of the particles and the constraints for the kinematic fitting:

Jet treatment: The parametrisation for the hadronic jets from the Higgs bosons follows sec. 8.6 with E, θ, ϕ . Herein, the jet error parametrisation from eq. 8.19 has been used for ZHH processes for kinematic fitting. Since the Higgs bosons decay into $b\bar{b}$, it should be mentioned that the composition of the jets contains a much higher fraction of semi-leptonic decays compared to WW processes, decaying into u, d, s, c quarks.

Lepton treatment: As explained in sec. 8.2.1 electrons can also be parametrized with E, θ, ϕ . Here, $\sigma E / \sqrt{E} = 10\% / \sqrt{E}$ is used for the electrons. This is an adequate value for a combination of the much more precise track momentum measurement (see eq. 3.9) and the resolution of $\sim 17\% / \sqrt{E}$ for the ECAL measured in a test beam [158].

Constraints: The lepton channel of the Higgs self-coupling offers a full range of con-

straints which can be applied in kinematic fitting:

- $\sum E_{jets} + \sum E_{leptons} = \sqrt{s}$, the whole energy should be conserved.
- $\sum \vec{p} = 0$, the momentum should be conserved.
- $M_{\ell\ell} = M_Z$, the invariant mass of the leptons should be equal to the Z boson mass within the natural width of the Z boson. Due to the good energy and angular resolution of the electrons, the mass resolution for $Z \rightarrow e^+e^-$ is better than the natural width of the Z boson. In consequence, if the invariant Z mass deviates slightly from 91.18 GeV it is highly probable that this deviation does not originate from the measurement resolution, but from the natural width of the Z boson. A consideration of the natural width of the Z boson can be done by applying a so called *Soft Mass Constraint*. The soft mass constraint determines the invariant mass of a dijet system with respect to the natural width of the Z boson. For the Z boson, an invariant mass of 91.18 GeV with a natural width of 2.495 GeV is set as soft mass constraint. It should be mentioned that the applied soft mass constraint assumes a gaussian form of the invariant mass distribution, since a gaussian function provides better contributions to the χ^2 of the kinematic fit for higher mass deviations from the nominal Z mass compared to a Breit-Wigner function. In order to specify Γ_Z from the Breit-Wigner function in units of σ from a gaussian function, a k factor is used [159]:

$$\sigma^2 = \frac{k^2 \Gamma_Z^2}{2 \ln(4k^2 + 1)}. \quad (9.4)$$

The aim is to find a σ which provides similar contributions to the χ^2 as a Breit-Wigner function for small mass deviations of the customized invariant mass to the nominal Z mass. Herein, the k factor determines the distance from the nominal Z mass where the gaussian- and Breit-Wigner function are equal. [159] determines $k = 1.0$ as an optimal value which gives $\sigma^2 = 1/0.805 \cdot (\Gamma_Z/2)^2 = 1.9335 \text{ GeV}^2$ for the soft mass constraint.

- $M_{j_1 j_2} = M_{j_3 j_4}$: The invariant mass of the two dijet systems should be equal. The natural width of the Higgs is not known and expected to be in range of a few MeV. Therefore, the natural width Γ_H can be neglected with respect to the detector resolution and an average invariant Higgs mass for both dijet systems can be assumed, which justifies the use of $M_{j_1 j_2} = M_{j_3 j_4}$ for this analysis.

9.3 Mass Resolution and Separation from ZZH events

This section refers to the golden sample of ZHH and ZZH processes from sec. 8.4.3, unless otherwise stated. Applying a kinematic fit on ZHH processes with a parametrisation of E, θ, ϕ for the electrons and hadronic jets with the constraints from the previous section, the impact of kinematic fitting on the mass resolution and the separation of ZHH from ZZH processes can be studied. In sec. 9.4, the impact from ISR will be discussed. The assignment of the hadronic jets to the corresponding dijet systems was made as described in sec. 8.5.2.

9.3.1 Mass Reconstruction of ZHH events

Due to the good resolution of the electrons the kinematic fit will have a small influence on the mass resolution of the Z -boson. Fig. 9.2 shows the invariant mass of the Z -boson before (orange histogram) and after the use of the kinematic fit (green histogram). It is expected that the mass distribution follows a relativistic Breit-Wigner distribution with an additional smearing of the mass caused by the limited detector resolution. This smearing is considered as an additional gaussian distribution. To analyze the distribution, the *Voigt function* ($V_{\sigma,\Gamma}(x)$) is used. $V_{\sigma,\Gamma}(x)$ is a convolution of a gaussian function ($G(x)$, eq. 9.6) and a non-relativistic Breit-Wigner function ($L(x)$, eq. 9.7) with a gaussian width σ and a Lorentz width Γ (eq. 9.5).

$$V_{\sigma,\Gamma}(x) = (G * L)(x) = \int G(\tau)L(x - \tau)d\tau \quad (9.5)$$

$$G(x) = \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{x^2}{2\sigma^2}} \quad (9.6)$$

$$L(x) = \frac{\Gamma}{2\pi(x^2 + \Gamma^2/4)} \quad (9.7)$$

Both histograms in fig. 9.2 are fitted with the Voigt function. Parameter $p0$ corresponds to the amplitude, $p1$ to the mean of the fitted invariant mass, $p2$ represents σ and $p3$ presents Γ_Z . The invariant mass distribution before kinematic fitting corresponds to the expectations given by Γ_Z and the detector resolution. After kinematic fitting, the invariant mass distribution is artificially narrowed by the soft mass constraint. This was expected, since the resolution of the electrons is very good. This is visible in the small σ of the detector resolution. In addition, the peak of the invariant mass distribution is not shifted, which could be caused by the energy constraint of the kinematic fit. For the Z mass after fitting, the mean of the Z -boson is found at 91.33 GeV, which is in a reasonable agreement with 91.18 GeV and the width of the Z boson is artificially narrowed by 18%.

For the Higgs bosons the reconstruction is driven by the equal mass constraint with the result that the invariant mass of both Higgs bosons are the same after the fit. Since

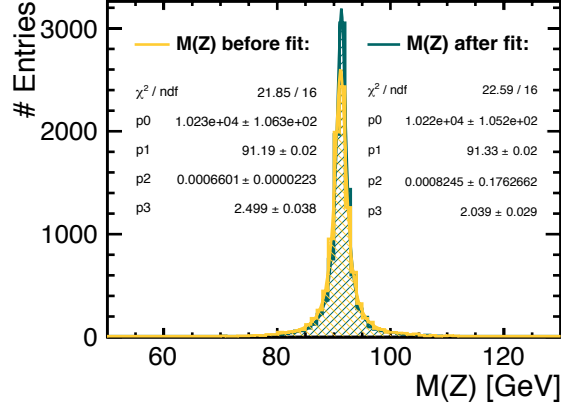


Figure 9.2 – Invariant mass of the reconstructed Z boson before (orange histogram) and after kinematic fitting (green histogram) from the electron di-system.

the natural width of the Higgs is expected to be in the MeV range, it is expected that the mass distribution of the Higgs is dominated by the detector resolution. Therefore, using the Voigt function is not strictly necessary for the Higgs masses, but it is used here as well for consistency. Fig. 9.3 shows the invariant mass of ZHH processes for both Higgs bosons, before (red histogram) and after (blue histogram) kinematic fitting. The figure shows that the kinematic fit improves the mass resolution. Before kinematic fitting, the mass distributions do not follow a Breit-Wigner distribution anyhow. The resulting reconstructed invariant mass for the Higgs bosons after the kinematic fit is 124.45 GeV, which is in a reasonable agreement to the generated mass value of the Higgs boson of 125 GeV. The width is dominated by the detector resolution as expected and agrees with $\sigma = 7.1$ GeV with the assumed 7.2 GeV of the standard analysis from sec. 9.1. Also the natural width with $\Gamma_H = 2.6$ MeV corresponds to the expectations. Compared to the Z boson, where $\Gamma_Z = 2.499$ GeV agrees very well with the expected natural width of $\Gamma_Z = 2.495$ GeV shows that the fit works quite good in order to separate the impact of detector resolution and natural width.

