Fermi National Accelerator Laboratory

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Search for $\tilde{W}_1\tilde{Z}_2$ Production via Trilepton Final States in p$\bar{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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Search for $\widetilde{W}_1\widetilde{Z}_2$ Production via Trilepton Final States in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have searched for associated production of the lightest chargino, $\widetilde{W}_1$, and next-to-lightest neutralino, $\widetilde{Z}_2$, of the Minimal Supersymmetric Standard Model in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at the Fermilab Tevatron collider. Data corresponding to an integrated luminosity of 12.5 ± 0.7 pb^{-1} were examined for events containing three isolated leptons. No evidence for $\widetilde{W}_1\widetilde{Z}_2$ pair production was found. Limits on $\sigma(\widetilde{W}_1\widetilde{Z}_2)\mathrm{Br}(\widetilde{W}_1 \to l\nu\widetilde{Z}_1)\mathrm{Br}(\widetilde{Z}_2 \to l\bar{l}\widetilde{Z}_1)$ are presented.

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Supersymmetry (SUSY) is a symmetry which relates bosons and fermions. Supersymmetric extensions of the Standard Model (SM) are attractive because they remove the "fine tuning" problem associated with loop corrections to the mass of the Higgs boson and provide a basis for gauge coupling unification at a high mass scale. One consequence of these models is the introduction of a SUSY partner (sparticle) for each SM state. Every sparticle and SM particle is assigned an internal quantum number called R-parity. If R-parity is conserved (as assumed in this analysis), then sparticle states are produced in pairs and there must be one sparticle which does not decay. This sparticle is referred to as the Lightest Supersymmetric Particle (LSP). The SUSY framework which introduces the fewest additional particles is known as the Minimal Supersymmetric Standard Model (MSSM) [1]. If the requirement is made that SUSY be a locally invariant gauge symmetry, the result is a theoretical framework known as supergravity (SUGRA) [2].

In the MSSM and minimal SUGRA there are two chargino ($\widetilde{W}_{i,i=1,2}$) and four neutralino mass eigenstates ($\widetilde{Z}_{i,i=1,4}$), corresponding to mixtures of the SUSY partners of the Higgs bosons, W and Z bosons, and the photon. In most regions of the SUGRA parameter space not excluded by previous experiments, the LSP is the lightest neutralino and thus escapes detection. The best limits to date on the masses of the $\widetilde{W}_1$ and $\widetilde{Z}_2$ states come from the LEP experiments [3]; the current limits are $M_{\widetilde{W}_1} > 45$ GeV/c^2 and (for $\tan\beta > 2$) $M_{\widetilde{Z}_2} > 40$ GeV/c^2.

At $p\overline{p}$ colliders charginos and neutralinos can be produced in pairs, with $\widetilde{W}_1\widetilde{Z}_2$ pairs having the largest cross section over much of the parameter space [4]. The dominant production mechanism proceeds through $q\bar{q}'$ annihilation to a virtual W boson, which then couples to a $\widetilde{W}_1\widetilde{Z}_2$ pair. Cross sections $\mathcal{O}$(100–10) pb are possible at the Tevatron for $\widetilde{W}_1$ masses between 45 and 100 GeV/c^2 [5,6]. The $\widetilde{W}_1$ can decay into $q\bar{q}'$ or $l\bar{\nu}$ plus an LSP, while the $\widetilde{Z}_2$ can decay into $q\bar{q}$ or $l\bar{l}$ plus an LSP. The presence of neutrinos or LSP's among the decay products will generally lead to missing transverse energy ($\not\!\!E_T$) [7]. The final state consisting of three charged leptons [8] and $\not\!\!E_T$ (and little hadronic activity) has few SM backgrounds and is the subject of the present analysis.

The spectra of the transverse momenta (p_T) of the final state leptons can be relatively soft due to the three-body decays of the $\widetilde{W}_1$ and $\widetilde{Z}_2$ involving massive non-interacting particles. Figure 1 shows the expected p_T spectra of the final state leptons as well as the $\not\!\!E_T$ distribution at the physics generator level for simulated $\widetilde{W}_1\widetilde{Z}_2 \to 3l$ events, with $M_{\widetilde{W}_1} = 56$ GeV/c^2. These Monte Carlo events follow the mass relation common to many SUSY models: $M_{\widetilde{W}_1} \approx M_{\widetilde{Z}_2} \approx 2M_{\widetilde{Z}_1}$ [9].

The data used in this analysis were obtained using the DØ detector at the Fermilab Tevatron $p\overline{p}$ collider operating at a center of mass energy of 1.8 TeV. The total integrated luminosity used in this analysis from the 1992–1993 Tevatron run was 12.5 ± 0.7 pb^{-1}.

