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Search for Chargino-Neutralino Associated Production at the Fermilab Tevatron Collider

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Abstract

We have searched in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV for events with three charged leptons and missing transverse energy. In the Minimal Supersymmetric Standard Model, we expect trilepton events from chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) pair production, with subsequent decay into leptons. We observe no candidate $e^+e^-e^\pm$, $e^+e^-\mu^\pm$, $e^\pm\mu^+\mu^-$ or $\mu^+\mu^-\mu^\pm$ events in 106 pb^{-1} integrated luminosity. We present limits on the sum of the branching ratios times cross section for the four channels: $\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0} \cdot \mathrm{BR}(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 3\ell + X) < 0.34$ pb, $\mathrm{M}_{\tilde{\chi}_1^\pm} > 81.5$ GeV/c^2 and $\mathrm{M}_{\tilde{\chi}_2^0} > 82.2$ GeV/c^2 for $\tan\beta = 2$, $\mu = -600$ GeV/c^2 and $\mathrm{M}_{\tilde{q}} = \mathrm{M}_{\tilde{g}}$.

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The Minimal Supersymmetric Standard Model (MSSM) [1] contains two Higgs doublets and supersymmetric partners to all the Standard Model (SM) particles. The superpartners of the electroweak gauge bosons and Higgs bosons are two charged and four neutral fermions ($\tilde{\chi}$'s). Further assumptions, namely the Grand Unified Theory hypothesis provided by Supergravity [2], Supergravity-inspired slepton/sneutrino mass constraints [3], degeneracy of five of the squarks, and R-parity conservation, lead to models with only six parameters. R-parity conservation implies the creation of superpartners in pairs and the stability of the lightest supersymmetric partner (LSP). Within this framework we expect, for certain regions of parameter space, a measurable rate for the reaction $q\bar{q}' \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, where $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \ell^{\pm}\nu$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$, and $\tilde{\chi}_1^0$ is the LSP. The ν and two LSPs do not interact with the detector and manifest themselves as missing energy. The resulting final state is three isolated charged leptons plus missing energy [4]. In this Letter, we report on a search for direct production of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, via virtual $W^{\pm}$ s-channel and virtual squark t-channel diagrams, in the trilepton channels e^+e^-e, $e^+e^-\mu$, $e\mu^+\mu^-$ and $\mu^+\mu^-\mu$. Additional trilepton production arising from squark and gluino cascade decays was not included. We add 87 pb^{-1} of data recorded in 1994-95 to a previously analyzed sample of 19 pb^{-1} collected in 1992-93 [5].

The Collider Detector at Fermilab (CDF) is described in detail elsewhere [6]. The components of the detector relevant to this analysis are the vertex chamber, which provides r-z tracking information; the central tracking chamber, which is situated inside a 1.4 T solenoidal magnetic field and provides a combination of r-ϕ, z and transverse momentum (p_T) information for charged particles; the central ($|\eta| < 1.1$) and endplug ($1.1 < |\eta| < 2.4$) electromagnetic calorimeters, which are located outside the solenoid and are segmented in a projective tower geometry; and the central muon chambers. We define pseudorapidity $\eta \equiv -\ln\tan(\theta/2)$ and θ and ϕ to be the polar and azimuthal angles with respect to the beam axis.

We begin with a sample of 87 pb^{-1} recorded in 1994-95. It contains 3.3×10^6 events that have an electron or muon with $p_T > 8$ GeV/c and $|\eta^e| < 1.1$ or $|\eta^\mu| < 0.6$ and a second electron or muon with $p_T > 3$ GeV/c and $|\eta^e| < 2.4$ or $|\eta^\mu| < 1.0$. We select events from this sample by requiring an electron with $E_T^e > 11$ GeV and $|\eta^e| < 1.1$ or a muon with $p_T^\mu > 11$ GeV/c and $|\eta^\mu| < 0.6$. We require two additional charged leptons (excluding taus) with $E_T^e > 5$ GeV and $|\eta^e| < 2.4$ or $p_T^\mu > 4$ GeV/c and $|\eta^\mu| < 1.0$. At least one lepton passing the high threshold cut must pass stringent lepton identification cuts [5–9]. We require electron candidates to have lateral and longitudinal shower profiles consistent with an electron and be well matched to a charged track. Muon candidates must be identified in the muon chambers, be well matched to a charged track, and deposit energy in the calorimeter consistent with a minimum ionizing particle. To improve the integrity of these events, we require that all three leptons originate from a common vertex within 60 cm of the center of the detector. The 60 cm requirement is to preserve the projective tower geometry of the calorimetry. We find 59 events meeting these requirements.

