Search for Anomalous Production of Multi-lepton Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a search for the anomalous production of events with multiple charged leptons in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV using a data sample corresponding to an integrated luminosity of 346 pb^{-1} collected by the CDF II detector at the Fermilab Tevatron. The search is divided into three-lepton and four-or-more-lepton data samples. We observe six events in the three-lepton sample and zero events in the $\geq$4-lepton sample. Both numbers of events are consistent with standard model background expectations. Within the framework of an R-parity violating supergravity model, the results are interpreted as mass limits on the lightest neutralino ($\tilde{\chi}_1^0$) and chargino ($\tilde{\chi}_1^\pm$) particles. For one particular choice of model parameters, the limits are $M(\tilde{\chi}_1^0)$>110 GeV/c^2 and $M(\tilde{\chi}_1^\pm)$>203 GeV/c^2 at 95% confidence level; the variation of these mass limits with model parameters is presented.

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Numerous attempts to resolve theoretical problems with the standard model of elementary particle physics (SM) require the existence of new particles with masses at the electroweak scale, $\sim$100 GeV/c^2 [1–4]. At the Tevatron and LHC hadron colliders, the production cross sections for these particles are predicted to be orders of magnitude smaller than for SM processes. Analysis methods for reducing background levels while preserving new physics signals include searching for leptons (ℓ) [5] with large momentum transverse to the beam axis (p_{T}), like-sign leptons, or signatures with transverse energy imbalance ($\not\!\!E_{\mathrm{T}}$). Requiring several leptons effectively reduces the SM backgrounds while maintaining sensitivity to low $\not\!\!E_{\mathrm{T}}$ regions. In this Letter, we present a search for an excess of events containing three or more leptons above the SM prediction. We use a data sample with an integrated luminosity of 346 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV collected by the CDF II detector from March 2002 to August 2004.

Several new physics models predict final states with four or more leptons that can be produced in $p\overline{p}$ collisions, including R-parity violating supersymmetry ($\not\!\!R_p$ SUSY) [6], non-minimal supersymmetric models (nMSSM) [7], and production of doubly-charged Higgs pairs [8]. In $\not\!\!R_p$ SUSY, the lightest supersymmetric particle (LSP) may decay directly into two leptons and a neutrino. With a pair of LSPs in each event, there could be at least four leptons plus $\not\!\!E_{\mathrm{T}}$. Another possibility is the nMSSM, which includes an expanded Higgs sector and their supersymmetric partners. "Cascade" decays of these particles may result in multiple leptons, jets, and less $\not\!\!E_{\mathrm{T}}$ than in other SUSY models. Alternatively, doubly-charged Higgs ($H^{\pm\pm}$) may be produced in pairs in left-right symmetric models [9]. Under certain conditions, the $H^{\pm\pm}$ primarily decays into two leptons, producing a final state of four leptons without $\not\!\!E_{\mathrm{T}}$ or jets. In order to be sensitive to multiple new physics models, no $\not\!\!E_{\mathrm{T}}$ or jet cuts are applied. The results of this search are interpreted using an $\not\!\!R_p$ SUSY model within an mSUGRA framework only. A brief introduction to mSUGRA and $\not\!\!R_p$ SUSY phenomenology is included below.

In the minimal supersymmetric model [4], there are two Higgs doublets, as well as supersymmetric partners for every SM particle that differ by 1/2 unit of spin. The superpartners of the electroweak gauge bosons and Higgs bosons mix to produce four neutral mass states ($\tilde{\chi}^0_{1-4}$) and four charged states ($\tilde{\chi}^{\pm}_{1,2}$). The supergravity framework (mSUGRA) [3] has five free parameters: the universal gaugino mass ($M_{1/2}$), the universal scalar mass (M_0), the ratio of the Higgs vacuum expectation values (tanβ), the trilinear coupling (A_0), and the sign of the higgsino mass parameter (μ).

