Same-sign multileptons at the LHC

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Searching for New Physics in Leptonic Final States

- Very large Standard Model backgrounds for fully hadronic final states at the LHC
- Signals with leptons have relatively less backgrounds
- Widely discussed for BSM search: OS and SS dileptons, trileptons, four or higher leptons

Giving attention to the Lepton Charge: Beyond Same-sign Dileptons

- SSD is enhanced in presence of strongly interacting self-conjugate particles Example: Majorana gluinos in MSSM
- SM backgrounds: relatively lower, leptons from b-decays important (largest rates from $t\bar{t}$)
- *Are there new physics scenarios giving rise to signals with three or more same-sign leptons?*
- Will be almost background-free: very low rates within the Standard Model
- We shall mainly focus on SM and BSM sources of same-sign trileptons (SS3l)

Signal and Background Analysis: Cuts Used

Cut-1: Primary selection of leptons

- $p_T^\ell \geq 10$ GeV; $|\eta^\ell| \leq 2.5$; $\Delta R_{\ell\ell} \geq 0.2$; $\Delta R_{\ell j} \geq 0.4$ $(E_T^j \geq 20$ GeV)
  $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$

- Relative isolation from hadronic activity : $\sum p_T$ (hadrons) $/p_T^\ell \leq 0.2$
  (Sum within a cone of $\Delta R \leq 0.2$ around the lepton)

- Gaussian smearing: transverse momenta (energies) of leptons, jets
- Effect of $B^0 - \bar{B}^0$ mixing on lepton signs: taken into account within PYTHIA

Cut-2: Stronger p_T-cuts

- Stronger cuts on p_T^ℓ's: (30,30,20) GeV for SS3l; (20,20,20,20) GeV for SS4l

- $\not{E}_T > 30$ GeV $\rightarrow$ reduce jets faking leptons

SS3l in the Standard Model: Extremely small contribution

Sources: leptonic decays of b- and c- quarks important

- $t\bar{t} \rightarrow$ negligible after Cut-1 (Barger and Phillips; 1984!)
- $t\bar{t}W^{\pm} \rightarrow$ Largest Source, harder SS leptons from two W's
- $t\bar{t}t\bar{t}$ or $t\bar{t}b\bar{b} \rightarrow$ very small, perturbatively suppressed

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}

- $\sqrt{s} = 14$ TeV
- Simulated using: ALPGEN and PYTHIA
- Fake rates very small :Ozcan, Sultansoy, Unel (2009)

SS3l in BSM: Lepton Number (L) violating SUSY

MSSM superpotential $+\Delta L = 1$ terms

$$W_{\not L} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2$$

SS3l: Four cases in L-violating SUSY

1. Neutralino LSP with λ-type couplings
2. Stau LSP with λ-type couplings
3. Neutralino LSP with λ'-type couplings
4. Neutralino LSP with bilinear couplings

How do we get same-sign trileptons?

Dominant source of three same-sign leptons:
Two from the RPV-decay of the two LSP's
One from the RPC-decay of a chargino in the cascade

Three principal factors determine the rate of SS3l events:

- $M_{\tilde{g}}$, $M_{\tilde{q}} \longrightarrow$ initial SUSY production cross-section
- Decay of the two LSP's: Probability of obtaining an SS lepton pair
- Splitting between $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\ell}}$ ($M_{\tilde{\nu}}$): $\longrightarrow$ Probability of obtaining a charged lepton of the same-sign from the cascade

Case-1a

$\tilde{\chi}_1^0$ LSP, λ-type coupling

$$\tilde{\chi}_1^0 \xrightarrow{\lambda_{ijk}} l_i^{\pm} l_j^{\mp} \nu_k$$

- A pair of SS leptons from a pair of $\tilde{\chi}_1^0$'s in 50% of the cases when
  1. One of the charged leptons produced is a τ (if one index in $\{ijk\}$ is 3)
  2. The τ decays hadronically
- Additional lepton of the same sign from a $\tilde{\chi}_1^{\pm} \rightarrow$ SS3l

