Impact of R-parity violation on supersymmetry searches at the Fermilab Tevatron

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We evaluate cross sections for $\not{E}_T$, 1ℓ, and various dilepton and multilepton event topologies that result from the simultaneous production of all sparticles at the Fermilab 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.

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The search for supersymmetric (SUSY) particles has become a standard item on the agenda of experiments at high energy colliders. The nonobservation of events with missing transverse energy ($\not{E}_T$) and acollinear lepton and/or jet pairs in experiments at the CERN e^+e^- collider LEP, allows us to infer lower limits [1] $\sim \frac{M_Z}{2}$ on the masses of squarks, sleptons, and the charginos. From an analysis of the $\not{E}_T$ event sample, the Collider Detector at Fermilab (CDF) and D0 Collaborations at the Tevatron have inferred a lower limit [2] of about 150 GeV on the masses of gluinos and squarks ($\sim$ 200 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 $\not{E}_T$ 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 $R = 1(-1)$ for ordinary particles (sparticles). It is, however, possible [3] to construct phenomenologically viable models that do not conserve 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 $\not{E}_T$ analyses cease to be applicable. The somewhat weaker bounds [4] on sparticle masses from the measurement [5] of the Z width at LEP, of course, continue to be valid.

The phenomenology of R-parity-violating models can be very different from that of the MSSM. 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 [6,7] and at the DESY ep collider HERA [8]. The resulting modifications are sensitively dependent on the strength and form of R-violating interactions, and can be essentially negligible if these couplings are small relative to the gauge couplings. Then, the main impact of R-parity violation is, as we mentioned above, that the LSP decays visibly, invalidating experimental analyses based on the classic $\not{E}_T$ 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^0 decays. In fact, since Z^0 decays to LSP pairs can lead to observable signals if R parity is violated, the nonobservation of spherical events at LEP [9] translates to a limit $\sim \frac{M_Z}{2}$ 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 [10] in an R-parity-violating scenario.

The corresponding situation at the Tevatron is quite different. Since the $\not{E}_T$ signals are greatly degraded, the isolated multilepton signals from the cascade decays [11] of gluinos and squarks offer the main hope for the detection of these sparticles at the Tevatron. In the favorable case where R-parity violation is due to e or μ number violation, the multilepton signals would be enhanced [12]. 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 R-parity-violating interactions, assuming that these interactions do not significantly impact either production rates or decay patterns of sparticles other than the LSP [13].

R parity may be either broken spontaneously [by vacuum expectation values (VEV) for R-odd scalar neutrinos] or explicitly. Spontaneous breaking via VEV's of the isodoublet sneutrinos of the MSSM is phenomenologically excluded by measurements [5] of Γ_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

$$f_{\rm RPV} = \sum_{i,j,k} [\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c], \tag{1}$$

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 λ (λ'') 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 λ and λ' or λ'' 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, $\widetilde{Z}_1$) 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 [14] on B-violating λ''-type couplings that we are aware of comes from nonobservation of $n\bar{n}$ oscillations and requires [15] $\lambda''_{112}, \lambda''_{113} \lesssim 10^{-6}$. For the case of B-violating interactions, we therefore assume that the coupling λ''_{212}, on which there are no significant experimental constraints [16], dominates LSP decays. In this case, the LSP decays via

$$\widetilde{Z}_1 \to cds, \bar{c}\bar{d}\bar{s}, \tag{2}$$

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 flavor 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 τ leptons, we expect that the enhancement is maximal if the corresponding L-violating interactions involve only e and μ families. For definiteness, we assume that the coupling λ_{121} dominates, in which case $\widetilde{Z}_1$ decays via

$$\widetilde{Z}_1 \to \mu\bar{e}\nu_e, \bar{\mu}e\bar{\nu_e}, e\bar{e}\nu_\mu, e\bar{e}\bar{\nu_\mu}. \tag{3}$$

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 [10] of the gaugino-Higgsino content of the LSP. We note that λ_{121} can be as large as [17] $0.08(\frac{m_{\tilde{\ell}}}{200\ \text{GeV}})$ so that the LSP decays well inside the detector. Constraints on several other L-violating couplings are weaker than those on λ_{121}. In these cases, the LSP either decays as in (3) with μ replaced by τ and ν_μ by ν_τ (via λ_{131} interactions) or decays via $\widetilde{Z}_1 \to \ell jj, \nu_\ell jj$ (via various λ' 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 [Eqs. (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 sparticles other than the LSP.

