Discovering SUSY with $m_0^2 < 0$ in the First LHC Physics Run

Arvind Rajaraman and Bryan T. Smith

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

Abstract

In minimal supergravity, the parameter space where the slepton is the LSP is usually neglected, because of strong constraints on charged dark matter. When the gravitino is the true LSP, this region avoids these constraints and offers spectacular collider signals. We investigate this scenario for the LHC and find that a large portion of the ignored mSugra parameter space can lead to discovery within the first physics run, with 1-4 fb$^{-1}$ of data. We find that there are regions where discovery is feasible with only 1 day of running.

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I. INTRODUCTION

Some of the most highly motivated extensions of the standard model (SM) are models with supersymmetry (SUSY). SUSY solves the hierarchy problem, and provides a natural dark matter candidate if R-parity is exact. Furthermore, supersymmetry will be tested in a few years at the upcoming Large Hadron Collider (LHC).

On the other hand, supersymmetry is manifestly not a symmetry at low energies, and hence supersymmetry must be broken. The most general framework of supersymmetry breaking already has over a hundred parameters, and any analysis requires a simplified model. The most popular of these simplified models is minimal supergravity (mSugra) [1], which is usually taken to be specified by 5 parameters \(m_0^2, M_{1/2}, A_0, \tan \beta, \text{ and sign}(\mu)\), which are respectively the scalar mass squared, the gaugino mass, the trilinear term, the ratio of the up and down type Higgs boson vacuum expectation values, and the supersymmetric Higgs mass parameter. The first three are evaluated at the unification scale. Low energy parameters, such as superpartner masses and couplings, can be determined by the renormalization group evolution of these parameters.

One of the constraints which is usually imposed on the parameters of mSugra is that regions of parameter space where the lowest superpartner is a slepton are taken to be ruled out. This is because the lightest superpartner (LSP) is stable if R-parity is conserved (which we will assume henceforth.) If the slepton is the LSP, it appears as an absolutely stable charged massive particle (CHAMP), and there are very strong bounds on CHAMP masses, both from direct searches [2, 3], and from cosmological effects on nucleosynthesis [4, 5]. This constraint removes a large region of mSugra parameter space. In the \((m_0^2, M_{1/2})\) plane, all parameter values with \(m_0^2 < 0\) lead to a slepton LSP, and are excluded by this constraint. A thin triangular wedge in the \(m_0^2 > 0\) parameter space is also excluded.

However, as pointed out in [6], this constraint does not consider effects from the gravitino. In particular, if we are in the parameter space where \(m_0^2 < 0\), we can consider the possibility that the gravitino is the true LSP [7, 8, 9, 10, 11, 12, 13, 14]. In that case, the charged slepton will be the NLSP, and charged dark matter particles will decay to the gravitino in a short time period. The current dark matter will then be entirely composed of gravitinos, and CHAMP searches will not put any constraints on this scenario. Nucleosynthesis bounds are satisfied if the slepton lifetime is less than about \(10^3\) seconds [7, 8, 12, 14, 15, 16, 17, 18]. (In fact there are many cosmological virtues of a gravitino LSP, particularly in aspects regarding structure formation [19, 20, 21, 22, 23].) One can thus find models in the region with \(m_0^2 < 0\) which are consistent with all current limits.

This region of parameter space has unique signatures. The NLSP sleptons are stable on collider timescales, and exit the detector before decaying. Thus the signal of this region of SUSY parameter space will be heavy muon-like particles. This is radically different from the commonly considered situation where the neutralino is the LSP. In that situation, the neutralino escapes undetected, and supersymmetry is manifested in events with a large missing energy. In this new region, the signatures are quite different, and standard missing energy searches for SUSY may completely miss this entire region of parameter space.

In this paper, we will perform the first comprehensive analysis of the slepton NLSP region, with the primary aim of finding out how soon this region of parameter space can be discovered at the LHC. In particular, we will show that a large portion of parameter space can be probed at the first high energy run of the LHC with no more than 1-4 fb\(^{-1}\) of data,
and some points may have a “Day 1” discovery of SUSY.

While there has been a lot of earlier theoretical work on long lived sleptons in supersymmetric theories, it has mostly been focused on gauge-mediated SUSY breaking (GMSB) models (see eg. [24, 25]), and mSugra in the region where \( m_0^2 > 0 \) (e.g. [26]). Furthermore, these papers were oriented toward an analysis of mass reconstruction, and hence focused on special benchmark points. A complete scan of the slepton NLSP region (along the lines of [27, 28] for the neutralino LSP region) has not yet been performed, and is one of the goals of this paper.

