Search for Second-Generation Scalar Leptoquarks in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV

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We report on a search for pair production of second-generation scalar leptoquarks (LQ) in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV using an integrated luminosity of 198 pb^{-1} collected at the Fermilab Tevatron collider by the CDF detector. We observe no evidence for LQ production in the topologies arising from $LQ\overline{LQ} \rightarrow \mu q \mu q$ and $LQ\overline{LQ} \rightarrow \mu q \nu q$, and derive 95% C.L. upper limits on the LQ production cross sections as a function of β, where β is the branching fraction for $LQ \rightarrow \mu q$. The results are combined with those obtained from a CDF search in the topology arising from $LQ\bar{LQ} \rightarrow \nu q \nu q$ and 95% C.L. lower limits on the LQ mass as a function of β are derived. The limits are 226, 208 and 143 GeV/c^2 for $\beta = 1$, $\beta = 0.5$ and $\beta = 0.1$, respectively.

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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 could allow for interactions between them. Such interactions could be mediated by a new type of particle, the leptoquark,LQ[1], which carries both lepton and baryon number, is a color triplet boson with spin 0 or 1, and has fractional charge. Leptoquarks are predicted in many extensions of the SM (e.g. grand unification, technicolor, and supersymmetry with R-parity violation[2]). It is usually assumed that leptoquarks couple to fermions of the same generation to accomodate experimental constraints on flavor changing neutral currents and helicity suppressed decays. This allows one to classify leptoquarks as first- , second- , or third-generation. This also implies that second generation LQ are experimentally observable only at hadron machines, such as the Fermilab TeVatron, where they would be predominantly pair produced through $q\bar{q}$ annihilation (for $M_{LQ} > 100$ GeV/c^2) and gluon fusion. Such pair production mechanisms are independent of the coupling λ. The CDF and D0 experiments[3, 4] have set lower limits on the mass of second generation LQ using data from $p\bar{p}$ collisions at $\sqrt(s) = 1.8$ TeV. In this Letter, we present a search for second-generation scalar leptoquark pairs produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV for two cases: when both leptoquarks decay to a muon and a quark with a branching fraction (Br) β^2 where β is the leptoquark branching fraction into a muon and a quark and when one of the leptoquarks decays to a muon and a quark and the other to a neutrino and a quark with Br $= 2\beta(1-\beta)$. The final states consist of two muons with opposite charge and two jets ($\mu\mu jj$) or of a muon, two jets, and missing transverse energy corresponding to the neutrino which escapes detection ($\mu\nu jj$). These results are then combined with the result from a search for scalar leptoquark pairs decaying into $\nu\nu qq$, resulting in a jets and missing transverse energy topology[5].

CDF is a general–purpose detector built to study the physics of $p\bar{p}$ collisions at the TeVatron accelerator at Fermilab. The main components are a silicon vertex detector, central tracking drift chamber, central and forward calorimeters, and muon chambers. The detector is described in detail elsewhere [6]. The data used in the analysis were collected during the 2002-2003 TeVatron Run II. The integrated luminosity for this data sample is 198 $\pm$ 12 pb^{-1}. Events were required to pass the high P_T muon triggers, based on the requirement of track segments ("stubs") reconstructed in the muon chambers and matched to single tracks. The efficiency of the trigger combinations used in the $\mu\mu jj$ and $\mu\nu jj$ analyses have been measured using data. They are ~90% . Muons are reconstructed offline based on track requirements and energy deposition in the calorimeters. We select tight muons based on the requirement of a track segment ("stub") reconstructed in the muon chambers with positions well matched to the extrapolation of a single track, or loose muon when we require only an isolated track. In both cases the energy deposition in the calorimeters must be consistent with that of a minimum-ionizing particle. We apply a cut on the χ^2 of the track fit to eliminate kaons and pions which have decayed in flight. The coordinate of the lepton (also assumed to be the event coordinate) along the beamline must fall within 60 cm of the center of the detector (z_{vertex} cut) to ensure a good energy measurement in the calorimeter. This cut is 95% efficient, from studies with minimum bias events. The efficiencies of the identification cuts, the trigger selection and the vertex cut, measured using the data were taken into account using proper weightings of the MC events. Jets are reconstructed using a cone of fixed radius $\Delta R = 0.7$ in the $\eta - \phi$ plane. They are required to have $|\eta| < 2.0$. The energy measurement of the jets has been calibrated as a function of the jet transverse energy and η by balancing energy in the photon plus jets events. Neutrinos produce missing transverse energy, $\not{E}_T$, which is measured by balancing the calorimeter energy in the transverse plane. Cosmic-ray muons contaminate the muon sample. The timing capability of the COT is used to reject events with two muon tracks, one of which travels toward the beam pipe. We also require that the muon track passes close to the beam line, whithin distances less than 0.02 cm (0.2 cm) for tracks with (without) silicon hits.

