UNIVERSITY OF CALIFORNIA
SANTA CRUZ

AN INCLUSIVE SEARCH FOR THE DECAY OF A BOOSTED HIGGS BOSON IN THE $H \to b\bar{b}$ 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

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 Quandum 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 Incjecton 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 Tracking with the Inner Detector 17
4.2 Calorimetry 17
4.3 Muon Spectrometer 17

5 Boosted Higgs at the LHC **18**
5.1 Physics beyond the Stnadard Model 19
5.2 Higgs Production Mechanisms 19
5.3 Branching Ratios 19
5.4 Discovery 19
5.5 Fermion Decay Modes 19
5.6 Boosted Higgs 19

III The HbbISR Analysis **20**

6 Data and Simulation Preparation **21**
6.1 Data Used 21
6.2 Monte Carlo Samples 21

7 Physics Object Selection **22**
7.1 Calorimeter Jets 23
7.2 Track Jets 23
7.3 Fat Jets 23
7.4 B-tagged Jets 23
7.5 Muons 23
7.6 Overlap Removal 23

8 Event Selection **24**
8.1 Selected Triggers 24
8.2 Pre-selection Studies 24
8.3 Signal Selection 24
8.4 Optimisation 24

9 Background Estimation **25**
9.1 Multi-jet QCD estimation 25
9.2 $t\bar{t}$ control region 25
9.3 Single top estimation 25
9.4 Hadronic vector boson channel 25

10 Systematic Uncertanties **26**
10.1 Theoretical Uncertanties 26
10.2 Experimental Uncertanties 26

11 Statistical Fit **27**
11.1 Profile Likelihood Function 27
11.2 Fit Configruation 27
11.3 Statistical Tests 27

12 Results **28**
12.1 Expectations 28
12.2 Statistical Analysis Results 28
12.3 Measurements and Limits 28

IV Conclusion **29**

13 Conclusion **30**

Bibliography **30**

A Hadronic Vqq Sherpa Studies **32**

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 $H \to b\bar{b}$

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. Furthemore, 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, backgrouand, 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 Quandum 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 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 wonderfuly 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 Incjecton 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$4000km/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