The full topology of the invariant mass distribution of ZHH events before and after kinematic fitting can be seen in fig. 9.4(a) and fig. 9.4(b), which underlies the improvement of the mass resolution after kinematic fitting.

9.3.2 Separation from ZZH events

Running the kinematic fit on ZHH events has shown that the mass resolution is improved, this also implies for the Higgs self-coupling measurement that the separation of ZHH events compared to other background signals, like ZZH could be improved, even if the kinematic fit moves the peaks of ZHH and ZZH events closer together due to the equal mass constraint for the dijet systems.

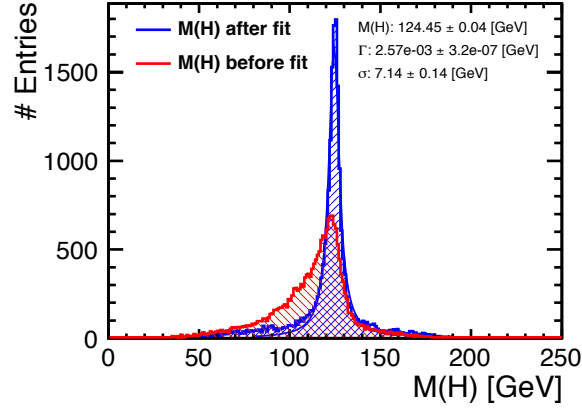


Figure 9.3 – a) Invariant mass before (red histogram) and after (blue histogram) kinematic fitting for the Higgs bosons in ZHH events fitted with a Voigt function. The values after kinematic fitting with a mass of 124.45 GeV, a detector resolution of $\sigma = 7.1$ GeV and a natural width of $\Gamma_H = 2.6$ MeV agrees very well with the standard analysis.

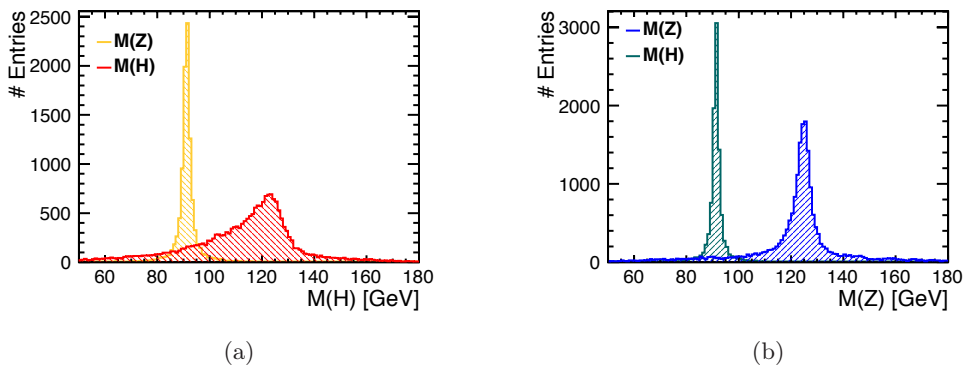


Figure 9.4 – a) Invariant mass before kinematic fitting for the Z and the two Higgs bosons and b) after kinematic fitting.

Fig. 9.5 shows the invariant masses of both processes before kinematic fitting is applied on the samples. The red histogram displays the ZZH process and the blue histogram the ZHH process. In case of the ZZH process a double peak structure is visible. These peaks are caused if either a Z or a Higgs boson is reconstructed, because in case of ZZH events both hadronic particles can be either a Z or a Higgs boson.

Fig. 9.6 shows the reconstructed invariant masses for the second Z - and the Higgs boson

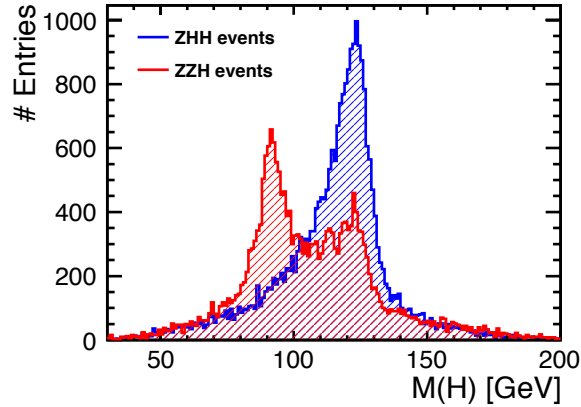


Figure 9.5 – Reconstructed invariant masses of the two dijet systems for ZZH and ZHH events for both Higgs bosons. The red histogram displays ZZH events and the blue histogram ZHH events for invariant masses before kinematic fitting.

for ZZH processes. As already mentioned in fig. 9.5, also fig. 9.6 shows the double peak structure before kinematic fitting is applied (the red histogram). After kinematic fitting (blue histogram) the equal mass constraint found a reconstructed mass which lies between the Z - and Higgs boson. This was expected because the equal mass constraint of the two dijets forces $m_{j_1j_2} = m_{j_3j_4}$. The reconstructed mass after the kinematic fit should help

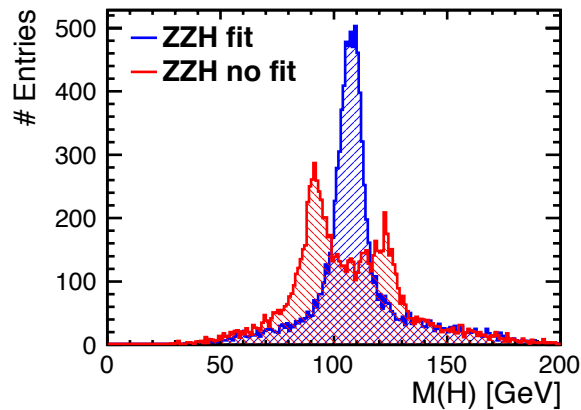


Figure 9.6 – a) Invariant mass distribution for two bosons decaying hadronically for ZZH events before (red histogram) and after (blue histogram) kinematic fitting.

to improve the distinction between ZHH and ZZH processes. To evaluate this more in detail, the purity (π) and efficiency (ϵ) of ZHH and ZZH processes can be studied:

$$\pi = \frac{N_s}{N_s + N_b}, \quad (9.8)$$

$$\epsilon = \frac{N_s}{N_{\text{signal before cut}}}. \quad (9.9)$$

N_s is the number of signal events (ZHH events in a certain mass range), N_b is the number of background signals (ZZH events in a certain mass range) and $N_{\text{signal before cut}}$ is the number of all signal events. $1/\sqrt{\pi \cdot \epsilon}$ is proportional to the uncertainty of the cross section [160]:

$$\frac{\delta\sigma}{\sigma} = \frac{1}{\sqrt{\pi \cdot \epsilon}} \cdot \frac{1}{\sqrt{\int \mathcal{L} dt \cdot \sigma}} \quad (9.10)$$

Fig. 9.7(a) shows a 2d histogram of both Higgs masses for ZHH (blue histogram) and ZZH processes (red histogram). Both histograms have to be analyzed to filter out N_s and N_b . Integrating each histogram in the considered mass range determines the number of signal and the number of background events. Here, a lower and an upper mass cut for both dijet systems is used, while both dijet systems use the same mass cut. Looking at the blue histogram (ZHH events) an upper mass cut for the signals at 140 GeV for both Higgs masses seems to be suitable. For the lower mass cut a range between 0 and 140 is tested. An integration of the blue histogram from the starting point up to 140 GeV is defined as N_s . In case of the red histogram this integration is defined as N_b . The integration of the full mass range of the blue histogram gives $N_{\text{signalbeforecut}}$. With these quantities, π and ϵ can be determined. Varying the starting point by scanning through the mass range, the optimal mass cut can be determined, which determines the best uncertainty on the cross section [160]. Fig. 9.7(b) shows the corresponding result for π and ϵ depending on the mass cut of the integration. Before the kinematic fit is used the best uncertainty on the cross section is gained at a cut of $M_H \approx 100$ GeV with $\pi \cdot \epsilon \approx 0.25$. The same study can be done after kinematic fitting, but instead of a 2d histogram a 1d histogram can be analyzed, since in a 2d histogram all masses would be aligned on a diagonal caused by the equal mass constraint. Fig. 9.8(a) shows the invariant mass for ZHH - and ZZH -events after the use of kinematic fitting. Doing the same integration to determine N_s , N_b and $N_{\text{signalbeforecut}}$ gives the following results in fig. 9.8(b). The best uncertainty on the cross section is gained when requiring for $M_H > 117$ GeV with $\pi \cdot \epsilon \approx 0.35$, which corresponds to a relative improvement of $\approx 40\%$ on $\pi \cdot \epsilon$. In conclusion, using eq. 9.10, $\delta\sigma/\sigma$ improves by a factor of $\sqrt{\frac{\pi \cdot \epsilon_{\text{KinFit}}}{\pi \cdot \epsilon}} \approx 1.18$ with $\pi \cdot \epsilon_{\text{KinFit}}$ after the application of kinematic fitting. Therefore $\delta\sigma/\sigma$ improves by $\approx 18\%$. It should be noted that here, $\delta\sigma/\sigma$ is a first estimate based on the mass cuts, in a real analysis the masses would be used as input parameters for a neural net.

