

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

Jacob Martin Pasner

October 2019

The Dissertation of Jacob Martin Pasner
is approved:

Professor Jason Nielsen, Chair

Professor Abraham Seiden

Professor Michael Hance

Dean Lori Kletzer
Vice Provost and Dean of Graduate Studies

Copyright © by
Jacob Martin Pasner
2019

Table of Contents

List of Figures	vi
List of Tables	vii
Abstract	viii
Dedication	ix
Acknowledgments	x
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	3
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	13

4	The ATLAS Detector	17
4.1	ATLAS Coordinate System	18
4.2	Tracking with the Inner Detector	18
4.3	Calorimetry	18
4.4	Muon Spectrometer	18
5	Boosted Higgs at the LHC	19
5.1	Physics beyond the Standard Model	20
5.2	Higgs Production Mechanisms	20
5.3	Branching Ratios	20
5.4	Discovery	20
5.5	Fermion Decay Modes	20
5.6	Boosted Higgs	20
III	The HbbISR Analysis	21
6	Data and Simulation Preparation	22
6.1	Data Used	22
6.2	Monte Carlo Samples	22
7	Physics Object Selection	23
7.1	Calorimeter Jets	24
7.2	Track Jets	24
7.3	Fat Jets	24
7.4	B-tagged Jets	24
7.5	Muons	24
7.6	Overlap Removal	24
8	Event Selection	25
8.1	Selected Triggers	25
8.2	Pre-selection Studies	25
8.3	Signal Selection	25
8.4	Optimisation	25
9	Background Estimation	26
9.1	Multi-jet QCD estimation	26
9.2	$t\bar{t}$ control region	26
9.3	Single top estimation	26
9.4	Hadronic vector boson channel	26
10	Systematic Uncertainties	27
10.1	Theoretical Uncertainties	27
10.2	Experimental Uncertainties	27

11 Statistical Fit	28
11.1 Profile Likelihood Function	28
11.2 Fit Configuration	28
11.3 Statistical Tests	28
12 Results	29
12.1 Expectations	29
12.2 Statistical Analysis Results	29
12.3 Measurements and Limits	29
IV Conclusion	30
13 Conclusion	31
Bibliography	31
A Hadronic Vqq Sherpa Studies	33

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

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 electrical 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 before the LHC comes with the Super Proton Synchrotron where the same technologies

