Is it SUSY?

AseshKrishna Datta\textsuperscript{1}, Gordon L. Kane\textsuperscript{2} and Manuel Toharia\textsuperscript{3}

Michigan Center for Theoretical Physics (MCTP)
University of Michigan, Ann Arbor, MI 48109, USA

Abstract

If a signal for physics beyond the Standard Model is observed at the Tevatron collider or LHC, we will be eager to interpret it. Because only certain observables can be studied at a hadron collider, it will be difficult or impossible to measure masses and spins that could easily establish what physics was being seen. Nevertheless, different underlying physics implies different signatures. We examine the main signatures for supersymmetry, with some emphasis on recognizing supersymmetry in parts of parameter space where generic signatures are reduced or absent. We also consider how to distinguish supersymmetry from alternatives that most closely resemble it, such as Universal Extra Dimensions (UED). Using the robust connection between spins and production cross section, we think it will not be difficult to distinguish UED from supersymmetry. We expect that by considering patterns of signatures it is very likely that it will not be difficult to find a compelling interpretation of any signal of new physics.

\textsuperscript{1}asesh@umich.edu
\textsuperscript{2}gkane@umich.edu
\textsuperscript{3}mtoharia@umich.edu
1 Introduction

An exciting era in particle physics will begin with the commencement of the Large Hadron Collider (LHC) at CERN in about 2007. While we do not know for sure what is waiting for us there, we do have a concrete wish list and rather solid directions to follow, which evolved from hints based on previous phenomena. Understanding Electroweak Symmetry Breaking (EWSB), especially in terms of the Higgs mechanism, is still the main priority.

A well known issue intimately related to the presence of a fundamental scalar in the Standard Model (SM) is the hierarchy problem. New physics such as supersymmetry (SUSY) at the weak scale has long been known to cure this problem at a fundamental level. There is ample reason to expect a deeper connection between a weakly coupled Higgs-induced EWSB phenomenon and weak-scale SUSY. A large part of the LHC program is based on this anticipation. As a bonus, on the cosmological front, the lightest of the supersymmetric particles (the LSP) in a model with a conserved discrete symmetry ($R$-parity) provides us with a viable dark matter candidate which is lacking in the SM.

Efforts have been underway for 15-20 years to study the collider signatures of different SUSY models at a theoretical level. Also, recent and ongoing experiments at CERN-LEP and the Fermilab Tevatron had/have dedicated programs to directly find the SUSY partners of Standard Model particles. Imprints of new kind of physics were/are also expected in numerous other experiments involving proton decay, electric and magnetic dipole moments, rare decays, heavy-quarks (the $B$-factories) and dark-matter experiments. So far there is no unambiguous positive signal for SUSY from these experiments. For direct observations this is not discouraging, since LEP and the Tevatron with their low available center of mass energies and luminosities could only probe the lower end of the SUSY parameter spectrum. They already did a good job of ruling out certain regions of the SUSY parameter space in direct searches.

Here, we revisit approaches to recognizing SUSY in future data. There should be two intimately related but potentially distinct programs: first, to be confident that a signal is SUSY and nothing else and, second, to learn as much as possible about the effective lagrangian, which should provide hints about how supersymmetry is broken, and about the underlying theory. Of course, there are a number of signals that would be inconsistent with an $R$-parity conserving SUSY interpretation, such as wide $WW$ or jet-jet resonances, or no missing transverse energy.

The most characteristic feature of the SUSY partners for SM particles is their spin: $i.e.$, spin ‘0’ (scalar) partners for every known (spin 1/2) SM fermions and partner fermions for spin ‘1’ gauge bosons of the SM. However measuring spins of newly observed particles at the LHC has not been studied until very recently [1] (see also [2] and [3]).

Indeed, except in very special cases, it will not be possible to isolate individual candidate superpartners at all, and measure their masses or spins, because of the nature of hadron collider data. It will also be very hard to test whether electroweak superpartners have correct gauge quantum numbers and couplings.
In this paper we will study both typical and less typical observables that are expected if the new physics is supersymmetry. We examine in some detail what happens when some common leptonic channels are suppressed, while other signatures remain robust. Such a situation is not commonly encountered in minimal Supergravity (mSUGRA) based ‘benchmark’ scenarios which have been overwhelmingly used in mapping out the search strategies. It may be important to be aware of such possibilities beforehand. On the other hand, we point out that such low event rates may help decipher the underlying spectrum.

Then we examine what a signal could be if it is not SUSY. We will discuss the example most often proposed as difficult to distinguish from SUSY, universal extra dimensions (UED), and study a little how to distinguish it with LHC observables. We propose one method, based on the robust relation between spins and production cross sections, of distinguishing SUSY and UED (and other models). Essentially, once there is data to input to an analysis, cross sections determine spins even at a hadron collider. We also note that patterns of signatures for SUSY and for UED are rather distinguishable.

Throughout this work special reference is made to events with Same-Sign (known also as Like-Sign) Dilepton (SSD). These events have been long known [1-10] to be very clean and robust signatures at the hadron colliders for physics Beyond the Standard Model (BSM), because the Standard Model (SM) background for the SSD events is known to be very small and can be effectively eliminated. In the context of supersymmetry, the presence of a heavy majorana fermion like the gluino (the superpartner of the SM gluon) is a natural source of SSD. In fact, gluinos give not only SSD’s but also predict their rate to be equal to that for the Opposite-Sign Dilepton (OSD) pair [2-5]. This makes the SSD very characteristic of physics beyond the SM, particularly SUSY. As is expected, extensive studies, some involving detailed simulation of this final state, are already present in the literature [4-10]. However, most of them addressed the SSD events along with other conventional leptonic and/or jets final states that arise in a specific SUSY scenario (like the minimal Supergravity (mSUGRA)) or in some limited corner of an otherwise more general framework, like the Minimal Supersymmetric Standard Model (MSSM). Instead, in this work, our focus is primarily on the SSD events in the full MSSM.

While the SSD events potentially constitute “smoking-gun” signals for some non-standard physics, two pertinent issues need to be addressed carefully:

1. What could be the implications of observing non-SM signals but few or no SSD’s?

2. How far can they go in singling out a particular BSM scenario like SUSY; i.e. could there be more than one candidate scenario to explain the SSD events?

In short, though wonderfully characteristic, how robust and useful are the SSD events for actual purposes?

In this paper we want to be as phenomenological as possible. The low scale world could be supersymmetric but not described by the minimal case, even the full MSSM.
All usual constraints, such as electroweak symmetry breaking, dark matter, $b \rightarrow s \gamma$, etc., are significantly model dependent, so we should not and do not impose any of them.

The paper is organized as follows. Our discussion will be in the context of a $pp$ collider like the upcoming Large Hadron Collider (LHC). Much of the discussion is also relevant for the Tevatron, but for simplicity we focus on the LHC. In Section 2 we discuss how the SSD could be produced and point out some associated features. Basic requirements for having the SSD are sorted out and we discuss to what extent these are unique and/or robust for SUSY scenarios. This leads to the question whether SUSY can thrive without the SSD. Section 3 introduces the set-up for our SUSY analysis, the general assumptions and some tools. Event rates for the SSD along with other possible final states for representative MSSM spectra are studied. In Section 4 we critically review situations where SSD events are absent. We discuss how such null-observations, when combined with a careful study of the other channels (inclusive studies), could provide a wealth of informations on the underlying framework. In section 5 we clarify whether a different theoretical framework could possibly lead to very similar observations and thus could fake SUSY. We then conclude.

