

UNIVERSITY OF CALIFORNIA

SANTA CRUZ

**AN INCLUSIVE SEARCH FOR THE DECAY OF A BOOSTED
HIGGS BOSON IN THE $H \rightarrow b\bar{b}$ CHANNEL WITH THE ATLAS
DETECTOR**

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

PARTICLE PHYSICS

by

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Table of Contents

List of Figures	vii
List of Tables	ix
Abstract	x
Dedication	xi
Acknowledgments	xii
1 Introduction	1
I Theoretical Motivations and the Standard Model	2
2 The Standard Model and Beyond	3
2.1 The Standard Model	3
2.2 Quantum Chromodynamics	3
2.3 Quantum Electrodynamics	4
2.4 Spontaneous Symmetry Breaking	4
2.5 The Higgs Mechanism	4
2.6 Parton Distribution Function	4

II	Experimental Apparatus and Associated Facilities	5
3	The Large Hadron Collider	6
3.1	Particle Injection Chain	7
3.2	LHC layout and design	9
3.3	Performance	12
3.4	Pile-up at the LHC	14
4	The ATLAS Detector	16
4.1	ATLAS Coordinate System	19
4.2	Tracking with the Inner Detector	23
4.3	Calorimetry	24
4.4	Muon Spectrometer	24
5	Boosted Higgs at the LHC	25
5.1	Physics beyond the Standard Model	26
5.2	Higgs Production Mechanisms	26
5.3	Branching Ratios	26
5.4	Discovery	26
5.5	Fermion Decay Modes	26
5.6	Boosted Higgs	26
III	The HbbISR Analysis	27
6	Data and Simulation Preparation	28
6.1	Data Used	28
6.2	Monte Carlo Samples	28

7	Physics Object Selection	29
7.1	Calorimeter Jets	30
7.2	Track Jets	30
7.3	Fat Jets	30
7.4	B-tagged Jets	30
7.5	Muons	30
7.6	Overlap Removal	30
8	Event Selection	31
8.1	Selected Triggers	31
8.2	Pre-selection Studies	31
8.3	Signal Selection	31
8.4	Optimisation	31
9	Background Estimation	32
9.1	Multi-jet QCD estimation	32
9.2	$t\bar{t}$ control region	32
9.3	Single top estimation	32
9.4	Hadronic vector boson channel	32
10	Systematic Uncertainties	33
10.1	Theoretical Uncertainties	33
10.2	Experimental Uncertainties	33
11	Statistical Fit	34
11.1	Profile Likelihood Function	34
11.2	Fit Configuration	34
11.3	Statistical Tests	34

12 Results	35
12.1 Expectations	35
12.2 Statistical Analysis Results	35
12.3 Measurements and Limits	35
 IV Conclusion	 36
 13 Conclusion	 37
 Bibliography	 37
 A Hadronic Vqq Sherpa Studies	 39

List of Figures

3.1	CERN accelerator complex	8
3.2	THE LHC	10
3.3	Depiction of a LHC dipole magnet 2-in-1 design	11
3.4	Luminosity!	14
3.5	Pileup for data taking periods 2015 - 2018	15
4.1	[2] Here we see a cut-away side view of the ATLAS detector with the major components labeled. Note that within each of these labeled components there may exist multiple different detector technologies. For scale two people in red are shown standing between the disk muon chambers on the left side of the figure.	17
4.2	This slice of the ATLAS detector depicts how different particles interact with each component of the detector it crosses. A dashed line indicates no interaction while a solid line indicates interaction. Electrons (yellow/green) and charged hadrons (red) interact with the tracker and curve in the solenoid's magnetic field. Electrons and photons (yellow/green) are absorbed by the Electromagnetic calorimeter. All hadrons (red/yellow) are absorbed by the Hadronic calorimeter. The muons (orange) curve in both the solenoid and torroid magnetic fields before exiting the detector. Finally, the neutrinos (white) pass through the entire detector without interacting.	20

4.3	A cartoon view of the the LHC from above showing the SPS, LHC and the four main experiments of the LHC: ATLAS, CMS, LHCb, and ALICE. The standard cartesian coordinate system is shown with its origin at the ATLAS interaction point, the positive x -axis towards the center of the LHC, the positive y -axis pointing upwards, and the positive z -axis pointing along the beamline towards the "A-side"	21
4.4	Modified from [3] this cartoon represents a selection of pseudorapidity (η) values overlaid with some cartesian coordinates (dashed black lines). The redlines are drawn for $\eta = \pm 0.5, 1.0, 3.0$	22
4.5	[4] Diagram of inner detector	23
4.6	[5] Schematic of the Inner Detector including eta lines	24

List of Tables

Abstract

An Inclusive Search for the decay of a Boosted Higgs boson in the $H \rightarrow b\bar{b}$
channel with the ATLAS detector

by

Jacob Martin Pasner

This is an abstract placeholder

To my family

You never doubted me

And always made me laugh

Acknowledgments

I would like to thank my committee for their dutiful efforts to make this document one I can be proud of for the rest of my life. Furthermore, I would like to thank the SCIPP collaboration and UCSC Physics Department for their support in both academic and personal arenas.

Chapter 1

Introduction

Every dissertation should have an introduction. You might not realize it, but the introduction should introduce the concepts, background, and goals of the dissertation.

Part I

Theoretical Motivations and the Standard Model

Chapter 2

The Standard Model and Beyond

2.1 The Standard Model

The pinnacle of humanities ability to represent the fundamental fields and particles that build the universe, the Standard Model is the guiding theoretical basis of particle physics.

2.2 Quantum Chromodynamics

Quantum chromodynamics is super wack

2.3 Quantum Electrodynamics

Quantum Electrodynamics is the first model created in the QFT image.

