Same-sign trileptons at the LHC: a window to lepton-number violating supersymmetry

Satyanarayan Mukhopadhyay\textsuperscript{*} and Biswarup Mukhopadhyay\textsuperscript{†}

Regional Centre for Accelerator-based Particle Physics
Harish-Chandra Research Institute
Chhatnag Road, Jhusi
Allahabad - 211 019, India

Abstract

We present a detailed investigation to establish that lepton-number (L) violating supersymmetry (SUSY) can be effectively probed at the LHC in the practically background-free same-sign trilepton (SS3\(\ell\)) and same-sign four-lepton (SS4\(\ell\)) channels. With this in view, we extend our earlier analysis of SS3\(\ell\) and SS4\(\ell\) signals by considering situations based on minimal supergravity as well as a phenomenological SUSY model. We find that the R-parity violating scenario predicts large event rates, for both the 7 and 14 TeV runs. Furthermore, we show that it is extremely unlikely to ever achieve similar rates in R-parity conserving SUSY. In addition, we show how SS3\(\ell\) and SS4\(\ell\), in conjunction with the mixed-sign trilepton and four-lepton channels, can be used to extract dynamical information about the underlying SUSY theory, namely, the Majorana character of the decaying lightest neutralino and the nature of L-violating couplings. We define suitable variables and relationships between them which can be verified experimentally and which are largely independent of the SUSY production cross-sections and the cascade decay branching fractions. These theoretical predictions are validated by Monte Carlo simulations including detector and background effects.

\textsuperscript{*}satya@hri.res.in
\textsuperscript{†}biswarup@hri.res.in
1 Introduction

Discovering new physics at the Large Hadron Collider (LHC) is a cherished dream. In this context, it is always useful to isolate signals which are distinctive of specific new scenarios on the one hand, and are less background-prone on the other. Final states containing a multitude of leptons undoubtedly satisfy the second criterion. In order to address the first criterion through them, it is often necessary to probe additional features of the leptons. One such feature is the sign(s) of the leptonic charge(s). It is well-established now that same-sign dilepton (SSD) carries a rather distinct signature of supersymmetry (SUSY) [1], and other new physics scenarios [2], once we carefully apply the event selection criteria to suppress the top-antitop background.

A curiosity that immediately arises is whether same-sign leptons of higher multiplicity can tell us something more. Although this idea of same-sign trileptons ($SS3\ell$) was floated originally in the context of top quark signals [3], its efficacy in new physics search was unexplored until very recently. This is somewhat unfortunate, because the standard model (SM) backgrounds for them are extremely small. Some studies in the context of heavy neutrino signals were reported, though with rather limited scope [4]. In a more recent work, we pointed out that $SS3\ell$ as well as its four-lepton extension ($SS4\ell$) had considerable potential in unearthing scenarios where $Z_2$-type discrete symmetries were broken in a limited manner [5]. In particular, we showed that various R-parity violating SUSY scenarios [6] (with $R = (-1)^{(3B+L+S)}$, $B$, $L$ and $S$ being baryon number, lepton number and spin, respectively) predicted large signal rates for $SS3\ell$ and moderate rates for even $SS4\ell$, with hardly any backgrounds. The $SS3\ell$ signal is substantial over a range of the parameter space in the 7 TeV run, while the predictions for both $SS3\ell$ and $SS4\ell$ are copious for 14 TeV. This suggestion has since been utilized in a number of subsequent studies [7]. In this paper, we present a more extensive study in the same direction, pointing out a number of new possibilities of the $SS3\ell$ signal.

Let us begin with some explanation of why such a study is relevant. First of all, the LHC searches for new physics, particularly SUSY, at the initial stage, are concentrating on signals with large missing transverse energy. So far the results have been negative. If they continue to be so, some possibilities to consider will be (a) SUSY without R-parity, (b) a highly compressed SUSY spectrum, and (c) SUSY with stable visible particles. While the signatures of each of the above scenarios have been proposed and investigated in the literature, the $SS3\ell$ and $SS4\ell$ signals are exclusively indicative of SUSY without R-parity, with lepton number violation. Since such signals can arise with large rates even during the early run, they are worth studying seriously, from the sheer event counting point of view.

L-violating SUSY has considerable appeal, because mechanisms of neutrino mass generation are suggested there. It is also being increasingly realised nowadays that one may end up with a dark matter candidate such as the axino or the gravitino in spite of R-parity violation. Some search limits for R-parity violating SUSY exist in the literature, based on multilepton ($\geq 3\ell$) signals. However, $SS3\ell$ is a rather more unequivocal indication of R-parity violation, since it is very difficult to produce three leptons of the same sign unless the seed of lepton number violation is there. Moreover, as will be discussed later in this paper, enhanced rates for such signals are very unlikely to be found in R-parity conserving versions of SUSY, even in a purely phenomenological scan of its parameter space. The background
is also vanishingly small, in contrast with the other channels advocated so far. With this in view, we also demonstrate regions in the parameter space where one can have five signal events with zero (in practice, \( \leq 1 \)) background events for some luminosity.

The enhanced signal rates were predicted in our earlier study within the framework of a minimal supergravity (mSUGRA) scenario. It is, however, important to go beyond the most simple of ‘top-down’ models and investigate SUSY signals at the LHC in a phenomenological, ‘bottom-up’ approach. In the current work, we have taken such an approach and looked at the SUSY parameter space in a relatively unbiased manner, although some simplification has been inevitable in order to keep the number of free parameters manageable. This allows us to point out features of the SUSY spectrum, for which same-sign multileptons are most likely to be observed.

We have opened another new direction in the present study. There are a number of ways in which R-parity can be violated via L, since one can have the so-called \( \lambda \)-type, \( \lambda' \)-type and the L-violating bilinear terms in the superpotential. Besides, the lightest neutralino need not be the lightest SUSY particle (LSP) when R-parity is violated, the stau-LSP scenario being the most common possibility. We contend here that the SS3\( \ell \) and SS4\( \ell \) signal rates, in conjunction with their mixed-sign counterparts of the same multiplicity, display certain mutual relations which distinguish among at least some of the candidate scenarios. And these relations are largely independent of the detailed information of the SUSY cascades. Consequently, one may use these signals to find out in a generic way the distinction among the \( \lambda \)-type, \( \lambda' \)-type or bilinear couplings. Although our discussion is largely based on scenarios with a neutralino LSP, alternative scenarios, for example, with stau LSP, can be brought within its scope, as has been briefly indicated in the paper.

It should be noted that same-sign multileptons in general, and SS3\( \ell \) in particular, can be seen in some other non-standard scenarios as well. In most cases, however, the rates are considerably smaller than what one would expect for R-parity violating cases with new particles with similar masses. The first example of this is minimal SUSY standard model (MSSM) where R-parity is conserved; our scan of its parameter space, with the usual constraints satisfied, reveals rather low event rates for SS3\( \ell \). One has predictions of some interest for Little Higgs theories where T-parity is broken by the Wess-Zumino-Witten anomaly terms [8, 9, 10]. However, it has been shown in our previous study that the rates are much smaller than those for R-parity violating SUSY with a spectrum of similar masses [5]. In addition, models with heavy charged leptons and Majorana neutrinos [4] and triply charged heavy leptons [11] can also lead to an SS3\( \ell \) signature.

The paper is organized as follows. Section 2 is devoted to the standard model contributions to same-sign and mixed-sign multilepton channels, and we suggest event selection criteria that suppress such contributions as potential backgrounds to the new physics signals. In section 3, we review the different cases of R-parity violating SUSY, and show the event rates for different benchmark points for mSUGRA, for both the 14 and 7 TeV runs. Section 4 contains a study where the parameters are varied in a more phenomenological manner, and regions where R-parity violating SUSY shows up in the SS3\( \ell \) channel are pointed out. We also explain in the same section why the SS3\( \ell \) and SS4\( \ell \) signals are not expected to occur with appreciable rates when R-parity is conserved, even in a generic MSSM model. In section 5, we show how we can extract information on the Majorana character of the lightest neutralino and the dynamics of R-parity violation from SS3\( \ell \) and SS4\( \ell \) signals. We
summarise and conclude in section 6.

