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RAL Report
RAL-94-047

HEP

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V Barger M S Berger P Ohmann and R J N Phillips

June 1994

Rutherford Appleton Laboratory Chilton DIDCOT Oxfordshire OX11 0QX

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MAD/PH/831

RAL-94-047

Revised

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Multilepton SUSY signals from R-parity violation at the Tevatron

V. Barger[a], M.S. Berger[a], P. Ohmann[a] and R.J.N. Phillips[b]

[a]*Physics Department, University of Wisconsin, Madison, WI53706, USA*

[b]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK*

Abstract

The expected trilepton signals from $p\bar{p} \to \chi_1^\pm \chi_2^0 \to (\chi_1^0 \ell^\pm \nu)(\chi_1^0 \ell'^+ \ell'^-)$ will be converted into hadronically quiet multilepton signals, if the two final χ_1^0 have leptonic R-parity-violating (RPV) decays $\chi_1^0 \to \ell\ell'\nu$. We make illustrative calculations of the acceptance for these spectacular RPV signals, and point out that distinctive multilepton signals are possible even when the R-conserving trilepton signals are blocked by the "spoiler mode" $\chi_2^0 \to h^0 \chi_1^0$. Other channels such as $p\bar{p} \to \chi_1^\pm \chi_2^0 \to (\chi_1^0 \ell^\pm \nu)(\chi_1^0 \nu\nu)$, $p\bar{p} \to \chi_1^\pm \chi_1^0 \to (\chi_1^0 \ell\nu)\chi_1^0$ and $p\bar{p} \to \chi_1^+ \chi_1^- \to (\chi_1^0 \ell^+ \nu)(\chi_1^0 \ell'^- \nu)$ can also give quiet multileptons from RPV. We investigate these signals in the context of supersymmetric models with radiative electroweak symmetry breaking, using examples in the low-$\tan\beta$ λ_t fixed-point region.

There is intense interest in searching for signatures of Supersymmetry (SUSY) at the Fermilab Tevatron $p\bar{p}$ collider, where the highest present CM energy $\sqrt{s} = 1.8$–2 TeV is accessed. An important possibility is the pair production of charginos and neutralinos [1], whose leptonic decay modes lead to many promising signatures [2–6]. Recently, much theoretical [3,6] and experimental [7,8] attention has centered on trileptons from the production/decay sequence

$$p\bar{p} \to \chi_1^{\pm}\chi_2^0 \to (\chi_1^0\ell^{\pm}\nu)(\chi_1^0\ell'^{+}\ell'^{-}) \, . \tag{1}$$

Here $\chi_i^{\pm}$ and χ_j^0 are charginos and neutralinos (i, j denote mass ordering) and χ_1^0 is the lightest SUSY particle (LSP); see Figs. 1(a) and 1(b). These trilepton events are distinctively "quiet" (little accompanying hadronic excitation); measurable rates are predicted for interesting ranges of SUSY parameters, but are lost in certain parameter regions e.g. where the "spoiler mode" $\chi_2^0 \to \chi_1^0 h$ is kinematically accessible and suppresses all other χ_2^0 decays (h being the lightest Higgs scalar), or where one of the leptons is constrained to be soft and becomes undetectable [3,6].

The popular scenario above assumes the LSP is stable and therefore practically invisible, due to R-parity conservation (RPC). The picture changes dramatically with R-parity violation (RPV) [9]. In particular, if explicit RPV occurs through $L_i L_j \bar{E}_k$ terms in the superpotential, the LSP will decay via $\chi_1^0 \to \ell\ell'\nu$ to a neutrino plus two charged leptons that may have different flavors (see Fig. 1(c)) thus converting the RPC trilepton signal into multileptons [10] with up to seven charged leptons appearing in the final state. Even when the spoiler mode is active, suppressing RPC trileptons, a total of five charged leptons are still present in the decay of $\chi_1^{\pm}\chi_2^0$ with RPV. Also, the channels $\chi_1^{\pm}\chi_2^0 \to (\chi_1^0\ell^{\pm}\nu)(\chi_1^0\nu\nu)$, $\chi_1^{\pm}\chi_1^0 \to (\chi_1^0\ell\nu)\chi_1^0$ or $\chi_1^{+}\chi_1^{-} \to (\chi_1^0\ell^{+}\nu)(\chi_1^0\ell'^{-}\nu)$ give quiet signals with up to five or six leptons. The actual multiplicity of observed leptons depends on the experimental thresholds and angular acceptances; in the present paper we give some sample calculations illustrating the high visibility of these multilepton signals.

In the framework of the minimal supersymmetric standard model (MSSM) with grand unification (GUTs), the masses and couplings of the charginos $\chi_i^\pm$ and neutralinos χ_j^0 are determined by known quantities such as the gauge couplings plus a number of parameters at the SUSY mass scale: (a) the gluino mass $m_{\tilde{g}}$; (b) the Higgsino mass mixing coefficient μ; (c) the ratio of vacuum expectation values for the two Higgs doublets, $v_2/v_1 = \tan\beta$; (d) the squark masses $m_{\tilde{q}}$ and (e) the CP-odd neutral Higgs mass m_A. Unification constraints on gauge and Yukawa couplings at the GUT scale lead to a greatly reduced parameter set at the SUSY mass scale, through the renormalization group equations (RGE). Such approaches also explain electroweak symmetry breaking as a radiatively induced effect. Recent analyses of the sparticle masses and couplings expected in supergravity models can be found in Refs. [11–16]. A particularly attractive scenario is the occurence of an infrared fixed point of the top-quark Yukawa coupling [17], which predicts the relation [12]

$$m_t(pole) \simeq (200\ GeV)\sin\beta\ . \tag{2}$$

In the following we adopt this scenario and use the value $m_t = 168$ GeV, for which the RGE solutions of Ref. [13] were constructed, consistent with $m_t = 174 \pm 10^{+13}_{-12}$ GeV from the CDF top-quark candidate events [18]. For this m_t choice $\tan\beta = 1.5$. Our analysis of the chargino and neutralino signatures will be based on Ref. [13] where m_0 and $m_{1/2}$ are input parameters at the GUT scale M_G (along with trilinear couplings $A = 0$ at M_G), obtained with a naturalness condition $|\mu| < 0.5$ TeV on radiative symmetry breaking. The allowed region in $(m_{1/2}, m_0)$ parameter space is shown in Fig. 8 of Ref. [13]. The remaining parameters are determined by the RGE analysis within a twofold ambiguity, corresponding to positive or negative μ.

