

École polytechnique
Laboratoire Leprince-Ringuet

THÈSE

Pour l'obtention du titre de
DOCTEUR DE L'ÉCOLE POLYTECHNIQUE
SPECIALITÉ PHYSIQUE

présentée

le 16 novembre 2009

par

Marcel Reinhard

*Violation de CP dans le secteur du Higgs avec un détecteur de
nouvelle génération à l'ILC*

*CP violation in the Higgs sector with a next-generation detector at
the ILC*

Soutenue devant la Commission d'examen composé de :

M. Henri	VIDEAU	Président du jury
M. Jean-Claude	BRIENT	Directeur de thèse
M. Hans-Christian	SCHULTZ-COULON	Rapporteur
M. Fabian	ZOMER	Rapporteur
M. Imad	LAKTINEH	Examineur
M. Wolf-Dieter	SCHLATTER	Examineur

École polytechnique
Laboratoire Leprince-Ringuet

THÈSE

Pour l'obtention du titre de
DOCTEUR DE L'ÉCOLE POLYTECHNIQUE
SPECIALITÉ PHYSIQUE

présentée

le 16 novembre 2009

par

Marcel Reinhard

*Violation de CP dans le secteur du Higgs avec un détecteur de
nouvelle génération à l'ILC*

*CP violation in the Higgs sector with a next-generation detector at
the ILC*

Soutenue devant la Commission d'examen composé de :

M. Henri	VIDEAU	Président du jury
M. Jean-Claude	BRIENT	Directeur de thèse
M. Hans-Christian	SCHULTZ-COULON	Rapporteur
M. Fabian	ZOMER	Rapporteur
M. Imad	LAKTINEH	Examineur
M. Wolf-Dieter	SCHLATTER	Examineur

Contents

1	Theory	3
1.1	The Standard Model of particle physics	4
1.2	Electroweak symmetry breaking and Higgs mechanism	7
1.3	CP violation in the Standard Model	8
1.4	The τ lepton	9
1.4.1	τ physics	9
1.4.2	Formalism for τ decays	11
1.5	CP violation in the neutral Higgs sector	14
2	The International Linear Collider	19
2.1	ILC physics program	20
2.2	ILC Reference Design	22
2.2.1	ILC subsystems	23
3	Designing ILC detectors	27
3.1	Requirements for an ILC detector	28
3.2	Particle Flow and its conclusions	28
3.3	The ILD detector concept	30
3.3.1	Tracking system	31
3.3.2	Calorimetric system	32
3.4	An illustration of the impact of different segmentation and materials in the calorimeters for particle flow	34
3.5	The ECAL for ILD and its implementation in the simulation	34
3.6	Software and Computing	38
4	Electromagnetic showers	39
4.1	A description of electromagnetic showers	40
4.2	Threshold	41
4.3	Electromagnetic showers in the ILD ECAL	42
4.4	Influence of the magnetic field on electromagnetic showers	43
4.5	Transverse shower profile	44

4.6	Measurement of the Molière radius	45
4.7	Longitudinal shower profile	48
4.8	The barrel-endcap overlap region	52
4.9	Conclusion for reconstruction algorithms for photon showers	55
5	GARLIC - GAMMA Reconstruction for a LInear Collider experiment	57
5.1	The GARLIC algorithm	58
5.2	General idea	58
5.2.1	Step-by-step description	59
5.3	Performance and efficiency	71
5.3.1	Single-particle events	71
5.3.1.1	Single γ efficiency	75
5.3.1.2	Rejection of fake clusters	77
5.3.2	Error on the impact position	79
5.3.3	Application on jets	79
6	The CALICE Si/W ECAL prototypes	83
6.1	Technical description	84
6.2	Beam Tests	88
6.3	Detector calibration	88
6.3.1	Effects with influence on the detector calibration	89
6.3.2	Procedure	89
6.3.3	Results CERN 2006	91
6.3.4	Results CERN 2007	93
6.3.5	Evaluation of the long-term stability	99
6.3.6	Conclusions on the hardware design	99
6.4	GARLIC's prototype version	99
6.4.1	Performance studies with the CALICE Si/W ECAL prototype	104
6.4.2	Event Selection	105
6.4.3	Linearity and energy resolution	107
6.5	EUDET prototype	113
7	Optimization studies	115
7.1	Software optimization	116
7.1.1	Energy resolution	116
7.1.1.1	Method	116
7.1.1.2	Naive estimation of the energy deposit in stack 1 and 2	117
7.1.1.3	Optimizing the weighting of stack 1 and 2	117
7.1.1.4	Difference in energy deposit in odd and even layers	119
7.1.1.5	Using the number of hits	120
7.1.1.6	Combining the two measurements	122

7.1.1.7	Impact on the energy resolution	125
7.2	Hardware optimization	126
7.2.1	ECAL cell size	126
7.2.2	Material budget in front of the ECAL	127
8	Measurement of CP violation via spin-correlations in $H \rightarrow \tau\tau$ decays	131
8.1	Event structure: production and decays	132
8.2	Event generation	134
8.3	Defining observables	134
8.3.1	Reconstructing the Higgs boson	135
8.3.2	Estimation of the τ direction	138
8.3.3	Identification of the τ decay	143
8.4	Event sample	149
8.4.1	Signal: $e^+e^- \rightarrow ZH \rightarrow \mu\mu\tau\tau$	149
8.4.2	Background from $e^+e^- \rightarrow ZZ \rightarrow \mu\mu\tau\tau$	149
8.4.3	Beam polarization	150
8.4.4	Background reduction	150
8.5	Inclusive τ decays	153
8.6	Results	157
8.6.1	Extension of the event sample	157
8.6.2	Distributions of $\Delta\varphi$	157
8.6.3	Extraction of the CP violating phase ψ	158
8.6.3.1	MC toy study	159
8.6.3.2	Full simulation events	161
	Conclusion	165
	Bibliography	168

Introduction

This thesis takes place in the frame of detector development for the future linear collider ILC (International Linear Collider). This machine shall collide electrons and positrons with a center-of-mass energy varying from the mass of the Z boson (90 GeV) to 1 TeV. Primary physics goals at the ILC contain detailed studies of the electroweak symmetry breaking and of the Higgs boson which is likely to be responsible for it. At the same time the high precision of indirect measurements at the ILC creates a discovery potential that outreaches the one of the direct measurements at the Large Hadron Collider (LHC).

One of the quantities that will have to be measured is the CP state of the Higgs particle. An observation of a CP state differing from the even one predicted by the Standard Model of particle physics would have big implications on its nature. It is improbable that this quantity can be extracted at the LHC. The present thesis tries to establish a measurement procedure for the Higgs CP state at the ILC. Higgs production is considered in the channel $e^+e^- \rightarrow ZH$ with the subsequent decay $H \rightarrow \tau^+\tau^-$. Transverse spin correlations of the τ 's allow then to extract the Higgs CP state. The theoretical foundations of this measurement are given in Chapter 1.

Chapter 2 places the analysis in the bigger picture of the ILC physics goals, together with a description of the accelerator and its subsystems.

The precision measurements intended place stringent requirements on the detector performance in order to extract the maximal information also out of final states with difficult signatures. In particular, the method of Particle Flow has been introduced to improve the jet energy resolution. The ILD detector model, one of the proposed detector designs for the ILC, and the model used in this analysis is optimized for the Particle Flow. ILD together with the Particle Flow Approach are described in Chapter 3. The principal challenge of Particle Flow, to separate different particles and to reconstruct them individually, is not only present in jet environments but also in τ physics. An analysis like the one presented here requires a good identification of the τ decay channel, especially for the distinction between the hadronic decays into π , ρ and a_1 . This gives a special importance to the electromagnetic calorimeter (ECAL). To separate photons between themselves or from nearby hadrons it has to be very compact with a high granularity. ILD's ECAL, a silicon-tungsten sampling calorimeter, is detailed in the same chapter.

To understand the concept behind the electromagnetic calorimeter it is necessary to study electromagnetic showers. Chapter 4 deals with the properties of electromagnetic showers and

how they are detected in the ILD ECAL.

Specialized algorithms are needed to reconstruct particle showers in the calorimeters and to identify their origin. Photon showers give a distinctive signature in the ILD ECAL. GARLIC, an algorithm for the clustering of electromagnetic showers and photon identification is described in Chapter 5.

Silicon-tungsten calorimeters have already been used in past experiments but one with such a big volume and as many channels as in ILD has never been realized. It will consist of about 2400 m^2 of silicon with over one hundred million channels. Special prototype work is hence needed to validate the concept. A prototype with nearly ten thousand channels has been constructed in the frame of the CALICE collaboration and been exposed to test beams over several years. Chapter 6 introduces this prototype as well as the procedure for its calibration and long-term characterization of the silicon diodes. GARLIC has then been applied to events from test beams of the prototype to extract its impact on the linearity and energy resolution of the detector from real data.

Although a basic design for the detector simulation is fixed, optimization studies are still very important for future progress. These optimizations can take place on the software or on the hardware side. The first part of Chapter 7 presents a method to improve the energy resolution of low-energy electromagnetic showers in an ILD-like ECAL. The second part treats of the impact of the ECAL cell size as well as the material budget in front of the ECAL on the Particle Flow performance.

With the right understanding of electromagnetic showers and the appropriate tools for photon ID at hand, Chapter 8 describes the method for the measurement of the Higgs CP state in a full simulation study. The technical advantages of the collider and the detector allowed to establish very efficient reconstruction techniques. With the extreme precision on the collision point and the high performance of the ILD detector in the measurement of charged and neutral particles, a new innovative method that allows the reconstruction of both τ 's independently as well as the restraining of the initial state radiation could be developed. The Higgs CP state is then extracted with a fit involving angular distributions of the τ decay products.

Chapter 1

Theory

Contents

1.1	The Standard Model of particle physics	4
1.2	Electroweak symmetry breaking and Higgs mechanism	7
1.3	CP violation in the Standard Model	8
1.4	The τ lepton	9
1.4.1	τ physics	9
1.4.2	Formalism for τ decays	11
1.5	CP violation in the neutral Higgs sector	14

This chapter contains the theoretical foundations necessary for the understanding of this thesis. First a brief description of the Standard Model of particle physics is given, along with a motivation for CP violation. Since we are investigating CP violation in the Higgs sector a brief repetition of the properties of a Higgs particle will follow. Then the consequences of allowing CP violation in the Higgs coupling are shown.

1.1 The Standard Model of particle physics

The Standard Model (SM) of particle physics is the theory describing the elementary particles of our universe and the interactions between them. This theory says that matter is composed out of two types of fundamental particles. These particles are of spin $\frac{1}{2}$ and follow thus the Fermi-Dirac statistics ($\rightarrow$ fermions). The two types are leptons and quarks. For each type exist 6 particles that can furthermore be classified in 3 generations as doublets (of the weak isospin, see below) that are usually ordered by ascending mass. For each particle exists an anti-particle. For the leptons these doublets consist of a charged particle (electron, muon or tau) and its corresponding neutrino:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Particles in the second line are of charge -1, while the neutrinos are chargeless. In the usual description of the SM, the neutrino masses are 0. The doublets for the quarks look as follows:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

The u (up), c (charm) and t (top) quarks are of charge $\frac{2}{3}$, while the d (down), s (strange) and b (bottom) quarks are of charge $-\frac{1}{3}$. The quarks carry a color charge that is related to the strong interaction. They cannot exist freely, but have to form bound states so that the resulting state is "colorless". Since the existence of states with more than three quarks is generally not considered to be proved, there are two possible combinations: either a quark is bound with an anti-quark forming a meson (boson) or three (anti-)quarks are forming a (anti-)baryon (fermion). These two particle types are called hadrons. As mentioned above the particles of the first generation are the lightest ones. Except the neutrinos the particles of the 2nd and 3rd generations are unstable, thus giving the first generation the privilege to form all ordinary matter.

The interactions between all these particles are carried by particles with spin 1, called gauge bosons¹. The gauge bosons do also interact between themselves. Three interactions are included in the Standard Model:

¹Or maybe spin 2 for the gravitino, the gauge boson associated to gravitation

- The electromagnetic interaction affects all particles of non-zero electromagnetic charge. Its associated gauge boson is the photon (γ). The associated charge is the electric charge.
- The weak interaction affects all fundamental fermions. It has three associated gauge bosons, W^+ , W^- and Z . The associated charge is the weak charge.
- The strong interaction affects only the quarks and is carried by eight gluons (g). The associated charge is called "color". The fourth fundamental interaction, the gravitation could not be fully described with quantum field theory up to now. It is hence not included in the Standard Model.

The properties of the vector bosons are summarized in table 1.1.

The intermediate vector bosons					
Boson	Mass [GeV]	Electric charge	Weak charge	Strong charge	Ass. interaction
γ	0	0	0	0	electromagnetic
Z^0	91.1876 ± 0.0021	0	1	0	weak
$W^\pm$	80.398 ± 0.025	± 1	1	0	
g	0	0	0	1	strong

Table 1.1: The intermediate vector bosons of the Standard Model, see [1].

In gauge theories, the bosons are massless. To generate the masses for the gauge bosons and also for the quarks and leptons, another particle of spin 0, the Higgs particle is postulated. It has not yet been observed experimentally.

The Standard Model has been extended from models developed in the 1960's by Glashow, Weinberg and Salam (c.f. [2]). It is based on the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. $SU(3)_C$ is the group of color symmetry, whose dynamics are described with the help of Quantum Chromo Dynamics (QCD). It represents the strong interaction whose mediator boson is called gluon (g). $SU(2)_L$ is the group of the weak isospin symmetry and $U(1)_Y$ the one for the hyper-charge symmetry. The symmetry $SU(2)_L \otimes U(1)_Y$, also electroweak symmetry, combines the weak and the electromagnetic interaction. The associated gauge bosons are the Z^0 , $W^\pm$ and the photon (γ). Its dynamics is described with Quantum Electro Dynamics (QED). This symmetry is broken spontaneously by the Higgs mechanism ($SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$). With the organization of the quark fields (Q) and lepton fields (Ψ) into multiplets,

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \quad u_R, d_R \quad \text{and} \quad \Psi_L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}, \quad l_R,$$

where L and R indicate left and right chiralities, the electroweak part of the SM Lagrangian is

$$\mathcal{L}_{EW} = i \{ \bar{Q}_L \gamma_\mu \mathcal{D}^\mu Q_L + \bar{u}_R \gamma_\mu \mathcal{D}^\mu u_R + \bar{d}_R \gamma_\mu \mathcal{D}^\mu d_R + \bar{\Psi}_L \gamma_\mu \mathcal{D}^\mu \Psi_L + \bar{\nu}_R \gamma_\mu \mathcal{D}^\mu \nu_R + \bar{l}_R \gamma_\mu \mathcal{D}^\mu l_R \}$$

with the covariant derivative

$$\mathcal{D}^\mu = \partial^\mu + i\frac{g}{2}\tau_j W_j^\mu + 2ig'Y B^\mu.$$

τ_j are the Pauli matrices in the $SU(2)_L$ space, Y is the hyper-charge. g is the coupling constant associated with the gauge fields W_j ($j = 1, 2, 3$) that are related to the weak isospin symmetry group $SU(2)_L$ and g' is the coupling constant associated with the gauge field B that is related to the hypercharge symmetry group $U(1)_Y$. The charged vector bosons $W^\pm$ are combinations of the fields $W_{1,2}$:

$$W^{\mu\pm}(x) = \frac{W_1^\mu \mp iW_2^\mu}{\sqrt{2}}$$

Also, by introducing the weak mixing angle θ_W , one can define the fields associated to the Z boson (Z^μ) and the photon (A^μ) as combinations of W_3^μ and B^μ :

$$\begin{aligned} Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \end{aligned}$$

The couplings of the fermions to the gauge bosons have the form

$$\gamma_\mu(v - a\gamma_5).$$

In the standard model we obtain for v and a :

$$\begin{aligned} \text{couplings to } Z^0 : \quad v &= 1 - 4|q_f| \sin^2 \theta_W, \text{ where } q_f \text{ is the fermion charge} \\ a &= 1 \\ \text{couplings to } W^\pm : \quad v &= 1 \\ a &= 1 \end{aligned}$$

The couplings are visible in the part of the Lagrangian describing the interactions. It is divided in a part describing the charged current (CC) and one describing the neutral current (NC):

$$\begin{aligned} \mathcal{L}_{CC} &= \frac{g}{2\sqrt{2}} (J_\mu^+ W^{-,\mu} + J_\mu^- W^{+,\mu}) \\ \mathcal{L}_{NC} &= eJ_\mu^{em} A^\mu + \frac{g}{2\cos \theta_W} J_\mu^0 Z^{0\mu} \end{aligned}$$

where:

$$\begin{aligned} J_\mu^+ &= \bar{u}\gamma_\mu(1 - \gamma_5)d + \bar{c}\gamma_\mu(1 - \gamma_5)s + \bar{t}\gamma_\mu(1 - \gamma_5)b + \bar{\nu}_e\gamma_\mu(1 - \gamma_5)e + \bar{\nu}_\mu\gamma_\mu(1 - \gamma_5)\mu + \bar{\nu}_\tau\gamma_\mu(1 - \gamma_5)\tau \\ &\text{and } J^- \text{ its hermetian conjugate} \\ J_\mu^{em} &= \sum_f q_f \bar{f}\gamma_\mu f \\ J_\mu^0 &= \sum_f \bar{f}\gamma_\mu(v - a\gamma_5)f \end{aligned}$$

and f runs over all fermion flavors.

1.2 Electroweak symmetry breaking and Higgs mechanism

At this point, in contradiction to the experimental observations, the gauge bosons are massless. The boson and fermion masses are generated via the Higgs mechanism and the spontaneous breaking of the electroweak symmetry. The Higgs field is introduced as an isospin doublet of complex scalar fields:

$$\Phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} \quad \tilde{\Phi} = i \cdot \tau_2 \cdot \Phi = \begin{pmatrix} \phi_0^* \\ \phi_- \end{pmatrix}.$$

The Lagrangian depending on the Higgs field is then

$$\mathcal{L}_H = \mathcal{D}^\mu \Phi^\dagger \mathcal{D}_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

and $\mathcal{D}^\mu$ is the covariant derivative from Equation 1.1. With $\lambda > 0$ and $\mu^2 < 0$ in the Higgs field potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

one can see that $V(\Phi)$ has a local maximum at $\Phi = 0$ and a global minimum at $\Phi = \sqrt{\frac{-\mu^2}{2\lambda}}$. This minimum, the vacuum expectation value is degenerate. By choosing a non-zero value for the Higgs potential in the vacuum state, the electroweak symmetry is broken spontaneously. A usual choice is to set $\phi_+ = 0$ and to make ϕ_0 real:

$$\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \text{ with } v = \sqrt{\frac{-\mu^2}{2\lambda}}.$$

In the kinematic part of $\mathcal{L}_H$ (i.e. $\mathcal{D}^\mu \Phi^\dagger \mathcal{D}_\mu \Phi$) quadratic terms in the fields W^μ and B^μ arise. These are mass terms for the $W^\pm$ and Z^0 bosons. They take the values

$$M_W = \frac{v g}{2} \quad \text{and} \quad M_Z = \frac{v g}{2 \cos \theta_W}.$$

To obtain the masses for quarks and leptons, we write the Lagrangian for the Yukawa interaction with the Higgs field:

$$\mathcal{L}_{YU} = Y_{ij}^d \bar{Q}_{L_i} \Phi d_{R_j} + Y_{ij}^u \bar{Q}_{L_i} \tilde{\Phi} u_{R_j} + Y_{ij}^l \bar{L}_{L_i} \Phi l_{R_j} + h.c. ,$$

where i and j run over all generations. If we concentrate on the part for the quarks only, we can introduce the quark mass matrix

$$M_{ij}^{u,d} = \frac{Y_{ij}^{u,d} \cdot v}{\sqrt{2}} \tag{1.1}$$

and the respective part of the Lagrangian becomes

$$\mathcal{L}_M = M_{ij}^d \bar{d}_{L_j}^{int.} d_{R_j}^{int.} + M_{ij}^u \bar{u}_j^{int.} u_{R_j}^{int.} + h.c. ,$$

with i and j again running over all generations.

The mass of the Higgs boson The Higgs boson obtains its mass via self-coupling. It has not been experimentally observed but the search for it is still ongoing and there are already strong constraints for its mass. The combined results on the direct searches for the Higgs boson at LEP conclude that the Standard Model Higgs boson must be heavier than 114.4 GeV at 95% confidence level (C.L.) [4] and hints for the direct observation of the Higgs signal around 116 GeV have been reported. Precision measurements of the electroweak sector of the Standard Model allow to constrain the Higgs mass to be smaller than 163 GeV at 95% C.L. Additionally the experiments CDF and D0 at the Tevatron exclude a Higgs mass between 160 GeV and 170 GeV at 95% C.L. [5]. So experimental data point to a light Standard Model Higgs boson. A usual input value for simulations involving the Higgs boson is thus 120 GeV.

1.3 CP violation in the Standard Model

The operators C, P and T play a very big role in particle physics. The charge conjugation operator C changes a particle in its anti-particle, the parity operator P changes any spacial vector $\vec{r}$ to $-\vec{r}$. and the time reversal operator T reverses the time axis. The combination of these three operators CPT is an exact symmetry as described with Quantum Field Theory and thus the SM. A violation of any of the symmetries has so far only been observed to be induced by the weak interaction. CP violation has first been seen in the neutral kaon system and has as well been observed in the sector of the B meson. To account for CP violation in the Standard Model, one has to resume the investigation of the matrix M from Equation 1.1. In the basis of the weak interaction eigenstates in which we have been working so far, this matrix is not diagonal. The quark mass eigenstates are different from those for the weak interaction. If M is real, CP will be conserved. Any complex term in M would become its complex conjugate under the application of CP and the symmetry would be violated. To pass to the basis formed by the quark mass eigenstates, one has to diagonalize the matrix M . This is done with multiplication of two more matrices that are unitary:

$$\mathcal{M}^f = V_L^f M^f V_R^f \quad , \quad f = u, d.$$

If we now rewrite the electroweak charged current in terms of the mass eigenstates (labelled with m), we get

$$\mathcal{L}_{CC} = i \frac{g}{2} \bar{u}_{L_i}^m \gamma^\mu (V_{L_{ik}}^u V_{L_{kj}}^{d\dagger}) d_{L_j}^m \tau_a W_\mu^a.$$

The so-called CKM matrix (Cabibbo, Kobayashi and Maskawa) [3] $V_{CKM} = V_{L_{ik}}^u V_{L_{kj}}^{d\dagger}$ relates the quark eigenstates of the weak interaction with their mass eigenstates:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d^m \\ s^m \\ b^m \end{pmatrix}$$

A possible parametrization for this matrix is using three real Euler angles and six complex phases. It is possible to redefine the phase of the quark fields in the basis of the quark mass eigenstates such that the mass eigenstate matrix remains unchanged but at the same time, five of the above mentioned phases disappear from the CKM matrix. The one leftover phase is the source for CP violation in the Standard Model. No other source of CP violation has been found by any experiment up til now.

1.4 The τ lepton

The τ lepton was discovered in 1975 at SLAC [6]. As far as measurements show today, it is just continuing the electron-muon universality chain, only with a higher mass. But just because of its relatively high mass it can decay into hadrons. This allows to make better use of polarity and spin measurements that are measurable with a lot better precision than in the case of leptonic decays. This makes the τ useful as a probe for Quantum Chromo Dynamics (QCD) and many electroweak phenomena. After the end of the data taking of the LEP [7] experiments and CLEO [8], analyzes on τ physics are still ongoing at the B factory experiments, BaBar and Belle. In parallel, the experiment KEDR is improving its measurements and BESIII has started data taking. In the future, besides the LHC with some limited prospects, a proposed super B factory ([9],[10]), a tau-charm factory [11] or the ILC could play a major role in tau physics.

1.4.1 τ physics

Beautiful overviews over tau physics can be found in [12], [13] and especially [14]. Here we shall give only a short summary: One foundation of the Standard Model is lepton universality, i.e. that the electroweak couplings of all three leptons g_e , g_μ and g_τ are the same. Tests for lepton universality involving the τ require measurements of its mass, its lifetime and of the leptonic branching fractions. The semi-hadronic decays of the τ allows a measurement of the strong coupling constant at the scale m_τ . Decays including strangeness enable measurements of the mass of the strange quark and the CKM matrix element V_{us} .

τ mass The world average for the τ mass is [15]

$$m_\tau = 1776.84 \pm 0.17 \text{ MeV.} \quad (1.2)$$

The most precise measurements for the tau mass come from threshold scans in e^+e^- collisions, in particular from KEDR [16] and BESII [17]. The ARGUS collaboration has introduced the mass measurement via the pseudomass endpoint method [18], based on kinematic limits, that was also recently performed by the Belle [19] and BaBar [20] collaborations to obtain preliminary results. Even more precise measurements are expected from BESIII.

τ lifetime The to-date average for the τ lifetime is

$$\tau_\tau = (290.6 \pm 1.0) \times 10^{-15} \text{ s}. \quad (1.3)$$

taking into account only measurements by the LEP experiments and CLEO (see [15] and references therein).

Leptonic branching fractions The best measurement for the leptonic branching ratios of the τ are still from the LEP experiments. The precision on both branching ratios ($\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \rightarrow e^- \bar{\nu}_\mu \nu_\tau$) is just under 0.3%.

Strong coupling constant α_s The hadronic width of the τ allows a measurement of α_s that is now limited by the theoretical uncertainties:

$$\alpha_s(m_\tau) = 0.344 \pm 0.005_{exp} \pm 0.007_{th}.$$

If this is extrapolated to the scale of the Z mass [21], one obtains

$$\alpha_s(m_\tau \rightarrow m_Z) = 0.1212 \pm 0.0011$$

which is in good agreement with the value obtained from hadronic decays of the Z :

$$\alpha_s(m_Z) = 0.1191 \pm 0.0027.$$

This comparison over such a big energy range is an impressive experimental test for the running of the QCD coupling constant, i.e. of asymptotic freedom.

CKM sector Measurements of $|V_{us}|$ usually use the ratio of the branching fraction from decays in single kaons to the one of decays in single pions. The systematic errors limit the measurements here [22]. To extract additionally a value for the mass of the strange quark, further work is needed on the branching fractions for strange decays. There is still a lot of expectation for results from BaBar and Belle.

Beyond the Standard Model Other searches including τ leptons with effects beyond the Standard Model are ongoing. An example is lepton flavor violation. To have evidence for this effect would though require data from a future experiment, since the not yet analyzed datasets of BaBar and Belle have not enough statistics to reach a 5σ level. Differences in the τ^+ and τ^- lifetimes would indicate violation of CPT . While experiments using the mass threshold have high precisions for the mass measurement, they cannot measure any mass difference. In the indirect measurements like for BaBar and Belle for example, many systematics cancel out between the two sides. Both experiments have reported upper limits on the mass difference with precisions of some 10^{-4} [23]. A preliminary report on the difference in lifetime is only available from BaBar [24]. Finally there is the possibility of violation of CP only, either from the known Standard Model effect in the neutral kaon system or - as we will see in Section 1.5 - in the Higgs sector.

1.4.2 Formalism for τ decays

The argumentation here follows closely references [47] and [58] since both use similar conventions. Let us consider the decay of a τ into the final state X :

$$\tau^- \rightarrow \nu_\tau + X \quad (1.4)$$

The associated spin-averaged decay matrix element then has the form

$$\overline{\mathcal{M}} = \frac{G}{\sqrt{2}} \bar{u}(N) \gamma^\mu (v + a\gamma_5) u(P) J_\mu, \quad (1.5)$$

where N denotes the 4-vector of the τ neutrino, P the 4-vector of the τ and J_μ the current responsible for the final state X :

$$J_\mu = \langle X | V_\mu - A_\mu | 0 \rangle. \quad (1.6)$$

Denoting s^μ the spin 4-vector of the τ , the differential partial width for such a decay is then

$$\frac{d\Gamma}{dLips} = \frac{1}{2m_\tau} |\mathcal{M}|^2 (\omega + H_\mu s^\mu) = \frac{1}{2m_\tau} G^2 \frac{v^2 + a^2}{2} (\omega + H_\mu s^\mu), \quad (1.7)$$

with

$$\begin{aligned} \omega &= P^\mu (\Pi_\mu - \gamma_{va} \Pi_\mu^5) \\ H_\mu &= \frac{1}{m_\tau} (m_\tau^2 \delta_\mu^\nu - P_\mu P^\nu) (\Pi_\nu^5 - \gamma_{va} \Pi_\nu) \\ \Pi_\mu &= 2 [(J^* \cdot N) J_\mu + (J \cdot N) J_\mu^* - (J^* \cdot J) N_\mu] \\ \Pi^{5\mu} &= \text{Im} \epsilon^{\mu\nu\rho\sigma} J_\nu^* J_\rho N_\sigma \\ \gamma_{va} &= -\frac{2va}{v^2 + a^2}, \text{ which yields 1 in the Standard Model} \end{aligned}$$

and where $Lips$ stands for the Lorentz invariant phase space. Here, the neutrinos are considered massless. A neutrino mass along with non Standard Model $V - A$ currents could be introduced with additional terms (c.f. [47]). To obtain the quantities for the decay of a τ^+ , all momenta in the final state current J_μ have to be read as those of the anti-particles. Also the terms proportional to γ_{va} reverse their signs and for final states with contributions from the vector as well as the axial-vector current at the same time, one has to reverse the relative sign of the two contributions. In the Standard model case, it can be shown (see [58]), that

$$H_\mu H^\mu = -\omega^2 \quad (1.8)$$

Now we can define the polarimeter vector as

$$h_\mu \equiv H_\mu / \omega. \quad (1.9)$$

It is unitary ($h_\mu h^\mu = -1$). In the τ rest frame, we choose to set the time components of s_μ and h_μ to zero:

$$\begin{aligned} s_0 &= 0 \\ h_0 &= 0. \end{aligned}$$

The differential partial width from Equation 1.7 writes then as:

$$\frac{d\Gamma}{dLips} = \frac{1}{2m_\tau} G^2 \frac{v^2 + a^2}{2} \omega \left(1 + \vec{h} \cdot \vec{s} \right). \quad (1.10)$$

where the first term

$$\frac{1}{2m_\tau} G^2 \frac{v^2 + a^2}{2} \omega$$

represents the differential partial width for a non-polarized state. Polarization makes intervene the modification term $\left(1 + \vec{h} \cdot \vec{s} \right)$. Let us denote the angle between the τ direction and the polarimeter vector as φ :

$$\varphi = \angle(\hat{\tau}, \vec{h}). \quad (1.11)$$

The distribution of the vector $\vec{h}$ can then be written as

$$W(\cos \varphi) = \frac{1}{2}(1 + P_\tau \cos \varphi), \quad (1.12)$$

where $P_\tau \in [0, 1]$ is the τ polarization. The distribution of $\cos \varphi$ is thus isotropic in case of no polarization ($P_\tau = 0$) and linear otherwise. By measuring the φ distribution one can thus conclude on the polarization of the decayed τ lepton.

Now let us have a look what is the actual relation between the polarimeter vector and measurable quantities. We will distinguish here leptonic and semi-leptonic decays:

Leptonic τ decays For leptonic decays of the form

$$\tau^- \rightarrow \nu_\tau l^- \bar{\nu}_l, \text{ with } l = e, \mu \quad (1.13)$$

J_μ reads:

$$J_\mu = \bar{u}(q_l) \gamma_\mu (1 - \gamma_5) u(q_\nu), \quad (1.14)$$

where q_l is the 4-vector of the lepton and q_ν the 4-vector of its associated neutrino. In contrary to the more general current used for the τ in Equation 1.5, only the pure $V - A$ current predicted by the Standard Model is given here for the light leptons. As shown in [47], one finds:

$$H^\mu = (v + a)^2 m_\tau q_l^\mu (N \cdot q_\nu) - (v - a)^2 m_\tau q_\nu^\mu (N \cdot q_l) + (v^2 + a^2) m_{\nu_\tau} q_l^\mu (P \cdot q_\nu) - (v^2 - a^2) m_{\nu_\tau} q_\nu^\mu (P \cdot q_l) \quad (1.15)$$

If we limit ourselves to the Standard Model case also for the τ , i.e. $v = -a = 1$ and $m_{\nu_\tau} = 0$, this simplifies to:

$$H^\mu = -4m_\tau q_\nu^\mu (N \cdot q_l). \quad (1.16)$$

This means that $\vec{h}$ lies along the flight direction of the neutrino associated to the light lepton. Since one cannot reconstruct this direction, the polarization measurement cannot be performed with the full sensitivity of the polarimeter. One has to use other variables sensitive to the polarization, e.g. the energy of the light lepton.

Hadronic τ decays In hadronic τ decays, only one neutrino is involved. Its direction can thus be reconstructed by measuring all other decay products. We will limit us here to the two decay channels that are used in this thesis:

Decay into one pion

$$\tau^- \rightarrow \nu_\tau \pi^- \quad (1.17)$$

With the hadronic current being proportional to the 4-vector of the pion (Q_μ),

$$J_\mu = f_1 Q_\mu, \quad (1.18)$$

an explicit calculation (c.f. [47]) yields:

$$\begin{aligned} \vec{h} &= -2\gamma_{va} f_1^2 m_\tau^2 \vec{Q} / \omega. \\ &= -\hat{n}_\pi \end{aligned}$$

The polarimeter vector is thus antiparallel to the pion direction.

Decay into two pions

The decay into two pions is dominated by ρ production:

$$\tau^- \rightarrow \nu_\tau \rho^- \rightarrow \nu_\tau \pi^- \pi^0 \quad (1.19)$$

By denoting $q = q_{\pi^-} - q_{\pi^0}$ the difference of the 4-momenta of the two pions, the hadronic current can be written as (see [47] for details)

$$J_\mu = f_2 q_\mu. \quad (1.20)$$

The polarization vector is then

$$\begin{aligned} \vec{h} &= -2\gamma_{va} m_\tau^2 |f_2|^2 \frac{2(q \cdot N) \vec{q} - q^2 \vec{N}}{\omega}. \\ &= \text{Norm} \left[2(q \cdot N) \vec{q} - q^2 \vec{N} \right]. \end{aligned}$$

The neutrino 4-vector N can be written as $N = P - q_\rho$, with q_ρ being the 4-vector of the ρ system.

We have seen that the polarimeter vector can be reconstructed for the hadronic decays in one or two pions and so the angle φ between the polarimeter vector and the τ direction can be measured. A measurement of the φ distribution will then allow conclusions on the τ polarization.

1.5 CP violation in the neutral Higgs sector

Once a Higgs boson has been discovered and its mass been measured, there are still some fundamental questions on the nature of the particle to be answered. A measurement of its CP state will allow to distinguish between predictions of various theoretical models. In the Standard Model, the Higgs boson is CP-even. A measurement of the SM Higgs CP value could thus be a stringent test of the theory itself. The Minimal Supersymmetric Model (MSSM) introduces two CP-even and one CP-odd neutral Higgs boson. Already one can see that the distinction between odd and even CP eigenstates is very important. But one can go even further and search the analog to the CP violation in the quark sector as described earlier. There are models that postulate Higgs mass eigenstates with mixed CP state. To accommodate this mixture in a theory, one needs at least two doublets. Examples for such models are the simplest non-supersymmetric two-Higgs-doublet model (2HDM) or the supersymmetric Higgs two-doublet plus singlet model.

Identifying the CP nature of a given particle can be imagined with many different methods. Given the possible photon collider option at the ILC (see 2.1), one could simply imagine to compare the production rates of the Higgs particle at various photon polarizations. More indirect methods suggest to use correlations between the Higgs's decay products. This is only possible if the spin or helicity distributions of the decay products can be reconstructed. For example, for Higgs decays in vector boson pairs, WW or ZZ , correlations in the energy or the decay planes of secondary decay fermions can be used. But one has to consider another important fact with big impact even on the present analysis: a CP-odd Higgs boson has zero tree-level couplings to WW and ZZ . For the above example, this means that the investigated Higgs would mostly decay directly into a fermion pair. A CP-mixed Higgs would be equally not observable: one would only observe CP-even correlations since the CP-even component would account for essentially all of the coupling strength.

This leaves one with the possibility to investigate directly $H \rightarrow f\bar{f}$ decays, where f is a fermion. Suitable are especially the $t\bar{t}$ channel (at sufficient values for m_H), the associated Higgs production $t\bar{t}H$ and $\tau^-\tau^+$ channels because their high masses lead to high branching ratios. The latter case is used in this thesis.

Let us recall some of the principle assumptions in this analysis:

To accommodate a mixed scalar-pseudoscalar case in our framework, let us consider the general Higgs boson Yukawa coupling to the τ lepton

$$g\bar{\tau}(a + ib\gamma_5)\tau H \quad (1.21)$$

The z -axis shall now be fixed to the τ^- line of flight. Following the conventions in [59], we will denote the projections of the spins of the τ 's in their respective rest frames along the z -axis for the τ^+ and opposite for the τ^- with $+$ or $-$. The coupling from equation 1.21 produces the $\tau^+\tau^-$ spin states

$$\frac{1}{\sqrt{2}} [|+ - \rangle + e^{i\xi} |- + \rangle] \quad (1.22)$$

Figure 1.1 shows the effect on the operators C,P and T on the $\tau^+\tau^-$ state. CP changes $|+-\rangle$ to $|-+\rangle$. The state of Equation 1.22 is thus a CP= +1 state for $\xi = 0$ and a CP= -1 state for $\xi = \pi$. The spin density matrix for the above state has the following non-zero components:

$$\begin{aligned} C_{xx} = C_{yy} &= \frac{a^2\beta^2 - b^2}{a^2\beta^2 + b^2} \\ C_{xy} = -C_{yx} &= \frac{2ab\beta}{a^2\beta^2 + b^2} \\ C_{zz} &= -1, \\ \text{with } \beta &= \sqrt{1 - 4\frac{m_\tau^2}{m_H^2}}. \end{aligned}$$

Let us introduce the scalar-pseudoscalar mixing angle ψ :

$$g\bar{\tau}(\cos\psi + i\sin\psi\gamma_5)\tau H \quad (1.23)$$

In this new notation the components of the spin density matrix are

$$\begin{aligned} C_{xx} = C_{yy} &= \frac{\cos^2\psi\beta^2 - \sin^2\psi}{\cos^2\psi\beta^2 + \sin^2\psi} \\ C_{xy} = -C_{yx} &= \frac{2\cos\psi\sin\psi\beta}{\cos^2\psi\beta^2 + \sin^2\psi}. \end{aligned}$$

Neglecting m_τ^2/m_H^2 , i.e. the limit $\beta \rightarrow 1$, they become

$$\begin{aligned} C_{xx} = C_{yy} &= \cos 2\psi \\ C_{xy} = -C_{yx} &= \sin 2\psi. \end{aligned}$$

They are equal to the components of a rotation matrix around the z -axis with the rotational angle -2ψ . Furthermore we can identify the phase $\xi = 2\psi$. We reproduce the pure scalar case for $\psi = 0$ because then $C_{xx} = +1$, $C_{yy} = +1$ and $C_{zz} = -1$. For the pure pseudoscalar case, $\psi = \pi/2$, so that $C_{xx} = -1$, $C_{yy} = -1$ and $C_{zz} = -1$. We have now seen that the information about the Higgs CP value has to be extracted from the correlations of the τ^+ and τ^- spins in the plane transverse to the $\tau^+\tau^-$ axis. Thereby we know already that these spin states are reflected by the polarimeter vector. The correlated decay distribution can be expressed in the following intuitive form (see [60]):

$$W \sim 1 - h_{\parallel}^{\tau^+} h_{\parallel}^{\tau^-} + h_{\perp}^{\tau^+} C(2\psi) h_{\perp}^{\tau^-} \quad (1.24)$$

where $h^{\tau^\pm}$ are the polarization vectors defined earlier and C can be seen as a rotational operator around the $\parallel$ -axis (i.e. the z -axis defined earlier). To obtain the complete correlated decay distribution, let us express the decay amplitudes of the different τ spin states with the help of

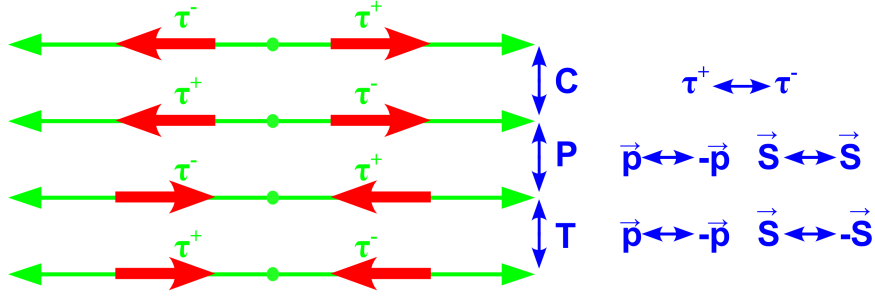


Figure 1.1: Behavior of the $\tau^+\tau^-$ state under C,P and T.

the angles $\theta^\pm$ and $\varphi^\pm$, where $\theta^\pm$ is the polar angle in the $\tau^\pm$ rest frame between the polarimeter vector h and the above defined z -axis and $\varphi^\pm$ is the respective polar angle:

$$\begin{aligned} \tau^- : \quad |+\rangle &\rightarrow \cos \frac{\theta^-}{2} e^{i\varphi^-/2} \\ &|-\rangle \rightarrow \sin \frac{\theta^-}{2} e^{-i\varphi^-/2} \\ \tau^+ : \quad |+\rangle &\rightarrow -\sin \frac{\theta^+}{2} e^{i\varphi^+/2} \\ &|-\rangle \rightarrow \cos \frac{\theta^+}{2} e^{-i\varphi^+/2} \end{aligned}$$

When introducing these in Equation 1.22 and with the substitution $\Delta\varphi = \varphi^+ - \varphi^-$, one obtains for the complete correlated decay distribution

$$W_3(\cos \theta^+, \cos \theta^-, \Delta\varphi) = \frac{1}{8\pi} [1 + \cos \theta^+ \cos \theta^- - \sin \theta^+ \sin \theta^- \cos(\Delta\varphi - 2\psi)] \quad (1.25)$$

One can simply integrate out the polar angles to obtain the distribution of the azimuthal angle:

$$W_1(\Delta\varphi) = \frac{1}{2\pi} \left[1 - \frac{\pi^2}{16} \cos(\Delta\varphi - 2\psi) \right] \quad (1.26)$$

Let us emphasize explicitly that since a Lorentz transformation will not change components perpendicular to the boost axis, $\Delta\varphi$ is the angle between the two planes spanned by the τ^- flight direction and the polarimeter vector of the respective τ . Measuring the decay distribution statistically in function of $\Delta\varphi$ will thus be a direct measurement of ψ (and the CP-violating phase ξ).

Prospects for the measurement at the LHC In [25] a method to detect CP violation in the Higgs sector with a measurement at the LHC involving subsequent τ decays in three charged

prongs is presented. This is possible because the $\tau^\pm$ reference frames can be reconstructed in this case. At the LHC, this is not possible decays with only one charged prong. Instead, in [26] a method is given that defines different observables where reconstruction of the $\tau^\pm$ rest frames are not necessary. Any one prong decay can be used with the method (including purely leptonic decays). Among with the momentum of the resulting charged tracks, the $\tau^+\tau^-$ production vertex needs to be measured with a good precision. The observables allow then to distinguish between either *CP*-even and *CP*-odd states and/or between a *CP*-violating and a *CP*-conserving Higgs sector. The measurement of the actual mixing value is not possible. It is estimated that for the discrimination several years of high-luminosity runs at the LHC would be necessary.

Chapter 2

The International Linear Collider

Contents

2.1	ILC physics program	20
2.2	ILC Reference Design	22
2.2.1	ILC subsystems	23

The International Linear Collider (ILC) is one of the proposed particle accelerators for the time after the start of the Large Hadron Collider (LHC). Although not all parameters are fixed yet, since they will strongly depend on early LHC results, a baseline proposal was released in 2007 ([27]). The ILC will collide electrons and positrons with an initial center-of-mass energy of 500 GeV, upgradable to 1 TeV. Both beams will have the capability to be polarized which is important for many measurements. Several options, namely running at the Z-pole as well as $\gamma\gamma$, $e\gamma$ and e^+e^- collisions are also considered.

2.1 ILC physics program

The upcoming start of the LHC will mark a new and hopefully fruitful period in experimental particle physics. The discovery potential of this machine is well known and undoubted. It shall be colliding two proton beams at $E_{beam} = 7$ TeV each and reaches thus energies that are unprecedented. If new particles, like Higgs or supersymmetric particles, exist in this range it is near certain that the two LHC multi-purpose experiments, ATLAS and CMS, will discover them. The same holds for indications about extra-dimensions. But what limits the LHC is the fact that it is a hadronic machine with a huge amount of background and unknown initial state. This makes it challenging for precision measurements that are mandatory to determine the intrinsic properties of the newly discovered particles. Knowledge about these is a necessity to distinguish between different theoretical models.

The advantage of the ILC is the fact that it produces clean events. The kinematics of the collisions is well known. Additionally via polarization of the beams, one has a statistical knowledge about the spin state of the incoming particles. The ILC is hence optimal for precision measurements.

This enables access to a very rich variety of physics, a large part of which can be extracted from indirect measurements involving quantum corrections. These are easily accessible in Z or WW production. Measurements of the top quark will surely play an important role alongside the numerous measurement possibilities for Higgs physics. SUSY particles or those from alternative scenarios will be accessible as well as new heavy gauge bosons.

The ILC should be able to run at the Z-pole (GigaZ). With the expected luminosities, statistics 100 times higher than at LEP will be collected easily. These events can on one hand be used to calibrate the detector and the machine. But with indirect measurements at this energy, for example of the top mass using M_Z , Γ_Z and M_W one has also a very important tool to cross-check the underlying theory and experimental results. The importance of the top mass in the radiative corrections allows then as well indirect measurements of the Higgs mass, another vital parameter to confirm the understanding of a theory. Measurements of the couplings to fermions via forward-backward asymmetries or dependencies of the cross section on the polarization will put strong constraints on physics beyond the standard model. All these precision measurements require a knowledge on the center-of-mass energy in the order of

a few MeV. This is also true for the measurement of the W mass at the WW threshold. Here, the dominating production is via the t channel. Using beam polarization could help to control the backgrounds. Also triple gauge boson couplings that appear in the s channel production allow to establish constraints on new physics. The different couplings will be separated using the angular distribution of the W and from W polarization studies. If beam polarization is available at very high levels one can even distinguish $WW\gamma$ and WWZ for coupling measurements.

The top mass is a very important input parameter for many indirect measurements. To really make use of these, its current measurement error of about 4 GeV needs to be reduced considerably. Being the heaviest elementary particle discovered so far the top quark has a unique position with respect to the Higgs particle. With a scan of the $t\bar{t}$ excitation threshold, its mass could be measured to better than 100 MeV and its width to a few percent. This makes a big improvement on the input parameters for indirect measurements. Also the axial and vector parts of the $t\bar{t}Z$ coupling can be measured separately.

A Higgs particle is expected to be found at the LHC but many of its quantities will not be measurable. The ILC physics program will hence contain a large amount of precision measurements of Higgs physics. Its mass is best extracted from recoil mass measurements in the Higgsstrahlung production ZH with $Z \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}$. Its parity and spin can then be extracted with a threshold scan, the spin alone also with the angular distribution of the production via Higgsstrahlung. This is also possible from correlations in $ZH \rightarrow 4f$ or $H \rightarrow WW^*, ZZ^* \rightarrow 4f$ processes. Spin correlations in fermion pair final states ($H \rightarrow \tau^+\tau^-, t\bar{t}$), are used to determine its CP value and spin. Branching ratio measurements will give information about individual Yukawa coupling strengths and about the correctness of the principle that the couplings are proportional to the masses. The Higgs self-coupling is principally accessible through ZHH and $\nu\nu HH$. The $\gamma\gamma$ option for the ILC is particularly interesting for Higgs measurements. More than 20.000 $\gamma\gamma \rightarrow H$ events per year can be expected for a Higgs at 120 GeV and because a single Higgs particle is produced, a higher mass range can be explored.

These considerations need of course to be modified with the scenario on hand, confirmed either at LHC or ILC. If no Higgs particle is found at the LHC, a popular assumption is that the Z and W bosons could get strongly coupling at high energies. This would be visible in measurements of WW scattering at high center-of-mass energies, either with a resonance (ρ) or with the change in the cross section with the energy. This is a good example for the importance of the jet energy resolution of the detector for ZZ and WW separation. But if the Higgs particle decays such that it is invisible at the LHC, it could still be detected at the ILC with a recoil mass measurement in the Higgsstrahlung process. The most interesting case that neither a Higgs particle nor any other new particles are discovered at the LHC would have strong consequences for the ILC. Probably you could stop reading this thesis here since the realization of the project would be not very likely. The only hope in this scenario could be the return to the Z-pole.

In several supersymmetric scenarios the sleptons are light enough to be produced at the ILC. They can be directly observed in the energy spectrum of the final state leptons from the

decay cascades or by the production cross sections at threshold. For the stop/sbottom squark this could be also possible with the upgrade to 1 TeV. For the rest of the superpartners, the ILC will only contribute indirectly to reduce the error on their masses measured at the LHC. Additional Higgs bosons can be seen indirectly by the modification they induce to the ZZH coupling. The option to select the beam polarities plays an important role in these studies because it helps to reduce backgrounds and allows to probe differences between several SUSY scenarios. Again the cleanliness of events at the ILC holds the advantage over the LHC.

Several theoretical models ("Little Higgs", higgsless models) predict also the existence of a new heavy gauge boson (Z'). Already in the GigaZ mode, the indirect measurements at the ILC will be sensitive to a Z' way beyond its direct production range and the direct searches at LHC (heavier than 10 TeV in some scenarios). The upgrade to 1 TeV center-of-mass will give additional sensitivity. Thanks to the good measurements of the beam polarization and luminosity, discrimination between different models is possible for a Z' mass up to 7 TeV.

Next to the baseline design, several options for upgrades are included in the studies. The $\gamma\gamma$ collider option can not only be used to produce a high number of Higgs particles at threshold but also for the production of spin 2 states. e^-e^- collisions allow for a high precision measurement of the selectron mass. Also some uncommon measurements would be accessible, like the production of doubly charged Higgs bosons or lepton flavor/number violating modes.

2.2 ILC Reference Design

The description given here is based on the ILC Reference Design Report released in 2007. With the large amount of R&D work ongoing, many of the subsystem designs and parameters are still changing frequently. Firmer choices are expected with the ILC Technical Design Report in 2012.

The ILC physics goals can be achieved with a maximum center-of-mass energy of 500 GeV and a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The layout of the machine is mainly cost driven. A sketch of the ILC site for the baseline design and the involved sub-systems is shown in Figure 2.1. Electrons and positrons are created and pre-accelerated in the respective sources. Damping Rings ("DR") are used to reduce the beam emittance. Then the beams are transported in the Ring To Main Linac ("RTML"), where they are accelerated to the desired center-of-mass energy. Final focus to the interaction point ("CL") is done in the Beam Delivery System ("BDS"). The total site length is ~ 31 km. Some nominal values for important parameters of the ILC baseline are summarized in Table 2.1.

Next to the default parameters, other sets are being considered, since some of the design goals of the sub-systems may not be achieved due to cost or technical limitations. Options like Low-P (low power), Low-N (smaller number of particles per bunch) and Large-Y (increased emittance in the vertical plane) are studied to allow for flexibility in case of necessary divergence from the baseline design.

Also, several options are being planned, like e^-e^- , γe^- or $\gamma\gamma$ collisions.

E_{CM}	91, 200 – 500 GeV
Peak luminosity	$2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Particles per bunch	2×10^{10}
Bunches per train	2625
Bunch spacing	369 ns
Repetition Rate	5 Hz
RMS bunch length	300 μm
RMS beam size horizontal (at IP)	640 nm
RMS beam size vertical (at IP)	5.7 nm
RMS energy loss due to beamstrahlung	2.4%
N beamstrahlung photons per event	1.77

Table 2.1: Nominal values for some of the ILC baseline parameters.

2.2.1 ILC subsystems

Electron Source Electrons are produced with a laser hitting a photocathode in a DC gun. The pulse length is roughly 1 ms. Producing electrons over such a long time, puts very challenging requirements on the laser system. The electrons are captured, bunched and pre-accelerated with normal conducting structures. A superconducting linac accelerates them to 5 GeV. Then the spin vector is rotated to the vertical to be aligned with the B field in the damping ring, in which the beam is injected after energy compression.

Positron Source Being accelerated to 150 GeV, the electron beam is extracted to a parallel beam line, used for positron creation and then returned to the electron main linac. In this parallel beam line the electrons pass through a helical undulator with a length of 150 m. This produces a monochromatic and polarized photon beam ($\sim 10 \text{ MeV}$). Part of this polarization is conserved when the photons hit a rotating Ti-alloy target to produce electron and positron pairs. The beam is then captured, focused and pre-accelerated in a normal-conducting device. After separation and dumping of the electrons and photons, the positrons enter another phase of acceleration (to 400 MeV) with focussing. Then they are transported further downstream entering a superconducting linac that accelerates them to 5 GeV. Before injection into the damping rings the spin vector is rotated to the vertical and energy compression is performed. The polarization of the beam is about 30% and is foreseen to be upgraded to 60% later.

An alternative approach uses compton scattering of a laser beam on an electron beam from a storage ring or a linac. The laser beam is stored in optical cavities that provide several interaction points. The scattered photons are polarized. This polarization is kept with a high purity during their conversion on a fixed target. The resulting positrons are stacked in the damping ring. The independence of the system avoids the disturbance of the main electron beam due to the pass through the undulator. The cavities and the laser system are still in the

focus of R&D work.

Damping Rings In order to achieve the design luminosity, the beam emittance has to be lowered by five orders of magnitude. This is achieved in two separate damping rings, the one for positron and the other one for electrons with a circumference of ~ 6.7 km. They are housed in a single tunnel around the central region of the ILC. The damping has to be done within the time spacing of two machine pulses (200 ms). A low operation energy of 5 GeV has been chosen. The frequency for the integrated superconducting RF system is half the frequency used in the main linac to be able to easily handle different bunch patterns.

Ring To Main Linac (RTML) Following extraction from the damping rings the beam enters the Ring To the Main Linac. After collimation of the beam halo generated in the damping ring, the particles have to be transported for ~ 15 km upstream, at an energy of 5 GeV, until they arrive at a 180° turnaround. Next, the spin vector of the beam particles that had been oriented vertically in the sources, is rotated in any direction desired at the IP. A two-stage bunch compressor system will reduce the bunch length from 9 mm by a factor of 30 to achieve the baseline length at the IP, while accelerating to ~ 15 GeV to reduce fractional energy losses.

Main Linac The compressed bunch is ready to enter the Main Linac. During a distance of about 11 km the beam particles will be accelerated to 250 GeV. The underlying technology is based on supra-conducting 1.3 GHz RF units.

Although in a warm technology approach higher frequencies can be achieved, the cold supra-conducting technology has been favored in the technology choice. A long wavelength allows long machine pulses. This has an immediate advantage for the final focalization at the IP. While the QD_0 is expected to be stable against vibrations to 50 nm, the transverse beam size of 5 nm requires an approach using fast feedback. The first few bunches in every train (2625 are foreseen per pulse) can be used to obtain focalization parameters that are valid for all the remaining bunches. This is not possible in the short trains with warm technologies. The trade-off for the cold technology is the energy loss in the cavities. Their operation at 2 K makes the extraction of these losses very cost intensive. Therefore stationary waves are used despite their lower efficiencies with respect to the propagating ones usually used with warm technologies. At the same time the R&D for ILC will profit from a wide range of applications, not least from the pioneering XFEL [28] project.

The average accelerating gradient is 31.5 MV/m. Three cryomodules, containing 26 nine-cell cavities make up so called RF units. About 280 of those are needed for each of the main linacs. This makes some 17.000 cells in total. High resolution beam pair monitors will allow to have precise orbit control in order to preserve the small beam emittances over the acceleration. The upgrade to a center-of-mass energy of 1 TeV will need an extension of another 11 km on each side.

Beam Delivery System After exiting the main linacs the beam enters the Beam Delivery System. One of the first things needed is a measurement of the beam, its energy, polarization and emittance. Corrections are then applied on the way to the IP, including the removal of the beam halo to avoid large backgrounds in the detector. A fast extraction system can be used to protect the detector and the beam line in case of failure or miss-steered beams.

The interaction region is shared by two detectors in a so called "push-pull" configuration. The quadrupoles for final focus closest to the interaction point are integrated into the detector to facilitate the push-pull operation. The beam crossing angle is 14 mrad. This angle reduces the cross section for the interaction. To provide effective head-on collisions, Crab cavities will be used to turn the beams in the horizontal plane.

After the interaction and a second measurement of their properties to cross-check their stability, the beams are extracted and dumped.

Machine Detector Interface MDI plays a very important role on the way to achieve the physics goals at the ILC. Part of the beam delivery system will be integrated into the detector. The beam passes through a conical beam-pipe of minimal radius, as low as 15 mm at the IP. In the very forward region, sub-detector systems will record remnants of the interaction and monitor beam properties. These detectors will suffer big radiation doses.

The background produced in beam-beam interactions is a major issue. In particular the large number of electron-positron pairs or photons going to the very forward region created by beamstrahlung can induce problems due to the non-zero crossing angle, as well as minijets created in interactions of photons. Also muons or neutrons can be created in interactions of the beam halo with beam line components. To reduce this backgrounds, the charged particles have to be directed along the outgoing beam line. This is achieved by superposing the small field of an additional dipole (anti-DID - Detector Integrated Dipole) locally on the main field of the detector.