2 Standard model backgrounds

As we have discussed in Ref. [5], the SM backgrounds to SS3ℓ are vanishingly small. Though the channels $t\bar{t}$, $t\bar{t}W$, $tt\bar{b}$ and $ttt\bar{t}$ can give rise to such events, the only appreciable contribution after various kinematic cuts comes from $t\bar{t}W$. These cuts are designed mainly to suppress the leptons coming from semi-leptonic bottom and charm decays [12].

We select events with three and only three leptons in the signal (for SS3ℓ), all of which have to be of the same-sign. In addition, we demand the following basic selection criteria:

1. $p_T^{l_1} > 30$ GeV, $p_T^{l_2} > 30$ GeV, $p_T^{l_3} > 20$ GeV, where $l_1$, $l_2$ and $l_3$ are the three leptons ordered according to their $p_T$’s

2. Missing transverse energy, $E_T > 30$ GeV (in order to reduce events with jets faking as leptons).

3. Lepton rapidity $|\eta| < 2.5$.

4. Lepton-lepton separation $\Delta R_{ll} \geq 0.2$, where $(\Delta R)^2 = (\Delta \eta)^2 + (\Delta \phi)^2$ quantifies the separation in the pseudorapidity-azimuthal angle plane.

5. Lepton-jet separation $\Delta R_{lj} \geq 0.4$ for all jets with $E_T \geq 20$ GeV.

6. Relative isolation criterion to restrict the hadronic activity around a lepton has been used, i.e., we demand $\sum p_T \text{(hadron)} / p_T \text{(lepton)} \leq 0.2$, where the sum is over all hadrons within a cone of $\Delta R \leq 0.2$ around the lepton.

7. Electron and muon selection efficiencies were taken to be 70% and 90% respectively [15].

The events for the above-mentioned SM background processes contributing to SS3ℓ were generated with the code ALPGEN [13], and showering, decays and hadronisation were done using PYTHIA 6.421 [14]. The effect of $B^0 - \bar{B}^0$ mixing on lepton signs has been taken into account within PYTHIA. We have approximated the detector resolution effects by smearing the energies (transverse momenta) of the leptons and jets with Gaussian functions [15, 16]. After imposing the above cuts the total SS3ℓ contribution from the SM at 14 TeV LHC turns out to be $2.50 \times 10^{-3}$ fb, of which $2.44 \times 10^{-3}$ fb comes from the $t\bar{t}W$ process. At 7 TeV LHC, the total SM cross-section for SS3ℓ comes down to $7.01 \times 10^{-4}$ fb. We have used CTEQ6L1 [17] parton distribution functions for all our signal and background calculations. As mentioned before, for further details on these backgrounds we refer the reader to our previous study in Ref. [5].

Needless to say, the SM backgrounds to the SS4ℓ channel will be even smaller than SS3ℓ, and can be safely neglected. As we shall see later in section 5 we can construct certain observables which depend only on the Majorana nature of the LSP and the L-violating coupling involved and not upon other parameters determining the cascade decays. In addition to the SS3ℓ and SS4ℓ cross-sections, these variables shall also depend upon the total trilepton
(3ℓ) and four-lepton (4ℓ) cross-sections in a given scenario, with specific kinematic criteria. Thus we need to evaluate and include the SM backgrounds in the 3ℓ and 4ℓ channels, and subject them to the same set of cuts irrespective of the sign of leptons. Therefore, while a Z-veto (removing events containing same flavour, opposite-sign leptons with invariant mass around the Z-boson mass) is often used to reduce the SM backgrounds in the sign-inclusive 3ℓ and 4ℓ channels, we cannot use such a veto here. Also, we use kinematic variables that only depend upon the lepton p_T’s and the E_T in an event. We find it useful to select events in terms of the variables m_ℓ_eff and m_eff, defined as follows:

\[ m_\ell_{\text{eff}} = \sum p_T^{\text{leptons}} \]  

\[ m_{\text{eff}} = \sum p_T^{\text{leptons}} + E_T, \]  

where the missing transverse energy is given by

\[ E_T = \sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2}. \]  

Here the sum goes over all the isolated leptons, the jets, as well as the ‘unclustered’ energy deposits.

| Cut          | W^±(Z_0/γ^*) | tt | tt(Z_0/γ^*) | ttW^± | Total  |
|--------------|--------------|----|-------------|--------|--------|
| Basic cuts   | 34.50        | 9.88| 2.82        | 0.73   | 47.93  |
| m_ℓ_eff > 100 GeV | 33.53 | 8.23| 2.80        | 0.71   | 45.27  |
| m_ℓ_eff > 200 GeV | 5.01 | 0.00| 1.43        | 0.33   | 6.77   |
| m_eff > 150 GeV   | 32.06        | 8.23| 2.80        | 0.72   | 43.81  |
| m_eff > 250 GeV   | 6.18         | 1.65| 1.81        | 0.48   | 10.12  |

Table 1: SM contributions to the trilepton channel at 14 TeV LHC. The m_ℓ_eff or m_eff cut is applied one at a time. All the cross-sections are in femtobarns.

| Cut          | (Z_0/γ^*)(Z_0/γ^*) | tt(Z_0/γ^*) | Total   |
|--------------|---------------------|-------------|---------|
| Basic cuts   | 9.33                | 0.46        | 9.79    |
| m_ℓ_eff > 100 GeV | 9.25   | 0.46        | 9.71    |
| m_ℓ_eff > 200 GeV | 3.71   | 0.32        | 4.03    |
| m_eff > 150 GeV   | 7.87                | 0.45        | 8.32    |
| m_eff > 250 GeV   | 1.67                | 0.36        | 2.03    |

Table 2: SM contributions to the four-lepton channel at 14 TeV LHC. The m_ℓ_eff or m_eff cut is applied one at a time. The tt contribution is zero after the basic lepton selection and isolation cuts. All the cross-sections are in femtobarns.

The SM contributions coming from the sign-inclusive 3ℓ and the 4ℓ channels are shown in Tables 1 and 2 respectively. The predictions for the 14 TeV run only are presented here;
although the predictions for 7 TeV, too, are very small, we do not expect enough statistics for performing our suggested analysis there. We show the cross-sections after different cuts on the $m_{eff}$ and $m_{e_{ff}}$ variables. In the $3\ell$ channel the major backgrounds are $W^{\pm}(Z_0/\gamma^*)$, \(tt\), $tt(Z_0/\gamma^*)$ and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference. In the $4\ell$ channel, the dominant SM contributions come from $(Z_0/\gamma^*)(Z_0/\gamma^*)$, $tt$, and $ttW^{\pm}$. Here, the $W^{\pm}(Z_0/\gamma^*)$ and $tt(Z_0/\gamma^*)$ processes include the effect of $Z$, $\gamma^*$ and their interference.
Although most of the analysis we have presented for such couplings is based on a $\tilde{\chi}_1^0$-LSP scenario, we shall see later that one with $\tilde{\tau}_1$-LSP, too, has potential for SS3$\ell$ events.

**Case 3:** With bilinear R-parity breaking terms ($\sim \epsilon_i$), the most spectacular consequence is the mixing between neutralinos and neutrinos as well as between charginos and charged leptons. Consequently, over a substantial region of the parameter space, a $\tilde{\chi}_1^0$ LSP in this scenario decays into $W\mu$ or $W\tau$ in 80% cases altogether, so long as the R-parity breaking parameters are in conformity with maximal mixing in the $\nu_\mu - \nu_\tau$ sector [20]. From the decay of the two $\tilde{\chi}_1^0$'s, one can obtain SSD's either from these $\mu$'s, or from the leptonic decay of the $W$'s or the $\tau$'s. An additional lepton from the SUSY cascade results in SS3$\ell$ again. Adding up all the above possibilities, the rates can become substantial.

Again, in addition to a $\tilde{\chi}_1^0$-LSP, a $\tilde{\tau}_1$-LSP also can lead to the signals under consideration. We shall briefly mention such possibilities later in our discussion.

