Search for Trilepton Signatures from Associated Gaugino Pair Production

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We report on a search for the trilepton decay 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 $\mathcal{R}$ parity. This search uses 95 pb^{-1} of $p\bar{p}$ data taken at $\sqrt{s} = 1.8$ TeV with the D0 detector. No evidence of a trilepton signature has been found, and a limit on the product of cross section times branching fraction to trileptons is given as a function of $\tilde{\chi}_1^{\pm}$ mass. [S0031-9007(98)05302-2]

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The standard model (SM) is very successful; however, the necessity of fine-tuning the parameters of the Higgs scalar potential in order to obtain a Higgs mass near the electroweak scale suggests the SM will break down at the TeV scale unless it is extended. Furthermore, to eliminate the fine-tuning problem, the new physics must contain mass states below the 1 TeV scale, potentially accessible at current colliders. Supersymmetry (SUSY), among the leading possibilities for an extension of the SM, relates bosons to fermions and introduces for every SM particle a supersymmetric partner that differs in spin by $1/2$. The SUSY electroweak gauge particles (gauginos) are mixtures of the SUSY partners of the W, Z, γ, and Higgs bosons. The charged and neutral gauginos are denoted by $\tilde{\chi}_i^{\pm}$ $\{i = 1,2\}$ and $\tilde{\chi}_i^0$ $\{i = 1,2,3,4\}$. In SUSY models $\mathcal{R}$ parity is a new multiplicative quantum number, $+1$ for SM particles and -1 for SUSY particles. $\mathcal{R}$-parity conservation requires that SUSY particles be produced in pairs and that the lightest SUSY particle (LSP) be stable. In the models we investigate, this LSP is the $\tilde{\chi}_1^0$ and is a candidate for cold dark matter.

This Letter describes a search for the production via an off-shell W boson of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pairs which decay producing three isolated charged leptons plus missing transverse energy ($\not\!\!E_T$) [1]. The $\tilde{\chi}_2^0$ in this case decays into two charged leptons plus an LSP, and the $\tilde{\chi}_1^{\pm}$ decays into a charged lepton, a neutrino, and an LSP. We restrict our search to four channels: eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$. Tau leptons that decay to hadrons produce a signature that has large backgrounds, and the leptonic decays of taus have a low branching fraction times acceptance, which is not included in our signal efficiencies. Limits are obtained on the cross section times branching fraction for a restricted class of SUSY models.

The data used in this search were collected with the D0 detector during the 1994–1995 Tevatron collider run at $\sqrt{s} = 1.8$ TeV. Previous searches [2,3] at the Tevatron for trilepton signatures used the considerably smaller 1992–1993 data sample. The D0 detector is described in detail elsewhere [4]. Electrons with a minimum energy E of 2 GeV are measured with an energy resolution of $\sigma(E)/E = 0.15/\sqrt{E} \oplus 0.012$, and muons with a minimum momentum p of 3 GeV/c are measured with a resolution of $\sigma(p)/p = 0.18(p - 2)/p \oplus 0.003p$ (where $\oplus$ indicates that the two terms in the equation are to be added in quadrature). In a typical minimum bias event, which roughly approximates the underlying event in $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ events, the $\not\!\!E_T$ resolution is $1.1 + 0.02 \times \sum E_T$ (GeV). $\sum E_T$ is the scalar sum of the transverse calorimeter energy from the underlying event.

The backgrounds to the four trilepton signatures are small. The primary backgrounds are instrumental, since the SM background of WZ boson pairs is negligible with an expected production of less than one event per channel. The sources of the instrumental backgrounds are (i) Drell-Yan (DY) production of a lepton pair with an additional fake "electron" (denoted as ε) originating from a jet which fluctuated into an electromagnetic cluster or from a converted photon which produced two unresolved electrons, (ii) DY plus an isolated muon from the decay of an associated heavy quark (b or c), and (iii) isolated leptons from heavy quark pairs with an additional ε. Backgrounds involving taus are generally negligible, and in most cases are not considered. The main background for the eee channel is DY plus ε. The main sources of background for the $ee\mu$ channel are DY with an additional isolated muon, and heavy quarks plus ε. DY or heavy quarks plus ε are the dominant backgrounds for the $e\mu\mu$ channel, and the $\mu\mu\mu$ backgrounds are dominated by heavy quarks.

