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Search for Supersymmetry at CDF

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Abstract

We have conducted a search for trilepton events from supersymmetry (SUSY) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. In the Minimal Supersymmetric Standard Model (MSSM), trilepton events are expected from chargino-neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pair production, with subsequent decay into leptons. In all possible combinations of electron and muon channels in 19 pb^{-1} data, we observe no events which pass our trilepton selection criteria. Employing the GUT hypothesis within the framework of the MSSM, our preliminary analysis excludes $M(\tilde{\chi}_1^{\pm})$ <46 GeV/c^2 for $-500 < \mu < -400$ GeV, $2.0 < \tan(\beta) < 15.0$, and $M(\tilde{q}) = 1.2 \times M(\tilde{g})$.

1 Introduction

The first indication of supersymmetric grand unification arose from precision measurements of the Standard Model (SM) coupling constants $\alpha_1(M_Z)$, $\alpha_2(M_Z)$, and $\alpha_3(M_Z)$ at energy scale $Q = M_Z$ [1]. When the SM + grand unified theory renormalization group equations (RGE's) are used to propagate these coupling constant values to high energy, there is no clear unification point. However, the coupling constants do indeed converge at the same energy scale ($\sim 10^{16}$ GeV), using the RGE's arising from the combination of supersymmetry (SUSY), as embodied in the Minimal Supersymmetric Standard Model (MSSM[2]), and supergravity. This behavior suggests that SUSY must be involved in any reasonable approach to grand unification. Thus, a direct search for SUSY phenomena at high energy particle accelerators is clearly very important.

The most distinctive signatures of gluino ($\tilde{g}\tilde{g}$), squark ($\tilde{q}\tilde{q}$), gluino-squark ($\tilde{g}\tilde{q}$) and chargino-neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pair production are multi-jets associated with large missing transverse energy ($\not{E}_T$), same-sign dileptons and trilepton events. The multi-jets+$\not{E}_T$ approach is sensitive to $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production followed by direct cascade decays. Such a data analysis begins with a high $\not{E}_T$ sample ($\not{E}_T$ >35 GeV). The cross section for these events is large, but the details of $\not{E}_T$ measurement must be well understood. Same-sign dilepton events probe $\tilde{g}\tilde{g}$ production, with corresponding cascade decays. Since this cross section is expected to be very small, much data is required for a sensitive measurement. Finally, trilepton events are one of the most promising channels for the discovery of SUSY at

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a hadron collider [3]. Chargino-neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pairs are produced via s-channel virtual W's or virtual squark exchange (t-channel), with subsequent leptonic decays ($\tilde{\chi}_1^{\pm} \rightarrow \ell\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell\bar{\ell}\tilde{\chi}_1^0$). The striking signature of these events is thus three isolated leptons, with minimal jet activity. Standard Model backgrounds in this mode are expected to be small.

Our data sample consists of 19 pb^{-1} total integrated luminosity of $\sqrt{s}$ = 1.8 TeV $p\bar{p}$ collisions accumulated with the Collider Detector at Fermilab (CDF) [4]. These data were obtained during the 1992-93 run of the Fermilab Tevatron. In this paper, we present a preliminary search for SUSY trilepton events using this data sample.

2 Theoretical Predictions of the MSSM

Theoretical predictions of the MSSM were obtained using ISAJET 7.06 [5]. Listed below are the parameter values and settings used for most of our Monte Carlo simulations :

μ	$-400 \leftrightarrow -500$ GeV
M(top)	170 GeV/c^2
tan(β)	$2.0 \leftrightarrow 15.0$
structure function	CTEQ 2L
$M(\tilde{g})$	$140 \leftrightarrow 240$ GeV/c^2
$M(\mathrm{H_A})$	500 GeV/c^2
$M(\tilde{q})/M(\tilde{g})$	1.2
$\mathrm{A_t}$	0.0
α_S	0.12
p_T range	$3 \leftrightarrow 300$ GeV/c

Slepton and sneutrino masses were determined from tan(β), $M(\tilde{g})$, and $M(\tilde{q})$ using the renormalization group equations [6].

3 Data Analysis

With the present integrated luminosity, we are sensitive to $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ masses in the range ~40-50 GeV/c^2. Therefore, the three-way split of the gaugino energies between two leptons and the lightest neutralino ($\tilde{\chi}_1^0$) lead to lepton transverse momenta which are typically lower than the transverse momenta of leptons from W and Z^0 decays. Thus, our analysis begins with the inclusive electron and muon data samples.

