Search for Experimental Evidence of Supersymmetry at the Large Hadron Collider

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Abstract

This thesis describes a search for the general gauge-mediated model of supersymmetry in the first 35.5 pb^{-1} of proton-proton interactions at 7 TeV to be recorded at LHC by the CMS experiment. In this version of supersymmetry, the neutralino serves as the next-to-lightest supersymmetric particle which decays to a gravitino, the lightest supersymmetric particle, and a high energy photon. R-parity conservation requires the neutralinos are pair produced yielding a topology of two highly energetic, isolated photons and at least one hadronic jet. The missing transverse energy spectrum of these events, due to the gravitino escaping detection, is compared to the expected spectrum resulting from standard model processes. No excess events in the high missing transverse energy region are observed. An upper limit between 0.3 and 1.1 pb depending on the mass of the supersymmetric particles has been determined for the cross-section of the general gauge-mediated model and a 95% confidence limit exclusion region has been determined on the neutralino, squark, and gluino masses.

Dedictation

This thesis is dedicated to my grandfather, who instilled in me an inquisitive nature and a desire to know the truth. It is also dedicated to my wife, whose unwavering love and support has helped me to see this project through.

Acknowledgements

I would like to acknowledge the work of the thousands of people who made the LHC and CMS experiment possible. I also want to acknowledge the help of my analysis group at CMS, especially Bernadette Heyburn, Alexander Ledovskoy and Rachel Yohay with whom I have had the pleasure of learning with and from over the last few years. Finally, I want to acknowledge Dr. Bradley Cox who has been the ideal advisor over the past five years. He has always looked out for what is in my best interest and had the perfect balance of allowing independent but still guided work.

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Glossary

E_T transverse energy.

$\not{E}_T$ missing transverse energy.

P_T transverse momentum.

APDs avalanche photo diodes.

CERN European Center for Nuclear Research.

CL confidence limit.

CMS Compact Muon Solenoid.

ECAL electromagnetic calorimeter.

EM electromagnetic.

EW electroweak.

GGM general gauge-mediated.

HCAL hadronic calorimeter.

HLT high level trigger.

JPT jet plus track.

LHC Large Hadron Collider.

LSP lightest supersymmetric particle.

NLO next-to-leading-order.

NLSP next to lightest supersymmetric particle.

QCD quantum chromodynamics.

QED quantum electrodynamics.

SM standard model.

SUSY supersymmetry.

VPTs vacuum photo diodes.

WIMP weakly interacting massive particle.

1 Introduction

The standard model (SM) of particle physics, after nearly 40 years of testing and prediction, has proven to be a robust model of the subatomic world. However, it is known to be incomplete. For example, the SM does not explain the breaking mechanism for electroweak symmetry that gives mass to the W and Z gauge bosons nor can it account for observed neutrino oscillations. In particular, the Higgs boson, predicted by the SM and playing a crucial role in symmetry breaking, has not yet to be observed and would have a quadratically divergent mass due to radiative corrections (see section 2.2.1). One possible solution to this problem is a theory known as supersymmetry (SUSY). SUSY is a symmetry that states for every spin $\frac{1}{2}$ fermion, there is a spin 0 superpartner and for every spin 1 gauge boson there is spin $\frac{1}{2}$ superpartner. These additional particles provide the quantum corrections needed to reconcile the expected mass of the Higgs boson with the theoretical and experimental bounds.

Search for experimental evidence of SUSY has been on going at the Tevatron, located at Fermi National Laboratory outside of Chicago, Illinois, for many years. Unfortunately, the masses of these supersymmetric particles appear to be too large to be seen in 2 TeV center of mass energy proton-antiproton collisions. However, on March 30, 2010 the Large Hadron Collider (LHC) located at European Center for Nuclear

Research (CERN) in Geneva, Switzerland, began to produce proton-proton interactions at a center of mass collision energy of 7 TeV. The 7 TeV collision energy opens a whole new realm of physics exploration and brings the discovery of supersymmetric particles within reach. The Compact Muon Solenoid (CMS) detector, one of the two large multipurpose detectors at the LHC, was ready and began recording data (see figure 1.1). An event display for the first recorded collision by CMS is shown in figure 1.2.

