Search for a High Mass Higgs Boson in the Channel $H \to ZZ \to llbb$ and Digital Filtering for the ATLAS Level-1 Calorimeter Trigger

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Abstract

The Standard Model of particle physics predicts the existence of a new massive state: the Higgs Boson. The discovery or exclusion of this particle is one of the main goals of the ATLAS experiment.

One of the greatest experimental challenges at the LHC is to achieve efficient triggering. The ATLAS first level calorimeter trigger uses reduced granularity information from the calorimeters to search for high E_{T} e, γ, τ and jets as well as identifying high $E_{\mathrm{T}}^{\mathrm{miss}}$ and total E_{T} events. A Finite Impulse Response (FIR) filter combined with a peak finder is applied to identify signals, determine their correct bunch-crossing and improve the energy measurement. A study to determine the optimum filter coefficients is presented. The performance of these filters is investigated with commissioning data and cross-checks of the calibration with initial beam data are shown.

In this thesis a study of the search sensitivity in the channel $H \to ZZ \to llbb$ is presented. This channel can contribute to the Higgs search in the high mass region that has been unexplored by previous lower energy colliders. The dominant backgrounds, without b-tagging applied, are extracted from 34.6 pb^{-1} of early LHC data. The event yields are found to be consistent with the Standard Model expectation.

Dedicated to Mom and Dad.

Author's Contribution

The work presented in this thesis is my own (with the exceptions listed below). However, by its very nature particle physics involves close collaboration with colleagues. In particular I have collaborated closely with members of the Birmingham Particle Physics group and the ATLAS Level-1 Calorimeter Trigger group.

- All results presented rely on the ATLAS software as well as external software packages including ROOT [1] and the Monte Carlo event generators listed in Appendix A.

- Chapter 3 provides a review of Higgs physics and contains no original research.

- Chapter 4 describes the LHC and the ATLAS detector. Many of the images are taken from other published ATLAS documents. See the references provided within that chapter.

- The Monte Carlo samples used in chapters 5 and 6 were centrally generated by the ATLAS.

- The model used in the kinematic fit shown in chapter 5 was constructed by myself using the tools provided by RooFit [2].

- The CLs limits shown in chapter 5 were calculated with MCLIMIT [3] [4].

- The data corrections applied in the analysis shown in chapter 6 were all official corrections provided by various ATLAS working groups.

- Chapter 7 describes the ATLAS Level-1 Calorimeter Trigger. Many of the images are taken from other ATLAS publications. See the references provided within that chapter.

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Chapter 1

Non-technical Summary

The following pages attempt to explain the motivation for this research and summarise the results at a level suitable for a non-particle physicist. Expert readers should skip onto chapter 2 on page 20.

There are four known fundamental forces in the universe: gravity and electromagnetism, the forces we are familiar with in our day-to-day lives; the weak force, which is responsible for nuclear decays; and the strong force, which binds together the nucleus and its constituents. The Standard Model of particle physics describes all of these forces, with the notable exception of gravity. It is one of the greatest achievements of modern science and represents our deepest understanding of the fundamental physics of the universe. The model describes how the fundamental matter particles, 6 leptons, 6 quarks and their anti-particles, interact through the exchange of the force-carrying particles: the photon, the mediator of the electromagnetic force; the $W^{\pm}$ and Z, the mediators of the weak force; and the gluons, the mediators of the strong force.

This theory has been remarkably successful at describing nature. It also has a compelling theoretical motivation: the equations that govern these forces come from underlying symmetries in nature.

There is, however, a problem with this picture: electroweak symmetry, the symmetry that gives rise to the electromagnetic and the weak forces, can only be true if the mediators of those forces are massless. This contradicts the experimentally observed fact that the $W^{\pm}$ and Z bosons have mass (and very large masses, the Z is almost one hundred times heavier than the proton). Rather than discard the entire Standard Model, a new element is introduced: the Higgs field. This field spontaneously breaks the symmetry in just the right way to produce the observed weak interactions, and produce the masses for the $W^{\pm}$ and Z particles, leaving the photon massless. The Higgs field also provides a mechanism for all of the other particles of the Standard Model to acquire their masses. The Higgs field has an associated physical state, the Higgs boson, that can be produced and measured in experiment. At the time of writing, it is the only particle of the Standard Model that has not yet been directly observed.

Understanding the mechanism of electroweak symmetry breaking is one of the main unsolved problems of particle physics today. It is a problem that we hope to solve at current and future high energy physics experiments. The Standard Model Higgs boson, if it exists, should be within reach of the Large Hadron Collider (LHC), the worlds highest energy particle accelerator. The LHC is a 27 km accelerator ring located deep underground at the European Organisation for Nuclear Research, CERN. It circulates two proton beams in opposite directions. The beams are not continuous, instead they consist of discrete bunches. At four points around the ring the beams cross and the bunches collide. Built around these interaction points are the four main LHC experiments: ATLAS, CMS, LHCb and ALICE. Each of these experiments have wide-ranging physics programmes which aim to test the current model and to search for new physics. ALICE is designed to study the high temperature and high density environment produced in heavy ion collisions. LHCb is designed for precision measurements of CP violation and rare decays. ATLAS and CMS are general purpose detectors designed to reconstruct a variety of particles over a wide range of energies.