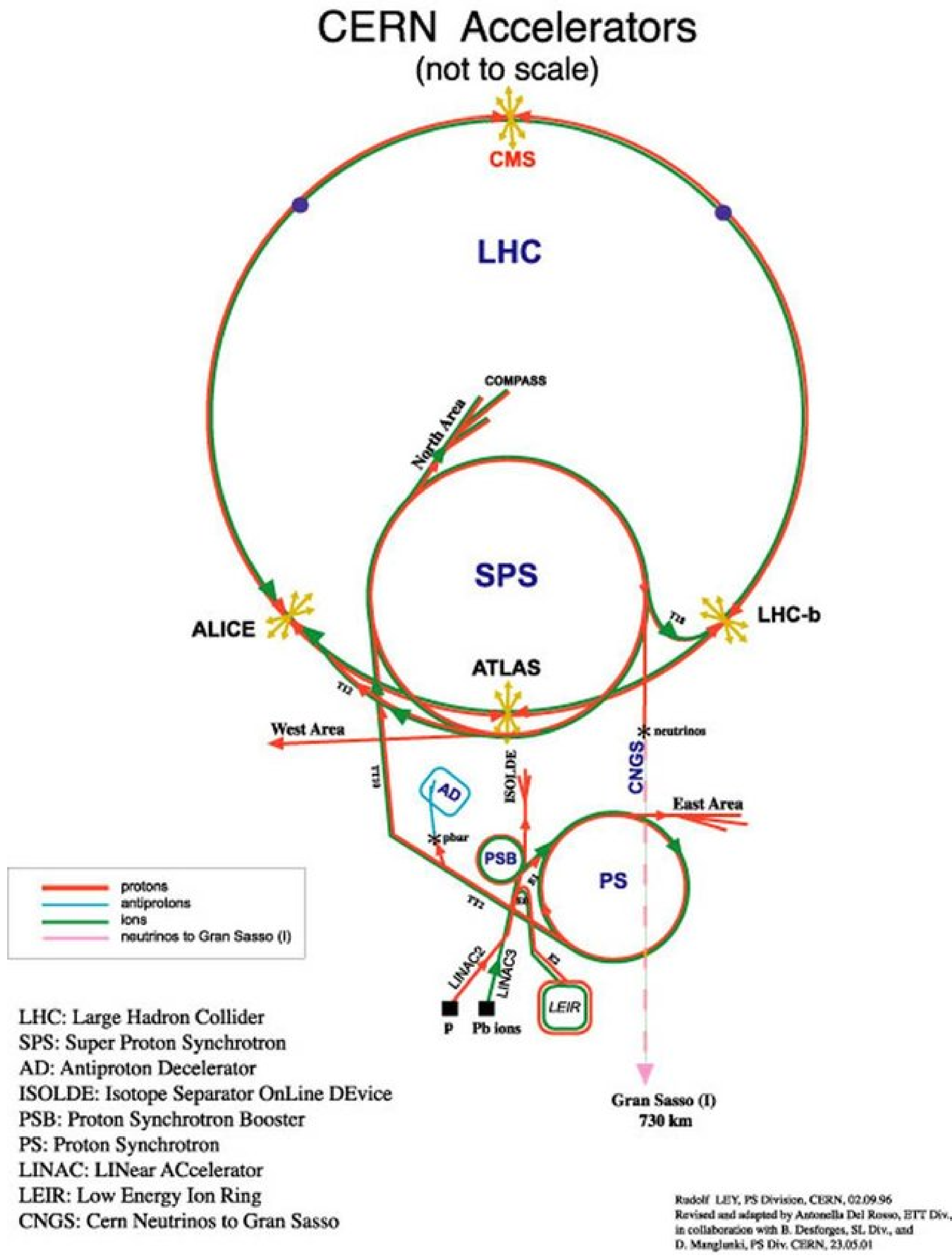


Figure 3.1: CERN accelerator complex

are implemented to produce 450 GeV protons, ready for injection into the LHC. A diagramatic 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 occupoied 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