There has also been a lot of experimental work searching for long-lived charged particles at colliders, again typically focused on GMSB models. Experimental searches at LEP and the Tevatron have so far given null results, putting constraints on the masses and cross sections of these particles [29]. There have also been a number of experimental studies of the detection of these particles at the LHC [30]. We shall review the experimental search strategies below in Sec. II, and see how they can be utilized to probe this new parameter region.

After a discussion of the experimental signals, we apply our analysis to two benchmark points, which were previously discussed in [6]. We find a set of cuts to isolate the signal from the background, and show that both points can be discovered in the first physics run of the LHC. In Sec. IV we extend this to a scan over the extended mSugra parameter space (including the previously ignored \( m_0^2 < 0 \) region). We show that much of this parameter space can be probed with 1-4 fb\(^{-1}\) of data. We conclude with a discussion of our results in Sec. V.

II. GENERAL CONSIDERATIONS

Since the slepton appears in the detector as a heavy muon, one of the crucial elements in an analysis of the \( m_0^2 < 0 \) parameter space is to find a way to distinguish these sleptons from the large background of muons produced from Standard Model processes. There are two important observables which are commonly used to perform this separation: time-of-flight (TOF) measurements and ionization loss (dE/dx) measurements.

A. Time-of-flight (TOF)

The TOF method uses the fact that a slepton is moving significantly slower than a muon of the same momentum. Every muon is travelling at essentially the speed of light. The sleptons on the other hand have a velocity \( v = \beta \tilde{c} = \frac{p \tilde{c}}{E_\tilde{l}} \). Since the masses of the sleptons are at least 100 GeV, the corresponding \( \beta \) can be significantly different from 1 even at LHC energies.

The smaller velocity of the sleptons means that they arrive at the farther parts of the detector (typically the muon chambers) at a later time than the muons. The time delay is \( \Delta t = \frac{d}{\tilde{c}} - \frac{d}{c} \) (\( d \) is the size of the detector). By measuring this time delay, the velocity can be calculated. By requiring the velocity to be significantly different from the speed of light, we can remove most of the muon background.

The resolving power of this method depends on both the size of the detector and the time resolution. The time resolution of ATLAS and CMS is the same at 1 ns. Since the ATLAS
detector is bigger, it has a better resolving power. We will therefore focus on the ATLAS detector for the remainder of this paper.

ATLAS’s muon system measures the TOF through its resistive place capacitors (RPC) for $\eta < 1$ and thin gap capacitors (TGC) for $1 < \eta < 2.4$. For $\eta > 2.4$ a TOF measurement can not be made, and hence we limit our study to sleptons candidates within $0 < \eta < 2.4$.

B. Ionization loss

While the TOF technique achieves a very clean separation between muons and sleptons, it also leads to a huge decrease in the signal, since most sleptons are produced with $\beta$ very close to 1. Accordingly it is useful to find other methods to reduce the background.

The second technique to separate muons from sleptons is through the measurement of ionization energy loss (sometimes referred to as the measurement of $dE/dx$). The ionization energy loss of a charged particle depends on $\beta$, and is given by the Bethe-Bloch formula. By measuring the energy deposition as the charged particle passes through the detector, one can estimate its velocity, and thereby distinguish muons from sleptons. (For discussion of this method in the context of R-hadrons, see [31]).

The muon system is capable of measuring the ionization energy loss, through the monitor drift tubes (MDT), which measure the total charge ionized by a charged particle that travels through them. Slow moving sleptons will deposit more charge in the MDTs than a muon. It has been shown that this charge difference can be measured and used to distinguish between long-lived sleptons and muons [32]. In this paper, it is claimed that the background can be reduced by $10^8$ while reducing the signal only by a factor $10^2$.

In addition, the Transition Radiation Tracker can be used to distinguish ultra relativistic particles from slower moving particles [33]. Charged particles passing through the ATLAS TRT deposit ionization energy, and particles with $\beta\gamma > 1000$ also lose energy through transition radiation. This energy can be picked up by the straws in the TRT. A particle that deposits energy greater than 5.5 keV is recorded as a high-threshold hit for that straw, while if the deposition is above the lower threshold of 200 eV, the time for which the signal is above the threshold is also recorded. Both the number of high-threshold hits and the total time over-threshold for the low threshold hits depend on the total energy deposition. We can therefore use the TRT to separate slow particles from ultrarelativistic particles.

