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Abstract

We present the results of a search for first generation scalar leptoquarks ($\mathcal{S}_1$) using 110 ± 7 pb^{-1} of data collected by the CDF experi-

ment at Fermilab. We search for $\mathcal{S}_1\bar{\mathcal{S}}_1$ pairs where both leptoquarks decay to an electron and a quark. Three candidate events, with masses below 140 GeV/c^2 and consistent with background expectations, are observed. We obtain a 95% C.L. upper limit on the production cross section as a function of the leptoquark mass. Using a NLO calculation of $\mathcal{S}_1\bar{\mathcal{S}}_1$ production, we exclude scalar leptoquarks with mass less than 213 GeV/c^2 at 95% C.L. for a branching ratio into eq equal to 1.
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Leptoquarks are hypothetical color-triplet bosons, which carry both lepton and baryon number and appear in several extensions of the Standard Model (SM)[1]. Leptoquarks light enough to be produced at current accelerators are usually assumed to couple to quarks and leptons within the same generation, in order to avoid large flavor-changing neutral current processes [2]. First generation scalar leptoquarks ($\mathcal{S}_1$) are assumed to decay to an electron or positron and a first generation quark or antiquark with branching ratio β. Lower limits on the leptoquark mass at 95% confidence level (C.L.) have been reported by the CDF collaboration ($M_{\mathcal{S}_1}$ >113 (80) GeV/c^2 for $\beta(\mathcal{S}_1 \rightarrow eq)$=1 (0.5) from a data sample corresponding to 4.05 pb^{-1} of integrated luminosity [3]), and by the D∅ collaboration ($M_{\mathcal{S}_1} > 133$ (120) GeV/c^2 for $\beta(\mathcal{S}_1 \rightarrow eq)$=1 (0.5) for an integrated luminosity of 15 pb^{-1} [4]). Searches at LEP-1 have excluded leptoquarks with masses below 45 GeV/c^2 independent of the branching ratio [5]. Limits from ep colliders exclude masses up to 230 GeV/c^2 [6] for values of the leptoquark-lepton-quark coupling λ larger than $\sqrt{4\pi\alpha_{em}}$. The limits are weaker for smaller values of the coupling. First generation leptoquarks with a mass of about 200 GeV/c^2 have been suggested as a possible explanation for the recent observations of an excess of events at very large values of the negative square of the momentum transfer Q^2 over the SM expectations by the H1[8] and ZEUS[9] experiments at HERA. Such a hypothesis implies a 100% branching ratio into the electron-jet channel[7].

Leptoquarks can be produced in pairs in $p\bar{p}$ collisions via the strong interaction through gluon-gluon fusion and $q\bar{q}$ annihilation. Production mediated by the leptoquark-lepton-quark coupling is negligible, due to existing constraints on λ [6] in the $M_{\mathcal{S}_1}$ region to which we are sensitive. The production cross section for a pair of scalar leptoquarks can therefore be calculated entirely within QCD, and is known up to next-to-leading order (NLO) accuracy [10].

In this paper we present a search for first generation scalar leptoquarks based on 110$\pm$7 pb^{-1} of data collected with the Collider Detector at Fermilab (CDF) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during the 1992-95 Tevatron runs. The distinctive signature for these events is two high-energy jets plus two isolated, high-energy electrons, where the invariant mass of each electron-jet system from a leptoquark decay corresponds to the leptoquark mass.

