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We have searched for chargino-neutralino production ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) in 1.8 TeV $p\overline{p}$ collisions, followed by their leptonic decays $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \ell^{\pm} \nu$ and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$. These trilepton events are expected within a framework of the minimal supersymmetric standard model (MSSM). In a 19.1 pb^{-1} data sample collected with a Collider Detector at Fermilab, no trilepton events were observed. Upper limits on $\sigma(p\overline{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0) \cdot BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3\ell + X)$ were obtained for various MSSM parameter space regions, yielding new 95% confidence level lower limits for the neutralino ($\tilde{\chi}_2^0$) mass which extend as high as 49 GeV$/c^2$. [S0031-9007(96)00325-0]

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Although the standard model (SM) provides remarkable agreement with current high energy physics data, it fails to provide insight into several important issues. Among these are the apparently arbitrary energy scale of electroweak symmetry breaking, the appearance of divergences in the Higgs boson self-energy [1], and the failure of coupling constants to unify at large energy scales [2]. A simple extension to the SM to solve these difficulties is the minimal supersymmetric standard model (MSSM) [3].

In the MSSM, there are two charged and four neutral supersymmetric (SUSY) partners ($\tilde{\chi}$'s) of electroweak gauge bosons and Higgs bosons. In $p\overline{p}$ collisions the lightest chargino ($\tilde{\chi}_1^{\pm}$) and the second lightest neutralino ($\tilde{\chi}_2^0$) could be pair produced. They can decay leptonically $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \ell^{\pm} \nu$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$, in which $\tilde{\chi}_1^0$ is the lightest neutralino (lightest supersymmetric particle or LSP) and is stable. We expect an appreciable rate of the cross section times branching ratio ($\sigma \cdot BR$) for the resulting trilepton final state in the MSSM with the grand unified theory (GUT) hypothesis provided by supergravity [4] and slepton/neutrino mass constraints [5]. The trilepton final state has small SM backgrounds, making it an excellent discovery signature at hadron colliders [6].

We present results of the search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \ell^{\pm}\ell^+\ell^- + X$ events ($\ell = e$ or μ) using 19.1 pb^{-1} of data from $p\overline{p}$ collisions at a center of mass energy of $\sqrt{s} = 1.8$ TeV. The data sample was collected at the Collider Detector at Fermilab (CDF) during the 1992–93 run of the Fermilab Tevatron. The CDF detector is described in detail elsewhere [7]. The portions of the detector relevant to this analysis will be described briefly here. The location of the $p\overline{p}$ collision event vertex (z_{vertex}) is measured along the beam direction with a time projection chamber (VTX). The transverse momenta (P_T) of charged particles are measured in the pseudorapidity region $|\eta| < 1.1$ by the central tracking chamber (CTC), which is situated in a 1.4 T solenoidal magnet field. Here $P_T = P \sin\theta$, $\eta = -\ln\tan(\theta/2)$, and θ is the polar angle with respect to the proton beam direction. The electromagnetic (EM) and hadronic (HA) calorimeters are located outside the tracking chambers, segmented in a projective tower geometry, and covering the central (CEM, CHA; $|\eta| < 1.1$) and plug (PEM, PHA; $1.1 < |\eta| < 2.4$) regions. Muon identification is available in the central muon (CMU, CMP; $|\eta| < 0.6$) and muon extension (CMX, $0.6 < |\eta| < 1.1$ detectors.

The trilepton candidates are selected from an initial sample of 6.3×10^6 events that have fired the inclusive central electron or muon triggers with $P_T > 9.2$ GeV/c. We require the events to contain at least one lepton candidate passing strict lepton identification requirements and at least two additional lepton candidates with less stringent requirements. A strict electron candidate must deposit at least 11 GeV transverse energy ($E_T = E \sin\theta$) in the CEM, exhibit lateral and longitudinal shower profiles consistent with an electron, and be well matched to a charged track with $P_T \geq E_T/2$. A strict muon candidate must produce a track segment in the CMU and/or CMP chambers, be well matched to a charged track with $P_T \geq 11$ GeV/c, and deposit calorimeter energy consistent with a minimum ionizing (MI) particle. Loose electron selections accept CEM or PEM energy clusters, whose shower profiles are consistent with an electron, with $E_T \geq 5$ GeV. The CEM electron is required to be well matched to a charged track with $P_T \geq E_T/2$, while the PEM electron must be correlated with a high occupancy of hits in the VTX. Loose muon selections identify track segments in the CMU, CMP, or CMX with $P_T \geq 4$ GeV/c. In addition, a charged track with $P_T \geq 10$ GeV/c outside the central chamber coverage [7] is considered a central MI (CMI) muon if it deposits energy in the central calorimeters consistent with a MI particle. Finally, we remove tracks consistent with photon conversions ($\gamma \to e^+e^-$).

