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SUSY Multilepton Signatures at Tevatron[1]

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Abstract.
One of the most striking signature of supersymmetric models with electroweak symmetry breaking is the presence of multilepton event topologies in the decay products. In this paper searches are presented for physics beyond the Standard Model (SM) in final states containing charged leptons from proton-antiproton collision data at a center-of-mass energy of 1.96 TeV, collected with Run II CDF and DØ Detectors in 2002-2006, and corresponding to integrated luminosities of up to 1.1 fb^{-1}. In any of the searches no excess of candidates was observed with respect to the SM predictions and limits on masses and production cross-sections are set at the 95 % CL.

Keywords: Supersymmetry; Hadron Colliders; New Physics; Lepton Decays.

INTRODUCTION

Supersymmetric extensions of the Standard Model (SM) provide a consistent framework for gauge unification and stabilisation of electroweak scale [1]. Within the minimal supersymmetric extension of the SM model (MSSM) the stability of the Lightest Supersymmetric Particle (LSP) is ensured by the multiplicatively conserved quantum number $R = (-1)^{3B+L+2S} = 1(-1)$ for ordinary particles (sparticles), where B, L, S are the baryon, lepton and spin quantum numbers, respectively. This assumption has phenomenological consequences: SUSY particles are only pair produced and the LSP interacts weakly with ordinary matter. The description of electroweak symmetry breaking requires more than 100 parameters, which can be significantly reduced in certain models. A minimal supergravity model (mSUGRA) with R-parity (R_p) conservation, which is the framework for many experimental searches at Tevatron, has only 5 free parameters: m_0, $m_{1/2}$ are the common scalar (Higgs, sleptons and squarks) and gaugino (bino, wino and gluino) masses, respectively, A_0, the trilinear scalar coupling; $\tan\beta$, the ratio of vev's of two Higgs doublets; sign(μ), the Higgs sector mass parameter.

However, neither gauge invariance nor SUSY require R_p conservation. Allowing R-parity violation requires 45 extra parameters. The most general superpotential $W = W_{MSSM} + W_{RPV}$ contains explicit R-parity violating trilinear ($\not{R}_p$), allowing the LSP to

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decay into SM particles, and bilinear ($B\not{R}_p$) terms [2]:

$$W_{RPV} = \frac{1}{2}\lambda_{ijk}L_iL_j\overline{E_k} + \lambda^{'}_{ijk}L_iQ_j\overline{D_k} + \frac{1}{2}\lambda^{''}_{ijk}\overline{U_i}\,\overline{D_j}\,\overline{D_k} + \mu_iL_iH_u \quad (1)$$

where L and Q are left-handed lepton and quark $SU(2)$ doublet superfields, E,U and D are right-handed lepton and quark singlet superfields and i, j, k indicate flavour indices. The last term describes the bilinear interactions between left-handed lepton and Higgs superfield. It is also assumed that $\not{R}_p$ couplings are small compared to gauge strength and have a negligible effect on the Renormalization Group Equations (RGE) and on the running of the soft-supersymmetry breaking parameters and lepton Yukawa coupling.

An overview of several key multilepton signatures at Tevatron, followed by the experimental results of SUSY searches both in R_p-conserving and $\not{R}_p$ scenarios are presented in this paper. Finally, "signature-based" searches are discussed.

MULTILEPTON SIGNALS FROM SUPERSYMMETRY

Leptons represent the most powerful discriminating signatures at hadron colliders. Despite the fact that leptonic branching ratios are not always favourable, multilepton signals of new physics can become competitive to the SM backgrounds for a wide range of the SUSY parameter space of masses and couplings. In the following, we would like to discuss few distinctive multilepton signatures, which might yield evidence for supersymmetric particle production at Tevatron, as luminosity increases.

Table 1. Example of SUSY Multilepton Signatures at Tevatron in R-parity (R_p) Conserving and R-parity Violating ($\not{R}_p$) Scenarios. Different decay modes between the $\tilde{\ell}_L$, $\tilde{\ell}_R$ and $\tilde{q}_L$, $\tilde{q}_R$ are not shown.

Signature	Production	Decay
R-Parity (R_p) Conserving Signatures → LSP ($\tilde{\chi}_1^0$) is stable		
$2\ell + \not{E}_T$	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$
	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\nu\nu$
	$\tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to \tilde{\chi}_1^0\ell^\pm$, $\tilde{\ell} \to \tilde{\chi}_1^\pm\nu$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$
$\geq 3\ell + \not{E}_T$	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$
	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$
	$\tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to \tilde{\chi}_2^0\ell^\pm$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$
	$\tilde{\ell}\tilde{\nu}$	$\tilde{\ell} \to \tilde{\chi}_2^0\ell^\pm$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$, $\tilde{\nu} \to \tilde{\chi}_1^\pm\ell^\mp$
$2\ell + \geq 1$ jet $+\not{E}_T$	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0qq^{'}$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$
	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q}$	$\tilde{g} \to \tilde{\chi}_1^\pm qq^{'}$, $\tilde{q} \to \tilde{\chi}_1^\pm q^{'}$
	$\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$
$\geq 3\ell + \geq 1$ jet $\not{E}_T$	$\tilde{\chi}_1^\pm\chi_3^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$, $\chi_3^0 \to \tilde{\chi}_2^0qq$
	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\tilde{g} \to \tilde{\chi}_1^\pm qq^{'}$, $\tilde{g} \to \tilde{\chi}_2^0qq$, $\tilde{q} \to \tilde{\chi}_2^0q$
R-parity Violating ($\not{R}_p$) Signatures → LSP ($\tilde{\chi}_1^0$) decays to SM particles		
$\geq 2\ell + \geq 0\,jet + \not{E}_T$	$\tilde{\ell}, \tilde{\nu}$	$\tilde{\ell} \to \ell\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qq^{'}\ell$, $\tilde{\nu} \to \ell\ell$
$\geq 3\ell + \geq 0\,jet + \not{E}_T$	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\tilde{\chi}_2^0, \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^0 \to \ell\ell\nu$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$

Charginos and Neutralinos. At Tevatron, charginos and neutralinos can be pair produced via their electroweak couplings to the gauge bosons (γ, W, Z) in the s-channel and to squarks in the (t,u)-channel of $q\overline{q}$ annihilation (see Fig. 1). The production cross section is not only a function of chargino and neutralino masses but depends strongly on the gaugino-higgsino model-dependent mixing and the squark masses. In most regions of mSUGRA parameter space, masses of $\chi^0_{1,2}$ and $\tilde{\chi}^{\pm}_1$ and gluino behave gaugino-like, i.e depend on $m_{1/2}$. Analytical expressions for the squark ($\tilde{q}$) and slepton ($\tilde{\ell}$) mass parameters can be obtained when the corresponding Yukawa couplings are negligible. For small values of $\tan\beta$, masses of $\tilde{q}$ and $\tilde{\ell}$ depend both on m_0 and $m_{1/2}$.