The CDF detector is described in detail in Ref. [11]. The data sample for this analysis was collected with a high transverse-energy (E_T) central electron trigger (E_T >18 GeV, pseudorapidity $|\eta| < 1$ [12]). Electrons are detected with the central and plug electromagnetic and hadronic calorimeters, the central tracking chambers (CTC), and the central strip chambers (CES). Details of the electron selection can be found in Ref. [13]; the requirements most relevant for this analysis are listed here. We require two isolated electrons with $E_T > 25$ GeV, one in the central calorimeter passing tight selection criteria, and a second one in the central or plug ($1.1 < |\eta| < 2.4$) calorimeters and passing looser criteria. With respect to Ref. [13] we use a looser requirement of $E/P < 4$ for both electrons, and a less stringent fiducial requirement on the second electron. The electron identification efficiencies are measured from a sample of $Z \to e^+e^-$ to be 86%$\pm$3%, 94%$\pm$3%, and 89%$\pm$3% for the tight central, loose central and loose plug selection, respectively.

Jet reconstruction is performed using a cone algorithm with radius R=0.7 in (η, ϕ) space. Corrections are applied for energy lost in calorimeter cracks, energy outside the cone, and energy deposited inside the cone from the underlying event. We require one jet with $E_T > 30$ GeV and a second jet with $E_T > 15$ GeV in the pseudorapidity region $|\eta| <4.2$.

The main background in this search is due to the Drell-Yan process $Z/\gamma \to e^+e^-$ plus two or more jets from initial state radiation. Consequently, the invariant mass of the two electrons is required to be outside the Z boson mass window, $76 < M_{ee} < 106$ GeV/c^2. The radiated jets in Drell-Yan events are expected to be softer than the jets from $\mathcal{S}_1$ decays, in which the energies of the electrons and jets are similar. Therefore we require $\Sigma E_{T_{j1,j2}} = E_{T_{j1}} + E_{T_{j2}} > 70$ GeV and $\Sigma E_{T_{e1,e2}} = E_{T_{e1}} + E_{T_{e2}} > 70$ GeV (denoted as the ΣE_T requirement).

For the signal, the masses (M_{ej}) of the two electron-jet pairs in each event are expected to be the same within experimental resolution in the absence of final state radiation. The invariant masses of the e−jet systems are recon-

	Events
Inclusive Sample	609K
Cut	
$E_{T_{e1,e2}} > 25$ GeV	7466
$E_{T_{j1,j2}} > 30$, 15 GeV	228
M_{ee} cut	27
$\Sigma E_{T_{e1,e2}}$, $\Sigma E_{T_{j1,j2}}$ >70 GeV	12
$M_{e,jet}$ cuts	3

Table 1: Number of events in the data passing the kinematical cuts.

structed using the two highest E_T electrons that pass our selection criteria and the two highest E_T jets. We resolve the ambiguity in the electron-jet assignment by choosing the pairing that gives the smallest mass difference between the two pairs. Figure 1 shows the scatter plot of the two electron-jet masses in each event passing the selection criteria for the data and for the Monte Carlo simulation of 200 GeV/c^2 leptoquark pairs (described below). Mis-assignment in the electron-jet pairing, due mainly to the presence of extra jets from gluon radiation, results in events outside the mass peak. To ensure that the candidate events are consistent with leptoquark production, we accept events with M_{ej_1} and M_{ej_2} in the region defined by the two lines in Fig. 1, corresponding to two sigma in the mass difference resolution with respect to the diagonal ($M_{ej_1} = M_{ej_2}$). Three events pass the selection criteria. Table 1 shows the number of events in the data remaining after each cut. For events surviving all selection requirements, we calculate the mean of the two electron-jet pair masses, $\langle M_{ej} \rangle$. The largest mean mass of the three candidates is 140 GeV/c^2. Figure 2 shows the $\langle M_{ej} \rangle$ distribution for the three events in the data, together with predicted distributions for Drell-Yan and $t\bar{t}$ backgrounds (described below), normalized to the respective number of expected events. Also shown is the expected distribution from a Monte Carlo simulation of 200 GeV/c^2 leptoquark production, normalized to the integrated luminosity using the theoretical cross section [10]. Of the three observed events one has two photons that are interpreted as neutral jets, therefore satisfying the selection criteria, and one has a jet tagged as a b quark, which is consistent with this event originating from $t\bar{t}$ background.

