Search for single production of scalar leptoquarks in $p\bar{p}$ collisions decaying into muons and quarks with the D0 detector

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We report on a search for second generation leptoquarks (LQ_2) which decay into a muon plus quark in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV in the D0 detector using an integrated luminosity of about $300\,\mathrm{pb}^{-1}$. No evidence for a leptoquark signal is observed and an upper bound on the product of the cross section for single leptoquark production times branching fraction β into a quark and a muon was determined for second generation scalar leptoquarks as a function

of the leptoquark mass. This result has been combined with a previously published D0 search for leptoquark pair production to obtain leptoquark mass limits as a function of the leptoquark-muon-quark coupling, λ. Assuming $\lambda = 1$, lower limits on the mass of a second generation scalar leptoquark coupling to a u quark and a muon are $m_{\mathrm{LQ_2}} > 274\,\mathrm{GeV}$ and $m_{\mathrm{LQ_2}} > 226\,\mathrm{GeV}$ for $\beta = 1$ and $\beta = 1/2$, respectively.

The observed symmetry in the spectrum of elementary particles between leptons and quarks motivates the existence of leptoquarks [1]. Leptoquarks are bosons carrying both quark and lepton quantum numbers and fractional electric charge. Leptoquarks could in principle decay into any combination of a lepton and a quark that carry the correct charge. Experimental limits on lepton number violation, on flavor-changing neutral currents, and on proton decay, however, lead to the assumption that there would be three different generations of leptoquarks. Each of these leptoquark generations couples to only one quark and one lepton family and, therefore, individually conserves the family lepton numbers [2]. In this Letter, second generation leptoquarks refer to leptoquarks coupling to muons. Since there is no explicit connection between a given lepton generation with any of the three quark generations in the standard model, the second generation leptoquark that couples to muons could couple to a quark from any one of the three generations.

Figure 1 shows mechanisms for leptoquark production and decay in $p\bar{p}$ collisions. Leptoquarks can be either pair produced via the strong interaction or single leptoquark can be produced in association with a lepton. The cross section for single leptoquark production depends on the a priori unknown leptoquark-lepton-quark coupling λ. In $p\bar{p}$ collisions, the production cross section for single leptoquarks coupling to up and down quarks is significantly larger than that for single leptoquarks coupling to second generation quarks, and for the search described in this Letter, we only considered this scenario. For other quark flavors, the inclusion of single leptoquark production would not improve the sensitivity from the pair production search even for large couplings.

This search was performed assuming both leptoquark pair and single production contribute to the expected signal. Therefore both the final state with two jets and two muons and the final state with two muons and one jet were considered. The former has been studied in previously published analyses of leptoquark pair production [3, 4]. In addition, limits are given if one assumes that only single leptoquark production contributes to the expected signal. The cross section limit for this scenario can be interpreted as limit on a final state containing two energetic muons and a high E_T jet. The inclusion of single leptoquark production in a Tevatron search has been previously discussed in Ref. [5].

The D0 detector [6] consists of several layered elements. First is a magnetic central tracking system which is comprised of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. Jets are reconstructed from energy depositions in the three liquid-
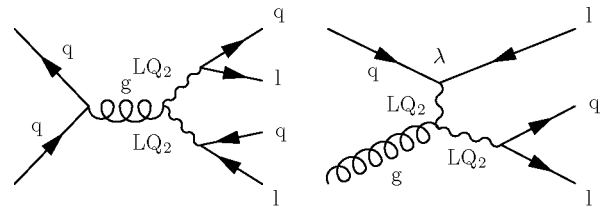

FIG. 1: Examples of leading-order Feynman graphs for pair-production (left) and single-leptoquark production (right) of leptoquarks.

argon/uranium calorimeters: a central section (CC) covering pseudorapidities, $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the proton beam direction, up to $|\eta| \approx 1$, and two endcap calorimeters (EC) extending coverage to $|\eta| \approx 4$, all housed in separate cryostats [7]. Scintillators between the CC and EC cryostats provide sampling of developing showers at $1.1 < |\eta| < 1.4$. A muon system [8] resides beyond the calorimetry and consists of a layer of proportional wire tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two similar layers after the toroids. The muon system is used for triggering and identifying muons. The muon momenta are measured from the curvature of the muon tracks in the central tracking system.