R-parity (R_p) is a quantum number defined such that

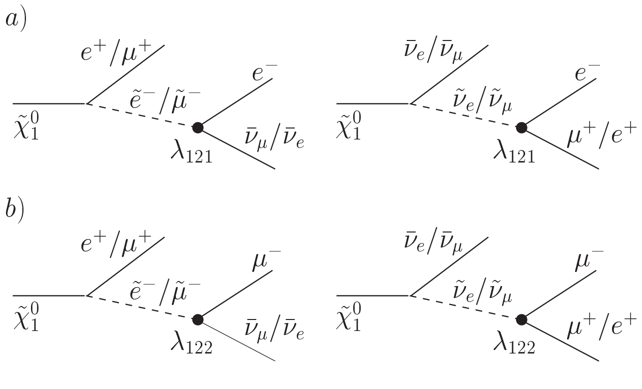

FIG. 1: Lowest order Feynman diagrams for $\not\!\!R_p$ SUSY decay of the LSP via virtual sleptons governed by a) the λ_{121} coupling, and b) the λ_{122} coupling.

all SM particles have value +1 and all superpartners have value -1. Many searches assume that R_p is conserved so that the LSP is stable, although there are viable SUSY models with R_p violation. One scenario includes a single $\not\!\!R_p$ term in the renormalizable superpotential, $\lambda_{ijk}L_iL_j\overline{E}_k$, where λ_{ijk} are lepton number violating coupling strengths; i,j, and k are family indices ranging from 1-3; L_i is the left-handed lepton doublet superfield; and $\overline{E}_i$ is the right-handed charged lepton singlet superfield. In this scenario, superpartners are produced in pairs at hadron colliders. Muon decay measurements [6] constrain $\lambda_{12k} \lesssim 0.14$ so that heavier superpartners will cascade decay into the LSP with nearly 100% branching ratio, producing at least two LSPs per event. The LSP, which is the $\tilde{\chi}^0_1$ in mSUGRA for the values of $M_{1/2}$ pertinent to this study, will then decay into two leptons plus a neutrino, as shown in Fig. 1, resulting in a final state of four or more leptons. The detector acceptance limits our sensitivity to $\lambda_{12k} \gtrsim 3 \cdot 10^{-3}$, since a smaller value will result in the LSP decaying far from the interaction region [10]. At least two of the four leptons will be electrons (muons) for LSP decays governed by the λ_{121} (λ_{122}) coupling. Final states with taus are not used since they are less efficiently identified. Recently, lower mass limits have been set by the DØ Collaboration on the $\tilde{\chi}^0_1$ ranging from 115-119 GeV/c^2 and on the $\tilde{\chi}^{\pm}_1$ from 229-234 GeV/c^2 in this type of $\not\!\!R_p$ SUSY model, by searching for three leptons plus $\not\!\!E_{\mathrm{T}}$ [11]. Previously, the limits from LEP were $\sim$53 GeV/c^2 on the $\tilde{\chi}^0_1$ and 103 GeV/c^2 on the $\tilde{\chi}^{\pm}_1$ [12].

The components of the CDF II detector relevant to this analysis are briefly described here; a more complete description can be found elsewhere [13]. The p_{T} and η [14] of charged particles are measured by a silicon strip detector [15] and a 96-layer drift chamber (COT) [16] inside a 1.4 T solenoidal magnetic field. The COT provides coverage with high efficiency for $|\eta| < 1$. For $1 < |\eta| < 2$, the silicon detector is mainly used. Electromagnetic (EM) and hadronic calorimeters surround the tracking system. They are segmented in a projective tower geometry and

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measure energies of charged and neutral particles in the central ($|\eta| < 1$) and end-plug ($1.1 < |\eta| < 3.6$) regions. Each calorimeter has an EM shower profile detector positioned at the shower maximum. Four layers of planar drift chambers located outside the central hadron calorimeters and another set behind a 60 cm thick steel absorber detect muons with $|\eta| < 0.6$. Additional drift chambers and scintillation counters detect muons in the region $0.6 < |\eta| < 1.0$. Gas Cherenkov counters [17] measure the average number of inelastic $p\overline{p}$ collisions per bunch crossing and thereby determine the luminosity.