2 The Same Sign Dileptons: Origin, Anatomy and the Caveats

2.1 The Origin

At hadron colliders, the source of SSD originally discussed [2-5] was the pair-production of gluinos followed by their leptonic decays (assuming $m_{\tilde{g}} > m_{\tilde{q}}$),

$$pp \rightarrow \tilde{g} \left( \tilde{q} \rightarrow q \tilde{\chi}_{1}^{\pm} (\ell^{\pm} \nu_{\chi_{0}^{i}}) \right) + \tilde{g} \left( \tilde{q} \rightarrow q \tilde{\chi}_{1}^{\pm} (\ell^{\pm} \nu_{\chi_{0}^{i}}) \right).$$

Because of the majorana nature of the gluino$^{4}$, it has an equal probability to decay into $\chi_{i}^{+}$ and $\chi_{i}^{-}$ [3, 6]. This means an equal rate for decay through an off-shell $\tilde{q}$ or via its charge conjugate state. The sign of charge on the leptons follows that of the chargino which, in turn, follows the off-shell squark. Thus in half of the cases gluinos decay into same-sign charginos leading to SSD.

The associated production of a squark and a gluino can lead to an SSD event where the matching-charge lepton comes from the gluino decay, or SSD events could even originate from less likely cascades of same sign squarks, viz.,

$$\tilde{q} \rightarrow q' \tilde{\chi}_{1}^{\pm} \rightarrow q' \ell^{\pm} \nu \chi_{0}^{i}$$

$^{4}$The authors of [5] used a broader definition of ‘Majorana’ to include neutral particles which transform under real representations of the underlying SM gauge group. In Section 5 we discuss how this generalization works for an alternative scenario.
Also, the associated production of a squark and a gluino can lead to an SSD event where the matching-charge lepton comes from the gluino decay; if squarks are not heavy this is an important channel.

Note that if the gluino or the squark is massive enough to decay into the charginos, these decays dominate over its decays into the neutralinos, \( \tilde{g} \rightarrow q\bar{q}\chi^0_i \) \[14, 15, 16\]. Whatever the relative masses of the squark and the gluino, effectively only the left-handed squarks take part in the EW cascade leading to the chargino when the latter is gaugino-dominated \( (\mu >> M^2) \). When the chargino is higgsino-dominated \( (\mu << M^2) \) both do take part but the yukawa-like couplings are only proportional to the corresponding quark-masses.

Decays of heavier neutralinos (which are also majorana fermions) to charginos and \( W^{\pm} \) bosons followed by the leptonic decay of either of the latter could also contribute to SSD events:

\[
\chi^0_i \rightarrow \chi^{\pm}_j W^{\mp}
\]

These neutralinos could be directly produced in the hard scattering via weak-interactions (in which case they are suppressed at the LHC) or be present in the cascade of a squark or a gluino.

### 2.2 The Anatomy

Interestingly, cascades of pair-produced gluinos would lead not only to an equal number of SSD and OSD events but also to the same number of \((++)\) and \((-\ldots)\) lepton-pairs. The majorana nature of the gluino guarantees both. Thus, any significant charge-asymmetry in SSD events would mean they are not solely originating in gluino-cascades \[9, 13\].

On the other hand, usually\(^5\) it takes a squark pair of the same sign when their cascades (involving charginos) lead to SSD (as is the case when \( m_{\tilde{g}} > m_{\tilde{q}} \)). When these squarks come from the strong decay of the heavier gluino once again one expects an equality of \((++)\) and \((-\ldots)\) pairs. However, squarks produced directly would more likely be positively charged, the LHC being a \( pp \) machine. Hence the LHC would see a charge-asymmetry in having more of \((++)\)-SSD pairs compared to \((-\ldots)\) ones \[9, 13\]. This would reflect on squark-gluino mass hierarchy with squarks being lighter than the gluino.

Also, the cascade-patterns discussed in Section 2.1 indicate that the jet-multiplicity is expected to be larger for gluino-cascades \[13\] compared to squark-cascades. This could be another useful observable.

Hence, the typical source of an SSD event is the availability of two same-sign charginos at any stage of the decay chains (see footnote). Note that parton-level hard scattering never leads to such a doubly-charged configuration in a two-body final state.

\(^5\)SUSY cascades involving multiple top and bottom quarks can do the job as well when one of the leptons come from a leptonic b quark decay. This is the same mechanism, albeit under a SUSY cascade, that accounts for a reducible SM background to SSD events \[13\].
Association of the SSD events with majorana fermions, though very characteristic, may not be unique. The necessary and an \textit{a priori} sufficient requirement is the presence of a “chargino-like” massive state in the spectrum with an electroweak quantum number (thus coupling to SM fermions and gauge bosons, see footnote 4 for a rather futuristic generalization in the original paper on this subject) which is kinematically accessible for a cascade. In section 5 we provide a scenario which gives SSD by exploiting this feature and does not contain any ‘majorana fermion’. Until then we restrict ourselves to SUSY scenarios, and the MSSM in particular.

2.3 The Caveats

Over the last two decades numerous studies have confirmed the connection of SUSY and SSD both theoretically and at the level of simulations. We do not know of any work where the contrary has been systematically addressed before the present paper.

As mentioned in the Introduction, one of the main purposes of the present work is to understand how necessary SSD’s are if SUSY exists. With an understanding of the origin of the SSD as discussed in last two sections we now describe situations where SUSY might not lead to SSD. A signal of new physics combined with the absence of SSD in the initial LHC data from a low luminosity run could immediately turn attention to some definite regions of the SUSY parameter space. In practice, indications for SUSY might start coming simultaneously from several channels. However, given that the SSD events are exceptionally clean, analyzing and interpreting them is likely to be less complicated and hence, fast.

We now briefly discuss some situations within the MSSM where the SSD signal would turn out to be rather feeble:

- Few SSD events would result if the charginos are not kinematically accessible down the cascades. This happens when the squarks or the gluino, whichever is lighter (and initiates the electroweak cascade), is almost degenerate with or lighter than the charginos.

- When the gluino mass lies between the masses of different squarks, it is possible that the supersymmetric decays show a preference to non-leptonic channels. An example is when left handed squarks are heavier than the gluino, which in turn is heavier than right handed squarks. In this case left handed squarks, if directly produced, will preferably decay into gluinos. The main decay channel of these will be into quark and right handed squark, and then depending on the EW gaugino spectrum right handed squarks may decay mainly into quarks and LSP, thus eliminating leptons from the SUSY cascade.

- In the split SUSY scenarios \[17\ 18\ 20\] with very heavy sfermions, it was recently pointed out \[21\] that the 3-body decays of the gluino may become marginal due to the presence of strong 2-body radiative decays \((\bar{g} \rightarrow g\chi^0_i)\) enhanced by large logs
coming from the higgsino content in the neutralino\textsuperscript{6}. Having a new decay channel for the gluino opens the possibility of depleting leptons in new ways.

Then there are situations where SSD’s are depleted as a result of an interplay of the SUSY spectrum on the theoretical side and the detector and the simulation criteria employed on the experimental side. For example,

- A wino-like lighter chargino and the LSP neutralino can be very degenerate in the Anomaly-Mediated SUSY Breaking (AMSB) scenarios \cite{23,24}. This renders the decay-lepton in $\chi^\pm_1 \rightarrow \ell^\pm \nu \chi^0_1$ too soft to pass the usual lepton-trigger at the LHC.

- In the “effective” (or “virtual”) Lightest SUSY Particle scenario (VLSP) \cite{35,36,37} the sneutrino mass lies between the mass of the two lightest neutralinos. All decays of the second lightest neutralino $\chi^0_2$ go into invisible neutrino-sneutrino pairs, thus eliminating a possible source of leptons. When the mass difference between the sneutrinos and the lightest chargino $\chi^\pm_1$ is small enough, leptons produced in $\chi^\pm_1$ decays might be too soft to trigger on.

In the next two sections we take up all these issues systematically.

3 Event Rates: the Usual paradigm

Following the existing studies, the channels that we discuss in addition to SSD’s are (i) OSDs with two or more jets, (ii) 1-lepton + two or more jets, (iii) trilepton+jets and (iv) inclusive multi-jets ($n_{jets} \geq 3$).

We do not discuss various backgrounds as they are quite generic, well-known and much studied. We always use the ATLAS \cite{25} criterion for the definition of reach for the masses of the SUSY particles in different channels which looks for at least 10 events with $N_{signal}/\sqrt{N_{background}} > 5$ for an integrated luminosity of 10 fb\textsuperscript{-1}. In practice, we would assume the SSD events to be free from SM backgrounds thus looking for only 10 events for it at 10 fb\textsuperscript{-1}. Our main results are not sensitive to these criteria.

