Searches for vector-like quarks and leptoquarks at D0

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We report on a search for vector-like quarks and leptoquarks at D0. In the absence of any significant excess over the expectations, we present the most stringent limits to date.

1. Introduction

The standard model (SM) of particle physics accurately describes interactions at the electroweak scale. Several theories are proposed to describe physics beyond the SM. Every new theory introduces a new spectrum of particles. The D0 experiment at the Fermilab Tevatron Collider has searched for many of these new particles. We present here a search for first generation leptoquarks and vector-like quarks.

2. Search for First Generation Leptoquarks

2.1. Motivation

Leptoquarks (LQs) [1, 2] are predicted by many extensions of SM, such as supersymmetry [3], grand unified theories [4], and string theory [5]. LQs are mediating bosons that allow leptons and quarks to interact with each other. Although LQs can be scalar or vector fields, this proceedings will focus on scalar particles. At the Fermilab Tevatron Collider LQs are produced as leptoquark-antileptoquark pairs via quark-antiquark annihilation and gluon-gluon fusion. The production cross section is known at next-to-leading order (NLO) [6]. In the low energy limit there is no intergenerational mixing, thus we search for the first generation LQ pair production that further decays to a pair of the first generation lepton and quark. In this paper, we report result where one LQ decays to eq and the other to $\nu_e q'$ (charge conjugate states are assumed in the paper) [7]. If $\beta = \mathcal{BR}(LQ \to eq)$ then $\sigma \times \mathcal{BR}(LQLQ \to eq\nu_e q')$ is maximized for $\beta = 0.5$.

Limits on the production of first generation leptoquarks have been reported by the DELPHI [8], OPAL [9, 10], H1 [11, 12], ZEUS [13], CDF [14], and D0 [15] Collaborations. Recently, CMS [16, 17], and ATLAS [18] published the first searches for scalar LQ pair production at the CERN LHC.

2.2. Analysis

The D0 detector is described elsewhere [19–21]. In this proceedings we report the result from 5.4 fb^{-1} of data collected between 2002 and 2009. Signal and SM background processes that contain real electrons are modeled with Monte Carlo (MC) and include V+jets ($V = W, Z$), $t\bar{t}$, single top and diboson (WW, WZ, ZZ) processes. Diboson processes are generated with PYTHIA [22], and their cross sections are calculated at next-to-leading order (NLO). V+jets and $t\bar{t}$ are produced with ALPGEN [23], interfaced to PYTHIA for subsequent parton showering and hadronization and their cross sections are known at next-to-next-to-leading order. Multijet (MJ) background, where a jet mimics an electron, is estimated from data [24]. Scalar leptoquark pair MC samples are generated using PYTHIA for different LQ masses between 200 and 360 GeV. The corresponding cross sections at NLO are listed in Table I.

Table I: Scalar LQ pair production cross sections, calculated at NLO, for different M_{LQ} [6].

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

We explored ways to correctly pair jets and e or ν_e which are originating from the same LQ. We did not put any requirement on the number of jets, but we considered the two leading in p_T jets for pairing. Thus, there are two possible combinations, pairing the leading jet to either the e or the ν_e. We tried four different methods:

- matching by minimizing differences in p_T from the combination of (jet,e) and (jet,ν_e);

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

- reconstructing the LQ from the both combinations, and pick the combination such that the distance in transverse plane, $\Delta\phi(LQ_1, LQ_2)$, is closest to π;
- matching by minimizing $\Delta\phi$ between the decay products of the LQs;
- matching by minimizing the differences in transverse mass, m_T, reconstructed from (jet,e) and (jet,ν_e), since the LQs are produced with the same mass.

The most effective algorithm, with success rate of $\sim 75\%$ is the one requiring that the differences between transverse mass are minimal.

