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We present a search for chargino-neutralino associated production using like electric charge dilepton events collected by the CDF II detector at the Fermilab Tevatron in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV. One lepton is identified as the hadronic decay of a tau lepton, while the other is an electron or muon. In data corresponding to 6.0 fb^{-1} of integrated luminosity, we obtain good agreement with standard model predictions, and set limits on the chargino-neutralino production cross section for simplified gravity- and gauge-mediated models. As an example, assuming that the chargino and neutralino decays to taus dominate, in the simplified gauge-mediated model we exclude cross sections greater than 300 fb at 95% credibility level for chargino and neutralino masses of 225 GeV/c^2. This analysis is the first to extend the LHC searches for electroweak supersymmetric production of gauginos to high $\tan\beta$ and slepton next-to-lightest supersymmetric particle scenarios.

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Supersymmetry (SUSY) is an appealing extension to the standard model (SM) of particle physics as it mitigates the hierarchy problem, provides a dark matter candidate, and allows for gauge-coupling unification at high energy [1–8]. Extensive searches for SUSY phenomena have been performed at the LEP [9], Tevatron [10–15], and LHC [16–21] colliders. To date, no evidence of SUSY has been found. The LHC analyses provide stringent limits on the SUSY partners of light quarks and the gluon, the squarks and the gluino, with mass limits in excess of 1 TeV/c^2. Typical searches assume strong production of squarks and gluinos with cascade decays to the gauginos (the SUSY partners of the electroweak gauge and Higgs bosons, the charginos and neutralinos), followed by hadronic or leptonic decays. These final-state particles are accompanied by two or more of the lightest SUSY particle (LSP), that is stable if R_p parity is

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conserved [22]. In the minimal supersymmetric standard model (MSSM) with gravity mediation, the LSP is often the lightest neutralino $\tilde{\chi}_1^0$, which provides a cosmological dark matter candidate. Alternatively, in gauge-mediated models [23, 24], the gravitino plays the role of the LSP, and the phenomenology depends on the nature of the next-to-lightest SUSY particles. If these are the SUSY lepton partners (sleptons), their decays lead to detectable leptons. Both models produce an appreciable momentum imbalance in the plane transverse to the beam direction due to the undetected LSPs [25].

Given the lack of evidence of strongly-produced SUSY particles, searches for direct electroweak production of charginos and neutralinos are particularly well-motivated at present. This production can lead to the striking signature of sparse events with two or three leptons and a transverse momentum imbalance. Most SUSY searches also assume $\tan\beta \lesssim 10$, where $\tan\beta$ is the ratio of the vacuum expectation values for the two Higgs doublets, which results in similar gaugino decay-widths to electrons, muons, and tau leptons. At high values of $\tan\beta$, e.g., $\tan\beta \simeq 30$, appreciable left-right mixing drives the mass of the lighter SUSY tau particle (stau, $\tilde{\tau}$) to lower values, and results in enhanced branching fractions to taus as two-body decays become kinematically accessible. As the value of $\tan\beta$ is a free parameter of the theory, searches sensitive to tau leptons can play a critical role in the search for SUSY phenomena. ATLAS [26] and CMS [27] have recently published searches for SUSY electroweak production with leptonic decays. ATLAS searches for trilepton signals with electrons and muons in the final state, and does not consider tau-enriched scenarios. CMS searches for dilepton and trilepton signals including those with hadronic tau decays, and places bounds on flavor-universal and tau-enriched scenarios. While these results are generally more stringent than what is possible at the Tevatron, there are regions of parameter space still unexplored by the LHC experiments. These include the high $\tan\beta$ case where all gaugino decays produce taus, and gauge-mediated scenarios with slepton next-to-lightest SUSY particles. The current situation provides strong motivation for this analysis, which probes these unexplored regions for the first time.

