Fermi National Accelerator Laboratory

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**DØ**

# Search for the Trilepton Signature from the Associated Production of SUSY $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ Gauginos

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## Abstract

We report on a search for the trilepton signature from the associated production of supersymmetric gaugino pairs, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, within the context of minimal supersymmetric models that conserve $R$-parity. This search uses 95 pb$^{-1}$ of data taken with the DØ detector at Fermilab's Tevatron collider at $\sqrt{s} = 1.8$ TeV. No evidence of a trilepton signature has been found, and a limit on the production cross section times branching fraction to trileptons as a function of $\tilde{\chi}_1^{\pm}$ mass is given.

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The Standard Model (SM) is very successful, but there are a number of theoretical arguments that suggest it will break down at the TeV scale unless it is extended. One argument involves the necessity of fine-tuning the parameters of the Higgs scalar potential in order to obtain a Higgs mass near the electro-weak scale. Supersymmetry (SUSY) is among the leading possibilities for an extension of the SM. SUSY relates bosons to fermions and introduces for every SM particle a supersymmetric partner that differs in spin by 1/2. The SUSY electro-weak gauge particles (gauginos) are mixtures of the SUSY partners of the $W$, $Z$, $\gamma$ and Higgs bosons. The charged and neutral gauginos are denoted by $\tilde{\chi}_i{}^{\pm}\,\{i=1,2\}$ and $\tilde{\chi}_i{}^{0}\,\{i=1,2,3,4\}$. We consider only minimal supergravity (SUGRA) [1] models or minimal unified scale (GUT) [2] inspired models that are $R$-parity conserving. $R$-parity conservation requires that SUSY particles be produced in pairs and that the lightest SUSY particle (LSP) be absolutely stable. In the models we investigate, this LSP is the $\tilde{\chi}_1^0$, which is a candidate for cold dark matter.

This letter describes a search for the production of $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ pairs which decay producing three isolated charged leptons plus missing transverse energy ($\not\!\!E_T$) [3]. The $\tilde{\chi}_2^0$ in this case decays into two charged leptons plus a LSP, and the $\tilde{\chi}_1^{\pm}$ decays into a charged lepton, a neutrino, and a LSP. The backgrounds to this hadronically quiet trilepton signature are small. The two highest transverse energy ($E_T$) leptons have moderate to high $E_T$ (>15 GeV), while the lepton with the third highest $E_T$ can be rather soft. Even though two LSP's and a neutrino contribute to the $\not\!\!E_T$, the angular correlation between these particles is weak resulting in moderate $\not\!\!E_T$. The $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ production cross section times branching fraction to trileptons ($\sigma \times B(3\ell)$) varies greatly as a function of the model parameters.

We search for evidence of $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ production in four channels containing electrons ($e$) and muons ($\mu$): $eee$, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$. Due to detection inefficiencies, we ignore taus and their leptonic decay products. The integrated luminosities for the search in the above four channels are respectively 94.9 pb$^{-1}$, 94.9 pb$^{-1}$, 89.5 pb$^{-1}$, and 75.3 pb$^{-1}$, obtained during the 1994–1995 Tevatron collider run at $\sqrt{s} = 1.8$ TeV. Previous searches [4] [5] at the Tevatron for trilepton signatures were conducted using the 1992–1993 collider data.

The DØ detector is described in detail elsewhere [6]. It consists of central tracking chambers without a magnetic field, a finely segmented, hermetic uranium/liquid-argon sampling calorimeter, and a muon spectrometer. Electrons are measured with an energy resolution of $15\%/\sqrt{E}$, and the muon momentum is measured with a resolution expressed as $\sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.003$ ($E$, $p$ measured in GeV and GeV/c).

The event selection is optimized based on signal and background Monte Carlo simulations and background data. We require three isolated leptons satisfying standard DØ identification requirements [7]. Electrons are required to satisfy the isolation requirement $\mathcal{I} < 0.1$, where $\mathcal{I} = (E_{\rm TOT} - E_{\rm EM})/E_{\rm EM}$. $E_{\rm TOT}$ is the energy of the electron candidate within the electromagnetic (EM) and hadronic portions of the calorimeter that is within a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$, where $\eta$ is the pseudorapidity and $\phi$ is the azimuthal angle. $E_{\rm EM}$ is the energy of the candidate electron within the EM calorimeter and first layer of the hadronic calorimeter that is within a cone of $R = 0.2$. Muons are required not to have any reconstructed jet ($E_T > 8$ GeV) within $R = 0.5$. The minimum lepton $E_T$ is 5 GeV; however, one or two of the leptons are required to be 2 GeV above the trigger thresholds. The triggers used in this analysis are listed in Table I.

