IMPACT OF R-PARITY VIOLATION ON SUPERSYMMETRY
SEARCHES AT THE TEVATRON

Howard Baer\textsuperscript{1}, Chung Kao\textsuperscript{2} and Xerxes Tata\textsuperscript{3}
\textsuperscript{1}Department of Physics, Florida State University, Tallahassee, FL 32306, U.S.A.
\textsuperscript{2}Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, U.S.A.
\textsuperscript{3}Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, U.S.A
(January 30, 2020)

Abstract

We evaluate cross sections for $B_T$, $1\ell$ and various dilepton and multilepton event topologies that result from the simultaneous production of all sparticles at the Tevatron collider, both within the minimal model framework as well as in two different $R$-parity violating scenarios. Our analysis assumes that these $R$-violating couplings are small, and that their sole effect is to cause the lightest supersymmetric particle to decay inside the detector. We reassess future strategies for sparticle searches at the Tevatron, and quantify by how much the various signals for supersymmetry could differ from their minimal model expectations, if $R$-parity is not conserved due to either baryon number or lepton number violating operators. We also evaluate the Tevatron reach in $m_{\tilde{g}}$ for the various models, and find that rate-limited multilepton signals ultimately provide the largest reach for both $R$-parity conserving and $R$-parity violating cases.
The search for supersymmetric (SUSY) particles has become a standard item on the agenda of experiments at high energy colliders. Non-observation of events with missing transverse energy (E\text{T}) and acollinear lepton and/or jet pairs in experiments at LEP, allows us to infer lower limits \( \sim \frac{M_Z^2}{2} \) on the masses of squarks, sleptons and the charginos. From an analysis of the E\text{T} event sample, the CDF and D0 collaborations at the Tevatron have inferred a lower limit \( \sim 150 \text{ GeV} \) on the masses of gluinos and squarks (\( \sim 200 \text{ GeV} \), if \( m_{\tilde{q}} = m_{\tilde{g}} \)). These analyses implicitly assume that the lightest supersymmetric particle (LSP) is stable and only weakly interacting, and so escapes detection in the experimental apparatus yielding the classic E\text{T} signature for SUSY. Within the minimal supersymmetric model (MSSM), which is the framework for most experimental analyses, the stability of the LSP is guaranteed since there is a multiplicatively conserved quantum number \( \mathcal{R} = 1 (-1) \) for ordinary particles (sparticles). It is, however, possible \( \mathcal{R} \)-parity violating models that do not conserve \( \mathcal{R} \)-parity, but instead conserve either the baryon number (\( B \)) or the lepton number (\( L \)) (but not both). In this case, the LSP decays into ordinary quarks and leptons, and so, all mass limits based on E\text{T} analyses cease to be applicable. The somewhat weaker bounds \( \mathcal{R} \) on sparticle masses from the measurement \( \mathcal{R} \) of the Z width at LEP, of course, continue to be valid.

The phenomenology of \( \mathcal{R} \)-parity violation can be very different from that of the MSSM. \( \mathcal{R} \)-violating interactions, if they are of sufficient strength, can alter the decay patterns of sparticles from their MSSM expectations. These interactions also allow sparticles to be produced singly at colliders, and can lead to resonance production of squarks or sleptons at the Tevatron \( \mathcal{R} \) and at HERA \( \mathcal{R} \). The resulting modifications are sensitively dependent on the strength and form of \( \mathcal{R} \)-violating interactions, and can be essentially negligible if these couplings are small relative to the gauge couplings. Then, the main impact of \( \mathcal{R} \)-parity violation is, as we mentioned above, that the LSP decays visibly, invalidating experimental analyses based on the classic E\text{T} signature. In the clean environment of LEP experiments, it should nonetheless be possible to search for sparticles by looking for an excess of spherical events in Z\text{0} decays. In fact, since Z\text{0} decays to LSP pairs can lead to observable signals if \( \mathcal{R} \)-parity is violated, the non-observation of spherical events at LEP \( \mathcal{R} \) translates to a limit \( \sim \frac{M_{\tilde{\chi}_1}}{2} \) on the mass of the LSP, assuming of course that LSP pair production is not extremely suppressed by mixing angle factors. As a result, parameter values experimentally allowed in LEP experiments may be excluded \( \mathcal{R} \) in an \( \mathcal{R} \)-parity violating scenario.

The corresponding situation at the Tevatron is quite different. Since the E\text{T} signals are greatly degraded, the isolated multilepton signals from the cascade decays \( \mathcal{R} \) of gluinos and squarks offer the main hope for the detection of these sparticles at the Tevatron. In the favourable case where \( \mathcal{R} \)-parity violation is due to e or \( \mu \) number violation, the multilepton signals would be enhanced \( \mathcal{R} \). In contrast, if the LSP decays via B-violating interactions, the additional hadronic activity from LSP decays frequently causes leptons in SUSY events to fail the lepton isolation criteria, resulting in a reduction of the multilepton signal. The purpose of this paper is to quantify how much the various SUSY signals can vary from their canonical MSSM values if the LSP decays via \( \mathcal{R} \)-parity violating interactions, assuming that these interactions do not significantly impact either production rates or decay patterns of sparticles other than the LSP \( \mathcal{R} \).