The principal backgrounds to the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ signature are real trilepton events from $W^{\pm}Z^0$, Z^0Z^0, $t\bar{t}$ and $b\bar{b}$ and dilepton plus fake lepton [10] events from W^+W^-, Z^0 and the Drell-Yan process. To remove background from $b\bar{b}$, $c\bar{c}$ and $t\bar{t}$ production and fake leptons, each lepton must be isolated, where isolation is defined by requiring less than 2 GeV E_T in the calorimeter inside an η-ϕ cone of radius $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the lepton, excluding the energy deposited by the lepton. There must be at least one e^+e^- or $\mu^+\mu^-$ pair, the η-ϕ distance between any two leptons ($\Delta R_{\ell\ell}$) must be greater than 0.4 (to remove background from $b\bar{b}$ production, as well as some anomalously reconstructed cosmic ray events) and the difference in azimuthal angle between the two highest p_T leptons ($\Delta\phi_{\ell_1\ell_2}$) in the event must be less than 170° (to remove background from the Drell-Yan process and cosmic rays) [9]. Events containing a same flavor $\ell^+\ell^-$ pair with invariant mass in the regions of the resonances J/ψ (2.9-3.3 GeV/c^2), Υ (9-11 GeV/c^2) and Z^0 (75-105 GeV/c^2) are removed. These requirements select 6 events (see Table I). In the previous data sample [5] these criteria selected zero events.

The presence of two LSPs and a neutrino in the final state of the signal can lead to substantial missing transverse energy ($\not\!\!E_T$). The dominant remaining backgrounds, $b\bar{b}$ production and the Drell-Yan process, do not have significant $\not\!\!E_T$. As seen in Table I, requiring $\not\!\!E_T > 15$ GeV reduces the background by 85% while retaining 82% of the expected signal for $M_{\tilde{\chi}_1^\pm} \approx 70$ GeV/c^2. No events pass the $\not\!\!E_T$ cut.

For the remainder of the analysis we combine this data with the previous 19±1 pb^{-1} sample [5] for a total Run I integrated luminosity ($\int \mathcal{L}dt$) of 106±7 pb^{-1} and zero candidate trilepton events.

To determine the SM background and the signal acceptance, we use the ISAJET Monte Carlo program [11] with a CDF detector simulation. For background due to vector boson pair production we use theoretical calculations of cross sections and branching ratios [12]. For background due to $t\bar{t}$ production and the Drell-Yan process we use cross sections measured by CDF [7]. The rate of lepton misidentification was determined from a $W^\pm \rightarrow \ell\nu$ data sample to be (0.29±0.04)% per event. After all cuts are applied the total expected background is 1.2±0.2 events in 106 pb^{-1}.

The total detection efficiency (ϵ^{tot}) is a product of the trigger efficiency, the isolation efficiency, the lepton identification efficiency and a geometric and kinematic acceptance factor. The triggers used were single lepton and dilepton triggers, with single lepton trigger efficiencies of $\epsilon_e^{trig} = (87^{+4}_{-5})\%$ above 11 GeV and $\epsilon_\mu^{trig} = (87 \pm 3)\%$ above 11 GeV/c. We determine the lepton isolation and identification efficiencies by studying the second lepton in $Z^0 \rightarrow \ell^+\ell^-$ events. The isolation efficiency is (90±4)% per lepton. The per-event trilepton identification efficiency ranges from (59±1)% to (82±1)%, depending on the combination of leptons in the event. The geometric and kinematic acceptance is determined using ISAJET and the CDF detector simulation. The total efficiency (ϵ^{tot}) is mainly a function of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses, which are nearly equal for the region of the search. The efficiency increases linearly from 3% at 50 GeV/c^2 to 12% at 100 GeV/c^2, because massive $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ lead to more central and more energetic leptons which are detected with higher efficiency.