We further require (a) each lepton to pass a lepton isolation (ISO) cut in which the total calorimeter E_T in an η-ϕ cone of radius $R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the lepton, excluding the lepton E_T, must be less than 2 GeV; (b) $|z_{\text{vertex}}| \leq 60$ cm; (c) the η-ϕ distance ($\Delta R_{\ell\ell}$) between any two leptons to be greater than 0.4; (d) the difference in azimuthal angle ($\Delta\phi_{\ell_1\ell_2}$) between the two highest P_T leptons in the event to be less than 170°; (e) at least one e^+e^- or $\mu^+\mu^-$ pair; (f) removal of events containing an $\ell^+\ell^-$ pair with invariant mass in the regions 2.9–3.3 GeV/c^2 (J/ψ), 9–11 GeV/c^2 (Υ), and 75–105 GeV/c^2 (Z^0). After imposing these criteria, we are left with zero SUSY trilepton candidate events (see Table I).

We use the ISAJET Monte Carlo program [8] and a CDF detector simulation program to determine the total trilepton acceptance (ϵ^{tot}), which consists of geometric and kinematic acceptance, trigger efficiency, isolation efficiency, and lepton identification (ID) efficiency.

The trigger efficiency curves for single e's and μ's are obtained from data samples which are not biased by the inclusive lepton triggers. These curves reach a plateau above 11 GeV/c at $(84.3 \pm 1.5)\%$ for e's and $(88.6 \pm 0.7)\%$ for μ's. The isolation efficiencies for e and μ are determined from leptons in $Z^0 \to \ell^+\ell^-$ events (whose underlying event activity should be similar to that in SUSY events), where no isolation cut is imposed on the lepton. The isolation efficiencies are $(95 \pm 1)\%$ for central leptons and $(80 \pm 3)\%$ for plug electrons. Lepton ID efficiencies are also determined from the second leptons in $Z^0 \to \ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ events where no ID criteria are imposed on the second lepton. The values obtained from Z^0 and J/ψ events agree well, indicating that the ID efficiencies are independent of the lepton P_T. The resulting lepton ID efficiencies are listed in Table II.

The SM backgrounds can be divided into two classes: (i) direct trilepton events ($W^{\pm}Z^0, Z^0Z^0, t\overline{t}, b\overline{b}$, and $c\overline{c}$ production) and (ii) dilepton (Drell-Yan, Z^0, and W^+W^-) plus fake lepton events. The additional fake lepton is an object identified as a lepton, which does not come from the main physics process. Each of these backgrounds is estimated using ISAJET and the CDF detector simulation program.

In the first category of backgrounds, the production cross sections for $W^{\pm}Z^0, Z^0Z^0$, and $t\overline{t}$ are taken to be 2.5 [9], 1.0 [9], and 7 pb (top quark mass of 170 GeV/c^2)

TABLE I. Cumulative number of events left after each cut in the trilepton analysis, listed separately for the electron and muon trigger samples. The total data remaining after each cut is also listed, for comparison with the expected MC background. The original CDF data sample corresponds to $\int \mathcal{L}\, dt = 19.1 \pm 0.7$ pb^{-1}.