### 3.1 mSUGRA benchmark points and rates for 14 TeV

In [5], the SS3$\ell$ cross-sections for a few representative points from the mSUGRA parameter space were presented, for both the 7 TeV and 14 TeV runs. Those benchmark points, corresponding to the various cases discussed in the previous sub-section, are shown in Table 3. We show the values of $M_0$ and $M_{1/2}$ ($M_0$ and $M_{1/2}$ being respectively the universal scalar and gaugino mass at high scale), the ratio of the vacuum expectation values of the two Higgs doublets tan $\beta$, as well as the values of other relevant SUSY parameters at the electroweak scale (fixed here at $\sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}}$, where $\tilde{t}_1$ and $\tilde{t}_2$ are the two mass eigenstates of the top squarks). We use fixed values for the other mSUGRA parameters, namely, the universal soft-breaking trilinear scalar interaction $A_0 = 0$ and the Higgsino mass parameter $\mu > 0$. Since the values of the L-violating couplings are very small, they do not affect the renormalisation group running of mass parameters from high to low scale [21]. We have therefore generated the spectrum using SuSpect 2.41 [22] and interfaced it with SDECAY [23] by using the programme SUSY-HIT [24] (for calculating the decay branching fractions of the sparticles) and finally have interfaced the spectrum and the decay branching fractions to PYTHIA, which is used to generate all possible SUSY production processes. Also, we have neglected the role of R-violating interactions in all stages of cascades excepting when the LSP is decaying. The value of each trilinear coupling ($\lambda, \lambda'$) used for illustration is 0.001. For case 3, The values of the $\epsilon$-parameters are chosen consistently with the neutrino data; essentially, they are tuned to sneutrino vacuum expectation values of the order of 100 keV, in a basis where the bilinear terms are rotated away from the superpotential. The values of $\epsilon_i$ are also of this order in the absence of any additional symmetry. The exact values of $\epsilon_i$ that correspond to points 3(1) and 3(2) in Table 3 depend also on other parameters of the model, such as the L-violating soft terms in the scalar potential [25]. However, the range of values of these parameters is of little consequence to the neutralino decay branching ratios. Therefore, with appropriate values of these soft terms, $\epsilon_3 \approx 100$ keV, $\epsilon_1 = \epsilon_2 = 0$ is consistent with all our results. In order to demonstrate the reach of the LHC in the SS3$\ell$ channel, we show in Figure 1 the boundary contours of regions in the $M_0 - M_{1/2}$ plane, where at least 5 signal events (with zero background event expected) can be obtained with a given integrated luminosity. This scan was performed for a sample case (case 1) with fixed values for the other mSUGRA parameters ($\tan \beta = 10, A_0 = 0, \mu > 0$). Similar discovery reaches are expected for the other
cases also. This plot, which we also presented in Ref. [5], has now been improved by using proper interpolation routines for points lying in between the simulated grid in the $M_0$-$M_{1/2}$ plane. In addition, in Figure 1 we have used a 5 signal events discovery criterion while in Ref. [5] we used a 10 signal events discovery criterion. Since we do not expect any background event in the SS3$\ell$ channel even with 30 fb$^{-1}$ integrated luminosity, 5 signal events should be sufficient for a discovery. Note that there is a sharp fall observed in each curve of Figure 1. As we increase $M_0$ for a given $M_{1/2}$, the first two family sleptons eventually become heavier than the chargino, thereby reducing the branching fraction of $\tilde{\chi}^\pm_1 \rightarrow l^\pm \nu \tilde{\chi}^0_1$. This leads to a drop in the SS3$\ell$ cross-section, giving rise to the faster fall in the curves.

We refer the reader to [5] for the total signal cross-sections for the various other cases of R-parity violation. It is clear that, with at least 30 fb$^{-1}$ of integrated luminosity, they can enable one to perform the analysis suggested in later sections for extracting the exact dynamics of R-parity violation.

| Case | $M_0$ (GeV) | $M_{1/2}$ (GeV) | tan$\beta$ | $m_{\tilde{g}}$ (GeV) | $m_{\tilde{\chi}_1^0}$ (GeV) | $m_{\tilde{\chi}_1^\pm}$ (GeV) | $m_{\tilde{\tau}_1}$ (GeV) | $m_{\tilde{e}_L}$ (GeV) | RPV Coupling |
|------|------------|----------------|-----------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1a(1) | 75         | 275            | 15        | 661            | 200            | 108*           | 115            | 204            | $\lambda_{123}$ |
| 1a(2) | 200        | 250            | 40        | 610            | 183            | 99*            | 139            | 265            | $\lambda_{123}$ |
| 1a(3) | 100        | 435            | 5         | 1009           | 331            | 176*           | 191            | 309            | $\lambda_{123}$ |
| 1a(4) | 300        | 435            | 40        | 1016           | 337            | 178*           | 246            | 418            | $\lambda_{123}$ |
| 1b(1) | 0          | 325            | 10        | 770            | 241            | 129            | 118*           | 222            | $\lambda_{123}$ |
| 1b(2) | 160        | 250            | 40        | 608            | 182            | 98             | 94*            | 236            | $\lambda_{123}$ |
| 1b(3) | 50         | 435            | 5         | 1008           | 330            | 176            | 171*           | 297            | $\lambda_{123}$ |
| 1b(4) | 150        | 435            | 40        | 1009           | 336            | 178            | 109*           | 328            | $\lambda_{123}$ |
| 2(1)  | 75         | 275            | 15        | 661            | 200            | 108*           | 115            | 204            | $\lambda_{112}$ |
| 2(2)  | 200        | 250            | 40        | 610            | 183            | 99*            | 139            | 265            | $\lambda_{112}$ |
| 2(3)  | 100        | 435            | 5         | 1009           | 331            | 176*           | 191            | 309            | $\lambda_{112}$ |
| 2(4)  | 300        | 435            | 40        | 1016           | 337            | 178*           | 246            | 418            | $\lambda_{112}$ |
| 3(1)  | 100        | 435            | 5         | 1009           | 331            | 176*           | 191            | 309            | $\epsilon_i$ |
| 3(2)  | 300        | 435            | 40        | 1016           | 337            | 178*           | 246            | 418            | $\epsilon_i$ |

Table 3: mSUGRA benchmark points defined in Ref. [5] for the various cases discussed in the text (e.g., 1a(1) corresponds to the first example in case 1a). The LSP in a given point is indicated by a * against its mass. The low-scale MSSM parameters were generated in an mSUGRA framework (with $A_0 = 0$ and $\mu > 0$). The $\lambda$ and $\lambda'$ couplings are set at 0.001, and the $\epsilon_i$ are within the limits set by neutrino data. The SS3$\ell$ cross-sections after various cuts in these benchmark points can be found in Ref. [5].

### 3.2 A resume of the 7 TeV results

In our previous study [5], for the 7 TeV run, we presented the points which can be discovered with an integrated luminosity of 2 fb$^{-1}$. Since the LHC experiments are collecting data at a fast pace and there is every chance of continuing the 7 TeV run up to at least 5 fb$^{-1}$, we update our 7 TeV results in cMSSM to include more points which can now be accessed. In
particular, with this increase of luminosity, we find that benchmark points with the squark-gluino masses in the TeV range can also be accessed in the SS3$\ell$ channel. These benchmark points include cases with $\tilde{\chi}_1^0$ LSP and $\lambda$-type couplings (points 1a(3) and 1a(4)) and also $\tilde{\tau}_1$ LSP with $\lambda$-type couplings (point 1b(3)). For $\tilde{\chi}_1^0$ LSP with $\lambda'$-type couplings, the SUSY sparticle mass-reach is somewhat smaller, and we can access masses slightly higher than 650 GeV during the 7 TeV run (point 2(1) in Table 4), if we insist on seeing 10 signal events without backgrounds with $5 \text{ fb}^{-1}$ of integrated luminosity. For 3 signal events with $\leq 1$ background event, however, the reach is considerably higher. Thus, on the whole, the 7 TeV run has extremely encouraging prospects for more than one R-parity violating scenarios, from the viewpoint of total event rates.