\( \mathcal{R} \)-parity may be either broken spontaneously (by vacuum expectation values (VEV) for \( \mathcal{R} \)-odd scalar neutrinos) or explicitly. Spontaneous breaking via VEVs of the isodoublet
sneutrinos of the MSSM is phenomenologically excluded by measurements of $\Gamma_Z$, and so, is only viable if additional singlet neutrino superfields are introduced. We will, therefore, confine ourselves to explicit $R$-parity violation via superpotential interactions which, assuming the MSSM particle content, take the general form,

$$f_{RPV} = \sum_{i,j,k} [\lambda_{ijk} L_i L_j E_c^k + \lambda'_{ijk} L_i Q_j D_c^k + \lambda''_{ijk} U_c^i D_c^j D_c^k],$$

where $i, j$ and $k$ denote generations, and the fields have been defined so that the bilinear lepton number violating operators have been rotated away. The coupling constants $\lambda$ ($\lambda''$) are antisymmetric in the first (last) two indices. The first two terms lead to lepton number violation, while the last one violates baryon number conservation. Since the simultaneous presence of both sets of terms would cause proton decay at a catastrophic rate (unless the couplings are so tiny as not to be of interest in collider analyses), only $\lambda$ and $\lambda'$ or $\lambda''$ type interactions can be present.

The large number of the unknown $R$-parity violating couplings in Eq. (1) make phenomenological analyses very difficult. In particular, the decay patterns of the LSP (which, as in the MSSM, is frequently the lightest neutralino, $\tilde{Z}_1$) depend on these couplings. Since we are primarily interested in exploring the range over which the Tevatron signals vary, we confine our attention to extreme cases. The only significant published limit on $B$-violating $\lambda''$-type couplings that we are aware of comes from non-observation of $n\bar{n}$ oscillations and requires $\lambda''_{112}, \lambda''_{113} \lesssim 10^{-6}$. For the case of $B$-violating interactions, we therefore assume that the coupling $\lambda''_{212}$, on which there are no significant experimental constraints, dominates LSP decays. In this case, the LSP decays via

$$\tilde{Z}_1 \rightarrow c\bar{d}s, \bar{c}d\bar{s},$$

where CP invariance determines the branching fraction of each of the two modes to be 50%. Since we do not attempt to tag $c$ jets, our results are insensitive to the assumed flavour structure of this decay. For the case where the LSP decays via lepton number violating interactions, the multilepton signals are expected to be enhanced. Since electrons and muons are much easier to detect than tau leptons, we expect that the enhancement is maximal if the corresponding $L$-violating interactions involve only $e$ and $\mu$ families. For definiteness, we assume that the coupling $\lambda_{121}$ dominates, in which case $\tilde{Z}_1$ decays via,

$$\tilde{Z}_1 \rightarrow \mu\bar{e}\nu_e, \bar{\mu}e\nu_e, e\bar{e}\nu_\mu, e\bar{e}\nu_\mu.$$  

Assuming that lepton Yukawa interactions are negligible and that the sleptons all have the same mass, the four modes each have a branching fraction of 25%, independent of the gaugino-Higgsino content of the LSP. We note that $\lambda_{121}$ can be as large as $0.08(m_\tilde{\chi}/200\text{ GeV})$ so that the LSP decays well inside the detector. Constraints on several other $L$-violating couplings are weaker than those on $\lambda_{121}$. In these cases, the LSP either decays as in (3) with $\mu$ replaced by $\tau$ and $\nu_\mu$ by $\nu_\tau$ (via $\lambda_{131}$ interactions) or decays via $\tilde{Z}_1 \rightarrow \ell j j, \nu_\ell j j$ (via various $\lambda'$ interactions). The various branching fractions depend on the parameters of the neutralino mass matrix, and it is not clear whether these decays will lead to enhancement or degradation of the signal. What is clear, however, is that any enhancement of the signal will be smaller than in the case where the LSP decays as in (3), and that the degradation
will be less than that when the LSP decays as in (2). We thus expect that these cases (Eq. 2 and 3) represent the extreme limits of SUSY signals at the Tevatron, assuming only that the $R$-violating interactions are too small to significantly affect sparticle production mechanisms or the decay patterns of any particles other than the LSP.

