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Resonant Slepton Production at Hadron Colliders in R-parity Violating Models

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Abstract

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RESONANT SLEPTON PRODUCTION AT HADRON COLLIDERS IN R-PARITY VIOLATING MODELS

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Single s-channel production of sleptons, such as $\tilde{\tau}$'s and/or $\tilde{\nu}_\tau$, with their subsequent decay into purely leptonic or dijet final states is possible in hadronic collisions via R-parity violating couplings. We examine the impact of slepton production on bump searches in both the Drell-Yan and dijet channels and examine whether the lepton charge asymmetry in the $\ell\nu$ channel provides for additional search sensitivity. As a consequence, search reaches in the slepton mass-R-parity violating coupling plane are obtained for both the Tevatron and LHC. The possibility of using the leptonic angular distributions and the lepton charge asymmetry to distinguish slepton resonances from new gauge bosons is also analyzed.

1 Introduction

As is well known, the conventional gauge symmetries of the supersymmetric extension of the Standard Model(SM) allow for the existence of additional terms in the superpotential that violate Baryon(B) and/or Lepton(L) number. One quickly realizes that simultaneous existence of such terms leads to rapid proton decay. These phenomenologically dangerous terms can be written as

$$W_R = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \epsilon_i L_i H \,, \tag{1}$$

where i, j, k are family indices and symmetry demands that $i < j$ in the terms proportional to either the λ or λ'' Yukawa couplings. In the MSSM, the imposition of the discrete symmetry of R-parity removes by brute force all of these 'undesirable' couplings from the superpotential. However, it easy to construct alternative discrete symmetries that allow for the existence of either the L- or B-violating terms [1] in W_R (but not both kinds). As far as we know there exists no strong theoretical reason to favor the MSSM over such R-parity violating scenarios. Since only B- or L-violating terms survive when this new symmetry is present the proton now remains stable in these models. Consequently, various low-energy phenomena then provide the only significant constraints [2] on the Yukawa couplings λ, λ' and λ''.

If R-parity is violated much of the conventional wisdom associated with the MSSM goes by the wayside, *e.g.*, the LSP (now not necessarily a neutralino!) is unstable and sparticles may now be produced singly. In particular, it is now possible that some sparticles can be produced as s-channel resonances, thus appearing as bumps in cross sections if kinematically accessible. In the case of the two sets of trilinear L-violating terms in W_R, which we consider below, an example of such a possibility is production of a $\tilde{\nu}_\tau$ via $d\bar{d}$ annihilation at the Tevatron or LHC (through λ' couplings). If this sneutrino decays to, *e.g.*, opposite sign leptons (through the λ couplings) then an event excess, clustered in mass, will be observed in the Drell-Yan channel similar to that expected for a Z'. Similarly, the corresponding process $u\bar{d} \to \tilde{\tau} \to \ell\nu$ may also occur through these couplings and mimics a W' signature. In addition to these leptonic final states, both $\tilde{\tau}$ and $\tilde{\nu}$ resonances may decay hadronically via the same vertices that produced them, hence leading to potentially observable peaks in the dijet invariant mass distribution. Thus resonant slepton production, first discussed in Ref. [3], clearly offers a unique way to explore the R-parity violating model parameter space. It is important to note that R-parity violation also allows for other SUSY particles, such as $\tilde{t}$ and/or $\tilde{b}$, to be exchanged in the non-resonant $t, u-$channels and contribute to Drell-Yan events. However, it can be easily shown that their influence on cross sections and various distributions will be quite small if the low energy constraints on the Yukawa couplings are satisfied [4].