A combined study using all these signals has apparently not yet been performed. Using the ionization energy loss and transition radiation measurements would therefore require a full detector simulation, which is in progress [34]. For this paper, we will not consider ionization loss, and instead focus on the TOF measurements and appropriate kinematic cuts to reduce the background from SM muons.

III. ANALYSIS OF BENCHMARK POINTS

A. Spectra and Signatures

We start by looking at two benchmark models, labelled model A and model B, from our previous paper [6]. The mass spectra of the two models are shown in Fig. 1 and are produced from ISAJET v7.71 [35] modified to calculate the SUSY mass spectrum for $m_0^2 < 0$. 

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TABLE I: Parameters of our two benchmark models.

| Model   | $m_0^2$      | $M_1/2$   | $A_0$ | $\tan \beta$ | sign($\mu$) |
|---------|--------------|-----------|-------|---------------|-------------|
| Model A | -(40)^2 GeV^2 | 300 GeV   | 0 GeV | 10            | +           |
| Model B | -(700)^2 GeV^2 | 1900 GeV  | 0 GeV | 60            | +           |

Each of the models has a different signature. Model A is a “typical” SUSY spectrum where squarks and gluinos dominate the production of SUSY particles. The colored SUSY particles cascade down to the NLSP charged lepton. The signature is two hard jets, two charged staus, and two leptons. In this model the cascade decay of the squarks and gluinos produces a large amount of transverse energy.

Model B, on the other hand, has a mass spectrum where Drell-Yan production of the light charged sleptons dominates the SUSY production. There are two charged sleptons in the final state, and no jets.

In addition, the velocity distributions of the sleptons are somewhat different. More slow sleptons are produced in Drell-Yan processes as compared to cascade decays. The TOF method therefore works better for the situations where Drell-Yan processes dominate, as in model B.

B. Background analysis

The background comes from Standard Model events in which two muons are produced. The dominant sources of these events are listed in table II.

We generated $10^6$ events of each source with PYTHIA 6.404 [36]. To reduce these backgrounds we use a series of cuts:

a. **Muon number**: Two muon-like particles must be produced.

b. **Rapidity cuts**: Both muon-like particles must be within $\eta < 2.4$.

c. **Isolation cuts**: Both muon-like particles should contain less than 10 GeV of transverse momentum in a cone of $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ around each muon-like particle.

d. **Momentum cuts**: Both muon-like particles must have a momentum greater than 100
Once these cuts are imposed, the dominant background to Drell-Yan production is $Z$-production. To reduce this background, we add a cut on the invariant mass. We thus define the event should pass cuts (a), (b), (c), (d); in addition, the invariant mass of the two muon-like particles must be greater than 120 GeV.

For the cascade decays, on the other hand, the dominant background after the cuts (a), (b), (c), (d) is $Z$+jets. To reduce this background we impose a requirement of having hard jets. We therefore define the event should pass cuts (a), (b), (c), (d); in addition, we require that the 4 most energetic objects among the jets and leptons each have an energy greater than 70 GeV.

The results of these cuts on the signal and background can be seen in Table II. To estimate the QCD background we generated $10^6$ events with $b\bar{b}$. We found no events passing these cuts, which corresponds to a direct limit on this cross-section of 700 fb. We expect the other QCD processes to contribute even fewer events, and so we have very conservatively estimated the cross section from QCD processes to be less than 1 pb.

C. TOF cuts

Finally, we can reduce the background by using the time-of-flight methods as described in section II. The ionization loss method could also potentially be used, but we shall not use it in this analysis.

The background SM muons are required to have a momentum larger than 100 GeV by our cuts. The time delay of such muons to the farthest part of the detector is orders of magnitude smaller than the detector resolution of 1 ns. (The sleptons, on the other hand, have a significant time delay as seen in Fig. 2) However, mismeasurements of the time can lead to apparent time delays. The probability of a mismeasurement of $\Delta t$ ns, is expected to go as $\exp(-\Delta t^2)$, assuming a gaussian resolution to the TOF measurement. We will use a TOF cut where we require both muons to have a time delay greater than some value $\Delta t$. Our TOF cut therefore reduces the SM background by a factor of $\exp(2\Delta t^2)$.

