Search for Chargino-Neutralino Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for associated production of the chargino and neutralino supersymmetric particles using up to 1.1 fb^{-1} of integrated luminosity collected by the CDF II experiment at the Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV. We analyze events with a large transverse momentum imbalance and either three charged leptons or two charged leptons of the same electric charge. The numbers of observed events are consistent with standard model expectations. Upper limits on the production cross section are derived in different theoretical models.

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Supersymmetry (SUSY) [1] is one of the most appealing theories for physics beyond the standard model (SM). SUSY predicts the existence of a superpartner (sparticle) for each SM particle, sharing the same quantum numbers but differing by half a unit of spin. SUSY addresses several problems of the SM: it can solve the "hierarchy problem" [2], it can provide a good candidate for the cold dark matter in the Universe [3], and it makes possible a unification of the fundamental forces at high energies [4]. A natural solution to the hierarchy problem and the prospect of gauge coupling unification suggest that sparticle masses are near the electroweak scale and thus may be observable at the Tevatron.

We present a search for the associated production of the lightest chargino $\tilde{\chi}_1^{\pm}$ and the second-to-lightest neutralino $\tilde{\chi}_2^0$, the mass eigenstates of the superpartners of the electroweak gauge and Higgs boson. Chargino-neutralino production, $p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + X$, is one of the most interesting SUSY processes at the Tevatron in models in which the gauginos are light. It can be detected through the observation of isolated charged leptons [5] and a large imbalance in the transverse energy ($\not{E}_T$) from the decays $\tilde{\chi}_1^{\pm} \to \ell^{\pm}\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$, where $\ell = e$, μ, τ, and $\tilde{\chi}_1^0$ is the lightest SUSY particle, assumed to be stable and to escape detection. This signature has the experimental advantage that at hadron colliders leptons are relatively rare compared to the copiously produced jets, they are well identifiable, and the SM backgrounds are rather small, as they arise primarily from electroweak processes. We use three benchmark models based on the minimal supersymmetric standard model (MSSM) to interpret the data. The models differ mostly in the leptonic branching ratios of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ and in the kinematic properties of the leptons.

Previous searches at LEP excluded $\tilde{\chi}_1^{\pm}$ masses below 103.5 GeV$/c^2$ [6] at the 95% confidence level (C.L.). This constraint is very robust and does not change much within minimal supergravity-inspired SUSY models. The D0 Collaboration recently constrained the $\tilde{\chi}_1^{\pm}$ mass to be larger than 117 GeV$/c^2$ at 95% C.L. in a specific scenario [7].

This Letter summarizes and interprets the results from seven individual search channels with different lepton flavors and kinematic properties in the final state. The analyses use $p\bar{p}$ collision data taken by the CDF II detector at the Tevatron accelerator with a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The data, collected between March 2002 and February 2006, correspond to an integrated luminosity between 0.7 and 1.1 fb^{-1}, depending on the decay signature.

The CDF II detector [8] is cylindrically symmetric around the beam pipe in which the protons and antiprotons collide [5]. The transverse momentum of charged particles, p_T, is measured by a tracking system composed of an eight-layer silicon strip detector and a 96-layer drift chamber; both are located inside a solenoid providing a magnetic field of 1.4 T aligned along the beam axis. Electromagnetic and hadronic calorimeters surrounding the solenoid measure the energies of particles up to $|\eta| < 3.6$. Wire chambers and scintillators are installed around the hadronic calorimeter to detect muons with $|\eta| < 1.4$. Gas Cherenkov counters [9] measure the average number of $p\bar{p}$ inelastic collisions per bunch crossing and thereby determine the beam luminosity.