### 3.3 Other possibilities in L-violating SUSY

We now discuss some other possible cases in L-violating SUSY where one can also get SS3$\ell$ events. In case of a $\tilde{\tau}_1$ LSP with $\lambda'_{ijk}$-type couplings, the $\tilde{\tau}_1$ will directly decay to two quarks if the index $i$ takes the value 3. For the other two cases where $i$ takes the value 1 or 2, $\tilde{\tau}_1$ cannot decay via two-body L-violating modes. In this case, it will go through a 4-body decay via an intermediate off-shell chargino or neutralino. In mSUGRA type of models, the lighter stau is mostly composed of the right-chiral field, in which case it will couple primarily to the bino component of the neutralino. Also, the lighter chargino there is mostly heavier than the lightest neutralino, and therefore the propagator suppression is more for off-shell chargino. Thus, the mode through off-shell neutralino will dominate. Thus, we shall find the dominant decay pattern for a $\tilde{\tau}_1$ to be $\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_1^0(\ast) \rightarrow \tau l^\pm qq'$. SS3$\ell$ events arise then in
| Case | $\sigma_{SSu}$ (fb) |
|------|------------------|
| 1a(1) | 19.82 |
| 1a(2) | 29.45 |
| 1a(3) | 4.29 |
| 1a(4) | 2.01 |
| 1b(1) | 30.74 |
| 1b(2) | 6.46 |
| 1b(3) | 3.35 |
| 2(1) | 2.07 |
| 2(2) | 4.03 |

Table 4: SS3$\ell$ cross-sections after all selection cuts ($\sigma_{SSu}$) at $\sqrt{s} = 7$ TeV for the different cases defined in Table 3.

In a very similar fashion as in the case of a $\tilde{\chi}_1^0$ LSP with $\lambda'$-type couplings.

Since the intermediate neutralino in $\tilde{\tau}_1^\pm$-decay is a Majorana particle, we shall not have equal rates for the $\tau^\pm l^+ q\bar{q}'$ and the $\tau^\pm l^- q\bar{q}'$ final states. Also, the production of the $\tilde{\tau}_1$ in the decay of each neutralino has also an accompanying tau, which is another source of leptons. Consequently, with two taus decaying together with two staus, there is a favourable combinatoric factor for SS3$\ell$, which partially offsets the suppression due to branching ratios. The exact numerical evaluation of the relevant branching fractions and the resulting event rates is a detailed exercise by itself. In any case, we expect substantial cross-sections in the SS3$\ell$ channel, with the usual reduction of events in the presence of $\lambda'$-type couplings compared to the presence of $\lambda$-type couplings.

In presence of bi-linear L-violating couplings, a $\tilde{\tau}_1$ which is the LSP can mix with a charged Higgs, thereby leading to the decay mode $\tilde{\tau}_1 \rightarrow \tau \nu_z$, since the charged Higgs will couple more to the tau lepton than to electrons or muons. Thus, starting from a pair of neutralinos which can be produced in cascades, one can obtain two same-sign tau leptons, whose further leptonic decays can give rise to two leptons of the same sign. The third lepton of the same sign can come in the usual way from $\tilde{\chi}_1^\pm$ decay giving rise to SS3$\ell$. Evidently, the rates in this case are expected to be rather small for various branching fraction suppressions. A detailed study of SS3$\ell$ in the $\tilde{\tau}_1$-LSP scenario for both of the above cases will be reported in a forthcoming publication [26].

4 SS3$\ell$ in phenomenological MSSM (pMSSM)

4.1 pMSSM with L-violation

Next we discuss the case of phenomenological MSSM, which includes many more possibilities than mSUGRA, as far as the mass spectra are concerned. In particular, the three gaugino mass parameters at the weak scale then need not be in the approximate ratio $M_1 : M_2 : M_3 = 1 : 2 : 6$. Thus the lighter chargino may not be about twice as massive as the lightest neutralino, a fact that can affect electroweak phenomenology considerably. Since one of the
leptons in the SS3ℓ signal comes from the cascade decay of the chargino (via on or off-shell $W$'s and sleptons) $\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 l^\pm \nu$, we need to look into other hierarchies between $M_1$ and $M_2$.

If $M_1 \simeq M_2$, $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ are all very close in mass, and therefore the lepton coming from chargino decay is rather soft in the $\tilde{\chi}^\pm_1$ rest frame. But, if the $\tilde{\chi}^\pm_1$ is resulting from the decay of the gluino or squarks, which could be much heavier, it can have a large boost, giving rise to high $p_T$ leptons which will pass the required cuts.

Another interesting situation arises if $M_1 > M_2$. Here, the $\tilde{\chi}^0_1$ and the $\tilde{\chi}^\pm_1$ are mostly composed of wino components. This is what happens, for example, in the case of anomaly mediated SUSY breaking. The degeneracy in their masses is even more severe in this case, and some fine-tuning is necessary to make their mass difference of the order of pion mass. Here, one can have an additional channel in the cascade, from which a third lepton can arise. The second lightest neutralino can decay to a charged lepton, a neutrino and the $\tilde{\chi}^\pm_1$. The lepton produced in this way can have sufficient $p_T$ to be detectable. The $\tilde{\chi}^\pm_1$, on the other hand, goes to the $\tilde{\chi}^0_1$ and an extremely soft pion (or lepton + neutrino), and the $\tilde{\chi}^0_1$ pair can be the source of same-sign dileptons, which, when of the same-sign as that of the initial lepton, leads to SS3ℓ. We also look into the case of $M_1 < M_2$ in pMSSM but with a wider mass separation than expected in mSUGRA, namely, $M_2 = 3M_1$. Here the rates of SS3ℓ are somewhat enhanced. Finally, we look into a kind of non-universality between the low-energy selectron (or smuon) and stau soft masses. This can lead to a scenario where all the sleptons except stau are lighter than $\tilde{\chi}^\pm_1$ and the BF of $\tilde{\chi}^\pm_1$ to leptons is around 95%. Needless to say, this enhances the SS3ℓ rates.

In order to be conservative, we fix the squark soft masses and $M_3$ at 1 TeV. We have already shown in Ref. [5] that the strongly interacting sparticle mass scale of around 600 GeV is easily accessible at the LHC in the SS3ℓ channel during the 7 TeV run. The benchmark points chosen here are just to emphasize that the SS3ℓ signal can probe a generic MSSM model up to considerable higher masses of strongly interacting superparticles even during the early run. In addition, the situation of relatively closely spaced low-lying charginos/neutralinos, including those with an inverted hierarchy compared to mSUGRA, also turn up with substantial event rates. We present the most important parameters in the pMSSM benchmark points in Table 5 and the SS3ℓ cross-sections at these points in Table 6. As mentioned above, we have fixed the squark soft masses and $M_3$ at 1 TeV while $A_t$, $A_b$, $A_s$ and the $\mu$ parameter have been fixed at $-500$, $-500$, $-250$ and 975 GeV respectively. $\tan \beta$ has been fixed at 10, and the R-parity violating coupling used for illustration is $\lambda_{123} = 10^{-3}$. The cross-sections have been calculated for both the 7 TeV and the 14 TeV runs at the LHC, and we also give the required luminosities for a five-event discovery, with no events expected from the backgrounds. The overall usefulness of SS3ℓ in probing low missing-energy SUSY scenarios is thus brought out quite emphatically by the results presented by us. To this is added the rather striking prospect of extracting dynamic information (like the presence of Majorana gauginos and the exact nature of L-violating couplings) from the SS3ℓ and SS4ℓ channels, as will be explained in detail in section 5, again on the basis of a model-independent scan of the SUSY parameter space.
Table 5: Values of \( M_1 \), \( M_2 \) and some other relevant parameters for the SS3\( \ell \) channel in the pMSSM benchmark points. The squark and gluino masses are fixed at \( \sim 1 \) TeV.

