

Something something something physics

Steven Green
of Emmanuel College

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Abstract

This thesis describes the optimisation of the calorimeter design for collider experiments at the future Compact Linear Collider (CLIC) and the International Linear Collider (ILC). The detector design of these experiments is built around high-granularity Particle Flow Calorimetry that, in contrast to traditional calorimetry, uses the energy measurements for charged particles from the tracking detectors. This can only be realised if calorimetric energy deposits from charged particles can be separated from those of neutral particles. This is made possible with fine granularity calorimeters and sophisticated pattern recognition software, which is provided by the PandoraPFA algorithm. This thesis presents results on Particle Flow calorimetry performance for a number of detector configurations. To obtain these results a new calibration procedure was developed and applied to the detector simulation and reconstruction to ensure optimal performance was achieved for each detector configuration considered.

This thesis also describes the development of a software compensation technique that vastly improves the intrinsic energy resolution of a Particle Flow Calorimetry detector. This technique is implemented within the PandoraPFA framework and demonstrates the gains that can be made by fully exploiting the information provided by the fine granularity calorimeters envisaged at a future linear collider.

A study of the sensitivity of the CLIC experiment to anomalous gauge couplings that effect vector boson scattering processes is presented. These anomalous couplings provide insight into possible beyond standard model physics. This study, which utilises the excellent jet energy resolution from Particle Flow Calorimetry, was performed at centre-of-mass energies of 1.4 TeV and 3 TeV with integrated lumi-

nosities of 1.5ab^{-1} and 2ab^{-1} respectively. The precision achievable at CLIC is shown to be approximately one to two orders of magnitude better than that currently offered by the LHC.

Finally, a study into various technology options for the CLIC vertex detector is described.

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

Andy Buckley

Acknowledgements

Of the many people who deserve thanks, some are particularly prominent, such as my supervisor...

Preface

This thesis describes my research on various aspects of the LHCb particle physics program, centred around the LHCb detector and LHC accelerator at CERN in Geneva.

For this example, I'll just mention Chapter ?? and Chapter ??.

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*“Writing in English is the most ingenious torture
ever devised for sins committed in previous lives.”*

— James Joyce

Chapter 1

Particle Flow Calorimetry and Linear Collider Detectors

“I am fond of pigs. Dogs look up to us. Cats look down on us. Pigs treat us as equals.”

— Winston Churchill

1.1 Particle Flow Calorimetry

The premise of particle flow calorimetry is to measure the energy of individual particles in detector using the sub-detector that offers the best energy resolution. For particle collider experiments, the biggest contrast to tradition calorimetry is that the energy of charged particles is measured using the curvature of the tracks they produce in the tracker instead of measuring their energy in calorimeters. The energy resolution for these charged particles is significantly better when using the particle flow approach to calorimetry, which leads to exceptionally good jet energy resolutions that can be used for characterising multi-jet final states in physics processes of interest at the linear collider experiment. Furthermore, these energy resolutions are highly beneficial for quantifying those final states involving charged leptons and missing momentum, due to the presence of neutrinos.

Particle flow calorimetry is challenging to put into practice as it requires a precise reconstruction for all long-lived particles within a detector. Charged particles have

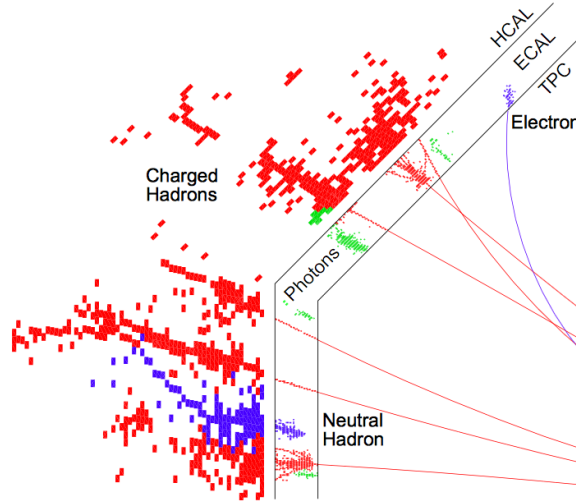


Figure 1.1: A typical simulated 250 GeV jet in the CLIC_ILD detector, with labels identifying constituent particles. Image taken from [4].

