Search for Supersymmetry in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using the Trilepton Signature of Chargino-Neutralino Production.

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We use the three lepton and missing energy "trilepton" signature to search for chargino-neutralino production with 2.0 fb^{-1} of integrated luminosity collected by the CDF II experiment at the Tevatron $p\bar{p}$ collider. We expect approximately 11 supersymmetric events for a specific choice of parameters of the mSUGRA model, but our observation of 7 events is consistent with the standard model expectation of 6.4 events. We constrain the mSUGRA model of supersymmetry and rule out chargino masses up to 145 GeV/c^2 for a specific choice of parameters.

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Supersymmetry [1] posits the existence of boson (fermion) "superpartners" for standard model fermions (bosons). This resolves the "hierarchy problem" [2] in the standard model (SM) wherein an artificial cancellation of large mass terms is required for the Higgs boson mass to be at the electroweak breaking scale. The lightest supersymmetric particle (LSP), if stable and neutral, is an excellent dark matter candidate [3]. Since superpartners have not been observed at the same masses as the SM particles, supersymmetry (SUSY) cannot be an exact symmetry. There are several models for breaking SUSY while retaining its advantages [4]. A leading model is mSUGRA [5], a grand unified theory (GUT) that incorporates gravity. It has five parameters defined at the GUT scale ($\sim 10^{16}$ GeV): a common scalar mass m_0, a common gaugino mass $m_{1/2}$, the ratio of the Higgs vacuum expectation values $\tan\beta$, the trilinear scalar coupling A_0, and the sign of the higgsino mass parameter μ. These parameters determine the superpartner mass spectrum and coupling values at all scales.

Charginos ($\tilde{\chi}^{\pm}$'s) and neutralinos ($\tilde{\chi}^{0}$'s) are mass eigenstates formed by the mixture of gauginos and higgsinos, which are the fermionic superpartners of the gauge and Higgs bosons [5]. At the Tevatron, associated production of the lightest chargino with the next-to-lightest neutralino $p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + X$ may occur with a detectable rate. Depending on the mSUGRA parameter values, the $\tilde{\chi}_1^{\pm}$ and the $\tilde{\chi}_2^0$ can decay as follows: $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$, where $\ell = e, \mu, \tau$ and $\tilde{\chi}_1^0$ is the stable LSP. The neutrino and the LSP's are weakly interacting and escape undetected. This gives three leptons with large missing transverse energy as our experimental signature for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production. Since jets are abundant at hadron colliders while leptons are rare, the trilepton signature is perhaps the best avenue for observing supersymmetric events.

Prior searches at the LEP e^+e^- collider exclude chargino masses below 103.5 GeV/c^2 with minimal constraints [6]. At the Tevatron, the CDF and DØ collaborations have searched for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with 1 fb^{-1} of data [7, 8], but these trilepton searches have placed no further constraints on mSUGRA beyond those imposed by LEP experiments. In this analysis of 2.0 fb^{-1} of CDF data, we are able to probe mSUGRA beyond the LEP limits due to higher statistics and an improved technique.

The CDF II detector [9] has cylindrical symmetry around the proton-antiproton beam axis. Our analysis is restricted to the central region of the detector defined by pseudorapidity $|\eta| < 1.1$ [10]. The tracking system, used to measure the trajectory and momentum of charged particles, consists of multilayered silicon strip detectors and a drift chamber in a 1.4 T solenoidal magnetic field. Particle energies are measured with concentric electromagnetic and hadronic calorimeters. Muon detectors consisting of wire chambers and scintillators are placed at the outer radial edge of the detector to allow for the absorption of most other particles in the intervening material.

An electron typically deposits almost all ($\sim$93%) of its energy in the electromagnetic calorimeter producing a characteristic electromagnetic shower. We identify an electron as a track with an energy deposit that is consistent with its momentum (E/p requirement) with further constraints on the shower shape. "Tight" electrons meet these requirements whereas "loose" electrons satisfy a weaker shower shape criterion and need not meet the E/p requirement. A "tight muon" is a track which leaves a minimum-ionizing energy deposit in the calorimeter and reaches a muon detector. "Loose muons" are minimum-ionizing tracks outside the coverage of the muon detectors. We do not explicitly identify τ-leptons. Instead, the electron and muon candidates can come from τ decays. In addition, we allow isolated tracks [11] as indicators of the hadronic decays of τ-leptons to single charged particles. Together, the e, μ, and isolated track selection makes this analysis sensitive to $\sim$85% of τ decays, subject to the detector acceptance. The isolated track category also serves to accept poorly reconstructed electrons and muons, albeit at the expense of a higher background.