The effect of $L$ non-conserving, $R$-parity violating decays of the LSP on gluino and squark events at the Tevatron was first quantitatively discussed in Ref. [12] using a parton-level Monte Carlo program. It was assumed that the LSP is a light photino, and further, that gluinos and squarks had only direct decays to the LSP; i.e. cascade decays of gluinos and squarks were ignored. The impact of $L$-violating LSP decays on signals from $\tilde{W}_1\tilde{Z}_{1,2}$ production at the Tevatron has recently been studied in Ref. [18]. Here, we use ISAJET 7.13 [19] to study the impact of $R$-parity violation on the MSSM signals, and force the decay of the LSP with branching fractions discussed above. This improves previous studies in several respects:

- ISAJET automatically incorporates the cascade decays of gluinos and squarks as given by the MSSM.
- We include contributions from all SUSY processes that are kinematically accessible, not just $\tilde{q}$ and $\tilde{g}$ production. Since $m_{\tilde{g}} > m_{\tilde{W}_1}, m_{\tilde{Z}_{1,2}}$, the production of charginos and neutralinos can make a significant contribution, especially when gluinos and squarks are heavy.
- Unlike Ref. [12] which focussed on the comparison of SUSY predictions with the Tevatron dilepton data, we study the impact of $R$-parity violation on all leptonic signals.
- We also study the impact of baryon number violating operators on the signal.
- Finally, ISAJET, which includes effects of radiation from initial and final states, provides a more realistic simulation of lepton isolation than a parton-level calculation. This may be especially important for the discussion of multi-lepton topologies.

For our simulation [20] of SUSY events, we use CTEQ2L structure functions [21]. We model experimental conditions using a toy calorimeter with segmentation $\Delta \eta \times \Delta \phi = 0.1 \times 0.09$ and extending to $|\eta| = 4$. We assume an energy resolution of $0.7/\sqrt{E_T}$ ($0.15/\sqrt{E_T}$) for the hadronic (electromagnetic) calorimeter. Jets are defined to be hadron clusters with $E_T > 15$ GeV in a cone with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$. Leptons with $p_T > 8$ GeV and within $|\eta_\ell| < 3$ are considered to be isolated if the hadronic scalar $E_T$ in a cone with $\Delta R = 0.4$ about the lepton is smaller than $E_T(\ell)/4$. Finally, since we use the MSSM as the reference model, we require $E_T > 20$ GeV in all events. The events are classified as follows.

1. For $E_T$ events, we require $n_{\text{jet}} \geq 4$ with at least one of the jets in the central region, $|\eta| < 1$, and following the recent analysis by the D0 collaboration [4], $E_T \geq 75$ GeV. We veto events with either isolated leptons with $E_T \geq 15$ GeV (to reduce $W$ backgrounds), or a jet within 30° of $E_T$.

2. Single lepton events are defined to have exactly one isolated lepton with $E_T \geq 15$ GeV. We reject events with 60 GeV $\leq m_T(\ell, E_T) \leq 100$ GeV which have large backgrounds from $W$ production.
3. The opposite sign (OS) dilepton sample is defined to have two opposite sign isolated lepton with $p_T \geq 15$ GeV and $30^\circ \leq \Delta \phi_{\ell^+\ell^-} \leq 150^\circ$ and no other isolated leptons. To eliminate backgrounds from $Z$ production, we reject events with $80$ GeV $\leq m(\ell^+\ell^-) \leq 100$ GeV.

4. The same sign (SS) dilepton sample is required to have exactly two isolated leptons, each with $p_T \geq 15$ GeV, and no other isolated leptons.

5. The $n_\ell \geq 3$ event sample is defined to have exactly $n_\ell$ isolated leptons, with $p_T(\ell_1) \geq 15$ GeV and $p_T(\ell_2) \geq 10$ GeV.

The cross sections for the various SUSY signals calculated within the MSSM ($R$-conserving) framework are shown in Fig. 1 for (a) $m_\tilde q = m_\tilde g + 10$ GeV, (b) $m_\tilde q = m_\tilde g - 10$ GeV, and (c) $m_\tilde q = 2m_\tilde g$. Here, we have fixed $\tan \beta = 2$, $\mu = -m_\tilde g$ (this is motivated by supergravity models), $m_t = 170$ GeV, and taken the pseudoscalar Higgs boson mass to be 500 GeV. The slepton masses are determined in terms of $m_\tilde g$ and $m_\tilde q$ using renormalization group equations to evolve from a common sfermion mass at the GUT scale. Unlike as in Ref. [20], where multilepton rates only from $\tilde g$ and $\tilde q$ production were shown, the production of all sparticles at rates expected in the MSSM is included in this figure. This explains why the ordering of the various signals sometimes differs from that in Ref. [20] and is also the reason why the curves in Fig. 1 are significantly flatter than those in our previous study — while the production of gluinos and squarks dominates for low values of $m_\tilde g$ the production of charginos and neutralinos constitutes $50-90\%$ of the total SUSY production cross section (before cuts) if gluinos and squarks are heavy. Thus, for the very heavy gluino cases in Fig. 1, we expect that the multilepton signals will be relatively free of jet activity. This is also the reason why, for large values of $m_\tilde g$, the rate for $R_T$ events (for which we require $n_{jet} \geq 4$) falls below that of the $1\ell$ event sample on which there is no such requirement. Finally, we note that the OS and SS dilepton cross sections in Fig. 1b increase sharply for $m_\tilde g = 200 - 250$ GeV because the decay $\tilde Z_2 \to \tilde \nu \nu$, which is the only accessible two body decay of $\tilde Z_2$ when $m_\tilde g \lesssim 200$ GeV, becomes kinematically forbidden as $m_\tilde g$ is increased from 200 GeV to 250 GeV. As a result, three body leptonic decays of $\tilde Z_2$ (which were negligible for smaller gluino masses) now add to the dilepton signals, which for $m_\tilde g \leq 200$ GeV, can come only from chargino decays [20].