The kinematical acceptance for leptoquark masses in the range 140 to 240 GeV/c^2 was studied with samples of 10000 leptoquark pairs decaying into eq produced with the PYTHIA generator[14] and passed through a detailed detector simulation. The samples were generated using the CTEQ4L [15] parton distribution functions, with the renormalization and factorization scale $Q^2 = M_{\mathcal{S}_1}^2$. The acceptance after the electron E_T and isolation requirements varies from 56% to 65% for leptoquark masses of 140 to 240 GeV/c^2. The jet E_T requirement reduces the leptoquark acceptance to 49% to 58% for the same $M_{\mathcal{S}_1}$ range. After the M_{ee} and ΣE_T requirements the acceptance varies from 40% to 54%, and after the mass difference requirement from 33% to 44%. The acceptance estimates were checked by releasing the requirements on the jet transverse energies and comparing the value of the production cross section of the Z boson, as a function of the number of jets in the event, with the published values [16].

The Drell-Yan background is estimated using the PYTHIA Monte Carlo program. The Drell-Yan sample is normalized to the number of events in the data in the $76 < M_{ee} < 106$ GeV/c^2 interval with at least one jet with $E_T >$ 30 GeV and a second one with $E_T > 15$ GeV. The expected background is estimated to be 12.1$\pm$2.9 events before the mass difference requirement and 4.4$\pm$2.2 events after this requirement. These estimates are in agreement with the results from an exact matrix element calculation for the Drell-Yan plus two jets cross section. The amount of background from $t\bar{t} \rightarrow W^+W^-b\bar{b}$ production when both W bosons decay to $e\nu$ is estimated to be 2.2$\pm$0.5 events before and 1.4$\pm$0.3 events after the mass difference requirement. The $t\bar{t}$ sample was generated with PYTHIA, and normalized with the CDF measured $t\bar{t}$ cross section of $7.5^{+1.9}_{-1.6}$ pb [17].

Other backgrounds, from $b\bar{b}$ and $Z\rightarrow \tau^+\tau^-$, are negligible due to the electron isolation and large transverse energy requirements on the electron and jets.

