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Same-sign trileptons as a signal of sneutrino lightest supersymmetric particle

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ABSTRACT

Contrary to common expectation, a left-sneutrino can occasionally be the lightest supersymmetric particle. This has important implications in both collider and dark matter studies. We show that same-sign tri-lepton (SS3L) events at the Large Hadron Collider, with any lepton having opposite sign vetoed, distinguish such scenarios, up to gluino masses exceeding 2 TeV. The *jets* + *MET* signal rate is somewhat suppressed in this case, thus enhancing the scope of leptonic signals.

Supersymmetry (SUSY), or a symmetry between elementary bosons and fermions, has been a matter of great interest over several decades. In the form where lepton (L) and baryon (B) numbers are conserved, SUSY offers a stable particle which is the dark matter (DM) candidate for the universe. Therefore, physicists not only ponder on possible discovery channels for SUSY at the Large Hadron Collider (LHC) [1,2] but also wish to know how, if discovered, we can identify the lightest SUSY particle (LSP) which is the DM candidate. In the minimal SUSY standard model (MSSM) or its immediate extensions, the DM candidate [3] usually is χ_1^0, the lightest neutralino (a linear superposition of the 'partners' of the photon, the Z-boson and the neutral Higgs-like spinless particles), the gravitino (partner of the graviton) [4,5], or the axino (partner of an axion) [6,7]. The signals at the LHC are dominantly jets with missing transverse energy (MET) [8,9] occasionally with leptons and/or photons alongside.

In contrast, it is difficult to have a SUSY spectrum with a left-chiral sneutrino ($\tilde{\nu}_L$, the spinless partner of a neutrino) as the DM candidate. Such an LSP has unsuppressed interaction with the Z-boson and is therefore disfavoured from direct DM search experiments, unless its mass is well above a TeV. However, in case this restriction is avoided (as seen below) and one has a (left) sneutrino LSP, finding its distinct signature at the LHC is a desideratum. We show here that the scenario is distinguishable through same-sign trileptons (SS3L) at the LHC. Extensive scans carried out by us [1,2] over the parameter space fail to turn up regions where, in an R-parity conserving SUSY spectrum, containing only superpartners of Standard Model (SM) particles alone, can lead to SS3L signals with such abundance. Moreover, compared to the case of a χ_1^0 LSP, the 0 *lepton* + *jets* + *MET* events get suppressed, and the leptonic final states gain more importance, thus warranting a revision of collider search strategies.

A $\tilde{\nu}_L$ DM can be allowed, if there is a mass-splitting between the scalar ($\tilde{\nu}_1$) and pseudoscalar ($\tilde{\nu}_2$) components of $\tilde{\nu}_L = \dfrac{\tilde{\nu}_1 + i\tilde{\nu}_2}{\sqrt{2}}$. The Z couples to $\tilde{\nu}_1\tilde{\nu}_2$. A splitting of a few hundred keV prevents the scattering of the lighter of $\tilde{\nu}_1$ and $\tilde{\nu}_2$ (which is the DM candidate) into the heavier one via such coupling. The energy barrier created by this split is insurmountable unless the dark matter candidate has a speed exceeding its escape velocity in our galaxy [10–13]. This mass difference can occur, for example, from a tiny Majorana neutrino mass, for which the necessary conditions have been discussed in the literature [12]. Also, the sneutrino can be the lightest in the MSSM spectrum, just above a gravitino, an axino or even a right-chiral sneutrino LSP. Such spectrum has been considered in [14,15]. All these scenarios are addressed by the SS3L signal which is otherwise highly suppressed in R-parity conserving SUSY where $R = (-1)^{(3B+L+2S)}$.