We see no signal candidates and thus set limits on the available parameter space. A particular point in parameter space is excluded if the predicted number of events exceeds the number of events (s) expected at the 95% confidence level limit given that zero events were observed. The predicted number of events is a function of the cross section times branching ratio ($\sigma(p\bar{p} \rightarrow \tilde{\chi}_1^\pm\tilde{\chi}_2^0 + X) \cdot \mathrm{BR}(\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow 3\ell + X)$) and $\epsilon^{tot} \cdot \int \mathcal{L}dt$. We calculate cross section times branching ratio ($\sigma \cdot$ BR) using ISAJET 7.20 with CTEQ-3L [13] parton distribution functions and calculate s by convolving the total systematic uncertainty as a Gaussian smearing with a Poisson distribution. The total systematic uncertainty is 15%, which includes uncertainty in the total integrated luminosity (±7%), the parton distribution (±7%), the trigger efficiency

($\pm 6\%$), and the trilepton-finding efficiency ($\pm 2\%$), leading to $s = 3.1$. To calculate the uncertainty due to the parton distribution function we compare CTEQ-3L with a variety of other parton distribution functions. We use the largest uncertainty in the efficiency of any single lepton trigger for all events.

Using the model assumptions listed in the first paragraph, four parameters determine the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses, production cross sections and decay branching ratios: the ratio of the Higgs vacuum expectation values ($\tan\beta$), the Higgsino mass parameter (μ), the gluino mass ($\mathrm{M}_{\tilde{g}}$) and the squark-to-gluino mass ratio ($\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}}$). To make the analysis more independent of details of the Higgs sector, we consider a region in the MSSM where there is no significant chargino or neutralino branching fraction into Higgs particles. Technically, we do this by choosing the mass of the pseudoscalar Higgs (M_A) to be above the chargino/neutralino mass and use $\mathrm{M}_A = 500$ GeV/c^2. The production and decay of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ are independent of the remaining MSSM parameter, the trilinear top squark coupling (A_t). We fix $A_t = \mu/\tan\beta$ for consistency with other CDF analyses [14]. The search is more sensitive at low values of $\tan\beta$; $\tan\beta \gtrsim 10$ leads to higher branching ratios to taus, for which we do not search. We consider $1.1 \le \tan\beta \le 8$. We use -1000 GeV/c$^2 < \mu < -200$ GeV/c^2 because the search is more sensitive to negative values of μ and $|\mu|$ is expected to be on the order of the energy scale at which supersymmetric phenomena should be observable. Also, small $|\mu|$ increases the Higgsino content of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, which decreases the branching ratio to leptons. ISAJET requires $\mathrm{M}_{\tilde{g}}$ and $\mathrm{M}_{\tilde{q}}$ as input parameters to calculate $\mathrm{M}_{\tilde{\chi}_1^\pm}$. The slepton/sneutrino mass constraints [3] use $\mathrm{M}_{\tilde{g}}$ and $\mathrm{M}_{\tilde{q}}$ to determine $\mathrm{M}_{\tilde{\ell}}$ and $\mathrm{M}_{\tilde{\nu}}$; large differences in $\mathrm{M}_{\tilde{g}}$ and $\mathrm{M}_{\tilde{q}}$ lead to heavy sleptons and sneutrinos and decreases the branching ratio to leptons. Thus, this analysis considers $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} > 1$ to avoid invisible decays through light sneutrinos and $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} < 2$ to enhance leptonic final states. For the regions of parameter space we examine $\mathrm{M}_{\tilde{g}} \approx 3\mathrm{M}_{\tilde{\chi}_1^\pm}$, so we use 150 GeV/c$^2 \le \mathrm{M}_{\tilde{g}} \le 340$ GeV/c^2.

Figure 1 shows the limit for a few representative points in the $\mathrm{M}_{\tilde{\chi}_1^\pm} - (\sigma\cdot\mathrm{BR})$ plane. All points above the solid line are excluded. For comparison, we include the result of the DØ collaboration [15]. DØ reports the *average* $\sigma\cdot$BR over the four trilepton modes; we use the sum. Figure 2 shows the limit on $\mathrm{M}_{\tilde{\chi}_1^\pm}$ as a function of μ and $\tan\beta$ [16]. These limits are compared to the limits from ALEPH [17] in Figure 2. The ALEPH result is from a search for all possible final states. The OPAL, L3 and DELPHI collaborations report similar limits [18].