their energy measurements taken from the curvature of the track they transverse, but they also produce calorimetric energy deposits, as shown in figure 1.1, and if both energy measurements are included the energy of the charged particle will be double counted. Therefore, the precise reconstruction has to associate charged particle tracks to their corresponding calorimetric energy deposits. This can only be realised by using calorimeters with fine segmentation so that it is possible to resolve individual particle showers within them. This is the basis for the design of the linear collider calorimeters. While double counting of energy of charged particles is possible, it is also possible to omit the energy measurements of neutral particles. This occurs if a neutral particle calorimetric energy deposit, which is the only energy measurement produced for a neutral particle, is incorrectly associated to a track. In such a case the calorimetric energy deposit will not be used as the reconstruction believes the energy is from a charged particle and so will come from the track and the neutral hadron energy will be lost. These two effects form the confusion contribution to the jet energy resolution, which acts to degrade the energy resolution of a particle flow calorimetry based detector.

The magnitude of the improvements offered by particle flow calorimetry can be explicitly seen when considering the different contributions to the measurement of jet energies, which is summarised in table 1.1. After the decay of short lived particles approximately 60% of the energy of a jet is carried in the form of charged particles, 30% in the form of γ s and 10% in the form of neutral hadrons. A negligible amount of

Jet Component	Detector	Energy Fraction	Energy Resolution	Jet Energy Resolution Contribution
Charged Particles (X^\pm)	Tracker	$\sim 0.6E_j$	$10^{-4} \times E_{X^\pm}^2$	$< 3.6 \times 10^{-5} \times E_j^2$
Photons (γ)	ECal	$\sim 0.3E_j$	$0.15 \times \sqrt{E_\gamma}$	$0.08 \times \sqrt{E_j}$
Neutral Hadrons (X^0)	HCal	$\sim 0.1E_j$	$0.55 \times \sqrt{E_{X^0}}$	$0.17 \times \sqrt{E_j}$

Table 1.1: The approximate fractions, energy resolutions and jet energy resolution contributions made by charged particles (X^\pm), photons (γ) and neutral hadrons (X^0). Table taken from [5].

energy is also carried in the form of invisible energy i.e. neutrinos. In the traditional calorimetric approach γ s are measured within the ECal, with an energy resolution of $\sim 0.15 \times \sqrt{E_\gamma}$, and the remaining particles are measured in the HCal, with an energy resolution of $\sim 0.55 \times \sqrt{E_X}$. This gives contributions to the jet energy, E_j , resolution of $\frac{0.08}{\sqrt{E_j}}$ and $\frac{0.46}{\sqrt{E_j}}$ from γ s and other particles respectively. These add in quadrature to give a total jet energy resolution of $\frac{0.47}{\sqrt{E_j}}$. In the particle flow paradigm the energy of charged particles is measured in the tracker, which has such a good energy resolution that its contribution to the jet energy resolution is negligible. Therefore, contributions to the jet energy resolutions only come from γ s and from neutral hadrons, which when added in quadrature give a total jet energy resolution of $\frac{0.19}{\sqrt{E_j}}$. This jet energy resolution is significantly better than that offered by the traditional calorimetric approach, however, it must be emphasised that this is an upper limit on the performance as the effect of confusion will degrade the jet energy resolution. By applying sophisticated pattern recognition algorithms this confusion can be minimised and exceptional performance achieved. While numerous approximations have been made in the above calculation it is clear that particle flow calorimetry has the potential to revolutionise detector design for high energy physics experiments.