The corresponding cross sections in an $R$-parity violating model with $B$ violation via the $\lambda''_{212}$ coupling ($L$ violation via the $\lambda_{121}$ coupling) are shown in Fig. 2 (Fig. 3) for the same three cases of squark mass in Fig. 1. We remind the reader that these cases should yield the extreme deviations of the SUSY signals from their MSSM expectations. As before, the $m_\tilde g = 150$ GeV point in Fig. 2b and Fig. 3b is excluded because of constraints on the total width of the $Z$ [4], and also, because these events would lead to novel visible signatures since the LSP is unstable. We have also checked that the summed branching fraction for $Z$ decays via $\tilde Z_2\tilde Z_2, \tilde Z_1\tilde Z_2$ (and because the $\tilde Z_1$ is visible) or $\tilde Z_1\tilde Z_1$ is $\sim 4 \times 10^{-6}$, which is on the edge of observability of LEP experiments which have each accumulated a sample of 2M $Z$ events (in fact, for the lepton number violating case of Fig. 3, this point may well be already excluded by these data). The following features of Fig. 2 and Fig. 3 are worthy of note:

- As expected, the $E_T$ signal is considerably reduced since, in these R-violating scenarios, neutrinos are the sole physics source of $E_T$. The reduction is typically a factor 5-10,
but can be as much as two orders of magnitude in the case of the $L$-violation. In fact, it is interesting to see that the $E_T$ event topology has the smallest cross section in this $L$-violating class of models. This is because there are a minimum of four charged leptons (from the decays of the two $\tilde{Z}_1$'s) in each event, and it is rather unlikely that they all escape detection (recall the lepton veto for the $E_T$ sample).

- The ordering of the leptonic signals in $B$-violating models in Fig. 2 is qualitatively the same as in the MSSM. This is not surprising since the only difference in the two cases is the hadronic decay of the LSP. Notice that this additional hadronic activity makes it harder for the leptons to satisfy the isolation criteria and results in the anticipated reduction of the leptonic signals. It is, however, instructive to note that the signals in Fig. 2 are generally larger than those in Fig. 1; i.e. the loss of signal from lepton non-isolation is smaller than the contribution to the signal from the $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ production, if $m_{\tilde{q}} \sim m_{\tilde{g}}$.

- We see from Fig. 3 that if the LSP decays exclusively via the $\lambda_{121}$ coupling in Eq. (1), the essentially background-free $3\ell$ and $4\ell$ events will be the dominant SUSY signals at the Tevatron. Furthermore, $\sigma(n_\ell \geq 3) \geq 0.6 \, pb$ even for $m_{\tilde{g}} = 300 \, GeV$, so that $\geq 10$ such spectacular events would already be present in the CDF and D0 data samples, for the set of parameters that we have chosen. We have not studied the sensitivity of the cross section as a function of other parameters, and as such, Fig. 3 cannot be taken to mean that $m_{\tilde{g}} \leq 300 \, GeV$ is excluded by experiment. As also pointed out in Ref. [15] where multilepton signals from $\tilde{W}_1\tilde{Z}_{1,2}$ production were analysed within a similar framework, our analysis shows that the CDF and D0 experiments are indeed probing ranges of parameters not accessible to them if $R$-parity is conserved. Indeed we see from Fig. 3, that if sparticle mass patterns are the same as in the MSSM, $\sigma(n_\ell \geq 4)$ exceeds $10 \, fb$ for $m_{\tilde{g}} \leq 700 \, GeV$ — we have checked that the bulk of these events come from $\tilde{W}_1\tilde{W}_1$ and $\tilde{W}_1\tilde{Z}_2$ production, which is why the cross section is largest in case (c) for which the (negative) interference between the s- and t-channel diagrams is suppressed [23]. Since events with $n_\ell \geq 4$ are essentially free of SM backgrounds, Tevatron experiments should be able to indirectly probe gluino masses of 700-800 GeV, after about one year of Main Injector operation. It should, however, be kept in mind that there is no reason for the $\lambda_{121}$ operator to be dominant, so that the signals may be significantly smaller even in the presence of $L$-violating LSP decays. Fig. 3 shows just how big these signals can get.