Events are selected if they have one electron with $p_T > 15$ GeV, missing transverse energy $\not\!\!E_T > 15$ GeV and at least two jets with $p_T > 20$ GeV. To suppress MJ background, it is further required that $\not\!\!E_T/50 + M_T^{e\nu_e}/70 \geq 1$, where $M_T^{e\nu_e}$ is the transverse mass of the (e, ν_e) combination, and $\not\!\!E_T$ and $M_T^{e\nu_e}$ are in GeV. After these requirements, 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 $M_T^{e\nu_e}$ distribution for the data and SM processes. To suppress the dominant background at this stage, V+jets, we select events that fulfill $M_T^{e\nu_e} \geq 110$ GeV. We use the pairing algorithm described previously to reconstruct M_{LQ}. Since the z component of the neutrino momentum is not measurable, for the $LQ \to \nu_e q'$ we reconstruct the visible part of the $M_{LQ} = M(\text{jet} + \nu_{\text{vis}})$, 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 $LQ \to eq$ and the visible mass of the decay $LQ \to \nu_e q'$ after the requirement $M_T^{e\nu_e} \geq 110$ GeV. We then use $\sum M_{LQ}$ to reduce SM backgrounds, further requiring that $\sum M_{LQ} > 350$ GeV. The final requirement is imposed on the scalar sum of the p_T of lepton, neutrino and two jets, S_T, shown in Fig. 1(c) after the previous selection. We select events with $S_T > 450$ GeV. Event count after each selection requirement is shown in Table II.

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
$M_T^{e\nu_e} > 110$ 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

2.3. Result

As shown in Fig. 1(c) after the final requirement, we don't observe any significant excess, so we proceed to set limits. 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 [25]. Signal and background normalizations and shape variations due to systematic uncertainties are incorporated assuming Gaussian priors.

Figure 2 shows the limits on the cross section multiplied by the branching fraction and the theoretical LQ cross section for $\beta = 0.5$. We exclude the production of first generation LQs with $M_{LQ} < 326$ GeV for $\beta = 0.5$ at the 95% C.L. We also determined the limit as a function of β, which is shown in Fig. 3 and compared with previous D0 [15], and recent ATLAS [18] and CMS [16, 17] results.

3. Search for Vector-Like Quarks

3.1. Motivation

Many new theories predict the existence of vector-like quarks, massive particles which share many characteristics with SM quarks. They include, among others, little Higgs models [26], warped extra dimensions [27], and universal extra dimensions [28]. Vector-like quarks are fermions (despite the name) and their left-and right-handed components transform in the same way under $SU(3) \times SU(2)_L \times U(1)$. In $p\bar{p}$ collisions such as at the Tevatron Collider vector-like quarks can be produced in pairs via the strong interaction, or singly via the electroweak interaction. In some scenarios (e.g. warped extra dimensions), corrections to SM quark couplings