The data used in this analysis were collected between August 2002 and July 2004, corresponding to an integrated luminosity of $294 \pm 19\,\mathrm{pb}^{-1}$. Only events which pass single- or di-muon triggers were considered. At the first trigger level, a muon was triggered by a coincidence of hits in at least two of the three scintillator layers of the muon system within a time window consistent with muons coming from the interaction point. At the second trigger level, a muon track was identified from the hits in the proportional wire tracking detectors and the scintillators of the muon system. The overall trigger efficiency for $\mu j + \mu j$ and $\mu + \mu j$ events fulfilling the selection criteria of this analysis was measured to be $(89 \pm 3)\%$.

Muons in the region $|\eta| < 1.9$ were reconstructed from hits in the three layers of the muon system which could be matched to isolated tracks in the central tracking system. Cosmic muon events were rejected by cuts on the timing in the muon scintillators and by removing back-to-back muons. Jets were reconstructed using the iterative midpoint cone algorithm [9] with a cone size of 0.5. The jet energies were calibrated as a function of the jet transverse energy (E_T) and η by imposing transverse energy balance in photon-plus-jet events. Only jets which

were well-contained within the detector were considered by requiring $|\eta| < 2.4$.

For this search, the background is dominated by Drell-Yan production and Z decays: $Z/\gamma^* \rightarrow \mu\mu$ (+jets) (Z/DY). Additional backgrounds coming from QCD multijet production and from W+jets events (with at least one reconstructed muon originating not from the hard scattering) were estimated and found to be negligible. To evaluate the contribution from the Z/DY background, samples of Monte Carlo (MC) events were generated with PYTHIA (Version 6.202) [10]. Samples of $t\bar{t}$ ($m_t = 175\,\text{GeV}$) and WW production were also generated with PYTHIA. The signal efficiencies were calculated using PYTHIA samples of $\text{LQ}_2 + \mu \rightarrow \mu j + \mu$ and $\text{LQ}_2\overline{\text{LQ}_2} \rightarrow \mu j + \mu j$ MC events for leptoquark masses (m_{LQ_2}) from 140 to 280 GeV in steps of 20 GeV. All MC events were processed using a full simulation of the D0 detector based on GEANT [11] and the standard event reconstruction. Differences in the trigger and reconstruction efficiencies between data and Monte Carlo were taken into account using proper weightings of the MC events.

The search for leptoquarks required two muons with transverse momenta $p_T > 15\,\text{GeV}$ and either one or two jets with $E_T^j > 25\,\text{GeV}$. To reduce the Z/DY background at high dimuon mass due to occasionally poorly reconstructed muon tracks, advantage was taken of the fact that no or little missing transverse energy is expected in either signal or Z/DY events. The missing transverse energy was determined from the transverse energy imbalance of all muons and jets ($E_T > 20\,\text{GeV}$) in the event, and the momentum of the muon opposite to the direction of the missing transverse energy (i.e. with the larger azimuthal angle relative to the direction of the missing transverse energy) was corrected such that the missing transverse energy parallel to the muon vanished. This degraded the muon momentum resolution and shifted the dimuon mass to lower values in both data and MC. However, this correction allowed the suppression of poorly reconstructed Z boson events shifted into the high mass region where the search for leptoquarks was taking place.