| BP | \( M_1 \) (GeV) | \( M_2 \) (GeV) | \( \tilde{M}_{\chi^0_1} \) (GeV) | \( \tilde{M}_{\tilde{\chi}^\pm_1} \) (GeV) | \( \tilde{M}_{\tilde{g}} \) (GeV) | \( \tilde{M}_{\tilde{q}} \) (GeV) |
|----|----------------|----------------|----------------|----------------|----------------|----------------|
| 1  | 150            | 150            | 146.54         | 154.80         | 254.13         | 180.91         |
| 2  | 160            | 150            | 154.08         | 154.80         | 254.13         | 217.69         |
| 3  | 100            | 300            | 97.69          | 395.30         | 254.10         | 180.68         |
| 4  | 125            | 250            | 121.65         | 254.35         | 156.76         | 217.52         |

Table 6: SS3\( \ell \) cross-sections in the different pMSSM benchmark points at 7 TeV and 14 TeV LHC. We also show the luminosities required to obtain 5 signal events at the two centre of mass energies.

| BP | \( \sigma_{7 \text{ TeV}} \) (fb) | \( \mathcal{L}_{7 \text{ TeV}} \) (fb\(^{-1}\)) | \( \sigma_{14 \text{ TeV}} \) (fb) | \( \mathcal{L}_{14 \text{ TeV}} \) (fb\(^{-1}\)) |
|----|-------------------------------|---------------------------------|-------------------------------|---------------------------------|
| 1  | 0.91                          | 5.49                            | 4.60                          | 1.09                            |
| 2  | 0.41                          | 12.20                           | 1.62                          | 3.09                            |
| 3  | 2.81                          | 1.78                            | 20.67                         | 0.24                            |
| 4  | 8.78                          | 0.57                            | 42.93                         | 0.12                            |

4.2 pMSSM with conserved R-parity

If lepton number is conserved in the MSSM, then it is extremely difficult to find a scenario where one can obtain a same-sign trilepton signal (We specifically design the cuts to suppress leptons coming from b-decays, since otherwise they can boost the standard model backgrounds as well.) In fact, we do not find any such scenario in the simple mSUGRA picture. If one considers a purely phenomenological MSSM, one can of course generate a wide variety of mass spectra. We find one particular such spectrum where one can obtain SS3\( \ell \), but at a negligibly low rate because of branching fraction suppressions which are difficult to avoid. Thus, as far as we could analyze the MSSM processes with conserved R-parity, it is not possible to generate SS3\( \ell \) with significant cross-section. Therefore, it seems, within a supersymmetric framework, a reasonably large cross-section of SS3\( \ell \) is a clear indication of L-violation.

To convince the reader of this, let us outline a scenario in MSSM, where, in principle, it is possible to obtain an SS3\( \ell \) signal, albeit with a small rate. Consider a situation where the sbottom is lighter than the stop. In this case, let us look at stop pair production (\( \tilde{t}_1\tilde{t}_1^* \)), followed by the decay \( \tilde{t}_1 \to \tilde{b}_1 W^+ \) (and a charge-conjugate decay process for \( \tilde{t}_1^* \)). The produced \( \tilde{b}_1 \) can then decay to \( t\tilde{\chi}_1^- \), although with a very low branching fraction. The top quark, of course, then decays to \( bW^+ \). Thus starting from the initial \( \tilde{t}_1\tilde{t}_1^* \) we can obtain a final state (\( W^+\tilde{\chi}_1^-\tilde{b}W^+ \))/(\( W^-\tilde{\chi}_1^+\bar{b}W^- \)). We can re-write this final state as (\( bb \))(\( W^+W^+\tilde{\chi}_1^+ \))(\( W^-W^-\tilde{\chi}_1^- \)). Now, it can be clearly seen that if a set of three same-charge \( W^\pm \)'s and \( \tilde{\chi}_1^\pm \)'s decay leptonically and the other set decays hadronically, we have a same-sign trilepton signal. In order to demonstrate the branching fraction suppression of this SS3\( \ell \) final
state, let us consider a typical pMSSM spectrum with $M_{\tilde{t}_1} = 522\text{ GeV}$ and $M_{\tilde{b}_1} = 482\text{ GeV}$. We keep the first two generation squark masses at $\sim 5\text{ TeV}$ in order to separate out the third generation squark production, which is the only relevant process for the SS3$\ell$ channel. The gluino mass is $\sim 1050\text{ GeV}$, while the chargino and neutralino masses are at $264\text{ GeV}$ and $120\text{ GeV}$ respectively. With these parameters the SS3$\ell$ cross-section after all the cuts turns out to be $2.72 \times 10^{-2}\text{ fb}$ at the 14 TeV LHC, which is evidently very small.

5 Observable patterns in L-violating LSP decays

We have now reasons to feel reasonably confident that substantial SS3$\ell$ (or SS4$\ell$) rates are unlikely to be seen in R-parity conserving SUSY, and that R-parity (read lepton number) violation will be strongly suggested by them. More pointedly, L-violation by odd units and the existence of more than one Majorana fermions in the scenario work together towards the enhancement of such signals.

The total rate of SS3$\ell$ in a particular L-violating scenario depends not only on the L-violating coupling and the LSP involved, it is also dictated by SUSY production cross-section and other parameters determining the cascade decay patterns. We shall now show that it is possible to extract the information on the different L-violating couplings, through which a Majorana neutralino LSP decays, once we make use of the SS3$\ell$ and SS4$\ell$ final states.

With this in view, we construct certain variables which involve not only the SS3$\ell$ and SS4$\ell$ rates in a given scenario, but also on the total rates in the 3$\ell$ and 4$\ell$ channels. In a generic MSSM scenario with a particular L-violating coupling, it is possible to make definite predictions involving these variables based on simple probability arguments and neutralino branching fraction information in different combinations of charged lepton final states. We then verify these predictions using Monte Carlo simulations, where we also show the effect of selection and isolation cuts, as well as the effect of adding the SM backgrounds in the 3$\ell$ and 4$\ell$ channels. Although we have demonstrated the results using some mSUGRA benchmark points for simplicity, the conclusions are generic to phenomenological scenarios.

5.1 Neutralino LSP with $\lambda$-type couplings

A neutralino LSP in presence of $\lambda_{ijk}$-type couplings contributes to same-sign trileptons only if one of the indices in $\{ijk\}$ is 3. As $\lambda_{ijk}$ is anti-symmetric in $i$ and $j$, there are nine independent couplings of $\lambda$-type. Out of these nine couplings, seven have 3 as one index, and only two do not have the index 3 anywhere. Now consider the generic decay mode of the $\tilde{\chi}_{1}^{0}$ where $\tilde{\chi}_{1}^{0} \rightarrow \tau^{\pm}l^{\mp}\nu$ ($l = e, \mu$). The produced $\tau^{\pm}$ will decay leptonically in $\sim 35\%$ of the time, and hadronically in rest of the cases. Now consider the ratio of the number of same-sign trilepton (SS3$\ell$) events to the total number of trilepton events (which includes both same-sign trileptons (SS3$\ell$) and mixed-sign trileptons (MS3$\ell$)). This ratio can be calculated independent of the other SUSY parameters as follows. In the above case, in a trilepton event, we know that at most one of the leptons is coming from the cascade as the pair of neutralinos produced at the end of the decay chains will always give rise to at least 2 leptons.

As mentioned before, the produced $\tau^{\pm}$'s decay to a semi-leptonic final state in $\sim 35\%$ of the cases, and to hadronic final states in $65\%$ cases. Therefore, as the two $\tilde{\chi}_{1}^{0}$ decays will produce
two leptons when both the $\tau^\pm$'s decay hadronically, the fraction of cases a pair of $\tilde{\chi}_1^0$'s goes to 2 leptons and jets and neutrinos is $(0.65)^2 = 0.4225$. Similarly, a pair of neutralinos can go to 3 leptons in a fraction $(2 \times 0.65 \times 0.35) = 0.455$ of all cases (i.e., when one $\tau^\pm$ decays leptonically and the other one decays hadronically). In rest of the cases they decay to a four-lepton final state (when both the $\tau^\pm$'s decay leptonically) which we are not considering in this case. Thus out of all possible trilepton events, in $\approx 42\%$ cases one lepton comes from the cascade and in $\sim 46\%$ cases no lepton comes from the cascade. We can summarise the situation in Table 7.

| No. of leptons (Cascade) | No. of leptons (LSP Decay) | Fraction of cases | SS3$\ell$ Fraction | MS3$\ell$ Fraction |
|-------------------------|---------------------------|------------------|-------------------|-------------------|
| 1                       | 2                         | 0.42             | 0.25              | 0.75              |
| 0                       | 3                         | 0.46             | 0                 | 1                 |

Table 7: Fraction of trilepton events with different origins for the leptons, and the fractions of SS3$\ell$ and MS3$\ell$ events among them (see explanation in text).

