

This Dissertation  
entitled  
SEARCH FOR GAUGE-MEDIATED SUPERSYMMETRY BREAKING  
typeset with NDdiss2 $\epsilon$  v3.2013 (2013/04/16) on November 28, 2017 for  
Allison Reinsvold Hall

This L<sup>A</sup>T<sub>E</sub>X 2 $\epsilon$  classfile conforms to the University of Notre Dame style guidelines as of Fall 2012. However it is still possible to generate a non-conformant document if the instructions in the class file documentation are not followed!

Be sure to refer to the published Graduate School guidelines at <http://graduateschool.nd.edu> as well. Those guidelines override everything mentioned about formatting in the documentation for this NDdiss2 $\epsilon$  class file.

It is YOUR responsibility to ensure that the Chapter titles and Table caption titles are put in CAPS LETTERS. This classfile does *NOT* do that!

*This page can be disabled by specifying the “noinfo” option to the class invocation. (i.e., \documentclass[... ,noinfo]{nddiss2e} )*

**This page is *NOT* part of the dissertation/thesis. It should be disabled before making final, formal submission, but should be included in the version submitted for format check.**

NDdiss2 $\epsilon$  documentation can be found at these locations:

<http://www.gsu.nd.edu>  
<http://graduateschool.nd.edu>

# SEARCH FOR GAUGE-MEDIATED SUPERSYMMETRY BREAKING

A Dissertation

Submitted to the Graduate School  
of the University of Notre Dame  
in Partial Fulfillment of the Requirements  
for the Degree of

Doctor of Philosophy

by

Allison Reinsvold Hall

---

Michael Hildreth, Director

Graduate Program in Physics

Notre Dame, Indiana

November 2017

This is the abstract.

# CONTENTS

FIGURES . . . . .	iv
TABLES . . . . .	v
CHAPTER 1: INTRODUCTION . . . . .	1
CHAPTER 2: Theoretical Motivation . . . . .	2
2.1 The Standard Model of particle physics . . . . .	2
2.2 Supersymmetry . . . . .	2
2.3 Gauge-mediated supersymmetry breaking . . . . .	2
CHAPTER 3: The Large Hadron Collider . . . . .	3
3.1 Introduction . . . . .	3
3.2 Injector Chain . . . . .	3
3.3 Vacuum and magnet system . . . . .	3
3.4 Operating parameters . . . . .	3
CHAPTER 4: CMS DETECTOR . . . . .	4
4.1 Coordinate system . . . . .	4
4.2 Superconducting solenoid . . . . .	5
4.3 Tracker . . . . .	6
4.3.1 Pixel detector . . . . .	6
4.3.2 Strip detectors . . . . .	7
4.3.3 Tracker performance . . . . .	7
4.4 Electromagnetic Calorimeter (ECAL) . . . . .	7
4.5 Hadron calorimeter (HCAL) . . . . .	7
4.6 Muon system . . . . .	8
CHAPTER 5: Event Reconstruction in the CMS Detector . . . . .	9
5.0.1 Particle Flow Algorithm . . . . .	9
5.0.2 Jet reconstruction . . . . .	9
5.0.3 Pileup subtraction . . . . .	9

CHAPTER 6: TRIGGER SYSTEM . . . . .	10
6.1 Overview of CMS trigger system . . . . .	10
6.2 Analysis triggers . . . . .	10
6.3 Trigger efficiency . . . . .	10
CHAPTER 7: Event Selection . . . . .	11
CHAPTER 8: Data analysis and background estimation methods . . . . .	12
8.1 Overview . . . . .	12
8.2 Irreducible background . . . . .	12
CHAPTER 9: Results and Interpretations . . . . .	13
9.1 Comparing observed and expected numbers of events . . . . .	13
9.2 Simplified Models . . . . .	13
9.3 Signal acceptance and efficiency . . . . .	13
9.4 Limits . . . . .	13
CHAPTER 10: Conclusions . . . . .	14
BIBLIOGRAPHY . . . . .	15

## FIGURES

4.1	Schematic of the CMS detector. . . . .	5
4.2	Schematic of the CMS tracker system. Detector modules are represented by single lines, and back-to-back modules are represented by double lines. . . . .	7

## TABLES

## CHAPTER 1

### INTRODUCTION

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the largest machine in the world and an incredible feat of engineering and science. This machine is used to study elementary particles and their interactions. Proton At the LHC, proton-proton collisions occur at center-of-mass energies up to 13 TeV.