The fixed-point solution exhibits some simple characteristics, which can be qualitatively understood from the tree-level relationship

$$\frac{1}{2}M_Z^2 = \frac{m_{H_1}^2 - m_{H_2}^2\tan^2\beta}{\tan^2\beta - 1} - \mu^2\ . \tag{3}$$

At the electroweak scale, $m_{H_2}^2 \lesssim 0$ and hence $|\mu|$ must be large, and in fact $|\mu|$ is found to be substantially larger than M_2, the SU(2) gaugino mass. Consequently the $\tilde{W}$-$\tilde{H}$ mass matrix is approximately diagonal and the lightest chargino eigenstate χ_1^+ is almost a pure $\tilde{W}^+$ state. Also, χ_1^0 is nearly a pure U(1) gaugino $\tilde{B}$ while χ_2^0 is almost purely $\tilde{W}^0$. A direct result is that the $W^+\chi_1^-\chi_2^0$ and the $Z\chi_1^+\chi_1^-$ couplings are almost the maximal gauge couplings, and that the $W^+\chi_1^-\chi_1^0$ coupling is suppressed (however this suppression may be somewhat offset by more phase space for the light χ_1^0). The dominant production subprocesses $q\bar{q}' \to W^* \to \chi_1^+\chi_2^0$ and $q\bar{q} \to Z, \gamma \to \chi_1^+\chi_1^-$ are then determined mainly by the final state particle masses. The masses of χ_1^0, χ_2^0, χ_1^+, h are illustrated in Fig. 2 versus $m_{1/2}$ for four typical choices of m_0 and the sign of μ. For the case $\mu > 0$ the strongest phenomenological bound comes from the lightest Higgs mass, which is known to be larger than about 60 GeV. As has been emphasized recently [14], radiative corrections are not known very accurately in this case as the tree-level mass is very small, so we indicate this bound with a dashed line. For the case $\mu < 0$ the strongest general phenomenological bound comes from the lightest chargino mass, which must be larger than about 45 GeV; but in RPV scenarios with $\chi_1^0 \to \ell\ell'\nu$ the absence of any corresponding $e^+e^- \to \chi_1^0\chi_1^0$ signal at LEP would further require $m_{\chi_1^0} \gtrsim 45$ GeV. There are also weaker bounds coming from the naturalness condition $|\mu| < 0.5$ TeV [13]; taken literally this condition would exclude the higher $m_{1/2}$ ranges in Fig. 2, but since it is somewhat subjective we do not apply it strictly. The production cross sections for $\chi_1^\pm\chi_2^0$, $\chi_1^\pm\chi_1^0$, $\chi_1^+\chi_1^-$, obtained from the ISAJET program [19], are shown in Fig. 3.

We address the situation where the superpotential contains a possible lepton-number violating term $\lambda_{ijk}L_L^iL_L^j\bar{E}_R^k$ where E_R is the superfield containing the right-handed charged-lepton singlets and L_L contains the lepton doublets; the i, j, k are generation indices. These interactions break R-parity, since they involve an odd number of supersymmetric particles. The Lagrangian generated by this superpotential term has the form

$$\mathcal{L} = \lambda_{ijk}\left[\tilde{\nu}_L^i\bar{e}_R^k e_L^j + \tilde{e}_L^j\bar{e}_R^k\nu_L^i + \left(\tilde{e}_R^k\right)^*\left(\bar{\nu}_L^i\right)^c e_L^j - (i \leftrightarrow j)\right] + h.c. \tag{4}$$

in four-component Dirac notation. A fundamental RPV interaction of this kind could mediate the decay of any chargino or neutralino, as illustrated in Fig. 1(c) for χ_i^0. It is natural to assume a hierarchy of interactions, in which the RPV coupling λ_{ijk} is small compared to electroweak gauge couplings; then RPC approximately holds in decays of the heavier gauginos, and RPV is manifest only in the otherwise forbidden decay of the LSP χ_1^0. Thus the next stage of our analysis is to evaluate the branching fractions for χ_1^+ and χ_2^0 RPC decays, which can be found using the ISASUSY program [19]. Figure 4 shows that the leptonic $\chi_1^+ \to \chi_1^0 \ell^+ \nu$ fraction is typically 20–30% (summing $\ell = e, \mu$), which sometimes goes via $\chi_1^0 W^+, \tilde{\ell}^+ \nu$ or $\ell^+ \tilde{\nu}$ on-shell intermediate states. Figure 5 shows that $\chi_2^0 \to \chi_1^0 \ell\ell$ is often substantial; the branching fraction sometimes depends on intermediate $\tilde{\ell}\ell$ states and sometimes is suppressed due to competition with $\chi_2^0 \to \chi_1^0 h$, which always dominates when kinematically allowed.