SS3L is inevitable in the scenarios discussed above, because the $\tilde{\nu}_L$ states are close in mass to the charged sleptons ($\tilde{l}_L$), as dictated by $SU(2)_L$ invariance. The latter (leaving aside the staus and their mixing) are slightly more massive, mainly because of D-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 ratios. $\tilde{l}_L$ undergoes three-body decays, producing the corresponding sneutrino and two soft-jets or a soft lepton and a neutrino. The soft leptons do not mostly survive the event selection criteria. Thus all SUSY cascades resulting in the lightest neutralino lead

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to two leptons in about half of the cases. The Majorana nature of neutralinos causes these two leptons to be of the same type in half the cases among such events. Further, a third lepton of the same sign can come from cascades, via either a top quark or a chargino. Thus one has three (or even four) leptons of the same sign.[1]

Unlike in Refs. [14,15], our main focus is on SS3L events. Further, contrary to the brief discussion in [15], we demonstrate that SS3L may be obtained from a simple spectrum and its observation need not imply the presence of a right-slepton (in addition to a left-slepton doublet) in the low energy spectrum. We emphasize that a simple spectrum with left-sneutrino LSP, without any additional SUSY particles, may lead to the rather distinct SS3L signal. We also demonstrate that the decay mode $\tilde{t}_1 \to b\chi_1^+$ adversely affects SS3L events when $\chi_1^\pm$ decays into sleptons or sneutrinos.

Throughout our discussion we will assume the first two generations of $SU(2)_L$ doublet sleptons to be degenerate. Further, both e, μ will be described as *leptons* (ℓ), and their scalar counterparts, as *sleptons* ($\tilde{\ell}$). Further, since various mechanisms may be responsible for the production of DM in the early Universe [16–18] and there may even be additional DM candidate(s) possibly from hidden sector, we will not restrict the collider analysis by assuming thermal production of sneutrinos.

For simplicity, we assume the first two families of squarks to be decoupled. A stop well within the reach of the LHC is retained, thus providing a semblance of naturalness, and the gluino is assumed to be heavier than the stop. Other than the light charged sleptons, sneutrinos and χ_1^0, we have used benchmark points in the SUSY parameter space with both light and heavy $\chi_1^\pm$ and χ_2^0. The parameter μ and thus the Higgsino-dominated states are kept above a TeV without any loss of generality. The channels of our interest are both $\tilde{t}_1\tilde{t}_1^*$ production, and cascade production of the lighter stop (or the anti-stop with the same rate) from the decay of the gluino ($\tilde{g}$). This is a conservative choice from the viewpoint of the SS3L signal, since larger event rates should be expected if the first two families of squarks are also produced.

We assume a bino-like χ_1^0 and wino-like $\chi_1^\pm$ and χ_2^0. When one has a sneutrino LSP, the first two families of $SU(2)_L$ doublet sleptons are the next-to-lightest ones (assumed to be degenerate for simplicity). The stau mass is taken to be at least a TeV; staus lighter than χ_1^0 can cause some reduction to our predicted signals, but keeps it within the same order of magnitude. Based on the nature of the intermediate neutralino(s), the following scenarios have been considered as representative.

1. In the simple scenario (A) with just the χ_1^0 within reach, direct production of a stop-antistop pair causes each (anti)stop to decay directly into χ_1^0. While these χ_1^0's give rise to two same-sign leptons as already explained, the third lepton of the same sign comes from the decay of a (anti) top produced in (anti)stop decay. The number of SS3L events is further enhanced in the non-decoupling gluino case where additional (anti-)stops are produced from $\tilde{g}$ decay. It should be noted that SS4L is also possible, though with a reduced rate, if a pair of gluinos decay into two top-stop pairs. This happens when both the W's, produced from the decay of two (anti)top quarks, yield leptons of identical sign.
2. In scenarios (B) and (C), in addition to the bino-like χ_1^0, a wino-like chargino $\chi_1^\pm$ and the corresponding neutralino χ_2^0 also occur below $\tilde{t}_1$ in the spectrum. There is consequently an additional decay mode, namely, $\tilde{t}_1 \to b\chi_1^+$. However, the branching ratio in this channel depends on the composition of $\tilde{t}_1$. While $\tilde{t}_1$ is dominantly right-type in scenario (B), significant amount of left-right mixing is allowed in scenario (C). Because of its large hypercharge, an R-type ($SU(2)_L$ singlet) $\tilde{t}_1$ will dominantly decay into χ_1^0, while for an L-type ($SU(2)_L$ doublet) $\tilde{t}_1$ there is a substantial branching ratio into the $b\chi_1^\pm$ channel. In such a situation, both of the stops in the two decay chains will tend to produce charginos which tend to undergo two-body decays into charged sleptons. This makes it difficult to have SS3L final states in the direct stop pair-production, and one has to depend only on cascades from gluino decay. Thus, while both the scenarios B and C include a light chargino, scenario C represents a situation where the composition of the lighter stop tends to reduce the rate of SS3L. As we shall see below, one still expects to see this signal with a rate sufficient to discern the sneutrino-LSP scenario. It should be mentioned in addition that both scenarios B and C retain the possibility of seeing SS4L (albeit with smaller rates) whenever SS3L is allowed.

