Resonant Slepton Production at the LHC

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Abstract

We consider the resonant production of charged sleptons at the LHC via R-parity violation (Rp) followed by gauge decays to a charged lepton and a neutralino which then decays via Rp. This gives a signature of two like-sign charged leptons. In the simulation we include the full hadronisation via Monte Carlo programs. We find a background, after cuts, of 5.1 ± 2.5 events for an integrated luminosity of 10 fb−1. A preliminary study of the signal suggests that couplings of 2 × 10−3 for a smuon mass of 223 GeV and smuon masses of up to 540 GeV for couplings of 10−2 can be probed.

1 Introduction

In R-parity violating (Rp) models the single resonant production of charged sleptons in hadron-hadron collisions is possible. The most promising channels for the discovery of these processes, at least with small Rp couplings, involve the gauge decays of these resonant sleptons. In particular if we consider the production of a charged slepton, this can then decay to give a neutralino and a charged lepton, i.e. the process

\[ u + \bar{d} \rightarrow \tilde{\ell}^+ \rightarrow \ell^+ + \tilde{\chi}^0. \]  

In addition to this s-channel process there are t-channel processes involving squark exchange. The neutralino decays via the crossed process to give a charged lepton, which due to the Majorana nature of the neutralino can have the same charge as the lepton from the slepton decay. We therefore have a like-sign dilepton signature which we expect to have a low Standard Model background.

2 Backgrounds

The dominant Standard Model backgrounds to this process come from

• Gauge boson pair production, i.e. production of ZZ or WZ followed by leptonic decays of the gauge bosons with some of the leptons not being detected.

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• t¯t production. Either the t or ¯t decays semi-leptonically, giving one lepton. The second top decays hadronically. A second lepton with the same charge can be produced in a semi-leptonic decay of the bottom hadron formed in the hadronic decay of the second top, i.e.

\[
t \rightarrow \ W^+b \rightarrow e^+\bar{\nu}_e b,
\]
\[
\bar{t} \rightarrow \ W^-\bar{b} \rightarrow q\bar{q}\bar{b}, \quad \bar{b} \rightarrow e^+\bar{\nu}_e \bar{c}.
\]

(2)

• b¯b production. If either of these quarks hadronizes to form a B^0_{d,s} meson this can mix to give a B^0_{d,s}. This means that if both the bottom hadrons decay semi-leptonically the leptons will have the same charge as they are both coming from either b or ¯b decays.

• Single top production. A single top quark can be produced together with a b quark by either an s- or t-channel W exchange. This can then give one charged lepton from the top decay, and a second lepton with the same charge from the decay of the meson formed after the b quark hadronizes.

• Non-physics backgrounds. There are two major sources: (i) from misidentifying the charge of a lepton, e.g. in Drell-Yan production, and (ii) from incorrectly identifying an isolated hadron as a lepton. This means that there is a major source of background from W production with an additional jet faking a lepton.

Early studies of like-sign dileptons at the LHC \cite{1,2} only studied the backgrounds from heavy quark production. It was found that by imposing cuts on the transverse momentum and isolation of the leptons the heavy quark backgrounds could be significantly reduced. However more recent studies of the like-sign dilepton production at the LHC \cite{3,4} and the Tevatron \cite{5–8} suggest that a major source of background to like-sign dilepton production is from gauge boson pair production and from fake leptons. Here we will consider the backgrounds from gauge boson pair production as well as heavy quark production. The study of the non-physics backgrounds (e.g. fake leptons) requires a full simulation of the detector and it is therefore beyond the scope of our study. In particular the background from fake leptons cannot be reliably calculated from Monte Carlo simulations and must be extracted from data \cite{3,4}. We can use the differences between the \( R_p \) signature we are considering and the MSSM signatures considered in \cite{3,4} to reduced the background from gauge boson pair production.

We impose the following cuts

• A cut on the transverse momentum of the like-sign leptons \( p_T > 40 \) GeV.

• An isolation cut on the like-sign leptons so that the transverse energy in a cone of radius \( R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4 \) about the direction of each lepton is less than 5 GeV.

