# ZZ Production at $\sqrt{s} = 13\,\text{TeV}$ in Four-Lepton Events Using the CMS Detector at the CERN LHC

*by*

Nathaniel Woods

A dissertation submitted in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

(Physics)

*at the*

University of Wisconsin – Madison

2017

Defended on X August 2017

Dissertation approved by the following members of the Final Oral Committee:

Wesley Smith · Bjorn Wiik Professor of Physics

Sridhara Dasu · Professor of Physics

Matthew Herndon · Professor of Physics

Someone · Professor of Physics

Someone · Professor of Something

# Abstract

This thesis presents some cool stuff.

# Acknowledgements

Nice people are nice.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# The Standard Model

## 1.1 Introduction

Some history and stuff

## 1.2 Matter and Force

Does this need subsections? Not the way it's structured in my head right now, but maybe it could have one subsection for fermions and another for gauge bosons.

## 1.3 Electroweak Symmetry Breaking and the Higgs Boson

Everybody's favorite fundamental scalar boson

## 1.4 Diboson Physics

Really only ZZ, but you get the point

### 1.4.1 Vector Boson Scattering

Scatter scatter

## 1.5 Limitations and Possible Extensions

It misses a few things

### 1.5.1 Anomalous Gauge Couplings

Pro tip: we won't see them

# Chapter 2

# ZZ Phenomenology and Previous Results

Phenomenal!

## 2.1 Proton-Proton Collisions

Bang

## 2.2 ZZ Production and Decay

Dibosons come, dibosons go

### 2.2.1 Nonresonant Production

Working hard not to call this “Standard Model production”

#### 2.2.1.1 Nonresonant $Z\gamma^*$ Production

Virtual particles. Spoooooooooky!

#### 2.2.1.2 Vector Boson Scattering

Them jets tho

#### 2.2.1.3 Prior Measurements

The literature before I got here

## 2.3 Resonant $ZZ^*/Z\gamma^*$ Production

This resonates with me

### 2.3.1 Z Boson Decays to Four Leptons

Prior measurements of this probably don't need their own subsubsection

### 2.3.2 Higgs Boson Production

#### 2.3.2.1 Prior Measurements

Discovery!

## 2.4 Background Processes

Basically, Z+jets and ttbar

## 2.5 Anomalous Gauge Couplings

Triple and quartic

# Chapter 3

# The CMS Experiment and the CERN LHC

Production of controlled high-energy particle collisions, and detection of the decay products resulting from those collisions, are monumental technical challenges. The apparatus used to obtain the results presented in this thesis are the result of decades of work by thousands of scientists and engineers, with many of the techniques used developed in the course of building and operating previous experiments. The CERN Large Hadron Collider (LHC) [1], [2] accelerates pairs of charged hadron (proton or lead ion) beams to high energies and collides them to provide a source of data to several fully independent detectors, including the Compact Muon Solenoid (CMS) [3], which collected the data used in the studies presented here. Detailed descriptions of the LHC and CMS follow.

## 3.1 The CERN Large Hadron Collider

The LHC, the most powerful particle accelerator and collider ever built, is a 26.7 km circumference ring of superconducting magnets running through tunnels roughly 100 m below the suburbs and countryside near Geneva, Switzerland. It first produced collisions suitable for collecting physics data in 2010 before generating large datasets with beam energies of 3.5 TeV in 2011 and 4 TeV in 2012. Following a shutdown for upgrades an repairs, it returned in 2015 and 2016 to deliver beam energies of 6.5 TeV. Beams collide head-on so that the center-of-mass frame of the proton-proton system is the rest frame of the detectors, giving proton-proton center-of-mass energies of 7, 8, and 13 TeV respectively for collisions in 2010–2011, 2012, and 2015–2016. Each successive energy was the highest ever acheived in controlled proton-proton collisions, giving unprecedented access to previously unobserved processes at every step.

In addition to increasing collision energies, the LHC increased its rate of collisions with each new machine configuration. The average event rate $\mathrm{d}N/\mathrm{d}t$ for a process with production cross section $\sigma$ is determined by the instantaneous luminosity $\mathscr{L}$ of the collider,

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathscr{L}\sigma \tag{3.1}$$

so a high instantaneous luminosity is vital to the timely observation of rare processes like Higgs boson production. The LHC's unprecedented luminosities have allowed collection of the largest physics datasets in history.