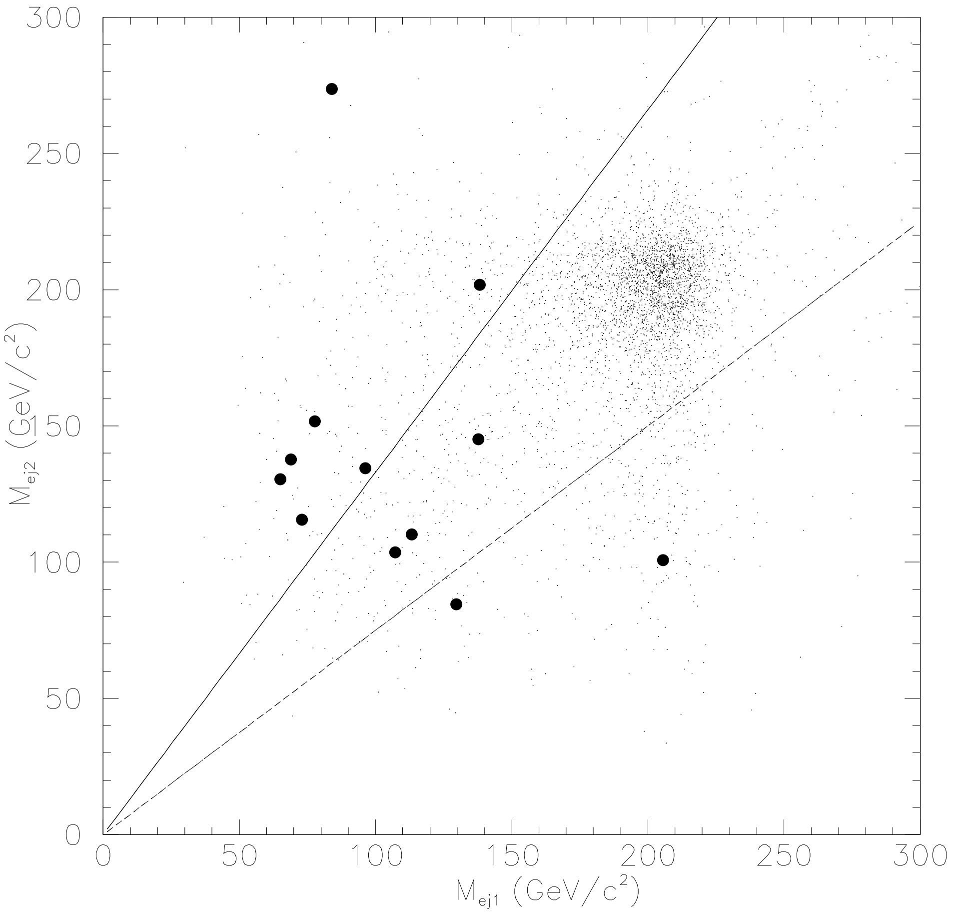

Figure 1: Distribution of M_{ej1} vs M_{ej2} for events passing all requirements except the mass difference requirement, for data (full circles) and leptoquark Monte Carlo with $M_{\mathcal{S}_1} = 200$ GeV/c^2 (dots). The Monte Carlo events correspond to a total integrated luminosity of 50 fb^{-1}. The lines define the region where the masses of the two electron-jet pairs in the event are considered consistent with $\mathcal{S}_1\bar{\mathcal{S}}_1$ pair production.