We also examined a string-inspired SU(5) $\times$ U(1) one-parameter supergravity model [19]. This model requires $\mathrm{M}_{\tilde{\chi}_1^\pm} \lesssim 87$GeV/c^2 and $\mathrm{M}_{\tilde{\chi}_2^0} \lesssim 91$GeV/c^2 and has a nearly maximized trilepton branching ratio via $\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell$ and $\tilde{\ell}_R \to \ell\tilde{\chi}_1^0$. As shown in Figure 3, we exclude most of this model and set $\mathrm{M}_{\tilde{\chi}_1^\pm} > 80.5$ GeV/c^2, $\mathrm{M}_{\tilde{\chi}_2^0} > 86.7$ GeV/c^2 and $\sigma\cdot\mathrm{BR}(\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to 3\ell + X) <$ 0.48 pb.

In conclusion, we find no evidence for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production in 1.8 TeV $p\bar{p}$ collisions and set limits on $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses and $\sigma\cdot$BR within the framework of MSSM models which have $\mathrm{M}_{\tilde{\chi}_1^\pm} \approx \mathrm{M}_{\tilde{\chi}_2^0} \approx 2\mathrm{M}_{\tilde{\chi}_1^0}$ and three-body decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. The strongest limit is $\sigma_{\tilde{\chi}_1^\pm\tilde{\chi}_2^0}\cdot\mathrm{BR}(\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to 3\ell + X) < 0.34$ pb, $\mathrm{M}_{\tilde{\chi}_1^\pm} > 81.5$ GeV/c^2 and $\mathrm{M}_{\tilde{\chi}_2^0} > 82.2$ GeV/c^2 for $\tan\beta = 2$, $\mu = -600$ GeV/c^2 and $\mathrm{M}_{\tilde{q}} = \mathrm{M}_{\tilde{g}}$.

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TABLES

TABLE I. Events remaining after each cut in the 1994-95 data (87 pb^{-1}). One Z^0 event and one J/ψ event are removed with the resonance cuts. For comparison we indicate the expected background (BG) and an expected signal from a representative MSSM Monte Carlo (MC) sample ($\mathrm{M}_{\tilde{q}} = \mathrm{M}_{\tilde{g}} = 200$ GeV/c^2, $\tan\beta = 2$, $\mu = -400$ GeV/c^2, $\mathrm{M}_{\tilde{\chi}_1^\pm} \simeq \mathrm{M}_{\tilde{\chi}_2^0} \simeq 70$ GeV/c^2, $\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0} = 4.8$ pb, $\epsilon^{tot} = 6.7\%$).

Cut	Events	Expected BG	MSSM MC
Dilepton data set	3,270,488		
Trilepton data set	59		
∘ Isolation < 2 GeV	23		
∘ Require e^+e^- or $\mu^+\mu^-$	23		
∘ $\Delta R_{\ell\ell} > 0.4$	9		
∘ $\Delta\phi_{\ell_1\ell_2} < 170°$	8	9.6±1.5	6.2±0.6
∘ J/ψ, Υ, Z^0 removal	6	6.6±1.1	5.5±0.5
∘ $\not{E}_T > 15$ GeV	0	1.0±0.2	4.5±0.4
Total Run I data (106 pb^{-1})	0	1.2±0.2	5.5±0.4