2.4 Spontaneous Symmetry Breaking

Spontaneous symmetry breaking occurs when a system loses an inherent symmetry in order to attain a lower energy configuration.

2.5 The Higgs Mechanism

The Higgs Mechanism is the system by which particles attain mass through the spontaneous breaking of the Higgs potential, thus causing all particles it interacts with to have mass.

2.6 Parton Distribution Function

Before QFT the proton was thought to be a hard ball containing no smaller constituents. However, we know now that the strong field inside the proton allows for any strong object to exist with some probability which changes based off of the total energy of the proton. This behavior is represented then by a Probability Distribution Function.

Part II

Experimental Apparatus and Associated Facilities

Chapter 3

The Large Hadron Collider

Located 100 meters under the Swiss / French boarder lies the 26.7 kilometer Large Hadron Collider (LHC) [1]. The culmination of a huge international collaboration, this apparatus is used to produce proton and heavy ion collisions for observation by the four major experiments at the LHC: ATLAS, CMS, LHCb, and ALICE. The system was designed for a maximum center-of-mass energy of $\sqrt{s} = 14$ TeV and a peak instantaneous luminosity of $L = 10^{34} \text{cm}^{-2} \text{s}^{-1}$.

The first LHC workshop was held in 1984 in Lausanne at the European Organization for Nuclear Reserach (CERN). The nearly 30 year old case for a machine that would push towards the discovery of the elusive Higgs Boson was presented using the existing CERN accerlerator facilities and the Large Electron Positron (LEP) collider tunnel. The proposal became reality on September 10, 2008 when the first proton beams were circulated, only to have calamity strike 9 days later in the form of a catastrophic elec-

trical fault. The repairs and improvements lasted until November 2009 when the LHC restarted. Since then this modern marvel has worked wonderfully and, as hoped, lead to the discovery of the Higgs Boson by the CMS and ATLAS collaborations July 4, 2013.

The following chapter provides a brief introduction to the worlds most powerful accelerator starting with the little red bottle of hydrogen in building XXX, and ending with the interaction point where protons collide at the highest energies ever produced.

3.1 Particle Injecton Chain

We begin with the most common element in the Universe, hydrogen, as our source of protons. A bottle of hydrogen gas provides 100 microsecond pulses of raw H_2 which is then injected into a Duoplasmatron. There, a strong electric field and free elctrons from a cathode ionize the molecule into bare H^+ aka a proton! These protons are then accelerated by a 90kV field, leaving the Duoplasmatron with 1.4% speed of light ($\sim 4000\text{km/s}$) or, in relativistic units, about 83keV. The bare protons are then fed into the accelerating RadioFrequency (RF) cavities of Linear Accelerator 2 (LINAC2). Inside, conductors charged by a powerful oscillating electromagnetic field accelerate the protons resulting in a 50MeV energy. Along the way, small quadrupole magnets shape the proton packet insuring they remain in a tight beam. This pattern of accleration with RF cavities and shaping/turnig with magnets is then repeated with CERN's first synchrotron, the Proton Synchrotron (PS) rendering a 1.4 GeV beam. The final step