For determining our sensitivity to the trilepton signature and optimizing our event selection, we consider minimal supergravity (SUGRA) [5] models or minimal unified scale (GUT) [6] inspired models that are R-parity conserving. In these models, for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ masses that are of order 100 GeV/c^2 or less, the two highest transverse energy (E_T) leptons have moderate to high E_T ($>$15 GeV), while the third lepton can be rather soft. The angular correlation between the two LSP's and neutrino is weak resulting in moderate $\not\!\!E_T$.

The event selection is optimized based on the background estimates, discussed below, and on signal Monte Carlo events. The triggers used in this analysis are listed in Table I, and the event selection requirements are summarized in Table II. We require three isolated leptons satisfying standard identification requirements [7]. Electrons must satisfy the isolation requirement $\mathcal{I} < 0.1$, where $\mathcal{I}$ is the fraction of the electron energy found in the annular region $0.2 < R < 0.4$ about its direction. Here, $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where η is the pseudorapidity and ϕ is the azimuthal angle. Isolated muons are required not to have the axis of any jet ($E_T > 8$ GeV) within $R = 0.5$. These isolation requirements greatly reduce the heavy quark backgrounds. The minimum lepton E_T is 5 GeV; however, depending on the two or three triggers used in each channel, one or two of the leptons are required to be 2 GeV above the trigger thresholds to reduce trigger bias. Electrons are required to have $|\eta| < 3.5$ but are not reconstructed in the range $1.2 < |\eta'| < 1.4$, where η' is determined relative to the center of the detector. Muons are required to have $|\eta| < 1.0$.

Since the instrumental backgrounds have typically less $\not\!\!E_T$ than $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ events, we require a minimum $\not\!\!E_T$ in each

TABLE I. Triggers used in the 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
μ	$\geq 1\mu, E_T > 15$ GeV
$\mu\mu$	$\geq 2\mu, E_T > 3$ GeV

TABLE II. Selection criteria, luminosity, background estimates, and number of observed events. The isolation probability for muons from the decay of heavy quarks is 56 ± 5% per muon.

	Channel							
	eee	Trigger	$ee\mu$	Trigger	$e\mu\mu$	Trigger	$\mu\mu\mu$	Trigger
Minimum lepton	22, 5, 5	$e\not\!\!E_T$	$22(e), 5, 5$	$e\not\!\!E_T$	$9(e), 10, 5$	$e\mu$	17, 5, 5	μ
E_T^1, E_T^2, E_T^3	14, 9, 5	$2e\not\!\!E_T$	$14, 9, 5(\mu)$	$2e\not\!\!E_T$	$5, 17(\mu), 5$	μ	5, 5, 5	$\mu\mu$
(GeV)			$9(e), 5, 10(\mu)$	$e\mu$	5, 5, 5	$\mu\mu$		
Mass cut (GeV/c^2)	$\lvert M_{ee} - M_z\rvert > 10$		⋯		$M_{\mu\mu} > 5$		$M_{\mu\mu} > 5$ All combinations	
$\not\!\!E_T$ (GeV)	15		10		10		10	
Angle$(\ell\ell)$ Cuts (radians)	$\lvert\pi - \Delta\phi_{e,e}\rvert > 0.2$ 2 Leading e's		⋯		$\lvert\pi - \Delta\phi_{\mu,\mu}\rvert > 0.1$		$\lvert\pi - \Delta\phi_{\mu,\mu}\rvert > 0.1$ All combinations	
Angle$(\mu\ \not\!\!E_T)$ Cuts (radians)	⋯		$\lvert\pi - \Delta\phi_{\mu,\not E_T}\rvert > 0.1$ Leading μ		$\lvert\pi - \Delta\phi_{\mu,\not E_T}\rvert > 0.1$ Leading μ		$\lvert\pi - \Delta\phi_{\mu,\not E_T}\rvert > 0.1$ Leading μ	
	⋯		$\lvert\Delta\phi_{\mu,\not E_T}\rvert > 0.1$		$\lvert\Delta\phi_{\mu,\not E_T}\rvert > 0.1$		$\lvert\Delta\phi_{\mu,\not E_T}\rvert > 0.1$	
$\int \mathcal{L}\, dt$ (pb^{-1})	94.9 ± 5.0		94.9 ± 5.0		89.5 ± 4.7		75.3 ± 4.0	
Background	0.34 ± 0.07		0.61 ± 0.36		0.11 ± 0.04		0.20 ± 0.04	
Observed	0		0		0		0	
ε Fake rates	Rate	Source	Rate	Source	Rate	Source	Rate	Source
(%)	1.1 ± 0.1	DY	0.10 ± 0.03	DY	0.10 ± 0.03	DY	⋯	⋯
			0.06 ± 0.02	$b\bar{b}$	0.10 ± 0.05	$b\bar{b}$		
	Background consistency check with relaxed cuts							
Background	4.8 ± 0.7		13.6 ± 3.4		27.3 ± 5.5		0.75 ± 0.27	
Observed	5		14		31		1	