Cut	e triggers	μ triggers	$e + \mu$ (data)	$e + \mu$ (MC)
Original sample	3,677,903	2,707,852		
Dilepton events	5,472	6,606		
Trilepton events	94	136		
ISO $<$ 2 GeV	5	21		
$\lvert z_{\text{vertex}}\rvert < 60$ cm	5	21		
$\Delta R_{\ell\ell} > 0.4$	3	2	5	6.5
$\Delta\phi_{\ell_1\ell_2} < 170°$	2	2	4	3.4
Require e^+e^- or $\mu^+\mu^-$	2	2	4	3.2
Z^0 removal (75–105 GeV/c^2)	0	1	1	1.8
J/ψ removal (2.9–3.3 GeV/c^2)	0	1	1	1.8
Υ removal (9–11 GeV/c^2)	0	0	0	1.8

[10], respectively. It should be noted that the ISO distributions for b and c decay leptons in ISAJET agree well with those from the CLEOQQ program (optimized for heavy flavor decays) [11]. The total expected background from these processes is 1.12 ± 0.62 events, arising entirely from $b\bar{b}$ and $c\bar{c}$ production, with negligible contributions from $W^{\pm}Z^0, Z^0Z^0$, or $t\bar{t}$.

Since the primary mechanism of Drell-Yan, Z^0, and W^+W^- productions is the Drell-Yan process, an accurate fake rate (e.g., misidentified pions, photon conversions, decays in flight, b/c semileptonic decay leptons from initial state radiation, etc.) can be estimated by analyzing well-identified $W^{\pm} \rightarrow \ell^{\pm}\nu$ events (without any restriction on jets): $(0.273 \pm 0.036)\%$ fake leptons per event. The fake rate is then applied to the estimated rates of Drell-Yan, Z^0, and W^+W^- productions. We use the Drell-Yan and Z^0 production cross sections measured by CDF [12,13], while the W^+W^- production cross section is taken as 9.5 pb [9]. We estimate these background yields to be 0.58 ± 0.13 Drell-Yan events, 0.14 ± 0.03 Z^0 events, and negligible contribution from the W^+W^- process.

The total of all expected backgrounds is thus 1.8 ± 0.6 events. This is consistent with our observation of zero events.

There are four primary sources of systematic uncertainty in the $\sigma \cdot BR$ measurement: trigger efficiency, trilepton-finding efficiency, structure functions, and total integrated luminosity. The single muon trigger efficiency has the largest uncertainty ($\pm 2.7\%$), which we conservatively use for all events. The combined systematic uncertainty of all trilepton-finding efficiencies (kinematic, geometric, reconstruction, identification, and isolation) is $\pm 12.9\%$, mainly from the geometric and kinematic uncertainties in the detector simulation program. The trilepton acceptance was studied with the CTEQ 2L structure function [14] as the nominal choice, and various other structure functions [15]. We take the maximum deviations from the CTEQ 2L predictions as our systematic uncertainty $^{+8.2}_{-1.8}\%$. The systematic uncertainty of the total integrated luminosity is $\pm 3.6\%$. Combining these four uncertainties gives a total systematic uncertainty in $\sigma \cdot BR$ of $^{+15.6}_{-14.4}\%$.

Based on an observation of zero trilepton events, we set a 95% confidence level (C. L.) upper limit of 3.1 events on the mean number of events expected. This result is obtained by convolving the total systematic uncertainty of $\pm 15.6\%$ (as a Gaussian smearing) with a Poisson distribution. Given the ISAJET prediction on $\sigma \cdot BR$, we exclude a particular MSSM parameter space if

$$\sigma \cdot BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \longrightarrow 3\ell + X) > \frac{3.1}{\epsilon^{\text{tot}} \int \mathcal{L}\, dt}. \quad (1)$$

The value of ϵ^{tot} ranges from $\sim 1\%$ to 7% in the parameter region described below, and is approximately linearly dependent on the $\tilde{\chi}_1^{\pm}$ mass (40–70 GeV/c^2).

Assuming relations of the slepton and sneutrino masses to the gluino and squark masses [5], the MSSM predictions from ISAJET depend on the ratio of Higgs vacuum expectation values $\tan\beta$, the Higgs mixing parameter μ, the gluino mass $M(\tilde{g})$, the squark-to-gluino mass ratio $M(\tilde{q})/M(\tilde{g})$, the pseudoscalar Higgs mass $M(H_A)$, and the trilinear top-squark ($\tilde{t}$) coupling A_t. The last two parameters are fixed [$M(H_A) = 500$ GeV/c^2, $A_t = 0$], since they do not significantly alter the trilepton yield. Generally, allowed values of $\tan\beta$ are in the range from 1 to ~ 60. Values close to 1 are theoretically disallowed (the lightest $\tilde{t}_1$ becomes the LSP). For $\tan\beta \gtrsim 10$, the bottom squark ($\tilde{b}_1$) and tau slepton ($\tilde{\tau}_1$) can become

TABLE II. Lepton ID efficiencies (ϵ) obtained from $Z^0 \rightarrow \ell^+\ell^-$ and $J/\psi \rightarrow \ell^+\ell^-$ events in CDF data.