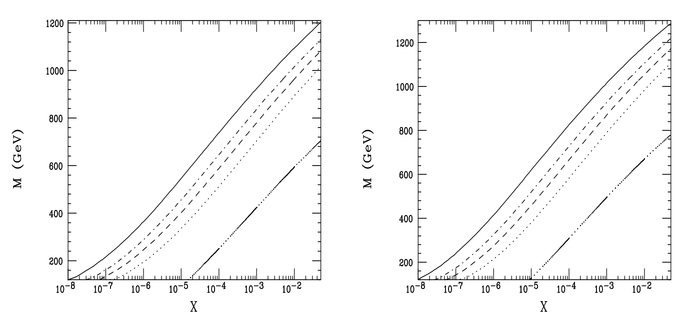

Figure 1: Discovery regions (lying below the curves) in the mass-coupling plane for R-parity violating resonances in the neutral (left) and charged (right) Drell-Yan channels at the Run II Tevatron. From top to bottom the curves correspond to integrated luminosities of 30, 10, 5 and 2 fb^{-1}. The estimated reach for Run I is given by the lowest curve. The parameter X is defined in the text.

The questions we address in this analysis are: (i) what are the mass and coupling reaches for slepton resonance searches at the Tevatron and LHC in the Drell-Yan and dijet channels and (*ii*) how can slepton resonances, once discovered, be distinguished from Z', W' production. Below we will mainly concern ourselves with the third generation sleptons but our analysis is easily extended to those of the first and second generation as well.

2 The Drell-Yan Channel

In the case of Drell-Yan production the search reach analysis is straightforward being nearly identical to that used for new gauge boson production, apart from acceptance issues, *i.e.*, we now have spin-0 and not spin-1 resonances. Since sleptons are expected to be narrow, the narrow width approximation is adequate and we can directly follow the analysis presented in Ref. [5]. In addition to the slepton mass itself, the only other parameter in this calculation is the product of the appropriate Yukawa couplings, λ', from the initial state $d\bar{u}$ or $d\bar{d}$ coupling vertex, and the slepton's leptonic branching fraction, B_ℓ. Calling this product $X = (\lambda')^2 B_\ell$, we can obtain the search reach as a function of X in the charged and neutral channels for both the Tevatron and LHC; these results are shown in Figures 1 and 2. Not only is it important to notice the very large mass reach of these colliders for sizeable values of $X \sim 10^{-3}$, but we should also observe the small X reach, $X \sim 10^{-(5-7)}$ and below, for relatively small slepton masses. Clearly these results show the rather wide opportunity available to discover slepton resonances over extended ranges of masses and couplings at these hadron colliders. Note that for fixed values of X the search reach is greater in the charged current channel due to the higher parton luminosities.

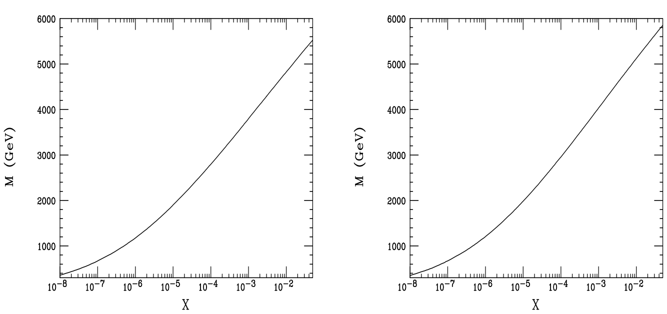

Figure 2: Same as the previous figure but now for the LHC with an integrated luminosity of 100 fb^{-1}.

Our next issue concerns identifying the resonance (or Jacobian peak) as a slepton instead of a new gauge boson. One immediate difference which would signal $\tilde{\nu}$ production would be the observation of the very unusual $e\mu$ final states which are allowed by the generational structure of the superpotential; such final states are not expected to occur for a Z' and would be a truly remarkable signature for R-parity violation. Clearly if the $e\mu$ or SUSY decay modes of the slepton dominate there will be no identification problem. If the R-parity violating modes dominate it is best to look for universality violations, *e.g.*, if the resonance decays to only one of e^+e^- or $\mu^+\mu^-$ or if these two rates are substantially different. Most new gauge bosons which are kinematically accessibly are not anticipated to have substantially different couplings to the first two fermion generations. In the case of a $\tilde{\nu}$ versus a Z', it is well known that most Z' bosons have parity violating fermionic couplings which would lead to a forward-backward asymmetry, A_{FB}, in their leptonic decay distributions. The $\tilde{\nu}$, being spin-0, would always produce a null asymmetry. A_{FB} is more easily measured and requires less statistical power than does the reconstruction of the complete angular distribution. This is important since, whereas only 10 or so background free events would constitute a discovery many more, $\sim 100-200$ are required to determine the asymmetry. This would imply that the reach for performing this test is somewhat if not substantially less than the discovery reach. For example, the Tevatron may discovery a $\tilde{\nu}$ with a mass of 700 GeV for a certain value of X but only for masses below 500 GeV would there be enough statistics to extract A_{FB} for this same X value.