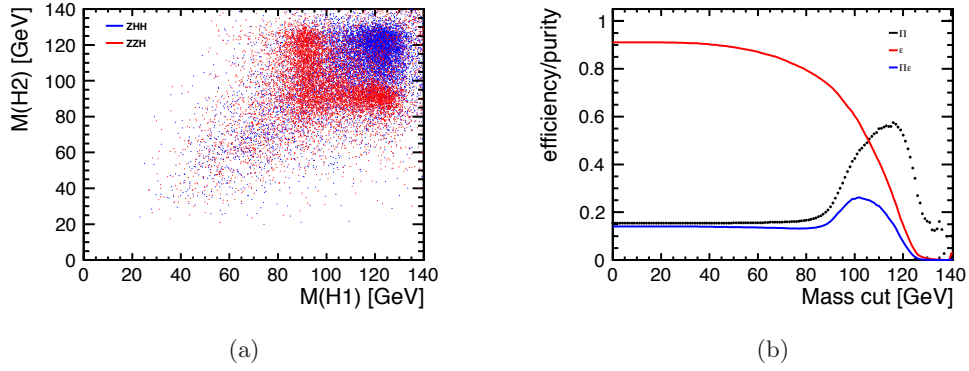


Figure 9.7 – a) correlation of the reconstructed masses of the two bosons decaying hadronically of ZHH - and ZZH -events before a kinematic fit is applied, b) the purity, the efficiency and product of both for ZHH - and ZZH -events before kinematic fitting.

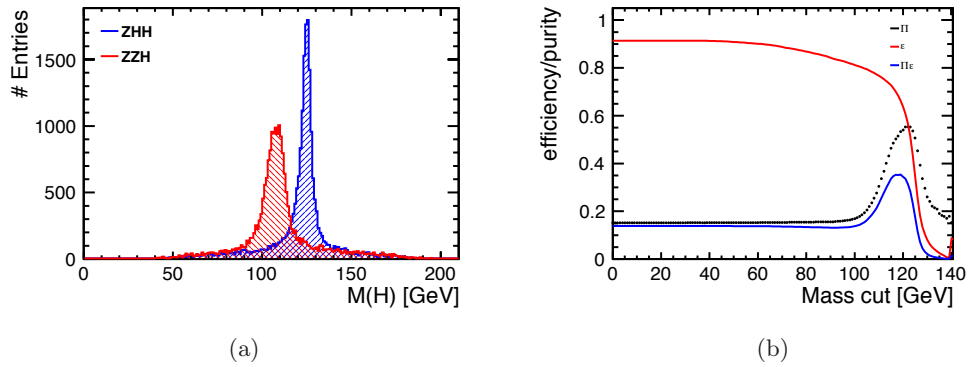


Figure 9.8 – a) reconstructed mass of ZHH - and ZZH -events after a kinematic fit is applied, b) the purity, the efficiency and product of both for ZHH - and ZZH -events after kinematic fitting.

9.3.3 Fit Probability Weighting

By studying the fit probabilities for both kinds of processes (ZHH and ZZH), as shown in fig. 9.9 it can be tested if a weighting with $P(\chi^2)$ will improve $\pi \cdot \epsilon$. This is indicated in the tendency to lower fit probabilities in the red histogram. In case of ZZH events, the kinematic fit forces the two dijet systems to have equal mass. Since one dijet system corresponds to a Z boson while the other corresponds to the Higgs boson, the deviation of the reconstructed mass after kinematic fitting compared to the reconstructed mass of ZHH events is rather big, as depicted in fig. 9.6. The bigger deviation should be noticeable in the fit probability. Looking at the invariant mass in dependency of the fit probability, fig. 9.10 shows that neither in case of ZHH events (fig. 9.10(a)) nor ZZH events (fig. 9.10(b)) a dependence of $P(\chi^2)$ on the reconstructed mass is visible. Only a slightly bigger spread of the invariant masses in case of ZZH events is visible. This makes the possibility to weight the events with $P(\chi^2)$ to improve the mass resolution not very attractive. Alternatively, using a fit hypothesis for ZZH events and comparing the fit probabilities $P(\chi^2(ZHH))$ and $P(\chi^2(ZZH))$ of both events with each other could be useful to improve $\pi \cdot \epsilon$ further, but this was not part of discussion in this thesis.

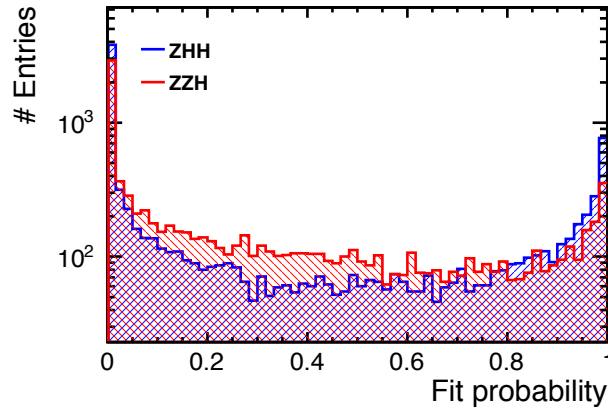


Figure 9.9 – Fit probability for both types of events, ZHH - and ZZH -events.

9.4 Impact of ISR

In the previous analysis, kinematic fitting was applied on the golden sample of ZHH and ZZH processes, which exclude most of the ISR photons due to the constraint $\sqrt{s'} > 495 \text{ GeV}$ (see fig. 8.4 and tab. 8.4). For analysis of the impact of ISR photons, an additional sample have be considered which includes ISR photons. Therefore, the golden sample is used, where the $\sqrt{s'} > 495 \text{ GeV}$ cut is removed while the α and θ cut from sec. 8.4 are still applied. Thus for analysis, 29582 and 27559 ZHH and ZZH events remains respectively. Fig. 9.11(a) shows the invariant masses before kinematic fitting

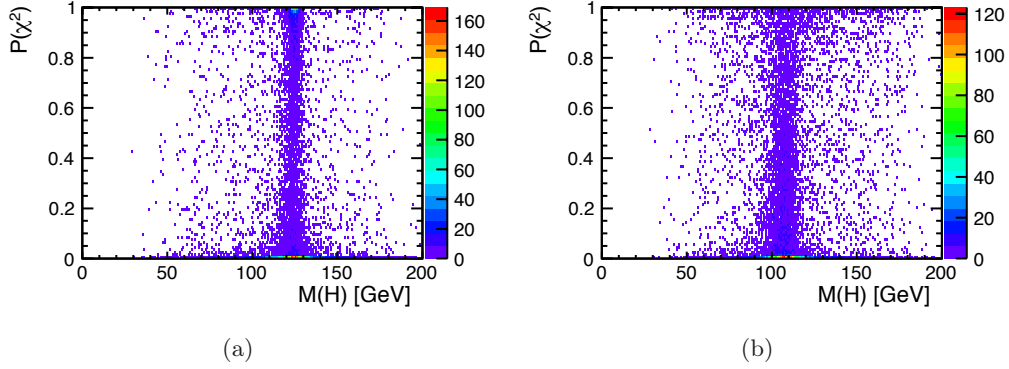


Figure 9.10 – a) $P(\chi^2)$ in dependency of the reconstructed invariant mass of one Higgs boson per ZHH events, b) per ZZH events (either a Z or a Higgs boson).