In the following subsections we outline the broad theoretical framework, the scope of the study and the set-up for the analysis followed by a selection of representative sets of MSSM parameters for demonstration.

3.1 The Framework and the Set-up

The popular phenomenological framework we adopt for this section is broadly characterized by having the $U(1)$ and the $SU(2)$ gaugino masses lighter than the $SU(3)$ gaugino mass at the weak scale, \textit{i.e.}, $M_1, M_2 < M_3$.

\textsuperscript{6}A subsequent work \cite{22} with improved treatments (resummed logs) confirms the trend (gluino 2-body decays can overcome easily 3-body decays), although the effect is smoothed out when the SUSY breaking scale becomes very large in which case the log resummation becomes a necessary computation.
We divide our study broadly into two cases: (1) $m_{\tilde{q}} > m_{\tilde{g}}$ and (2) $m_{\tilde{g}} > m_{\tilde{q}}$; which provide two functionally distinct sources for SSD’s— the gluino in the first case and the squark in the latter, as already discussed in section 2.1.

We work at the parton-level, and do not consider tau or bottom decays, or initial or final state radiation (unless explicitly stated). Neither do we consider beam-induced effects like beam remnants, minimum-bias or pile-ups, and jets are pure partonic in nature, not treated with any jet-algorithm (jet-merger was not done). We do not include any efficiency factor other than what is already implied by the choice of triggers and the nominal kinematic cuts (used by the LHC collaborations). However, we make general comments on expectations under a full simulation. None of these effects would make qualitative changes in our conclusions. We generated events with Pythia v6.316 [26] which uses the SUSY Les Houches Accord (sLHA) interface [27] to a SUSY spectrum generator like SuSpect v2.33 [28]. The parton distribution we use is CTEQ5L [30] which is the default to Pythia v6.316. We stick to this set-up throughout this work.

On the experimental side, we consider LHC-data expected from the first year of a low-luminosity run (∼ 10 fb$^{-1}$ over a year), where a detailed study of the SSD’s could prove specially informative. Nominal triggers and kinematic cuts used in the present analysis are motivated by the ones used in the inclusive SUGRA studies by the ATLAS Collaborations [25]. To be specific, these are:

$$p_T^{jet} > 100 \text{ GeV}, \quad E_T > 100 \text{ GeV}, \quad p_T^{lepton} > 20 \text{ GeV} \quad \text{and} \quad \eta_{lepton} < 2.5 .$$

While we move on to slightly different theoretical framework(s) in the subsequent section(s), the set-up described above remains the same throughout this work unless otherwise indicated.

### 3.2 Choice of MSSM parameters and the Event Rates

In this subsection we discuss the event rates for the relative hierarchies between squark and the gluino masses as described above. We set soft squark masses at the weak scale to be degenerate, and the trilinear $A$ parameters are also taken to be degenerate and kept small so that the mixings in the sfermion sector are in turn small and no specific phenomenology emerges dominantly from that sector. The three soft gaugino masses are defined at the weak scale with arbitrary mutual ratios, as opposed to scenarios which presume a gauge coupling unification at a high scale. We initially take $M_1 < M_2 < M_3$, and discuss later how things change with different hierarchies. The higgsino mass parameter $\mu$ and $\tan \beta$ are also input. As mentioned above, we do not impose EWSB conditions since they do not hold in extended MSSMs, and we want to study the parameter space more generally.

The upper panel of Fig. 1 illustrates the cases for $m_{\tilde{q}} > m_{\tilde{g}}$. $\text{Br}[\tilde{q} \rightarrow q\tilde{g}]$ is almost 100% and only electroweak cascades of gluinos matter. Situations with (i) varying soft squark masses with a fixed gluino mass and (ii) varying gluino masses with a fixed soft squark masses are presented which reflect the trends over the squark-gluino mass
Figure 1: Inclusive rates in a somewhat usual paradigm of $M_1 < M_2 < M_3$ with an arbitrary choice of $M_2 = 1.3 M_1$ and with (i) $m_{\tilde{q}} > m_{\tilde{g}}$ in the upper panel and (ii) $m_{\tilde{g}} > m_{\tilde{q}}$ in the bottom panel. The upper (bottom) left one is with a fixed squark/sfermion mass of 4 TeV (500 GeV) and varying gluino mass while for the upper (bottom) right it is the reverse variation with the gluino mass fixed at 500 GeV (1.5 TeV). Other relevant parameters are $\mu = 500$ GeV, $M_2 = 300$ GeV, $\tan \beta = 10$.

If squarks (gluino) are not too heavy, the production rates for squarks (gluinos) contribute significantly to the cascades via the gluino (squark) decay to SSD events, as does the associated production of gluinos and squarks. For a given $m_{\tilde{g}}(m_{\tilde{q}})$, the squark (gluino) contribution to SSD events decreases gradually with increasing $m_{\tilde{q}}(m_{\tilde{g}})$. As expected, with increasing mass, the residual events in the inclusive signal come mainly from the production of lighter gauginos. Observation of such a kind of event-pattern would immediately indicate a decoupled spectrum for the squarks (sfermions in general) and the gluino while suggesting lighter gauginos. It could also be suggestive of some kind of non-universality of gaugino masses at some high scale.

Table 1 shows how the squarks and the gluinos gradually decouple from the inclusive signatures with growing masses as is indicated by the constancy of the numbers. These
are residual events coming mainly from the electroweak gaugino production which remains unaffected as squarks and the gluino get heavier. Table 1 also shows that SSD could be the only signature surviving if the gauginos are light enough.

| \(m_{\tilde{q}, \tilde{g}}\) (GeV) | \(m_{\tilde{g}}\) (GeV) | SS Dilepton | Trilepton | OS Dilepton | 1-lepton | \(\geq 3\)-jets |
|---|---|---|---|---|---|---|
| 1250 | 1250 | 29 | 21 | 122 | 720 | 2462 |
| 1250 | 1500 | 8 | 7 | 52 | 337 | 1183 |
| 1500 | 1500 | 10 | 7 | 39 | 219 | 714 |
| 1500 | 1750 | 3 | 2 | 18 | 112 | 387 |
| 1750 | 1750 | 3 | 2 | 16 | 87 | 244 |
| 1750 | 2000 | 1 | 1 | 9 | 54 | 149 |
| 2000 | 2000 | 1 | 1 | 8 | 43 | 102 |
| 2000 | 2500 | 1 | 0 | 5 | 31 | 58 |

Table 1: Gradual decoupling of gluino and squarks in the inclusive signatures via electroweak cascades. All the final states have accompanying hard missing transverse energy and the leptonic final states have at least two hard jets in addition. The MSSM parameters are as described in Fig. 1.

## 4 Depleted SSD’s and SUSY

If there are regions of MSSM parameter space where SSD’s could be depleted, it would make it initially harder to identify SUSY. In the present section, we study some definite but still generic situations with significantly depleted SSD’s and the associated patterns in the MSSM spectrum.

In most studies a channel is dropped from the discussion once its significance falls below a critical level of observability. Here we emphasize that a null observation as part of a pattern with other observations may be very instructive, both in identifying the basic new physics origin (i.e. is it SUSY), and for implications about the underlying theory.

In Section 2.3 we mentioned some generic situations when SSD’s can be depleted. Here we examine them.
Figure 2: Inclusive rates as a function of (a) $M_2$ with $\mu = 750$ GeV and (b) $\mu$ for $M_2 = 400$ GeV when $m_\tilde{q}(1 \text{ TeV}) > m_\tilde{g}(500 \text{ GeV})$. Other relevant inputs are $M_2 = 2 M_1$ and $\tan \beta = 10$.

Case I: Heavy charginos

This is the case when either the gluino or the squark, whichever effectively cascades, is lighter than or almost degenerate with the lighter chargino.

