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Searches for SUSY by CDF

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Data from proton-antiproton collisions at center-of-mass energy of 1.8 TeV are searched for evidence of SUSY particles. One analysis looks for the three-lepton final state from chargino-neutralino production. No events are observed. Another analysis looks for three or more jets and large missing energy as a signal of squark or gluino pair production. No significant excess of data above background is observed. The results of these searches are to extend limits on SUSY models beyond previous limits within a restricted parameter space of the models.

INTRODUCTION

Supersymmetric theories which allow a solution to the hierarchy problem of grand unified theories predict the existence of new SUSY partner particles with masses below 1 TeV/c^2. Most models include a multiplicative R-parity quantum number which is $^-1$ for supersymmetric particles and $^+1$ for Standard Model particles. R-parity implies that supersymmetric particles are produced in pairs, and that the decay chain of every such reaction must result in production of at least two of the lightest SUSY particle (LSP). The LSP particle is believed to be neutral and weakly interacting, and will therefore carry away energy from the reaction invisibly like a neutrino.

Preliminary results from two SUSY particle searches by CDF are described in this paper: a search for three-lepton events from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production and decay, and a search for $\geq$ 3-jet plus $\not\!\!E_T$ events from squark and gluino pair production. To put the SUSY searches at the Tevatron in perspective (1), it is useful to compare to SUSY limits from other experiments, most notably those from LEP (3) which exclude most SUSY particles from having masses below $M_Z/2 = 45$ GeV/c^2, including $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$, loosely termed zino and wino, respectively. The Tevatron search for three-lepton events from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production should therefore extend beyond 45 GeV/c^2 in order to have discovery potential.

Limits from LEP can also be related to the search for squarks and gluinos at the Tevatron. The simplest model, the Minimal Supersymmetric Standard Model (MSSM), contains relations between the masses of the new particles, such that the gluino is of order three times as massive as $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ (which have almost exactly the same mass). Therefore, the LEP results indirectly disfavor gluino masses below approximately 140 GeV/c^2. Previous CDF searches (4) require $m(\tilde{g}) > 100$ GeV/c^2 for arbitrary $m(\tilde{q})$ and $m(\tilde{g}) > 218$ GeV/c^2 for $m(\tilde{g}) = m(\tilde{q})$. In the MSSM, the lightest neutralino, $\tilde{\chi}_1^0$, is also the lightest supersymmetric particle (LSP) and has mass of order two and a half times lower than $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$. Present LEP results, therefore, require $m_{\tilde{\chi}_1^0} \geq 18$ GeV/c^2.

SEARCH FOR CHARGINO-NEUTRALINO PAIRS

Chargino-neutralino pair production and decay to a three-lepton final state has long been suggested as a promising SUSY discovery channel at the Tevatron (6), due to a striking signature and small backgrounds from Standard Model processes. The production proceeds from quark-antiquark annihilation to a virtual W boson which couples to chargino-neutralino. The chargino subsequently decays to a lepton, neutrino, and the LSP; while the neutralino decays to two leptons and the LSP. The experimental signature is therefore three leptons, missing energy, and little else. The leptons have typically lower momenta than leptons from W and Z decay because of the three-body decays, and also because present searches probe chargino and neutralino masses which are lower than M_W.

There are a number of potential backgrounds. One class of background is production of three or more leptons from, for example: WZ production and leptonic decay, top quark production and semileptonic decay followed by b quark semileptonic decay. Another class of background is production of fewer than three leptons plus misidentification of jets as leptons by the detector, in, for example: $b\bar{b} + jets \rightarrow (\ell\nu X)(\ell\nu X) + jets$ or J/$\Psi + jets \rightarrow \ell^+\ell^- + jets$.

The trilepton search begins with 2.7 million $e + X$ and 3.7 million $\mu + X$ events on data tapes from the 1992-3 CDF data run, representing 19 pb^{-1} of proton-antiproton collisions at 1.8 TeV center-of-mass energy. These events come from single electron and muon triggers which have E_T and P_T thresholds of approximately 11 GeV and 9 GeV/c, respectively. All combinations, eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$ are allowed, but tau leptons are not included. In order to be accepted in the final data sample, one lepton must have $E_T > 11$ GeV (e) or $P_T > 11$ GeV/c (μ), and pass tight identification requirements. Two more leptons must be identified with $E_T > 5$ GeV (e) or $P_T > 4$ GeV/c (μ) and looser identification requirements (6). All three leptons must be very well isolated, with less than 2 GeV of additional energy in a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around each lepton. Pairs of leptons consistent with coming from J/Ψ, Υ, or Z^0 resonance decays are removed by invariant mass cuts: 2.9$-$3.3 GeV/c^2, 9$-$11 GeV/c^2, and 75$-$105 GeV/c^2, respectively.