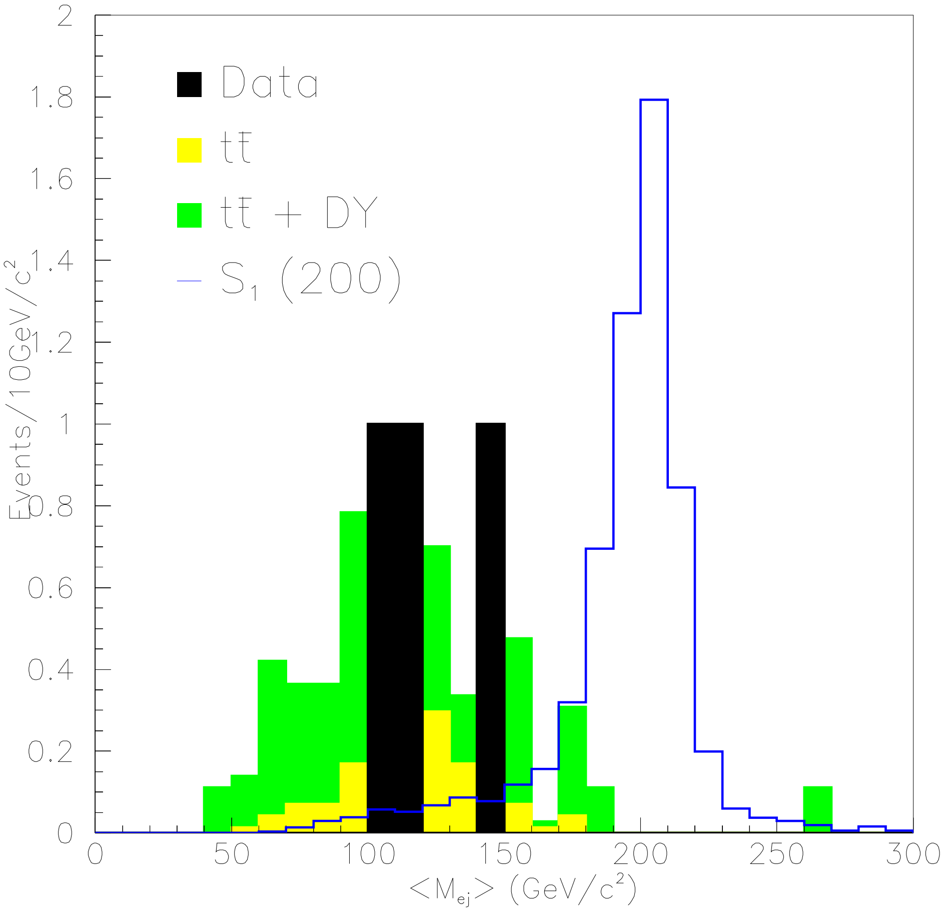

Figure 2: Distribution of $\langle M_{ej}\rangle$ for the data. Superimposed are the distributions for the $t\bar{t}$ and $t\bar{t}$ plus Drell-Yan backgrounds, normalized to the relative estimated numbers. The line histogram represents the expected $\langle M_{ej}\rangle$ distribution for a 200 GeV/c^2 leptoquark for an integrated luminosity of 110 pb^{-1}, using the NLO cross section.

We have considered systematic uncertainties on the acceptance from the following sources: gluon radiation (9%), choice of the parton distribution functions (5%), electron identification efficiency (4%), jet energy scale (2%), and Monte Carlo statistics (2%). The resulting total systematic uncertainty is 13%, including the 7% uncertainty on the luminosity.

The data shown in Fig. 2 are used to set a limit on the $\mathcal{S}_1\bar{\mathcal{S}}_1$ production cross section versus $M_{\mathcal{S}_1}$. The number of candidates for a given leptoquark mass is defined as the number of observed events with $\langle M_{ej}\rangle$ in a $\pm 3\sigma$ interval around that mass, σ being the experimental resolution. We take all observed events to be candidates to obtain a conservative 95% C.L. upper limit on the cross section as a function of $M_{\mathcal{S}_1}$. The limit calculation accounts for the statistical uncertainty on the number of observed events and the total systematic uncertainty. The values of the 95% C.L. limits for $\sigma(\mathcal{S}_1\bar{\mathcal{S}}_1)$ are listed in Table 2 for different leptoquark masses, together with the final acceptance times electron identification efficiency. Also listed are the next-to-leading order theoretical calculation of the cross sections for pair production of scalar leptoquarks at the Tevatron, calculated with the CTEQ4M parton distribution functions for two choices of the Q^2 scale [10]. For a leptoquark mass of 200 GeV/c^2 we obtain a limit on the cross section of 0.1 pb. The same limits are shown in Fig. 3, for $\beta(\mathcal{S}_1 \to eq) = 1$, along with the theoretical cross section expectations. By using these estimates of $\sigma(\mathcal{S}_1\bar{\mathcal{S}}_1)$, we obtain a lower limit for $M_{\mathcal{S}_1}$ of 213 GeV/c^2 for β =1 at the 95% C.L.

In conclusion, we have presented a search for first generation $\mathcal{S}_1$ pair production with the CDF experiment. Three events, consistent with SM background expectations, have been observed. Limits on the $\mathcal{S}_1\bar{\mathcal{S}}_1$ production cross section as a function of mass are obtained. The existence of scalar leptoquarks with mass below 213 GeV/c^2 for β =1 is excluded at the 95% C.L.

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$M_{\mathcal{S}_1}$(GeV/c^2)	95% CL $\sigma(\mathcal{S}_1\bar{\mathcal{S}}_1)$(pb) ($\beta$=1)	Acc.$\times$ eff.	$\sigma(\mathcal{S}_1\bar{\mathcal{S}}_1)_{theor.}$(pb) Q^2=$M^2_{\mathcal{S}_1}/4$	$\sigma(\mathcal{S}_1\bar{\mathcal{S}}_1)_{theor.}$(pb) Q^2=$4M^2_{\mathcal{S}_1}$
140	0.19	0.23	1.98	1.54
150	0.18	0.24	1.30	1.01
160	0.18	0.25	0.87	0.68
170	0.17	0.26	0.59	0.46
180	0.10	0.27	0.41	0.32
190	0.10	0.27	0.29	0.22
200	0.10	0.28	0.20	0.16
210	0.10	0.28	0.14	0.11
220	0.10	0.28	0.10	0.08
230	0.10	0.28	0.07	0.06
240	0.10	0.28	0.05	0.04