(a) $m_\tilde{g} < m_\tilde{q}$: In this case, the gluino undergoes the electroweak cascade. When $M_3 < M_2$, the gluino may be lighter than or almost degenerate with the lighter chargino (including the large radiative corrections to the gluino mass). This is an unconventional but possible region of parameter space.

In the following situations ((a),(b)) we choose masses of gluino and squarks within the reach of the LHC (500 GeV and 1 TeV or vice-versa). This guarantees a large production cross section for these sparticles. Later, in situation (c) we demonstrate what happens for larger masses with a particular example.

In Fig. 2a, we illustrate how events with SSD’s drop out as the lighter chargino mass approaches the mass of the gluino which is fixed at 500 GeV while the generic squark mass is 1 TeV. The variation of the chargino mass is implied by that in $M_2$ along the x-axis: in fact we fix $\mu = 750$ GeV so the mass of the lighter chargino is close to $M_2$ when $M_2 < \mu$ as applicable for this figure. In Fig. 2b, the variation with $\mu$ is shown for a fixed $M_2 = 400$ GeV. In both cases, the SSD disappear.

(b) $m_\tilde{q} < m_\tilde{g}$: In this case, the spectrum is reversed and the squarks undergo the electroweak cascade. In Figs. 3a and 3b we present situations with gluinos as heavy as 1 TeV and squarks around 500 GeV when $\mu$ and $M_2$ are varied respectively keeping the other ones fixed.

(c) $m_\tilde{q} \sim 5$ TeV and $m_\tilde{g} = 1$ TeV: Here we discuss a generic situation with heavier squarks and gluinos. For all practical purposes, the squarks cease to contribute to the
final rates significantly. The mass of the gluino is still kept relatively low so that it contributes adequately to the leptonic final states we are interested in. In Figs. 4a and 4b we illustrate the event rates again as functions of $M_2$ and $\mu$ respectively. The event rates drop as the primary production cross sections decrease. However, the variations with $M_2$ and $\mu$ still have the same physics explanation as before.

Note that in all these cases the suppression of SSD’s occurs by suppressing the cascades of gluino/squarks to the lighter chargino. On the other hand, even for such parameters the second lightest neutralino always turns out to be roughly degenerate with the lighter chargino and similar in composition, given the structure of the chargino and the neutralino mass matrices in the MSSM. Inevitably, electroweak cascades of squarks/gluino to the second lightest neutralino, which is another source of leptons
under cascades, get suppressed. Thus, in general, depletion in SSD’s is not an isolated phenomenon but is accompanied by depletion in other leptonic channels. However, given different combinatoric factors involved in determining the rates of different leptonic final states they get affected in somewhat different proportions, as is seen from Figs. 2-4.

The SSD’s and the trileptons have a similar rate. In Figs. 2-4 we see that the trileptons lose out to the SSD’s and deplete to unobservable levels before SSD’s do. The channels surviving when both of these get critically depleted are the OSDL+jets, 1-lepton+jets and the inclusive jet events. While the depletion gives a pretty good idea of the relative hierarchy of the EW gaugino masses, the event rates for the surviving modes (especially the jets) hint at the squark and gluino mass scales and their relative hierarchies. When combined with clues from the electroweak gaugino sector this could shed light on non-universality of gaugino masses.

For Figs. 2-4, we maintained to the relation $M_2 = 2 M_1$ for the $SU(2)$ and the $U(1)$ gaugino masses. As is well known, this is what happens in mSUGRA type scenarios with gaugino mass unification at a high scale. In Fig. 1 we also considered a somewhat different relation $M_2 = 1.3 M_1$ as an alternative to unification. Now we study the impact of gaugino mass relations on the leptonic events.

The relation between $M_1$ and $M_2$ affects the leptonic rates by altering the branching fractions (BF) of gluinos or squarks to the lighter chargino and the second lightest neutralino. The latter two are two important sources of leptons in cascades at hadron colliders. We fix $M_2$ so that the ratio of $M_3/M_2$ remains fixed while varying $M_1$. With increasing (decreasing) $M_2/M_1$ the mass of the LSP decreases (increases) which in turn affects the decays of squarks and gluinos to the LSP, the lighter chargino and the second lightest neutralino. For $M_2/M_1 \gtrsim 1$ the BF’s compete and the BF to lighter charginos usually dominates over that to a rather heavy LSP. Under such circumstances, one still expects copious production of SSD’s. However, as the LSP mass approaches the mass of the lighter chargino, the decay $\chi_1^{±} \rightarrow \chi_0^{±} \ell ± \nu$ gets suppressed thus depleting the leptons and hence the SSD’s. On the other hand, with growing $M_2/M_1$ the LSP mass decreases and the BF to LSP increases thus depleting the leptons (and SSD’s). This does not continue long as the competing BF’s get saturated, and does not deplete SSD’s beyond a certain point. For $M_2/M_1 = 2$ such a saturation is already reached.

In Table 2 we present the variation in the rates as a function of $M_2/M_1$. We chose the inputs from Fig. 2a for direct comparison and fix $M_2 = 400$ GeV. The trends are clearly as expected and as discussed above.

In most of the cases in Figs. 2-4 the trilepton final state gets a similar or worse suppression than the SSD’s. But the OSDL or 1-lepton final states could still be statistically significant thanks either to the combinatorics or the low lepton-multiplicity involved or both. Such a situation suggests a near degeneracy of the squarks/gluino and the lighter electroweak gauginos. However, one should keep in mind that unlike SSD’s these leptonic channels are likely to have significant SM backgrounds which might not be put under control with the naive ATLAS-type cuts [25] we employ here (which have
Table 2: Variation in the rate of Same-Sign Dileptons as a function of $M_2/M_1$ with $M_2 = 350$ GeV. The other relevant parameters are the same as in Fig. 2a, i.e., $m_{\tilde{g}} = 500$ GeV, $m_{\tilde{q}} = 1$ TeV, $\mu = 750$ GeV and $\tan \beta = 10$.

mainly been studied for mSUGRA scenarios and need further examination.

Case II: When $m_{\tilde{q}_R} < m_{\tilde{g}} < m_{\tilde{q}_L}$ or $m_{\tilde{t}_1} < m_{\tilde{g}} < m_{\tilde{q}_L} \simeq m_{\tilde{q}_R}$

A spectrum like this can arise from non-universal soft scalar masses at a high scale with natural splitting between left and right handed ones \[32, 31, 33, 34\]. Also, $m_{\tilde{t}_1}$ can be comparatively light at the weak scale even in universal scenarios as $m_{\tilde{q}}$ runs down faster due to its large yukawa coupling. Apart from that, from a pure MSSM standpoint this kind of a spectrum could have interesting phenomenology. Here, all left handed (or heavy) squarks would decay mostly to gluino and a quark followed by the gluino decaying to right handed squark (or $\tilde{t}_1$) and a quark (top quark). The right handed squark mostly undergoes a decay to quark and the LSP thus depleting leptons in the final states. The phenomenon is illustrated in the left side of Fig. 5.

If $\tilde{t}_1$ is the only squark lighter than the gluino, the result is a little bit involved. The gluino would have a 100% (in contrast to only a few percent when all other right handed squarks are lighter than the gluino) decay branching fraction to $t\bar{t}$ shared equally by $Br[\tilde{g} \rightarrow \tilde{t}_1\bar{t}]$ and $Br[\tilde{g} \rightarrow \tilde{t}_1^*t]$. Note this ensures having some same sign tops from the decay of gluinos which in turn would lead to the SSD. In fact, the associated stops could boost the SSD count through combinatorics if $Br[\tilde{t}_1 \rightarrow t\chi^0_1]$ dominates. This gives leptons from top quarks. Hence, enhancements in all the leptonic channels are present and illustrated in the right of Fig. 5 for a similar variation of the heavier squark mass scale as for the left figure. Final states with 4 tops is a very likely possibility.

Left handed squarks may still have significant branching fractions to quarks and electroweak gauginos if they are not heavy compared to the gluino. Decays of these gauginos may result in some leptons.