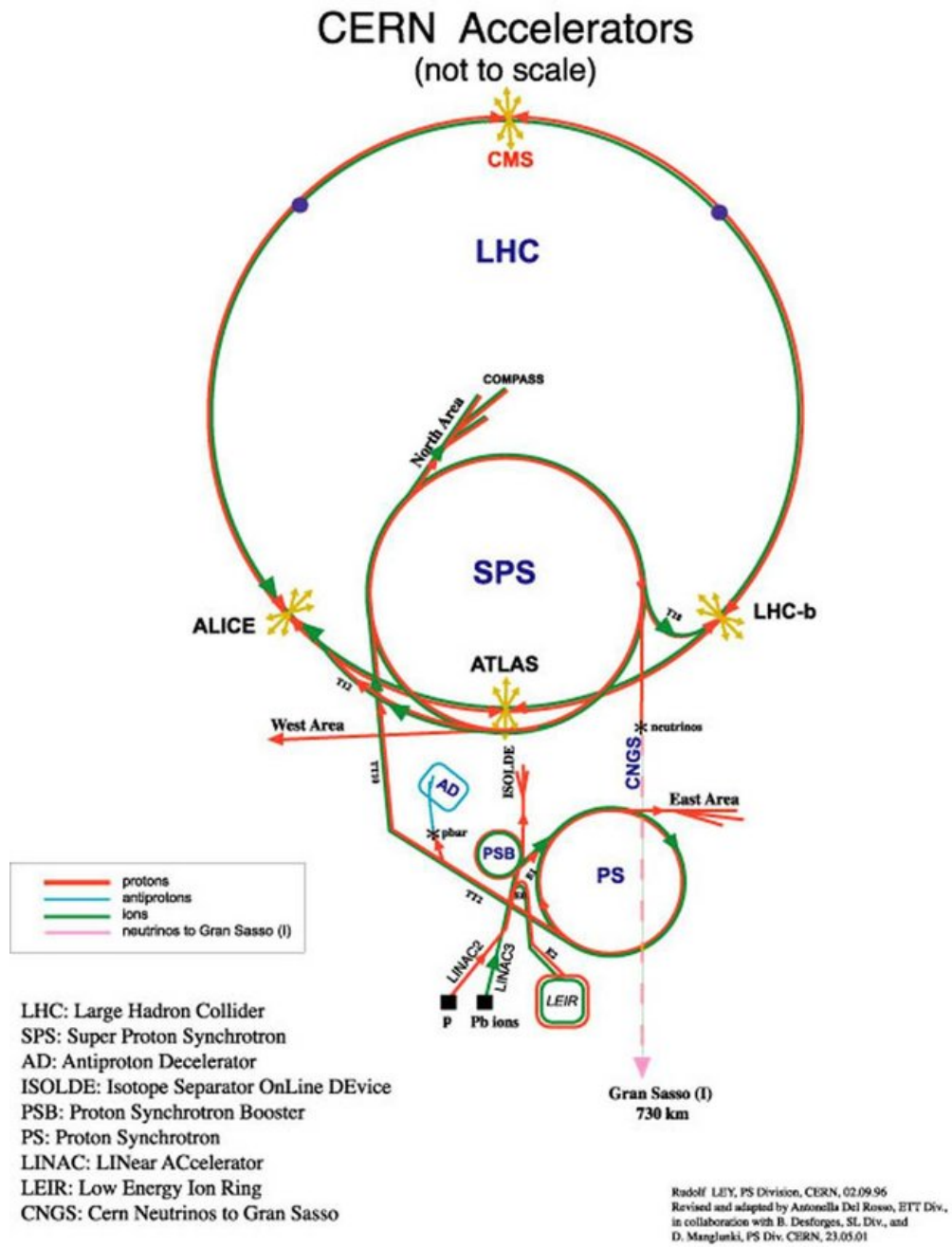


Figure 3.1: CERN accelerator complex

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, 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 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