We define two class of leptons: 'gold' and 'ordinary'. Gold leptons are required to pass cuts which are tighter than the inclusive electron or muon trigger criteria. The minimum gold lepton p_T is 11 GeV/c and gold electrons (muons) are accepted in the pseudo-rapidity range $|\eta| < 1.1$ ($|\eta| < 0.6$). The ordinary leptons have lower E_T or p_T thresholds and generally pass looser quality cuts. The minimum p_T value for ordinary electrons (muons) is 5 GeV (4 GeV/c); ordinary electrons (muons) are accepted in the pseudo-rapidity range $|\eta| < 2.4$ ($|\eta| < 1.2$). Details of the lepton selection criteria can be found in Ref. [7].

We impose the following criteria on trilepton event candidates :

- Event must contain at least one gold lepton
- All leptons require $ISO < 2$ GeV
- $\Delta R_{ll} > 0.4$ for all lepton pairs
- Existence of an e^+e^- or $\mu^+\mu^-$ pair
- Pass mass cuts for unlike sign pairs
- $|Z_{vertex}| <60$ cm
- $\Delta\phi(\ell_1\ell_2) < 170°$

The ISO variable is the total transverse energy within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ $= 0.4$ around the lepton (excluding the lepton E_T). We cut on this variable to reject $b\bar{b}$ events. The ΔR_{ll} variable is the opening angle between two leptons in η-ϕ space. This cut reduces contamination from conversions. Drell-Yan backgrounds are reduced by the back-to-back veto ($\Delta\phi(\ell_1\ell_2)$, where ℓ_1 and ℓ_2 refer to the two highest p_T leptons in the event). The lepton pair mass ranges rejected are 75-105 GeV/c^2 for Z^0, 9-11 GeV/c^2 for the Υ's and 2.9-3.3 GeV/c^2 for J/ψ. Table 1 shows the number of events left after each trilepton selection cut. After all cuts, we are left with zero event candidates.

4 Detection Efficiency

The total detection efficiency for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3lX$ is obtained from

$$\epsilon^{tot} = \sum_{xxx}(\epsilon^{MC}_{xxx} \cdot \epsilon^{trig}_{xxx} \cdot \epsilon^{ISO})$$

where :

- ϵ^{MC} is the acceptance with all analysis cuts, excluding the isolation requirement (ISO <2)
- ϵ^{ISO} is the efficiency of the ISO <2 requirement alone
- ϵ^{trig} is the trigger efficiency
- xxx = eee, eeμ, e$\mu\mu$, or $\mu\mu\mu$ mode

The isolation efficiency ϵ^{ISO} was determined from data to be 88% [7] and is equivalent for each mode. The principal trigger for this trilepton search is a single lepton with $p_T >$ 9 GeV (avoiding the turn-on region of this 9 GeV trigger threshold is what primarily motivates our 11 GeV gold lepton cut). These trigger efficiencies were determined to be ϵ_{trig}(muon) = (84.33 ± 2.30)% and ϵ_{trig}(electron) = (87.73 ± 1.53)%. Since the species of leptons in each mode are different, the trigger efficiencies will be different for each mode.

Table 1: Events remaining after trilepton cuts. The entire CDF Run 1A data sample was analysed.

cut	muon	electron
Original Sample	2,707,852	3,677,903
Dilepton data sample	28,474	34,055
Dilepton data sample (removing bad runs)	26,069	31,081
Dilepton selection without ISO cuts	7,120	5,709
Trilepton selection without ISO cuts	148	86
Trilepton selection with $ISO < 4$	36	14
Trilepton Event Selection		
∘ $ISO(0.4) < 2$ GeV	22	4
∘ $\|Z_{vertex}\| <60$	22	4
∘ $\Delta R_{\ell\ell} > 0.4$	2	3
∘ $\Delta\phi(\ell_1\ell_2) < 170°$	2	1
∘ $\|Q_1 + Q_2 + Q_3\| < 3$	2	1
∘ Require e^+e^- or $\mu^+\mu^-$	2	1
∘ Z^0 removal (75-105 GeV/c^2)	1	0
∘ J/ψ removal (2.9-3.3 GeV/c^2)	1	0
∘ Υ removal (9-11 GeV/c^2)	0	0
$\int \mathcal{L}dt$ [pb^{-1}]	18.09 ± 0.72	19.11 ± 0.76

The trigger efficiency for each mode is estimated to be an average of the single lepton trigger efficiencies, weighted according to the lepton content in the mode. For example, :

$$\epsilon^{trig}_{ee\mu} = \frac{2}{3}\epsilon^{trig}_{e} + \frac{1}{3}\epsilon^{trig}_{\mu} \cdot \mathrm{C} \quad (1)$$

Other mode efficiencies are calculated similarly. Note the inclusion of the factor C in this expression (C = 0.95). This factor is applied to the muon trigger efficiency only and corrects for a difference in total integrated luminosity available in the inclusive muon and inclusive electron data samples (due primarily to different numbers of bad runs, in which the muon or electron detectors experienced problems). Thus, this correction factor gives us an "effective" muon trigger efficiency.