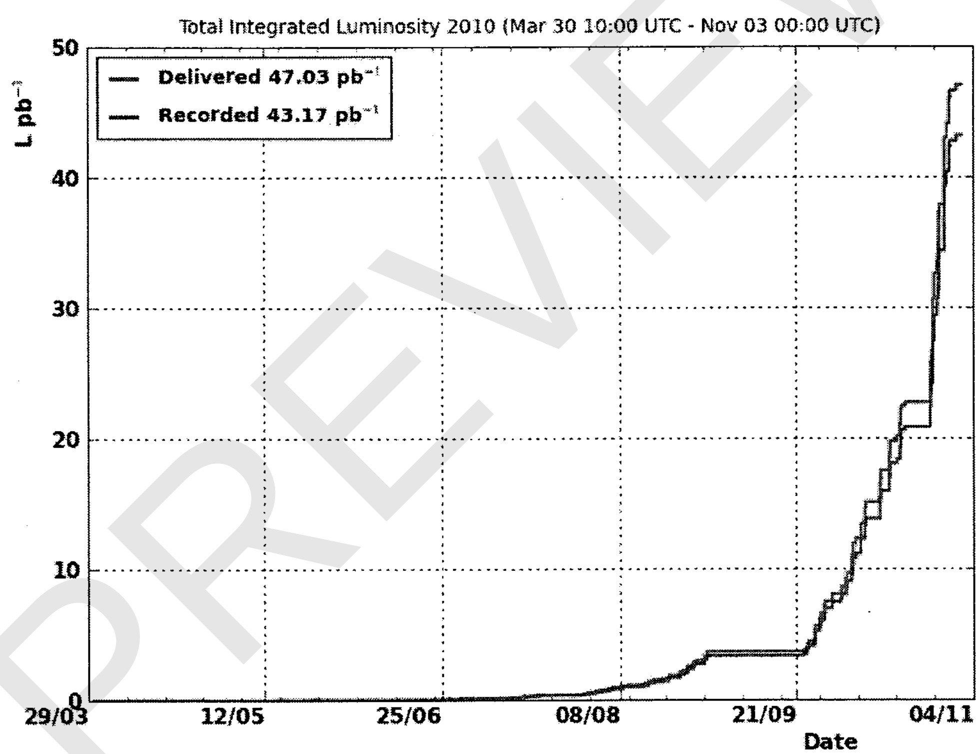

Figure 1.1: CMS's Total Integrated Luminosity - Total integrated luminosity[1] delivered by the LHC and recorded by the CMS detector in 2010.

[1]Luminosity is a measurement of the number of particles per unit area per unit time times the opacity of the target measured in $barns^{-1} * seconds^{-1}$. In the case of the LHC, the luminosity can be expressed as