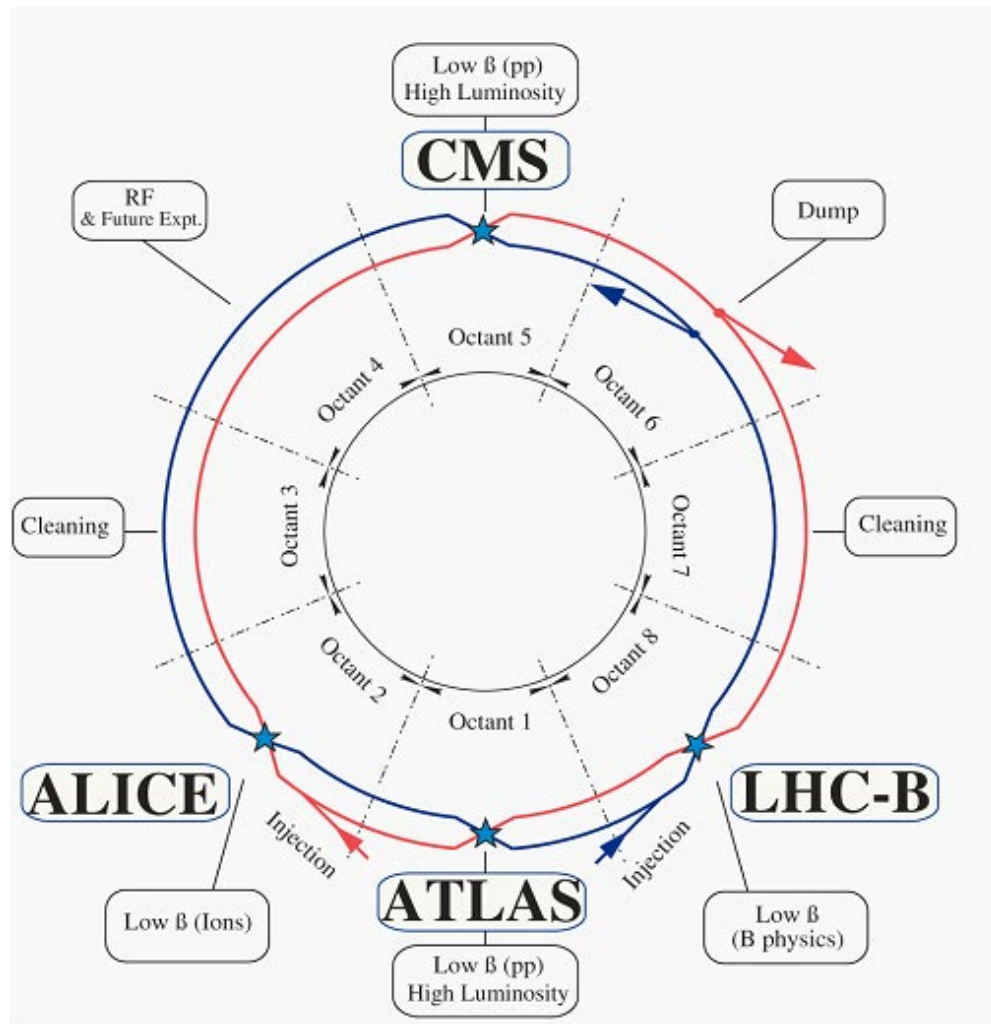


Figure 3.2: THE LHC

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.

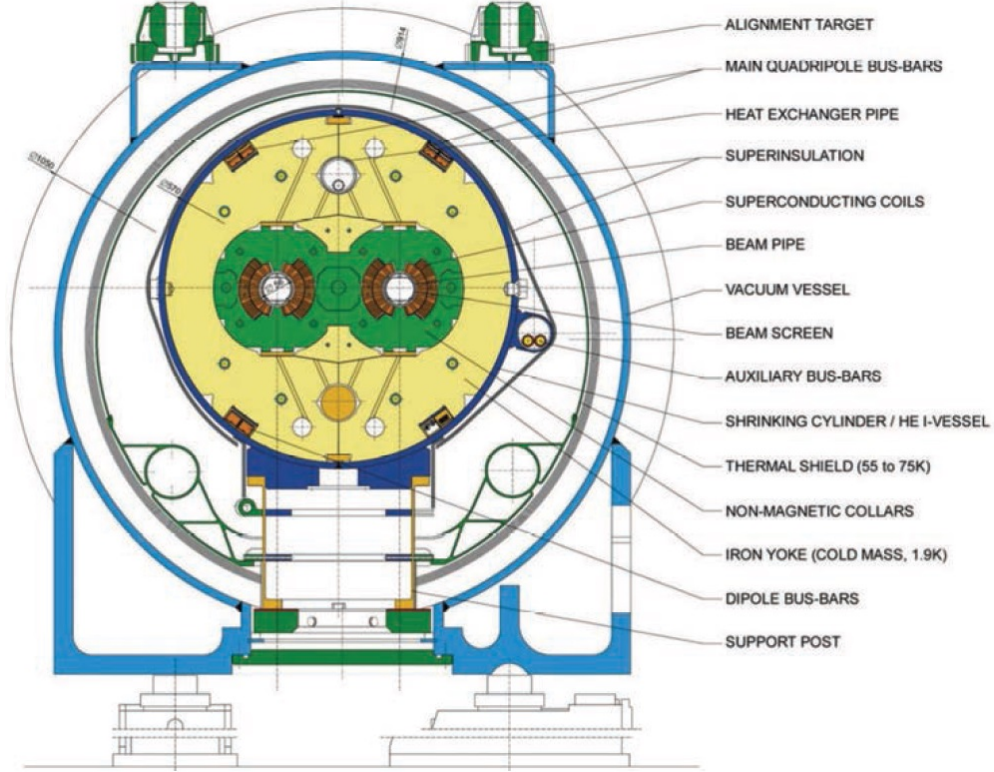


Figure 3.3: Depiction of a LHC dipole magnet 2-in-1 design

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 chosen data period as seen in equation 3.1.