Electron identification criteria include a reconstructed track associated with a cluster of energy in the EM calorimeter for $|\eta| < 2.0$. "Tight" central electrons and end-plug electrons are required to have high track quality, calorimeter cluster E_T that is consistent with the track p_{T}, a high fraction (usually 95%) of the total calorimeter energy deposition in the EM section, and an EM lateral shower profile consistent with test beam measurements. A "loose" central electron sample is also collected by removing the shower profile requirements. Muons are identified for $|\eta| < 1$ by a charged track consistent with being minimum ionizing in the calorimeters matched to a reconstructed track segment ("stub") in one of the muon drift chambers. Stubless muons are also accepted for $|\eta| < 1$ if all other criteria are satisfied except for the stub requirement and the track does not point to any of the muon drift chambers. All tracks associated with electrons or muons must be consistent with being produced at the $p\overline{p}$ collision point. Leptons are required to be separated from each other by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ and to have $|z| < 60$ cm at the point of closest approach to the primary vertex. Leptons are required to be isolated such that E_{T}^{iso} divided by the E_{T} of the electron or p_{T} of the muon is less than 0.1, where E_{T}^{iso} is the transverse energy within a cone of $\Delta R < 0.4$ that is unassociated with the lepton.

The data were collected with lepton triggers requiring at least one central electron (muon) candidate with $E_{\mathrm{T}} > 18$ GeV ($p_{\mathrm{T}} > 18$ GeV/c). We select events with two or more leptons that have E_{T} (p_{T}) > 20, 8, and 5 GeV (GeV/c) for the first, second, and additional leptons, respectively. At least one identified lepton must pass the trigger requirements. From this sample, trilepton and $\geq$4-lepton events that pass additional cuts (described below) are used as signal candidates, while dilepton events are used to validate the background prediction.

Several SM processes result in final states with three or more isolated leptons. The dominant contributions include dileptons from the Drell-Yan Z/γ^* process (DY) with additional leptons from photon conversions or misidentified jets, and secondary contributions from diboson (WZ, ZZ) production. Except for those due to misidentified jets, the backgrounds are estimated using Monte Carlo (MC) simulation. The simulated detector acceptances are not a 100% accurate representation of the data and therefore are corrected by $\epsilon_{\mathrm{data}}/\epsilon_{\mathrm{MC}}$, where ϵ_{data} (ϵ_{MC}) is the efficiency for lepton reconstruction, lepton identification, and photon conversion removal requirements measured in data (MC). This correction varies from 0.6-1.0 per event, depending on the number and types of identified leptons. Lepton reconstruction and identification efficiencies are measured from DY and J/ψ dilepton events in data and MC simulation. Trigger efficiencies are determined from $W \rightarrow e\nu$ events for electrons and from $Z \rightarrow \mu\mu$ events for muons. The probability for a jet to be mis-identified as a lepton is determined as a function of E_{T} for electrons and p_{T} for muons from jet data samples, by counting the numbers of jets that remain after applying the lepton identification requirements. A similar procedure is described in more detail in [18].

Samples of $\not{R}_p$ SUSY simulated events are generated using PYTHIA [19] within the mSUGRA framework with input of the supersymmetric couplings and particle masses from ISAJET [20]. For each point in the SUSY parameter space, the next-to-leading-order cross section is calculated with PROSPINO2 [21]. In all cases $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production dominate and are the only processes generated. The $\tilde{\chi}_1^0$ mass, which is roughly proportional to $M_{1/2}$, has the largest impact on the signal acceptance. The $\tilde{\chi}_1^0$ mass is also affected by the sign(μ), but has little dependence on M_0, tanβ, and A_0. Therefore, three of the five mSUGRA parameters are held constant: $M_0 = 250$ GeV/c^2, tan$\beta = 5$, and $A_0 = 0$; while sign(μ) and $M_{1/2}$ are allowed to vary. Since the $\tilde{\chi}_1^0$ mass decreases with larger values of M_0 and tanβ, the chosen values are expected to produce conservative results.

To reduce SM background contamination, an event is removed if any of the following conditions are met for opposite-sign, same-flavor lepton pairs: invariant mass between 76-106 GeV/c^2 ("Z veto"), invariant mass below 15 GeV/c^2, or $160^\circ < \Delta\phi < 200^\circ$. Identified cosmic ray events are removed. Electrons are removed if there is a partner track identified as coming from a photon conversion. An event is also rejected if the invariant mass of the two highest transverse energy leptons is below 20 GeV/c^2 to reduce heavy flavor and radiative photon conversion backgrounds. In order to improve signal-to-background in the 3-lepton data sample only, we require that one of the two leading leptons be an electron when evaluating the λ_{121} scenario, and a muon for the λ_{122} scenario. This definition leads to a 22% overlap for the background and $\sim$15% overlap for the signal (depending on model parameters) between the trilepton event samples. After all selection criteria, the signal acceptances are $\sim$11% and $\sim$4% for the trilepton and $\geq$4-lepton data samples, respectively.