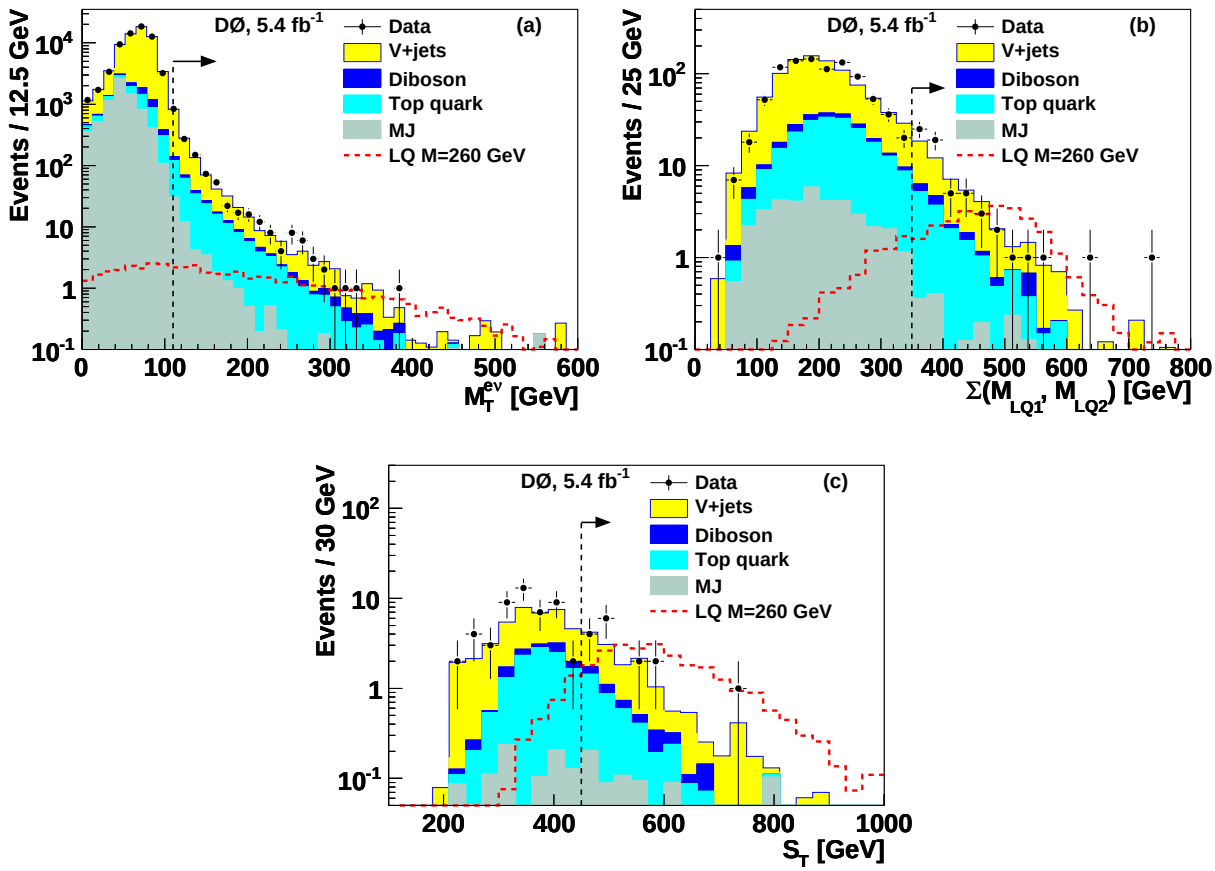

Figure 1: (a) $M_T^{e\nu_e}$ distribution after preselection, (b) $\sum M_{LQ}$ for $M_T^{e\nu_e} > 110$ GeV, (c) the S_T for $M_T^{e\nu_e} > 110$ GeV and $\sum M_{LQ} > 350$ GeV, which is used to set an upper limit on the LQ pair production cross section after the final selection.

due to mixing with vector-like quarks can cancel, and then single electroweak production at Tevatron will be enhanced [29]. Electroweak couplings between vector-like quarks and SM quarks depend on a parameter κ_{qQ}:

$$\kappa_{qQ} = \frac{v}{m_Q}\tilde{\kappa}_{qQ} \tag{1}$$

where v is the vacuum expectation value of the SM Higgs field, m_Q is the mass of the vector-like quark, and $\tilde{\kappa}_{qQ}$ is the coupling strength. We present here results from a search of a singly produced vector-like quark in 5.4 fb^{-1} of data collected with D0 detector [30].

3.2. Analysis

Vector-like quarks can either decay to $W + q$ or $Z + q$, and they are always produced together with another quark. Thus, we are looking at final states consistent with two jets and either $W \to l\nu$, i.e. single lepton channel, or $Z \to ll$, i.e. dilepton channel. The main background for the single lepton channel is W+jets, while Z+jets is the main background for the dilepton channel. Other backgrounds include $t\bar{t}$, single top, diboson, and MJ. V+jets and $t\bar{t}$ are modeled with ALPGEN interfaced with PYTHIA, single top with COMPHEP [31], and diboson with PYTHIA. MJ backgrounds are estimated using data driven techniques. Signal samples are generated using MADGRAPH [32], with CTEQ6L1 [33] parton distribution functions, LO cross sections from Ref. [29] and the vector-like quark resonance widths calculated with BRIDGE [34]. Subsequent parton shower evolution is generated with PYTHIA. For simplicity, we assume $\tilde{\kappa}_{uD} = 1$, $\tilde{\kappa}_{uU} = \sqrt{2}$ and $\tilde{\kappa}_{dU} = \tilde{\kappa}_{dD} = 0$, i.e. $\mathcal{BR}(QD \to Wq) = \mathcal{BR}(QU \to Zq) = 100\%$, where QU and QD are up-type and down-type vector-like quark, respectively.

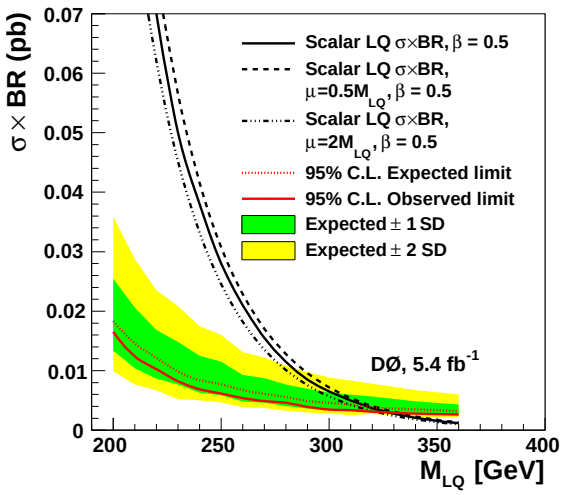

Figure 2: Expected and observed upper limits calculated at the 95% C.L. on the LQ cross section as a function of M_{LQ} for a scalar LQ compared with the NLO prediction for $\beta = 0.5$. The NLO cross section is shown for different choices of the renormalization and factorization scales, $\mu = M_{LQ}$,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