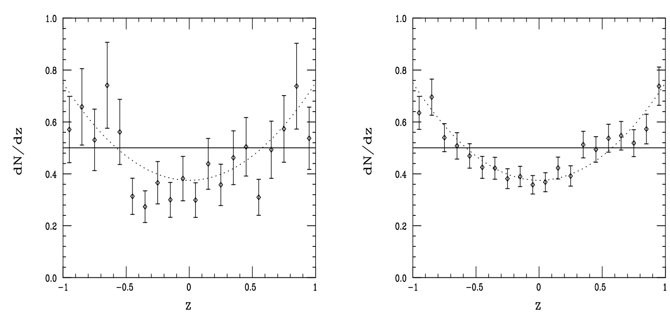

Figure 3: Comparison of the Monte Carlo generated normalized angular distribution for the leptons in Z' decay with that for a $\tilde{\nu}$ assuming a (left)400 event sample or a (right)2000 event sample; the errors are purely statistical. The Z' is assumed to have no forward-backward asymmetry due to its fermionic couplings. The $1+z^2$ angular distribution is also shown. The effect of potential acceptance losses in the two outer bins has not been included.

A more complex and interesting situation arises when the Z' naturally has $A_{FB} = 0$ as in, *e.g.*, some E_6 models; [6] in this case the on-resonance asymmetry data alone is insufficient. If A_{FB} could be measured throughout the resonance region, it would be possible to deduce through detailed line-shape studies whether or not the new contribution interferes with the SM amplitude (something that does not occur in the case of $\tilde{\nu}$ production). Besides requiring substantial statistics, finite dilepton mass resolution, especially for the $\mu^+\mu^-$ final state, may disrupt this program.

Of course, with a plethora of statistics the complete angular distribution can be obtained as shown in Fig.3. Here we compare Monte Carlo generated data for a Z' with a zero forward-backward asymmetry with both the flat distribution and the $\sim 1+z^2$ distribution hypotheses($z = \cos\theta$) and ignore complications due to possible acceptance losses arising from rapidity cuts in the forward and backward directions. Such a distribution has been measured by CDF both on the Z and above. [7] Both analyses would seem to indicate that of order ~ 1000 events are required to make a clean measurement, a sample approximately 100 times larger than that required for discovery. Although such measurements would be conclusive as to the identity of the resonance, the required statistics results in a significant loss in the mass range over which it can be performed. In our Tevatron example above where the search reach was 700 GeV we would find that the angular distribution could only be determined for masses below $\sim$ 400 GeV assuming the same X value.

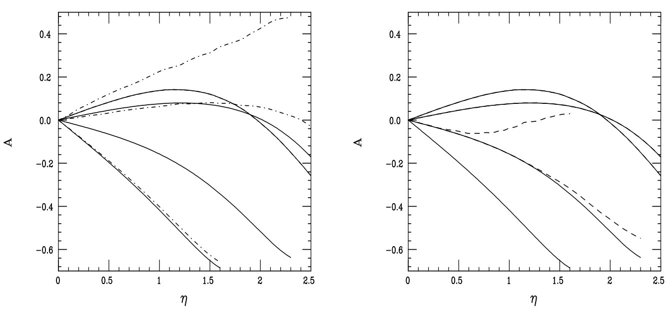

Figure 4: The lepton charge asymmetry in the charged current Drell-Yan production channel at the 2 TeV Tevatron for the SM (solid curves)and with 250(700) GeV $\tilde{\tau}$ exchange (the dash-dotted or dashed curves) assuming $\lambda, \lambda' = 0.15$ for purposes of demonstration. From top to bottom in the center of the figure, the SM curves correspond to M_T bins of 50-100, 100-200, 200-400 and > 400 GeV, respectively. Note that for M_T in the 50-100 GeV range there is no distinction between the SM result and that with a $\tilde{\tau}$.