Table 1
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 masses are in GeV.

Parameter	BP-A	BP-B	BP-C
$m_{\tilde{g}}$	1600	1600	1600
$m_{\tilde{t}_1}$	1000	1000	1000
$m_{\chi_1^0}$	590	441	443
$m_{\chi_2^0}$	–	620	620
$m_{\chi_1^+}$	–	620	620
$m_{\tilde{\nu}}$	293	293	293

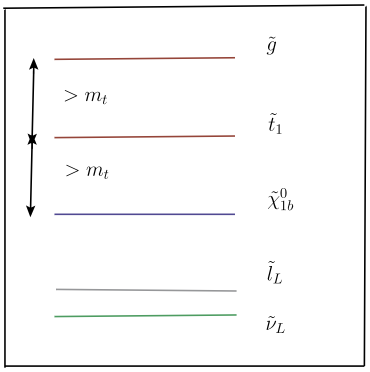

Fig. 1. The mass hierarchy required to obtain SS3L. In the simplest scenario, only a bino-like χ_1^0 has been introduced between $\tilde{t}_1$ and the (first two generations of) slepton doublets.

All the three scenarios are allowed by the 8 TeV data so far [19]. The above discussion shows that, while BP A has no wino-like state affecting the phenomenology, even the presence of such states affects the suggested SS3L signal only if the lighter stop has a substantial left component, and thus BP B and BP C have different LHC implications. While a stop decays almost entirely into a top and the χ_1^0 in BP A, this branching ratio becomes 91% in BP B and 56% in BP C. The branching ratio for $b\chi_1^\pm$ ($t\chi_2^0$), on the other hand, is 6% (3%) and 31% (13%), respectively, for BP B and C. The important aspects of the spectrum with each of the three benchmark points (BP) mentioned above are summarized in Table 1. The nature of the spectrum for BP A is also shown in Fig. 1. Note that the presence of a right-slepton above the neutralino(s) does not affect the signal.

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[1] This leaves out the situation where the lighter chargino is decoupled and the lighter stop is so close to χ_1^0 that it decays only into $c\chi_1^0$.

Table 2
Estimated number of SS3L (SS2L) 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. Note that for SS2L events both leptons are required to have $p_T >$ 30 TeV.

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	5.8 ± 3.4 (51.66 ± 9.94)	13.88 ± 5.24 (60.16 ± 10.70)	8.38 ± 4.08 (67.24 ± 11.36)	22.50 ± 6.66 (94.04 ± 13.4)
B	4.44 ± 2.98 (43.84 ± 9.18)	13.4 ± 5.14 (54.64 ± 10.22)	7.90 ± 3.96 (62.30 ± 10.94)	18.08 ± 5.98 (89.58 ± 13.08)
C	3.62 ± 2.68 (34.60 ± 8.20)	8.38 ± 4.08 (52.04 ± 9.98)	2.96 ± 2.44 (50.48 ± 9.90)	16.02 ± 5.64 (85.12 ± 12.76)

We have generated the SUSY spectrum using the publicly available code `SuSpect` [20]. The branching ratios of the relevant sparticles have been computed using `SUSYHIT` [21]. Since three-body decay modes of the left-sleptons are not computed by `SUSYHIT`, we have used `calcHEP` [22] to compute them. We define SS3L + X as our signal, where X does not include l or $\bar{l}$. The rates for this signal are calculated for both the 13 and 14 TeV runs of the LHC.