of the channels. The $\not\!\!E_T$ cuts used in the eee channel and in the other three channels differ due to their different $\not\!\!E_T$ resolutions. To reduce instrumental backgrounds having large mismeasured $\not\!\!E_T$ from tails in the muon momentum resolution, we use azimuthal angle cuts between muons and the $\not\!\!E_T$ [Angle$(\mu\ \not\!\!E_T)$] as given in Table II. The $\lvert\Delta\phi_{\mu,\not E_T}\rvert > 0.1$ cut is applied to all muons required by the event signature.

Cosmic rays are a copious source of dimuon events with a narrow back-to-back angular distribution. The angle cut [Angle$(\ell\ell)$] suppressing back-to-back muons greatly reduces this source of background and attenuates the DY to dimuon background. A back-to-back cut is applied to dielectrons in the eee channel to reject DY. The dimuon cut is less stringent because it targets primarily cosmics. A more severe cut does not improve the ratio of the signal to the dominant $b\bar{b}$ component of the remaining backgrounds, because the dimuons from the $b\bar{b}$ pair are more broadly distributed in $\Delta\phi$ than the DY dielectrons.

The mass and Angle$(\ell\ell)$ cuts in the eee channel greatly reduce the main background of DY + ε. Similar cuts are not made on the two electrons in the $ee\mu$ channel since the rate of DY + heavy quark $\rightarrow ee + \mu$ events is smaller by about an order of magnitude than the rate of DY + ε background events in the eee channel. To reject low mass dimuon events (e.g., J/ψ) in the $e\mu\mu$ and $\mu\mu\mu$ channels, we require that the dimuon invariant mass be greater than 5 GeV/c^2. The high electron trigger thresholds in the eee and $ee\mu$ channels exclude $J/\psi \rightarrow ee$ events.

The DY + ε backgrounds are calculated from the kinematic acceptance of DY Monte Carlo events convoluted with estimates of electron fake rates and lepton identification efficiencies derived from the data. We use the ISAJET [8] Monte Carlo generator cross sections. The DY plus muon background is calculated similarly using an estimate of the isolation probability for muons from heavy quark decay derived from data. The backgrounds from heavy quark pairs were calculated from data sets that are orthogonal to the signal sample. For these data sets, we count the number of events satisfying the kinematic requirements of our event selection. However, we require the muons in the events to be nonisolated to ensure that the events selected are primarily events with a heavy quark pair. We then apply the electron fake rates and a muon isolation probability (56 ± 5%).

A summary of the total backgrounds expected for our final event selection and the integrated luminosity, $\int \mathcal{L}\, dt$, are given in Table II. Also given are the lepton fake rates for the background sources for each channel. The fake rates vary due to differences in the underlying background physics processes and the use of multiple lepton identification criteria used to optimize efficiencies and reduce low E_T bias. The luminosities vary due to different prescales for the individual triggers.