In addition, events with electron pairs from gamma conversions are removed, the leptons are required to be separated by $\Delta R > 0.4$ and opposite sign pairs must not be back-to-back in ϕ within 10 degrees. The event vertex must also lie within 60 cm of the nominal interaction point.

After all cuts, no events remain. Combining Poisson statistics with the effect

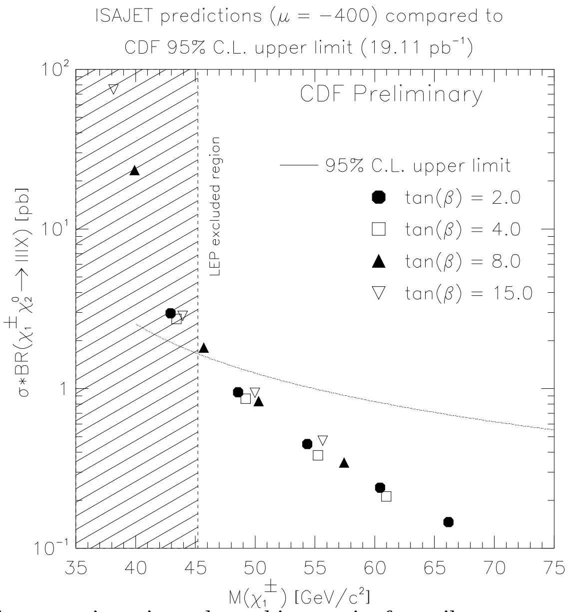

FIG. 1. Cross-section times branching ratio for trilepton search for SUSY. The solid line indicates the 95% confidence level upper limit from this analysis, while the points show predictions from the SUSY Monte Carlo generator of ISAJET. The shaded region corresponds to the LEP limit. Other constraints on MSSM parameters are $m(H^+) = 500$ GeV/c^2 and $m_{\tilde{q}} = 1.2 \times m_{\tilde{g}}$.

of systematic errors $\left({}^{+17\%}_{-14\%}\right)$, we can exclude at 95% confidence level those SUSY models which predict more than 3.1 events. The trilepton efficiency is estimated separately for each decay mode, and can be broken into the product of (i) lepton trigger efficiency, (ii) isolation cut efficiency, and (iii) lepton identification and kinematic efficiency. The isolation cut efficiency (88%) and the trigger efficiencies (84% for muons, 88% for electrons) are estimated using W and Z data. The lepton identification and kinematic efficiencies in each trilepton mode are estimated using a Monte Carlo simulation based on ISAJET version 7.06 (5). The kinematic efficiencies depend strongly on the masses of chargino and neutralino. For example, the kinematic efficiency of the $e^+e^-e^+$ mode rises from 2% to 7.5% between 43 GeV/c^2 and 72 GeV/c^2, while in the $\mu^+\mu^-\mu^+$ mode it rises from 3.5% to 12% over the same mass range. Resulting limits on production cross-section times trilepton branching ratio are shown in figure 1, along with predictions from the MSSM model with parameters as shown. The measurement requires chargino and neutralino masses > 46 GeV/c^2 for $\mu = -400$ GeV/c^2, slightly above the LEP limit.

SEARCH FOR SQUARK AND GLUINO PAIRS

Pairs of squarks and gluinos; $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, and $\tilde{q}\tilde{g}$; should be produced at the Tevatron via the strong interaction from quark and gluon collisions, with cross-sections limited by the high masses of these particles. Depending on the relative masses of squarks and gluinos; production of $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, or $\tilde{g}\tilde{g}$ may predominate. Direct decays of each $\tilde{q}$ and $\tilde{g}$ to the LSP result in one and two quark jets, respectively, while cascade decays through charginos and neutralinos may result in two or more additional jets. Therefore, the events always contain two jets and most contain three or more jets, in addition to missing energy. This analysis initially identifies events with missing energy and two or more jets. Events with electrons or muons are rejected. The final data sample requires three or more jets.

There are many potential sources of background to the signal of jets and missing energy. Some predictable 'physics' backgrounds are $Z + nj \rightarrow \nu\bar{\nu} + nj$ (nj denotes production of n jets); and $W + nj \rightarrow \ell\nu + nj$ in which the lepton is unobserved, perhaps because of low lepton P_T or because the lepton is at high rapidity and escapes detection.