• A cut on the transverse mass, \( M_T^2 = 2|p_{T\ell}|\,|p_{T\nu}|(1 - \cos \Delta\phi_{\ell\nu}) \), where \( p_{T\ell} \) is the transverse momentum of the charged lepton, \( p_{T\nu} \) is the transverse momentum of the
neutrino, assumed to be all the missing transverse momentum in the event, and $\Delta \phi_{\ell \nu}$ is the azimuthal angle between the lepton and the neutrino, i.e. the missing momentum in the event. We cut out the region where $60 \text{ GeV} < M_T < 85 \text{ GeV}$.

- A veto on the presence of a lepton in the event with the same flavour but opposite charge (OSSF) as either of the leptons in the like-sign pair if the lepton has $p_T > 10 \text{ GeV}$ and which passes the same isolation cut as the like-sign leptons.

- A cut on the missing transverse energy, $E_T^{\text{miss}} < 20 \text{ GeV}$.

While these cuts were chosen to reduce the background we have not attempted to optimize them. The first two cuts are designed to reduce the background from heavy quark production. As can be seen in Fig. 1, these cuts reduce this background by several orders of magnitude. The remaining cuts are designed to reduce the background from gauge boson pair, in particular WZ, production which is the major source of background after the imposition of the isolation and $p_T$ cuts. The transverse mass cut is designed to remove events with leptonic W decays as can be seen in Fig. 2a. The veto on the presence of OSSF leptons is designed to remove events where one lepton from the dilepton pair comes from the leptonic decay of a Z boson. The missing transverse energy cut again removes events with leptonic W decays, this is mainly to reduce the background from WZ production, as seen in Fig. 2b. The effect of these cuts on the heavy quark and gauge boson pair backgrounds are shown in Figs. 1 and 2, respectively.
Figure 2: Transverse mass and missing transverse energy in WZ events

Figure 3: Effect of the isolation cuts on the WZ and ZZ backgrounds. The dashed line gives the background before any cuts, the solid line shows the effect of the isolation cut described in the text. The dot-dash line gives the effect of all the cuts.
| Background Process | Number of Events |
|--------------------|------------------|
|                    | After $p_T$ cut | After isolation and $p_T$ cuts | After all cuts |
| WW                 | $2.8 \pm 0.6$   | $0.0 \pm 0.1$                   | $0.0 \pm 0.1$  |
| WZ                 | $226 \pm 3$     | $189 \pm 3$                     | $4.1 \pm 0.5$  |
| ZZ                 | $50.4 \pm 0.9$  | $40.6 \pm 0.8$                  | $0.9 \pm 0.1$  |
| $t\bar{t}$        | $(4.8 \pm 0.3) \times 10^4$ | $0.34 \pm 0.14$ | $0.06 \pm 0.06$ |
| $b\bar{b}$        | $(5.69 \pm 0.8) \times 10^4$ | $0.0 \pm 2.4$ | $0.0 \pm 2.4$ |
| Single Top         | $11.5 \pm 0.3$  | $0.0 \pm 0.008$                 | $0.0 \pm 0.008$ |
| Total              | $(6.2 \pm 0.8) \times 10^4$ | $230 \pm 4$ | $5.1 \pm 2.5$ |

Table 1: Backgrounds to like-sign dilepton production at the LHC. The numbers of events are based on an integrated luminosity of 10 fb$^{-1}$. We used the cross sections from the Monte Carlo simulation for $b\bar{b}$ and single top production, the next-to-leading order cross section for gauge boson pair production from [11] and the next-to-leading order with next-to-leading-log resummation cross section from [12] for $t\bar{t}$ production. We estimate an error on the cross section from the effect of varying the scale between half and twice the hard scale, apart from gauge boson pair production where we do not have this information for the next-to-leading order cross section. The error on the number of events is then the error in the cross section and the statistical error from the simulation added in quadrature.

The backgrounds from the various processes are summarized in Table 1. The simulations of the $b\bar{b}$, $t\bar{t}$ and single top production were performed using HERWIG6.1 [9]. The simulations of gauge boson pair production used PYTHIA6.1 [10]. The major contribution to the background comes from WZ production the major contribution to the error comes from $b\bar{b}$. For the $b\bar{b}$ simulation we have required a parton-level cut of 40 GeV on the transverse momentum of the bottom quarks. This should not affect the results provided we impose a cut of at least 40 GeV on the $p_T$ of the leptons. We also forced the $B$ meson produced to decay semi-leptonically. In events where there was one $B_{d,s}$ meson this meson was forced to mix, if there was more than one $B_{d,s}$ then one of the mesons was forced to mix and the others forced to not mix. Even with these cuts it is impossible to simulate the full luminosity with the resources available, due to the large cross section for $b\bar{b}$ production. This gives the large error on the estimate of this background.

