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We present a search for the pair production of first generation scalar leptoquarks (LQ) in data corresponding to an integrated luminosity of 5.4 fb^{-1} collected with the D0 detector at the Fermilab Tevatron Collider in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. In the channel $LQLQ \to eq\nu_e q'$, where q, q' are u or d quarks, no significant excess of data over background is observed, and we set a 95% C.L. lower limit of 326 GeV on the LQ mass, assuming equal probabilities of LQ decays to eq and $\nu_e q'$.

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Because of the limitations of the standard model (SM), several extensions have been proposed, among them supersymmetry (SUSY) [1], grand unified theories [2], and string theory [3]. Many of these extensions predict the existence of particles that directly connect the lepton and quark sectors. By combining leptons and quarks in multiplets of a larger symmetry group, they are expected to interact with each other through new mediating bosons called leptoquarks (LQ) [4, 5]. LQs can be either scalar or vector fields. This Letter will focus on the search for scalar LQs, and in the following we will not distinguish particles from antiparticles. This search is performed within effective models [6, 7], and thus is independent of specific extensions of the SM.

In $p\bar{p}$ collisions such as those that occur at the Tevatron Collider, LQs can be produced in leptoquark-antileptoquark pairs. LQ pair production can occur via both quark-antiquark annihilation and gluon-gluon fusion, although quark-antiquark annihilation is expected to be dominant. The production cross section for scalar LQs depends only on the strong coupling constant and on the LQ mass, and is known at next-to-leading order (NLO) [8].

Once produced, LQs can decay to two final states: lq and $\nu q'$ (where $l = e, \ \mu, \ \text{or} \ \tau$). It is assumed that in the low energy limit there is no intergenerational mixing. For first generation LQ pairs, the final state will contain a pair of leptons (e or ν_e) and a pair of quarks (u or d) of the first generation. In this Letter, the case in which one LQ decays to eq and the other to $\nu_e q'$ is considered (charge conjugate states are assumed in the Letter).

We define β to be the branching ratio of a first generation LQ to decay to eq. Then the probability for a LQ to decay to $\nu_e q'$ is $(1 - \beta)$, and the probability for a LQ pair to decay to the final state $eq\nu_e q'$ is $BR(LQLQ \to eq\nu_e q') = 2\beta(1 - \beta)$. Thus, the probabil-

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ity for the final state $eq\nu_e q'$ is maximized when $\beta = 0.5$.

Limits on the production of first generation LQs have been reported by the DELPHI [9], OPAL [10, 11], H1 [12, 13], ZEUS [14], CDF [15], and D0 [16] Collaborations. Recently, CMS [17, 18], and ATLAS [19] published the first searches for scalar LQ pair production at the CERN LHC. Both LHC experiments have a similar sensitivity with expected limits of 345 GeV (CMS) and 350 GeV (ATLAS), respectively, for $\beta = 0.5$.

The D0 detector consists of tracking, calorimeter, and muon systems [20–22]. The central-tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoid. A liquid-argon and uranium calorimeter consists of a central section (pseudorapidity $|\eta| < 1.1$ [23]) and two end sections ($1.5 < |\eta| < 4.2$). The calorimeters have fine transverse and longitudinal segmentation with three principal layers identified as electromagnetic, and fine and coarse hadronic. An outer muon system ($|\eta| < 2$) consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [24]. Data were collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider operating at $\sqrt{s} = 1.96$ TeV between August 2002 and June 2009, and correspond to an integrated luminosity of 5.4 fb^{-1}.

An electron is identified from energy deposits in the electromagnetic calorimeter that are consistent with the shower development expected for an electron and have a matching track extrapolated from the central tracker.

Jets are reconstructed using a midpoint cone algorithm, with a cone size of 0.5 [25]. The jet energy is corrected to the particle level using jet energy scale corrections determined from data [26]. The missing transverse energy ($\not\!\!E_T$) is reconstructed from all the cells of the electromagnetic and hadronic calorimeters, except for the coarse hadronic sector where a noise-reduction algorithm is applied. Additional corrections are then applied for all identified objects including jets, electrons, and muons.

Events must satisfy at least one trigger from the single-electron and electron+jets suites of triggers. For all data samples, trigger objects are required to match the reconstructed objects. The trigger efficiencies are measured in data and parameterized for specific lepton and jet identification criteria.

Scalar LQ pair Monte Carlo (MC) samples are generated using PYTHIA [27] with CTEQ6L1 [28] parton density functions. Signal samples are produced for different LQ masses between 200 and 360 GeV. The corresponding cross sections at NLO are listed in Table I.

