Same-sign tri-leptons with a left-sneutrino as the lightest minimal supersymmetric particle

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Assuming that $SU(2)_L$ doublet sneutrinos are the lightest among the MSSM particles, we show that it is possible to obtain same-sign tri-lepton (SS3L) events in the R-parity conserving supersymmetric scenarios. We consider the cascade decay of the lightest stop or the gluino above it to the lightest sneutrino via an intermediate on-shell gaugino-like neutralino and/or chargino and show that such processes can lead to SS3L events. We discuss the prospect of observing these SS3L events at Large Hadron Collider (LHC) and comment on discovering or constraining the proposed spectrum from future LHC data.

One usually expects missing transverse energy ($E_T$) together with jets, leptons or photons as signals of supersymmetry (SUSY) with conserved R-parity at the Large Hadron Collider (LHC)\cite{1, 2}. While R-parity (defined as $R = (-1)^{(3B + L + 2S)}$) ensures a stable lightest SUSY particle (LSP) as a dark matter (DM) candidate, the LSP is the lightest neutralino ($\chi^0_1$) in the majority of models but the gravitino\cite{3, 4} or the axino\cite{5} in some of them. In the latter class, SUSY signals are often characterised by hard photons from neutralino decay along with $E_T$.

On the other hand, it is difficult to identify a SUSY spectrum with a sneutrino ($\tilde{\nu}_L$) at the bottom of the minimal SUSY standard model (MSSM) spectrum. In general, a left-chiral sneutrino ($\tilde{\nu}_L$) LSP is unsuppressed interaction with the Z-boson and is therefore strongly disfavoured from direct dark matter search experiments. However, keeping some exceptional situations in mind, it is desirable to have a way of identifying the signature of a (left) sneutrino LSP in accelerator experiments. If there is a gravitino or axino LSP, there is of course no constraint from dark matter search. But the $\tilde{\nu}_L$, being the lightest among MSSM particles, will decay invisibly into a $\nu$ and the gravitino (axino), yielding the same MET spectrum and jets/leptons as in the case of $\chi^0_1$ LSP. We show here that a rather striking distinction of both the scenarios mentioned above comes through same-sign trileptons (SS3L) at the LHC.

As stated above, a SUSY spectrum with a left sneutrino LSP is usually considered impossible. However, as has been shown in some recent works, a $\tilde{\nu}_L$ DM can, after all, be allowed, if there is a mass-splitting between the scalar ($\tilde{\nu}_1$) and pseudoscalar ($\tilde{\nu}_2$) parts of $\tilde{\nu}_L = \tilde{\nu}_1 + i\tilde{\nu}_2$. Since a Z couples to $\tilde{\nu}_1\tilde{\nu}_2$, a mass splitting of a few hundred keV's prevents the scattering of the lighter of $\tilde{\nu}_1$ and $\tilde{\nu}_2$ (which can be the DM candidate) into the heavier one, since otherwise the dark matter candidate must have a speed exceeding its escape velocity in our galaxy\cite{6}. The mass-splitting can be organised with, for example, a tiny Majorana neutrino mass, for which the necessary conditions on the SUSY model have been discussed in the literature\cite{7}. It is important from the angle of SUSY search to distinguish the above situation in accelerator experiments. In addition, in the unconstrained situation where the sneutrino is lowest down in the MSSM spectrum but can further decay into a gravitino, an axino or even a right-chiral sneutrino LSP, one wishes to have a characteristic signal. Both of the above scenarios are addressed by the SS3L signal, something that is highly suppressed in R-parity conserving SUSY with the $\chi^0_1$ as the LSP or just above a gravitino, an axino or a right-sneutrino.

The primary cause of inevitable SS3L in the scenarios discussed above is the fact that the $\tilde{\nu}_i$ states are closely spaced in mass to the charged sleptons ($\tilde{l}_L$), as dictated by $SU(2)_L$ invariance. The latter (leaving aside the stau) are slightly more massive because of D-term (and F-term) contributions. Therefore, if the lightest (gaugino-like) neutralino is the next massive state in the spectrum, it decays either to a charged slepton and an anti-lepton (or to its conjugate state) or to the left-sneutrino(s) and a neutrino with comparable branching ratio. $\tilde{L}_L$ then undergoes three-body decays, producing the corresponding sneutrino and two soft-jets or a soft lepton and a neutrino. Due to their small transverse momentum, these soft decay products are difficult to observe at LHC. Thus all SUSY cascades which result in the lightest neutralino can lead to multileptons, the proliferation coming from either a top or a chargino as intermediate. The Majorana nature of neutralino allows combinations of final states where one has three (or even four) leptons, all with the same sign\footnote{A pathological situation that may escape detection via this signal is one where the lighter chargino is decoupled and the lighter stop is so close to to $\chi^+_1$ that it decays only into c$\chi^+_1$.}.