In Table 7, the first two columns represent the number of leptons coming from the two different sources that we distinguish, namely, from the cascade and from the decay of the two $\tilde{\chi}_1^0$ LSP’s. As explained above, there are only two such possibilities in a trilepton event. Those two possibilities are described in the two rows of the table. The third column describes the fraction of cases in which each of these possibilities occur. We have explained the numbers in this column above. Finally, the last two columns represent the fraction of SS3$\ell$ and MS3$\ell$ events in each of the possible ways of obtaining a trilepton event, as explained below.

From Table 7, we see that in the first case where two of the leptons come from the LSP-pair decay, and one from the cascade, the probability of getting an $l^+l^+$ pair from the LSP’s is 0.25, and same for obtaining an $l^-l^-$ pair (this stems from the fact that the $\tilde{\chi}_1^0$ is Majorana). Now, in a trilepton event, let $P_1$ be the probability of the single lepton coming from the cascades being of positive charge, and $P_2$ for it to be of negative charge. Then, the probability of obtaining an SS3$\ell$ event is $0.25 \times P_1 + 0.25 \times P_2 = 0.25$ as $P_1 + P_2 = 1$. Therefore, the probability of obtaining an MS3$\ell$ event is $1 - 0.25 = 0.75$. In the second case, where all three of the leptons are coming from the LSP decay, all the trilepton events are of MS3$\ell$-type. Note that, we are demanding only three leptons in the final state, therefore any event with additional leptons (four or more) are vetoed out. Let us now define the ratio

$$x = \frac{\sigma_{SS3\ell}}{\sigma_{SS3\ell} + \sigma_{MS3\ell}}$$

(5)

From Table 7, we see that we can easily calculate this ratio as follows

$$x = \frac{\sigma_{total} \times 0.42 \times 0.25}{\sigma_{total} \times [(0.42 \times 0.25) + (0.42 \times 0.75 + 0.46)]} \approx 0.12,$$

(6)

where $\sigma_{total}$ is the total SUSY production cross-section which cancels out among the numerator and the denominator. As we have explained above, the trilepton events are a fraction of all possible SUSY events and SS3$\ell$ and MS3$\ell$ events are subsets of all 3$\ell$ events.
This value of the ratio \( x \simeq 0.12 \) is therefore a prediction stemming from the L-violating decay mode of the neutralino under study and also the Majorana character of the neutralino. Whatever be the values of the other SUSY parameters, as long as we have a \( \tilde{\chi}_1^0 \) LSP decaying via a \( \lambda_{123} \) type of coupling, this ratio is fixed. In particular, this ratio is independent of the probabilities of obtaining a charged lepton of either sign from the cascade. One should note, however, that if the L-violating couplings are so large as to compete with the gauge couplings for the decay of sparticles other than the LSP, this result can change. But, flavour physics and neutrino physics experiments suggest that these Yukawa couplings would take rather small values if SUSY models are to explain the above phenomena.

| Point | \( \sigma_{SSM} + \sigma_{MSM} \) (fb) | \( \sigma_{SSS} \) (fb) | \( x \) |
|-------|-------------------------------------|-----------------|--------|
| 1a(1) | 928.32                              | 75.11           | 0.08   |
| 1a(2) | 1084.26                             | 110.06          | 0.10   |
| 1a(3) | 228.24                              | 27.51           | 0.12   |
| 1a(4) | 149.47                              | 14.20           | 0.10   |

Table 8: The 3\( \ell \) (signal+SM background) and SS3\( \ell \) (signal) cross-sections at 14 TeV LHC after the \( m_{eff} > 250 \) GeV cut and the ratio \( x \) calculated including the SM background contribution. The total SM background in the 3\( \ell \) channel after the above cut is 10.12 fb. Note that the predicted value of \( x \) in this case is ~ 0.12, which shifts somewhat after including the effects of lepton isolation, detection efficiencies, other cuts and the SM backgrounds. The agreement with the predicted value is within 20\% in most cases.

In realistic situations, where we have to consider the experimental triggers, detector efficiencies etc., the ratio \( x \) can fluctuate around the predicted value of ~ 0.12. Unfolding these effects in an event by event basis is not an easy exercise, and we abstain from trying to do so. In Table 8 we present the ratio \( x \) obtained by Monte Carlo simulations with proper cuts in different benchmark points with widely varying SUSY parameters. We see that to within 20\% one always gets a ratio as predicted, thereby validating the above analysis. Thus we find that this ratio of SS3\( \ell \) to the total trilepton production cross-section gives us dynamic information about the underlying SUSY theory, in particular the L-violating coupling involved and the Majorana nature of the decaying LSP.

What happens if we change the L-violating coupling? Note that, in the presence of a generic \( \lambda_{ijk} \)-type coupling a \( \tilde{\chi}_1^0 \) decays to two charged leptons and a neutrino. Only if one of these leptons is a tau, which in turn can decay hadronically, one can obtain an SS3\( \ell \) signal. Therefore, one of the indices in \( \{i,j,k\} \) has to be 3. Moreover, we find the ratio \( x \simeq 0.12 \) only for the none-zero coupling \( \lambda_{123} \). The reason for this is that if \( i = 3 \) or \( j = 3 \) (which are equivalent due to the antisymmetry of \( \lambda_{ijk} \) in the indices \( i, j \)), then the \( \tilde{\chi}_1^0 \) can also decay to a \( \nu_\tau \) instead of a \( \tau^\pm \), thereby changing the ratio. For example, for the set of couplings \( \{131, 132, 231, 232\} \) we find this ratio to be approximately \( x \sim 0.14 \), while for the set \( \{121, 122\} \), \( x = 0 \), since no SS3\( \ell \) events are expected in these cases.

The above analysis thus shows that the dynamic information of a Majorana \( \tilde{\chi}_1^0 \) decaying via \( L_i L_j E_k^- \)-type couplings can be captured in a quantity easily measurable at the LHC experiments. Since the cross-sections in the 3\( \ell \) and SS3\( \ell \) channels are rather large (see
Table 8 at the 14 TeV LHC, one can acquire a reasonably good statistics within $1 - 5 \text{fb}^{-1}$ of integrated luminosity. Therefore, these cross-sections can be measured and the ratio $x$ calculated fairly accurately in the early periods of the 14 TeV run.

5.2 Neutralino LSP with $\lambda'$-type couplings

The case for $\tilde{\chi}_1^0$ LSP with $\lambda'$-type couplings is somewhat more complicated than that for the $\lambda$-type couplings. No unique prediction (which is independent of the other SUSY parameters) can be made there about the ratio $x$. One can, however, construct a similar ratio with four-lepton events. Subsequently, we obtain a linear relation between these two ratios, which is then independent of the parameters determining the cascade decays.

In the presence of a $\lambda'$-type coupling, a $\tilde{\chi}_1^0$ decays either to two quarks and a neutrino, or to two quarks and a charged lepton. SS3$\ell$ signals can arise in the second case. But now we have more ways in which one can obtain trilepton events. Let us define the fraction of cases in which a $\tilde{\chi}_1^0$ decays via $\tilde{\chi}_1^0 \rightarrow l^\pm qq$ to be $\alpha$. Now let us note the various possible ways of obtaining trilepton events in Table 9. The structure and meaning of the different entries in this table are same as explained in detail for Table 7.

| No. of leptons (Cascade) | No. of leptons (LSP Decay) | Fraction of cases | SS3$\ell$ Fraction | MS3$\ell$ Fraction |
|--------------------------|--------------------------|------------------|-------------------|-------------------|
| 3                        | 0                        | $(1 - \alpha)^2$ | 0                 | $\frac{1}{2}$      |
| 2                        | 1                        | $2\alpha (1 - \alpha)$ | $\frac{1-P_3}{2}$ | $\frac{1+P_3}{2}$ |
| 1                        | 2                        | $\alpha^2$       | 0.25              | 0.75              |

Table 9: Fraction of trilepton events with different origins for the leptons, and the fractions of SS3$\ell$ and MS3$\ell$ events among them (see explanation in text).

