Search for scalar leptoquark pairs decaying to $\nu\bar{\nu}q\bar{q}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for the pair production of scalar leptoquarks (LQ), using 191 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the Tevatron. The leptoquarks are sought via their decay into a neutrino and quark yielding missing transverse energy and several jets of large transverse energy. No evidence for LQ production is observed, and limits are set on $\sigma(p\bar{p} \rightarrow \mathrm{LQ}\overline{\mathrm{LQ}}X \rightarrow \nu\bar{\nu}q\bar{q}X)$. Using a next-to-leading order theoretical prediction of the cross section for LQ production, we exclude first-generation LQ in the mass interval 78 to 117 GeV/c^2 at the 95% confidence level for $BR(\mathrm{LQ} \rightarrow \nu q) = 100\%$.

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The remarkable symmetry between quarks and leptons in the standard model (SM) suggests that some more fundamental theory may exist, which allows interactions between them. Such interactions may be mediated by a new type of particle, a leptoquark [1], which carries both lepton and baryon number. A leptoquark is a color-triplet boson with spin 0 or 1, and has fractional electric charge. Leptoquarks are predicted in many extensions of the SM (e.g. grand unification, technicolor, and supersymmetry with R-parity violation). The Yukawa coupling of the leptoquark to a lepton and quark and the inclusive branching ratio to a charged lepton and quark, denoted by β, are model dependent. Usually it is assumed that leptoquarks couple to only one generation to accommodate experimental constraints on flavor-changing neutral currents [2], which allows one to classify leptoquarks as first-, second-, or third-generation, with decay products corresponding to the three generations of fermions in SM. In $p\bar{p}$ collisions, leptoquarks can be produced in pairs via the strong interaction through gg fusion or $q\bar{q}$ annihilation. The produc-

tion rate for scalar leptoquarks is essentially model-independent and is determined by the known QCD couplings and leptoquark mass. On the other hand, vector leptoquark interactions with the gluon field include model-dependent couplings. The production cross section for vector leptoquarks [3] is expected to be about an order of magnitude larger than that for scalar leptoquarks.

We report on a search for pair production of scalar leptoquarks, with LQ decaying to νq, resulting in a jets and missing transverse energy ($\not\!\!E_T$) topology. We use 191 ± 11 pb^{-1} [4] of $p\bar{p}$ collision data at a center-of-mass energy of 1.96 TeV recorded by the collider detector at Fermilab (CDF) during the Tevatron Run II. This analysis is sensitive to leptoquarks of all three generations with $\beta \approx 0$. However, we would not be able to distinguish between the different generations of leptoquarks, if they are present in the signal, since we do not identify the quark content of the jets. The previous lower mass limit of 98 GeV$/c^2$ [5] on first-generation leptoquarks in this final state was set by the DØ Collaboration. The CDF Collaboration has also published [6] lower mass limits of 123 GeV$/c^2$ and 148 GeV$/c^2$ respectively on second- and third-generation LQ in the $\not\!\!E_T$ plus heavy-flavor jets final state. Limits on leptoquark production from the Tevatron Run I and HERA experiments as of 1999 are summarized in [7]. The limits from HERA experiments depend on the unknown Yukawa couplings, which are assumed to be of the electro-weak coupling strength. The OPAL collaboration published [8] mass limits of 97 GeV$/c^2$ independent of the Yukawa couplings for the scalar LQ production into $\nu\bar{\nu}q\bar{q}$ final state in e^+e^--collision.

CDF is a general-purpose detector that is described in detail elsewhere [9]. The components relevant to this analysis are briefly described here. The charged-particle tracking system is closest to the beam pipe, and consists of multilayer silicon detectors and a large open-cell drift chamber covering the pseudorapidity [10] region $|\eta| < 1$. The tracking system is enclosed in a superconducting solenoid, which in turn is surrounded by a calorimeter. The CDF calorimeter system is organized into electromagnetic and hadronic sections segmented in projective tower geometry, and covers the region $|\eta| < 3.6$. The electromagnetic calorimeters utilize a lead-scintillator sampling technique, whereas the hadron calorimeters use iron-scintillator technology. The central muon-detection system, used for this analysis, is located outside of the calorimeter and covers the range $|\eta| < 1$.

This search centers on selecting events with large $\not\!\!E_T$ and a pair of jets that are acollinear in the transverse plane, because of the neutrinos in the final state. The $\not\!\!E_T$ [10] is defined as the energy imbalance in the plane transverse to the beam direction. A jet is defined as a localized energy deposition in the calorimeter and is reconstructed using a cone algorithm with fixed radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in $\eta - \phi$ space [11]. We correct [11] jet E_T measurements and $\not\!\!E_T$ for detector effects.