However, as expected, and can be seen in Fig. 5 with increasing masses for the left handed squarks (with the masses of the gluino and the right handed squarks kept fixed)
the strong decay branching fraction for $\tilde{q}_L \rightarrow q \tilde{g}$ starts dominating and depleting the leptons in the final state.

In any case, the SS dileptons and the trileptons get heavily depleted to an unobservable level for such a spectrum.

**Case III: When the radiative decay $\tilde{g} \rightarrow g \chi_i^0$ is significant**

As pointed out in Section 2.3, the spectrum here is reminiscent of a Split SUSY scenario [17, 18, 20] with very high squark masses ($\geq \mathcal{O}(10)$ TeV). A gluino, which is comparatively light becomes the only interesting strongly interacting sparticle to study. Decays of gluinos in such a framework have recently been studied in Refs. [21, 22]. In the first reference, an interesting scenario was discussed, in which stops are lighter than the other squarks. Depending on the gaugino-higgsino spectrum, the 2-body radiative decays can then dominate by the interplay of various suppressions in the 3-body decays. Radiative decays are enhanced inside the loop by lighter stop masses, and they also benefit from large logs (this is a Split SUSY effect, requiring the presence of some higgsino content in the neutralino). There is also some phase space enhancement of 2-body versus 3-body decays. Finally the dominant 3-body decays of the gluino into a final state containing at least one top (because of lighter stops) might be kinematically forbidden or suppressed (given the large mass of the top quark this is not an unreasonable situation). In this case, 2 gluon jets + missing energy might be the main signal for SUSY at LHC, and leptons would be completely depleted in the signal. It is something to keep in mind if signals for physics BSM prove themselves hard to find at LHC.

We did not find any generic region of parameter space where the inclusion of radiative decays of the gluino\(^7\) could affect an otherwise healthy rate for SSD significantly for not

\(^7\)We do not know of any event generator which includes these radiative gluino decay modes. The
too heavy a squark mass ($\lesssim 5$ TeV). The reason is simple. To deplete the SSD we need a handful of them from the decays of charginos which in turn demands a significant $\text{Br}[\tilde{g} \to \chi_1^\pm q\bar{q}']$ to start with. Note that the latter requires a high gaugino content in the chargino (unless $\tilde{t}_1$ mediated gluino decay becomes important) and ensuring that inevitably increases the gaugino content of the LSP. As pointed out in Ref. [21] this does not favor $\text{Br}[\tilde{g} \to \chi_1^0]$. Hence, a mixed gaugino-higgsino region of the SUSY parameters would be needed. But such an arrangement requires the LSP to be heavy enough ($\sim m_{\chi^\pm_1} \lesssim m_{\tilde{g}}$) such that $\tilde{g} \to q\bar{q}\chi_1^0$ could gradually start losing out to the radiative 2-body decay. In the absence of heavy squark propagators (as in Split SUSY) this is the only way to prevent $\tilde{g} \to q\bar{q}\chi_1^0$ from leading. This leads to a rather fine-tuned (but possible) region of parameter space by requiring at the same time not too degenerate a $\chi_1^\pm$ and a $\chi_1^0$ such that the leptons from the chargino decay are still observable.

**Case IV: When lighter chargino is accessible down the cascade but degenerate with the LSP**

![Figure 6: Event-rates for different lepton and jet final states (left) and top quark content in SSD events (right panel) as a function of the ratio between third and lighter generation squark masses. Shown in the figures are the MSSM inputs used: a typical AMSB gaugino spectrum with $\mu$ chosen to be larger than the mass of the gluino, and with $\tan\beta = 25$ (we checked that with a value of $\tan\beta = 5$ we did obtain results with no visible differences). The heights of the respective bars on the right figure directly correspond to the total SSD event-rates in the left figure and the length of each shaded portion on the right indicates the proportional contributions.](image)

In this case, leptons from the decay $\chi_1^\pm \to \ell^\pm\nu\chi_1^0$ would be too soft to be observed because of the chargino-LSP degeneracy. This depletes leptons in the final states and SSD in particular. The presence of soft charged pions and a displaced vertex from the decay $\chi_1^\pm \to \pi^\pm\chi_1^0$ would be very characteristic in this situation [19].

only publicly distributed decay code known to us that includes these modes is SDECAY [29]. Since Pythia uses its own decay routines, we had to supplement it with the results from SDECAY.
We consider such a spectrum as a part of the MSSM. As already noted, the issue central to depleting leptons is the mass-hierarchy among the gauginos (including the gluino) and the squarks. Hence, we freely vary these soft parameters as before within the framework of the MSSM. Thus, we end up with a spectrum which looks like that of the AMSB gaugino sector (but without restricting ourselves to that specific scenario); i.e. the LSP is Wino like and almost degenerate with the lighter chargino. The second lightest neutralino is Bino-like. The gluino is heavier than these electroweak gauginos. The squarks, the sleptons and the higgsinos are all more massive. Thus, production of gluinos and their subsequent decays constitute the dominant SUSY process at the LHC. In such a scenario we focus on the hard lepton+jets+\not{E}_T events.

In such a scenario SSD events are generally associated with multiple top quarks. The reason for this is as follows. Decays of the lighter chargino would not lead to SSD events for the reason mentioned above. Also, the second lightest neutralino being Bino-like (for heavy enough \(\mu\)) its decay to \(W^\pm\) and Wino-like lighter chargino, \(\chi_2^0 \rightarrow \chi_1^\pm + W^\mp\) is heavily suppressed. This rules out another source of leptons (and specifically SSD) in \(W^\pm\)'s. With heavier gauginos somewhat decoupled (with masses \(O(\mu)\)), the only significant source for SSD's are \(W\)'s coming from the decays of Same-Sign top quarks, which in turn appear in decays of the gluino into charginos and/or neutralinos:

\[
\tilde{g} \stackrel{t\bar{t}, b\bar{b}}{\rightarrow} tt(b)\chi_i^0(\chi_i^\pm) \quad \text{with} \quad t \rightarrow bW^\pm.
\]

Thus charges on hard leptons could be traced back to those on the top quarks pointing to Same-Sign or Opposite-Sign top quark pairs down the cascade. Of course, Same-Sign top pairs or bottom pairs could be as valuable a signature as SSD in general.

One would therefore expect the hard lepton signals to gradually turn weaker as stops and/or sbottoms grow in mass compared to squarks from the first two generations. In fact, this is reflected in the left of Fig. 6. When varying the value of the third generation squarks mass up to 1.6 times the generic squark mass for the lighter generations, the SSD, the OSD and the trilepton signals weaken to an unobservable level for a 10 fb\(^{-1}\) of LHC data.

The 1-lepton final state, though weakening, continues to enjoy the usual combinatorial advantage of low-multiplicity and still has a healthy rate. Since hard jets predominantly come from initial cascades, the 3-jet inclusive rate, in our case, gets a predominant contribution from jets in the \(\tilde{g}\) decay. Squarks with masses around 2 TeV are sub-dominant at their production level, more so for individual squark flavors like \(\tilde{t}\) or \(\tilde{b}\). Hence, increasing these masses does not affect the jet rates noticeably.

In the right panel we show the admixture of top-multiplicities and their charge-content in the SSD events as a function of the same variable as for the left figure. Clearly, ‘topless’ SSD events are extremely rare while the majority of SSD events contain two top quarks. Such an association of SSD events with top quarks seems to be very characteristic of a AMSB-like gaugino mass hierarchy (when \(\mu > m_{\tilde{g}}\) such that decays like \(\tilde{g} \rightarrow \chi_3^0, \chi_3^\pm\) are kinematically forbidden) and could help understand possible new events at the LHC.
Figure 7: Variation in different event rates as a function of $M_2$, such that $M_1 = M_2 + 200$ GeV, $m_{\tilde{g}} = 750$ GeV, and $\mu$ is fixed at 800 GeV. The mass of third generation squarks is $m_{\tilde{q}_3} = 1.6$ TeV while for the first and second generations we take $m_{\tilde{q}_{1,2}} = 2$ TeV. As the gaugino masses $M_1$ and $M_2$ increase while maintaining the gluino mass fixed, the phase space for top events in gluino decays is reduced and so are the SSD events, which in this scenario all come from top decays.