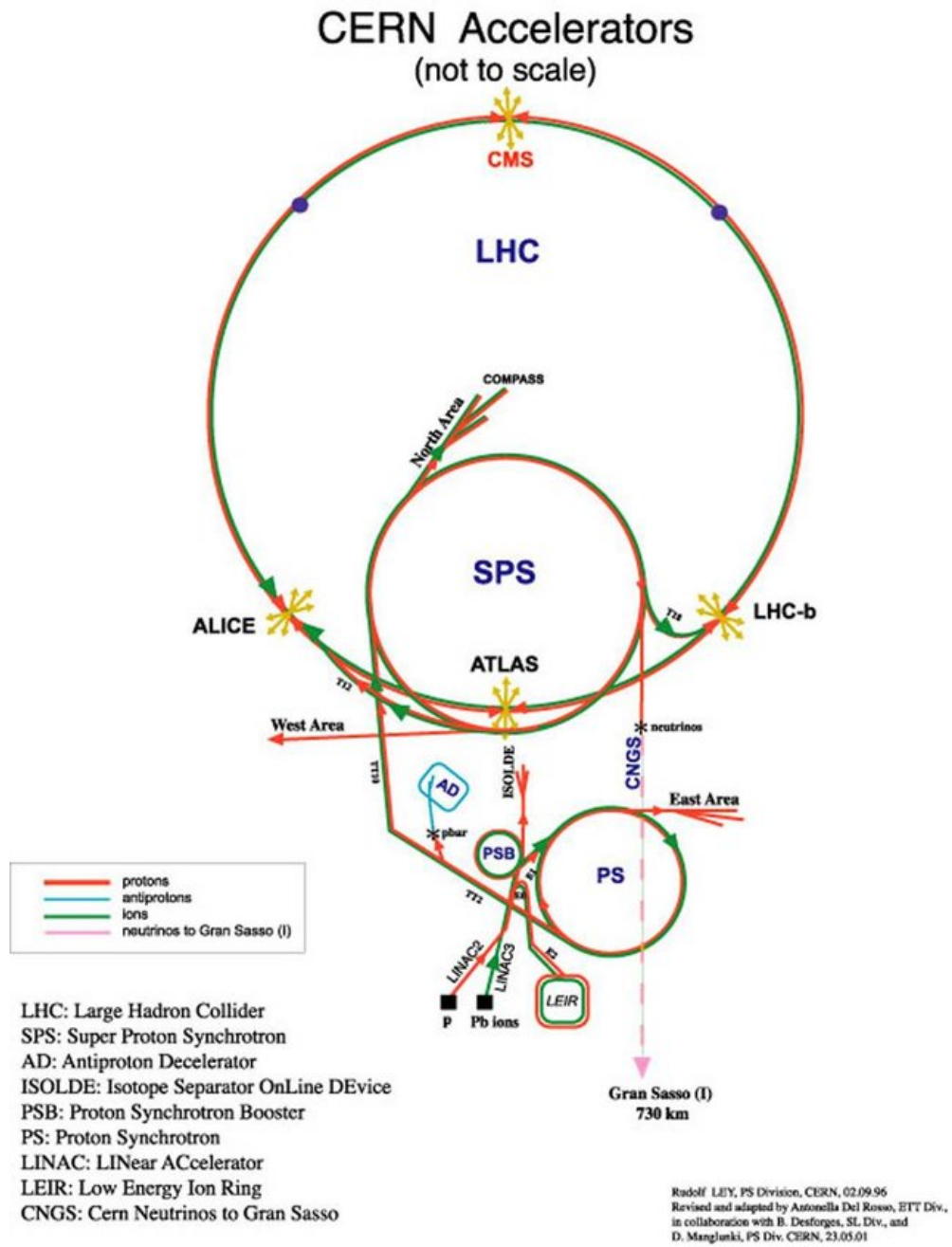


Figure 3.1: CERN accelerator complex

before the LHC comes with the Super Proton Synchrotron where the same technologies are implemented to produce 450 GeV protons, ready for injection into the LHC. A diagrammatic representation of this chain can be seen in figure [\[injection chain\]](#)

In order to produce proton-proton collisions the LHC uses two beams circulating in opposite directions. The beams are not continuous, but instead consist of bunches, or buckets, of $\mathcal{O}(10^{11})$ protons with a spacing of 25ns. Given the LHC circumference this allows for 3564 buckets, however only 2808 are filled per beam due to safety requirements and injection limitations. Each beam takes 4 minutes and 20 seconds to fill and then an additional 20 minutes to for the protons to reach their maximum energy of 7 TeV TeV, or 99.99999991% the speed of light! Under normal operating conditions these beams can be used for many hours.

3.2 LHC layout and design

While often depicted as a perfect circle the LHC is in reality an octagon with rounded edges, called arcs, as can be seen in figure 3.2. Here you can see the counter circulating beams of protons depicted in red and blue. These beams are focused and collided at the 4 dedicated interaction points at rates of up to 40 MHz. Two of these points are occupied by the ATLAS and CMS experiments, both of which are high luminosity, multi-purposed experiments.

The exact design of the tunnel is due to the experimental constraints of the original

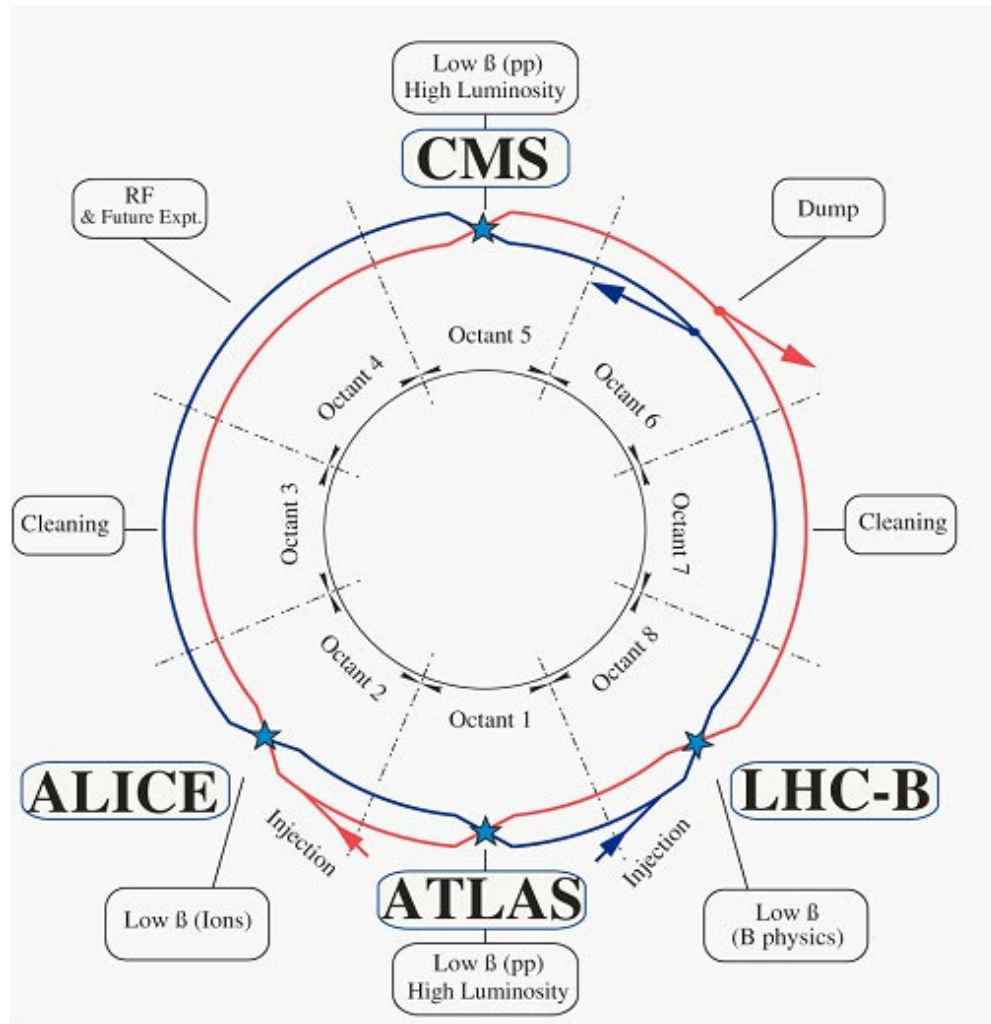


Figure 3.2: THE LHC

machine for which it was built, the Large Electron Positron (LEP) Collider. For the $\sim 2,000$ times lighter electron the maximum energy was limited by the synchrotron radiation, proportional to $\frac{1}{m^4}$, requiring long straight sections of accelerating RF cavities to recouperate the lost energy. Given that this effect is $\mathcal{O}(10^{13})$ times smaller for the proton the LHC is instead limited by our ability to design and construct magnets strong enough to bend the beam given the already determined curvature of the 8 arcs.

