# A Search for Supersymmetric Gauge Particle Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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## Abstract

The CDF experiment has conducted a search for supersymmetric gauge particle pair production ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) in 1.8 TeV $\mathrm{p\bar{p}}$ collisions at the Fermilab Tevatron. The Minimal Supersymmetric Standard Model (MSSM) predicts an appreciable production cross section for $\mathrm{p\bar{p}}\rightarrow\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, and large branching fractions for the leptonic decay modes $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\chi}_1^0\ell^{\pm}\nu$ and $\tilde{\chi}_2^0\rightarrow\tilde{\chi}_1^0\ell^+\ell^-$. Consequently, we have searched for an excess of events containing three leptons, as a signature of gaugino production. In $\sim$19 $\mathrm{pb}^{-1}$ data collected during the 1992-93 Tevatron run, no trilepton events consistent with gaugino pair production were observed. Upper limits on $\sigma(\mathrm{p\bar{p}}\rightarrow\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)\cdot\mathrm{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow 3\ell + \mathrm{X})$ are obtained for various regions of the MSSM parameter space, yielding lower limits on the gaugino masses.

13.38+c, 12.15.Ff, 14.80.Er, 13.10.+q ????

Although the Standard Model (SM) provides remarkable agreement with current high energy physics data, it fails to provide insight into several important issues. Among these are the apparently arbitrary energy scale of electro-weak symmetry breaking, the appearance of divergences in the Higgs boson self-energy [1], and the failure of coupling constants to unify at large energy scales [2]. An extension to the SM which may alleviate these difficulties is Supersymmetry (SUSY) [3,2].

In SUSY, SM particles are given SUSY partners with identical quantum numbers but different spin assignments: fermions get bosonic partners, bosons receive fermionic partners. The simplest SUSY extension to the SM is the Minimal Supersymmetric Standard Model (MSSM) [4], which contains four neutral and two charged electro-weak gauge particles ($\chi$'s), in addition to the known W and Z gauge bosons. The production cross section for $p\bar{p}\rightarrow\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ at $\sqrt{s}=$ 1.8 TeV is expected to be $O$(few) pb [5]. Furthermore, assuming slepton and sneutrino mass constraints [6] motivated by Supergravity (SUGRA) [7] and the GUT hypothesis [8], the leptonic decays $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\chi}_1^0\ell^{\pm}\nu$ and $\tilde{\chi}_2^0\rightarrow\tilde{\chi}_1^0\ell^+\ell^-$ can become appreciable ($\sim$ 20%). The resulting trilepton final state has small SM backgrounds, making it an excellent discovery signature. Consequently, we have searched for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\ell^+\ell^-\ell X$ events and report our findings in this Letter.

The data for this analysis were obtained in $\sqrt{s}$=1.8 TeV $p\bar{p}$ collisions at the Fermilab Tevatron during the 1992-93 Collider Run. The Collider Detector at Fermilab (CDF) was used to record these data, amounting to $\sim$19 pb$^{-1}$ total integrated luminosity. As the CDF has been described in detail previously [9], only the portions of the detector relevant to this analysis will be mentioned here. The CDF consists of charged particle tracking chambers near the event vertex, surrounded by energy calorimeters and muon chambers. Charged particle tracking is obtained from the vertex chamber (VTX), and the central tracking drift chamber (CTC). These devices have approximately cylindrical geometry and are situated in a 1.4 T solenoidal magnet field. The CTC provides high resolution transverse momentum ($p_T$) measurement in the pseudo-rapidity region $|\eta| <$ 1.1. Outside the tracking chambers are the electromagnetic(EM) and hadronic(HA) calorimeters, segmented in a projective tower geometry, and covering the central (CEM+CHA, $|\eta| < 1.1$) and plug (PEM+PHA, $1.1 < |\eta| < 2.4$) regions. Finally, muon identification is available in the central muon (CMU+CMP, $|\eta| < 0.6$) and muon extension (CMX, $0.6 < |\eta| < 1.1$) detectors. The CDF was originally constructed with only the CMU detector; the CMP and CMX detectors were added later (providing additional hadron absorber and improved pseudo-rapidity coverage, respectively).

Our event triggering strategy is motivated by Monte Carlo studies performed with the ISAJET V.7.06 program [10]. In a SUSY trilepton event, there is typically at least one central lepton with $p_T > 10$ GeV/c. Thus, we select events which have fired the CDF central electron or muon triggers (which require $p_T > 9.2$ GeV/c), giving us an initial sample of $\sim 6 \times 10^6$ events.