The Standard Model of particle physics describes fundamental particles and their interactions to an incredible level of precision. This is described in more detail in Chapter XX.

The CMS detector and various subsystems will be described in Chapter 4. Finally, Chapter XX will include a discussion of the results of this analysis and suggestions for future work.

Introduction

Chapter 1: Theory Motivation Standard Model Why we need BSM SUSY GMSB

Chapter 2: LHC About CERN How the accelerator works Chapter 3: CMS Detector

Chapter 4: Object Reconstruction

Chapter 5: Trigger

Chapter 6: Event Selection Including object cleaning



## CHAPTER 2

### Theoretical Motivation

2.1 The Standard Model of particle physics

2.2 Supersymmetry

2.3 Gauge-mediated supersymmetry breaking

## CHAPTER 3

### The Large Hadron Collider

#### 3.1 Introduction

The Large Hadron Collider is a particle accelerator located at CERN, the European Organization for Nuclear Research.

#### 3.2 Injector Chain

#### 3.3 Vacuum and magnet system

#### 3.4 Operating parameters

## CHAPTER 4

### CMS DETECTOR

The Compact Muon Solenoid (CMS) detector is a multi-purpose detector designed to accurately measure the energy of all particles produced in proton-proton collisions. Figure 4.1 shows a schematic of the detector as a whole. Each subdetector will be described in more detail in the following sections. Moving radially outward from the interaction point, the subdetectors are the silicon pixel and strip tracker (Section 4.3), the electromagnetic calorimeter (Section 4.4), the hadron calorimeter (Section 4.5), and the muon system (Section 4.6). For a full description of the CMS detector, see [1]. The full length of the CMS detector is 21.6 m, the diameter of the detector is 21.6 m, and the total weight is 12500 t.

#### 4.1 Coordinate system

The origin of the CMS detector coordinate system is located at the nominal collision point. The  $z$ -axis is oriented along the beam direction, with the positive  $z$ -axis pointing in the counter-clockwise direction when viewing the LHC from above. The  $y$ -axis points vertically upward, and the  $x$ -axis points toward the center of the LHC. The  $xy$ -plane is referred to as the transverse plane.

Due to the nature of particle collisions, however, Cartesian coordinates are often not the most convenient. Because protons are not elementary particles, it is actually the individual quarks or gluons within the proton that interact during the collision. This means that the collision will not be at rest in the lab frame, but will have some

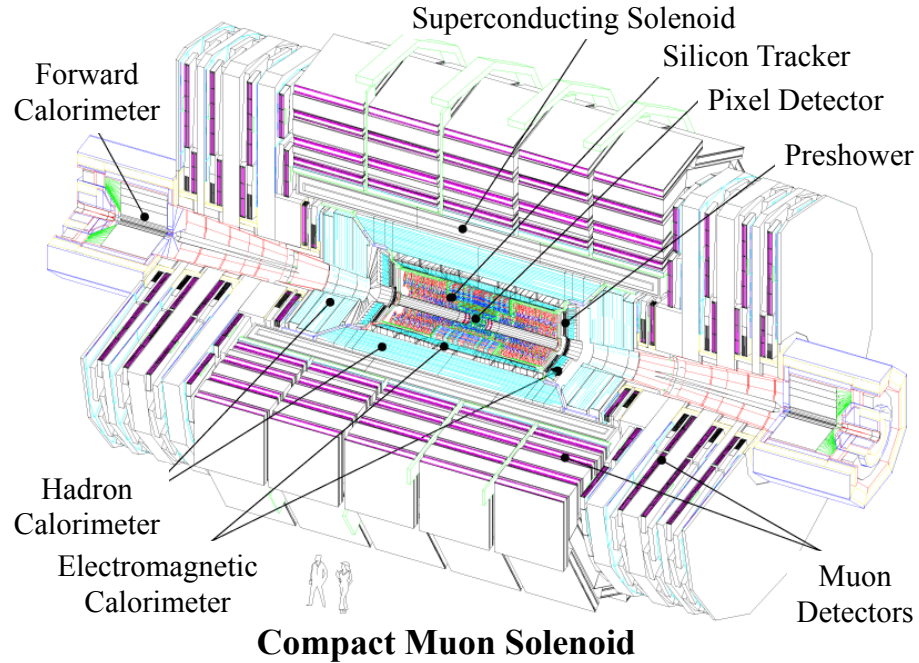


Figure 4.1. Schematic of the CMS detector.

