Search for Supersymmetry in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using the Trilepton Signature for 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 an excess of approximately 11 supersymmetric events for a 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 posits the existence of boson (fermion) "superpartners" for standard model fermions (bosons) [1]. 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 scale. The lightest supersymmetric particle (LSP), if stable and neutral, is an excellent dark matter candidate [3]. However, 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. Its five parameters, m_0, $m_{1/2}$, $\tan\beta$, A_0, and the sign of μ, defined at the GUT energy scale, 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 $\ell = e$, μ, τ 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 SUSY events.

Prior searches at the LEP e^+e^- collider exclude chargino masses below 103.5 GeV/c^2 with minimal assumptions [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 $p\bar{p}$ 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 (EM) 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.

A typical electron deposits most ($\sim 93\%$) of its energy in the EM calorimeter producing an electromagnetic shower. We identify an electron as a track whose energy deposit is consistent with its momentum (E/p requirement). "Tight" electrons satisfy electromagnetic shower shape requirements; "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 is detected by 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. The isolated track category also serves to accept poorly reconstructed e's and μ's, 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 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, 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 $\vec{\not{E}}_T = -\Sigma_i E_T^i \hat{n}_i$, where the unit vector $\hat{n}_i$ in the azimuthal plane points from the beam axis to the ith calorimeter tower. We correct $\not{E}_T$ for the presence of candidate muons and isolated tracks.

Trilepton candidate events are collected with triggers that require at least one tight electron (muon) with $E_T > 18$ GeV ($p_T > 18$ GeV/c) or two tight electrons (muons) with $E_T > 4$ GeV ($p_T > 4$ GeV/c). An event must have at least two leptons (e's or μ's); the third "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.

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

TABLE I. The E_T (p_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_T (p_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

TABLE II. The number of expected events from background sources and for the nominal mSUGRA point. The number of observed events in data is also shown. l_t = tight lepton, l_l = loose lepton, and T = isolated track (lepton = e, μ). The sums shown (rightmost column) are illustrative and not used in this analysis.

Channel	$l_t l_t l_t$	$l_t l_t l_l$	$l_t l_l l_l$	$l_t l_t T$	$l_t l_l T$	$\sum$ (channels)
Drell-Yan	0.05	0.01	0.0	1.63	1.32	3.01
Diboson	0.29	0.20	0.08	0.61	0.38	1.56
Top-pair	0.02	0.01	0.03	0.22	0.18	0.46
Fake lepton	0.12	0.04	0.03	0.75	0.41	1.35
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

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’s produced with jets result in significant background when one jet gives a fake lepton and another gives an isolated track.

To remove backgrounds containing an 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$/c^2$. We reject events with a fourth lepton or track with $p_T > 10$ GeV$/c$, principally to reduce the ZZ background. To suppress backgrounds from Drell-Yan and 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 between oppositely charged lepton-lepton (lepton-track) pairs to be less than 2.9 (2.8) radians. To suppress the $t\bar{t}$ background, we allow no more than one jet with $E_T > 15$ GeV and $|\eta| < 2.5$ in an 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 (or WW) + additional isolated track are determined by scaling the corresponding estimate 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 fake lepton accompanies a dilepton event 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 described above.

Table II also lists uncertainties due to various systematic sources. Significant uncertainties in signal (background) estimates are 4% (2.5%) due to lepton selection efficiency, 4% (2.5%) due to imperfect QCD radiation modeling, 2% (1.5%) due to the PDF uncertainty and 0.5% (5%) due to jet energy measurement uncertainty. There is a 6% uncer-

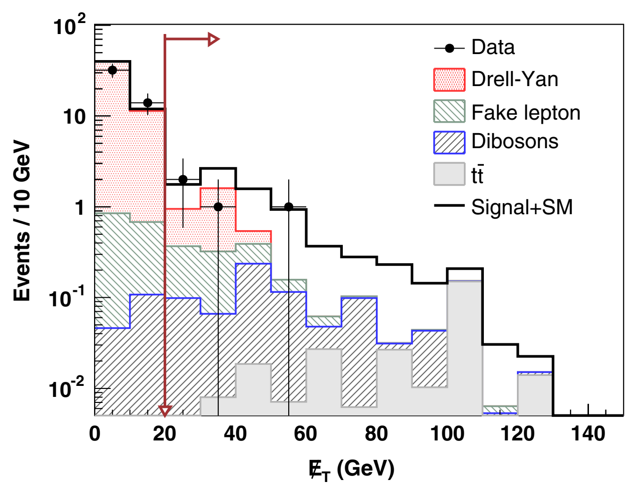

FIG. 1 (color online). $\not\!\!E_T$ distribution for the $l_t l_l T$ channel after all other selection criteria are applied. The observed data (points) compare well to the stacked sum of standard model contributions. The open histogram shows the sum of SM contributions and expected signal for the nominal mSUGRA point. We keep events with $\not\!\!E_T > 20$ GeV.