In Table III the signal and background of our benchmark points are shown for TOF cuts.

|          | Total cross-section | After Drell-Yan cuts | After Cascade cuts |
|----------|---------------------|----------------------|-------------------|
| Model A  | 18pb                | 9pb                  | 8pb               |
| Model B  | 43fb                | 28fb                 | 1fb               |
| QCD      | $10^2$mb            | < 1pb                | < 1pb             |
| $\gamma^*/Z \rightarrow \mu\mu$ | 100mb | 3pb | 100fb |
| $W$+jet  | 360nb               | < 40fb               | < 40fb            |
| $Z$+jet  | 150nb               | 7pb                  | 300fb             |
| $t\bar{t}$ | 800pb              | 430fb                | 80fb              |
| WW,WZ,ZZ | 2.5nb               | 150fb                | 25fb              |

TABLE II: Signal and backgrounds for Drell-Yan and cascade cuts

GeV and a transverse momentum greater than 20 GeV.

The background SM muons are required to have a momentum larger than 100 GeV by our cuts. The time delay of such muons to the farthest part of the detector is orders of magnitude smaller than the detector resolution of 1 ns. (The sleptons, on the other hand, have a significant time delay as seen in Fig. 2) However, mismeasurements of the time can lead to apparent time delays. The probability of a mismeasurement of $\Delta t$ ns, is expected to go as $\exp(-\Delta t^2)$, assuming a gaussian resolution to the TOF measurement. We will use a TOF cut where we require both muons to have a time delay greater than some value $\Delta t$. Our TOF cut therefore reduces the SM background by a factor of $\exp(2\Delta t^2)$.
FIG. 2: The distribution of the time delay for $2 \times 10^5$ sleptons that survive the Drell-Yan cuts. The left panel shows results for model A and the right panel shows results for model B.

| Time delay of | 0ns | 1 ns | 2ns | 3ns | 4ns | 5ns |
|---------------|-----|------|-----|-----|-----|-----|
| Drell-Yan; background | 10pb | 1.35pb | 3.3fb | 0.2ab | < 0.1ab | < 0.1ab |
| Drell-Yan; Model A | 9pb | 5.2pb | 2.9pb | 1.8pb | 1.1 pb | 750fb |
| Drell-Yan; Model B | 28fb | 23fb | 18 fb | 14fb | 11 fb | 9.4fb |
| Cascade; background | < 1pb | < 134fb | < 340ab | < 0.1ab | < 0.1ab | < 0.1ab |
| Cascade; Model A | 8pb | 4.3pb | 2.4pb | 1.4pb | 910fb | 590fb |
| Cascade; Model B | 190ab | 87ab | 41ab | 22ab | 13ab | 7ab |

TABLE III: Signal and backgrounds as a function of TOF cut.

between 1-5 ns. For a 3 ns time delay cut on each slepton we reduce our background to less than 1ab, which is negligible (there will be no background events over the entire running of the LHC.)

A discovery claim requires $S > 10$ and $S/\sqrt{B} > 5$, where $S$ is the number of signal events and $B$ is the number of background events. The 3 ns time delay cut lowers the background so much that the second requirement is automatically met if there are 10 signal events. The only criterion for discovery is then the requirement $S > 10$.

With model A having a cross section after our Drell-Yan cuts of $\sigma_A = 1.8pb$, an integrated luminosity of $5.6pb^{-1}$ is required for discovery. For model B with a cross section of $\sigma_B = 14fb$, an integrated luminosity of $720pb^{-1}$ is required for discovery. Both benchmark points can be discovered in the first physics run at the LHC, where the expected luminosity is between 1-4 $fb^{-1}$. Model A could feasibly be seen on the very first day of the first physics run.

IV. SCANNING THE PARAMETER SPACE

We now extend the analysis to a scan of the $(m_0^2, M_{1/2})$ parameter space with a slepton NLSP and gravitino LSP. In the scan, we set $A_0 = 0$ and $\mu > 0$ with $\tan\beta = 10$ and $\tan\beta = 60$. The contour plots in Fig. 4 use the notation $m_0 \equiv \text{sign}(m_0^2)\sqrt{|m_0^2|}$ and use the following color scheme: green (dark) for the experimentally excluded region, yellow (medium) for the stau LSP region, magenta (darkest) for the selectron LSP region, and white for the neutralino LSP region.
The mesh size for our scan was 25 GeV for both $m_0$ and $M_{1/2}$. For each point we generated 10000 events with PYTHIA 6.404 to get the fraction of events that pass the 3 ns time delay cut with the Drell-Yan or cascade cuts, and the total SUSY cross section.

The shape of the total SUSY cross sections, shown in Fig. 3, is determined by the mass of the squarks and right handed sleptons. For larger $m_0$, the SUSY cross section tends to be dominated by squark and gluino production. The SUSY cross section contours follow contours of constant squark and gluino masses, which are flat as a function of $m_0$. As $m_0$ decreases, the sleptons become lighter, and the SUSY production is eventually dominated by Drell-Yan production of right handed sleptons. After this point the total SUSY cross section follows contours of constant slepton mass, which are concave upward.