To create statistically independent signal bins, events were first classified as either leptoquark pair or single leptoquark candidates. Events were classified as leptoquark pair candidates if they contained two jets with $E_T > 25\,\text{GeV}$, had a dimuon mass $M_{\mu\mu} > 105\,\text{GeV}$ (to remove Z boson events), and fulfilled the requirement $\hat{S} = S_T/\text{GeV} - 0.003 \times (M_{\mu\mu}/\text{GeV} - 250)^2 > 250$, with S_T defined as the sum the sum of the absolute values of the transverse energies of the two jets and the transverse momenta of the two muons forming the $\mu j + \mu j$ system. Events not classified as leptoquark pair candidates were classified as single leptoquark candidates if they contained at least one jet with $E_T > 50\,\text{GeV}$, had a di-muon mass $M_{\mu\mu} > 110\,\text{GeV}$ and fulfilled the requirement $\hat{E} = (M_{\mu\mu}/\text{GeV} - 110) \times (E_T^j/\text{GeV} - 50) > 500$ (see Fig. 2). The optimum choice of variables and cut values has been determined to optimize the sensitivity to the signal. These selections have been cross-checked
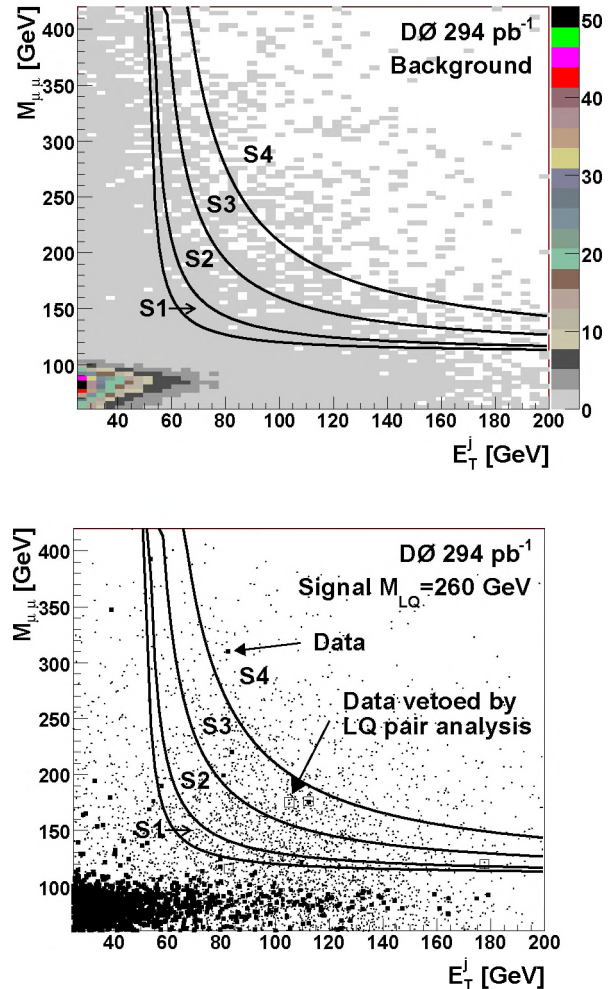

FIG. 2: Distributions of $M_{\mu\mu}$ vs. the highest jet E_T^j for background (upper plot) and signal and data (lower plot). The curved lines show the edges of the signal bins (see text for definition). The bottom plot shows as small dots the expected signal distribution from single leptoquark production ($m_{\text{LQ}_2} = 260\,\text{GeV}$). The bottom plot also shows the observed data for events not classified as leptoquark pair candidates (small black boxes) and classified as leptoquark pair candidates (open boxes).

with a neural net optimization, which gave similar results. Eleven events were either classified as leptoquark pair candidates or single leptoquark candidates while $6.6 \pm 0.5\,\text{(stat)} \pm 1.1\,\text{(syst)}$ are expected from standard model background. A small excess of data over background was observed. The probability that 6.6 ± 1.2 expected events fluctuate up to 11 observed events is 9.2%.

Candidate events were arranged in bins of increasing signal to background ratio. For leptoquark pair candidates, bin boundaries of $\hat{S} = 320$ and 390 are used to define bins P1, P2 and P3 [3]. For single leptoquark candidates, boundaries of $\hat{E} = 1000, 2500, 5000$ were used to define signal bins S1, S2, S3 and S4 (Fig. 2).

Table I summarizes the efficiency of the single lepto-

TABLE I: Signal efficiency ($\varepsilon_{\text{single}}$) for selecting single leptoquarks for $\beta = 1$, number of data events (N_{data}), and number of predicted background events ($N_{\text{pred}}^{\text{bgd}}$). The first uncertainty on $N_{\text{pred}}^{\text{bgd}}$ is due to limited Monte Carlo statistics, the second denotes the systematic uncertainty. The first two lines indicate the total number of events after the initial event selection while the other lines indicate the numbers for the individual bins of the leptoquark pair candidates (P1–P3) and single leptoquark candidates (S1–S4) as described in the text.