Let us now describe the typical spectrum. Throughout our discussion we will assume the first two generations of $SU(2)_L$ doublet sleptons to be degenerate. Further, both $e$, $\mu$ will be termed as leptons ($\tilde{l}$), and their scalar counterparts will be denoted as sleptons ($\tilde{l}$).
From whatever hope SUSY still has for solving the naturalness problem, a stop within the reach of the LHC is desirable, either with or without accessible gluinos alongside. We include the situation where the first two families of squarks are decoupled. The decay of a pair of light (anti-)stops ($\tilde{t}_1$) followed by the cascade decay of the same is of our primary interest. We explore direct pair-production of $\tilde{t}_1 \tilde{t}_1^*$, and cascade production of the lightest stop from the decay of the gluino ($\tilde{g}$) and the first two generation squarks ($\tilde{g}$) (when they are non-decoupled). In the non-decoupled cases, one has $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{g}$ productions. All of these final states contribute to $\tilde{g}$ production, since $\tilde{g}$ can decay to $\tilde{g}\tilde{g}$. Finally $\tilde{g}$ decays to $\tilde{t}\tilde{t}^*$ or $\tilde{t}\tilde{t}^*$ with equal branching fraction. While the decay of a pair of $\tilde{g}$ can lead to interesting signatures, it also enhances the stop production effectively.

We assume a bino-like and/or two wino-like states below the lightest stop. In order to correspond to the situation of our interest, the first two generations of $SU(2)_L$ doublet sleptons are at the bottom of the MSSM spectrum. Based on the nature of the intermediate neutralino(s), the following two distinct scenarios have been considered.

In scenario A, we have taken $\tilde{\chi}_1^0$ to be bino-like. Figure 1 demonstrates the mass hierarchy we are interested in. SS3L also comes in scenario B where a play in LHC phenomenology is played by a bino-like neutralino together with wino(higgsino)-like intermediate neutralino and chargino states. Consequently the decay mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ could also be allowed. The relevant cascade decay of $\tilde{t}_1$ and $\tilde{t}_1^*$, in scenario B, has been shown in figs. 2 and 3 respectively.

![FIG. 1. The mass hierarchy required to obtain SS3L. In the simplest scenario, only a bino-like $\tilde{\chi}_1^0$ has been introduced between $\tilde{t}_1$ and the (first two generations of) slepton doublets.](image)

- In the simple scenario (A) with just the $\tilde{\chi}_1^0$ within reach, starting from direct production of $\tilde{t}_1$, $\tilde{t}_1^*$ it is possible to extract up to SS3L ($3l/3l+2b+2j+E_T$ along with 2 soft jets). While two same-sign (anti-)leptons can be obtained from the decay of $\tilde{\chi}_1^0$ (produced from the decay of $\tilde{t}_1$ and $\tilde{t}_1^*$); the other (anti-)lepton appears if ($W^+$) $W^-$ boson, produced from the decay of (anti) $\tilde{t}$, decays into leptonic channels. If the ($W^+$) $W^-$ boson decays to hadrons, SS2L ($2l/2l+2b+6j+E_T$) would be possible. It may be noted that depending on the decay modes of both $\tilde{\chi}_1^0$ and $W^\pm$ various (up to four) hard multi-lepton final states would be possible. Since SS3L has the smaller background from Standard Model (SM), we will mostly focus on this.

The number of SS3L events are further enhanced in the non-decoupling gluino/squark case. Additional (anti-)stops are produced from $\tilde{g}$ decay. Also, $\tilde{g}$ decays to $\tilde{g}\tilde{g}$ and/or $q\tilde{\chi}_1^0$. Subsequent decays of these (s)particles lead to SS3L as already described. Additional parton jets are also produced. It should be noted that, SS4L is also possible if a pair of $\tilde{g}$ decays to produce a pair of $\tilde{t}_1$ (or their conjugate) state. This is achieved when both $W^-$ ($W^+$), produced from the decay of two anti-top (top) squarks, decay into (anti-)leptons and both $\tilde{\chi}_1^0$, produced from the decay of two $\tilde{t}_1$ (or their conjugate), decay into (anti-)leptons.

- In scenario (B), in addition to the bino-like neutralino, a wino-like neutralino and the corresponding chargino also remain in between $\tilde{t}_1$ and $\tilde{l}_L$ in the spectrum. Consequently, an additional decay mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$. However, depending on the composition of $\tilde{t}_1$, the branching ratio in this channel is determined. For example, because of its large hypercharge an R-type ($SU(2)_L$ singlet) $\tilde{t}_1$ would dominantly decay to the bino-like neutralino; while for an L-type (charged under $SU(2)_L$) $\tilde{t}_1$ the dominant decay modes will include a wino-like neu-

![FIG. 2. The relevant decay channel for $\tilde{t}_1$. Note that $W^*$ denotes an off-shell $W$; $j$ and $j_s$ denote (hard) parton jets and soft parton jets respectively.](image)

![FIG. 3. The relevant decay channel for $\tilde{t}_1^*$. Note that $W^*$ denotes an off-shell $W$; $j$ and $j_s$ denote (hard) parton jets and soft parton jets respectively.](image)
tialino and/or chargino.