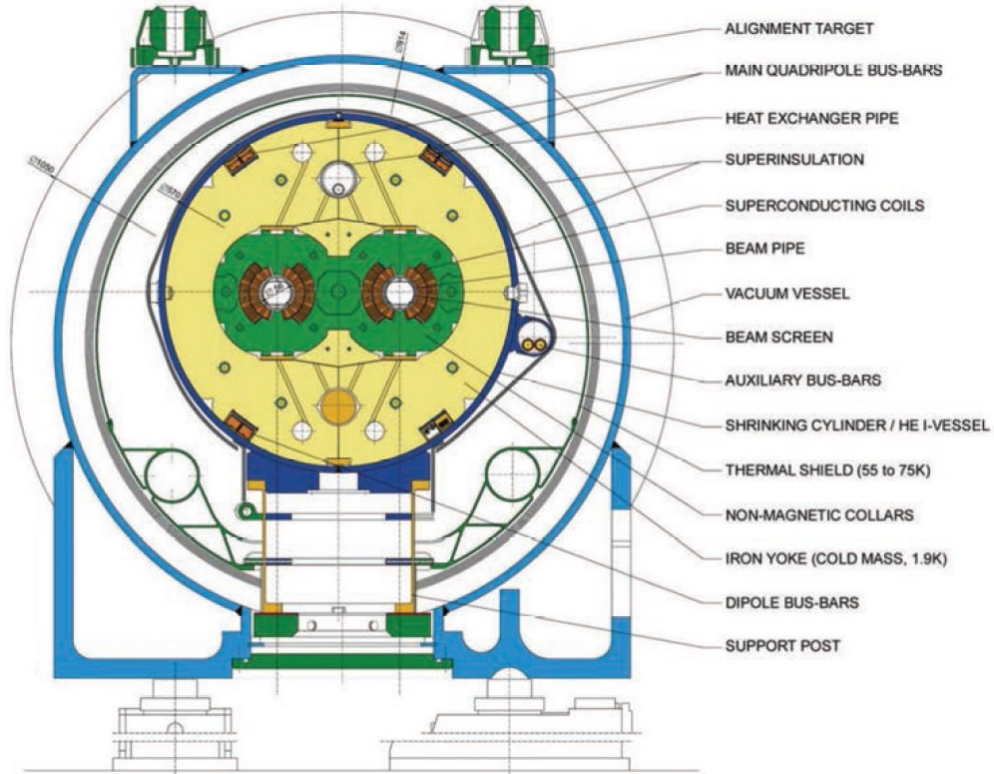


Figure 3.3: Depiction of a LHC dipole magnet 2-in-1 design

The oppositely rotating beams must each have their own ring and magnetic field which lead to the creation of a twin-bore (i.e. "two-in-one") magnet design, a cross section of

which can be seen in figure 3.3. These magnets are constructed using NbTi superconductors which are cooled to 2K using superfluid helium. These magnets are designed to provide the needed 8.33 T magnetic field required to bend the beams at the design beam energy of 7 TeV. In total 1231 of these 15 m long bending dipole magnets are used, in association with 392 5-7m long quadrupole magnets which are responsible for keeping the proton bunches in a tight beam by squeezing them either horizontally or vertically.

3.3 Performance

Since the beginning of its stable running in 2010 the LHC has performed well, even exceeding our expectations. While the experiment itself is incredibly complex, the performance of the machine, for the purposes of our analysis, can be reduced to two numbers; the familiar center of mass energy of the beams and a less common quantity known as the integrated luminosity.

For particle physics the integrated luminosity is proportional to the total number of collisions recorded during a specified time period, while the instantaneous luminosity is proportional to the bunch crossing rate along with the cross section of a proton-proton interaction and represents the potential number of collisions per second. Knowing this we can see that the integrated luminosity, L_{int} is simply the integral of the instantaneous

luminosity $L_{inst.}$ for a choosen data period as seen in equation 3.1.

$$L_{int} = \int L_{inst.} dt \quad (3.1)$$

For a standard Gaussian beam, $L_{inst.}$ can be written as

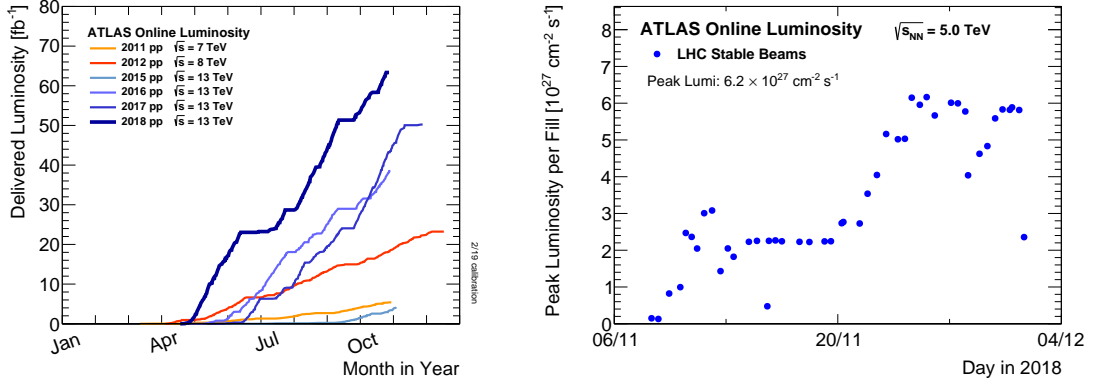
$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (3.2)$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the collision point, and F the geometric luminosity reduction factor due to the crossing angle at the interaction point given by

$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-1/2} \quad (3.3)$$

where θ_c is the full crossing angle at the interaction point, σ_z is the RMS bunch length, and σ^* is the transverse RMS beam size at the interaction point.

