Inclusive Search for Anomalous Production of High-p_T Like-Sign Lepton Pairs in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for anomalous production of events with at least two charged, isolated, like-sign leptons, each with $p_T > 11$ GeV/c using a 107 pb^{-1} sample of 1.8 TeV $p\overline{p}$ collisions collected by the CDF detector. We define a signal region containing low background from standard model processes. To avoid bias, we fix the final cuts before examining the event yield in the signal region using control regions to test the Monte Carlo predictions. We observe no events in the signal region, consistent with an expectation of $0.63^{+0.84}_{-0.07}$ events. We present 95% confidence level limits on new physics processes in both a signature-based context as well as within a representative minimal supergravity ($\tan\beta = 3$) model.

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Numerous attempts to resolve theoretical problems with the standard model (SM) require the existence of new particles with masses at the electroweak scale, $\sim$100 GeV/c^2 [1–3]. A productive method of searching for new particles at this scale has been to search for lepton production at $p\overline{p}$ colliders with high momentum transverse to the beam axis (p_T). Such searches led to the discovery of the W and Z bosons at the CERN $Sp\overline{p}S$ and to the discovery of the t quark at the Fermilab Tevatron. Recently, searches for anomalous high-p_T lepton production have been used to constrain supersymmetric extensions to the SM. For example, production of charginos ($\tilde{\chi}^{\pm}$) and neutralinos ($\tilde{\chi}^0$) were constrained by searches for events with three high-p_T leptons [4,5]. Limits on gluino production were likewise placed by searching for events with two like-sign leptons, two jets, and transverse energy imbalance, $\not{E}_T$ [6,7]. These analyses achieved the necessary suppression of background processes by requiring three or more reconstructed objects in the final state and constraints on their kinematical properties.

In this Letter we present a search for new particles with masses at the electroweak scale using a minimal number of required objects or kinematical cuts. Specifically, we search for two like-sign, isolated leptons in the final state, but do not require any other objects or $\not{E}_T$. We define a signal region with less than one event expected from SM background but broad acceptance for typical models of new particle production resulting in like-sign signatures [8–10]. To avoid bias, we fix the final cuts before examining the event yield in the signal region [11].

We examine 107 pb^{-1} of data collected by the Collider Detector at Fermilab (CDF) during the 1992–95 data run of the Tevatron. The CDF detector [12] is an azimuthally and forward-backward symmetric solenoidal detector designed to study $p\overline{p}$ reactions at the Tevatron. A time projection chamber measures the distance of the $p\overline{p}$ collision event vertex (z_{vertex}) from the center of the detector along the beam direction. The central tracking chamber measures the trajectories of charged particles traversing a uniform 1.4 T magnetic field with a resolution of $\delta p_T/p_T^2 = 8 \times 10^{-4}$ (GeV/c^2)$^{-1}$. Outside the solenoid, a lead/scintillator central electromagnetic sampling calorimeter detects electromagnetic showers with an energy resolution of $13.5\%/\sqrt{E\sin\theta} \oplus 2\%$. Steel/scintillator hadronic calorimeters directly behind the electromagnetic calorimeters measure the hadronic component of deposited energy. Drift chambers located behind the steel detect muon candidates with momenta above 3 GeV/c.

We begin with a sample of 457 478 loosely selected dilepton events [13]. We select candidate events in a manner similar to previous CDF trilepton searches [4]. We identify charged leptons as electrons or muons each with $p_T > 11$ GeV/c using the "strict" selection criteria of those analyses. As in the previous analyses, we remove events consistent with photon conversions or cosmic rays. We reject background where one lepton is a partner of known resonances by removing events consistent with any ψ, $\Upsilon(1S)$, or Z resonance. We require $|z_{\text{vertex}}| <$ 60 cm and $|z_{\text{lepton}} - z_{\text{vertex}}| < 5$ cm for each lepton to ensure that both leptons came from the same primary collision and are well measured. We identify the two highest-p_T leptons with like-sign charges as the like-sign (LS) dilepton pair. To reduce background from back-to-back QCD dijet events in which both jets are misidentified as leptons, we require the lepton pair to have vector sum transverse momentum of $p_T^{\ell\ell} >$ 20 GeV/c and invariant mass of $m_{\ell\ell} > 10$ GeV/c^2.