The effect of L nonconserving, 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 $\widetilde{W}_1\widetilde{Z}_{1,2}$ production at the Tevatron has recently been studied in Ref. [18]. Here, we use ISAJET 7.13 [19] to study the impact of R-violating operators 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 $m_{\tilde{g}} \gg m_{\widetilde{W}_1}, m_{\widetilde{Z}_{1,2}}$, the production of charginos and neutralinos can make a significant contribution, especially when gluinos and squarks are heavy.

Unlike Ref. [12] which focused 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 multilepton topologies.

For our simulation [20] of SUSY events, we use CTEQ2L structure functions [21]. We model experimental conditions using a toy calorimeter with segementation $\Delta\eta \times \Delta\phi = 0.1 \times 0.09$ and extending to $|\eta| = 4$. We assume an energy resolution of $\frac{0.7}{\sqrt{E_T}}$ $(\frac{0.15}{\sqrt{E_T}})$ 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 $\frac{E_T(\ell)}{4}$. Finally, since we use the MSSM as the reference model, we require $\not{E}_T > 20$ GeV in all events. The events are classified as follows.

(1) For $\not{E}_T$ events, we require $n_{\rm jet} \geq 4$ with at least one of the jets in the central region, $|\eta| < 1$, and following the recent analysis by the D0 collaboration [2], $\not{E}_T \geq 75$ GeV. We veto events with either isolated leptons with $E_T \geq 15$ GeV (to reduce W backgrounds), or a jet within 30° of $\mathbf{E}_T$.

(2) Single lepton events are defined to have exactly one isolated lepton with $E_T \geq 15$ GeV. We reject events with 60 GeV $\leq m_T(\ell, \not{E}_T) \leq 100$ GeV which have large backgrounds from W production.

(3) The opposite sign (OS) dilepton sample is defined to have two opposite sign isolated leptons 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_ℓ 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(a) for $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV, Fig. 1(b) $m_{\tilde{q}} = m_{\tilde{g}} - 10$ GeV, and Fig. 1(c) $m_{\tilde{q}} = 2m_{\tilde{g}}$. Here, we have fixed $\tan\beta = 2$, $\mu = -m_{\tilde{g}}$, $m_t = 170$ GeV, and taken the pseudoscalar Higgs boson mass to be 500 GeV. Our choice of μ is motivated by supergravity models with radiative symmetry breaking, where typically, the value of $|\mu|$ scales with the gluino mass. The precise value of $|\mu|$ is relatively unimportant as long as it is substantially larger than the electroweak gaugino masses. This then ensures that the lighter charginos and neutralinos are gauginolike, and the heavier ones Higgsino-like, which is all one requires to obtain the qualitative features of the phenomenology. 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 grand unified theory (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 $\geq$ 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 $\not{E}_T$ events (for which we require $n_{\rm jet} \geq 4$) falls below that of the 1ℓ event sample on which there is no such requirement. Finally, we note that the OS and SS dilepton cross sections in Fig. 1(b) increase sharply for $m_{\tilde{g}} = 200 - 250$ GeV because the decay $\widetilde{Z}_2 \to \tilde{\nu}\nu$, which is the only accessible two-body decay of $\widetilde{Z}_2$ 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 $\widetilde{Z}_2$ (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-

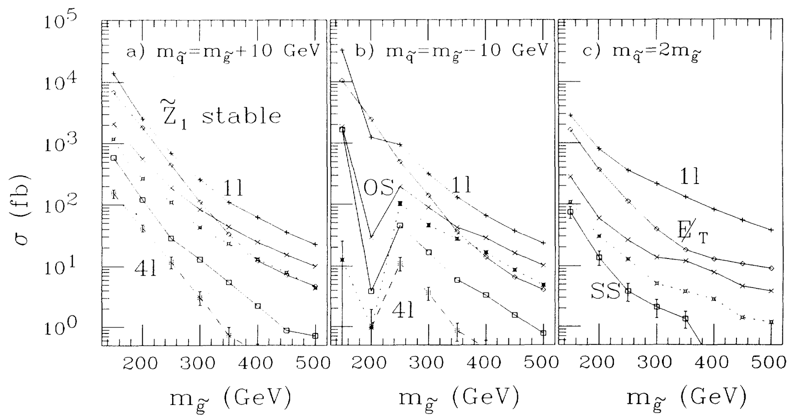

FIG. 1. Cross sections at the Tevatron ($\sqrt{s} = 1.8$ TeV) in fb for various event topologies after cuts given in the text for the R-parity-conserving MSSM, for three choices of squark mass. We take $|\mu| = -m_{\tilde{g}}$, $\tan\beta = 2$, $A_t = A_b = -m_{\tilde{q}}$, and $m_{H_p} = 500$ GeV. The $\not{E}_T$ events are labeled with diamonds, the 1-ℓ events with crosses, the $\ell^+\ell^-$ events with $\times$'s and the SS with squares. The dotted curves are for 3-ℓ signals, while dashes label the 4-ℓ 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 (b) is already excluded by LEP constraints on the Z width, since this implies $m_{\tilde{\nu}} = 26$ GeV.