For the ATLAS experiment the integrated luminosity for each year can be seen in figure 3.4a as well as an example of the instantaneous luminosity for the choosen year in figure 3.4b.



(a) Integrated Luminosity 2011 - 2018 (b) 2018 Peak Instantaneous Luminosity

Figure 3.4: Luminosity!

3.4 Pile-up at the LHC

Given the large number of protons per bunch and the cross-section of a proton-proton interaction, the probability to observe multiple interactions per bunch crossing is quite high. These multiple-interaction are known as pile-up, μ or the time averaged representation $\langle\mu\rangle$, and come in two different forms:

1. **In-time pile-up:** These are the other proton-proton collisions that occur during the same bunch crossing as the primary interaction that caused the Data Acquisition (DAQ) system to trigger. These are the standard extra interactions we expect to observe as stated above.
2. **Out-of-time pile-up:** These are interactions that occur either before or after a bunch crossing that causes the DAQ to trigger. This effect is generally due to the

long integration times of some detector electronics.

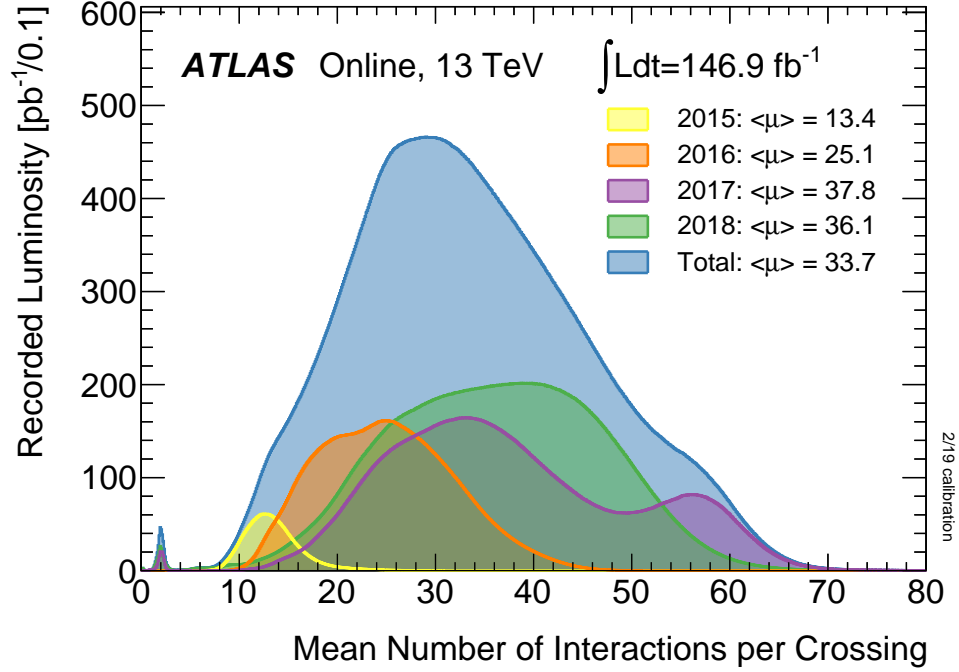


Figure 3.5: Pileup for data taking periods 2015 - 2018

The pile-up profile for past years can be seen in figure 3.5. The width of this distribution is due to a combination of Poissonian statistics, the decrease in number of protons per bunch over the lifetime of a single run, and optimization tweaks to the beam's profile during runtime. Understanding and eliminating the noise from these pile-up events is crucial to reconstructing physics variables to represent the primary interaction we hope to observe.

Chapter 4

The ATLAS Detector

Given the immense energies available at the LHC, and the veritable zoo of particles we are trying to detect, we require a general-purpose experiment in order to fully exploit the full range of physics opportunities provided. Two international collaborations rose to this challenge, the CMS (Compact Muon Solenoid) and ATLAS (A Torroidal LHC ApparatuS) experiments. While both have similar physics goals and each of them strengths and weaknesses, this dissertation will focus on the ATLAS experiment and the intricacies of its three main sub-detectors and two massive magnet systems depicted in figure ??.

Originally proposed in 1994 the ATLAS experiment was completed in 2008. On July 4th, 2012 in a joint announcement the ATLAS and CMS experiments announced the discovery of the long predicted Higgs Boson. The collaboration now boasts over 3000 physicists from 175 institutions spread across 38 countries and continues to probe