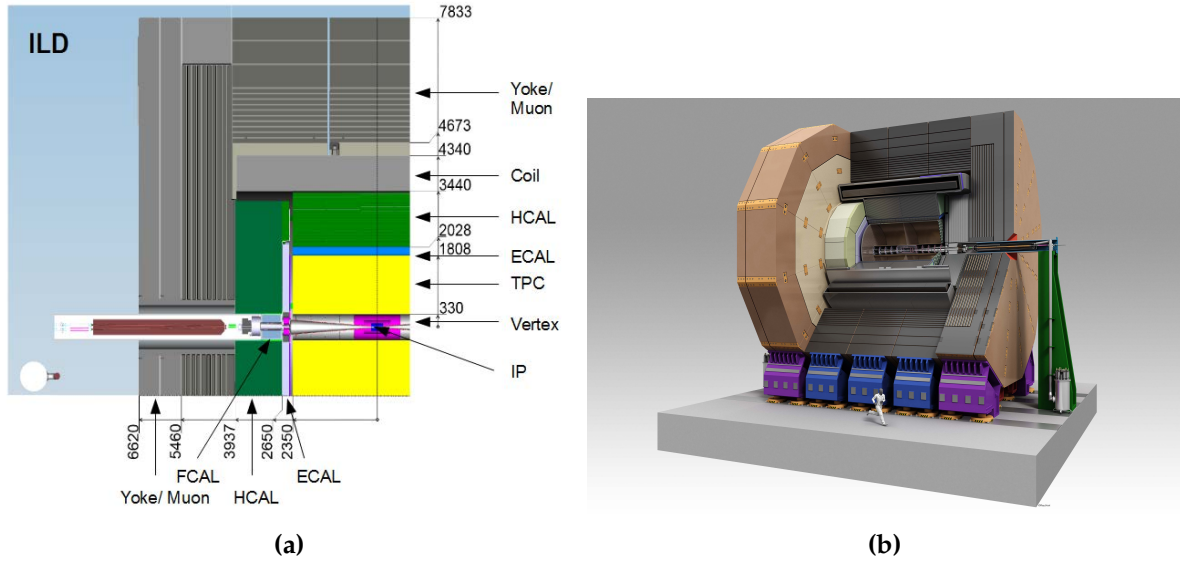


Figure 1.2: (a) Quadrant view of the ILD detector concept. The interaction point is in the lower right corner of the picture. Dimensions are in mm. (b) View of the ILD detector concept. Figures taken from [2].

1.2 Linear Collider Detectors

All detector concepts for the linear collider have been purposely built to make particle flow calorimetry possible. While there are a number of different concepts that are under consideration for both the ILC and CLIC one of the most prominent, and the focus of this work, is the International Large Detector (ILD). The ILD detector, shown in figure 1.2 realises very high spatial resolution for all sub-detector systems thanks to its highly granular calorimeters and central tracking system, all of which is encompassed within a 3.5 T magnetic field. When combined with sophisticated pattern recognition software provided by PandoraPFA, particle flow calorimetry can be realised and the jet energy resolution can reach the goal of 3.8% which is required to allow separation of hadronic decays from W and Z bosons. Details on each of the various sub-detector systems for ILD will now be discussed.

1.2.1 Tracking System

The tracking system for the ILD detector consist of a multi-layer pixel-vertex detector, which is surrounded by a system of silicon strip and pixel detectors. These are purposed to give precise information about displaced vertices with respect to the

impact point, which are crucial for the study of short lived particles such as the D or B mesons. Outside of the vertex detector the central tracker of ILD, which is a Time Projection Chamber (TPC). The TPC allows each charged particle track to be sampled at many space points giving precise information that can be used to extract the curvature of the track and the momentum of the charged particle transversing the track. Finally, a further silicon strip detector surrounds the TPC to give an additional, high precision, space point to aid in the tracking performance.

Vertex System

The main goal of the ILD vertex detector is to achieve a resolution on the impact parameter of charged particle tracks of $\sigma_b < 5 \oplus \frac{10}{p \sin(\theta)^{3/2}} \mu\text{m}$, where the first term is the transverse impact parameters resolution and the second is a multiple-scattering term. This makes it possible to precisely tag secondary vertices from charm and bottom mesons, which typically have relatively short proper lifetimes, τ , such that $c\tau \approx \mathcal{O}(100 - 500) \mu\text{m}$. To achieve this impact parameter resolution a spatial resolution of better than $3 \mu\text{m}$ is required near the IP will be required. Furthermore, a low material budget of less than $0.15 \% X_0$ per layer is needed to ensure that little energy is lost and that few electromagnetic showers are initiated within the tracker. A low pixel occupancy will be essential for determining the trajectory of individual tracks in the detector. The detector will have to be radiation hard to cope with the intense conditions found close to the IP due to the beam induced background, predominantly beamstrahlung. Furthermore, consideration will have to be given as to the mechanical structure of the detector, power consumption and cooling.

There are a number of different pixel technology options under consideration for the vertex detector for the ILD detector and this is an active area of ongoing research and development for the linear collider collaboration. The current design of the vertex detector consists of three concentric layers of double-sided ladders that are close to being cylindrical. Each ladder has two pixel sensors on each side and the ladder thickness is approximately 2 mm . The inner most radii of the ladders ranges from 16 mm to 60 mm from the IP. In the simulation of the vertex detector silicon is used as the sensitive material and both support material and a cryostat is included for realism.