This Letter reports the results of a search for chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) associated electroweak production yielding tau-dominated final states using data collected with the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider at a center-of-mass energy of 1.96 TeV. The analysis considers a single W-boson-mediated s-channel amplitude, while the t-channel squark exchange amplitude is insignificant with the assumption of heavy squarks, as motivated by the LHC limits. Using a simplified framework [25], we study two distinct cases. In the first, charginos decay promptly into a single lepton through a slepton $\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}^{\pm(*)}\, \nu_\ell \rightarrow \tilde{\chi}_1^0\, \ell^\pm\, \nu_\ell$ and neutralinos similarly decay into two detectable leptons $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm(*)}\, \ell^\mp \rightarrow \tilde{\chi}_1^0\, \ell^\pm\, \ell^\mp$. The second case assumes the same gaugino decays, followed by the gauge-mediated slepton decays $\tilde{\ell} \rightarrow \ell\tilde{G}$, where $\tilde{G}$ is the LSP gravitino. Both cases yield events with three electrically-charged leptons accompanied by undetectable particles. However, requiring the detection of all three leptons would degrade the search sensitivity, especially for the case of decays to tau leptons, which is the focus of this analysis. Instead, we require detection of either an electron or muon plus a hadronically-decaying tau lepton. Tau leptons decay hadronically, with a branching fraction of about 65%, as $\tau \rightarrow X_h\, \nu_\tau$, where X_h is a system of hadrons consisting of charged and neutral pions or kaons. A like-sign (LS) requirement on the light lepton (e, μ) electric charge and net electric charge of the tau decay-products efficiently rejects prominent SM backgrounds such as Z boson, WW bosons, and top-antitop quark production, which yield opposite-sign (OS) leptons. We perform a counting experiment and compare the yield of LS lepton-tau events in data with SM background predictions folded with sources of misidentified taus, and validate the results with control samples of OS events. In this Letter, "lepton" and "tau" (or τ) refer to e or μ and hadronically-decaying tau leptons, respectively. The LS signature is common in many SUSY models. Our search has sensitivity for high $\tan\beta$ due to a dedicated tau reconstruction, and since the identified e or μ can result from a leptonic tau decay.

The CDF II detector is described in Ref. [28]. The innermost components are multi-layer silicon-strip detectors and an open-cell drift chamber tracking system covering $|\eta| < 1$ [29] inside a 1.4 T superconducting solenoid. Surrounding the magnet are sampling electromagnetic and hadronic calorimeters, segmented in projective-tower geometry, covering $|\eta| < 3.6$. Strip-wire chambers in the central electromagnetic calorimeter at a depth approximately corresponding to the maximum development of the typical electromagnetic shower aid in reconstructing electrons, photons, and $\pi^0 \rightarrow \gamma\gamma$ decays in the region $|\eta| < 1.1$. At larger radii are scintillators and wire-chambers for muon identification: the central muon ($|\eta| < 0.6$) and the forward muon ($0.6 < |\eta| < 1$) detectors.

Data corresponding to an integrated luminosity of 6.0 fb^{-1}, collected between 2002 and 2010 by a dedicated online event-selection (trigger) [30], are used. This trigger requires a charged particle reconstructed with the silicon and drift chamber detectors with $p_T > 8$ GeV/c matched to an electron (muon) signal in the central electromagnetic calorimeter (central or forward muon detector), and an additional isolated charged particle with $p_T > 5$ GeV/c that seeds the tau reconstruction. At trigger level a charged particle is isolated if no additional charged particles with $p_T > 1.5$ GeV/c are reconstructed in the annular region between 10 and 30 degrees around the track direction. No requirement on the relative charge of the lepton and tau is imposed at the trigger level, providing a control sample.