One notable difference from previous analyses is a modification to the lepton isolation variable (ISO) which separates leptons from jets. ISO is the scalar sum of the transverse energy (E_T) measured in each calorimeter cell, $\sum E_T$, added in quadrature to the scalar sum of the p_T measured in the central tracking chamber, $\sum p_T$, within a cone $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ of each lepton candidate. The energy of the lepton candidate is removed from the ISO sum by subtracting the p_T of the lepton candidate track, p_T^{cand}, and the calorimeter E_T of the lepton candidate, E_T^{cand}, from $\sum p_T$ and $\sum E_T$, respectively,

$$ISO = \sqrt{\left(\sum E_T - E_T^{\text{cand}}\right)^2 + \left(\sum p_T - p_T^{\text{cand}}\right)^2}. \quad (1)$$

E_T^{cand} is the scalar sum of the E_T in the calorimeter cell to which we extrapolate the lepton candidate track (the "seed" cell) and the two cells adjacent to either side of the seed cell in η to account for lateral energy leakage between cells: $E_T^{\rm cand} = E_T^{\rm seed} + E_T^{\rm leakage}$. In this analysis we have changed $E_T^{\rm leakage}$ so that the lepton is excised from $\sum E_T$ more effectively by modeling the energy leakage between cells in greater detail [14]. In addition to the usual cut at $ISO_{\Delta R=0.4} < 2$ GeV, we have added a cut on an identically defined *ISO* cone with radius of 0.7, $ISO_{\Delta R=0.7} < 7$ GeV. The combination of double-cone cut and redefined $E_T^{\rm leakage}$ is the "new" *ISO*.

To evaluate the efficacy of the new *ISO* cut, we demonstrate an increased separation of lepton signal from background from jets misidentified as leptons with the new *ISO*. We select leptons from 1255 $Z \rightarrow e^+e^-$ and 1389 $Z \rightarrow \mu^+\mu^-$ events with no *ISO* requirement on the leptons. From bias-removed jet control samples with 20 and 50 GeV thresholds on the jet E_T we select a sample of 292 (237) jets passing all the LS dilepton analysis electron (muon) identification requirements except *ISO*. Figs. 1(a) and 1(b) compare the energy in the new $ISO_{\Delta R=0.4}$ cone between the lepton and jet samples for electrons and muons, respectively. Figs. 1(c) and 1(d) show efficiency (ϵ) for electrons and muons, respectively, from the $Z \rightarrow \ell^+\ell^-$ samples as a function of ϵ for background from the jet control samples for original and new *ISO*. We generate the ϵ curves by varying the $ISO_{\Delta R=0.4}$ cut between 1 and 4 GeV within each sample. With the nominal cuts, new *ISO* reduces background from jets being misidentified as leptons by a factor of 2 from the original cut while retaining the same efficiency for leptons.

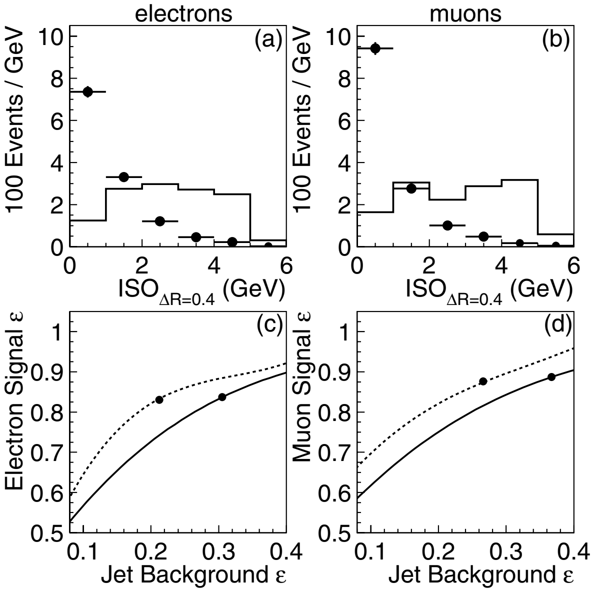

FIG. 1. (a) and (b) show the energy in the $ISO_{\Delta R=0.4}$ cone for electrons and muons, respectively, in the Z dilepton data set (points) and jet background data set (histogram). Errors shown are statistical only. (c) and (d) show ϵ for electrons and muons, respectively, as a function of jet background ϵ for original *ISO* (solid line) and new *ISO* (dashed line). The markers indicate the position of the nominal original and new *ISO* cuts on the ϵ curves.