Results: LHC $\sqrt{s} = 14$ TeV

LSP: $\tilde{\chi}_1^0$, RPV coupling: $\lambda_{123} = 10^{-3}$

Case	$\tan\beta$	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)	$m_{\tilde{e}_L}$ (GeV)	σ^1_{SS3l} (fb)	σ^2_{SS3l} (fb)
1a(1)	15	661	200	108*	115	204	465.22	195.97
1a(2)	40	610	183	99*	139	265	811.20	301.36
1a(3)	5	1009	331	176*	191	309	81.54	55.31
1a(4)	40	1016	337	178*	246	418	55.52	31.83

σ^1_{SS3l}: after Cut-1; σ^2_{SS3l}: after Cut-2

Simulation within mSUGRA (cMSSM) framework using
`SuSpect-SDECAY (SUSY-HIT)-PYTHIA`
For larger values of RPV couplings need to use RG eqns. including RPV effects, see Allanach, Bernhardt, Dreiner, Kom, Richardson; 2007 (can then use `SOFTSUSY-ISAWIG-ISAJET-Herwig`)

Case-1b

$\tilde{\tau}_1$ LSP, λ-type coupling

$$\tilde{\tau}_1^{\pm} \xrightarrow{\lambda_{ijk}} l_i^{\pm} \nu_j$$

- Two same-sign $\tilde{\tau}_1$'s can be produced from two $\tilde{\chi}_1^0$'s, thanks to its Majorana character.
- Each $\tilde{\tau}_1$ goes into a lepton and a neutrino (if at least one of $\{ijk\}$ is $3 \rightarrow$ two-body decays of $\tilde{\tau}_1$ allowed)
- When two-body decay modes are open, $\tilde{\tau}_1$ LSP with λ'-type terms cannot lead to SS3l $\rightarrow \tilde{\tau}_1 \xrightarrow{\lambda'_{ijk}} qq'$ (when the $\tilde{\tau}_1$ undergoes a four-body decay via an off-shell neutralino/chargino, one can again get SS3l)

  Details on stau LSP scenario: Dreiner, Grab, Trenkel; 2009
  Desch, Fleischmann, Wienemann, Dreiner, Grab; 2010

Results: LHC $\sqrt{s} = 14$ TeV

LSP: $\tilde{\tau}_1$, RPV coupling: $\lambda_{123} = 10^{-3}$

Case	$\tan\beta$	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)	$m_{\tilde{e}_L}$ (GeV)	σ^1_{SS3l} (fb)	σ^2_{SS3l} (fb)
1b(1)	10	770	241	129	118*	222	416.62	296.26
1b(2)	40	608	182	98	94*	236	100.27	61.62
1b(3)	5	1008	330	176	171*	297	53.00	42.74
1b(4)	40	1009	336	178	109*	328	20.05	13.41

Case-2

$\tilde{\chi}_1^0$ LSP, λ'-type coupling

$$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{ijk}} l_i^{\pm} u_j d_k / \nu_i d_j d_k$$

- A pair of SS leptons from a pair of $\tilde{\chi}_1^0$'s roughly in 12.5% of the cases
- Another lepton of the same sign from a $\tilde{\chi}_1^{\pm} \rightarrow$ SS3l
- Large boost of the $\tilde{\chi}_1^0 \rightarrow$ collimated jets and leptons $\rightarrow$ some leptons do not pass the isolation cut $\rightarrow$ reduction of rates

Results: LHC $\sqrt{s} = 14$ TeV

LSP: $\tilde{\chi}_1^0$, RPV coupling: $\lambda'_{112} = 10^{-3}$

Case	$\tan\beta$	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)	$m_{\tilde{e}_L}$ (GeV)	σ^1_{SS3l} (fb)	σ^2_{SS3l} (fb)
2(1)	15	661	200	108*	115	204	59.96	20.97
2(2)	40	610	183	99*	139	265	136.35	38.21
2(3)	5	1009	331	176*	191	309	21.76	12.26
2(4)	40	1016	337	178*	246	418	15.27	8.21

