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 Proton-Proton Collisions

Bang

1.5 Diboson Physics

Really only ZZ, but you get the point

1.5.1 Vector Boson Scattering

Scatter scatter

1.6 Limitations and Possible Extensions

It misses a few things

1.6.1 Anomalous Gauge Couplings

Pro tip: we won't see them

1.7 Topics Covered In This Thesis

Chapter 2

ZZ Phenomenology and Previous Results

Phenomenal!

2.1 Nonresonant ZZ/Zγ^* Production and Decay

Dibosons come, dibosons go

2.1.1 Nonresonant Zγ^* Production

Virtual particles. Spoooooooooky!

2.1.2 Vector Boson Scattering

Them jets tho

2.1.3 Prior Measurements

The literature before I got here

2.2 Resonant $ZZ^*/Z\gamma^*$ Production

This resonates with me

2.2.1 Z Boson Decays to Four Leptons

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

2.2.2 Higgs Boson Production

2.2.3 Prior Measurements

Discovery!

2.3 Anomalous Gauge Couplings

Triple and quartic

2.3.1 Previous Limits

Pro tip: they aren't there

2.4 Background Processes

Basically, Z+jets and ttbar

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 σ 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 q$\bar{\text{q}}$-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$\bar{\text{q}}$-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 1.4.

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 π^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 intensity (i.e. number of protons in the bunch) N_b, orbiting the ring with frequency f_{rev} and relativistic factor $\gamma = E_p/m_p$, the instantaneous luminosity is give by

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

where β^* is the amplitude of the beams' betatron oscillations around the nominal ring path at the interaction point, the normalized emittance ϵ_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 θ_c is the beams' crossing angle, and σ_z and σ^* 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. Many of the design parameters, in particular the energy and number of colliding bunches, have not been met due to a failure during initial testing in September 2008. A fault in a superconducting bus bar connection between a dipole and a quadrupole caused an electrical arc which ruptured the cryostat, leading to a rapid and destructive reslease of helium gas [10]. When LHC was brought back online in 2010 after repairs and upgrades intended to prevent similar incidents in the future, its operating parameters were changed to reduce the risk of future incidents, with some luminosity-related parameters adjusted to mitigate the resulting loss of physics discovery potential as much as possible. Further upgrades have improved machine performance, with some parameters now meeting or exceeding the design specification.

3.1.2.2 Run I

The LHC was brought back online in 2010 at half its design energy, with 3.5 TeV beam energy, which was increased to 4 TeV in 2012. The bunch intensity was also

Table 3.1: LHC beam parameters as designed and in practice. As stated in the text, n_b is the number of colliding bunches, N_b is the number of protons in each bunch, β^* is the betatron amplitude at the interaction point, ϵ_N is the normalized emittance, and $\mathscr{L}_{(int)}$ is the instantaneous (integrated) luminosity.

	Design	Run I			Run II	
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
$\beta^* \, (\mathrm{m})$	0.55	3.5	1.0	0.6	0.8	0.4
$\epsilon_N \, (\mathrm{mm\,mrad})$	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
$\mathscr{L}_{int} \, (\mathrm{fb}^{-1})$		0.04	6.1	23.3	4.2	41.1

lower, with bunches spaced 50 ns apart instead of 25 ns. The longer bunch spacing was chosen to allow full exploitation of excellent injection chain performance [11]. Beams exiting the SPS had bunch intensity as much as 50% higher than anticipated in the original LHC design and beam emittance as low as 67% of nominal. This allowed the LHC to achieve 77% of its design instantaneous luminosity in 2012 despite having roughly half as many bunches in each beam.

Machine availability was overall good considering the complexity and relative newness of the LHC, with about 36% of scheduled time spent in stable beams. In all, LHC delivered $6.1\,\mathrm{fb}^{-1}$ to CMS and ATLAS in 2011 and $23.3\,\mathrm{fb}^{-1}$ in 2012, enough to allow discovery of the Higgs boson.

3.1.2.3 Run II

The LHC shut down for 2013 and 2014 to allow a number of repairs and upgrades, including measurements, repairs and upgrades on the electrical connections and cryogenic safety systems like the ones that failed in 2008. Beam energies could then be

increased to $6.5\,\mathrm{TeV}$, close to the nominal $7\,\mathrm{TeV}$. The bunch spacing was decreased to $25\,\mathrm{ns}$ while maintaining low emittance and high bunch intensity with the implementation of the beam compression merging and splitting (BCMS) scheme in which bunches are merged in the PS before they are split for injection into SPS, allowing higher bunch intensity [12]. This was offset by vacuum problems in the SPS beam dump, which limited the total number of colliding bunches to around 2200 [13]. Improvements in collimators and beam optics reduced β^* to $40\,\mathrm{cm}$ in 2016, lower than the design β^* of $55\,\mathrm{cm}$. Overall instantaneous luminosities were substantially higher than originally designed.