Muon type	ϵ (%)	Electron type	ϵ (%)
Strict CMU and CMP	89.0 ± 2.6	Strict CEM	82.5 ± 1.5
Loose CMU and CMP	93.5 ± 2.0	Loose CEM	85.0 ± 1.4
Loose CMX	94.0 ± 2.9	Loose PEM	89.0 ± 1.5
Loose CMI	92.5 ± 4.2		

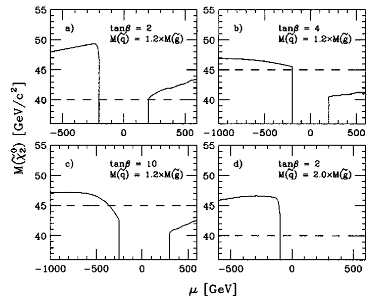

FIG. 1. Neutralino ($\tilde{\chi}_2^0$) mass lower limits obtained in the trilepton analysis (solid line). The SUSY parameters used for each plot were (a) $\tan\beta = 2$, $M(\tilde{q}) = 1.2M(\tilde{g})$; (b) $\tan\beta = 4$, $M(\tilde{q}) = 1.2M(\tilde{g})$; (c) $\tan\beta = 10$, $M(\tilde{q}) = 1.2M(\tilde{g})$; (d) $\tan\beta = 2$, $M(\tilde{q}) = 2.0M(\tilde{g})$. The dashed line is the limit extracted from LEP measurements [16]. Note that μ only extends down to -600 GeV for $\tan\beta = 2$.

light, due to mixing in these sectors. Consequently, the branching ratios for $\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau$ and $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ increase. Thus, the sensitivity of the search is somewhat degraded for $\tan\beta$ values above 10. Our trilepton sensitivity is lost for $|\mu| < 100$ GeV (where the leptonic branching ratios of the chargino and neutralino decrease significantly), and $|\mu|$ is favored to be $\lesssim 1000$ GeV (the approximate energy scale below which SUSY phenomena should be observable). Finally, the $M(\tilde{q})/M(\tilde{g})$ ratio is theoretically favored to be greater than unity [5], and the trilepton yield drops rapidly when this ratio exceeds 2 (this is due to sleptons becoming heavy, which reduces the neutralino leptonic branching ratio). Thus, we have scanned the following ranges of MSSM parameters: $\tan\beta = 2, 4, 10$; 200 GeV $< |\mu| <$ 1000 GeV; $M(\tilde{g}) = 120 \sim 250$ GeV$/c^2$; $M(\tilde{q})/M(\tilde{g}) = 1.0, 1.2, 2.0$.

This analysis is insensitive to $\tilde{\chi}_1^\pm$ masses above 47 GeV$/c^2$ for any choice of MSSM parameters. However, Fig. 1 shows several parameter space regions for which the results of this analysis can be compared with the existing $\tilde{\chi}_2^0$ mass limit [16], reaching as high as 49 GeV$/c^2$ at $\tan\beta = 2$. With Eq. (1), we also provide the 95% C.L. upper limits on $\sigma \cdot BR$ (single trilepton mode). At a particular choice of the MSSM parameters [$\tan\beta = 2, M(\tilde{q})/M(\tilde{g}) = 1.2, \mu = -400$ GeV], it is determined to be 1.4, 0.6, and 0.4 pb for $\tilde{\chi}_1^\pm$ masses of 45, 70, and 100 GeV$/c^2$, respectively.

In conclusion, we find no events consistent with $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair production in 1.8 TeV $p\overline{p}$ collisions, and set lower limits on the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses. The resulting $\tilde{\chi}_1^\pm$ mass limits are less than or equal to existing bounds. However, the $\tilde{\chi}_2^0$ mass lower limits obtained are as high as 49 GeV$/c^2$ in particular regions of the MSSM parameter space, improving previous bounds [16].

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