Muons are required to have $\mid \eta \mid < 1.0$. To eliminate instrumental backgrounds with large mismeasured $\not\!\!E_T$ due to tails in the muon momentum distribution, $\Delta\phi$ between the highest $E_T$ muon and the $\not\!\!E_T$ must be $< (\pi - 0.1)$ radians and any signature muon must have $\Delta\phi > 0.1$ relative to the $\not\!\!E_T$. To reject the cosmic ray background, we require that any two signature muons have $\Delta\phi_{\mu\mu} < (\pi - 0.1)$ radians. This dimuon back-to-back cut also helps to eliminate a significant portion of the $Z/\gamma^*$ boson to dimuon background.

We also require signature specific cuts in the four channels. For the $eee$ channel, we require the $e\not\!\!E_T$ or $2e\not\!\!E_T$ trigger, and we require $\not\!\!E_T > 15$ GeV. We exclude events with an invariant mass from the two highest $E_T$ electrons in the mass range of 81 to 101 GeV/c$^2$, and the two highest $E_T$ electrons must have $\Delta\phi_{ee} < (\pi - 0.2)$ radians. These cuts eliminate the main background of $Z/\gamma^*$ bosons with an additional "electron" (denoted as $\varepsilon$) originating from a jet which fluctuated into an EM cluster or from a converted photon which produced two unresolved electrons. The effect on the background of altering the cuts on the $\not{E}_T$ and the $E_T$ of the third most energetic electron as estimated from Monte Carlo studies is given in Table II. Also given is the actual number of events seen. The data agree well with the $Z/\gamma^*$ boson background estimates. With the cuts of 5 GeV on the third electron and $\not{E}_T$ $> 15$ GeV, we see no events in the $eee$ channel with an expected background of 0.34$\pm$0.07 events.

For the $ee\mu$ channel we require the $e\not{E}_T$, $2e\not{E}_T$, or $e\mu$ trigger. We also require $\not{E}_T > 10$ GeV. With these selections and the above generic requirements on electrons and muons, we see no events. We expect 0.61$\pm$0.36 background events from three main sources: $Z/\gamma^* \rightarrow \tau\tau+\ \varepsilon$, semi-leptonic decays of heavy ($b$ or $c$) quark pairs + $\varepsilon$, and $Z/\gamma^* \rightarrow ee + \mu$ from a heavy quark decay. Mass and angle cuts are not made on the electrons in this channel, since the rate of $Z/\gamma^* \rightarrow ee + \mu$ events is smaller by about an order of magnitude than the rate of $Z/\gamma^*$ + $\varepsilon$ background events in the $eee$ channel. Relaxing the isolation requirement on the muon and the 10 GeV $\not{E}_T$ requirement allows one event to pass with an expected background of 1.41$\pm$0.67 events. This event has a dielectron mass of 90 GeV/c$^2$ indicating that it is a $Z \rightarrow ee + \mu$ candidate, which is consistent with this background source being the largest contributor to the total background for these cuts.

The major backgrounds for the $e\mu\mu$ channel are $Z/\gamma^*$ bosons + $\varepsilon$, $J/\psi$ + $\varepsilon$, and heavy quark pairs + $\varepsilon$. For this channel, we require the $\mu$, $2\mu$, or $e\mu$ trigger. To reject low mass dimuon events (e.g., $J/\psi$), we require that the dimuon invariant mass be greater than 5 GeV/c$^2$. We also require $\not{E}_T > 10$ GeV. With this selection we see no candidate events with an expected background of 0.11$\pm$0.04 events. To verify our background estimate, we relax the electron identification requirements, thereby dramatically increasing the number of events with misidentified electrons. We see 31 events with 27.3$\pm$5.5 events expected. About 80% of this is estimated to come from heavy quark pairs.