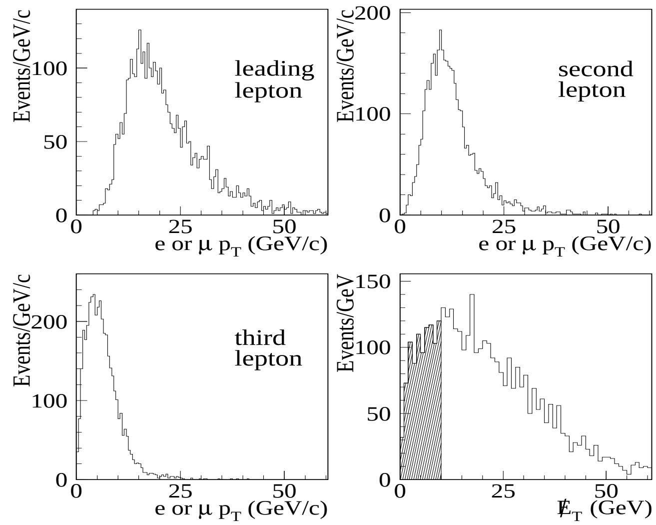

FIG. 1. The p_T distributions of final state leptons and the $\not\!\!E_T$ distribution in $\widetilde{W}_1\widetilde{Z}_2 \to 3l$ events. Events were generated with $M_{\widetilde{W}_1} \approx M_{\widetilde{Z}_2} = 56$ GeV/c^2. The shaded area shows the region excluded by the 10 GeV $\not\!\!E_T$ cut in the eee channel.

The DØ detector has three major subsystems: central tracking detectors, uranium–liquid argon electromagnetic and hadronic calorimeters, and a muon spectrometer. The detector is described in detail elsewhere [10]. The central tracking system is used to identify charged tracks in the pseudorapidity range $|\eta| \leq 3.5$. The calorimeters provide full angular coverage for $|\eta| \leq 4.0$, with transverse segmentation $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where ϕ is the azimuthal angle. The muon system consists of proportional drift chambers and magnetized iron toroids with coverage extending to $|\eta| \leq 3.3$.

Electrons were identified as calorimeter clusters having at least 90% of their energy deposition in the electromagnetic calorimeter, with one or more tracks pointing to the cluster. Jets were reconstructed from energy deposition in the calorimeters using a cone algorithm [11] with cone size $\mathcal{R} = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$. Muon tracks were reconstructed using hits in the muon drift chambers; their momenta were calculated from the bend of the tracks in the toroids.

Combinations of single lepton and dilepton triggers were used for the four final states (eee, $ee\mu$, $e\mu\mu$, and $\mu\mu\mu$). These triggers included: a single muon with $p_T^\mu > 15$ GeV/c; two muons with $p_T^\mu > 3$ GeV/c; one muon with $p_T^\mu > 5$ GeV/c plus one electromagnetic cluster with $E_T^e > 7$ GeV; one electromagnetic cluster with $E_T^e > 20$ GeV; and two electromagnetic clusters with $E_T^e > 10$ GeV. The integrated luminosity per channel is given in Table I.

Events passing the trigger requirements were selected offline by requiring three or more reconstructed leptons (electrons or muons) having $E_T^e > 5$ GeV or $p_T^\mu > 5$ GeV/c, with $|\eta_e| < 2.5$ or $|\eta_\mu| < 1.7$. There were 2827 events in this initial data sample. Electrons and muons in these events were then required to pass the quality cuts described below.

Electrons were required to have transverse and longitudinal shower profiles consistent with expectations based on detailed Monte Carlo studies [11], to have no more than two tracks pointing to the calorimeter cluster, and to have an electromagnetic isolation $\mathcal{I} < 0.15$, where $\mathcal{I} = [E_{\rm tot} - E_{\rm EM}]/E_{\rm EM}$, $E_{\rm tot}$ is the total cluster energy inside a cone of radius $\mathcal{R} = 0.4$, and $E_{\rm EM}$ is the electromagnetic energy inside a cone of $\mathcal{R} = 0.2$. For electrons with E_T between 5 and 10 GeV, the isolation cut was relaxed to $\mathcal{I} < 0.2$ to increase efficiency.

Muons were required to have a separation from any jet of at least $\mathcal{R} = 0.5$, to be aligned with minimum ionizing energy deposition in at least 50% of all calorimeter layers and in at least 60% of the hadronic calorimeter layers, and to have either a matching track in the central detectors or impact parameters in the rz (bend) and xy (non-bend) views consistent with the muon having been produced at the primary event vertex [11]. To reduce cosmic ray background, muons were required to be in time with the beam crossing and any muon pair having both polar and azimuthal opening angles greater than 165° was rejected.