We now outline the seven individual analyses that are then combined to achieve maximum sensitivity. The like-sign (LS) analyses ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$) [10] require two leptons of the same electric charge and do not require the detection of a third lepton. In the trilepton analyses, the third lepton candidate can either be a fully reconstructed electron or muon ($e\ell\ell$, $\mu\ell\ell$ [11], $\mu\mu\ell$ [12], $\ell = e, \mu$) or a "track" from a charged particle (eet). The eet analysis gains acceptance in detector areas where the electron or muon detection is less efficient and adds sensitivity to hadronic decays of τ leptons. There is up to 30% overlap among the individual analyses which is accounted for in the combination, as explained later in this Letter.

The dominant SM background sources are diboson production with three or more prompt leptons (WZ, ZZ) and Drell-Yan (DY) events in which the third lepton results either from the conversion of a bremsstrahlung photon ($Z + \gamma$, with $\gamma \to e^+e^-$) or from a misidentified hadron. With Z we denote the production of a Z or a virtual photon γ^*. For the LS analyses $W\gamma$ production with a photon conversion is also a significant background. Smaller background contributions arise from $t\bar{t}$ and $b\bar{b}$ production with semileptonic b- and c-hadron decays. All these background sources are modeled using Monte Carlo (MC) event generators. Backgrounds from $t\bar{t}$, ZZ, and DY production are generated using PYTHIA [13]. The $W\gamma$ and WZ backgrounds are generated using for the hard-scattering process a program by Baur and Berger [14] and MADEVENT [15], respectively. In all cases PYTHIA is used for the parton showering and hadronization and the parton distribution functions are parametrized using CTEQ5 [16]. All MC events are subsequently passed through the CDF II detector simulation based on the GEANT3 [17] framework, and reconstructed and analyzed in the same way as the data. The $b\bar{b}$ background was determined using a combination of MC and data estimates [12] and is negligible in most of the analyses. An additional background source is hadrons that are misidentified as leptons ("mis-id"). We determine the misidentification probability in jet data samples as a function of the lepton p_T or E_T using jets and tracks and apply it to the two leptons (one lepton) data sample for the trileptons (LS) analyses [10,11].

In the LS, $e\ell\ell$, and $\mu\ell\ell$ analyses, events are triggered on one well-identified central electron with $E_T > 18$ GeV or muon with $p_T > 18$ GeV$/c$. In the eet ($\mu\mu\ell$) analysis events are triggered on two central electrons (muons) with $E_T > 4$ GeV ($p_T > 4$ GeV$/c$). We select additional electrons in the central and the forward calorimeters. They are required to have a shower shape consistent with that expected for an electron and a track matched to the calorimeter cluster. Muons are required to deposit an amount of energy in the calorimeter consistent with the expectation for a minimum ionizing particle; additionally, trigger muons must have associated hits in the muon detectors. Dedicated algorithms reject photon conversions and cosmic rays [11]. We require all leptons to be isolated from other particles in the event. For the electrons and muons in the $e\ell\ell$, $\mu\ell\ell$, eet, and $\mu\mu\ell$ analyses the isolation requirement is based only on the calorimeter energy deposits. For the track of the eet analysis it is based only on charged tracks, and for electrons and muons in the LS analyses it is based on both.

We exclude events in which two leptons form an invariant mass $m_{\ell\ell} < 15$ GeV$/c^2$ or $76 < m_{\ell\ell} < 106$ GeV$/c^2$ in order to remove DY and diboson events. The lower mass threshold additionally removes $b\bar{b}$ background. For the $e\ell\ell$ (LS) analysis the lower mass value is raised to 20(25) GeV$/c^2$. For the LS analyses the mass interval near the Z resonance is changed to $66 < m_{\ell\ell} < 116$ GeV$/c^2$. Backgrounds from DY production are further reduced by requiring $\not{E}_T > 15$ GeV (for the eet analysis $\not{E}_T > 20$ GeV). The $t\bar{t}$ background is reduced by vetoing events with large hadronic jet activity. Requirements on the angles between the leptons and $\not{E}_T$ are placed in order to reduce the cosmic-ray background. A detailed description of the selection requirements is given elsewhere [10–12].