- We see that unlike as in Fig. 1 and Fig. 2 where $\sigma(\ell^+\ell^-) > \sigma(\ell^\pm\ell^\pm)$, the OS and SS dilepton cross sections are essentially equal in Fig. 3. This is because in the former case $\tilde{Z}_2$ decays are frequently the dominant source of OS event topologies, while in the $L$-violating case this signal mainly comes from the decays of the LSP's, which result in equal amounts of SS and OS lepton pairs. For the same reason, OS pairs in Fig. 1 and Fig. 2 predominantly have the same flavour, whereas in Fig. 3, like and unlike flavours are equally probable.

- We should mention that the cuts used in this simulation were motivated by SUSY searches in the MSSM framework and are not necessarily suitable for searches when the LSP is unstable. For instance, if the LSP decays via $\tilde{Z}_1 \rightarrow dcs$, the requirement...
$E_T \geq 20$ GeV will clearly exclude some $4\ell$ events where each gluino in a $\tilde{g}\tilde{g}$ event decays via $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_2$, $\tilde{Z}_2 \rightarrow \ell\bar{\ell}\tilde{Z}_1$. Our purpose here was to study the impact of $R$-violation on usual SUSY searches, and not to devise optimal cuts for $R$-violating scenarios.

The physics backgrounds to these event topologies within the SM framework are shown in Table I for a top quark mass of 150 GeV and 175 GeV. We have not attempted to compute detector-dependent backgrounds to multilepton signals from misidentification of jets as isolated leptons [23] or to the $E_T$ signal from mismeasurement of QCD jets which, because of the $E_T > 75$ GeV cut, should be small. We see that while SUSY signals and SM backgrounds are of comparable magnitude in the $E_T$ and OS dilepton channels, the signal cross sections substantially exceed backgrounds in the SS and $n_\ell = 3$, and in some cases, $n_\ell \geq 4$ isolated lepton channels. We have estimated the reach of the Tevatron by requiring that the SUSY signal (in any channel) exceed the background by $5\sigma$; i.e. $N_{\text{sig}} > 5\sqrt{N_{\text{back}}}$, where $N_{\text{sig}}$ ($N_{\text{back}}$) are the expected number of signal (background) events in a collider run, and where we have used the $m_t = 150$ GeV background numbers. We attempt to incorporate systematic uncertainties inherent to these calculations by further requiring (somewhat arbitrarily) that $N_{\text{sig}} > 0.25N_{\text{back}}$. We have illustrated the reach of the Tevatron for the nine cases in Fig. 1–Fig. 3 in Table II, both for an integrated luminosity of 0.1 fb$^{-1}$ that is expected to be accumulated by the end of the current Tevatron run, and, in parenthesis, for an integrated luminosity of 1 fb$^{-1}$ that should be accumulated after one year of Main Injector operation. In Table II, we have required a minimum of five (ten for the Main Injector reach) signal events in each channel. For the SS and $3\ell$ samples where the expected background is very small (so that the $5\sigma$ criterion is not meaningful), we have checked that the Poisson probability for the background to fluctuate to this minimum event level is $\leq 2 \times 10^{-4}$ and $< 10^{-5}$, respectively. Several features of Table II are worth noting:

- The single lepton signal always appears to be swamped by background from $W$ production.

- Even in the MSSM framework, the SUSY reach in the rate-limited SS and especially the $3\ell$ channels substantially exceeds the corresponding reach in the $E_T$ channel (it is possible that the $E_T$ reach may be increased by using a harder $E_T$ cut [23] provided a large enough integrated luminosity can be accumulated, as will be the case at the Main Injector.

- For the $B$-violating scenarios in Fig. 2, the $E_T$ signals are strongly suppressed (except perhaps in Fig. 2b); here, the multilepton signals offers the most promising prospect for SUSY discovery. It is interesting to see that with the Main Injector, experiments should be able to probe values of $m_{\tilde{g}}$ up to 200 GeV (350 GeV) if the squarks are heavy (if $m_{\tilde{g}} \sim m_{\tilde{q}}$), in the $3\ell$ channel. Notice that it is possible that in the worst case scenario of Fig. 2c, there may be no observable signal after the current Tevatron run even if the experiments accumulate an integrated luminosity of 100 pb$^{-1}$ as anticipated. (Values of $m_{\tilde{g}}$ substantially below 150 GeV would lead to observable signals from $Z$ decays at LEP, which is why we do not show the cross sections here.)