The studies presented in this thesis all relate to the ATLAS experiment. The ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) detector is often likened to a digital camera. The detector records snapshots, or events, of each collision, comprising the measurements made of the final states of those collisions. Typically, the heavy particles believed to be associated with new physics, the Higgs boson included, decay very quickly and only their decay products can be seen directly in the detector. By studying the signatures left behind we hope to discover and identify any new physics that manifests at high energy. In this thesis, the study of one particular signature that the Higgs boson may produce is presented, the $H \to ZZ$ channel where one of the Z bosons decays to leptons, and the other to b quarks.

The theory predicts every property of the Higgs boson except for its mass. This search channel is useful if the Higgs boson has a high mass. However, it is not as simple as looking for events with 2 leptons and 2 b quarks. There are other processes that can create the same signature, referred to as backgrounds. From measurements of the final state particles the mass of the

Higgs boson can be reconstructed. The mass distribution of the backgrounds is different from the Higgs signal. The Higgs boson appears as a peak above background in the mass distribution. Many events must be collected to prove that signal has been observed (or that no signal exists).

At design luminosity[1], the LHC will collide bunches of protons at a rate of 40 MHz. It is technically impossible to record events at this rate. Instead, the data must be processed in real time, the signatures of the event identified, and a decision made whether or not to record the event for permanent storage. This job is done by the ATLAS *Trigger*. The Trigger is divided into several levels. The first level systems make a very fast decision (every 25 ns) based on limited information. If an event passes the first level, the data are readout from the detector and processed by the High Level Trigger, where the full event information is available. Only once an event passes this level will it be permanently stored and available for physics analysis.

The first level itself is divided into several sub-systems. One of these sub-systems is the *Calorimeter Trigger*[2]. The Calorimeter Trigger receives signals from the calorimeters, digitises them, and runs algorithms to identify objects such as electrons/photons and jets[3]. For efficient operation of the Trigger, it is essential that the energies of these signals are accurately measured, that they are assigned to the correct event and that noise is suppressed. To this end, signals are passed through a digital filter. If correctly configured, the

[1]Luminosity is a property of the beam that affects how often collisions happen. The event rate is directly proportional to the luminosity.

[2]A calorimeter is a type of detector which measures a particles energy by stopping and absorbing them.

[3]Quarks and gluons do not normally exist as free particles, instead they form a *jet* of many composite particles.

digital filter greatly improves the energy measurement, identification of small signals with the correct event, and noise suppression. From the studies presented in this thesis, the initial configuration of the digital filter was decided, and used for data taking during the LHC 2010 run.

Chapter 2

Introduction

The search for the Standard Model Higgs boson [5–7] is one of the main objectives of the ATLAS experiment. The theory predicts all of its properties except for its mass. Direct searches from previous experiments place lower limits around 114 GeV [8]. Theoretical constraints place upper limits on its mass of ~ 1 TeV [9]. The LHC General Purpose Detectors (GPDs) must search for the Higgs boson over this entire mass range. The high mass range is particularly interesting as this region is unexplored by previous lower energy colliders. Also, the discovery of a high mass Higgs Boson would be a strong indication of beyond-the-standard-model (BSM) physics as Standard Model fits to precision electro-weak data prefer a low mass Higgs boson.

At High mass, the channel $H \to ZZ \to llll$ provides a beautifully clean signature. However, it is statistically limited. The focus of this thesis is the channel $H \to ZZ \to llbb$. While this channel suffers from larger backgrounds, it has a higher branching fraction than the 4 lepton channel. This channel may be used to improve the combined search sensitivity of the experiment.

It may also provide an independent cross-check should a high mass excess be observed.

In chapter 3 the theoretical motivations for the Higgs mechanism, the properties of the Higgs boson and the current limits imposed on its mass are reviewed.LEP (Large Electron Positron collider) In chapter 4 the LHC and the ATLAS detector are described. In chapter 5 a study of the sensitivity to the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ \rightarrow llbb$ is presented. Chapter 6 shows background studies with early data.

At the front-line of LHC physics is the Trigger: a physicist cannot analyse events that were not written to disk! The huge event rate at the LHC makes it unfeasible to readout and record every event. The Trigger must reject most events while retaining events with signatures of interest.

The ATLAS trigger is divided into multiple levels. The first level is implemented in custom-built hardware and makes a real-time decision to accept or reject events based on reduced information. If the first level Trigger accepts the event the entire detector is readout and the information is passed to the High Level Trigger. The High Level Trigger algorithms are implemented in software running on large computer farms and make the final trigger decision using the full detector information.

The first level trigger is further divided into subsystems. The focus of this thesis is the first level Calorimeter Trigger. The Calorimeter Trigger uses reduced granularity information from the calorimeters to search for high E_{T} e, γ, τ and jets as well as identifying high $E_{\mathrm{T}}^{\mathrm{miss}}$ and total E_{T} events. Signals from the calorimeters are pre-processed to determine their energy and timing before being transmitted to the Processor modules which implement the trigger algorithms. During the pre-processing, input signals are passed through a Finite Impulse Response (FIR) filter. This filter increases the signal to noise ratio and improves the energy measurement, noise rejection and bunch crossing assignment. In this thesis a study to determine the optimum filter coefficients is presented. The performance of these filters is investigated with commissioning data and cross-checks of the calibration with initial beam data are shown. From the studies presented in this thesis, the initial configuration of the digital filter was decided, and used for data taking during the LHC 2010 run.

An overview of the ATLAS Trigger can be found in chapter 4. In chapter 7 the ATLAS Level-1 Calorimeter Trigger is described in detail. In chapter 8 a study of the digital filter for the Calorimeter Trigger is described. In chapter 9 the results and conclusions are summarised.