The default option will be the push-pull configuration, with two detectors sharing the luminosity at one single interaction point. The design of the detectors is hence also addressing the goal of a quick moving in and out of the interaction region. Nevertheless a beam delivery system for two detectors in parallel is still included in the investigations.

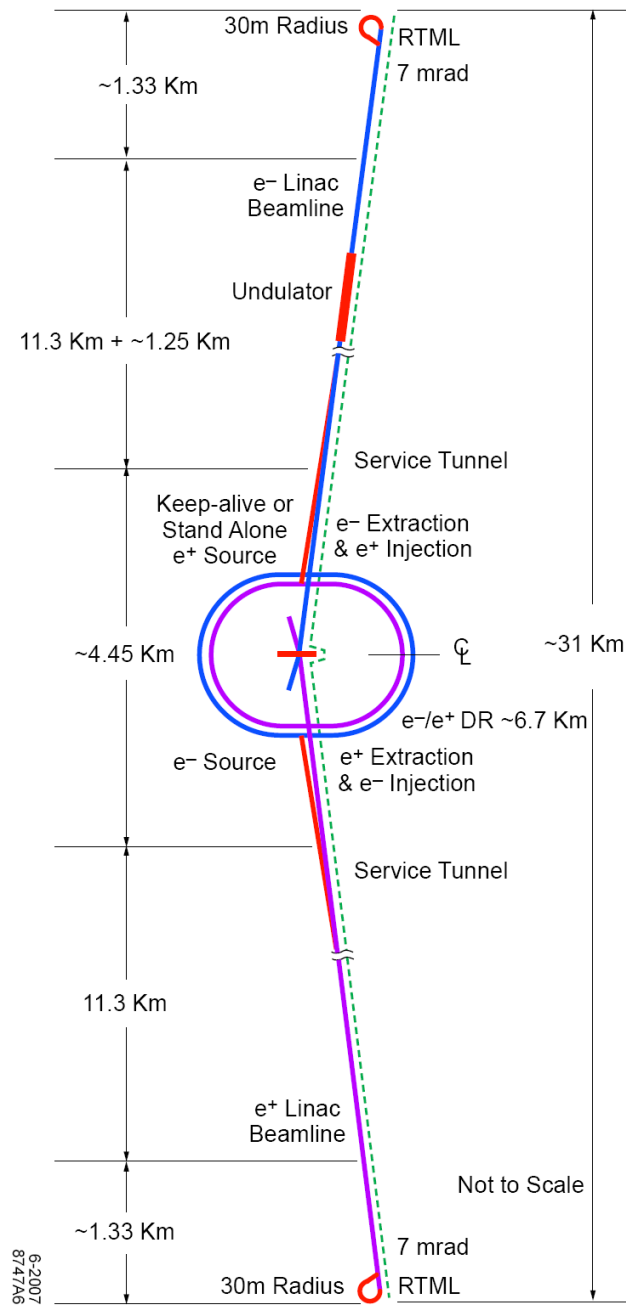


Figure 2.1: Schematic view of the site for the ILC baseline.

Chapter 3

Designing ILC detectors

Contents

3.1	Requirements for an ILC detector	28
3.2	Particle Flow and its conclusions	28
3.3	The ILD detector concept	30
3.3.1	Tracking system	31
3.3.2	Calorimetric system	32
3.4	An illustration of the impact of different segmentation and materials in the calorimeters for particle flow	34
3.5	The ECAL for ILD and its implementation in the simulation . . .	34
3.6	Software and Computing	38

Having seen the main physics goals and the resulting characteristics of the ILC baseline design, we review here the driving factors for ILC detector design. Four more or less independent detector concepts emerged from previous studies, LDC, GLD, SiD, 4th concept, where the LDC and GLD groups decided to work together on a common baseline concept, called "ILD" ¹. The studies in this thesis are based on the detector model ILD_00. Detailed information about each detector concept can found in the respective Letters of Intent:

- ILD [29]
- SiD [30]
- 4th concept [31]

3.1 Requirements for an ILC detector

There are basically two groups of typical final states at the ILC. The first one contains leptons with high momentum, notably electrons and muons that require excellent tracking and identification capabilities, supported by a strong magnetic field. Other typical final states consist of several hadronic jets (typically 2-6), frequently together with leptons with high momentum and/or missing energy. Moreover, inside these jets one can find leptons with low momentum. Identifying these leptons is crucial as indication of neutrinos in the jets which have to be corrected for in the analysis. Decays including τ leptons are to be classified somewhere in between these two cases since they can also decay in a semi-leptonic way.

The determination of the final state relies often on the identification and distinction of Z and W bosons decaying into two jets. Of course, one would wish that the resolution for these measurements is comparable to the natural decay width of the primary particle, i.e. 2-3 GeV. To accomplish this goal effectively a di-jet mass resolution of about 3% for jets of energies below 100 GeV has to be achieved. This translates to a jet energy resolution of $30\%\sqrt{E}$. A broadly accepted approach to reach these resolutions is the "particle flow" concept. We will see that this method will impose constraints on the detector that demand a very special design that has never been attempted before.

3.2 Particle Flow and its conclusions

The classical approach of basing jet measurements on the calorimetric system presents conceptual disadvantages. The measurement of hadronic showers is very difficult due to the uncertainties in the shower structure. Nevertheless, studies on approaches to use compensated calorimeters are still ongoing. Instead of hardware compensation, aiming for an equal response to the hadronic and electromagnetic showers, compensation can also be achieved via software,

¹ILD stands for International Large Detector, underlining its superior radius to the other detector concepts

i.e. the effective separation of measurements of the hadronic and electromagnetic part of the shower, either by separated readout or by recognition of the different contributions in the shower itself (imaging calorimetry). As mentioned above a strong magnetic field is mandatory at the ILC for the high momentum leptonic final states. This is another important disadvantage, since the curvature of particles at lower energies is so high that they will not attain the calorimeters, so that they will remain unmeasured.

To surpass these obstacles a new concept of measurement has been developed [32]. One can imagine that the best jet energy resolution would be achieved if it is possible to reconstruct every single particle in the jet separately and measure its energy with an appropriate resolution. In average, jets are composed of 65% charged particles, 26% photons and 9% neutral hadrons. This makes another advantage of particle flow is apparent: in contrary to a purely calorimetric approach, 65% of the jet particles can be measured with the tracking system that yields a lot better resolutions. So firstly one needs a very efficient tracking system with high hermiticity to measure the momentum of the charged components of the jet. Additionally in the calorimeters one then wants to measure the neutral contribution of the jet by separating the energy deposit from the charged particles from the one of the neutrals, i.e. of photons and neutral hadrons. The key point is then to avoid double counting the energy deposit of these charged particles in the calorimeters. This leads immediately to the needs of high transversal and longitudinal segmentation in the calorimeters to keep separation as good as possible while working with jets with high particle densities. Confusion appears especially when particle showers can not be separated from MIP tracks. For example, a rough figure of merit for the minimal distance where separation is possible between a photon shower and a nearby MIP track is $d_{min} = \sqrt{\frac{R_M^2 + z_{cell}^2}{4}}$, with R_M the Molière radius of the calorimeter and z_{cell} the size of its cells. The major factors on the particle flow capabilities are thus a small Molière radius and small cell sizes. For now, cell sizes of about $1 \times 1 \text{ cm}^2$ for the electromagnetic calorimeter, yielding a separation distance of 11 mm, and larger but still comparable cellsizes for the hadronic calorimeter are expected to fullfill the particle flow tasks. Smaller cell sizes, especially $5 \times 5 \text{ mm}^2$ for the ECAL would bring several additional advantages as the pattern recognition capabilities improve.

Ideally the jet energy resolution would then be the square sum of the individual resolutions for each particle class:

$$\sigma_{jet}^2 = \sigma_{charged}^2 + \sigma_{\gamma}^2 + \sigma_{neutral \text{ hadrons}}^2 \quad (3.1)$$

The charged particles are measured with very good precision. An estimation with typical resolutions of $15\%/\sqrt{E}$ for photons and $40\%/\sqrt{E}$ for neutral hadrons² yields a jet energy resolution of $14\%/\sqrt{E}$ which is far better than results obtained in an calorimetric approach so far. Due to the imperfection several other terms have to be introduced. The first one is a term that accounts for misidentification of a charged cluster as a neutral or vice versa, including shower overlay and debris from widely spread hadronic showers. The second one accounts for

²Energy resolutions of this order have already been achieved in test beams with physics prototypes of the CALICE collaboration, see [42] and [33].

losses due to the imperfect reconstruction efficiency, depending on energy and angle of incidence of the particle. For each particle species, there will be a certain threshold in energy under which the particle will escape detection and the relevant energy will be lost, especially important due to the fluctuations in the low energy part in the fragmentation process of the jet. The third term takes into account the effect of these thresholds:

$$\sigma_{jet}^2 = \sigma_{charged}^2 + \sigma_{\gamma}^2 + \sigma_{neutral\ hadrons}^2 + \sigma_{confusion}^2 + \sigma_{efficiency}^2 + \sigma_{threshold}^2 \quad (3.2)$$

To pass from the "ideal" 14% to the envisaged 30% resolution, the contribution of the three last terms should not exceed 26%.

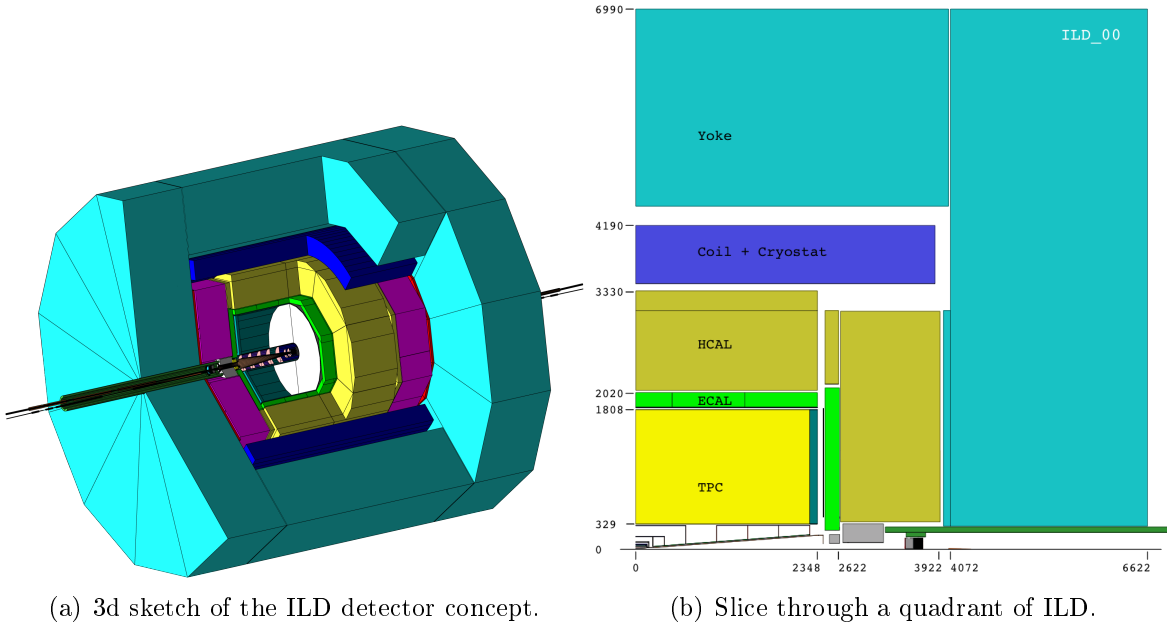


Figure 3.1: The ILD detector.

3.3 The ILD detector concept

Fig 3.1(a) shows a sketch of the ILD detector concept. Its tracking and calorimetric components are optimized for the particle flow approach. The key to fulfill the needs of PFA are a very efficient tracking that is very illustrative at the same time (big number of measurement points) followed by a hermetic calorimeter. Hermetic in this sense includes both, the coverage over the solid angle as well as in depth. For some subdetectors different designs exist. A brief description of the individual components with some arguments for the respective choice are given here. The focus is on ILD's reference simulation model for the Letter of Intent [29],

where additional information on the individual performances can be found. ILD takes the classical cylindrical shape of a multi-purpose detector in a high energy physics experiment with colliding beams. It is symmetric to the $x - y$ -plane at the interaction point. Furthermore it is divided in a barrel part and two endcaps. Fig 3.1(b) shows a slice through a quadrant of ILD including all of its subdetectors.

3.3.1 Tracking system

Vertex Detector - VTX The VTX consists of six layers of silicon pixels grouped in pairs. Optimal point resolution (as low as $2.8 \mu\text{m}$) while keeping a low material budget are the primary design goals. This needs to be combined with a first measurement point very close to the interaction point (i.e. 15 mm), which is imposed by the extreme radiation conditions as well as the strong pair background at this distance.

SIT - Silicon Internal Tracker The strong background imposes another constraint: even with a strong magnetic field, the core component of the tracking, the Time Projection Chamber, has to be kept at a distance of approximately 30 cm from the IP. To provide linking points between the VTX and the TPC, two layers of Si strips are installed in the barrel region. This will not only improve pattern recognition and the momentum resolution but give also time stamps for each bunch crossing.

Time Projection Chamber - TPC The apparent advantage of a TPC over a silicon based tracking system is the high number of spacepoints provided per track (up to 224 in ILD). This will play a major role in achieving the goal for a visual tracking. It will not only be possible to identify backscattering from the calorimeters, to see kinks in a track, V_0 reconstruction, as well as to recover pair production or hadronic interactions in the tracker region. Another advantage over silicon tracking is the lower material budget, a must for the best calorimeter performance. A focus for ongoing studies is thus the TPC endplate where the readout electronics and cables increase the material in front of the calorimeters. Additionally particle ID can be performed by measuring $\frac{dE}{dx}$. This holds for $K\pi$ separation to isolate Kaon modes as well as for $e\text{electron}\pi$ separation that is especially important at low energies where ID based on the calorimeter is not so good.

SET - Silicon External Tracker Another set of two layers of silicon strip detectors in the barrel region are providing additional high precision spacepoints. These will not only improve the precision on the momentum measurement but can also be used to align the TPC in interplay with the SIT. Furthermore a measurement point so close to the ECAL entry can be used as starting point for clustering algorithms.

FTD - Forward Tracking Discs A set of disks equipped with silicon-pixels or silicon-strips extends the tracking down to essentially the radius of the beam tube (see 3.3.1).

ETD - Endcap Tracking Detector Three layers of silicon strips situated after the TPC endcap assure additional high precision spacepoints for the endcap region. Like the SET in the barrel, the ETD links the TPC with the ECAL. Due to the presence of the TPC readout electronics and cables, this gains even more in importance as interaction of hadrons as well as pair production from photons are more probable and can thus be recovered.

Beamtube integration The part of the beamtube that is integrated in the detector volume will be a conical shape of machined beryllium. Its smallest radius will be 14 mm. This is still enough to contain the core of the machine-related background that is trapped by the magnetic field.

3.3.2 Calorimetric system

The particle flow approach requires excellent pattern recognition in the calorimeters to reconstruct individual particles. This is only possible with a very high granularity, with cell sizes inferior to the Molière Radius. The design of the calorimeters is driven by this goal and not by the optimization of single particle energy resolutions, although these needs still to be taken into consideration in order to achieve the desired jet energy resolutions (see 3.2). Both the electromagnetic as well as the hadronic calorimeters are planned as sampling calorimeters with highly segmented active layers.

ECAL The materials proposed for the ECAL are tungsten as absorber and silicon as active material. It has a high longitudinal (30 layers) as well as transversal segmentation ($5 \times 5 \text{ mm}^2$ cell size). Since the ECAL is a principal component of this thesis an entire section (3.5) has been dedicated to it. Alternative designs include signal collection in scintillators, implemented as strips with alternating orientation to match effectively the separation capabilities of smaller area square cells, as well as a concept for a digital ECAL, realized with Monolithic Active Pixel Sensors (MAPS). Pixel-sizes in the order of $50 \mu\text{m}$ can ensure linearity up to high energies, leading to a total number of pixels of the order of 10^{12} for the complete ECAL.

HCAL The HCAL is as well highly segmented (48 layers, $3 \times 3 \text{ cm}^2$ cellsize). Scintillators, read out in an analog mode are interleaved with steel plates as passive absorber. As a side effect of the high granularity, one additionally obtains the possibility to perform software compensation by separating MIP tracks and electromagnetic showers inside a hadronic shower. Another proposition is to increase even more the granularity in order to further improve the imaging capabilities of the HCAL. The cell size could be reduced to $1 \times 1 \text{ cm}^2$. This would multiply the number of channels by 9, making it very difficult to handle their readout. To overcome this

problem, cells would not read out in a digital or semi-digital mode. Gaseous detectors, RPC's or Micromegas, are proposed to serve as active mediums. Different absorber materials are still investigated for both approaches.

Forward Calorimetry A system of three additional detectors will be installed in the very forward region. Bhabha scattering has will be used for the measurement of the luminosity in the LumiCAL. The physics goals at the ILC impose this measurement to be extremely precise. The BeamCAL allows to have a fast estimation of relative changes in the luminosity. It is equally important to monitor the beam parameters and to have an estimate for beamstrahlung effects that can be critical in searches including high missing energy and momentum. The LHCAL extends the HCAL endcap region down to the beampipe, thus improving the hermiticity of the calorimeter, especially important for very forward SUSY signatures.

Coil A superconducting coil providing a nominal field of 3.5 Tesla and representing 2.2 interaction lengths surrounds the two calorimeters. A field of this strength will contain the core of the pair background in the beampipe. Also the curvature of the track of a charged particle scales proportional to B . This means improvement in the momentum resolution with higher field strength as well as a bigger separation of charged tracks from neutrals at a given inner radius of the calorimeter.

Return Yoke and Muon System A magnetic field of this strength has to be closed to minimize stray fields. An iron yoke is used for this purpose. This yoke is then instrumented with RPC's. The system serves like this as tagger for high energy muons.

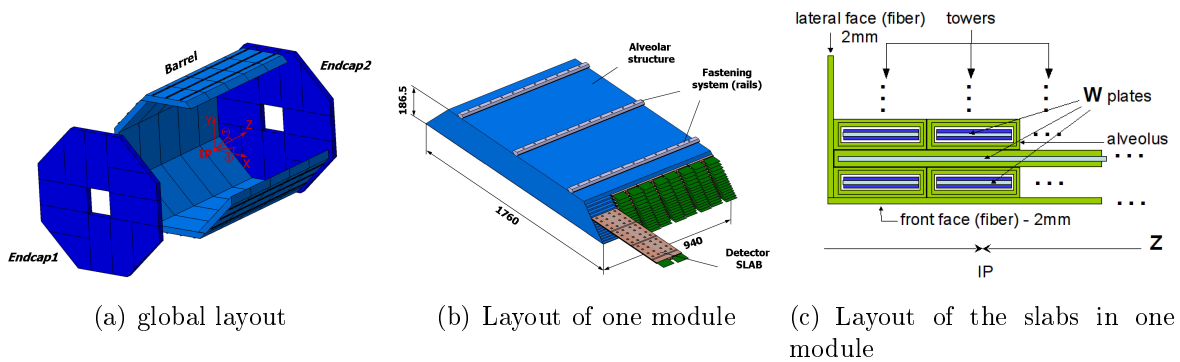


Figure 3.2: Layout of the ECAL in ILD

3.4 An illustration of the impact of different segmentation and materials in the calorimeters for particle flow

A u jet from a 500 GeV E_{cm} event is shown in the group of Figures 3.3 at different ECAL cell sizes (Fig. 3.3(a), 3.3(b), 3.3(d): $1 \times 1 \text{ mm}^2$, Fig. 3.3(c): $5 \times 5 \text{ mm}^2$) and using different absorber materials for the semi-digital HCAL model (here $5 \times 5 \text{ mm}^2$), either tungsten (Fig. 3.3(b)) or steel (Fig. 3.3(d)).

The energy of the individual hits is shown in a brown scale where lighter color means more energy. Alternatively the hits are colored like the corresponding tracks revealing the nature of the particle that caused them (red: $\pi^\pm$, blue: $e^\pm$, green: γ , salmon: K^0 , yellow: proton).

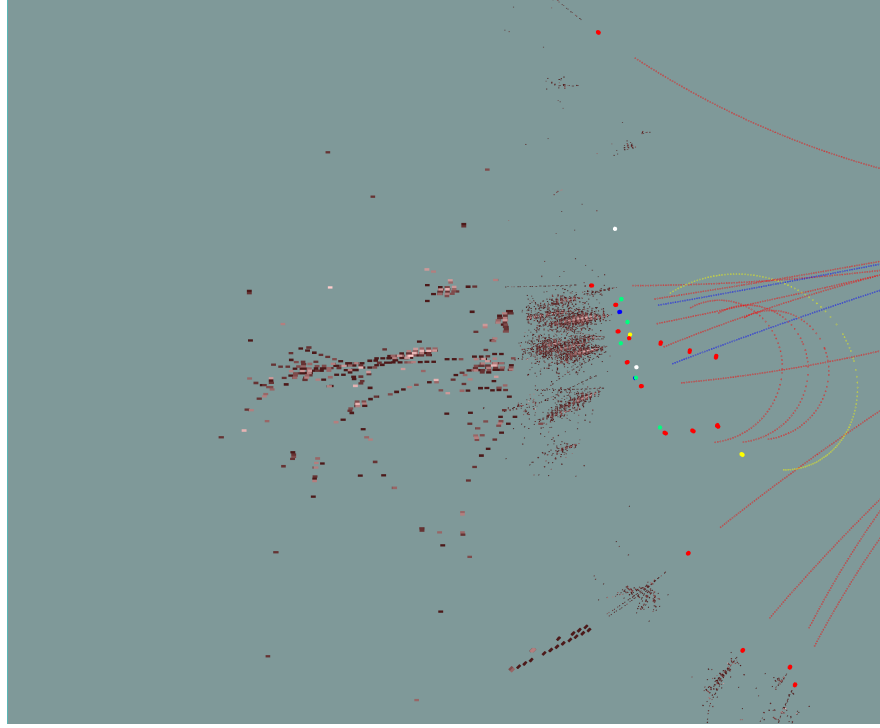
The jet is particularly rich in K^0 's. Two of them make their way into the hadronic calorimeter. Two more decay in the tracker region to a pair of π^0 's in the one case and a pair of charged pions in the other.

It is obvious that the fine ECAL granularity yields advantages in the cluster-track and cluster-cluster separation. By using not only the transverse shape but also the information in depth it should be possible to extract tracks at a distance far below the Molière Radius. Also two-shower separation should be easily possible as long as the two shower cores are separated as it is the case everywhere in the present event. With a coarser ECAL this task gets more challenging for the dense parts of the jet. Track-shower separation should nevertheless still be possible to distances down to about 1 cm.

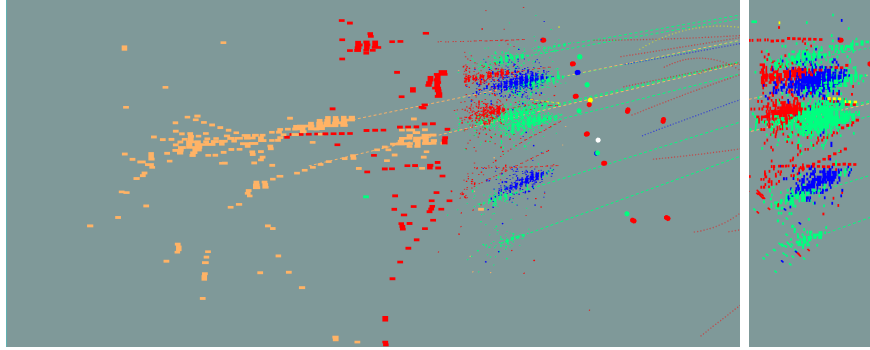
Even at the high HCAL granularity simulated, reconstruction of the dense jet part and linking with the ECAL seems very tough with the steel absorber. The low radiation length of tungsten gives a far clearer image of the showers because the electro-magnetic part is reduced to a very small space and the tracks can be easily reconstructed. If the gain in pattern recognition can make up for the decreased energy resolution of the e-m part will have to be investigated in future studies.

3.5 The ECAL for ILD and its implementation in the simulation

As mentioned before the proposed solution for the ILD ECAL is a sampling structure of tungsten absorber interleaved with layers of silicon diodes for the signal readout. Tungsten makes it possible to keep the system very compact ($\sim 24X_0$ within 18 cm) and to have a good ratio of interaction to radiation length (λ/X_0 : 27.4). This will make hadronic interactions in the ECAL less probable, i.e. charged hadrons leave in most cases only a MIP track in the ECAL or at least the shower starts late. This will help particle flow a lot as it makes it easier to distinguish hadronic showers from electromagnetic ones and reduces thus confusion between photon and hadron showers. It has as well a small Molière radius ($R_M = 9 \text{ mm}$), producing showers that are compact in the transverse direction.

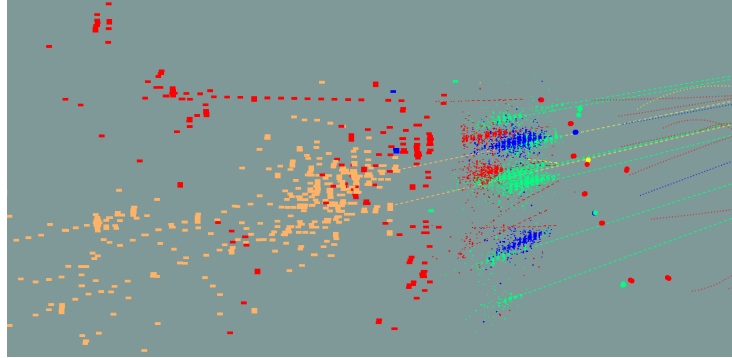


(a)



(b)

(c)



(d)

Figure 3.3: A 250 GeV u jet with different segmentation and absorber material in the ILD calorimetric system. The default configuration is: ECAL- $1 \times 1 \text{ mm}^2$ cells, HCAL- $5 \times 5 \text{ mm}^2$ cells, W absorber. (a) : the complete jet with the energy deposit in a brown scale, while lighter color means more energy. (b) : origin of the particles in the jet core. (c) : lower ECAL granularity ($5 \times 5 \text{ mm}^2$) cells. (d) : steel as HCAL absorber.

To achieve the necessary resolution in energy, 30 active layers will be installed. They are arranged in two stacks. The first active layer in the first stack has no absorber in front of it, then follow 20 layers with an absorber of 2.1 mm thickness. The second stack holds 9 layers with an absorber thickness of 4.2 mm. A high segmentation is achieved with cells as small as $5 \times 5 \text{ mm}^2$.

The global layout of the ECAL can be seen in Figure 3.2(a). An octagon has been chosen to approximate the circular symmetry around the beam axis. The big structures help minimizing insensitive space between modules and optimize at the same time the mechanical feasibility. One eighth of the barrel octagon is called a stave. In earlier experiments using trapezoidal ECAL modules, they were usually arranged completely symmetrical with the small face inside and the larger one outside, leaving cracks between adjacent modules pointing to the interaction point. For ILD, the modules are inverted, i.e. the large face is the inside one. Additionally, the modules have an offset to be able to close the octagon neatly. As a result, the natural order of layers of stack one and stack two is not assured anymore. A sketch can be seen in Figure 3.5. This solution gives also rise to another problem: in the overlap zones between two staves the total depth (in X_0) of the ECAL is 15% reduced. A scan of the X_0 of the ECAL along ϕ over two of those stave transitions can be seen in Figure 3.4(b). Higher fold symmetries have as well been considered. The big advantage of the octagonal approach is its simplicity of the geometry thereby facilitating the production process and allowing very small distance between ECAL and HCAL while keeping the integration easy. Furthermore, rising the angle between staves would also widen the drop in X_0 in the overlap region.

The space between barrel and endcap is dominated by the space needed for the hardware to read out the TPC, i.e. basically cables passing to the exterior of the detector. In the reference simulation model this gap has been fixed to 10 cm. To assure shower containment also in this overlap region, the outer radius of the endcap exceeds the one of the barrel. A scan of the X_0 seen by a particle coming from the interaction point can be seen in Figure 3.4(a). The Barrel and Endcap region are shown separately along with their resulting sum, so that the transition region can clearly be identified. The design of the module arrangement in the endcaps leaves a square hole around the beam pipe. The space in between is filled with a separate module, the ECAL ring. Its final design has the same layer-absorber structure as the main part of the endcap. In the simulation the layout is somewhat simpler with just alternating tungsten and silicon layers and without any inter-wafer gaps.

Along the z -axis the barrel is divided in 5 wheels. The layout of one of these modules can be seen in Figure 3.2(b). Integration of the active layers is done by the means of so called detector slabs that are slid into an "alveolar" structure of tungsten wrapped in carbon fiber, as can be seen on the figure. In depth these slabs build towers. The layout of the slabs in one module is sketched in Figure 3.2(c). Every slab is enveloped by two more layers of fiber, each of a thickness of $150 \mu\text{m}$. Five towers build up one module, each tower consisting of 15 slabs where each slab holds two active layers. Figure 3.5 gives a sketch of the current design. The very front-end electronics will be embedded directly into the slab. This will help to keep

the system compact and with a low number of dead areas despite of the 100 million channels that have to be treated. The heart of each slab is an H structure of carbon fiber that wraps a tungsten absorber plate. The silicon wafers for the two active layers are placed directly on both sides of the absorber plate together with a copper/kapton layer for the high voltage supply, followed by the PCB's and another copper layer for heat diffusion. The principal components are all well modelled with the correct dimensions, only the material used for simulation differs in some cases.

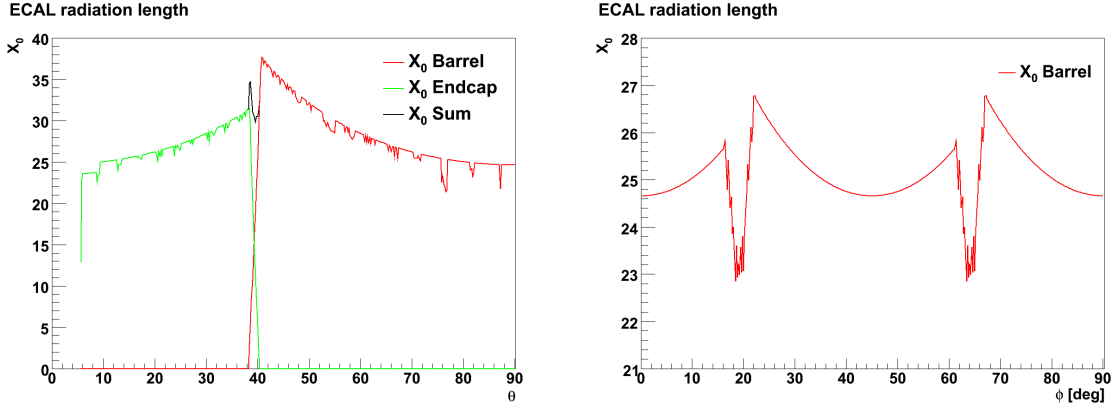
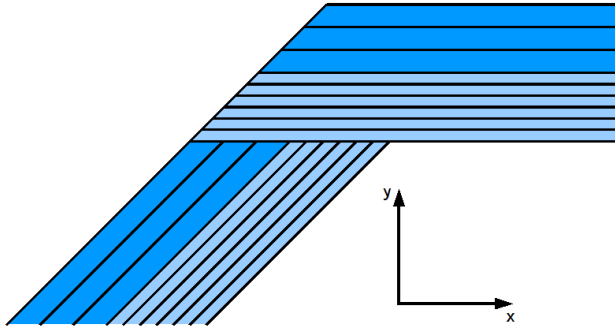
(a) Scan in θ direction at $\phi = 0$ deg(b) Scan in ϕ direction at $\theta = 0$ deg and at $z = 45$ mmFigure 3.4: Scan of the radiation length represented by the ECAL along the θ and ϕ directions.

Figure 3.5: Sketch of the ECAL at a stave transition. The parts of low (high) absorber thickness are indicated in light (dark) blue.

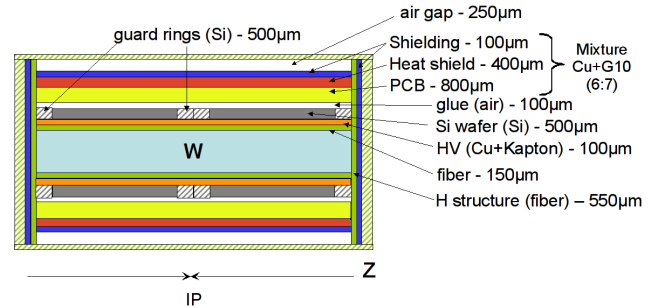


Figure 3.6: Slab design as implemented in the ILD simulation

3.6 Software and Computing

The development and analysis in this thesis has been performed within the standard framework used in the ILD community. The "ILC Soft" package has been assembled regrouping all main applications needed for such work.

LCIO (Linear Collider Input Output) [34] is the persistency framework defining the basic data model. It is used in both simulation and analysis software.

Simulation is done in the **MOKKA** [35] software, a **Geant4** [36] based application for full simulation of a detector for the future linear collider.

The detector geometry from the simulation is stored by **GEAR** (GEometry Api for Reconstruction) [37] to be reused in the reconstruction phase. A file in the "XML" format contains the information about the subdetector structure and dimensions.

The reconstruction chain is embedded in the **Marlin** (Modular Analysis & Reconstruction for the LINear collider) [38] framework for the processing of LCIO files. Different tasks are performed by separate modules that are implemented as so-called processors. These tasks usually imply the analyzing of LCIO collections in an event and the creation of additional output collections. The processors to be executed are defined in an "XML" steering file together with the values for their optional parameters.

The standard reconstruction for ILD is made up of modules for hit digitization, tracking reconstruction, a PFA algorithm, particle ID, jet finders, flavour tagging and linking modules between the reconstruction output and the Monte Carlo truth for performance estimation.

Being a collaboration for calorimeter R&D for the ILC, the CALICE specific software is built on top of the ILD framework. MOKKA is used for simulation and Marlin for the reconstruction of the entire test beam setups. Additional data base software allows access to the conditions data from different test environments.

The detailed simulation as well as the storage and processing of the data (simulated and from test beams) require a large amount of storage space and computing resources. The Worldwide Computing Grid is hence heavily used in both communities.

Chapter 4

Electromagnetic showers

Contents

4.1	A description of electromagnetic showers	40
4.2	Threshold	41
4.3	Electromagnetic showers in the ILD ECAL	42
4.4	Influence of the magnetic field on electromagnetic showers	43
4.5	Transverse shower profile	44
4.6	Measurement of the Molière radius	45
4.7	Longitudinal shower profile	48
4.8	The barrel-endcap overlap region	52
4.9	Conclusion for reconstruction algorithms for photon showers . . .	55

4.1 A description of electromagnetic showers

When high energy photons and electrons pass through matter they induce electromagnetic cascades. Photons will undergo pair-production and electrons will undergo bremsstrahlung. This leads to secondary particles with lower energy. These two alternating processes continue until the electrons reach an energy where ionization processes become more and more dominant. The critical Energy E_C can be defined as the energy where the loss from ionization per is equal to the loss by radiation. For particles with energies below E_C , ionization is the main contribution to energy losses. This is the point where the shower particles stop multiplying and the showering comes to an end. Some shower particles can though completely escape detection, in particular photons just above the thresholds for pair production have a very small cross section for interaction with matter. It is convenient to measure energies in units of E_C . In the longitudinal direction the behavior is governed by the high energy part of the shower, so the radiation length of the absorber material is the appropriate unit of measure for distances. To parametrize electromagnetic showers it is common practice to use the following two reduced variables:

$$t = x/X_0, \quad y = E_0/E_C,$$

where E_0 is the energy of the incoming particle. Like this the mean longitudinal profile of an electromagnetic showers can be described with:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \quad \text{where} \quad (4.1)$$

$$\int b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} dt = 1 \quad (4.2)$$

where the shower maximum is at

$$t_{max} = (a - 1)/b = 1.0 \times (\ln y + C_j), \quad j = e, \gamma \quad (4.3)$$

$$C_e = -0.5, \quad C_\gamma = +0.5 \quad (4.4)$$

The distinction is due to the difference in the cross section for the two possible initial processes. Pair production is less probable than radiation. A fit of this function to the energy deposit of a 10 GeV photon in the ILD ECAL is shown in Figure 4.1. An additional normalization factor has been applied to account for the fact that the raw energy deposit in the silicon is used. Also, only the tungsten has been included in the calculation of the radiation length to estimate the layer position in units of t . With these approximations, the longitudinal shower profile is reasonably well described by Equation 4.1.

When plotting the ratio of the shower energy contained in a radius r from the main shower axis and the total shower energy as a function of r (c.f. Figure 4.8), one realizes that the

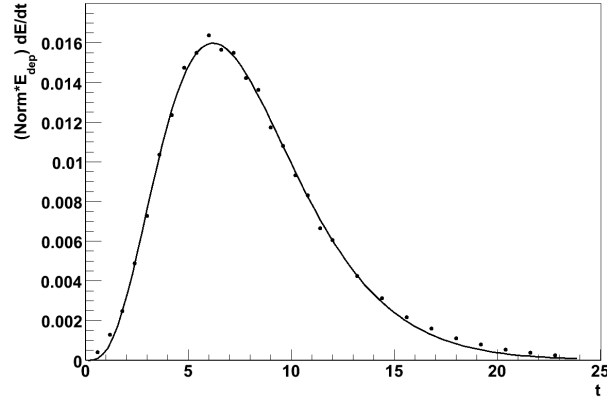


Figure 4.1: Energy deposit per layer in the ILD ECAL endcap region. The fit showed here follows Equation 4.1.

resulting distribution is close to invariant for different shower energies. A universal scale for the transverse shower profile would thus be a radius within which a certain amount of the shower energy is contained. In the Molière radius R_{Mol} 90% of the shower energy are contained. As mentioned earlier pair production is the most important process for γ 's in the shower development. Compton scattering contributes only little and at the borders of the shower. The opening angle for pair production is quite small. The essential contribution to the lateral expansion of an electromagnetic shower is hence the multiple scattering from the electrons inside the shower. To parametrize the Molière radius, two properties of the material are thus important: R_{Mol} should scale directly with the radiation length. At the same time it should have a component that describes the importance of the scattering, so it should scale inverse to the critical energy:

$$R_{Mol} = X_0 E_S/E_C \quad (4.5)$$

with $E_S \approx 21 MeV$.

4.2 Threshold

Especially for showers at low energy the energy threshold that has to be surpassed for a cell to be counted is very important. To make the simulations more realistic, the ILD reconstruction chain contains a digitization that takes the raw energy deposit of a cell and artificially smears it with a Gaussian distribution representing the electronics noise. This threshold has therefore to be defined carefully. A sample of muons of 15 GeV (this is where a muon is in the minimum ionizing regime $\rightarrow$ MIP) has therefore been simulated at perpendicular incidence on the ECAL. The distribution of the non-digitized energy deposit per cell is shown in Figure 4.2.

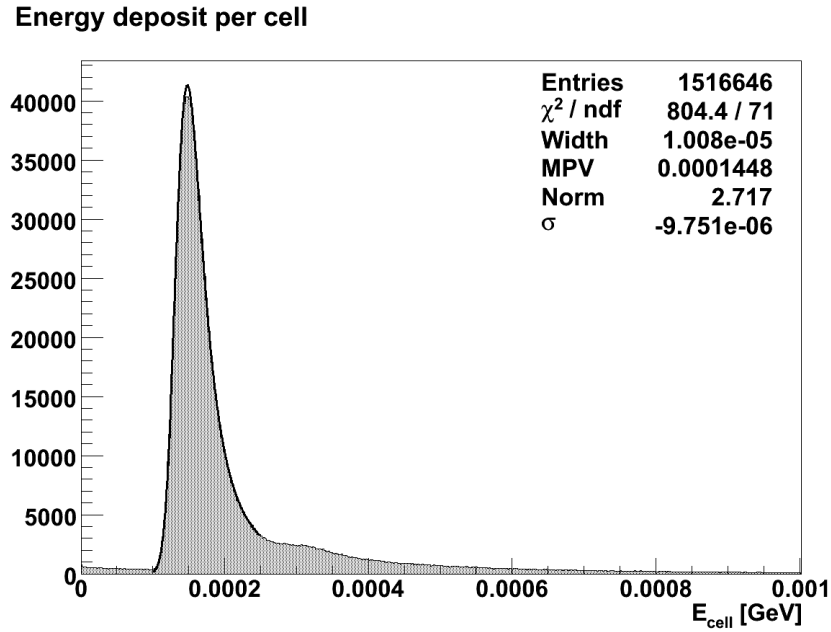


Figure 4.2: Energy response per cell to a MIP (15 GeV muon), fitted with the convolution of a Landau and a Gaussian function. The energy threshold used later is $E_{threshold} = 0.5 \text{ MIP} = 72.4 \text{ keV}$.

The main peak has been fitted with the convolution of a Landau and a Gaussian function. The Gaussian function would represent an enlarging due to the electronics noise. Although its contribution is small (no noise simulated), it helps to reproduce better the simulated distribution. Theoretically, the energy loss of a particle in a thin layer is described by a Landau function. What is actually measured though is the energy deposit of this particle. With this in mind, one can for example explain the second bump in the distribution of the energy deposit per cell. It is the signature of a knock-off electron (δ -ray) that leaves a second MIP track in the silicon until it is stopped or it leaves the active layer.

The most probable value of the Landau function is taken to be the response of a cell to a MIP. The good signal over noise ratio that it expected ($S/N = 10$) allows to set the threshold as low as 0.5 MIP, i.e. at 5σ of the noise. But even with a cut like this 1% ($\sim 10^6$) of the cells of the ECAL will still show a noise hit. The energy threshold is then fixed to $E_{threshold} = 0.5 \text{ MIP} = 72.4 \text{ keV}$.

4.3 Electromagnetic showers in the ILD ECAL

With its high granularity the ILD ECAL gives a detailed image of a particle shower. An example of a shower induced by a 10 GeV photon incident at 90° to the ECAL front face in the

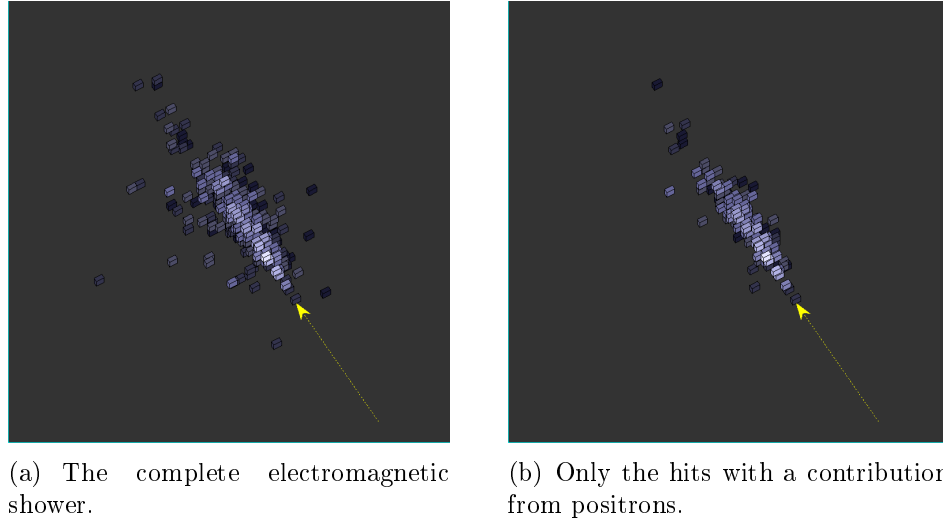


Figure 4.3: A photon shower at 10 GeV incident at 90° (along the yellow arrow) in the endcap of the ILD ECAL. Lighter colours reflect a higher energy deposit in the cell.

endcap region is shown in Figure 4.3(a). The yellow arrow indicates the direction of incidence, the color code gives the energy deposit in one cell. The lighter the color, the more energy has been deposited. One can already follow the development of the shower by eye. The two major components of electromagnetic showers can easily be identified: the shower core where there is a high density of hits with high energy deposit and the fluctuations at the shower borders where hits (of mostly low energy) are distributed sparsely. Part of these fluctuation will be suppressed by the threshold cut but their number can still be significant. Nevertheless, they contribute little to the total shower energy. These hits have their origin in photons at lower energies that have been deflected via Compton scattering. As already mentioned earlier they can have very small cross sections for interaction if they are just above the threshold for pair production, so they can travel quite far before finally either converting or undergoing the inverse Compton scattering. Figure 4.3(b) shows an event display of the same shower but this time only the cells with an energy contribution from positrons are shown. It is clearly visible that these cells are reduced to the very core of the shower. This directly confirms that the lateral shower expansion is governed by the multiple scattering of electrons.

4.4 Influence of the magnetic field on electromagnetic showers

Since an electromagnetic shower consists partly of charged particles one can expect that a magnetic field will have an influence on the development of the shower. Moreover the field

foreseen for ILD is quite strong (3.5 T). A two dimensional field map can be seen in Figure 4.4. Due to the direction of the field lines parallel (endcap region) or orthogonal (barrel region) to the direction of a shower incident at 90° to the ECAL surface, this influence is expected to be different for the barrel and endcap regions. Moreover, in the barrel, one component of the transverse shower direction is parallel to the field lines while the other one is perpendicular, breaking the radial symmetry of the shower. All this will alter the transverse and longitudinal shower profiles and even make visible the underlying structure of the ECAL itself.

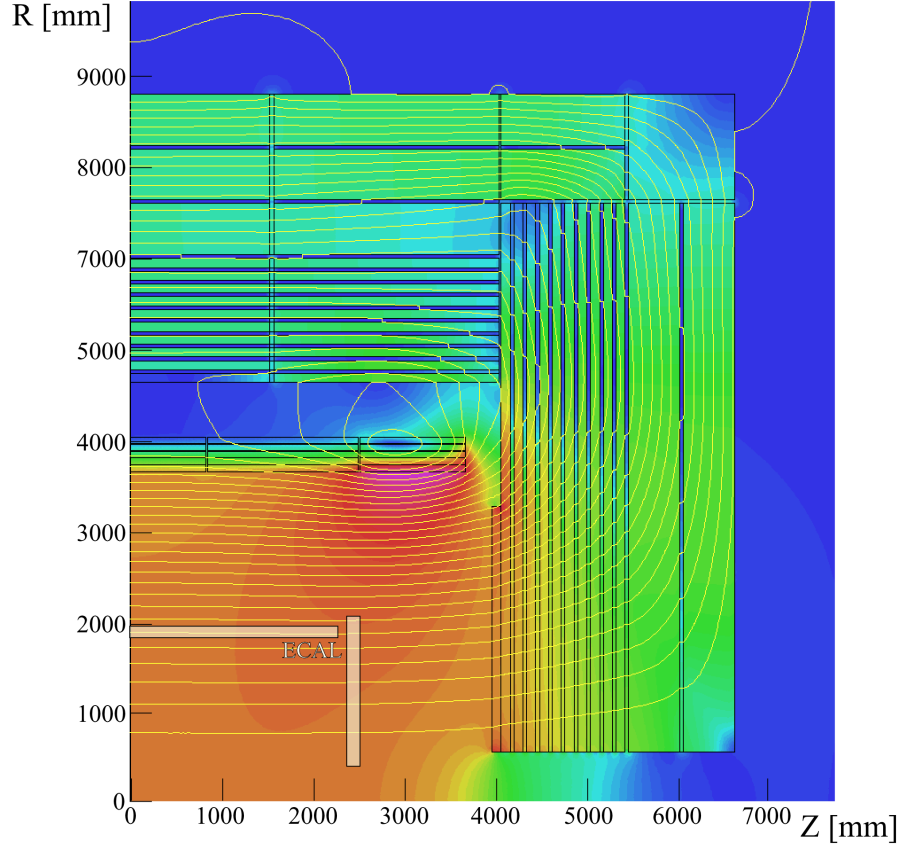


Figure 4.4: One quadrant of the two dimensional field map of the magnetic field for ILD.

4.5 Transverse shower profile

The transverse shower profile of a 50 GeV photon at 90° incidence is shown in the group of Figures 4.5. Five hundred events with a smearing of the impact position have been averaged. The point (0,0) in the spacial coordinates $((x, y)$ for the endcaps and (x, z) for the barrel) corresponds to the impact point on the ECAL frontplane for each event. The energy deposit

per bin of the histogram is given in logarithmic scale on the third axis or the color code respectively. The 3-dimensional representation (left plots) shows how close the shape is to a 2-dimensional Gaussian distribution. This means, that in normal scale the transverse shower profile is extremely peaked with a very narrow core.

The plots on the right hand side allow us a decomposition along the spacial directions. In the barrel the shower seems to be wider in the x -direction than in the z -direction. This is the effect of the magnetic field discussed earlier. The x -component of the flight direction of charged shower particles will be affected stronger than the z -component since the magnetic field lines are along the z axis, resulting in an effective widening of the shower along x . In the endcaps the radial symmetry of the shower is not disturbed. On the other hand we can see that showers in the endcap appear a lot more focused, this also being due to the presence of the magnetic field. Since the field lines are here along the main shower direction, the charged shower particles are forced on trajectories around the z -axis. The real impact of the magnetic field in the two regions can be seen in Figure 4.6. Here the ratio of the energy contained in the radius r around the main shower axis and the total energy deposit of the shower is plotted as a function of r with or without application of the magnetic field. It was already mentioned that these distributions are independent of the initial particle energy. While the two black curves match almost perfectly - as expected, since there is no intrinsic difference between barrel and endcap modules -, it is obvious that the magnetic field makes the shower less wide in the endcap. In the barrel we can see an opposite effect. Furthermore, the effective increase in the width of the shower is bigger than the reduction seen in the endcap. To further illustrate this difference between barrel and endcap, again the ratio of the energy contained in the radius r around the main shower axis and the total energy deposit of the shower is plotted as a function of r in Figure 4.7. The bins of the original histogram (in 0.5 mm steps) have been interpolated linearly to make the effect more visible. The difference in radial expansion can be as big as 10% at certain parts of the shower.

4.6 Measurement of the Molière radius

As can be seen from equation 4.5 the Molière radius is independent from the shower energy. To estimate R_{Mol} for the ILD ECAL, a sample of photons at 1, 10 and 50 GeV has been simulated. Figure 4.8 shows the fraction of the energy contained in the radius r over the total energy deposit as a function of r , separately for barrel and endcap due to the reasons given above. The Molière Radius is found to be more or less independent of the shower energy. The small residual differences are very likely due to the impact of the magnetic field. The Molière radius of the ILD ECAL is estimated to:

$$R_{Mol}^{Barrel} = 18.0 \text{ mm} \quad (4.6)$$

$$R_{Mol}^{Endcap} = 16.5 \text{ mm} \quad (4.7)$$

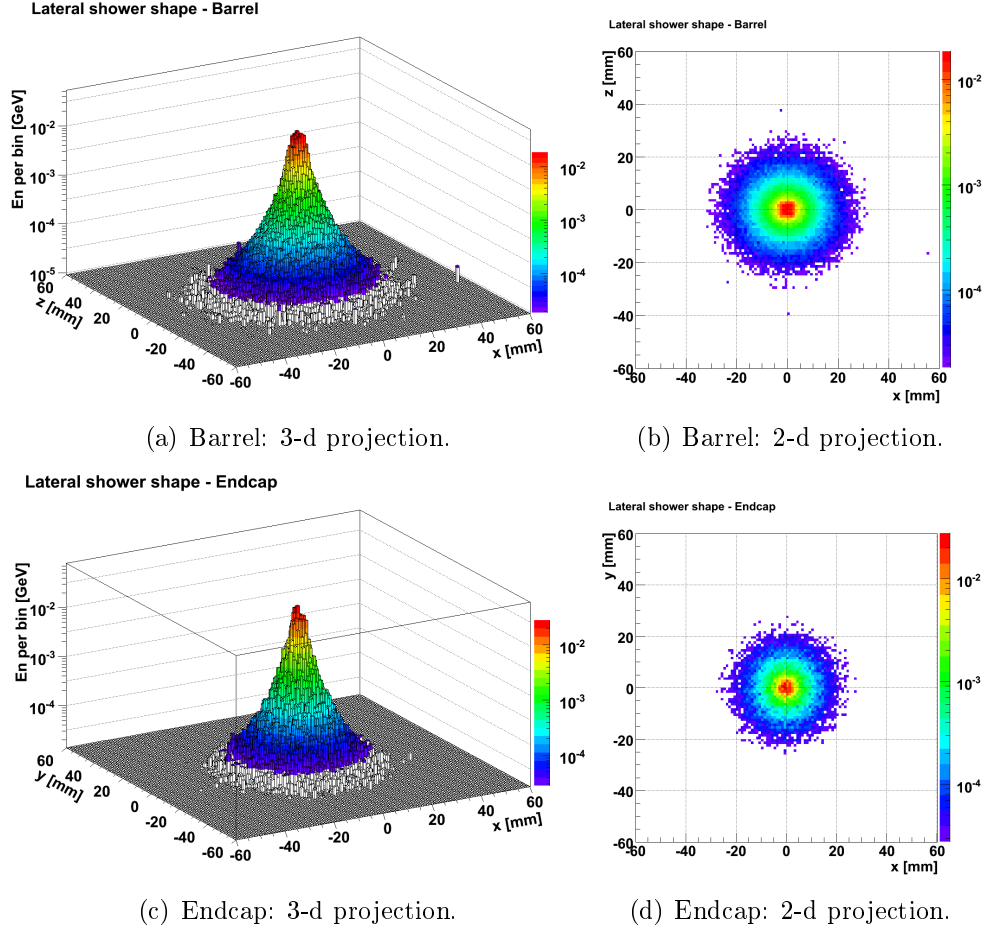


Figure 4.5: The shape of 50 GeV photon showers as a projection of the energy deposit on a plane perpendicular to the impact direction. The two left plots show the averaged energy deposit in one bin in logarithmic scale. The resulting shape is very close to a 2-dimensional Gaussian distribution. The two right plots show only the projection in the plane of the two space variables with the averaged energy deposit in the color code.

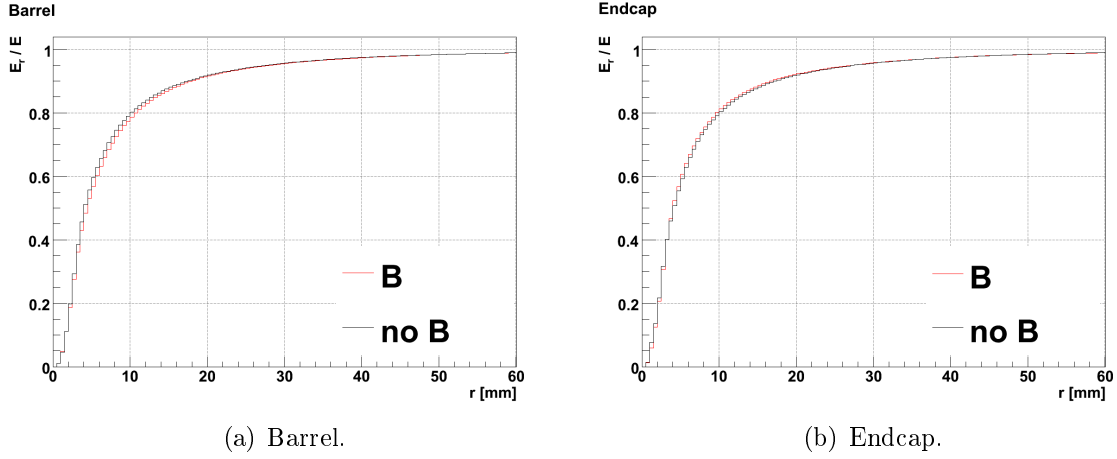


Figure 4.6: Influence of the magnetic field on the radial containment of a 10 GeV in the barrel and endcap regions.

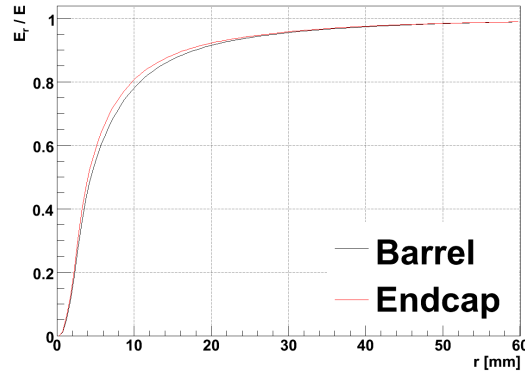


Figure 4.7: Difference in the ratio of energy deposit in the radius r and the total energy deposit as a function of the average radius r for a 10 GeV photon shower.

As expected R_{Mol} is significantly smaller in the Endcap. These small values were the actual motivation for the choice of tungsten as the absorber material. Pure tungsten has a Molière radius of 9 mm. The increase is a result of the other materials interleaved between the absorber plates. Nevertheless, as expected both values present excellent premises for the Particle Flow approach.