Diboson production, WZ and ZZ, where "Z" denotes a mixture of the Z and γ^*, produces an irreducible source of SM background. Although the Z resonance cut removes most of these events, some survive because the Z is off shell or we fail to find one of the leptons from the Z. We model this background using the Monte Carlo programs PYTHIA [15] and MCFM [16] which include off shell contributions. The two processes contribute 0.25 ± 0.09 and 0.07 ± 0.02 events, respectively, to the signal region. The only other significant background is $W +$ jets and $Z +$ jets production where one of the jets is misidentified as a lepton. Because the rate of lepton misidentification is beyond the scope of the Monte Carlo programs and simulations, we anchor this calculation in the data. First, we verify that PYTHIA correctly models the observed rate of isolated tracks as a function of p_T in $Z \rightarrow \ell^+\ell^-$ events, excluding the two tracks from the legs of the Z. Second, we use several control samples to measure the probability that such isolated tracks pass all lepton ID requirements: $(2.5 \pm 0.7)\%$ with no measurable p_T dependence. Third, we multiply the PYTHIA prediction for production of a W or Z with an underlying isolated track by this factor to estimate backgrounds to be 0.30 ± 0.08 and 0.03 ± 0.01 events, respectively; for a complete description of this method, see [17]. Using ISAJET [18] we estimate the small contribution, $0.008^{+0.006}_{-0.004}$, from $t\bar{t}$, $b\bar{b}$, and $c\bar{c}$. Finally, we set an upper limit to the contribution from events in which both lepton candidates are jets misidentified as leptons, $0.0^{+0.83}_{-0.0}$, using event yields outside the signal region. We find negligible background due to charge misassignment by using Z events and track curvature studies.

We use kinematical regions having sensitivity to different background sources to test the background predictions. Events near the signal region shown in Fig. 2 are compared to background predictions in Table I. The consistency of these control regions indicates the reliability of the lepton misidentification estimates. With all the nominal cuts but the Z-removal cut inverted, we predict 0.11 ± 0.03 events and see zero. If, instead of requiring like-sign, we require an opposite-sign pair and an additional isolated $p_T > 3$ GeV/c track, we predict 68 ± 9 events and observe 62, thereby testing the Monte Carlo modeling of the effect of lost Drell-Yan leptons.

In the signal region we predict $0.63^{+0.84}_{-0.07}$ total events and observe zero. Hence this analysis provides no indication of physics beyond the SM and we proceed to set limits on new physics using a Bayesian technique [19]. Following the methodology of previous analyses, we apply sources of systematic uncertainty including trigger efficiency, luminosity, lepton ID efficiency, structure function choice, and Q^2 variations [4] to each model of particle production considered below.

Because we perform this search without considering any one particular model for new physics, we evaluate the

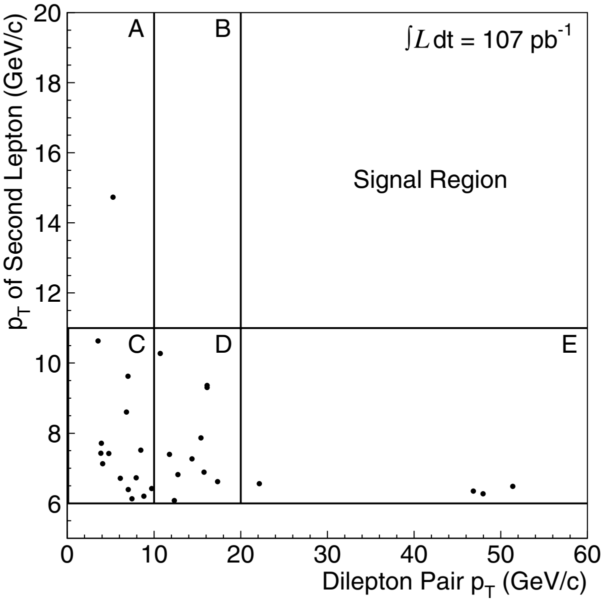

FIG. 2. Observed events in kinematical regions adjacent to the signal region; see Table I.

result as a general limit on particle production leading to the LS dilepton signature. As an example, we generate WZ pairs with PYTHIA using standard couplings and spins. However, we allow the masses of the W-like and Z-like particles to vary. After forcing the bosons to decay leptonically, we find the efficiencies range from 3% to 8% as the W-like and Z-like masses vary from 100 to 300 GeV/c^2. Exclusion limits on the cross section times branching ratio including a 16% systematic uncertainty are shown in Fig. 3.

In addition to such signature-based limits, we derive a limit within the framework of mSUGRA [20], a supergravity-inspired extension to the minimal supersymmetric standard model [3]. We take representative parameters $\tan\beta = 3$, $\mu < 0$, and $A_0 = 0$, but allow m_0 and $m_{1/2}$ to vary and use PYTHIA to calculate event yields. The simulation allows all particles to decay according to their calculated branching ratios so that charged leptons may be produced at any stage of cascade sparticle and particle decays. Within the context of this model, the selection is reoptimized according to the 95% confidence expected upper limit on the signal cross section, leading to an improved sensitivity by lowering the $p_T^{\ell\ell}$ cut from 20 to 10 GeV/c^2. In this mSUGRA model, LS dilepton events are primarily produced by the decay $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0\tilde{\chi}_1^0\nu$. However, this analysis is sensitive as well to LS dileptons produced in the sequential decays

TABLE I. Comparison of SM background to events selected in the data in the control regions shown in Fig. 2.