Machine availability in Run II was excellent, with over 60% of planned time spent in stable beams [13]. Mechanical problems kept LHC out of commission for much of 2015, and only $4.2\,\mathrm{fb}^{-1}$ were delivered to Points 1 and 5, but the integrated luminosity in 2016, $41.1\,\mathrm{fb}^{-1}$, was far above the roughly $25\,\mathrm{fb}^{-1}$ expected and more than all previous runs combined.

3.2   The Compact Muon Solenoid Detector

The CMS detector [3] is a general-purpose particle detector located in a cavern roughly $100\,\mathrm{m}$ below LHC Point 5. Though designed to do a wide range of physics analyses, CMS was designed specifically with Higgs boson discovery in mind. Primary design goals include

- High-efficiency reconstruction of charged particles with precise measurement of their trajectories and momenta

- Good electromagnetic energy resolution, including diphoton and dielectron mass resolution

- Hermetic calorimetry for good missing transverse energy and dijet mass resolution

- Good muon identification, momentum resolution (including dimuon mass resolution), and charge determination over a broad range of energies

To this end, CMS features a silicon tracker, a scintillating crystal electromagnetic calorimeter (ECAL), and a hermetic hadronic calorimeter (HCAL) inside a 3.8 T solenoid magnet surrounded by ionized gas muon tracking devices. Decisions on which events to read out are made on-line by a two-level trigger system. Descriptions of these systems follow.

3.2.1 Terminology and Geometry

The CMS detector systems are arranged in cylindrical layers with the interaction point at the center, serving as the origin for the coordinate system. The coordinate system is defined with the positive-x direction pointing toward the center of the ring, positive-y pointing vertically up, and positive-z pointing parallel to the beam in the counterclockise direction when the LHC ring is viewed from above. Particle momenta are typically expressed in quasicylindrical coordinates $(p_\mathrm{T}, \eta, \phi)$. Here p_T is the magnitude of the particle's momentum transverse to the beam

$$p_\mathrm{T} \equiv \sqrt{p_x^2 + p_y^2}, \tag{3.5}$$

and ϕ is the azimuthal angle, i.e. the angle from the x-axis to the particle's trajectory in the x-y plane. The pseudorapidity η is defined as

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{3.6}$$

where θ is the polar angle measured from the z-axis. In the limit of massless particles, the pseudorapidity is the same as the rapidity

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right).$$ (3.7)

Pseudorapidity is preferred to rapidity because it is purely geometrical, with no dependence on the particle energy. Both are preferred over θ because rapidity differences are invariant under longitudinal boosts, and because hadron flux at colliders is roughly constant as a function of rapidity. The transverse energy E_T is the the magnitude of the particle's four-momentum transverse to the beam, equal to p_T in the limit of massless particles. Spatial coordinates are expressed as (r, η, ϕ), where r is the distance from the beam in the x-y plane.

3.2.2   Magnet and Inner Tracking System

A particle of charge q moving through a uniform magnetic field of strength B that points in the z direction will travel in a helix of radius R, given by

$$R = \frac{p_\mathrm{T}}{|q|B}$$ (3.8)

with the chirality of the helix determined by the sign of q. Thus one can determine the transverse momentum of the particle by measuring its path through the magnetic field and finding the radius of curvature. In practice, all but the lowest-energy particles leave too short an arc in the detector for direct measurement of the radius, so the sagitta s of the arc is used instead, given by

$$s = \frac{qBL^2}{8p_\mathrm{T}}$$ (3.9)

where L is the length of the chord spanning the arc (typically equal to the radius of the tracking system). The transverse momentum resolution varies as

$$\frac{\delta p_\mathrm{T}}{p_\mathrm{T}} \propto \frac{p_\mathrm{T}}{BL^2},$$ (3.10)

so a strong field and a large tracking volume are vital to keeping measurements precise even at high energies.