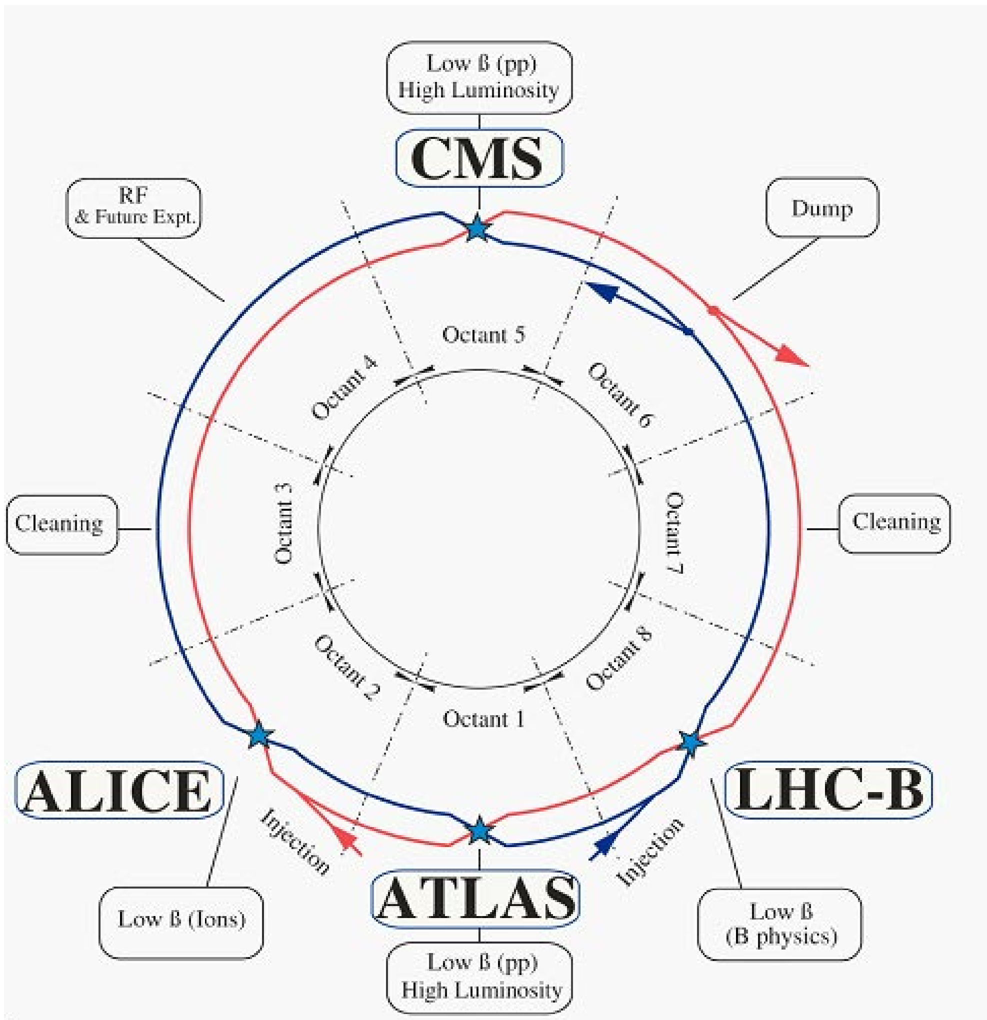


Figure 3.2: THE LHC

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.

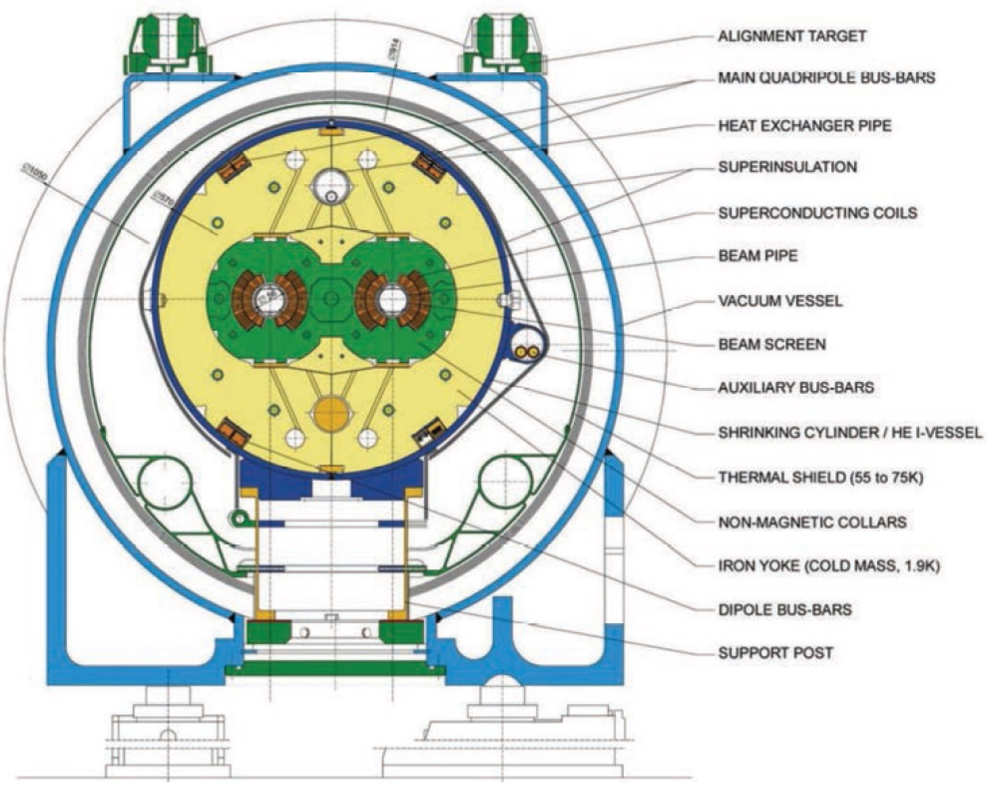


Figure 3.3: Depiction of a LHC dipole magnet 2-in-1 design

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 begining 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.