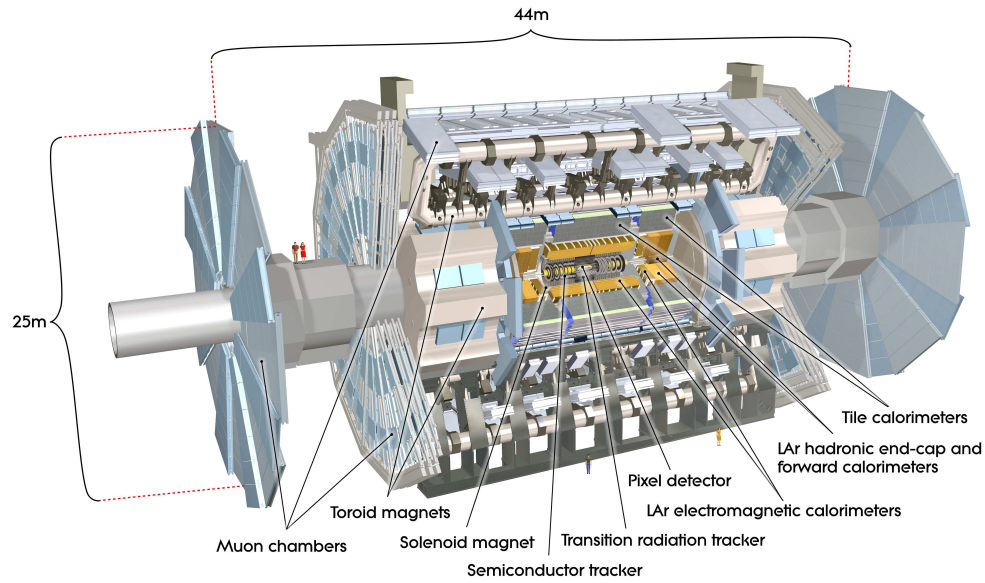


Figure 4.1: [2] Here we see a cut-away side view of the ATLAS detector with the major components labeled. Note that within each of these labeled components there may exist multiple different detector technologies. For scale two people in red are shown standing between the disk muon chambers on the left side of the figure.

the limits of the Standard Model in pursuit of answers to some of Humanities deepest questions.

Located approximately 100 meters underground in a vast excavated chamber, the ATLAS detector rests its 7000 metric tonnes on a bed of concrete reinforced steel. Out of it flows the signals of over 100 million electronic channels through a zip tied mass of greater than 3000 kilometers of cabling. At its very center is one of the four interaction points of the LHC, specifically Point 1, where the two counter circulating proton beams are skillfully shaped and then collided by a series of magnets. The energetic particles resultant from this collision then fly out in all directions into the bulk of the ATLAS detector.

The first sub-system they meet is the Inner Detector (ID) and its many layers of strip and pixel silicon detectors along with a transition radiation gaseous wire detector, all bathed in the 2T magnetic field of the surrounding superconducting solenoidal magnet. This system exploits the ionization of charged particles to track their curved trajectory through the magnetic field. This curvature gives us charge information, a momentum measurement, and precision 3D vertices crucial to the identification of the secondary vertices of a b-hadron decay.

Outside of the solenoid the particles are faced with first the Electromagnetic and then the Hadronic sampling calorimeters. Here, layers of scintillator and high radiation length materials are implemented to measure the energy of electrons, photons, and hadrons. As the goal is to completely absorb the energy of all outgoing particles the calorimeter

has a nearly 4π solid angle coverage.

Finally we have the muon system surrounding the calorimeter and equipped with its own torroidal magnet system. Here the charged muon bends in the magnetic field while leaving a trail of ionization in the muon spectrometer before exiting the detector completely. Neutrinos are the only other standard model particle that leave the detector, however they do so without detection. A depiction of the various particle interactions with the different detector sub-systems can be seen in figure 4.2

In the following sections I will explain our choosen coordinate system and give a more detailed reveiw of these 3 detector sub-systems.

4.1 ATLAS Coordinate System

Using the nominal interaction point as the origin, ATLAS uses a right handed coordinate system where the positive x -axis points towards the center of the LHC ring, the positive y -axis points upwards, and the positive z -axis is defined by the counter clockwise circulating beam direction as viewed from above shown in figure 4.3 [2].

Using these coordinates we can define the physical momentum of the objects measured as $\vec{p} = (p_T, p_z)$ with p_T being the momentum of the object in the transverse plane and p_z the momentum along the beam axis. Given the cylindrical symmetry of ATLAS it is desireable to define the polar angle θ from the beam axis with the $r - \phi$ plane being perpendicular to that axis. Since the particles we observe are relativistically boosted