In Fig. 7, we show that the hard lepton signals would also get reduced to an unobservable level with increasing Wino and Bino masses, because the phase space for top events gets reduced in the decay $\tilde{g} \rightarrow \tilde{t}^\tau \tilde{t} (b) \chi^0_i (\chi^\pm_i)$. Significantly enough, even the single lepton events could disappear for $M_2$ as heavy as 600 GeV in our present example. Although reduced, the trijet channel remains still quite populated for the same reasons discussed before.

Case V: The Higgsino LSP region

Next we look into the case where the gluino decays to lighter chargino which is almost a pure higgsino, unlike in Case II where it was mainly Wino. This is achieved by having $\mu < M_1, M_2$. In this case $\chi^0_1, \chi^0_2$ and $\chi^\pm_1$ constitute the set of lighter gauginos (and also the lightest of the sparticles) with $m_{\chi^0_1} \sim m_{\chi^0_2} \sim m_{\chi^\pm_1} \sim \mu$ and all of them are higgsino dominated. The third lightest neutralino used to have a mass $m_{\chi^0_3} \sim \min(M_1, M_2)$ and be correspondingly Bino- or Wino-like while the reverse is true for the heaviest neutralino and the heavier chargino. Here, for the purpose of demonstration, we will consider two cases: (a) $\mu << M_1 < m_{\tilde{g}}$ and (b) $\mu < m_{\tilde{g}} < M_1$. In both cases we will forbid gluino-to-Wino decays by fixing $M_2$ large ($M_2 = 900$ GeV).

For case (a), the main phenomenological difference with the AMSB-like scenario is that the Binos ($\chi^0_3$ in this case) produced from the gluino decays do couple with the
Figure 8: Same sign dilepton rate in the higgsino LSP region and the multiplicity of the associated top quarks for (a) $\mu < M_1 < m_{\tilde{g}}$ (left) and (b) $\mu < m_{\tilde{g}} < M_1$ (right). The input parameters used are indicated in the figures.

Higgsino-like lighter chargino and thus could undergo the decay $\chi_3^0(\tilde{B}) \rightarrow \ell^\pm \nu \chi_\pm^\mp(\tilde{H}^\pm)$. These leptons can be hard enough for large $\Delta M = M_1 - \mu$. Thus we get an extra source of leptons in the form of $\chi_3^0(\tilde{B})$ which, unlike the AMSB-like case, does not necessarily have accompanying top quark(s). Indeed, the left of Fig. 8 shows how topless SSD events first gain significance and then dominate as stops and sbottoms grow in mass.

In case (b), when gluinos only have access to the light higgsinos we expect a similar behavior as in AMSB, namely a direct association of SSD and top events. The right panel of Fig. 8 illustrates this correlation. However, this time, a comparison with the right panel of Fig. 6 reveals that a depletion in SSD events is harder to achieve with an increasing ratio of third to lighter generation squark masses, because of the yukawa enhanced couplings between (s)tops and higgsinos (unlike (s)tops and the winos in the AMSB-like scenario).

Figure 9 shows that by increasing both $\mu$ and $M_1$ starting at the values of case (IIIa), in which gluinos can decay both into Binos and Higgsinos, we only manage to reduce the hard lepton signals to minimal levels when $M_1 > m_{\tilde{g}}$ and when tops become kinematically forbidden in gluino decays (with $\mu = 600$ GeV and $M_1 = 800$ GeV). Of course we can also eliminate the leptons in case (IIIb) above by increasing $\mu$ (i.e. by making the lighter higgsinos heavier, as shown in Fig. 9). With the Bino channel closed from the start, top quarks gradually get kinematically disfavored in the decay $\tilde{g} \rightarrow tt(\tilde{b})\chi_1^0(\chi_1^\pm)$ in a way similar to when $M_1$ and $M_2$ were increased to achieve the same effect as illustrated in Fig. 6.

Then, just as in the AMSB case, SSD events do exist but do not pass the usual cuts due to their extreme softness.

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8Of course, $\tilde{g} \rightarrow tt\chi_{1,2,3}^0$ and $\tilde{g} \rightarrow tb\chi_1^\pm$ are all possibilities which would involve top quarks. However, unlike previously, this time these top quarks are not unique sources of observable leptons.
Figure 9: Depleting leptons by increasing $\mu$ and $M_1$ simultaneously. The mechanism of depleting leptons in the higgsino LSP region has in it a parallel of what shown in Fig. 7 with varying $M_2$.

**Case VI:** When $m_{\chi^0_1} < m_{\tilde{\nu}} < m_{\chi^0_2} \simeq m_{\chi^\pm_1} < m_{\tilde{\ell}_L}$

This is the scenario with “effective” (or “virtual”) Lightest SUSY Particles (ELSP or VLSP) [35, 36, 37]. The cascade $\chi^0_2 \to \tilde{\nu} \to \nu \chi^0_1$ has a 100% branching fraction. This ensures both $\chi^0_2$ and $\tilde{\nu}$ decay invisibly, “effectively” like the LSP. $\chi^0_2$ ceases to be a source of leptons thus depleting them in the final state.

For the lighter chargino, which is almost degenerate with $\chi^0_2$, $\text{Br}[\chi^\pm_1 \to \tilde{\nu} \to \nu \chi^0_1 \ell^\pm]$ would be 100%. For small $\Delta m = m_{\chi^\pm_1} - m_{\tilde{\nu}}$ (which is the case as we will see below) the leptons could be too soft to trigger on, so $\chi^\pm_1$ would decay invisibly [38].

The mass-splitting between $\tilde{\nu}$ and its partner slepton in the doublet (at the lowest order) is given by

$$m^2_{\tilde{\ell}_L} = m^2_{\tilde{\nu}} - m^2_W \cos 2\beta$$

and constrained by the $SU(2)$-breaking $D$-term. The splitting is thus a function of $\tan \beta$ and goes down sharply with increasing slepton mass. For example, the achievable splitting for $m_{\tilde{\ell}} \approx 500$ GeV (1 TeV) is around 7(3) GeV for large $\tan \beta$.

In Fig. 10 we present the leptonic activity for a VLSP spectrum (in red, the middle bars) and compare it to other situations. For the choice of inputs, see the figure and its caption.

A very low SSD count for an ideal VLSP spectrum is not due to a suppressed leptonic branching fraction $^{10}$ of $\chi^\pm_1$, but this is an artifact of a small $\Delta m$ when the emerging lepton is too soft to pass the $p_T$ trigger.

\footnote{Such a spectrum can easily be accommodated in popular SUSY-GUT scenarios with gaugino mass unification at the GUT scale [38].}

\footnote{Br[$\chi^\pm_1 \to \tilde{\nu} \ell^\pm$] = 100% which could potentially be a copious source of SSD with gluinos effectively cascading.}

\[20\]
As one makes the sleptons lighter two things happen. Charged sleptons could become kinematically accessible in the 2-body decay of $\chi^\pm_1$. The leptons in the decay $\tilde{\ell}^\pm \to \ell^\pm \chi^0_1$ could easily be hard enough (when $\Delta m' = m_{\tilde{\ell}} - m_{\chi^0_1}$ is large enough, which is the case here) to pass the $p_T^{\text{lepton}}$ cuts and thus contribute to the SSD signal. For even smaller slepton (and hence sneutrino) masses, leptons from $\chi^+_1 \to \tilde{\nu}_\ell^\pm$ start getting harder as well thus reinforcing the SSD count. This is well described by the green bars (the leftmost bars).

For heavier sleptons, the 2-body decay modes of the lighter gauginos close up. Democracy is thus restored among all possible 3-body decay modes involving both leptons and the jets with usual dependence on the masses and the couplings. These tend to restore the lepton counts in the final state. In Fig. 10 the effect is presented in blue bars (the rightmost ones).