Table 2: The experimental $\mathcal{S}_1\bar{\mathcal{S}}_1$ cross section limit, acceptance $\times$ electron identification efficiency, and the theoretical cross section versus $M_{\mathcal{S}_1}$.

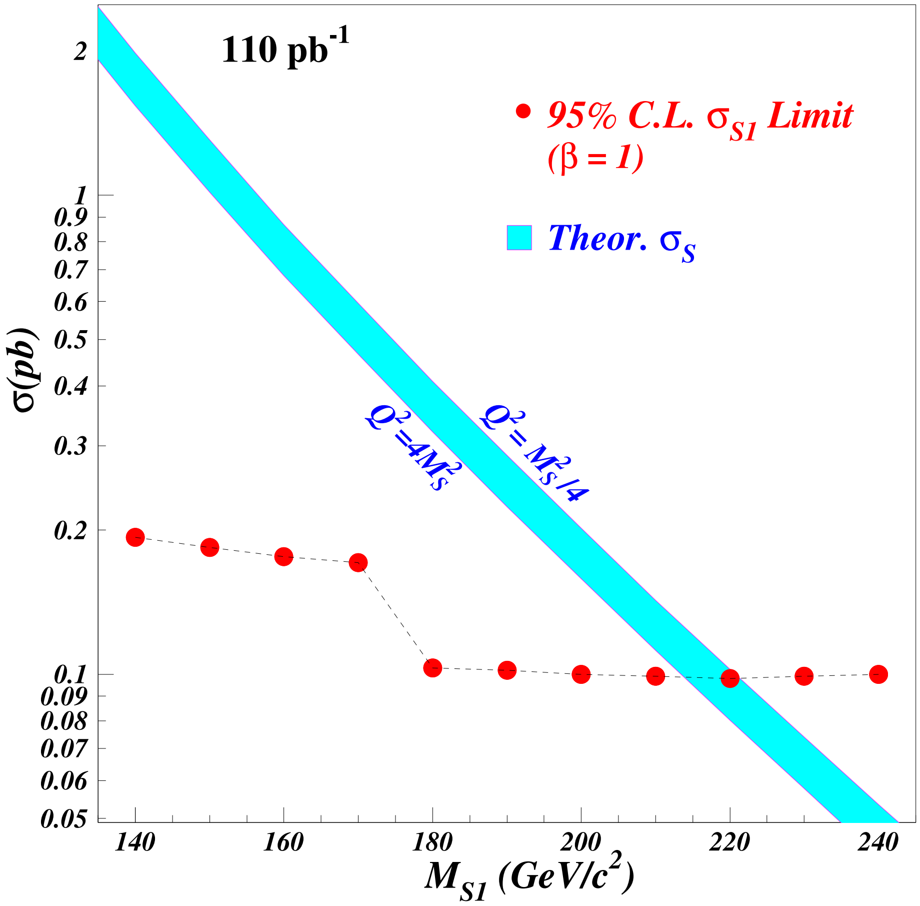

Figure 3: The 95% C.L. upper limit on the cross section for $\mathcal{S}_1$ pair production, assuming β=1. The band represents the spread of the NLO calculation of $\sigma_{\mathcal{S}_1\bar{\mathcal{S}}_1}$ of Ref. [10] as a function of the Q^2 scale, with the CTEQ4M parton distribution functions.

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is the momentum of the track associated with the particle as measured in the CTC. Similarly, E_T is defined as $E_T = E\sin\theta$, where E is the energy associated with the particle as measured in the calorimeters.

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