which is similar to fig. 9.5 for the golden sample. Fig. 9.11(b) shows the impact of ISR photons after kinematic fitting is applied, if fig. 9.11(b) is compared with fig. 9.8(a) for the golden sample. The longer left tails for the invariant masses after kinematic fitting caused by ISR photons are clearly visible. The kinematic fit calculates with an energy sum of $\sqrt{s} = 500$ GeV, due to the ISR photons this value is not conserved. As result, the missing energy of the ISR photons are causing a bias for the invariant masses. The kinematic fit tries to compensate the missing energy by increasing the momenta (and therefore the energy) of the jets. Looking at eq. 8.13 this leads to a higher mass of the dijet system. Therefore, the performance of the kinematic fit will depend crucially on the treatment of the initial state radiation. It has been shown that this can be ensured by including a photon in the fit [135]. With this technique, the same resolution has been achieved for WW events with and without significant ISR. This should be investigated in the future.

9.5 Fit Probability and Jet Pairing

Another possible impact of kinematic fitting is the improvement of the jet pairing. The difference between the standard analysis of the Higgs self-coupling and this analysis is that the standard analysis uses eq. 9.2 for the jet pairing and up to now the kinematic fit uses a jet pairing given by the best fit probability. Therefore, the events are evaluated with different χ^2 probabilities. The result of different χ^2 s is the determination of different jet pairings. This analysis has been done on the golden sample and on the data which includes ISR photons. The kinematic fit uses eq. 8.2, which result in a χ^2 probability as given in eq. 8.6, while the standard analysis uses eq. 9.2, which result in a χ^2 probability of:

$$P(\chi^2, 2) = \frac{1}{2} \int_X^\infty e^{-\frac{1}{2}t} dt = e^{-\frac{\chi^2}{2}}, \quad (9.11)$$

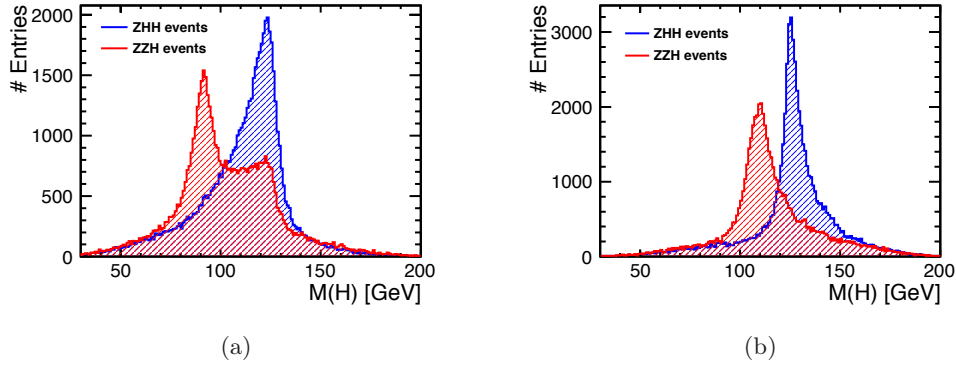


Figure 9.11 – a) Reconstructed invariant masses before a kinematic fit is applied for ZZH and ZHH events by considering the presence of ISR photons. The red histogram displays ZZH events and the blue histogram ZHH events. b) reconstructed invariant masses after a kinematic fit is applied for ZZH and ZHH events by considering the presence of ISR photons. The red histogram displays ZZH events and the blue histogram ZHH events.

It should be noted that this $P(\chi^2)$ chooses a dijet system by looking for the smallest deviation of the reconstructed invariant mass compared to a 125 GeV H -boson. In case of the kinematic fit, $P(\chi^2)$ evaluates the dijet systems by considering additionally the constraints for the energy and momentum conservation, but the information on the expected Higgs boson mass is not used. The impact of the different fit probabilities and the resulting different jet pairing are part of discussion in this section.

9.5.1 Fit Probabilities

The main difference between eq. 8.2 and eq. 9.2 lies in the used constraints for the χ^2 . Looking on how the kinematic fit evaluates the events for both χ^2 probabilities will give a deeper understanding. The study has been done for the golden sample and for the data set which incorporates ISR photons.

9.5.1.1 Fit Probabilities on the Golden Sample

Analyzing the initial values of the energy sum and momentum sum (initial values means values before kinematic fitting is applied) on the golden sample shows that the initial values are evaluated differently. In fig. 9.12 the different evaluation for the initial values of the energy sum for both χ^2 s are depicted, and in fig. 9.13 the momentum sum. Either for the energy sum or the momentum sum, the kinematic fit evaluates events where the energy (fig. 9.12(a)) and momentum deviation (fig. 9.13(a)) is getting larger with lower fit probabilities compared to the standard analysis. For both $P(\chi^2)$ s the probability is smaller for large deviations of the jet energy sum from 500 GeV and the momentum sum from "0". But the effect is more pronounced in case of the χ^2 probability from the kine-

matic fit, which is visible in the sharp edge of fig. 9.12(a) compared to fig. 9.12(b), and highlighted the dominance of the energy constraint. The dependence for the momentum constraint is not clear visible in fig. 9.13(a) and fig. 9.13(b).

The deviation of the energy sum in fig. 9.12 is larger than 5 GeV. This effect can not be explained with the impact of ISR since the golden sample includes events with $\sqrt{s'} > 495$ GeV on generator level. Also, the detector resolution can be excluded, because the detector resolution will cause a gaussian smearing which is indeed visible in fig. 9.12 by the positive entries, but also this effect is negligible. The major part of the deviation can be associated to the b jets from the decay of the Higgs. The impact of semi-leptonic decays in case of b jets can not be ignored. The generation of neutrinos from semi-leptonic decays is responsible for the missing energy and momentum in fig. 9.12 and fig. 9.13. Therefore, ISR and semi-leptonic decays are responsible for missing energy and momentum in the reconstruction. While ISR cause a shift to higher masses in the reconstruction, as discussed in sec. 9.4 and visible in fig. 9.11(b), it is different for semi-leptonic decays. A shift to higher masses is not visible in the reconstruction of the invariant masses in fig. 9.8(a). ISR cause of reduction of $\sqrt{s}$ to $\sqrt{s'}$ and for semi-leptonic decays $\sqrt{s'}$ is guaranteed but the energy gets lost in the development of the jet. The reason why a shift to higher invariant masses is not visible lies in the error parametrisation of the jets. The allowed uncertainties gives the kinematic fit the opportunity to compensate the missing energy and momentum. Most of the jets lie in the region of $\sim 10\%$ as an excepted jet energy resolution. 10% from 500 GeV justifies the entries at ~ 50 GeV.

Nevertheless, both $P(\chi^2)$ s reacts with lower fit probabilities for events with higher fraction of missing energy or momentum. Another aspect can be shown if a projection of fig. 9.12 on the y axis is analyzed. A projection on the y axis gives the fit probability distribution from fig. 9.9. The reason for the peaks at "0" in fig. 9.9 were named as a bad error estimation or a wrong fit hypothesis for the events. Now, with fig. 9.12 it becomes clear that this evaluation is caused by the missing energy/momentum due to the semi-leptonic decays. For these events the error parametrisation is not sufficient and it becomes relevant to consider the non-gaussian tails from fig. 8.20 for the jet energy parametrisation. Vice versa for events with less missing energy and momentum, both $P(\chi^2)$ s evaluate them with higher fit probabilities. Here, it would be sufficient to consider a smaller range of the core for the jet energy resolution. Both effects, high and low fractions of missing energy/momentum could be handled with an improved error parametrisation of b jets. Here, as already mentioned, a multi variable transformation or a likelihood fit are named as possible candidates for further improvements.