Diboson (WW, WZ and ZZ) background samples are produced with PYTHIA making use of the parton distribution functions CTEQ6L1. The $t\bar{t}$ and $V(V = W$ or $Z)$+jets events are simulated with the matrix-element generator ALPGEN [29], interfaced to PYTHIA for subsequent parton showering and hadronization. Single top quark production is simulated using COMPHEP [30]. The cross sections for background processes are calculated

TABLE I: Scalar LQ pair production cross sections, calculated at NLO, for different M_{LQ} [8].

M_{LQ} (GeV)	200	210	220	230	240	250	260	270
σ (fb)	268	193	141	103	76	56	42	31
M_{LQ} (GeV)	280	290	300	310	320	340	360	
σ (fb)	23	17	13	10	7.4	4.2	2.4	

at NLO (diboson [31]) and next-to-next-to-leading order (NNLO) (V+jets [32] and $t\bar{t}$ [33]). We correct the generated spectrum of the transverse momentum (p_T) of the Z boson in MC to match a corresponding dedicated measurement [34]. The p_T spectrum of the W boson is corrected taking into account the differences between predicted Z and W boson p_T spectra at NNLO [35].

A full GEANT-based detector simulation program [36], followed by the same reconstruction program as utilized for data, is used to process signal and background events from MC. In order to model detector noise and contributions from the presence of additional $p\bar{p}$ interactions, events from randomly selected beam crossings with the same instantaneous luminosity profile as data are overlaid on the simulated events. Background from multijet production (MJ), where one of the jets mimics an electron, is evaluated from data using a data driven technique [37]. In MC simulations, electron energies are corrected so that they match the energy resolution in data. In addition, residual differences in jet energy scale and resolution between data and MC are reduced by applying dedicated corrections to MC events. All corrections are evaluated in independent samples. Electron related corrections are obtained from $Z \to ee$ samples, and jet related from either photon+jets or Z+jets samples.

In the $eq\nu_e q'$ final state, it is not known *a priori* how to assign the jets to the LQ decaying to eq or $\nu_e q'$. Therefore, to reconstruct the properties such as mass and p_T of the LQs from the final products, an algorithm is needed to choose the best pairing. We do not impose a requirement on the number of jets, but we use only the two leading p_T jets for pairings. There are two possible combinations, corresponding to the leading jet pairing with either the electron or the neutrino. We found that it is most effective to choose the pairing that minimizes the difference between the transverse masses, $M_T = \sqrt{E_T^2 - \vec{p}_T^{\,2}}$, where E_T and $\vec{p}_T$ are the transverse energy and the transverse momentum vector of the two LQs. This pairing algorithm is successful in making the correct assignment in about 75% of MC signal events.

Events are selected to be consistent with the $LQLQ \to eq\nu_e q'$ process. We require one electron with $p_T > 15$ GeV in the central calorimeter region $|\eta_e| < 1.1$; $\not\!\!E_T > 15$ GeV, to be consistent with the undetected neutrino; and at least two jets with $p_T > 20$ GeV and $|\eta_{\rm jet}| < 2.5$. To suppress MJ background, events are required to satisfy $\not\!\!E_T/50 + M_T^{e\nu}/70 \geq 1$, where $M_T^{e\nu}$ is the transverse mass of the (e, ν) combination, and $\not\!\!E_T$ and $M_T^{e\nu}$ are in GeV.

TABLE II: Event counts and the predicted number of signal events for $M_{LQ} = 260$ GeV and $\beta = 0.5$ after each selection requirement.

	Data	Total background	Signal
Preselection	65992	65703 ± 5958	50 ± 7
$M_T^{e\nu} > 110$ GeV	990	986 ± 82	34 ± 5
$\sum M_{LQ} > 350$ GeV	64	55 ± 4	27 ± 4
$S_T > 450$ GeV	15	15 ± 1	24 ± 3