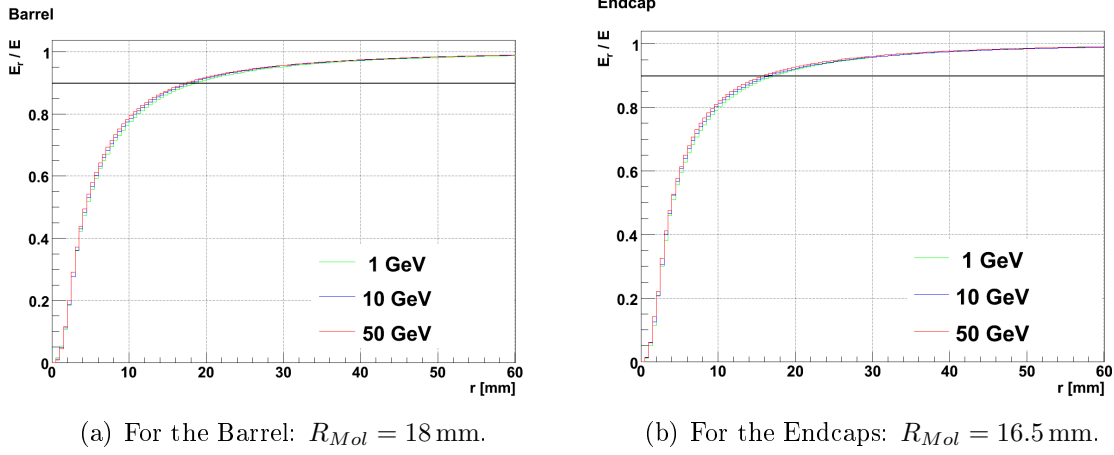


Figure 4.8: The fraction of the energy contained in the radius r from the point of impact over the total energy deposit as a function of r . The horizontal line indicates a ratio of 90% which is used for the definition of the Molière radius R_{Mol} .

4.7 Longitudinal shower profile

The average longitudinal profile of 10 GeV electromagnetic showers as measured layer-by-layer in the ILD ECAL is shown in the Figures 4.9 in terms of energy deposit (4.9(a)) and number of hits (4.9(b)) per layer. The first layer that has no absorber in front is neglected in all the following discussions. Distances in depth are calculated from the first active layer with absorber.

Energy deposit The general shower shape is the same in both regions following essentially the theoretical prediction. One can clearly identify the zone at the beginning of the shower where the energy deposit is increasing from layer to layer until the shower maximum is reached and the energy deposit is decreasing again. There is an apparent odd-even effect from one layer to the next.

Revisiting the description of the ECAL slab design in Section 3.5 and especially Figure 3.5 one can correlate this effect to the symmetry around the tungsten absorber plate inside one slab. This plate is surrounded directly by the silicon wafers, followed by the PCB and additional

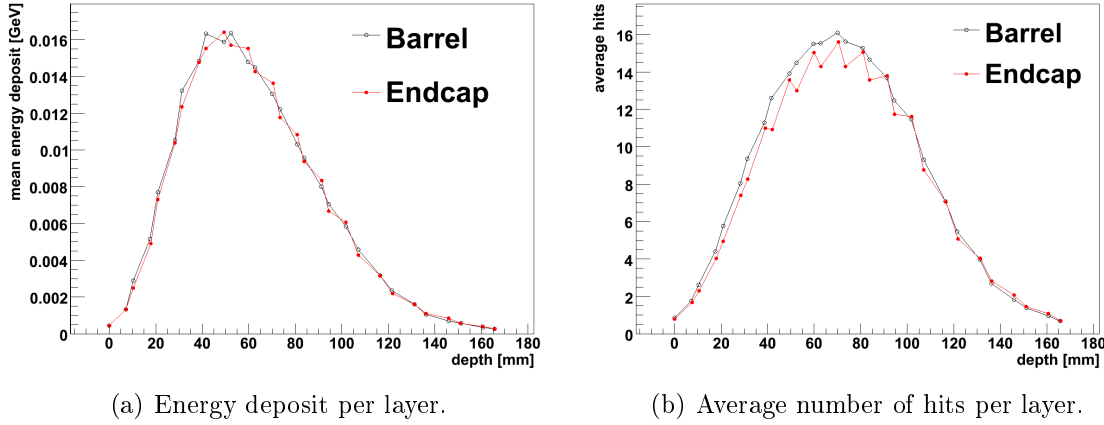


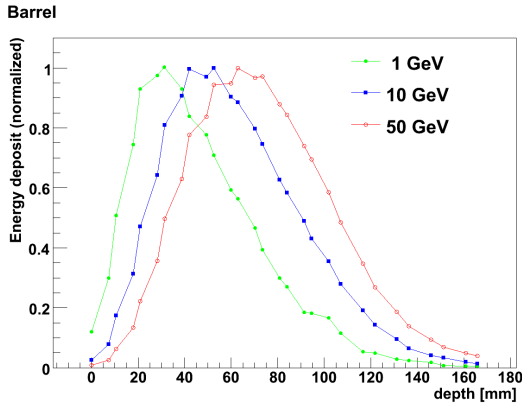
Figure 4.9: Mean energy deposit and average number of hits per layer from a 10 GeV photon shower in the ILD Si/W ECAL for the barrel and endcap regions.

copper/kapton layers. This structure leads to a difference in the material budget as well as the actual type of material in front of the two active layers in one slab. The shower maximum seems to appear a bit later in the endcap than it does in the barrel.

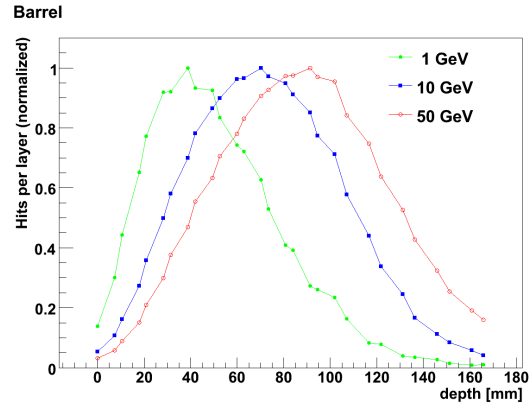
Number of hits In the number of hits per layer (Figure 4.9(b)) the difference between barrel and endcap is even more striking. The overall shape is still the same but again the maximum seems to be attained in the endcap slightly later than in the barrel.

Energy dependence It is interesting to compare the shower profile at different shower energies. Therefore the profiles for 1 GeV, 10 GeV and 50 GeV showers have been normalized to the highest energy deposit or the highest number of hits respectively and plotted in the group of Figures 4.10. In terms of the energy deposit the shower maximum in both endcap and barrel varies with about $\log(E)$, as expected from Equation 4.3. The strength of the odd-even effect increases with the energy.

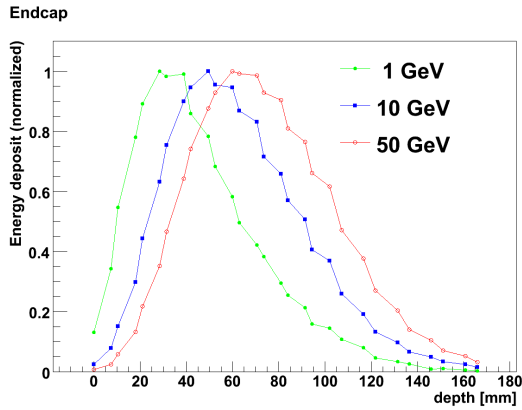
Effect of the B field The differences between endcap and barrel parts point to the magnetic field. The different distributions with the magnetic field switched on or off are shown in Figures 4.11. Additionally there is the distribution for a hypothetical calorimeter traced where the thicknesses of all the components except the tungsten and silicon layers have been set to very small values in order to minimize the odd-even difference. The magnetic field actually smooths out the odd-even effect. It not only increases the number of hits in the layers with less material in front, but it also seems to decrease the energy deposit of the layers with additional material in front. In the endcap the effect is very subtle because of the different orientation of the field.



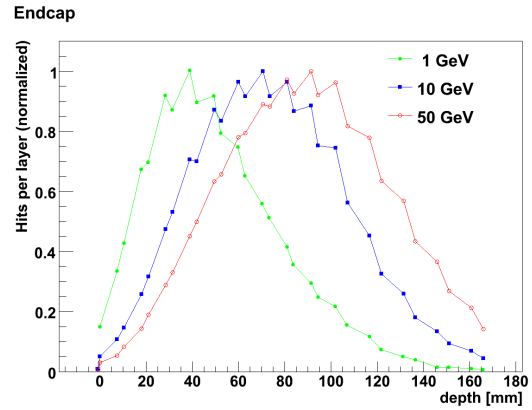
(a) Energy in the barrel.



(b) Hits in the barrel.

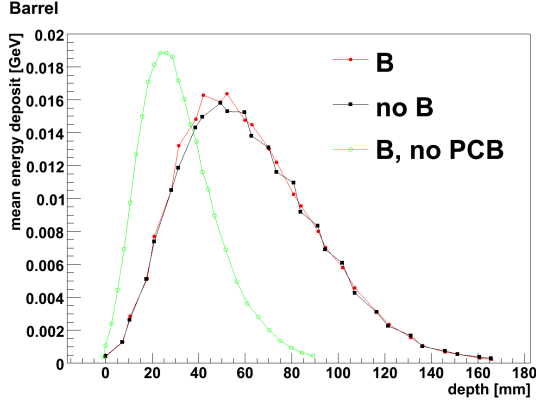


(c) Energy in the endcap.

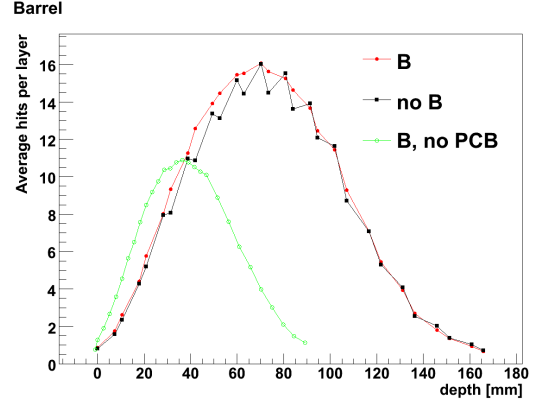


(d) Hits in the endcap.

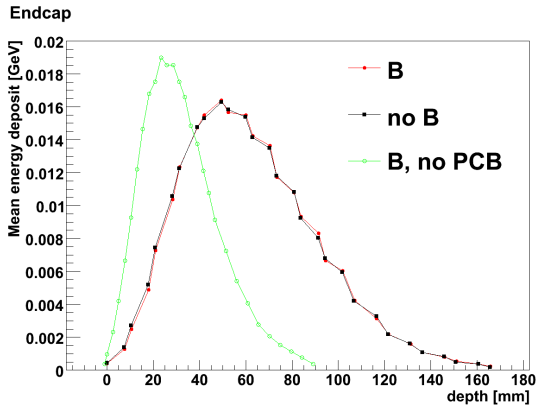
Figure 4.10: Averaged energy deposit and number of hits per layer at various impact energies in the barrel and endcap regions.



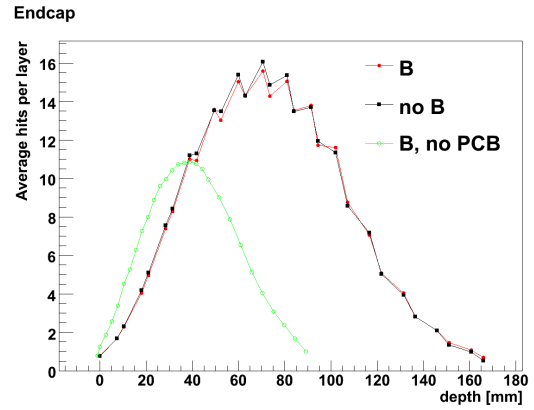
(a) Energy in the barrel.



(b) Hits in the barrel.



(c) Energy in the endcap.



(d) Hits in the endcap.

Figure 4.11: Impact on the magnetic field on the mean energy deposit and the average number of hits per layer of a 10 GeV shower in barrel and endcap. Additionally the distributions for a hypothetical calorimeter with only Si and W layers (no PCB) is shown for comparison.

The odd-even effect The odd-even effect is intrinsic to the special symmetric structure of the detector slabs. The group of Figures 4.12 gives an overview of this effect in the endcap part with the two types of layers colored differently.

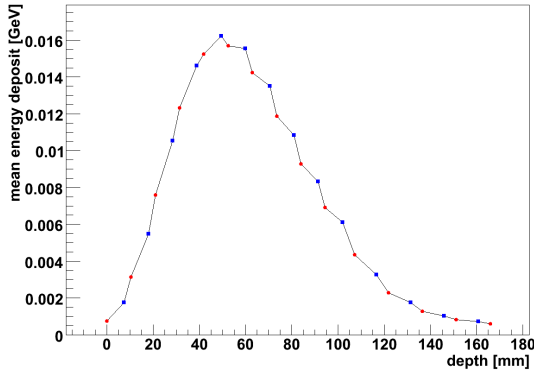
The material simulated for the PCB's (G_{10}) along with the copper is a low Z material compared to tungsten. It is clear that the interaction of the shower particles will be different for both media and this in an energy-dependent manner. Also, several different effects would have to mix in order to explain the behavior, especially the differences between the beginning and end of the shower. To reveal all theses contributions it would be mandatory to follow each single shower particle separately.

Although the physics impact of the effect is small, it can nevertheless be used to tune the simulations when compared to test beam data. The PCB density for example has already been corrected with data analysis from the CALICE Si/W ECAL prototype. The effect of inversion on the other hand is not observed in the data runs or the simulation of the prototype. The basic material simulated for the PCB is the same but the slab integration with other layers (in order to include other components) differs quite a lot. Within the CALICE R&D effort, this level of detail in the simulation has to be achieved in order to enhance comparison of data and simulations that will for example be used to estimate and tune hadronic shower models.

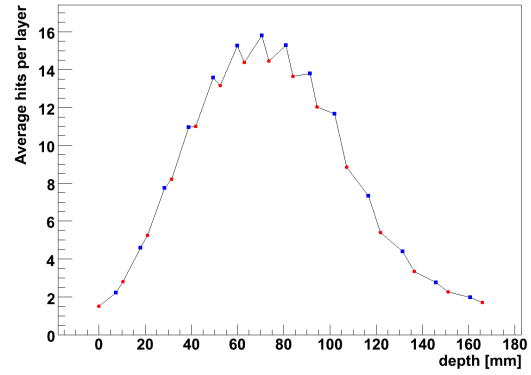
4.8 The barrel-endcap overlap region

An electromagnetic shower starting in the barrel part of the ECAL can continue its way in this gap and finally attain the endcap. The absence of a high density material in the gap has as a consequence that the development of the shower is interrupted. At this point the effects on the two basic shower components are different. Being neutral the photons will continue their way straight ahead unaffected by the magnetic field while the quite low energetic electrons and positrons are trapped and spiral parallel to the z -direction. This results in an effective separation of the two parts and therefore an enlargement of the shower when reentering the calorimeter in the endcap. An event display of such a case can be seen in Figure 4.13(a). The trajectories from the shower particles in the overlap region are shown in Figure 4.13(b). Electrons are in red while positrons are in blue. The effect of the B field on the charged part is clearly visible, whereas the photons continue straight and convert when reentering the ECAL in the endcap.

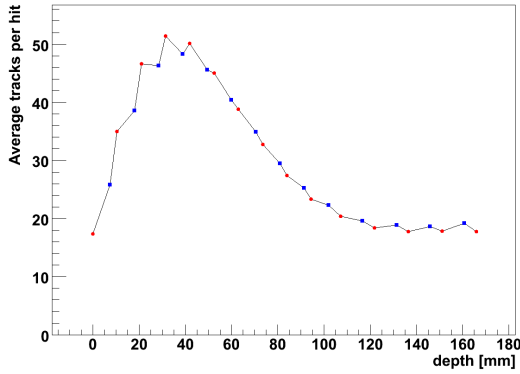
When tracing the energy deposit of a shower as a function of θ in the proximity of the gap, as it is done in Figure 4.13(c) one can see that additionally part of the shower energy is lost.



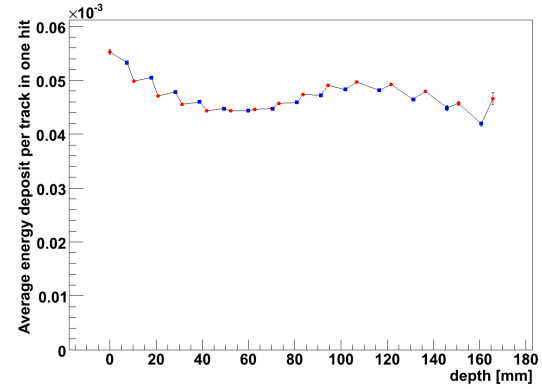
(a) Mean energy deposit.



(b) Average number of hits.

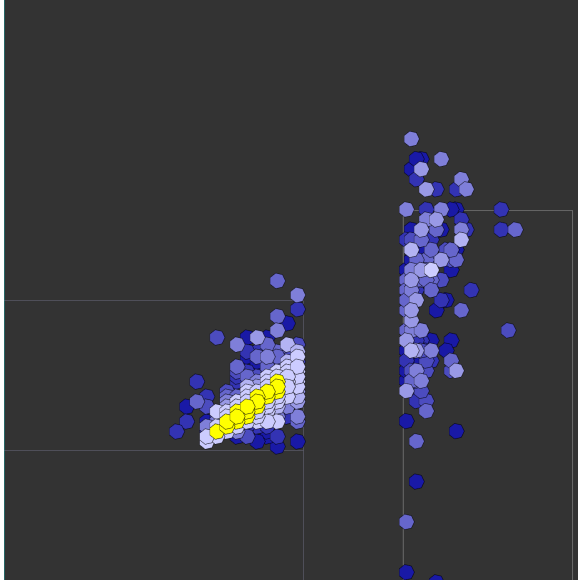


(c) Average density of tracks in one cell.

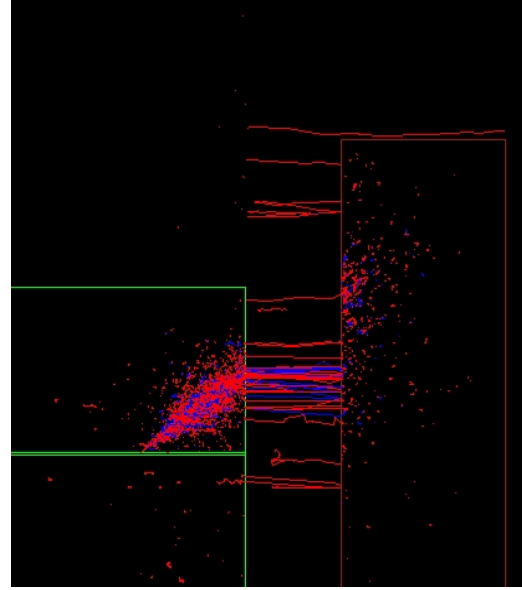


(d) Average energy deposit of one track in one cell.

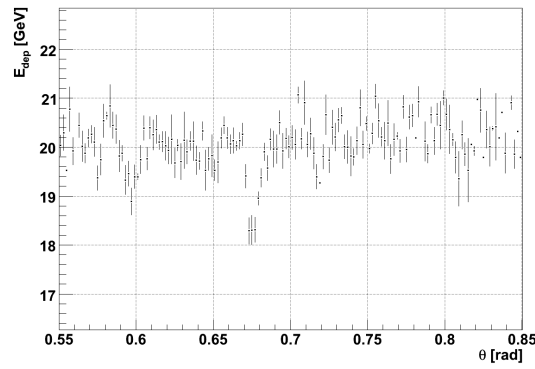
Figure 4.12: Different quantities of 10 GeV e.-m. showers per layer in the ECAL. To study the odd-even effect, layers with additional material in front of them are represented by red dots, while the others are represented by blue squares.



(a) Profile of the dispersion of a photon shower when passing the endcap-barrel overlap region.



(b) Tracks of the shower particles in the overlap region. Electrons are colored in red, positrons in blue.



(c) Energy profile for events in the barrel-endcap overlap region, where a drop is visible at $\theta \sim 0.67$.

Figure 4.13: The complexity of the barrel-endcap overlap region, illustrated with 20 GeV photon showers.

4.9 Conclusion for reconstruction algorithms for photon showers

The investigation of the transversal profile of electromagnetic showers makes one of their features very apparent: the high density core. We have seen that the Molière Radius in which 90% of the shower energy are contained is quite small for the proposed ILD ECAL. But since the cell size is still three to four times smaller, the shower core will still be spread over several cells. To identify the shower core, where the energy density is high, it could be attempted to regroup hits with no/little distance between each two of them. The fact that the peripheral hits carry only a very small part of the shower energy would then assure that the resolution on the shower energy would not be too much disturbed or maybe even improved. The balance between ensuring a certain fraction of the shower energy to be clustered in order to enhance the energy resolution and limit the clustering radius in order to keep the separation capabilities high, is an essential point for a clustering algorithm designed for Particle Flow. This holds equally for clustering in the longitudinal direction. Criteria have to be found to interrupt the clustering as soon as the peripheral zone with a sparse distribution of hits is attained.

What has also been very apparent is the differences between barrel and endcap due to the influence of the magnetic field. To take for example the smaller Molière Radius in the endcap into account would mean to reduce also the clustering radius in this region. Even the asymmetry in the transversal shower profile in the barrel region could probably be exploited.

Also hardware effects like the odd-even effect need to be taken into account. This can mean both trying to make use of them for improvements in the measurement or just to tighten cluster criteria. In the next chapter an algorithm for the clustering of photon-induced showers in the ILD ECAL is presented that incorporates several of the considerations mentioned above.

Chapter 5

GARLIC - GAMMA Reconstruction for a Linear Collider experiment

Contents

5.1	The GARLIC algorithm	58
5.2	General idea	58
5.2.1	Step-by-step description	59
5.3	Performance and efficiency	71
5.3.1	Single-particle events	71
5.3.2	Error on the impact position	79
5.3.3	Application on jets	79

5.1 The GARLIC algorithm

GARLIC is an algorithm designed for GAMMA Reconstruction at a LInear Collider experiment, to provide the initial phase concerning the calorimeters to a complete Particle Flow analysis. The first step for photon reconstruction is to create clusters, i.e. to regroup hits in the calorimeter that could be induced by an electromagnetic shower. The properties of these clusters are then used to recognize the shower origin - electromagnetic or not. As it was mentioned at the end of the previous chapter, electromagnetic showers have special properties that a clustering algorithm must make use of in order to reach maximum performance.

To follow the principles of Particle Flow, a very high reconstruction efficiency over a wide energy range is mandatory, while keeping the background from debris of hadronic showers low. This has to go hand in hand with a reasonable resolution on the cluster energy and good two-shower as well as shower-track separation capabilities. GARLIC is designed to reconstruct (nearly) pointing photons. With the present versions, studies for comparison of different ECAL cell sizes for ILD as well as on test beam data of the CALICE Si/W ECAL physics prototype have been performed.

Implementation GARLIC is integrated in the C++ Marlin framework (see [38]) which makes it compatible for use in future PFA environments. It is designed to be executed in a complete reconstruction chain so that track collections and digitized calorimeter hits are already provided by other processors. To be adaptable to specific physics needs, many of GARLIC's parameters can be changed by the user in the "XML" steering file like it is usual in the Marlin framework. Default values for these parameters are provided within the software package and explanations are given in the text.

Two versions of GARLIC exist. One is adapted to the ILD detector models. The other one is fit for the CALICE Si/W ECAL prototype. The principles of seed search and the actual clusterization mechanism translate 1:1 between these two versions. The differences are only due to the different geometries treated. A simple correction for the inter-wafer and inter-module gaps is integrated in the algorithm of both versions. Furthermore the algorithm has special track-based capabilities for rejection of debris from charged hadron showers. The version described here in detail is the one for ILD, differences in the prototype version are given in Section 6.4.

5.2 General idea

The main clustering mechanism is based on the high density of electromagnetic showers with their narrow shower core. Extrapolations of tracks into the ECAL volume are used to reject hits induced from charged hadrons. Thereafter seeds for the clusters are searched using only the first part of the ECAL in order to avoid early interactions of hadrons. From a seed a shower core is build by following the direction from the IP to the seed location in depth of

the detector. Starting from this core, hits are added over several iterations with a neighboring criterion. A decision over the electromagnetic origin of the cluster is then taken with pre-trained neural networks. An example of the clustering of a 10 GeV photon shower with GARLIC can be seen in Figure 5.1

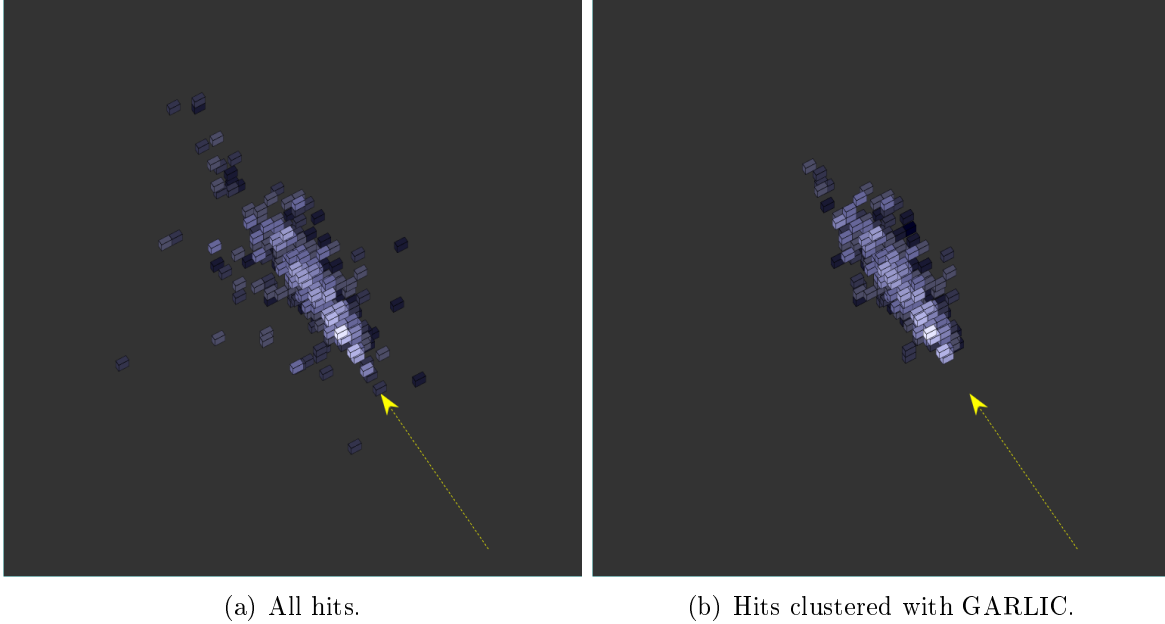


Figure 5.1: Application of GARLIC on a 10 GeV photon, incident along the yellow arrow, in the endcap of the ILD ECAL. Lighter colours reflect a higher energy deposit in the cell.

5.2.1 Step-by-step description

Initialization On a per-run basis GARLIC reads some information provided via a GEAR geometry file created by the simulation with MOKKA, like the strength of the magnetic field, the dimensions of the sub-detectors as well as the ECAL symmetry and layer layout. In the barrel GARLIC uses the same system of pseudo layers as introduced in the PandoraPFA [56] algorithm. A sketch is shown in Figure 5.2. It allows to treat the entire ϕ region uniformly thus suppressing the difficulty of the stave overlaps. The layer positions are calculated with the knowledge about the internal structure of the detector slabs.

The algorithm treats hits by certain regions of interest (ROI). These ROIs are chosen to be far from each other so that they can be considered as independent. This facilitates the steps involving the detector geometry because only the local surrounding volume has to be considered. Also the calculation time is improved considerably. To isolate this step GARLIC takes as an input clusters created by a pre-clustering processor that is based on iterative clustering with a simple 3d-distance criterion (default: 200 mm).

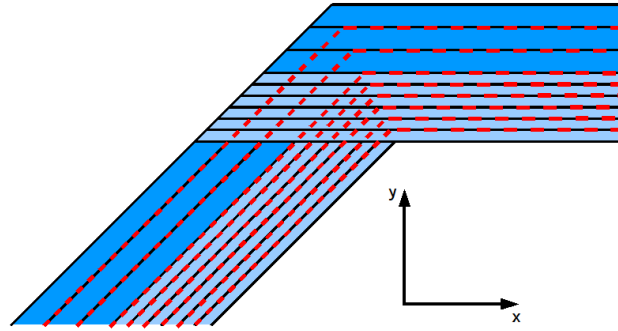


Figure 5.2: Schematic view of the ECAL in the region of a stave transition. The parts of low (light blue) and high (dark blue) tungsten thickness are indicated as well as the Pseudo Layers (dashed red lines).

The following steps are performed by GARLIC per event:

1. Preparation of track collection

GARLIC uses extended track objects that hold besides the LCIO track object also a helix object with the same parametrization and a 3d-spacepoint corresponding to where the extrapolated helix enters the ECAL. The default option is to read a track collection created prior in the reconstruction chain. If such a collection is not available, it exists either the option to cheat the tracks with the MC information or to read a textfile with parameters suitable for the initialization of a helix.

2. Preparation of the hit collection from the pre-clustering

Next the clusters created in the pre-clustering processor are read one by one. Since the hits from the first layer without any absorber in front of it are not included in the "official" data stream, GARLIC reads these hits directly from the simulation and applies the default threshold cut.

The basic LCIO calorimeter hit object has also been extended. The extended calorimeter hit holds the LCIO calorimeter hit itself, its corresponding pseudo layer number, a pointer to the cluster it has been attributed to and also information about its placement (if in the first layer and if in the barrel or endcap part).

All extended hits from a pre-cluster are stored in a vector and attributed to an object extended from the LCIO cluster class. This extended cluster holds additional information filled by GARLIC, notably the vector with the clustered hits, a pointer to the pre-cluster it has been created from, its location inside the ECAL (barrel, endcap, barrel-endcap overlap, ECAL ring), its seeding point, "ghost hits" added by the gap correction, an ellipsoidal shape fitted to the cluster, plus a set of cluster parameters that either hold values before and after the different corrections applied or are helpful in the identification of the

shower origin. Additionally there are some functions to perform comparisons between cluster objects, i.e. in terms of the number of hits, energy etc.

3. **MC information** At this point, the Monte Carlo information, especially from single-particle events can be read optionally. This is only interesting during the tuning phase of the algorithm.

After this preparation phase, the actual clustering can begin:

4. **Rejection of hits close to tracks**

The tracks of charged hadrons give a powerful tool to avoid clustering fragments of their showers. Even an early interacting charged hadron will usually just leave a MIP track in the first part of the ECAL. This track needs to be excluded from the search for possible seeds in the second step of the algorithm. Therefore tracks found in previous reconstruction steps are extrapolated into the ECAL and hits close to these are marked not to be used in seed-finding and clusterization. The maximal distance is user defined. By default it is set to 2 times the respective cell-size in each layer for cell sizes of 5 mm and smaller and the cell size itself otherwise. The removed hits are stored in a separate collection for record and possible reiterative clusterization in future PFA frameworks. This process is shown in the event display of an early interacting pion in Figure 5.3.

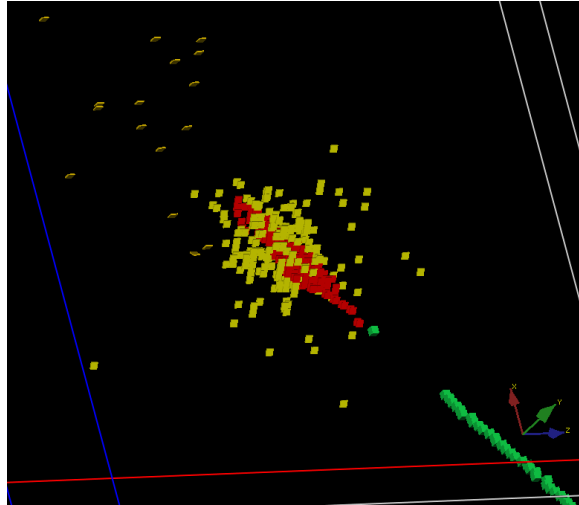
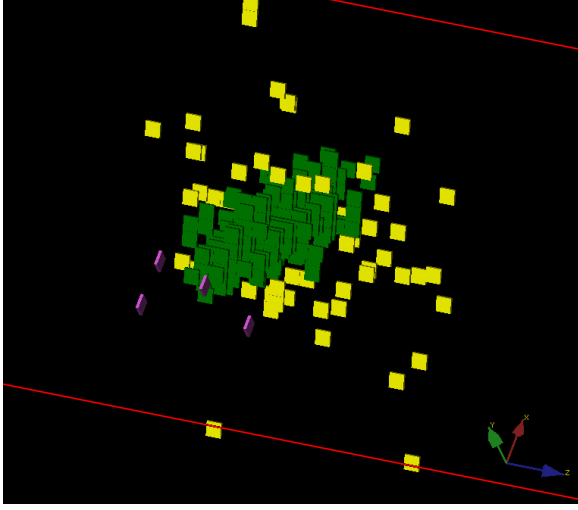
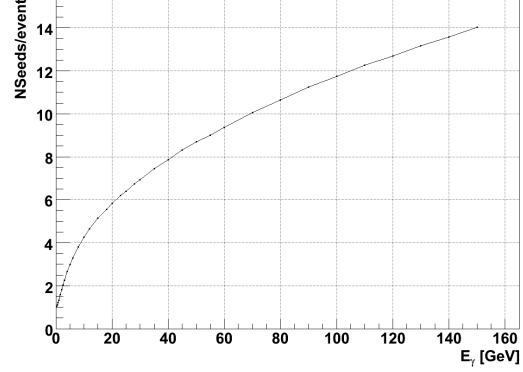


Figure 5.3: A 20 GeV pion starting its shower in the ECAL. The track recorded with hits in the TPC and SiT (green boxes) is extrapolated into the ECAL to exclude hits in its vicinity (red) from seed finding and clustering.

Starting from this point on, all steps are executed per ROI:



(a) The shower of a 10 GeV photon. Clustered hits are shown in green, the seeds found in pink.



(b) The mean number of seeds found per event as a function of the shower energy.

Figure 5.4: Seed finding in GARLIC.

5. Seed-finding and validation

The first step of clustering is to define seeds for the clusters. A seed is the starting point for the algorithm to search for hits. As many hadronic showers as possible should already be rejected at this point. The first ECAL stack, comprising the first 20 layers, represent roughly 0.5λ . The hits from tracks of charged hadrons have already been removed in the previous step. Only hits in a certain amount of layers (default: 12, corresponding to $\sim 7X_0$) are used to define the seeds.

The energy deposit of the included hits is projected on a surface that is different depending on the location of the ROI. In the barrel, it is a cylinder with a radius equal to the minimal distance of the ECAL front face to the origin at $z = 0$. In the endcap, the ECAL frontplane itself is used. In the barrel-endcap overlap region, the projection is done onto a sphere with a radius equal to the distance of the IP to the hit, that is closest to it.

A two-dimensional histogram is filled with the energy projections. The histogram borders are calculated on-the-fly with the minimal and maximal values of the considered hits. The bin size in both coordinates is then estimated as the projection of a regular cell situated at the mean of the histogram in both coordinates. At the same time another two-dimensional histogram with the same dimensions is filled. It records the number of hits projected to each bin. Bins are grouped iteratively (direct neighbors) starting from the one with the highest energy deposit. In the two first iterations all bins are forced to be added. Then follow two more iterations, where only bins with less deposit in energy are added in order not to disturb two-particle separation.

By default a minimum of 5 hits is required to validate a seed. Figure 5.4(a) shows the seed-finding on an example of a 10 GeV shower. Four seeds are found in this case. One well centered on the shower, the other three at its borders. Figure 5.4(b) shows the mean number of seeds found per event in function of the shower energy. Going to higher energies the number of seeds raises further. The principal motivations not to tighten the criteria on the seeds are the two-particle separation (for the cut in distance) and the goal to detect also photons at very low energies (for the minimum energy). As we will see later, other procedures have been developed to efficiently reject or merge clusters artificially created due to the high number of seeds (so called satellite clusters). The seeds are stored as 3d-spacepoints, ordered by energy.

6. Core building

Since GARLIC's primary goal is to identify (almost) pointing photons, the direction of a shower is assumed to be along the vector from the IP to the seed position that has been found in the previous step. A core can then be defined via the projected distance of a hit to this direction. The limit in distance is fixed to be less than one times the cell size in the layer of the hit. Hits are searched pseudo layer by pseudo layer from front to back. Until reaching about $10 X_0$, a minimum of hits (default: 5) has to be found, if not, the core building is cancelled and the next seed will be treated. Longitudinal "holes" with less than three empty layers are allowed in the first stack. In the second stack, only holes of one empty layer are allowed. The barrel-endcap overlap region presents itself as quite tricky due to the enlargement of the shower in the gap. So after the transition to the endcap part, hits are searched in a wider radius.

If a core could be constructed successfully, GARLIC proceeds to the next step before treating any other seed. This yields a good compromise between two-particle separation and avoiding satellite clusters.

7. Iterative clustering

Starting with the core of the cluster, hits are added in several iterations (default: 3) with a neighboring criterion (default: $\sqrt{2} \times$ cell size). The order of treatment is always from lower to higher pseudo layer numbers. Including the distance already covered by the core finding, one would not like to make the total clustering radius surpass the Molière radius by far, except in special cases where only isolated photons are expected. The default values have been chosen to achieve a good compromise between the fraction of energy clustered and the two-particle separation capabilities. Changes in this default should be handled with great care since they would require a large amount of retuning, especially for the estimation of the cluster energy. The clustering distance is furthermore modified by the thickness of guardring or module gaps if a neighboring hit could be on the other side of such a gap. Neighbors for a hit are searched in the layer of the hit itself and in the two following layers. Once the clustering is completed, there is the option to add additional hits around the cluster to increase the ratio of clustered energy. This will

deteriorate the two-particle separation and is hence not performed by default.

8. Simple verification

The completed cluster needs verification. Two simple criteria are used to reject artificial clusters:

- A minimum energy of 150 MeV.
- A minimum distance of $1.5 \times$ cell size from the nearest track. This second criterion has a critical impact on the performance at different cell sizes. It has been found that without recovering algorithms this topological cut is necessary in a first iteration of photon finding. This definition is hence also kept at bigger cell sizes.

At this point, GARLIC considers one seed to be fully treated and it will proceed to the next one, starting with the core building until all seeds of the ROI were treated.

9. Gap correction

The design concept of the Si/W ECAL features some ineffective areas, induced by the guard-rings of the silicon wafers and the supporting carbon fiber between modules. They are modeled to great detail within the simulation. While the inter-wafer gaps are only 1 mm and gaps between two slabs of the same module 2 mm wide, inter-module gaps add up to 5 mm which is the equivalent of one entire cell for the default configuration.

A correction has to be independent of the angle of incidence of the incoming particle. The simplest approach, as currently implemented in GARLIC, is to correct layer-by-layer while meaning the energy deposit of the cells facing each other across a gap. So called "Ghost Hits" are introduced between the hits on opposite edges of such gap (or diagonal in case of a corner area). The hit energy for this virtual cell is calculated as the average of the neighboring real hits, scaled with the ratio of the actual inefficient area and the area of a regular cell.

This linear extrapolation method is sensitive to the position of the gap with respect to the shower core and also the angle of incidence with respect to the gap. The accuracy depends strongly on the initial particle energy. In the barrel, this leads to big over- and underestimation phenomena depending on the position of the cluster. To avoid the dependence on θ , the energy attributed to a ghost hit is scaled with $|\sin \theta_{cluster}|$. The energy dependence is corrected with another modification factor that describes a falling exponential function. If the product of all those modifiers (area, θ , energy) still exceeds 0.7, the hit is also taken into account for the number of total hits of a cluster.

The performance of the method can be seen in Figures 5.5 for three different energies. With the current parameters, the correction has only a very subtle effect on the distributions. Only at very high energies, an improvement is clearly visible. A more advanced correction could use a Gaussian distribution around the center of gravity of a shower to

reweigh the energy extrapolation for a ghosthit. This would help avoiding the dependence on the position of the shower barycenter. Also the θ and energy dependencies would need more studies.

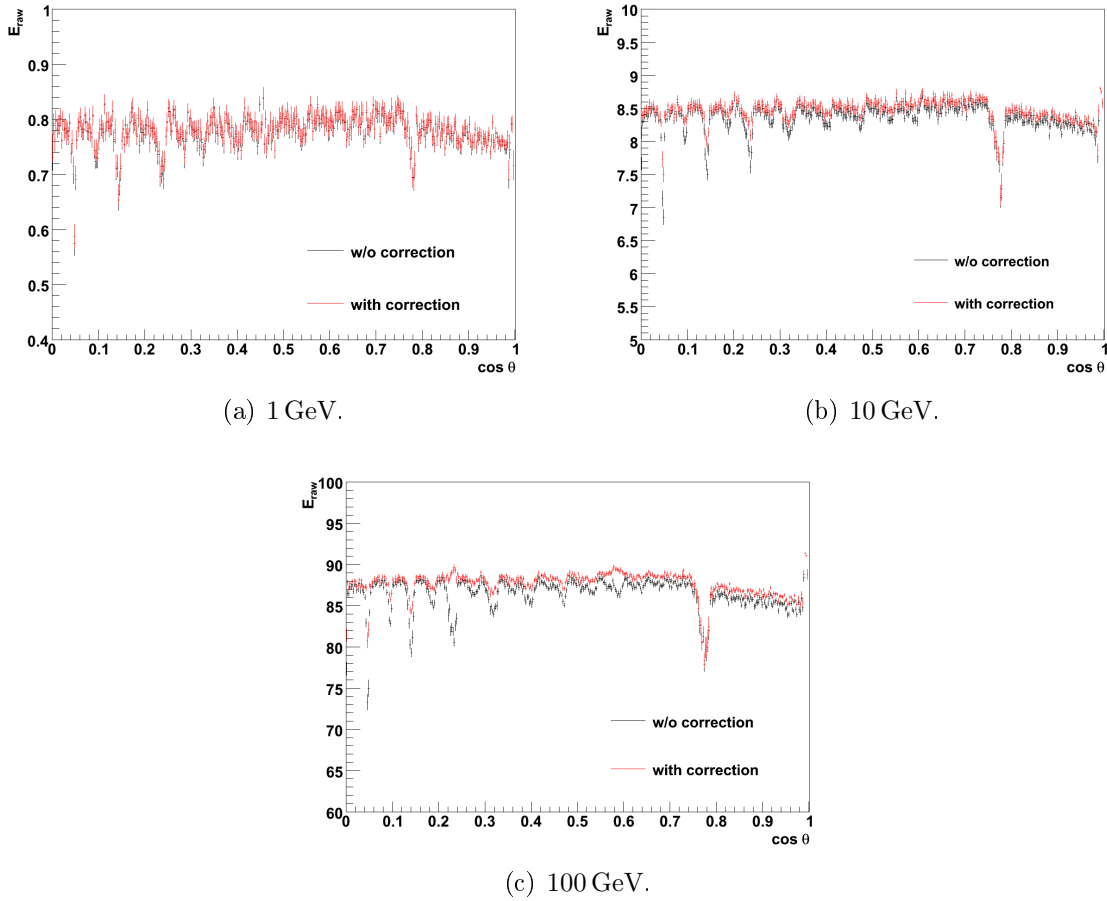


Figure 5.5: Effect of the gap correction at different shower energies.

10. Filling the cluster parameters

In this step all clusters are ordered by descending energy. Then the relevant parameters for each cluster are computed. This includes not only the ones used later in the verification with the neural network but also the distance of a cluster to the biggest cluster in the ROI and the nearest track.

11. Neural Network Verification

To reject clusters created from debris of hadronic showers and satellite clusters created at the borders of real electromagnetic showers, energy dependent cuts on previously trained neural network outputs (implementation in the TMVA package [57]) are used. To achieve

the desired discrimination capabilities, numerous regions had to be defined at low energies. The NN were then trained with large samples of single-particle events. Due to the cut on the cluster distance from the nearest track, the energy regions need to be defined as a function of the cell size to keep the training samples at sufficient sizes. Many of the default TMVA values were found to be well suited. The network used is a Multi Layer Perceptron with 2 hidden layers and 500 cycles.

In regard of the question of separation of two photons from a π^0 decay, clusters having a total energy of 20 GeV or more are automatically declared to be true clusters, if they are not extremely close to an extrapolated charged track (closer than 12 mm). By this means a cluster regrouping two photon showers can still be accepted while clusters from very early starting hadronic showers are rejected. Implicitly this assumes a 100% efficient tracking. The variables used for discrimination of clusters at an energy inferior to 20 GeV can be regrouped by the shower property they make use of:

Longitudinal profile: • Position of cluster start.

- Position of cluster end.
- Depth of cluster.
- The difference between cluster depth and cluster start.
- Ratio of the energy deposit in the last 5 layers and the total energy. (only for $E_{cl} > 3 \text{ GeV}$)

Transverse profile: • Ratio of E_1 and total energy, where E_1 is defined as the energy deposit from hits that have a distance of maximal $1 \times$ cell size from the principal shower axis.

- Ratio of E_4 and total energy, where E_4 is defined as the energy deposit from hits that have a distance of maximal $\sqrt{2} \times$ cell size from the principal shower axis.
- Ratio of E_9 and total energy, where E_9 is defined as the energy deposit from hits that have a distance of maximal $\sqrt{8} \times$ cell size from the principal shower axis.

Combined: • The cosine of the angle between the shower direction calculated from all the hits of the shower and the position vector of the cluster.

- The cosine of the angle between the seed direction calculated only from the hits that made up the cluster seed and the position vector of the cluster.
- Cluster width, defined as the energy-weighted mean distance of the cluster hits to the main axis.
- Cluster eccentricity, defined as the ratio of the cluster width and the length of the main cluster axis.

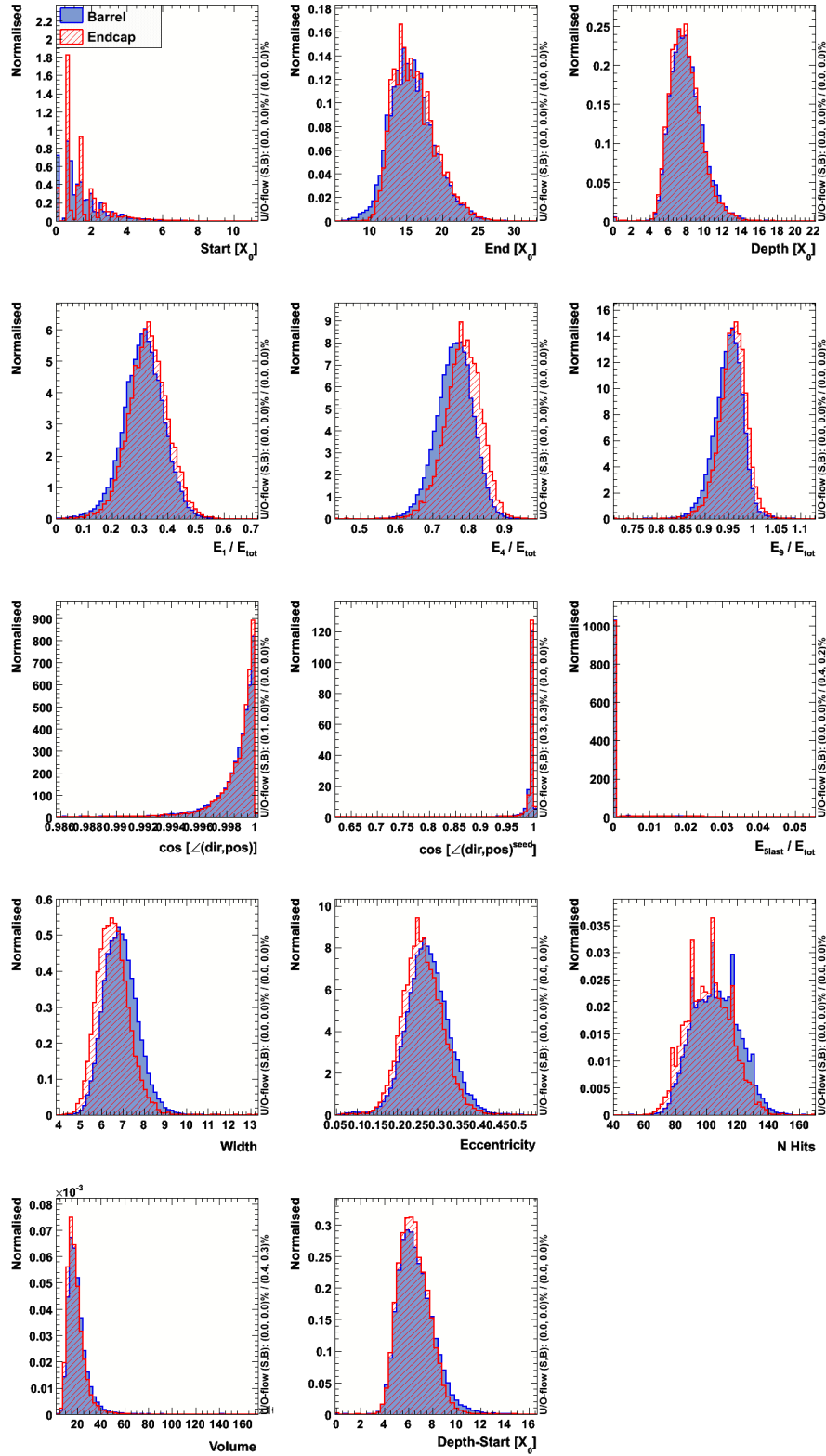


Figure 5.6: Distributions for the parameters used for the NN discrimination of real and fake clusters ($3 \text{ GeV} < E_{cluster} < 5 \text{ GeV}$) for barrel and endcap.

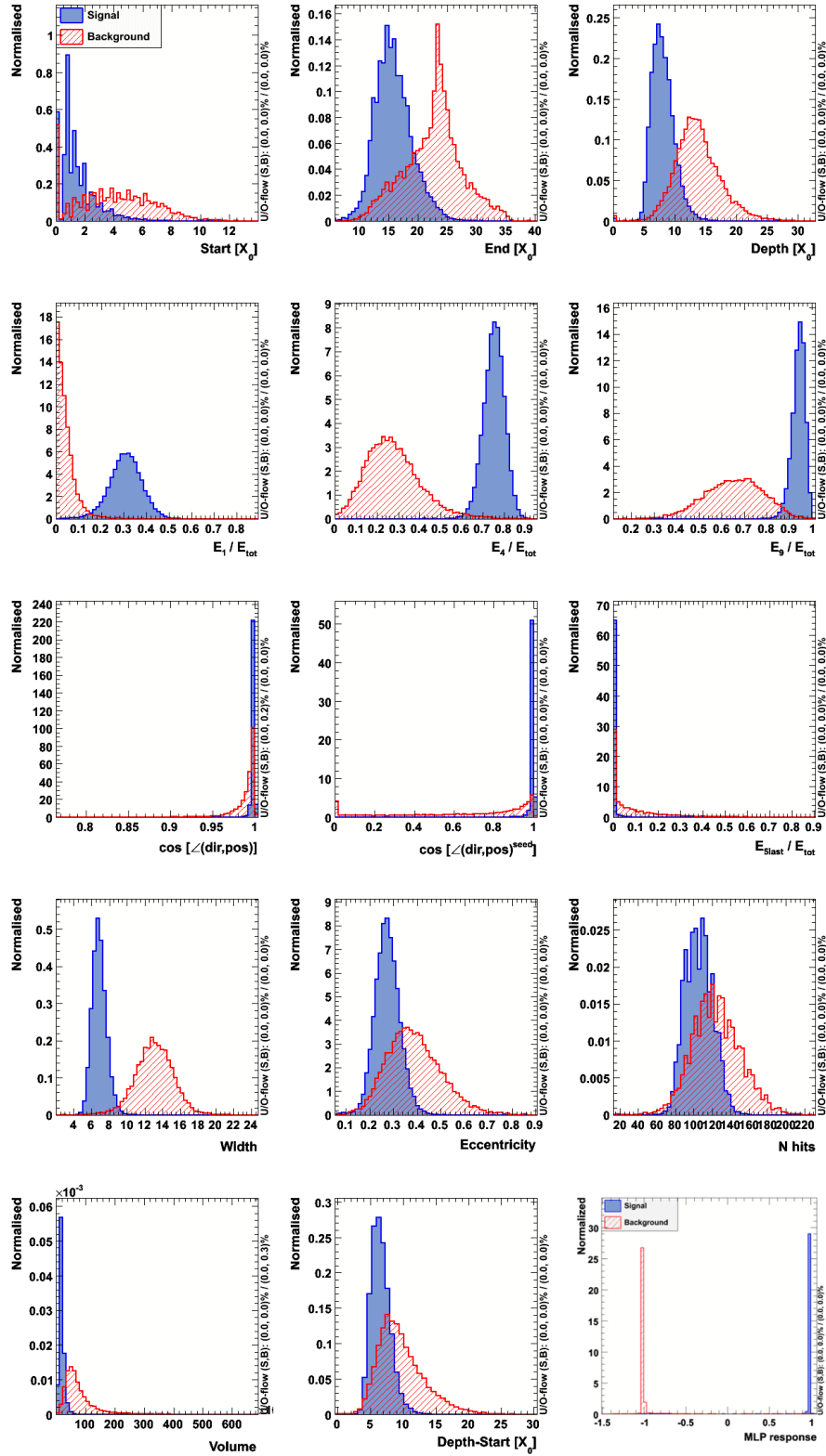


Figure 5.7: Distributions for the parameters used for the NN discrimination of real photon clusters (signal) and those created from debris of hadronic showers (background) for $3 \text{ GeV} < E_{\text{cluster}} < 5 \text{ GeV}$.

- Number of hits in the cluster.
- Volume of an ellipsoid fitted to the cluster.

Following the argumentation in Section 4.4, these variables will have different distributions in the barrel and in the endcap. The two regions are compared for clusters between 3 and 5 GeV in Figure 5.6. Especially the variables connected to the cluster width show the expected difference. An example for the difference in the distributions of the variables for signal (photon clusters) and background (clusters from debris of hadronic showers) in the energy region of 3 – 5 GeV is shown in Figure 5.7 for the barrel region, with the corresponding MLP output.

12. Merging of satellite clusters

As mentioned earlier, higher energy cluster can be split in two or more fragments due to the limitation in distance for clustering. If more than one of these fragments are declared to be real clusters one could draw wrong conclusions in a physics analysis depending on the total number of photons present. For particle flow jet measurements this would not have any effect since the energy is not actually lost but only redistributed (staying in the correct particle species). To decide whether to re-merge these fragments into one cluster three values incorporating properties of both clusters are computed:

- Relative distance between the two clusters
- The angle between the position vectors of the two clusters
- Ratio of energy of the smaller fragment with respect to the bigger one

Typical values for fragmented clusters have been studied over a wide energy range with single photon events so that sharp limits are set for merging. The distance between main and satellite cluster must be less than 20 mm (30 mm) for main cluster energies inferior (superior) to 15 GeV. The two latter criteria are then compared to reference values obtained by a parametrization as a function of the main cluster energy. As an example Figure 5.8 illustrates the effect of the merging procedure on the number of clusters found per event in a sample of 30 GeV photon showers. The method clearly helps to reduce the number of events where 2 or 3 clusters are found. For events with more clusters, the shower is usually spread very wide, so that the satellite clusters are at a big distance from the main cluster and the distance criterion prevents their merging.

13. Correction of stave transitions

As it has been described in Section 3.5, the design of the ECAL leads to a reduced response in the transitions between adjacent staves. The resulting dip in the energy spectrum of photon clusters over one of these corners is visible in Figure 5.9(a) (black points). The loss in the center of the dip attains about 8% and is nearly independent of the shower energy. The width of the dip in the contrary depends on the shower energy. The energy

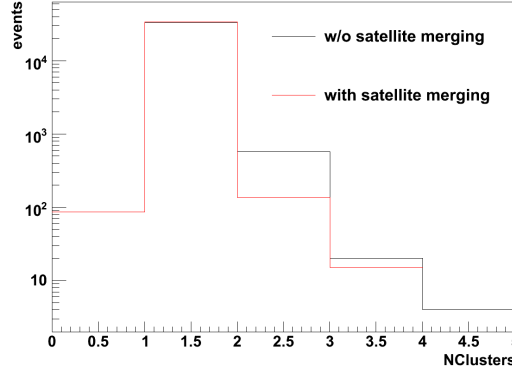


Figure 5.8: Number of clusters found per event for 30 GeV photon showers, with (red) and without (black) application of the procedure for satellite merging.

loss is approximated with a Gaussian shape, as indicated in Figure 5.9(b). Ideally, in later versions of the algorithm one would use a bifurcated Gaussian function. When fitting, the cluster energy is normalized to the MC energy in order not to affect the linearity.

$$f_{fit} = \alpha \times f_{correction} \quad (5.1)$$

$$f_{correction} = 1 - \exp\left(-\left(\frac{(\phi - \mu)}{\sigma}\right)^2\right) \quad (5.2)$$

The parameters μ and σ can be estimated for each nominal energy point and then parametrized for use inside the algorithm. The corrected cluster energy is then

$$E_{corrected} = E_{uncorrected} / f_{correction}. \quad (5.3)$$

The red points in Figure 5.9(a) show the effect of the correction on the concerned region. The use of a simple Gaussian function leaves over- and undercorrections so that the use of a bifurcated Gaussian function will surely be implemented later on.