The angular distribution approach cannot be used to separate between the $\tilde{\tau}$ and W' cases due to the missing energy in the event. However, there are two useful observables in this situation. First, one can examine the transverse mass (M_T) distribution associated with the new Jacobian peak region to see if interference with SM amplitudes is occurring. This is far more difficult than in the $\tilde{\nu}$ case again due to the missing energy and mass smearing. A second possibility is to examine the leptonic charge asymmetry, $A(\eta)$, for the electrons or muons in the final state as a function of their rapidity. We remind the reader that $A(\eta)$ is defined as

$$A(\eta) = \frac{dN_+/d\eta - dN_-/d\eta}{dN_+/d\eta + dN_-/d\eta}\,, \qquad (2)$$

where $N_\pm$ are the number of positively/negatively charged electrons of a given rapidity, η. In the SM, the charge asymmetry is sensitive to the ratio of u-quark to d-quark parton densities and the $V-A$ production and decay of the W. [8] Since the coupling structure of the W has been well-measured, any deviations in this asymmetry within the M_T bin surrounding the W have been attributed to modifications in the parton distributions (PDF's). Here, we are more interested in events with larger M_T. Note that $A(-\eta) = -A(\eta)$ if CP is conserved(which we assume) so that we will only need to deal with $\eta \geq 0$ in the following discussion.

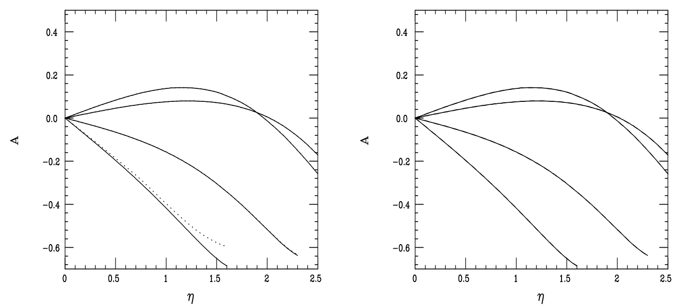

Figure 5: Same as the previous figure but now for 1000(1500) GeV $\tilde{\tau}$ exchange corresponding to the the dotted or dashed curves in the left(right) panel.

Consider the case for $\tilde{\tau}$ production at the Tevatron. Fig.4 shows the lepton charge asymmetry, within four M_T bins corresponding to $50 < M_T < 100$ GeV, $100 < M_T < 200$ GeV, $200 < M_T < 400$ GeV, and $400 < M_T < 1800$ GeV for the SM and how it is modified by the presence of a 250(700) GeV $\tilde{\tau}$ with, for purposes of demonstration, $\lambda, \lambda' = 0.15$. In particular we observe that the lepton charge asymmetry can be significantly altered for larger values of M_T in the bins associated with the new Jacobian peak. Note, however, that there is essentially no deviation in the asymmetry in the transverse mass bin associated with the W peak, $50 < M_T < 100$ GeV, so that this M_T region can still be used for determination of the PDFs. Fig.4 also shows that the presence of the $\tilde{\tau}$ tends to drive the asymmetry to smaller absolute values as perhaps might be expected due to the presence of a spin-0 resonance which provides a null 'raw' asymmetry. In Fig.5 we see that the asymmetry is still visible in the last M_T bin for the case of a 1 TeV $\tilde{\tau}$ but becomes essentially non-existent for these values of the Yukawa couplings when the mass is raised to 1.5 TeV.