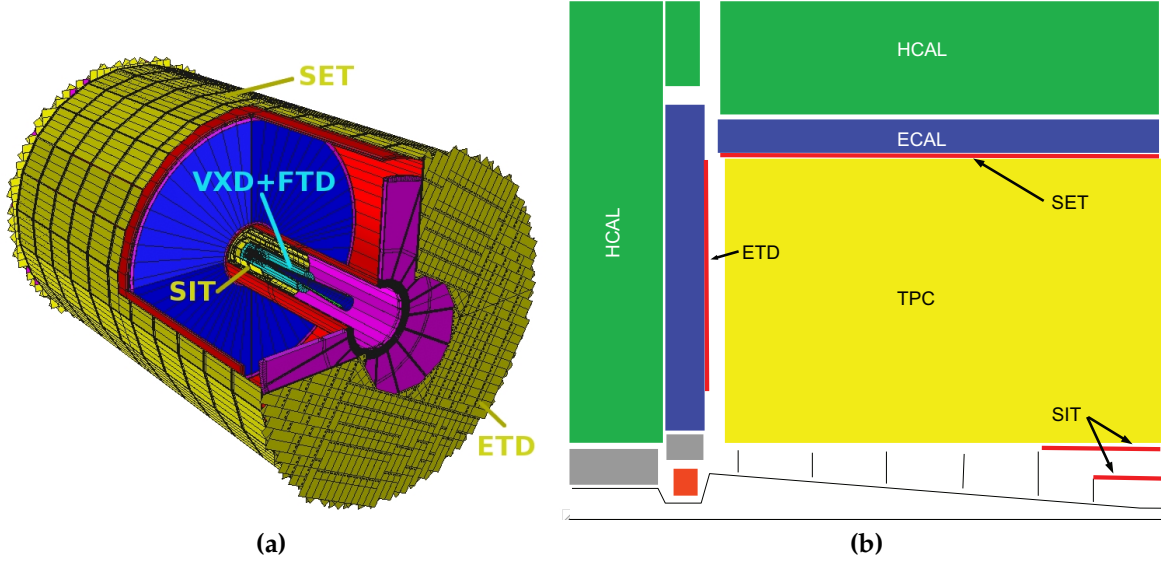


Figure 1.3: (a) A quadrant view of the ILD silicon envelope made of the four components SIT, SET, ETD and FTD as included in the full MOKKA simulation. (b) a 3D detailed GEANT4 simulation description of the silicon system. Figures taken from [2].

Silicon Tracking System

There are four components that make up the silicon tracking system for ILD, shown in figure 1.3. These are the:

- Silicon Inner Tracker (SIT) and Silicon External Tracker (SET). These are both barrel components, which are positioned immediately inside and outside the TPC. They act to provide additional space points that can be used in track fitting. In particular these help to link the vertex detector with the TPC and help with extrapolation of TPC tracks into the calorimeter. These silicon sensors will have a $50 \mu\text{m}$ pitch and will contain $200 \text{ m}\mu$ thick silicon.
- Endplate of the TPC (ETD). This sensor is identical to the SET, but is positioned in front of the ECAL endcap calorimeter to extend the coverage of this silicon envelope.
- Forward tracker (FTD). This detector consists of seven silicon disks, which extends the coverage of the tracking down to small angles which the TPC does not cover.

The requirements for these sensors is similar to those of the vertex detector in terms of requiring low material budget and low occupancy, however, as the sensors are further away from the IP radiation hardness is less crucial. The technology options for

these sensors is also under development as was the case for the vertex detector. In the detector model simulations all of these elements are included with additional material added to represent the support structure.

TPC

The central tracking system for the ILD detector is a TPC, which is shown in figure 1.4. The TPC consists of two chambers of gas that has a high voltage applied across it. Charged particles passing through the TPC ionise the gas and the ionised molecules drift in the high voltage to the end plates where they are collected and measured. The drift time is then used to calculate the position of the ionisation point. TPCs have the advantage over silicon tracking as they continuously track any charged particle passing through them unlike silicon detectors, which are only sensitive within the silicon layer. This compensates for the worse single point resolution that TPCs have in comparison to a silicon detectors and makes TPCs a viable option for the ILD detector. Furthermore, the TPC has a very low material budget, which benefits calorimetry in ILD. The TPC will operate within a 3.5 T magnetic field and under these conditions a point resolution of better than $100\ \mu\text{m}$ and a double hit resolution in ϕ of less than 2 mm can be achieved. Several readout technology options that are dependent upon the gas mixture used for the TPC are currently under development. For all potential options it is envisaged that the readout pads would be $\approx 1 \times 6\text{mm}^2$ giving a total of approximately 10^6 on the TPC endplates.