![Figure 10: Leptonic activities for a VLSP spectrum and spectra just away from it. The VLSP spectrum in MSSM is generated through Suspect v2.33 with the following major inputs: $M_2 = 1.2 M_1 = 412$ GeV, $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = 412$ GeV except for $m_{\tilde{\tau}_R} = 419$ GeV, $M_3 = 650$ GeV, $m_{\tilde{q}_L} = m_{\tilde{q}_R} = 800$ GeV, $\mu = 900$ GeV and $\tan \beta = 3$. For heavier slepton case the slepton masses were set at 425 GeV while for the lighter slepton analysis a value of 400 GeV was set. Rest of the inputs were kept fixed to those in the VLSP case.](image)

The discussion again holds for the trilepton counts. However, for OSDL and single leptons channels the combinatorics and/or lepton-multiplicity ensure already healthy rates even for the VLSP spectrum. In these cases, slipping to either side of the spectrum leads to nothing drastic.

On the other hand, the inclusive 3-jet signal seems insensitive to such variations of spectrum. This indicates that these jets are predominantly primary jets in the decay of squarks and the gluino which are hard enough to survive a strong $p_T^{\text{jet}}$ cut. One could exploit the jet-count (possibly supplemented by effective mass distributions) to have a reasonably fair idea of the squark and the gluino masses. The low leptonic activity
compared to the jets then suggests VLSP sleptons as a viable explanation.

5 SSD’s and New Physics

SSD’s are not only very characteristic for SUSY but perhaps also for a scenario like the recently proposed Universal Extra Dimensions \[39\] where they could be generated in a manner analogous to the way they are in SUSY, even though the UED spectrum does not contain any majorana fermion.

In UED, the level 1 Kaluza-Klein (KK) excitations of the SM particles (which are the so-called level ‘0’ modes in KK language) could all lie in the TeV range and mimic a SUSY spectrum except for their spins. For example, there is a one to one correspondence between each and every scalar-fermion in SUSY to a level 1 KK-fermion (level 1 quarks and leptons), between a (fermionic) gaugino in SUSY to a level 1 excitation of an SM gauge boson, \(\gamma_1\), \(Z_1\), \(W_{1\pm}\) etc.. Thus the UED spectrum looks similar in appearance to SUSY, which motivated some recent studies \[40, 41, 42\] on its collider phenomenology vis-a-vis SUSY.

In this section, we discuss how cascades involving level-1 UED excitations could turn out to be very similar to the corresponding ones in SUSY. This is possible since in both SUSY and UED the couplings among different species are related to their SM counterparts. With an inbuilt discrete symmetry called \(K\)-parity the UED phenomenology resembles that of SUSY with conserved \(R\)-parity. Level 1 quarks (\(q_1\)) and the \(g_1\) can be produced at the LHC much in the same way as the squarks and the gluino in SUSY. The similarity in couplings, a similar spectrum and the imposed \(K\)-parity ensure analogous decay chains for these strongly interacting particles. A \(g_1\) produced in the hard scattering could undergo a \(q_1\) mediated 3-body decay to a pair of SM quarks and a \(W_{1\pm}\) much in the same way as the gluino in SUSY decays into a chargino:

\[
g_1 \rightarrow q'\bar{q}W_{1\pm}.
\]

On the other hand, level 1 quarks could follow a similar path in their cascades to that of the squarks in SUSY. If a pair of same sign \(q_1\) is produced in hard scattering, they may undergo the following electroweak cascade in a way similar to squarks in SUSY,

\[
q_1 \rightarrow \bar{q}'W_{1\pm}.
\]

In either case the \(W_{1\pm}\) could undergo the following decay

\[
W_{1\pm} \rightarrow \ell^\pm\gamma_1,
\]

again like a chargino does in SUSY. Here \(\gamma_1\) is the level 1 excitation of the SM photon (more precisely the U(1) gauge boson of the SM, since the effective electroweak mixing angle at the first KK-level is known to be small). Thus, in close analogy to SUSY cascades the level 1 gluon (again, a color octet vector boson) or a level 1 quark (an
electromagnetically charged fermion) in UED, when produced in pairs (or in association) at the LHC, would lead to the SSD’s. It does not take majorana fermions to end up with SSD’s.

Qualitatively much of SUSY phenomenology (at colliders) could have a close correspondence to UED and these two approaches could potentially fake each other. The difference in the spins for corresponding particles in SUSY and the UED is one direct probe into what is being observed. Recently this issue has been addressed \[40, 41, 42\] in the context of a future linear collider. There are recent studies on probing the spins directly \[2, 43\]. Below we will propose a possible way to address this issue and perhaps largely solve the problem.

The framework used in Refs.\[40, 41\] is the minimal version of the UED where one makes a simplifying assumption that the boundary kinetic terms vanish at the cut-off scale \[44\]. That assumption, however, restricts the spectrum such that the splitting among different KK excitations may not be enough to result in hard enough jets and/or leptons that could pass the stringent cuts at the LHC. Thus, such a (minimal) version of the UED is not likely to show up at the LHC.

On the other hand, the boundary terms receive divergent contributions thus requiring counter terms. As observed in Ref.\[44\], the finite parts of these counter terms remain undetermined and are free parameters of the theory. These arbitrary extra degrees of freedom could be exploited to end up with an unconstrained UED (UUED) scenario where the different KK excitations are reminiscent of an unconstrained MSSM spectrum. In Ref.\[44\] a close analogy has been pointed out between these two scenarios and a similarity between the unknown soft masses of MSSM and the unknown counter terms of the UED is drawn. A qualitatively similar effect is discussed recently in the context of an explicit Lorentz violation within UED by studying a subset of operators that leaves 4-D Lorentz invariance intact while breaking it in the 5-th dimension\[45\]. Phenomenologically, these provide us with a broad scenario where faking (between SUSY and UED) could be rather complete qualitatively. This is especially significant at the LHC where the kinematic cuts would help rule out the minimal version of the UED (MUED) scenario.

Table 3 gives us an impression of how efficient such a faking could be by comparing the corresponding MSSM and the UUED production cross sections and the cascade branching fractions for the particles involved. The input MSSM parameters used are $M_1 = 325 \text{ GeV}$, $M_2 = 375 \text{ GeV}$, $M_3 = 494 \text{ GeV}$, $\mu = 1 \text{ TeV}$, $\tan \beta = 10$ leading to $m_{\tilde{g}} = 600 \text{ GeV}$, $m_{\tilde{\chi}_1^0} = 322 \text{ GeV}$, $m_{\tilde{\chi}_2^0} = 385 \text{ GeV}$. The soft scalar masses are fixed at 1 TeV while the $A$ parameters are somewhat arbitrarily taken to be 200 GeV to ensure the sfermion mixing does not become much of an issue. An unconstrained version of UED \[46\] was then tuned in CalcHEP/CompHEP \[47\] to have an identical spectrum. The effective cascade rates in different final states were then calculated by folding the basic cross sections (without cuts) with the respective branching fractions for both MSSM and the UUED keeping track of the combinatoric factors\[11\].

\[11\] A detailed comparison of the different final states at the generator level is rather involved and
The parton-distribution function is set at $Q = m_{g_1}(m_{\tilde{g}})$. We see from Table 3 that the production cross section for the $g_1$ pair in UUED far exceeds (an order of magnitude) that for the $\tilde{g}$-pair in MSSM for identical spectra$^{12}$, because the $g_1$ has spin 1 [2, 48]. Next we find that the branching fractions of $\tilde{g}$ and the $g_1$ to chargino and $W_1^\pm$ are identical. This reflects the known similarity of couplings found in the MSSM and the UED, especially when the lighter chargino is predominantly a $\tilde{W}^\pm$ (which is the case here as $\mu(500 \text{ GeV}) \gg M_2(300 \text{ GeV})$). As we proceed with the cascade, a flipping of the leptonic and jet branching fractions is noted for the decaying chargino when compared to a decaying $W_1^\pm$. Actually, the chargino branching fractions resemble the same for $W^\pm$ in the SM. This is because its 3-body decay is mainly mediated by $W^\pm$, the sfermions being almost decoupled for the purpose because of their heaviness. In UED $W_1^\pm$, a pure $SU(2)$ adjoint state, does not couple to $B_1$, the pure $U(1)$ state. Thus, the 3-body decay of $W_1^\pm$ is solely mediated by heavy KK-fermions$^{13}$. $B_1$ appears in the secondary vertex and since it has only hyper-charge couplings to fermions the leptonic widths are larger than the jet ones. This is especially true when the fermions involved are left-handed in nature since they couple to $W_1^\pm$.