A type of background which is less easily predicted comes from QCD multi-jet production, which should be well balanced except for jet mismeasurement. The level of this background depends on tails of the calorimeter energy resolution, as well as cracks and detector malfunctions, and is therefore not easily reproduced by a detector simulation.

There are sources of background which cannot be predicted at all. For example, a cosmic ray bremmstrahlung or an air shower or detector malfunction which produces one or more extra jets, in the presence of balanced jets from QCD di-jet production, will produce the desired SUSY signature.

The search begins with 2.0 million events on full DST data tapes from the 1992-3 CDF data run, representing 19 pb^{-1} of proton-antiproton collisions at 1.8 TeV center-of-mass energy, which are selected by the CDF exotic data stream. The exotic data stream includes $\not\!\!E_T$-triggered events as well as τ lepton-triggered events. The $\not\!\!E_T$-triggered events pass the following cuts: the CDF level 2 'hardware' trigger requires $\not\!\!E_T > 35$ GeV summed over calorimeter trigger towers of size $(\Delta\eta = 0.2) \times (\Delta\phi = 15°)$ having $E_T \geq 1$ GeV; and the level 3 trigger processor farm requires $\not\!\!E_T > 30$ GeV as calculated, like the offline $\not\!\!E_T$ calculation, using a low tower energy threshold and removal of spurious energy depositions from, e.g., phototube breakdown. Unlike the offline calculation, however, the vertex is fixed at the center of the detector, $z = 0$. Also, the level 3 $\not\!\!E_T$ trigger discards most cosmic ray events by timing of TDC signals from the hadronic calorimeter. The actual $\not\!\!E_T$ threshold imposed by the multi-level trigger is determined mainly by the level 2 trigger and only becomes fully efficient for offline $\not\!\!E_T > 50$ GeV.

Because of the unpredictable backgrounds, the data is reduced in stages. Each stage reduces the size of the data sample by about an order of magnitude. The cuts imposed at each stage are chosen after handscanning data, while monitoring the efficiency of possible cuts using SUSY Monte Carlo simulated events. Four stages of cuts reduce the data sample to 409 events.

The cuts fall into three categories: First, 'junk removal' cuts to eliminate cosmic ray events, accelerator particle losses, and other events having energy deposits unrelated to the $p\bar{p}$ collisions. These cuts are: $\sum P_T > 5$ GeV/c where the sum includes only charged tracks having $P_T > 2$ GeV/c; at least one jet with $E_T > 15$ GeV must have charged tracks with $\sum P_T/E_T > 0.15$ pointing at it; total event calorimeter energy $E < 2$ TeV; and the event must contain < 10 GeV of out-of-time energy, i.e. energy which is not coincident in time with the bunch crossing as determined by TDCs in the central hadronic calorimeter. Second, topology cuts are imposed to reduce background from QCD jet mismeasurement: at least two jets with $E_T > 15$ GeV are required; the angle between the $\not\!\!E_T$ direction and the leading jet must be $< 160°$; and the angle between the $\not\!\!E_T$ direction and any jet with $E_T > 20$ GeV must be $> 30°$. Third, the $\not\!\!E_T$ threshold is raised to 60 GeV. A higher $\not\!\!E_T$ cut, in combination with topology cuts, greatly reduces the number of events from QCD mismeasurement.

These cuts are effective at removing events with $\not\!\!E_T$ from spurious detector- and accelerator-related backgrounds and cosmic rays, as well as events with QCD jet mismeasurement. The dominant background at this point, however, is from leptonic W (and to a smaller extent, Z) boson decays which produce real $\not\!\!E_T$ from neutrinos, or from muons which do not deposit their energy in the calorimeter. The final stage of data reduction removes any event having an electron or muon identified with loose cuts and low energy/momentum thresholds ($E_T > 10$ GeV for electrons and $P_T > 10$ GeV/c for muons). Lepton removal reduces the data sample from 409 events to 186 events. The 'signal' region is then the subsample of 38 events having ≥ 3 jets within $|\eta| < 2$. Two more events are removed following handscanning because they contain energy from particles lost by the Fermilab main ring, leaving 36 events in the final data sample.