In the detector simulation the TPC is simulated as a cylindrical volume of the gas mixture, $\text{Ar}:\text{CH}_4:\text{CO}_2$ (95:3:2) [1], which is surrounded by a realistic field cage. Furthermore, a conservative estimate of the endplate is included in the simulation, which accounts for the support structure, electronics and cooling pipes. Estimations have also been made for the material budget for power and readout cables that will serve the inner tracking detector. These are included in the simulation as an aluminium cylinder between the beam pipe and the field cage of the TPC.

1.2.2 Electromagnetic Calorimeter

A highly segmented electromagnetic sampling calorimeter (ECal) surrounds the ILD tracking system, which has been designed with particle flow calorimetry in mind. To that extend the spatial resolution of particle showers within the ECal takes as much, if

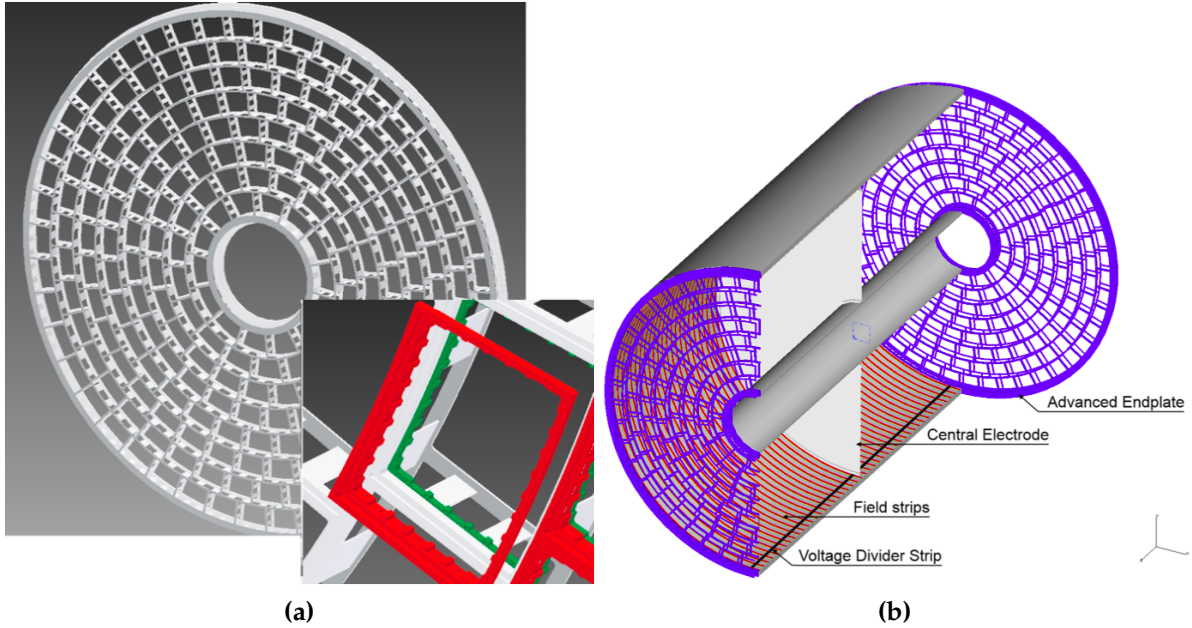


Figure 1.4: (a) Drawing of the proposed end-plate for the TPC. (b) Conceptual sketch of the TPC system showing the main parts of the TPC (not to scale). Figures taken from [2].

not more, precedence than the energy resolution. The nominal ILD ECal is a silicon tungsten sampling calorimeter, which contains 30 layers and uses square cells with side length 5 mm, however, a scintillator strip option is also being considered.

