Minimal Supergravity with R-Parity Violation and $\tilde{\chi}_1^0$ LSP in Lepton Final State

Eric Williams

Advisor: Prof. Sunil Somalwar

Department of Physics and Astronomy
Rutgers University

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Abstract

In this analysis, we present a search for Beyond Standard Model physics in 9.2 $fb^{-1}$ of $\sqrt{s}=8$ TeV pp collision data from the Compact Muon Solenoid at the Large Hadron Collider. In particular, we consider leptonic R-Parity violations with $\lambda_{122} = 0.005$ in the mSUGRA parameter space characterized by $m_0=1000$ GeV/$c^2$, $m_1=900-1400$ GeV/$c^2$, $A_0=0$, $\tan\beta=40$, $\mu > 0$, and $m_{top}=172$ GeV/$c^2$. This study is carried out using Monte Carlo simulations and $CL_s$ statistical data analysis methods. We present an exclusion curve showing $\sigma$ as a function of $m_{\tilde{\chi}_1^0}$, indicating excluded regions of the parameter space, and suggest further study of an identified region of interest.
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1 Introduction

Since the 1970s, the Standard Model has acknowledged the existence of six quarks, six leptons, and four bosons. Recently, the Standard Model was "confirmed" with the finding of a 126 GeV/c² Higgs-like boson at the Large Hadron Collider. Although the Higgs is considered by some to be the 'final piece of the puzzle,' it is by no means the end of our questions about the universe. Indeed, there is much more to consider that goes beyond the Standard Model.

1.1 SuperSymmetry - SUSY

One such extension of the Standard Model is called SuperSymmetry (SUSY), which posits that every Standard Model (SM) particle has a superpartner with a higher mass and complementary spin. Just as the Standard Model allows for every "regular" matter particle to have an anti-matter partner that differs by electric charge\(^1\), there may exist another symmetry that allows SM particles to have a SUSY partner differing in other properties, i.e. mass and spin. Therefore, SUSY would merely extend this two-fold symmetry into a four-fold symmetry: every "regular matter particle" has an anti-particle, and each of these has a superpartner.

The supersymmetric model is an attractive candidate because it solves the Hierarchy problem\(^2\), allows for the unification of forces at the high energy GUT scale\(^3\), and offers a potential explanation for Dark Matter\(^4\).

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\(^1\)also baryon number, quark color, lepton flavor, strangeness, charm, bottomness, and topness as applicable

\(^2\)Why is the Higgs mass (125 GeV/c²) so much lighter than the Planck mass (\(10^{19}\ \text{GeV/c}^2\))?

\(^3\)GUT scale: The energy level at which a Grand Unification Theory, combining the electromagnetic, strong, and weak forces, is possible - i.e., \(10^{16}\ \text{GeV}\).

\(^4\)Dark Matter and Dark Energy make up about 95 % of the universe’s mass, but are unexplained by the Standard Model.
1.2 Minimal Supergravity - mSUGRA

Minimal Supergravity is one model of SuperSymmetry in which physics greatly simplifies at very high energy. According to mSUGRA, physicists need only concern themselves with six parameters at the GUT scale: $m_0$, $m_{\frac{1}{2}}$, $A_0$, $\tan \beta$, $\mu$, and $m_{\text{top}}$. They are defined as follows:

- $m_0$ - the universal scalar mass
- $m_{\frac{1}{2}}$ - the universal gaugino mass
- $A_0$ - soft-breaking trilinear coupling constant
- $\tan \beta = \frac{v_u}{v_d}$ - the ratio of VEVs of the two Higgs fields
- $\text{sign}(\mu)$ - the sign of the Higgsino mass parameter ($\mu > 0$ or $\mu < 0$)
- $m_{\text{top}}$ - the mass of the top quark; taken as 172 GeV/$c^2$

By universal scalar mass, it is meant that all spin-0 particles take on the same (universal) mass value. The universal gaugino mass is the corresponding universal mass of all spin-1/2 particles. The soft-breaking trilinear coupling constant, $A_0$, is set to zero to simplify the parameter space. In $\tan \beta$, $v_u$ ($v_d$) is the vacuum expectation value of the neutral component of the Higgs field $H_u$ ($H_d$) that couples exclusively to up-type (down-type) fermions [4]. The bilinear Higgsino coupling constant, $\mu$, is a boundary condition whose only significance is its sign; we will choose $\mu > 0$. The official mass of the top quark according to the Particle Data Group is 172.9 ± 1.5 GeV/$c^2$, but is often reported as 172, 173, or 175 GeV/$c^2$ depending on the context. For our purposes, it was taken as 172 GeV/$c^2$.

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5For a discussion of nonzero trilinear coupling, see Ref. [13]
1.3 R-Parity Violation - RPV

Typically\(^6\), the mSUGRA model assumes conservation of the quantity R-Parity, defined as

\[ R = (-1)^{2S+3B+L} \]

where S is the particle spin, B is the baryon number, and L is the lepton number. All Standard Model particles have R=1, while Supersymmetric particles have R=-1 (Consider an electron e with S=\(\frac{1}{2}\), B=0, L=1 and a selectron \(\tilde{e}\) with S=0, B=0, L=1). Since R-Parity is a multiplicative symmetry, R-Parity Conservation would prevent a single SUSY particle from decaying to any number of only Standard Model particles; in turn, this would make the LSP\(^7\) “stable.” Such models are popular because they point to the LSP as a possible candidate for Dark Matter, as discussed earlier.