3 Signal

We used HERWIG6.1 [9] to simulate the signal. This version includes the resonant slepton production, including the $t$-channel diagrams, and the R-parity violating decay of the neutralino including a matrix element for the decay [13]. We will only consider first generation quarks as the cross sections for processes with higher generation quarks are suppressed by the parton distributions. There are upper bounds on the $R_p$ couplings from low energy experiments. The bound on $\lambda'_{111}$ from neutrino-less double beta decay [14–17] is very strict
Figure 4: Number of signal events passing the cuts and the efficiency for $M_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan \beta = 2$, $\text{sgn} \mu = +$, with the $R_p$ coupling $\lambda'_{211} = 0.01$. The dashed line gives the number of events needed for a 5\(\sigma\) discovery.

so we consider muon production via the coupling $\lambda'_{211}$, which has a much weaker bound,

$$\lambda'_{211} < 0.059 \times \left( \frac{M_{\tilde{d}}}{100\text{GeV}} \right),$$

from the ratio $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\mu)$ \cite{14, 18}.

We have performed a scan in $M_0$ using HERWIG with the following SUGRA parameters, $M_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan \beta = 2$, $\text{sgn} \mu = +$, and with the $R_p$ coupling $\lambda'_{211} = 0.01$. The number of events which pass the cuts given in Section 2 are shown in Fig. 4a, while the efficiency of the cuts, i.e. the fraction of the signal events which have a like-sign dilepton pair passing the cuts, is shown in Fig. 4b. The dip in the efficiency between $140$ GeV < $M_0$ < $180$ GeV is due to the resonant production of the second lightest neutralino becoming accessible. Just above threshold the efficiency for this channel is low due to the low $p_T$ of the lepton produced in the slepton decay.

If we conservatively take a background of 7.6 events, i.e. 1\(\sigma\) above the central value of our calculation, a 5\(\sigma\) fluctuation of the background would correspond to 20 events, using Poisson statistics. This is given as a dashed line in Fig.4a. As can be seen for a large range of values of $M_0$ resonant slepton production can be discovered at the LHC, for $\lambda'_{211} = 0.01$. The production cross section depends quadratically on the $R_p$ Yukawa coupling and hence it should be possible to probe much smaller couplings for small values of $M_0$.

As can be seen in Fig. 5, at this SUGRA point the sdown mass varies between $622$ GeV at $M_0 = 50$ GeV and $784$ GeV at $M_0 = 500$ GeV. The corresponding limit on the coupling $\lambda'_{211}$ varies between 0.37 and 0.46. We can probe couplings of $\lambda'_{211} = 2 \times 10^{-3}$ for $M_0 = 50$ GeV.
which corresponds to a smuon mass of 223 GeV, and at couplings of $\lambda_{211}' = 10^{-2}$ we can probe values of $M_0$ up to 500 GeV, i.e. a smuon mass of 540 GeV. This is more than an order of magnitude smaller than the current upper bounds on the $\mathcal{R}_p$ coupling given above for these values of $M_0$. This is a greater range of couplings and smuon masses than can be probed at the Tevatron\cite{19,20}. The backgrounds are higher at the LHC but this is compensated by the higher energy and luminosity leading to significantly more signal events.

4 Conclusions

We have considered the backgrounds to like-sign dilepton production at the LHC and find a background after cuts of $5.1 \pm 2.5$ events for an integrated luminosity of $10 fb^{-1}$. This means, taking a conservative estimate of the background of 7.6 events, that 20 events would correspond to a $5\sigma$ discovery. For a full analysis however, non-physics backgrounds must also be considered.

A preliminary study of the signal suggests that an efficiency for detecting the signal in excess of 20% can be achieved over a range of points in SUGRA parameter space. At the SUGRA point studied this means we can probe $\mathcal{R}_p$ couplings of $2 \times 10^{-3}$ for a smuon mass of 223 GeV and up to smuon masses of 540 GeV for couplings of $10^{-2}$, and higher masses for larger couplings.

A more detailed scan of SUGRA parameter space for this signal remains to be performed.
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