- If instead the LSP decays via the lepton number violating $\lambda_{121}$ coupling, truly spectacular multilepton signals would enable experiments at the Tevatron to (indirectly)
probe gluino masses up to $\sim 800$ GeV. We have checked that as much as about $\frac{1}{3}$ of the $n_\ell \geq 4$ events contain 5, or more, isolated leptons if the gluino is very heavy. Once again, we emphasize that the magnitude and event topologies in the $L$-violating case will be sensitively dependent on the details of the various lepton number violating couplings, and the results in Fig. 3 should be regarded as upper limits on the ranges of various signals.

In summary, we have examined SUSY signals from the simultaneous production of all sparticles at the Tevatron. Within the MSSM framework, we find that at the Main Injector the multi-lepton signatures should make it possible to probe gluino masses considerably beyond what can be probed via $E_T$ searches. We have also studied the impact of explicit $R$-parity violating interactions on supersymmetry searches at the Tevatron [24], assuming that the sole effect of these interactions is to cause the LSP to decay inside the detector. If the $R$-violating couplings are small enough, the LSPs would be rather long-lived, and their presence in SUSY events might be inferred by searching for events with displaced vertices. If this is not the case, the only impact of the $R$-violating LSP decays would be to alter the cross sections for the various event topologies from their MSSM values. Most importantly, the cross section for $E_T$ events is substantially degraded, so that many experimental lower limits (based on $E_T$ searches) are no longer applicable. The large number of independent $R$-parity violating couplings that could be present makes a general phenomenological analysis quite intractable. In this study we have focussed on two models which, we have argued, cause the maximum variation of the signals from expectations in the MSSM framework. In the first model, where we assume that the LSP decays hadronically via $B$-violating interactions, both $E_T$ as well as isolated multi-lepton signals (shown in Fig. 2) are substantially degraded from their values in the MSSM. These signals should be relatively insensitive to the assumed flavour structure of the $B$-violating interactions. In contrast, SUSY signals are extremely model-dependent if the LSP decays via lepton number violating interactions. Multilepton cross sections from SUSY sources are maximally enhanced if the LSP decays into a pair of charged leptons ($e$ or $\mu$) and a neutrino, as is the case for the model illustrated in Fig. 3. In such a framework, experiments at the Tevatron, even now, could be probing gluinos as heavy as 300 GeV, and would be sensitive to gluinos as heavy as 700-800 GeV after the Main Injector upgrade. It would, however, be really fortuitous if nature had chosen to violate $R$-parity in just the right way as to maximize the Tevatron signal; a more likely situation is to be between the extremes illustrated in Fig. 2 and Fig. 3. Our projected reach for SUSY searches at the Tevatron for the various models is summarized in Table II. The main message of our study is that SUSY may manifest itself quite differently from MSSM expectations. There are perfectly viable models where there may be no observable signal in the $E_T$ channel but observable signals in multilepton channels may be present. In fact, even within the MSSM framework, multilepton channels will provide the maximum reach in $m_{\tilde{g}}$, once the Main Injector begins operations. We urge our experimental colleagues to keep this in mind in designing future SUSY search strategies.

ACKNOWLEDGMENTS

We thank H. Dreiner for conversations. This research was supported in part by the U. S. Department of Energy under grant numbers DE-FG-05-87ER40319, DE-FG-03-94ER40833,
and DE-FG-02-91ER40685.
REFERENCES

[1] D. Decamp et al. (ALEPH Collaboration), Phys. Rep. 216, 253 (1992); P. Abreu et al. (DELPHI Collaboration), Phys. Lett. B247, 157 (1990); O. Adriani et al. (L3 Collaboration), Phys. Rep. 236, 1 (1993); M. Akrawy et al. (OPAL Collaboration), Phys. Lett B240, 261 (1990); for a review, see G. Giacomelli and P. Giacomelli, Riv. Nuovo Cim. 16, 1 (1993).

[2] M. Paterno, Ph.D. thesis; D. Claes (D0 Collaboration), presented at the 8th DPF meeting, Albuquerque, NM, Aug. 1994; F. Abe et al., (CDF Collaboration), Phys. Rev. Lett. 69, 3439 (1992).

[3] C. S. Aulakh and R. N. Mohapatra, Phys. Lett. B119, 316 (1982); L. J. Hall and M. Suzuki, Nucl. Phys. B231, 419 (1984); S. Dawson, Nucl. Phys. B261, 297 (1985); S. Dimopoulos and L. Hall, Phys. Lett. B207, 210 (1987); L. Hall, Mod. Phys. Lett. A5, 467 (1990).

[4] See e.g. H. Baer, M. Drees and X. Tata, Phys. Rev. D41, 3414 (1991).

[5] S. Olsen, Plenary talk at the 8th DPF meeting, Albuquerque, NM, Aug. 1994.