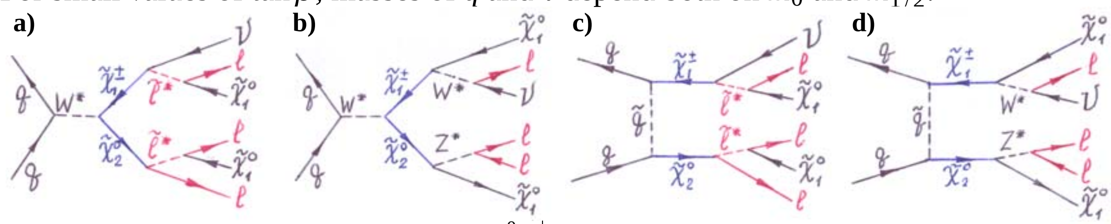

Figure 1. Feynman diagrams for associated $\tilde{\chi}^0_2\tilde{\chi}^{\pm}_1$ production at leading order in electroweak *s*-channel (a,b) and *t*-channel (c,d) reactions of a quark and anti-quark and subsequent decays via sleptons (a,c) or via vector bosons (b,d). The χ^0_1 is assumed to be the LSP in mSUGRA.

In R_p-conserving scenario, one of the most promising channels for SUSY searches is the trilepton signature arising from the chargino-neutralino production ($p\overline{p} \to \tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$) with subsequent leptonic decays ($\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1\ell\nu$, $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\ell\ell$). The overall $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2 \to 3\ell$ detection efficiency depends on the relative contribution from the $\tilde{\ell}$ and W/Z-exchange graphs, which varies as a function of $m_{\tilde{\ell}}$. At large values of m_0 ($m_0 \sim 1$ TeV) sleptons are heavy, thus slepton mediated diagrams of $\tilde{\chi}^0_2/\tilde{\chi}^{\pm}_1$ are suppressed, and gauginos decay to trilepton final states dominantly via real (at large $m_{1/2}$) or virtual (small $m_{1/2}$) W/Z-boson exchange (see Fig. 1 (b,d)). As the m_0 decreases, the slepton masses also decrease and the $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ decays via virtual sleptons (3-body decay $\tilde{\chi}^0_2 \to \tilde{\ell}^*\ell \to \tilde{\chi}^0_1\ell\ell$) become maximally enhanced at $m_0 \sim 100$ GeV ($m_{1/2} \sim 200$ GeV). For even lower values of m_0 ($m_0 \leq m_{1/2}/2$) sleptons are lighter than $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ and gaugino dominantly decays to the on-shell sleptons (2 body decay $\tilde{\chi}^0_2 \to \ell\tilde{\ell}$), as shown in Fig. 1 (a,c). If charginos ($\tilde{\chi}^{\pm}_{1,2}$) and neutralinos ($\tilde{\chi}^0_{2,3,4}$) are not too heavy (low $m_{1/2}$) they can contribute to the multilepton signatures (at low m_0) via $\tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_2\tilde{\chi}^0_3, \tilde{\chi}^{\pm}_1\tilde{\chi}^0_3, \tilde{\chi}^{\pm}_2\tilde{\chi}^0_3$ production (see Table 1).

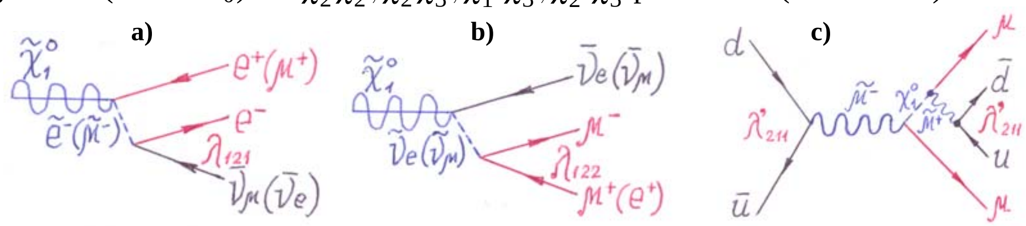

Figure 2. Representative diagrams for the *R*-parity violating ($\not{R}_p$) decays of $\tilde{\chi}^0_1$ (assumed as LSP) via $LL\overline{E}$ couplings: (a) λ_{121} and (b) λ_{122}. Example of resonant smuon production and decay via $\lambda'_{211}LQ\overline{D}$ coupling (c).

The popular R_p-conserving scenario assumes that the LSP is stable and neutral (for cosmological reasons) and therefore escapes detection in the experiment. This picture changes dramatically with $\not{R}_p$. The LSP is no longer stable and carries away transverse energy, and the $\not{E}_T$ signal, which is the mainstay of SUSY searches in R_p-conserving models, is greatly degraded. A fundamental $\not{R}_p$ interaction could mediate the decay of any chargino or neutralino[2], as illustrated in Fig. 2 (a,b) for $\tilde{\chi}_1^0$, thus converting the R_p signal $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell$ into final state with up to seven charged leptons. Even when R_p conserving leptonic decays of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ are suppressed at least 4 leptons can still be present in $\not{R}_p$-decay via λ-coupling. Furthermore, $\not{R}_p$ multilepton signals can also appear from $\tilde{\chi}_1^{\pm}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \nu\nu), \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}\chi_1^{\mp}$ channels, that give no R_p trileptons. The actual multiplicity of observed leptons depends on the exact $\not{R}_p$ scenario[3], the experimental thresholds and angular acceptances, in general, leading to high visibility of the multilepton signals. The presence of bilinear $B\not{R}_p$ coupling can generate neutrino masses, in agreement with the atmospheric neutrino data, and to enhance SUSY multilepton signals, especially at moderate and large m_0 [3].