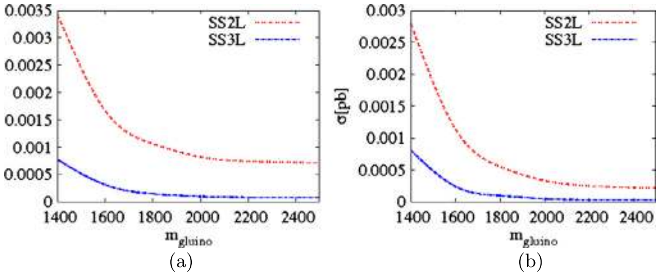
We have used `Prospino` [23] to obtain the NLO cross-sections for $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{g}$ production at the LHC. `MADGRAPH` [24]has been used for event generations; subsequent decays, showering and hadronization has been taken care of by `PYTHIA` [25]; `FASTJET` [26] and `DELPHES` [27] has been used for jet clustering (using anti-k_T algorithm) and (ATLAS) detector simulation respectively. We have used `MADANALYSIS` [28] to analyse the events.

The signal event selection criteria are:

1. $E_T^j > 20$ GeV; $|\eta_j|, |\eta_l| < 2.5$.
2. Lepton–lepton separation $\Delta R_{ll} > 0.2$; lepton-jet separation $\Delta R_{lj} > 0.4$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.
3. For leptons in decreasing order of hardness, $p_T \geq 30, 30$, 15 GeV;
4. Missing transverse energy $MET > 100$ GeV;
5. $E_T^{hadron}/E_T^{lepton} \leq 0.1$ within a cone of $\Delta R \leq 0.2$ around each electron; $\Sigma E_T^{hadron} \leq 1.8$ GeV within a similar cone around each muon.
6. The electron and muon detection efficiencies are taken as 85%–95% (following DELPHES).

The background for SS3L from the Standard Model is negligibly small. It has been computed using `ALPGEN` [29] with similar cuts mentioned above [1]. The standard model cross-section for SS3L events is $\lesssim 2.5 \times 10^{-3}$ fb, to which $t\bar{t}W$ contributes the most. However, some background may come from standard model processes with (a) lepton charge misidentification, and (b) jets faking as leptons. Imposing the *MET* cut of 100 GeV, which generically reduces standard model contributions, the total background to SS3L is indeed negligible. Note that, for the kind of LSP masses considered, one can in principle raise the MET cut even higher without really affecting the signal, and thus the backgrounds can threaten us even less.

In Table 2, we list the number of SS3L events with an integrated luminosity of 100 fb^{-1}, for both the 13 and 14 TeV runs, for the three benchmark points chosen above. Contributions from both $\tilde{t}_1\tilde{t}_1^*$ direct production and gluino-pairs are shown separately. The total number of SS3L events 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. The corresponding number of same-sign dilepton (SS2L) events are also shown within parenthesis. The corresponding background at 14 TeV can be brought under control with a MET cut of 100 GeV, and an appropriate hardness cut ($\gtrsim$30 GeV), as used in our analysis [30,31]. Clearly, while direct stop-pair production channel is sufficient to yield background-free SS3L events that can be detected with the integrated luminosity of one-or two hundred fb^{-1}, the rate goes up several times through gluino pair-production. This is due to (i) the colour and spin multiplicity of the gluino, and (ii) the Majorana nature of the gluino, which yields leptons of either sign with equal probability in the cascade. It should also be noticed that BP A, B and C have progressively decreasing SS3L rates, the reason for which has been explained earlier. While the presence of a light chargino in BP B causes the loss of some events, the loss is more in BP C where the light stop has more left chiral component. On the whole, however, one obtains distinguishable SS3L rates, even for a gluino as massive as 1.6 TeV. Relatively heavier stops (which are lighter than the gluino) do not affect the total number of events very significantly. It should also be noted that the rate of SS3L events drop drastically if the positions of the neutralinos (at least two) and a chargino are swapped with the left-slepton doublet in the spectrum. This is because the left-sleptons are produced much more restrictively from strong sparticle production processes.