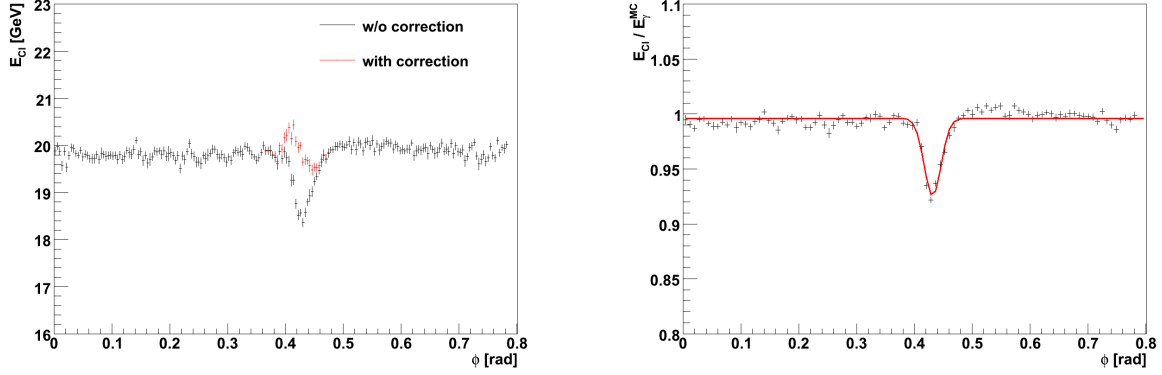
14. Determination of cluster energy

The method of clustering introduces a slight non-linearity at high energies, while the energy threshold does the same at very low energies, so that a correction on the total cluster energy has to be applied. Additionally the behavior is different at low and at high energies due to the finite cell size and the neighboring criterion.

Two 2nd order polynomials are combined to estimate the final cluster energy:

$$E_{Cl}(GeV) = aE_{raw}^2 + bE_{raw} + c, \text{ for } E_{Cl} < 20 \text{ GeV} \quad (5.4)$$

$$E_{Cl}(GeV) = \alpha E_{raw}^2 + \beta E_{raw} + \gamma, \text{ for } E_{Cl} > 20 \text{ GeV}. \quad (5.5)$$



(a) Effect of the stave transitions on the deposited shower energy and the correction implemented in GARLIC.

(b) The fitting function used to evaluate the relative energy correction.

Figure 5.9: Correction for the stave transitions in ϕ with photons at 20 GeV.

The parameters are constrained so that the function value and the first derivative of the two functions are equal at $E_{Ci} = 20$ GeV. The residuals to this function with respect to the MC energy are shown in Figure 5.10(a) for barrel and endcap. A first estimation for the energy resolution is shown in Figure 5.10(b). A fit with the usual parametrization for the energy resolution in calorimeters

$$\frac{\Delta E}{E} = \frac{s}{\sqrt{E[\text{GeV}]}} \oplus c \quad (5.6)$$

in the region $[0.5, 150]$ GeV yields:

$$\text{Barrel: } s = (17.43 \pm 0.11)\% \quad c = (2.0 \pm 0.1)\% \quad (5.7)$$

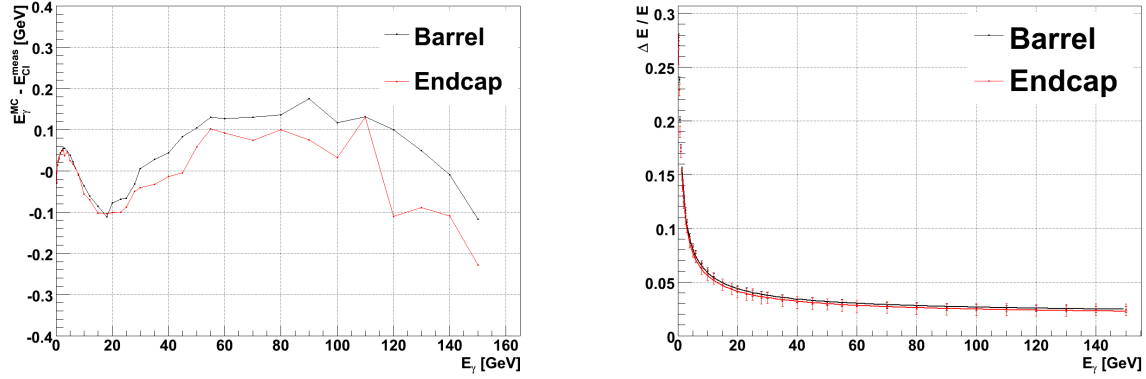
$$\text{Endcap: } s = (16.67 \pm 0.21)\% \quad c = (1.8 \pm 0.2)\% \quad (5.8)$$

This values are quite satisfying keeping in mind that no event cuts are applied, so also events in the gaps and the endcap-barrel overlap region are contained.

5.3 Performance and efficiency

5.3.1 Single-particle events

A clustering algorithm should ideally have a uniform behavior over all the detector volume. The geometry of the detector itself makes this challenging, since at the same time one would not want to introduce too many position- or angle-driven parameters. So the most important



(a) Residuals to linearity for the energy estimation with Equation 5.4.

(b) Resolution on the cluster energy estimated with Equation 5.4.

Figure 5.10: Estimation of the cluster energy.

things are a uniform response and a uniform efficiency. Investigating fractions of energies and hits clustered allows to characterize the behavior of the algorithm in certain regions of the detector.

Fraction of energy clustered The group of Figures 5.11 shows the fraction of the raw energy clustered in function of θ and ϕ for three different energies. For all energies, the dependence in θ shows clearly effects due to the inter-module gaps and the barrel-endcap overlap region. Also, at high impact angles, the fraction of clustered energy is higher. For a shower at those angles, the density of hits per volume in the shower core is higher. All those cells will be clustered, while low-energy hits induced by fluctuations will still be ignored due to the neighbor criterion. This argument holds as well for the variations in the distributions in ϕ . The plots show only ϕ values from 0° to 45° , with the inter-stave transition, around which the impact angle is maximal, in the middle of the distribution. At low energies, one can also see a small disturbance where the stave transition is located, probably because of the additional dispersion of hits in this region. The values for the clustered fraction attain 85% at 1 GeV and over 90% at 10 GeV.

Fraction of hits clustered The distributions for the fraction of clustered hits mirror the ones for the energy. Instead of retracing the equivalent quantity, the ghost hits from the gap correction have been included in the number of clustered hits (Figures 5.12). This is well visible at the inter-module gaps and the stave transitions in ϕ . One can see as well that while the absolute value is at the same level for 1 and 10 GeV, it diminishes at very high energies. Here the showers can have a bigger total radius in terms of numbers of hits.

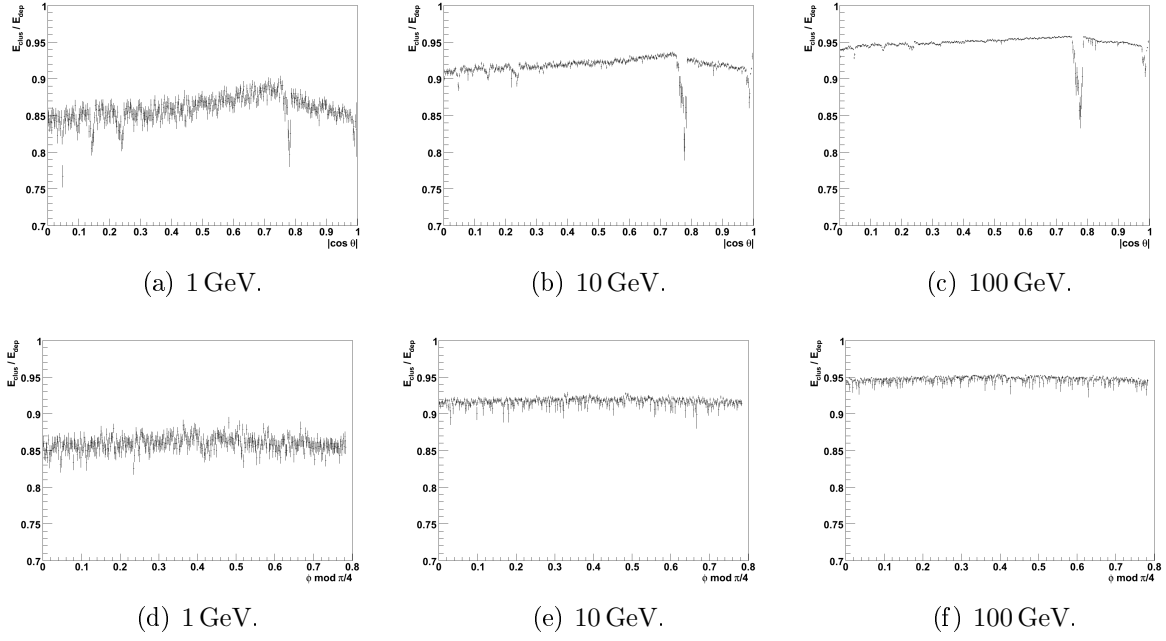


Figure 5.11: Fraction of energy clustered.

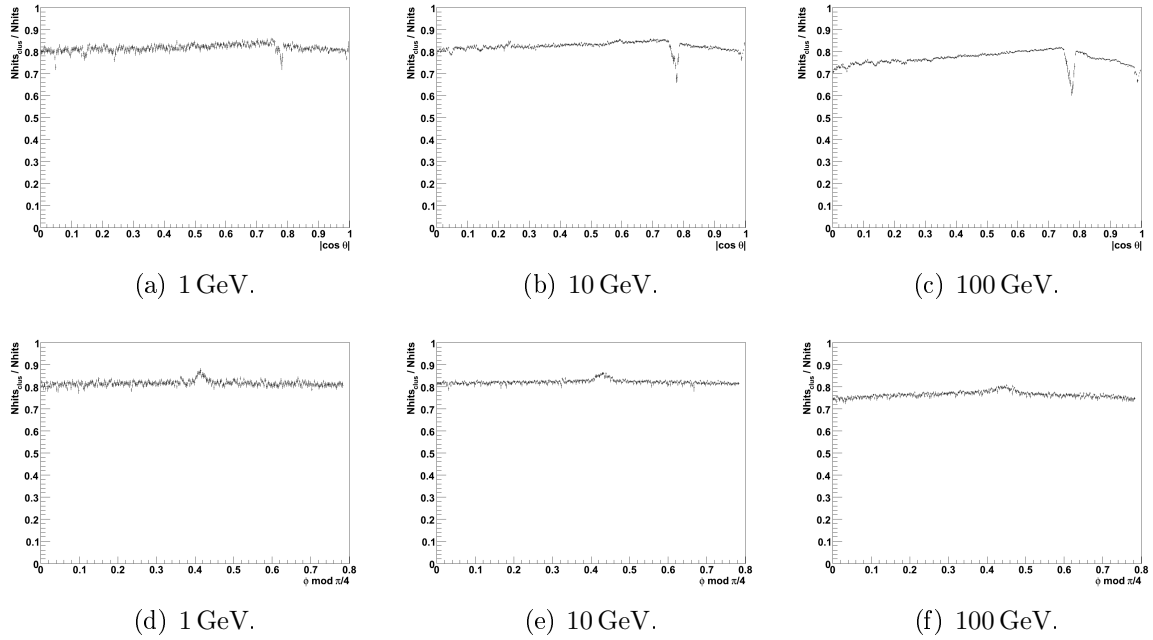


Figure 5.12: Fraction of hits clustered.

Efficiency of cluster finding To identify any problematic regions concerning the efficiency to find a cluster, maps in the ϕ and θ coordinates are shown in the group of Figures 5.13. The number of entries per bin is fable, so that these plots are very sensitive if even a single shower has not been detected. The barrel-endcap overlap zone and the module-gaps can be identified as problematic zones. The latter are even less important at higher energies.

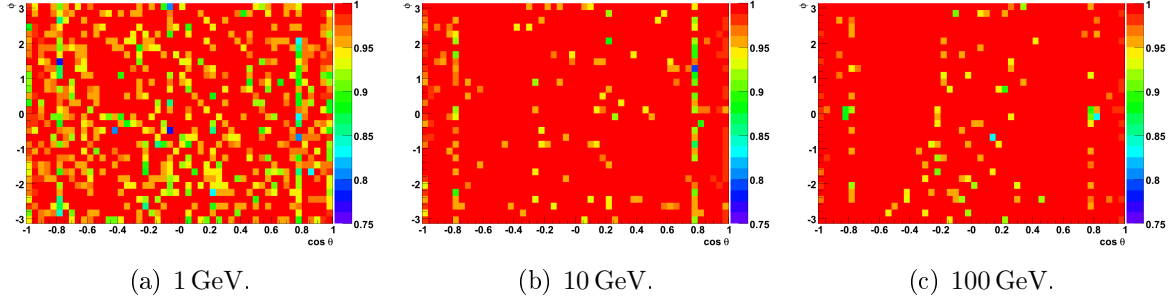


Figure 5.13: Efficiency to find a cluster.

Uniformity of the response The group of Figures 5.14 shows the response as a function of ϕ and θ . Along ϕ the response is very uniform for all energies except for the variations after the correction on the stave transitions. In θ one can notice a slight increase with higher impact angles for 10 and 100 GeV. This is due to the energy losses by longitudinal leakage. Showers at higher impact angles are better contained in the ECAL. The most problematic zone is the endcap-barrel overlap region.

Barrel-endcap overlap region In Section 4.8 it is shown that the magnetic field provokes an effective separation of the neutral and the charged particles inside an electromagnetic shower. Clustering in two different directions in the endcap will worsen the two-particle separation capabilities, while following the original shower direction, i.e. the photon part, will result in a reduced fraction of clustered energy. The second approach is implemented in GARLIC for simplicity reasons. It has the advantage, that the position estimation of the cluster is not biased by the deviation of the charged part. An example for a clustered event in the overlap region is shown in Figure 5.15(a). This is the reason for the decreased fraction of energy clustered in this part as well as the loss in clustering efficiency.

A minimization of this gap would of course yield big advantages. The separation of photons and electrons/positrons inside the shower would be less obvious. This can be seen in Figure 5.15(b) for the case where the cable gap is reduced from 10 cm to 4 cm. To account for the residual change in the main shower direction, GARLIC has a steering parameter that will modify the search direction by scaling the x and y coordinates. With a smaller gap, not only the fraction of clustered energy is smoother (c.f. Figure 5.15(c)) but also the efficiency in this

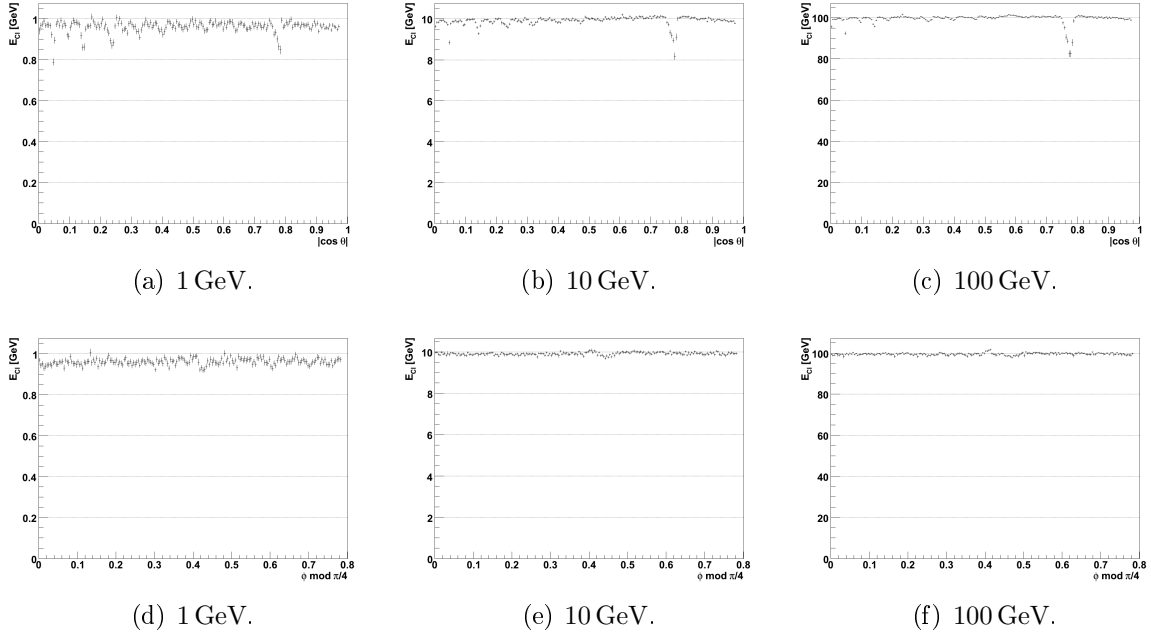


Figure 5.14: Uniformity of the response.

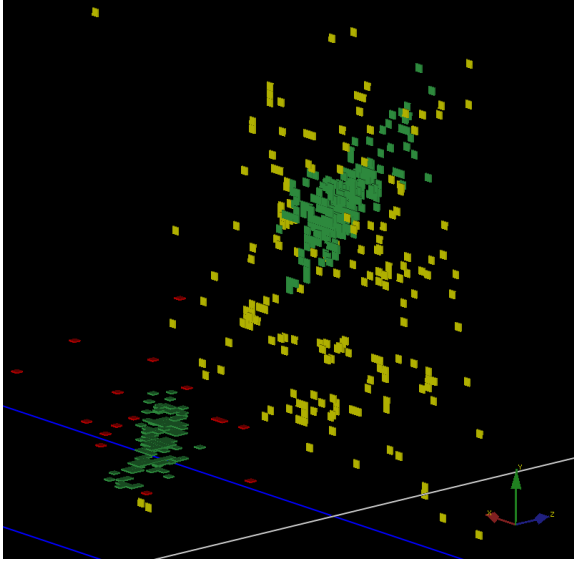
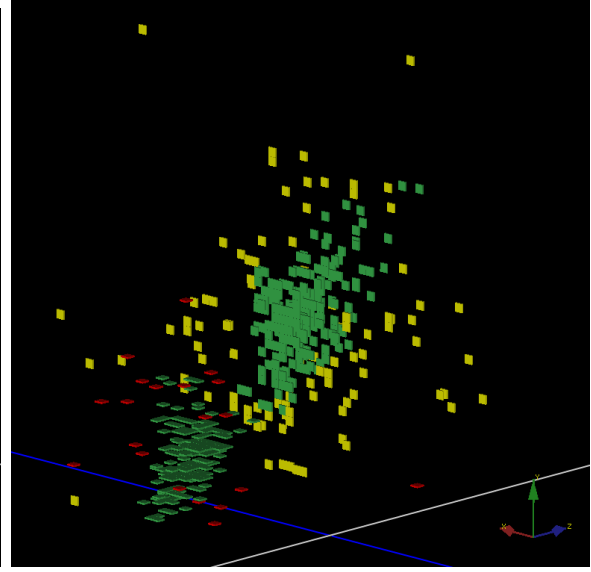
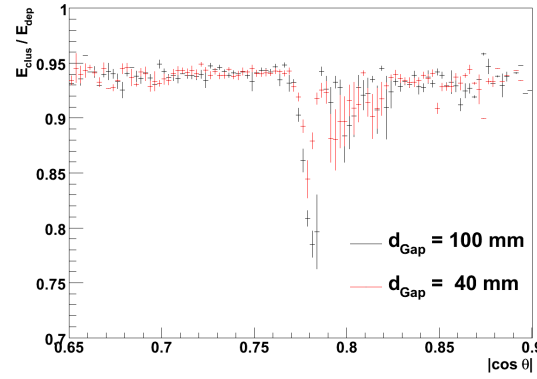
region rises. Although current R&D is still focussing on the size of the cable gap, 4cm seems to be a very challenging goal.

5.3.1.1 Single γ efficiency

Figure 5.16 shows the efficiency to find at least one cluster in single photon events as a function of the energy of the simulated particle, while intergrating over all the ECAL volume. The major parameters of the clustering that are determining this number are:

- Limited seed search in first $7X_0$
- Minimal energy cut at 150 MeV
- Minimal hits cut at 5
- Neural Network cuts

At 200 MeV the efficiency is quite low with just above 50%. The NN cuts are especially tight at these low energies because of the high background rates. At 1 GeV it is already 98%, at 1.5 GeV 98.6% and larger than 99% at energies bigger than 2 GeV. In an environment with other particles, these numbers will be modified by the distance cut to the nearest track.

(a) $d_{Gap} = 100$ mm.(b) $d_{Gap} = 40$ mm.

(c) Fraction of the deposited energy clustered by GARLIC at the barrel-endcap overlap region with default (black) and reduced (red) size of the cable gap.

Figure 5.15: GARLIC's behavior in the barrel-endcap overlap region, illustrated with 20 GeV photon showers. In the two event displays, hits are colored in red for the barrel, in yellow for the endcap and in green if they have been clustered.

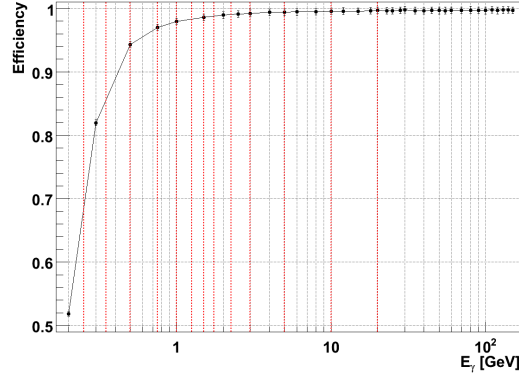


Figure 5.16: GARLIC's efficiency to find at least one cluster in single- γ events. The dashed red lines in the plot indicate the boundaries of the energy regions used in the neural network verification.

5.3.1.2 Rejection of fake clusters

Charged hadrons Misidentification of debris from showers of charged hadrons as a photon is checked with single π^- -events from 1 – 100 GeV. Figure 5.17(a) shows the average number of clusters with an energy E_{Cl} (regrouped in the regions of the NN cuts) that is created per event in charged hadron events of a given energy (colored graphs). The interaction of hadrons in the tracker region plays a very important role (see also Section 7.2.2). Rejection of π^0 's and of resulting fragments that do not have any tracking information proves near impossible. By taking into account only hadrons that do not interact in front of the ECAL the background level is divided by two. The number would be already less than 0.025 for clusters below 250 MeV and less than 0.01 for superior cluster energies for all checked hadron energies. With the interactions in the tracker region however, the mean number of fake clusters is as high as 0.05 below 250 MeV and inferior to 0.03 for higher energies. The good discrimination of e.-m. showers implies that a large part of these fake clusters are real γ 's produced in the interaction.

Neutral hadrons The corresponding background level for neutral hadrons (from K_L^0 events) are shown in the Figures 5.17(c) and 5.17(d). Missing the possibility of track extrapolation, neutral hadrons are somewhat more difficult to reject than their charged counterparts. While it would not necessarily harm the particle flow approach to identify a neutral hadron as a photon, it is likely that only part of the hadron shower will be clustered, which would make the energy measurement unusable. The electromagnetic part of a hadronic shower is generally part of the first interaction and hence centered on the direction of flight of the hadron. For charged hadrons clustering of this part is suppressed by the track extrapolation procedure. Since it is surrounded by other shower fragments, a cluster will in many cases not fulfill all shape criteria of an e.-m. shower and hence be rejected. This presents a problem at higher hadron energies, where

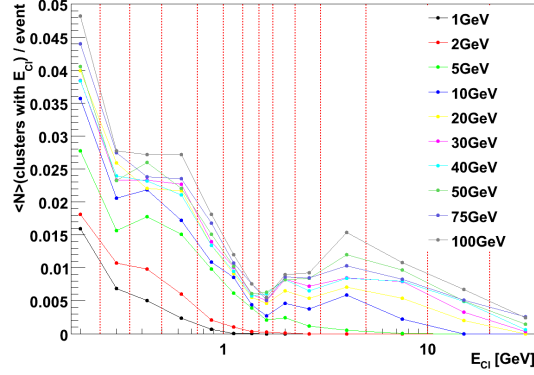
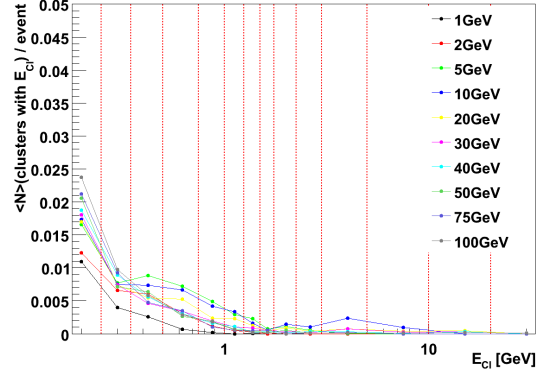
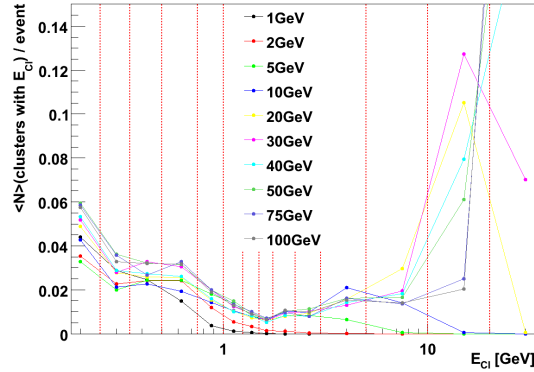
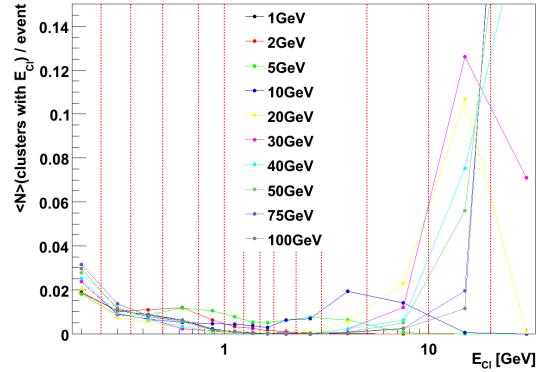
(a) π^- allowing interaction in the tracker region.(b) π^- excluding interaction in the tracker region.(c) K_L^0 allowing interaction in the tracker region.(d) K_L^0 excluding interaction in the tracker region.

Figure 5.17: Average number of clusters of energy E_{Cl} created in single particle events with charged and neutral hadrons at various energies when allowing (left plots) or excluding (right plots) interaction in the tracker region. The dashed red lines in the plot indicate the boundaries of the energy regions used in the neural network verification. For each region the point indicates the mean.

the energy in the e-m. part including the first interaction exceeds the level where GARLIC considers a cluster as a photon without any NN decision. This leads to a high mean number of clusters found above 20 GeV. Trying to reject these clusters would mean to search for near tracks to find evidence for an hadronic interaction. This necessitates an algorithm combining clustering of hadronic and e-m showers which exceeds GARLIC's capabilities.

5.3.2 Error on the impact position

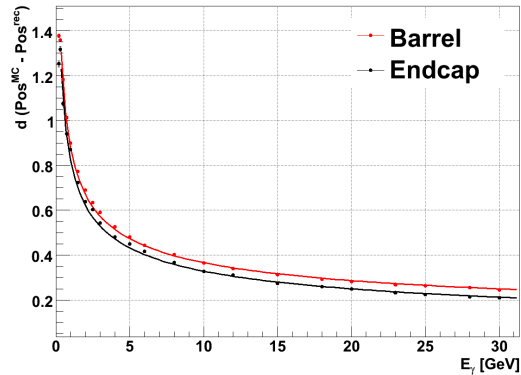
An estimation for the error on the impact position is shown in Figure 5.18(a). The distance between the two projections of the Monte Carlo direction and the cluster barycenter on the ECAL front face as a function of the photon energy is shown. The parametrization used is

$$d = \frac{s}{\sqrt[n]{E_\gamma}} \oplus c \quad (5.9)$$

where $n \approx 2.5$. At 1 GeV the precision on the impact position is:

$$d^{Barrel}(1 \text{ GeV}) = 0.90 \text{ mm} \quad (5.10)$$

$$d^{Endcap}(1 \text{ GeV}) = 0.87 \text{ mm}. \quad (5.11)$$



(a) Impact position.

Figure 5.18: Errors on the impact position on the ECAL front face and the cluster direction.

5.3.3 Application on jets

One of the goals of GARLIC is to optimize the resolution on the part of the jet energy that is carried by photons. It has to isolate the photon clusters so clustering algorithms that follow later in the reconstruction chain can complete the particle flow. GARLIC has been tested on

2000 events with two light jets ($u\bar{u}$) at $E_{cm} = 500$ GeV. To disentangle geometry effects and GARLIC's performance, the evaluation is limited to photons in the ECAL barrel and endcap volume, excluding the ECAL ring and with an energy accepted by GARLIC (i.e. higher than 150 MeV). The energy sum and the number of these photons from simulation will be called $(E/N)_{\gamma s}^{visible}$ respectively, whereas for the clustered photons this will be $(E/N)_{clusters}$. The two jets are not distinguished, so the sum is over all γ 's in the event.

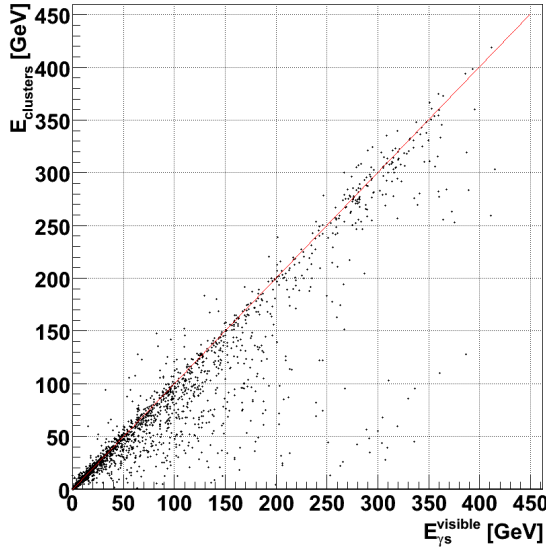
Figure 5.19(a) shows the correlation between clustered and visible MC energy. The correlation is good, even up to very high total energies where high energy photons from the radiative return to the Z boson appear. A general tendency is obvious that GARLIC rather misses photons than that it creates energetic fake clusters. Combined with the correlation of the number of clusters and MC photons (Figure 5.19(b)) this indicates that GARLIC misses only a small number of photons but it can be also those carrying a large amount of the total photon induced energy.

In Figure 5.19(c) the difference of the clustered energy and the visible photon energy as given by the simulation is shown. The large tail from missed energy when selecting all visible photons (red histogram) is considerably reduced when only selecting visible photons that did not convert in the tracker region (black histogram). This means that the energy from the converted photon was not visible to GARLIC. There are a lot of other cases though where GARLIC finds the energy of a converted photon, for example when no track information for the electron-positron pair is available, giving rise to the tail at negative values.

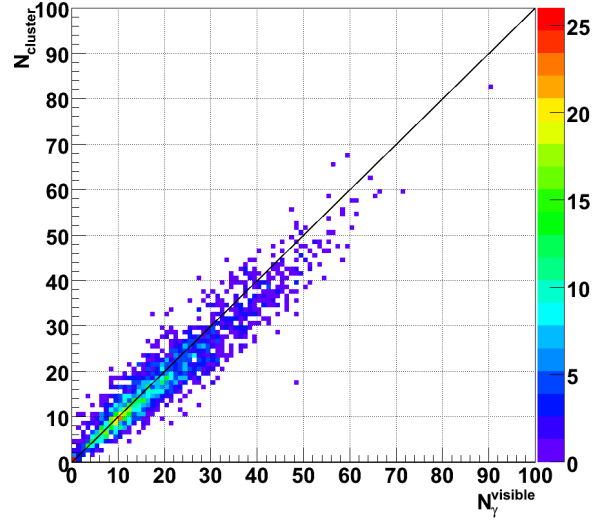
Out of approximately 50000 visible photons, GARLIC misses about 23%, but 52% of those photons were lost because they have converted in the tracker region. So "only" 11% are not found due to the performance of the algorithm. Nearly half of these have an energy of less than 500 MeV. The distribution of the missed photons in energy and along $\cos(\theta)$ can be seen in Figure 5.19(d). Certain problematic areas can be defined, like the barrel-endcap overlap at $\cos(\theta) \sim 0.78$ but also the transition to the ECAL ring at the highest $\cos(\theta)$ values, as well as some of the inter-module gaps in the central barrel region (see also Figures 5.13).

In order to estimate GARLIC's efficiency to reject debris from hadron showers, Figure 5.19(e) shows a 2d-histogram with the number of fake clusters per event that is created by GARLIC, as a function of the total energy that is wrongly identified as photon-induced. About half of the total events show at least one fake cluster. Most of the time only little energy is falsely identified as coming from photons. But also hadrons interact in the tracker region of the detector. As mentioned previously, this can create π^0 's that will then be identified as photon contribution of the jet. In over 70% of the events with fake clusters, all of the wrongly attributed energy is due to hadronic interaction in the tracker region (c.f. Figure 5.19(e)). The residual fake clusters created are concentrated in the large $|\cos(\theta)|$ region, where the tracking efficiency and

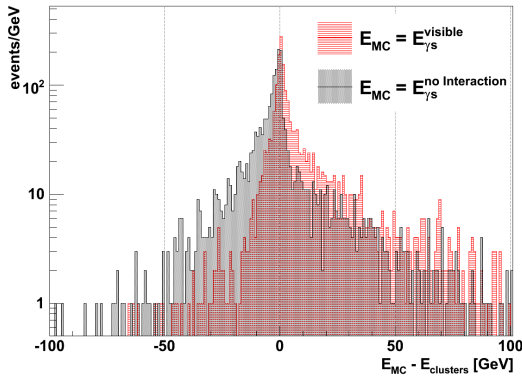
accuracy are reduced.



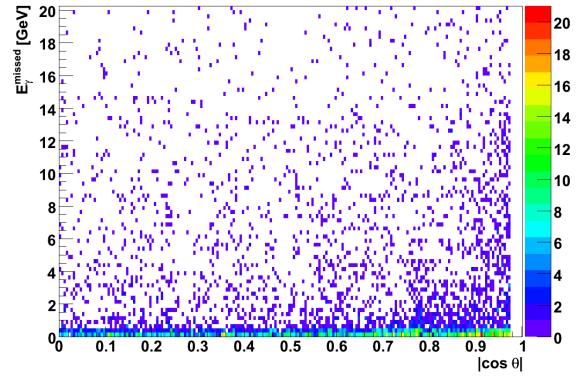
(a) Correlation between clustered energy and visible photon energy.



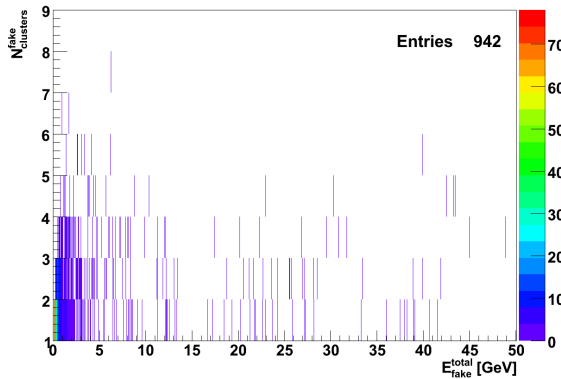
(b) Correlation between number of clusters and visible photons.



(c) Difference between clustered energy and visible photon energy (red) and when selecting only photons that are not converted in the tracker region (black).



(d) Distribution in energy and $|\cos \theta|$ of the photons missed by GARLIC.



(e) Number of fake clusters and the total energy (f) Fraction of the fake energy induced by interaction of hadrons in the tracker region.

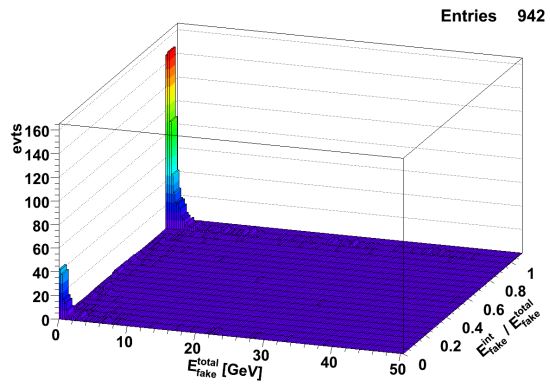


Figure 5.19: Application of GARLIC on di-jet events at $E_{cm} = 500$ GeV.

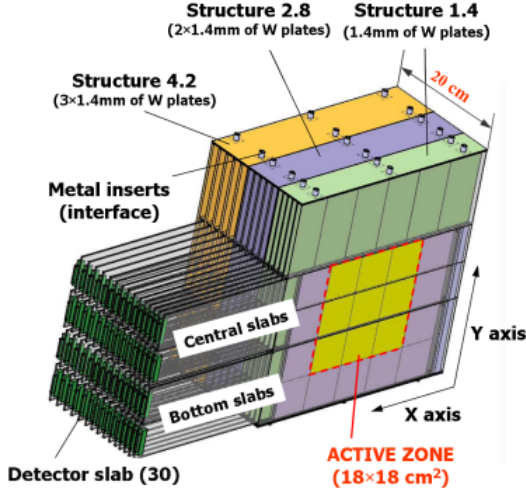
Chapter 6

The CALICE Si/W ECAL prototypes

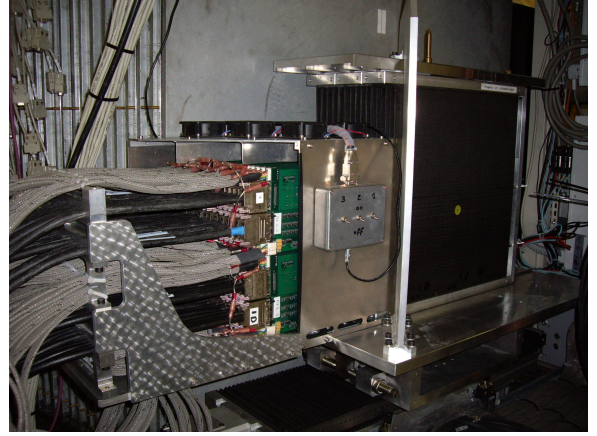
Contents

6.1	Technical description	84
6.2	Beam Tests	88
6.3	Detector calibration	88
6.3.1	Effects with influence on the detector calibration	89
6.3.2	Procedure	89
6.3.3	Results CERN 2006	91
6.3.4	Results CERN 2007	93
6.3.5	Evaluation of the long-term stability	99
6.3.6	Conclusions on the hardware design	99
6.4	GARLIC's prototype version	99
6.4.1	Performance studies with the CALICE Si/W ECAL prototype	104
6.4.2	Event Selection	105
6.4.3	Linearity and energy resolution	107
6.5	EUDET prototype	113

Studies for the ILC and its detectors are mostly based on simulations. But to prove the validity of these simulations as well as the technical feasibility and the proof of principle, prototypes for subdetectors have to be built and tested in beams. In the CALICE collaboration ([39]) different types of electro-magnetic and hadronic calorimeters have been built and tested. This chapter will describe an ECAL prototype based on silicon and tungsten and the studies that were performed to obtain its characteristics.



(a) Schematic view.



(b) Photo of the test beam configuration.

Figure 6.1: The CALICE Si/W ECAL prototype.

6.1 Technical description

As described in the previous chapters, fine longitudinal and transverse granularity is one of the most important requirements to be able to follow the particle flow approach. The choice of the absorber material is based on both the need for a small Molière radius to separate particles effectively in jets, and compactness of the calorimetric system to reduce the cost for the surrounding magnet. At the same time the ratio of interaction to radiation length (λ_{int}/X_0) should be as big as possible to avoid early starting hadronic showers. Tungsten has been chosen as passive material for the ECAL physics prototype, its properties being highly adapted to the presented needs:

- Molière radius: 9 mm
- X_0 : 3.5 mm
- λ_{int}/X_0 : 27.4

The Molière radius of the calorimeter is estimated to about 2 cm. Silicon pads of $1 \times 1 \text{ cm}^2$ have been chosen as active material, so that the cell size is comparable with the Molière radius. Thirty layers have been estimated to provide sufficient longitudinal sampling. A total material budget of $24X_0$ ensures containment of high energy showers (99.5% at 5 GeV and more than 98% at 50 GeV).

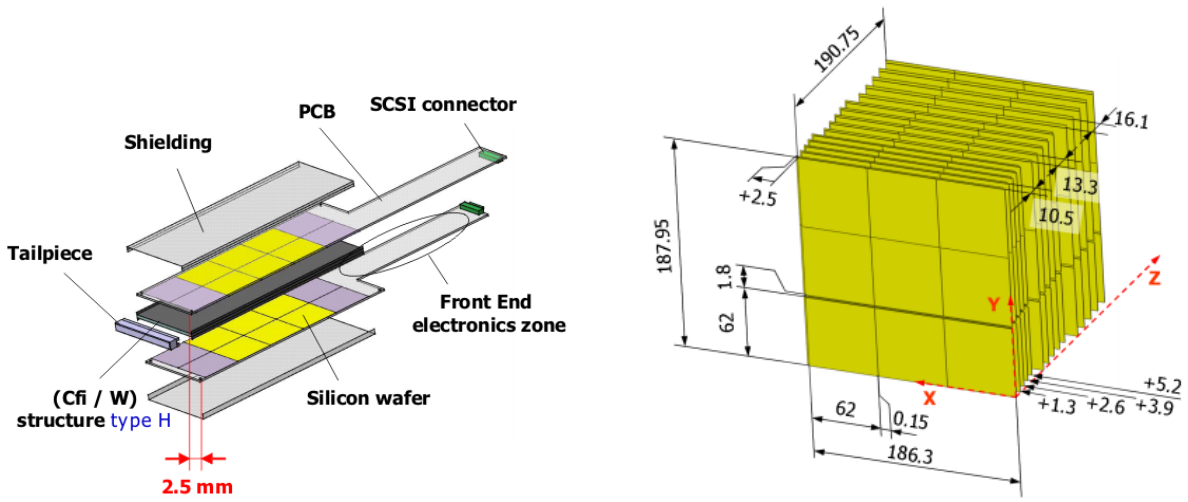
A schematic view of the prototype is shown in Fig 6.1(a). It is composed of three mechanically independent alveolar structures of tungsten wrapped in carbon fiber (also called stacks), each one holding ten layers. The thickness of the tungsten layers are different for each stack (1.4 mm, 2.8 mm and 4.2 mm). This ensures a good energy resolution also at small energies.

The prototype is divided in a central and a bottom part, separated by a layer of carbon fiber for mechanical stability. So called detector slabs are slid into the resulting alveolas. The scheme of such a slab can be seen in Fig 6.2(a). It is built of two active layers interleaved with one tungsten layer. Each PCB of an active layer can hold up to 6 silicon wafers with an area of $6 \times 6 \text{ cm}^2$ each, placed in two rows of three. In the center part, the PCB's are fully equipped, while in the bottom part only one row of wafers is present. The prototype thus has an active area of 3×3 wafers, i.e. $\sim 18 \times 18 \text{ cm}^2$, giving a total of 9720 channels.

A large effort has been undertaken to reduce dead areas in the calorimeter, in particular in connection with the silicon wafers. Three guard rings are placed around the matrix of active pads in order to prevent lateral leakage effects. They occupy a space of 1 mm. Together with the mounting gaps (0.15 mm) they present a main contribution to the total dead area. The two guard rings, mounting gaps, aluminum shielding and the carbon H-structure at the transition from the bottom to the central part add up to a total of 3.8 mm, leaving another wide gap. To avoid the inter-wafer gaps from being projective in the x -direction, layers in one slab are offset by 2.5 mm and slabs of one stack additionally are offset by 1.3 mm. The offset is illustrated in Fig 6.2(b). A very detailed description of the technical aspects of this prototype can be found in [41].

Silicon sensors The silicon wafers are 4 inch in diameter. $6 \times 6 \text{ cm}^2$ can be used as the active area. It is surrounded by three guard rings taking up a total space of 1 mm, thus totalling to a covered area of $62 \times 62 \text{ mm}$. A photo of such a silicon wafer can be seen in Figure 6.3(a). The wafers are $525 \mu\text{m}$ thick to obtain a high signal-to-noise ratio (~ 10) at the end of the read out chain. With a resistivity of $5 \text{ k}\Omega/\text{cm}$ full depletion at a bias voltage of about 150 V is ensured. The nominal operation voltage is chosen to be 200 V. Because the final detector will need about 2400 m^2 of such diodes, the production process is kept to a minimum number of steps and made as easy as possible. The wafers are then glued with a conductive glue onto the PCB's. The first wafers have been glued in 2005 and the glue shows still no signs of aging effects.

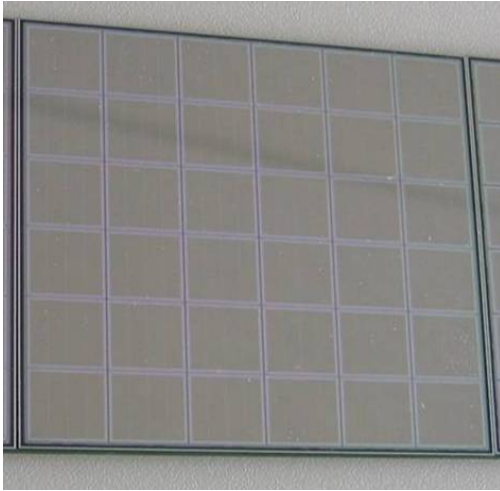
It has been observed in the test beam data that charge propagation along the guard rings around the silicon wafers can occur when a particle deposits some of its energy in the guard rings themselves. The distributed charge will induce a current in the pads next to guard ring,



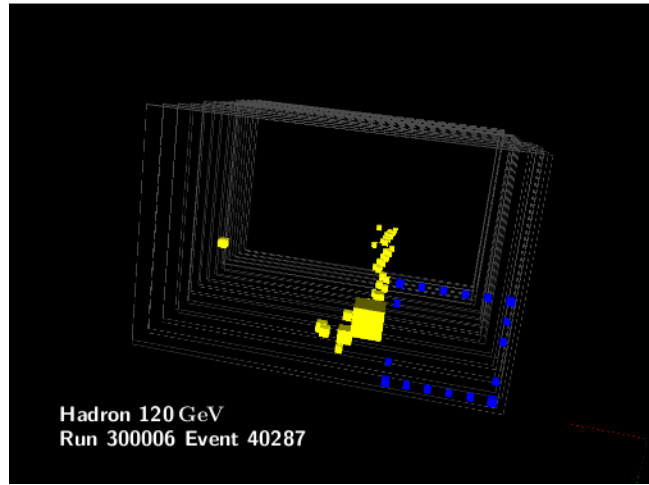
(a) Scheme of a detector slab with its components.

(b) Illustration of offsets between active layers as well as passive areas in the physics prototype - all measurements in mm.

Figure 6.2: Layout and positioning of the active layers.



(a) A silicon wafer like the ones used in the prototype. The space occupied by the guard rings can be identified by its darker color.



(b) A 120 GeV pion leaving a track (hit cells colored in yellow) in the ECAL and hitting one of the wafer guard rings. Due to charge propagation additional hits (blue) adjacent to the guard ring are created.

Figure 6.3: The silicon wafers used in the CALICE Si/W ECAL prototype and an example for an event with charge propagation in the guard rings.

leading to additional hits. This effect is shown in the event display of Figure 6.3(b). A major R&D effort is going on to solve this problem and first tests with segmented guard rings are very promising (see [40]). Also internal guard rings crossing the wafer itself can introduce such effects. Their identification and an estimation of their impact is even harder since normally they are present in the core of a shower.

Front-end electronics and data acquisition The chip used for the front-end electronics of the prototype ("FLC_PHY3") reads out 18 channels. Each silicon wafer is hence read out by two chips. The input of each channel is followed by a preamplifier with variable gain. The amplified signal is then fed to two parallel shaping filters with different gain (1 and 10) and a peaking time of 180 ns. A sample and hold device then performs the signal estimation at a given point in time (the hold time t^{hold}) which it receives from the off-detector electronics. This chain then drives a single multiplexed output. The transmission of the signal is analogue. The analogue to digital conversion is performed in off-detector boards.

Pedestal subtraction When there is no beam present, the output signal measured is the pedestal value. Originally, the determination of the pedestal per channel was foreseen with a sample of pedestal events taken in a cycle with the beam events but with random trigger outside the spill period.

Unfortunately it has been observed that during the beam operation the pedestal for all the channels of one PCB can frequently suffer a significant shift. The reason is that the power supply lines for the PCB's are not isolated. This results in a random change in the working point of the output signal lines. Hence it is necessary to calculate the pedestals on an event-by-event basis. First the average pedestal value obtained in the pedestal events is subtracted from the signal in each channel. For each PCB, wafers without signal hits are then selected and the mean value over these channels is calculated in an iterative procedure to exclude bias from a residual signal in any of the channels of these wafers. The mean value is then used as the new pedestal. This procedure has proved successful in correcting for the correlated pedestal shifts. However, recent tests have revealed that the shift can actually be different from chip to chip on the same PCB. A correction per chip inside a shower is hardly possible. Consequently, a residual effect of the shift is to be expected.

A different effect with influence on the pedestals can occur for wafers that record a high signal. The pedestal will drop in strong correlation to the amplitude of the total signal in the wafer. A correction similar to the one used for the pedestal shifts per PCB has been established by considering averages per wafer while discarding cells with a hit. It is equally successful in the correction of the effect for not too high occupancies. A review of the electrical circuits has revealed that this effect can be avoided by changing values of capacities connected to the silicon diodes. As discussed in Ref [41] the total pedestal subtraction is performed with an accuracy of 0.1 ADC counts, corresponding to 0.2% of a MIP.

6.2 Beam Tests

From 2006 to 2008 this prototype was exposed to particle beams over 4 time periods at 3 major particle physics institutes. Tab. 6.1 lists the different periods of data taking with particle beams. Every period included physics (hadrons, electrons) as well as calibration (muons) events (except DESY) at several different impact positions and angles from 0 to 45 degrees. Data taking over a period of three years also allows tests of the long-term stability of the detector and its components. For each period a detailed simulation model exists in the Mokka [35] framework representing the whole test beam setup, including parts of the beam delivery system, upstream detectors (if present) and the other participating CALICE calorimeters.

Year	Location	Instrumented channels	Physics data taken
2006	DESY	5184	e^- from 1 to 6 GeV
2006	CERN	6480	e^-/e^+ : 6 - 45 GeV π^-/π^+ : 6 - 60 GeV
2007	CERN	up to 9072	e^-/e^+ : 6 - 90 GeV π^-/π^+ : 6 - 180 GeV
2008	FNAL	9720	e^-/e^+ : 1 - 30 GeV π^-/π^+ : 1 - 60 GeV

Table 6.1: Summary of data taken in test beams.

At DESY, the test environment does not allow to generate muon beams, for all the other periods high statistics muon data samples were taken to perform the MIP calibration of the silicon pads. Additionally, after assembly, each detector slab has been tested with a "Cosmics test bench". Like this, calibration constants could as well be obtained with cosmic muons. Because the data acquisition was different during these cosmics tests, direct comparison with the constants obtained from beam data is not possible. The studies here were limited to measure correlations. All in all, these data present an excellent basis to show the excellent stability of the response signal of the detector over the time range of several years.

6.3 Detector calibration

A natural unit to quantify the response of a calorimeter is the energy deposited by a minimum ionizing particle (MIP). The calibration factor from ADC counts to the MIP equivalent needs to be extracted per channel. Fully assembled detector slabs were tested on a cosmics test bench before the actual construction of the module. These results obtained before installation in the prototype assure the possibility to perform long-time studies on degradation on the signal quality, the number of dead channels or the signal/noise ratio at the MIP level. During the test beam periods muon events have been recorded to calibrate the detector in the in situ setup.

To provide a coverage of the whole active area of the prototype the only change needed in the setup is the use of a trigger different from the one for beam events. In order to cover also the full active area of the other CALICE prototypes present, muon events have in general been recorded with a $1 \times 1 \text{ m}^2$ scintillator counter, while triggers of smaller sizes were used for beams of other particle species. Due to the difference in response time, cable length and signal shape the MIP response is not necessarily expected to match perfectly with the one in beam events.

6.3.1 Effects with influence on the detector calibration

Silicon thickness The thickness of the Silicon layers ($525 \mu\text{m}$) is guaranteed within a tolerance of $16 \mu\text{m}$. The signal of a MIP, i.e. the number of electron-hole pairs created in the silicon is proportional to the thickness passed. So the variation of the calibration constants due to the silicon thickness is of the order of 3%.

High Voltage The gain depends linearly on the size of the depletion zone in the silicon. This size is controlled via the applied high voltage. At the nominal operation of 200 V, the silicon wafers are fully depleted, so that the size of the depletion zone does not change. The minimum accepted breakdown voltage is 400 V, but it can be as high as 800 V in some cases. In this regime, the gain is completely stable.

Temperature As for the high voltage, the gain of the Si diodes is insensitive to changes in temperature. What will be influenced though is the gain of the read out electronics. The change is estimated not to exceed 0.1 MIP/deg.

Hold value As described earlier, the signal of a channel is passed through a shaper with a shaping time of 180 ns after the pre-amplification and then sampled at the hold value t^{hold} . Ideally the signal is sampled at its maximum. t^{hold} is usually measured starting from the event trigger. This means that it has to be well adapted to the experimental setup and in particular re-adapted in case of any changes (e.g. change of trigger, cable-length etc.). Figure 6.4 shows the theoretical shape of the read out signal with the parameters of the electronics used in the prototype. As an example read out at two different hold values are shown, with $t_1^{\text{hold}} = 180 \text{ ns}$ being the ideal value and $t_2^{\text{hold}} = 224 \text{ ns}$ an example for a very bad determination. The signal amplitude changes by 2.5%. This has a direct influence on the calibration constants.

6.3.2 Procedure

The MIP signal is obtained channel per channel with a large amount of data to minimize statistical fluctuations. The starting point for the calibration procedure are pedestal subtracted values. The accuracy on the pedestal subtraction mentioned earlier gives a systematic error on the calibration constants. All cells are first calibrated with a constant calibration factor of

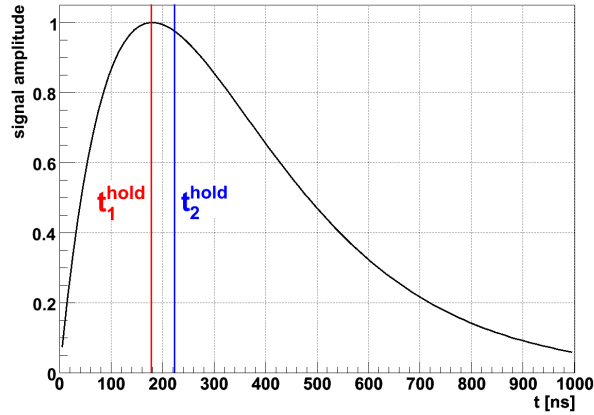


Figure 6.4: Theoretical shape of the signal output from a 180 ns shaper as it is used in the prototype electronics. The plotted function is $f(x) = x e^{(1-x)}$, with $x = t/180\text{ns}$.

50 ADC counts per MIP that has been estimated from early measurements with cosmic muons with the DAQ system used for beam data. The actual calibration constants are then calculated relative to this constant value.

Event selection is performed by requiring reconstruction of a MIP track in the detector. These tracks are built of segments of minimum 3 hits at a distance of less than 30 mm from each other. The built-up tracks are then validated by asking at least 10 hits and a minimal total signal amplitude of 5 MIP. Furthermore a line fit is applied to the track and a cut-off of 3 has been chosen for the χ^2/NDF of this fit.

A histogram per channel is then built from the signal response in the selected events. The entries in this histograms vary between the different running periods as well as over the surface of the detector since the surface coverage is not completely uniform. The function used to extract the relevant parameters is a Landau convoluted with a Gaussian function. The most probable value of the Landau function gives the calibration constant. At the same time the standard deviation of the Gaussian gives an estimation of the noise for the same channel. To avoid effects from δ -rays (see Section 4.2) and to cut out the electronic noise, the fitting range has been limited from 25 to 78.5 ADC counts. An example of the fit is shown in Fig 6.5.

If one extends the fitting range over the whole signal spectrum, the difference found is 0.00 ± 0.02 ADC counts average over all channels. The spread between the channels is 0.146 ± 0.001 ADC counts. This together with the uncertainty on the pedestal subtraction make up a total systematic uncertainty of about 0.18 ADC counts, corresponding to 0.4% of a MIP. The mean spread between chips being 0.78 ± 0.02 ADC counts, this value is taken as additional systematic error for the cells that had to be calibrated with a neighboring cell.

Some silicon pads show a higher contribution of the noise. For these pads - an example is shown in Fig 6.6 - the noise contribution has been fitted with a falling exponential function

and then subtracted from the histogram before applying the actual fit. Furthermore a few pads had to be calibrated using neighboring pads due to a deformed spectrum in the signal output. One wafer has been found to be not fully depleted when connected to the nominal voltage, thus showing no MIP signals above 25 ADC counts. From the results during the cosmic test bench the ratio of the mean signal of this wafer and one of its neighbors has been found to be 0.517. Using this value a relative calibration of the cells in this wafer has been applied.

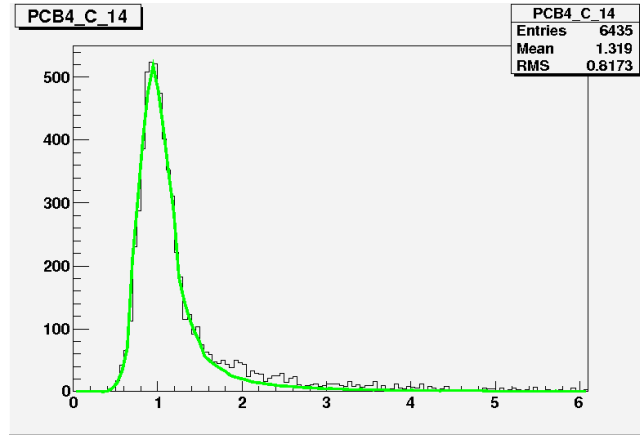
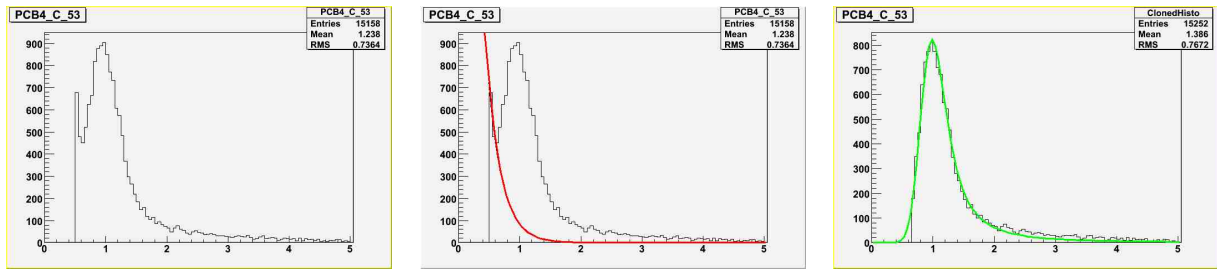


Figure 6.5: Example histogram of the response signal of one silicon cell to muons. The cell has been pre-calibrated with $1MIP = 50$ ADCcounts. The fitted function corresponds to the convolution of a Landau and a Gaussian function.