To check our background estimate, we relaxed the electron identification requirements for the lowest E_T electron in the $ee\mu$ and $e\mu\mu$ channels and removed the muon isolation requirement in the $ee\mu$ channel. This dramatically increases the number of events with misidentified electrons and muons from b quarks. In the eee channel we relaxed the $\not{E}_T$ cut from 15 to 10 GeV and the E_T cut on the lowest E_T electron from 5 to 2 GeV. We have also removed the $\not{E}_T$ cut in the $\mu\mu\mu$ channel. As can be seen in Table II, the total expected background with relaxed cuts in the four channels is 46.5 ± 9.9 events; we see a total of 51 events.

The signal and DY background kinematic efficiencies are derived from ISAJET Monte Carlo processed with a GEANT [9] simulation of the D0 detector and a simulation of the D0 trigger. For the signal, the model parameters for this 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 or GUT inspired models. We have also required that the SUSY partners of the leptons and quarks ($\tilde{l}$ and $\tilde{q}$) be heavy and not involved in the decay of the gauginos, though this requirement on $M_{\tilde{l}^\pm}$ can be relaxed under the conditions on $M_{\tilde{l}^\pm}$ given below without adversely affecting the signal efficiency.

The efficiencies for each of the four channels are given in Table III. They apply for any choice of model parameters which satisfies the gaugino mass relations described above within the given tolerances. In order to understand the effect of excursions outside these tolerances, 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 parameters in the SUGRA model. We find that 99% of the scenarios studied with $M_{\tilde{\chi}_2^0}/M_{\tilde{\chi}_1^0} \geq 1.8$, $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^\pm} \geq -1$ GeV$/c^2$, and $M_{\tilde{\chi}_1^\pm} > 45$ GeV$/c^2$ have efficiencies, not including branching fractions, that are at least 90% of the efficiency for the cases where $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 2M_{\tilde{\chi}_1^0}$. Masses for $\tilde{\chi}_1^\pm$ below 45 GeV$/c^2$ have been excluded by previous searches at CERN Large Electron-Positron Collider [10]. These scenarios with relative efficiency $\geq$90% include cases where the masses of the charged sleptons $\tilde{l}^\pm$ are lighter than the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ gaugino masses, provided that $M_{\tilde{\chi}_2^0} - M_{\tilde{l}^\pm} > 7$ GeV$/c^2$, $M_{\tilde{\chi}_1^\pm} - M_{\tilde{l}^\pm} > 7$ GeV$/c^2$, and $M_{\tilde{l}^\pm} - M_{\tilde{\chi}_1^0} > 15$ GeV$/c^2$. If our cross section times branching fraction $[\sigma \times B(3\ell)]$ upper bound is increased by 10%, it can be reasonably applied to any choice of parameters within SUGRA or GUT inspired models, provided that the resulting gaugino masses conform to these expanded tolerances.

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% C.L. upper limit [11] on $\sigma \times B(3\ell)$ for any one channel for models with equal branching fractions to the four channels. Our limit takes into account the total statistical and systematic uncertainties of the analysis, which range from 10% for the eee channel to 20% for the $\mu\mu\mu$ channel and come mostly from the statistics of the signal Monte Carlo samples and of the data samples used to determine the lepton identification efficiencies. A 5.3% systematic uncertainty on the luminosity is included.

Our previously published limit, based on 12.5 pb^{-1} of 1992–1993 data [2], is shown as a function of $\tilde{\chi}_1^\pm$ mass as the top solid curve A in Fig. 1. The limit from the 1994–1995 data is shown as the middle solid curve B, and the limit from the combined data set is shown as the lower solid curve C. We exclude the region above these curves. The combined limit ranges from 0.66 pb at $M_{\tilde{\chi}_1^\pm} = 45$ GeV$/c^2$ to 0.10 pb at $M_{\tilde{\chi}_1^\pm} = 124$ GeV$/c^2$. The dashed curves (i) and (ii) are theoretical cross sections from ISAJET times $B(3\ell)$ showing the typical variation of $\sigma \times B(3\ell)$ within SUSY models (but in some scenarios the branching fraction can approach zero). Also shown

TABLE III. The kinematic (kin), kinematic + trigger (kin + trig), and total efficiencies in percent. The total efficiencies include the kin + trig efficiencies, the electron tracking efficiency (85% per e), and the electron and muon identification efficiencies.