[6] S. Dimopoulos et al., Phys. Rev. D41, 2099 (1990).

[7] H. Dreiner and G. Ross, Nucl. Phys. B365, 597 (1991).

[8] J. Butterworth and H. Dreiner, Nucl. Phys. B397, 3 (1993).

[9] Bounds on unstable photinos which can be produced at LEP via t-channel selectron exchange have been studied in the context of an L violating model by P. Acton et al. (OPAL Collaboration), Phys. Lett. B313, 333 (1993).

[10] R. Godbole, P. Roy and X. Tata, Nucl. Phys. B401, 67 (1992).

[11] H. Baer et al., Phys. Lett. B161, 175 (1985); G. Gambarini. Z. Phys. C30, 605 (1986); H. Baer, V. Barger, D. Karatas and X. Tata, Phys. Rev. D36, 96 (1987); G. Gambarini, G. Giudice, B. Mele and G. Ridolfi, Phys. Lett. 203B, 453 (1988); R. M. Barnett, J. Gunion and H. Haber, Phys. Rev. D37, 1892 (1988); A. Bartl, W. Majerotto, B. Mosslacher and N. Oshimo, Z. Phys. C52, 477 (1991).

[12] D. P. Roy, Phys. Lett. B283, 270 (1992).

[13] If all R-parity violating couplings are small enough, they do not make significant contributions (via renormalization effects) to sparticle masses and mixings. Thus sparticle mass patterns are not significantly modified from minimal model expectations.

[14] It was thought that cosmological arguments requiring GUT-scale baryogenesis not get washed out require that the $\lambda''$-type couplings are $\lesssim 10^{-7}$. It has since been shown (see e.g. H. Dreiner and G. Ross, Nucl. Phys. B210, 188 (1993)) that these bounds are model-dependent and can be evaded in reasonable scenarios.

[15] F. Zwirner, Phys. Lett. B132, 103 (1983); R. Barbieri and A. Masiero, Nucl. Phys. B267, 679 (1986).

[16] Because of intergenerational mixing there should be (weaker) bounds on the other $\lambda''$ couplings (especially on $\lambda''_{311}$) than the one on $\lambda''_{112}$ obtained in Ref. [13]. The important thing is that several of these couplings may be large enough so that the LSP would decay within the detector. There is essentially no experimental bound on the $\lambda''_{223}$ coupling (upper bounds obtained by requiring that the $B$-violating couplings remain perturbative up to a GUT scale do not lead to interesting phenomenological constraints, as discussed by B. Brahmachari and P. Roy, Phys. Rev. D50, 39 (1994)). If this coupling dominates $B$-violating interactions, signatures would be very similar to the ones we discuss, with
the $d$-quark in the LSP being replaced by a $b$. Except that an accidently non-isolated lepton would occasionally contribute to the leptonic signals discussed below, the signals we discuss are quite insensitive to the flavour structure of the $B$-violating interaction (we do not consider the possibility of tagging the $b$-quarks from LSP decay).

[17] V. Barger, G. Giudice and T. Han, Phys. Rev. D40, 2987 (1989).
[18] V. Barger, M. Berger, P. Ohmann and R. Phillips, Phys. Rev. D50, 4299 (1994).
[19] F. Paige and S. Protopopescu, in Supercollider Physics, p. 41, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in Proceedings of the Workshop on Physics at Current Accelerators and the Supercollider, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory pub. ANL-HEP-CP-93-92, 1993).

[20] H. Baer, C. Kao and X. Tata, Phys. Rev. D48, R2978 (1993).
[21] J. Botts et. al. Phys. Lett. B304, 159 (1993).
[22] H. Baer, C. Kao and X. Tata, Phys. Rev. D48, 5175 (1993).
[23] T. Kamon, J. Lopez, P. McIntyre and J. T. White, Texas A and M preprint, CTP-TAMU-19/94 (1994), have argued that Drell-Yan + jet production, where a fluctuation causes the jet to be misidentified as a lepton is the leading background to the trilepton sample. We have not included this (detector-dependent) background in Table 1, since it may be possible to eliminate it with a modest $E_T$ cut with just a small loss of signal (except perhaps in the case where $R$-parity conservation is broken by $B$-violating operators.

