

Calorimetry at a Future Linear Collider

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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

Introduction

“There, sir! that is the perfection of vessels!”

— Jules Verne, 1828–1905

The Standard Model has proven to be one of the greatest accomplishments of modern day particle physics. It has have been used to make countless predictions of various physics processes across a wide range of energies that have proven to be consistent with experimental measurements. The final piece of the Standard Model to be discovered was the Higgs boson, which was found by the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) in 2012.

Despite the remarkable descriptive power of the Standard Model, there are a number of features in the universe that it does not provide a description for. How does gravity fit into the Standard Model? Why is there an excess of matter over antimatter in the observable universe? How does the "dark matter" predicted by astronomers couple with the particles in the Standard Model? What are the properties of the Higgs field in the Standard Model? While the LHC and previous generations of particle collider experiment have had enormous success in validating the Standard Model and searching for new physics, it is clear that there is more work to be done.

The linear collider experiments are proposals for the next generation of particle collider experiment. They aim to provide precise measurements that will complement those made at the LHC and extend our understanding of particle physics. One of the primary goals of the linear collider experiments is to study the Higgs field of the Standard Model. A detailed description of the Higgs field is likely to help in the

description of "dark matter" as many extensions of the Standard Model Higgs field contain particles that fit the properties of "dark matter". The linear collider experiments will also provide a detailed description of the properties of the top quark. This will complement the Higgs study as the strongest couplings for the Higgs in the Standard Model occurs with the top quark. Another goal of the linear collider experiments is to provide high precision measurements of the electroweak sector in the Standard Model. As the electroweak sector is the only place in the Standard Model where CP violation can occur, a detailed description will help to determine why there is an excess of matter over antimatter in the universe. Furthermore, the linear collider will expand the descriptive reach for many Standard Model extensions such as supersymmetry (SUSY).

The linear collider experiments place emphasis on precision measurements. As well as searching for beyond Standard Model physics, these precision measurements will guide the future direction of experimental particle physics. Precision measurements have helped to guide the course of particle physics experiments in the past; LEP electroweak data, which gave indirect information about the lightness of the Higgs boson, was used to build the physics case for the LHC. The precision measurements will be achieved through the application of particle flow calorimetry, which is a revolutionary technique in detector design that offers exceptional energy resolution for jets. This paradigm shift means the linear collider detectors are significantly different from those found in previous generations of particle colliders. As the detector design is continually evolving, the ongoing research in this area is vital for determining the overall success of these experiments.

This thesis is organised as follows. Chapter ?? contains a summary of the Standard Model as well as an outline of the physics of interest related to the analysis presented in chapter ?. Chapter ?? presents a study into a novel technology option for the Compact Linear Collider (CLIC) vertex detector. Chapter ?? contains numerous studies related to the treatment of energy deposits in the linear collider simulation. This begins with an outline of the calibration procedure for the linear collider detector simulation. This is followed by a number of novel software techniques aimed at improving the energy resolution of a calorimeter designed for particle flow calorimetry. Finally, the chapter concludes with a study of the timing requirements applied in the software trigger that will be used at the linear collider experiment. Chapter ?? presents an optimisation study of the linear collider calorimeters. The starkest contrast in detector design when comparing particle flow calorimeter and traditional calorimeter is the design

of the calorimeters. As the linear collider experiments will be the first experiments purposefully built with particle flow calorimetry in mind, there is no precedence for the detector design. Therefore, these studies are vital for guiding detector design. Chapter ?? contains a study into anomalous gauge couplings that are sensitive to massive gauge boson quartic vertices at the CLIC experiment. This study is of particular interest as it provides a detailed probe of the electroweak symmetry breaking sector of the Standard Model as well as showing CLICs sensitivity to a possible extension to the Standard Model. The thesis concludes with a summary in chapter ??.

1.1 The International Linear Collider

1.2 The Compact Linear Collider

1.2.1 Experimental Conditions at CLIC

The CLIC experiment will operate in a unique environment in comparison to previous generations of lepton colliders and this must be properly accounted for to get an accurate measure of the physics potential that CLIC has to offer. The following aspects of the CLIC experiment present the largest challenges to the physics potential for the CLIC experiment:

- The high bunch charge density. The small beam size at the impact point produces very large electromagnetic fields. These fields can interact with the opposite beam particles causing them to radiate photons in an effect known as beamstrahlung. Beamstrahlung acts to reduce the collision energy of the e^+e^- pairs.
- Beam related backgrounds. Beamstrahlung photons can subsequently interact to produce background events that must be accounted for. Dominant backgrounds of this form that cannot be easily vetoed in the reconstruction include incoherent pair production of e^+e^- and $\gamma\gamma \rightarrow \text{Hadron}$.
- Fast readout technology is crucial. The CLIC bunch train consists of 312 bunches with a repetition rate of 50 Hz. Each bunch is separated by 0.5ns, therefore, it will be necessary to integrate over multiple bunch crossing when reading out the

detectors. This places tight constraints on all detector electrical readout speeds and time resolutions.