The VECBOS (8) Monte Carlo is used to generate backgrounds from $W + nj \rightarrow \ell\nu + nj$ and $Z + nj \rightarrow (\nu\bar{\nu}) + nj$, while ISAJET is used for $t\bar{t}$ backgrounds. Parton distributions used are MSRD0 for $W + nj$, MRSD0' for $Z+nj$, and CTEQ2L for $t\bar{t}$. Since $W+nj$ and $Z+nj$ production cross-sections are subject to considerable normalization uncertainty, a normalization factor is applied to the background estimates from these channels. Since our background consists of events in which no lepton is identified, the normalization factor is determined using $W + nj \rightarrow e\nu + nj$ events in which the electrons are well identified. In an inclusive electron data sample; 602, 125, and 32 events are seen in $W+1j$, $W+2j$, and $W+3j$ samples, respectively; whereas the Monte Carlo predicted 1149, 285, and 50 events, respectively. Therefore, we choose a uniform normalization factor of 0.5 ± 0.2 to apply to the Monte Carlo predictions (9). For $t\bar{t}$ production, we use the measured CDF value $\sigma = 6.8 \pm 3.0$ pb (10). A total of 28.7 ± 10.6 events are predicted from these backgrounds. dTherefore, the 36 events in our final data sample do not show a significant excess over the $W/Z/t\bar{t}$ backgrounds. The $\not\!\!E_T$ and jet multiplicity spectra for data and background are shown in Figure 2.

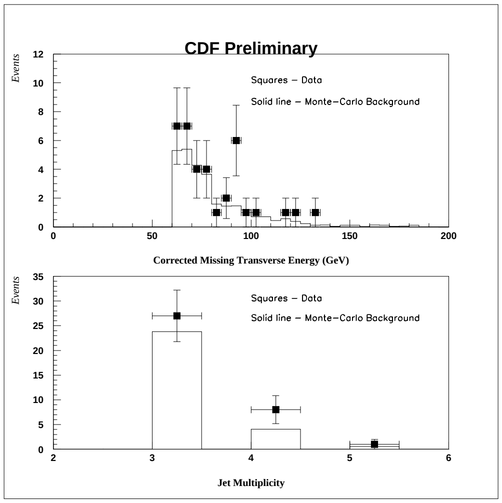

FIG. 2. $\not\!\!E_T$ (top plot) and jet multiplicities (bottom plot) for final $\not\!\!E_T + jets$ data sample (data points) and estimated backgrounds (histograms).

In plots of jet angles with respect to the $\not\!\!E_T$ direction, there is no evidence for significant additional background from QCD mismeasurement. For placing limits on SUSY models, we can be conservative by estimating this and other additional backgrounds to contribute zero events. From the 36 signal events, 28.7 ± 10.6 estimated background events, and 19 pb^{-1} integrated luminosity, we rule out at 95% confidence level those points in MSSM parameter space which predict a detected cross-section of > 1.4 pb (> 27.4 events) passing all cuts. The cross-section falls rapidly as the minimum of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ increases, and is estimated using the ISAJET V7.06 generator with CTEQ2L parton distributions. The region of the $m_{\tilde{q}} - m_{\tilde{g}}$ plane which is excluded by this analysis is shown in Figure 3. For arbitrary $m_{\tilde{q}}$ the data require $m_{\tilde{g}} > 160$ GeV/c^2, and for $m_{\tilde{g}} = m_{\tilde{q}}$ we deduce $m_{\tilde{g}} > 220$ GeV/c^2.

I. ADDITIONAL SUSY SEARCHES IN CDF

Two other SUSY searches conducted by the CDF collaboration will soon produce results and therefore ought to be briefly mentioned.

One search is for same-sign dileptons events arising from gluino production and subsequent leptonic 'cascade' decays of charginos and neutralinos. In principle, this search is orthogonal to the previously mentioned $\not\!\!E_T$+jets SUSY search, which *vetoes* on leptons which could arise from cascade decays. Besides two same-sign leptons of moderate P_T, the present analysis requires two additional jets and $\not\!\!E_T$.