We require that the candidate leptons be isolated from hadronic activity in the detector. Lepton and isolated track candidates which are consistent with photon conversions or cosmic rays are rejected. The selected leptons have a small contamination from hadrons misidentified as leptons. These, along with leptons from semileptonic b and c quark decays and residual photon conversions, are labeled as "fake leptons".

Neutrinos and the LSP's escape the detector, leading to significant missing transverse energy $\not\!\!E_T$ in the event. $\not\!\!E_T$ is defined as the magnitude of $-\Sigma_i E_{\rm T}^i \hat{n}_i$, where the unit vector $\hat{n}_i$ is in the azimuthal plane and points from the beam axis to the ith calorimeter tower. We compensate $\not\!\!E_T$ for the presence of candidate muons and isolated tracks and also account for the corrections to jet energies due to effects such as non-linear calorimeter response.

Trilepton candidate events are collected with triggers that require at least one tight electron (muon) with $E_{\rm T} > 18$ GeV ($p_{\rm T} > 18$ GeV/c) or two tight electrons (muons) with $E_{\rm T} > 4$ GeV ($p_{\rm T} > 4$ GeV/c). An event must have at least two leptons (e's or μ's); the third

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"lepton" can be an isolated track, with the sum of the lepton charges required to be ± 1. We define five trilepton channels: $l_t l_t l_t$, $l_t l_t l_l$, $l_t l_l l_l$, $l_t l_t T$, and $l_t l_l T$ where l_t, l_l, and T, refer to a tight lepton, a loose lepton, and an isolated track, respectively. Table I shows the lepton energy thresholds for the five exclusive channels.

TABLE I: The $E_{\rm T}$ ($p_{\rm T}$) thresholds for electrons (muons, isolated tracks) for the five channels. l_t=tight lepton, l_l=loose lepton, and T=isolated track (lepton=e, μ).

Channel	$E_{\rm T}$ ($p_{\rm T}$) GeV (GeV/c)
$l_t l_t l_t$	15, 5, 5
$l_t l_t l_l$	15, 5, 10
$l_t l_l l_l$	20, 8, 5 (10 if μ)
$l_t l_t T$	15, 5, 5
$l_t l_l T$	20, 8 (10 if μ), 5

Several SM processes can mimic the trilepton signature. The leptonic decays of WZ, ZZ, and $t\bar{t}$ can produce three or more leptons. Dilepton processes, such as Drell-Yan or WW accompanied by a bremsstrahlung photon conversion ("brem conversion"), a fake lepton, or an isolated track, are also a source of background. For channels with isolated tracks, W production in association with jets gives significant background when one jet gives a fake lepton and another gives an isolated track.

To remove backgrounds containing on-shell Z, we reject events when the invariant mass of either of the oppositely charged lepton-lepton or lepton-track pairs is between 76 and 106 GeV/c^2. To suppress Drell-Yan background and backgrounds from resonances such as J/Ψ and Υ, we require invariant masses of both pairs to be > 13 GeV/c^2 and at least one mass to be > 20 GeV/c^2. The Drell-Yan background is further suppressed by requiring $\not\!\!E_T > 20$ GeV and the azimuthal angle $\Delta\phi$ between oppositely charged lepton-lepton (lepton-track) pairs to be less than 2.9 (2.8) radians. To supress the $t\bar{t}$ background, we allow no more than one jet with $E_{\rm T}$ >15 GeV and $|\eta| < 2.5$ per event.

The mSUGRA parameters for our nominal signal point are $m_0 = 60$ GeV/c^2, $m_{1/2} = 190$ GeV/c^2, $\tan\beta = 3$, $A_0 = 0$, and $\mu > 0$. These parameter values are typical of the mSUGRA region in which this analysis is sensitive. Simulated signal events are generated using the sparticle mass spectrum from ISAJET [12], followed by hard scattering in PYTHIA [13]. We use the MADEVENT [14] generator for the WZ background simulation [15]. The remaining background samples are generated using PYTHIA. Final stages of all signal and background simulation consist of hadronization using PYTHIA followed by CDF II detector simulation using GEANT3 [16]. For all generators we use the CTEQ5L [17] parton distribution functions (PDF).

We estimate WZ, ZZ, Drell-Yan (+ brem conversion) and WW (+ brem conversion) backgrounds using simulation. The number of events from Drell-Yan (WW) + additional isolated track are determined by scaling the number of Drell-Yan (WW) events estimated from simulation by the rate at which we expect an additional isolated track in the event. This rate is measured using Z events in data. We use data alone to measure backgrounds when a dilepton event is accompanied by a fake lepton. We estimate this background by applying the fake lepton probability measured in the multijet data sample to the jets in the dilepton data events. We use the same technique when lepton+track processes such as W+jets result in background for channels with isolated tracks. Table II shows the number of expected background and signal events for the nominal signal point

TABLE II: The number of expected events from background sources as well as for the nominal mSUGRA point. The number of observed events in data in each channel is also shown. l_t=tight lepton, l_l=loose lepton, and T=isolated track.