Stop Quarks. Squarks of the 3^{rd} generation deserve a special attention, since due to the impact of the large top Yukawa coupling on the RGE the stop mass drops to the lowest value in the squark spectrum. Moreover, the top quark eigenstates in the weak bases $\tilde{t}_L$ and $\tilde{t}_R$ will strongly mix due to the large m_t, leading to a small mass value of $\tilde{t}_1$ possibly much lighter than other squarks. At hadron colliders, the cross sections for the production of a light scalar top pairs $gg/q\overline{q} \to \tilde{t}_1\overline{\tilde{t}_1}$ depend essentially only on the $m_{\tilde{t}_1}$ and very little on the other SUSY parameters (i.e. $m_{\tilde{g}}$, $m_{\tilde{q}}$ and the mixing angle in the top squark sector), which affect only the higher-order corrections. The Tevatron lower limits on $m_{\tilde{q}}$ are derived assuming ten degenerate squark flavours and not applicable to $\tilde{t}_1$.

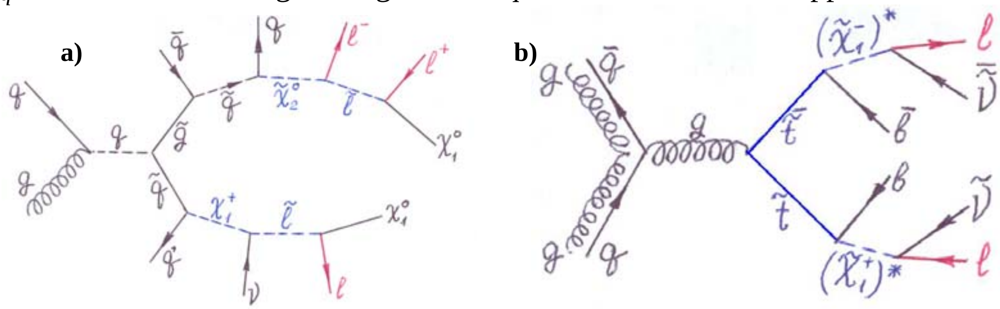

Figure 3. (a) Feynman diagram for squark/gluino production with subsequent decays leading to 3 leptons, jets and $\not{E}_T$ final state. (b) Example of the $\tilde{t}_1$ decay to lepton and sneutrino, via virtual gaugino. When the 3-body decay into $b\ell\tilde{\nu}$ is kinematically allowed, the subsequent invisible decay of $\tilde{\nu} \to \nu\tilde{\chi}_1^0$ has no influence on kinematics.

The signals from top squark $\tilde{t}_1$ at colliders depend on its decay pattern. The most explored signature for a light stop $\tilde{t}_1$ production at Tevatron is a loop-induced and flavor-changing decay: $\tilde{t}_1 \to c\tilde{\chi}_1^0$, when the main tree-level diagrams $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ ($\tilde{t}_1 \to t\tilde{\chi}_1^0$) for medium (heavy) stop quarks are kinematically forbidden [4]. However, recent studies also favour 3-body decays $\tilde{t}_1 \to t^*(\chi_1^0) \to bW\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b(\tilde{\chi}_1^{\pm})^* \to b\tilde{\ell}\nu, b\ell\tilde{\nu}$, and, if kinematically not allowed, even 4-body decay $\tilde{t}_1 \to b\ell\nu\tilde{\chi}_1^0$ [5]. The later mode is mediated by virtual chargino and is the same order of perturbation theory as the loop-

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[2] For sparticles other than the LSP, the $\not{R}_p$ decays will in general compete with R_p-conserving "cascade decays" initiated by gauge interactions.

[3] The results are very model dependent, owing to the large parameter space in the $\not{R}_p$ sector. While LSP decays via L-violating $\not{R}_p$ (λ, λ')-terms give rise to multilepton and lepton+jets final states, the χ_1^0 decays via $\not{R}_p$ λ''-coupling lead to the QCD multijet final states, difficult to access at hadron colliders.

induced $\tilde{t}_1 \to c\tilde{\chi}_1^0$ decay, i.e $O(\alpha^3)$. The 3-body $\tilde{t}_1 \to b\ell\tilde{\nu}$ decay might be favoured over $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\ell}\nu$[4] due to the relatively weak constraint on the sneutrino mass at LEP $m_{\tilde{\nu}} > 45$ GeV [6]. The experimental signature for the 3-body $\tilde{t}_1\overline{\tilde{t}_1}$ decay, via virtual gauginos, is 2ℓ+$2b$-jets+$\not\!\!E_T$ (see Fig. 3 (b)), assuming R-parity conservation. This mode can even dominate at Tevatron for $m_{\tilde{t}_1} < 200$ GeV if charginos and sleptons masses are not too much larger than their present experimental bounds [7].

Gluinos and Squarks. At Tevatron, heavy gluinos ($\tilde{g}$) and squarks ($\tilde{q}$), produced via their $SU(3)_c$ coupling to quarks and gluons, tend to decay via sequence of cascades through charginos ($\tilde{\chi}_1^{\pm}$) and neutralinos ($\tilde{\chi}_2^0$) modes which, unless suppressed by phase space, frequently dominate the R_p-conserving decays of $\tilde{q}_L$ and $\tilde{g}$. The subsequent leptonic decays of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ yield events with hard jets accompanied by 1-3 isolated leptons and $\not\!\!E_T$ (see Fig. 3 (a)). The kinematics of signal events is usually harder than that of SM backgrounds for large squark-gluino masses[5]. In contrast, the difference in the lepton momenta might be not very pronounced as signal leptons are produced far down in cascade decay chain, thus loosing "memory" about the hardness of the original process. While there are substantial backgrounds from W+jet and QCD multijet to ℓ topology, the physics backgrounds in the $\ell^+\ell^-$, $\ell^{\pm}\ell^{\pm}$ [6] and 3ℓ channels can be better controlled, so that these searches are essentially rate limited. The experimental signature ($\geq 2\ell$)+jets+$\not\!\!E_T$ provide a complimentary ways to search for gluinos and squarks at Tevatron to the classic $\not\!\!E_T$ +multijet signatures.

Sleptons. Charged sleptons and sneutrinos can be pair produced at hadron colliders via the Drell-Yan mechanism $p\overline{p} \to Z^*/\gamma^* \to \tilde{\ell}\tilde{\ell}$ and can be detected through the slepton decays $\tilde{\ell} \to \ell\tilde{\chi}_1^0$ in a clean $\ell^+\ell^-$ + $\not\!\!E_T$ final states. This channel have received rather limited attention at Tevatron due to the smallness of cross section: $\sigma(\tilde{\ell}\tilde{\ell}) \sim 10-50$ fb for $m_{\tilde{\ell}} \sim 100$ GeV. Untangling a few slepton events from the major $WW, Z/\gamma^*$ would be very difficult, since the SM contributions is at least few times larger than the expected SUSY signal. This makes unlikely for Tevatron to detect sleptons in R_p conserving scenarios beyond the range of LEP [6]. In $\not\!\!R_p$ models, slepton and sneutrino resonant production occurs through the new λ'_{ijk} interactions. Tevatron data allows a search for a single slepton production over a considerable range of masses and for λ'_{ijk} values down to 10^{-2} (see Fig. 2 (c)).