Starting from direct production of $\tilde{t}_1\tilde{t}_1^*$ and assuming both $\tilde{t}_1$ and $\tilde{t}_1^*$ decay into charginos, it is impossible to obtain two or more leptons with same sign. However, assuming one of the stops decays into chargino and the other one decays into neutralino, it is possible to obtain SS2L, since $l$ of either sign can be extracted from a neutralino decay. The cascade decay of a pair of gluinos, in this scenario, can lead to significant number of SS3L events. To elaborate, a pair of gluino decays to one of the following states: $tt\tilde{t}_1\tilde{t}_1^*$ and its charge conjugate. In all these cases, SS3L can be realized if one of the stops decays into chargino and the other decays into a neutralino eventually producing SS2L as discussed; another lepton of the same sign appears when a $W$ boson, appearing from the decay of a top quark, decays into leptons. The latter two channels ($tt\tilde{t}_1\tilde{t}_1^*$ and its conjugate) can also lead to SS3L when $W$ bosons from both top quarks decay into leptonic modes, and one of the stops decay into a neutralino. SS4L can also be obtained, as before, when both the stops decay into neutralinos. However, the last two cascades discussed do not make use of the decay mode involving the chargino.

Note that the presence of a right-slepton above the neutralino(s) does not affect the signal. In Table I, we consider two benchmark points, BP-A and BP-B, to illustrate scenarios (A) and (B) respectively. Note that, in scenario (B) the composition of the lightest stop, together with the composition of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ affects the decay products of the lightest stop. In BP-B, we have assumed $\tilde{t}_1$ to be dominantly R-type, and wino-like states lie above the bino-like neutralino with little bino-wino mixing in the neutralino sector. This ensures that the light stop decays mostly to the bino-like neutralino and a top quark. The branching ratios of $\tilde{g}$, $\tilde{t}_1$ and the relevant neutralino(s) are tabulated in Table II.

To generate the benchmark points, we have used the publicly available code Suspect[8]. The branching ratios of the relevant sparticles have been computed using SUSYHIT[9]. Since three-body decay modes of the left-sleptons are not computed by SUSYHIT, we have used calcHEP[10] to compute the same. In the following we discuss the viability of observing such SS3L signal events in the context of our benchmark scenarios in the inclusive channels (i.e. we define SS3L+X as our signal) at LHC focusing on the 13 and 14 TeV run for 100 $fb^{-1}$ data set.

We have used Prospino[11] to compute the NLO cross sections for $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{g}$ production at LHC. MADGRAPH has been used for event generations; subsequent decays, showering and hadronization has been taken care of by PYTHIA[12]; FASTJET[13] and DELPHES[14] has been used for jet clustering (using anti-$k_T$ algorithm) and (ATLAS) detector simulation respectively. The following selection criteria have been applied on (inclusive) SS3L signal events:

- lepton rapidity $|\eta| < 2.5$;
- lepton-lepton separation $\Delta R_{ll} > 0.2$ and lepton-jet separation $\Delta R_{lj} > 0.4$, where $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ denotes the separation in the pseudorapidity-azimuthal angle plane;
- ordering the leptons as $l_1$, $l_2$ and $l_3$ according to their $p_T$, we require: $p_T(l_1) \geq 30$ GeV, $p_T(l_2) \geq 30$ GeV, $p_T(l_3) \geq 15$ GeV;
- missing transverse energy $E_T > 100$ GeV;
- the hadronic activity within a cone of $\Delta R \leq 0.2$ is constrained by demanding $p_T^{hadron}/p_T^{lepton} \leq 0.1$;
- although $p_T$ dependent, the electron and muon detection efficiencies have been taken to be around

| Parameter | BP-A | BP-B |
|-----------|------|------|
| $m_{\tilde{g}}$ | 1450 | 1450 |
| $m_{\tilde{t}_1}$ | 1000 | 1000 |
| $m_{\tilde{\chi}_1^0}$ | 588 | 440 |
| $m_{\tilde{\chi}_2^0}$ | - | 610 |
| $m_{\tilde{\chi}_1^+}$ | - | 610 |
| $m_{\tilde{\nu}_\tau}$ | 293 | 293 |

| Decay Modes | BP-A | BP-B |
|-------------|------|------|
| $\tilde{g} \rightarrow \tilde{t}_1^* + c.c.$ | 100 | 100 |
| $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + c.c.$ | 100 | 91 |
| $\rightarrow \tilde{\chi}_2^0$ | - | 3 |
| $\rightarrow \tilde{\chi}_1^+$ | - | 6 |
| $\chi_1^0 \rightarrow \tilde{t}_1^* + c.c.$ | 49 | 48 |
| $\rightarrow \tilde{\nu}_\tau + c.c.$ | 51 | 52 |
| $\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 + c.c.$ | - | 50 |
| $\rightarrow \tilde{\nu}_\tau + c.c.$ | - | 50 |