The desire for high luminosities drove the decision to collide protons with other protons instead of with antiprotons as was done at Tevatron, LHC's predecessor at Fermilab in Batavia, IL. Antiprotons simply cannot be produced in sufficient quantities for a collider on this scale. Many of the physics processes Tevatron was designed to study are $\mathrm{q\bar{q}}$-initiated, so it is useful to have valence antiquarks available in the collisions. The LHC was designed with Higgs boson production in mind, and the two most important Higgs production modes are proton/antiproton agnostic. Even for $q\bar{q}$-initiated processes, valence antiquarks are less critical at the LHC because, for equal parton momenta, protons have larger antiquark content at LHC energies than at Tevatron energies (1.98 TeV center-of-mass energy) as discussed in Section 2.1.

In addition to protons, the LHC can accelerate beams of lead nuclei to 2.51 TeV per nucleon, also the highest ever achieved. All studies presented in this thesis were performed on proton-proton collision data, rendering the details of so-called "heavy ion" beams beyond the scope of this document.

Beams are maintained and manipulated with magnets, most of them made of superconducting NbTi winding cooled to 1.9 K by superfluid helium. Dipole magnets with fields up to 8.33 T bend the beam around the ring, interspersed with quadrupoles for focusing. More quadrupoles and higher-moment magnets apply a number of corrections and squeeze the beams for collisions. Superconducting radio frequency (RF) cavities operating at 400 MHz accelerate the beam, maintain it at its final energy, and maintain bunch shape and spacing.

### 3.1.1 Accelerator Chain, Layout, and Detectors

The LHC was built in tunnels originally constructed for the Large Electron-Positron Collider (LEP), an $e^+$-$e^-$ collider that operated from 1989 to 2000. Using existing caverns, tunnels, and infrastructure was a substantial cost-saving measure, but imposed several important constraints on the LHC's design. In LEP, the electron and positron beams could be accelerated in opposite directions by the same magnets, because they are oppositely charged. Conversely, proton beams require opposite magnetic fields for the two beams. Because the tunnels were not wide enough to accommodate two completely separate beam lines, most of the magnets in the LHC use a twin-bore design in which the pipes and windings for the two beams share a common cryogenic system. The electromagnetic, mechanical, and cryogenic coupling of the two beamlines represents a significant engineering challenge.

Because no single accelerator has the dynamic range necessary to take a stationary proton to TeV-scale energies, a chain of smaller accelerators repurposed from previous experiments feeds moderate-energy protons into LHC. Protons are obtained by ionizing hydrogen atoms, then accelerated to 50 MeV by the Linac 2 linear accelerator and injected into the Proton Syncrotron Booster (PSB), the first of several circular accelerators. The PSB feeds 1.4 GeV protons into the Proton Synchrotron (PS), which in turn injects them into the Super Proton Synchrotron (SPS) at 26 GeV. The protons are then accelerated to 450 GeV in the SPS before being injected into LHC.

The ring is divided into eight sectors, each of which features a 528 m straight section connected to the adjacent sections by 2.45 km arcs. The straight section length was set by the need for RF cavities to accelerate LEP beams to counteract synchrotron radiation, which is a primary factor limiting electron and positron beam energy. This is not ideal for proton beams; protons' much higher mass means they radiate less and need fewer RF cavities. The straight sections feature "insertion" points numbered with Point 1 at the main CERN site in Meyrin, Switzerland, and the rest numbered 2–8, increasing in the clockwise direction when viewed from above. Points 1, 2, 5, and 8 have beam crossing points and host detectors to study the resulting proton-proton collisions. Points 3 and 7 feature collimators to remove nonuniformities in the beams. The RF cavities are at Point 4 and the beams are dumped after use into absorbers at Point 6.

The CMS detector is at Point 5 in Cessy, France, the furthest point on the ring from the Meyrin site and Point 1, which houses ATLAS [4], a similar but fully independent general-purpose particle detector. CERN and the science funding agencies support CMS and ATLAS equally so that any measurement or discovery made by one can be made concurrently or verified by the other. The other two experimental insertions feature specialized detectors studying collisions at lower-luminosity beam interaction points. The LHCb detector [5], at Point 8, studies hadronic physics with an emphasis on b-mesons, and ALICE [6] studies heavy ion collisions at Point 2. Three smaller experiments share interaction points with the larger detectors, with TOTEM [7] studying proton structure and the total proton-proton interaction cross section next to CMS; LHCf [8] studying the $\pi^0$ energy spectrum and multiplicity near ATLAS; and MoEDAL [9] searching for magnetic monopoles or other heavy, stable, ionizing particles at Point 8 with LHCb.