Signature-based Searches. Motivated by the detection of the CDF Run I $ee\gamma\gamma\not\!\!E_T$ event (on a background of $< 10^{-6}$), a $\mu\mu\gamma\gamma jj$ event (on a background of $< 10^{-5}$) and 2.7 sigma excess above the SM predictions in the $\ell\gamma\not\!\!E_T$ final state [8], "signature-based" inclusive searches became an important experimental method at Tevatron. In particular, model-independent anomalous production of $\ell\gamma$+X ($\ell\gamma\not\!\!E_T, \gamma\gamma\not\!\!E_T, \ell\gamma\gamma, \ell\ell\gamma$) events, expected in gause-mediated models of supersymmetry or in the production of excited leptons, can be sensitive to any new physics beyond the SM.

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[4] At small $\tan\beta$, decays into sneutrino are more important than into charged sleptons as a result of different spin structure of corresponding matrix elements [7].

[5] The p_T of primary jets and $\not\!\!E_T$ are expected to scale with $m_{\tilde{g}}$ and $m_{\tilde{q}}$.

[6] Gluino pair production is a copious source of like-sign dilepton pairs. Since gluino is a Majorana particle it decays with the same probability into chargino of either sign.

SUSY SEARCHES WITH R-PARITY CONSERVATION

Both CDF and DØ have exploited the classical SUSY trilepton signature coming from $p\overline{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production followed by $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \ell^{\pm} \nu$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$ decays, with hadronic activity coming only from QCD radiation. Common challenges for analysis are the estimation of the third lepton misidentification probability and conversion modelling.

DØ has searched for the $3\ell + \not{E}_T$ final state in 6 different analyses, including those with hadronic τ decays (τ_{had}), listed in Table 2 [9, 10]. While very few SM processes contribute to the trilepton signature, the leptons from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ can be very soft, requiring efficient lepton identification and multilepton triggering at low p_T[7]. The analysis strategy is to require two isolated leptons ($\ell = e, \mu, \tau_{had}$) with $p_T^{\ell 1\ (\ell 2)} > 12\ (8)$ GeV satisfying analysis dependent topological cuts and the presence of large missing $\not{E}_T$ in the event. In all the channels the dilepton invariant mass must be in excess of 15-25 GeV to suppress QCD, J/ψ, Υ and $W\gamma^*$ contributions and be away from the Z-mass region. $t\bar{t}$ background is discriminated by vetoing events with large jet activity, while $b\overline{b}/c\overline{c}$ leptons carry low p_T and appear non-isolated in calorimeter. To minimise lepton identification inefficiencies at low p_T, the third lepton is reconstructed as an isolated, high-quality track with $p_T^{\ell 3} > 3-5$ GeV originating from the same vertex as the two identified leptons [8]. The track (calorimeter) isolation for the third track is designed to be efficient for all lepton flavours ($\ell = e, \mu, \tau_{had}$). Alternatively, the three-lepton mode is relaxed to a same-sign $\mu^{\pm}\mu^{\pm}$ selection, where SM background is low enough. The dominant irreducible background consists of WZ/ZZ associated production with subsequent leptonic decays of gauge bosons. The major SM backgrounds remaining after selection cuts are due to W+jet/γ, Z/γ^* and WW pair production, where the light (u,d,s)-quark jets and/or photon conversions are misidentified as leptons.

Table 2. Number of observed data events, compared to the number of events expected from SM background processes, for different CDF and DØ final states. The luminosity used is also given.

DØ Analysis	L_{int} (fb^{-1})	Data	SM bkg	CDF Analysis	L_{int} (fb^{-1})	Data	SM bkg
ee + track	1.1	0	0.82±0.66	$e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$	1.0	7.9±1.3	13
$e\mu$ + track	0.3	0	0.31±0.13	$\mu\mu + e/\mu$ low-p_T	1.0	0.4±0.1	1
$\mu\mu$ + track	0.3	2	1.75±0.57	ee + track	1.0	0.97±0.3	3
$\mu^{\pm}\mu^{\pm}$	0.9	1	1.1 ±0.4	$e + e/\mu$+e/μ	1.0	0.73±0.1	0
$e\tau_{had}$ + track	0.3	0	0.58±0.14	$\mu\mu + e/\mu$ high-p_T	0.75	0.64±0.2	1
$\mu\tau_{had}$ + track	0.3	1	0.36±0.13	$\mu e + e/\mu$	0.75	0.78±0.1	0

No evidence for the supersymmetry has been observed in any of DØ analysis. The SUSY expectations were optimized for 3-body decays via virtual $\tilde{\ell}^*$ ($\tilde{\chi}_2^0 \to \tilde{\ell}^* \ell \to \tilde{\chi}_1^0 \ell\ell$), which are enhanced for $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^{\pm}} \leq m_{\tilde{\ell}}$ ($m_0 \sim 90-130$ GeV, $m_{1/2} \sim 170-220$ GeV). DØ observed limits for the combination of ee+track, $e\mu$+track, $\mu\mu$ + track and $\mu^{\pm}\mu^{\pm}$ channels are presented in Fig. 4: (a) as a function of the $\tilde{\chi}_1^{\pm}$ mass and (b) of the mass dif-

[7] DØ uses combination of single lepton, lepton+track and dilepton triggers to select data events.

[8] Relaxing the third lepton requirement to an isolated low-p_T track also increases the sensitivity of the search to τ lepton decays, whose contribution becomes dominant at large $\tan\beta$ scenarios.