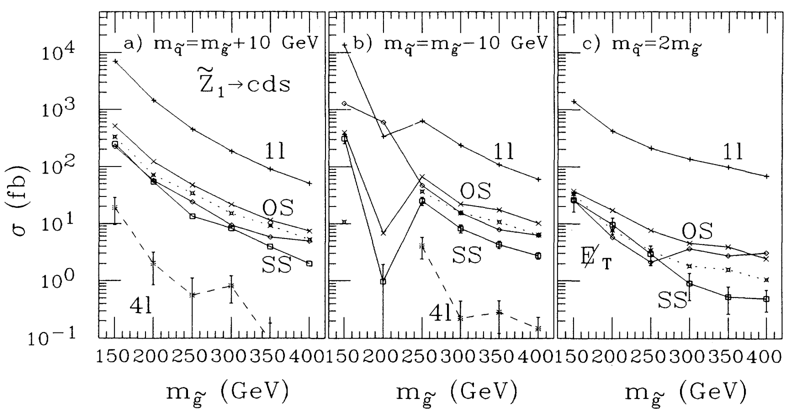

FIG. 2. Same as Fig. 1, except that the LSP is assumed to decay via $\widetilde{Z}_1 \to cds$ or $\bar{c}\bar{d}\bar{s}$ due to the R-parity violating λ''_{212} coupling.

violating model with B violation via the λ''_{212} coupling (L violation via the λ_{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 Figs. 2(b) and 3(b) 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 $\widetilde{Z}_2\widetilde{Z}_2$,$\widetilde{Z}_1\widetilde{Z}_2$ (and because the $\widetilde{Z}_1$ is visible) or $\widetilde{Z}_1\widetilde{Z}_1$ 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 $\not{E}_T$ signal is considerably reduced since, in these R-violating scenarios, neutrinos are the sole *physics* source of $\not{E}_T$. The reduction is typically a factor 5–10, but can be as much as 2 orders of magnitude in the case of the L violation. In fact, it is interesting to see that the $\not{E}_T$ 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 $\widetilde{Z}_1$'s) in each event, and it is rather unlikely that they all escape detection (recall the lepton veto for the $\not{E}_T$ 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(a) are generally larger than those in Fig. 1(c); i.e., the loss of signal from lepton nonisolation 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 λ_{121} coupling in Eq. (1), the essentially background-free 3ℓ and 4ℓ 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 $\gtrsim 10$ 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. [18] where multilepton signals from $\widetilde{W}_1\widetilde{Z}_{1,2}$ production were analyzed 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

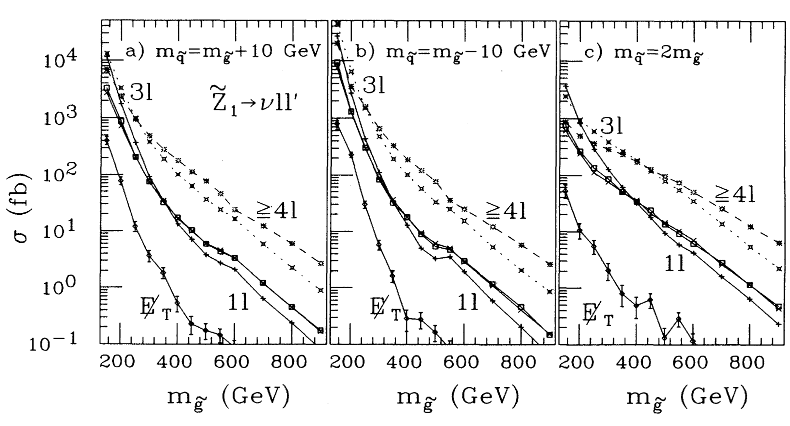

FIG. 3. Same as Fig. 1, except here $\widetilde{Z}_1 \to \mu\bar{e}\nu_e$, $\bar{\mu}e\bar{\nu}_e$, $e\bar{e}\nu_\mu$ or $e\bar{e}\bar{\nu}_\mu$, each 25% and that the dashed curve includes $n_\ell \geq 4$ events. The multilepton cross sections shown here should be interpreted as upper limits on cross 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.