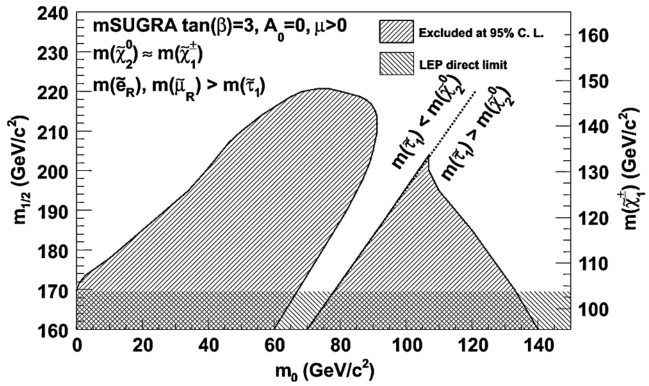

FIG. 2. Excluded regions in mSUGRA as a function of m_0 and $m_{1/2}$ for $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$. Corresponding $\tilde{\chi}_1^{\pm}$ masses are shown on the right-hand axis.

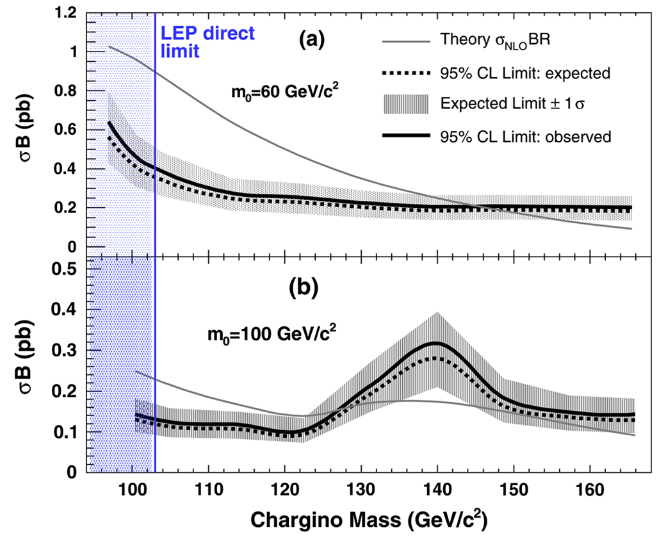

FIG. 3 (color online). Observed and expected $\sigma\mathcal{B}$ and prediction from theory as a function of the chargino mass. We rule out chargino masses below 145 GeV$/c^2$ (where the theory and the experimental curves intersect) for (a) $m_0 = 60$ GeV$/c^2$ and below 127 GeV$/c^2$ for (b) $m_0 =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

tainty in the integrated luminosity measurement and a 10% theoretical uncertainty [18] in the signal cross section. The total background estimate has a 10% uncertainty due to the lepton misidentification rate measurement, and uncertainties due to theoretical cross sections for background vary from 2.3 to 6.0%.

Prior to revealing candidate trilepton events in data, we verify the accuracy of background prediction for numerous regions defined by $\not{E}_T$ and invariant mass of the leading lepton pair. 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 ± 9.1 events and observe 61 trilepton events. A number of such "control region" comparisons and a detailed description of this analysis can be found in [19]. 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.

Table II shows that the observation is consistent with the expected background in each channel, i.e., there is no evidence for physics beyond the standard model. We combine the individual channels following the method in [20,21] and calculate the limits on the cross section times branching fraction ($\sigma\mathcal{B}$). Comparing the observed limits with the theoretically expected $\sigma\mathcal{B}$ calculated at next-to-leading order using PROSPINO2 [22] gives the 95% C.L. mSUGRA exclusion region.

Figure 2 shows the exclusion in 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 approximately 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 $\tilde{\chi}_1^{\pm}$ 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, the region immediately left of the dashed line), the decay of the $\tilde{\chi}_2^0$ via a slepton ($\tilde{\chi}_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$) leads to a lepton that is too soft to be detected. This loss in acceptance results in a gap in the exclusion between the two regions in the $m_0 - m_{1/2}$ plane as seen in the figure.

We calculate the expected limits under the assumption that there is no physics beyond the SM. Figure 3 compares the observed and expected $\sigma\mathcal{B}$ limits with the theoretical predictions for two choices of m_0: 60 GeV$/c^2$ in the light-slepton exclusion region and 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 $\sim$130 GeV$/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 other SUSY models and to mSUGRA parameter space which we have not explored here can be found in [23].

In conclusion, we have searched for 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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