

Search in the Two-Photon Final State for Evidence of New Particle Production at the Large Hadron Collider

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Chapter 1

Introduction

Chapter 2

Overview of the Standard Model of Particle Physics

I call it...the Aristocrats.

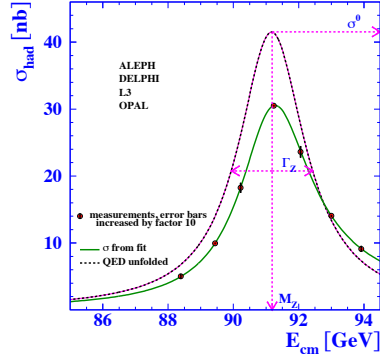
In the 1960s, Sheldon Glashow, Steven Weinberg, and Abdus Salam proposed a mathematical framework that unified the electromagnetic and weak forces at an energy scale in the hundreds of GeV/c, as well as a mechanism for breaking the electroweak symmetry at low energies [1]. At the same time, Murray Gell-Mann introduced the concept of quarks to describe hadron spectroscopy, a concept that would later grow into quantum chromodynamics (QCD), the full theory of the strong force [2]. These two key developments motivated the unified representation of particle physics as a set of fields whose dynamics are invariant under the Standard Model gauge group

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_{EM} \quad (2.1)$$

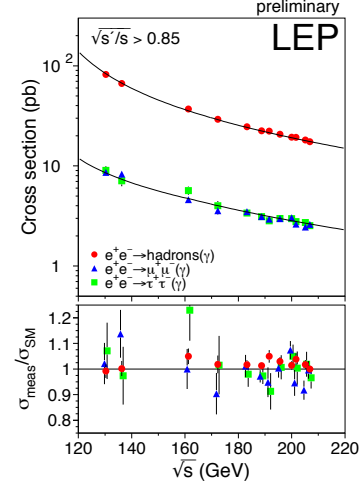
where $SU(3)_C$ describes the quark QCD interactions, $SU(2)_L$ describes the weak interactions among quarks and leptons, and $U(1)_{EM}$ describes the electromagnetic interaction.

The Standard Model, in particular the electroweak theory, has been an extremely successful predictor of particle production and interaction cross-sections and decay rates, as well as of the exact masses of the electroweak force carriers. The case for the validity of the Standard Model was bolstered by the many precision QCD and electroweak measurements carried out at the Large Electron-Positron (LEP) collider, which ran from 1989-2000 at center-of-mass energies between 65 and 104 GeV/c [3]. Figure 1 shows some of the highlights of the LEP program.

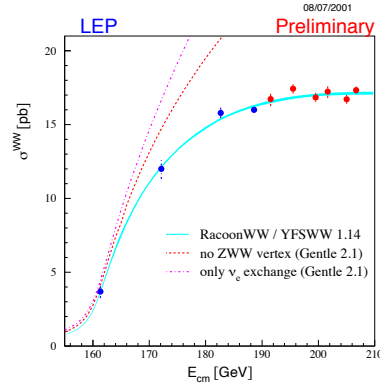
However, there are still deep theoretical problems with the Standard Model, stemming from the introduction of the Higgs scalar into the theory to break electroweak symmetry [4]. Since the Higgs self-energy diagram is quadratically sensitive to the ultraviolet cutoff scale (footnote: this is a general property of scalar fields), and assuming that there are no new important energy scales of physics between the weak scale ($\mathcal{O}(10^2 \text{ GeV/c})$) and the Planck scale ($\mathcal{O}(10^{19} \text{ GeV/c})$), in order to be consistent with experimental measurements, this diagram must include a remarkable 17-orders-



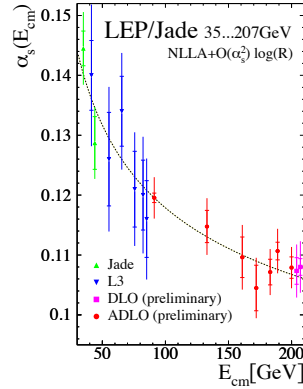
(a) Total hadronic cross-section as a function of collider center-of-mass energy.



(b) Measured and predicted dependence of the $q\bar{q}$, $\mu^+\mu^-$, and $\tau^+\tau^-$ pair production cross sections on LEP center-of-mass energy.



(c) Measured and predicted dependence of the W^+W^- pair production cross section on LEP center-of-mass energy.



(d) Measured and predicted dependence of the strong coupling constant α_s on LEP center-of-mass energy.

Figure 2.1: Selected LEP measurements demonstrating its contribution to the precise understanding of the Standard Model. Reprinted from [3].

of-magnitude cancellation that is otherwise poorly motivated [5]. The quest to find new physics at an intermediate energy scale between the weak and Planck scales, and thus extend the Standard Model, was the driving force behind the construction of the Large Hadron Collider (LHC) in 2009, the world's highest energy particle accelerator to date.