$$L = fn\frac{N_1 N_2}{A} \tag{1.1}$$

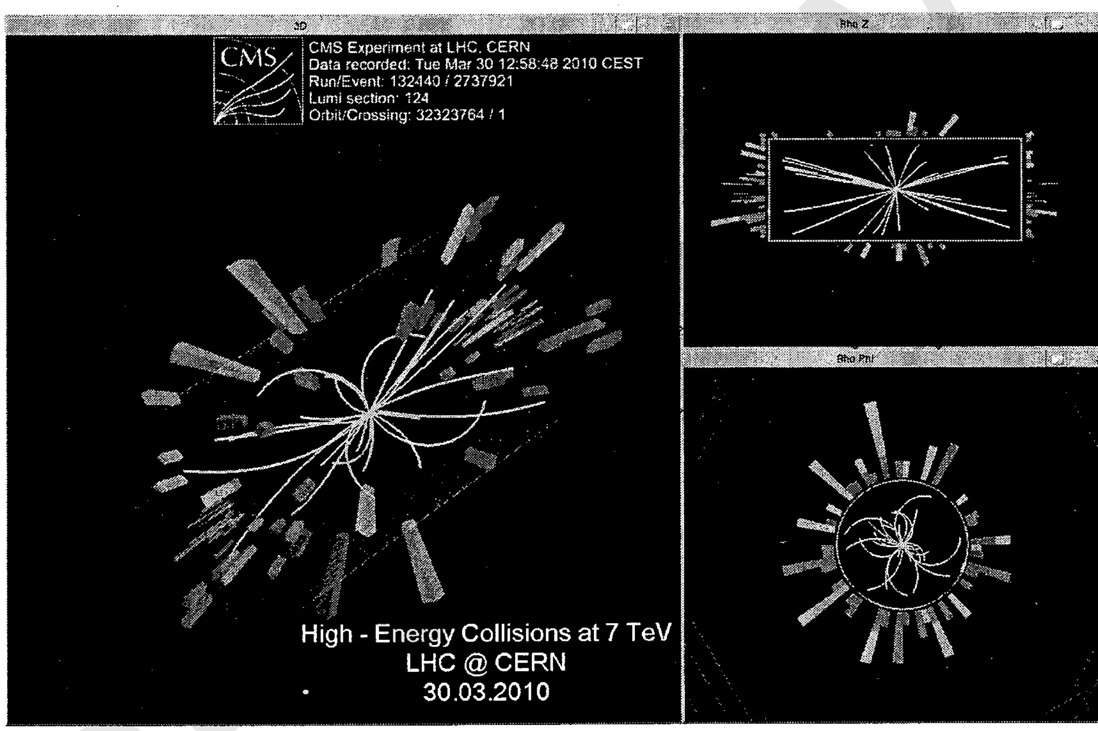

Figure 1.2: Event Display of CMS's First Recorded Collision - An event display of CMS's first recorded collision at 7 TeV on March 30, 2010.

This analysis performs one of the first experimental searches for supersymmetry at 7 TeV. In particular, a search for the general gauge-mediated (GGM) model of supersymmetry is outlined and performed on the first 35.5 pb^{-1} of data to be recorded at the LHC. While discovery cannot yet be claimed, one event matching the GGM signature was found hinting it might be right around the corner. In the meanwhile, an upper limit has been set on the cross-section of the GGM model and a 95% confidence limited (CL) exclusion region on the neutralino, squark and gluino masses has been produced. A paper [1] has been published based on this analysis which can be found at http://arxiv.org/abs/1103.0953.

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where f is the revolution frequency, n is the number of bunches in one beam, N_i is number of particles per bunch in beam i, and A is the cross section of the beam. The total integrated luminosity is the integral of luminosity with respect to time and is traditionally used to characterize the size of a dataset.

2 Theory

2.1 The Standard Model

In the 1970's a unified theory of particle physics took form. This theory, known as the standard model (SM) [2, 3, 4], brought together the quantum electrodynamics (QED), the weak interaction, and quantum chromodynamics (QCD) theories into one internally consistent model of all known particles and their interactions. The quarks, leptons, and gauge bosons observed are the fundamental particles of the SM. Their properties, which are not predicted by the SM, are outlined in figure 2.1. For each particle in the SM there is an anti-particle that differs in that it possesses either the opposite electric charge.

		down	up	strange	charm	bottom	top
Quarks (spin=1/2):	Name:	down	up	strange	charm	bottom	top
	Charge:	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$
	Mass:	0.005	0.002	0.1	1.5	5	173.1
Leptons (spin=1/2):	Name:	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ
	Charge:	-1	0	-1	0	-1	0
	Mass:	0.000511	~ 0	0.106	~ 0	1.777	~ 0
Gauge bosons (spin=1):	Name:	photon (γ)	$W^\pm$	Z^0	gluon (g)		
	Charge:	0	± 1	0	0		
	Mass:	0	80.4	91.2	0		

Figure 2.1: Standard Model Particles - Table of spin $\frac{1}{2}$ and spin 1 particles comprising the standard model. All masses in GeV. (Proton mass = 0.938 GeV.) Not shown: antiparticles of quarks, leptons.