At this stage we observe 65992 data events, while we expect $65703 \pm 61(\text{stat}) \pm 5958(\text{sys})$ from SM background and $50.4 \pm 0.4(\text{stat}) \pm 6.8(\text{sys})$ events from scalar LQ production for $M_{LQ} = 260$ GeV and $\beta = 0.5$. Figure 1(a) shows the $M_T^{e\nu}$ distribution for the data and SM processes. Data are consistent with the SM predictions. To reduce the dominant SM V+jets background, we require $M_T^{e\nu} \geq 110$ GeV. The pairing algorithm described previously allows us to reconstruct M_{LQ}. Since the longitudinal component of the neutrino momentum, p_z, is not measurable, we reconstruct only the visible mass of the decay $LQ \rightarrow \nu_e q'$ as $M_{LQ} = M(\text{jet} + \nu_{\text{vis}})$, where the four vector of ν_{vis} is given as $(\not{p}_x, \not{p}_y, 0, \not{E}_T)$. Figure 1(b) shows the distribution of the sum $\sum M_{LQ}$ of the invariant mass of the decay $LQ \rightarrow eq$ and the visible mass of the decay $LQ \rightarrow \nu_e q'$ after the requirement $M_T^{e\nu} \geq 110$ GeV. We then use $\sum M_{LQ}$ to reduce SM backgrounds, further requiring that $\sum M_{LQ} > 350$ GeV. Finally, we require that the scalar sum of the p_T of the lepton, the $\not{E}_T$, and the two jets, S_T, shown in Fig. 1(c) after all selections, be greater than 450 GeV. Selection criteria are optimized to achieve the best expected sensitivity for $M_{LQ} = 260$ GeV. This yields 15 observed events for an expected background of $14.8 \pm 0.6(\text{stat}) \pm 1.1(\text{sys})$ events. The event counts after each requirement are shown in Table II.

Systematic uncertainties which affect only the normalization of the background and the signal efficiency include uncertainties on cross sections of signal (10%) and background (6% − 10%) processes, normalization of the MJ background (20%), integrated luminosity (6.1%), and lepton trigger and identification (4%). Uncertainties which also affect the differential distribution of S_T which is the quantity used to set the limits on LQ are due to the jet energy resolution and scale, jet identification efficiency, parton distribution functions, and the modeling of the jet p_T distribution of the dominant W+jets background. Their impacts are evaluated by repeating the analysis with values varied by ±1 standard deviation (SD). For the uncertainty on the jet p_T modeling, the impact is estimated by comparing the jet p_T distributions between ALPGEN and data unfolded to particle level from the recent D0 measurement [38]. The ratio is applied as weight to the W+jets jet p_T distribution, and the new distribution is taken as ±1 SD band.

The distribution of the S_T after all selection requirements, shown in Fig. 1(c), is used as a discriminant to