To this end, CMS contains the world's largest superconducting magnet[1], a solenoid 13 m long and 6 m in diameter, which generates a nearly-uniform 3.8 T field in the centralmost part of the detector. To measure the paths of charged particles in the field, the volume closest to the interaction point contains layers of silicon sensors that detect hits from charged particles with high efficiency and excellent position resolution, between 4.4 cm and 1.1 m from the beam for 2.7 m on either side of the interaction point. This system, called the inner tracker, consists of an inner pixel detector surrounded by a larger silicon strip detector. Both consist of concentric cylinders of sensors covering the barrel of the detector capped by discs covering the high-η region, up to $|\eta| < 2.5$. With a total of roughly $200 \, \text{m}^2$ of silicon, the inner tracker is the largest silicon tracker in the world, which means that tracks may be reconstructed with hits in as many as 14 layers. The downside of this is that the tracker represents a substantial amount of material for electrons and photons to interact with before they reach the calorimeters, with total material budget between 0.4 radiation lengths ($\eta = 0$) and 1.8 radiation lengths ($|\eta| \approx 1.4$). The tracker-only p_T uncertainty is around 1.2% at 200 GeV and 15% at 1 TeV.

3.2.2.1 Pixel Detector

The pixel detector, consisting of three layers in the barrel and two in the endcap, is responsible for accurate reconstruction of primary proton-proton interaction vertices and secondary vertices from b-meson decays, as well as providing "seed" tracks that may be used in strip tracker reconstruction. As the system closest to the interaction point, the pixel system experiences the highest charged-particle flux must have

---

[1]Largest in the sense of having the largest stored energy when at constant full field. The largest by size is the ATLAS barrel toroid.

extremely fine granularity to differentiate between nearby particles. The 66 million pixels in the system have a cell size of $100 \times 150\,\mu\mathrm{m}^2$. Interpolation of the analog signals from the individual pixels allows a final spatial resolution of $15\,\mu\mathrm{m}$ in each direction. The outermost barrel layer is $10.2\,\mathrm{cm}$ from the beam, and the second endcap disk is $46.5\,\mathrm{cm}$ from the interaction point. The sensor modules are arranged such that at least three sensors cover the solid angle within the pixels' acceptance.

3.2.2.2   Strip Tracker

Outside the pixels is the silicon strip tracker, extending out to $1.1\,\mathrm{m}$ in the r direction and $\pm2.8\,\mathrm{m}$ in the z direction. The tracker is divided into inner and outer subdetectors, each of which has both barrel cylinders and endcap discs. In total, there are ten layers in the barrel and nine in each of the endcaps. The inner tracker uses $320\,\mu\mathrm{m}$-thick sensors with a typical strip cell size of $10\,\mathrm{cm} \times 80\,\mu\mathrm{m}$, leading to hit resolutions of 23–$35\,\mu\mathrm{m}$. The outer tracker uses $500\,\mu\mathrm{m}$-thick sensors with typical strip sizes up to $25\,\mathrm{cm} \times 180\,\mu\mathrm{m}$, leading to hit resolutions of 35–$53\,\mu\mathrm{m}$.

3.2.3   Electromagnetic Calorimeter

Outside of the tracker is the electromagnetic calorimeter (ECAL), which is designed to absorb and measure the energy of electrons and photons. ECAL is made of 68,524 lead tungstate ($PbWO_4$) crystals arranged in a cylindrical barrel (EB) covering $|\eta| < 1.444$ and two endcap discs (EE) covering $1.566 < |\eta| < 3.0$. The small gap between the barrel and endcap is necessary to accommodate cabling and support structures for the tracker. $PbWO_4$ crystals scintillate blue-green light and are optically transparent, so the resulting light can be read out by avalanche photodiodes (APDs) in the barrel and vacuum phototriodes (VPTs) in the endcap. ECAL's granularity is set by $PbWO_4$'s small Molière radius of $2.2\,\mathrm{cm}$, which is also the size of the square front faces of the

barrel crystals, which flare out to 2.6 cm at the back, giving them a truncated pyramid shape covering a roughy 0.0174×0.174 area of η-ϕ space. The endcap crystals go from 2.86 cm squares at the front to 3.0 cm at the back.

One of the primary design innovations of CMS—the eponymous compactness— was to place the calorimetry inside the magnet so that tracks can be unambiguously associated with energy deposits in the calorimeters without interference from scattering in the magnet coils. This is possible in part thanks to the high density $(8.28\,\mathrm{g/\,cm^3})$ and short radiation length $(0.89\,\mathrm{cm})$ of $PbWO_4$, which allow ECAL crystals to be only 23 cm long in the barrel and 22 cm long in the endcap while still spanning 25.8 and 24.7 radiation lengths, respectively. This is enough to ensure that essentially no electrons or photons escape ECAL with any appreciable remaining energy.

