Resonant Slepton Production

H. Dreiner∗, P. Richardson†, and M.H. Seymour∗

∗Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, U.K.
†Department of Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, U.K.

Abstract. We consider the production of resonant sleptons via \( R_p \) followed by gauge decays to a charged lepton and a neutralino which then decays via \( \bar{R}_p \). This gives a signature of two like-sign charged leptons. We find a background at run II of \( 0.14 \pm 0.13 \) events with an integrated luminosity of \( 2 \) fb\(^{-1}\). This enables us to probe \( R_p \) couplings of \( 2 \times 10^{-3} \) for slepton mass of 100 GeV and up to slepton masses of 300 GeV for \( \bar{R}_p \) couplings of \( 10^{-2} \).

INTRODUCTION

Sleptons can be produced on resonance at the Tevatron via the \( R_p \) term in the superpotential. The slepton can then decay again via the \( \bar{R}_p \)-Yukawa coupling. This has been considered elsewhere [1–3]. It can also decay via the standard gauge decays of the MSSM [1] which we consider here. There are two possible gauge decays of the charged slepton, i.e.

\[
\begin{align*}
\tilde{\ell}_i^+ &\rightarrow \ell_i^+ \tilde{\chi}^0, \\
\tilde{\ell}_i &\rightarrow \tilde{\nu}_i \tilde{\chi}^+.
\end{align*}
\]

We focus on the decay of the slepton to a neutralino and charged lepton. The neutralino in turn will then decay via the \( \bar{R}_p \)-operator \( L_i Q_j D_k \),

\[
\tilde{\chi}^0 \rightarrow \{\ell_i^- + u_j + \bar{d}_k; \nu_i + d_j + \bar{u}_k\}.
\]

Since the neutralino is a Majorana fermion it can also decay to the charge conjugate final states, with equal probability. In spirit, this is similar to the HERA process considered in [4].

The tree-level Feynman diagrams for the slepton production and the neutralino decay are shown in Fig. 1 and Fig. 2, respectively. Due to the Majorana nature of the neutralino, we have a signature of two like-sign charged leptons. In the following we shall consider only electrons or muons, i.e. we focus on the operators \( L_i Q_j D_k \) and \( L_i Q_k D_j \).

We expect these leptons to have high transverse momentum, \( p_T \), and be well isolated whereas the leptons from the Standard Model backgrounds have lower \( p_T \) and are also poorly isolated. We therefore hope that this signature can be seen above the background if we apply isolation and \( p_T \) cuts.

BACKGROUNDS

In the following we combine the backgrounds for both electrons and muons. The main backgrounds to this like-sign dilepton signature are as follows

1. \( b\bar{b} \) production followed by the production of at least one \( B^0_{d,s} \) meson, which undergoes mixing. If the two \( b \)-quarks in the event decay semi-leptonically this gives two like-sign charged leptons.

2. \( t\bar{t} \) production followed by \( t \rightarrow W^+ b \rightarrow e^+ \nu_e b \), and \( \bar{t} \rightarrow W^- \bar{b} \rightarrow q\bar{q} \tilde{b} \rightarrow q\bar{q} W^+ \tilde{c} \rightarrow q\bar{q} e^+ \nu_e \tilde{c} \).

3. Single top production \( (s \text{ and } t \text{ channel}) \) followed by semi-leptonic decays of the top and the B-meson produced after hadronization.

1) supported by PPARC, UK.
FIGURE 1. Production of $\tilde{\chi}^0 \ell^+$. 

FIGURE 2. LQD decay of $\tilde{\chi}^0$. The neutralino is a Majorana fermion and decays to the charge conjugate final state as well.

4. Non-physics backgrounds from fake leptons and charge misidentification. There are also backgrounds due to the production of weak boson pairs, i.e. WZ and ZZ, where at least one of the charged leptons is not detected [5]. These require a full simulation including the detector. We do not consider them here.