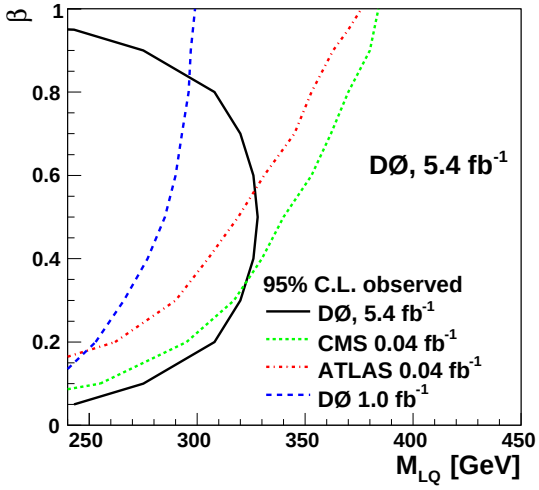

Figure 3: 95% C.L. observed limit for $\mu = M_{LQ}$ on the LQ mass as a function of β compared with the previous D0 result [15], and CMS [16, 17] and ATLAS [18] results.

In the dilepton channel events are selected if they have two oppositely charged leptons with $p_T > 15$ GeV, and if dilepton invariant mass is consistent with the mass of the Z boson, i.e. $70 < M_{ll} < 110$ GeV. It is further required that events contain at least two jets with $p_T > 20$ GeV and no significant $\not\!\!E_T$, i.e. $\not\!\!E_T < 50$ GeV. Since the signal in this final state is a heavy resonance decaying to a Z boson and a jet, we further optimize cuts by requiring that $p_T^{ll} > 100$ GeV, transverse momentum of the leading jet $p_T > 100$ GeV, and that distance between the two leptons $\Delta R(l, l) < 2.0$, where $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.

In the single lepton channel we select events with one lepton with $p_T > 15$ GeV, $\not\!\!E_T > 15$ GeV and at least two jets with $p_T > 20$ GeV. To suppress MJ background we further require $2 \times M_T^W + \not\!\!E_T > 80$ (M_T^W and $\not\!\!E_T$ are in GeV). Selection requirements are optimized in the single lepton channel requiring that lepton $p_T > 50$ GeV, leading jet $p_T > 100$ GeV, $\not\!\!E_T > 40(50)$ GeV for electron(muon) channel, $M_T^W < 150$ GeV and $\Delta\phi(l, \not\!\!E_T) < 2.0$. In $Qq \to Wqq$ events the second jet originates from SM quark produced in association with a vector-like quark,

thus it will be forward and relatively soft. The direction of this jet is strongly correlated with the charge of the produced vector-like quark, and thus also with the charge of the lepton from its decay. The final requirement is then $Q_l \times \eta_{jet2} > 0$, where Q_l is the lepton charge and η_{jet2} is the pseudorapidity of the second jet. The efficiency of this cut is $\sim 85\%$ for signal events and $\sim 50\%$ for SM backgrounds.

3.3. Results

Figure 4(a) shows the reconstructed transverse mass of a vector-like quark, i.e. transverse mass of the lepton, $\not\!\!E_T$ and leading jet, for the single lepton channel, and Fig. 4(b) shows the reconstructed invariant mass of a vector-like quark, i.e. invariant mass of the two leptons and leading jet, for the dilepton channel. Since we do not observe any significant excess in data over SM backgrounds, we proceed to set 95% C.L. limits on the production cross section for a single vector-like heavy quarks. We employ semi-frequentist CL_s method based on a Poisson log-likelihood test statistic [25]. Figure 5 and 6 show 95% C.L. limits on the vector-like quark production cross sections for the single lepton and dilepton channels, respectively. We exclude at 95% C.L. vector-like heavy quarks with masses below 693 GeV for $Q \to Wq$ and with masses below 449 for $Q \to Zq$, assuming $\kappa_{qQ} = 1$.