The trilepton event acceptance (ϵ^{MC}) was determined from ISAJET 7.06 Monte Carlo data. We generated $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ events using the range of parameter values listed above and forcing the decay modes $\tilde{\chi}_1^{\pm} \to \ell\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell\bar{\ell}\tilde{\chi}_1^0$, where ℓ is an electron or muon. Separate runs were performed for each mode, since the mode acceptances are different.

Figure 1 shows a plot of ϵ^{MC} vs. $\tilde{\chi}_1^{\pm}$ mass for the eee decay mode. The ϵ^{MC} vs. $M(\tilde{\chi}_1^{\pm})$ plots for the other modes are qualitatively similar. The points in this figure were obtained with the following ISAJET parameter values :

- μ : −500, −450, −400 GeV

- $\tan(\beta)$: 2.0, 4.0, 15.0
- $M(\tilde{g})$: 140, 150, 160, 170, 180, 200, 240 GeV/c^2

Parameters not mentioned in this list were set to the values discussed previously. Not every single combination of parameter values was used to generate an acceptance point. However, points using extreme values in the ranges listed above were generated in order to explore the maximum variation in acceptance. Within this range of parameter values, the acceptance is primarily dependent on $M(\tilde{\chi}_1^{\pm})$. The acceptance does not directly depend on $\tan(\beta)$ or μ. Furthermore, the acceptance is quite linear over the mass range of interest (40< $M(\tilde{\chi}_1^{\pm})$ <70 GeV/c^2). There does appear to be some scatter of points but this is believed to be statistical fluctuation. Our statistical error reflects this. Therefore, we have fit straight lines through the data points and will use the equations of these lines as closed form expressions of ϵ^{MC} :

$$\epsilon^{MC}_{eee}(\%) = 0.191 \cdot M(\tilde{\chi}_1^{\pm}) - 6.09 \quad (2)$$
$$\epsilon^{MC}_{ee\mu}(\%) = 0.204 \cdot M(\tilde{\chi}_1^{\pm}) - 5.99 \quad (3)$$
$$\epsilon^{MC}_{e\mu\mu}(\%) = 0.256 \cdot M(\tilde{\chi}_1^{\pm}) - 7.60 \quad (4)$$
$$\epsilon^{MC}_{\mu\mu\mu}(\%) = 0.276 \cdot M(\tilde{\chi}_1^{\pm}) - 8.41 \quad (5)$$

We note that it has been demonstrated that the acceptance points at high mass do not significantly alter the fit. If the high mass points are omitted, the fit parameter values are essentially unchanged.).

5 Backgrounds

The principal backgrounds to the SUSY trilepton analysis are from Drell-Yan, $Z+X$, diboson (WZ, ZZ), and b$\bar{\text{b}}$ events. ISAJET Monte Carlo was generated for each of these processes (forcing leptonic decays only, and forcing τ's to decay to e or μ). These events were then run through the CDF detector simulation QFL, the offline reconstruction software and the trilepton finding code. The resulting yield gives us our background estimate. However, only the diboson and b$\bar{\text{b}}$ modes have an appreciable probability of yielding three leptons directly from the physics process. Drell-Yan and $Z+X$ both can produce two leptons directly and may only be mistaken for a SUSY trilepton if there is a third "fake" lepton in the event. We use the term "fake" to mean incorrectly identified leptons, leptons from photon conversions, decays in flight, etc.

We have estimated the lepton fake rate using real data, since it is always desirable to avoid using Monte Carlo when possible. We start with a clean sample of $W^{\pm} \rightarrow \ell^{\pm}\nu$ events, in which we expect there to be only a single lepton (from the W decay). We then look for leptons which satisfy our "ordinary" criteria (mentioned above). The resulting rate of finding a fake lepton in a W event is $(0.25 \pm 0.03)\%$. This measurement is a conservative overestimate since we have not removed from this fake rate opposite sign lepton pairs which may be coming from Drell-Yan or Z contamination in our "clean" W sample.