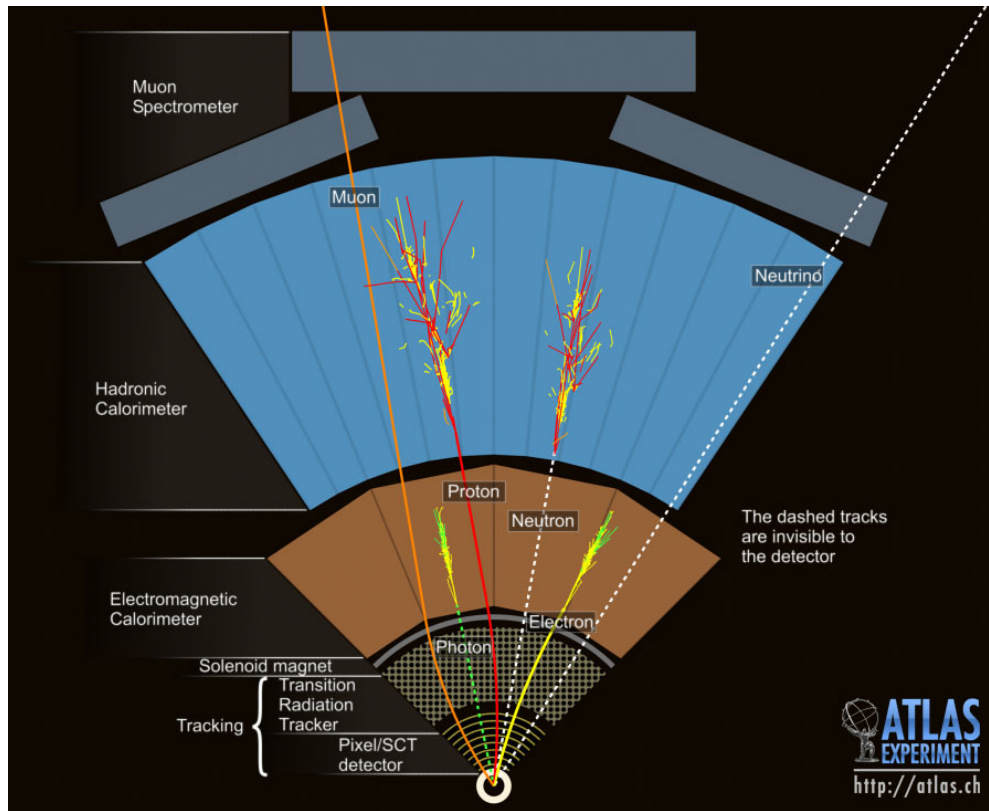


Figure 4.2: This slice of the ATLAS detector depicts how different particles interact with each component of the detector it crosses. A dashed line indicates no interaction while a solid line indicates interaction. Electrons (yellow/green) and charged hadrons (red) interact with the tracker and curve in the solenoid's magnetic field. Electrons and photons (yellow/green) are absorbed by the Electromagnetic calorimeter. All hadrons (red/yellow) are absorbed by the Hadronic calorimeter. The muons (orange) curve in both the solenoid and torroid magnetic fields before exiting the detector. Finally, the neutrinos (white) pass through the entire detector without interacting.

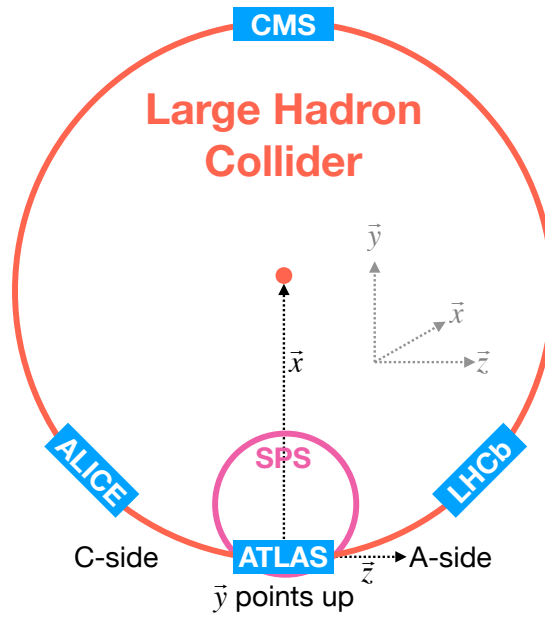


Figure 4.3: A cartoon view of the the LHC from above showing the SPS, LHC and the four main experiments of the LHC: ATLAS, CMS, LHCb, and ALICE. The standard cartesian coordinate system is shown with its origin at the ATLAS interaction point, the positive x -axis towards the center of the LHC, the positive y -axis pointing upwards, and the positive z -axis pointing along the beamline towards the "A-side"

in the z -axis it is desirable to use the Lorentz invariant quantity pseudorapidity (η) defined in terms of the polar angle by

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right). \quad (4.1)$$

where $\eta = 0$ is in the $x - y$ plane and larger values of $|\eta|$ being closer to the beam axis as can be seen in figure 4.4.

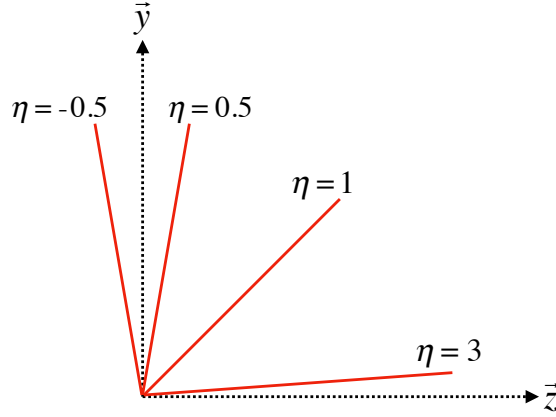


Figure 4.4: Modified from [3] this cartoon represents a selection of pseudorapidity (η) values overlaid with some cartesian coordinates (dashed black lines). The redlines are drawn for $\eta = \pm 0.5, 1.0, 3.0$

In this analysis the angular separation between objects in the detector is calculated and represented using the geometric quantity

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \quad (4.2)$$

4.2 Tracking with the Inner Detector

With its closest component, the insertable b-layer (IBL) [4], only 3.3 cm from the beampipe The Inner Detector (ID), shown in figure 4.5 [ATLAS-TDR-4, ATLAS-TDR-5] faces the incredible challenge of providing precision momentum resolution and identification of both primary and secondary vertex measurements of charged tracks all while receiving the highest fluence of any detector.