non-zero velocity along the  $z$ -axis. To deal with this, it is beneficial to use coordinates that are invariant under boosts in the  $z$  direction. CMS follows the particle physics convention of describing the position of a particle in terms of its transverse momentum, azimuthal angle, and pseudorapidity. The transverse momentum  $p_T$  is defined as the magnitude of the momentum in the  $xy$  plane. The azimuthal angle  $\phi$  is defined in the transverse plane, with  $\phi = 0$  corresponding to the positive  $x$ -axis. Finally, the pseudorapidity is defined as  $\eta = -\ln \tan(\theta/2)$ , where the polar angle  $\theta$  is measured from the  $z$ -axis.

## 4.2 Superconducting solenoid

One of the most important components of the CMS detector is the superconducting solenoid. The solenoid provides the bending power necessary to precisely measure the momentum of all charged particles produced in the collision. The mag-

net is located between the calorimeters and the muon system. It is 13 m long and has an inner diameter of 6 m. It is capable of producing magnetic fields up to 4 T, although the magnet is generally operated at 3.8 T to prolong its lifetime. At full current, the magnet has a stored energy of 2.6 GJ. A 10,000 ton iron yoke made up of 5 wheels in the barrel and 6 endcap disks serves to return the magnetic flux. A detailed description of the CMS magnet can be found in [2].

### 4.3 Tracker

The innermost subdetector is the silicon tracker [3, 4]. The overall dimensions of the tracker are 5.6 m long and 1.2 m in radius. The full tracking system is cylindrical in shape and is comprised of a barrel and two endcaps, each of which is split into layers of silicon pixel detectors and layers of silicon micro-strip detectors. In total, there are 66 million  $150 \times 100 \mu\text{m}$  pixels and 9.6 million strips that are between 80 and  $180 \mu\text{m}$  wide. Figure 4.2 shows a schematic drawing of the layout of the tracker subsystems.

#### 4.3.1 Pixel detector

Due to the high occupancy of the tracker within 10 cm of the beam pipe, pixel detectors rather than strip detectors are used as the innermost layers of the tracker. Three barrel layers and two disks of pixel detectors in the endcap give three high-precision points for every charged particle moving away from the interaction point. The small pixel size of  $150 \times 100 \mu\text{m}$  is critical to allow for good secondary vertex reconstruction and for forming seed tracks that are used for high level triggering (see Chapter 6) and for the reconstruction of every charged particle in the event (see Chapter 5). The three barrel layers are 53-cm long and are located at mean radii of 4.4, 7.3 and 10.2 cm. The endcap modules extend radially from 6 to 15 cm in radius and are placed on each side at  $z = \pm 34.5$  and  $z = \pm 46.5$  cm. The endcaps extend