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 $\widetilde{W}_1\widetilde{W}_1$ and $\widetilde{W}_1\widetilde{Z}_2$ 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 [22]. 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 1 year of Main Injector operation. It should, however, be kept in mind that there is no reason for the λ_{121} operator to be dominant, so that the signals may be significantly smaller even in the presence of L-violating LSP decays. Figure 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 $\widetilde{Z}_2$ 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 flavor, whereas in Fig. 3, like and unlike flavors 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 $\widetilde{Z}_1 \to dcs$, the requirement $\not{E}_T \geq 20$ GeV will clearly exclude some 4ℓ events where each gluino in a $\tilde{g}\tilde{g}$ event decays via $\tilde{g} \to q\bar{q}\widetilde{Z}_2$, $\widetilde{Z}_2 \to \ell\bar{\ell}\widetilde{Z}_1$. 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 $\not{E}_T$ signal from mismeasurement of QCD jets which, because of the $\not{E}_T > 75$ GeV cut, should be small. We see that while SUSY signals and SM backgrounds are of comparable magnitude in the $\not{E}_T$ 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 5σ; i.e., $N_{\rm sig} > 5\sqrt{N_{\rm back}}$, where $N_{\rm sig}$ ($N_{\rm back}$) 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 $N_{\rm sig} > 0.25N_{\rm back}$. We have illustrated the reach of the Tevatron for the nine cases in Figs. 1–3 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 3ℓ samples where the expected background is very small (so that the 5σ criterion is not meaningful), we have checked that the Poisson probability for the background to fluctuate to this minimum event level is $\leq 2\times10^{-4}$ and $< 10^{-5}$, respectively. Several features of Table II are worth noting.

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 τ leptons.

Case	$\not{E}_T$	$1\ \ell$	OS	SS	$3\ \ell$	$\geq 4\ \ell$
$t\bar{t}(150)$	270	1200	190	0.8	0.7	–
$t\bar{t}(175)$	145	590	90	0.3	0.3	–
W+jet	710	1.2×10^6	–	–	–	–
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	1.2×10^6	390	2.9	1.1	–
Total BG(175)	1175	1.2×10^6	290	2.4	0.7	–

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 3ℓ channels substantially exceeds the corresponding reach in the $\not{E}_T$ channel (it is possible that the $\not{E}_T$ reach may be increased by using a harder $\not{E}_T$ 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 $\not{E}_T$ signals are strongly suppressed [except perhaps in Fig. 2(b)]; 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 $m_{\tilde{q}} \sim m_{\tilde{g}}$), in the 3ℓ channel. Notice that it is possible that in the worst case scenario of Fig. 2(c), 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 λ_{121} coupling, truly spectacular multilepton signals would enable experiments at the Tevatron to (indirectly) probe gluino masses up to ~ 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 our analysis of the various signals in Figs. 1–3 and the bounds in Table II, we have not studied the variation of the signals with μ and $\tan\beta$. An exhaustive scan of

TABLE II. Reach in $m_{\tilde{g}}$ 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	$\not\!\!E_T$	$1\,\ell$	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)

the multidimensional parameter space is not really practical, considering the large number of parameters. For the MSSM, the dependence of the signal on μ and $\tan\beta$ has been examined, e.g., in Ref. [20]. One of the main points of Table II is to illustrate how R-parity-violating decays of the LSP would alter MSSM expectations, and to give the reader an idea of the reach of the Tevatron for the three models studied. Appropriate caution must be exercised in interpreting the table for other values of $\tan\beta$ and μ for which the reference MSSM cross sections are different from those in Fig. 1. While the MSSM cross sections only vary relatively slowly over a wide range of μ, the 3ℓ and SS cross sections may well be significantly smaller if $\tan\beta$ is very large [20]. While this could impact on the detectability in the baryon-number-violating (BNV) case, we expect that our qualitative conclusions [particularly for the lepton-number-violating (LNV) case] will remain valid for a large range of parameters.

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 multilepton signatures should make it possible to probe gluino masses considerably beyond what can be probed via $\not\!\!E_T$ 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 LSP's 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 $\not\!\!E_T$ events is substantially degraded, so that many experimental lower limits (based on $\not\!\!E_T$ 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 focused 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 $\not\!\!E_T$ as well as isolated multilepton signals (shown in Fig. 2) are substantially degraded from their values in the MSSM. These signals should be relatively insensitive to the assumed flavor 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 μ) 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 $\not\!\!E_T$ 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.

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