However, in this analysis we do not follow that assumption; instead, we will allow violations. R-Parity can be violated in three ways, as shown by the following three RPV terms that contribute to the superpotential

\[ W_{RPV} = \lambda_{ijk} L^i L^j \bar{E}^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda''_{ijk} \bar{U}^i \bar{D}^j \bar{D}^k \]

which correspond to leptonic, semi-leptonic, and hadronic, respectively [11]. Each \(\lambda_{ijk}\) is a Yukawa coupling constant, and ijk refers to the three generations of matter (1,2,3). As it happens, these three different methods of R-Parity Violation are naturally listed in order of increasing complexity. Therefore, for simplicity’s sake, we will only consider leptonic RPV, so named because such decays violate Conservation of Lepton Number. One example of such a decay is:

\[ \tilde{\chi}_1^0 \rightarrow e^- + \mu^+ + \nu_\mu \]

In this process, the lightest neutralino decays into an electron, an anti-muon, and muon-neutrino. Although \(L_\mu\) is conserved in this decay, \(L_e\) is violated\(^8\). Hence R-Parity is

\(^6\)Many SUSY searches rely on R-Parity Conservation to explain apparent violations of momentum conservation that we observe at CMS, and thus do not consider RPV. A notable exception is the ATLAS collaboration’s study of RPV mSUGRA with \(\tilde{\tau}_1\) LSP [2]. We will consider \(\tilde{\chi}_1^0\) LSP instead, which is closer to traditional mSUGRA studies.

\(^7\)Lightest Supersymmetric Particle

\(^8\)\(L_\mu\) is \(\mu\)-lepton number, \(L_e\) is \(e\)-lepton number.
violated, and we see a decay mode in which a SUSY particle decays directly into SM particles. (Note that since the final state of this decay is $e^- \mu^+ \nu_\mu$, this decay occurs by means of the $\lambda_{122}$ coupling: the electron belongs to the first generation, while the muon and $\mu$-neutrino belong to the second generation.)

In general, our final state will consist of $l_i^\pm l_j^\mp \nu_k$, where $(i,j,k) \in (1,2,2)$ due to our choice of $\lambda_{ijk} = \lambda_{122}$. Since the products are all Standard Model particles resulting from a SUSY decay, we must find a signal that exceeds the SM background of lepton production.

## 2 Monte Carlo Methods

In order to study an observed R-Parity violating mSUGRA signal, we must know what to look for. To this end, we used Monte Carlo event simulations to show what such a signal would theoretically look like. Then we compared the CMS data to theory.

In creating Monte Carlo simulations, several software packages were used in concert with each other. First, the executable ISASUGRA was used to create SLHA\(^9\) files with $\tilde{\chi}_1^0$ LSP. Second, the mass spectra contained within these SLHA files were used by Pythia 6.4 to simulate R-Parity violating events. Third, CMSSW version 532 patch 4 was used to create ntuples of each particle’s properties, as well as histograms displaying these properties. Fourth, a modified version of LandS\(^10\) was used to overlay the histograms and create an exclusion curve.

### 2.1 SLHA

The program ISASUGRA is a derivative of the larger ISAJET package\(^11\), and is described in Ref \cite{9}. ISASUGRA allows the user to specify the values of $m_0$, $m_{\tilde{\chi}_1^0}$, $A_0$, $\tan \beta$, $\mu$, and $m_{\text{top}}$. These parameters determine the mass spectra and decay tables particles beyond the Standard Model according to the SUSY Les Houches Accord \cite{12}. This information

\(^9\)SUSY Les Houches Accord

\(^10\)LandS modified extensively by Peter Thomassen, a graduate student at Rutgers University

\(^11\)See also ISASUSY
is then stored in the aptly-named SLHA files.

### 2.2 LHE

The SLHA files are then fed into Pythia 6.425\footnote{For brevity, Pythia 6.425 will often be referred to as Pythia 6.4, Pythia 6, or even just Pythia.}, an event-generating tool based on Fortran. Using the input mass spectra, Pythia simulates a prescribed number of events that could happen in nature according to the theoretical model. Since we are interested in R-Parity violating events, Pythia’s internal RPV switches were used \cite{11}. Leptonic RPV calls for use of the $\text{RVLAM}(i,j,k)$ switch where $i,j,k \in (1,2,3)$ matter generations as usual.

$$\lambda_{122} = 0.005$$ was set using $\text{RVLAM}(1,2,2)=0.005$

The results of these event simulations are stored in the Les Houches Events format as LHE files. Of particular interest are the cross-sections of certain decay modes\footnote{On occasion, some cross-sections were found to be negative. Since this is entirely unphysical, negative cross-sections were manually set to zero.}.

