

Same-sign trileptons and four leptons as signatures of new physics at the Large Hadron Collider

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We point out that same-sign multilepton events, not given due attention yet for new physics search, can be extremely useful at the Large Hadron Collider. After showing the easy reducibility of the standard model backgrounds, we demonstrate the viability of same-sign trilepton signals for R-parity breaking supersymmetry, at both 7 and 14 TeV. We find that same-sign four-leptons, too, can have appreciable rates. Same-sign trileptons are also expected, for example, in Little Higgs theories with T-parity broken by anomaly terms.

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Finding physics beyond the standard electroweak theory is an important goal of the Large Hadron Collider (LHC). However, most proposed signals are beset with backgrounds from processes driven by the standard model (SM) itself, and the reduction of backgrounds requires a Herculean effort. It is by and large agreed that signals containing leptons (electrons or muons) are helpful from this angle. Thus one finds a lot of interest in signals comprising dileptons, trileptons as well as final states with higher lepton multiplicity. In addition, same-sign dileptons (SSD) are relatively background-free if the event selection criteria are properly chosen [1].

Here we stress the importance of some unexplored signals, namely, same-sign leptons of higher multiplicity. Among these, we mainly focus on same-sign trileptons (SS3l). In spite of the fact that the charge of an electron or a muon can be identified with high efficiency [2], not enough attention has been paid yet to signals with lepton multiplicity higher than two, with all of them having the same sign of charge. Although SS3l has been discussed in the context of top quark production at hadron colliders of yesteryears [3], its capacity to reveal new physics is still a path which remains to be explored in detail. We shall demonstrate below that the SM backgrounds to the SS3l signal at the LHC can be made vanishingly small. On the other hand, substantial rates for SS3l events are predicted in some well-motivated scenarios beyond the standard model. They are, in fact, particularly enhanced when one has (a) lepton number (L) violation by odd units, and (b) the presence of self-conjugate massive particles. We illustrate this in the context of several supersymmetric (SUSY) scenarios with R-parity violation [4]. We also point out that other new physics scenarios, such as Little Higgs models with T-parity broken through anomaly terms [5], can predict a signal of this kind. Based on these observations, we conclude that framing the experimental

strategies to capture SS3l events can open a new door to the study of physics beyond the SM at the LHC. We further show that such scenarios can yield enough same-sign four-lepton (SS4l) events, which are background-free and reveal important information on the underlying new physics.

We start by taking a look at the SM contributions to the SS3l signal. The main sources here are (i) $t\bar{t}$, (ii) $t\bar{t}W$, (iii) $t\bar{t}b\bar{b}$ and (iv) $t\bar{t}t\bar{t}$ production. Of the various processes, $t\bar{t}$ production, copious as it is, generates SS3l if a lepton comes from a charm quark produced from a b which in turn results from top-decay. This causes a significant degradation of momentum of at least the softest lepton, and judicious lepton isolation and hardness cuts suppress it. The other channels, too, suffer from either perturbative suppression at the initial production level or low branching ratios in the cascades. We summarize the SM backgrounds to SS3l in Table I. The events were generated with the code ALPGEN [6], and decays and hadronization were done using PYTHIA 6.421 [7]. We have primarily selected leptons with $p_T \geq 10$ GeV, $|\eta| \leq 2.5$, where p_T and η are, respectively, the transverse momentum and pseudorapidity of the lepton. 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

TABLE I. Dominant same-sign trilepton SM background cross sections (σ_{SS3l}) for $\sqrt{s} = 14$ TeV after the basic isolation cuts (Cut-1) and after demanding that $p_T^{l_1} > 30$ GeV, $p_T^{l_2} > 30$ GeV, $p_T^{l_3} > 20$ GeV and $\cancel{E}_T > 30$ GeV, which are collectively referred to as Cut-2. Here l_1 , l_2 and l_3 are the three leptons ordered according to their p_T 's. Note that the $t\bar{t}$ contribution falls drastically after Cut-1 itself.