We use HERWIG 6.0, [6–8], to simulate these background processes. The program includes the computation of the supersymmetric spectrum and the MSSM decay branching ratios from the ISASUSY program [9]. Due to the high cross section for the production of $b\bar{b}$ it was necessary to impose a parton-level cut of 20 GeV on the $p_T$ of the $b$ and $\bar{b}$ to enable us to simulate a sufficient number of events. In Fig. 3 we show the distribution of events (using the full Monte Carlo simulation) as a function of the (parton-level) $p_T$ of the bottom quark for two different values of the lepton $p_T$ cut. We did not simulate any events for which the $p_T$ of the bottom quark was below 20 GeV since the cross section is too large. If we extrapolate using Figs. 3a, b to lower b-quark $p_T$ we can see that for a lepton $p_T$ cut of 20 GeV, Fig. 3b, our approximation should be good, i.e. we expect the area under the curve for $p_T(b) < 20$ GeV to be negligible. For $p_T(\ell) > 15$ GeV, Fig. 3a, we would still expect a significant number of events at $15$ GeV $< p_T(b) < 20$ GeV. Besides the parton-level cut, we forced the B-mesons to decay semi-leptonically. This means we neglect the production of leptons from the decay of charmed mesons which should also be a good approximation as we expect the leptons produced from these decays to be poorly isolated.
TABLE 1. Summary of the Background Simulation

| Process       | Cross section before Cuts /nb simulated | No. of Events | Expected No. of Events after cuts, for 2 fb$^{-1}$ luminosity |
|---------------|----------------------------------------|---------------|---------------------------------------------------------------|
| $b\bar{b}$ mixing | $(9.3 \pm 2.3) \times 10^4$           | $8.3 \times 10^4$ | $0.12 \pm 0.12$                                              |
| $t\bar{t}$     | $6.81 \pm 0.31$                      | $2.0 \times 10^5$ | $0.02 \pm 0.02$                                              |
| single top     | $1.55 \pm 0.12$                      | $3.5 \times 10^4$ | $0.00 \pm 0.03$                                              |
| Total          |                                        |               | $0.14 \pm 0.13$                                              |

Figure 4 displays the effect of the lepton isolation cut on the $b\bar{b}$ background for two different values. The effect of the isolation cut on the $t\bar{t}$ and single top backgrounds is shown in Fig. 5. As can be seen in Figs. 4, 5, by imposing an isolation cut of 5 GeV and a cut on the $p_T$ of the leptons of 20 GeV the background can be almost eliminated.

Table 1 shows the backgrounds with a $p_T$ cut on the leptons of 20 GeV and an isolation cut of 5 GeV. We have used the leading-order cross section for the $b\bar{b}$ and single top backgrounds and the next-to-leading order cross section, with next-to-leading-log resummation, from [10] for the $t\bar{t}$ cross section. In both cases the error on the cross section is the effect of varying the scale between half and twice the hard scale, and the error on the number of events is the error in the cross section and the statistical error from the simulation added in quadrature. Realistically we cannot reduce these statistical errors due to the large number of events we would need to simulate. We have implemented the full hadronization using HERWIG 6.0.

With these cuts and using Poisson statistics, a 5$\sigma$ fluctuation of the total background corresponds to 4 events with an integrated luminosity of 2 fb$^{-1}$. Hence we consider 4 signal events to be sufficient for a discovery of the new $R_p$ signal process.

SIGNAL

To simulate the signal and the effect of the cuts, we modified HERWIG 6.0, [6–8], to include the production process, the MSSM decay of the slepton, and the $R_p$ decay of the neutralino. The decay rate of the neutralino and its branching ratios were calculated in the code and a matrix element for the neutralino decay [11,12] was implemented in the Monte Carlo simulation.

We use the program to estimate the acceptance of the signal process, i.e. the fraction of the like-sign dilepton events which pass the cuts multiplied by the branching ratio to give a like-sign dilepton event. Fig. 6 shows the acceptance for two different SUGRA points, with an isolation cut on the leptons of 5 GeV and a cut $p_T(\ell) > 20$ GeV. As can be seen in Fig. 6b, the acceptance drops in two regions. For lower values of $M_0$, the slepton is not much heavier than the neutralino. The charged lepton from the decay of the slepton is then quite soft and gets rejected by the $p_T$ cut. For large values of $M_0$ the slepton is much heavier than the neutralino. The neutralino then gets a
significant boost from the slepton decay. The neutralino decay products are folded forward in the direction of this boost causing the event to be rejected by the lepton isolation cut.