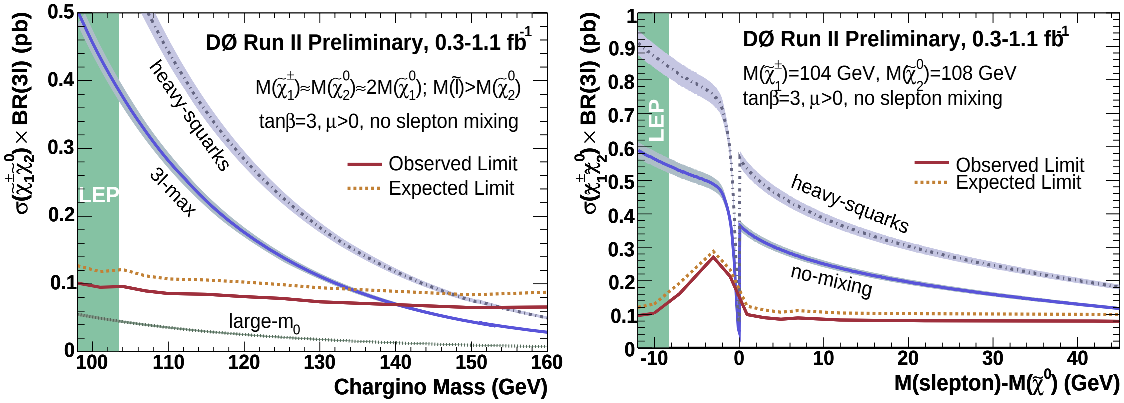

Figure 4. DØ observed limits on $\sigma(\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}) \times BR(3\ell)$ in comparison with the expectation for several SUSY scenarios with degenerate slepton masses, no slepton mixing, $A_0 = 0$ and $\tan\beta = 3$: (a) as a function of chargino mass ($\tilde{\chi}_1^{\pm}$) in the 3-body decay region and (b) as a function of the slepton-neutralino ($\tilde{\ell}$-$\tilde{\chi}_2^0$) mass difference for $m_{\tilde{\chi}_1^{\pm}} = 104$ GeV and $m_{\tilde{\chi}_2^0} = 108$ GeV. PDF and renormalisation/factorisation scale uncertainties are shown as shaded bands. The limits are compared with the predictions of three MSSM benchmark scenarios: "heavy squarks", "3ℓ-max" and "large-m_0" (see text).

ference $\Delta m = m_{\tilde{\ell}} - m_{\tilde{\chi}_2^0}$[9]. Assuming the mSUGRA-inspired mass relation $m_{\tilde{\chi}_1^{\pm}} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$, the limit on $\sigma(\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}) \times BR(3\ell)$ can be compared with predictions from three SUSY benchmark scenarios (see Fig. 4). W/Z exchange is dominant at large $m_{\tilde{\ell}}$ ($m_{\tilde{q}}$) masses, obtained by raising m_0 to the TeV scale and assuming scalar mass unification. This results in small $BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell)$, set by W/Z branching ratio into leptons, and does not allow any mass limit to be placed ("large m_0" scenario). The trilepton final states are maximally enhanced for $\tilde{\ell}^*$-mediated 3-body decays ($BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell) \sim 30\%$) for $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^{\pm}} \leq m_{\tilde{\ell}}$ ("3ℓ-max" scenario). The $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production cross section is maximal for the "heavy-squark scenario", when destructive interference between s and t channels is suppressed due to the heavy squark masses. This scenario is realized by relaxing scalar mass unification, when squarks are assumed to be heavy while sleptons remain light. DØ limits exclude $m_{\tilde{\chi}_1^{\pm}} < 140$ GeV for $\sigma \times BR \sim 0.07$ pb in "3ℓ-max" and $m_{\tilde{\chi}_1^{\pm}} < 155$ GeV for $\sigma \times BR \sim 0.07$ pb in "heavy-squark" scenarios.

Starting from "3 ℓ-max" and "heavy squark" benchmark points with $m_{\tilde{\chi}_1^{\pm}}(m_{\tilde{\chi}_2^0}) = 104(108)$ GeV, $\sigma(\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}) \times BR(3\ell)$ is scanned as a function of the slepton mass, assuming no $\tilde{\tau}$-mixing. The contribution of $\tilde{\ell}^*$-mediated 3-body decays increases for both scenarios with decreasing $\Delta m = m_{\tilde{\ell}} - m_{\tilde{\chi}_2^0} > 0$, resulting in a larger SUSY trilepton cross section. For mass-degenerated $\tilde{\ell}$ and $\tilde{\chi}_2^0$, $\sigma \times BR$ vanishes since the phase space for the ℓ and on-shell $\tilde{\ell}$ is very small and $\tilde{\chi}_2^0 \to \nu\nu\tilde{\chi}_1^0$ decay dominates. The trilepton branching ratio is further enhanced when 2-body decays via on-shell $\tilde{\ell}$ ($\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0\ell\ell$) dominate

[9] Adding τ-leptons ($e + \tau_{had} + \ell$ and $\mu + \tau_{had} + \ell$ analysis) was found to improve limits by ~ 10 % for low $\tan\beta = 3$. For large values of $\tan\beta$, the $\tilde{\tau}$ becomes the lightest slepton increasing the branching ratios to final states with 3 τ's. The smaller $m_{\tilde{\tau}}$ also leads to a lower τ_{had} transverse momenta in the final state.

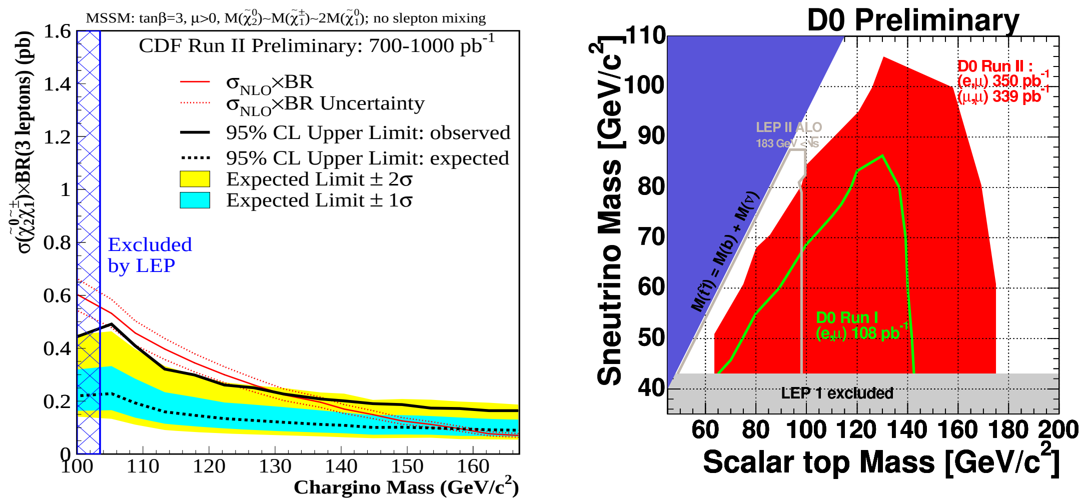

Figure 5. (a) CDF expected and observed limits as a function of chargino mass ($\tilde{\chi}_1^{\pm}$) in the MSSM with degenerate slepton masses and the slepton mixing off. (b) DØ exclusion domains at 95 % CL in the $(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ plane for the combination of $e\mu$ and $\mu\mu$ analysis, within the framework of general MSSM. The results are also compared to the LEP I, LEP II and Tevatron Run I exclusion limits [13].

at $m_{\tilde{\ell}} - m_{\tilde{\chi}_2^0} < 0$. For $m_{\tilde{\ell}} - m_{\tilde{\chi}_2^0} < 6$ GeV one of the leptons from $\tilde{\chi}_2^0$ have a very low p_T and only $\mu^{\pm}\mu^{\pm}$ analysis remains sensitive in this region.