The total trigger efficiency is the product of the efficiency for selecting a tau and the efficiency for selecting a lepton. These are determined using independent data samples of multijet and high-p_T lepton events [28, 31]. Jets are sprays of hadronic particles produced in the fragmentation and hadronization of quarks and gluons, and are clustered using a fixed-cone algorithm [32] with a radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. Jets with $E_T > 8$ GeV and $|\eta| < 2.5$ are used. Here, $\Delta\eta$ ($\Delta\phi$) is the difference relative to the jet axis in η (ϕ) space. Comparison with simulated $Z \to \tau\tau$ events yields a trigger efficiency for real taus inside the detector-acceptance region of (91 ± 3)% [31]. The trigger efficiencies for reconstructed electrons, central muons, and forward muons are (96.0 ± 0.3)%, (86.6 ± 0.7)%, and (89.9 ± 0.7)%, respectively [28]. These efficiencies include a degradation by less than 10% with increasing number of overlapping $p\bar{p}$ interactions per bunch crossing that occur at high-luminosity Tevatron operations.

The event selection proceeds as follows. Electrons (muons) are required to satisfy an E_T (p_T) requirement of 10 GeV (GeV/c), along with quality criteria to increase the purity of the samples [28]. In particular, electrons and muons must be isolated in the tracker and calorimeters, satisfying $\Sigma {p_T}^{iso} < 2.0$ GeV/c and $E^{iso}/E_T < 0.1$ or $E^{iso} < 2.0$ GeV. Here $\Sigma {p_T}^{iso}$ is the sum of the transverse momenta of any additional charged particles in a cone of radius $\Delta R = 0.4$ around the candidate lepton, and E^{iso} is the additional energy deposited in the calorimeters in the same cone. Hadronic tau decays are identified as systems of one ("one-prong") or three ("three-prong") charged particles in a narrow cone, pointing toward a central calorimeter cluster with $|\eta| < 1$. Momenta of photons from neutral pions are reconstructed using the central shower-maximum detector. The visible transverse energy of the tau candidate, defined as ${p_T}_\tau = \Sigma {p_T}_{tracks} + \Sigma {E_T}_{\pi^0}$, must be greater than 15 (20) GeV/c for one-prong (three-prong) taus. Upper thresholds on the tau invariant mass and calorimeter or tracker activity in an isolation annulus built around the highest p_T (leading) track reduce contamination from quark and gluon jets. Additional criteria on the ratio of deposited calorimeter energy to leading track p_T reject electrons and muons that could mimic the signal [33].

The event energy-imbalance transverse to the beam direction ($\vec{\not{E}}_T$) is defined by $\vec{\not{E}}_T = -\sum_i E_T^i \hat{n}_i$, where the sum is over all calorimeter towers with $|\eta| < 3.6$ and $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the ith calorimeter tower. We also define $\not{E}_T = |\vec{\not{E}}_T|$. To reduce the considerable backgrounds from the production of multijet events, we use a requirement on the scalar sum (H_T) of p_T of the tau, p_T of the lepton, and $\not{E}_T$. We require $H_T > 45$ GeV (50 GeV) for one-prong tau plus muon (electron) events, and $H_T > 55$ GeV for events with three-prong taus [34]. We require $\Delta\phi(\ell, \tau) > 0.5$ to ensure that the lepton and tau isolation cones do not overlap, and remove events with OS same-flavor leptons consistent with Z boson decay.

Depending on the relative charges of the lepton and the tau, events that pass the selection are divided into an OS control region and an LS signal region. The OS control region is mainly composed of SM processes yielding real taus, such as Drell-Yan, $t\bar{t}$, and diboson production, plus events with jets misidentified as taus. These large backgrounds would overwhelm any potential SUSY signal. For the LS signal region, events with misidentified jets are dominant; these include events with a W boson produced in association with jets (W + jets), multijet production, and events with photon conversions to e^+e^- pairs. Because of the kinematic similarity between the SUSY signal and W + jet events, the latter dominates the background composition. Backgrounds from lepton or tau charge mismeasurement are insignificant [28].