[24] The impact of $R$-parity violation on the isolated like-sign dilepton signal at hadron supercolliders has been discussed by J. Gunion and P. Binetruy, Davis preprint, UCD-88-32 (1988) and by H. Dreiner, M. Guchait and D. P. Roy, Phys. Rev. D49, 3270 (1994).
### TABLE I. Standard Model background cross sections in fb for various event topologies after cuts described in the text, for $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The $W + jet$ and $Z + jet$ results include decays to $\tau$ leptons.

| case       | $E_T$ | 1 $\ell$ | OS | SS | 3 $\ell$ | $\geq 4 \ell$ |
|------------|-------|----------|----|----|----------|---------------|
| $tt(150)$  | 270   | 1200     | 190| 0.8| 0.7      |               |
| $tt(175)$  | 145   | 590      | 90 | 0.3| 0.3      |               |
| $W + jet$  | 710   | $1.2 \times 10^6$ | –  | – | –      |               |
| $Z + jet$  | 320   | 2200     | 69 | –  | –      |               |
| $WW$       | 0.4   | 110      | 130| –  | –      |               |
| $WZ$       | 0.04  | 4.3      | 1.2| 2.1| 0.4     |               |
| total BG(150) | 1300 | $1.2 \times 10^6$ | 390| 2.9| 1.1     |               |
| total BG(175) | 1175 | $1.2 \times 10^6$ | 290| 2.4| 0.7     |               |

### TABLE II. Reach in $m_{\tilde{q}}$ via various event topologies for a) R-parity conserving (RPC) MSSM, b) baryon number violating (BNV) model, and c) lepton number violating (LNV) model, assuming an integrated luminosity of 0.1 fb$^{-1}$ (1 fb$^{-1}$), at the Tevatron collider. We use $m_t = 150$ GeV for the background.

| case       | $E_T$ | 1 $\ell$ | OS | SS | 3 $\ell$ | $\geq 4 \ell$ |
|------------|-------|----------|----|----|----------|---------------|
| a) MSSM    |       |          |    |    |          |               |
| $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV | 240 (260) | — (—) | 225 (290) | 230 (320) | 290 (425) | 190 (260) |
| $m_{\tilde{q}} = m_{\tilde{g}} - 10$ GeV | 245 (265) | — (—) | 160 (235) | 180 (325) | 240 (440) | — (—)     |
| $m_{\tilde{q}} = 2m_{\tilde{g}}$     | 185 (200) | — (—) | — (180) | 160 (210) | 180 (260) | — (—)     |
| b) BNV     |       |          |    |    |          |               |
| $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV | — (—) | — (—) | 165 (210) | 200 (280) | 220 (350) | — (165)   |
| $m_{\tilde{q}} = m_{\tilde{g}} - 10$ GeV | 200 (210) | — (—) | 150 (165) | 165 (235) | — (360) | — (—)     |
| $m_{\tilde{q}} = 2m_{\tilde{g}}$     | — (—) | — (—) | — (—) | — (200) | — (190) | — (—)     |
| c) LNV     |       |          |    |    |          |               |
| $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV | — (150) | — (—) | 240 (300) | 330 (450) | 480 (650) | 540 (740) |
| $m_{\tilde{q}} = m_{\tilde{g}} - 10$ GeV | 160 (180) | — (—) | 250 (300) | 330 (450) | 460 (640) | 520 (710) |
| $m_{\tilde{q}} = 2m_{\tilde{g}}$     | — (—) | — (—) | 190 (260) | 340 (540) | 540 (730) | 600 (840) |
FIGURES

FIG. 1. Cross sections at the Tevatron ($\sqrt{s} = 1.8$ TeV) in $fb$ for various event topologies after cuts given in the text for the $R$-parity conserving MSSM, for three choices of squark mass. We take $|\mu| = -m_{\tilde{g}}$, $\tan \beta = 2$, $A_t = A_b = -m_{\tilde{q}}$ and $m_{H_u} = 500$ GeV. The $E_T$ events are labelled with diamonds, the 1-\ell events with crosses, the $\ell^+\ell^-$ events with x’s and the SS with squares. The dotted curves are for 3-\ell signals, while dashes label the 4-\ell signals. For clarity, error bars are shown only on the lowest lying curve; on the other curves the error bars are considerably smaller. We note that the $m_{\tilde{g}} = 150$ GeV case in Fig. 1 is already excluded by LEP constraints on the $Z$ width, since this implies $m_{\tilde{\nu}} = 26$ GeV.

FIG. 2. Same as Fig. 1, except that the LSP is assumed to decay via $\tilde{Z}_1 \to cds$ or $\bar{c}\bar{d}s$ due to the $R$-parity violating $\lambda''_{121}$ coupling.

FIG. 3. Same as Fig. 1, except here $\tilde{Z}_1 \to \mu\bar{\nu}_e$, $\mu\bar{\nu}_e$, $e\bar{e}\nu_\mu$ or $e\bar{e}\mu$, each 25% and that the dashed curve includes $n_\ell \geq 4$ events. The multilepton cross sections shown here should be interpreted as upper limits on cross sections in models where the sole effect of $R$-parity violation is to cause the LSP to decay inside the detector. The $m_{\tilde{g}} = 150$ GeV points may already be excluded by LEP data as discussed in the text.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9410283v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9410283v1
This figure "fig1-3.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9410283v1