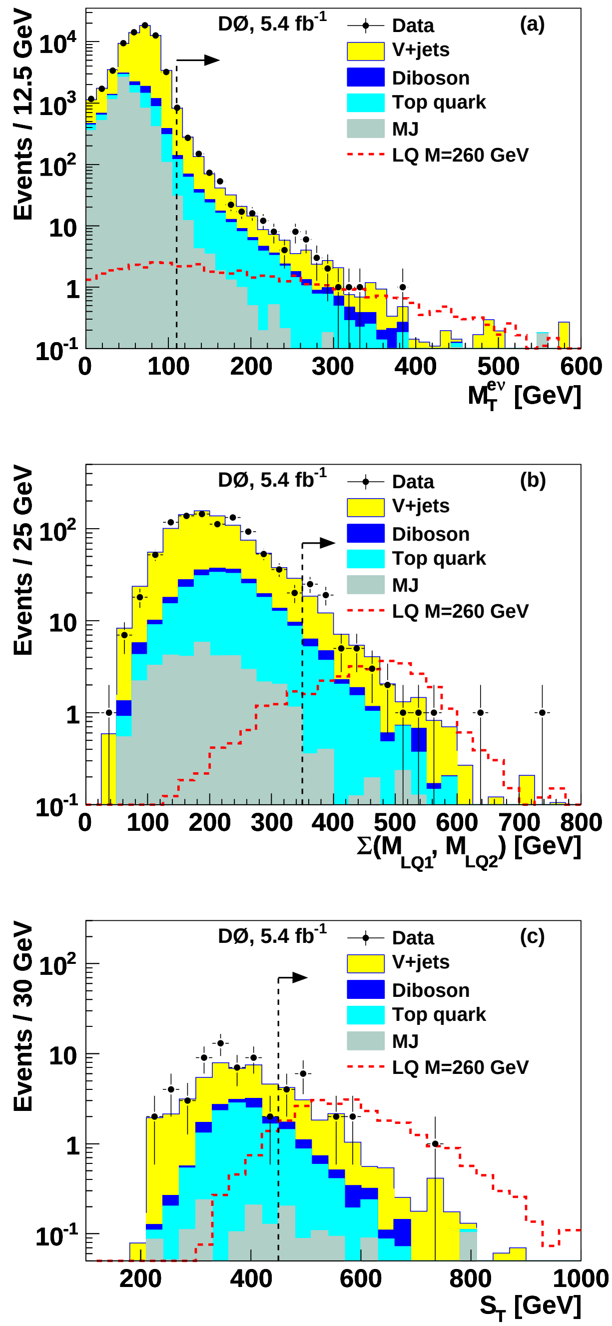

FIG. 1: (color online) (a) $M_T^{e\nu}$ distribution after preselection, (b) $\sum M_{LQ}$ for $M_T^{e\nu} > 110$ GeV, (c) the S_T for $M_T^{e\nu} > 110$ GeV and $\sum M_{LQ} > 350$ GeV, which is used to set an upper limit on the LQ pair production cross section after the final selection.

set an upper limit on the LQ pair production cross section in the $eq\nu_e q'$ channel. For each generated M_{LQ}, the limit is calculated at the 95% C.L. using the semi-frequentist CL_s method based on a Poisson log-likelihood test statistic [39]. Signal and background normalizations and shape variations due to systematic uncertainties are incorporated assuming Gaussian priors. The best fit to the background distributions is evaluated by minimizing a profile likelihood function with respect to the observed data and various sources of uncertainty, maintaining all correlations among systematic uncertainties [40]. Limits on the cross section multiplied by the branching fraction and the theoretical LQ cross section for $\beta = 0.5$ are shown in Fig. 2. Considering β as a free parameter [41], the limit on the LQ mass as a function of β is determined as shown in Fig. 3, and compared to the previous D0 [16], CMS [17, 18], and ATLAS [19] results.

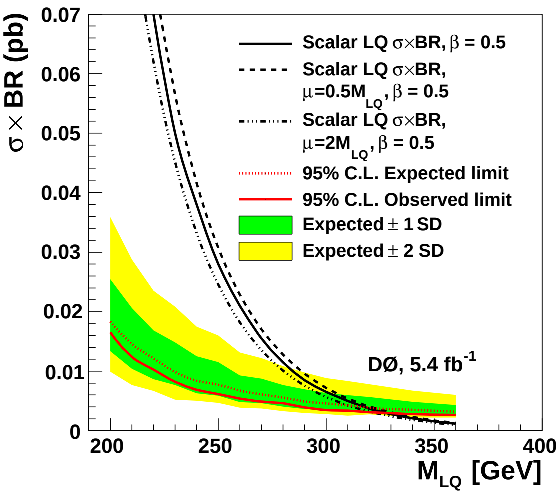

FIG. 2: (color online) Expected and observed upper limits calculated at the 95% C.L. on the LQ cross section as a function of M_{LQ} for a scalar LQ compared with the NLO prediction for $\beta = 0.5$. The NLO cross section is shown for different choices of the renormalization and factorization scales, $\mu = M_{LQ}$, $\mu = 0.5 \times M_{LQ}$, and $\mu = 2 \times M_{LQ}$.

In summary, we have searched for scalar LQ pair production in the $eq\nu_e q'$ final state in 5.4 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. In the absence of a signal, we exclude the production of first generation LQs with $M_{LQ} < 326$ GeV for $\beta = 0.5$ at the 95% C.L. If the $LQ \to lq$ and $LQ \to \nu q'$ couplings are not too large ($\beta \leq 0.3$) [13], this result represents the most stringent limit to date.

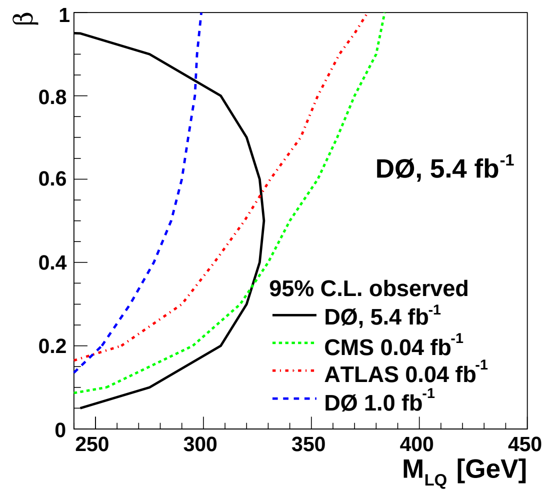

FIG. 3: (color online) 95% C.L. observed limit for $\mu = M_{LQ}$ on the LQ mass as a function of β compared with the previous D0 result [16], and CMS [17, 18] and ATLAS [19] results.

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