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

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

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

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

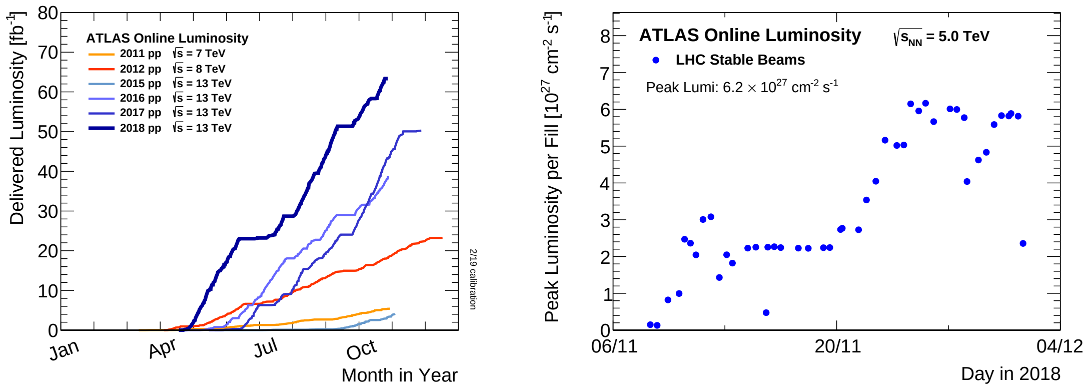
$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-1/2} \tag{3.3}$$

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 cauesd the Data Aquisition (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 **??**. The width of this distributino is due a combination of Poisonian 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

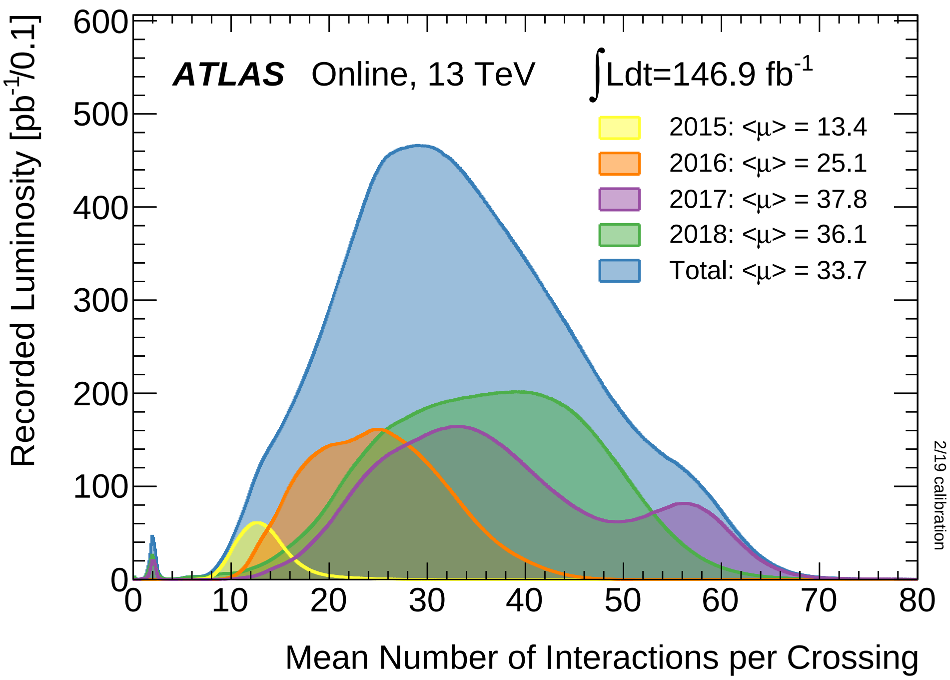


Figure 3.5: Pileup for data taking periods 2015 - 2018

interaction we hope to observe.

Chapter 4

The ATLAS Detector

4.1 Tracking with the Inner Detector

4.2 Calorimetry

4.3 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 Stnadard 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 anlysis chain which runs both real data and simulated samples through the same processing, assuring a final result which is as comprable 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 dimentional 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 ttbar 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 Uncertanties

10.1 Theoretical Uncertanties

10.2 Experimental Uncertanties

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 Configruation

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 secion 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.