In this chapter I will briefly describe the Standard Model particle content, the theory and major results of electroweak symmetry breaking (EWSB), and the problems that the Standard Model is as yet ill-prepared to address.

2.1 Particle Content

2.2 Electroweak Symmetry Breaking and the Higgs Mechanism

2.3 The Hierarchy Problem, The Origins of Mass, and Fine Tuning

Chapter 3

The Supersymmetric Extension to the Standard Model

3.1 SUSY Lagrangian and Particle Content, SUSY Breaking

3.2 Dark Matter and the WIMP Miracle

3.3 Gauge-Mediated SUSY Breaking

3.4 Experimental Status of SUSY

Collider searches for evidence of supersymmetry began in earnest in the 1980s ([6]) and continue to this day. Most recently, the LHC and Tevatron¹ experiments have set the strictest limits on a variety of SUSY breaking scenarios, including GMSB and mSUGRA (discussed below).

Figure X shows the current limits set by the CMS experiment on the mSUGRA model (with $\tan \beta = 10$) in the m_0 - $m_{1/2}$ plane. (Note that although the plot is truncated at $m_0 = 1000 \text{ GeV}/c^2$, some searches are sensitive out to $m_0 \sim 2000 \text{ GeV}/c^2$.) Although the LHC has pushed m_0 above $\sim 1 \text{ TeV}/c^2$ for $m_{1/2}$ up to $\sim 400 \text{ GeV}/c^2$, casting some doubt onto the theory's prospects for solving the hierarchy problem, there is still a sizable chunk of mSUGRA parameter space that is not ruled out by collider experiments. Furthermore, parts of the CMS unexplored regions overlap with areas allowed by astrophysics experiments [8].

Figure X shows the most up-to-date limit (using 1 fb^{-1} of integrated luminosity collected by the ATLAS experiment [10] at the LHC) on the Snowmass Points and Slopes (SPS) model of minimal GMSB (mGMSB), dubbed SPS8 [11]. SPS8 represents the simplest class of GMSB models described in Sec. X. The best limits on a variety of general gauge mediation (GGM) models, from the same ATLAS study, are shown

¹Located on the Fermilab site in Batavia, Illinois, the Tevatron was a proton-antiproton collider operating at 1.96 TeV center-of-mass energy. The Tevatron ran from 1987 to 2011 [7].

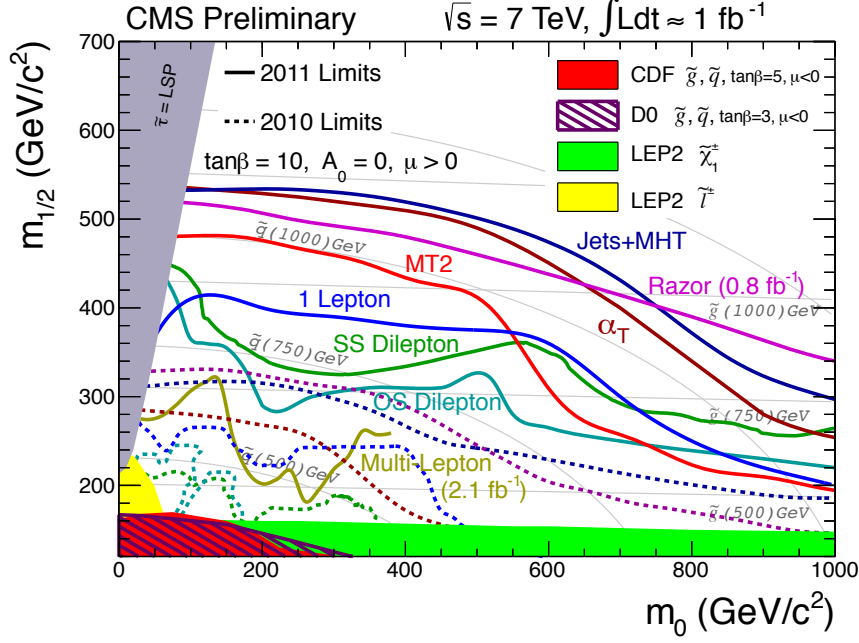


Figure 3.1: CMS limits on mSUGRA with $\tan \beta = 10$. The limits set by individual searches are shown as separate colored lines. Solid lines refer to 2011 searches (i.e. using an integrated luminosity of $\sim 1 \text{ fb}^{-1}$), while dashed lines refer to 2010 searches ($\sim 36 \text{ pb}^{-1}$). Reprinted from [9].

in Figure X. In these models, no assumptions are made about the specific parameters common to many gauge mediation models (e.g. the number of messengers or the relationship between the messenger mass and the SUSY breaking scale). Instead, it is only assumed that the lightest neutralino is light enough to be produced on-shell at the LHC (by setting M_1 and M_2 appropriately, see Sec. X) and that it decays to a gravitino, that the gravitino is extremely relativistic (mass of order eV-keV), and that the gravitino is stable. The one-dimensional scan over SUSY breaking scales in the SPS8 model (in which the full sparticle spectrum is specified by the model parameters) is replaced by a two-dimensional scan over gluino and lightest neutralino mass in the GGM models (in which all sparticles except the gluino, first- and second-generation squarks, and neutralinos are forced to be at $\sim 1.5 \text{ TeV}/c^2$, effectively decoupling them from the dynamics that can be probed with 1 fb^{-1} at a 7 TeV/c pp collider).