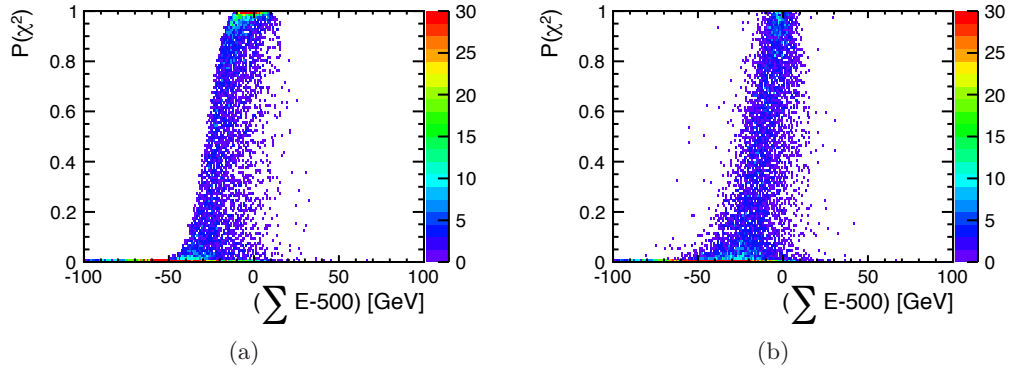


Figure 9.12 – a) $P(\chi^2)$ in dependence of the energy sum given by the kinematic fit, b) given by the standard analysis.

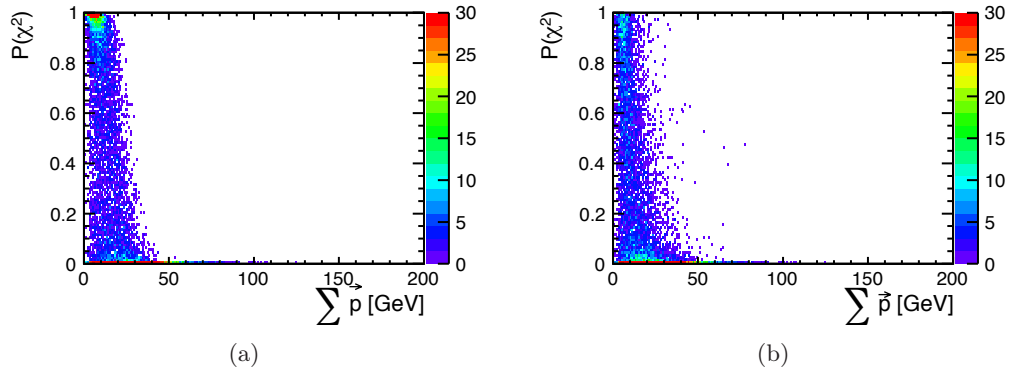


Figure 9.13 – a) $P(\chi^2)$ in dependence of the momentum sum given by the kinematic fit b) given by the standard analysis.

9.5.1.2 Fit Probability with the Presence of ISR Photons

Considering the presence of ISR photons shows similar observations as in case of the golden sample. Fig. 9.14 and fig. 9.15 shows the evaluation for the initial values of the energy sum and momentum sum with the presence of ISR photons. Also in presence of ISR photons, the probability is smaller for both $P(\chi^2)$ s for large deviations of the energy sum from 500 GeV and the momentum sum from "0". Also a sharp edge is visible for $P(\chi^2)$ of the kinematic fit in fig. 9.14(a) compared to fig. 9.14(b), but additionally with ISR photons the difference for both $P(\chi^2)$ s is more pronounced. Additionally, this effect becomes clearer also for the momentum in fig. 9.15(a) and fig. 9.15(b). The analysis of the data with ISR photons shows that the deviation of the energy sum and momentum sum is dominated by two effects. First, the impact of ISR and second as it was case for the golden sample, semi-leptonic decays of the jets. The impact of both effects are the same. While ISR photons can be considered, as shown in [135], the semi-leptonic decays can be handled with a better error parametrisation of the b jets by considering the non-gaussian tails in fig. 8.20.

The data set with ISR photons underlines the dominance of the energy and momentum constraint from the $P(\chi^2)$ from kinematic fitting.

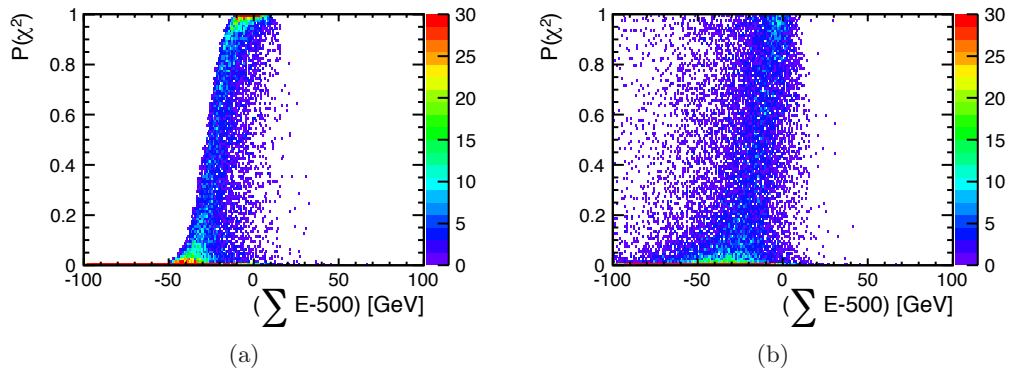


Figure 9.14 – a) $P(\chi^2)$ in dependence of the energy sum given by the kinematic fit with the presence of ISR photons, b) given by the standard analysis.

9.5.2 Jet Pairing

Another aspect of both χ^2 probabilities is the performance of the jet pairing. Due to the different evaluation of the events, it is possible that in both cases different jet/boson assignments for one event is chosen. To compare the jet pairing for both χ^2 probabilities with each other, the developed procedure for the angle sum between primary quarks and reconstructed jets from sec. 8.5.3 is used. The jet pairing with the smallest angle sum is defined as the correct jet pairing. Defining this as reference jet pairing allows a comparison with both jet pairings determined by both χ^2 probabilities. The events are

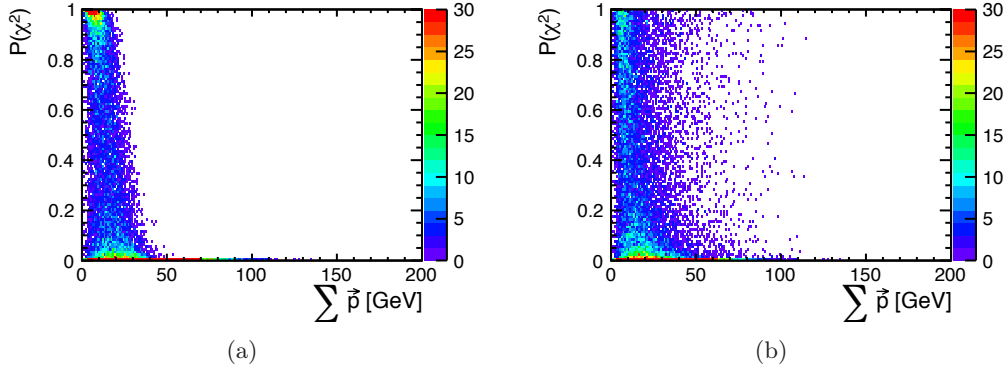


Figure 9.15 – a) $P(\chi^2)$ in dependence of the momentum sum given by the kinematic fit in presence of ISR photons and b) given by the standard analysis.

counted as agreeing when the jet pairing found in the reconstruction is the same as the one resulting from the reference jet pairing.