Process	σ_{SS3l} (fb) [Cut-1]	σ_{SS3l} (fb) [+ Cut-2]
$t\bar{t}W$	2.80×10^{-2}	2.44×10^{-3}
$t\bar{t}b\bar{b}$	4.45×10^{-3}	$< 1.11 \times 10^{-3}$
$t\bar{t}t\bar{t}$	8.40×10^{-4}	6.45×10^{-5}
Total	3.33×10^{-2}	2.50×10^{-3}

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and jets with Gaussian functions [2]. We further demand a 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. We also demand a lepton-jet separation $\Delta R_{lj} \geq 0.4$ for all jets with $E_T \geq 20$ GeV. Also, a 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. A missing- E_T (\cancel{E}_T) cut of 30 GeV is also included, in order to reduce the probability of jets faking leptons [8]. Subsequently, stronger p_T -cuts (as mentioned in the caption of Table I) are applied, in order to ensure minimum hardness for even the softest of the three leptons [9]. This, together with the demand on lepton isolation, strongly suppresses the b- (and c-) induced leptons, and makes the SM contributions quite small, as shown in Table I.

Encouraged by the above observation, we first illustrate the usefulness of the SS3l channel in new physics scenarios. As we have mentioned already, our purpose is not to highlight any particular new theory; we stress that such signals, experimentally quite tractable as they are, speak for new physics unequivocally, and they are indeed expected with large rates in a number of cases. As the same-sign multileptons are facilitated when L-violation takes place, R-parity violating (RPV) SUSY is our best example, where one further has Majorana fermions in the form of gluinos and neutralinos, from whose cascade decays leptons of either charge are expected with the same rate. We present several cases below, with quantitative predictions for each of them.

SS3l in RPV SUSY: The superpotential in RPV SUSY can contain the following $\Delta L = 1$ terms, over and above those present in the minimal SUSY standard model (MSSM):

$$W_{\cancel{L}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2.$$

Case 1: With the λ -type terms, we consider two possibilities, namely, having (a) the lightest neutralino ($\tilde{\chi}_1^0$) and (b) the lighter stau ($\tilde{\tau}_1$) as the lightest SUSY particle (LSP). In (a), SS3l can arise if $\tilde{\chi}_1^0$ decays into a neutrino, a tau (τ) and a lepton of either of the first two families. With the τ decaying hadronically, the two leptons from two $\tilde{\chi}_1^0$'s produced in SUSY cascades are of identical sign in 50% of the cases. An additional lepton of the same sign, produced in the decays of chargino ($\tilde{\chi}_1^\pm$) in the cascade, leads to SS3l. If there is just one λ -type coupling (we have used λ_{123} for illustration), there is no further branching fraction suppression in LSP decay, and one only pays the price of $\tilde{\chi}_1^\pm$ -decay into a lepton of the same sign. In (b), two same-sign $\tilde{\tau}_1$'s can be produced from two $\tilde{\chi}_1^0$'s, thanks to its Majorana character. Each of these $\tilde{\tau}_1$'s goes into a lepton and a neutrino; these two leptons, together with one of identical sign from the cascade, lead to SS3l signals.

Case 2: With λ' -type interactions, a $\tilde{\chi}_1^0$ -LSP decays into two quarks and one charged lepton or neutrino. If the LSP is not much heavier than the top quark, and if the effect of the difference between up and down couplings of the neutralino can be neglected, we obtain SSD's from a pair of $\tilde{\chi}_1^0$'s roughly in 12.5% of the cases. If another lepton of the same sign arises from a $\tilde{\chi}_1^\pm$, SS3l is an immediate consequence. Therefore, the overall rate of SS3l can be sizable in this case as well. Here (and also partially in case 1(b)) the large boost of the $\tilde{\chi}_1^0$ can lead to collimated jets and leptons. Thus some events may not pass the isolation cut. It should also be noted that a $\tilde{\tau}_1$ -LSP with λ' -type terms cannot lead to SS3l, as the $\tilde{\tau}_1$ decays into two quarks only.