$$L_{int} = \int L_{inst.} dt \tag{3.1}$$

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

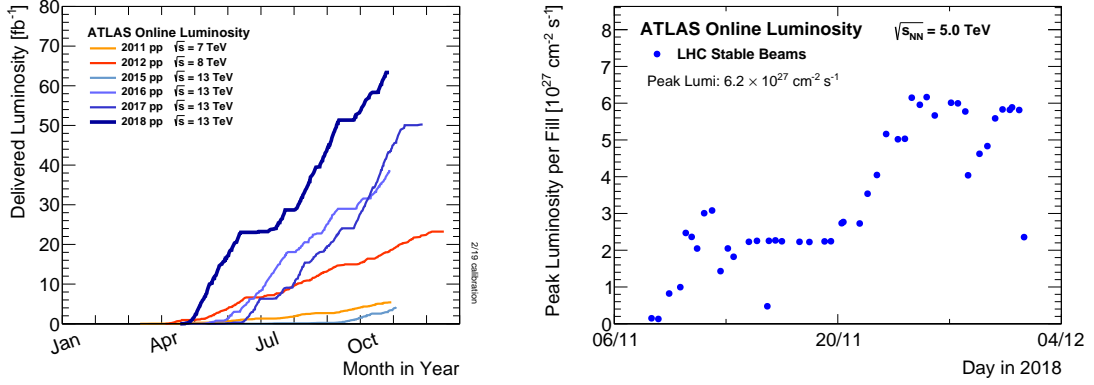
$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-1/2} \quad (3.3)$$

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.

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:



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

Figure 3.4: Luminosity!

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.

The pile-up profile for past years can be seen in figure 3.5. The width of this distribution is due 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

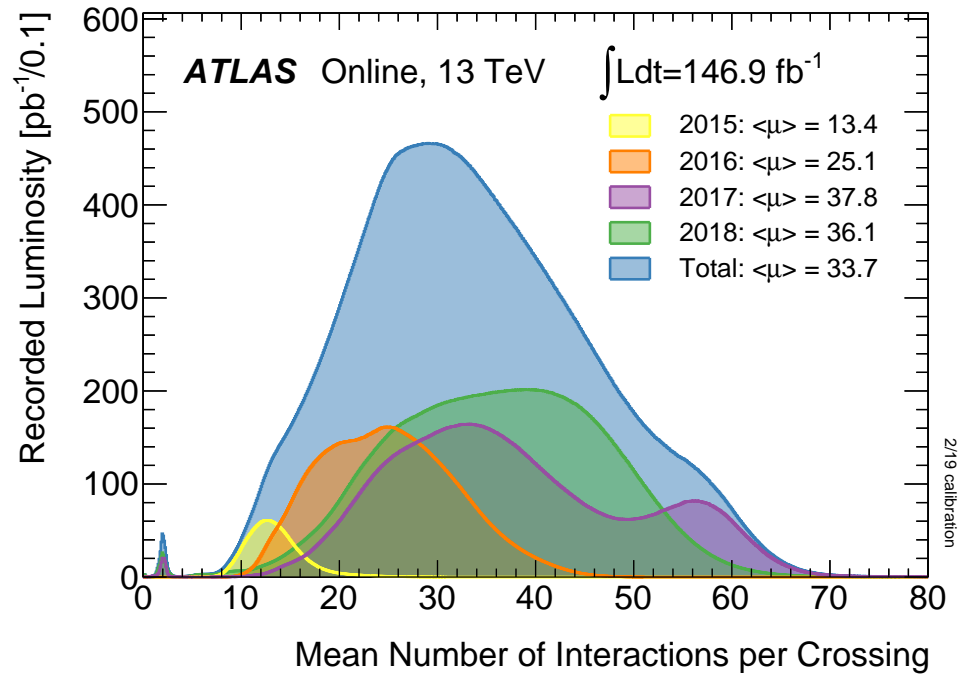


Figure 3.5: Pileup for data taking periods 2015 - 2018

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 Toroidal 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.

Located approximately 100 meters underground in a vast excavated chamber, the ATLAS detector rests its 7000 metric tonnes on a bed of concrete and tungsten. 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 solenoid. This system exploits the ionization of charged particles to track their trajectory as they curve through the magnetic field. This curvature gives us charge information, a momentum measurement, and a precision 3D vertex 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 calorimeter.

4.1 ATLAS Coordinate System

4.2 Tracking with the Inner Detector

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 Vqq 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

Bibliography

- [1] Lyndon Evans and Philip Bryant. “LHC Machine”. In: *JINST* 3 (2008), S08001.

DOI: 10.1088/1748-0221/3/08/S08001 (cit. on p. 6).

Appendix A

Hadronic Vqq Sherpa Studies

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