Table 3 thus indicates larger event rates both in the leptonic and jet final states for the UUED. While a suppressed hadronic branching fraction of $W_1^\pm$ somewhat compensates for an enhanced $g_1$-pair cross section it is always a win-win situation for the leptonic final state. Hence, for a similar spectrum a larger imbalance in lepton and jet events is expected in UUED. However, unless we have information about the actual masses involved, it could be difficult to decide on one or the other candidate scenario solely by looking at the event rates. The problem is thus very generic in nature and not limited to SSD’s. More specifically, almost any given channel could be made to be the same for SUSY at UUED. But, most importantly, the patterns for several signatures are different, so it should not be difficult to distinguish them with sufficient data. Particularly the above-noted flipping of leptonic and jet branching ratios, when normalized appropriately can distinguish.

In fact, it is likely that one can use the connection of spin to production cross section to distinguish between SUSY and UUED if a discovery that seems naively to be consistent with both should occur. As pointed out earlier UUED enjoys a larger cross section compared to MSSM for a given mass scale. Thus to distinguish, one has to associate the observed event rates to a mass scale relevant to the process. Here we examine a simple way to do this and find a very robust result. Presumably more careful definitions of the mass scales will strengthen the result when there is data.

As is well-known, a kinematic distribution related to the mass scale of new physics technically challenging (handling multibody final states with 8 to 10 particles in the final state with full matrix elements as is characteristic for the CalcHEP/CompHEP). Nonetheless, the basic production cross sections and the branching fractions presented here are likely to provide a fair estimate.

$^{12}$We will get back to this issue later in this section.

$^{13}$This is best reflected in the decay width of $W_1^\pm$ which, in the present case, is $\mathcal{O}(10^{-10} \text{ GeV})$ and almost 6 orders of magnitude smaller than the chargino width. The latter might get further enhanced as the mediating $W^\pm$ gets closer to being on-shell.
Table 3: Cross-sections for $\tilde{g}$-pair and $g_1$ pair productions in MSSM and UUED respectively for an identical spectrum (see text) along with relevant branching fractions in their cascades.

that could be studied at the LHC is the so-called effective mass $M_{eff}$

$$M_{eff} = E_T^{miss} + \sum_{jet} p_{T, jet}.$$
Figure 11: Lowest order cross sections from CompHEP as a function of final state mass for $pp \rightarrow \tilde{g}\tilde{g}(g_1,g_1)$ in the MSSM(UUED) at the LHC with $\sqrt{s} = 14$ TeV. The bands are obtained by varying the squark/level-1 quark masses and the renormalization/factorization scale $\mu$ over the range $\frac{m_{\tilde{g}(g_1)}}{2} \leq \mu \leq 2m_{\tilde{g}(g_1)}$. The CTEQ5L parton distribution is used. This shows that for a given experimentally determined mass scale the cross sections are very different, and are likely to allow distinguishing between such interpretations of an LHC signal.

This peaks at around twice the mass scale defined naively as

$$M = \min(m_{g^*}, m_{q^*})$$

where $g^*$ and $q^*$ are the excited gluon and quark states of SUSY or UED in our present study. Thus for a given position of the peak of $M_{eff}$ a much larger event rate would occur for UUED than for SUSY. A definitive conclusion would require that the resulting event rates did not significantly overlap.

Fig. 11 illustrates the variation of cross sections for gluino-pair (level-1 gluon pair) production against the mass scale which is the gluino (level-1 gluon) mass for the MSSM (UEED) with squarks (level-1 quarks) being much heavier. In both cases the bands are obtained by varying the squark/level-1 quark masses and the renormalization/factorization scale $\mu$ which have the strongest impact on the cross sections at the lowest order. We note that these theoretical bands never overlap over a significant range of the mass scale. Thus, a conclusion favoring one or the other scenario should be rather robust. Of course, one has to critically estimate higher order effects on the theoretical side and check many of the experimentally involved issues. There may be a better procedure than identifying the peak of the effective mass curve with the mass scale. We expect that once there is data fitted by SUSY and UED models, then sharper procedures will easily be implemented. The basic point is that for given masses the connection between spin and cross section is fundamental, and is a tool that can remove any confusion. It
becomes useful once data sets the mass scales. Our comparison of UUED and SUSY was
done at mass scales that might already be excluded for UUED by the recent analysis of
Flacke, Hooper and March-Russell [50]. Their improved analysis of precision EW data
sets new lower limits on the UED compactification scale. In the context of UUED these
limits might perhaps change, but even if they survive, our conclusions will remain if we
increase the mass scales.

6 Conclusions

Minimal SUGRA along with other prominent SUSY breaking scenarios have found enor-
mous use in developing benchmarks for systematic studies both at theoretical and ex-
perimental levels. These are helping us to learn beforehand how to better prepare to
recognize what is discovered, and how to analyze it. It is important to maintain a critical
attitude towards any model dependent approach, so that it does not lead to oversimpli-
fication and overlooking other possibilities. One such possibility is the weakening of the
leptonic signals at the LHC.

Same-sign dilepton signals (SSD) are a rather robust signature of SUSY. But one
might wonder if the SSD signature is a “sufficient” and “necessary” signature of SUSY.
There are situations when SSD’s can get depleted to an unobservable level while (bro-
en) SUSY could still be a valid description of Nature (i.e. they are not “necessary”).
Second, the existence of the SSD signal alone does not automatically exclude alternative
descriptions of nature, viz. in the form of Universal Extra Dimensions (UED) (they are
not “sufficient” either). We analyze both of these situations.

Once we give up mSUGRA and start working in the MSSM, depletion of SSD events
may occur in several possible ways as discussed in the text.

Leptons in different leptonic channels tend to have the same origin in the decay
cascades. Thus typically all leptonic final states have decreased rates if SSD do, though
at different rates, dictated mainly by the combinatorics. Also, we outline how some
leptonic depleted modes can actually serve as a powerful input for our understanding.

Depletion in some channel(s) may not mean reinforcement in some others. This is
counter to naive expectations on the grounds of conservation of normalizations of differ-
ent branching fractions down the cascades. An apparent violation of such normalizations
could show up when kinematic cuts affect preferably some particular final states. Such
apparent violations can be drastic when one of the channels has a low event rate and
is on the verge of being unobservable while others have a rather healthy rate to start
with. If a Same-Sign dilepton signal is found, the default hypothesis is that a signal for
supersymmetry has been seen. Even in the full MSSM parameter space there will be
consistency checks with other channels. If a signal is seen but it does not include Same-
Sign Dileptons, a SUSY interpretation implies constraints on rates in other leptonic
channels.

On the other hand, it might turn out that a completely different physics scenario (an
unconstrained UED or UUED in our study) is behind a particular signature (SSD, in our
case) otherwise thought to be a “smoking gun” signature for SUSY. The phenomenology of the UED at the hadron colliders provides a rather concrete example of a scenario that could apparently fake SUSY. Recently such situations have been studied for linear colliders [40, 41, 42]. For the SUSY/UEED case we have noted that the close and basic connection between spins and cross section at a given mass is likely to allow distinguishing them at LHC, once data on the mass scales is available, and further study of patterns of relative rates in different channels will also be helpful.

We conclude that once one has a signal to analyze, it is reasonable to be optimistic that one will quickly be able to recognize whether it is likely to be the discovery of supersymmetry, even at a hadron collider. If it is, then the challenges of measuring the effective Lagrangian at the collider scale, and of trying to probe the underlying theory [51, 52, 53] will begin.

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