To illustrate the model sensitivity of the search we use three example SUSY models. The first is the scenario of minimal supergravity (mSUGRA) [18], a grand unified theory including gravity which has five independent parameters, fully determining all the masses and couplings of the SUSY particles. Since the present analysis is most sensitive to the common gaugino mass $m_{1/2}$, we fix the other four parameters: the common scalar mass is set to $m_0 = 60$ GeV$/c^2$, the higgsino mixing parameter (μ) is taken to be positive, the trilinear coupling (A_0) is set to 0, and the ratio of the vacuum expectation values of the two Higgs fields ($\tan\beta$) is set to 3. In mSUGRA the lightest slepton is a SUSY partner of the τ leading to a larger branching ratio ($\mathcal{B}$) into τ leptons: about 90% of the events contain at least one τ lepton. The second model we call "MSSM (W/Z model)": all the parameters are taken to be the same as in the above model, but the $\mathcal{B}$ of $\tilde{\chi}_1^\pm(\tilde{\chi}_2^0)$ into leptons is fixed to be the same as the $\mathcal{B}$ of the $W(Z)$ gauge boson into leptons. In the third model, the "MSSM (no $\tilde{\ell}$ mixing)", the slepton chirality eigenstates are the mass eigenstates, resulting in nearly equal branching ratios of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ to all three lepton flavors. In this model about 30% of the events contain no τ leptons. For all three scenarios the relationship between the masses of the gauginos is $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$. The slepton mass value is approximately $0.31 \times m_{\tilde{\chi}_1^\pm} + 67$ GeV$/c^2$. For the first and second models, the most stringent constraint on the $\tilde{\chi}_1^\pm$ mass to date is the LEP limit of 103.5 GeV$/c^2$ while for the third model the most stringent limit is 117 GeV$/c^2$ [7].

For the signal simulation we use SOFTSUSY [19] and ISAJET [20] to compute the sparticle mass spectrum; PYTHIA is used to generate the hard-scattering events, the parton radiation, and the hadronization. CTEQ5 is used for the parton distribution functions. The CDF II detector's response to these events is then simulated. The signal acceptance for the process $p\bar{p} \to \tilde{\chi}_1^\pm\tilde{\chi}_2^0 + X \to \ell\ell\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0 + X$, ($\ell = e, \mu, \tau$), in the MSSM (no $\tilde{\ell}$ mixing) scenario varies from 2.7% at $m_{\tilde{\chi}_1^\pm} \approx 105$ GeV$/c^2$, where only the LS analyses are sensitive, to 6.2% at $m_{\tilde{\chi}_1^\pm} \approx 160$ GeV$/c^2$, where the acceptance of the trilepton analyses is maximal. The acceptance in the MSSM (W/Z model) rises from 3.0% at low $m_{\tilde{\chi}_1^\pm}$ to 4.0% at $m_{\tilde{\chi}_1^\pm} \approx 150$ GeV$/c^2$. The acceptance for mSUGRA is only 1.0%, independent of $m_{\tilde{\chi}_1^\pm}$, due to the enhanced decay of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ into τ leptons.

There are systematic uncertainties on both the signal acceptance and the background prediction that have been evaluated by many comparisons of data and simulation [10–12]. The signal acceptance has an uncertainty due to the lepton selection (1.5%–13%) and trigger (<0.5%) efficiencies, the modeling of QCD radiation (2%–12%), the parton distribution functions (1%), the integrated luminosity (6%), and the jet energy measurement (1%–5%). The background is also affected by the lepton- and jet-related uncertainties and the luminosity uncertainty. Additionally, we consider uncertainties on the lepton misidentification rate (50% for the trilepton and 10%–20% for the LS analyses), the conversion background (3%–16%), and the theoretical cross sections (7% for diboson, 10% for $t\bar{t}$, and 5% for DY production). Finally, the statistical uncertainties on the Monte Carlo samples are taken into account.