Backgrounds are estimated using a combination of Monte Carlo (MC) simulations and data-driven methods. The most significant backgrounds after the LS requirement are due to jet misidentification and are determined directly from data. We use the PYTHIA 6 MC simulation [35] to generate samples of events that produce genuine taus from diboson, $t\bar{t}$ and Z boson processes, while $W \to \tau\nu$ events are generated using ALPGEN 2.10′ [36] interfaced with PYTHIA for parton showering and hadronization. These samples are processed with the CDF II detector simulation based on GEANT 3 [37]. The sample sizes are normalized to their SM cross sections [38] and are appropriately scaled to account for MC-data differences in trigger, identification, and reconstruction efficiencies.

The jet-to-tau misidentification rate is determined using jet-triggered events in data to account for the dominant background processes, extending the treatment in Refs. [33, 39]. As quark jets and gluon jets are misidentified as taus with different probabilities, we apply a correction for gluon-jet dominated γ + jets events with $\gamma \to e^+e^-$ [34]. We parameterize the misidentification rates in terms of η_τ, the number of tracks in the tau signal cone, and the total E_T in the tau signal and isolation cones, and apply these rates to jets in events that satisfy the remaining selection criteria to determine this contribution to the final event sample. We verify this technique using data samples enriched in multijet events, selected by requiring at least 3 GeV/c (GeV) of additional p_T (E_T) in the tracking system (calorimeters). We also verify this technique in W + jets events, by requiring a W-like event topology, and in γ + jets events, by requiring $\gamma \to e^+e^-$.

The main source of systematic uncertainty arises from the jet-to-tau misidentification rate, taken as the misidentification-rate difference between the leading and second-highest-p_T jets (25%). These jets are the most

TABLE I: Backgrounds and observations in data for OS control region and LS signal region. The signal region values include the H_T requirement described in the text. For each entry, the statistical, followed by the systematic uncertainty, is given. The signal corresponds to the simplified gauge-mediated model, with $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) = 300$ fb, $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0) = 200$ GeV$/c^2$, and $m(\tilde{\ell}) = 160$ GeV$/c^2$. For this specific scenario, the optimized requirement is $\not\!\!E_T > 98$ GeV.

Process	OS events	LS events ($\not\!\!E_T > 20$ GeV)
$Z \to \tau\tau$	$6967 \pm 56 \pm 557$	10±2±1
Jet$\to \tau$	$4527 \pm 27 \pm 1065$	1153±15±283
$Z \to \mu\mu$	$263 \pm 20 \pm 21$	–
$Z \to ee$	$83 \pm 9 \pm 7$	–
$W \to \tau\nu$	$372 \pm 12 \pm 36$	97±6±10
$t\bar{t}$	$36.3 \pm 0.3 \pm 5.1$	0.7±0.0±0.1
Diboson	$61 \pm 1 \pm 6$	4.3±0.2±0.4
Total	12308 ± 67 ± 1202	1265±17±283
Data	12268	1116
	Signal	64 ± 1 ± 6
	Optimized $\not\!\!E_T$ requirement	($\not\!\!E_T > 98$ GeV)
	Total background	6 ± 1 ± 1
	Signal	10 ± 1 ± 1
	Data	3