2.1.1 The Standard Model Particles

2.1.1.1 Fermions

The first category of SM particles are those with spin $\frac{1}{2}$, these particles are known as fermions. Fermions are further broken down based on their interactions with other particles and their physical properties. All fermions interact via the weak force and possess a property known as weak isospin. Fermions that do not have strong interactions are known as leptons and have an integer electric charge. Fermions that interact with weak, electromagnetic and strong forces are known as quarks, they have strong color charge (see section 2.1.2.3), weak isospin and fractional electric charge. Fermions are also divided into generations. The first generation, comprised of the up, down, electron and electron neutrino are the lightest particles and thus do not decay. Everyday matter is comprised of electrons, protons and neutrons where the proton is made up of two up quarks and a down quark and the neutron is made up of one up quark and two down quarks.

2.1.1.2 Gauge Bosons

The second category of particles are those with spin 1, these particles are known as gauge bosons. Gauge bosons serve as the mediators of the electromagnetic, weak and strong forces. The electromagnetic force is mediated by the massless and chargeless photon and described by QED. The weak force is mediated by three massive particles known as the W^+, W^- and the Z^0. These three particles coupled with the photon are combined written together as one force known as the electroweak force. Finally, the strong force is mediated by eight massless self interacting gluons described by QCD. More details of the SM forces can be found in section 2.1.2.

2.1.1.3 Higgs Boson

The final particle of the SM is the yet undiscovered spin 0 scalar known as the Higgs boson. The experimental collaborations comprising both the LHC and the Tevatron have been putting great effort into the discovery of this particle and the determination of its mass (see section 2.2.1). The coupling constants of the Higgs boson to the other fundamental particles determine a particle's mass. For example, the top quark has an especially strong Higgs coupling and is thus very massive.

2.1.2 The Standard Model Forces

The standard model has three forces each governed by a fundamental theory of nature and mediated by gauge bosons. While QED, the weak interaction and QCD are well modelled, a satisfactory theory of quantum gravity has yet to be worked out. A summary of particle interactions can be found in figure 2.2.

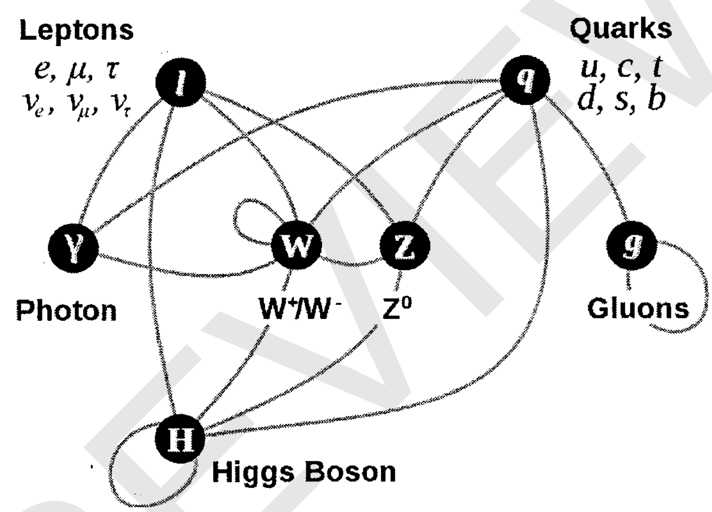

Figure 2.2: Summary of Standard Model Interactions - Summary of Standard Model particle interactions and their mediators.

2.1.2.1 Quantum Electrodynamics

QED describes the interaction of electrically charged particles through the meditation of a chargeless photon. It is simplest of all the forces to model and can be reduced to combinations of the Feynman diagrams shown in figure 2.3. It states that a charged particle, represented as e, can emit or absorb a photon. While simple, all QED