Following offline reconstruction, events containing a single lepton with $p_T \geq 9$ GeV/c are selected to produce a low $p_T$ lepton sample. No explicit trigger requirement is imposed, since we wish to maximize our acceptance. In keeping with our triggering strategy, we then select events containing at least one high quality "tight" lepton (ie., that would likely have passed our trigger), and at least two additional "loose" leptons with less stringent requirements. A tight electron must deposit at least 11 GeV transverse energy ($E_T$) in the CEM, exhibit lateral and longitudinal shower profiles consistent with an electron, and be well matched to a charged track with $p_T \geq E_T/2$. A tight muon must produce a cluster in the CMU and CMP chambers, be well matched to a charged track with $p_T \geq 11$ GeV/c, and deposit calorimeter energy consistent with a minimum ionizing particle.

We now describe the various categories of loose leptons admitted in our analysis. Loose electrons are accepted in the CEM or PEM, and must have $E_T \geq 5$ GeV. In both cases, the calorimeter shower shape must be consistent with an electron, and central electrons must be well matched to a charged track with $p_T \geq E_T/2$. Since our central tracking chamber does not allow high efficiency track reconstruction into the plug calorimeter, we require a plug electron to be correlated with a high occupancy of hits in the appropriate sector of the VTX, as evidence that a charged particle produced the shower. Loose muons are muon chamber clusters in the CMU+CMP or CMX regions with $p_T \geq 4$ GeV/c, and satisfying the same muon identification criteria as those for tight muons. In addition, a charged track with $p_T \geq$ 10 GeV/c is considered a muon, even without any muon chamber hits, if it deposits energy in the central calorimeters consistent with a minimum ionizing particle (this is termed a CMIO muon).

Having specified our criteria for selecting three leptons, we now turn to event quality and background rejection cuts. Since it is possible for events containing heavy flavor quarks (ie., b and c) to produce multiple leptons via semi-leptonic decay, we require each lepton to be well isolated from other particles in the event. Leptons from heavy flavor are usually embedded in jets and we thus demand that the lepton isolation, defined as the total calorimeter $E_T$ in an $\eta - \phi$ cone of radius R = 0.4 (where $R = \sqrt{(\delta\phi)^2 + (\delta\eta)^2}$ ) surrounding the lepton, be $< 2.0$ GeV (excluding the $E_T$ of the lepton itself). We require the longitudinal position of the reconstructed primary event vertex to lie within 60 cm of the center of the CDF. In order to remove photon conversions and pion punch-through, we require the $\eta - \phi$ distance ($\delta$R) between any two leptons to be greater than 0.4. Background from Drell-Yan processes is reduced by requiring the difference in azimuthal angle between the two highest $p_T$ leptons in the event to be less than 170°. Assuming lepton number conservation, SUSY trilepton candidates must possess at least one $e^+e^-$ or $\mu^+\mu^-$ pair. Finally, an event is rejected if it contains an $\ell^+\ell^-$ pair with invariant mass in any of the following regions : 2.9-3.3 GeV/$c^2$ ($J/\psi$), 9-11 GeV/$c^2$ ($\Upsilon$), 75-105 GeV/$c^2$ ($Z^0$). After imposing all of these criteria, we are left with zero SUSY trilepton candidate events (see Table I).

The efficiency with which CDF can reconstruct trilepton events consists of four principal components: geometric and kinematic acceptance, trigger efficiency, isolation efficiency, and lepton identification (ID) efficiency. We now discuss each of these.

The geometric and kinematic acceptance was determined via Monte Carlo simulation. ISAJET was used to generate SUSY trilepton events, which were then passed through a CDF detector simulation program and the trilepton analysis code. The resulting trilepton yields give acceptances in the range of $\sim 2 - 12\%$, depending on the MSSM parameters used.

The trigger efficiency curves for single electrons and muons were obtained from CDF data samples which were not biased by the inclusive lepton triggers. These curves rise sharply around the trigger threshold of 9.2 GeV/c, and reach a plateau of $84.3 \pm 1.5\%(88.6 \pm 0.7\%)$ for muons (electrons) above 11 GeV/c. In order to properly account for the possibility that more than one lepton in a SUSY event could have fired the trigger, these trigger efficiencies were directly installed in the simulation software, providing event-by-event weighting.