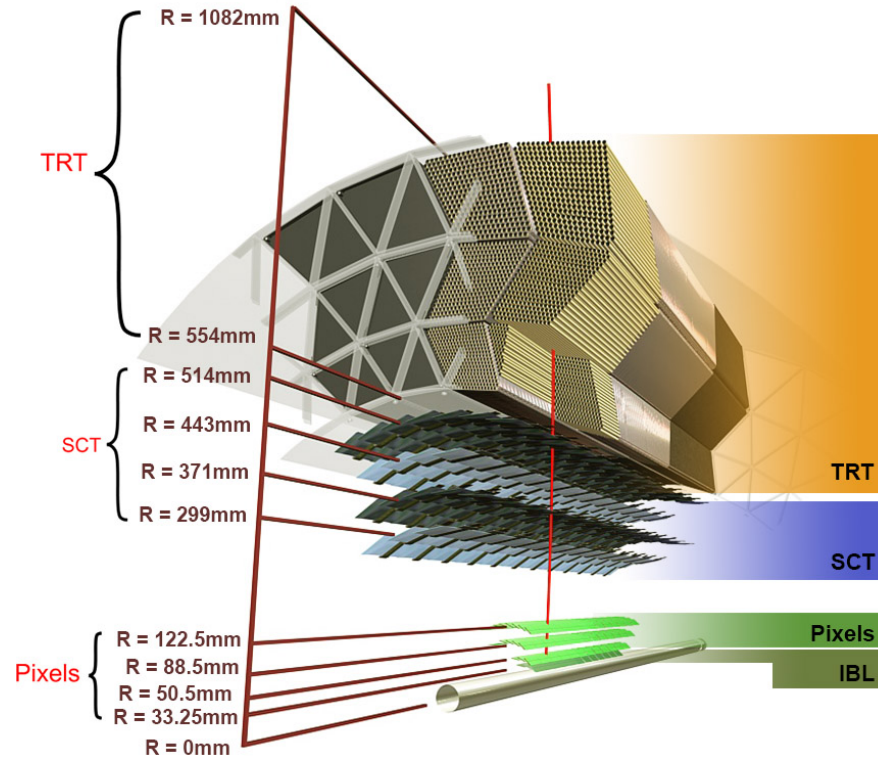


Figure 4.5: [4] Diagram of inner detector

It is designed to be very compact to fit inside the 2T solenoid and to give excellent momentum resolution above the nominal p_T threshold of 0.5 GeV and within the pseu-

dorapidity range of $|\eta| < 2.5$ as shown in figure 4.6

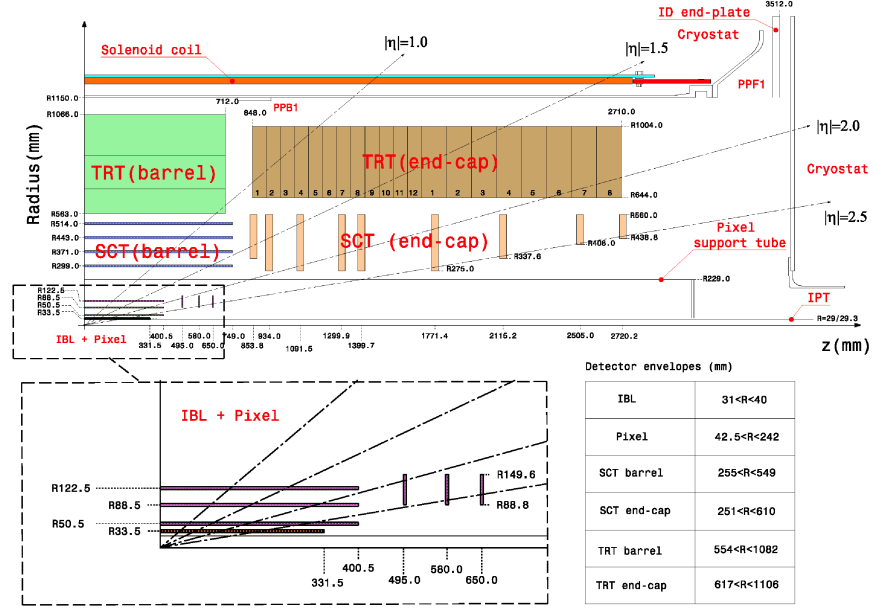


Figure 4.6: [5] Schematic of the Inner Detector including eta lines

4.3 Calorimetry

4.4 Muon Spectrometer

Chapter 5

Boosted Higgs at the LHC

Its July 4th, 2012 and the walls of building 500 are reverberating as Particle Physicists around the world rejoice the discovery of the particle that gives all things mass, the Higgs Boson.

5.1 Physics beyond the Standard Model

5.2 Higgs Production Mechanisms

5.3 Branching Ratios

5.4 Discovery

5.5 Fermion Decay Modes

5.6 Boosted Higgs

Part III

The HbbISR Analysis

Chapter 6

Data and Simulation Preparation

In order to compare data to theory ATLAS has developed an analysis chain which runs both real data and simulated samples through the same processing, assuring a final result which is as comparable as possible.

6.1 Data Used

6.2 Monte Carlo Samples

Chapter 7

Physics Object Selection

After the ATHENA Digitization step both data and monte carlo have the same format, representing the three dimensional energy deposits. In order to analyze these deposits they are cleaned, clustered and checked for overlap resulting in physics objects useful for our specific analysis.

7.1 Calorimeter Jets

7.2 Track Jets

7.3 Fat Jets

7.4 B-tagged Jets

7.5 Muons

7.6 Overlap Removal

Chapter 8

Event Selection

Having created our physics objects we begin to make selections of what types of events we want to consider given the goal of our analysis. In our boosted topology this means considering things like momentum, jet collection efficiencies and background rejection.

8.1 Selected Triggers

8.2 Pre-selection Studies

8.3 Signal Selection

8.4 Optimisation

Chapter 9

Background Estimation

The dominant background was QCD. I worked on the $t\bar{t}$ control region. The V_{qq} and single top backgrounds were estimated from monte carlo.

9.1 Multi-jet QCD estimation

9.2 $t\bar{t}$ control region

9.3 Single top estimation

9.4 Hadronic vector boson channel

Chapter 10

Systematic Uncertainties

10.1 Theoretical Uncertainties

10.2 Experimental Uncertainties

Chapter 11

Statistical Fit

The statistical fit in our analysis was accomplished using a framework developed for Higgs searches.

11.1 Profile Likelihood Function

11.2 Fit Configuration

11.3 Statistical Tests

Chapter 12

Results

12.1 Expectations

12.2 Statistical Analysis Results

12.3 Measurements and Limits

Part IV

Conclusion

Chapter 13

Conclusion

I conclude that this section is the conclusion

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Appendix A

Hadronic Vqq Sherpa Studies

Ancillary material should be put in appendices, which appear after the bibliography.