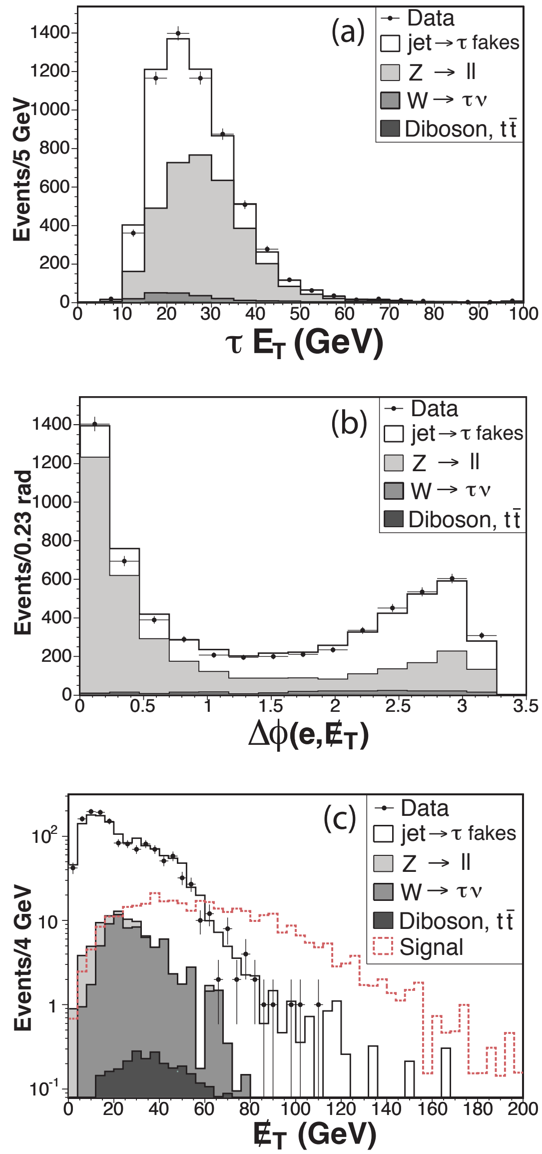

FIG. 1: Distribution of (a) tau cluster E_T and (b) $\Delta\phi(e, \not\!\!E_T)$ for OS $e + \tau$ events. Distribution of (c) $\not\!\!E_T$ for LS (signal-region) $\mu + \tau$ events. Overlaid is a signal distribution corresponding to the simplified gauge-mediated model, with $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) = 3000$ fb for visibility, $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0) = 200$ GeV$/c^2$, and $m(\tilde{\ell}) = 160$ GeV$/c^2$.

likely to be misidentified as taus. Less significant are uncertainties on the SM background processes cross-sections (ranging from 2 to 10%) and the uncertainty on the integrated luminosity (6%). The 30% uncertainty on the photon-conversion-finding efficiency has only a minor effect on the final result. We consider a possible systematic uncertainty on the reconstructed tau energy by comparing p_T spectra for one- and three-pronged taus in data and simulated $W \to \tau\nu$ samples. The best agreement is obtained by shifting the tau energy scale in the simulation by 1%. Finally, the uncertainty on the hadronic jet-energy scale leads to a 1.5% systematic uncertainty on the reconstructed tau energy for events with real taus.

The background determination is validated using the OS control region. Results are given in Table I, and show good agreement in both the OS control region and in the LS signal region. Figure 1 shows representative kinematic distributions for the OS control region and the LS signal region.

Given the good agreement between the data and the background prediction, we interpret the results as exclusion limits on the rates of SUSY processes. We set upper limits at 95% credibility level (C.L.) on the cross section for chargino-neutralino production as a function of chargino mass (assumed mass degenerate with $\tilde{\chi}_2^0$), slepton mass, LSP mass (for the case of the simplified gravity-mediated model), and branching fraction of the chargino (and neutralino) to the stau. Limits are extracted using a Bayesian technique and incorporating the systematic uncertainties described above [40]. We generate SUSY signal samples using MADGRAPH [41]. For each set of signal parameters we optimize the $\not\!\!E_T$ requirement above 20 GeV to minimize the median value of the excluded cross section assuming the observation exactly matches the background prediction (expected limit). The chosen value accounts for the various differences between the SUSY particle masses, while the 20 GeV minimum value is motivated by the selection in Ref. [10]. Table I also shows a comparison of an example signal with the background expectation and data before and after this requirement. Representative cross-section upper limit contours are shown in Figs. 2 and 3 for simplified gauge- and gravity-mediated models. We emulate the effect of raising $\tan\beta$ by directly altering the branching fraction of the chargino and neutralino to a stau, and consider both 33% and 100%, corresponding to lepton universality and tau-dominated scenarios, respectively. For the simplified gravity-mediated model, we determine limit contours for $m(\tilde{\chi}_1^0) = 120$ and $220\ \mathrm{GeV}/c^2$. As the chargino and neutralino masses increase, the cross-section limits for both models become more stringent due to the increased acceptance, and then vanish at the Tevatron kinematic limit for new particle production, corresponding to 1.96 TeV for the mass sum for all produced particles. The gaps in exclusion at high mass between the exclusion curves and the kinematic limits, shown as diagonal lines, are due to the tau and lepton p_T requirements as well as the optimized $\not\!\!E_T$ requirements for each mass pair.