$\tilde{\chi}_1^\pm$ Mass (GeV$/c^2$)		Channels eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
45	kin	8.5 ± 0.6	6.1 ± 0.5	5.0 ± 0.5	2.3 ± 0.3
	kin + trig	6.6 ± 0.6	4.6 ± 0.5	3.8 ± 0.4	1.9 ± 0.3
	Total	1.6 ± 0.2	0.97 ± 0.13	0.82 ± 0.16	0.54 ± 0.14
65	kin	25 ± 1	16 ± 1	9.9 ± 0.7	4.9 ± 0.5
	kin + trig	21 ± 1	13 ± 1	8.7 ± 0.6	4.1 ± 0.5
	Total	5.3 ± 0.5	3.1 ± 0.3	2.1 ± 0.4	1.2 ± 0.3
96	kin	37 ± 1	24 ± 1	13 ± 1	6.6 ± 0.6
	kin + trig	34 ± 1	22 ± 1	11 ± 1	5.6 ± 0.5
	Total	9.7 ± 0.8	5.7 ± 0.6	3.0 ± 0.5	1.6 ± 0.3
124	kin	41 ± 1	29 ± 1	15 ± 1	8.4 ± 0.6
	kin + trig	40 ± 1	27 ± 1	13 ± 1	7.4 ± 0.6
	Total	11 ± 1	7.4 ± 0.8	3.7 ± 0.6	2.2 ± 0.5

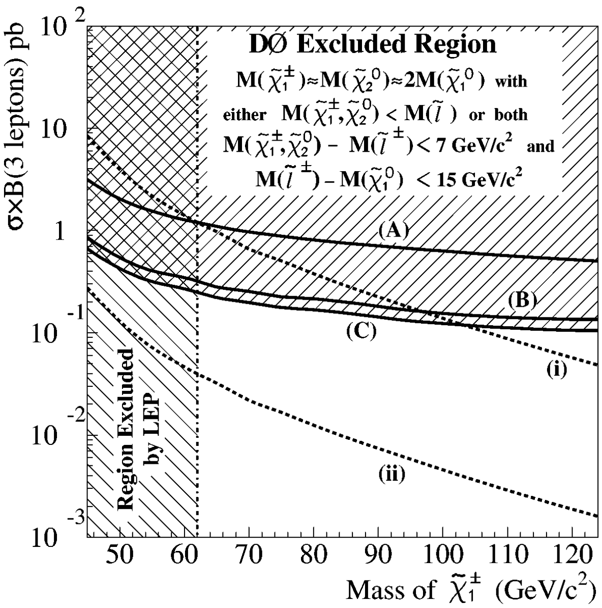

FIG. 1. The 95% C.L. upper limit on $\sigma \times B(3\ell)$ versus $\tilde{\chi}_1^\pm$ mass for any given channel. (A) Limit from 1992–1993 data; (B) limit from 1994–1995 data; (C) combined limit; (i) theoretical (GUT inspired model) $\sigma \times B(3\ell)$, where $B(3\ell)$ is the maximum $(1/9)$ for any single trilepton channel, and (ii) theoretical $\sigma \times B(3\ell)$, where $B(3\ell)$ is the product of SM branching fractions for W and Z bosons to charged leptons (0.0036).

as the shaded region to the left is the 95% C.L. lower limit of 62 GeV$/c^2$ on the $\tilde{\chi}_1^\pm$ mass from the OPAL $\sqrt{s} = 161$ GeV data [12].

For small values of the common scalar mass, m_0, which are compatible with the LEP limit shown in Fig. 1, the $\tilde{l}$ masses can be light while the $\tilde{q}$ masses are always heavy relative to those of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. Light $\tilde{l}^\pm$s can play a role in the decay of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, increasing the branching fraction to charged leptons up to 100%. The theoretical curve (i) in Fig. 1 corresponds to this case. We exclude $\tilde{\chi}_1^\pm$ masses up to 103 GeV$/c^2$ for some of these light $\tilde{l}^\pm$ scenarios.

In conclusion, we find no evidence of trileptons from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production in the current D0 data set. We set a 95% C.L. upper limit on $\sigma \times B(3\ell)$ to any one channel as a function of $\tilde{\chi}_1^\pm$ mass in the context of SUGRA and GUT inspired SUSY models which conserve R parity.

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