Channel	$l_t l_t l_t$	$l_t l_t l_l$	$l_t l_l l_l$	$l_t l_t T$	$l_t l_l T$	Σchannels
Drell-Yan	0.05	0.01	0.0	1.63	1.32	
Diboson	0.29	0.20	0.08	0.61	0.38	
Top-pair	0.02	0.01	0.03	0.22	0.18	
Fake lepton	0.12	0.04	0.03	0.75	0.41	
Total	0.49	0.25	0.14	3.22	2.28	6.4
Uncertainty	± 0.09	± 0.04	± 0.03	± 0.72	± 0.63	
Observed	1	0	0	4	2	7
SUSY Signal	2.3	1.6	0.7	4.4	2.4	11.4

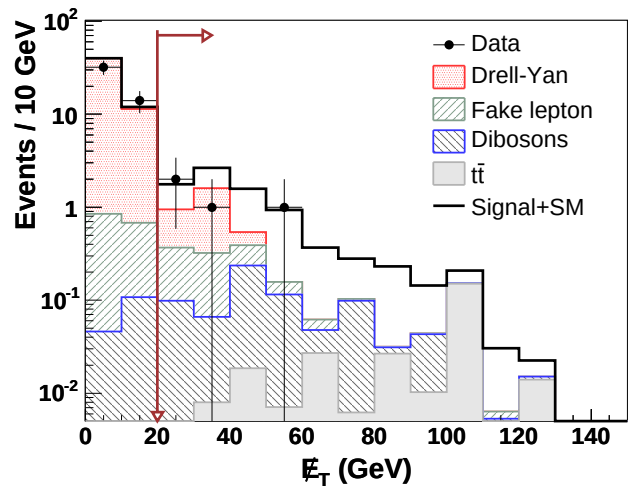

FIG. 1: $\not\!\!E_T$ distribution for the $l_t l_t T$ channel after all other selection criteria are applied. The observed data (points) compare well to the stacked sum of standard model contributions. The open histogram shows the sum of SM contributions and expected signal for the nominal mSUGRA point described in the text. We keep events with $\not\!\!E_T$ >20 GeV as indicated by the arrow. Other four channels show similar agreement.

described above.

Table II also lists uncertainties due to various systematic sources. Impact of effects such as imperfect QCD radiation modeling are estimated from the variation in the number of accepted signal and background events. Measurement uncertainties such as those in lepton selection efficiencies also affect the number of estimated signal and background events. Significant uncertainties in signal (background) estimates are 4% (2.5%) due to lepton selection, 4% (2.5%) due to QCD radiation, 2% (1.5%) due to the PDFs and 0.5% (5%) due to jet energy measurement. There is a 6% uncertainty in the integrated luminosity measurement and a 10% theoretical uncertainty [18] in the signal cross section. In addition, the total background estimate has a 10% uncertainty due to the lepton misidentification rate measurement. Uncertainties due to theoretical cross sections for background vary from 2.3 to 6.0%.

We verify the accuracy of background prediction for numerous regions defined by $\not\!\!E_T$ and invariant mass of the leading lepton pair *prior* to revealing candidate trilepton events in data. For example, in the region with $\not\!\!E_T >$ 15 GeV and invariant mass from 76 to 106 GeV/c^2, i.e, a 15 GeV/c^2 window around the Z mass, we predict $60.5 \pm$ 9.1 events and observe 61 trilepton events. We also test the $\not\!\!E_T <$ 10 GeV region (inside the Z mass window and outside) for trilepton and dilepton events and find the observations consistent with our expectations in each case. Figure 1 shows the $\not\!\!E_T$ distribution for the $l_t l_t T$ channel. The observed and predicted distributions agree well over the entire range. The figure also shows the candidate trilepton events in this channel.

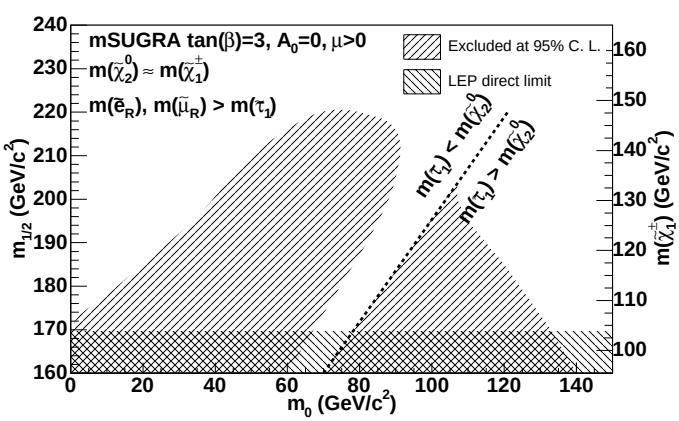

FIG. 2: Excluded regions in mSUGRA as a function of m_0 and $m_{1/2}$ for $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$. Corresponding $\tilde{\chi}_1^{\pm}$ masses are shown on the right-hand axis.