Cut	$\varepsilon_{\text{single}}$ ($m_{\text{LQ}_2} = 200\,\text{GeV}$)	$\varepsilon_{\text{single}}$ ($m_{\text{LQ}_2} = 240\,\text{GeV}$)	N_{data}	$N_{\text{pred}}^{\text{bgd}}$
$M_{\mu\mu} > 110\,\text{GeV}$ $E_T^j > 25\,\text{GeV}$	0.145 ± 0.013	0.176 ± 0.015	43	$44.75 \pm 1.74 \pm 6.13$
$M_{\mu\mu} > 110\,\text{GeV}$ $E_T^j > 50\,\text{GeV}$	0.122 ± 0.012	0.158 ± 0.014	20	$13.41 \pm 0.92 \pm 1.57$
P1	0.011 ± 0.002	0.015 ± 0.002	2	$0.96 \pm 0.25 \pm 0.28$
P2	0.006 ± 0.001	0.011 ± 0.002	2	$0.39 \pm 0.10 \pm 0.11$
P3	0.006 ± 0.001	0.012 ± 0.002	0	$0.27 \pm 0.10 \pm 0.08$
S1	0.018 ± 0.002	0.014 ± 0.002	2	$2.01 \pm 0.33 \pm 0.57$
S2	0.028 ± 0.003	0.030 ± 0.003	1	$1.61 \pm 0.27 \pm 0.44$
S3	0.016 ± 0.002	0.029 ± 0.003	3	$0.87 \pm 0.17 \pm 0.29$
S4	0.015 ± 0.002	0.029 ± 0.004	1	$0.44 \pm 0.08 \pm 0.06$
Signal bins (P1-P3,S1-S4)	0.100 ± 0.010	0.140 ± 0.013	11	$6.55 \pm 0.53 \pm 1.08$

quark selection for two leptoquark masses as well as the number of expected background events and the distribution of the data in the three pair and four single leptoquark bins.

The dominant uncertainties on the predicted number of background events are Monte Carlo statistics, varying between 7% and 25% for the seven signal bins, the jet-energy scale uncertainty [(2 − 12)%], and the uncertainty on the shape of the jet transverse energy distribution of Z/DY events [(20 − 30)%]. The latter has been estimated by a comparison of the PYTHIA [10] simulation with Monte Carlo events generated with the ALPGEN [12] event generator. For leptoquark pair candidates, the uncertainty due to the two jet requirement was estimated to be 16% [3]. In addition, the following sources of systematic uncertainties were taken into account: luminosity (6.5%), theoretical cross section of the Z/DY processes (3.6%), and muon triggering and identification (5%). The systematic uncertainties, added in quadrature, are shown in Table I.

The systematic uncertainties on the signal efficiencies arise from the jet-energy scale uncertainty [(3 − 17)%], muon triggering and identification (5%), limited Monte Carlo statistics [(4 − 14)%, uncorrelated between bins], and parton distribution function uncertainty (2%).

Limits on the cross section for single leptoquark production were calculated from the observed and expected events in the seven signal bins (P1-P3 and S1-S4). Three different scenarios were considered: (a) the only contribution to the signal region came from standard model background and from single leptoquark production, (b) contributions to the signal region came from standard model background and single leptoquark production plus leptoquark pair production corresponding to the nominal leptoquark pair cross section [13] with $\beta = BR(LQ \rightarrow \mu q) = 1/2$, and (c) as (b) but with $\beta = 1$. For scenarios (b) and (c) leptoquark pair events in the signal bins
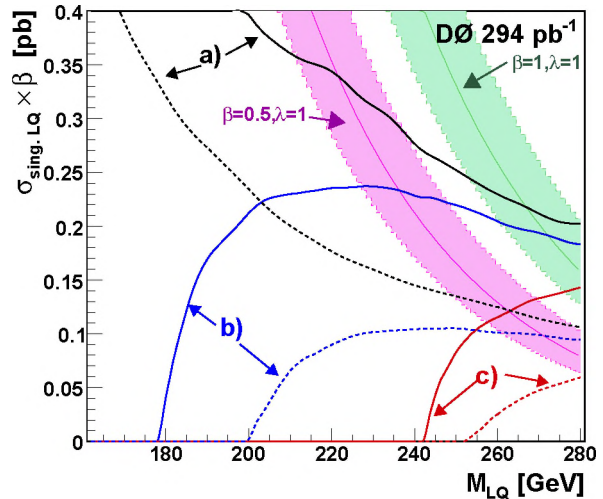

FIG. 3: Cross section upper limits at 95% C.L. for the production of single leptoquarks for the three scenarios (a) no contribution from leptoquark pair production, (b) pairs contribute with a $\sigma \times \beta^2$ corresponding to $\beta = 1/2$, and (c) pairs contribute with a $\sigma \times \beta^2$ corresponding to $\beta = 1$. The solid line is the observed limit and the dashed line the average expected limit assuming that no signal is present. Also indicated are the predicted single leptoquark production cross sections for $\lambda = 1$, $\beta = 1$ and $\lambda = 1$, $\beta = 1/2$. The shaded region is the variation of the cross section using renormalization and factorization scales of $2 \times m_{\text{LQ}_2}$ and $0.5 \times m_{\text{LQ}_2}$, respectively.

P1-P3 are treated exactly the same way as in [3]. The analysis described above can therefore be considered as a combination of the search for singly produced leptoquark with the leptoquark pair analysis published in [3].