This can be checked by comparing the cross sections relative to the mass contours plots in the extended mSugra region presented in [6]. For example, in the tan$\beta = 10$ panels the total SUSY cross section of 10 fb cross section starts on the right following an approximately 2 TeV mass average of the squarks and gluinos. As we follow the contour to the left, it turns up to follow the contours of constant slepton mass of approximately 200 GeV. A similar behavior can be seen in the tan$\beta = 60$ panels as well.

In Fig. 4, the left panels show our results for tan$\beta = 10$, and the right panels show our results for tan$\beta = 60$. The total SUSY cross section after time delay cut of 3ns and our Drell-Yan cuts (solid) and cascade cuts (dashed) is shown. The cross sections are shown for three values: 10 fb, 2.5 fb, and 0.33 fb. The 10 fb dashed lines correspond to 1 fb$^{-1}$ of integrated luminosity for discovery at the LHC, while the 2.5 fb and 0.33 fb dashed lines correspond to discovery at 4 fb$^{-1}$ and 30 fb$^{-1}$ of integrated luminosity respectively.

One important (and somewhat surprising) result from this analysis is that the Drell-Yan cuts have a better reach than the cascade cuts, even in regions dominated by cascade production. The basic reason is that the Drell-Yan cuts remove less of the signal than the cascade cuts. It is true that the cascade cuts remove more SM background than the Drell-Yan cuts, but since the background is negligible after TOF cuts, this does not lead to an improvement for the $S/\sqrt{B}$ ratio.

Our main result is that a significant portion of the extended mSugra parameter space will be probed with our cuts in the first physics run at the LHC, expected to have an integrated luminosity of 1-4 fb$^{-1}$. A 4 fb$^{-1}$ integrated luminosity will produce a discovery of long
FIG. 4: Luminosities required for discovery using either Drell-Yan (DY) or cascade (CD) cuts. Left panel is $\tan\beta = 10$, right panel is $\tan\beta = 60$.

lived sleptons for all parameter space with $M_{1/2} < 1000$ GeV as well as a large portion of $M_{1/2} > 1000$ GeV for the more negative values of $m_0$. All of the presented parameter space with $m_0 < 0$ for $\tan\beta = 60$ will be probed with 4 fb$^{-1}$ integrated luminosity, while all of the $\tan\beta = 60$ parameter space shown will be probed with 30 fb$^{-1}$.

V. CONCLUSION

The first physics run of the LHC is expected to start in 2008. The first task of this run will be to calibrate and understand the detectors. The SM must also be understood at these new energies of 14 TeV \[37\]. An exciting prospect is that new physics can be discovered even with just this first fb$^{-1}$ of data.

In this paper, we have analyzed a region of supersymmetric parameter space where the slepton appears as a nearly stable particle. We have shown that it is possible that a discovery of such models could be made with the data from the first physics run. Both of our benchmark models can be discovered with the first fb$^{-1}$ of data. In fact, a large portion of our extended mSugra parameter space (including the $m_0^2 < 0$ region) can be probed in the first physics run of the LHC.

Once the existence of new physics has been established, the nature of this physics can be studied. For example, our benchmark model A produces signals both from Drell-Yan production as well as from cascade decays. By combining these signals, it may be possible to calculate both the squark and gluino masses as well as the masses of the right handed sleptons. With sufficient statistics, it may also be possible to calculate the spins of these particles, and thereby distinguish SUSY scenarios from extra dimensional models. An analysis of this will be presented in future work.

The discovery of apparently stable charged particles at the LHC will also have implications for cosmology. A stable charged particle would be highly problematic for cosmology, and so it is likely that the slepton would be metastable with a lifetime long on collider scales, but short on cosmological scales (in the range $10^{-6}$ to $10^{3}$ seconds). The lifetime of the long lived sleptons will need to be measured, possibly by building traps as proposed in \[38, 39\]. The measurement of the lifetime can give both the mass of the gravitino, which we assumed the sleptons decays to in this extended mSugra framework, and a high energy measurement.
of the Planck mass once the mass of the NLSP slepton is constrained \[40\]. This will also allow an accurate prediction of the relic density, which can be compared to cosmological data.

To conclude, the regions of MSSM parameter space with slepton NLSP and gravitino LSP will manifest themselves almost immediately in signals of heavy muon-like objects. Thus there are very exciting prospects of discovering supersymmetry almost immediately at the LHC. The discovery of supersymmetry may be just around the corner.

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