$Z/\gamma^*$ bosons and heavy quark pairs are the major contributors of background to the $\mu\mu\mu$ channel. In this channel we require the $\mu$ or $2\mu$ trigger. The dimuon invariant mass for any two of the three muons must be greater than 5 GeV/c$^2$. We also require $\not{E}_T > 10$ GeV. We see no events with this selection. We expect 0.20±0.04 background events. Without the $\not\!\!E_T$ cut we find one event with an expected background of 0.75±0.27 events. We interpret this event to be consistent with a heavy quark pair with $\not\!\!E_T = 1.3$ GeV.

The channel specific selection requirements are summarized in Table III. A summary of the total backgrounds expected for our final event selection and the integrated luminosity is given in Table IV. The luminosities vary from channel to channel due to different prescales for the various triggers.

The signal efficiencies are derived from ISAJET [8] Monte Carlo processed with a GEANT [9] simulation of the DØ detector and a simulation of the DØ trigger. The model parameters for our full simulation were chosen to give $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0}$ within 1 GeV and $M_{\tilde{\chi}_2^0} = 2M_{\tilde{\chi}_1^0}$ within 10%, since these relationships hold approximately for many choices of parameters in SUGRA models. We generate events in the four signatures with $\tilde{\chi}_1^\pm$ masses between 45 and 124 GeV/c$^2$. The efficiency ranges from 1.6% at 45 GeV/c$^2$ to 11.1% at 124 GeV/c$^2$ for the $eee$ channel and decreases as the signature includes more muons down to the range of 0.54% to 2.17% for the $\mu\mu\mu$ channel. The efficiencies for the channels with muons are smaller due to the reduced $\eta$ acceptance of muons compared to electrons and the lower identification efficiency for muons.

These efficiencies and our resulting limit on $\sigma \times B(3\ell)$ are applicable to many choices of SUSY model parameters. To estimate under what conditions our signal efficiencies apply, we have studied the ISAJET particle spectra from $\tilde{\chi}_1^\pm\,\tilde{\chi}_2^0$ production for a large number of choices (scenarios) of the five SUGRA model parameters. These parameters and the chosen range of values are: the common scalar mass at the unified (GUT) scale, $1 \leq m_0 \leq 100$ GeV/c$^2$; the common fermion mass at the GUT scale, $60 \leq m_{1/2} \leq 155$ GeV/c$^2$; the ratio of the vacuum expectation values of the two Higgs doublets at the electroweak scale, $1.5 \leq \tan\beta \leq 6$; the soft trilinear SUSY breaking parameter at the GUT scale, $-200 \leq A_0 \leq 200$; and the sign of the Higgsino mass term, $\mu$.

We find that 99% of the scenarios studied with $M_{\tilde{\chi}_2^0}/M_{\tilde{\chi}_1^0} \geq 1.8$, $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^\pm} \geq -1.0$

GeV/c$^2$, and $M_{\tilde{\chi}_1^\pm} > 45$ GeV/c$^2$ have efficiencies that are $\geq 0.9$ times the efficiency for the case where $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 2M_{\tilde{\chi}_1^0}$. However, if the masses of the SUSY partners of the charged leptons, $\tilde{l}$, are lighter than one or both of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$, in order for our efficiencies to be applicable, $M_{\tilde{\chi}_2^0} - M_{\tilde{l}} > 7.0$ GeV, $M_{\tilde{\chi}_1^\pm} - M_{\tilde{l}} > 7.0$ GeV, and $M_{\tilde{l}} - M_{\tilde{\chi}_1^0} > 15.0$ GeV.

