Search for Supersymmetry with Like-Sign Lepton-Tau Events at CDF

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Search for Supersymmetry with Like-Sign Lepton-Tau Events at CDF

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 (sleptons), their decays lead to detectable leptons. ATLAS searches for trilepton signals with electrons and muons in the final state and does not consider tau-enriched scenarios. CMS searches for

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., \( \tan\beta \approx 30 \), 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 leptonically decaying. ATLAS searches for trilepton signals with electrons and muons in the final state and does not consider tau-enriched scenarios. CMS searches for

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 gluinos, 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 conserved [22]. In the minimal supersymmetric standard model 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.
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 β case, where all gaugino decays produce taus, and gauge-mediated scenarios with sleptons 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 (χ± 1, χ0 2) associated electroweak production yielding tau-dominated final states data collected with the CDF II detector at the Fermilab Tevatron p̄p 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 χ± 1 → ℓ±(ν)ντ → χ0 1ντ, and neutralinos similarly decay into two detectable leptons χ0 2 → ℓ±(ν)ντ → χ0 1ℓ± ℓ±. The second case assumes the same gaugino decays, followed by the gauge-mediated slepton decays ℓ → ℓG, where 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 τ → Xμντ, where Xμ 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 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, 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 β 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 multilayer silicon-strip detectors and an open-cell drift chamber tracking system covering |η| < 1 [29] inside a 1.4 T superconducting solenoid. Surrounding the magnet are sampling electromagnetic and hadronic calorimeters, segmented in projective-tower geometry, covering |η| < 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 π0 → γγ decays in the region |η| < 1.1. At larger radii are scintillators and wire chambers for muon identification: the central muon (|η| < 0.6) and the forward muon (0.6 < |η| < 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 pT > 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 pT > 5 GeV/c that seeds the tau reconstruction. At trigger level a charged particle is isolated if no additional charged particles with pT > 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 by using independent data samples of multijet and high-pT lepton events [28,31]. Jets are sprays of hadronic particles produced in the fragmentation and hadronization of quarks and gluons and are clustered by using a fixed-cone algorithm [32] with a typical ΔR = [(Δη)2 + (Δφ)2]1/2 = 0.4. Jets with ET > 8 GeV and |η| < 2.5 are used. Here, Δη (Δφ) is the difference relative to the jet axis in the (η, φ) space. Comparison with simulated Z → ττ 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 an increasing number of overlapping p̄p interactions per bunch crossing that occur at high-luminosity Tevatron operations.

The event selection proceeds as follows. Electrons (muons) are required to satisfy an ET (pT) 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 ΣpTiso < 2.0 GeV/c and Eiso/E > 0.1 or Eiso < 2.0 GeV. Here ΣpTiso is the sum of the transverse momenta of any additional charged particles in a cone of radius ΔR = 0.4 around the candidate lepton, and Eiso 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 |η| < 1. Momenta of photons from
neutral pions are reconstructed by using the central shower-maximum detector. The visible transverse energy of the tau candidate, defined as \( p_T = \sum p_T \text{tracks} + \sum E_T^{\text{iso}} \), 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 (\( \vec{E}_T \)) is defined by \( \vec{E}_T = -\sum E_i \hat{n}_i \), 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 \( i \)th calorimeter tower. We also define \( \vec{E}_T = |\vec{E}_T| \). 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 \( \vec{E}_T \). 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 signal region values leading track \( p_T \) reject electrons and muons that could mimic the signal [33].

The jet-to-tau misidentification rate is determined by 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 \( \gamma + \) jets events with \( \gamma \rightarrow e^+ e^- \) [34]. We parametrize the misidentification rates in terms of \( \eta_T \), 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 by 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 \( \gamma + \) jets events, by requiring \( \gamma \rightarrow e^+ e^- \).

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 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 \( W \rightarrow \tau \nu \) samples. The best agreement is achieved with the following uncertainties: +0.6% (−0.8%) for the one-prong (three-prong) taus.

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### TABLE I. Backgrounds and observations in data for the OS control region and LS signal region. The signal region values lead to a significant excess over the expected values. The total background is estimated by subtracting the signal from the data.

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<tr>
<th>Process</th>
<th>OS events</th>
<th>LS events ( (E_T &gt; 20 ) GeV)</th>
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<tr>
<td>( Z \rightarrow \tau \tau )</td>
<td>6967 ± 56 ± 557</td>
<td>10 ± 2 ± 1</td>
</tr>
<tr>
<td>Jet ( \rightarrow \tau )</td>
<td>4527 ± 27 ± 1065</td>
<td>1153 ± 15 ± 283</td>
</tr>
<tr>
<td>( Z \rightarrow \mu \mu )</td>
<td>263 ± 20 ± 21</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( Z \rightarrow ee )</td>
<td>83 ± 9 ± 7</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( W \rightarrow \tau \nu )</td>
<td>372 ± 12 ± 36</td>
<td>97 ± 6 ± 10</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>36.3 ± 0.3 ± 5.1</td>
<td>0.7 ± 0.0 ± 0.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>61 ± 1 ± 6</td>
<td>4.3 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td>Total</td>
<td>12 308 ± 67 ± 1202</td>
<td>1265 ± 17 ± 283</td>
</tr>
<tr>
<td>Data</td>
<td>12 268</td>
<td>1116</td>
</tr>
<tr>
<td>Signal</td>
<td>( \cdots )</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>Optimized ( E_T ) requirement ( (E_T &gt; 98 ) GeV)</td>
<td>( \cdots )</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>Total background</td>
<td>6 ± 1 ± 1</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>Signal</td>
<td>10 ± 1 ± 1</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>Data</td>
<td>3</td>
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corresponding to the simplified gauge-mediated model, with limits on the rates of SUSY processes. We set upper limits at background prediction, we interpret the results as exclusion signal region.

Figure 1 shows good agreement in both the OS control region and in the LS

(Fig. 1 (color online). Distribution of (a) tau cluster $E_T$ and (b) $\Delta \phi(e, E_T)$ for OS $e + \tau$ events. Distribution of (c) $E_T$ for LS (signal-region) $\mu + \tau$ events. Overlaid is a signal distribution corresponding to the simplified gauge-mediated model, with $\sigma(\tilde{\chi}^\pm_1 \tilde{\chi}^0_2) = 3000 \text{fb}$ for visibility, $m(\tilde{\chi}^\pm_1) = m(\tilde{\chi}^0_2) = 200 \text{GeV}/c^2$, and $m(\tilde{\chi}) = 160 \text{GeV}/c^2$.

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 by 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 I 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 $\tilde{\chi}^0_2$), 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 by using a Bayesian technique and incorporating the systematic uncertainties described above [40]. We generate SUSY signal samples by using MadGraph [41]. For each set of signal parameters we optimize the $E_T$ 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 $m(\tilde{\chi}^0_2) = 120$ and 220 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 $E_T$ requirements for each mass pair.

In summary, we search for a like-sign lepton-tau signal in CDF run II data corresponding to 6.0 fb$^{-1}$ of integrated
Our results, presented in simplified gravity-mediated model for \( m_{\tilde{g}} = 120 \text{ GeV} \) and 100%, for two different values of LSP mass. The shaded regions correspond to cross-section limits of \( \sigma(\tilde{\chi} \rightarrow \tau + X) \leq 5 \text{ pb} \), as functions of the gaugino and slepton masses.

The 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.

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