### 3.1.2 Operating Parameters

With the beam energy set by the radius of the ring and the strength of available magnets, the number of interesting physics events produced in LHC collisions depends only on the integrated luminosity

$$\mathscr{L}_{int} = \int \mathscr{L} \mathrm{d}t, \tag{3.2}$$

where $\mathscr{L}$ is the instantaneous luminosity defined in Eq. 3.1 and the integral runs over the time the machine spends in collisions mode. LHC's availability for collisions depends on the electrical and mechanical stability of the accelerators and their support systems, including the cryogenics and the vacuum in the beam pipe. The instantaneous luminosity while running depends only on the beam parameters. For symmetric beams which each have $n_b$ colliding gaussian bunches of $N_b$ protons orbiting the ring with frequency $f_{rev}$ and relativistic factor $\gamma = E_p/m_p$, the instantaneous luminosity is give by

$$\mathscr{L} = f_{rev} \frac{n_b N_b^2 \gamma}{4\pi\beta^* \epsilon_N} R, \tag{3.3}$$

Table 3.1: LHC beam parameters as designed and in practice.

| | Design | Run 1 | | | Run 2 | |
|---|---|---|---|---|---|---|
| Year | | 2010 | 2011 | 2012 | 2015 | 2016 |
| Energy per beam (TeV) | 7 | 3.5 | 3.5 | 4 | 6.5 | 6.5 |
| Bunch spacing (ns) | 25 | 150 | 50 | 50 | 25 | 25 |
| $n_b$ | 2808 | 348 | 1331 | 1368 | 2232 | 2208 |
| $N_b\,(10^{11})$ | 1.15 | 1.2 | 1.5 | 1.7 | 1.15 | 1.25 |
| $\beta^*$ (m) | 0.55 | 3.5 | 1.0 | 0.6 | 0.8 | 0.4 |
| $\epsilon_N$ (mm mrad) | 3.75 | 2.2 | 2.3 | 2.5 | 3.5 | 3.0 |
| Peak pileup | FIXME | 4 | 17 | 37 | 22 | 49 |
| Peak $\mathscr{L}$ $(10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$ | 1 | 0.02 | 0.35 | 0.77 | 0.52 | 1.53 |
| $\mathscr{L}_{int}$ $\left(\mathrm{fb}^{-1}\right)$ | | 0.04 | 6.1 | 23.3 | 4.2 | 41.1 |

where $\beta^*$ is the amplitude of the beams' betatron oscillations around the nominal ring path at the interaction point, the normalized emittance $\epsilon_N$ is a measure of the beams' spread in both position and momentum space, and $R$ is a geometrical factor accounting for the beam crossing angle,

$$R = \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}. \tag{3.4}$$

Here $\theta_c$ is the beams' crossing angle, and $\sigma_z$ and $\sigma^*$ are respetively the longitudinal and transverse RMS widths of the bunches in the lab frame.

#### 3.1.2.1 Design

The machine parameters in the LHC design specification can be seen in the first column of Table 3.1.

#### 3.1.2.2 Run I

#### 3.1.2.3 Run II

. . . and what we got

## 3.2 The Compact Muon Solenoid Detector

It's big [3]

### 3.2.1 Terminology and Geometry

Something something definition of $\eta$ something

### 3.2.2 Magnet and Inner Tracking System

The magnet: how does it work?

#### 3.2.2.1 Pixel Detector

Basically the same as your cameraphone

#### 3.2.2.2 Strip Tracker

Silicon for days

### 3.2.3 Electromagnetic Calorimeter

Lots of crystals

### 3.2.4 Hadronic Calorimeter

More like HATECAL amirite?