(a) Initial MIP response.

(b) Refit of the noise with an exponential function.

(c) Fit of the resulting histogram after subtraction of the fitted noise.

Figure 6.6: Refitting Procedure of the MIP response for cells with elevated noise level.

6.3.3 Results CERN 2006

The first results presented here are from the sample taken at CERN during the October running period. This set of calibration constants served historically as reference since the first

electron data runs analyzed were taken in this period.

A calibration constant with the standard procedure could be obtained for 6403 of the 6480 instrumented channels of the prototype. Only nine channels, i.e. 0.14%, show read-out problems and are thus declare dead. For 32 channels the fit fails due to a high noise contribution. 18 are recovered by subtracting the fitted noise, for 14 the calibration constant of a neighbor is adopted.

For the August sample, 14 cells had to be declared dead (0.22%) because they did not show any usable signal. This means that some cells actually restarted working in the second running period. This allows to conclude that some of the problems are actually likely to be induced by the read out chain, i.e. very front-end electronics, SCASI connectors, cables etc., and not by the silicon matrices themselves. Values for seven cells had to be replaced by the ones of their neighbors, 26 had to be refitted with the advanced procedure.

The calibration constants ordered by the geometrical cell index¹ are shown in Figure 6.7(a) for August (top) and October (middle) separately. Both show the same trends. One can mark out three different levels of response. These can be identified with the production dates as well as the origin of the Si wafers. The first group, forming layers 0-13 as well as 20 (shown in red) were produced in 2004 in Moscow. The response of the second group (shown in green) is slightly higher. They have been produced in 2005/2006 at the same institute and equip now the layers 14 to 19, 21 and 24. The third group (shown in blue), making up layers 22, 23 and 25 to 29 has been manufactured in Prague in 2006.

To show their stability in time the calibration constants obtained in both periods have been compared. Figure 6.8(a) (left) shows the direct correlations. The correlation coefficient is 96.3%. The black line corresponds to a linear regression with a slope of 0.97 and an offset of 2.2 ADC counts. The outlier wafer is not shown on the plot but aligns very well with the black line. The global offset is further investigated with the absolute difference of the calibration constants (c.f. Figure 6.9(a)). It is overlaid by an additional effect that seems to depend on the PCB (or layer), to be identified by groups of 216 channels. In average the shift is of 0.76 ADC counts, i.e. 1.7%. This indicates a change in the trigger setup between the two running periods that has not been recorded in the log books.

Pion runs from both periods are used for futher comparison. As it has been mentioned earlier, the pion data were taken with a different trigger setup, i.e. a different hold setting. Because the statistics in these runs are limited, only cells with enough entries in the MIP signal histograms and for which the fitting procedure converges immediately, are used. For the comparison in the October period (Figure 6.9(b)) we can observe a shift of 1.8 ADC ($\sim 4\%$), while the values for the pion runs are bigger than those for the muon runs. This implies that the muon sample has probably not been taken with the optimal hold value. The same tendency is present in the August period. The difference here is 1.3 ADC ($\sim 2.9\%$). Again the pion values are superior to those obtained with muons.

¹The geometrical cell index for the central part of the prototype is defined as $i = 216 * LayerNr + 36 * (2 * WaferColumn + WaferRow - 1) + (6 * PadColumn + PadRow)$.

The differences observed are very big. With the help of the theoretical signal shape of Figure 6.4, one can estimate that a delay of 75 ns is necessary to account for the difference between muon and pion runs. Different trigger setups have been used for the two samples, but this means that the muon runs were clearly taken off-peak. Also the difference between the muon runs in August and October would necessitate a delay of the order of 35 ns. This is only possible with a major change in the trigger setup. The observed difference between the two periods of pion runs is only 0.02 ADC and thus negligible. This is hence an indication that the setup for pion and electron data taking was not changed between the periods and runs at different points of time are comparable without further corrections.

6.3.4 Results CERN 2007

In 2007 the prototype was gradually more equipped. To facilitate comparison with the results mentioned previously, we will treat the central and the bottom part of the detector separately.

Central part The number of broken pads (15) is slightly increased with respect to 2006 (9), totalling 0.23%. Not counted here is a read out problem shown in Figure 6.11, where a loose connector was responsible for the fact that 29 cells have not been read out during the muon calibration and parts of the other data taking periods. The problem shows a particular structure. One entire chip is not read out (three by six pads). Additionally the first value of each multiplex sample is omitted. For 215 channels, the refitting method with noise subtraction had to be applied. For 15 more cells the values have been adopted from their neighbors. Four of the cells that were declared dead for October 2006 show a signal in 2007.

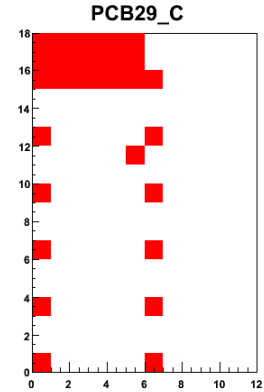
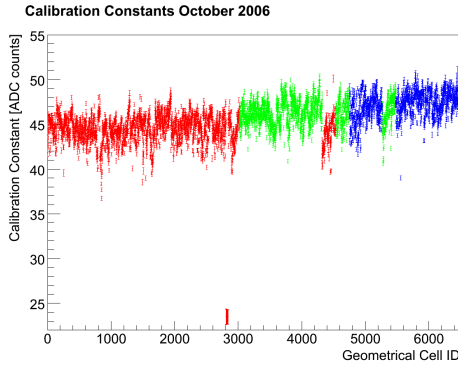


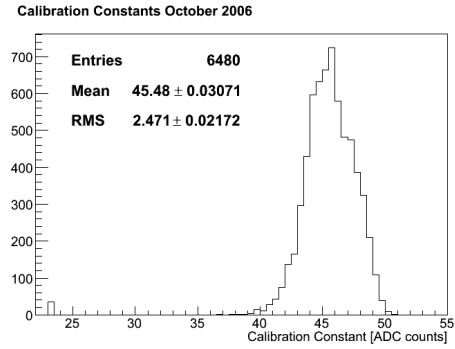
Figure 6.11: Read out problem for PCB29_C during the 2007 muon calibration: Shown is a map of the cells on the PCB. The 29 shown in red are not read out.

Comparison of the calibration constants with those of the previous running periods (c.f. Figure 6.7), show that the obtained values are globally higher. Also their spread has a higher level. When comparing them to the October'06 values (Figure 6.10(a)), one finds that the mean difference is 3.4 ADC counts, which corresponds to 7.6%. The correlation (to be seen in Figure 6.8(b)) still yields 89.2%. The black line corresponds to a linear regression with a slope of 0.974 and an offset of 4.62. This suggests a major change in the experimental setup with respect to the previous year.

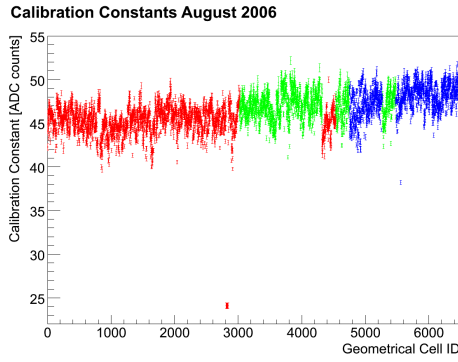
The obtained values from muon and pion runs for this period match very well (c.f. Fig-



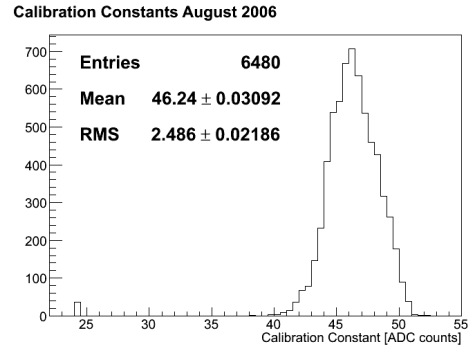
(a) October 2006



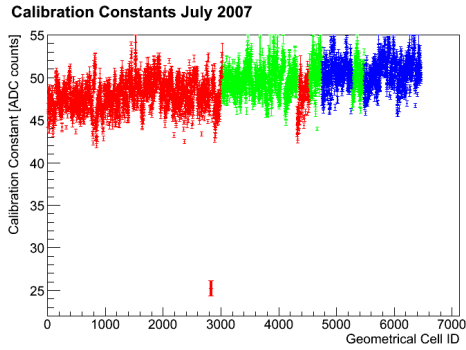
(b) October 2006



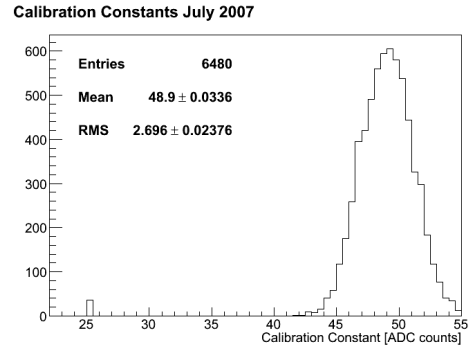
(c) August 2006



(d) August 2006



(e) July 2007



(f) July 2007

Figure 6.7: Absolute ADC counts per MIP (inverse calibration constant) in function of the geometrical cell index (left) and as a projection histogram (right) for different data taking periods.

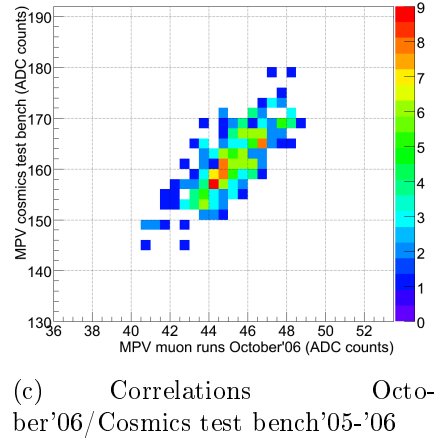
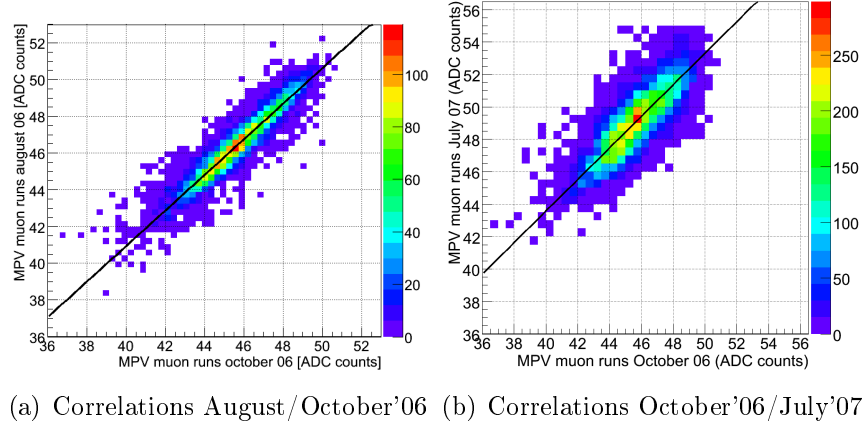
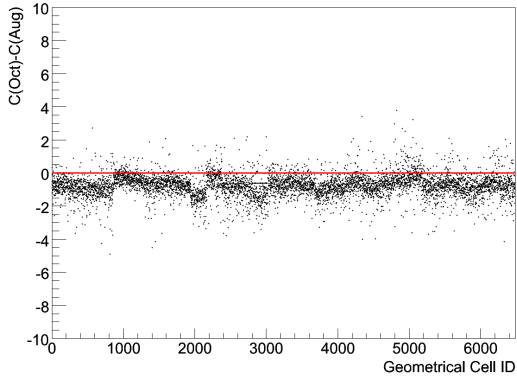


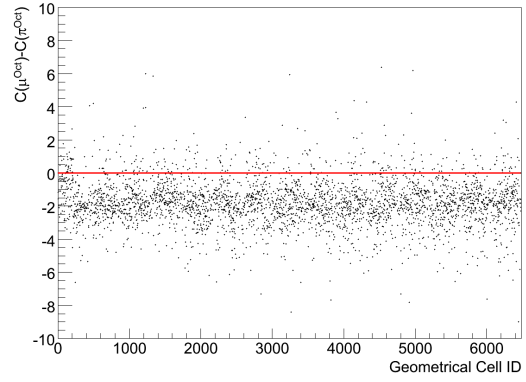
Figure 6.8: Correlations between the calibration constants obtained at various periods.

Absolute difference August'06/October'06

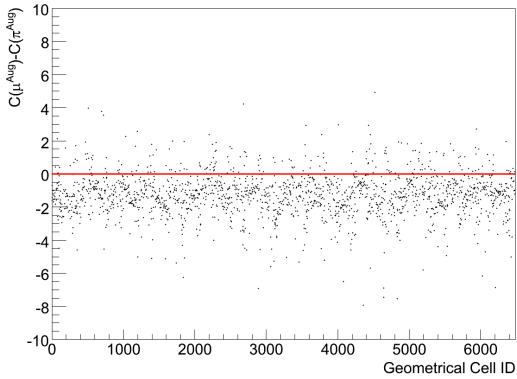


(a) muon runs: October'06 - August'06

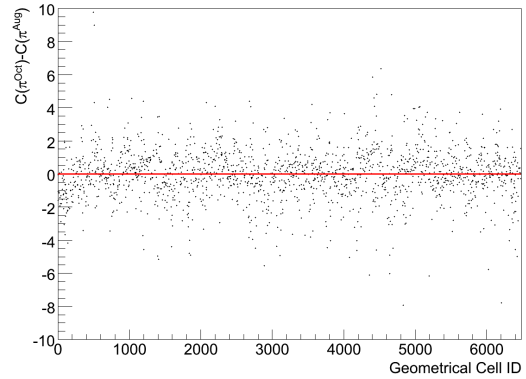
October '06 - Comparison with pion runs

(b) October'06: $\mu - \pi$

August '06 - Comparison with pion runs

(c) August'06: $\mu - \pi$

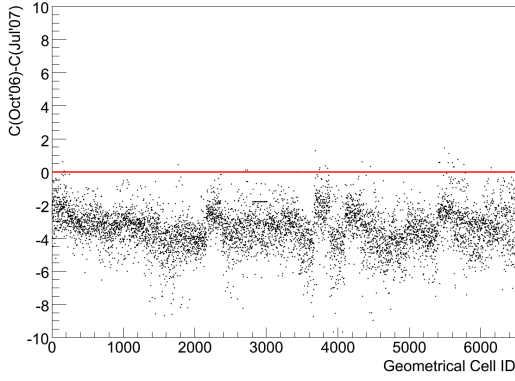
Comparison between pion runs in October/August '06



(d) pion runs: October'06 - August '06

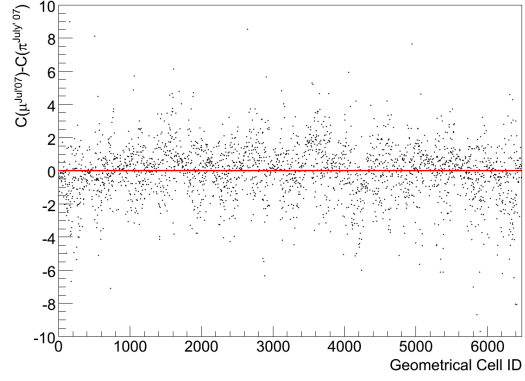
Figure 6.9: Absolute differences between various sets of calibration constants obtained with muon and pion runs in the August/October'06 data taking periods.

Absolute difference July'07/October'06

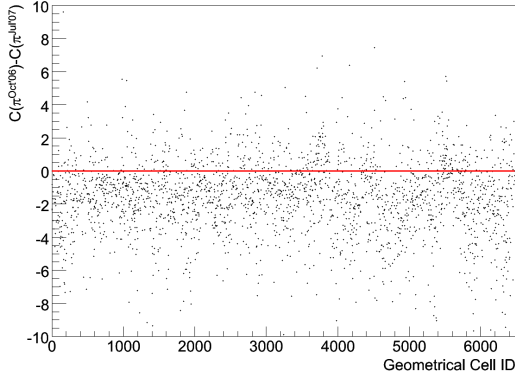


(a) muon runs: October'06 - July'07

July'07 - Comparison with pion runs

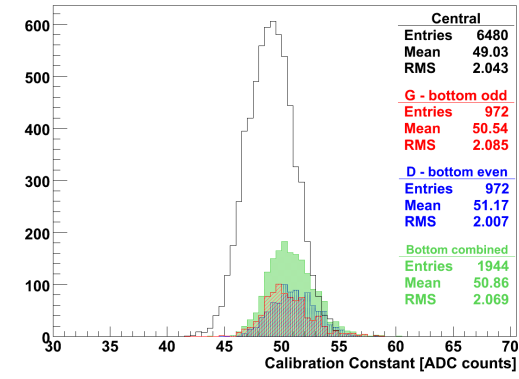
(b) July'07: $\mu - \pi$

Comparison between pion runs in October'06/July'07



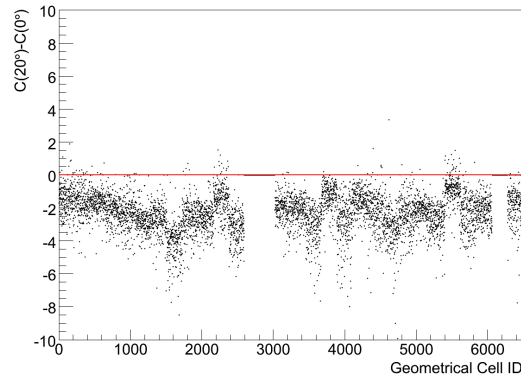
(c) pion runs: October'06 - July'07

Calibration Constants per zone



(d) July'07 calibration constants for central (C), bottom odd (G) and even (D) parts

Absolute difference - July' 07: 0°/20°



(e) July'07 at different impact angles: 0° - 20°

Figure 6.10: 2007 calibration: Absolute differences between various sets of calibration constants obtained with muon and pion runs in the October'06 and July'07 data taking periods and comparison between central and bottom parts of the prototype, as well as comparison at different impact angles.

ure 6.10(b)), with an offset of only 0.08 ADC. Comparing the same pion runs to those taken in 2006 (Figure 6.10(c) yields a global offset of 1.6 ADC (3.6%), so an analysis combining data of these two years will have to take this difference into account.

Bottom part A comparison between the calibration constants of the central and bottom part is shown in Figure 6.10(d). The bottom part of the prototype is divided into two groups. Since only one row of wafers is equipped here and every other PCB is flipped we distinguish between even (D) and odd (G) layers ².

We can see from Figure 6.10(d) that there is no significant difference between the two parts. The odd layers are shown in the blue vertically striped histogram, the even ones in the red diagonally striped histogram.

Because of the wide spread of the calibration constants for the central part, the difference in the means for the central part and the combined bottom part is quite big. Here one has to take into account that this part is equipped exclusively with silicon wafers produced in Prague after 2006. When we compare with Figure 6.7(e), we can see that the level of the blue group that represents the production at the same institute just one year earlier matches well with the now obtained values.

A notable problem is though the high number of non-functional cells: 123 cells in the odd layers and 63 in the even layers had to be declared dead. This is partly due to several cases where entire chips have not been read out (4 in the even, 1 in the odd layers). In a recent retesting of the concerned slabs with cosmic muons, these chips/cells have been found alive. Investigation of the origins of this problem is still ongoing.

At 20° incidence Data runs have been taken at different angles of incidence. To compare the detector performance, a calibration set at each of the different points analyzed could help to disentangle effects introduced by the rotation. Only the sample at 20° incidence is shown here. Statistics are limited but should still allow a solid conclusion.

Since the MIP signal should be proportional to the Si thickness crossed, one expects naively an increase of about 6.4% in the signal. This is in strong contradiction to what is observed. The mean absolute difference of the two sets of calibration constants, as shown in Figure 6.10(e), is of about 2.3 ADC counts (i.e. $\sim 5.1\%$), but herein the set for the rotated position is actually the one at lower values. This can again only be explained by changes in the setup. Several configurational changes have indeed been undertaken between the periods but none can be clearly identified to give rise to this contradiction. Since undocumented additional changes are very likely, the actual source of the problem remains unknown so far.

²"D" and "G" stand for French "droite" and "gauche" - right- and left-handed respectively

6.3.5 Evaluation of the long-term stability

The long-term stability can be tested by a comparison with the very first tests, performed in 2005 and 2006 at a test bench for cosmic muons. Since data taking at the test bench was done per chip, the calibration constants for the October'06 period have been regrouped respectively and are shown together with the results from cosmic muons in Figure 6.8(c). The correlation factor is 73.2%. This includes three outlying chips, two that are responsible for the read out of the non-fully depleted wafer and one that showed very high noise in the cosmics measurements.

In general, the correlations between the values obtained in the different periods are very good. This reflects the long-term stability of the detector. A problem that remains is though to understand the big global offsets observed. A big change in the trigger setups has not been documented and the only evident remaining explanation - the change of the hold values - is doubtful, since to obtain the observed differences, big shifts would have to be introduced. The most likely explanation is thus an unidentified exterior effect that amplifies these changes. The global offset between pion and muon runs should be subtracted when runs with the "data" trigger setup are analyzed.

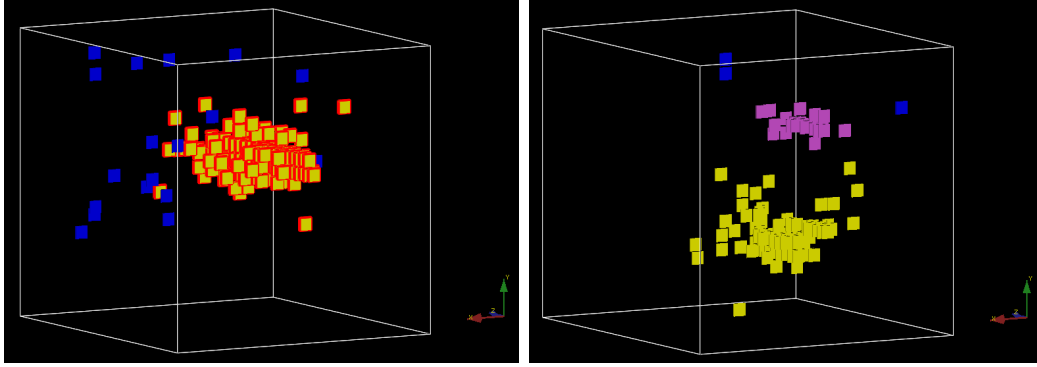
6.3.6 Conclusions on the hardware design

Already at this stage, the silicon wafers proved highly suitable for use in a long-lived high-energy physics experiment. After four years of operation, long and frequent transportation and several manipulations in (de-)installations at test beam facilities, neither the wafers themselves nor the conductive glue show any aging effects that lead to a rise of the noise level or a reduced signal output. The problems discovered could be traced back to the electronics or the data taking setup. Several corrections are already implemented in more recent versions of the read out chips. Also the design of the silicon wafers is revised to avoid known problems due to the guard rings. During the construction and installation phases, the alveolar structure and the concept of detector slabs proved practical and easy to manipulate. Also the mechanical design seems to be easily extendable to suit full detector dimensions.

6.4 GARLIC's prototype version

To test and validate the performance of the algorithm as well as its impact on linearity and energy resolution with real data, GARLIC has been adapted to reconstruct electron showers recorded in test beams of the CALICE Si/W ECAL prototype. Differences in this version with respect to the one used for the full detector studies are marginal. The main functions of the algorithm differ only where the two different geometries to be treated interfere. Furthermore the track extrapolation and the neural network verification are not performed. We will see that even without these two components, GARLIC delivers an excellent tool to perform event cleaning. An example of a reconstructed shower with GARLIC can be seen in Figure 6.12(a).

Since the treated cell size is $1 \times 1 \text{ cm}^2$, the incidence is perpendicular to the ECAL front face and the focus lies on energy resolution studies, a slightly bigger search radius for "neighbor" hits has been chosen. Two iterations with a maximum distance of two times the cell size are performed. This gives as well the possibility of additional cleaning of the event samples with simple means as described later (Paragraph "Event cleaning").



(a) A shower of a 6 GeV electron in the ECAL prototype. The cells marked yellow have been clustered with GARLIC. (b) An electron event with an upstream interaction. Two clusters were found by GARLIC (yellow and purple cells).

Figure 6.12: Event displays of electron showers in the CALICE Si/W ECAL with application of GARLIC.

Gap correction The gap correction in the prototype version is kept as simple as possible. The "Ghost Hits", as described in Section 5.2.1 under Item 9, are re-weighted by the area factor only. Figure 6.13 shows the location of all hits recorded integrated over several thousand electron events. In black the center of the silicon cells are shown. One can easily identify the gaps between individual wafers. "Ghost Hits" introduced by GARLIC to fill these gaps are shown in red.

The simplicity of the method features several disadvantages. At perpendicular incidence the additional virtual energy deposit introduced will strongly depend on the distance of the shower maximum to the gap. Some of the resulting effects are visible by eye in Figure 6.14(a) where the corrected and non-corrected energy deposit for 10 GeV electron events are shown in function of the x coordinate of the shower/cluster barycenter. The events have been constrained to the central part of the wafer row in y in order not to mix the two gap effects. In the central plateau a small artificial slope with increasing x can be observed in both distributions which indicates an exterior effect, e.g. the beam spread. The energy loss is reduced from about 15% to about 10%. Figure 6.14(b) shows the same comparison but at an angle of incidence of 20° and for electrons of 20 GeV. Here the effective width of the gaps is bigger and we see clearly an overcorrection at the edges of the gaps. If we accept this additional effect, the energy loss

is reduced considerably from 10% to a residual of a few %.

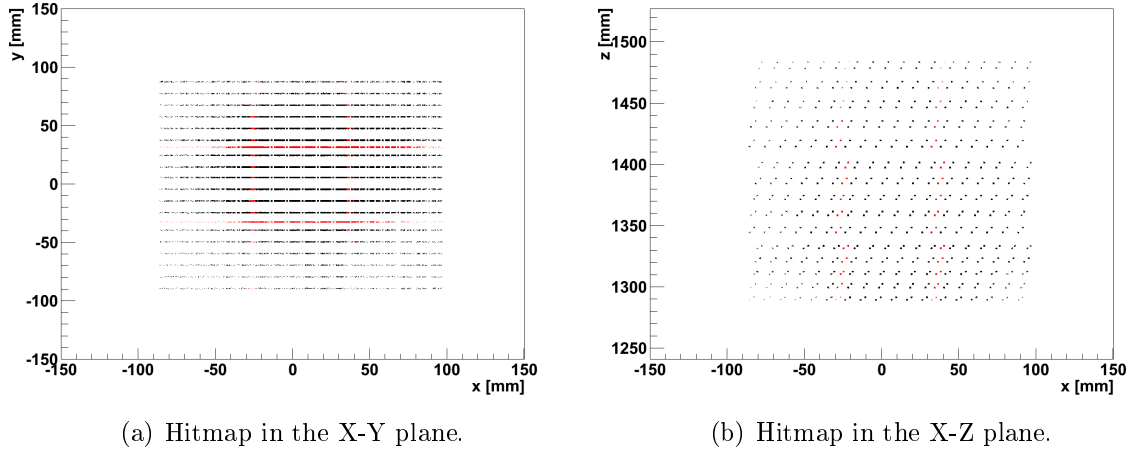


Figure 6.13: Hit maps for an electron during the CERN data taking in 2006. The "Ghost Hits" are shown in red while the real hits are shown in black.

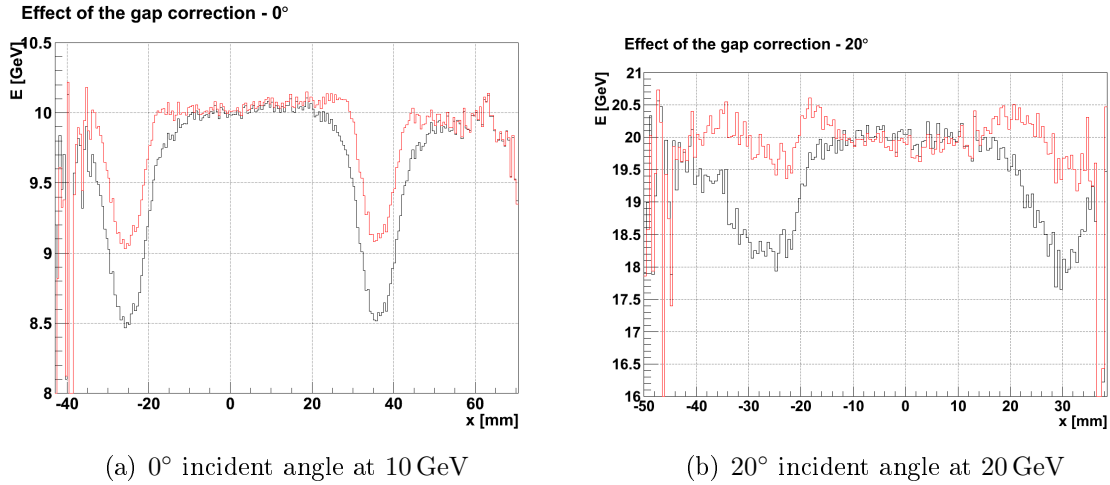


Figure 6.14: Energy loss in the wafer gaps in X direction for 0° and 20° incident angle, without (black line) and with (red line) application of GARLIC's gap correction.

The point where four wafers meet is affected the most by the gap effect. The configuration is shown in Figure 6.15(a). The position of the barycenter of 15 GeV showers in x and y is shown. The color code shows the reconstructed energy for a shower at this position. The gaps in x and y are clearly visible. The maximal loss is more than 30%. When applying the gap correction,

as it is shown in Figure 6.15(b), this loss can be reduced to less than 25% and the effective width of the gaps is reduced. Again a slight overcorrection at the gap edges is introduced.

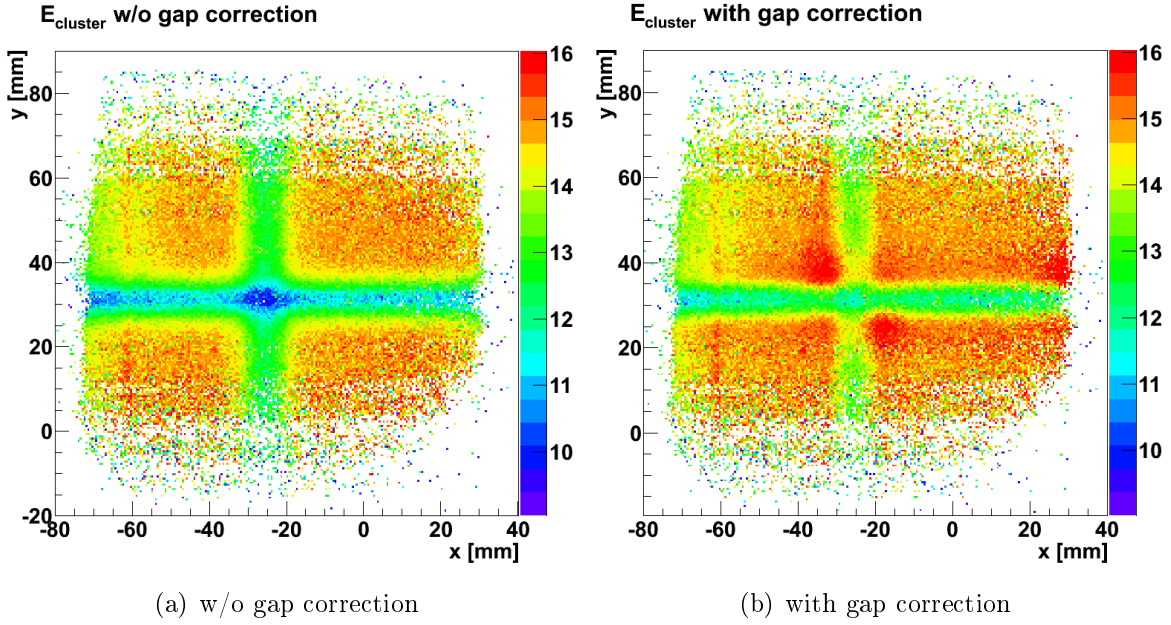


Figure 6.15: Effect of the gap correction on the transition area of four wafers. The losses are reduced from 20% to 15%.

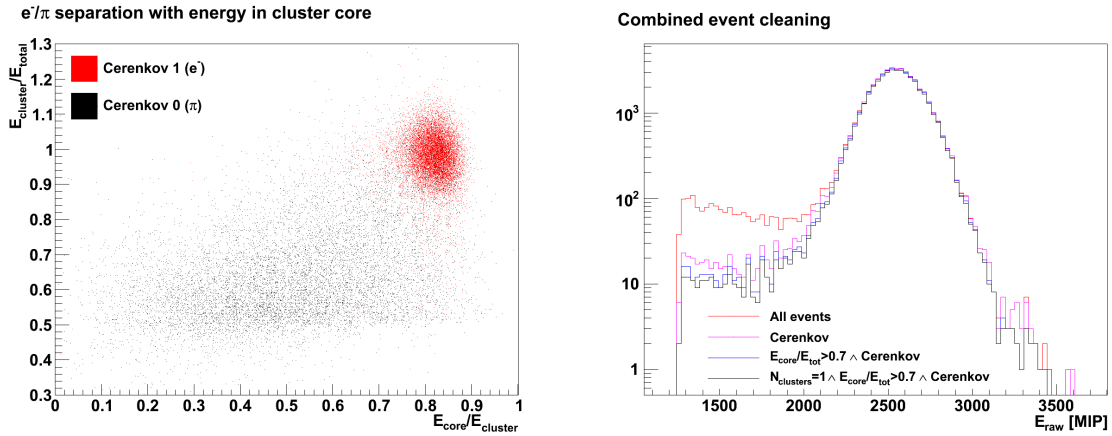
Event cleaning One of the primary goals of GARLIC is to identify a cluster as a true or fake electro-magnetic shower. Although the track-based pion rejection and the neural network decision have not been implemented in the version for the prototype, simple criteria can be used to clean event samples from pion contamination and upstream showers.

One of these criteria that is also used as neural network input in the ILD version, is the fraction of the total cluster energy contained in the cluster core, defined by the group of 2×2 cells around the main cluster axis. The distribution of this variable in a beam run is checked with the help of a Cerenkov counter that is tuned to discriminate between electrons and pions at the beam energy. As shown in Figure 6.16(a), particles identified as electrons by the Cerenkov counter (red) are contained in a small space in the plane given by the ratio of the cluster energy and the nominal beam energy and the fraction of the total cluster energy contained in the cluster core. Even a loose cut on the fraction of the core energy helps to reduce significantly the pion background. This is particularly important for runs, where the Cerenkov counter could not be used.

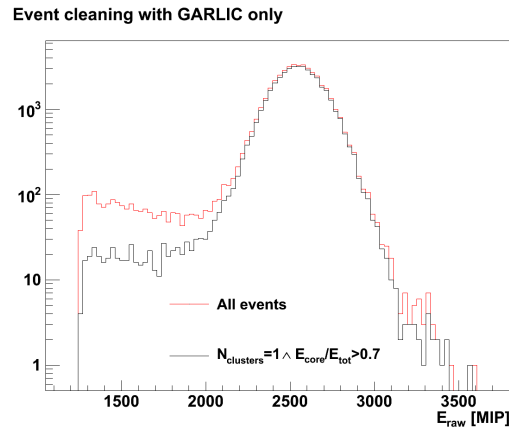
Another simple criterion for event cleaning is the number of clusters found with GARLIC. The event display in Figure 6.12(b) shows a case where the beam particle has started to shower

before entering the ECAL. Such events can be rejected simply by demanding that only one cluster has been found.

Figure 6.16(b) illustrates the different stages of sample cleaning with the means of the previously described cuts in an electron run. To show the capacity for a run without Cerenkov counter, the distribution for the same run is shown in Figure 6.16(c) when only GARLIC is used for event rejection. The efficiency of rejection is of the same level as with the usage of the Cerenkov counter.



(a) Separation of electrons and pions using the energy in the cluster core. (b) Combined event cleaning using the Cerenkov counter and GARLIC.



(c) Event cleaning using GARLIC only.

Figure 6.16: Using GARLIC to improve the rejection of upstream showers and residual pions/muons in an electron beam.

6.4.1 Performance studies with the CALICE Si/W ECAL prototype

During the test beam period in 2006 at CERN, single-electron events at energies from 6 – 45 GeV have been recorded (c.f. Table 6.1). An analysis of this data has been published in [42]. The present analysis has been performed on the same data but independently, while focussing on the application of GARLIC. The robustness of the algorithm has to be demonstrated on real data. The test sample from CERN as well as corresponding Monte Carlo Simulations have been processed to study the clustering performance as well as its impact on the shower energy resolution.

Differences to the analysis from [42] are that geometrical cuts are based on the shower barycenter as computed by GARLIC and event selection is performed by asking one single cluster found per event. The additional criterion of the energy fraction in the cluster core has not been applied in order not to modify too much the reference event sample. The effect of GARLIC's gap correction is expected to be negligible due to the geometrical cuts applied in the study that select events away from the gaps (see 6.4.2).

Test beam setup The test beam setup at the CERN H6 beam line is shown in Figure 6.17. A Cerenkov counter tunable for electron/pion discrimination at several energies is the first detector passed by the particle beam. During most of the running period, it was not included in the data stream. Scintillator counters of various sizes are marked with "Sc". The trigger for beam data was usually a coincidence between "Sc2" and "Sc4", each with an active area of $10 \times 10 \text{ cm}^2$. Three drift chambers ("DC") allow track reconstruction. The back plane of the one closest to the ECAL defines the origin of the right-handed coordinate system that is used (z along the beam direction, x is the horizontal and y the vertical axes, pointing upwards). Along with the Si/W ECAL there were two other CALICE detectors exposed to the beam, an analogue hadronic calorimeter (AHCAL) and a tail catcher/muon tagger (TCMT). "Mc1" and "Mc2" are the large-area scintillator counters that were used in coincidence for the muon calibration runs.

Monte Carlo simulations The experimental setup has been modeled simulated in high detail within the MOKKA [35] framework. In particular all the material upstream of the ECAL is taken into account, including the Cerenkov counter, the scintillator counters and the drift chambers. The raw energy deposit in the Si cells of the ECAL is passed to a digitization module. In this module, a Gaussian smearing is applied to simulate the electronics noise. As previously measured (c.f. [41]), the mean value for the noise of each channel is distributed along a Gaussian distribution with the mean of 0.13 MIP and a dispersion of 0.012 MIP. The cells declared dead during the calibration runs are not suppressed in the simulation. The beam is simulated parallel to the z axis. The beam particle momentum profile follows a Gaussian distribution with the respective width observed in the beam data for a given energy.

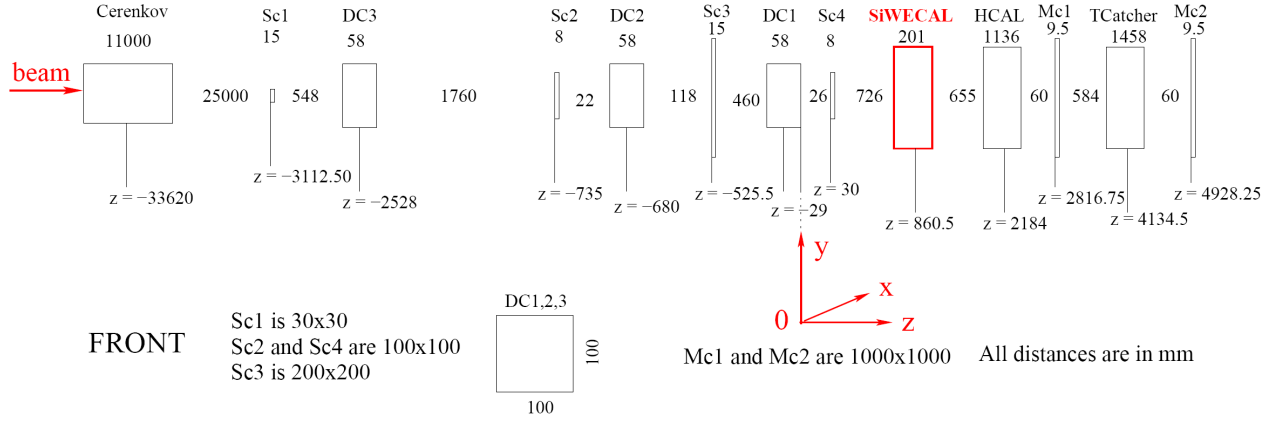


Figure 6.17: Sketch of the test beam setup at CERN in 2006. "Sc" denotes the scintillator trigger counters used for electron and pion beam events, "Mc" denotes the large-area scintillator counters used in coincidence for calibration events.

6.4.2 Event Selection

A threshold of 0.6 MIP is applied to suppress noise hits in the detector. This is valid both for data and simulation. The deposited energy for one event is then the sum of the energy deposits in the remaining cells, weighted with a factor depending on the stack they are situated in:

$$E_{raw} = \sum_{k=0}^{k=9} E_k + 2 \sum_{k=10}^{k=19} E_k + 3 \sum_{k=20}^{k=29} E_k, \quad (6.1)$$

where k is the layer index and E_k is the sum of the energy deposit of all cells in layer k . The weighting factors for the different stacks are chosen naively to correspond to the ratios of radiation lengths in front of each layer when only taking into account the tungsten absorber. The modification of the additional material is not taken into account. The same principle applies when treating the events reconstructed with GARLIC, while only clustered cells are taken into account.

Selecting clean electron events The distribution of E_{raw} for a 15 GeV electron run is shown in Figure 6.18. While the electron peak is easily visible, the muon contamination gives another peak at low energy. In between those peaks is a continuous background from pions that start their interaction in the ECAL. To select electron events, an energy window for the raw energy deposit is defined:

$$125 < \frac{E_{raw}[\text{MIP}]}{E_{beam}[\text{GeV}]} < 375 \quad (6.2)$$

Additionally - where present - the signal of the Cerenkov counter is used to reduce the pion background. These two cuts are also indicated in Figure 6.18. While in this way events with the right energy deposit are selected, there is still a number of events with particles starting to shower upstream of the ECAL. As already mentioned earlier only events with one single cluster found by GARLIC are accepted to suppress this effect.

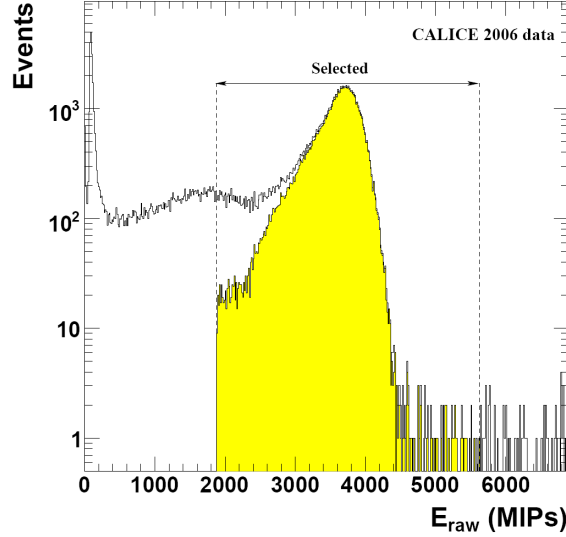


Figure 6.18: Effect on the distribution of the raw energy in MIPs for a 15 GeV electron run when applying the cuts of the allowed energy window and of a signal from the Cerenkov counter (filled).

Geometrical selections To reject events of particles in the beam halo, where an agreement with the nominal beam energy is no longer guaranteed, the mean response of the ECAL has been analyzed run by run. Geometrical cuts in x and y have been placed such that a uniform plateau is achieved.

The inter-wafer guard rings have a strong influence on the energy response of the calorimeter if a particle enters in the vicinity of these gaps. Although GARLIC includes a simple correction for this effect, the need to compare with the uncorrected data implies using the same cuts as in [42] to select only events where the effect is negligible. With a Gaussian parametrization of the energy loss in the gaps the barycenter of a shower has to have a distance d of 4σ from the gap. With the parametrization of [42], this is the case for $d_x = 12.76$ mm and $d_y = 17.2$ mm.

Also the edges of the prototype have to be considered. It has been estimated that 99% of the shower energy are contained in a radius of 32 mm around the shower axis. This same number is used to define the minimum distance between the shower barycenter and one of the detector edges for an event to be accepted.

Modification of the sampling fractions A correction for the odd-even layer structure is also used for the prototype studies. In [42] the modification factor η for the energy in odd layers has been determined to be $\eta = (7.2 \pm 0.2 \pm 1.7)\%$ using beam data. To achieve this, the energy deposit in each layer has been compared to the one in its neighboring layers and a mean has been established over odd and even layers respectively. Since the effect is likely to be energy dependent, we will later on take another approach and try to determine this factor with a fit to optimize the energy resolution (c.f. Section 7.1.1.4). To stay consistent with the prior analysis, the factor η as given above is used. This factor is then introduced where the energy deposit in odd layers is interfering when summing up the total event energy.

6.4.3 Linearity and energy resolution

The response of the detector is estimated per run from the mean of a Gaussian fit to the recorded energy distribution together with its respective error. The range of the fit is limited to $[-\sigma, +2\sigma]$ in order to cut residual tails from the pion background, upstream showers and the inter-wafer gap effects. Figure 6.19 shows the distribution of the raw recorded energy in a 30 GeV electron run, for both the clustered and the unclustered energy response with the corresponding Gaussian fits. The clustered distribution is shifted to higher energies. While low energy hits at the borders of the shower as well as noise hits are omitted, the integrated gap correction gives an additional contribution to the total energy. To estimate the uncertainty on the beam energy, the dispersion of the mean response in different runs at the same nominal beam energy has been used for a parametrization as:

$$\frac{\Delta E_{beam}}{E_{beam}} = \frac{0.12}{E_{beam}[\text{GeV}]} \oplus 0.1\% \quad (6.3)$$

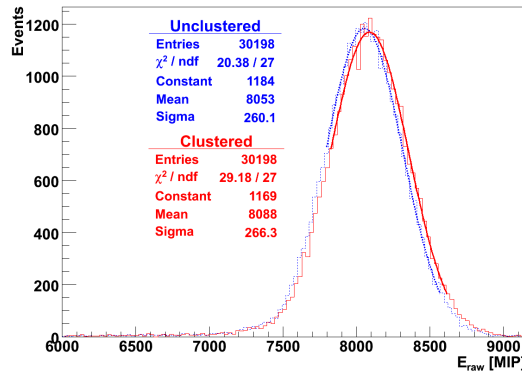


Figure 6.19: Clustered (continuous red line) and unclustered (discontinuous blue line) energy response for a 30 GeV electron run with the corresponding Gaussian fits.

The mean responses at each nominal beam energy are plotted in the group of Figures 6.20. The unclustered response has been linearly parametrized as

$$E_{res} = \beta E_{beam} + \alpha. \quad (6.4)$$

The actual values found for test beam data (TB) and simulation (MC) are:

$$\begin{aligned} \beta^{TB} &= 270.45 \pm 0.21 \\ \alpha^{TB} &= -97.72 \pm 3.17 \\ \beta^{MC} &= 261.79 \pm 0.49 \\ \alpha^{MC} &= -57.68 \pm 7.85. \end{aligned}$$

β gives a global MIP to GeV conversion factor, α depends on the energy threshold. To be consistent with GARLIC's ILD version where a much bigger range of energies has to be covered, the energy estimation will not be completely linear. Actually the inverse graph of Figure 6.20(b) and Figure 6.20(d) is fitted with a polynomial of 2nd degree. The parametrization is then

$$E_{beam} = aE_{res}^2 + bE_{res} + c, \quad (6.5)$$

with the fitted values

$$\begin{aligned} a^{TB} &= (-3.50 \pm 0.33) \times 10^{-9} \\ b^{TB} &= (3.70 \pm 0.01) \times 10^{-3} \approx 1/269.94 \\ c^{TB} &= 0.40 \pm 0.01 \\ a^{MC} &= (-5.49 \pm 2.70) \times 10^{-9} \\ b^{MC} &= (3.86 \pm 0.03) \times 10^{-3} \approx 1/259.20 \\ c^{MC} &= 0.19 \pm 0.08. \end{aligned}$$

We see that in both simulation and data the 2nd order term is very small and that the inverse linear term is not far from what has been found without clustering.

The residuals to the linearity functions are shown in the group of Figures 6.21. For the test beam data, they are given per run (black dots) and to the mean value per energy (red squares). For all energies, clustered or unclustered, they are within approximately the 1% level and consistent with zero non-linearity.

The relative energy resolution has been parametrized in the usual way with the quadratic sum of a stochastic (s) and a constant term (c):

$$\frac{\Delta E}{E} = \frac{s}{\sqrt{E[\text{GeV}]}} \oplus c \quad (6.6)$$

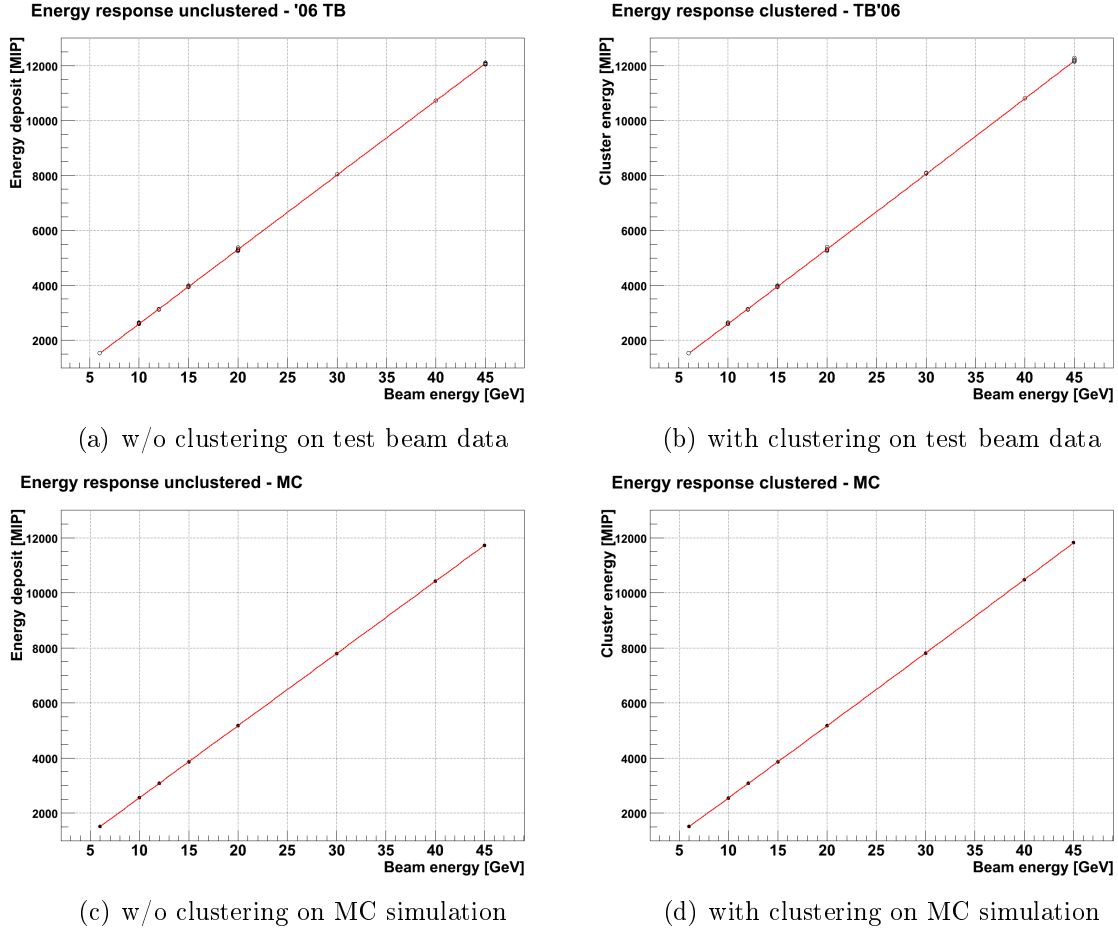


Figure 6.20: Comparison of the difference in response with or without application of GARLIC on test beam data and MC simulation with the CALICE Si/W ECAL prototype.

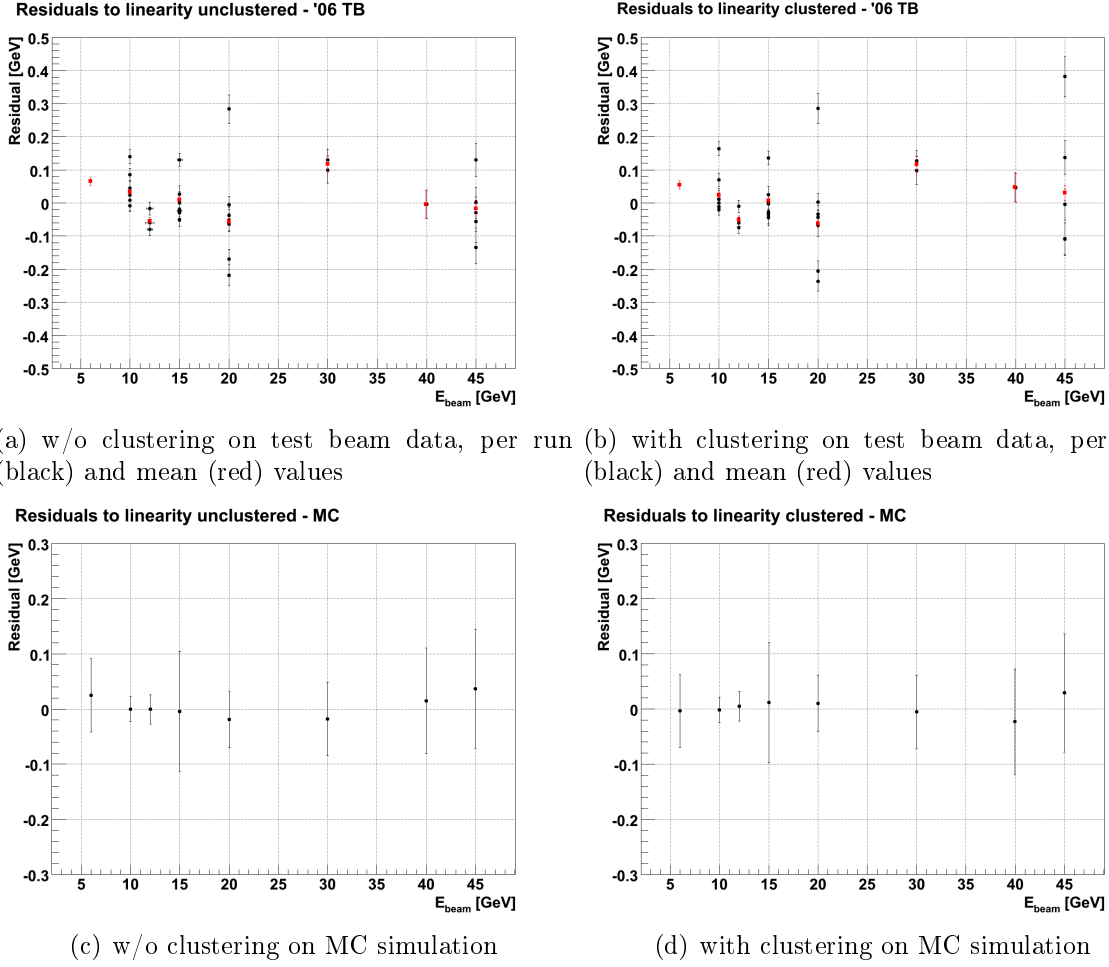


Figure 6.21: Comparison of the difference regarding the residuals to the linearity with or without application of GARLIC on test beam data and MC simulation with the CALICE Si/W ECAL prototype.

The corresponding plots can be found in the group of Figures 6.22. The fitted values for s and c are:

$$\begin{aligned} \text{Unclustered TB: } s &= (16.44 \pm 0.14)\% \quad c = (1.1 \pm 0.1)\% \\ \text{Clustered TB: } s &= (16.61 \pm 0.16)\% \quad c = (1.1 \pm 0.1)\% \\ \text{Unclustered MC: } s &= (17.35 \pm 0.26)\% \quad c = (0.8 \pm 0.3)\% \\ \text{Clustered MC: } s &= (17.48 \pm 0.26)\% \quad c = (0.8 \pm 0.3)\% \end{aligned}$$

Since the constant and the stochastic term are very correlated, we additionally tried to fix the constant term in the measurement of the resolution in the simulation to the values found in the test beam. The fit then yields

$$\begin{aligned} \text{Unclustered MC: } s &= (17.12 \pm 0.14)\% \quad c = (1.1)\% \text{ (fixed)} \\ \text{Clustered MC: } s &= (17.23 \pm 0.14)\% \quad c = (1.1)\% \text{ (fixed)} \end{aligned}$$

which improves the agreement slightly.

