Something something something physics

Steven Green
of Emmanuel College

A dissertation submitted to the University of Cambridge
for the degree of Doctor of Philosophy

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 **??**.

Contents

1 Introduction 1

2 Summary 5

Bibliography 9

List of figures 11

List of tables 13

“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 provides precise predictions of particle interactions over a wide range of energies that have been experimental verified. The final piece of the Standard Model to be discovered was the Higgs boson, which was found by the ATLAS [1] and CMS [3] 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? All of these questions demand answering and despite the great successes of the LHC and previous generations of particle physics experiments, there is much more work to be done.

The linear collider experiments aim to answer these questions. 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 properties 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 strongest coupling of the Higgs field to other Standard Model fields is, due to its mass, that of the top quark.

Therefore, the linear collider experiment will, alongside the description of the Higgs field, provide detailed description of the properties of the top quark. Another goal is to provide high precision measurements of the electroweak sector in the Standard Model. As the electroweak sector of the Standard Model is the only place where CP violation can occur, a detailed description will help 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 that a view to them guiding our understanding of the future particle physics. For example, LEP electroweak data gave indirect information about the lightness of the Higgs years before its discovery. The precision measurements are 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. Furthermore, the design of the detectors is continually evolving meaning that the work being performed now will have permanent impact on the linear collider throughout its lifetime.

The 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 multiple 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 and is followed by a number of novel software based techniques for fully exploiting the linear collider detector design. 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 contract in detector design when comparing particle flow calorimeter and tradition calorimeter is the design of the calorimeters. As particle flow calorimetry has never been fully used in a particle collider experiment before, these studies are of particular interest for guiding the detector design at the linear collider. 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 to the CLIC experiment as it provides a detailed probe of the electroweak symmetry breaking sector of the Standard Model as well as showing CLICs sensitivity to an extension to the Standard Model. The thesis concludes with a summary in chapter 2.

Chapter 2

Summary

"There, sir! that is the perfection of vessels!"
— Jules Verne, 1828–1905

The work presented in this thesis has made significant contributions to the future linear collider in terms of both detector design, event reconstruction and demonstration of physics potential.

A capacitively coupled pixel was prototyped and tested using both lab and test beam measurements to determine whether the devices were viable for use at the CLIC vertex detector. The performance of these prototyped devices was extremely good, even with significant offsets between the sensor and readout ASICs that could appear in the manufacturing process. Although modifications would be required for the final design of the sensor and readout ASICs, the technique of capacitively coupling is viable for use at the future linear collider.

Studies into the calorimeter design have helped to clarify the detector parameters that are crucial for achieving outstanding performance when using particle flow calorimetry. This allows for informed decisions to be made that minimise the cost of the detector, while retaining exceptional jet energy resolutions. Reliability in the conclusions of this study could only be achieved by employing the calibration procedure that was developed for the linear collider simulation.

Development of novel software techniques, which make full use of the segmentation of the linear collider calorimeters, led to a significant improvement in the energy resolution of the linear collider detector. This improvement in energy resolution would be extremely expensive if it were achieved by modifying the design of the calorimeters, therefore, as well as extending the physics reach of the detector a significant cost saving has been made.

This final study presented determined the sensitivity of the CLIC experiment to the anomalous gauge couplings α_4 and α_5 using the vector boson scattering process. The signal final state $\nu\nu$qqqq was selected for this analysis based on the relative sensitivities of final states showing sensitivity to these couplings. Background processes were then selected based on whether they could be confused with the signal. An event selection procedure was applied to separate the signal and backgrounds. The significance obtained from this event selection was 52.7 (90.6) for CLIC running at 1.4 (3) TeV. Finally, a χ^2 fit was applied to the distribution of the invariant mass of the system to determine the sensitivity of the CLIC experiment to the anomalous gauge couplings. The sensitivity manifested itself in the form of event weights for the signal final state. Using this procedure the one σ confidence limits on the couplings, assuming the corresponding coupling is zero, were found to be:

$$-0.0082 < \alpha_4 < 0.0116, \tag{2.1}$$
$$-0.0055 < \alpha_5 < 0.0078, \tag{2.2}$$
$$\tag{2.3}$$

at 1.4 TeV and:

$$-0.0010 < \alpha_4 < 0.0011, \tag{2.4}$$
$$-0.0007 < \alpha_5 < 0.0007, \tag{2.5}$$
$$\tag{2.6}$$

at 3 TeV. These limits significantly improve on the measurements made at the LHC, Run 1, by a factor of approximately 10 (100) at 1.4 (3) TeV [4]. This is a significant improvement indicating just one aspect of the physics capabilities of the linear collider. This study adds further weight to the argument for the construction of a linear collider.

Colophon

This thesis was made in $\LaTeX\,2_\varepsilon$ using the “hepthesis” class [2].

Bibliography

[1] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett.*, B716:1–29, 2012, 1207.7214.

[2] Andy Buckley. The hepthesis LaTeX class.

[3] Serguei Chatrchyan et al. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett.*, B716:30–61, 2012, 1207.7235.

[4] Daniel R. Green, Patrick Meade, and Marc-Andre Pleier. Multi-Boson Interactions at the Run 1 LHC. *Submitted to: Rev. Mod. Phys.*, 2016, 1610.07572.

List of figures

List of tables