Since $\alpha$ denotes the probability that a $\chi_1^0$ will decay leptonically, the fraction of cases a pair of $\chi_1^0$s give rise to two leptons is $\alpha^2$. Similarly, when both the $\chi_1^0$s decay to neutrinos and quarks, we do not obtain any leptons from LSP decays. This happens in $(1 - \alpha)^2$ fraction of trilepton events. And, finally, in the remaining $2\alpha (1 - \alpha)$ fraction of cases, we obtain one lepton from the decay of the two LSP’s. In the first case, when all three of the leptons come from the cascade, we do not obtain any SS3$\ell$ event, making the MS3$\ell$ fraction unity. In order to understand the second case, note that in Table 9 when two leptons come from the cascade, we define $P_3$ to be the probability of them being oppositely charged ($l^\pm l^\mp$). Thus, $(1 - P_3)$ is the probability of them being of same charge ($l^\pm l^\pm$). In such a case, in a trilepton event, evidently the third lepton comes from LSP decay. In half of such events the lepton coming from LSP decay will also have the same sign, thereby giving rise to an SS3$\ell$ event. Thus the probability of obtaining an SS3$\ell$ event is $\frac{1-P_3}{2}$. Consequently, the probability for obtaining a MS3$\ell$ event is $(1 - \frac{1-P_3}{2}) = \frac{1+P_3}{2}$. In the third case, where two of the leptons come from LSP decay, because of the Majorana nature of the decaying $\chi_1^0$ LSP, we get the corresponding fractions in the same way as in the previous sub-section, where we considered $\chi_1^0$ decay via $\lambda$-type terms.

In this case, therefore, we find the following formula for the ratio $x$ defined in eqn. 5.
\[ x = \alpha - \frac{3}{4} \alpha^2 - P_3 \left( \alpha - \alpha^2 \right) \]  

(7)

Now, the ratio \( \alpha \) is very weakly dependent on the sparticle mass spectra, especially the difference between the up and down-type squark masses entering the off-shell propagators in the 3-body \( \tilde{\chi}^0_1 \) decays. In most scenarios this difference is rather small, especially for the first two families. On the whole, \( \alpha \) is close to 0.5 in most cases.

As mentioned before, there is a residual dependence of \( x \) on \( P_3 \), thereby making this ratio vary as the other SUSY parameters vary (also the parton distribution functions affect \( P_3 \)). In order to eliminate \( P_3 \) and obtain a prediction that follows just from the Majorana nature of the \( \tilde{\chi}^0_1 \) and the L-violating coupling involved, we introduce another ratio \( y \) defined as

\[ y = \frac{\sigma_{SS\ell}}{\sigma_{SS\ell} + \sigma_{MS\ell}} \]  

(8)

where \( \sigma_{SS\ell} \) and \( \sigma_{MS\ell} \) are the same-sign four-lepton and mixed-sign four-lepton cross-sections respectively.

To calculate \( y \), we make a table similar to the one made for calculating \( x \).

| No. of leptons (Cascade) | No. of leptons (LSP Decay) | Fraction of cases | SS\ell Fraction | MS\ell Fraction |
|-------------------------|----------------------------|-------------------|-----------------|----------------|
| 4                       | 0                          | \((1 - \alpha)^2\) | 0               | 1              |
| 3                       | 1                          | \(2\alpha (1 - \alpha)\) | 0               | 1              |
| 2                       | 2                          | \(\alpha^2\)      | \(1 - P_3\)     | \(3 + P_3\)    |

Table 10: Fraction of four-lepton events with different origins for the leptons, and the fractions of SS\ell and MS\ell events among them (see explanation in text).

Since, the fraction of cases for the different possibilities are only dependent on the number of leptons coming from LSP decays, the entries in the third column of Table 10 can be understood in the same way as in the trilepton case, which we explained before while discussing Table 9. In the first two cases, where four and three leptons come from the cascade respectively, the MS\ell fraction is 1, since we cannot get more than two same-sign leptons from the cascade. In the third case, we define \( P_3 \) as before. Since \((1 - P_3)\) is the probability to have a same-sign lepton pair from the cascade, in order to obtain a same-sign four lepton event, we need the other two leptons coming from LSP decay to be of the same-sign as that of the cascade leptons. Now, since the \( \tilde{\chi}^0_1 \) is a Majorana particle, when it decays leptonically, the probability to obtain a same charge lepton as in the cascade is \(1/2\), and similarly for the second \( \tilde{\chi}^0_1 \), thus giving us a probability of \( \frac{1-P_3}{4} \) to obtain an SS\ell event. The rest of the events are of MS\ell variety, which come with a fraction of \( (1 - \frac{1-P_3}{4}) = \frac{3+P_3}{4} \). This completes the explanation of Table 10.

From Table 10 and eqn. 8 we find that

\[ y = \frac{\alpha^2}{4} - \frac{\alpha^2 P_3}{4} \]  

(9)

The total SUSY production cross-section \( \sigma_{\text{total}} \) cancels out in the ratio as in the case for \( x \). Combining these two equations for \( x \) and \( y \), we can eliminate \( P_3 \) to obtain the following equation relating \( x \) and \( y \):
\[ x = \frac{\alpha^2}{4} + 4y \left( \frac{1}{\alpha} - 1 \right) \]  

(10)

This equation is therefore a prediction based just on the Majorana nature of the decaying $\tilde{\chi}_1^0$ LSP and the presence of $\lambda'$-type couplings. In order to verify the above claim and also to see the deviations due to lepton selection and isolation effects we note the values of $x$ and $y$ obtained in different benchmark points and compare them with the above prediction taking $\alpha \sim 0.5$ and present the results in Table 11.

| Point | $y^S_{MC}$ | $x^S_{MC}$ | $x^S_{eqn.}$ | $y^{S+B}_{MC}$ | $x^{S+B}_{MC}$ | $x^{S+B}_{eqn.}$ |
|-------|-------------|-------------|--------------|----------------|----------------|-----------------|
| 2(1)  | 0.024       | 0.147       | 0.159        | 0.018          | 0.111          | 0.135           |
| 2(2)  | 0.023       | 0.154       | 0.155        | 0.020          | 0.126          | 0.143           |
| 2(3)  | 0.027       | 0.144       | 0.171        | 0.021          | 0.102          | 0.147           |
| 2(4)  | 0.044       | 0.175       | 0.239        | 0.025          | 0.094          | 0.163           |

Table 11: The ratios $x$ and $y$ after the $m_{\text{eff}} > 250$ GeV cut, before and after adding the SM background cross-sections. Here, $y^S_{MC}$ and $x^S_{MC}$ refer to the ratios $x$ and $y$ calculated only with the signal whereas $y^{S+B}_{MC}$ and $x^{S+B}_{MC}$ denote the ratios calculated adding up both the signal and the background cross-sections in the appropriate channels. $x^{S}_{eqn.}$ and $x^{S+B}_{eqn.}$ denote the values of $x$ calculated using eqn. (10) taking $\alpha = 0.5$, with $y^S_{MC}$ and $y^{S+B}_{MC}$ as the respective inputs.