In general, the lifetime of the lightest neutralino in GMSB models can take on any value between hundreds of nanometers to a few kilometers depending on the mass of the lightest neutralino and the SUSY breaking scale [13]. The search published in [12] (from which Figs. X and X are culled) considers only *prompt* neutralino variants, i.e. with neutralino lifetime short enough that the distance traveled by the neutralino before decay cannot be resolved by the detector. The most recent limits on non-prompt neutralino models were set by the Collider Detector at Fermilab (CDF) collaboration with $X \text{ fb}^{-1}$, and are shown in Figure X.

Table X summarizes the current best limits on the GMSB scenarios discussed in this section.

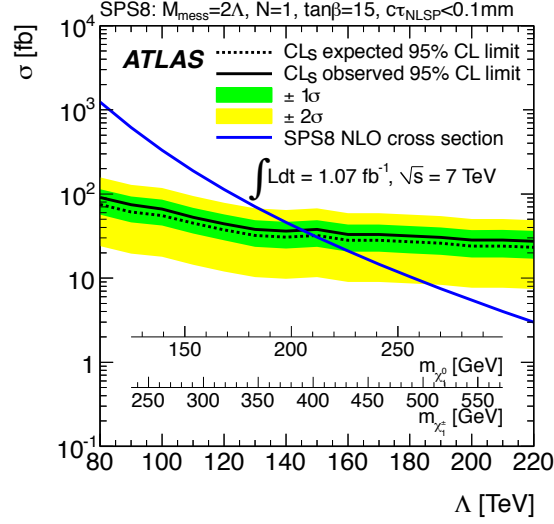


Figure 3.2: ATLAS cross section upper limit on the SPS8 [11] model of mGMSB as a function of SUSY breaking scale Λ , lightest neutralino mass $m_{\tilde{\chi}_1^0}$, or lightest chargino mass $m_{\tilde{\chi}_1^\pm}$. Values of Λ , $m_{\tilde{\chi}_1^0}$, or $m_{\tilde{\chi}_1^\pm}$ below the intersection point between the blue (predicted SPS8 cross section) and black (observed cross section upper limit) curves are excluded. The model parameters listed above the plot are defined in Sec. X. Reprinted from [12].

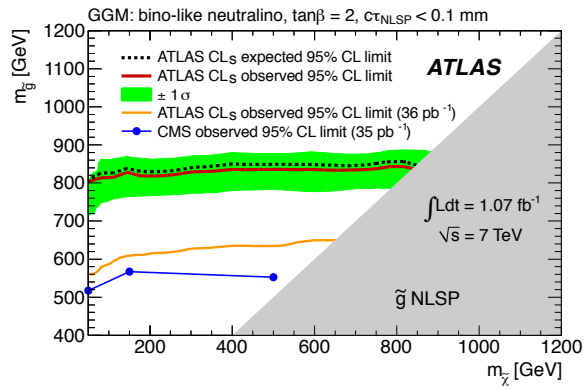


Figure 3.3: ATLAS exclusion contour in the $m_{\tilde{g}}-m_{\tilde{\chi}}$ plane. Values of $m_{\tilde{g}}-m_{\tilde{\chi}}$ below the red curve are excluded. The gray region is theoretically excluded in the GGM models considered. "Bino-like neutralino" means that $M_2 = 1.5 \text{ TeV}/c^2$. Reprinted from [12].

Chapter 4

The Large Hadron Collider

Chapter 5

The Compact Muon Solenoid Experiment

5.1 The Detectors and Their Operating Principles

5.1.1 Tracking System

Pixel Detector

Silicon Strip Tracker

5.1.2 Electromagnetic Calorimeter

5.1.3 Hadronic Calorimeter

5.1.4 Muon System

5.1.5 Far Forward Calorimetry

5.2 Triggering, Data Acquisition, and Data Transfer

5.2.1 Level 1 and High Level Trigger Systems

5.2.2 Data Acquisition System

5.2.3 Data Processing and Transfer to Computing Centers

Chapter 6

Event Selection

6.1 HLT

6.2 Object Reconstruction

6.2.1 Photons

6.2.2 Electrons

6.2.3 Jets and Missing Transverse Energy

6.3 Photon Identification Efficiency

Chapter 7

Data Analysis

7.1 Modeling the QCD Background

7.2 Modeling the Electroweak Background

7.3 Results

Chapter 8

Interpretation of Results in Terms of GMSB Models

8.1 Simplified Models

8.2 Upper Limit Calculation

8.3 Cross Section Upper Limits

8.4 Exclusion Contours

Chapter 9

Conclusion

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