9.5.2.1 Jet Pairing of the Golden Sample

Analyzing the jet pairing of the golden sample shows that the χ^2 of the standard analysis gives a better performance on ZHH events, but for ZZH events the χ^2 of the kinematic fitting works better. The results are displayed in tab. 9.1. Here the definition in both cases for the χ^2 gets relevant. The χ^2 of the standard analysis just accounts for the invariant mass of the dijet system compared to the Higgs mass. The χ^2 from the kinematic fit in turn takes into account the constraints with the result that the jet pairing of the kinematic fit on ZZH events is better compared to the χ^2 of the standard analysis. The better performance of the jet pairing from the standard analysis has an impact for the invariant mass of the events. In order to disentangle the effects of the jet pairing from the effects of the improved mass reconstruction by kinematic fitting, kinematic fitting is applied after the determination of the jet pairing according to both $P(\chi^2)$ s from the standard analysis and kinematic fitting. The reconstructed invariant mass for both cases before and after the fit for both masses are visible in fig. 9.16 and fig. 9.17. The dark (ZZH events) and light (ZHH events) blue histograms depicted the values from the best jet combination of the kinematic fit and the dark (ZZH events) and light (ZHH events) red histogram shows the values from the Higgs self-coupling study. The invariant mass distributions before and after kinematic fitting are slightly different, due to the differently chosen dijet systems. For ZHH events the better pairing of the standard analysis leads to a narrower Higgs peak (higher and a less low mass tail). For ZZH processes the better jet pairing leads to a slightly higher peak, but with a longer tail to higher masses, which makes the separation of ZHH and ZZH processes more difficult.

Correct jet pairing from $P(\chi^2)_{\text{kin. fit}}$:				Correct jet pairing from $P(\chi^2)_{\text{Higgs s.-c.}}$:			
Signal	Events	Agreement	[%]	Signal	Events	Agreement	[%]
ZHH	13049	8976	68.78	ZHH	13049	10583	81.18
ZZH	11566	1463	12.65	ZZH	11566	1132	9.78

Table 9.1 – Left table gives the correct jet pairing from $P(\chi^2)$ from kinematic fitting and the right table the correct jet pairing from $P(\chi^2)$ from the Higgs self-coupling study, studied on the golden sample.

One reason why the jet pairing of the standard analysis works better as the jet pairing of the kinematic fit is that events with a high impact of semi-leptonic decays are evaluated with a low fit probability, as discussed in sec. 9.5.1.1. Therefore, as already shown in fig. 8.11(b) for WW processes, the kinematic fit gets insensitive for very low fit probabilities to choose the right jet pairing. This is the case for events with a high impact of semi-leptonic decays. Here, it is better to consider only invariant masses, which explains the better performance of the standard analysis for the jet pairing.

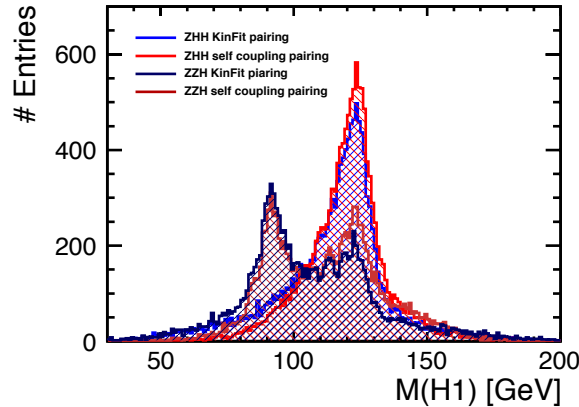


Figure 9.16 – Reconstructed invariant masses for the different jet pairings of kinematic fitting and the standard analysis depicted on hand of ZZH and ZHH events. The darker histograms are displaying ZZH events and the lighter histograms ZHH events for invariant masses before a kinematic fit is applied

9.5.2.2 Jet Pairing in Presence of ISR photons

Analyzing the jet pairing on a data set which includes ISR photons shows also a better performance for the standard analysis. The results are presented in tab. 9.2. For ZHH events, the presence of ISR photons result in a slightly lower fraction of agreement as it was the case for the golden sample, otherwise the observations are similar as in case of the golden sample. As for the golden sample, the standard analysis has less tails to smaller masses, but larger to higher masses. But in general compared to the golden sample, the

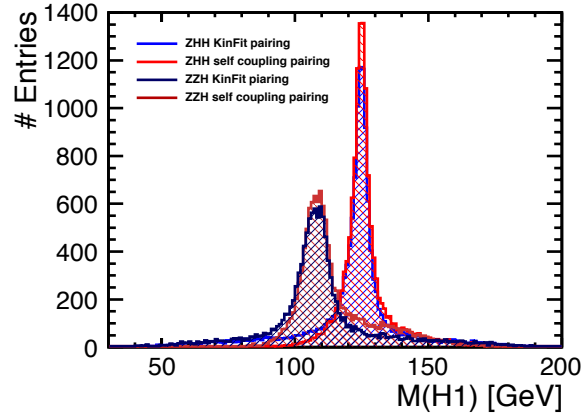


Figure 9.17 – Reconstructed invariant masses for the different jet pairings of kinematic fitting and the standard analysis depicted on hand of ZZH and ZHH events. The darker histograms are displaying ZZH events and the lighter histograms ZHH events for invariant masses after kinematic fitting.

Correct jet pairing from $P(\chi^2)_{\text{kin. fit}}$:				Correct jet pairing from $P(\chi^2)_{\text{Higgs s.-c.}}$:			
Signal	Events	Agreement	[%]	Signal	Events	Agreement	[%]
ZHH	29582	19735	66.71	ZHH	29582	23960	80.99
ZZH	27559	3676	13.34	ZZH	27559	2704	9.81

Table 9.2 – Left table gives the correct jet pairing from kinematic fitting and the right table the correct jet pairing from the Higgs self-coupling study. Both in the presence of ISR photons.

tails are much longer to higher masses. As already mentioned, the tails are a result of the missing energy from ISR.

In conclusion, in order to determine the jet pairing none of the methods are ideal. The kinematic approach has to handle the impact of semi-leptonic decays and the standard analysis only considers the invariant masses, which leads to the consideration of a different approach in the next section.

9.5.3 Optimized Kinematic Fitting

Studying the jet pairing with and without ISR photons with $P(\chi^2)$ from the kinematic fitting and with $P(\chi^2)$ from the standard analysis shows that in both cases the standard analysis has a better correct jet pairing fraction for ZHH events. In case of ZZH events it is vice versa. The jet pairing from kinematic fitting is dominated by semi-leptonic decays, which impact the energy sum and the momentum sum. For instance a large deviation in the energy sum is evaluated with a lower fit probability compared to the standard analysis. The lower fit probability is responsible that the fit gets insensitive in

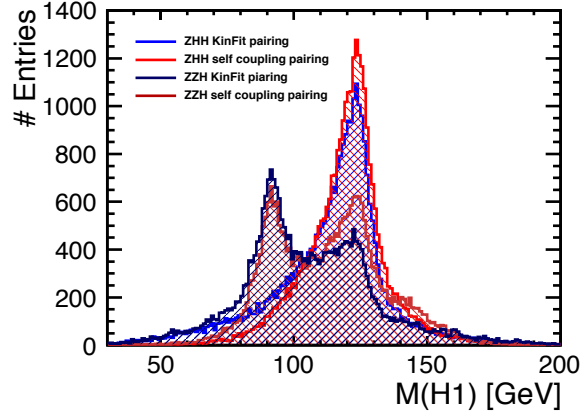


Figure 9.18 – Reconstructed invariant masses of the start values for the different jet pairings of kinematic fitting and the standard analysis depicted on hand of ZZH and ZHH events in presence of ISR photons. The darker histograms are displaying ZZH events and the lighter histograms ZHH events for invariant masses before a kinematic fit is applied

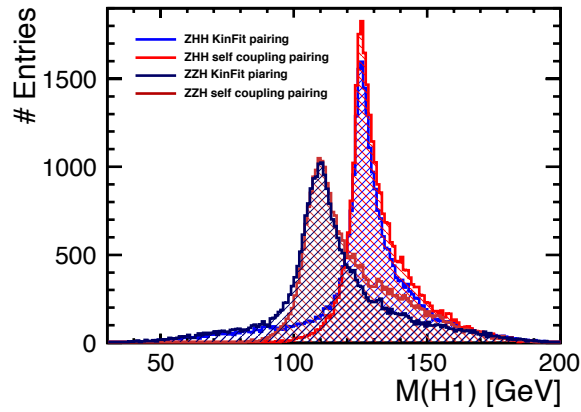


Figure 9.19 – Reconstructed invariant masses for the different jet pairings of kinematic fitting and the standard analysis depicted on hand of ZZH and ZHH events in presence of ISR photons. The darker histograms are displaying ZZH events and the lighter histograms ZHH events for invariant masses after kinematic fitting.