Uncertainties are determined separately for SM background and $\not{R}_p$ SUSY expectations, in each data sample. The sources of systematic uncertainty on the trilepton background prediction include jets misidentified as leptons (12-13%), lepton identification efficiency (5-6%), luminosity measurement (6%), choice of parton distribution functions (2%), cross section (5-6%), photon con-

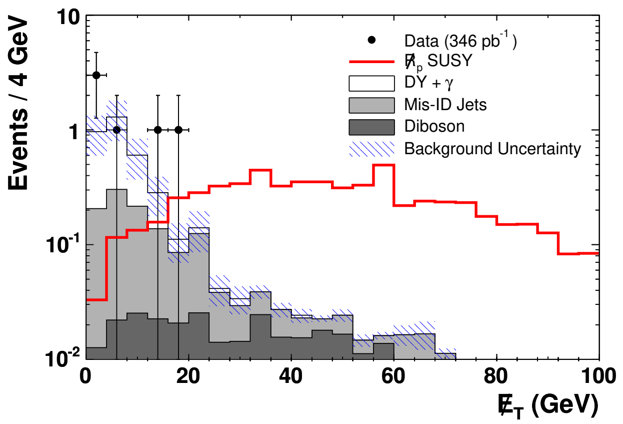

FIG. 2: $\not\!\!E_T$ for events in the trilepton signal samples. For comparison, an $\not\!R_p$ SUSY sample is shown with $M(\tilde{\chi}_1^0) = 99$ GeV/c^2.

version identification (3%), and initial state radiation (4%). For events with ≥4-leptons, the uncertainty on the background is dominated by jets misidentified as leptons (41%) and $Z/\gamma^* + \gamma$ MC statistics (38%). The total systematic uncertainty on the signal acceptance ranges from 12-15%, based on the number and types of leptons, where the largest contribution is due to the uncertainty on the low-p_T (< 20 GeV/c) lepton identification efficiency.

The background prediction is validated through the use of control regions in which one or more of the event selection criteria are inverted. For each control region, the SM prediction is compared to the data, as shown in Table I. In the ee and $\mu\mu$ dilepton control regions, the background is dominated by DY. In the case of $e\mu$ control regions, the largest background is $Z/\gamma^* \to \tau\tau$; however, there are also significant contributions from WW, $t\bar{t}$, and jets misidentified as leptons. For trilepton control regions, the largest backgrounds originate from DY events where the third lepton is due to either a photon conversion or a misidentified jet. The agreement between predicted and observed events in the control regions indicates that the backgrounds are validated, and we proceed to examine the signal data samples.

In the trilepton data samples, a total of 6 events are observed: 5 events with an expected background of 3.1 ± 0.7 (stat.) ± 0.4 (syst.) events for the λ_{121} scenario, and one event with an expected background of 1.9 ± 1.0 (stat.) ± 0.3 (syst.) events for the λ_{122} scenario. The $\not\!\!E_T$ distribution of the observed events are consistent with the background prediction, as shown in Fig. 2. No events are observed in the ≥4-lepton data sample, with an expected background of 0.008 ± 0.003 (stat.) ± 0.003 (syst.) events. We interpret the results as being consistent with the hypothesis of no signal and therefore set mass limits on the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ particles. The cross section limits are calculated by combining the 3-lepton and ≥4-lepton signal samples using a multi-channel Bayesian method similar to [22], shown for one $\not\!R_p$ SUSY scenario in Fig. 3. The limit calculation treats uncertainties as nuisance parameters that are allowed to be correlated between the 3-lepton and ≥4-lepton samples. The resulting mass limits, at 95% confidence level (C.L.), are presented in Table II.

In conclusion, we have performed a search for anoma-

TABLE I: Predicted and observed events found in the control and signal samples. The leptons are listed in order of decreasing transverse energy. The first lepton must either be a tight central electron or "stub muon." Systematic and statistical uncertainties are added in quadrature.