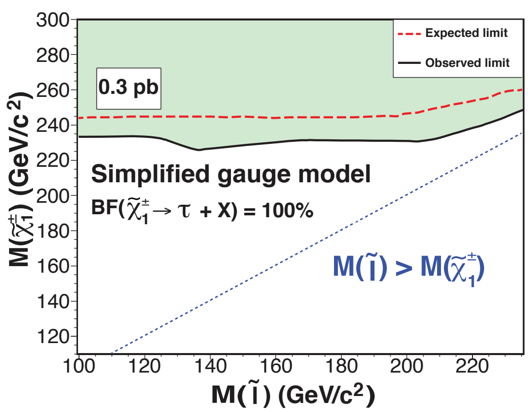

FIG. 2: Expected and observed contours of constant 95% C.L. cross-section upper limit in the chargino-slepton mass plane assuming the simplified gauge-mediated model for $BF(\tilde{\chi} \to \tau + X) = 100\%$. The shaded region corresponds to cross section limits of $\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0) \leq 300$ fb, as a function of the gaugino and slepton masses.

In summary, we search for a like-sign lepton-tau signal in CDF Run II data corresponding to 6.0 fb^{-1} of integrated luminosity. This distinctive signature is expected to be sensitive to SUSY models with direct chargino-neutralino associated production. Observing no significant excess of events in the data over standard model background predictions, we set upper limits on the cross section for this SUSY process as a function of the sparticle masses and branching fractions to taus. Our results, presented in simplified gravity- and gauge-mediated frameworks, are complementary to SUSY searches that require substantial hadronic jet activity. This analysis also constrains regions of electroweak gaugino production at high $\tan\beta$, where decays to taus dominate, and gauge-mediated parameter space with slepton next-to-lightest SUSY particles for the first time.

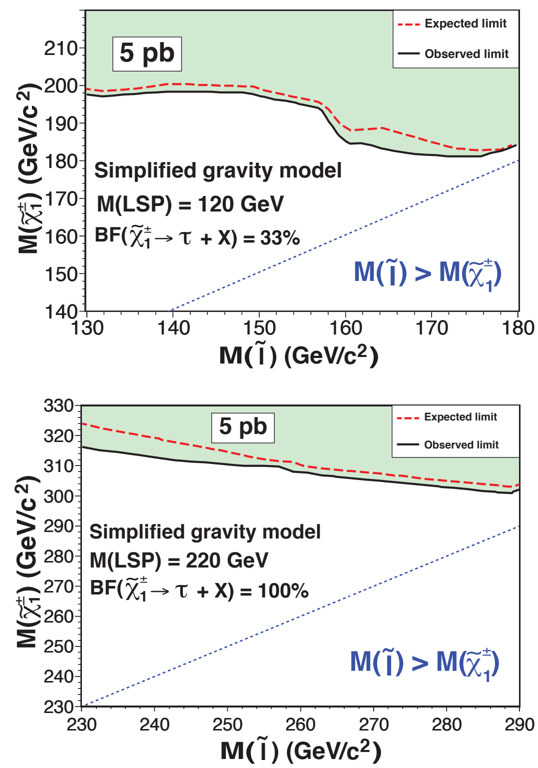

FIG. 3: Expected and observed contours of constant 95% C.L. cross-section upper limits in the chargino-slepton mass plane assuming the simplified gravity-mediated model for $BF(\tilde{\chi} \to \tau + X) = 33\%$ and 100%, for two different values of LSP mass. The shaded regions correspond to cross section limits of $\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0) \leq 5$ pb, as functions of the gaugino and slepton masses.

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