GARLIC has very little influence on the linearity and the energy resolution. But even the small deterioration of the energy resolution can easily be explained: the additional effect introduced is the gap correction. It is not very precise and sensitive to the point of impact etc. , but in a final detector such a correction will be mandatory. Moreover it has to be universal for all impact points and angles, which is the case with the present solution. Further development could be possible by reweighting the energy of a Ghost Hit with its position along the transversal and longitudinal shower shape.

Two-shower separation studies (see Figure 6.23(a)) will follow in the near future as well as studies on the fully equipped prototype - where noise hit suppression in GARLIC should make its advantages more apparent - , including energies down to 1 GeV.

Also the simulation is continually improved. The large discrepancies observed here are known to be because of the imperfection of the simulation. For example, the density of the PCB's is too low in the simulation. A lower density material has been used and no copper representing the electrical components on the PCB is included. Tests with an improved version are already in progress. The effect of signal propagation in the external and internal guard rings of the silicon wafers is also not included in the simulation, as well as the effects from the instable pedestals. The correction procedures for the shifts will be revised in the future to include the per-chip effects. Finally, a new digitization module will allow the creation of noise hits in the simulation.

The contribution of the collaboration for R&D and running experiments that are using similar techniques is essential. The results obtained so far are very promising. The goals for the electro-magnetic energy resolution for the Particle Flow Approach can be fulfilled with an ECAL such as the prototype present. At the same time, an adapted clustering algorithm will not have any negative influences. Hence, two important premises for the use of the Si/W ECAL technology optimized for Particle Flow in an experiment at the next linear collider could be shown to be fulfilled.

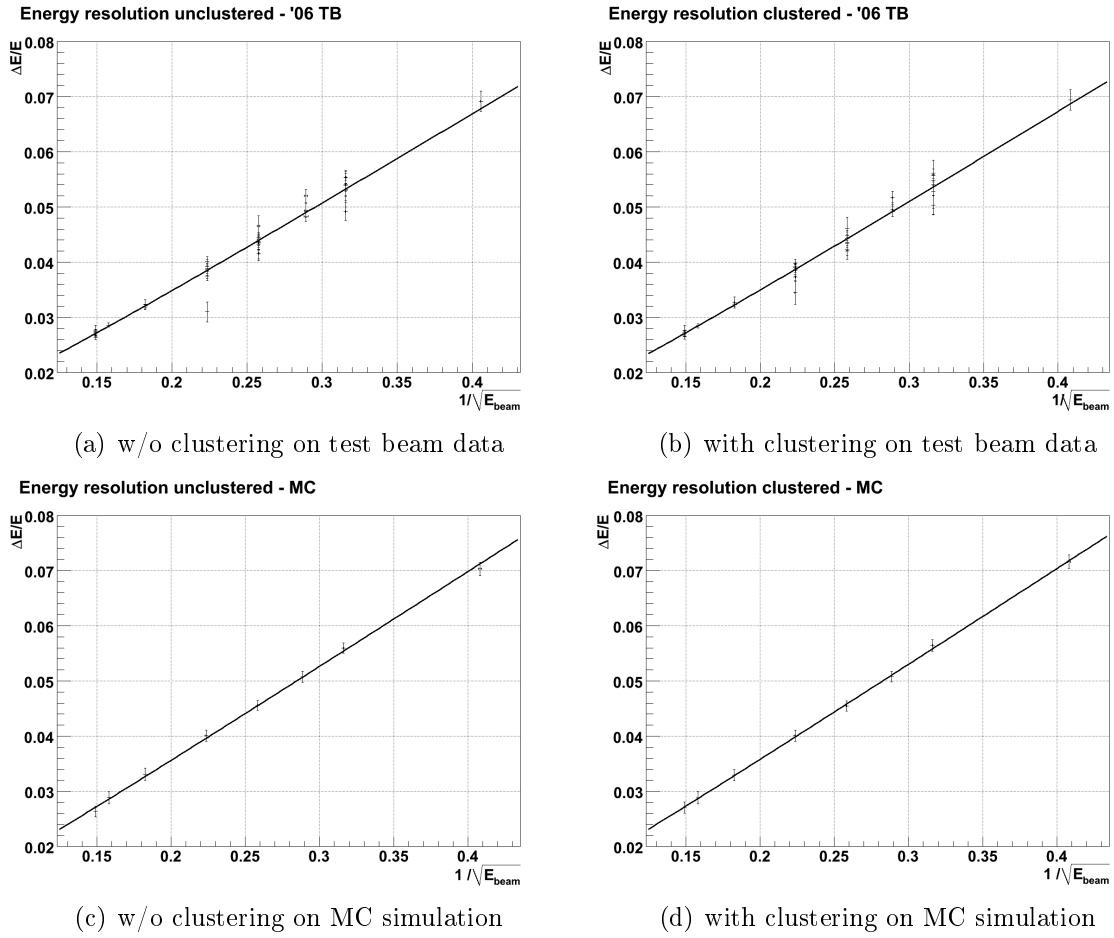
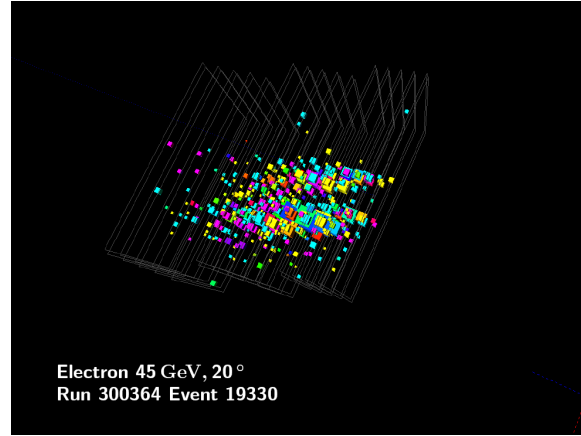


Figure 6.22: Comparison of the difference in energy resolution with or without application of GARLIC on test beam data and MC simulation with the CALICE Si/W ECAL prototype.



(a) A two-particle event in a 45 GeV electron run with 20° incident angle, used for separation studies.

Figure 6.23: Several different studies are still ongoing on data taken with the CALICE Si/W ECAL prototype.

6.5 EUDET prototype

The successful testing program of the physics prototype validated all the main concepts of the design of the Si/W ECAL. This includes the use of the alveolar structures, the concept of slabs, the gluing process of the Si wafers, the mechanical integration as well as its physics capabilities. The next-generation prototype in the EUDET framework [43] is already designed and in the production phase. Although tests with particle beams are also foreseen for this new generation, its primary goal is to further study and validate the technological concepts involved in the design. This includes the moulding process and the fabrication of large structures close to the dimensions of those foreseen for the final detector. The embedding of the very front-end electronics into the detector slab will also be tested, together with solutions for power pulsing and an efficient cooling system. There will also be a focus on the industrialization aspects during the construction of the module. Like this one can achieve a realistic cost estimation for the production of an entire detector module.

Chapter 7

Optimization studies

Contents

7.1	Software optimization	116
7.1.1	Energy resolution	116
7.2	Hardware optimization	126
7.2.1	ECAL cell size	126
7.2.2	Material budget in front of the ECAL	127

7.1 Software optimization

Once the design of a detector is fixed, software can still be used to further push its performance. There are typically two components that need to be approached. The first is to correct for any shortcomings or inhomogeneities present due to the hardware design. In the case of the calorimetric system, these are typically corrections for the geometrical layout. In particular the Barrel-Endcap overlap region or the module overlaps in phi direction as already seen in Section 5.2.1, as well as the module and inter-wafer gaps as described in Section 3.3.2 and Section 5.2.1 will need to be focused on.

The second component is to improve the measurements for interesting quantities like the optimization of the energy resolution on clusters that have been found by GARLIC. For the default cell size of 5×5 this method is embedded in the algorithm.

7.1.1 Energy resolution

At low shower energies, fluctuations are important in the energy deposit in an individual cell. The small cell size of the ILD Si/W ECAL provides the possibility to measure the total shower energy alternatively just by counting the hits in the cluster. This is due to the fact that the number of hits scales about linearly with the shower energy at low energies. Moreover the hit counting suppresses some of the already mentioned fluctuations in the energy deposit per cell. The energy resolution could benefit in this way. We will not only try to use either the one or the other method at a given energy but to establish an optimal linear combination of the two measurements.

The repartition in two stacks with different absorber thickness as well as the design of a slab itself as described in Section 3.5 and already treated in Section 4.7 need special attention. The different weighting factors reflect directly the level of fluctuations.

7.1.1.1 Method

When combining the measures with hits and energy deposit linearly it is important to make sure that one combines two terms that measure the same quantity, i.e. the energy of the particle (in GeV). The basic ansatz is thus:

$$E(\text{GeV}) = \lambda E_{en}(\text{GeV}) + (1 - \lambda) E_{hit}(\text{GeV}) \quad (7.1)$$

where E_{en} and E_{hit} are the estimations via the energy deposit and the hits respectively. In earlier approaches, by combining the two measurements more directly but while still imposing linearity, like with

$$E(\text{GeV}) = \alpha E_{en} + \beta E_{hit} , \quad \text{with } \alpha + \beta \neq 1, \quad (7.2)$$

i.e. where E_{en} and E_{hit} are not the energy estimations via energy deposit and hit counting respectively but only fractions of these, it was found that the parameters α and β are extremely

sensitive to changes in energy, so that they can be parametrized only with difficulty over all the interesting energy range.

At first, optimizations for the measurement with the energy deposit and the number of hits are performed individually. This results in parametrized functions $E_{en}(\text{energy deposit})$ and $E_{hit}(N_{hits})$ that will afterwards be combined by optimizing the factor λ of Equation 7.1 for each point in energy. All this is done with single-photon events at energies in the range from 200 MeV up to 150 GeV. A simple χ^2 - minimization is performed with the TMinuit ([44]) package for every energy point:

$$\chi^2 = \sum_{events} \left[\frac{E_{MC} - E_{meas}}{\frac{17\%}{\sqrt{E_{MC}}}} \right]^2 \quad (7.3)$$

This approach minimizes the resolution while imposing a linear response. To avoid crosstalk with the geometry effects, events in the module overlap region in ϕ as well as in the Barrel-Endcap overlap region have partly been excluded.

As already mentioned throughout earlier chapters, the barrel and the endcap parts show a significantly different response due to the direction of the magnetic field lines. Also photons originating from the IP can hit the barrel part with an impact angle of up to 51° , while the maximal angle for the endcap is only 39° . Separate optimizations for barrel and endcap are hence mandatory.

7.1.1.2 Naive estimation of the energy deposit in stack 1 and 2

The ratio of the tungsten absorber in stack 1 and 2 being 1 : 2 (2.1 mm : 4.2 mm), one can naively weight the energy deposit of hits in the second stack with a factor of two. Then we have only one free parameter to obtain the corrected energy:

$$E_{meas}^{en} = \alpha(E_1^{dep} + E_2^{dep}) \quad (7.4)$$

where E_1 and E_2 is the energy deposit in stack 1 and 2 respectively and the energy measured in cells of stack two are weighted with a factor of two. Figure 7.1 shows the evolution of α with the photon energy for the endcap and the barrel region separately. The difference between the two regions is apparent. Cells in the endcap region collect less energy than the one in the Barrel. As argued in Section 4.4 this is due to the focussing effect of the magnetic field in the endcaps. The actual difference is of the order of 2 – 3%. At very low energies as well as at high energies the clustered energy reflects better the energy of the incoming particle whereas at medium range energies the factor α is bigger. The variations are of about 10%.

7.1.1.3 Optimizing the weighting of stack 1 and 2

The naive weighting factor of 2 for the second stack seems intuitive at first glance but one can imagine additional considerations that need to be taken into account in order to improve

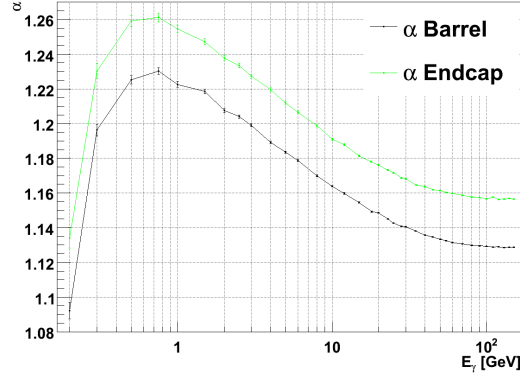
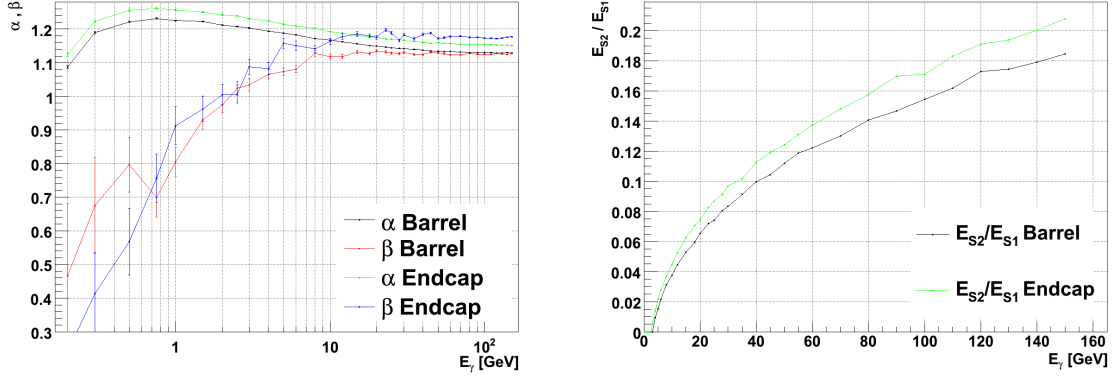


Figure 7.1: The factor α from Eq. 7.4 in function of the MC energy for the endcap and barrel regions.

the energy resolution. The sampling fraction in the first stack is higher than the one in the second stack (due to the different absorber thickness), i.e. the ratio of collected energy and energy deposited in the absorber is higher. A good energy resolution of showers at low energies should hence be guaranteed. The higher sampling fraction means that one is less sensitive to the statistical fluctuations. Additional information could be obtained by applying more weight to the first stack, at least for showers in a certain energy region. The prefactors for stack 1 and 2 are optimized independently while still imposing linearity:

$$E_{meas}^{en} = \alpha E_1^{dep} + \beta E_2^{dep} \quad (7.5)$$

where β is now a factor that modifies the naive weighting of stack 2. Figure 7.2(a) shows the evolution of α and β for both endcap and barrel. We can see that the evolution of α barely changed. β starts playing a role as soon as there is sufficient energy deposit in the second stack (i.e. a few GeV) and stays about constant from 20 GeV on. The ratio of α and β is different for barrel and endcap. While at high energies the ratio is about 1 in the barrel, β is more important in the endcap. With the control over this ratio we have intrinsically given a powerful tool to the fit: it can be used to partly account for longitudinal leakage which is more important in the endcap than in the barrel when integrating over all impact angles (since the barrel allows higher impact angles). At high energies there will be a higher deposit in the second stack, so it should gain in importance for the measurement. The difference between the two detector parts is also reflected in Figure 7.2(b) that shows the ratio of the two contributions used for the measurement, i.e. $\beta E_2^{dep} / \alpha E_1^{dep}$. The importance of the second part of Equation 7.5 grows steadily but never governs the measurement - not even at very high energies. It plays a bigger role in the endcap than in the barrel.



(a) Evolution of the factors α and β of equation 7.5 with the photon energy (b) Ratio of the contribution of the two terms of Equation 7.5 as a function of the photon energy

Figure 7.2: Evolution of the different parts of Equation 7.5, i.e. optimization of stack 1 and 2, with the photon energy.

7.1.1.4 Difference in energy deposit in odd and even layers

As described in Section 3.5 and 4.4, the design of the detector slabs, along with the strong magnetic field applied, induce a difference in the energy deposit for even and odd layers of the ECAL. The first layer that has no absorber in front of it, is treated apart. Counting this layer as the first one, we will refer to layers as even if they are in position 2, 4, 6,...30 and as odd otherwise.

Figures 4.10(a) and 4.10(c) show the energy deposit per layer of photons at various energies with an angle of incidence of 90° , representing the longitudinal profile of an electromagnetic shower. The curves are normalized to the highest energy deposit in the first stack. Like this, the relative difference between the energy deposit in even and odd layers is easily visible. The even layers accumulate more energy in the central and decreasing part of the shower, the odd ones in the increasing part. The relative difference of the energy deposit in odd and even layers has only a light dependence on the total energy of the shower. To account for the odd-even asymmetry, two more free parameters (f_1, f_2) are introduced in the parametrization of the measured energy:

$$E_{meas}^{en} = \alpha(f_1 E_1^{even} + (1 - f_1) E_1^{odd}) + \beta(f_2 E_2^{even} + (1 - f_2) E_2^{odd}) \quad (7.6)$$

where $E_{1/2}^{even}$ and $E_{1/2}^{odd}$ is the energy deposit in the even or odd layers of stack 1/2 only. The dependence of the factors f_1 and f_2 , that are characterizing the odd-even difference, on the energy of the incident photon are shown in Figure 7.3(c). Both start at a level below 0.5 and fall slightly with increasing energies. The plot reflects some of the observations already made in Section 4.7. The strength of the effect scales with increasing energy. In the barrel it is barely visible in the late part of the shower, so f_2 is nearly flat and near 0.5. In the endcap in the

contrary it is very pronounced also in the late part of the shower, so f_2 can take also values further away from 0.5.

The subtlety of the effect results in big variations of all four parameters from one energy point to another. A linear parametrization of f_{12} yields:

$$f_1^{Barrel} = -2.89 \times 10^{-4} E_\gamma + 0.49 \quad (7.7)$$

$$f_1^{EC} = -2.73 \times 10^{-4} E_\gamma + 0.49 \quad (7.8)$$

$$f_2^{Barrel} = -7.35 \times 10^{-5} E_\gamma + 0.49 \quad (7.9)$$

$$f_2^{EC} = -3.31 \times 10^{-4} E_\gamma + 0.49 \quad (7.10)$$

Due to the construction of equation 7.6 the absolute value of the parameters α and β has doubled. They show the same global behavior as seen earlier (c.f. Figure 7.2(a)). The impact of the consideration of the odd-even effect is obviously very small.

7.1.1.5 Using the number of hits

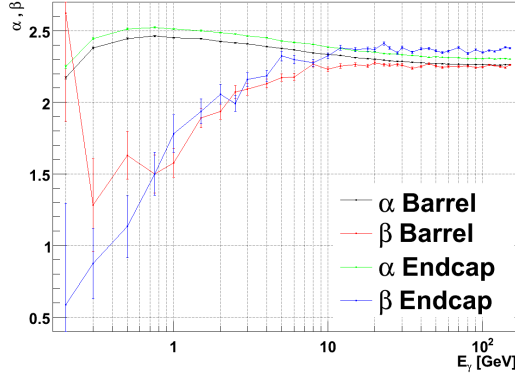
The high granularity of the ECAL allows another unique approach. While at high e.-m. shower energies the number of hits in the ECAL is highly non-linear as a function of the energy deposit due to the high energy density in the shower core which is not accounted for by simple hit counting, the relation is almost linear at low energies. This is illustrated in Figure 7.4(a) that shows the number of clustered hits as a function of the shower energy. The empirical fit shown is of the form

$$N_{hits} = a (E_\gamma + b)^c + d.$$

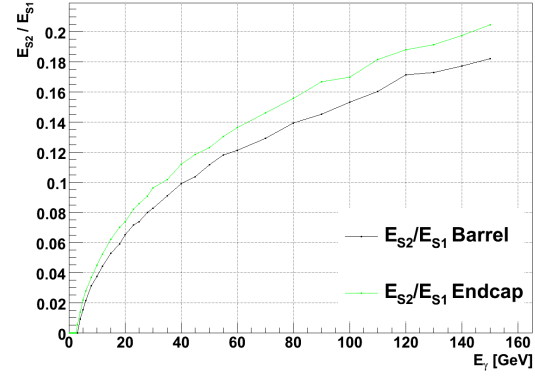
It deviates from the measurement points at high energies but still reflects the basic behavior. It is interesting to see that the number of hits scales basically with a factor $\sqrt{2}$ with the photon energy, probably pointing to the width of the electromagnetic shower. The noise cut for hits along with the higher importance of fluctuations in the energy deposit per cell at low shower energies imply that - at low shower energies - the energy resolution could be improved by using the ECAL in a "digital" mode instead of measuring the energy deposit in each cell. The digital energy measurement is

$$E_{meas}^{hit} = \gamma N_1 + \delta N_2, \quad (7.11)$$

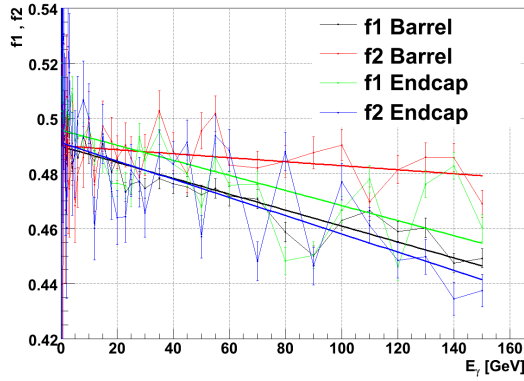
with $N_{1/2}$ being the number of hits in stack 1/2. In order not to complicate the measurement further, odd and even layers have not been treated separately. The dependency of γ and δ with the photon energy is shown in Figure 7.4(b). The values for γ are almost identical for barrel and endcap with only a small, nearly constant difference. In δ the difference is slightly increasing. The ratio of the two is approximately 1 : 2 with gaining importance of δ at higher energies. This ratio is as well used for leakage corrections, more visible in the endcap where integration takes place over smaller impact angles.



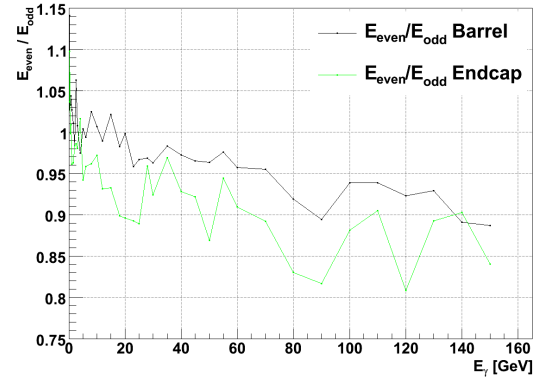
(a) Evolution of the factors α and β of equation 7.6 with the photon energy



(b) Ratio of the contribution of the two terms of equation 7.5 as a function of the photon energy

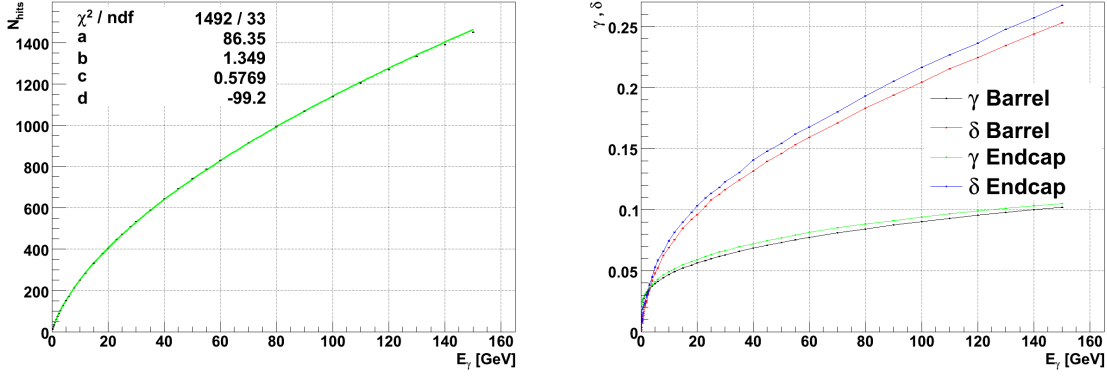


(c) The dependence of the factors f_1 and f_2 from Eq. 7.6 in function of the MC energy. The fits are layers to the measured energy as a function of the given in equation 7.7.



(d) Ratio of the contribution of the even and odd layers to the measured energy as a function of the photon energy

Figure 7.3: Evolution of the different parts of equation 7.6, i.e. optimization of stack 1 and 2 and ratio of even/odd layers with the photon energy.



(a) Dependence of the number of clustered hits on the shower energy. The fitting function is $N_{hits} = a(E_\gamma + b)^c + d$. (b) Evolution of the factors γ and δ of equation 7.11 with the photon energy.

Figure 7.4: Using the number of hits for a measurement of the shower energy.

7.1.1.6 Combining the two measurements

The two different measurements are combined linearly to a final estimation of the energy:

$$E(\text{GeV}) = \lambda E_{meas}^{en}(\text{GeV}) + (1 - \lambda) E_{meas}^{hit}(\text{GeV}) \quad (7.12)$$

To execute the linear combination it is mandatory that the E_{meas}^{en} and E_{meas}^{hit} are linear with the shower energy and the distribution at one energy point is well centered around the true energy. Then we can minimize

$$\chi^2 = \sum_{events} \left[\frac{\lambda (E_{meas}^{en} - E_{mean}^{en}) + (1 - \lambda) (E_{meas}^{hit} - E_{mean}^{hit})}{\frac{17\%}{\sqrt{E_{MC}}}} \right]^2 \quad (7.13)$$

If this assumption is not true the fit will additionally try to adjust linearity, resulting in weights for the energy and the hit part that reflect their deviation from the true energy.

Transfer to smooth functions The optimized values for all the parameters have so far been taken at a given energy point and then applied for all the events in the sample. On an event-by-event basis, the latter will not necessarily lead to the best values in the energy resolution but it is nevertheless very close to the optimum achievable.

To apply the method inside a clustering algorithm however, the energy dependence of the parameters needs to be approximated with smooth functions. For each cluster, first the energy needs to be estimated as well as possible with simple means, for example like it is described in Item 14 of Section 5.2.1. Then the parameters α , β , f_1 , f_2 , γ , δ and λ are evaluated at this pre-estimated energy and E_{meas}^{en} and E_{meas}^{hit} , as well as their linear combination are calculated. The

estimation is especially critical in the hit part of the measurement. Seen the dependencies of γ and δ with the initial energy, the transfer to an estimation of these parameters per event can only degrade the resolution of the hit part. The disturbance can be expected to be especially strong at low energies due to the high slope of the parametrized functions for γ and δ in the region.

In the optimization chain, a re-estimation of α and β after having parametrized f_1 and f_2 as in Equations 7.7 to 7.10 is performed.

One of the most problematic fits has turned out to be the one for α , due to the difficult shape of the dependency. An empirical function has been found that describes the shape rather well:

$$\alpha = a(\tanh(bE_\gamma - c) \left(e^{\frac{(-E_\gamma+d)}{e}} + e^{\frac{(-E_\gamma+f)}{g}} \right) + h.$$

For the barrel part, α is shown together with the fit in Figure 7.5(a). The result is not perfect but satisfactory over all the covered energy range. The factor β can be described quite easily with

$$\beta = a \left(1 - e^{-\frac{E_\gamma+b}{c}} \right),$$

as it is shown in Figure 7.5(b). The functions used for the parameters in the hit measurement are:

$$\begin{aligned} \gamma &= a(E_\gamma + b)^c + dE_\gamma \\ \delta &= a + b \log(cE_\gamma) + dE_\gamma + e, \end{aligned}$$

focussing on the low energy part where the hit measurement is expected to be important. The fits perform rather well (Figures 7.5(c) and 7.5(d)). Both functions reflect directly the non-linearity between the number of hits and the total photon energy.

Figure 7.6(a) shows the correlation factor between the measurements with the hitcounting and the energy deposit as a function of the total shower energy. Barrel and endcap show very different behaviors. While for both the correlations are high at very low energies, the two curves diverge at a few GeV. In the barrel the correlation continues to drop with increasing energy, in the endcap it stays at a more or less constant level. This must be induced by the more important leakage effects and the focusing effect of the magnetic field in the endcap.

To get a feeling of how to combine the two measurements best one needs to consider additionally the individual energy resolutions. These are shown in Figures 7.7. Only at energies below 1 GeV is the resolution with the hit measurement better than the one with the energy deposit. At higher energies the hit measurement gets worse and worse with respect to the energy measurement.

Figure 7.6(b) shows the evolution of the factor λ that represents the linear combination of the energy and hit measurements via Equation 7.12. It reflects the argumentation given above. At low energies λ is small, attributing a high importance to the measurements via the

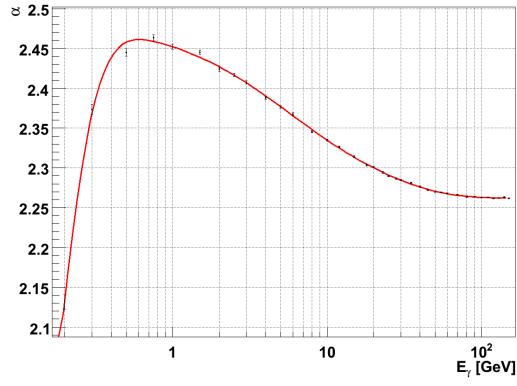
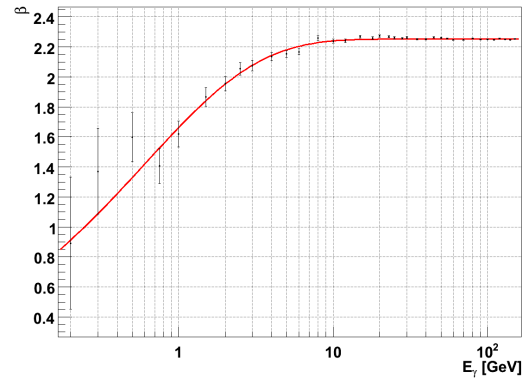
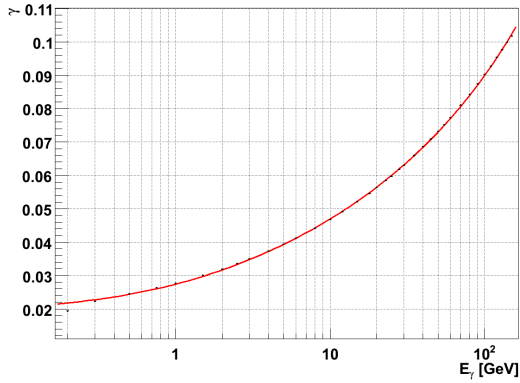
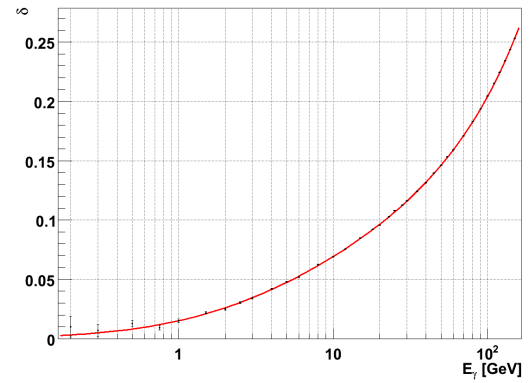
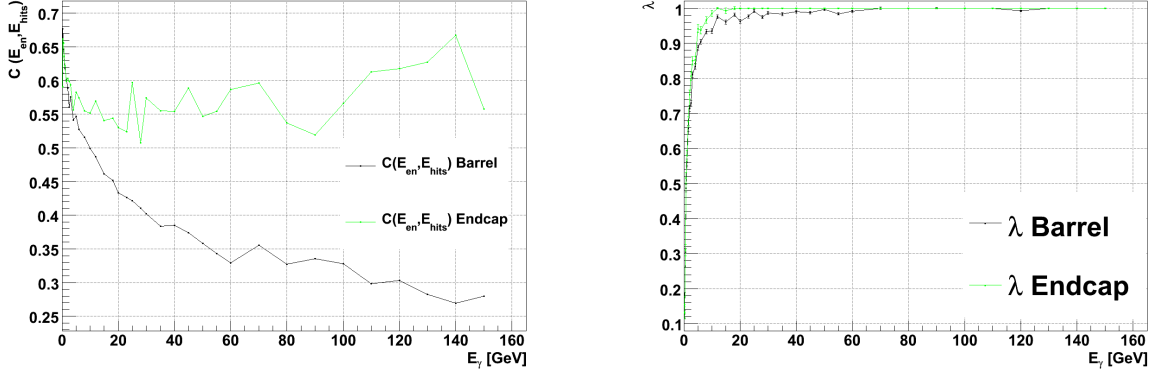
(a) α (b) β (c) γ (d) δ

Figure 7.5: The parameters α , β , γ and δ for the barrel part with the respective fits described in the text.

hits, but it increases rapidly with energy to surpass 0.9 at around 5 GeV. In the endcap, the measurement via energy deposit gains faster in importance due to the same effects described above.



(a) Correlation factor between the hit and the energy measurements as a function of the photon energy.

(b) Evolution of the factor λ from Equation 7.12 with the photon energy.

Figure 7.6: Combining the two measurements

7.1.1.7 Impact on the energy resolution

The fitting of the weighting factors for stack 1 and 2 independently as well as the inclusion of the odd-even effect brings hardly any improvement in the energy resolution with respect to the naive weighting. The real improvement is expected to come from the energy measurement by hitcounting. The two Figures 7.7 show a comparison of the pre-estimated energy as described in Item 14 of Section 5.2.1 and the steps in the combination of the energy measurement (E_{meas}^{en} , E_{meas}^{hit} and E_{meas}^{mix}). The improvement by combining the hit and energy measurements stays behind the expectations. At 1 GeV it is barely 1% on the absolute value of the resolution.

A disadvantageous starting point is the bad energy resolution at low energies via the measurement with the energy deposit. It is considerably worse than with the simple pre-estimated energy. The main reason for this is the estimation of the prefactor α . Its form is complicated and the fit cannot be expected to be good at very low energies (down from ~ 2 GeV) because the slope is very big and only a few points are available for the fit.

In this context, it is not a priory clear if the approach chosen here is the most efficient one. The variation of the weights of stack 1 and 2 could be seriously limited if a leakage correction with good performance can be established. If the resulting variations are only subtle a fit for the two parameters would have good chances to be more successful. The introduction of the odd-even layer structure may also lead to too much complication. Since this effect depends on

the angle of incidence, the energy estimation should either be broken down in several zone per angle or left out because one integrates over all angles.

In any case it is to be expected that this method can be refined so that the improvement in energy resolution will be more important than in the present example.

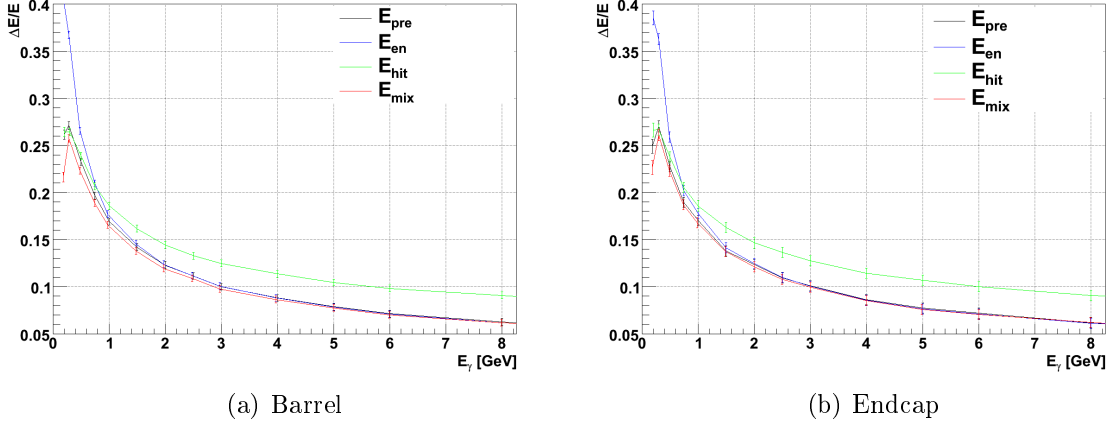


Figure 7.7: Gain in the energy resolution following the different steps of optimization described in the text.

7.2 Hardware optimization

7.2.1 ECAL cell size

The ECAL cell size dictates the track-cluster separation in jets. With increasing center-of-mass energy, the jet environment becomes more and more dense. Events with two light jets at $E_{cm} = 500$ GeV are used to compare the separation performance at different cell sizes.

Figure 7.8(a) shows the average fraction of photons per event having a distance d from the nearest track that is smaller than a given maximal distance d^{max} on the MC level. Events with radiative return to the Z pole are suppressed. Cell sizes of $5 \times 5 mm^2$, $10 \times 10 mm^2$ and $20 \times 20 mm^2$ are considered. With the current software, track-cluster separation is possible at a typical level of $d(\gamma, track)$ between 1.5 and 2 times the cell size. At $d^{max} \sim 20$ mm the fraction of photons closer to tracks starts to increase more steeply while it is growing slowly at smaller d^{max} . The change from $10 \times 10 mm^2$ to $20 \times 20 mm^2$ should bring considerably more losses than the change from $5 \times 5 mm^2$ to $10 \times 10 mm^2$.

GARLIC has been re-adapted for each different cell size, both the principal parameters for cuts in energy, number of hits and distances as well as the re-training of the neural networks. Correlations between the clustered energy and the visible photon energy as well as the number

of clusters and the number of visible photons, are shown in the group of Figures 7.9. The advantage of the smallest cell size is very apparent. Not only the correlation is higher but also the total number of lost photons is smaller. A key role in the performance on high energy jets has clearly the allowed distance between the cluster and the nearest track. For first-level clustering algorithms based on neighbor criteria like GARLIC, some topological cuts are nevertheless mandatory. An empty cell between an extrapolated track and a cluster helps a lot to keep fake clusters at a low number. In later iterations of PFA, recovery of these clusters could still be performed. In the present case, the excluded volume rises with the cell size.

An estimation of the differences induced from the cell size is given by the mean and RMS on the relative difference between clustered and simulated photon energy as shown in Figure 7.8(b). The two smaller cell sizes perform rather well. The tail at values towards 1 where a lot of energy has not been clustered is primarily made up of events with very dense jet environments. The peak itself is boosted by the radiative return that reduces the particle density. The cell size of $20 \times 20 \text{ mm}^2$ on the other hand seems not to be capable to deal with the environment at these energies.

In addition, a meaningful quantity is the number of events contained in a certain region around perfect agreement between simulation and reconstruction. For a relative difference between clustered and simulated photon energy of less than 10% the fraction of events is:

$5 \times 5 \text{ mm}^2$	:	49.1%
$10 \times 10 \text{ mm}^2$	:	38.6%
$20 \times 20 \text{ mm}^2$	:	19.8%.

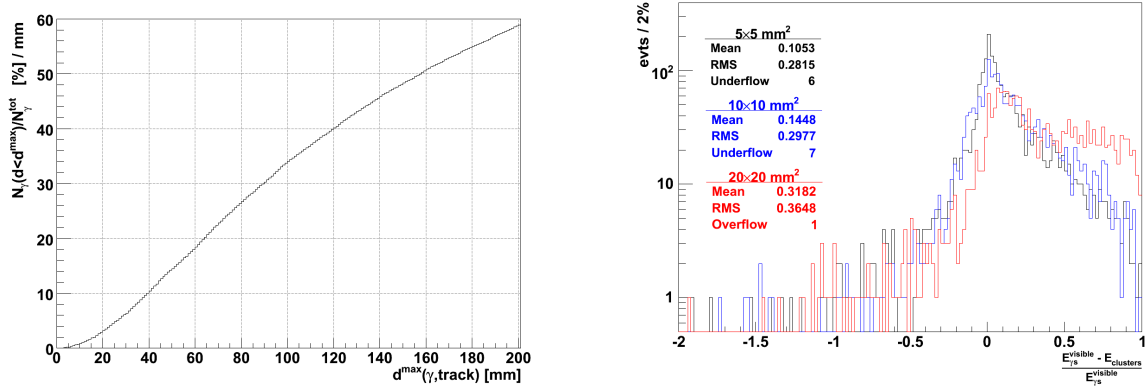
This shows the clear superiority in purity of the small cell size ($5 \times 5 \text{ mm}^2$), although the one of $10 \times 10 \text{ mm}^2$ performs as well reasonably.

For higher center-of-mass energies $5 \times 5 \text{ mm}^2$ or even smaller cells will clearly be mandatory. Although it is expected that the performance on the software side can be a lot improved, the intrinsic density of high energy jets will necessitate investigations of the lower limits in the production process of the cells.

7.2.2 Material budget in front of the ECAL

In Section 5.3.1.2 it has already been shown that the interaction of pions in the tracker region raises significantly the number of fake clusters created in the GARLIC clustering algorithm. Although these can be real photons from π^0 's created during the interaction, limiting their number would lower a lot the risk of confusion.

To study the effect of material in front of the ECAL on its particle flow performance, 4 GeV single charged pion events have been simulated. GARLIC has then been applied to the single pion events. Six percent of the simulated pions already interact in the tracker region. Figure 7.10 shows the position of the pion interaction point inside the detector. Photon clusters have been found in 55% (red points) of the events. The TPC endplates and gas give the largest



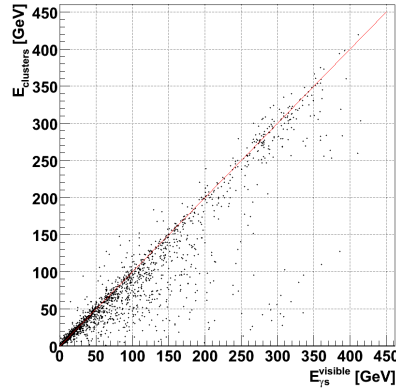
(a) Average fraction of the photons per event having a distance smaller than a given maximal distance d^{max} .

(b) Comparison of the clustered photon induced energy at different ECAL cell sizes.

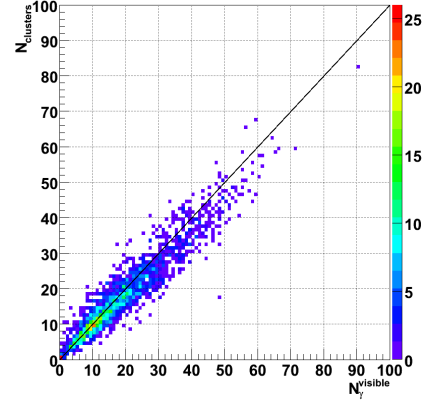
Figure 7.8: Studies on the clustering of photons in $E_{cm} = 500$ GeV di-jet events.

contribution to the total number of pion interactions in front of the ECAL. When only those interactions which give rise to identified photon clusters are considered, the detector components at the center of the detector, i.e. the vertex detector, SIT, beam tube and FTD support, also give significant contributions. Table 7.1 gives a breakdown of the contributions of the different subdetectors in the tracking region.

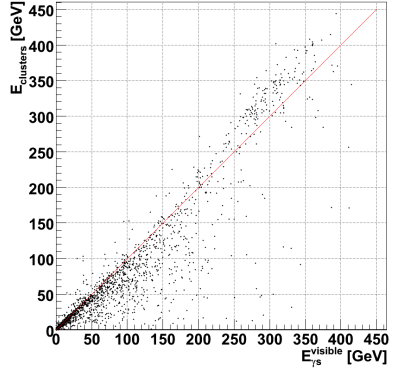
These numbers give only a first approximation. The currently implemented simulation will undergo serious revision in the future. Although R&D studies are in full progress, the material budget could not yet be estimated reliably in several cases, like for example for the TPC endplate.



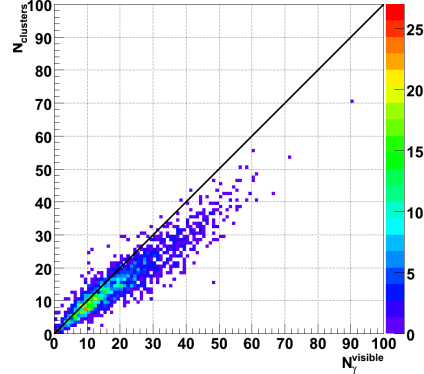
(a) Correlation between clustered energy and visible photon energy - $5 \times 5 \text{ mm}^2$.



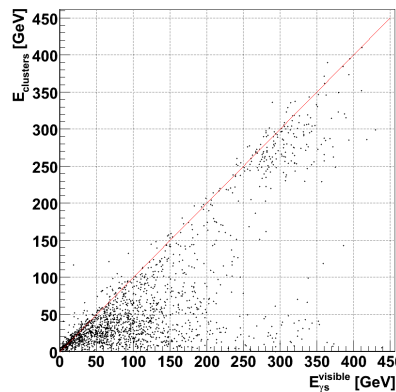
(b) Correlation between number of clusters and visible photons - $5 \times 5 \text{ mm}^2$.



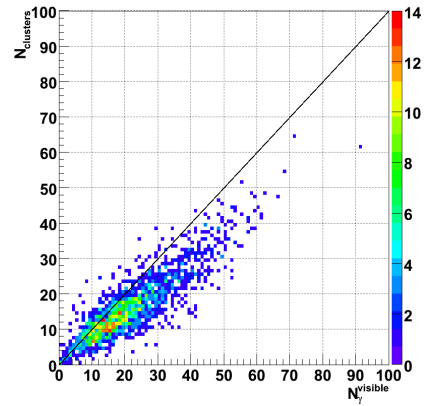
(c) Correlation between clustered energy and visible photon energy - $10 \times 10 \text{ mm}^2$.



(d) Correlation between number of clusters and visible photons - $10 \times 10 \text{ mm}^2$.



(e) Correlation between clustered energy and visible photon energy - $20 \times 20 \text{ mm}^2$.



(f) Correlation between number of clusters and visible photons - $20 \times 20 \text{ mm}^2$.

Figure 7.9: Comparison of different ECAL cell sizes with application of GARLIC on di-jet events at $E_{cm} = 500 \text{ GeV}$.

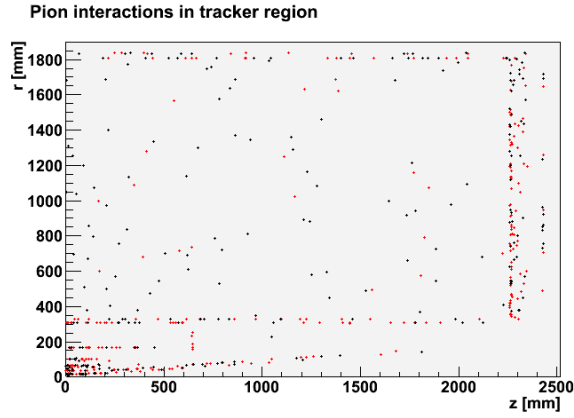


Figure 7.10: Points of interactions in the tracker region of ILD in single pion events. The black points correspond to interactions that lead to the creation of clusters in the GARLIC photon reconstruction while the red points correspond to interactions that did not create any clusters

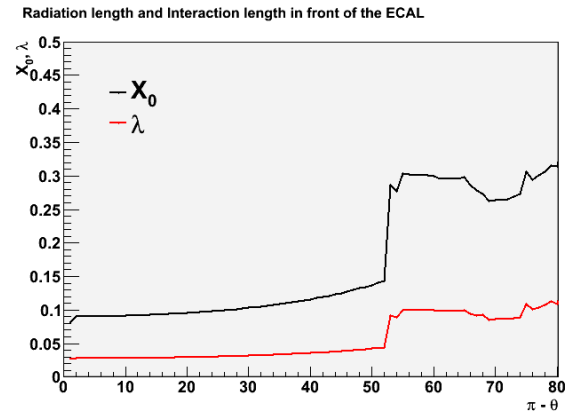


Figure 7.11: Radiation and Interaction length in front of the ECAL

	% of total interactions	% with clusters	% of total events with clusters
VTD	11.9	64.5	13.9
SIT	11.8	68.7	14.6
Beam pipe	10.4	62.9	11.8
FTD	8.9	66.1	10.6
TPC inner field cage	5.4	63.8	6.2
TPC gas	17.1	23.0	7.1
TPC outer field cage	6.5	50.6	5.9
TPC endplate	22.3	61.4	24.8
SET	3.1	58.0	3.3
ETD	2.8	35.1	1.8

Table 7.1: Interaction of pions in the different parts of the tracker region.

Chapter 8

Measurement of CP violation via spin-correlations in $H \rightarrow \tau\tau$ decays

Contents

8.1	Event structure: production and decays	132
8.2	Event generation	134
8.3	Defining observables	134
8.3.1	Reconstructing the Higgs boson	135
8.3.2	Estimation of the τ direction	138
8.3.3	Identification of the τ decay	143
8.4	Event sample	149
8.4.1	Signal: $e^+e^- \rightarrow ZH \rightarrow \mu\mu\tau\tau$	149
8.4.2	Background from $e^+e^- \rightarrow ZZ \rightarrow \mu\mu\tau\tau$	149
8.4.3	Beam polarization	150
8.4.4	Background reduction	150
8.5	Inclusive τ decays	153
8.6	Results	157
8.6.1	Extension of the event sample	157
8.6.2	Distributions of $\Delta\varphi$	157
8.6.3	Extraction of the CP violating phase ψ	158

As described in Section 1.5 one can use transverse spin correlations of the τ 's in $H \rightarrow \tau\tau$ decays to determine the CP state of a spin zero Higgs particle. To demonstrate the feasibility of this measurement while emphasizing the importance of the ECAL, full simulations of several hadronic τ decay channels in the ILD detector have been studied.

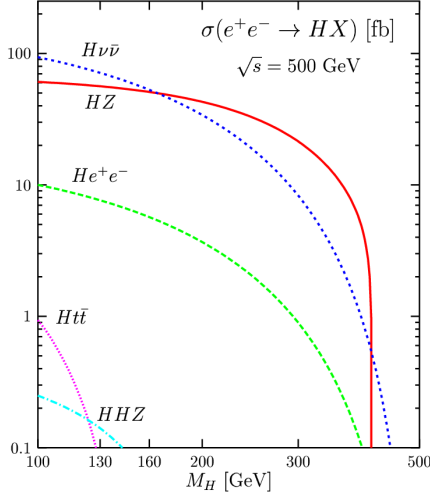


Figure 8.1: Cross sections for several Higgs production processes at $E_{CM} = 500$ GeV.

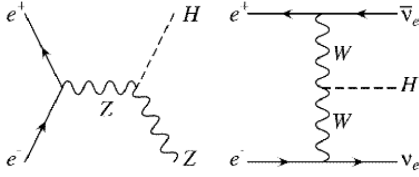


Figure 8.2: The two main mechanisms for Higgs production at the ILC: Higgsstrahlung and W boson fusion.

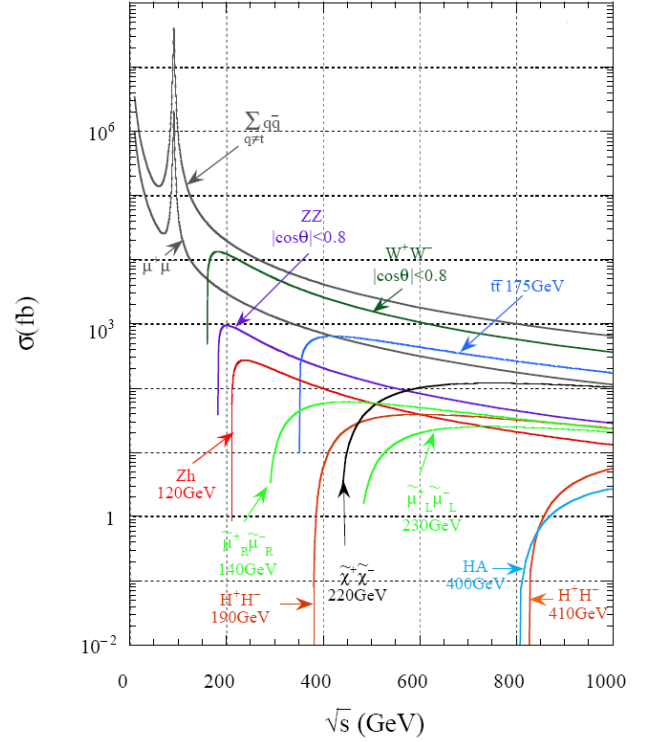


Figure 8.3: Production cross section for several processes at the ILC as a function of energy.

8.1 Event structure: production and decays

The cross sections for the production mechanisms of a Standard Model-like Higgs particle at the nominal center-of-mass energy at the ILC are shown in Figure 8.1 as a function of the Higgs mass. There are two main production modes for a Higgs particle at the ILC: W boson fusion and Higgsstrahlung (HS) from a Z boson. The corresponding Feynman diagrams are shown in Figure 8.2. Both modes will be used to measure the coupling of the Higgs to the W/Z

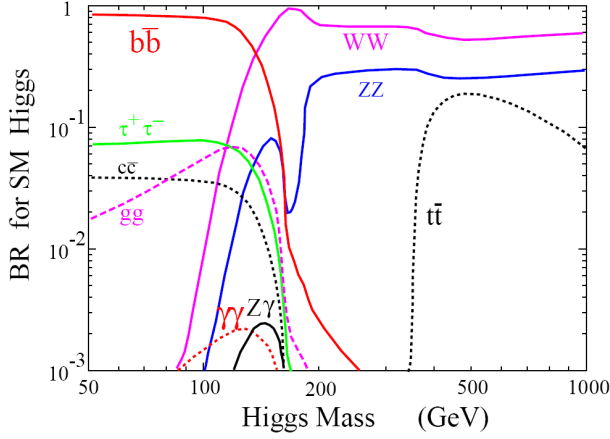


Figure 8.4: Branching fractions for a Standard Model Higgs particle in function of its mass.

Final state	Branching fraction
$e^- \bar{\nu}_e \nu_\tau$	$17.85 \pm 0.05\%$
$\mu^- \bar{\nu}_\mu \nu_\tau$	$17.36 \pm 0.05\%$
$\pi^- \nu_\tau$	$10.91 \pm 0.07\%$
$\rho^- \nu_\tau$ ($\rho^- \rightarrow \pi^- \pi^0$)	$25.52 \pm 0.10\%$
$a_1^- \nu_\tau$ ($a_1^- \rightarrow \pi^- \pi^0 \pi^0$)	$9.27 \pm 0.12\%$
$a_1^- \nu_\tau$ ($a_1^- \rightarrow \pi^- \pi^+ \pi^-$)	$8.99 \pm 0.06\%$
24 other modes	10.10%

Figure 8.5: Branching ratio for the main decays of the τ lepton.

boson respectively. While in the W fusion the two accompanying neutrinos add uncertainties to the final state, all the center-of-mass energy is taken by the intermediate Z boson in the HS process when neglecting effects from beamstrahlung and bremsstrahlung. The latter process is thus the production mechanism that is preferred for high precision measurements. If the Higgs particle exists and is relatively light, then a running at lower center-of-mass energies would be favorable. Assuming the Higgs mass to be $M_H = 120 \text{ GeV}$, the Higgsstrahlung process has its maximal cross-section at $E_{CM} \approx 230 \text{ GeV}$. Furthermore, this choice will put tight kinematic limits on the initial state radiation.

Z decays into two muons are selected, providing a very clear and easy to analyze signal. However the low branching fraction of this channel makes it unusable for stand-alone analyzes. On the other hand these studies can be extended to other decay channels if comparable qualities for the Z reconstruction can be expected. Decays into e^+e^- could be easily considered if the final state radiation is under control. Given the formidable jet energy resolution aimed for at the ILC, all the considerations can also be transferred to di-jet channels, $Z \rightarrow q\bar{q}$, where q is a light quark so that no missing neutrinos disturb the measurement. This would multiply the statistics allowing precise measurements in the early running phase of the ILC.

As it has been explained in Section 1.5, the hadronic decay channels of the τ allow to fully reconstruct the polarimeter vector, yielding the highest sensibilities to the Higgs CP state. The 3-prong decay channel $a_1^- \rightarrow \pi^- \pi^+ \pi^-$ or its complementary for a_1^+ is a very powerful mode because the τ decay point can be reconstructed directly with the three pion tracks. To emphasize the quality of the ECAL, the present analysis will be limited to the 1-prong hadronic decay channels. To use the correct polarimeter vector in the reconstruction of the event, a distinction between the τ decay channels is mandatory. The final states under consideration

differ only in the number of π^0 (and the resulting photons) involved:

$$\begin{aligned}
\tau\tau &\rightarrow \pi\nu\pi\nu \\
\tau\tau &\rightarrow \pi\nu\rho\nu \rightarrow \pi\nu\pi\pi^0\nu \\
\tau\tau &\rightarrow \pi\nu a_1\nu \rightarrow \pi\nu\pi 2\pi^0\nu \\
\tau\tau &\rightarrow \rho\nu\rho\nu \rightarrow \pi\pi^0\nu\pi\pi^0\nu \\
\tau\tau &\rightarrow \rho\nu a_1\nu \rightarrow \pi\pi^0\nu\pi 2\pi^0\nu \\
\tau\tau &\rightarrow a_1\nu a_1\nu \rightarrow \pi 2\pi^0\nu\pi 2\pi^0\nu.
\end{aligned}$$

Efficient γ reconstruction over a wide energy range is thus a necessity. The distinction between these channels will hence provide a good test for both, GARLIC and the Si/W ECAL itself. As it was already mentioned in Section 1.5 only π and ρ decays will be used for the measurement of the CP violating phase because of the model dependence of the calculation of the polarimeter for the decay involving the a_1 .