For the RPV effects, we shall assume that the decay leptons do not include τ and that the coupling is strong enough for χ_1^0 to decay near the production vertex, giving a lower limit to the RPV coupling constant [10,20] $\lambda > (\gamma/20)(m_{\tilde{\ell}}/100\ GeV)^2(1\ GeV/m_{LSP})^{2.5}$, where γ is the Lorentz boost factor of the LSP and $m_{\tilde{\ell}}$ is the mass of the intermediate slepton in the $\chi_1^0 \to \ell\ell'\nu$ decay. In our examples below this condition implies $\lambda \gtrsim 10^{-4}$–10^{-5}. The hierarchy mentioned above yields $\lambda \ll 1$, so that RPV terms do not significantly affect the RGE and existing bounds on the couplings [21] are respected. One obtains the modified RGE at one-loop

$$\frac{d\lambda_{ijk}}{dt} = \frac{\lambda_{ijk}}{16\pi^2}\left[-\frac{9}{5}g_1^2 - 3g_2^2 + (\delta_{j3} + 2\delta_{k3})\lambda_\tau^2\right] + \frac{1}{16\pi^2}\left[\mathcal{O}(\lambda_{lmn}^3)\right] , \tag{5}$$

where λ_{ijk} are the various RPV couplings, and δ_{ij} is the Kronecker delta. The existing bounds [21] require that the λ_{ijk} are small near the electroweak scale, and then from Eq. (5) it follows (for small $\tan\beta$ considered here) that they are small for all scales up to the GUT scale. Consequently the RPV couplings λ_{ijk} have a negligible effect on the lepton Yukawa coupling running and on the running of the soft-supersymmetry breaking parameters. [The situation may be different for the baryon-violating couplings, where the weaker electroweak scale bounds together with the fixed-point character of the associated RGE can yield large baryon-violating couplings near the GUT scale [22]; these couplings must be zero to avoid fast proton decay when lepton-violating couplings are nonzero]. Finally, we have tacitly assumed that the $L_iL_j\bar{E}_k$ terms dominate over possible $L_iQ_j\bar{D}_k$ RPV terms [9,10]; if the latter are not negligible, the LSP can also decay into quarks ($B(\chi_1^0 \to \ell\ell'\nu) < 1$), and the multilepton signals we present here become upper bounds. For multilepton acceptance we follow the CDF experiment [7] and require a central trigger lepton with transverse momentum $p_T(\ell) >$ 10 GeV and rapidity $|\eta(\ell)| < 1.1$; subsequent leptons have looser cuts $p_T(\ell) > 5$ GeV and $|\eta(\ell)| < 2.2$. This is approximately the CDF electron acceptance; their muon acceptance is somewhat less; there are also uninstrumented areas in azimuth ϕ and η, reducing the fiducial region by $70 - 80\%$, that we do not explicitly take into account. In the case of the spoiler mode $\chi_2^0 \to \chi_1^0 h$, we assume the dominant $h \to jj$ dijet decay and require all observed leptons to have separations $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$ from both of these jets. These cuts give a semi-realistic estimate of how many leptons may indeed be observable experimentally. We estimate acceptance factors by Monte Carlo methods, using phase-space decay distributions with full kinematic constraints from intermediate on-shell states.

The following four cases A–D illustrate interesting aspects of the RPC and RPV multilepton signals in the four parameter regions (a)–(d) of Figs. 2–5 above. All cases have $\tan\beta = 1.5$. We sum over lepton flavors $\ell = e, \mu$.

Case A: $m_{1/2} = 140$ GeV, $m_0 = 200$ GeV, $\mu < 0$.

This gives $m(\chi_1^+) = 92$ GeV, $m(\chi_2^0) = 94$ GeV, $m(\chi_1^0) = 49$ GeV, $m(\tilde{g}) = 380$ GeV, $m(h) = 83$ GeV. With RPC there is a straightforward $\chi_1^+\chi_2^0 \to (\chi_1^0\ell\nu)(\chi_1^0\ell\ell)$ trilepton signal (no spoiler mode, $\chi_2^0 \not\to \chi_1^0 h$). With RPV however, these final states give up to 7 leptons; also channels such as $\chi_1^\pm\chi_2^0 \to (\chi_1^0\ell\nu)(\chi_1^0\nu\nu)$ and $\chi_1^\pm\chi_1^0 \to (\chi_1^0\ell\nu)\chi_1^0$ give up to 5 leptons. Our calculations give the following cross sections σ_n for $\geq n$ leptons to pass acceptance cuts.

$$
\begin{array}{llcll}
\text{RPC:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0\ell\ell) & \Rightarrow & \sigma_3 & = 0.016\ pb\ ; \\
\text{RPV:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0\ell\ell) & \Rightarrow & \sigma_3, \sigma_4, \sigma_5, \sigma_6, \sigma_7 & = 0.026, 0.026, 0.025, 0.020, 0.010\ pb\ ; \\
 & \chi_1^\pm(\chi_2^0 \to \chi_1^0\nu\nu) & \Rightarrow & \sigma_3, \sigma_4, \sigma_5 & = 0.057, 0.052, 0.029\ pb\ ; \\
 & \chi_1^\pm\chi_1^0 & \Rightarrow & \sigma_3, \sigma_4, \sigma_5 & = 0.014, 0.012, 0.007\ pb\ ; \\
 & \chi_1^+\chi_1^- & \Rightarrow & \sigma_3, \sigma_4, \sigma_5, \sigma_6 & = 0.017, 0.017, 0.014, 0.008\ pb\ .
\end{array}
$$

This demonstrates that RPV can not only enhance the original RPC trilepton channel but can produce quiet multileptons from other channels too.

Case B: $m_{1\ 2}$ = 140 GeV, m_0 = 50 GeV, $\mu < 0$.

This gives $m(\chi_1^+)$ = 89 GeV, $m(\chi_2^0)$ = 93 GeV, $m(\chi_1^0)$ = 48 GeV, $m(\tilde{g})$ = 380 GeV, $m(h)$ = 79 GeV, $m(\tilde{\ell}_R)$ = 74 GeV, so again there is no spoiler mode. Here $\chi_2^0 \to \chi_1^0 \ell\ell$ decay proceeds almost entirely via $\chi_2^0 \to \tilde{\ell}\ell$, but with sufficient phase space for this primary lepton to be quite energetic. We obtain

$$\begin{array}{lllll}
\text{RPC:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0 \ell\ell) & \Rightarrow \sigma_3 & = 0.093\ pb\ ; \\
\text{RPV:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0 \ell\ell) & \Rightarrow \sigma_3, \sigma_4, \sigma_5, \sigma_6, \sigma_7 & = 0.130, 0.130, 0.125, 0.105, 0.055\ pb\ ; \\
 & \chi_1^\pm(\chi_2^0 \to \chi_1^0 \nu\nu) & \Rightarrow \sigma_3, \sigma_4, \sigma_5 & = 0.007, 0.007, 0.004\ pb\ ; \\
 & \chi_1^\pm \chi_1^0 & \Rightarrow \sigma_3, \sigma_4, \sigma_5 & = 0.060, 0.053, 0.030\ pb\ ; \\
 & \chi_1^+ \chi_1^- & \Rightarrow \sigma_3, \sigma_4, \sigma_5, \sigma_6 & = 0.054, 0.053, 0.044, 0.023\ pb\ .
\end{array}$$

In this example RPV enhances the trilepton signal and gives up to 7 final leptons.