### 3.2.5 Muon Spectrometer

There's also a return yoke

#### 3.2.5.1 Drift Tubes

Are in the barrel

#### 3.2.5.2 Cathode Strip Chambers

Are in the endcap

#### 3.2.5.3 Resistive Place Chambers

Also exist

### 3.2.6 Data Acquisition and Trigger

Somethigng about DAQ

#### 3.2.6.1 Level-1 Trigger

Obviously the best part

#### 3.2.6.2 High-Level Trigger

Many Computers

# Chapter 4

# Simulation

## 4.1 Monte Carlo Event Generation

It's like gambling

### 4.1.1 Matrix Element Generation

The real physics

### 4.1.2 Parton Shower, Hadronization, and Underlying Event

The way-too-real physics

### 4.1.3 Pileup Simulation

Lots of it

## 4.2 Detector Simulation

All kinds of fun

# Chapter 5

# Object Reconstruction and Selection

## 5.1 Track Reconstruction and Vertex Identification

So many fits

## 5.2 Particle Flow Reconstruction

The overview

### 5.2.1 PF Candidates

#### 5.2.1.1 Muons

yep

#### 5.2.1.2 Electrons and Charged Hadrons

uh huh

#### 5.2.1.3 Photons and Neutral Hadrons

yeah

### 5.2.2 Jets

sure

### 5.2.3 Missing Transverse Energy

ok

## 5.3 Object Identification and Selection

What to use in the actual analysis

### 5.3.1 Electrons

nice

### 5.3.2 Muons

even nicer

### 5.3.3 Jets

not as nice

### 5.3.4 Final State Photon Radiation

Bit of a mess

### 5.3.5 Misidentified Objects

Fake rates

## 5.4 ZZ Candidate and Event Selection

Explain the different classes of events (full spectrum, Higgs, on shell. . . )

### 5.4.1 Z Candidate Selection

Mass cuts and lepton pairing

### 5.4.2 ZZ Candidate Selection

Disambiguation for ¿4 leptons

### 5.4.3 Background Estimation

### 5.4.4 VBS Signal Selection

Dijets and so on

# Chapter 6

# Analysis Strategy

## 6.1 Background Estimation

Control regions for days

## 6.2 Systematic Uncertainties

Who knows?

## 6.3 Fiducial and Total Cross Section Calculation

### 6.3.1 Signal Strength Extraction

Fitting

### 6.3.2 $\mathrm{Z} \to 4\ell$ Branching Fraction

It is tiny

## 6.4 Differential Cross Sections

### 6.4.1 Unfolding

IT'S FREQUENTIST!

### 6.4.2 Propagation of Systematic Uncertainties

A small pain

## 6.5 VBS Signal Extraction

BDTs and other hip things

## 6.6 Anomalous Gauge Coupling Searches

# Chapter 7

# Results

## 7.1 Four-Lepton Yield and Distributions

### 7.1.1 Full Spectrum

Everything

### 7.1.2 $\mathrm{Z} \to 4\ell$ Resonance

Found it

### 7.1.3 Higgs Resonance

Found it too

### 7.1.4 ZZ Production

Including ZZ+jets

## 7.2 ZZ Fiducial and Total Cross Section

The big thing

### 7.2.1 $\mathrm{Z} \to 4\ell$ Branching Fraction

A nice little measurement

## 7.3 Differential Cross Sections

With awesome plots

## 7.4 Vector Boson Scattering

Electroweak signal's electrostrength

## 7.5 Anomalous Coupling Limits

Winning at not finding things

# Chapter 8

# Conclusions

Definitive

# Bibliography


[1] L. Evans and P. Bryant, "LHC Machine," *JINST*, vol. 3, S08001, 2008. DOI: 10.1088/1748-0221/3/08/S08001.

[2] O. Brüning, H. Burkhardt, and S. Myers, "The large hadron collider," *Prog. Part. Nucl. Phys.*, vol. 67, no. 3, pp. 705–734, 2012, ISSN: 0146-6410. DOI: https://doi.org/10.1016/j.ppnp.2012.03.001. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0146641012000695.

[3] CMS Collaboration, "The CMS experiment at the CERN LHC," *JINST*, vol. 3, S08004, 2008. DOI: 10.1088/1748-0221/3/08/S08004.

[4] ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST*, vol. 3, S08003, 2008. DOI: 10.1088/1748-0221/3/08/S08003.

[5] LHCb Collaboration, "The LHCb Detector at the LHC," *JINST*, vol. 3, S08005, 2008. DOI: 10.1088/1748-0221/3/08/S08005.

[6] ALICE Collaboration, "The ALICE experiment at the CERN LHC," *JINST*, vol. 3, S08002, 2008. DOI: 10.1088/1748-0221/3/08/S08002.

[7] TOTEM Collaboration, "The TOTEM experiment at the CERN Large Hadron Collider," *JINST*, vol. 3, S08007, 2008. DOI: 10.1088/1748-0221/3/08/S08007.

[8] LHCf Collaboration, "The LHCf detector at the CERN Large Hadron Collider," *JINST*, vol. 3, S08006, 2008. DOI: 10.1088/1748-0221/3/08/S08006.

[9] MoEDAL Collaboration, "The Physics Programme Of The MoEDAL Experiment At The LHC," *Int. J. Mod. Phys.*, vol. A29, p. 1 430 050, 2014. DOI: 10.1142/S0217751X14300506. arXiv: 1405.7662 [hep-ph].