The total scintillation light yield is relatively low, averaging just 4.5 photons per MeV deposited, The Poisson fluctuations in the yield are the largest contribution to ECAL energy resolution for most electron and photon energies. This is represented by the first term in the full resolution equation,

$$\left(\frac{\delta E}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + \left(\frac{0.12}{E/\mathrm{GeV}}\right)^2 + (0.30\%)^2 . \tag{3.11}$$

The second term comes from electronic noise and noise from pileup, and the last term represents intrinsic differences between crystals. The upside to $PbWO_4$'s scintillation is that it is fast: roughly 80% of the light is emitted in the 25 ns between bunch crossings.

3.2.4 Hadronic Calorimeter

Between ECAL and the magnet is the hadronic calorimeter (HCAL), responsible for measuring the energy of hadronic jets. HCAL is a sampling calorimeter, meaning

that the hadrons pass through dense, uninstrumented material and the products of the resulting interactions deposit energy in scintillators which are used to measure the total energy of the original incoming particles. The HCAL barrel (HB, $|\eta| < 1.305$) and endcap (HE, $1.305 < |\eta| < 3.0$) are made of layers of brass absorber interleaved with plastic scintillating tiles. The energy resolution in HB and HE is given by

$$\left(\frac{\delta E}{E}\right)^2 = \left(\frac{90\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + (4.5\%)^2. \tag{3.12}$$

The first term is from the stochastic evolution of hadronic showers in the absorber, the second is from calibration uncertainties.

The thickness of HB and HE is constrained by the size of the magnet, varying from 5.4 nuclear interaction lengths in the central barrel to more than 10 in the endcaps. Because HB is not enough to absorb all hadrons in the barrel, there is an extra outer HCAL component (HO) outside of the magnet, consisting of two more layers of scintillator on either side of a 20 cm-thick iron "tail catcher" covering $|\eta| < 1.3$. With HO and the 1.1 interaction lengths in ECAL considered, no part of the calorimeter system spans fewer than 11.8 interaction lengths except in the gaps between barrel and endcap, minimizing the flux of hadronic "punchthrough" making it to the muon system.

Closer to the beam line on each side, the forward hadronic calorimeter (HF, $3.0 < |\eta| < 5.2$) is made of iron instead of brass to maximize radiation hardness and acts as a Cherenkov detector with quatz fibers as the active detection element. Half the fibers extend the entire depth of HF, while the other half start after the hadrons have traversed 22 cm of iron, allowing electromagnetic and hadronic energy to be differentiated without ECAL. The energy resolution in HF is given by

$$\left(\frac{\delta E}{E}\right)^2 = \left(\frac{172\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + (9\%)^2, \tag{3.13}$$

where the terms have the same physical interpretation as those in Eq. 3.12. HF improves CMS's missing energy resolution by roughly a factor of three.

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

3.2.7   Luminosity Determination

BRIL and whatnot

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 $Z \to 4\ell$ 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 $Z \to 4\ell$ 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 $Z \to 4\ell$ 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

8.1   Summary

8.2   Outlook

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].

[10]   M. Bajko, F. Bertinelli, N. Catalan-Lasheras, S. Claudet, P. Cruikshank, K. Dahlerup-Petersen, R. Denz, P. Fessia, C. Garion, J. Jimenez, G. Kirby, P. Lebrun, S. Le Naour, K.-H. Mess, M. Modena, V. Montabonnet, R. Nunes, V.

Parma, A. Perin, G. de Rijk, A. Rijllart, L. Rossi, R. Schmidt, A. Siemko, P. Strubin, L. Tavian, H. Thiesen, J. Tock, E. Todesco, R. Veness, A. Verweij, L. Walckiers, R. Van Weelderen, R. Wolf, S. Fehér, R. Flora, M. Koratzinos, P. Limon, and J. Strait, "Report of the task force on the incident of 19th September 2008 at the LHC," CERN, Geneva, Tech. Rep. LHC-PROJECT-Report-1168. CERN-LHC-PROJECT-Report-1168, Mar. 2009. [Online]. Available: `http://cds.cern.ch/record/1168025`.

[11]   M. Lamont, "Status of the LHC," *Journal of Physics: Conference Series*, vol. 455, no. 1, p. 012 001, 2013. [Online]. Available: `http://stacks.iop.org/1742-6596/455/i=1/a=012001`.

[12]   Y. Papaphilippou, H. Bartosik, G. Rumolo, and D. Manglunki, "Operational beams for the LHC," 2014. arXiv: `1412.7857 [physics.acc-ph]`.

[13]   F. Bordry and C. Pralavorio, " LHC smashes targets for 2016 run," Nov. 2016. [Online]. Available: `http://cds.cern.ch/record/2235979`.