Case-3

$\tilde{\chi}_1^0$ LSP, bilinear RPV coupling

$$\tilde{\chi}_1^0 \xrightarrow{\epsilon_i} W^{\pm}\mu^{\mp}/W^{\pm}\tau^{\mp}/Z\nu$$

With bilinear R-parity breaking terms ($\epsilon_i L_i H_2$ + sneutrino vev):

- Mixing between neutralinos and neutrinos as well as between charginos and charged leptons $\rightarrow$ can explain neutrino masses and mixing
- Choose R-parity breaking parameters in conformity with maximal mixing in the $\nu_\mu - \nu_\tau$ sector
- Over a large region of parameter space $BR(\tilde{\chi}_1^0 \rightarrow W\mu \text{ or } W\tau) \approx 80\%$ (Mukhopadhyaya, Roy, Vissani; 1998 Hirsch, Diaz, Porod, Romano, Valle; 2002)
- Pair of SS leptons in many possible ways from the decay of the $\tilde{\chi}_1^0$-pair

Results: LHC $\sqrt{s} = 14$ TeV

LSP: $\tilde{\chi}_1^0$, RPV coupling: *Bilinear*

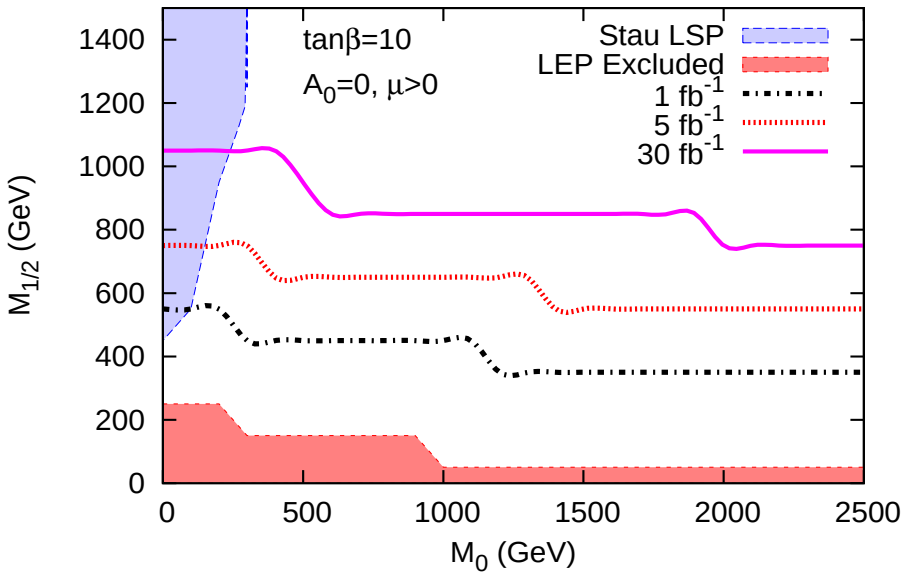
- The values of the ϵ-parameters are chosen in conformity with neutrino data (sneutrino vev $\sim$ 100 keV)

Case	$\tan\beta$	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)	$m_{\tilde{e}_L}$ (GeV)	σ^1_{SS3l} (fb)	σ^2_{SS3l} (fb)
3(1)	5	1009	331	176*	191	309	36.50	22.23
3(2)	40	1016	337	178*	246	418	23.28	12.52

LHC Reach for *RPV* SUSY in the SS3l channel

Reach in $m_0 - M_{1/2}$ plane

- No. of Background Events $B < 1$ for $30\,\mathrm{fb}^{-1}$ luminosity (B=0.075)
- Demand no. of Signal Events $S > 10$ for discovery
- $\sqrt{s} = 14$ TeV, $\lambda_{123} = 0.001$, after Cut-2