There were 19 events after these quality cuts. The following topological cuts were applied to these events. For the eee channel, events were required to have $\not\!\!E_T > 10$ GeV, with the $\not\!\!E_T$ reconstructed using only energy deposited in the calorimeters. This cut reduced background from $Z/\gamma \to e^+e^-$ events with a third electron from either a photon conversion (including $\pi^0 \to \gamma\gamma$) into an unresolved e^+e^- pair or a jet which was reconstructed as an electron. Since extra material in the forward region enhances the photon conversion probability, the data exhibit an excess of electrons in the forward region while the signal distributions peak in the central region. Therefore, a cut was applied in the eee and $ee\mu$ channels to exclude events with more than one electron in the region $|\eta| > 1.7$. For the $e\mu\mu$ and $\mu\mu\mu$ channels, muon pairs were required to have an invariant mass greater than 5 GeV/c^2, which reduced background from J/ψ events and the combinatoric background in the reconstruction of muons. Table I summarizes the effect of the cuts on each of the channels. We see no candidate events consistent with $\widetilde{W}_1\widetilde{Z}_2$ pair production and subsequent decay into trilepton final states.

Detection efficiencies were determined using a combination of data and Monte Carlo simulations. Monte Carlo signal events were generated using ISAJET [12] and processed with a full simulation of the DØ detector based on the GEANT [13] program. Seven sets of events were generated, with the mass of the $\widetilde{W}_1$ varying from 45 to 100 GeV/c^2. Because of the correlation between the masses of the $\widetilde{W}_1$, $\widetilde{Z}_2$, and $\widetilde{Z}_1$, efficiencies can be parametrized as a function of $M_{\widetilde{W}_1}$. These Monte Carlo events were used to determine kinematic and geometric acceptances only.

Channel	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$\int \mathcal{L}dt$ (pb^{-1})	12.5	12.5	12.2	10.8
Cuts	Events Remaining By Analysis Channel			
$N_e + N_\mu \geq 3$	13	42	297	2475
With Quality Cuts	5	2	5	7
$\not\!\!E_T > 10$ GeV	1	N/A	N/A	N/A
N_e forward < 2	0	0	N/A	N/A
$M_{\mu\mu} > 5$ GeV/c^2	N/A	N/A	0	0
Candidates	0	0	0	0
Background	0.8 ± 0.5	0.8 ± 0.4	0.6 ± 0.2	0.1 ± 0.1

TABLE I. Analysis cuts for each of the search channels, showing the number of events left after a cut has been applied (N/A=Not Applicable). No candidates are seen in any of the four channels. The predicted background per channel is also shown.

Electron identification efficiencies were determined from simulated single electron events generated in six E_T bins between 5 and 25 GeV. These were overlaid with minimum bias events from collider data in order to include the effects of the underlying event and any noise in the calorimeter on electron isolation and shower profile. The results of these studies for high E_T electrons were verified by analyzing a sample of $Z \to ee$ events [14] in which one electron was required to pass all cuts and the second electron was then used as an unbiased estimator for each cut.

Similarly, muon identification efficiencies were based on $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ event samples. These two sets provided independent estimates of efficiencies for both high and low p_T muons.

Electron and muon identification efficiencies were parametrized as a function of the electron E_T or muon p_T and incorporated with the topological cuts described above to determine the overall analysis efficiency for each set of Monte Carlo signal events. These efficiencies are shown in Fig. 2 for each final state, along with a parametrized fit [14], as a function of the $\widetilde{W}_1$ mass.

Backgrounds were estimated from data whenever possible, supplemented with Monte Carlo simulations. Standard Model processes which produce three or more isolated leptons, such as vector boson pair production and semileptonic decays in heavy flavor production, are expected to yield less than 0.1 event in any channel. Thus the primary sources of background are single lepton and dilepton events with one or more spurious leptons. The

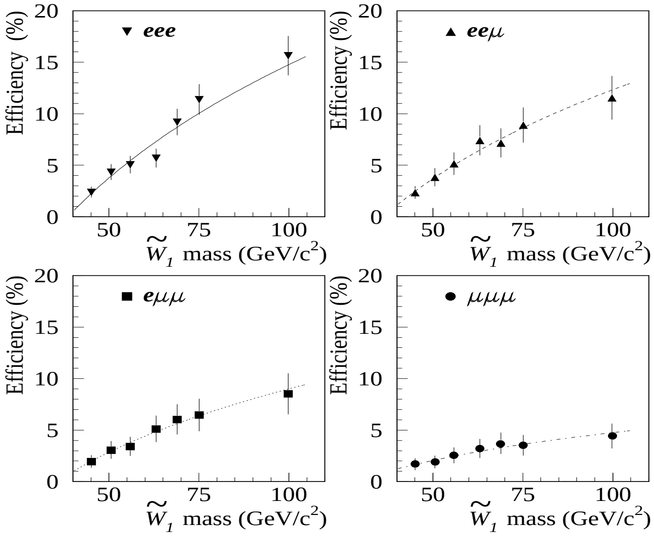

FIG. 2. Overall analysis efficiency for each final state as a function of the mass of the $\widetilde{W}_1$.