The data sample for this analysis was collected using an inclusive $\not\!\!E_T$ trigger, which is distributed across three levels of online event selection. In the first and second levels of the trigger, $\not\!\!E_T$ is required to be greater than 25 GeV and is calculated by summing over calorimeter trigger towers [12] with transverse energies above 1 GeV. At Level-3 $\not\!\!E_T$ is required to be greater than 45 GeV and is recalculated using full calorimeter segmentation with a tower energy threshold of 100 MeV. We use events from the inclusive high-p_T lepton (e or μ) samples to measure the trigger efficiency directly from data. To reduce systematic effects associated with the online trigger threshold, we select events offline with $\not\!\!E_T > 60$ GeV, where the trigger is fully efficient.

The event electromagnetic fraction ($F_{\rm em}$) and charged fraction ($F_{\rm ch}$) [13] are used to remove events associated with beam halo and cosmic ray sources. We reject events that contain little energy in the electromagnetic section of the calorimeter or that have mostly neutral-particle jets, by requiring $F_{\rm em} > 0.1$ and $F_{\rm ch} > 0.1$. There are 148 462 events in our analysis sample after the initial selection.

The dominant backgrounds to the leptoquark search in the jets and $\not\!\!E_T$ signature are QCD multijet production, W and Z boson production in association with one or more jets, and top quark pair production. The ALPGEN generator [14] was used for the simulation of the W and Z boson plus parton production, with HERWIG [15] used to model parton showers. As the W/Z + jets production cross sections calculated by ALPGEN are only in leading order, we use the exclusive $Z(\rightarrow ee) + 1$ jet data and simulation samples to determine a cross section scale-factor between data and simulation, and apply this scale-factor to all W/Z + jets simulation samples. HERWIG was also used to estimate the contribution from $t\bar{t}$ production. The top quark contribution was normalized to the luminosity of the data sample using the predicted theoretical cross section.

Data selection requirements were chosen to maximize the statistical significance of the leptoquark signal over background events based on studies of simulated event samples before the signal region data were examined. In addition to $\not\!\!E_T > 60$ GeV, the signal region is defined by requiring that the two highest E_T jets ($E_T^{j_1} > 40$ GeV, $E_T^{j_2} > 25$ GeV) be in the central region $|\eta| < 1$. A third jet with $E_T > 15$ GeV and $|\eta| < 2.5$ is allowed, and we veto events with any additional jets with $E_T > 15$ GeV and $|\eta| < 3.6$. To reject events with $\not\!\!E_T$ resulting from jet energy mismeasurement, we require that the opening angle in the transverse plane between the two highest E_T jets satisfy $80^\circ < \Delta\phi(j_1, j_2) < 165^\circ$. The $\not\!\!E_T$ direction must not be parallel to any of the jets; we require the minimum azimuthal separation between the direction of the jets and $\not\!\!E_T$ to satisfy $30^\circ < \min\Delta\phi(j, \not\!\!E_T) < 135^\circ$. The $\not\!\!E_T$ also must not be antiparallel to the leading E_T jet: $100^\circ < \Delta\phi(j_1, \not\!\!E_T) < 165^\circ$. These criteria reject most of the QCD multijet background events. To reduce the back-

ground contribution from W/Z + jets and $t\bar{t}$ production, we reject events with one or more identified leptons with $E_T > 10$ GeV (electron candidates) or $p_T > 10$ GeV/c (muon candidates). Criteria similar to those in [16] are used to identify the leptons. To further reduce this background we require each jet not to be highly electromagnetic (jet electromagnetic fraction <0.9) and to have 4 or more associated tracks for central jets ($|\eta| < 1$).

Two methods are employed to estimate the QCD multijet contribution in the signal region directly from the inclusive $\not\!\!E_T$ data sample. Among all the offline analysis selection requirements, the azimuthal angular separation requirement between the $\not\!\!E_T$ direction and a jet is most effective at removing QCD multijet events. Therefore, for the first method, in addition to the signal region we define a region which is rich in QCD multijet events by requiring that a jet is close to the $\not\!\!E_T$ direction ($20° < \min\Delta\phi(j, \not\!\!E_T) < 27°$). Studies of simulated QCD multijet samples show that the shape of the $\not\!\!E_T$ distribution in this region is similar to the $\not\!\!E_T$ distribution in the signal region. We use $\not\!\!E_T$ and $\min\Delta\phi(j, \not\!\!E_T)$ requirements to define four kinematic regions:

(A) $50 < \not\!\!E_T < 57$ GeV, $20° < \min\Delta\phi(j, \not\!\!E_T) < 27°$.
(B) $\not\!\!E_T > 60$ GeV, $20° < \min\Delta\phi(j, \not\!\!E_T) < 27°$.
(C) $50 < \not\!\!E_T < 57$ GeV, $30° < \min\Delta\phi(j, \not\!\!E_T) < 135°$.
(D) $\not\!\!E_T > 60$ GeV, $30° < \min\Delta\phi(j, \not\!\!E_T) < 135°$.