The lepton isolation efficiency was determined by studying $Z^0 \rightarrow \ell^+\ell^-$ events, which are expected to have an amount of hadronic activity similar to that in SUSY trilepton events. One of the leptons was required to satisfy "tight" criteria. The other lepton was required to pass all "loose" lepton cuts except the isolation cut. Comparing the number of $Z^0$s thus selected with the number remaining after an isolation cut on the second lepton gives the single lepton isolation efficiency: $0.95 \pm 0.01$ for central leptons and $0.80 \pm 0.03$ for plug electrons. The difference between central and plug leptons is due to the larger lateral shower leakage which occurs in the plug. These isolation efficiencies were then incorporated into the Monte Carlo software.

Lepton ID efficiencies were determined by studying $Z^0 \rightarrow \ell^+\ell^-$ and $J/\Psi \rightarrow \ell^+\ell^-$ events. One of the leptons was selected with tight ID cuts; no ID criteria were imposed on the second lepton. The dilepton invariant mass was required to be consistent with the $Z^0(J/\Psi)$ mass. The event yields resulting from the cuts above were then compared with the number of events obtained after imposing tight and loose lepton ID criteria on the second lepton. The resulting lepton ID efficiencies are listed in Table II. The values obtained from $Z^0$ and $J/\Psi$ events agree well, indicating that the ID efficiencies are independent of $p_T$. These efficiencies were then directly installed in the simulation software.

Using the trilepton efficiency information, the expected background yield from SM processes has been estimated. These processes can be divided into two classes: direct trilepton events and dilepton plus fake lepton events. First, we discuss the trilepton category, consisting of processes which can directly produce three or more leptons in an event: $WZ^0$,

$Z^0Z^0$, $t\bar{t}$, and heavy flavor production. Each of these backgrounds has been estimated by generating Monte Carlo events using ISAJET, the CDF detector simulation program, and the trilepton-event-finding code. The $WZ^0$ cross section was taken to be 2.5 pb and the $Z^0Z^0$ cross section was set to 1.0 pb [11]. For $t\bar{t}$ events, we used a top quark mass of 170 GeV/$c^2$ and a production cross section of 7.0 pb [12]. Heavy flavor production via ISAJET has one potential difficulty, the transverse energy isolation of leptons. We have investigated this by comparing heavy flavor production in ISAJET and CLEOQQ (a generator optimized for heavy flavor production [13]), and find good agreement in the lepton isolation distributions. The total expected background from SM direct trilepton processes (in 19.1 pb$^{-1}$) is 1.15 events, arising entirely from heavy flavor production, with negligible contributions from $t\bar{t}$, $WZ^0$, or $Z^0Z^0$.

In the second category of backgrounds, we consider processes which can yield only two leptons: Drell-Yan, $Z^0$, and WW events. Such an event could pass our trilepton-finding criteria if there exists an additional fake lepton in the event. We consider a fake lepton to be an object identified as a lepton but which does not come from the main physics process (eg., misidentified jets or pions, photon conversion, decays in flight, intial state radiation producing heavy flavor quarks which decay semileptonically, etc.). We have estimated the fake rate by analysing clean $W\rightarrow\ell\nu$ and $J/\Psi\rightarrow\mu^+\mu^-$ events in CDF data. No additional isolated leptons are expected in these events (other than the leptons which reconstruct the W or $J/\Psi$). The results obtained from these two samples are in agreement and have been averaged to obtain the final fake rate: $0.280\pm0.018\%$ fake leptons per event. We note that since W's and $J/\Psi$'s are produced in processes of different momentum transfer squared ($Q^2$), we conclude that the lepton fake rate is independent of $Q^2$.

The lepton fake rate was then combined with Drell-Yan, $Z^0$, and WW events generated with ISAJET and processed in the same manner as the previous category of trilepton background events. The background calculations for Drell-Yan and $Z^0$ events used production cross sections previously measured by CDF [14,15], while the WW production cross section was taken as 9.5 pb [11]. We estimate SM dilepton plus fake lepton background yields (in

19.1 pb$^{-1}$) to be 0.60 Drell-Yan events, 0.14 $Z^0 \to \ell\ell$ events, and negligible contribution from the WW process. The grand total of all expected backgrounds is thus 1.9 events in the CDF data sample. This is clearly consistent with our observation of zero events.