8.2 Event generation

The standard PYTHIA([46]) event generation does not preserve spin effects through the decay chains. Fortunately an interface (see Ref [45]) has already been well-established in the past to include these effects in τ decays via the TAUOLA decay library ([47]). The event generation follows the descriptions in Ref [52]: The CIRCE ([53]) program is used to simulate effects from Beamstrahlung with the parameters implemented for the TESLA project ([54]) which are quite close to those of the ILC. Then the PYTHIA (v.6.4.20) event generation is invoked to simulate the Higgsstrahlung production process and the subsequent decays:

$$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-\tau^+\tau^-. \quad (8.1)$$

The decays of the τ 's are neglected. They are left to TAUOLA and its spin-interface. The full spin correlation matrix is calculated depending on the input variable for the CP violating phase (ψ). With the spin correlations the distribution of the decay products can then be generated. Events for a pure scalar Higgs particle implying CP conservation ($\psi = 0$) are simulated as well as events with a scalar-pseudoscalar mixing angle of $\psi = -\pi/8$ implying CP violation.

8.3 Defining observables

There have already been several approaches to measure the spin-correlations in $H \rightarrow \tau\tau$ decays (see [48], [49], [50], [51], [52]). All of them are based on some observables that are somehow connected to the polarimeter vector defined in Section 1.4.2.

A central point is the reconstruction of the τ direction. The τ 's in the present analysis have typically energies between 30 and 110 GeV. At this low energies they do not attain the vertex

detector, so an alternative reconstruction method for their direction has to be developed. An enormous advantage of the ILC over earlier experiments is the fact that the interaction point is known with extreme precision, given by the beam size at the IP of $\sigma_x = 639 \text{ nm}$, $\sigma_y = 5.7 \text{ nm}$ and a bunch length of $\sigma_z = 300 \mu\text{m}$. We see that the only relevant incertitude is on the z coordinate. Additional constraints will be obtained from the reconstruction of the Z boson. All in all this means that it should be possible to completely reconstruct the directions of the two τ 's independently in the laboratory frame, so that all the information contained in the polarimeter vector can be exploited.

At higher center-of-mass energies ($500 - 600 \text{ GeV}$), a fraction of the τ 's can attain the first layer of the vertex detector, so that a direct reconstruction of the flight direction is possible.

8.3.1 Reconstructing the Higgs boson

Using the Higgsstrahlung production mechanism the Higgs boson can be defined entirely by measuring the recoil of the Z boson. Neglecting beamstrahlung, the momentum of the Higgs is then $\vec{p}_H = -\vec{p}_Z$. The expected beamstrahlung spectrum for the TESLA setup at $E_{CM} = 230 \text{ GeV}$ is shown in Figure 8.6. The choice of the center-of-mass energy will at the same time kinematically limit the initial state radiation as well as maximize the branching ratio for the Higgsstrahlungs process (compare Figure 8.3). Final state radiation on the side of the Z decay can be partly recovered by searching for photons close to the muon directions, as shown in Figure 8.8. A maximal angle of 0.2 rad is used to identify FSR photons. The improvement in the reconstruction of the Z mass is shown in Figure 8.9.

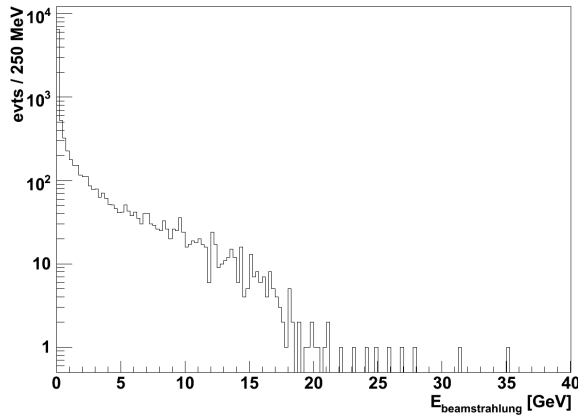


Figure 8.6: Spectrum for the energy loss by beamstrahlung for a sample of 10,000 events.

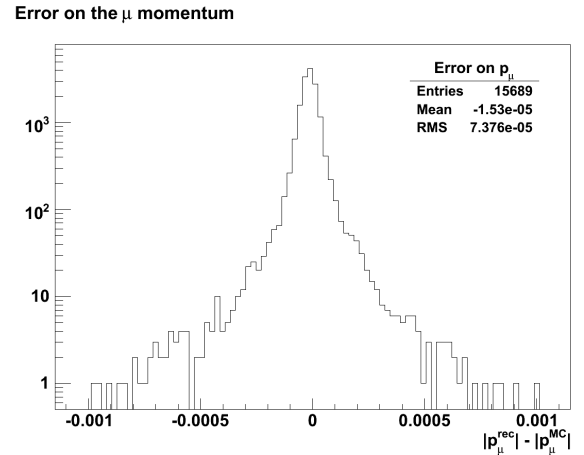


Figure 8.7: Difference between the reconstructed and simulated μ momentum.

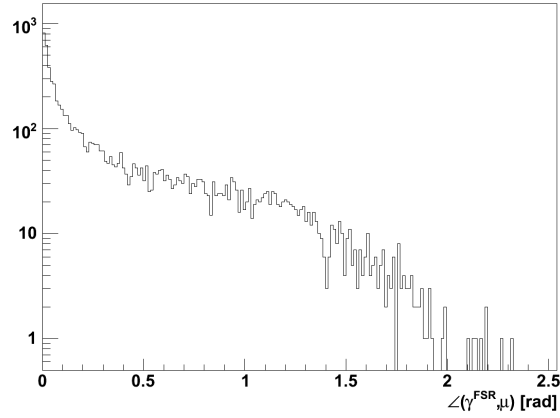
Alignment of a FSR γ with the nearest μ from the Z decay

Figure 8.8: Angle between an FSR photon and the muon from the Z boson decay that is closest by.

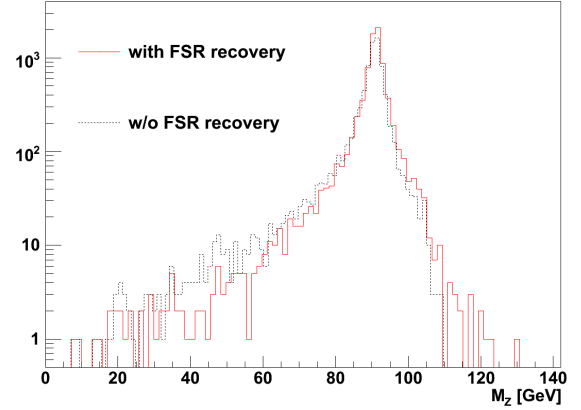


Figure 8.9: Gain in the reconstructed Z mass by reattaching FSR photons to the closest muon.

Z mass reconstruction

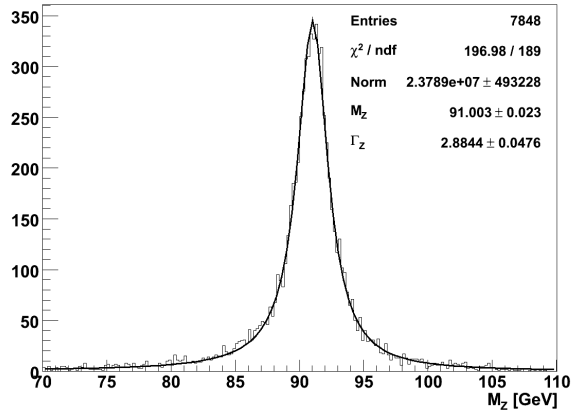


Figure 8.10: Reconstructed Z mass as obtained from $\mu^+\mu^-$ decays, fitted with a Breit-Wigner function.

Z recoil mass spectrum

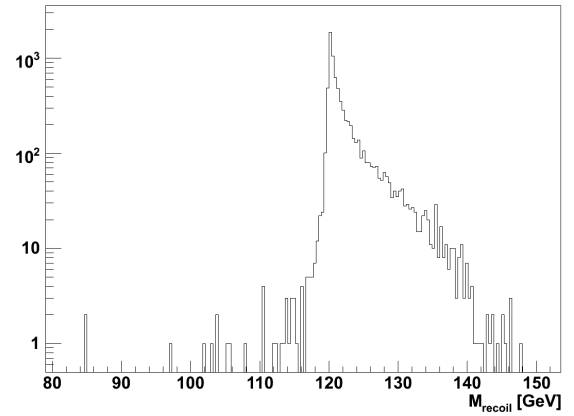


Figure 8.11: Recoil mass spectrum after applying a 5 sigma cut on the reconstructed Z mass.

Reconstruction quality Figure 8.7 shows the error on the estimation of the μ momentum. The excellent momentum resolution of ILD's tracking system is apparent. Combining the 4-vectors of the two muons with those of any FSR photons found, yields the estimation of the Z mass, like shown in Figure 8.10. The values of a fit with a Breit-Wigner to the distribution are given in the figure. The resolution is close to the natural width of the Z so that no Gaussian contribution is needed for the fit. A 5σ cut on the Z mass is then applied to reject events with too much ISR, miss-IDs or just poor μ reconstruction. Like this we obtain the recoil mass spectrum from Figure 8.11.

One of the arguments to use the easy to analyze muonic decay of the Z is the high precision in the reconstruction of the interaction point. Since the beams are very well defined in the x and y planes, the precision on the z -coordinate of the IP is the most important issue. This could be done by forcing the two muon tracks to cross each other on the z -axis when fitting. Here we are using an easier method. The z coordinate is calculated from the mean z_0 of the μ tracks (taken directly from the helix parametrization of the track), weighted by their errors:

$$IP_z = \frac{1}{(dz_0^1)^2 + (dz_0^2)^2} \left(\frac{1}{(dz_0^1)^2} z_0^1 + \frac{1}{(dz_0^2)^2} z_0^2 \right) \quad (8.2)$$

The resulting precision can be read from Figure 8.12(a). For the other decay channels mentioned earlier (e^+e^- , $q\bar{q}$), this would need a lot more reconstruction effort. Nevertheless a performance of the same order of magnitude can be expected. The resolution on the impact parameter of the muon track is given in Figure 8.12(b). Integration over a whole run will allow a very precise determination of the position of the IP. The constraints in the xy plane will then come from the (very small) beam size.

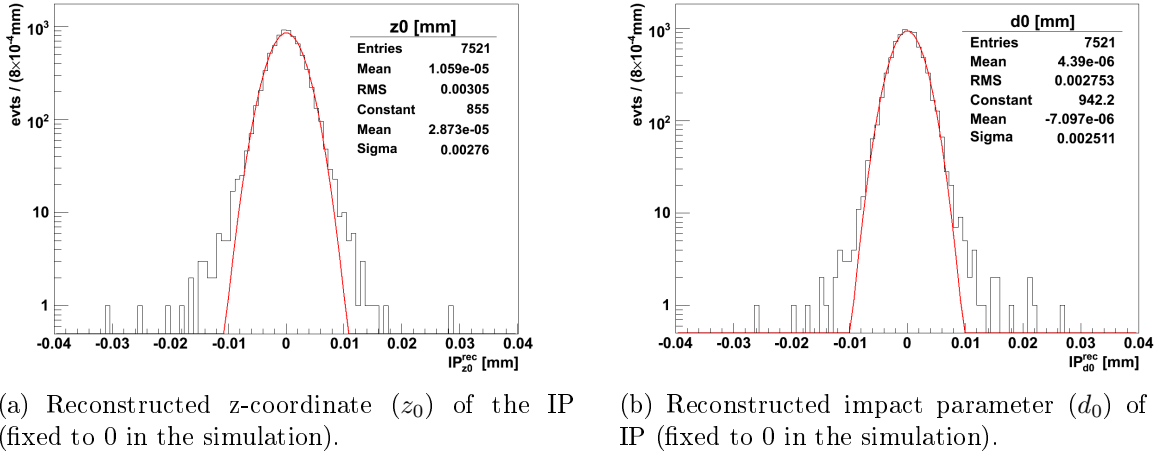


Figure 8.12: Reconstruction of the interaction point from the Z decay.

8.3.2 Estimation of the τ direction

Once the Higgs 4-vector has been measured one can proceed to the reconstruction of the τ directions. For now this reconstruction is only done for decays into π and ρ since in the case of the a_1 its strongly model-dependent internal structure has to be taken into account. Due to the similarity in the two considered decays, *had* will denote either a π or a ρ in the following depending on the observed decay. The reconstruction treats both τ 's independently. Note that this is only possible due to the excellent conditions given by the machine and the detector: the interaction point and the π impact parameters are known with excellent precision.

To better visualize the principle of reconstruction, Figure 8.13 shows a geometrical illustration of the concerned quantities as well as the method for a decay into a single pion. Except for the decay angle it is completely to scale. The top view is in the plane of the IP, and contains the π momentum as well as the Higgs line of flight. The bottom view is orthogonal to the top one while containing the IP. Quantities on the right (Higgs frame) are shown in lighter colors, their counterparts in the lab frame (left) in darker colors. Their components orthogonal to the Lorentz boost are connected with dash-dotted lines.

The small decay length of the τ 's (a few mm at most) allows the assumption that both the τ and the π trajectories can be approximated with straight lines in the region that is interesting for the reconstruction of the flight direction.

Designations are m_τ for the τ mass and $E_{h/\nu}$, $p_{h/\nu}$ for the energy and momentum of the hadron and the τ -neutrino respectively.

Relations in the τ rest-frame In the τ rest-frame the hadron and the neutrino are back-to-back. One can find expressions for the energy and the momentum of the hadron. Denoting the quantities in the τ rest-frame with (*), energy and momentum conservation gives the following relations:

$$m_\tau = E_h^* + E_\nu^* \quad (8.3)$$

$$\vec{0} = \vec{p}_h^* + \vec{p}_\nu^* \quad (8.4)$$

and one obtains

$$|\vec{p}_h^*| = \frac{1}{2} \frac{m_\tau^2 - m_h^2}{m_\tau} \quad (8.5)$$

$$E_h^* = \frac{m_h}{m_\tau} + |\vec{p}_h^*| \quad (8.6)$$

Transfer to the Higgs rest-frame The angle between the line of flight of the τ (as seen from the Higgs frame if in the τ RF) and the direction of the hadron from its decay is denoted with α . Since in a Lorentz boost components perpendicular to the boost (τ -direction) remain

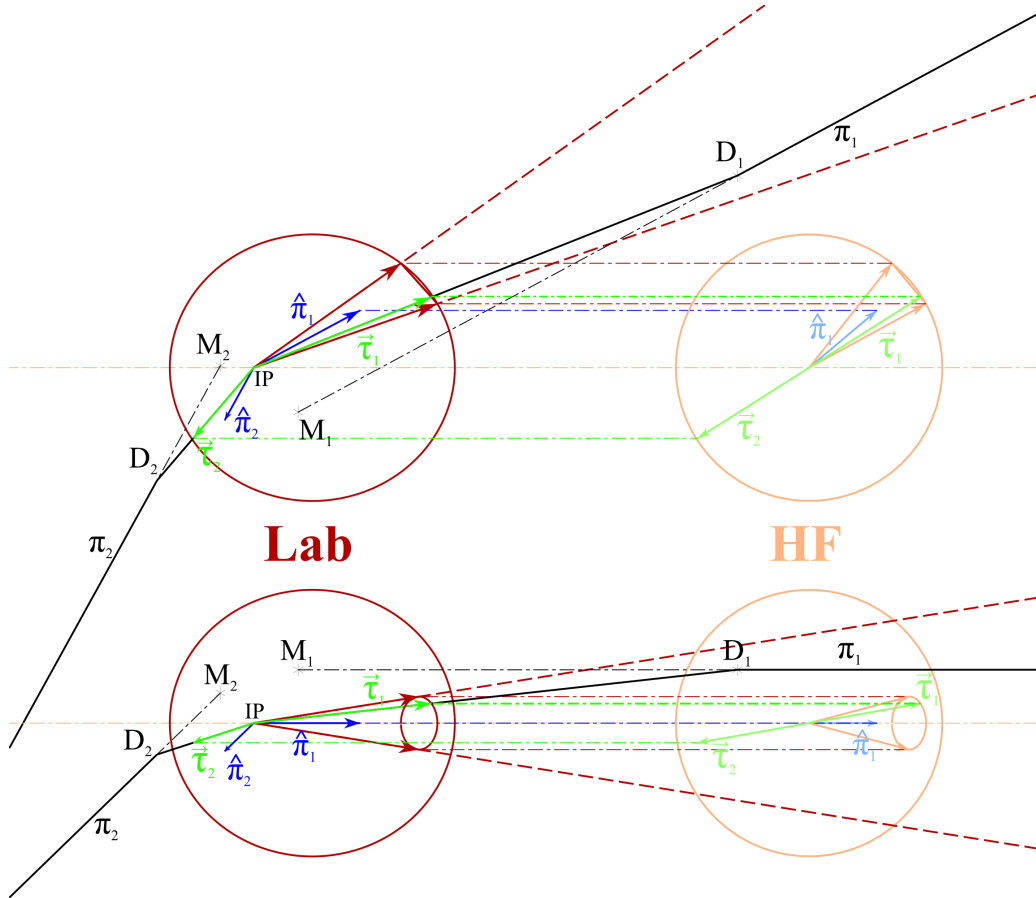


Figure 8.13: Geometrical interpretation of the quantities in a $\tau \rightarrow \pi \nu$ decay, in the Higgs (right) and the laboratory frame (left) - see text for details.

unchanged, one has (see also Figure 8.13):

$$E_h = \gamma_\tau E_h^* - \beta_\tau \gamma_\tau p_h^* \cos \alpha^* \quad (8.7)$$

$$\gamma_\tau p_h \sin \alpha = \gamma_\tau p_h^* \sin \alpha^*. \quad (8.8)$$

From these one can obtain an expression for the decay angle:

$$\alpha = \arcsin \left(\sqrt{\frac{p_h^{*2}}{p_h^2} - \frac{(E_h - \gamma_\tau E_h^*)^2}{\gamma_\tau^2 \beta_\tau^2 p_h^2}} \right) \quad (8.9)$$

The τ decay angle is well fixed in the Higgs rest-frame. Furthermore its energy ($m_H/2$) and momentum are well determined. Geometrically, this means that its direction lies on a cone with opening angle α around the hadron direction. Moreover a sphere is described with the fixed absolute value of the momentum as its radius. The intersection of the cone and the sphere, i.e. a circle gives the locus for the τ momentum. More generally it lies on a plane.

Transfer to the laboratory frame The Lorentz transformation to the laboratory frame will turn the obtained sphere into an ellipsoid. The plane will stay a plane. The intersection is transformed into an ellipse that lies itself in a plane that is perpendicular to the hadron momentum and the Higgs momentum. The τ momentum in the laboratory frame is collinear with its trajectory. At the point of decay it then crosses the pion trajectory, which can be approximated as a straight line passing through the point of closest approach (PCA) and along the π momentum. So the decay took place where the pion line of flight pierces the cone holding all possible solutions for the τ direction. The τ direction is contained in the plane through the IP, through the decay point and containing the hadron momentum.

In case of a decay into a single pion, this plane also contains the point of closest approach. In this case, the plane intersects with the ellipse in two points. Both solutions lie in the same plane, and cross the pion trajectory but one of them corresponds to a non-physical decay that is reversed in time. The decision can be easily taken when breaking down the τ direction in a component along the position vector of the point of closest approach and along the π momentum. The component of the PCA is negative in the case of the non-physical case but positive for the true direction and one ends up with a unique solution. This is illustrated in Figure 8.14(a).

For the case of a decay into a ρ , the situation is a bit more complicated. Depending on the decay angle of the ρ itself, the trajectory of the charged pion can pierce the cone with the possible solutions for the τ direction in one (c.f. Figure 8.14(b)) or two (c.f. Figure 8.14(c)) points (neglecting measurement errors in which case the trajectory could miss the cone completely). In the case of only one piercing point, the situation is similar to the pion case and the non-physical solution is removed in the same way. But in the case of two "real" solutions, the ambiguity is not solvable with the present information alone. One has to find another constraint, such as the acolinearity of the two τ 's in the Higgs RF.

Formalization The previous geometrical considerations can easily be put in a mathematical framework. The starting point are the following four equations (P_x corresponds to the 4-momentum of the particle x , whereas $\vec{p}_x$ is the 3-momentum):

$$P_\tau \cdot P_{had} = \frac{m_\tau^2 + m_{had}^2}{2} \quad (8.10)$$

$$P_\tau \cdot P_H = \frac{m_H^2}{2} \quad (8.11)$$

$$\vec{p}_\tau = \alpha \vec{p}_\pi + \beta \vec{M} \quad (8.12)$$

$$E_\tau^2 = \vec{p}_\tau^2 + m_\tau^2 \quad (8.13)$$

with $\vec{M}$ being the position vector of the point of closest approach. Equation 8.10 fixes the angle between the momenta of the τ and the hadron, the same does Equation 8.11 for the momenta of the τ and the Higgs. The fact that the τ direction is contained in the plane that contains the IP, the point of closest approach and the pion momentum is represented by Equation 8.12 and Equation 8.13 is just the relation of dispersion for the τ . Using Equations 8.10 and 8.11 we can find a linear parametrization in E_τ for α and β :

$$\alpha = \lambda E_\tau + \mu \quad (8.14)$$

$$\beta = \kappa E_\tau + \nu, \quad (8.15)$$

where λ, κ, μ and ν only depend on measured quantities and masses. When inserting these in Equation 8.12, one obtains a quadratic equation for E_τ containing only known quantities. The two solutions correspond to the two intersection points of the plane and the ellipse mentioned above. For the single-pion case, one of the solutions, inserted in Equation 8.15 will yield a negative β corresponding to the non-physical decay point reversed in time. Naturally one has to choose the solution with $\beta > 0$. In case of a ρ decay, there can be either one solution with positive and one with negative β , which corresponds to one single piercing of the cone in the geometrical interpretation (and again one has to choose the solution with $\beta > 0$), or there can be two solutions with positive β . In this case the solution(s) are chosen so that the colinearity of the two τ 's in the Higgs RF is maximal. In the case where the square root of the quadratic equation in E_τ becomes negative due to measurement errors, the square root is neglected and only the remaining part of the equation is taken into account. Like this, one single solution is forced. Including the intersection of the τ and π trajectory, we can effectively reconstruct the τ decay point, i.e. its decay length. Like this we do have an additional tool to detect anomalies in the reconstruction.

Reconstruction quality The Figures 8.15 show the reconstructed distribution of $c * t$ from τ decays to π and ρ . With the MC input of

$$c * t_\tau = 87.11 \mu\text{m}. \quad (8.16)$$

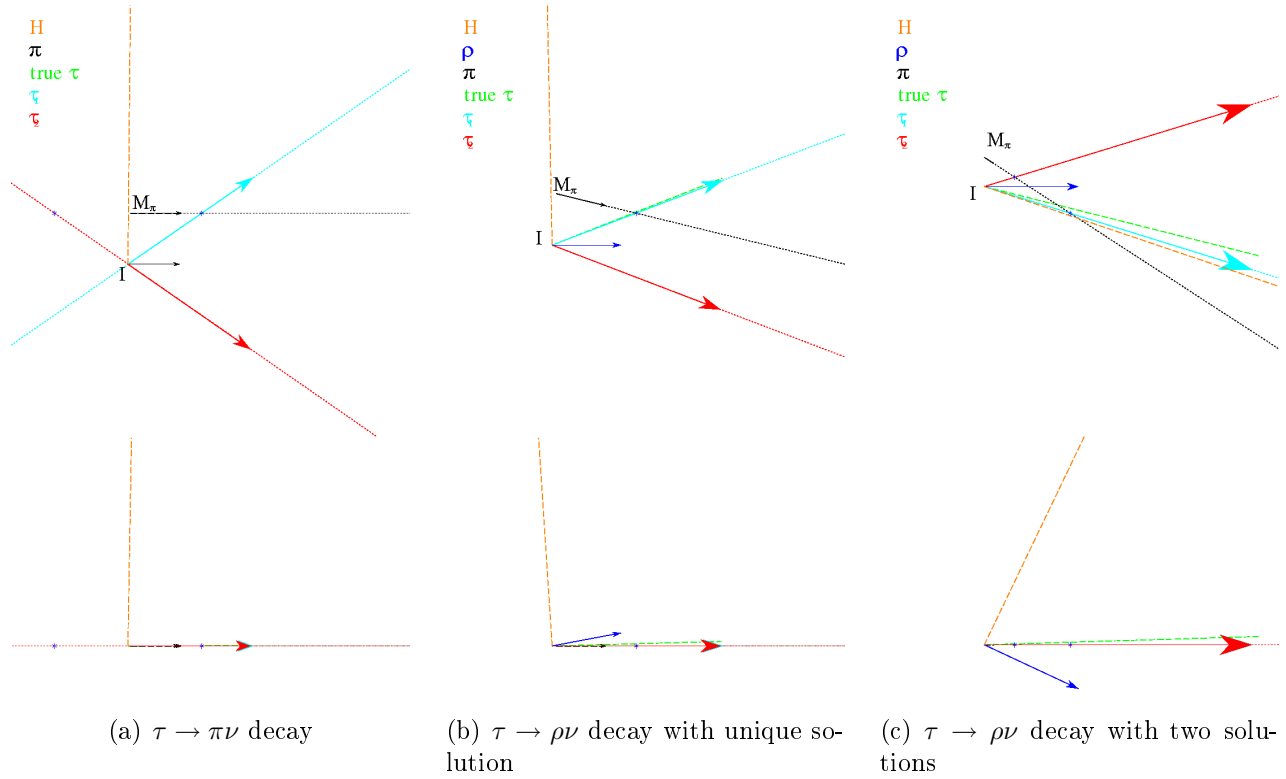


Figure 8.14: Schemes for the reconstruction of decays into π and ρ in the lab frame, showing the possible solutions for the τ direction (τ_1 (light blue) and τ_2 (red)). I is the interaction point, M_π the PCA of the charged pion. The top images show a view in the plane of the two τ solutions, the bottom ones an orthogonal one.

a value of $86.83 \pm 0.79 \mu\text{m}$ is found in the π channel and $88.91 \pm 1.05 \mu\text{m}$ in the ρ channel. In the ρ decays there is a slight tendency to overestimate $c * t$. This could be introduced by the cases in which one solution is forced.

Figure 8.16(a) shows the angle between the simulated and the reconstructed τ direction in degrees for both decay types. The histogram is normalized to the same number of entries. We see that the uncertainty is larger on the measurements in the ρ channel which adds both, the measurement errors on the associated photons and the uncertainties in the choice of the solution for the τ direction itself. This can be compared to the angle between the τ and π directions from $\tau \rightarrow \pi\nu$ decays (c.f. Figure 8.16(b)). If the uncertainty on the τ direction is bigger than the decay angle, the error on the measurement of the phase $\Delta\varphi$ will be very big. Although the decay angles are very small the method seems to be sure to work in a large fraction of the considered events.

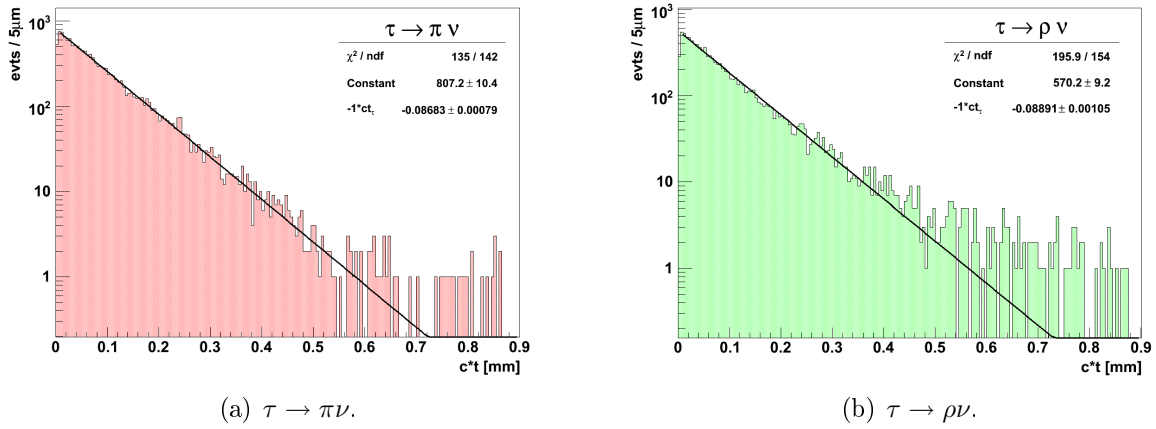
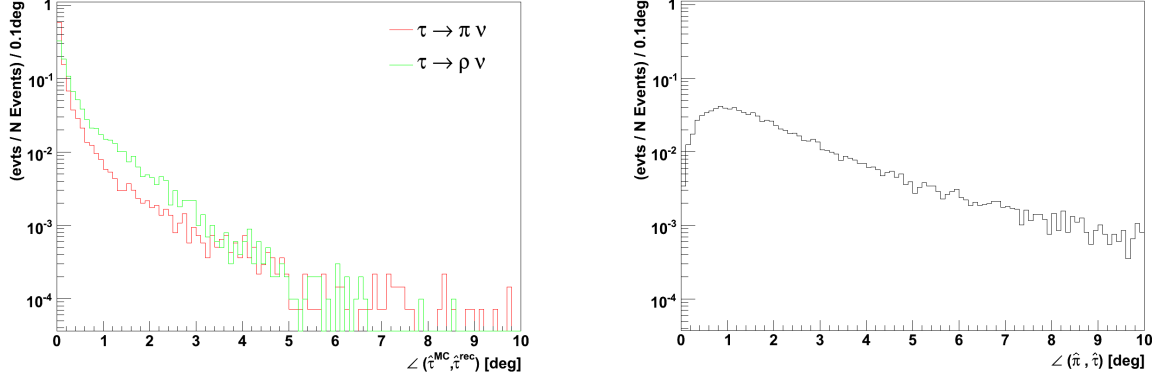


Figure 8.15: Verification of the reconstruction with a measurement of the τ decay length.

8.3.3 Identification of the τ decay

It has been mentioned earlier that the difference of the final states that are interesting in this analysis is only the number of associated photons. In case of full simulation and reconstruction though, the number of photons is a quantity very sensitive to losses due to energy thresholds or ineffective detector areas. The invariant mass of the τ "jet", i.e. the charged pion and the photons associated with it, is a less sensitive estimator. Low energy photons that are not reconstructed will then lose a big part of their impact.

After reconstruction of the charged pion on each side of the $H \rightarrow \tau\tau$ decay, the detector is divided in two equal hemispheres by the plane containing the IP and with its normal vector parallel to $\vec{p}_{\pi^1} - \vec{p}_{\pi^2}$. The Figures 8.17 show the Monte Carlo information of the angle between the momentum of the charged pion and the photons that are produced from the accompanying

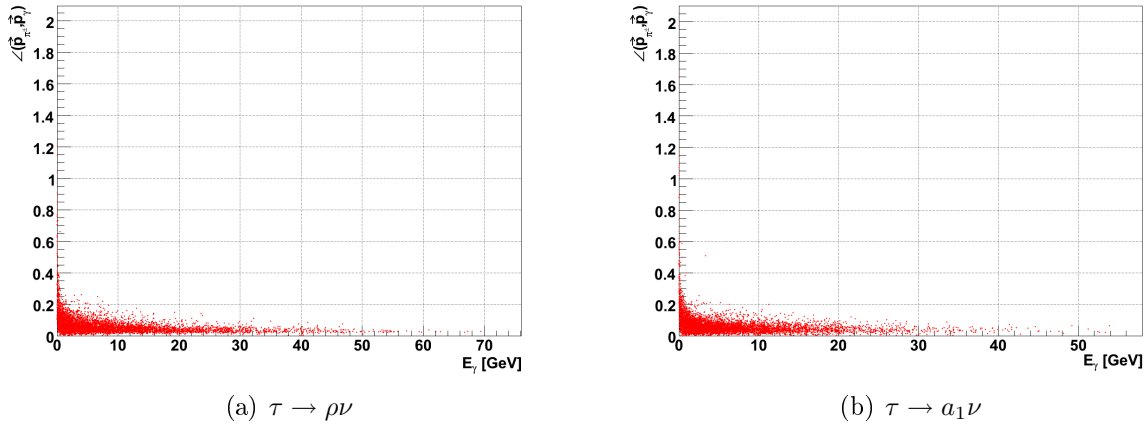


(a) Error of the reconstructed τ direction with respect to the simulated one.

(b) Angle between the τ and π flight directions in simulated $\tau \rightarrow \pi\nu$ decays.

Figure 8.16: Quality of the reconstructed τ direction with respect to typical decay angles.

π^0 decay in $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$ decays. To limit the possibility to attribute photons from initial and final state radiation to the charged π , a cut will be used on this angle. Most of the photons are contained within 0.4rad of the charged π direction and the ones at bigger angles are of low energies (i.e. < 500 MeV). Hence in the reconstruction only photons with angles inferior to 0.4rad will be considered for building the τ jet. To discriminate between the decay



(a) $\tau \rightarrow \rho\nu$

(b) $\tau \rightarrow a_1\nu$

Figure 8.17: Angle between the momentum of the charged π and the direction of the photons from subsequent π_0 decays for the channels $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$.

modes, the number of photons associated ($N_{\gamma s}$) is critical. Per number of attributed photons, the invariant mass of the jet is calculated. The resulting distributions from a large number of events (~ 2500 for each decay) are shown in Figure 8.3.3. Up to five photons are accepted.

With these distributions as a basis, the classification is done by defining different mass regions for π , ρ and a_1 after any eventual recovery:

- $N_{\gamma s} = 0$:
All events will be identified as single pion decays. The contribution of ρ and a_1 decays is very low.
- $N_{\gamma s} = 1$:
Events with $M_{jet} < 0.25 \text{ GeV}$ will be identified as single pion decays and thus stripped of their associated photon. The same is done for events with jet masses larger than the τ mass. Events between the lower mass cut and 1.45 GeV will be considered as ρ decays. There is still some contamination from π decays to which a final state radiation photon has been attributed.
- $N_{\gamma s} = 2$:
One can see a contribution from a_1 decays. This means that two photons have been lost for those decays, either both photons of a π^0 or one photon from each π^0 . The latter case can partly be removed by applying a cut on the reconstructed π^0 mass. Figure 8.3.3 shows that for a cut applied at 190 MeV a big fraction of the a_1 background is removed while nearly all the ρ decays are kept. The first case is not trivial to reduce. In most cases one photon is lost due to inefficiencies while the other is of too low energy and/or at a too high angle. Events with $0.25 \text{ GeV} < M_{jet} < m_\tau$ will be identified as ρ decays. Jets with higher mass will again be identified as π decay without any associated photon.
- $N_{\gamma s} = 3$:
These events are primarily from a_1 decays (identification for $0.25 \text{ GeV} < M_{jet} < m_\tau$). The underlying contamination from ρ decays can a priori not be removed. For lower jet masses a single π decay is assumed. For higher jet masses ρ decays with an additional FSR photon are dominant. The combination of two photons giving the best π^0 mass is searched. If the jet mass with only these photons is now inferior to the τ mass the decay is identified as a ρ decay with the two photons attributed to it.
- $N_{\gamma s} = 4$:
Decays with $M_{jet} < 0.6 \text{ GeV}$ are identified as single π decays, all others as a_1 decays.
- $N_{\gamma s} = 5$:
All decays with $0.6 \text{ GeV} < M_{jet} < m_\tau$ are identified as a_1 decays. Decays at lower masses remain unidentified. For higher masses a recovery is tried by choosing the two photon pairs closest to the π^0 mass. If the resulting jet mass remains higher than m_τ the decay stays unidentified, otherwise it is identified as an a_1 decay.

The cuts applied on the mass are shown in Table 8.3.3.

Figure 8.20 shows discrimination between the signal channels with the method mentioned above. The corresponding identification efficiencies are given in Table 8.2

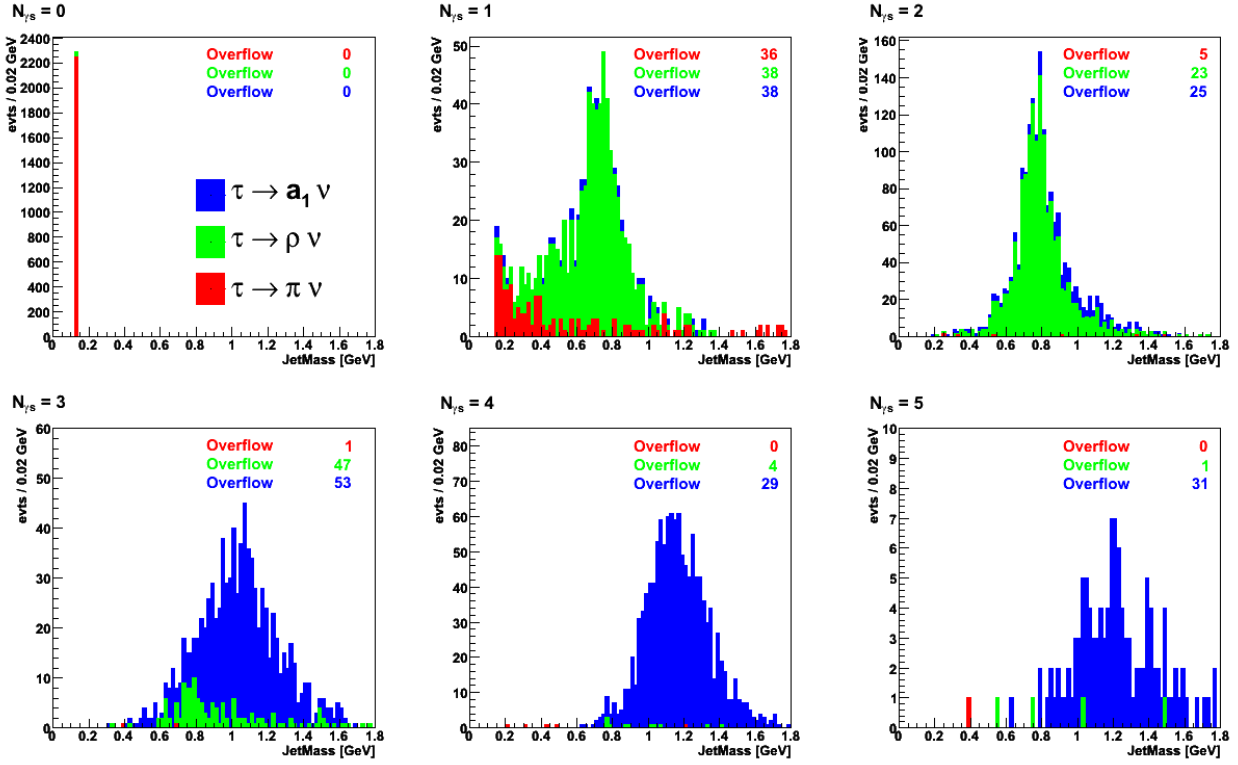


Figure 8.18: Reconstructed masses of the τ jet as a function of the photons attributed to the decay. These distributions are used as a reference to define the distinction between the different hadronic one-prong decay channels. The histogram overflows are additive (green=red+green, blue=red+green+blue).

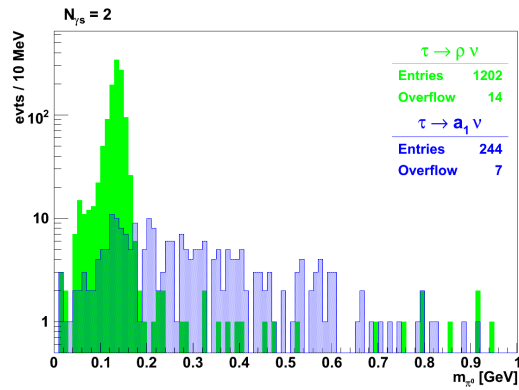


Figure 8.19: Distribution of the reconstructed π^0 mass from events with two photons attributed to the charged pion.

N ass. γ 's	π	ρ	a_1
0	$M_{jet} < 0.25$	—	—
1	$M_{jet} < 0.25$	$0.25 < M_{jet} < 1.45$	—
2	$M_{jet} < 0.25$	$0.25 < M_{jet} < m_\tau$	—
3	$M_{jet} < 0.25$	—	$0.25 < M_{jet} < m_\tau$
4	—	—	$0.6 < M_{jet} < m_\tau$
5	—	—	$0.6 < M_{jet} < m_\tau$

Table 8.1: Cuts (in GeV) on the τ jet mass (M_{jet}) to classify the different channels as a function of the number of associated photons. A "—" indicates that this channel is excluded for a given number of associated photons.

[%]	π^{sim}	ρ^{sim}	a_1^{sim}
π^{rec}	95.9	2.8	0.6
ρ^{rec}	3.9	90.8	11.2
a_1^{rec}	0.1	6.1	86.8
not identified	0.1	0.3	1.4

Table 8.2: Reconstruction efficiencies and purities for the decays $\tau \rightarrow \pi\nu$, $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$ (1-prong).

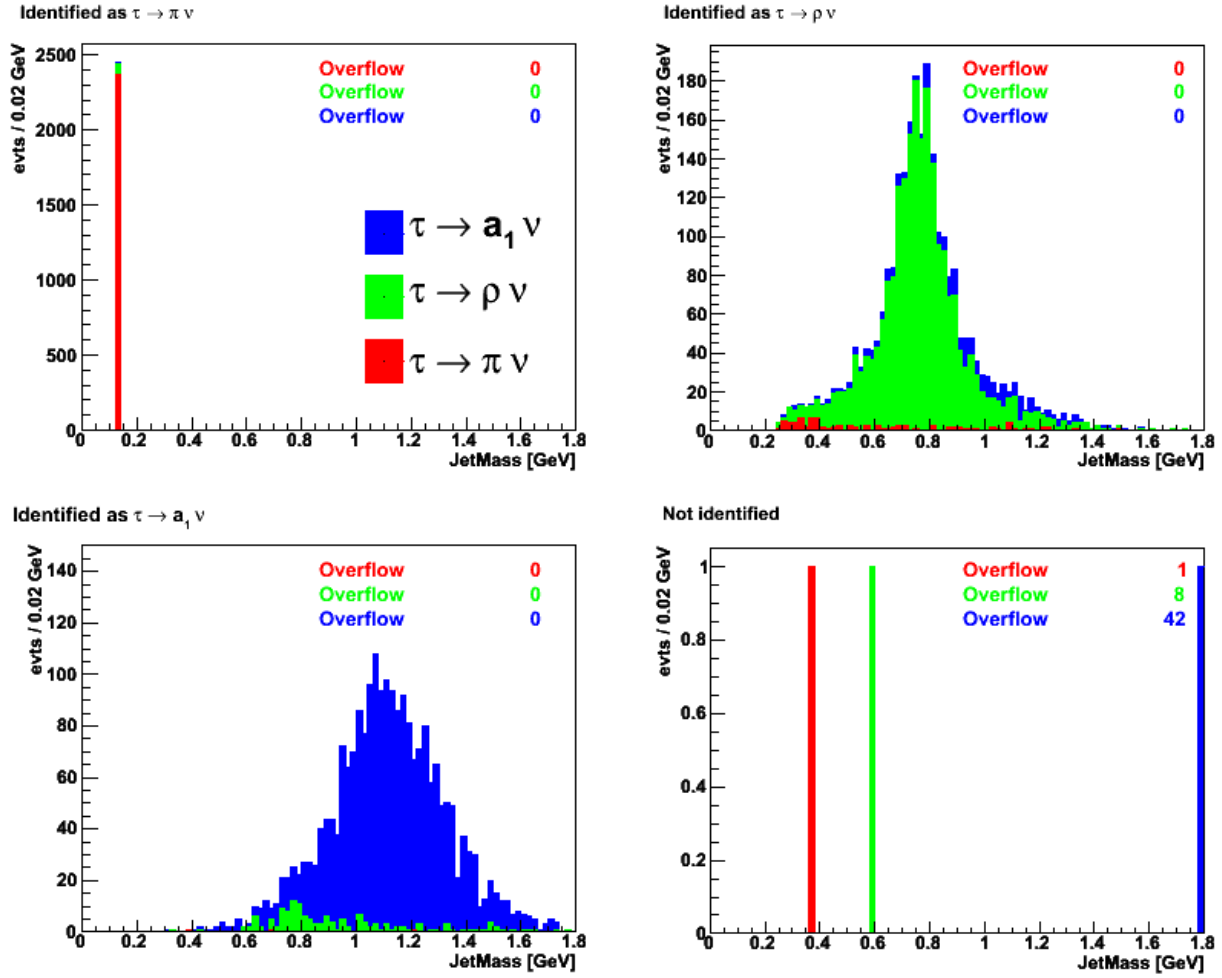


Figure 8.20: Discrimination between the τ decay channels used as signal for the present analysis. The corresponding efficiencies are listed in Table 8.2. The histogram overflows are additive (green=red+green, blue=red+green+blue).

8.4 Event sample

8.4.1 Signal: $e^+e^- \rightarrow ZH \rightarrow \mu\mu\tau\tau$

The design goal for the ILC is to collect an integrated luminosity of 500 fb^{-1} in the first four years of running. It is assumed here that this period will be dedicated to a precision measurement of the mass of a light Higgs particle ($M_H = 120 \text{ GeV}$) previously discovered elsewhere. In this case a running at $E_{CM} = 230 \text{ GeV}$ will be preferable also for the (recoil) mass measurement and all the luminosity could be used at this energy.

The cross section for the Higgsstrahlung process at $E_{CM} = 230 \text{ GeV}$ in the ILC baseline configuration with beamstrahlung as well as initial state radiation included is about 306.8 fb as calculated with the WHIZARD event generator [61]. The branching ratio of the channel $Z \rightarrow \mu\mu$ is 3.4%, the one for $H \rightarrow \tau\tau$ in case of a 120 GeV Higgs is about 8% (c.f. Figure 8.4), making a total of 417 events. The three hadronic one-prong τ decays here have a combined branching ratio of 46%, the two signal channels for the present measurement of the CP violating phase taking 36% (c.f. Figure 8.5). All in all this gives 54 signal events in the first ILC running period.

It has been argued (see [62] for example) that, because there is no CP-odd HZZ coupling at tree-level, even in the case of a CP mixed state of the Higgs, only the CP-even component is projected out. This is true for the Higgs production but not for the decay. The cross section will be reduced with a factor of $\cos^2\psi$. Only a light mixing will hence preserve good statistics. In the case of a mixing of $\pi/8$ this means a reduction in the cross section of 15%, yielding 46 signal events.

8.4.2 Background from $e^+e^- \rightarrow ZZ \rightarrow \mu\mu\tau\tau$

The only relevant background for the present analysis is the production of a Z boson pair (see Figure 8.21(b) for the Feynman diagram of the production), where one of the Z decays in a pair of muons and the other one in a pair of taus. The cross section in the ILC baseline configuration is about five times higher than the one for the Higgsstrahlung process (1860.1 fb). The branching ratio of $Z \rightarrow \tau\tau$ is just about 3.4%. With the combinatorial factor of 2 this gives 2150 $\mu\mu\tau\tau$ final state events, reducing to 279 in the channels used for the measurement, resulting in a signal-to-background of

$$S/B = 0.19 = \sim 1/5. \quad (8.17)$$

Several cuts can be established to reduce the number of background events. They will be described in Section 8.4.4.

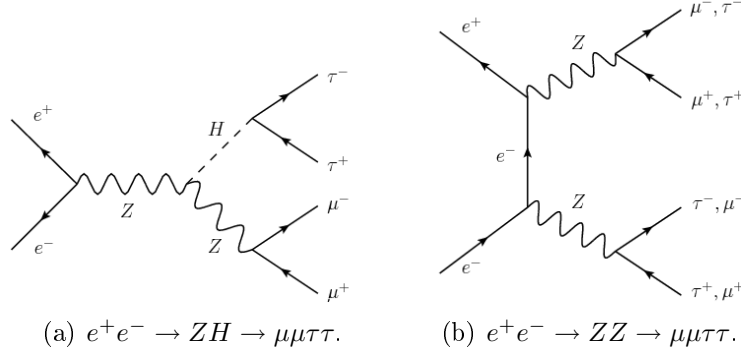


Figure 8.21: Feynman diagrams for signal and background.

8.4.3 Beam polarization

Chirality conservation in the $Zf\bar{f}$ coupling constrains the spin projection of the Z to -1 or $+1$. The cross section for the ZZ and ZH productions depend hence on the polarization of the incoming electron and positron beams. Table 8.3 summarizes the values at different polarizations, including values for complete polarization, no polarization, the ILC design goal of 80% polarized electrons and 30% polarized positrons as well as for the upgrade to 60% polarized positrons.

The ILC baseline design is used as a reference for the present analysis.

Polarization	$\sigma(ZZ)$ [fb]	$\sigma(ZH)$ [fb]	$\sigma(ZH)/\sigma(ZZ)$ [%]
$e^-(1,0), e^+(0,1)$	3224	524.5	16.3
$e^-(0,1), e^+(1,0)$	1330	336.7	25.3
$e^-(0,0), e^+(0,0)$	1139	214.4	18.8
$e^-(0.8,0), e^+(0,0.3)$	1860.1	306.8	16.5
$e^-(0.8,0), e^+(0,0.6)$	2347.9	384.4	16.4
$e^-(0.8,0), e^+(0,0)$	1517.3	252.9	16.7

Table 8.3: Cross sections for ZZ and ZH production with different beam polarizations.

8.4.4 Background reduction

Three variables have been investigated to reduce the background from $ZZ \rightarrow \mu\mu\tau\tau$:

1. Recoil Mass

Figure 8.22(a) shows the recoil mass spectrum to the Z boson that decays to $\mu\mu$ for signal and background. A mass window can be defined when evaluating the value of $S/\sqrt{S+B}$

for varying ranges of the lower and upper cuts (c.f. Figure 8.22(c)). In order not to limit statistics too much the cut has been chosen to

$$119 \text{ GeV} < M_{recoil}^{Z \rightarrow \mu\mu} < 129 \text{ GeV}. \quad (8.18)$$

It removes about 96% of the background and 9% of the signal, leaving a signal-to-background ratio of ~ 4 .

2. Angular distribution of $Z(\rightarrow \mu\mu)$

ZZ is produced in the T-channel (c.f. Figure 8.21(b)). This gives a distribution in $1 + \cos^2 \theta$. ZH on the other hand is distributed isotropically in θ . In principle a cut on the $|\cos \theta|$ value of the Z boson decay into two muons would be possible to further suppress the background. The gain is nevertheless small compared to the reduction of the number of signal events (c.f. Figure 8.22(d)), so that this cut is not used.

3. Angular distribution of the polarimeter vector

Figure 8.23 shows the behaviour of two of the different possible states of a $\tau\tau$ system from a H decay (left) and a Z decay (right) under application of C,P and T. In Section 1.5 the complete angular distribution of the polarimeter vectors from a $H \rightarrow \tau\tau$ decay has been found to be

$$W_3^H(\cos \theta^+, \cos \theta^-, \Delta\varphi) \propto [1 + \cos \theta^+ \cos \theta^- - \sin \theta^+ \sin \theta^- \cos(\Delta\varphi - 2\psi)], \quad (8.19)$$

with $\Delta\varphi = \varphi^+ - \varphi^-$. This distribution was obtained by calculation of the decay amplitude of the state

$$\frac{1}{\sqrt{2}} [|+ - \rangle + e^{i\xi} |- + \rangle]. \quad (8.20)$$

For the decay of a Z boson (spin 1), this state can be written as

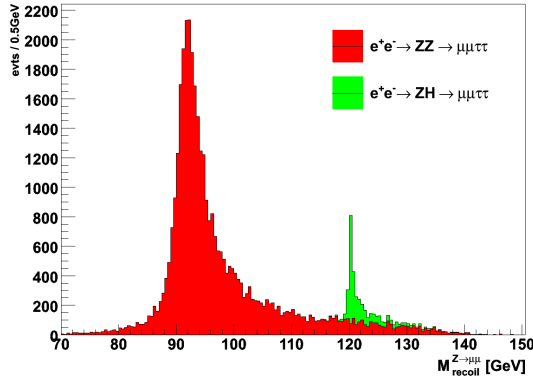
$$\frac{1}{\sqrt{2}} [e^{i\chi/2} |+ + \rangle + e^{-i\chi/2} |- - \rangle], \quad (8.21)$$

while the decay distribution takes the form

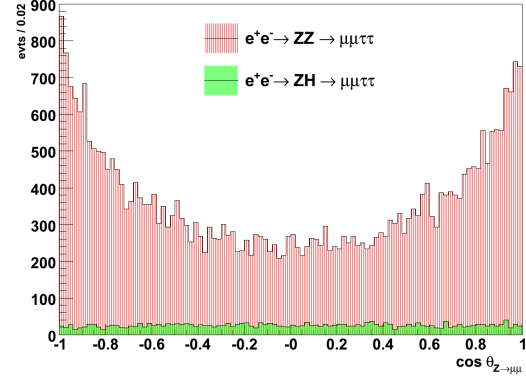
$$W_3^Z(\cos \theta^+, \cos \theta^-, \sigma\varphi) \propto [1 - \cos \theta^+ \cos \theta^- - \sin \theta^+ \sin \theta^- \sigma\varphi], \quad (8.22)$$

where $\sigma\varphi = \varphi^+ + \varphi^-$ is now the sum of the azimuthal angles. This reflects the spin 1 nature of the Z , while in the case of the spin 0 H , where the reference frame is arbitrary, only the difference of the two angles can appear. The distribution of the background in the variable $\Delta\varphi$ will hence be flat.

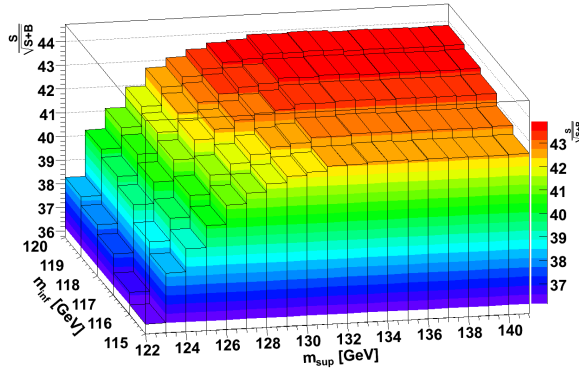
The two distributions Equation 8.19 and 8.22 show a different dependence on the product $\cos \theta^+ \cos \theta^-$, that can be exploited for background rejection. The two distributions are shown in Figure 8.24(a) with the proper S/B ratio after the cut on the mass window.



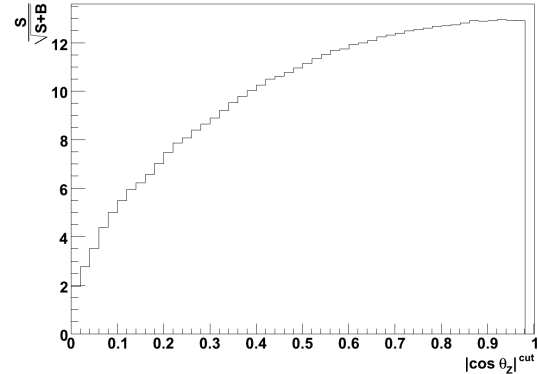
(a) Recoil mass spectrum to the $Z \rightarrow \mu\mu$ for signal and background events.



(b) Distribution in $\cos \theta$ of the the $Z \rightarrow \mu\mu$ for signal and background.



(c) Improvement of the signal significance with cuts by defining a Higgs mass window.



(d) Improvement of the signal significance with a cut on $\cos \theta_{Z \rightarrow \mu\mu}$.

Figure 8.22: Background from $ZZ \rightarrow \mu\mu\tau\tau$ decays and possibilities for cuts for background reduction.

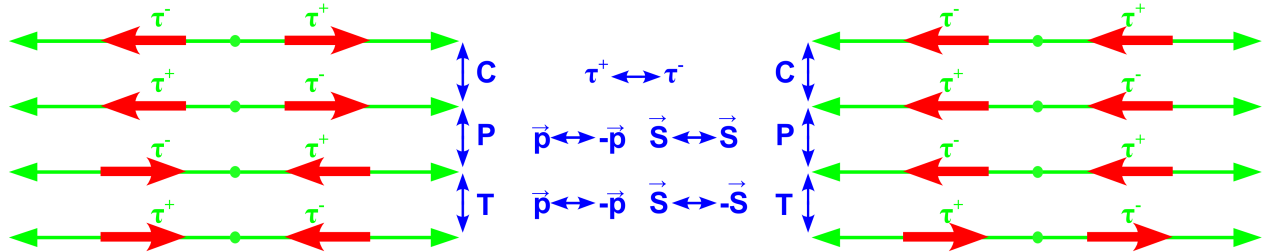


Figure 8.23: Behavior of two of the different $\tau^+\tau^-$ states under C,P and T.

Moreover the prefactors in the part of Equation 8.19 that is involving $\Delta\varphi$ can be interpreted as a weight of how much each event contributes to the measurement. When optimizing a cut on $\cos\theta^+\cos\theta^-$, this weight has to be taken into account. The corresponding distribution $\sin\theta^+\sin\theta^-$ is drawn in Figure 8.24(b). A cut of

$$\cos\theta^+\cos\theta^- > -0.4 \quad (8.23)$$

reduces the maximal weighted signal significance by just 0.4%. At the same time it removes about 19% of the background events by only 5% reduction of the signal events, which corresponds to 3% when weighting with the $\sin\theta$ functions.

8.5 Inclusive τ decays

All main τ decay channels from Table 8.5 plus the decays into K , K^* and $n\pi$ have been included. Although only π and ρ decays will be used in the measurement of the CP violating phase, all combinations of π , ρ and (1-prong) a_1 decays will be called signal events.