Combining all four channels and assuming that the branching fractions for the decay of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ to the four channels are equal, we calculate the 95% CL upper limit [10] on $\sigma \times B(3\ell)$ for any one channel. This limit takes into account the total statistical and systematic uncertainties of the analysis. These total uncertainties range from 10% for the $eee$ channel to 20% for the $\mu\mu\mu$ channel. The previously published limit (based on 12.5 pb$^{-1}$ of 1992–1993 data) [4] as a function of $\tilde{\chi}_1^\pm$ mass is given in Fig. 1 as the top solid curve (A). The limit from the 1994–1995 data is shown as the middle solid curve (B), and the limit from the combined data set is given as the lower solid curve (C). We exclude the region above this curve. The combined limit ranges from 0.66 pb at $M_{\tilde{\chi}_1^\pm} = 45$ GeV/c$^2$ down to 0.10 pb at $M_{\tilde{\chi}_1^\pm} = 124$ GeV/c$^2$. The top dashed curve (i) is the theoretical cross section (GUT inspired) for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production from ISAJET times the maximum branching fraction to trileptons of 1/9 for any one channel. This represents the maximum possible $\sigma \times B(3\ell)$ for one exclusive trilepton channel. The bottom dashed curve (ii) is the total cross section times the product of the SM branching fractions of $W$ and $Z$ bosons to any one generation of charged lepton (0.0036). This is given to illustrate the typical variation of $\sigma \times B(3\ell)$ within SUSY models, but in some scenarios the branching fraction can approach zero. Also given as the shaded region to the left is the 95% CL lower limit of 62 GeV/c$^2$ on the $\tilde{\chi}_1^\pm$ mass from the OPAL $\sqrt{s} = 161$ GeV data for the conditions on the SUSY model parameters as given in Ref. [11]. Other limits from the LEP 130 GeV and 136 GeV data are discussed in Ref. [12]. $\tilde{\chi}_1^\pm$ masses below 45 GeV/c$^2$ have been excluded by previous searches at LEP [13].

In conclusion we find no evidence of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production in the current DØ data set. We have set a 95% CL upper limit on $\sigma \times B(3\ell)$ to any one channel as a function of $\tilde{\chi}_1^\pm$ mass.

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# TABLES

TABLE I. Triggers used in SUSY gaugino search.

| Trigger | Requirements |
| --- | --- |
| $e\not\!\!E_T$ | $\geq 1e, E_T > 20$ GeV and $\not\!\!E_T > 15$ GeV |
| $2e\not\!\!E_T$ | $\geq 1e, E_T > 12$ GeV and $\geq 1e, E_T > 7$ GeV and $\not\!\!E_T > 7$ GeV |
| $e\mu$ | $\geq 1e, E_T > 7$ GeV and $\geq 1\mu, E_T > 8$ GeV |
| $\mu$ | $\geq 1\mu, E_T > 15$ GeV |
| $2\mu$ | $\geq 2\mu, E_T > 3$ GeV |

TABLE II. The number of events observed and background estimates for $Z/\gamma^* \rightarrow ee+ \varepsilon$ for various $\not\!\!E_T$ and third electron $E_T$ (denoted as $E_T^3$) cuts in the $eee$ selection.

| | $\not\!\!E_T > 10$ GeV | | $\not\!\!E_T > 15$ GeV | |
| --- | --- | --- | --- | --- |
| | #expected | #seen | #expected | #seen |
| $E_T^3$ (GeV) | | | | |
| 2 | 4.8±0.7 | 5 | 1.8±0.3 | 2 |
| 3 | 2.3±0.4 | 1 | 0.88±0.17 | 0 |
| 4 | 1.3±0.2 | 0 | 0.49±0.10 | 0 |
| 5 | 0.9±0.2 | 0 | 0.34±0.07 | 0 |

TABLE III. Summary of cuts used in SUSY gaugino search.

| Channel | $eee$ | $ee\mu$ | $e\mu\mu$ | $\mu\mu\mu$ |
|---|---|---|---|---|
| Trigger | $e\not\!\!E_T$, $2e\not\!\!E_T$ | $e\not\!\!E_T$, $2e\not\!\!E_T$, $e\mu$ | $e\mu$, $\mu$, $2\mu$ | $\mu$, $2\mu$ |
| Mass cut | $\mid M_{ee} - M_{Z^0} \mid > 10$ GeV/c$^2$ | – | $M_{\mu\mu} > 5$ GeV/c$^2$ | $M_{\mu\mu} > 5$ GeV/c$^2$ |
| | | | | (all 3 $\mu$ pairs) |
| $\not\!\!E_T$ | $> 15$ GeV | $> 10$ GeV | $> 10$ GeV | $> 10$ GeV |
| angle cuts | $\mid \pi - \Delta\phi_{ee} \mid > 0.2$ | – | $\mid \pi - \Delta\phi_{\mu\mu} \mid > 0.1$ | $\mid \pi - \Delta\phi_{\mu\mu} \mid > 0.1$ |
| | (two highest $E_T$ electrons) | | | (all 3 $\mu$ pairs) |
| Lepton $E_T$ | For all channels, 2 GeV above trigger for one or two leptons | | | |
| | and for all three leptons $E_T > 5$ GeV | | | |