There are four primary sources of systematic error in the $\sigma$·BR determined by this analysis: trigger efficiency, trilepton-finding efficiency, structure functions, and total integrated luminosity. A conservative estimate of the trigger efficiency uncertainty was obtained by assuming that all trilepton events were accepted on the single muon trigger path (as opposed to the single electron or multiple lepton paths), which has the largest efficiency uncertainty. The estimated trigger efficiency systematic error is thus $\pm 2.7\%$. The combined systematic error of all trilepton-finding efficiencies (kinematic, geometric, reconstruction, identification, and isolation) is $\pm 12.9\%$. This comes mainly from the geometric and kinematic uncertainties in the CDF detector simulation program. The CTEQ 2L structure functions [16] were used in all of our Monte Carlo studies. The SUSY trilepton production cross section and efficiency were studied by running ISAJET with various other structure functions [17] for various chargino mass values. We have used the maximum deviations from the CTEQ 2L predictions as our systematic error estimate: $^{+8.2}_{-1.8}\%$. Finally, the systematic error due to the uncertainty in the total integrated luminosity is $\pm 3.6\%$. Combining all of these uncertainties, we obtain a total systematic error in our cross section measurement of $^{+15.6}_{-14.4}\%$.

Based on our observation of zero trilepton events, we set a 95% confidence level upper limit of 3.1 events on the mean number of events expected. This result was obtained by convolving our total systematic uncertainty of 15.6% (as a Gaussian smearing) with a Poisson distribution. This limit can then be used to exclude the particular regions of the MSSM parameter space in which:

$$\sigma \cdot BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell + X) \cdot \epsilon^{tot} \cdot \int \mathcal{L}dt > 3.1 \tag{1}$$

where $\sigma \cdot$BR is determined by ISAJET and $\epsilon^{tot}$ has been determined from efficiency studies.

Assuming SUGRA constraints which tie the slepton masses to the gluino and squark masses, the SUSY predictions from ISAJET depend on the following quantities: the pseudoscalar Higgs mass $M(H_A)$, the trilinear top squark coupling $A_t$, the ratio of Higgs vacuum expectation values $\tan(\beta)$, the Higgs mixing parameter $\mu$, the gluino mass $M(\tilde{g})$, and the squark/gluino mass ratio $M(\tilde{q})/M(\tilde{g})$. The first two quantities were fixed ($M(H_A)$ = 500 GeV/$c^2$, $A_t$ = 0), since they do not significantly alter the trilepton yield. The remaining quantities do affect the predicted trilepton signal, and scanning ranges were determined as follows. ISAJET only allows $\tan(\beta)$ values in the range 1.0–10.0, and values close to 1.0 are theoretically disallowed ($\tilde{t}$ becomes the lightest SUSY particle). The $M(\tilde{q})/M(\tilde{g})$ ratio is theoretically favored to be greater than unity [6] and the trilepton yield drops rapidly when this ratio exceeds 2.0 (this is due to sleptons becoming heavy, which reduces the neutralino leptonic branching ratio). Finally, our trilepton sensitivity is lost for $|\mu|$ <100 GeV (where the leptonic branching ratios of the gauginos decrease significantly), and $|\mu|$ is favored to be $\lesssim$1000 GeV (the approximate energy scale below which SUSY phenomena should be observable). Thus, we have scanned the following ranges of SUSY parameters: $\tan(\beta)$ = 2.0, 4.0, 10.0; $M(\tilde{q})/M(\tilde{g})$ = 1.0, 1.2, 2.0; 200 GeV < $|\mu|$ < 1000 GeV; $M(\tilde{g})$ = 120~250 GeV/$c^2$.

The total SUSY trilepton-event-finding efficiency ranges from ~1-7% in this parameter region, and is approximately linearly dependent on the chargino mass. Equation 1 is then combined with the efficiency information to determine which points in the SUSY parameter space are excluded. This analysis is unable to increase the chargino mass lower limit beyond the current value (47 GeV/$c^2$ [18]) for any choice of SUSY parameters. However, Figure 1 shows several SUSY parameter space regions for which this analysis has increased the existing neutralino mass limit [18], reaching as high as 49 GeV/$c^2$. Our results can also be expressed in terms of gluino mass lower limits, but, once again, the limits set by this study are less stringent than previously existing bounds [19].