Region	Background(s)	Expected background	Data
A	QCD dijet	$2.2^{+1.8}_{-1.5}$	1
B	WZ,ZZ	$0.1^{+0.9}_{-0.1}$	0
C	QCD dijet	19.7 ± 8.4	14
D	QCD dijet	10.0 ± 4.5	10
E	$W +$ jets, QCD dijet	$6.0^{+1.6}_{-1.3}$	4

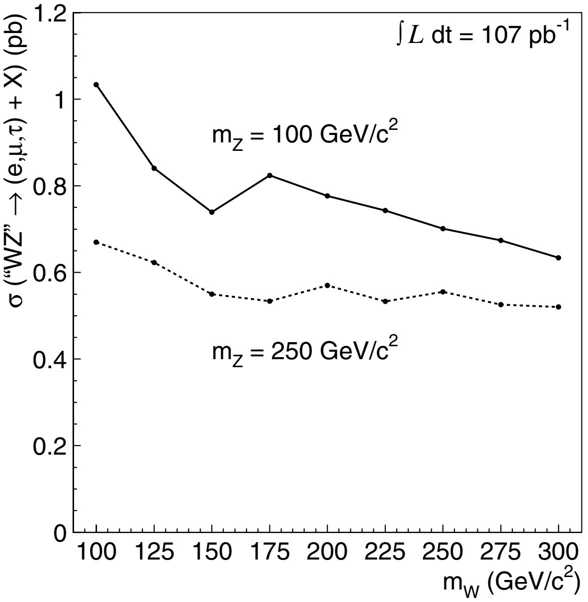

FIG. 3. The 95% confidence level limit on the cross section for "WZ-like" production as a function of the W-like particle mass, for two representative masses of the Z-like particle.

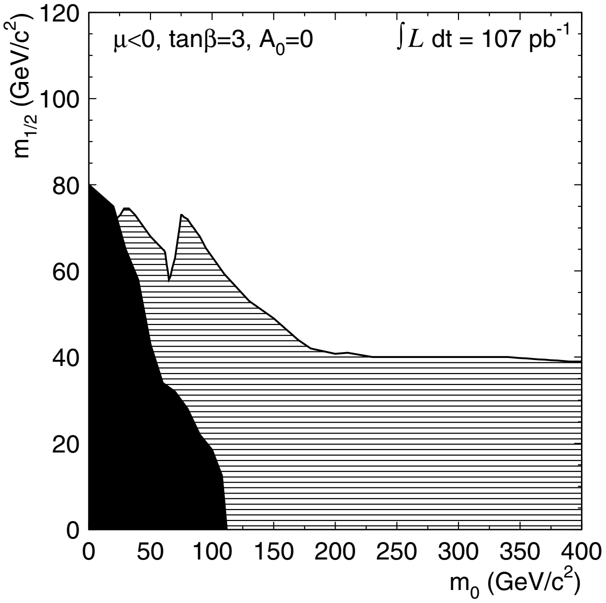

FIG. 4. The 95% confidence level limit on the parameters m_0 and $m_{1/2}$ in the mSUGRA framework for $\tan\beta = 3$, $\mu < 0$, and $A_0 = 0$ (hatched region). The shaded region is theoretically excluded. The dip near 75 GeV/c^2 results from the loss of sensitivity to the $\tilde{\chi}_1^{\mp}\tilde{\chi}_2^0$ signal due to decays of $\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_2^0$ to sneutrinos. At lower m_0, the limit is regained due to sensitivity to $\tilde{q}$ and $\tilde{g}$ production [20].

of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) and even to production of $\tilde{\chi}_1^{\pm}$ with $\tilde{g}$. Here the efficiency, which includes the branching ratio to leptons imposed by the model, ranges from 0.02% to 0.12%. We calculate exclusion limits on the cross section as a function of m_0 and $m_{1/2}$, including a 17% systematic uncertainty, to construct an excluded region in $m_0 - m_{1/2}$ space, as shown in Fig. 4. We use the available next-to-leading order corrections (20%–40%) to the cross sections [21,22]. Previous exclusions, based on $\not{E}_T$ in multijet events [23], have already covered all of this space, but with an entirely different technique.

We have shown in feasibility studies [17] that the LS dilepton signature considered here and the previously published trilepton signatures [4] can be significantly complementary. The Run II data can be analyzed simultaneously with both techniques to obtain a sensitivity to mSUGRA space greater than either analysis alone.

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