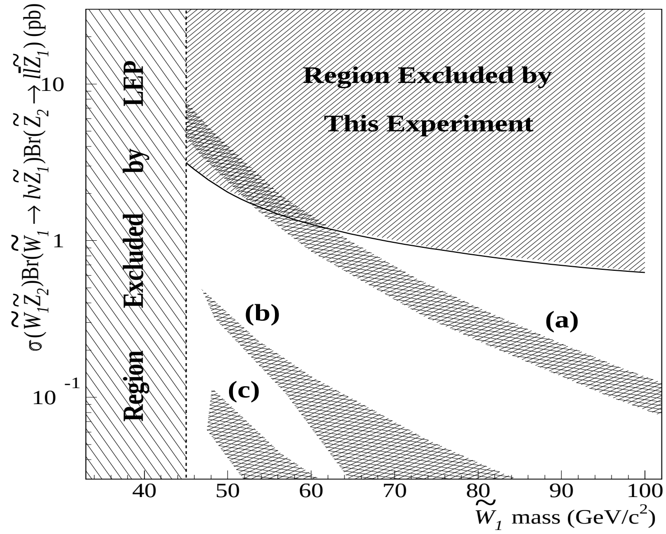

FIG. 3. The 95% C.L. limit on cross section times branching ratio into any one trilepton final state, as a function of $M_{\widetilde{W}_1}$, along with the region of $M_{\widetilde{W}_1}$ excluded by LEP. Also shown are bands of theoretical predictions, as described in the text.

sources of spurious electrons are jet fluctuations and unresolved e^+e^- pairs from photon conversions. The probability of a jet faking an isolated muon is negligible.

The background from fake electrons was calculated from data using dilepton events with one or more additional photons and/or jets. The expected number of events was determined by multiplying the number of events seen in data by the probability of a photon conversion or the rate for a jet to fake an electron [14]. The primary source of background in the $\mu\mu\mu$ channel is heavy flavor ($b\bar{b}$ and $c\bar{c}$) events with the muons produced at large angle to the jets. The total background for each final state is included in Table I.

Based on zero candidate events, we present a 95% confidence level upper limit on the cross section for producing $\widetilde{W}_1\widetilde{Z}_2$ pairs times the branching ratio into any one of the trilepton final states. The results from the four channels were combined in the calculation of the limit, with the assumption that Br(eee) = Br($ee\mu$) = Br($e\mu\mu$) = Br($\mu\mu\mu$). Uncertainties in this calculation include the uncertainty in the luminosity (5.4%) and uncertainties in the overall analysis detection efficiencies (between 15% and 25% of the value) due to Monte Carlo statistics, systematic errors in the determination of lepton identification efficiencies, systematic errors in the trigger efficiencies, and systematic errors arising from energy scale corrections. To construct this limit we used the Bayesian approach of [15], with the distribution of systematic errors represented by a Gaussian and a flat prior probability distribution for the signal cross section.

In Fig. 3 we show the resulting limit in the region above the LEP limit [3]. For comparison, we show three bands of theoretical curves. Band (a) shows the ISAJET production cross section obtained with a wide range of input parameters, multiplied by a branching ratio of $\frac{1}{9}$. The value of $\frac{1}{9}$ for a single trilepton channel is obtained when the $\widetilde{W}_1$ and $\widetilde{Z}_2$ decay purely leptonically and lepton universality is applied. Branching ratios of this order are predicted in models with light sleptons, as for example the model of Ref. [6]. Bands (b) and (c) show the $\sigma\times$Br values from ISAJET obtained with the following SUGRA input parameters: $m_0 = [200, 900]$ GeV/c^2, $m_{\frac{1}{2}} = [50, 120]$ GeV/c^2, $A_0 = 0$ and the sign of μ negative. Band (b) is for $\tan\beta = 2$ and band (c) for $\tan\beta = 4$.

In conclusion, we have searched for the associated production of chargino and neutralino pairs by looking for the reaction $p\bar{p} \to \widetilde{W}_1\widetilde{Z}_2 \to 3l + X$. We see no evidence for $\widetilde{W}_1\widetilde{Z}_2$ production in 12.5 pb^{-1} of data. This leads to upper limits on $\sigma(\widetilde{W}_1\widetilde{Z}_2)Br(\widetilde{W}_1 \to l\nu\widetilde{Z}_1)Br(\widetilde{Z}_2 \to l\bar{l}\widetilde{Z}_1)$ ranging from 3.1 pb for $M_{\widetilde{W}_1} = 45$ GeV/c^2 to 0.6 pb for $M_{\widetilde{W}_1} = 100$ GeV/c^2.

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