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 ν_μ - ν_τ sector [10]. From the decay of the two $\tilde{\chi}_1^0$'s, one can obtain SSD's either from these μ 's, or from the leptonic decay of the W 's or the τ 's. An additional lepton from the SUSY cascade results in SS3l again. Adding up all the above possibilities, the rates can become substantial.

Results: In Tables II and III, the predictions for all the aforementioned cases, corresponding to some representative points for each, are presented, for $\sqrt{s} = 14$ and 7 TeV, respectively. We have used CTEQ6L1 [11] parton distribution functions, with the renormalization and factorization scales kept at the PYTHIA default [7]. The value of each trilinear coupling (λ, λ') used for illustration is 0.001. For case 3, The values of the ϵ -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 ϵ_i are also of this order in the absence of any additional symmetry. The exact values of ϵ_i that correspond to points 3(1) and 3(2) in Table II depend also on other parameters of the model, such as the L-violating soft terms in the scalar potential [12]. 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.

Initial and final state radiation effects as well as multiple interactions are included in the PYTHIA simulation, where all SUSY production processes are taken into account. We show values of SUSY parameters at the electroweak scale (in this case it has been fixed at $\sqrt{\tilde{m}_{\tilde{\tau}_1} \tilde{m}_{\tilde{\tau}_2}}$, where \tilde{t}_1 and \tilde{t}_2 are the two mass eigenstates of the top squarks, respectively), though they have been generated, for the sake of

TABLE II. SS3l cross sections after Cut-1 (σ_{SS3l}^1) and Cut-2 (σ_{SS3l}^2) at $\sqrt{s} = 14$ TeV 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 an asterisk against its mass. The low-scale MSSM parameters were generated in an mSUGRA framework. The λ and λ' couplings are set at 0.001, and the ϵ_i are within the limits set by neutrino data (see discussion in the text).

Case	$\tan\beta$ (GeV)	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)	$m_{\tilde{e}_L}$ (GeV)	RPV Coupling	σ_{SS3l}^1 (fb)	σ_{SS3l}^2 (fb)
1a(1)	15	661	200	108*	115	204	λ_{123}	465.22	195.97
1a(2)	40	610	183	99*	139	265	λ_{123}	811.20	301.36
1a(3)	5	1009	331	176*	191	309	λ_{123}	81.54	55.31
1a(4)	40	1016	337	178*	246	418	λ_{123}	55.52	31.83
1b(1)	10	770	241	129	118*	222	λ_{123}	416.62	296.26
1b(2)	40	608	182	98	94*	236	λ_{123}	100.27	61.62
1b(3)	5	1008	330	176	171*	297	λ_{123}	53.00	42.74
1b(4)	40	1009	336	178	109*	328	λ_{123}	20.05	13.41
2(1)	15	661	200	108*	115	204	λ'_{112}	59.96	20.97
2(2)	40	610	183	99*	139	265	λ'_{112}	136.35	38.21
2(3)	5	1009	331	176*	191	309	λ'_{112}	21.76	12.26
2(4)	40	1016	337	178*	246	418	λ'_{112}	15.27	8.21
3(1)	5	1009	331	176*	191	309	ϵ_i	36.50	22.23
3(2)	40	1016	337	178*	246	418	ϵ_i	23.28	12.52

economy, in a minimal supergravity (mSUGRA) scenario. Since the values of the L-violating couplings are very small, they do not affect the renormalization group running of mass parameters from high to low scale [13]. We have therefore generated the spectrum using SuSpect 2.41 [14] and interfaced it with SDECAY [15] by using the program SUSY-HIT [16] (for calculating the decay branching fractions of the sparticles) and finally have interfaced the spectrum and the decay branching fractions to PYTHIA. Also, we have neglected the role of R-violating interactions in all stages of cascades except when the LSP is decaying.