Correct jet pairing for the golden sample:				Correct jet pairing with ISR:			
Signal	Events	Agreement	[%]	Signal	Events	Agreement	[%]
ZHH	13049	11378	87.19	ZHH	29582	23349	78.93
ZZH	11566	1255	10.85	ZZH	27559	3459	12.55

Table 9.3 – Left table gives the correct jet pairing from the optimized kinematic fitting on the golden sample and the right table the correct jet pairing from the optimized kinematic fitting with the presence of ISR photons.

order to determine the correct jet pairing. This result opens the question if it is possible to combine the best of both $P(\chi^2)$ methods. Modifying a kinematic fit processor to use instead of an equal mass constraint a mass constraint of 125 GeV, like it is the case in the standard analysis, would be such a synergy.

By using such a processor the fraction of correct jet pairing for the golden sample gives 87.19% and with the presence of ISR photons 78.93% for ZHH events, and for ZZH events 10.85% for the golden sample and 12.55% with ISR photons. The results are displayed in tab. 9.3. The jet pairing on the golden sample with such an optimized processor is clearly better than the standard analysis or the kinematic fit processor.

The distribution for the dependence of the energy sum to the fit probability are depicted in fig. 9.20(a) for the golden sample and fig. 9.20(b) with ISR photons. Either with or without ISR photons large deviations are evaluated with small fit probabilities. The same scenario can be seen for the momentum sum of the events (fig. 9.21(a) and fig. 9.21(b)).

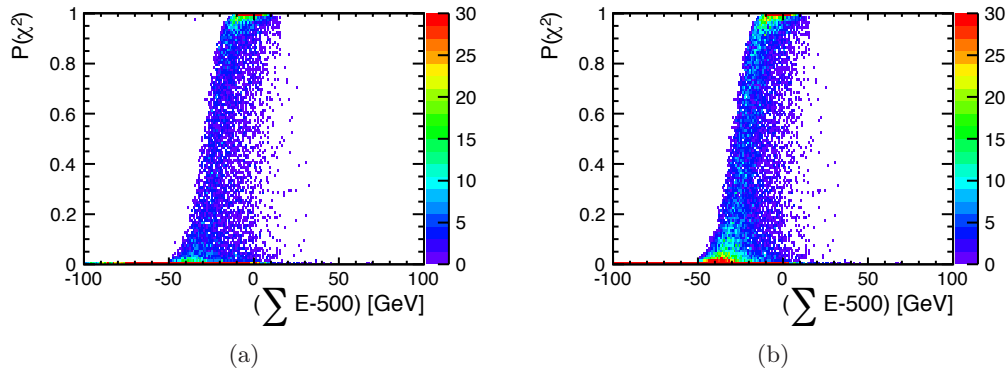


Figure 9.20 – a) $P(\chi^2)$ in dependence of the energy sum given by the kinematic fit without ISR photons and b) with ISR photons.

Due to the good correct jet pairing fraction, the optimized kinematic fit should also help to distinguish between signals and background. But the 125 GeV mass constraint shifts the invariant mass distribution for ZZH events close to 125 GeV which reduces the discriminative power between signal and background. Such a kinematic fit can be

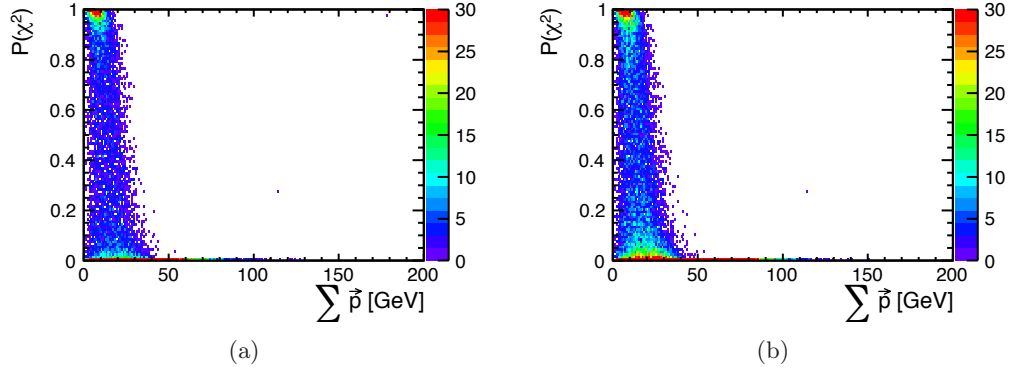


Figure 9.21 – a) $P(\chi^2)$ in dependence of the momentum sum given by the kinematic fit without ISR photons and b) with ISR photons.

used to choose the correct jet combination, which is superior compared to the standard analysis and a kinematic fit with equal mass constraint. Therefore, the best performance will be gained if two different fits will be used for the reconstruction: One for finding the correct jet combination with a 125 GeV mass constraint and another with an equal mass constraint for the reconstruction, which uses the jet combination determined by the first processor. Such a processor will be used in the standard analysis. Since the study is still ongoing no results can be shown here, but preliminary tests show an improvement of the precision in the lepton channel of $\sim 20\%$ [161]. This looks quite promising for the remaining channels.

9.6 Results

The analysis on kinematic fitting shows that kinematic fitting is a powerful tool in order to support and improve the performance of the Higgs self-coupling analysis. Nevertheless, certain aspects couldn't be tested, which offer additional potential for further improvements. In the following, the results of this part of this thesis will be given. Here, the most important achievements will be presented.

9.6.1 Jet Pairing

The correct assignment of the jets to bosons is a crucial criteria for the success of the standard analysis. This thesis discussed the jet pairing from the two χ^2 s from the standard analysis and kinematic fitting. The analysis showed that the jet pairing how it is performed in the standard analysis works best, since the χ^2 from kinematic fitting is dominated by the $\sum E, \vec{p}$ constraints and these constraints are independent of the jet pairing. Alternatively a kinematic fit for the jet pairing can be applied which only considers an equal mass constraint or a hard constraint with 125 GeV. As it was pointed

out in sec. 9.5.3 to find the correct jet pairing from two decaying bosons, a kinematic fit with a χ^2 using a 125 GeV mass constraint can be used. This combines the advantages of kinematic constraints and known mass. But for the reconstruction a χ^2 with an equal mass constraint should be used.

9.6.2 Fit Probability

In sec. 8.5.2 and sec. 8.5.3 two methods were developed to parametrize the errors of the jets. For both cases the fit probability shows an almost uniform distribution. The ZHH hypothesis gives a better fit probability for ZHH processes than for ZZH processes. A weighting of the events with the fit probability doesn't helped to improve the separation between ZHH and ZZH events. Alternatively, a hypothesis for ZZH processes can be used to determine a fit probability for ZZH processes. Comparing the fit probability for both hypothesis could help to identify ZHH and ZZH processes in a proper way. Herein, the fit probability for both event hypothesis could be used as input variables for the neural net of the standard analysis in order to increase the discriminative power between signal and background.

9.6.3 Initial State Radiation and Semi-Leptonic Decays

The impact of initial state radiation on kinematic fitting has been studied on two data samples. In sec. 9.4 it was pointed out that ISR has to be treated carefully, since ISR causes a bias in the reconstructed mass from kinematic fitting. [135] showed that this can be handled by implementing a photon in the fit, but this is an interesting topic for a future analysis. Besides ISR, the data incorporate jets generated from heavy b quarks. The resulting semi-leptonic decays lead to missing energy and momentum in reconstruction. These events are evaluated with a low fit probabilities. The kinematic fit loses its discriminative power to choose the correct jet pairing at very low fit probabilities. For future analyses, it is preferable to find a better error parametrisation for b jets which considers the non-gaussian tails. Two possible candidates could be a multi variable transformation or a likelihood fit.