Table 2 lists the expected background yields in 19 pb^{-1} data. The trigger efficiency we have used is a slight overestimate (90%). Estimated background from b$\bar{\text{b}}$ events is approximate because in a 16 pb^{-1} Monte Carlo sample, we observe no trilepton candidates from this

Table 2: Expected SUSY trilepton backgrounds in Run 1A data sample (19.11 pb^{-1}). All τ's are forced to decay to e or μ.

physics process	MC eff.	σ [pb]	Trigger eff.	ISO eff.	BR	fake rate	# events
DY $\gamma \to ll$	0.020	799.	0.90	0.88	1.0	2.52×10^{-3}	0.61
DY $\gamma \to \tau\tau$	0.003	400.	0.90	0.88	$(0.355)^2$	2.52×10^{-3}	5.76×10^{-3}
DY $Z \to ll$	0.006	418.	0.90	0.88	1.0	2.52×10^{-3}	9.57×10^{-2}
DY $Z \to \tau\tau$	0.037	209.	0.90	0.88	$(0.355)^2$	2.52×10^{-3}	3.72×10^{-2}
$ZW \to l^+l^-l\nu_l$	0.002	2.5	0.90	0.88	1.40×10^{-2}	-	1.11×10^{-3}
$ZW \to l^+l^-\tau\nu_\tau$	0.003	2.5	0.90	0.88	2.51×10^{-3}	-	2.99×10^{-4}
$ZW \to \tau^+\tau^-l\nu_l$	0.041	2.5	0.90	0.88	8.79×10^{-4}	-	1.43×10^{-3}
$ZW \to \tau^+\tau^-\tau\nu_\tau$	0.039	2.5	0.90	0.88	1.57×10^{-4}	-	2.42×10^{-4}
$ZZ \to l^+l^-l^+l^-$	0.006	1.0	0.90	0.88	4.46×10^{-3}	-	4.24×10^{-4}
$ZZ \to \tau^+\tau^-l^+l^-$	0.047	1.0	0.90	0.88	2.79×10^{-4}	-	2.08×10^{-4}
$ZZ \to \tau^+\tau^-\tau^+\tau^-$	0.118	1.0	0.90	0.88	1.75×10^{-5}	-	3.27×10^{-5}
$b\bar{b}$							$< \mathcal{O}(1)$
Total							0.75

source. The diboson and Drell-Yan cross sections were obtained from CDF measurements and theoretical calculations ([8] - [11]). BR listed in Table 2 is the product of all branching ratios that arise in the decay to e's or μ's. It is clear that the dominant background source is Drell-Yan. However, the sum of all expected backgrounds is less than one event, completely consistent with our observation of zero events.

6 Excluded Regions of the MSSM

Our observation of zero trilepton events folded in with our statistical error, determines an upper limit on $M(\tilde{\chi}_1^\pm)$. Table 3 shows our systematic error estimates. Lepton ID refers to various issues of lepton detection which require further study. When the total systematic error of 19% is convoluted (as a Gaussian smearing) with a Poisson distribution, we obtain a 95% confidence level upper limit of 3.2 events. The expression which relates this upper limit to σBR is:

$$N_{predict} = \sigma \cdot BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to 3\ell X) \cdot \int \mathcal{L}dt \cdot (\epsilon_{eee} + \epsilon_{ee\mu} + \epsilon_{e\mu\mu} + \epsilon_{\mu\mu\mu}) < 3.2$$

Note that these events come from the sum of four final states; $e^+e^-e^+$, $e^+e^-\mu^+$, $e^+\mu^-\mu^+$, and $\mu^+\mu^-\mu^+$. We make use of the fact that the branching ratios for each of these final states is the same; $BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to eeeX) = BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to e\mu\mu X) = BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to ee\mu X) = BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to \mu\mu\mu X) \equiv BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to 3\ell X)$. We derive an upper limit on $\sigma \cdot BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to$

Table 3: Systematic error estimates

source	error (%)
luminosity	3.6%
structure functions	2%
trigger efficiency	2.5%
Monte Carlo statistics	10%
lepton ID	15%
Total	19%

$3\ell X$) by solving this equation using the measured integrated luminosity for our data sample of 19.11 pb^{-1}, the isolation and trigger efficiencies (Equation 1), and the acceptance parametrizations (Equations 2 - 5). Thus,

$$\sigma \cdot BR(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell X) < \frac{3.2}{19.11\ \mathrm{pb}^{-1} \cdot (\epsilon_{eee} + \epsilon_{ee\mu} + \epsilon_{e\mu\mu} + \epsilon_{\mu\mu\mu})}$$