In Table II, we show the SS3l cross sections for two different gluino masses in each case, one around 600–800 GeV, and the other in the range of 1 TeV. We also have chosen different values of $\tan\beta$, and made allowance for different splittings and hierarchies between the $\tilde{\chi}_1^\pm$ and slepton masses. For each mass range, λ_{123} leads to the highest rates of the SS3l signal, as in this case the possibility of obtaining an isolated charged lepton from the LSP decay is higher than in the two other cases. Also, if the $\tilde{\chi}_1^\pm$'s are heavier than the first two family sleptons (and sneutrinos), the rates go up, owing to the increase in leptonic branching fraction of the $\tilde{\chi}_1^\pm$. Overall, the SS3l rates are substantial for all the cases; even moderate lumi-

TABLE III. SS3l cross-sections after Cut-1 (σ_{SS3l}^1) and after Cut-2 (σ_{SS3l}^2) at $\sqrt{s} = 7$ TeV for cases as defined in Table II. The RPV coupling in all the above cases is $\lambda_{123} = 0.001$.

Case	σ_{SS3l}^1 (fb)	σ_{SS3l}^2 (fb)
1a(1)	52.64	19.82
1a(2)	90.27	29.45
1b(1)	44.30	30.74
1b(2)	9.92	6.46

nosities can yield signals for gluino masses up to a TeV or so. In order to demonstrate the discovery reach of the LHC in this channel, we also show in Fig. 1 the boundary contours of regions in the M_0 - $M_{1/2}$ plane (M_0 and $M_{1/2}$ being, respectively, the universal scalar and gaugino mass at high scale), where at least 10 signal events 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. It should be pointed out here that, in the scenarios we consider, the reach in the SS3l channel is expected to be similar to the reach in channels with higher lepton multiplicity. This is because if we assume that the backgrounds in the multilepton channels can be reduced with similar efficiencies as shown here for SS3l, the signal cross sections for four-lepton and SS3l are expected to be

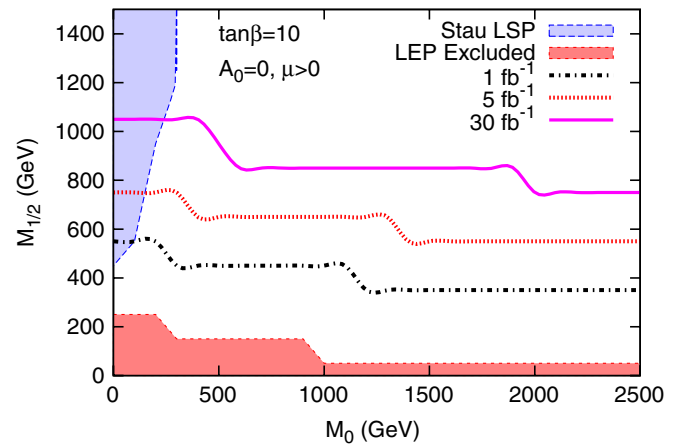


FIG. 1 (color online). 10-events LHC reach with SS3l in the M_0 - $M_{1/2}$ plane for R-parity violating mSUGRA, at $\sqrt{s} = 14$ TeV, with $\lambda_{123} = 0.001$, after Cut-2.

of similar order. While going from trileptons to SS3l we retain 25% of the signal, and a similar reduction will occur while going from trileptons to four-leptons, too (because of the $\tilde{\chi}_1^\pm \rightarrow l^\pm \nu \tilde{\chi}_1^0$ branching fraction).

Note that there are two kinks observed in each curve of Fig. 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 $\tilde{\chi}_1^\pm \rightarrow l^\pm \nu \tilde{\chi}_1^0$. This leads to a drop in the SS3l cross section, giving rise to the first kink. The second kink is coming from the drop in the total SUSY production cross section as the squarks become heavier as M_0 is increased, and after a certain point it is only the gluino pair production that dominates the total cross section. As we are using a 10-events discovery criterion (because of negligible backgrounds), the kinks look rather sharp.

Table III shows the points where we can get at least 10 signal events even at 7 TeV within an integrated luminosity of 2 fb^{-1} . The total SM background here, after both the cuts listed in Table I, is $7.01 \times 10^{-4} \text{ fb}$. While the λ' couplings lead to moderate rates here, rather handsome rates are predicted with λ -type ones, with both the $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ as the LSP. Thus we conclude that the prospect of discovering new physics in the SS3l channel in a background-free manner is rather bright even during the early run of the LHC.