In Table I, the number of observed events is compared to the background contributions for each analysis. The number of data events is consistent with the background expectation in all analyses and no evidence of non-SM

TABLE I. The numbers of expected and observed events for each analysis before events which are shared by more than one analysis are assigned to a single analysis. For the eet analysis the background from misidentified jets is included in the $Z + \gamma$ background estimate of this analysis.

	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e\ell\ell$	$\mu\ell\ell$	eet	$\mu\mu\ell$
$Z + \gamma$	0.49	0.62	—	0.18	0.30	0.54	0.06
$W\gamma$	1.54	1.63	—	—	—	—	—
$t\bar{t} + b\bar{b}$	0.01	0.03	0.01	0.04	0.03	0.22	0.06
WW, WZ, ZZ	0.32	0.82	0.53	0.39	0.66	0.21	0.09
Mis-id	0.60	0.90	0.38	0.14	0.27	—	0.20
Total	2.96	4.00	0.92	0.75	1.26	0.97	0.41
Uncertainty	±0.48	±0.57	±0.12	±0.36	±0.27	±0.28	±0.11
Observed	4	8	1	0	1	3	1

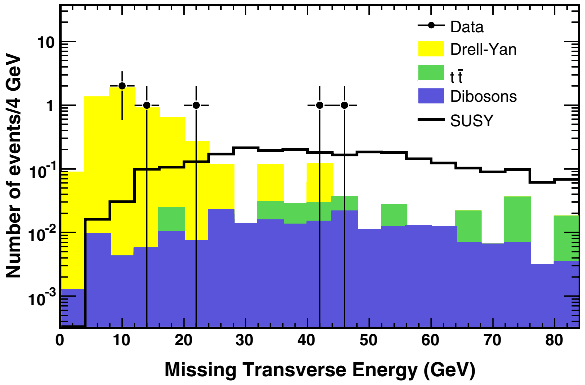

FIG. 1 (color online). $\not{E}_T$ distribution for the eet analysis after all the selection criteria are applied except for $\not{E}_T > 20$ GeV. The observed data (points) are compared to the sum of the SM contributions (stacked, filled histograms). The open histogram shows the expected SUSY contribution for the mSUGRA scenario described in the text with $m_{\tilde{\chi}_1^\pm} = 113\ \mathrm{GeV}/c^2$ and $\sigma \times \mathcal{B} = 0.16$ pb.

physics is observed. There is a slight excess of the data in the $e^\pm\mu^\pm$ and eet analyses. Figure 1 shows the $\not{E}_T$ distribution for the eet analysis. The observed data agree well with SM predictions at low values of $\not{E}_T$ where the background is dominant.

The data can be used to constrain the cross section times branching ratio, $\sigma \times \mathcal{B}$, and the allowed mass range of charginos for the SUSY scenarios discussed earlier. To remove the overlaps among the analyses, events which are selected by more than one analysis are assigned to the channel with the highest *a priori* signal-to-background ratio to obtain the best sensitivity. The frequentist-based "CL_s" method [21,22] is then used on the resulting non-overlapping analyses. The correlations between the systematic uncertainties of the individual analyses have been evaluated for both the signal and the background and are accounted for in the limit calculation. A mass limit for the $\tilde{\chi}_1^\pm$ is derived from the cross section limit by comparing the observed limit to the next-to-leading order calculation for the cross section [23]. An uncertainty of 10% on the signal theoretical cross section is included in the limit calculation [24].