The regions A, B, and C are used to extrapolate the QCD multijet contribution into the signal region D: $N_D = \frac{N_B}{N_A} N_C$, where N_A, N_B, and N_C are the remaining number of events in regions A, B, and C, after the W/Z + jets and $t\bar{t}$ contributions have been subtracted. For the second method, the combined selection requirement efficiency is measured as a function of $\not\!\!E_T$ in an independent inclusive jet sample at low $\not\!\!E_T$. The extrapolated results of this measurement is then applied to the inclusive $\not\!\!E_T$ sample after the W/Z + jets and $t\bar{t}$ contributions have been subtracted. We predict 15.0 ± 8.0 and 21.5 ± 12.4 multijet events for the first and second methods, respectively. We take the weighted average and uncertainty of the two methods as our estimate of the multijet background.

We check the simulation predictions for W/Z + jets with data in a control region, which is defined by requiring, in addition to 2 or 3 jets, $\not\!\!E_T > 60$ GeV and at least one electron or muon. We observe 144 events in our inclusive $\not\!\!E_T$ sample, which is in excellent agreement with 154.3 ± 27.9 events predicted from SM processes.

The total detection efficiency (ϵ_{LQ}) for the scalar leptoquark signal is estimated using the PYTHIA event generator [17], and the CDF detector simulation program. The PYTHIA underlying event simulation was tuned to reproduce CDF data [18]. The samples were generated using the CTEQ5L [19] parton distribution functions (PDF), with the renormalization and factorization scales set to $\mu = m_{\mathrm{LQ}}$. Table I lists the total detection efficiency, $\epsilon_{\mathrm{LQ_1}}$, for the first-generation scalar leptoquark signal and the corresponding total fractional uncertainty δ_{tot} for various leptoquark masses. The acceptances for second- and third-generation leptoquark signals are estimated to be 4% and 10% lower, respectively, than that for the first generation in the generated mass region due to semileptonic decays of heavy-flavor quarks. Also listed are the NLO cross sections [20] calculated for two choices of the μ scale. The systematic uncertainty on the signal acceptance includes the uncertainties due to modeling gluon radiation from the initial-state or final-state partons (10%), and the choice of the PDF (4%). The limited size of the leptoquark simulation samples gives a 3% statistical uncertainty. The signal acceptance uncertainty due to the jet energy scale varies from 4% to 26%, and the uncertainty on the luminosity is 6%. The uncertainty on the trigger efficiency is 1%. The theoretical uncertainties on the renormalization and factorization scales are not included here, since we conservatively choose the NLO cross section setting $\mu = 2m_{\mathrm{LQ}}$ to extract the limits on leptoquark mass. This choice of scale is found to reduce the cross section prediction by 15% relative to $\mu = m_{\mathrm{LQ}}$ [20].

TABLE I. Summary of the first-generation scalar leptoquark detection efficiency (ϵ_{LQ}), the relative uncertainty on detection efficiency (δ_{tot}), and the next-to-leading order cross section (σ_{NLO}) for two choices of the renormalization scale as functions of leptoquark mass.

			σ_{NLO}(pb)	
$m_{\mathrm{LQ_1}}$(GeV/c^2)	$\epsilon_{\mathrm{LQ_1}}$	δ_{tot} (%)	$\mu = m_{\mathrm{LQ_1}}$	$\mu = 2m_{\mathrm{LQ_1}}$
75	0.0073	29	69.4	58.8
80	0.0113	26	49.2	41.5
90	0.0187	23	26.0	22.1
100	0.0300	20	14.6	12.5
110	0.0431	16	8.4	7.4
115	0.0482	15	6.7	5.8
125	0.0590	15	4.2	3.6
150	0.0828	13	1.4	1.3
175	0.1010	12	0.57	0.51

TABLE II. The number of expected events from various SM sources in the leptoquark signal region. The first uncertainty is from the limited simulation statistics and the second is from the various systematics.