Fig.6 shows the corresponding modifications in the leptonic charge asymmetry due to an 800 GeV W'

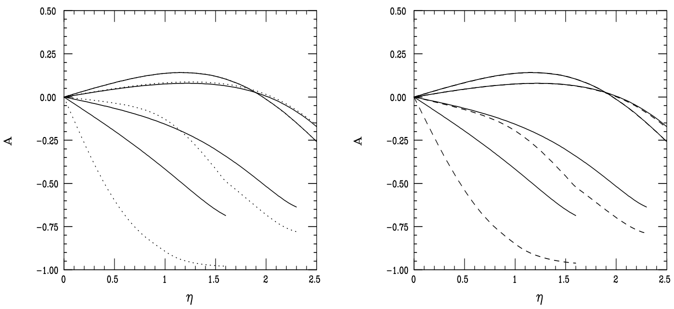

Figure 6: Same as the previous two figures but now for the case of a 800 GeV W' with purely left-handed(left panel) or purely right-handed(right panel) couplings.

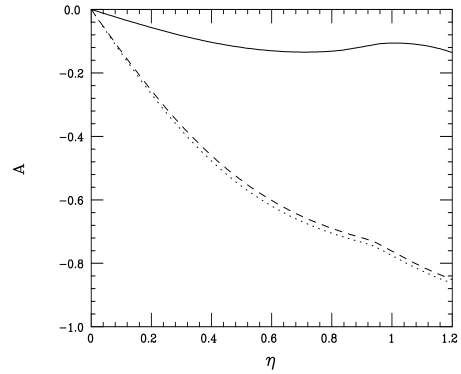

Figure 7: Direct comparison of the charge asymmetry induced by a 800 GeV $\tilde{\tau}$(solid) and a LH or RH W'(dot and dash) of the same mass at the 2 TeV Tevatron. For this comparison, a narrow bin in M_T was chosen: $600 < M_T < 900$ GeV. The Yukawa couplings are as in the earlier figures.

with either purely left-handed(LH) or purely right-handed(RH) fermionic couplings. Note that the W' with purely RH couplings, unlike the LH W', does not interfere with the SM amplitude, similar to the case of $\tilde{\tau}$ production. The deviation in the asymmetry due to either type of W' is very different than that for a $\tilde{\tau}$. Here we see that the W' substantially increases the magnitude of the asymmetry for both coupling types and that RH and LH W' bosons are *themselves* potentially distinguishable by using the data in the M_T bin below but not containing the Jacobian peak.

The M_T bins we have taken in this analysis are rather broad. We might expect that if we compress the width of the M_T bin around the W' or $\tilde{\tau}$ Jacobian peak we will increase the purity of the resonant contribution and have an even better separation of the two possibilities, at the price of reduced statistics. (Of course as we narrow this bin we will no longer be able to distinguish LH from RH W' bosons since this information comes from SM–W' interference.) These expectations come to fruition in Fig.7 which shows a more direct comparison of the lepton charge asymmetries for a $\tilde{\tau}$ and W' of the same mass (800 GeV) and narrowing the width of the M_T bin surrounding the Jacobian peak to only 300 GeV. Note that the LH and RH W' cases are no longer separable. Clearly such measurements will allow the production of W' and $\tilde{\tau}$ to be distinguished.

It is interesting to note that lepton asymmetry deviations can be used to probe indirectly for the exchange of $\tilde{\tau}$ through R-parity violating couplings. To demonstrate this let us fix the $\tilde{\tau}$ width to mass ratio to be $\Gamma/m = 0.004$ and subdivide each of the four M_T bins discussed above into rapidity intervals of $\Delta\eta = 0.1$. For a given $\tilde{\tau}$ mass we can then ask down to what value of the product of the Yukawa couplings, $\lambda\lambda'$, will the asymmetry differ significantly from SM expectations. For a fixed mass and integrated luminosity we generate Monte Carlo data for various values of the Yukawas and then perform a χ^2 analysis to obtain the sensitivity. The results of this analysis are shown in Fig.8 and one can see that the search reaches obtained in this manner are rather modest.