Figure 2 shows the 95% C.L. upper limit on the $\sigma \times \mathcal{B}$ as a function of the $\tilde{\chi}_1^\pm$ mass in the three theoretical scenarios mSUGRA, MSSM (W/Z model), and MSSM (no $\tilde{\ell}$ mixing). In each scenario the observed and the expected limits are compared with the theoretical $\sigma \times \mathcal{B}$ predictions. The expected limit is defined to be the median limit one would obtain in a sample of independent experiments in which no signal is present. It is used to estimate the *a priori* sensitivity of the search since it does not depend on the observed data. The observed limit is typically a factor of 2 larger than the expected, as the number of events observed is higher than the predicted background in the eet and $e^\pm\mu^\pm$ analyses. In the mSUGRA scenario

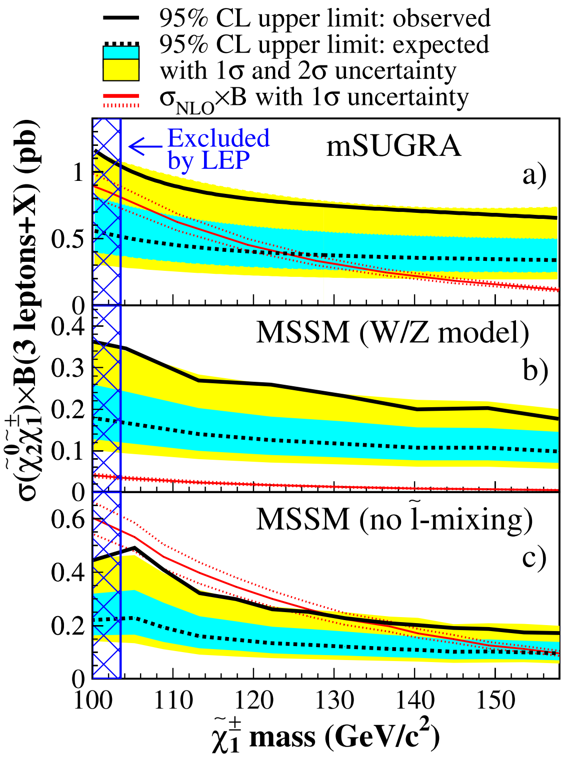

FIG. 2 (color online). $\sigma \times \mathcal{B}$ for $p\bar{p} \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0 + X \to \ell\ell\ell + X$ as function of the $\tilde{\chi}_1^\pm$ mass. Shown are the observed and expected experimental upper limits and the theoretical cross section for the mSUGRA (a), the MSSM (W/Z model) (b), and the MSSM (no $\tilde{\ell}$ mixing) (c) scenario described in the text. Also shown are the 1σ and 2σ ranges for the expected limit.

[Fig. 2(a)] $\sigma \times \mathcal{B} > 1$ pb is excluded for all $m_{\tilde{\chi}_1^\pm}$. The limit improves with increasing mass down to 0.8 pb at $m_{\tilde{\chi}_1^\pm} = 150\ \mathrm{GeV}/c^2$. In the MSSM W/Z model and no $\tilde{\ell}$ mixing scenarios [Fig. 2(b) and 2(c)] the limits on $\sigma \times \mathcal{B}$ range between 0.2 and 0.4 pb. In the MSSM (no $\tilde{\ell}$ mixing) scenario [Fig. 2(c)] we set a 95% C.L. lower limit on the $\tilde{\chi}_1^\pm$ mass of 129 GeV/c^2, which is the most stringent limit to date. In the mSUGRA and MSSM (no $\tilde{\ell}$ mixing) scenarios the expected $\tilde{\chi}_1^\pm$ mass limits are 122 GeV/c^2 and 157 GeV/c^2, respectively.

In conclusion, we present a search for the associated production of charginos and neutralinos using events with isolated leptons and large $\not{E}_T$. The observed data are consistent with standard model predictions. Limits are derived on the cross section times the leptonic branching ratio for this process and on the mass of the lightest chargino under different theoretical assumptions. In the MSSM (no $\tilde{\ell}$ mixing) scenario, chargino masses below 129 GeV/c^2 are excluded at the 95% C.L., extending the previous limits by 12 GeV/c^2.

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