Table I. Mass spectra for different benchmark points. BP-A and BP-B represent scenario (A) (with only the bino-like neutralino intermediate state) and scenario (B) (with a bino-like and a wino-like neutralino together with a wino-like chargino intermediate states) respectively (see text for details). All the masses are in GeV. The gluino masses are to be considered only in the context of the non-decoupling scenarios.

Table II. Branching ratios (in %) for various decay modes of $\tilde{g}$, $\tilde{t}_1$ and $\tilde{\chi}_1^0$ (and $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$ when relevant) for benchmark points BP-A and BP-B, “c.c” denotes the charge conjugate state.
As mentioned earlier, the background for SS3L from Standard Model is minuscule. It has been computed using \textsc{alpgen}[15] with similar cuts mentioned above. The SM cross-section for SS3L events are $2.5 \times 10^{-3}$ fb, to which $t\bar{t}W$ contributes the most.

However some contribution to the background may come from the fake standard model events. We minimize its probability by imposing the $E_T$ cut of 100 GeV, so that the total background is indeed negligible, without really affecting the signal.

In Table III, we list the number of SS3L events (inclusive) from $\tilde{t}_1\tilde{t}^*_1$ direct production assuming all the other squarks and gluino are decoupled; and also from the pair production of $\tilde{g}$ when it is not decoupled. The total number of SS3L events, when $\tilde{g}$ is not decoupled, can be estimated by adding the contributions from each of these initial states (\(\tilde{g}\tilde{g}\) and \(\tilde{t}_1\tilde{t}^*_1\)) together. Note that, similar number of SS3L events appear when three anti-leptons are demanded instead of three leptons.

As the numbers indicate, prospects of observing (or constraining) these benchmark scenarios, appears strong in the forthcoming LHC data. As mentioned earlier, the background for SS3L from SS3L, $\ell 2\ell$, $2\ell 2\ell$ can also be produced. If the off-shell $W^*$ (in the decay of $\tilde{L}$) goes to leptons, 2 additional leptons can be produced too; but those are expected to be soft. Among all these additional channels, SS2L events typically have the least SM background. So these could compete with SS3L events, and provide stronger evidence or constraint on the spectrum of our interest. We will consider this issue in a forthcoming revision.

To conclude, in this letter we have considered an MSSM spectrum with the $\nu_\ell$ appears at the bottom. The viability of this is assured with either a split between the scalar and pseudoscalar parts of $\nu_\ell$ or a gravitino, axino or right-chiral sneutrino lighter than it. Thanks to the close proximity between $\tilde{L}$ and $\nu_\ell$ states demanded by SU(2), SUSY cascades can lead to SS3L events, via decays (en route) of the top quark or a charmino. At the same time the jets + 0L + $E_T$ signal suffers from suppression, since SUSY cascades leading to $ch\tilde{1}_0$ can now end up charged slepton and leptons. Thus the importance of leptonic SUSY signals increases, and, among them, the SS3L events bear an unmistakable stamp of the scenario with $\nu_\ell$ at the bottom.

We estimate the number of such events with 100 fb$^{-1}$ of integrated luminosity from 13 and 14 TeV LHC. In addition, we observe that, the SS3L+SS2L events can exceed in importance the purely jetty final states. We leave these issues for a more detailed study.

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| BP   | 13 TeV   | 14 TeV   |
|------|----------|----------|
|      | $\tilde{t}_1\tilde{t}^*_1$ | $\tilde{g}\tilde{g}$ | $\tilde{t}_1\tilde{t}^*_1$ | $\tilde{g}\tilde{g}$ |
| A    | $5.3 \pm 2.3$ | $13.30 \pm 3.60$ | $7.9 \pm 2.8$ | $22.87 \pm 4.72$ |
|      | (12.39 \pm 3.48) | (20.92 \pm 4.52) | | |
| B    | $4.40 \pm 2.10$ | $12.31 \pm 3.47$ | $6.65 \pm 2.57$ | $19.71 \pm 4.39$ |
|      | (11.33 \pm 3.33) | (18.10 \pm 4.18) | | |

TABLE III. Estimated number of (inclusive) SS3L events for 13 and 14 TeV LHC (with 100 fb$^{-1}$ of integrated luminosity) from cascade decays of $\tilde{t}_1\tilde{t}^*_1$ and $\tilde{g}\tilde{g}$ after applying the relevant cuts.