CDF has also completed a search in $3\ell + \not{E}_T$ signature in different final states depending on the leptons flavour and trigger requirements [11]. Events were selected either with high-p_T single lepton trigger (indicated as "high p_T") requiring a lepton with $p_T > 18$ GeV, or dilepton trigger ("low p_T") requiring two leptons with $p_T > 4$ GeV. Three analysis ($e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$) were based on inclusive "high p_T" trigger and offline requirement that the two most energetic leptons are likesing with $p_T^{\ell} > 20(10)$ GeV. To increase acceptance for low p_T tracks the presence of the third lepton was not required in $\ell^{\pm}\ell^{\pm}$ events. The $\mu\mu + e/\mu$ final state was selected both with "high p_T" and "low p_T" triggers. In the former case two offline muons with $p_T^{\mu 1(\mu 2)} > 20(5)$ GeV were selected, while in the later case both muons were required to have $p_T^{\mu 1,\mu 2} > 5$ GeV. Finally, a third electron(muon) with $p_T^{\ell} > 5$ GeV was also required. Other trilepton channels were based on inclusive "high p_T" trigger. The $e + e/\mu + e/\mu$ analysis required one electron with $p_T^{e} > 20$ GeV, second electron(muon) with $p_T^{\ell} > 8$ GeV and third electron(muon) with $p_T^{\ell} > 5$ GeV. The ee+track channel required two isolated electrons with $p_T^{e1(e2)} > 15\ (5)$ GeV and an isolated track with $p_T > 4$ GeV. Additional cut included missing transverse energy $\not{E}_T > 15 - 20$ GeV, depending on the final states. Kinematic control region were established to investigate the correct understanding of the SM backgrounds; whereas the signal region results were studied only at the end. After requiring channel dependent selection criteria the observed data events agree with SM predictions within the errors, as shown in Table 2.

In the MSSM scenario with $\tan\beta = 3, A_0 = 0$ and $m_0 = 60$ GeV, $m_{1/2}$ ranging between 162 and 230 GeV and without slepton mixing ($BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell) \sim 60\%$), CDF excludes $m_{\tilde{\chi}_1^{\pm}} < 130$ GeV for $\sigma \times BR \sim 0.25$ pb, as shown in Fig. 5 (a). The expected limit is

$m_{\tilde{\chi}_1^\pm} < 160$ GeV for $\sigma \times BR \sim 0.1$ pb. The observed limit is approximately 2σ away from the expected limit, which reflects the excess of the number of observed events w.r.t the number of expected ones from SM background.

DØ also searched for $p\overline{p} \rightarrow \tilde{t}_1\overline{\tilde{t}_1}$ production followed by a three-body decay via a virtual chargino: $\tilde{t}_1 \rightarrow b(\tilde{\chi}_1^\pm)^* \rightarrow b\ell\tilde{\nu}$,[10] with either $\tilde{\nu}$ or $\tilde{\chi}_1^0$ being the LSP [12]. In R_p-conserving scenario, the experimental signature of $\tilde{t}_1\overline{\tilde{t}_1}$ decays is $2\ell + 2b$-quarks+$\not{E}_T$, very similar to those expected from $t\bar{t}$ production (see Fig. 3 (b)). While the top squark production is fixed by QCD in terms of $m_{\tilde{t}_1}$, its decay topology is solely determined by $m_{\tilde{t}_1}$ and $m_{\tilde{\nu}}$. DØ has studied $e\mu$ and $\mu\mu$ final states. To maximise sensitivity close to kinematic boundary, events with leptons transverse momenta $p_T^{\mu 1(\mu 2)} > 8(6)$ GeV for the $\mu^\pm\mu^\mp$ and $p_T^{e(\mu)} > 12(8)$ GeV for the $e^\pm\mu^\mp$ channels, $\not{E}_T$ >15-20 GeV and satysfying analysis dependent topological cuts were selected. After all selection criteria the major SM backgrounds are $t\bar{t}$ and WW in $e\mu$ and $t\bar{t}$ in $\mu\mu$ final states. Since stop quarks accessible at Tevatron are lighter than m_t and because the chargino, unlike W, decays via three-body mode into a massive LSP, stop signatures are generally softer than top events. Therefore, shapes of the topological variable $S_T = p_T^e + p_T^\mu + \not{E}_T$ for different $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$ regions and of the scalar sum of jet transverse energies $H_T = \Sigma p_T^{jets}$ were used to discriminate between $\tilde{t}_1\overline{\tilde{t}_1}$ signal and the SM background at the last analysis stage of the $e\mu$ and $\mu\mu$ analysis. No deviation from SM expectations were observed in ~ 350 pb^{-1} of data. Assuming lepton universality, $e\mu$ and $\mu\mu$ analysis were combined to exclude $\tilde{t}_1$ and $\tilde{\nu}$ masses in the framework of general MSSM. The resulting plot is shown in Fig. 5 (b) in the $(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ plane, assuming 3-body decay $\tilde{t}_1 \rightarrow b(\tilde{\chi}_1^\pm)^* \rightarrow b\ell\tilde{\nu}$. The right edge of the exclusion contour drops at $m_{\tilde{t}_1} \sim 175$ GeV due to the falling cross section. This edge is limited by luminosity, and additional data will push the contour to slightly higher $\tilde{t}_1$ masses. Because of lower p_T lepton requirements, a significant extension of the exclusion limit is achieved at small $m_{\tilde{t}_1} - m_{\tilde{\nu}}$ value.[11]

SUSY SEARCHES WITH *R*-PARITY VIOLATION

The search strategy for $\not{R}_p$ at Tevatron depends on the absolute value of Yukawa couplings Λ $(\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk})$ and the relative strength of the $\not{R}_p$ and gauge interactions. The small $\not{R}_p$ couplings[12], compared to electroweak interactions, are mostly to be felt through the decay of sparticles, otherwise pair produced via gauge couplings. The larger $\not{R}_p$ value could manifest itself in a resonant production of a single slepton or squark. In $\not{R}_p$ scenarios due to the trilinear terms, the SUSY particles are assumed to decay into SM particles

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[10] The $BR(\tilde{\chi}_1^{\pm *} \rightarrow b\ell\tilde{\nu})$ is assumed to be 100 % and the slepton parameters has been set to obtain equal branching ratios into all lepton flavours.