Table II shows the number of observed events in data in the signal region for each channel after all selections. The observation is consistent with the expected background in each channel and there is no evidence for physics beyond the standard model. Instead of adding signal and background in individual channels, we use the "CL$_s$" method [19, 20] to calculate the combined limits on the cross section times branching fraction ($\sigma \times \mathcal{B}$). Assuming that the number of observed events equals the SM expectation, we calculated the expected limits *prior* to revealing the trilepton candidate events in data. Comparing the observed limits with the theoretically expected $\sigma \times \mathcal{B}$ calculated at next-to-leading order using PROSPINO2 [21] gives the 95% C.L. mSUGRA exclusion region.

Figure 2 shows the mSUGRA m_0-$m_{1/2}$ plane divided in two regions: a heavy-slepton [m($\tilde{\tau}_1$)>m($\tilde{\chi}_2^0$)] region and a light-slepton [m($\tilde{\tau}_1$)<m($\tilde{\chi}_2^0$)] region. In the heavy-slepton region, the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ decay via virtual W, Z, or sleptons equally to the three lepton flavors. In the light-slepton region the predominant decay of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ is via intermediate sleptons. The $\tilde{\chi}_2^0$ decay is flavor-independent, but the $\tilde{\chi}_1^{\pm}$ decays mostly via $\tilde{\tau}$, thus favoring a τ-lepton in the final state. For small mass differences between $\tilde{\chi}_2^0$ and the sleptons (in Fig. 2, to the immediate left of the dashed line), the decay of the $\tilde{\chi}_2^0$ via a slepton ($\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp}$) leads to a lepton that is too soft to be detected. This loss in acceptance results in a gap in the exclusion between the heavy-slepton and light-slepton regions in the m_0-$m_{1/2}$ plane as seen in the figure.

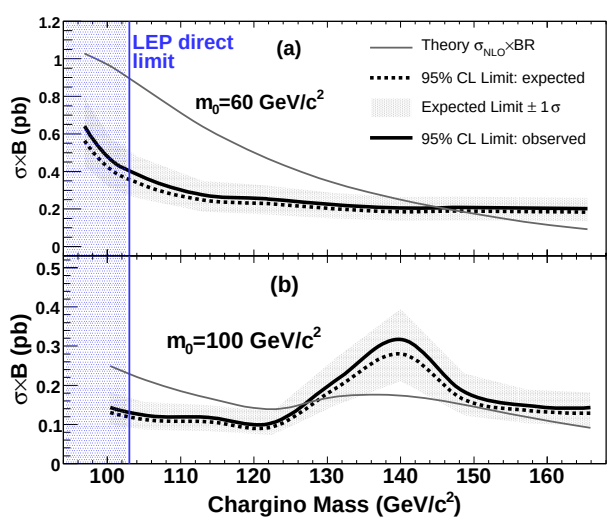

FIG. 3: Observed and expected $\sigma \times \mathcal{B}$ and prediction from theory as a function of chargino mass. We rule out chargino masses below 145 GeV/c^2 (where the theory and the experimental curves intersect) for (a) $m_0 = 60$ GeV/c^2 and below 127 GeV/c^2 for (b) $m_0 = 100$ GeV/c^2 .

In Fig. 3 we compare the observed and expected $\sigma \times \mathcal{B}$ limits with the theoretical predictions for two choices of m_0: $m_0 = 60$ GeV/c^2 in the light-slepton exclusion region and $m_0 = 100$ GeV/c^2 in the heavy-slepton region. For the 60 GeV/c^2 case, we rule out chargino masses

below 145 GeV/c^2. For the 100 GeV/c^2 case, the limits worsen as the slepton becomes lighter than the chargino for chargino masses above $\approx$ 130 GeV/c^2. Once the softest lepton p_T in the light-slepton region exceeds the detection threshold, the limit improves again. We rule out chargino masses below 127 GeV/c^2 in this case.

A study of how these trilepton search results apply to mSUGRA parameter space not explored here and to other models can be found in [22].

In conclusion, we have searched for the supersymmetric chargino-neutralino production using the three lepton and large $\not\!\!E_T$ signature with 2.0 fb^{-1} of data. Our observations are consistent with the standard model expectations. We exclude specific regions in the mSUGRA model's parameter space beyond LEP limits and rule out chargino masses up to 145 GeV/c^2 for a suitable choice of parameters.

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