To estimate the acceptance properly we need to run a scan of the SUGRA parameter space using the Monte Carlo event generator. This still remains to be done. To give some idea of what range of couplings and masses we may be able to probe instead we assume an acceptance of 10% using the same cuts as before. We can then estimate the range of couplings which may be accessible.

As can be seen in Figs. 7, 8 the production cross section for $\lambda'_{211} = 10^{-2}$ is sufficient to produce a signal which is more than 5$\sigma$ above the background for large regions of the SUGRA parameter space. In some regions where the neutralinos become Higgsino-like the cross section drops. The cross section also drops as we approach the region where the neutralino is heavier than the slepton and the resonance becomes inaccessible.

We focused on the coupling $\lambda'_{211}$ because the experimental bound on $\lambda_{111}'$ from neutrinoless double beta decay is very strict [13,14]. The bound on $\lambda_{111}'$ weakens as the squark mass squared and for squark masses above about 300 GeV (which we expect in the SUGRA scenario for the heavier slepton masses) $\lambda_{111}' \approx 10^{-2}$ is experimentally allowed and our analysis thus applies for this case as well. $\lambda_{211}' \approx 10^{-2}$ is well within the present experimental bounds [14].

In these figures we see that we are sensitive to slepton masses up to 300 GeV for couplings of $10^{-2}$. The production cross section scales with the square of the coupling. For slepton masses around 100 GeV, just above the LEP limits, we can thus probe couplings down to about $2 \times 10^{-3}$.
CONCLUSION

We have performed an analysis of the physics background for like-sign dilepton production at run II and find that with an integrated luminosity of 2 fb\(^{-1}\), a cut on the transverse momentum of the leptons of 20 GeV and an isolation cut of 5 GeV the background is 0.14 ± 0.13 events. This means that 4 signal events would correspond to a 5σ discovery, although in a full experimental analysis the non-physics backgrounds must also be considered.

Using a full Monte Carlo simulation of the signal including a calculation of the neutralino decay rate, its partial widths and a matrix element in the simulation of the decay we found that the acceptance for the signal varies but for a reasonable range of parameter space is 10% or greater.

When we then look at the cross section for the production of \( \tilde{\chi}_0^0 \ell^+ \) we find that we can probe \( R_p \) couplings of \( 2 \times 10^{-3} \) for slepton mass of 100 GeV and up to slepton masses of 300 GeV for \( R_p \) couplings of \( 10^{-2} \), and higher masses if the coupling is larger.

REFERENCES

1. S. Dimopoulos, et al., *Phys. Rev.* D41 (1990) 2099.
2. J.L. Hewett, T.G. Rizzo, hep-ph/9809525, and contribution in this workshop.
3. J. Kalinowski, R. Rückl, H. Spiesberger, P.M. Zerwas, *Phys. Lett.* B414 (1997) 297, hep-ph/9708272.
4. J. Butterworth, H. Dreiner, *Nucl. Phys.* **B397** (1993) 3.
5. CDF Collaboration (Jane Nachtman et al.), FERMILAB-CONF-99-023-E, hep-ex/9902010.
6. S. Moretti, K. Odagiri, M.H. Seymour and B.R. Webber ‘Implementation of supersymmetric processes in the HERWIG event generator’, *preprint* Cavendish-HEP-98/06, currently in preparation.
7. G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour and L. Stanco, *Comp. Phys. Comm.* **67** (1992) 465.
8. G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, M.H. Seymour and B.R. Webber, ‘HERWIG version 6.1, including supersymmetric processes in hadronic collisions’, *preprint* Cavendish-HEP-98/04, currently in preparation.
9. F.E. Paige, S.D. Protopescu, H. Baer and X. Tata, ‘Isajet 7.40’, *preprint* hep-ph/9810440.
10. R. Bonciani, S. Catani, M.L. Mangano, P. Nason, *Nucl. Phys.* **B529** (1998) 424.
11. E.A. Baltz and P. Gondolo, *Phys. Rev.* **D57** (1998) 2969.
12. H. Dreiner, P. Morawitz, *Nucl. Phys.* **B428** (1994) 31, hep-ph/9405253.
13. M. Hirsch, H.V. Klapdor-Kleingrothaus, S.G. Kovalenko, *Phys. Rev. Lett.* **75** (1995) 17; *Phys. Rev.* **D53** (1996) 1329, hep-ph/9502385.
14. H. Dreiner, hep-ph 9703444.