Beam-Related Backgrounds at CLIC

The primary sources of background for the CLIC experiment are as follows:

- e^+e^- pair creation from the interaction of a beamstrahlung photons with the opposing beam. The different mechanisms for pair creation are as follows:
 - **Coherent pair production.** This mechanism involves the interaction of a real beamstrahlung photon with the electromagnetic field from the opposing beam.
 - **Trident pair production.** This mechanism involves the interaction of a virtual beamstrahlung photon with the electromagnetic field from the opposing beam.
 - **Incoherent pair production.** This mechanism involves the interaction of a real or virtual beamstrahlung photon with the individual particles in the opposing beam.
- $\gamma\gamma \rightarrow \text{Hadron}$ from the interaction of real or virtual beamstrahlung photons with each other. Example Feynman diagrams for such processes is shown in figure ??.
- Beam halo muons that arise from interactions of the beam particles during collimation. The dominant mechanisms producing beam halo muons are photon conversions into muon pairs ($\gamma e^- \rightarrow \mu^+ \mu^- e^-$) and annihilation of positrons with atomic e^- into muon pairs ($e^+ e^- \rightarrow \mu^+ \mu^-$) [3].

Each of these has to be properly addressed to get a true measure of the physics potential at CLIC. Coherent and trident pair production is not a dominant source of background as they are produced at low transverse momenta, as figure 1.1 shows, and a simple cut would veto these backgrounds. This is not the case for incoherent pair production of e^+e^- , which are dominant in the forward regions of the detector, and $\gamma\gamma \rightarrow \text{Hadron}$, which are dominant in the tracker and the calorimeters (with the exception of low radii in the calorimeter endcaps) [4,5]. Beam halo muons are not a major source of background either as they can be easily removed during the reconstruction due to the clear signal they create in the detector. An algorithm was

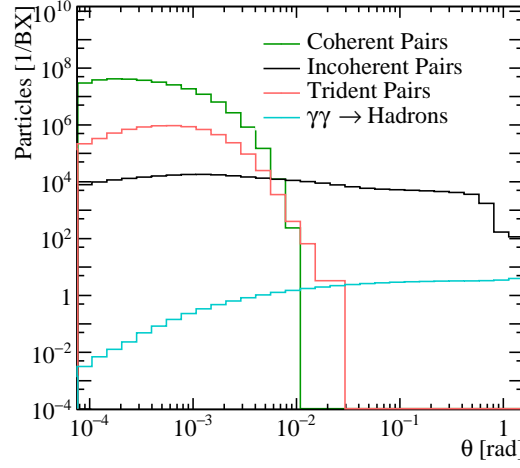


Figure 1.1: Angular distribution of number of particles for beam induced backgrounds for CLIC at $\sqrt{s} = 3$ TeV. Taken from CLIC CDR.

developed within the PandoraPFA framework for this purpose and it was found to be highly effective at removing the beam halo muons background [4].

$\gamma\gamma \rightarrow$ Hadron events are the most dominant source of background to consider at CLIC as these events deposit more energy throughout the detector than incoherent pair production of e^+e^- events [4]. The effect of the $\gamma\gamma \rightarrow$ Hadron background is incorporated into this analysis by overlaying $\gamma\gamma \rightarrow$ Hadron events onto the event samples used in this analysis. The overlaid backgrounds are added prior to reconstruction so that their effect on the reconstruction is fully accounted for. For a given event the exact number of background events overlaid is drawn from a Poisson distribution with a mean of 3.2 (1.3) events per bunch crossing at 3 (1.4) TeV. While incoherent pairs are still a source of background they will produce a second order effect in comparison to the $\gamma\gamma \rightarrow$ Hadron events.

The PFO choices described in section ?? are applied to veto the effect of PFOs that arise from the overlaid $\gamma\gamma \rightarrow$ Hadron events.

Colophon

This thesis was made in $\text{\LaTeX}2_\epsilon$ using the “hepthesis” class [\[6\]](#).

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