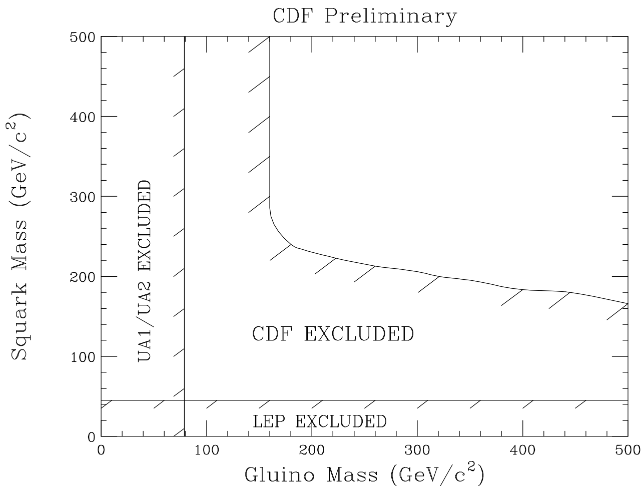

FIG. 3. The region of squark-gluino masses excluded at 95% confidence level by this analysis. Other MSSM parameters are fixed: $\tan\beta = 4$ and $\mu = -400$ GeV/c^2. Also shown are regions excluded by UA1/UA2 and LEP.

Another ongoing search is for stop quark pair production. The large mass of the top quark produces a splitting of SUSY quark masses such that one of the stop quarks may become quite light (11). The production cross-section of stop quark pairs is typically an order of magnitude lower than for top quark pairs of the same mass, however, it may be that the stop quark has a lower mass. The search for stop pairs is similar to the top quark search, e.g. b-quark tags in the silicon detector are a valuable signature. However, with the additional missing LSP particles and with a lower mass range which can be probed with present data samples, typical momenta of all partons from stop decay are lower than partons from top decay.

II. CONCLUSIONS AND OUTLOOK

The CDF search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production and decay to three leptons finds no events, and with cross-section limits of order 1 pb, places a limit ($>$ 46 GeV/c^2) which is very similar to LEP limits. The CDF direct search for squark/gluino strong production finds no evidence for a significant excess of signal above background estimates, and excludes a region of the $m_{\tilde{q}} - m_{\tilde{g}}$ plane which extends to higher masses than the previous CDF search (12), but is similar to the region excluded by the D0 experiment (7). The mass limits from this search are higher than gluino mass limits from LEP which are derived from GUTS assumptions relating gluino masses to $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ masses. To put the measurement in perspective, Figure 4 shows the CDF result, which has μ fixed at -400 GeV at present, together with limit curves

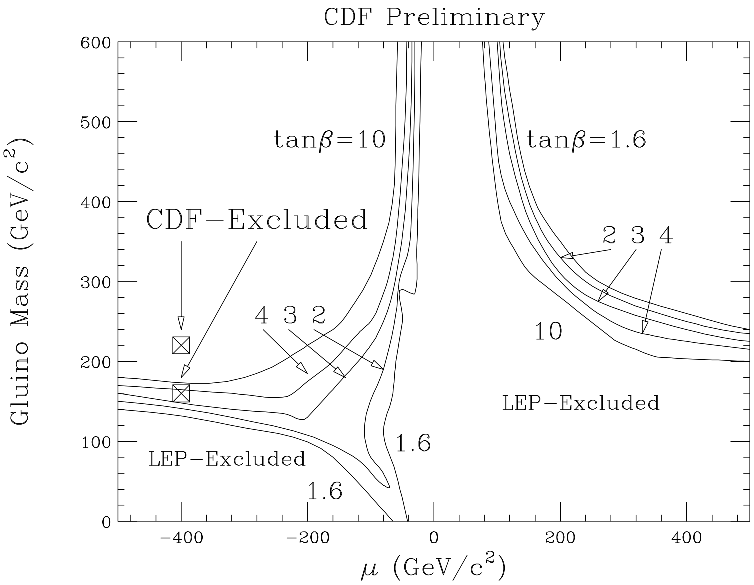

FIG. 4. Gluino masses excluded by the CDF jets plus $\not\!\!E_T$ search, placed in the context of LEP limits in the MSSM model. The contours represent LEP limits, while the CDF analysis excludes the two points shown at $\mu = -400$ GeV/c^2 with fixed tan$\beta = 4$: $m(\tilde{g}) > 160$ GeV/c^2 for arbitrary $m(\tilde{q})$, and $m(\tilde{g}) > 220$ GeV/c^2 for $m(\tilde{q}) = m(\tilde{g})$.

from LEP measurements in the $\mu - m_{\tilde{g}}$ plane.

Both of the searches described use 19 pb^{-1} data from Run 1a. The O(100 pb^{-1}) data sample now being accumulated in Run 1b at Fermilab, improved data analysis (e.g. to increase the efficiency of tri-lepton detection), and additional search channels give CDF and D0 experiments SUSY discovery potential before LEP-II turns on. In the longer term, large data samples expected from the Main Injector should allow Fermilab to probe beyond the reach of LEP-II in the competition to discover SUSY.

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