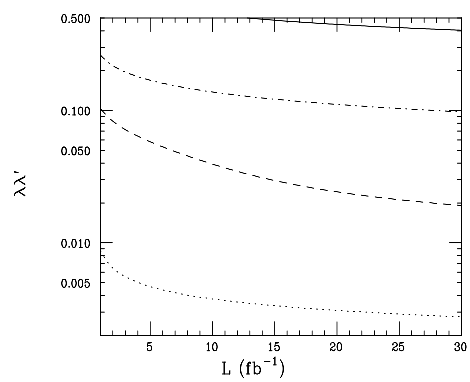

Figure 8: Search reach for $\tilde{\tau}$ exchange as a function of the 2 TeV Tevatron integrated luminosity assuming $\Gamma/m = 0.004$ for masses of 1500, 1000, 750 and 250 GeV(from top to bottom).

3 The Dijet Channel

Since $d\bar{d}$ and/or $u\bar{d}$ annihilation are responsible for producing the slepton resonances, it is obvious that the resonance must also decay into these same fermion pairs. This means that $\tilde{\tau}$ or $\tilde{\nu}$ will decay to dijets and may appear as observable peaks above the conventional QCD backgrounds. This hope will very hard to fulfill at the LHC where QCD backgrounds are expected to be severe for searches for narrow resonances which are not strongly produced. At the Tevatron, one can be much more optimistic. In fact, searches for such narrow dijet resonances have already been performed [9] at the Tevatron by both CDF and D0 during Run I. Using their results and scaling by appropriate factors of beam energy and integrated luminosities we may estimate the probable search reaches for CDF and D0 from Run II . (These estimates conform to the expectations given in Ref. [10].) The cross sections themselves are immediately calculable in the narrow width approximation in terms of the product $Y = (\lambda')^2 B_{2j}$, where λ' is the familiar Yukawa coupling and B_{2j} is the dijet branching fraction. The results of these calculations are shown in Fig.9. Here we clearly see that for values of $Y \sim 0.001 - 0.01$ or greater, the Tevatron will have a substantial mass reach for slepton induced dijet mass bumps during Run II. Note that as in the case of Drell-Yan, larger cross sections for fixed Y occur in the CC channel than in the NC channel due to the larger parton luminosities. Unfortunately, if such a bump is observed it will not be straightforward to identify it as a slepton resonance.

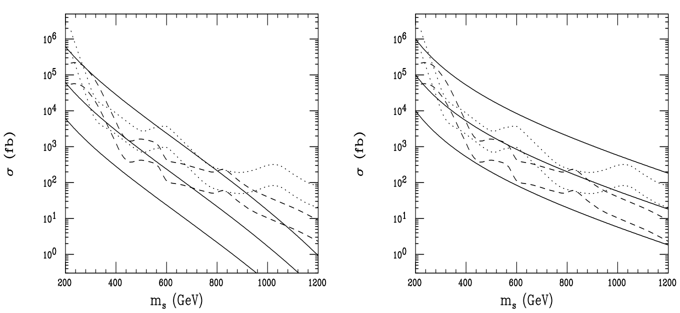

Figure 9: Cross sections for narrow dijet resonances(solid) at the 2 TeV Tevatron arising from $\tilde{\nu}$(left) or $\tilde{\tau}$(right) production in comparison to the anticipated search reaches of CDF(dots) and D0(dashes). The upper(lower) curve for each experiment assumes an integrated luminosity of 2(30) fb^{-1}. The three solid curves from top to bottom correspond to slepton resonance predictions for Y=0.1, 0.01 and 0.001, respectively, where Y is defined in the text.

4 Conclusion

As we have seen from the analysis above, resonant s-channel production of $\tilde{\tau}$ and/or $\tilde{\nu}$ with their subsequent decay into purely leptonic or dijet final states is observable over a wide range of parameters in hadronic collisions via R-parity violating couplings. We have obtained the corresponding search reaches in the slepton mass-R-parity violating coupling plane for both the Tevatron and LHC. If this signature is observed, we have demonstrated that the leptonic angular distributions and the lepton charge asymmetry can be successfully used to distinguish slepton resonances from those associated with new gauge bosons.

This process provides a clean and powerful probe of R-parity violating supersymmetric parameter space.

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