Case C: $m_{1\ 2}$ = 150 GeV, m_0 = 200 GeV, $\mu > 0$.

This gives $m(\chi_1^+)$ = 129 GeV, $m(\chi_2^0)$ = 129 GeV, $m(\chi_1^0)$ = 63 GeV, $m(\tilde{g})$ = 410 GeV, $m(h)$ = 61 GeV, so the spoiler mode $\chi_2^0 \to \chi_1^0 h$ dominates and suppresses the RPC trilepton signal. However, RPV gives multilepton plus $h \to jj$ final states from this spoiler mode, and in principle gives quiet multileptons from $\chi_1^\pm \chi_1^0$ and $\chi_1^+ \chi_1^-$ production.

$$\begin{array}{lllll}
\text{RPC:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0 \ell\ell) & \Rightarrow \sigma_3 & \simeq 0\ ; \\
\text{RPV:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0 h) & \Rightarrow \sigma_3, \sigma_4, \sigma_5 & = 0.028, 0.020, 0.008\ pb\ ; \\
 & \chi_1^\pm \chi_1^0 & \Rightarrow \sigma_3, \sigma_4, \sigma_5 & = 0.001, 0.001, 0.001\ pb\ ; \\
 & \chi_1^+ \chi_1^- & \Rightarrow \sigma_3, \sigma_4, \sigma_5, \sigma_6 & = 0.005, 0.005, 0.004, 0.002\ pb\ .
\end{array}$$

Here RPV rescues the normal spoiler mode. The somewhat smaller multilepton cross sections in this and the following case D (both with $\mu > 0$) are principally due to the smaller gaugino pair production cross sections; see Fig.3.

Case D: $m_{1\ 2}$ = 150 GeV, m_0 = 50 GeV, $\mu > 0$.

This case gives $m(\chi_1^\pm)$ = 133 GeV, $m(\chi_2^0)$ = 133 GeV, $m(\chi_1^0)$ = 65 GeV, $m(\tilde{g})$ = 410 GeV, $m(h)$ = 59 GeV, $m(\tilde{\ell}_R)$ = 77 GeV, $m(\tilde{\ell}_L) = m(\tilde{\nu})$ = 119 GeV. It is on the edge of being excluded by the m_h experimental bound, but we retain it to illustrate a class of solutions. Here the spoiler mode $\chi_2^0 \to \chi_1^0 h$ dominates but $\chi_2^0 \to \tilde{\ell}\ell \to \chi_1^0 \ell\ell$ modes manage to compete thanks to the on-shell intermediate state, so the conventional RPC trileptons are only partially suppressed. There is also an appreciable $\chi_2^0 \to \tilde{\nu}\nu \to \chi_1^0 \nu\nu$ fraction . The branching fraction $B(\chi_1^+ \to \tilde{\ell}\nu(\ell\tilde{\nu}) \to \chi_1^0 \ell\nu) = 0.65$ is remarkably large too. We obtain

$$
\begin{array}{lllll}
\text{RPC:} & \chi_1^\pm(\chi_2^0 \to \tilde{\ell}\ell \to \chi_1^0\ell\ell) & \Rightarrow & \sigma_3 & = 0.004\ pb\ ; \\
\text{RPV:} & \chi_1^\pm(\chi_2^0 \to \chi_1^0 h) & \Rightarrow & \sigma_3, \sigma_4, \sigma_5 & = 0.028, 0.021, 0.008\ pb\ ; \\
 & \chi_1^\pm(\chi_2^0 \to \tilde{\ell}\ell \to \chi_1^0\ell\ell) & \Rightarrow & \sigma_3, \sigma_4, \sigma_5, \sigma_6, \sigma_7 & = 0.005, 0.005, 0.005, 0.004, 0.003\ pb\ ; \\
 & \chi_1^\pm(\chi_2^0 \to \tilde{\nu}\nu \to \chi_1^0\nu\nu) & \Rightarrow & \sigma_3, \sigma_4, \sigma_5 & = 0.009, 0.008, 0.006\ pb\ ; \\
 & \chi_1^\pm \chi_1^0 & \Rightarrow & \sigma_3, \sigma_4, \sigma_5 & = 0.002, 0.002, 0.001\ pb\ ; \\
 & \chi_1^+ \chi_1^- & \Rightarrow & \sigma_3, \sigma_4, \sigma_5, \sigma_6 & = 0.026, 0.026, 0.024, 0.015\ pb\ .
\end{array}
$$

In this example, RPV rescues the dominant spoiler contributions and also gives quiet multileptons in other channels.

We remark that the trilepton rates in our examples are not very sensitive to relaxations in the acceptance cuts, since the geometrical acceptance factors for $n = 3$ leptons are typically of order 0.5 - 1 , but multilepton rates ($n > 3$) are more sensitive.

These illustrative RPV cross sections total $\sigma_3 = 0.11$, 0.25, 0.03, 0.07 pb, in cases A, B, C, D respectively, for events with $n \geq 3$ leptons. However, these numbers include overall p_T and η acceptance only, with no detector-specific efficiency factors, so any measured signal rates would be correspondingly smaller; for the RPC signals searched for at the Tevatron, these further efficiency factors are typically of order 15-20% [7,8]. The recent CDF and D0 trilepton searches [7,8], based on 19 pb^{-1} and 15 pb^{-1} luminosity respectively, found no candidate events. It therefore appears that none of the examples above are excluded by the present data, although cases A and B are not far from being tested. Future high-statistics data will put stronger constraints on parameters in the RPV scenario.