The entries of Table 11 have been explained in the caption of the table. The ratios $x$ and $y$ have been evaluated from cross-sections calculated for the 14 TeV LHC. As the total $3\ell$ and $4\ell$ cross-sections in the case of a $\tilde{\chi}_1^0$ LSP with $\lambda'$-type coupling are comparable to the SM backgrounds, the ratios $x$ and $y$ change after adding the backgrounds. In order to show that we present the ratios both before and after adding the SM background cross-sections. In order to validate the prediction derived in eqn. (10) we take the Monte Carlo prediction for $y$ as an input, and then calculate the value of $x$ from eqn. (10) and denote it by $x_{eqn}$. This $x_{eqn}$ is then compared with $x_{MC}$, the value obtained from Monte Carlo. The rather excellent agreement between the entries in the third and fourth columns in Table 11 demonstrates the viability of our claim in eqn. (10). As noted before, here we have used the approximate value of 0.5 for $\alpha$. We then again repeat the same calculation after adding the SM backgrounds in the $3\ell$ and $4\ell$ channels. Since the backgrounds are comparable to the signal in this case, the ratios change somewhat after the background addition, and the agreement between the prediction of eqn. (10) and the MC is not as good as with only the signal, which is expected. Also note that, in the benchmark points 2(2) and 2(4) we have the $\tilde{\chi}_1^\pm$ lighter than the $\tilde{e}_L$. This reduces the $\tilde{\chi}_1^\pm$ branching fraction to leptons, thereby leading to a reduction of trilepton and four-lepton events of same-sign and mixed-sign varieties. The lower branching fraction is compensated by the much larger total SUSY production cross-section in point 2(2). Point 2(4) thus suffers from lower number of multi-lepton events, and the accurate evaluation of the ratios $x$ and $y$ here would require much larger statistics. Also if SS3$\ell$ signals are indeed seen in the mass range of, say point 2(4), then the further reduction of backgrounds may be a pressing need in order to extract dynamics out of this signal.
5.3 Neutralino LSP with bi-linear couplings

In the presence of bi-linear L-violating couplings, the decay branching fractions of $\tilde{\chi}_1^0$ in different channels are dependent on various other soft SUSY-breaking parameters, too. Thus it is not possible to predict a specific equation which will be valid generically for all possible choices of the relevant parameters. Instead, we focus in a region where the $\tilde{\chi}_1^0$ decays either in the $W^\pm\mu^\mp$ or in the $Z\nu$ channel. This is largely the case when the slepton/sneutrino states have not-too-large mixing with the Higgs states [20]. In this case, we find an equation relating the $x$ and $y$-variables which is very similar to the equation of straight line found for the case of $\tilde{\chi}_1^0$ LSP with $\lambda'$-type couplings (with a different slope for the straight line!). Since the detailed evaluation of the relevant branching fractions in different combinations of charged-lepton final states is straightforward but cumbersome, we just note down the final results in the following tables.

| No. of leptons (Cascade) | No. of leptons (LSP Decay) | Fraction of cases | SS3\ell Fraction | MS3\ell Fraction |
|--------------------------|---------------------------|-------------------|------------------|------------------|
| 3                        | 0                         | 0.146             | 0                | 1                |
| 2                        | 1                         | 0.366             | $\frac{1-P_3}{2}$ | $\frac{1+P_3}{2}$ |
| 1                        | 2                         | 0.335             | 0.17             | 0.83             |
| 0                        | 3                         | 0.134             | 0                | 1                |

Table 12: Fraction of trilepton events with different origins for the leptons, and the fractions of SS3\ell and MS3\ell events among them, in the case of a $\tilde{\chi}_1^0$ LSP with bi-linear L-violating couplings (see explanation in text).

| No. of leptons (Cascade) | No. of leptons (LSP Decay) | Fraction of cases | SS4\ell Fraction | MS4\ell Fraction |
|--------------------------|---------------------------|-------------------|------------------|------------------|
| 4                        | 0                         | 0.146             | 0                | 1                |
| 3                        | 1                         | 0.366             | 0                | 1                |
| 2                        | 2                         | 0.335             | $0.17 - 0.17P_3$ | $0.83 + 0.17P_3$ |
| 1                        | 3                         | 0.134             | 0                | 1                |
| 0                        | 4                         | 0.020             | 0                | 1                |

Table 13: Fraction of four-lepton events with different origins for the leptons, and the fractions of SS4\ell and MS4\ell events among them, in the case of a $\tilde{\chi}_1^0$ LSP with bi-linear L-violating couplings (see explanation in text).

From Table 12 we find that

$$x = 0.24 - 0.19P_3$$  \hspace{1cm} (11)

and similarly, from Table 13 we find an expression for $y$

$$y = 0.06(1 - P_3)$$  \hspace{1cm} (12)

We can eliminate $P_3$ from equations (11) and (12) to obtain an equation of straight line relating $x$ and $y$.  

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\[ x = 3.529y + 0.063 \] (13)

As mentioned before, this equation is very similar to the equation obtained for the case of \( \tilde{\chi}_1^0 \) LSP with \( \lambda' \)-type couplings. The slope in the \( x-y \) plane, however, is slightly different in this case.

| Point | \( y_{MC}^S \) | \( x_{MC}^S \) | \( x_{MC}^{S+B} \) | \( y_{MC}^{S+B} \) | \( x_{MC}^{S+B} \) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 3(1)  | 0.012           | 0.096           | 0.107           | 0.012           | 0.088           | 0.105           |
| 3(2)  | 0.016           | 0.087           | 0.112           | 0.015           | 0.075           | 0.115           |

Table 14: Same as in Table [11] for the case of bi-linear L-violation.

In Table [13] which is similar to Table [11] we present a comparison of the MC calculation and the prediction from eqn. [13] for \( x \), with \( y \) calculated from MC as input. We find that the predictions agree with the MC calculations to within \( \sim 20\% \) or better. As for the \( \lambda' \) case, the prediction and MC calculations deviate a little bit more after adding the SM backgrounds, since the total signal cross-sections in the \( 3\ell \) and \( 4\ell \) channels are comparable to the backgrounds. Also, in this case as the total rates for multi-lepton events are rather small for the chosen benchmark points (with the squark and gluino masses \( \sim 1 \) TeV), we need a much larger statistics in order to calculate the ratios accurately.

### 6 Summary and conclusion

We have performed a detailed study of SS3\( \ell \) and SS4\( \ell \) signals in the context of the LHC, to arrive at a number of important conclusions. First, such signals are enhanced, to such a degree as to be appreciable even during the 7 TeV run (and also the 14 TeV run with low integrated luminosity), if there is (a) L-violation by odd units, and (b) the presence of self-conjugate fields. The outstanding theoretical scenario meeting the above requirements is SUSY with R-parity violated via lepton number. Therefore, we strongly advocate the investigation of such signals, especially as they are complementary to signals with large missing \( E_T \).

We have gone beyond the mSUGRA scenario and focused on different regions of the parameter space of a general SUSY model. It has been shown that sizable SS3\( \ell \) rates are expected over various regions of interest in the parameter space, so much so that up to a TeV in the scale of strongly interacting superparticle masses can be explored at the 7 TeV run itself. This in itself is quite remarkable for signals with such high multiplicity of leptons, and can be attributed to almost non-existent SM backgrounds. It is further shown that event rates of comparable magnitude are almost impossible to achieve in an L-conserving SUSY scenario of a general kind. This, we argue, further strengthens the motivation of studying same-sign multileptons.

The other really useful feature of SS3\( \ell \) and SS4\( \ell \) signals that we have emphasized is that they enable us to extract information on the dynamics of R-parity violation, namely, whether lepton number is violated through the \( \lambda \), \( \lambda' \) or the bilinear terms. Using SS3\( \ell \) and SS4\( \ell \) event
rates in conjunction with their mixed-sign counterparts, one is able to define certain ratios and their relationships which are typical of the type of R-parity violating terms, taken one at a time. More importantly, these ratios and their relations are largely independent of the SUSY spectrum and the nature of cascades, and depend centrally on the Majorana character of neutralinos, making our conclusions extremely general. We perform detailed simulation for a number of benchmark points to substantiate this claim. The simulations include the effects of experimental cuts as well the SM backgrounds for mixed-sign trileptons and four leptons.

Thus the overwhelming recommendation is for a careful analysis of SS3$\ell$ and SS4$\ell$ signals at the LHC. Such analysis should be concurrent with the search for events with large missing energy, because of its complementary nature.

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