(a) (b)

Fig. 2. In the left panel the effective NLO cross-sections for SS3L and SS2L events (for LHC 14 TeV run) have been plotted against the gluino mass assuming the simplest mass hierarchy as shown in Fig. 1. (a) shows the relevant numbers for $m_{\tilde{t}_1} = 1000$ GeV, while (b) demonstrates the same for $m_{\tilde{t}_1} = 1200$ GeV.

Table 3
Estimated number of $0l+ \geq 2j$ events at NLO for 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. Benchmark B represents the same scenario as benchmark A with the first two generations of slepton doublets decoupled. Thus χ_1^0 is the LSP in benchmark B.

BP	0l + 2j	
	$\tilde{t}_1\tilde{t}_1^*$	$\tilde{g}\tilde{g}$
A	272.7 ± 13.5	125.3 ± 10.5
χ_1^0-LSP case	460.6 ± 14.2	422.2 ± 15.5

The features mentioned at the end of the last paragraph become obvious in Fig. 2, where the signal rates are plotted against the gluino mass for two values of the lightest stop mass. The SS3L signal remains detectable for the gluino mass up to 2 TeV or more, somewhat marginally with an integrated luminosity of 100 TeV but rather strongly with twice that luminosity.

It may be contended that SS2L events, which are obviously more copious, render the SS3L events redundant. However, it should be borne in mind that the point under investigation here is the discernibility of a sneutrino dark matter scenario. Since this scenario in its common form is all but ruled out, its observation is a rather striking phenomenon which has wide implication in dark matter physics. The predicted SS3L signal makes this new scenario testable at the LHC.

Another new feature of this scenario is demonstrated in Table 3, where we present the rates for zero-lepton events (with MET) for BP A. The numbers of events, corresponding to both the $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{g}$ channels, are compared with the corresponding case with χ_1^0-LSP, where the charged leptons as well as sneutrinos are decoupled. It is clear from the table that the number of hadronic events becomes less than half in the situation with a sneutrino LSP, and thus the search limit based on such events are lowered in this case.

The same conclusion also holds when one goes beyond the MSSM spectrum, and there is a lighter axino or a gravitino. The sneutrino decays invisibly in that case, and all the results presented above are equally valid. Thus SS3L also constitutes the most distinct signal of the axino/gravitino LSP, sneutrino NLSP scenario. As mentioned above, similar scenarios have been studied [14,15,32] earlier. Of these, SS3L has been mentioned in [15] when the gravitino or the axino has to be necessarily present there, as well in [14,32]. Moreover, it may be possible to obtain SS3L events without necessarily having a light slepton doublet, for example, if $\tilde{t}_1 \to t\chi_i^0$ and $\chi_i^0 \to \chi_1^\pm W^\mp$, in certain possibly tuned MSSM scenarios. Since in such cases leptons are produced from W bosons (on or off-shell), the resulting SS3L events will be flavor blind. On the other hand, the presence of a light slepton doublet, as in the present context, would assure an excess of SS3L events or SS2L events with the leptons sharing the flavor of the light slepton doublets. Of-course, if all three generations of sleptons are light (and degenerate) then such a distinctive feature will be absent. The current study will hopefully bring out the full implication of SS3L in the context set here.

To conclude, we have considered *an MSSM spectrum with a* $\tilde{\nu}_L$ *dark matter*. The viability of this is assured with, for example, a split between the scalar and pseudoscalar parts of $\tilde{\nu}_L$, thus opening up a distinct SUSY dark matter scenario, finding whose experimental signature is crucial. Thanks to the close proximity between $\tilde{l}_L$ and $\tilde{\nu}_L$ states demanded by SU(2), SUSY cascades can lead to SS3L events, via decays of the top quark or a chargino. At the same time, the $jets + 0\ell + MET$ signal suffers from suppression, since SUSY cascades leading to χ_1^0 end up in charged sleptons and leptons in a significant fraction of cases. Thus the importance of leptonic SUSY signals increases, and, among them, the SS3L events serve as a useful diagnostic.

We estimate the number of such events at the 13 and 14 TeV runs of the LHC, and show that they can are detectable for gluino masses exceeding 2 TeV, for integrated luminosities around 100 fb^{-1} or a little higher up. A detailed study of the SUSY parameter space in such a scenario, including all signals with and without isolated leptons, will be presented in a later work.

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