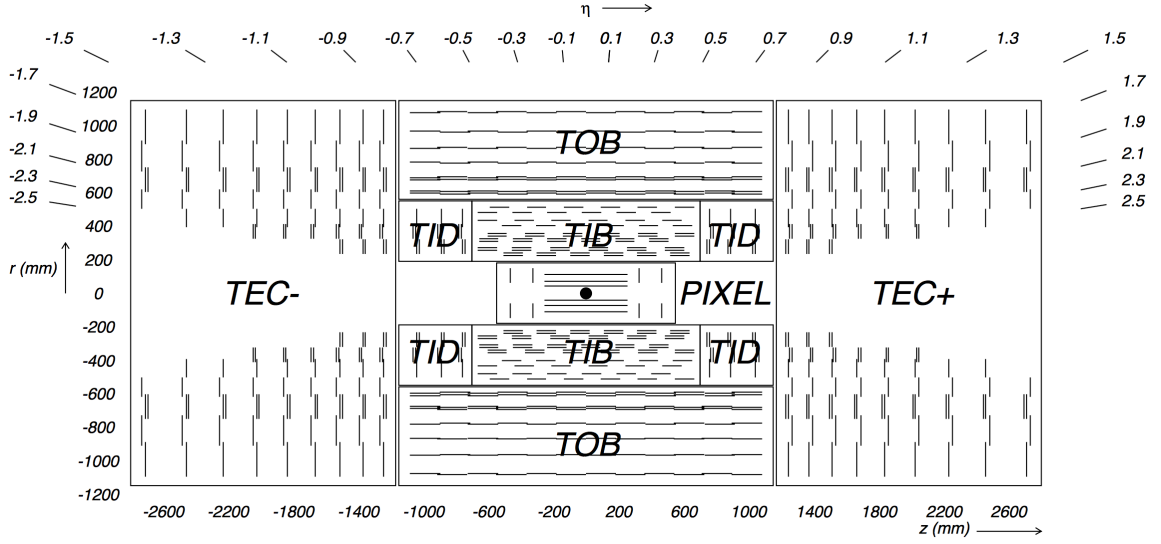


Figure 4.2. Schematic of the CMS tracker system. Detector modules are represented by single lines, and back-to-back modules are represented by double lines.

the coverage of the subdetector out to  $|\eta| < 2.5$ .

#### 4.3.2 Strip detectors

#### 4.3.3 Tracker performance

For charged hadrons with transverse momentum  $p_T$  less than 20 GeV, the  $p_T$  can be measured with a resolution of 1%.

### 4.4 Electromagnetic Calorimeter (ECAL)

Very important. Finds photons.

### 4.5 Hadron calorimeter (HCAL)

brass sampling calorimeter

## 4.6 Muon system

The muon subsystem is located outside of the solenoid and is embedded in the return yoke for the magnetic flux. Three different types of detectors are used in the muon system: drift tube chambers (DTC) = positively charged wire within gas volume. Muon knocks electrons off atoms in the gas, which are attracted to the wire. Can determine where electrons hit and where the muon was from the wire to get 2 coordinates for its position. Barrel Cathode strip chamber (CSC) = better for high flux areas. Crisscrossing positive and negative wires. Muons knock off electrons, which go to positive wires. Ions move toward negative wires. Two position coordinates. Endcaps.

## CHAPTER 5

### Event Reconstruction in the CMS Detector

5.0.1 Particle Flow Algorithm

5.0.2 Jet reconstruction

5.0.3 Pileup subtraction



## CHAPTER 6

### TRIGGER SYSTEM

6.1 Overview of CMS trigger system

6.2 Analysis triggers

6.3 Trigger efficiency

## CHAPTER 7

### Event Selection

## CHAPTER 8

### Data analysis and background estimation methods

#### 8.1 Overview

#### 8.2 Irreducible background

## CHAPTER 9

### Results and Interpretations

9.1 Comparing observed and expected numbers of events

9.2 Simplified Models

9.3 Signal acceptance and efficiency

9.4 Limits

## CHAPTER 10

### Conclusions

In this dissertation, a search for gauge-mediated supersymmetry breaking in events with two photons and missing transverse momentum was described. The analysis was performed with data taken with the CMS detector in 2016, but suggestions to improve the background estimation methods for the analysis of the 2017 data were also explored. Results were interpreted in the context of two simplified models, one assuming squark pair production and the other assuming gluino pair production. No evidence for gauge-mediated supersymmetry breaking (GMSB) was observed, and limits were placed on the masses of supersymmetric particles. Work is also ongoing to combine this analysis with other analyses targeting photon final states, in order to set limits on more comprehensive GMSB models.

## BIBLIOGRAPHY

1. S. Chatrchyan et al. The CMS experiment at the CERN LHC. *JINST*, 3:S08004, 2008. doi: 10.1088/1748-0221/3/08/S08004.
2. CMS Collaboration. The CMS magnet project: Technical Design Report. CMS Technical proposal CERN-LHCC-97-010, CMS-TDR-1, CERN, 1997. URL <https://cds.cern.ch/record/331056>.
3. CMS Collaboration. The CMS tracker system project: Technical Design Report. CMS Technical proposal CERN-LHCC-98-006, CMS-TDR-5, CERN, 1997. URL <https://cds.cern.ch/record/368412>.
4. CMS Collaboration. The CMS tracker: addendum to the Technical Design Report. CMS Technical proposal CERN-LHCC-2000-016, CMS-TDR-5-add-1, CERN, 2000. URL <https://cds.cern.ch/record/490194>.

*This document was prepared & typeset with pdfL<sup>A</sup>T<sub>E</sub>X, and formatted with NDdiss2<sub>ε</sub> classfile (v3.2013[2013/04/16]) provided by Sameer Vijay and updated by Megan Patnott.*