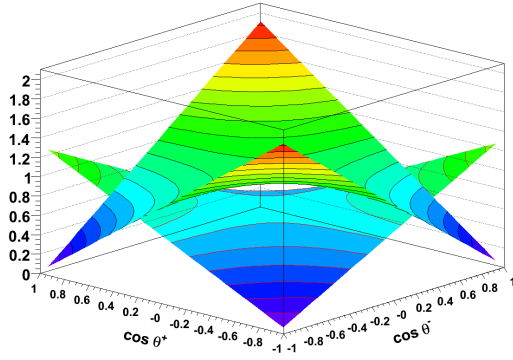
Due to the easy event signature tight pre-cuts can be applied:

- Exactly 2 muons found in the event.
- No electrons/positrons found in the event.
- 5σ cut on the reconstructed Z mass.

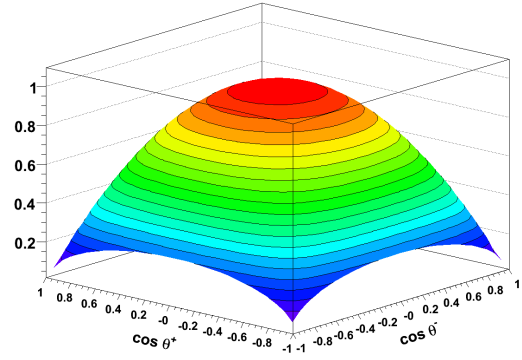
The effect of these cuts can be seen in Table 8.4.

The high reduction of the signal events to $\sim 64\%$ is induced by a poor performance of the particle identification. Much better values can be expected to be achieved in future versions of the ILD software.

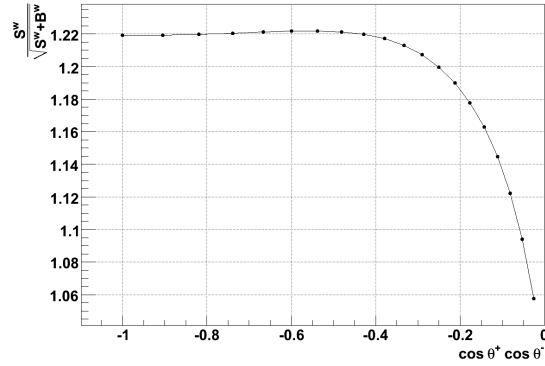
Also the identification of all inclusive τ decays is perturbed by the particle identification. About 3.5% of non-signal decays pass the cuts before the classification in signal channels. The identification of the remaining background events to the signal channels is given in Table 8.5 and a detailed breakdown per channel can be deduced from Figure 8.25. There is a high contamination of μ decays due to μ/π confusion. Additional non-signal contribution comes primarily from decays involving K 's or K^* 's. Possible π/K separation with dE/dx measurements in the TPC is not implemented yet. It is though questionable if the statistical knowledge of the particle nature will yield any big advantage. For these decays a wrong mass will be attributed. This means a loss in sensitivity but they will still contribute to the measurement because it will be performed by comparing the data to the MC simulation where the well-known fraction of K decays will be introduced. In the category involving several photons, also decays into final states with more than one charged and/or neutral π 's contribute.



(a) The functions $1 + \cos \theta^- \cos \theta^+$ (black contour line) and $1 - \cos \theta^- \cos \theta^+$ (red contour line) as appearing in Equations 8.19 and 8.22 for signal and background.



(b) The function $\sin \theta^+ \sin \theta^-$ that interferes as event weight for the measurement of $\Delta\varphi$ in Equation 8.19.



(c) Signal significance when applying a cut on $\cos \theta^- \cos \theta^+$. Signal and background are weighted with $\sin \theta^+ \sin \theta^-$.

Figure 8.24: Different parts of the angular decay distributions following Equations 8.19 and 8.22.

Cut	signal	others	ZZ
Total	2070	7930	51559
$N_\mu = 2$	1823 (88.1%)	4562 (57.5%)	32812 (63.6%)
$N_{e^\pm} = 0$	1328 (64.2%)	1474 (18.6%)	13560 (26.3%)
$C(\mu_1) \neq \mu_2$	1325 (64.0%)	1402 (17.7%)	13212 (25.6%)
M_Z	1269 (61.3%)	1278 (16.1%)	12227 (23.7%)
M_H	1158 (55.9%)	1170 (14.8%)	511 (1.0%)
$N_\pi = 2$	1087 (52.5%)	277 (3.5%)	301 (0.6%)
$N_{\gamma s} > 5$	1087 (52.5%)	274 (3.5%)	300 (0.6%)
$N_{\gamma s} > 5$	1087 (52.5%)	273 (3.4%)	299 (0.6%)
$N_{\gamma s} > 5$	1082 (52.3%)	247 (3.1%)	293 (0.6%)
Decay not identified	1077 (52.0%)	245 (3.1%)	292 (0.6%)
$\beta_{1/2} < 0$	1046 (50.5%)	235 (3.0%)	278 (0.5%)
$c * t_\tau^{1/2} > 10 * ct_\tau$	1037 (50.1%)	233 (2.9%)	276 (0.5%)
$\beta_{chosen} > 0$ but $c * t_\tau^{chosen} > 10 * ct_\tau$	1034 (50.0%)	233 (2.9%)	276 (0.5%)
π or ρ decays	654 (31.6%)	151 (1.9%)	175 (0.3%)
$\cos \theta^+ \cos \theta^- > -0.4$	616 (29.8%)	125 (1.6%)	157 (0.3%)

Table 8.4: Efficiency of the selection cuts on signal and background from 10.000 $ZH \rightarrow \mu\mu\tau\tau$ events and the corresponding background from ZZ .

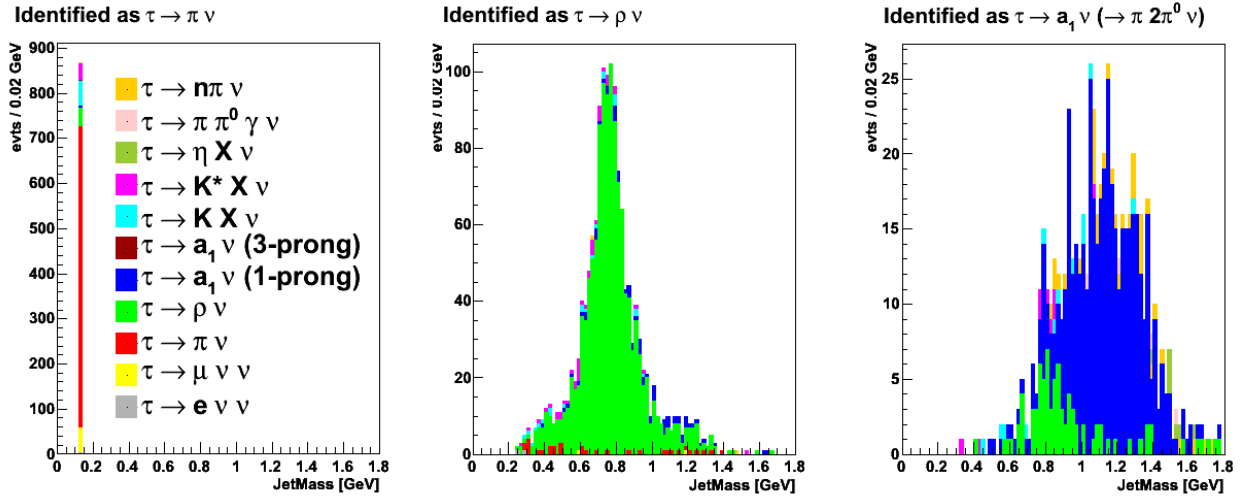


Figure 8.25: Selection of the τ decay channels used for the present analysis. The corresponding efficiencies are listed in Table 8.5.

[%]	π^{sim}	ρ^{sim}	a_1^{sim}	other
π^{rec}	95.5	2.7	0.6	49.1
ρ^{rec}	4.2	90.2	12.5	21.8
a_1^{rec}	0.0	5.9	85.0	19.7
rejected	0.3	1.2	1.9	9.3

Table 8.5: Identification efficiencies for all simulated τ decay channels before the selection of ρ and π decays.

[%]	$\pi\pi^{sim}$	$\pi\rho^{sim}$	πa_1^{sim}	$\rho\rho^{sim}$	ρa_1^{sim}	$a_1 a_1^{sim}$	other
$\pi\pi^{rec}$	59.4	1.4	0.5	0.2	0	0	0.6
$\pi\rho^{rec}$	8.7	46.5	8.1	3.3	0.4	0	1.0
πa_1^{rec}	0	3.8	46.7	0	0.8	0	0.4
$\rho\rho^{rec}$	0	1.6	0.9	41.8	4.6	1.0	0.4
ρa_1^{rec}	0	0	0.5	5.6	39.6	9.4	0.6
$a_1 a_1^{rec}$	0	0	0	0	2.5	30.2	0.1
other	31.9	46.7	43.3	49.1	52.1	59.4	96.9

Table 8.6: Efficiencies for the event categorization before the selection of ρ and π decays.

To estimate the reconstruction efficiencies per event, Table 8.6 summarizes the identification correlations with all cuts applied before the π and ρ channel selection (double horizontal line in Table 8.4). A large amount of signal events is rejected due to particle missidentification.

After the complete chain of cuts the ratio of events selected from ZH (signal S) and those from ZZ (background B) is about

$$\frac{S}{B} \sim 4.5 . \quad (8.24)$$

8.6 Results

It is obvious that given the low statistics of the signal channels paired with the high event rejection, the study cannot be performed with the simple assumptions from Section 8.4. Even a better particle identification would not be sufficient for a stand-alone measurement. The statistics need to be heavily increased.

8.6.1 Extension of the event sample

The limiting factor for the available statistics is the selection of $ZZ \rightarrow \mu\mu$ events. Using instead also e^+e^- events already doubles the statistics. With appropriate tools the losses by radiation should be partially recoverable. The tight physics program of the ILC will nevertheless impose an even faster measurement. Hence it is probably mandatory to include also Z decays in quark-antiquark pairs. The critical point is the degradation in the Z 4-vector that defines the Higgs 4-vector used in the analysis. For a limitation to the light quarks (u, d, s), so that neutrinos do not disturb the measurement, one still multiplies the statistics by 7.4 and comparable accuracies can be expected. The background considerations will have to be revised but since the background distribution remains flat in $\Delta\varphi$ there should be no significant impact even in the case of an increased level. To determine the limits with which precision the measurement of the Z has to be performed and hence to extract the limits for the extension of the event sample, will need a dedicated study.

Another extension that should not be forgotten is the a_1 decay channel. It takes a large part of the τ branching fraction and its 3-prong decay enables a measurement with an easy reconstruction of the τ direction via the three charged pion tracks.

8.6.2 Distributions of $\Delta\varphi$

From Section 1.5 the following Equation 1.26 is known:

$$W_1(\Delta\varphi) = \frac{1}{2\pi} \left[1 - \frac{\pi^2}{16} \cos(\Delta\varphi - 2\psi) \right] \quad (8.25)$$

Figure 8.26 shows the simulated and reconstructed distributions in $\Delta\varphi$ for a large number of events with $\pi\pi$, $\pi\rho$ and $\rho\rho$ decays for two values of the CP violating phase ψ . Both follow Equation 8.25 with the respective values for ψ (0, $-\pi/8$).

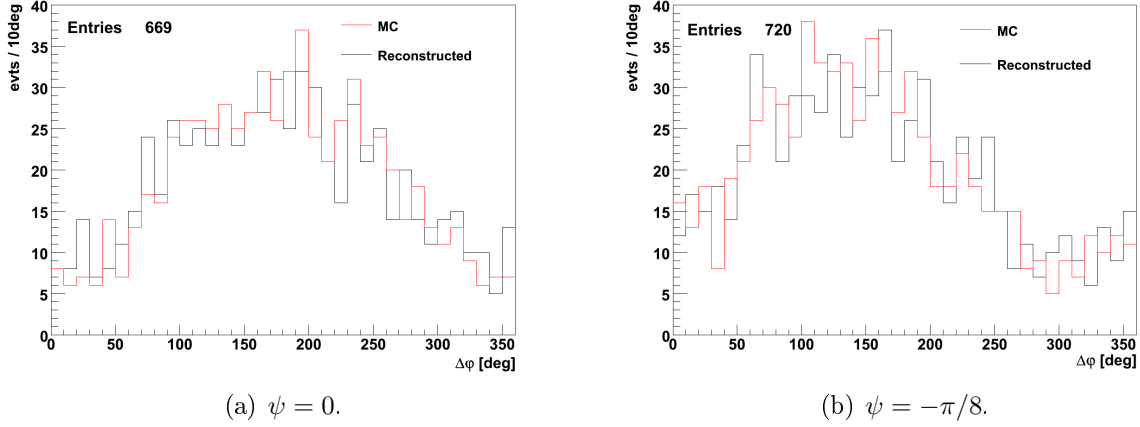


Figure 8.26: Simulated and reconstructed Distribution of $\Delta\varphi$ from $\pi\pi$, $\pi\rho$ and $\rho\rho$ events.

8.6.3 Extraction of the CP violating phase ψ

The pure signal distributions of Figures 8.26 are modified with the contamination from the misidentified τ decays and the flat distribution from the ZZ background. To extract ψ a χ^2 minimization with the function

$$W_{fit}(\Delta\varphi) = a (1 - b \cos(\Delta\varphi - 2c)) , \quad (8.26)$$

is used. The parameter a is a normalization factor. It accounts for the used statistics and is defined as

$$a = \frac{N_{entries}}{N_{bins}}. \quad (8.27)$$

b is connected to the fraction of signal and background by

$$\frac{S}{B} = \frac{b}{\frac{\pi^2}{16} - b}, \quad (8.28)$$

and c gives the phase ψ .

The binned χ^2 fit has certain disadvantages at low statistics as they exist here. To check the applicability of the χ^2 minimization, a Monte Carlo toy study has been performed.

8.6.3.1 MC toy study

The advantage of such a study is that a big number of pseudo-experiments can be performed and so the robustness of the method can be estimated in function of the sample statistics. The two values of ψ used in the full simulation have been investigated. As an input for the ratio S/B , the estimation from Equation 8.24 ($S/B = 4.5$, $b_{input} = 0.505$) has been used. For five thousand pseudo experiments, distributions are generated following

$$W_{PseudoExp}(x) = 1 + \frac{S}{B} \left(1 - \frac{\pi^2}{16} \cos(x - 2\psi_{input}) \right) \quad (8.29)$$

for several sample sizes and then fitted with the function of Equation 8.26. The fitted value, the error and the pull distribution of b and c are then estimated. A summary is given in Table 8.7 and an example for the different distributions in Figure 8.27. The method works fine even down to low statistics. The extraction of the phase is extremely robust. The estimation of the ratio S/B presents itself more difficult. The parameter b shows a slight bias to underestimated values. Fitting b instead of S/B directly yields the advantage of a more gaussian-like distribution. The transformation from b to S/B introduces a large tail to higher values so that the mean value for S/B appears actually overestimated.

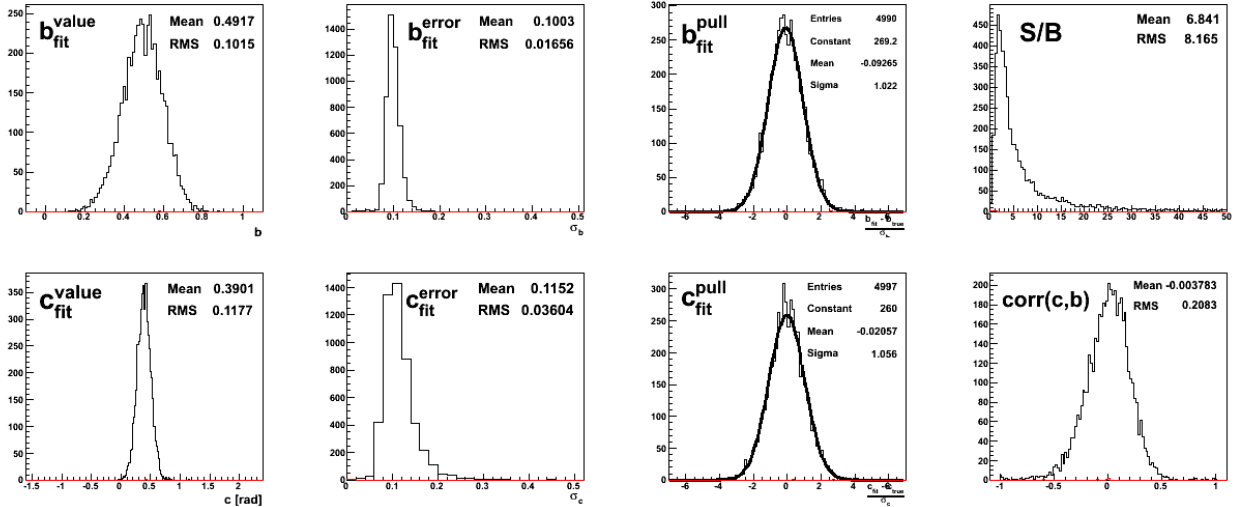


Figure 8.27: Example for the fit and pull distributions for $\psi_{input} = -\pi/8$ and 5000 pseudo experiments with 150 events each. Also shown is the correlation coefficient between the parameters b and c .

N_{events}	ψ_{input}	b_{fit}^{mean}	$b_{fit}^{meanerror}$	b_{pull}^{μ}	b_{pull}^{σ}	S/B_{fit}^{mean}	c_{fit}^{mean}	$c_{fit}^{meanerror}$	c_{pull}^{mean}	c_{μ}^{σ}
25	0	0.535	0.241	0.139	0.880	5.974	-0.009	0.320	-0.002	1.115
	$-\pi/8$	0.539	0.238	0.149	0.893	6.127	0.378	0.313	-0.022	1.168
50	0	0.485	0.162	-0.081	0.981	6.409	-0.000	0.211	-0.013	1.107
	$-\pi/8$	0.489	0.161	-0.063	0.982	6.358	0.389	0.208	-0.009	1.128
75	0	0.487	0.136	-0.099	1.008	6.581	-0.001	0.169	-0.006	1.065
	$-\pi/8$	0.486	0.137	-0.105	1.012	6.524	0.390	0.170	-0.013	1.081
100	0	0.489	0.120	-0.099	1.021	6.717	-0.002	0.144	-0.013	1.050
	$-\pi/8$	0.490	0.121	-0.085	1.014	6.728	0.393	0.144	-0.007	1.060
150	0	0.492	0.100	-0.095	1.003	6.805	0.004	0.115	0.0376	1.047
	$-\pi/8$	0.493	0.102	-0.087	0.989	6.808	0.396	0.115	0.025	1.024
200	0	0.494	0.087	-0.098	1.002	6.749	0.001	0.099	0.013	1.035
	$-\pi/8$	0.494	0.088	-0.107	0.992	6.580	0.392	0.099	-0.001	1.025
300	0	0.496	0.071	-0.099	1.013	6.344	-0.001	0.079	-0.014	1.055
	$-\pi/8$	0.497	0.072	-0.079	1.029	6.705	0.391	0.079	-0.017	1.027
500	0	0.496	0.055	-0.109	1.069	5.800	-0.001	0.060	-0.007	1.075
	$-\pi/8$	0.499	0.056	-0.101	1.047	5.919	0.392	0.061	-0.013	1.060
1000	0	0.450	0.039	-0.101	1.141	5.158	0.000	0.042	-0.007	1.168
	$-\pi/8$	0.501	0.041	-0.079	1.080	5.270	0.393	0.043	0.024	1.141

Table 8.7: Evaluation of the fitting method with a MC toy study. The pull distributions have been fitted with a Gaussian function. Results are given for $\psi = 0$ and $\psi = -\pi/8 = 0.393$, with $b_{input} = 0.505$.

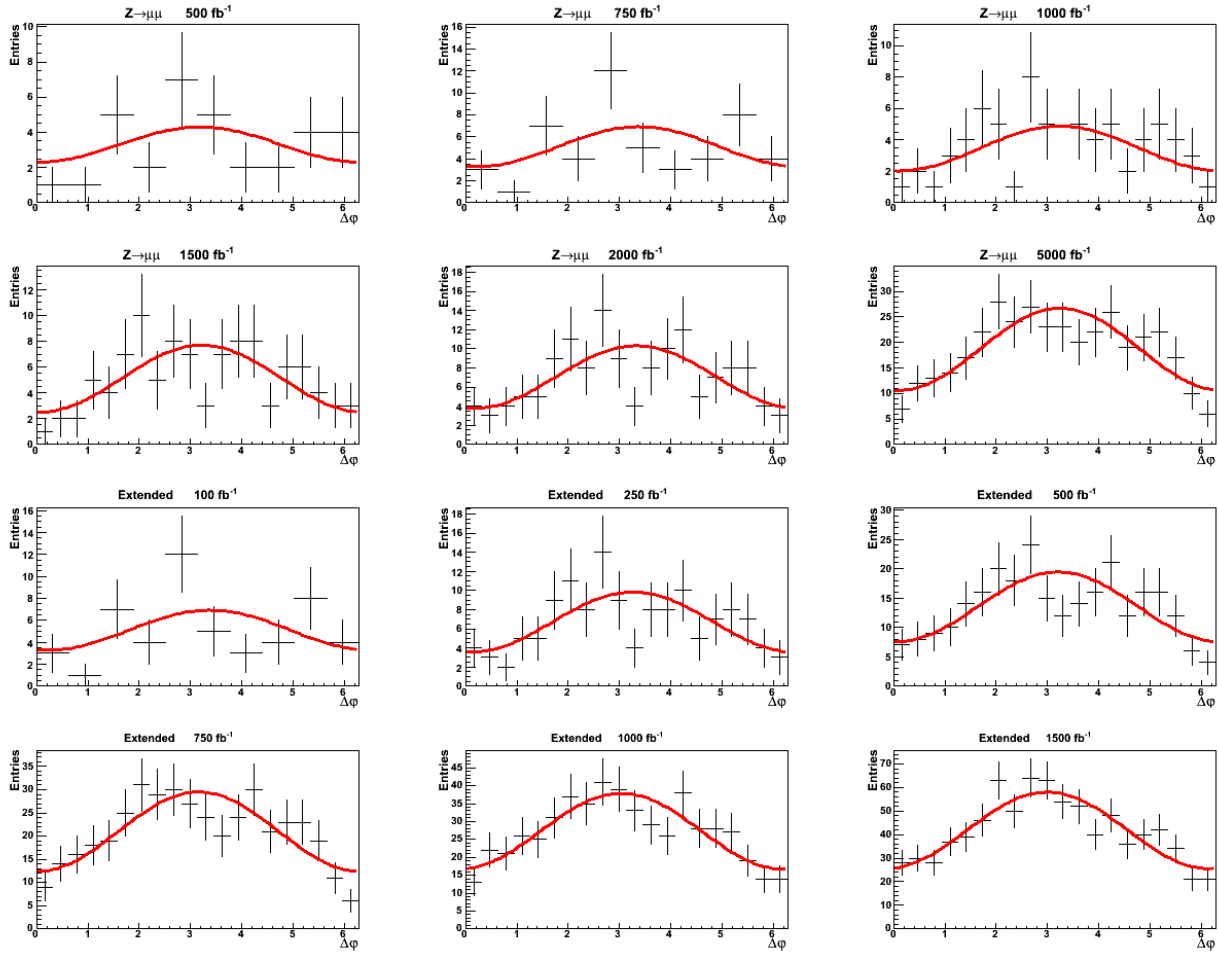
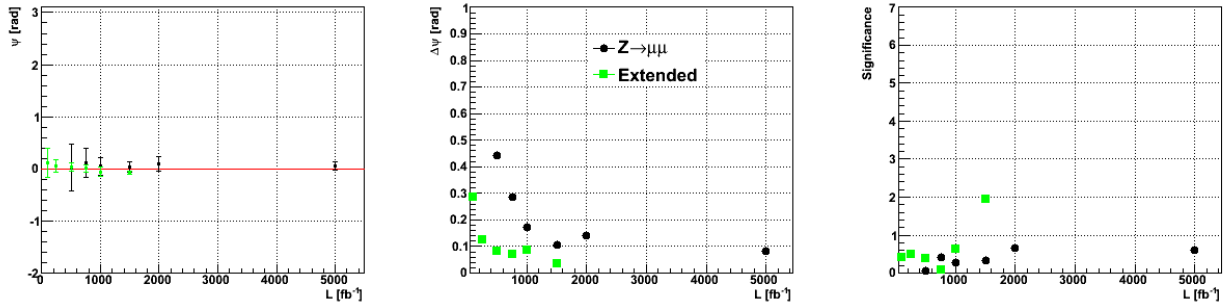
8.6.3.2 Full simulation events

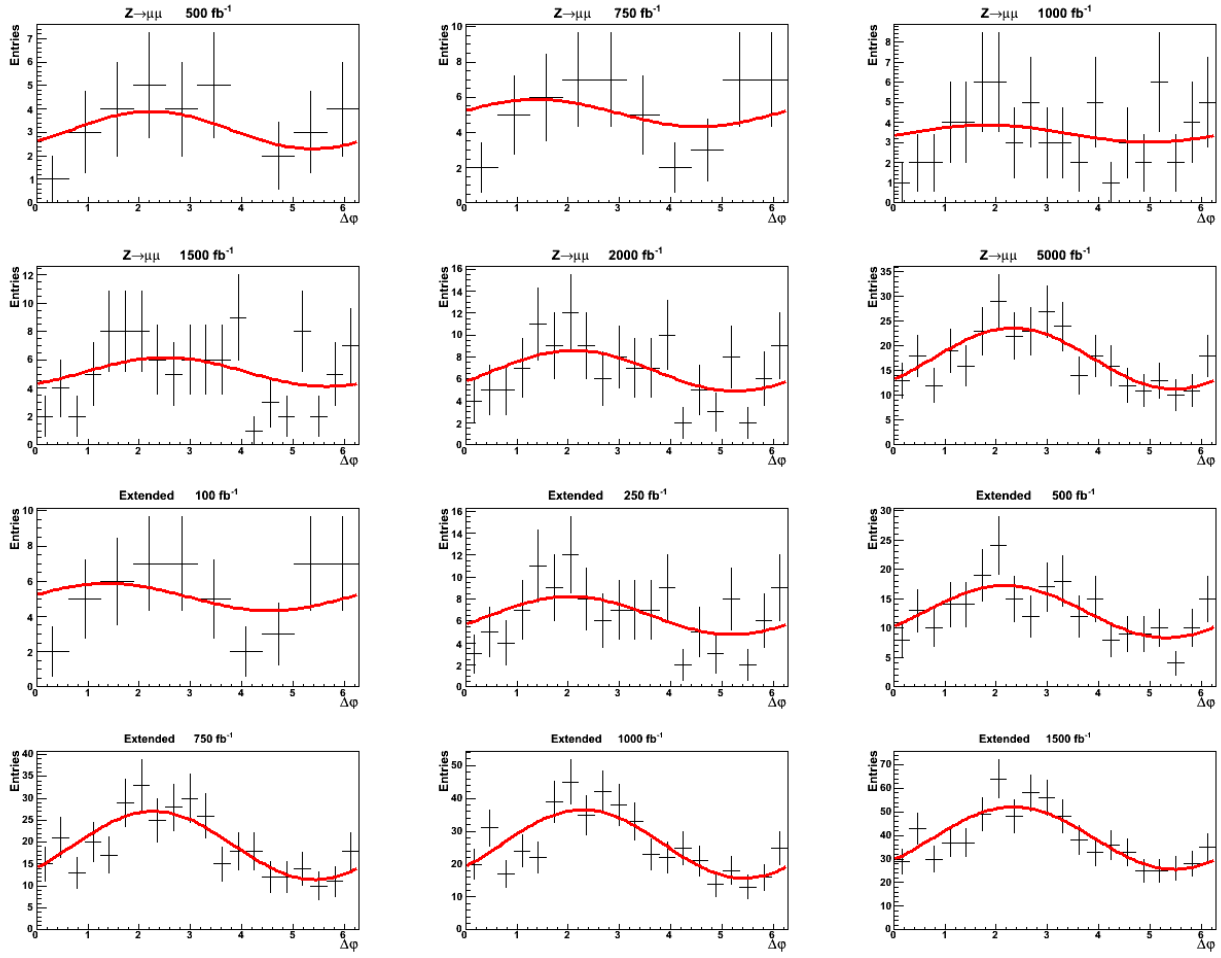
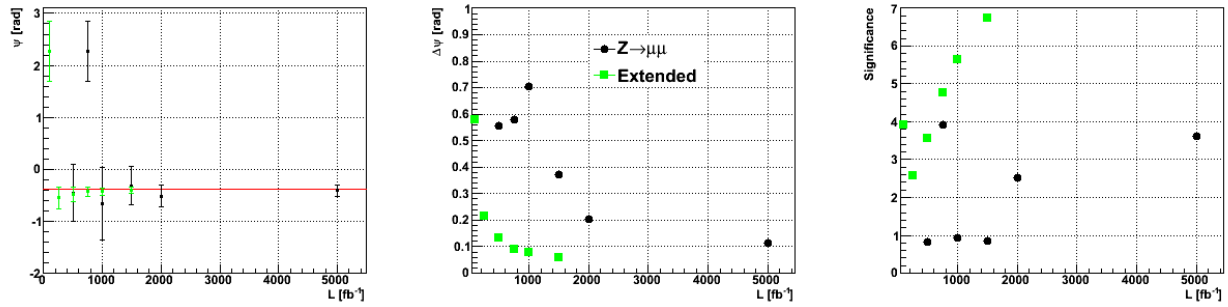
Table 8.8 summarizes the measurement for different luminosities with the $Z \rightarrow \mu\mu$ event sample for the two values of ψ . Additionally a hypothetical measurement corresponding to the statistics of the extended event sample with $Z \rightarrow e^+e^-, q\bar{q}$ ($q = u, d, s$) is given. The individual histograms, together with the fit are shown in the Figures 8.28(a) and 8.29(a), the quality of the measurement as a function of the used luminosity is shown in Figures 8.28(b) and 8.29(b) for $\psi = 0$ and $\psi = -\pi/8$ respectively.

The fits for ψ perform well also on the full simulation sample. The small statistics and the resulting large errors on each histogram bin make a reliable extraction of the fraction b and hence the ratio S/B all but impossible. This is partly due to the washing out of the distribution by reconstruction errors. A larger impact has though the missidentification of the τ decay that leads to a reconstruction of a wrong polarimeter vector. One can hope that this effect will be largely reduced with advanced methods for particle identification.

The limited statistics of the simulated sample did not permit to do several iterations with groups of signal events. One set of events is used per luminosity adding the additional events to the previous set. At low statistics the reduction of the signal events due to the suppression in the cross section, induced by the CP even part of the Higgs, has a critical impact on the measurement error. In presence of CP violation of the order that is investigated here, it is clear that the decay selection $Z \rightarrow \mu\mu$ will not provide enough statistics to give a sufficient measurement with a realistic estimation of the luminosity available ($\mathcal{L} \approx 500 \text{ fb}^{-1}$), even with inclusion of the a_1 decay channel. In an extended event sample on the other hand, indication for a CP violating phase of this order could be found quite early. One will have to worry about the stability of the fit however, like it is shown in Figure 8.29(a) where two of the fits yield largely overestimated values.

In the present simulation a CP violating phase of $\psi = -\pi/8 = 0.393$ could be measured with an error of 0.135 (i.e. to 28%) with an extended event sample and a luminosity of 500 fb^{-1} .

(a) Distributions in $\Delta\varphi$ and corresponding fits.(b) Value, error and significance (for $\psi \neq 0$) of the measured CP violating phase ψ as a function of luminosity.Figure 8.28: Measurement results for $\psi = 0$.

(a) Distributions in $\Delta\varphi$ and corresponding fits.(b) Value, error and significance (for $\psi \neq 0$) of the measured CP violating phase ψ as a function of luminosity.Figure 8.29: Measurement results for $\psi = -\pi/8$.

ψ_{sim}	Sample	$\mathcal{L}$ [fb ⁻¹]	N_{cuts}^{tot} (S+B)	$N_{cuts}^{selected}(S)$	$N_{cuts}^{selected}(B)$	ψ_{meas} [rad]	σ_{ψ} [rad]	Significance	b	S/B
$\psi = 0$	$Z \rightarrow \mu\mu$	500	2567	26	7	0.022	0.444	0.4	0.357 ± 0.231	0.961 ± 1.442
		750	3847	41	10	0.115	0.284	0.4	0.357 ± 0.226	1.371 ± 2.058
		1000	5134	52	17	0.049	0.172	0.3	0.414 ± 0.189	2.038 ± 2.823
		1500	7701	81	21	0.036	0.107	0.3	0.508 ± 0.132	4.684 ± 6.915
		2000	10268	112	29	0.091	0.140	0.7	0.463 ± 0.139	3.018 ± 3.637
	extended	5000	25682	300	73	0.051	0.083	0.6	0.431 ± 0.080	2.324 ± 1.436
		100	3798	41	10	0.115	0.284	0.4	0.357 ± 0.225	1.371 ± 2.056
		250	9499	106	28	0.060	0.124	0.5	0.468 ± 0.115	3.140 ± 3.191
		300	19003	214	36	0.031	0.081	0.4	0.438 ± 0.090	2.456 ± 1.751
		750	28508	341	78	0.007	0.070	0.1	0.409 ± 0.066	1.969 ± 0.940
$\psi = -\pi/8$	extended	1000	38013	442	104	-0.0552	0.086	0.6	0.387 ± 0.067	1.687 ± 0.805
		1500	57016	686	150	-0.072	0.037	1.9	0.388 ± 0.007	1.695 ± 0.081
	$Z \rightarrow \mu\mu$	500	2501	24	7	-0.456	0.555	0.8	0.256 ± 0.218	0.711 ± 1.039
		750	3752	41	10	2.265	0.579	3.9	0.152 ± 0.226	0.327 ± 0.644
		1000	5010	52	17	-0.660	0.702	0.9	0.124 ± 0.142	0.251 ± 0.359
		1500	7511	82	21	-0.315	0.372	0.8	0.198 ± 0.127	0.472 ± 0.445
		2000	10019	106	29	-0.516	0.205	2.5	0.274 ± 0.098	0.799 ± 0.515
	extended	5000	25055	276	73	-0.408	0.113	3.6	0.354 ± 0.061	1.345 ± 0.541
		100	3702	41	10	2.2653	0.579	3.91	0.152 ± 0.226	0.327 ± 0.644
		250	9270	102	28	-0.551	0.214	2.6	0.266 ± 0.105	0.757 ± 0.524
		500	18541	200	56	-0.482	0.135	3.6	0.347 ± 0.087	1.289 ± 0.737
		750	27811	307	78	-0.431	0.090	4.8	0.405 ± 0.072	1.907 ± 0.989
extended	extended	1000	37081	419	104	-0.431	0.077	5.6	0.399 ± 0.046	1.831 ± 0.597
		1500	55628	628	150	-0.403	0.060	6.7	0.340 ± 0.048	1.230 ± 0.385

Table 8.8: Measurement of the CP violating phase ψ at different luminosities.

Conclusion

Detector development for the next linear collider is in full progress, in case of the ILC towards a Reference Design Report in 2012. While R&D collaborations build subdetector prototypes to prove the feasibility of their concept and expose them to particle beams, full simulation studies are performed to define the characteristics and physics capabilities of the final detector.

This thesis covers both of these aspects, focussing on the ILD detector for the ILC and more specifically on the design and the optimization of the electromagnetic calorimeter.

Several properties of electromagnetic showers in general and within the ILD ECAL in particular have been studied. Their narrow shower core enables the possibility for clustering approaches on the basis of a neighbor criterion. Also the design of the ECAL itself could be characterized. Its Molière Radius has been estimated to be 18.0 mm in the barrel part and 16.5 mm in the endcap. A focus has been set to the impact of the magnetic field on the shower development in the different detector regions: the shower asymmetry in the barrel part, the shower focussing in the endcap and its dispersion in the barrel-endcap overlap region. All these will ideally be taken into account when designing clustering algorithms. Although not yet very well understood, the ECAL's internal structure has been investigated, leading to the odd-even effect in the energy deposition per layer. The actual impact of this effect on the energy resolution on the other hand is likely to be small.

To make use of the possibilities such a highly granular calorimeter opens up, specialized clustering algorithms are needed. Such an algorithm for the clustering of photon showers, GARLIC, has been developed for the ILD ECAL. It achieves very high efficiencies and a sufficient energy resolution to be suitable for usage in a Particle Flow framework. Fake cluster creation from charged hadrons is very limited. The rejection of the electro-magnetic part in high energetic neutral hadron showers that are already starting in the ECAL however will need the interplay with an algorithm specialized for hadronic shower clustering. Nevertheless tests on di-jet events at $E_{cm} = 500$ GeV have been promising. Thanks to a modular approach, GARLIC can easily be integrated into any Particle Flow framework. The geometry dependence is low so that it will be easy to adapt it to other geometries, cell sizes or layer designs.

Prototype testing is a crucial part of the R&D work for future experiments. The CALICE Si/W ECAL prototype has already undergone a large amount of such tests. Next to tools for data-quality checks during the running in test beams, a calibration procedure with muon beams in situ was co-developed in the frame of this thesis. The procedure proved very reliable and

allowed to confirm the long-term stability (over three years) of the detector. With a few per mille, the fraction of non-functional cells in the prototype has been found to be very low. The correlations of the calibration constants obtained in different running periods are as high as 90% and the ones obtained with the cosmics measurements are higher than 70%. The prototype studies worked out as a proof-of-principle for the Si/W ECAL design, both on the mechanical as well as the physics side. A previously estimated energy resolution on electro-magnetic showers could be confirmed to $\approx 16.5\%/\sqrt{E}$ with a constant term of $\approx 1\%$. The application of GARLIC on the test beam data showed very little influence on linearity and resolution. On the other hand it proved valuable for event cleaning and detection of two-particle events. This confirms the usefulness and even necessity of such an algorithm.

The high granularity of the calorimeter gives the possibility to suppress fluctuations in the energy deposit and hence to improve the energy resolution on showers of low energy by an estimation via the counting of hits. The method introduced here gives only very little improvement but still shows the potential of the concept. It is likely that a separate leakage correction and the subdivision of the detector into several zones that are optimized independently would make the gain far more apparent.

Hardware optimization of the design will play a very big role on the way to the Reference Design Report of the detector. The impact of the ECAL cell size on the reconstruction of the photon contribution in 250 GeV jets in combination with the GARLIC clustering has been tested. Although the separation performance of the algorithm is not optimal, the study gives a good indication about the importance of the cell size. It is clear that cell sizes bigger than $10 \times 10 \text{ mm}^2$ will decrease the detector performance significantly. The gain when going from $10 \times 10 \text{ mm}^2$ to $5 \times 5 \text{ mm}^2$ is still significant, so that further improvement can still be expected for even smaller cell sizes. These will definitely become necessary when higher center-of-mass energies like for the ILC upgrade to 1 TeV are considered.

The particle flow performance of an ILC detector will strongly depend on the material budget in front of the calorimeters. Hadron interactions in the tracker region will create additional particles, among these real photons, that will raise the confusion and hence degrade the jet energy measurements. An estimation of a maximal allowed material budget will strongly depend on the performance of algorithms that recover such interactions. The study here shows that the silicon tracking components in the current simulation contribute a lot to this effect.

The performance of the ECAL and the ILD detector itself has been estimated with a measurement of a CP violating phase ψ via spin correlations from $H \rightarrow \tau\tau$ and subsequent hadronic decays of the τ 's where a Higgs particle ($m_H = 120 \text{ GeV}$) is supposed to be produced in the Higgsstrahlung process $e^+e^- \rightarrow Z^* \rightarrow ZH$ at $E_{cm} = 230 \text{ GeV}$. The excellent definition of the interaction point of the ILC allowed to develop a new method for τ reconstruction that treats both τ 's independently. τ decays to π and ρ have then been considered for the measurement of ψ . The decay selection is largely dependent on the capability of photon reconstruction in the ECAL. The combination of the ILD ECAL and the GARLIC algorithm could hence be tested. A limiting factor in this study is the selection of the decay $Z \rightarrow \mu\mu$ and the resulting

lack of statistics at realistic luminosities. In principle an extension of the event sample with $Z \rightarrow e + e^-, q\bar{q}$ ($q = u, d, s$) and the inclusion of the a_1 decay channel of the τ should be possible with some caution. The statistics can then be multiplied by at least a factor of 8. Several efficient possibilities to control the background from $e^+e^- \rightarrow ZZ$ have been established, so that the effective ratio of signal over background can easily be raised to $S/B = 4.5$ or even higher if more statistics are available and more severe cuts are possible. In the extended event sample with a luminosity of 500 fb^{-1} corresponding to the first four years of ILC running, a CP violating phase of $\psi = -\pi/8$ could be measured to 28%. Indications for CP violation of this order above the 3σ level could already be found earlier. The extension of the event sample is not trivial though since the Higgs reference frame that is used in the reconstruction is defined by the quality of the measurement of the Z decay products. With the anticipated performance of an ILD like detector this goal seems nevertheless well achievable.

If a light Higgs particle is found at the LHC indication for CP violation in the Higgs decay may even be found there. The precision of the measurement will though not be sufficient for a discovery in a reasonable time span. This, among with a precision measurement of the CP violating phase ψ will be left for an experiment at the future linear collider. An ILD-like detector with an ECAL of the same performance as the Si/W ECAL described in this thesis, together with suitable algorithms for photon and charged hadron reconstruction will be well up to this challenge.

Bibliography

- [1] Particle Data Group, <http://pdg.lbl.gov>
- [2] S.L.Glashow, Nucl.Phys 22 (1961) 579. S.Weinberg, Phys. Rev. Lett. 19 (1967) 1264. A.Salam, Proceedings of the 8th Nobel Symposium, N.Svartholm editor, 367, NY 1968, Wiley Intescience.
- [3] N.Cabibbo, Phys. Rev. Lett. 10, (1963), 531. M.Kobayashi and T.Maskawa, Prog. Theor. Phys. 49, (1973), 652.
- [4] G.Abbiendi, et al. (the ALEPH Collaboration, the DELPHI Collaboration, the L3 Collaboration and the OPAL Collaboration, The LEP Working Group for Higgs Boson Searches), Phys. Lett. B 565 (2003) 61.
- [5] Tevatron New Phenomena, Higgs working group, for the CDF collaboration, DZero collaboration, FERMILAB-PUB-09-060-E, 2009, arXiv:0903.4001v1.
- [6] M.L.Pertl et al. , Phys. Rev. Lett. 35, (1975), 1489.
- [7] F.Matorras, arXiv:hep-ex/0211054v1.
- [8] A.Weinstein, arXiv:hep-ex/0210058v1.
- [9] SuperB Conceptual Design Report, arXiv:0709.0451v2.
- [10] A.G.Akeroyd et al., arXiv:hep-ex/0406071v2.
- [11] A.SchÄŕning, Nucl. Phys. B (Proc. Suppl.) 169, (2007), 387.
- [12] W.J.Marciano, Nucl. Phys. B (Proc. Suppl.) 189 (2009), 371.
- [13] A.Pich, arXiv:0806.2793v1, 2008.
- [14] G.D.Lafferty, Nucl. Phys. B (Proc. Suppl.) 189 (2009), 358.
- [15] C.Amsler et al. (Particle Data Group), Phys. Lett. B667, 1 (2008)

- [16] V.V.Anashin et al. , JETP Lett.85:347-352 , 2007.
- [17] J.Z.Bai et al. (BES Collaboration), Phys. Rev. D53 (1996), 20.
- [18] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 292 (1992) , 221.
- [19] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 99:011801 (2007).
- [20] P.Lund (BaBar Collaboration), Nucl. Phys. B (Proc. Suppl.) 189 (2009), 24.
- [21] M.Davier et al. , Rev. Mod. Phys. 78 (2006), 1043.
- [22] I.Nugent, "Measurement of the charged current lepton universality and $|V_{us}|$ using tau lepton decays at BaBar", presented at the Tau08 Workshop
- [23] P.Lund, "Tau mass measurements at BaBar", presented at Tau08 Workshop M.Shapkin et al., Phys. Rev. Lett. 99 (2007), 011801
- [24] A.Louisiani, Nucl. Phys. B (Proc. Suppl.) 144 (2005), 105.
- [25] S.Berge, W.Bernreuther, J.Ziethe, Phys. Rev. Lett. 100 (2008), 171605.
- [26] S.Berge, W.Bernreuther, Phys. Lett. B 671 (2009), 470.
- [27] ILC - Reference Design Report, ILC Global Design Effort and Worl Wide Study, 2007, ILC-REPORT-2007.
- [28] XFEL - Technical Design Report, European XFEL porject, 2007, see <http://xfel.desy.de/tdr/tdr/>.
- [29] The International Large Detector - Letter of Intent, ILD Concept Group, March 2009, <http://www.ilcild.org/documents/ild-letter-of-intentLOI.pdf>.
- [30] SiD - Letter of Intent, March 2009, <http://silicondetector.org/download/attachments/46170132/SiliconDetectorLetterOfIntent.pdf>.
- [31] Fourth Concept ("4th") - Letter of Intent, March 2009, <http://www.4thconcept.org/4LoI.pdf>.
- [32] J.-C.Brient,H.Videau, arXiv:hep-ex/0202004.
- [33] CALICE collaboration, <https://twiki.cern.ch/twiki/pub/CALICE/CaliceAnalysisNotes/CAN-015.pdf> (2009)
- [34] F.Gaede et al., arXiv:physics/0306114v1 (2003).

- [35] "MOKKA - A detailed Geant4 simulation for the International Linear Collider detectors", [http://polzope.in2p3.fr:8081 /MOKKA](http://polzope.in2p3.fr:8081/MOKKA)
- [36] S.Agostinelli et al., NIM A 506 (2003) 250-303.
- [37] see http://ilcsoft.desy.de/portal/software_packages/gear/
- [38] F.Gaede, NIM-A 559 (2006) , 177.
- [39] For information about the CALICE collaboration see [http://llr.in2p3.fr/activites/physique /flc/calice.html](http://llr.in2p3.fr/activites/physique/flc/calice.html)
- [40] R. Cornat, "Design of a Si-W electromagnetic calorimeter for the International Linear Collider and study of crosstalk in silicon sensors", preentation at the IEEE Nuclear Science Symposium, Medical Imaging Conference and 16th Room Temperature Semiconductor Detector Workshop, Dresden (Germany), 19-25/10/2008
- [41] CALICE collaboration, 2008 JINST 3 P08001 (2008).
- [42] CALICE collaboration, J.Phys.Conf.Ser.160:012065 (2009).
- [43] M.Anduze et al. , Eudet-Memo-2008-11, [http://www.eudet.org /e26 /e28 /e615](http://www.eudet.org/e26/e28/e615) , (2008).
- [44] "MINUIT - Function Minimization and Error Analysis", CERN Program Library entry D506 (1998), <http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html>.
- [45] M.Worek, Acta Phys. Pol. B 32 (2001) 3803, hep-ph/0110228.
- [46] T.Sjostrand, S.Mrenna, P.Skands, JHEP0605:026 (2006), hep-ph/0603175v2.
- [47] S.Jadach, J.H.Kühn, Z.Wąs, S.Jadach, Comput. Phys. Commun. 64 (1990) 275.
- [48] B.Grządkowski, J.F.Gunion, hys. Lett. B 350 (1995) 218.
- [49] Z.Wąs, M.Worek, Acta Phys. Polon. B33 (2002) 1875, hep-ph/0202007v2.
- [50] G.R.Bower, T.Pierzchala, Z.Wąs, M.Worek, Phys. Lett. B 543 (2002) 227.
- [51] K.Desch, Z.Wąs, M.Worek, Wur. Phys. J. C 29 (2003) 491.
- [52] K.Desch, A.Imhof, Z.Wąs, M.Worek, Pys. Lett. B 579 (2004) 157.
- [53] T.Ohl, Comput.Phys.Commun. 101 (1997) 269-288, hep-ph/9607454v1.
- [54] TESLA Technical Design Report Part II: The Accelerator, R.Brinkman (*et.al.*) DESY 2001-011.

- [55] E.Barberio and Z.Was, Comput. Phys. Commun. 79 (1994) 291–308.
- [56] M.A.Thomson, arXiv:0907.3577v1, 2009.
- [57] A.Hoecker et al., PoSACAT:040,2007, CERN-OPEN-2007-007, arXiv:physics/0703039v5, 2009.
- [58] L.Duflot, Thèse de Doctorat, Université de Paris-Sud (Orsay), 1993.
- [59] A.Rougé, arXiv:hep-ex/0505014v2, 2005.
- [60] M.Krämer, J.H.Kühn, M.L.Strong, P.M.Zerwas Z.Phys.C 64 ,1994, 21, hep-ph/9404280.
- [61] W.Kilian, T.Ohl, J.Reuter, arXiv:0708.4233v1, 2007.
- [62] P.S.Bhupal Dev et al., arXiv:0707.2878v1, 2007.

Remerciements

Tout d'abord je voudrais remercier Henri Videau d'avoir présidé mon jury de thèse. Henri, tu sais toi même que t'étais bien plus pour moi que ça. Cette thèse aurait pu être la tienne vu comment t'en as contribué. Merci aussi pour les possibilités que tu m'as ouvertes et pour tous tes conseils.

Je tiens également à remercier spécialement mon directeur de thèse, Jean-Claude Brient pour m'avoir donné la possibilité de réaliser cette thèse au Laboratoire Leprince-Ringuet. Merci, Jean-Claude pour ton soutien, ta confiance et l'aide que tu m'as donné.

Merci au reste du jury, Hans-Christian Schultz-Coulon et Fabian Zomer pour avoir accepté les rôles des rapporteurs ainsi que Imad Laktineh et Wolf-Dieter Schlatter.

Je remercie également Achille Stocchi de m'avoir accueilli au sein du master NPAC ce qui a fait tout ça possible.

Un vive merci aussi à Götz Gaycken. T'as une place spéciale ici. Sans toi j'essaierais toujours de compiler ma première ligne de c++. Tu as fait un travail énorme, tes macros me servaient comme modèle jusqu'aux deniers jours et je n'ai toujours pas compris la moitié de ton code. Dommage qu'on a eu seulement quelques mois ensemble.

Au moins aussi important pour ce travail était Daniel Jeans. Thanks Daniel de m'embrouiller mit allen möglichen languages. Thanks for correcting this thesis together with Henri, your criticism and your help, and for taking care of everything that followed. Bonne chance pour toi, Youko et Louis!

Un merci chaleureux aussi au reste du groupe CALICE/ILC: Vincent Boudry, Marc Verderi, Hayg Guler et André Rouget.

J'ai eu plein de collègues de bureau aussi. Salut et merci à vous tous (en ordre chronologique): Bruno Khelifi et Philippe Bruel quand j'étais en stage de master. Fabio Iervolino (j'espère que t'as trouvé ta place maintenant), Allister Sanchez (Allister, I hope you are finally reunited with your family, if not: you should!). Puis Louis Kluberg, Manqi Ruan (thanks Manqi for all your help!!!) et Khaled Belkhadi (De tout mon coeur je te souhaite bon courage, Khaled! Je crois en toi.) qui sont venus après un long temps de solitude et quelques jours avec Catherine Clerc (Alors, on se retrouve où maintenant?), Julia Duras et puis Amjad Suhail (Bonne chance à vous!).

Merci au groupe électronique, surtout à Jean-Charles Vanel (t'es une des personnes qui m'ont appris le plus pendant cette thèse, et sur le travail et sur les gens, merci!) et également Alain Debraine, Remy Cornat et Franck Gastaldi.

Et bien sûr un merci au groupe mécanique, les plus forts, tout le temps à la salle de muscu... Tout aux premières loges Marc Anduze (merci pour les instructions et que tu m'as prêté ton bébé de temps en temps) et Antoine Cauchois (Monsieur le plus rapide qui a pas besoin d'aide). Mais surtout un grand merci à Hamid Khaled; il est rare de trouver une personne aussi gentille et serviable.

Puis le groupe informatique: Gabriel Musat (sans toi je serais toujours en train de debugger

mon code sans savoir où commencer), Paolo Mora de Freitas (merci Paolo pour tes conseils et ton aide), Julien Tugler (merci de me distraire du travail - et tout le reste), Andrea Satirani ("J'ai un probleme avec la grille!"), Igor Semenouk ("la grille encore..."), Simon Chollet, David Decotigny, Pascale Hennion, Benjamin Taklifi, Ursula Brethon (pour une journée entière pour m'aider avec TMVA) et Eric Beyer.

Merci aussi aux autres physiciens et thésards du LLR, surtout à Giulia et Stéphanie.

N'oublions pas non plus le groupe administratif, Maïthé, Serge, Brigitte, Elodie et Véronique. Merci beaucoup pour votre aide et les mots encourageants.

Et aussi merci à tous les gens du LLR qui ne se sentaient pas trop importants pour me dire bonjour dans les couloirs.

Salut et merci aux amis du LAL: Roman, Patrick, François, Christophe (x2), Nathalie, Hengne, Philippe, Pierre, Cecile et Laurent (Je connais ta thèse par coeur maintenant!)

Un grand merci aussi aux gens de CALICE qui m'ont aidé et soutenu: Paul Dauncey, David Ward, Anne-Marie Magnan, Thies Behnke, Mark Thomson, und auch alle Leute vom DESY!

Je tiens aussi à remercier un groupe de gens qui ont changé ma vie pour toujours. J'ai eu la chance de pouvoir pratiquer le Lam Son Vo Dao pendant la durée de cette thèse. Merci à mes professeurs, Jacques Tran Van Ba, Alain Truong, Ai Quoc, Emmanuel Péronne et aux autres pratiquants, surtout Rivo, Pierre, Emma, Liêm, Guillaume, Nathalie, Adriane, Christiane, Jean-Marc, Patrick et tout le reste de la famille Lam Son.

Merci à tous mes amis physiciens et non-physiciens de Paris qui ont partagé cette expérience, João, Séverine, Andreas, Dimitra, Clement, Viola, Justine, Simon. Vous m'avez fait découvrir autant de choses. De la rationalité, vos pays, des histoires, de l'imagination et de l'inspiration, de la musique et des cultures, des boissons et de la nourriture étrange... merci pour plein de soirées chaleureuses, plein de rires, pour les voyages, pour votre soutien - en tout plein de mémoires qui vont pas se faire effacer facilement. Merci aussi à Joseph et Sabine pour m'avoir suivi du Norvège jusqu'à Paris. Je vous souhaite tous bonne chance sur votre chemin!

Thank you, Dimitri for sharing far more than just an apartment with me. Thank you for showing me Greece in all its detail, with everything that it can originate. You gave a lot of unique things to my life. But before all thanks for your friendship. I appreciate it very much.

En général, je remercie tout le monde qui m'a rendu visite aux hôpitaux...

Ein grosses Dankeschön auch an meine Freunde aus der Heimat. An alle, die mich während des Studiums begleitet haben und die ich viel zu selten sehe, danke Flo, Stefan, Judith, Gaby, Werner, Alex, Diana, Phillip und Richard.

Und natürlich auch ganz herzlichen Dank an all die, die mich noch länger kennen, auch euch sehe ich viel zu wenig! Ganz speziell danke ich euch, Johanna, Ruth und Line für all eure (Für-)Sorge und eure Geduld mit mir.

Mein tiefster Dank gilt auch meiner Familie. Eure Unterstützung war essentiell für mich und danke für alle Sorgen, die ihr euch um mich gemacht habt.

The last words of thanks go to my little Despoina. Thank you for being at my side, for your support and your faithfulness. You already advanced with me to the next chapter!

Abstract

This thesis focuses on detector development for the future linear collider ILC. The "Particle Flow" approach, a key element in the analysis of future experiments, requires photon identification with high purity and efficiency. The Si/W electromagnetic sampling calorimeter proposed for the ILD detector is described and characterized, and strategies to best exploit its granularity for photon finding are presented. An algorithm for the clustering of cells from photon showers, GARLIC, is presented. It achieves very high efficiency and purity with an energy resolution suitable for usage in a Particle Flow framework. This algorithm has also been applied to test-beam data collected by a prototype developed within the CALICE collaboration. The characteristics of this prototype have been studied and a procedure for the calibration of its ~ 10.000 cells with muons is presented. The performance of GARLIC with the ILD calorimeter has been evaluated with a full simulation study of the measurement of a CP violating phase in the Higgs sector via spin correlations from $H \rightarrow \tau\tau$ decaying themselves into hadrons. For this purpose, a new method for the τ reconstruction that makes use of the unique features of ILD and ILC, has been developed which treats both τ 's independently providing a test of reconstruction quality.

Résumé

Cette thèse s'inscrit dans le cadre du développement des détecteurs pour le prochain collisionneur linéaire électron-positron, l'ILC. La méthode d'analyse d'événements dite "Particle Flow", qui sera cruciale pour la physique avec un tel détecteur, nécessite une identification des photons d'une bonne efficacité et d'une grande pureté. Le calorimètre à échantillonnage Si/W proposé pour le détecteur ILD est décrit et caractérisé, des stratégies pour utiliser au mieux sa granularité dans la reconstruction des photons sont présentées. Un algorithme qui les réalise, GARLIC, est présenté ainsi que des évaluations de sa performance sur les simulations d'ILD et sur des données collectées lors de tests en faisceau d'un prototype de la collaboration CALICE. Les caractéristiques de ce prototype sont étudiées et une procédure pour étalonner ses quelques 10.000 canaux avec des muons est fournie. La performance de GARLIC sur le calorimètre d'ILD est finalement évaluée en mesurant, sur des simulations, la violation de CP dans le secteur du Higgs grâce aux corrélations de spin dans les désintégrations $H \rightarrow \tau\tau$ où les τ se désintègrent à leur tour en hadrons. A cette fin une nouvelle méthode pour la reconstruction des τ est établie. Elle traite les deux τ d'une manière indépendante exploitant les propriétés uniques d'ILD et de l'ILC.

Keywords: ILC, ILD, detector R&D, ECAL, photon finding, Higgs, $H \rightarrow \tau\tau$, CP violation