TABLE IV. Summary of expected backgrounds and integrated luminosity. No events were seen in any channel.

| Channel | $eee$ | $ee\mu$ | $e\mu\mu$ | $\mu\mu\mu$ |
|---|---|---|---|---|
| Luminosity | 94.9 pb$^{-1}$ | 94.9 pb$^{-1}$ | 89.5 pb$^{-1}$ | 75.3 pb$^{-1}$ |
| Background | 0.34±0.07 | 0.61±0.36 | 0.11±0.04 | 0.20±0.04 |

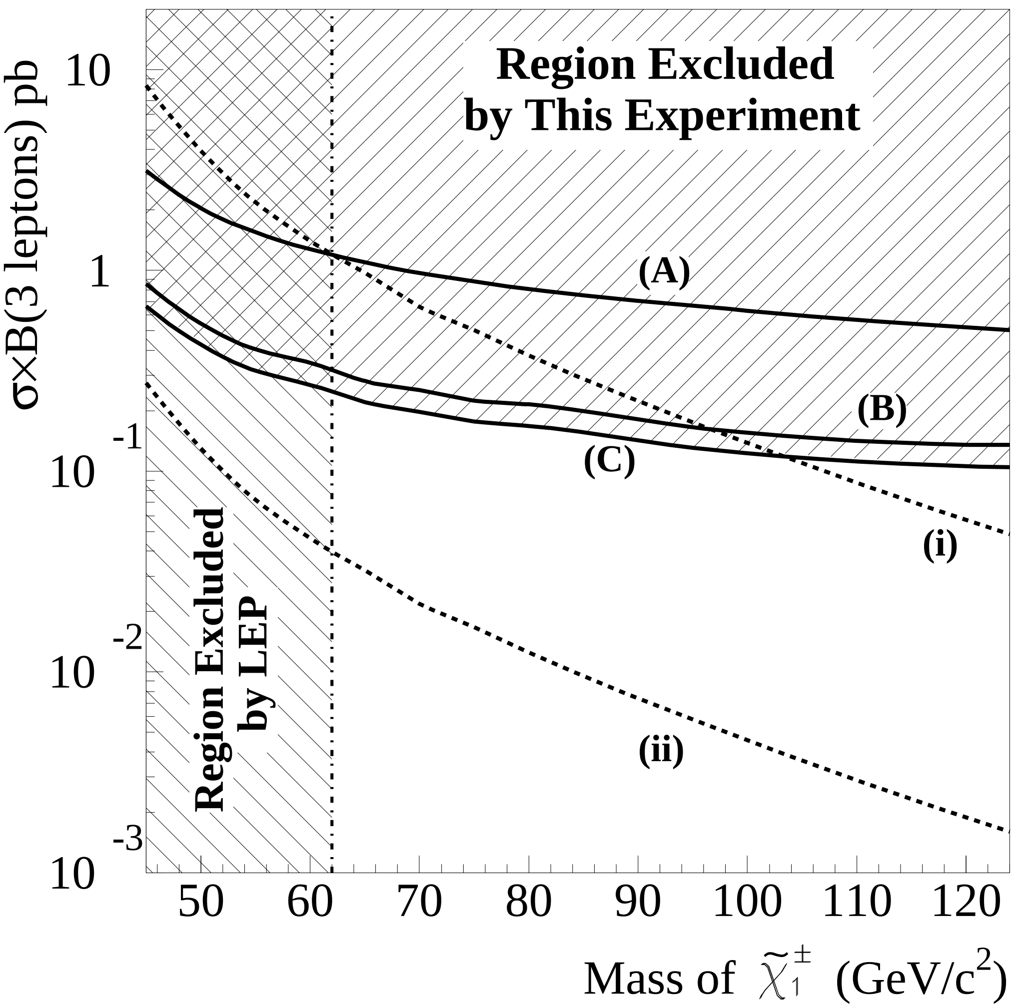


FIG. 1. The 95% CL upper limit on $\sigma \times B(3\ell)$ versus $\tilde{\chi}_1^\pm$ mass for any given channel. (A): limit from 1992–1993 data, (B): limit from 1994–1995 data, (C): combined limit, (i) and (ii): theoretical $\sigma \times B(3\ell)$.