### 2.3 Ntuples and Histograms

The events within the LHE files were then analyzed using the CMSSW package (Compact Muon Solenoid SoftWare) and Physics Analysis Toolkit, to extract information about the particles, e.g. $p_T$, $\eta$, charge, etc. These data were then stored in ntuples, which in turn are used to create histograms of the events in question for statistical analysis. In this study, CMSSW version 532 patch 4 was used in conjunction with a custom Rutgers EDAnalyzer.

### 2.4 Exclusions

The histograms undergo LHC-type CLs confidence limit analysis \cite{8, 10} using the LandS software package \cite{5} with the 3000 toys as recommended for CMS analyses \cite{7}; the result is an observed limit and an expected limit with one- and two-sigma uncertainty bands. This
so-called exclusion curve shows which model points are excluded, i.e. ruled out as not physically possible, and which are not. These exclusions may be used to eliminate regions of unphysical parameter space and identify regions of interest for further study.

3 Data Analysis

CMSSW 532 patch 4 was used to create ntuples from CMS data files in AODSIM format. From these ntuples, histograms and exclusions are made using the same method as described in the Monte Carlo section.

3.1 Event Selection

CMS data events are considered interesting and selected for analysis if they meet certain criteria, including $p_T \geq 10$ GeV and $|\eta| < 2.4$ as described in Ref. [7]. However, not all such events constitute valid RPV mSUGRA signal because there also exist Standard Model processes leading to a lepton-only final state. Therefore, a tag-and-probe method [6] is used with $Z \rightarrow l^+ l^-$ events, one such SM process\textsuperscript{14}, to estimate the efficiencies of lepton identification. We find that the simulation models the efficiencies correctly to within $\pm 1\%$ for muons and $\pm 2\%$ for electrons. These Standard Model processes are considered background.

3.2 Signal, Background, and Excess

We consider the quantity Signal - Background = Excess, which would ideally be positive. The Excess shows how much more often a process occurs than the Standard Model predicts it should, indicating that some non-SM interaction is responsible\textsuperscript{15}.

\textsuperscript{14}Strictly speaking, $Z \rightarrow l^+ l^-$ is missing something that our mSUGRA RPV signal has: the neutrino. However, the neutrino is invisible to our detector so the signal final state is 'effectively' the same as for $Z$ decay.

\textsuperscript{15}When considering Excess, $5\sigma$ is usually the required threshold to claim new physics.
The results of this data analysis go into the Exclusion Curve, joining the results from the Monte Carlo simulations.

4 Exclusion Curves and Interpretation

In Figure 1, we show the 95 % $CL_s$ exclusion limit contours in the mSUGRA space with non-zero $\lambda_{122}$ as a function of $m_{\tilde{\tau}}$. We also indicate the expected limits and theoretical cross section for this model, which has $m_0=1000 \text{ GeV}$, $A_0=0$, $\tan \beta=40$, $\mu>0$.

Figure 1: 95 % $CL_s$ Limits for leptonic RPV coupling $\lambda_{122}=0.005$ as a function of $m_{\tilde{\tau}}$ in the mSUGRA parameter space. The observed limits as well as the limits expected in absence of signal are shown, along with the uncertainty bands in the expectation. We also show the theoretical limit based solely on the model. The intersection of Theoretical $\sigma_{NLO}$ (blue) and observed (solid black) delineates the exclusion regions. To the left of this intersection, where Theory exceeds Observation, the model is excluded. To the right of this intersection, where Observation exceeds Theory, the model is not excluded.

The Theoretical $\sigma_{NLO}$ curve shows the cross section pertaining solely to the R-Parity violating mSUGRA signal, as calculated from the SLHA files. The Observed limit shows signal observations from the $9.2 fb^{-1}$ of data, while the Expected curve shows the limit that is expected in the absence of any signal (i.e., Standard Model background processes). Of particular interest is the intersection between the Theoretical and the Observed limits,
which occurs near $m_{\tilde{\chi}}^2=1225$ GeV. For all points to the left of this intersection, Theory exceeds Observation, which means the model is excluded for that mass value. For all points to the right of this intersection, Observation exceeds Theory, which means the model is not excluded. (However, this is suggestive that some non-mSUGRA RPV process may be occurring here.)

We also notice there is no observed correlation between $\sigma$ and $m_{\tilde{\chi}}^2$, contrary to the theory, which suggests we may wish to parameterize differently. We may consider plotting $\sigma$ vs $\tan \beta$ in the future.

Further study is needed to draw more meaningful conclusions from the exclusion curve; analysis of $19.5 \, fb^{-1}$ 2013 data is ongoing.

5 Conclusion

We have peformed a search for R-Parity violating physics in the mSUGRA parameter space. Agreement is found between observation and expectation, but not observation and theory. We have identified a region of exclusion below $m_{\tilde{\chi}}^2=1225$ GeV/$c^2$ for the mSUGRA RPV signal with nonzero $\lambda_{122}$ coupling. Additionally, we have found a region of interest above $m_{\tilde{\chi}}^2=1225$ GeV/$c^2$ that merits further analysis using 2013 data, which is currently ongoing.
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References