Figure 2 shows the 95% confidence level upper limit on σBR($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell$X), plotted as a smooth curve vs. $M(\tilde{\chi}_1^{\pm})$. The points in the figure are the ISAJET Monte Carlo predictions for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production (μ = -400, M(top) = 170 GeV/c^2, $M(\tilde{q}) = 1.2 \times M(\tilde{g})$, $M(\mathrm{H_A})$ = 500 GeV/c^2, $\mathrm{A_t} = 0$, $\alpha_S = 0.12$). It is apparent that $M(\tilde{\chi}_1^{\pm})$ <~ 46 GeV/c^2 are excluded by our data. Note that Figure 2 contains points from several different tan(β) values. The approximate $\tilde{g}$ mass values which correspond to $M(\tilde{\chi}_1^{\pm})$ = 46 GeV/c^2 (for $\mu = -400$) are :

- $\tan(\beta) = 2.0 : M(\tilde{g}) \simeq 131\,\mathrm{GeV/c^2}$
- $\tan(\beta) = 4.0 : M(\tilde{g}) \simeq 149\,\mathrm{GeV/c^2}$
- $\tan(\beta) = 8.0 : M(\tilde{g}) \simeq 161\,\mathrm{GeV/c^2}$
- $\tan(\beta) = 15.0 : M(\tilde{g}) \simeq 167\,\mathrm{GeV/c^2}$

The ISAJET Monte Carlo points for $\mu = -500$ GeV (not shown) describe an identical curve and yield the same 46 GeV/c^2 upper limit. This limit is comparable to the LEP result [12].

7 Conclusion

We have searched for evidence of the production and decay of SUSY chargino-neutralino pairs into trilepton events in 19 pb^{-1} of $\sqrt{s}$ = 1.8 TeV $p\bar{p}$ collision data at CDF. Using all possible electron and muon decay channels, no events are observed. We exclude $M(\tilde{\chi}_1^{\pm})$ <~ 46 GeV/c^2 for the MSSM parameter values previously stated.

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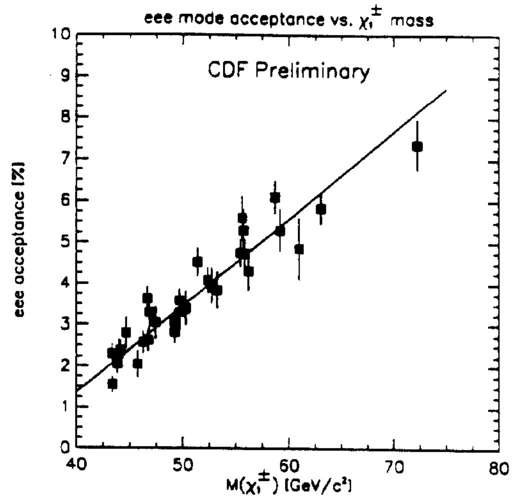

Figure 1: Trilepton event acceptance (ϵ^{MC}) vs. $\tilde{\chi}_1^\pm$ mass (GeV/c^2) for the eee decay mode (other modes are qualitatively similar). The acceptance is quoted in %. See text for description of ISAJET parameter values used to obtain these points.

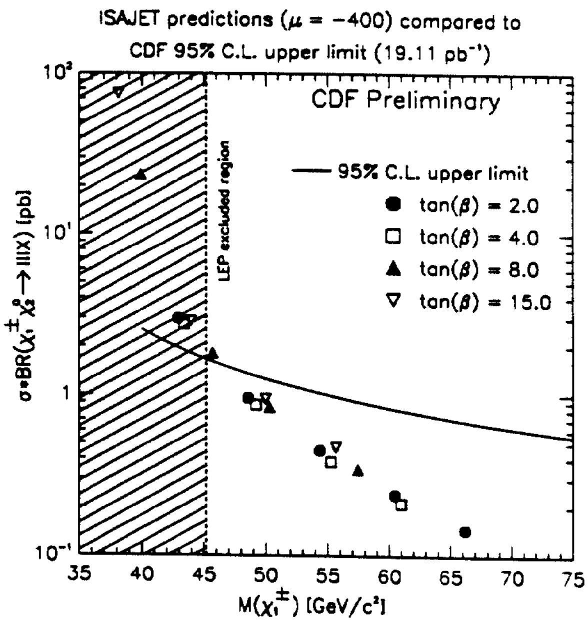

Figure 2: 95% confidence level upper limit on σBR($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to 3\ell$X) vs. $M(\tilde{\chi}_1^\pm)$. The data points are the predictions of ISAJET 7.06. Note that 3ℓ does NOT refer to the sum of all four modes, but rather any one of them individually (ex., eee). The shaded region corresponds to the LEP limit[12].