[11] The gap between the kinematic boundary and the left contour edge for low $m_{\tilde{t}_1} - m_{\tilde{\nu}}$ value reflects the impact of $\not{E}_T$ and lepton p_T cuts.

[12] For typical Λ values $0.001 < \Lambda < 0.01$, $\not{R}_p$ interactions introduces negligible changes in production and decay of SUSY particles, and the LSP is forced to decay within 1 cm from primary vertex ($\Lambda > 0.001$).

via a single (dominant) $\not{R}_p$ coupling.

CDF and DØ have investigated R_p-conserving gaugino pair production ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}\chi_1^{\mp}$), where the produced supersymmetric particles decays into the LSP (assumed to be $\tilde{\chi}_1^0$), with $\not{R}_p$ manifesting itself in $\tilde{\chi}_1^0$ decay only[13] [14, 15]. The decay patterns of the LSP depend on structure of $\not{R}_p$ interactions. In particular, if explicit $\not{R}_p$ occurs through $L_iL_j\overline{E_k}$ terms the $\tilde{\chi}_1^0$ decays via $\tilde{\chi}_1^0 \to \mu e \nu_e, ee\nu_\mu (\lambda_{121} \neq 0)$, $\tilde{\chi}_1^0 \to \mu\mu\nu_e, \mu e \nu_\mu (\lambda_{122} \neq 0)$ and $\tilde{\chi}_1^0 \to e\tau\nu_\tau, \tau\tau\nu_e(\lambda_{133} \neq 0)$ into neutrino and two charged leptons that may have different flavours (see Fig. 2). As the $\tilde{\chi}_1^0$ can be relatively light (the LEP lower mass limit $m_{\tilde{\chi}_1^0} > 50$ GeV for $\tan\beta = 5$ [2]), the leptons from its decay can have low p_T. Therefore, to enhance the signal sensitivity CDF and DØ select events with at least 3 leptons (electrons or muons) to probe λ_{121} and λ_{122}. In order for this search to be as model independent as possible, no jet veto and only weak $\not{E}_T$, $\Delta\phi(\ell\ell)$ cuts and $\Delta\phi(\ell, \not{E}_T)$ are applied to remove instrumental background and cosmic rays. This make this analysis sensitive to any new physics in multilepton final state. DØ has also studied λ_{133} term in the final state with two electrons and τ_{had}. The dominant SM backgrounds are similar to the R_p analysis. In summary, no evidence for $\not{R}_p$-SUSY has been found.

Table 3. DØ and CDF lower limits at the 95 % CL on the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^{\pm}$ masses obtained in the mSUGRA inspired model. To increase the sensitivity DØ combines $ee\ell$, $\mu\mu\ell$ and $ee\tau_{had}$ channels for each λ_{ijk}.

DØ (m_0 = 1 TeV)	$m_{\tilde{\chi}_1^0}$ **(GeV)**	$m_{\tilde{\chi}_1^{\pm}}$ **(GeV)**	**CDF (m_0 = 250 GeV)**	$m_{\tilde{\chi}_1^0}$ **(GeV)**	$m_{\tilde{\chi}_1^{\pm}}$ **(GeV)**
λ_{121}	121	234	λ_{121}	101	185
λ_{122}	119	230	λ_{122}	110	203
λ_{133}	87	167			

Table 3 summarises DØ (CDF) lower mass limits obtained in the mSUGRA framework for m_0 = 1 TeV[14] (m_0 = 250 GeV), $\mu > 0$, $\tan\beta = 5$, $A_0 = 0$ for each of the three $\lambda_{121}, \lambda_{122}, \lambda_{133}$ couplings. DØ also set limits for λ_{133} at small $m_0 = 100$ GeV and $\tan\beta \sim 20$, where the stau is the next-to-lightest supersymmetric particle, excluding chargino (neutralino) mass below 217 (115) GeV. Finally, Fig. 6 (left) shows DØ exclusion domain in the $(\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm})$ mass plane in the MSSM scenario with heavy sfermions but assuming no GUT-relation between M_1 and M_2. The cut-off at low $\tilde{\chi}_1^0$ masses $m_{\tilde{\chi}_1^0} > 30$ (50) GeV for $\lambda_{121}, \lambda_{122}$ (λ_{133}) is due to the loss of efficiency, coming from the combined effect of the coupling strength and the LSP decay length, required to be less than 1 cm. All limits significantly improve previous results obtained at LEP and at Tevatron Run I and the most restrictive to date.

DØ has searched for a resonant production of single sleptons ($\tilde{\mu}$ or $\tilde{\nu}_\mu$) via nonzero $\lambda'_{211}LQ\overline{D}$ coupling: $q\bar{q} \to \tilde{\mu}$ $(\tilde{\nu}) \to \tilde{\chi}_{1,2,3,4}^0\mu$ $(\tilde{\chi}_{1,2}^{\pm}\mu) \to \mu\mu\bar{q}q$ (see Fig. 2 (c)), assuming that it is large enough that the $\not{R}_p$ decay of the LSP does not produce a

[13] It is natural to assume a hierarchy of interactions, in which $\not{R}_p$ coupling λ_{ijk} is small compared to electroweak gauge couplings; then R-parity approximately holds in decays of the heavier gauginos and $\not{R}_p$ manifests itself in the otherwise forbidden decay of the LSP (assumed to be $\tilde{\chi}_1^0$ in mSUGRA).

[14] m_0 = 1 TeV corresponds to heavy sleptons, therefore exclusion limits are valid for any slepton mass.