To summarize, we have investigated purely leptonic RPV signatures in chargino-neutralino pair production at the Tevatron, using typical SUSY-GUT parameter sets taken from Ref. [13] in the low-$\tan\beta$ fixed-point region. These examples illustrate how RPV decays $\chi_1^0 \to \ell\ell'\nu$ convert the quiet trilepton production of the RPC scenario into multilepton signals and generate new signals in other final states. In particular they show that

i) the trilepton rate itself may be greatly enhanced;

ii) signals with 4 or 5 leptons are typically comparable with the unsuppressed RPC trilepton rate;

iii) when RPC trileptons are suppressed by the spoiler mode $\chi_2^0 \to \chi_1^0 h$, RPV multilepton signals can still be substantial, though some contain $h \to jj$ dijets;

iv) substantial quiet RPV multilepton signals can also come from $\chi_1^\pm(\chi_2^0 \to \chi_1^0\nu\nu)$, $\chi_1^\pm\chi_1^0$ and $\chi_1^+\chi_1^-$ channels, that give no RPC trileptons.

ACKNOWLEDGMENTS

We thank H. Baer, J. Beacom and E. Mirkes for discussions on technical aspects of the calculations, T. Kamon for clarification of the CDF acceptance and X. Tata for a helpful comment. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, and in part by the Texas National Laboratory Research Commission under Grant Nos. RGFY93-221 and FCFY9302. MSB was supported in part by an SSC Fellowship. PO was supported in part by an NSF Graduate Fellowship.

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FIGURES

1. Representative diagrams for (a) the pair production of charginos and neutralinos, (b) their RPC decay, and (c) the RPV decay of the lightest neutralino.

2. Masses of the particles in χ_1^+, χ_2^0 decay cascades, obtained from Ref. [12] for representative GUT-scale inputs. Note that $\tilde{e}_L = \tilde{e}_2$ and $\tilde{e}_R = \tilde{e}_1$ because the mixing angle is negligible.

3. Cross sections for chargino and neutralino pair production at $\sqrt{s} = 1.8$ TeV, for the SUSY-GUT parameters of Fig. 2.

4. Decay branching fractions of the lightest chargino χ_1^+.

5. Decay branching fractions of the second-lightest neutralino χ_2^0.

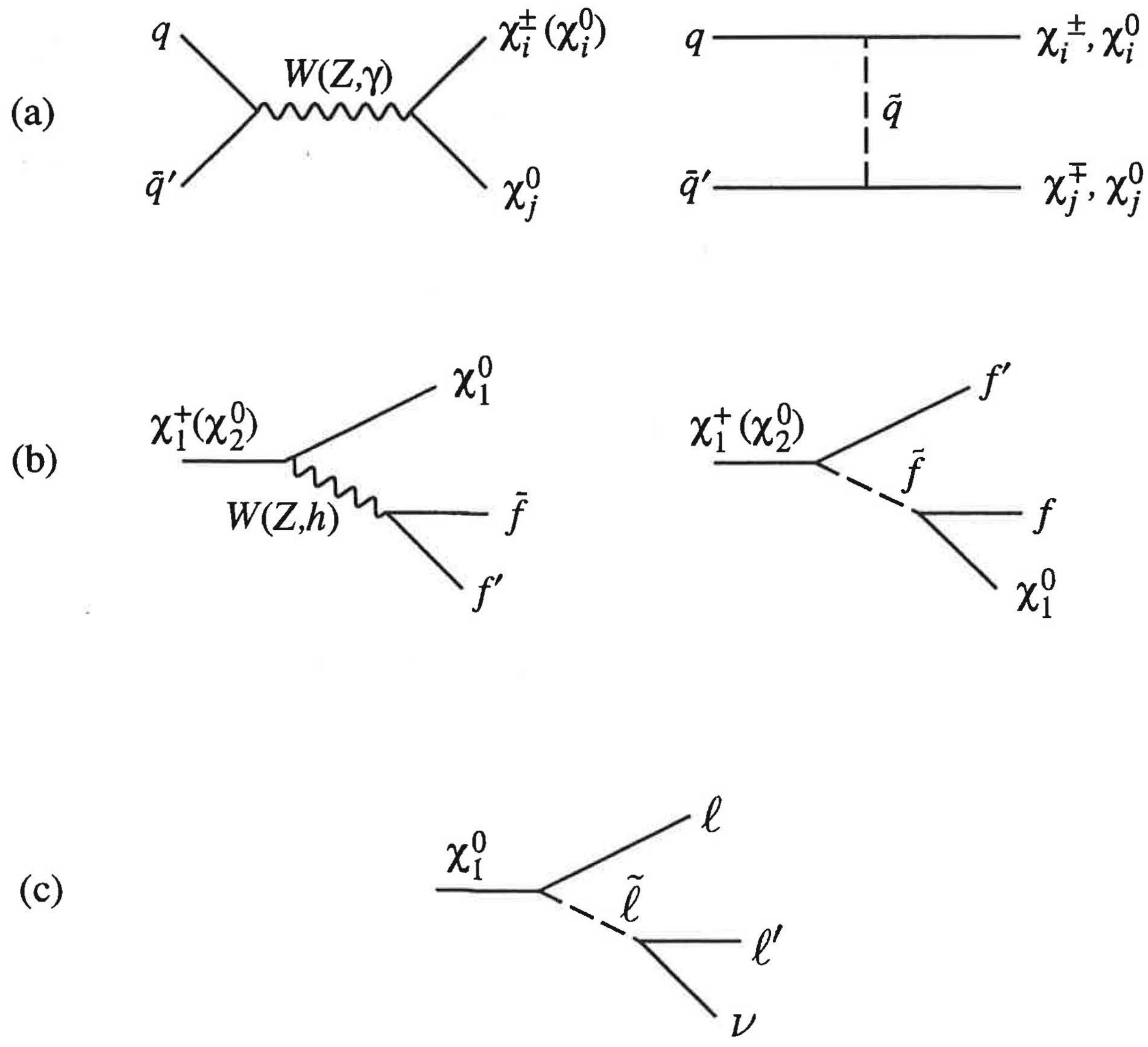

(a)
q
$\bar{q}'$
$W(Z,\gamma)$
$\chi_i^{\pm}(\chi_i^0)$
χ_j^0
q
$\bar{q}'$
$\tilde{q}$
$\chi_i^{\pm}, \chi_i^0$
$\chi_j^{\mp}, \chi_j^0$
(b)
$\chi_1^+(\chi_2^0)$
χ_1^0
$W(Z,h)$
$\bar{f}$
f'
$\chi_1^+(\chi_2^0)$
f'
$\tilde{f}$
f
χ_1^0
(c)
χ_1^0
ℓ
$\tilde{\ell}$
ℓ'
ν