These calculations were performed assuming a flat prior and Gaussian errors as described in Ref. [14] with
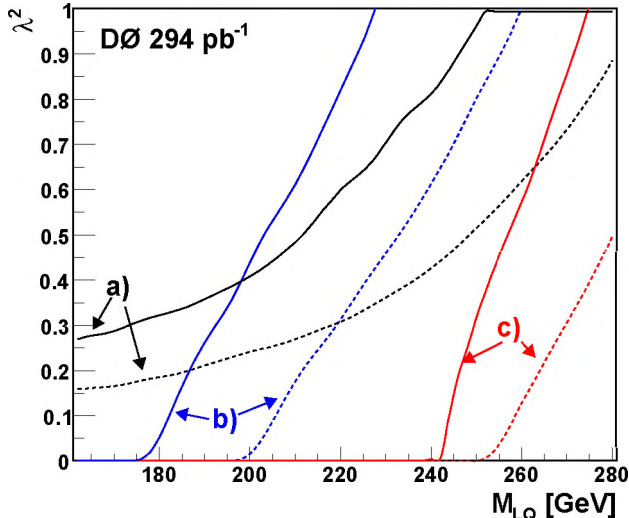
FIG. 4: Upper limits on λ^2 for the three scenarios: (a) no contribution from leptoquark pairs events and $\beta = 1$, (b) leptoquark pairs contribute with a $\sigma \times \beta^2$ corresponding to $\beta = 1/2$, and (c) leptoquark pairs contribute with a $\sigma \times \beta^2$ corresponding to $\beta = 1$. The solid line is the observed and the dashed line is the expected limit. The regions above the solid lines are excluded at 95% C.L.

the correlations between the systematic errors taken into account. The observed limit was calculated using the confidence level ratio [14] $CL_S = CL_{S+B}/CL_B$, where CL_{S+B} is the confidence level for the signal plus background hypothesis, and CL_B is the confidence level for the background only.

Figure 3 shows the 95% C.L. exclusion limits for the production cross section times branching fraction for single leptoquarks as functions of the leptoquark mass. The predicted cross section for single leptoquarks depends both on the coupling strength λ and on the leptoquark mass. Each point in Fig. 3 therefore corresponds to a specific value of λ and branching fraction. In scenarios (b) and (c), leptoquark masses are excluded independently of the single leptoquark cross section if they are already excluded because of the leptoquark pair production results. The average expected limits are better than the observed ones because of the small excess of data over background.

Also indicated are the predicted leading order cross

sections for single leptoquarks [15] for $\lambda = 1$ with $\beta = 1$ and $\beta = 1/2$. For the production cross sections, it was assumed that the leptoquark couples to the u quark and a muon. From the intersection of the cross section limit with the lower limit of the predicted cross section, which were derived by using renormalization and factorization scales of $2 \times m_{LQ_2}$, respectively, exclusion limits on the leptoquark mass as a function of the coupling strength λ can be estimated. Figure 4 shows the 95% C.L. exclusion regions as functions of the leptoquark mass and λ^2. For scenario (b), the reduction of expected events due to $\beta = 1/2$ applies to both single and pair production of leptoquarks. The intersection of the curves with $\lambda^2 = 0$ yields the result when only leptoquark pairs are considered.

The production of a leptoquark-like particle in association with a muon which decays into a jet and a muon can be excluded for cross section times branching fractions $\sigma \times \beta > 0.40$ pb for a particle mass of $200\,\text{GeV}$ and $\sigma \times \beta > 0.23$ pb for a particle mass of $260\,\text{GeV}$. The D0 Run II result for scalar leptoquarks and $\beta = 1$ of $m_{LQ_2}(\lambda^2 \ll 1) > 247\,\text{GeV}$, which only considered leptoquark pair production [3], is improved for an assumed leptoquark coupling to a u quark and a muon of $\lambda^2 = 1$ to $m_{LQ_2}(\lambda^2 = 1) > 274$ GeV. For $\beta = 1/2$, the improvement is from $m_{LQ_2}(\lambda^2 \ll 1) > 190\,\text{GeV}$ to $m_{LQ_2}(\lambda^2 = 1) > 226\,\text{GeV}$. For $\lambda^2 = 0.1$ the observed limits show no improvement while the expect limits increase by about $7\,\text{GeV}$. This analysis is the first search for single leptoquark production in $p\bar{p}$ collisions.

Acknowledgments

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