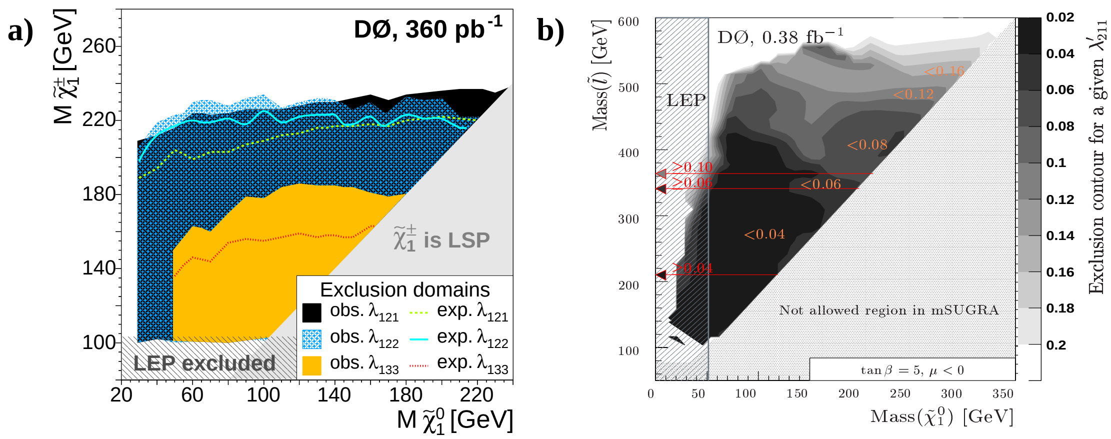

Figure 6. (a) DØ exclusion domains at the 95 % CL in the $(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)$ mass plane within the MSSM model for the $\lambda_{121}, \lambda_{122}, \lambda_{133}$ couplings (indices refer to lepton families). (b) DØ exclusion contour at the 95 % CL on $\lambda_{211}^{'}$ couplings within the mSUGRA framework for $\tan\beta = 5, \mu < 0, A_0 = 0$. The arrows indicate limits on the slepton mass $\tilde{\ell}$, for a given coupling $\lambda_{211}^{'}$.

displaced vertex [16]. At hadron colliders, due to the continuos energy distribution of the colliding partons, the resonance can be probed in a wide mass range of sparticle masses. The $\lambda_{211}^{'}$ coupling corresponds to the first generation of colliding partons and is not severely constrained by low energy experiments $\lambda_{211}^{'} < 0.059 \cdot m_{\tilde{q}}/100$ GeV, since $m_{\tilde{q}}$ can exceed 1 TeV for the first family [17]. The event topology searched is 2 isolated muons with $p_T^{\mu} > 15\ (8)$ GeV, respectively and 2 jets $p_T^{jet} > 15$ GeV. Using the next-to-leading muon and two leading jets the $\tilde{\chi}_1^0$ mass is reconstructed, while a peak in the invariant mass of the two leading muons and all found jets indicates the presence of slepton. No excess above the SM background was found in 375 pb^{-1} of data. Since $\sigma(\tilde{\ell}) \propto (\lambda_{211}^{'})^2$, a lower mass limits on the resonant slepton production is set with respect to the coupling strength $\lambda_{211}^{'}$. Slepton masses below 210 (363) GeV are excluded for $\lambda_{211}^{'}$ = 0.04 (0.10), independent of other masses (see Fig. 6 (b)).

SIGNATURE-BASED SEARCHES

CDF performed "signature-based" searches for anomalous production of events containing $\ell\gamma$+X, which are rare SM processes [18, 19].

An inclusive $\ell\ell\gamma$+X sample was selected by requiring a central photon with $E_T^{\gamma} >$ 25 GeV and a central e, μ with $E_T^{\ell} > 25$ GeV. The additional lepton was required to be $E_T^{\ell} > 20$ GeV. The dominant SM sources of $\ell\ell\gamma$ events are electroweak Z/γ^* production along with γ radiated from one of the charged particles involved in the process. The 53 $ee\gamma$ and 21 $\mu\mu\gamma$ were selected in 929 pb^{-1} of data, in agreement with SM expectations of 39.0±4.8 and 26.0±3.1, respectively. No $e\mu\gamma$ events were observed for an expected SM background of 1.01±0.33. Fig. 7 shows the distributions of $\not{E}_T$ for the $\mu\mu\gamma$ and $ee\gamma$ subsamples of the $\ell\ell\gamma$ sample. No excess of $\ell\ell\gamma$ events with anomalous large E_T or with multiple photons were observed in CDF Run II data.

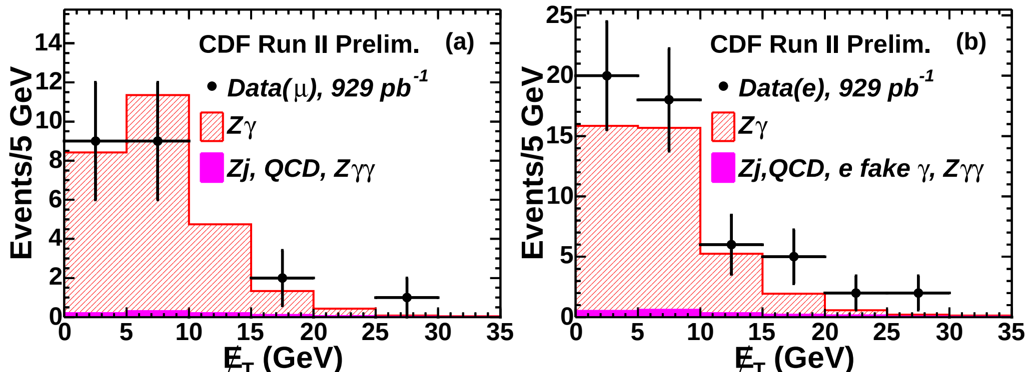

Figure 7. The distributions of $\not{E}_T$ in multilepton+photon inclusive searches: (a) $\mu\mu\gamma$ and (b) $ee\gamma$. The histograms show the expected SM background. In the $\ell\ell\gamma$ + X sample with $\not{E}_T > 25$ GeV 3 events observed for the SM expectation of 0.6±0.1 events.

SUMMARY AND OUTLOOK

CDF and DØ limits in multilepton final states presented in this paper, and based on the luminosities between 350 and 1100 pb^{-1}, have significantly improved Tevatron Run I and LEP II results over the large regions of SUSY parameter space [19, 20]. By the end of 2006, both experiments have already collected 2 fb^{-1} of data, which gives an opportunity to significantly extend searches for new physics beyond the SM. In particular, recent χ^2 analysis based on the present experimental results of the m_W, $sin^2\Theta_{eff}$, $(g-2)_\mu$ and $BR(b \to s\gamma)$ favour relatively small chargino mass $m_{\tilde{\chi}_1^\pm} \sim 200$ GeV [21], which might be within the reach of Tevatron Run II, depending on SUSY scenario.

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