Source	Events expected
$W(\rightarrow e\nu)$ + jets	$6.1 \pm 1.4 \pm 1.5$
$W(\rightarrow \mu\nu)$ + jets	$21.7 \pm 2.3 \pm 2.8$
$W(\rightarrow \tau\nu)$ + jets	$28.4 \pm 3.8 \pm 4.1$
$Z(\rightarrow \mu\mu)$ + jets	$1.1 \pm 0.2 \pm 0.2$
$Z(\rightarrow \tau\tau)$ + jets	$0.9 \pm 0.2 \pm 0.2$
$Z(\rightarrow \nu\nu)$ + jets	$39.1 \pm 2.8 \pm 3.6$
$t\bar{t}$	$4.3 \pm 0.4 \pm 0.3$
QCD	16.9 ± 6.7
Total events	118.5 ± 14.5

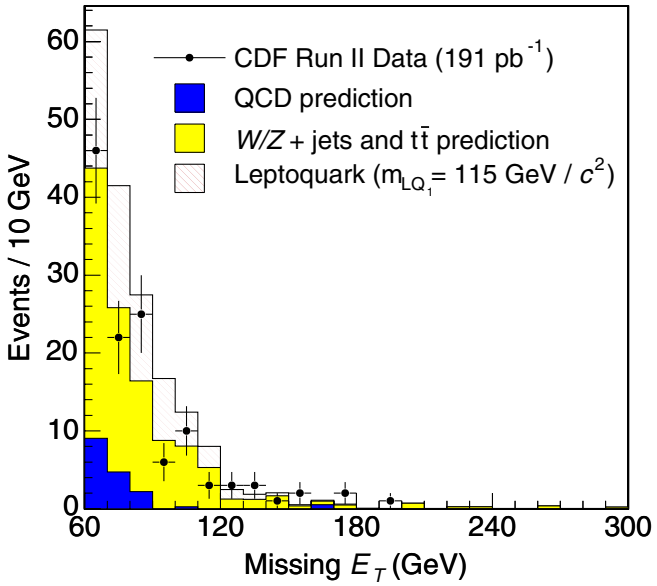

FIG. 1 (color online). The $\not\!\!E_T$ distribution in the leptoquark signal region for data (solid points) compared to SM background (shaded histograms). Also shown is the expected distribution arising from leptoquark production and decay at a mass of 115 GeV/c^2 (hatched histogram).

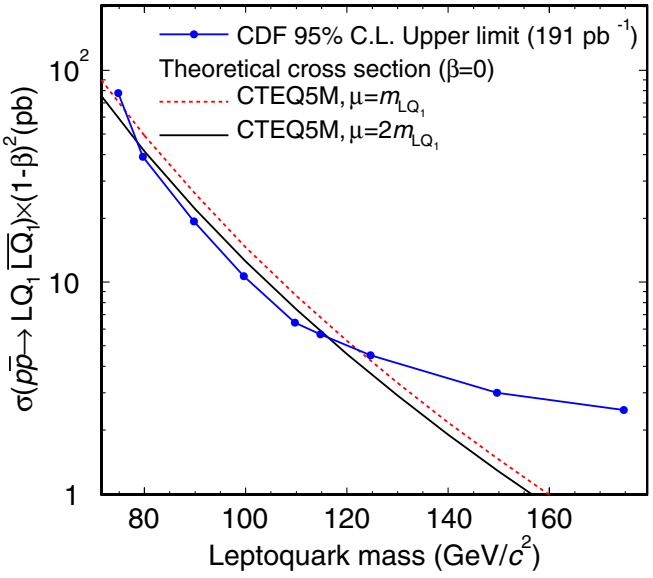

FIG. 2 (color online). The upper limit on the cross section times squared branching ratio for scalar leptoquark production in the jets and $\not\!\!E_T$ topology. Also shown is the NLO cross section for $\beta = 0$ for 2 choices of the factorization/renormalization scale: $\mu = m_{LQ_1}$, $\mu = 2m_{LQ_1}$.

In the signal region, we expect 118.5 ± 14.5 events from SM processes and observe 124 events. The predicted backgrounds from SM processes are summarized in Table II. In Fig. 1 the predicted $\not\!\!E_T$ distribution is compared with the distribution observed in data. No evidence for leptoquark production is observed. We calculate the upper limit at the 95% confidence level (C.L.) on the pair production cross section times the square of the branching ratio of the leptoquark to a quark and a neutrino using first-generation LQ acceptance and a Bayesian approach [21] with a flat prior for the signal cross section and Gaussian priors for acceptance and background uncertainties. The upper limit on the cross section times $(1 - \beta)^2$ is shown in Fig. 2 and is compared with the theoretical cross sections. The theoretical cross sections for scalar leptoquark production have been calculated at NLO using CTEQ5M [19] PDFs.

In conclusion, we performed a search for leptoquarks in the jets and $\not\!\!E_T$ topology using 191 pb^{-1} of CDF Run II data. No evidence for leptoquarks is observed. We set an upper limit on the production cross section at the 95% C.L. Assuming a leptoquark decays into a neutrino and quark with 100% branching ratio, we exclude the mass interval from 78 to 117 GeV/c^2 for first-generation LQ independent of the Yukawa coupling. This extends the previous limit for the first-generation LQ of 98 GeV/c^2 [5]. The limits for the second- and third-generation LQ are weaker than existing limits obtained from an exclusive search [6] identifying jet flavor.

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