FIGURES

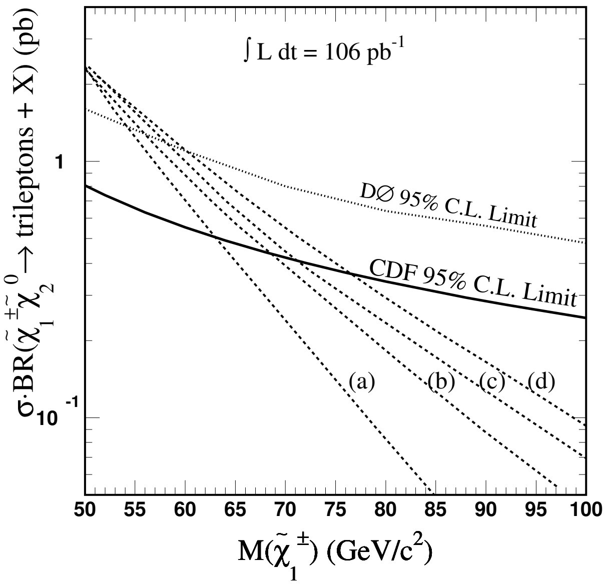

FIG. 1. $\sigma{\cdot}\mathrm{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell + X)$ versus $\tilde{\chi}_1^{\pm}$ mass for representative points in the MSSM parameter space, namely $\mu = -400$ GeV/c^2, $\tan\beta = 2$ and (a) $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} = 2.0$, (b) $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} = 1.5$, (c) $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} = 1.2$ and (d) $\mathrm{M}_{\tilde{q}}/\mathrm{M}_{\tilde{g}} = 1.0$. BR is the summed branching ratio into the four trilepton modes (e^+e^-e, $e^+e^-\mu$, $e\mu^+\mu^-$ and $\mu^+\mu^-\mu$). The solid line is the 95% confidence level upper limit based on an observation of zero events. We set a mass limit of 77.0 GeV/c^2 when $\mathrm{M}_{\tilde{q}}{=}\mathrm{M}_{\tilde{g}}$. All MSSM points in this plot yield three body decays of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$. The DØ limit [15] is for single trilepton mode which we scale up by 4 to match our notation.

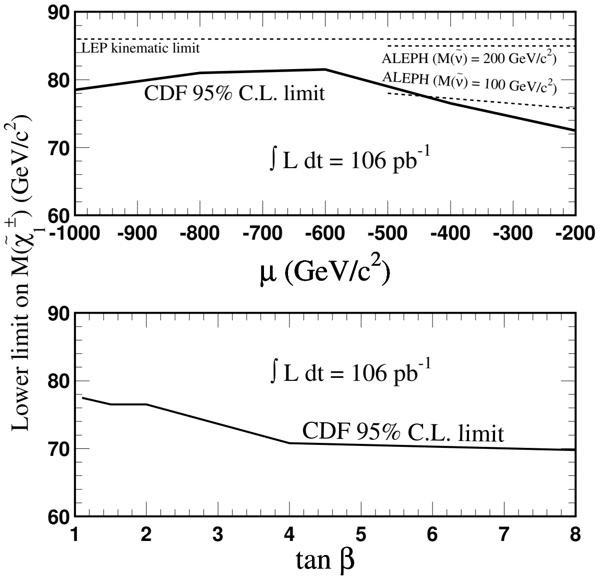

FIG. 2. The experimental limit on $M_{\tilde{\chi}_1^\pm}$ as a function of μ for $\tan\beta = 2$ and $M_{\tilde{q}} = M_{\tilde{g}}$ (upper) and as a function of $\tan\beta$ for $\mu = -400$ GeV/c^2 and $M_{\tilde{q}} = M_{\tilde{g}}$ (lower). The ALEPH limits shown [17] are from a search for all possible final states. In this analysis $M_{\tilde{\nu}} \approx 100$ GeV/c^2. Minimal SUGRA models favor the region of small $|\mu|$ values.

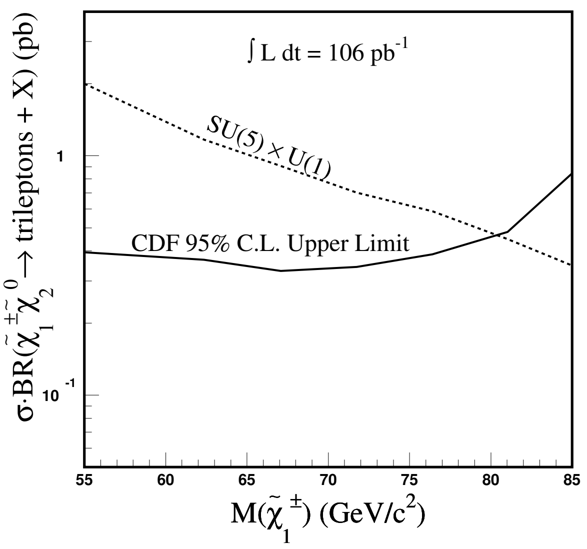

FIG. 3. $\sigma\cdot$BR$(\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to 3\ell + X)$ versus $\tilde{\chi}_1^\pm$ mass for the SU(5) $\times$ U(1) model [19]. This sets a mass limit of 80.5 GeV/c^2. In this model, the $\tilde{\ell}_R$ is lighter than the $\tilde{\chi}_2^0$, resulting in two body decays of the $\tilde{\chi}_2^0$. Note that the acceptance for events from this model decreases at large $\tilde{\chi}_1^\pm$ mass. In this region, the LSP mass approaches that of the $\tilde{\ell}$, resulting in soft final state leptons which are difficult to detect.