Figure 1

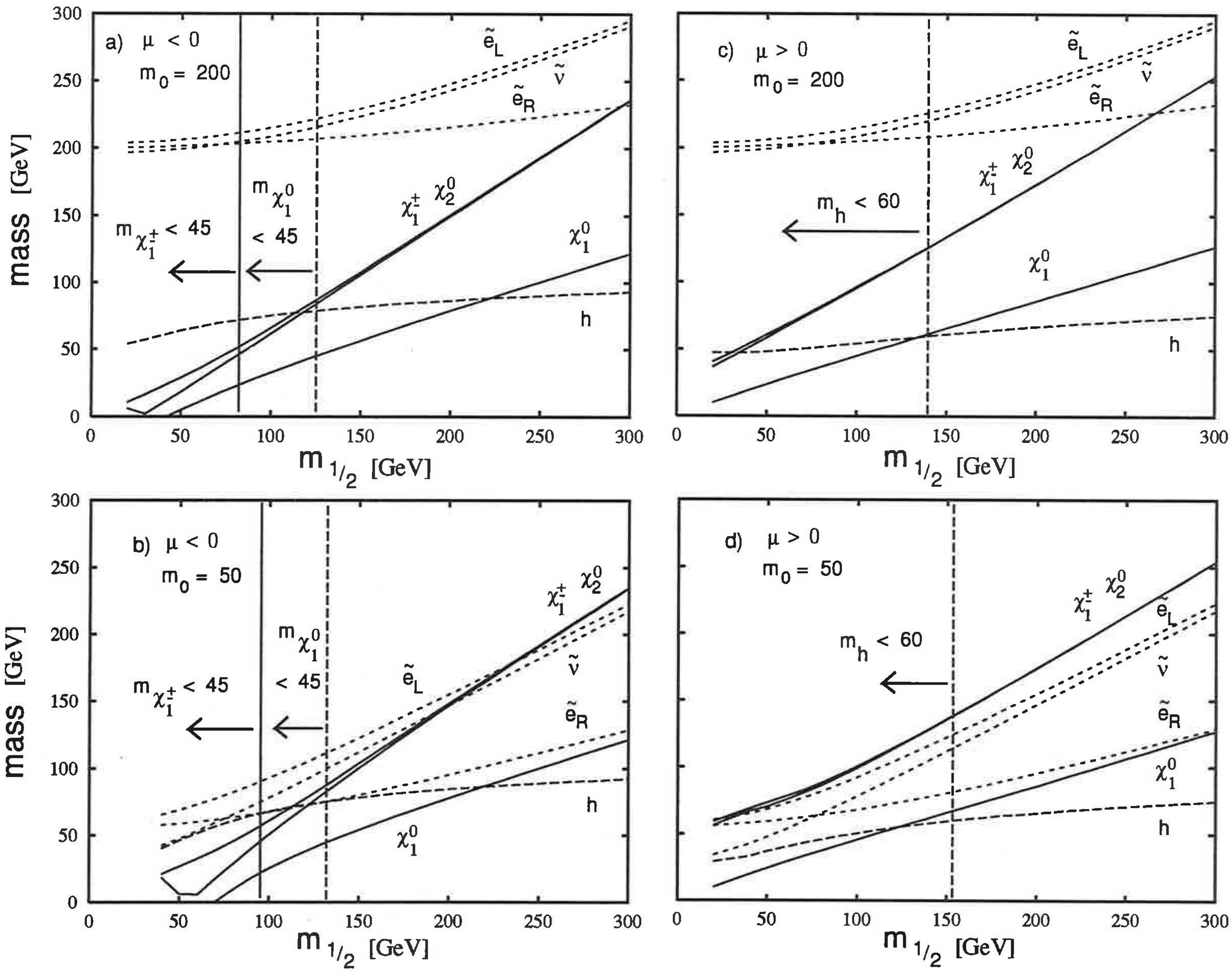
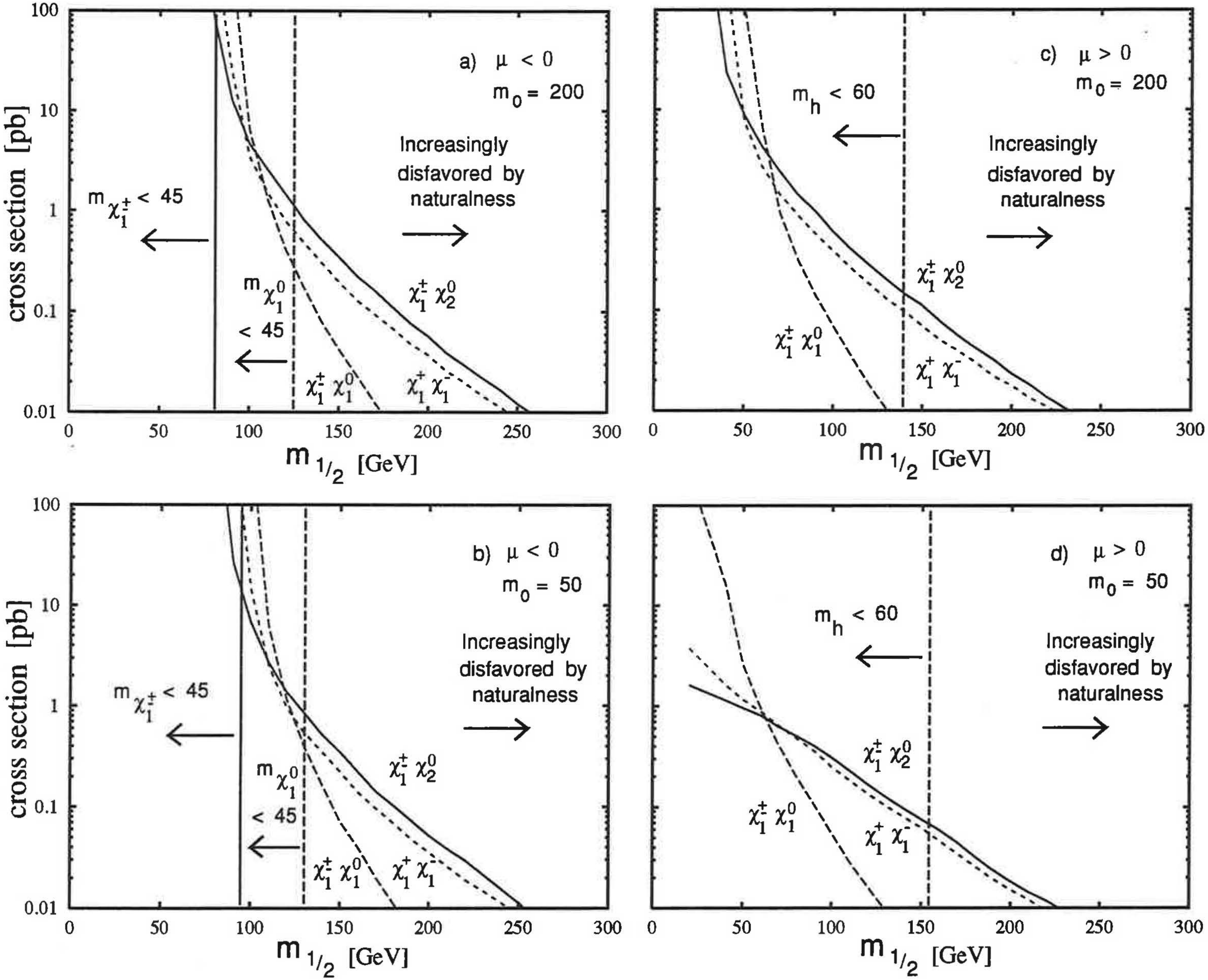
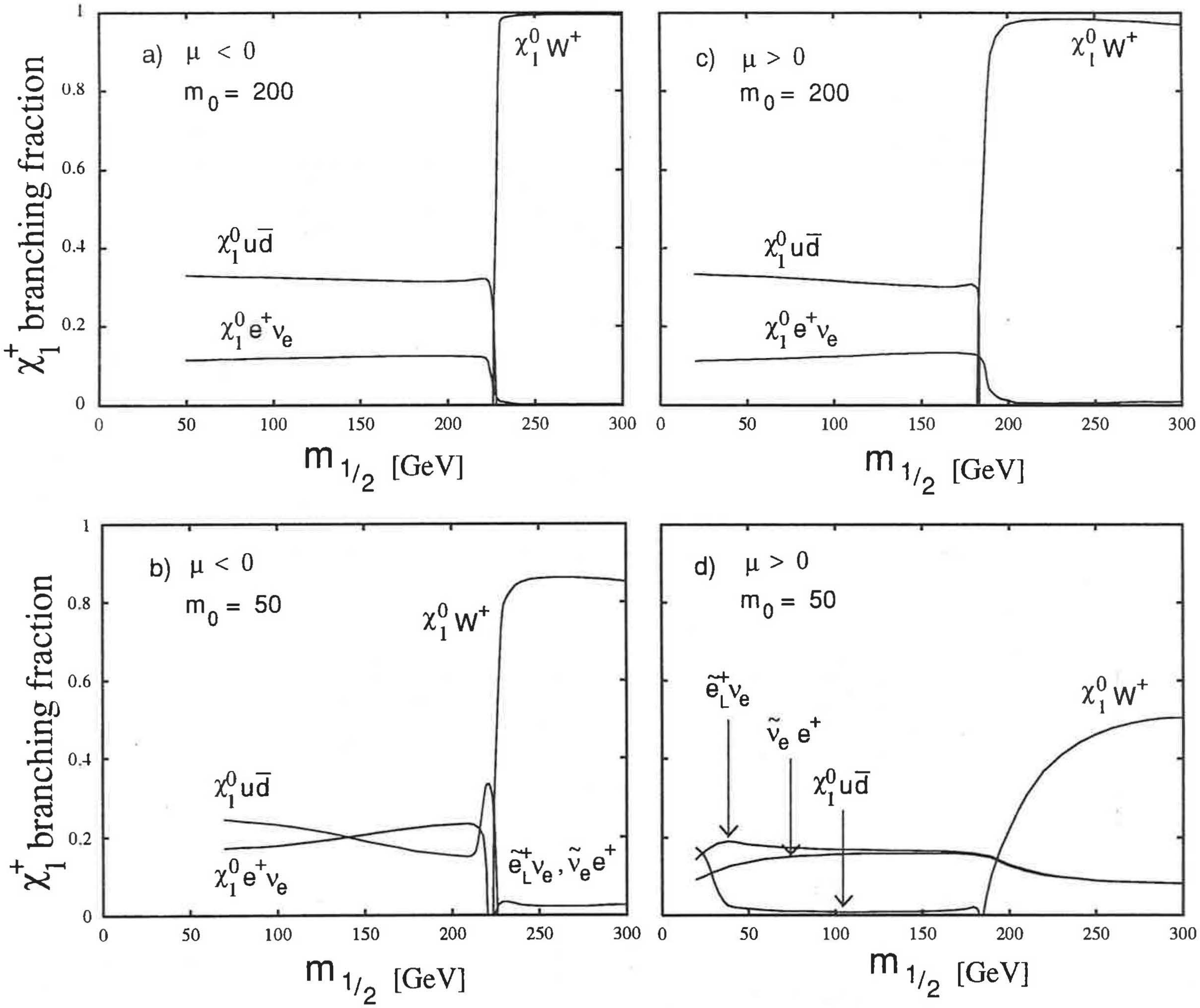

a) μ < 0
m0 = 200
b) μ < 0
m0 = 50
c) μ > 0
m0 = 200
d) μ > 0
m0 = 50
mχ1± < 45
mχ10 < 45
mh < 60
ẽL
ẽR
ν̃
χ1± χ20
χ10
h
mass [GeV]
m1/2 [GeV]