In conclusion, we have used the trilepton signature to search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production in 1.8 TeV $p\bar{p}$ collisions at the Fermilab Tevatron. We find no events consistent with this process and set lower limits on the gaugino masses. The resulting chargino mass limits are less than or equal to existing bounds. However, the neutralino mass lower limits obtained are as high as 49 GeV/$c^2$ (depending on the region of the SUSY parameter space), substantially improving previous bounds.

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## TABLES

TABLE I. Cumulative number of events left after each cut in the trilepton analysis, listed separately for the electron and muon trigger samples. The original CDF data sample corresponds to $\int \mathcal{L}dt = 19.1 \pm 0.7\ \mathrm{pb}^{-1}$.

| Cut | e triggers | $\mu$ triggers |
|---|---|---|
| Original sample | $3,677,903$ | $2,707,852$ |
| Dilepton events | $5,472$ | $6,606$ |
| Trilepton events | 94 | 136 |
| $ISO < 4$ GeV | 14 | 33 |
| $ISO < 2$ GeV | 5 | 21 |
| $\|z_{vertex}\| < 60$ cm | 5 | 21 |
| $\Delta R_{\ell\ell} > 0.4$ | 3 | 2 |
| $\Delta\phi_{\ell_1\ell_2} < 170°$ | 2 | 2 |
| Require $e^+e^-$ or $\mu^+\mu^-$ | 2 | 2 |
| $Z^0$ removal (75-105 GeV/$c^2$) | 0 | 1 |
| $J/\psi$ removal (2.9-3.3 GeV/$c^2$) | 0 | 1 |
| $\Upsilon$ removal (9-11 GeV/$c^2$) | 0 | 0 |

TABLE II. Lepton ID efficiencies obtained from $Z^0 \to \ell^+\ell^-$ and $J/\Psi \to \ell^+\ell^-$ events in CDF data. The top (bottom) portion of the table is for muons (electrons).

| lepton type | Efficiency (%) |
|---|---|
| Tight CMU and CMP | 89.0±2.6 |
| Loose CMU and CMP | 93.5±2.0 |
| Loose CMX | 94.0±2.9 |
| Loose CMIO | 92.5±4.2 |
| Tight CEM | 86.4±1.3 |
| Loose CEM | 89.0±1.2 |
| Loose PEM | 89.0±1.5 |

FIGURES

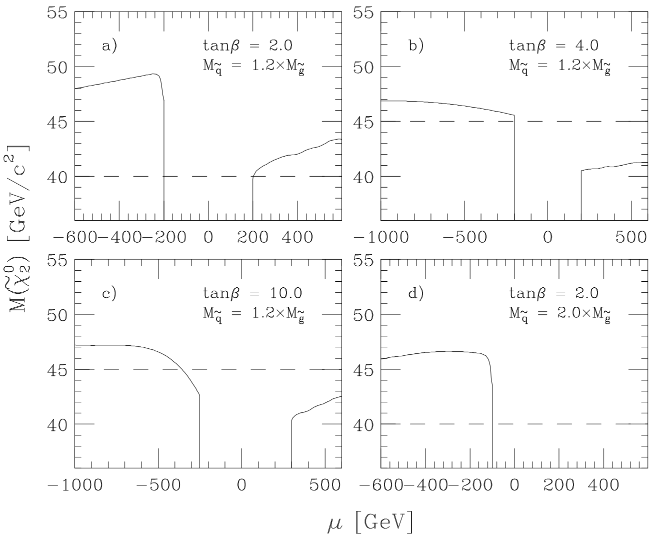


FIG. 1. Neutralino mass lower limits obtained in the trilepton analysis (solid line). The SUSY parameters used for each plot were: a) $\tan(\beta)$=2.0, $M_{\tilde{q}}$=1.2×$M_{\tilde{g}}$; b) $\tan(\beta)$=4.0, $M_{\tilde{q}}$=1.2×$M_{\tilde{g}}$; c) $\tan(\beta)$=10.0, $M_{\tilde{q}}$=1.2×$M_{\tilde{g}}$; d) $\tan(\beta)$=2.0, $M_{\tilde{q}}$=2.0×$M_{\tilde{g}}$. The dashed line is the limit extracted from LEP measurements. Note that $\mu$ only extends down to −600 for $\tan(\beta)$=2.0.