Region	**Criteria Failed**	**Predicted Background**	**Observed Events**
Two-Lepton Control Samples			
ee	Z veto	13948 ± 1536	14019
ee		2142 ± 230	2125
$\mu\mu$	Z veto	7474 ± 809	7499
$\mu\mu$		1264 ± 141	1339
$e\mu$		117.6 ± 12.9	112
μe		186.8 ± 22.9	203
Three-Lepton Control Samples			
$ee\ell$	Z veto	8.8 ± 1.9	12
$\mu\mu\ell$	Z veto	5.1 ± 1.2	2
$e\mu\ell$	Z veto	0.55 ± 0.04	0
$\ell\ell\ell$	Z veto	14.4 ± 2.9	14
$ee\ell$	$\Delta\phi$ only	2.1 ± 0.3	2
$\mu\mu\ell$	$\Delta\phi$ only	1.2 ± 0.2	4
$e\mu\ell$	$\Delta\phi$ only	0.35 ± 0.04	0
$\ell\ell\ell$	$\Delta\phi$ only	3.7 ± 0.3	6
Four-or-More-Lepton Control Samples			
$\ell\ell\ell\ell$	Z veto	0.15 ± 0.02	0
$\ell\ell\ell\ell$	$\Delta\phi$ only	0.006 ± 0.003	0
Three-Lepton Signal Samples			
λ_{121} scenario		3.1 ± 0.8	5
λ_{122} scenario		1.9 ± 1.0	1
Four-or-More-Lepton Signal Sample			
λ_{121}, λ_{122} scenarios		0.008 ± 0.004	0

TABLE II: Expected and observed 95% C.L. limits on the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ masses for $3 \cdot 10^{-3} \lesssim \lambda_{12k} < 0.14$, $M_0 = 250$ GeV/c^2, tan$\beta = 5$, and $A_0 = 0$.

$\not\!R_p$ SUSY	**M($\tilde{\chi}_1^0$) [GeV/c^2]**		**M($\tilde{\chi}_1^\pm$) [GeV/c^2]**	
scenario	**exp.**	**obs.**	**exp.**	**obs.**
λ_{121}, $\mu > 0$	105	102	192	185
λ_{121}, $\mu < 0$	101	98	192	186
λ_{122}, $\mu > 0$	108	110	198	203
λ_{122}, $\mu < 0$	103	106	195	202

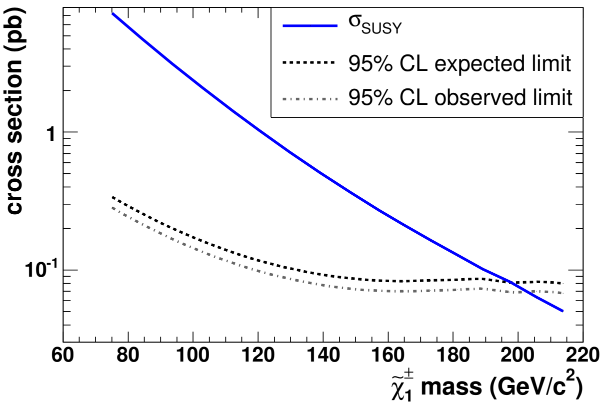

FIG. 3: Experimental 95% C.L. cross section limits and theoretical $\not{R}_p$ SUSY cross sections versus LSP mass, for $3 \cdot 10^{-3} \lesssim \lambda_{122} < 0.14$, $M_{1/2} = 260$ GeV/c^2, $M_0 = 250$ GeV/c^2, $\tan\beta = 5$, $A_0 = 0$, and $\mu > 0$.

lous production of events with three or more leptons using a sample of CDF Run II data corresponding to 346 pb^{-1} of integrated luminosity. Finding results consistent with the SM, we set limits on the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^{\pm}$ masses within an mSUGRA framework. The $\tilde{\chi}_1^0$ mass limits range from 98 to 110 GeV/c^2, while the chargino mass limits range from 185 to 203 GeV/c^2 at 95% C.L. depending on the choice of model parameters. These results significantly improve upon the LEP limits [12] and are comparable to the DØ limits [11]. While no evidence for new physics was found, the ≥4-lepton data sample is virtually background free and provides an excellent technique for detecting new physics with more luminosity in the future.

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