The primary goal of the ECal is to induce electromagnetic particles to shower within it and to record the energy deposited by those showers. To that extent the ECal is constructed using tungsten as the absorber material. As well as containing a large number of radiation lengths (X_0) per unit length, see table 1.2, tungsten also has a small Molière radius and a large ratio of the radiation length to the nuclear interaction length. The small Molière radius will lead to compact electromagnetic showers and make the separation of nearby showers easier, while the large ratio of the radiation length to nuclear interaction length will lead to greater longitudinal separation between electromagnetic and hadronic showers. The use of tungsten in the nominal ILD ECal allows for a large number of radiation lengths, $\approx 24X_0$, to be compacted within a relatively short distance, ≈ 20 cm, which is sufficient for containing all but the highest energy electromagnetic showers. The compact nature of the ECal also helps to reduce the overall size and cost of the detector. A good energy resolution can be achieved with this configuration if 30 sampling layers are used. The tungsten thickness is 2.1mm for the inner 20 layers and 4.2mm for the last 10 layers to reduce the number of readout channels and cost, while maintaining a high sampling rate at the start of

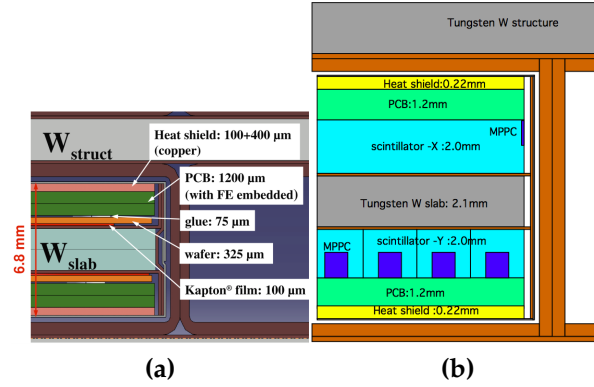


Figure 1.5: Cross section through ECal layer for (a) silicon and (b) scintillator option. Figures taken from [2].

the calorimeter. It should be noted that this offers no major gains in terms of energy resolutions in comparison to preexisting particle collider experiments ?? because the focus of this calorimeter is split between imaging the particle showers and recording their energy as opposed to purely focusing on the energy measurement. The 5 mm cell size for the ECal was chosen as a balance between being able to resolve nearby particle showers as well as reducing the overall cost of the calorimeter, which scales with the number of readout channels needed. An optimisation study of the various ECal parameters can be found in section ??.

Material	λ_I (cm)	X_0 (cm)	ρ_M (cm)	$\frac{\lambda_I}{X_0}$
Fe	16.8	1.76	1.69	9.5
Cu	15.1	1.43	1.52	10.6
W	9.6	0.35	0.93	27.4
Pb	17.1	0.56	1.00	30.5

Table 1.2: Comparison of the nuclear interaction length λ_I , radiation length X_0 and Molière radius for iron, copper, tungsten and lead. Table taken from [5].

As well as including the silicon tungsten sampling calorimeter, the simulation of the ILD ECal contains additional material to represent the instrumented region of the sensor and a heat shield as shown in figure 1.5.

1.2.3 Hadronic Calorimeter

Surrounding the ECal is a finely segmented hadronic calorimeter (HCal), which has the primary goal of measuring the energy deposits from charged and neutral hadrons. Similarly to the ECal the focus of this HCal is split between imaging nearby particle showers as well as having a good energy resolution. The nominal ILD HCal is a scintillator steel sampling calorimeter, which contains 48 layers and uses square cells with side length 30 mm.

Iron is used as the absorber material for the HCal as it has excellent mechanical properties that allow the HCal to be constructed without auxiliary supports, which would act as dead regions in the detector if they were needed. Furthermore, iron is relatively inexpensive and given the nuclear interaction length is sufficiently small, it is possible to achieve a compact calorimeter design for low cost.

1.2.4 Forward Calorimetry

A number of forward calorimeters are envisaged for the linear collider. The primary purpose of these calorimeters is to extend the coverage of the detector towards 4π and to monitor the beam quality.

1.2.5 Muon Chamber

Outside the HCal is the coil that generates the 3.5 T magnetic field and surrounding this is the iron yoke. The purpose of this yoke is to return the magnetic flux from the extremely large magnetic field and to serve as a muon detector and a tail catcher for the calorimetry. The yoke uses scintillator strip readout and for the simulations uses a $3 \times 3\text{cm}^2$ cells. This is in contrast to the ILD baseline, which plans to use 3 cm wide strips and 1 m long strips, however as the tail-catcher plays a minimal role in particle flow at ILC like energies this should have minimal impact.

1.2.6 CLIC ILD

1.3 PandoraPFA

Colophon

This thesis was made in $\text{\LaTeX}2_\epsilon$ using the “hepthesis” class [\[3\]](#).

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