SUSY Mass Reach

For $30\,\mathrm{fb}^{-1}$, $m_0 \simeq 500$ GeV,
$M_{1/2} \simeq 1000$ GeV
$M_{\tilde{g}} \sim 2.2$ TeV

SS3l at 7 TeV LHC

LSP: $\tilde{\chi}_1^0$ (1a); $\tilde{\tau}_1$ (1b); RPV coupling: $\lambda_{123} = 0.001$; $M_{\tilde{g}} \sim 600 - 800$ GeV

Case	σ^1_{SS3l} (fb)	σ^2_{SS3l} (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

Features

- Total SM background after all cuts: 7.01×10^{-4} fb
- Require at least 10 events with $1\,\mathrm{fb}^{-1}$ luminosity
- Both $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ LSP scenarios with λ-type couplings might be discovered, but not enough events with λ'-type couplings with $1\,\mathrm{fb}^{-1}$

Same-sign four-lepton ($SS4l$) signal:

LSP: $\tilde{\chi}_1^0$ (1a); $\tilde{\tau}_1$ (1b); RPV coupling: $\lambda_{123} = 0.001$; all leptons with $p_T > 20$ GeV; need $\sim 5\,\mathrm{fb}^{-1}$

Case	σ^1_{SS4l} (fb)	σ^2_{SS4l} (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

Features

- Majorana nature of gluino $\rightarrow$ possible to produce two $\tilde{\chi}_1^{\pm}$'s of the same sign in an event $\rightarrow$ a pair of SS leptons
- Two more leptons of identical charge from the LSP decays
- $\rightarrow$ same-sign four-leptons!
- Rates suppressed by another factor of branching fraction (and a factor of 1/2 for demanding same charge)

Other possible BSM scenarios with SS3l signal

- Littlest Higgs model with T-parity violated by the Wess-Zumino-Witten anomaly term
- The presence of self-conjugate LTP A_H (heavy photon) and also heavy charged gauge bosons ($W_H^{\pm}$) leads to such signals
- SS3l signal viable in a large region of parameter space
- Example: $f = 1150\ \mathrm{GeV}$, $\kappa_q = 0.5$, $\kappa_l = 0.25$ ($\rightarrow M_{q_H} = 809\ \mathrm{GeV}$, $M_{A_H} = 174\ \mathrm{GeV}$, $M_{W_H} = 747\ \mathrm{GeV}$ and $M_{l_H} = 407\ \mathrm{GeV}$) $\rightarrow \sigma^2_{SS3l} = 3.34\ \mathrm{fb}$ for $\sqrt{s} = 14\ \mathrm{TeV}$
- Also possible: heavy fourth generation leptons and Majorana neutrinos (Ozcan, Sultansoy, Unel; 2009)
- But rates are much smaller than in many cases of L-violating SUSY

Conclusions

- Same-sign trilepton signals have extremely low standard model backgrounds
- Therefore they are very striking from the angle of new physics search at the LHC
- SUSY with L-violation can be discovered at the LHC using this channel for different possible LSP's, different L-violating couplings and over a large range of relevant parameters (within a moderate integrated luminosity)
- Neutralino and stau LSP scenarios with λ-type RPV couplings can also be discovered at the 7 TeV LHC within $1\,\mathrm{fb}^{-1}$ (for gluino masses in the range of $600 - 800\ \mathrm{GeV}$)
- SS4l events can also have substantial rates in such scenarios
- Similar signals arise in other new physics proposals, such as Little Higgs theories with T-parity broken by anomaly terms
- Large rates of such signals in SUSY might point towards L-violation and the presence of more than one self-conjugate particles in the spectrum
- It will be interesting to watch out for same-sign multileptons at the LHC!