Figure 2



a) μ < 0
m0 = 200
Increasingly disfavored by naturalness
m χ1± < 45
m χ1⁰ < 45
χ1± χ2⁰
χ1± χ1⁰
χ1+ χ1-
b) μ < 0
m0 = 50
c) μ > 0
m0 = 200
mh < 60
d) μ > 0
m0 = 50
cross section [pb]
m 1/2 [GeV]

Figure 3



a) μ < 0
m0 = 200
χ10 W+
χ10 ud̄
χ10 e+νe
c) μ > 0
m0 = 200
b) μ < 0
m0 = 50
ẽL+νe , ν̃e e+
d) μ > 0
m0 = 50
ν̃e e+
χ1+ branching fraction
m1/2 [GeV]

Figure 4

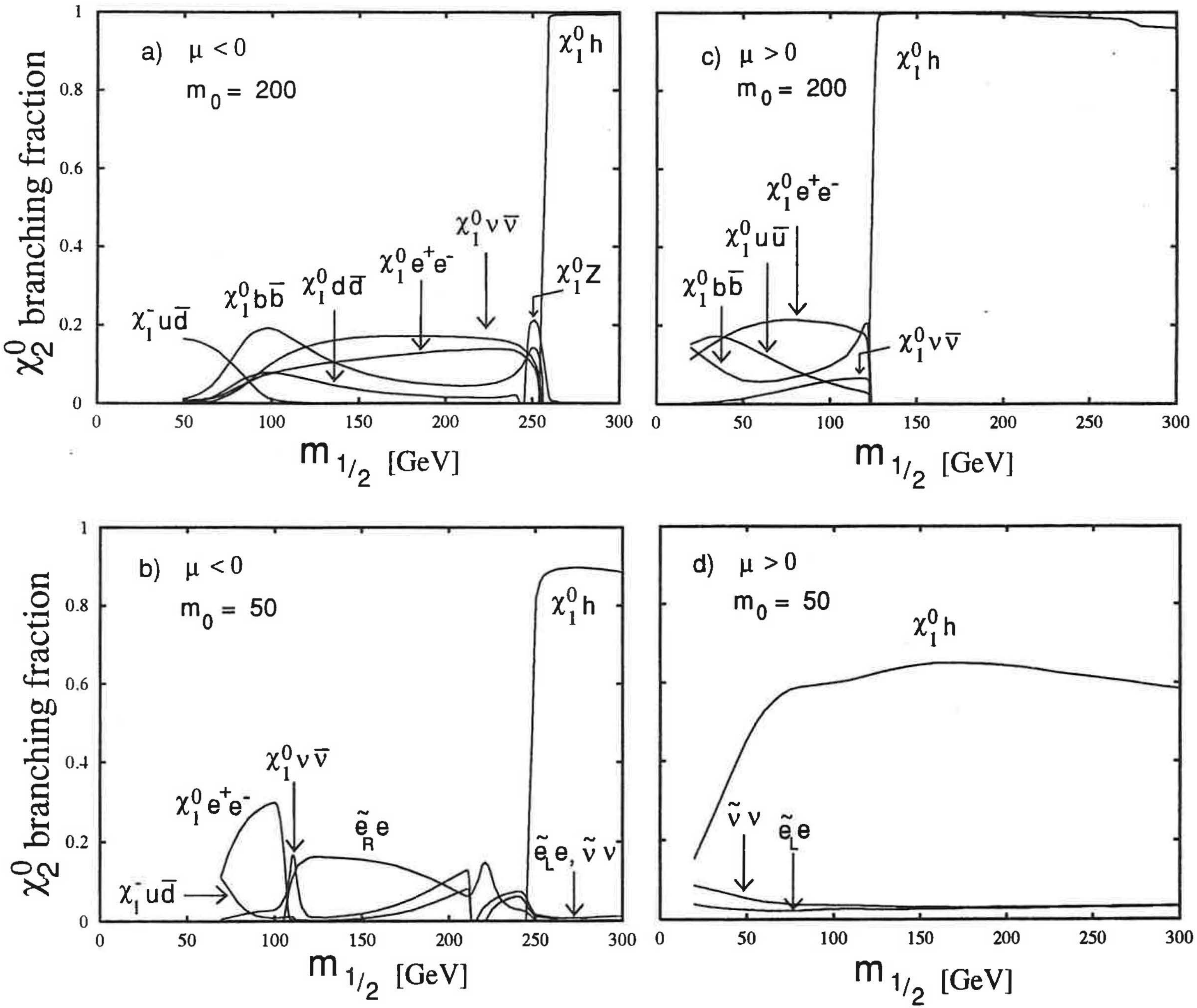

a) μ < 0
m0 = 200
χ⁰1 h
χ⁰1 ν ν̄
χ⁰1 e+e-
χ⁰1 d d̄
χ⁰1 b b̄
χ⁰1 Z
χ-1 u d̄
χ⁰2 branching fraction
m 1/2 [GeV]
c) μ > 0
m0 = 200
χ⁰1 h
χ⁰1 e+e-
χ⁰1 u ū
χ⁰1 b b̄
χ⁰1 ν ν̄
m 1/2 [GeV]
b) μ < 0
m0 = 50
χ⁰1 h
χ⁰1 ν ν̄
χ⁰1 e+e-
ẽR e
ẽL e, ν̃ ν
χ-1 u d̄
χ⁰2 branching fraction
m 1/2 [GeV]
d) μ > 0
m0 = 50
χ⁰1 h
ν̃ ν
ẽL e
m 1/2 [GeV]

Figure 5