Same-sign four-lepton (SS4l) signal: In all the cases discussed above, owing to the Majorana nature of the gluino, it is possible to produce two $\tilde{\chi}_1^\pm$'s of the same sign in an event. Thus, in addition to SS3l, one can also have four leptons with identical charge, coming from these two $\tilde{\chi}_1^\pm$'s and two LSP's. Such an SS4l signal has negligible backgrounds within the SM, particularly when strong isolation and lepton p_T cuts are used to suppress the rate of leptons coming from heavy flavor decays. Though a further branching fraction suppression will reduce this signal as compared to SS3l, we note in Table IV (in case 1 for illustration) that the event rates can still be quite sizable at the LHC, during the 14 TeV run, within an integrated luminosity of 5 fb^{-1} .

SS3l in Little Higgs: Finally, we would like to point out that the SS3l signal is also possible in other scenarios of new physics. An example is the Littlest Higgs model [17] with T-parity (LHT) violated via the Wess-Zumino-Witten anomaly term [5]. In this case, the heavy photon (A_H) (which in most models is the lightest T-odd particle) may decay into a $W^+ W^-$ pair. Pair-produced heavy quarks (q_H) can thus lead to four W 's, two of which can decay leptonically to give same-sign lepton pairs. The third additional lepton can easily come from the cascade via the decay of the heavy partner of the W boson (W_H). Thus we find that in the region of LHT parameter space where $M_{A_H} > 2M_W$

TABLE IV. SS4l cross sections after Cut-1 (σ_{SS4l}^1) and after Cut-2 (σ_{SS4l}^2) at $\sqrt{s} = 14 \text{ TeV}$ for cases as defined in Table II. For SS4l Cut-2 refers to demanding lepton $p_T > 20 \text{ GeV}$ for all the four leptons and a $\cancel{E}_T > 30 \text{ GeV}$. The RPV coupling in all the above cases is $\lambda_{123} = 0.001$.

Case	σ_{SS4l}^1 (fb)	σ_{SS4l}^2 (fb)
1a(1)	15.74	4.52
1a(2)	33.23	9.97
1a(3)	4.75	2.70
1a(4)	3.31	1.49
1b(1)	24.70	15.11
1b(3)	2.77	2.08

and $M_{q_H} > M_{W_H}$ one can have a SS3l signal. This, in fact, is a large region in the two-dimensional (f, κ_q) parameter space determining the heavy quark and gauge boson masses in LHT. In addition, if the T-odd leptons (l_H) are lighter than W_H , the SS3l rates will be further enhanced. This is achievable within this framework for appropriate values of κ_l . As an example, we have generated events for the parameter choices $f = 1150 \text{ GeV}$, $\kappa_q = 0.5$ and $\kappa_l = 0.25$, which correspond to $M_{q_H} = 809 \text{ GeV}$, $M_{A_H} = 174 \text{ GeV}$, $M_{W_H} = 747 \text{ GeV}$ and $M_{l_H} = 407 \text{ GeV}$ (the subscript H denotes T-odd partners of SM particles), with CalcHEP 2.5 [18,19] and interfaced them with PYTHIA. We obtain an SS3l cross section of 3.34 fb at $\sqrt{s} = 14 \text{ TeV}$, after Cut-2 as defined before.

In conclusion, same-sign multilepton signals are quite striking from the angle of the new physics search at the LHC, including its 7 TeV phase. Such signals can have large rates if more than one self-conjugate particles occur in a new physics scenario. This feature is better reflected in SS3l and SS4l than in SSD or general four-lepton signals. We have shown that clearly discernible rates for same-sign trileptons are expected over large regions of the parameter space of R-parity violating SUSY with broken L, even with moderate integrated luminosity. SS4l events, too, can have substantial rates in such scenarios. We also note that similar signals arise in other new physics proposals, such as Little Higgs theories with T-parity broken by anomaly terms. Due attention to this class of signals at the LHC is therefore a desideratum.

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