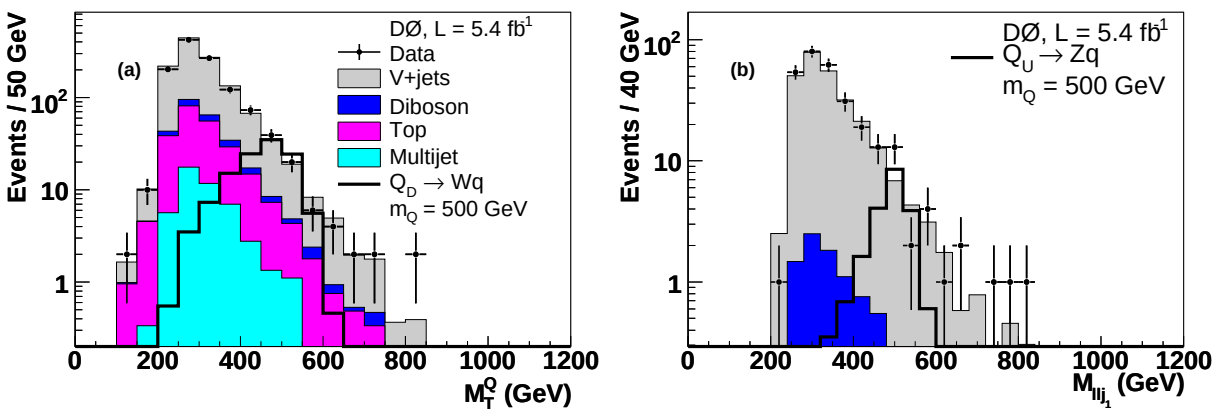

Figure 4: (a) Vector-like quark transverse mass and (b) vector-like quark mass for the single lepton and dilepton channels, respectively.

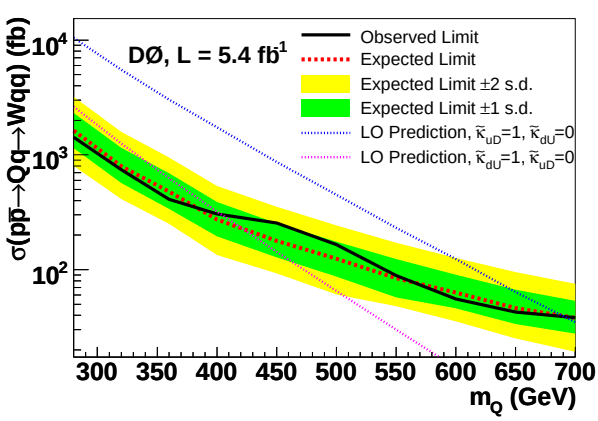

Figure 5: Limit on the production cross section for a vector-like quark $Q \to Wq$ as a function of m_Q, compared to LO predictions of vector-like quark production with different $\tilde{\kappa}_q Q$.

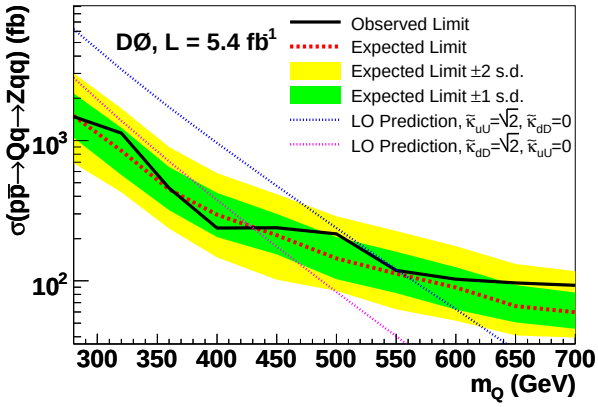

Figure 6: Limit on the production cross section for a vector-like quark $Q \to Zq$ as a function of m_Q, compared to LO predictions of vector-like quark production with different $\tilde{\kappa}_q Q$

4. Summary

In summary, we present results from the search for first generation leptoquarks and heavy vector-like quarks. The observed data is consistent with the expectation from SM backgrounds. We exclude pair production of scalar leptoquarks with masses below 326 GeV for $\beta = 0.5$. We set the most stringent limits on pair production of scalar leptoquarks for $\beta < 0.3$. We also exclude vector-like heavy quarks with masses below 693 GeV for $Q \to Wq$ and with masses below 449 for $Q \to Zq$, respectively. These limits are the best to date.

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

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