9.6.4 Mass reconstruction

The mass resolution of dijets could be improved significant with kinematic fitting. In order to quantify the improvement of the mass resolution $\pi \cdot \epsilon$ was determined and showed an relative improvement of $\sim 40\%$. This result in an improvement for the uncertainty of the cross section of 18%. So far this was only performed on a "golden sample". For events which include ISR, the impact of ISR on the mass resolution should be negligible if ISR are considered as mentioned in [135], but this have to be tested in the future. In a first test an improvement of the precision of the standard analysis in the lepton

channel of about $\sim 20\%$ [161] can be seen by using the reconstructed invariant masses from the kinematic fit as selection variables for the neural net. Also the prospects for the remaining search modes of the analysis look promising.

9.7 Outlook

Kinematic fitting offers additional potential for further improvements. Based on the results of this analysis a road map for a strategy to apply kinematic fitting in the standard analysis can be given:

- The identification and consideration of ISR is important, since the impact on the reconstructed invariant masses is significant. In this analysis ISR was excluded on the generator level. For further analysis this can be done on the reconstruction level with the missing energy E_{miss} or the angle distribution $\cos\theta$, since ISR photons are very forward directed. A consideration of ISR can be done as shown in [135].
- An improved determination of the jet energy resolution for b jets is necessary in order to minimize the impact of semi-leptonic decays. In a first approach only the core of the energy distribution has been used for the determination of the jet energy resolution. As it was shown in this analysis it is necessary to consider the non-gaussian tails. This can be done with a multi variable transformation or likelihood fit. This will help to consider semi-leptonic decays in a sufficient way.
- In order to improve the jet pairing a special fit can be used as it was shown. Here, it could be tested if an exclusion of the energy or momentum constraint gives further benefit.
- The invariant mass distributions can be used as input variables for the neural net. This analysis showed the uncertainty of the cross-section could be improved by 18% which leads in a very first test to an improvement in the lepton channel in the standard analysis of $\sim 20\%$ [161]. Furthermore, the fit probabilities of the fit for ZHH or ZZH processes could give additional discriminative power between signal and background for the neural net of the standard analysis.

Another aspect is that the kinematic fit as it is performed in the lepton channel can also be applied in the two other channels, where the Z boson decays either as $Z \rightarrow \nu\bar{\nu}$ or $Z \rightarrow q\bar{q}$. The only difference are the decay products of the Z -boson, which will have an impact on the constraints of the kinematic fit. Both channels have in common that the invariant masses of the dijets should fulfill an equal mass constraint $M_{j_1j_2} = M_{j_3j_4}$ or alternatively correspond to $M_H = 125\text{ GeV}$. The difference of the channels are named in the following:

Neutrino Channel of ZHH: In case of the neutrino channel the Z -boson decays into two neutrinos. This will have a large impact on the constraints for the kinematic fit, because the neutrinos are unmeasurable objects in the detector, the measured energy and momentum are not conserved. The constraints for the kinematic fit are:

- The missing energy and momentum should fit to the invariant mass of the Z -boson, $M_{missing} = M_Z$.

Quark Channel of ZHH: In case of the quark channel the Z -boson decays into a $q\bar{q}$ -pair, therefore the constraints for the kinematic fit are:

- The energy sum of all 6 jets are equal to the center of mass energy, $\sum E_j = \sqrt{s}$.
- The momentum sum of all jets is conserved, $\sum \vec{p} = 0$.
- Soft mass constraint for the 2 remaining jets with $M_{j_5 j_6} = M_Z$, which corresponds to the Z boson with a natural width of 2.495 GeV, since these jets are reconstructed in the tracking system.

One main difference of both channels is in case of the neutrino channel the missing energy due to the neutrinos, which leads to a non-conserved energy and momentum for the kinematic fit, while in case of the quark channel these quantities are conserved. Another aspect in case of the quark channel is the jet pairing, since 6 jets complicate the correct jet/boson assignment, while in the neutrino channel the topology is rather clear. These points are more a technical issue rather than a physical. The targeted statements for kinematic fits for the standard analysis could be demonstrated by the lepton channel, so the other channels were not subject of this analysis.

10 Conclusion

The International Linear Collider (ILC) offers the potential to address open questions to the Standard Model of particle physics. Of particular interest on the agenda of the ILC is to understand the nature of electroweak symmetry breaking. The measurement of the double Higgs production cross-section gives direct access to the Higgs self-coupling, which is needed to determine the shape of the Higgs potential. The measurement is very challenging, since an excellent reconstruction of the final states is needed, which can end up in 6. To reach the needed precision for this and other measurements, new detector technologies, e.g. a particle flow calorimeter and highly sophisticated analysis tools are needed.

The particle flow concept reconstruct each particle by the detector component which gives the best resolution for the particle. In order to distinguish between individual calorimeter clusters, the particle flow concept requires a highly segmented calorimeter system, which results in an unprecedented amount of readout channels. The number of readout channels makes an auto-triggering system for each channel necessary. Also an approach for the gain equalisation in order to guarantee a uniform response of the detector is needed. In addition, the detector requires an avoidance of an extra cooling system due the need of a minimum of unmonitored material in the detector. The resulting stringent constraint on the power consumption can be reached with a detector operated in a power pulsed mode exploiting the beam structure of the ILC.

In this thesis it could be shown that it is possible to meet most of the needed requirements. On the basis of an engineering prototype, the successful operation of the detector technology could be demonstrated in a test beam campaign at CERN in 2012.

For calibration issues, a study of the gain equalisation with a channel-wise adjustment of the threshold showed that the dynamic range of the electronics covers a range of 0.1 MIP, but a calibration of the detector with this approach was not sufficient due to a shifting of the global threshold of one chip when the channel-wise adjustment was activated. Nevertheless, the detector could be calibrated with a gain equalisation with the preamplifiers in each channel [120] and the channel-wise threshold adjustment could be used in the future to correct small channel-to-channel variations.

In order to construct a detector optimized for power consumption, the power pulsing mode has been studied. The study showed that the general operation of such a detector is possible, but in the current setup the total power consumption is ~ 30 times too high.

Additionally, the activation time which is needed to ensure an optimal performance of the electronics is found to be larger than expected with ~ 1 ms at the moment. Additional concepts like the development of a Power On Digital module look promising but it still need further development, even if it improves the power consumption by a factor of 3.5. Furthermore, the stability of the detector running in beam tests has to be monitored. Here, the pedestal of the detector has been studied. A method to determine the pedestal could be established and the study showed that the pedestal of the detector was stable during the test beam. The pedestal only varies about ± 5 ADC units which is negligible since the measurement of the energy is not sensitive to so small fluctuations of the pedestal. The stability of the pedestal is important for a detector in order to ensure a consistent quality of the measurements.

On the other hand, not only the detector performance with an outstanding jet energy resolution is relevant for the measurements at ILC. In general, the effects of fragmentation, hadronisation and the correct jet finding influence the measurements. Kinematic fitting is one analysis tool which can improve the measurements of hadronic jets at ILC. For example, kinematic fitting was important for the measurements of the W boson at LEP. At ILC the detector technology is much better, but the detector environment has to handle a huge impact of ISR and beamstrahlung photons. Therefore, this thesis discusses the impact of kinematic fitting at ILC in context of the lepton channel of the Higgs self-coupling measurement. Herein, an improvement of the mass resolution in terms of the uncertainty of the cross section by up to 18% could be gained and the assignment of quarks to jets could be improved by 13% with a modified fit processor. Though, an improvement of the separation of signal and background in the mass spectrum couldn't be gained with kinematic fitting, but testing the background with corresponding fit hypotheses looks promising in order to improve the separation in the future.

In summary, the current analysis of the Higgs self-coupling has the potential to reach an improvement by up to 20% when kinematic fitting is applied in all channels, even with the rather simple approach employed here as a first test. Exploiting the full potential of the particle flow concept for the error estimation based on the neutral hadron fraction in each individual jets could lead to further improvements.

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Erklärung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Benjamin Hermberg

Hamburg, den 6. Juli 2015