In the dimuon + jets topology, from the inclusive muon triggers dataset we select events offline with two reconstructed isolated muons with $P_T > 25$ GeV/c. The first

muon is required to be tight, i.e. to have a stub associated to a track, while the second one can be stubless. Events are further selected if there are at least two jets with $E_T > 30$ and 15 GeV/c. The dataset selected above is dominated by QCD production of Z bosons in association with jets and $t\bar{t}$ production (where both the W's from top decay into muon and neutrino). To reduce these backgrounds the following cuts are applied: i) veto of events whose reconstructed dilepton mass falls in the window $76 < m_{\mu\mu} < 110$ GeV/c^2 to remove the Z + jets contribution and $m_{\mu\mu} < 15$ GeV/c^2 to avoid contamination from J/Ψ and Υ production; ii) $E_T(j_1) + E_T(j_2) > 85$ GeV/c and $E_T(e_1) + E_T(e_2) > 85$ GeV/c, iii) $\sqrt{((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)} > 200$ GeV/c. We studied the properties of the Z + jets and $t\bar{t}$ backgrounds by generating the process Z + 2 jets with Alpgen[8] and $t\bar{t}$ with PYTHIA[9] and passing them through a complete simulation of the CDF II detector based on GEANT[10] and complete event reconstruction. The background arising from multijet events, where a jet is mismeasured as a muon or where the muon comes from pion decay (QCD/fake), is calculated using data. In the $\mu\mu jj$ analysis to estimate the contamination from this type of background, we examine the data for same-sign events remaining after each kinematical cut. We estimate the background contribution to be twice the number of same sign events, in the assumption that the probability of negative charge found in the highest P_T track in a jet is roughly the same as for positive charge. In the $\mu\nu jj$ analysis the contribution from the QCD/fakes background is estimated by examining the phase space of the $\not\!\!E_T$ vs the muon fractional isolation for data events in which the muon isolation requirement is not enforced. Here the muon fractional isolation is defined as the ratio between the calorimetric energy not associated with the lepton in a cone of $\Delta R = 0.4$ around the lepton and the energy of the lepton. The following assumptions are made: since jets are produced in association with other particles, the isolation fraction of a jet will be generally larger than the one corresponding to a muon; there is no correlation between the isolation of the muon and $\not\!\!E_T$, and in the region where the $\not\!\!E_T$ is small and the isolation of the muon is large the LQ contribution is expected to be negligible. We will call these background-dominated regions. With these assumptions, from the ratio of the number of events in the background-dominated regions we can extrapolate the contribution in the signal region. Other backgrounds from $b\bar{b}$, $Z \to \tau\bar{\tau}$, WW are negligible due to the muon isolation and large muon and jet transverse energy requirements. To normalize simulated events to data we use the theoretical cross sections for $t\bar{t}$ from [11] and for $\gamma/Z \to ee$ + 2 jets from [12]. The expected number of Z + 2 jets events is 1.7 ± 0.1. The expected number of $t\bar{t}$ events is 0.22 ± 0.03 events. We estimate 1 ± 1 fake events The overall background estimate is: 3.0 ± 1 events. We checked the prediction of our background sources with data in a control region defined by requiring two muons with $P_T > 25$ GeV/c and $75 < m_{\mu\mu} < 105$ GeV/c^2 and 2 jets with $E_T > 30$,15 GeV/c and found 110 events as opposed to 88 ± 10 expected. The efficiency to detect our signal was obtained from MC simulated LQ (PYTHIA) to account for kinematical and geometrical accetpance. The total efficiencies for a LQ signal are reported in Table I. The following systematic uncertainty is considered when calculating signal acceptance and background predictions: i) luminosity: 6% ii) choice of parton distribution functions: 2.1% iii) statistical error of MC < 1.2% iv) jet energy scale < 1% v) muon reconstruction : 0.8% vi) z_{vertex} cut : 0.5%. After all selection cuts, 2 events are left in our data.

TABLE I: Efficiencies after all cuts, relative errors and 95% C.L. upper limits on the production cross section × branching fraction Br, as a function of M_{LQ}, for the two channels.

$M_{\rm LQ}$(GeV/c^2)	$\mu\mu jj$		$\mu\nu jj$	
	ϵ	$\sigma\times$Br(pb)	ϵ	$\sigma\times$Br(pb)
100	0.02 ± 0.17	1.35	0.005 ± 0.10	-
120	0.05 ± 0.09	0.52	0.07 ± 0.07	0.86
160	0.13 ± 0.08	0.18	0.07 ± 0.08	0.73
200	0.19 ± 0.08	0.13	0.11 ± 0.07	0.41
220	0.21 ± 0.08	0.11	0.13 ± 0.08	0.24
240	0.24 ± 0.08	0.10	0.13 ± 0.07	0.24
260	0.26 ± 0.08	0.09	0.14 ± 0.07	0.21

In the search in the muon, neutrino and two jets topology, from the inclusive lepton dataset we select events offline with one reconstructed tight muon with $P_T > 25$ GeV/c. We veto events with a second loose or tight muon to be orthogonal to the previous analysis. We then select events where there is large missing transverse energy, $\not\!\!E_T > 60$ GeV/c and at least two jets with E_T >30 GeV/c. The dataset selected is dominated by QCD production of W bosons in association with jets and $t\bar{t}$ production where either the W's from the top pair decay into $l\nu$, and one lepton is mismeasured, or one of the W's decays leptonically and the other hadronically. A small source of background is from Z + 2 jets, where one of the muons is not identified. To reduce these backgrounds the following cuts are applied: i)$\Delta\phi(\not\!\!E_T - jet) > 5^o$ to veto events where the transverse missing energy is mis-measured due to a mis-measured jet, and $\Delta\phi(\not\!\!E_T - \mu) < 175^o$ to insure that that the missing energy does not come from mis-measurement of a muon. ii)$E_T(j_1)+E_T(j_2) > 80$ GeV/c, iii)$M_T(\mu\nu) > 120$ GeV/c^2 to reduce the W + 2 jets background. We studied the properties of the W + jets, $t\bar{t}$ and Z + 2 jets backgrounds as described above. The background from $W \to \nu\tau$ + 2 jets (studied with events generated with Alpgen) is negligible after the final window mass cut (see below). The QCD background estimate is described above. Our final cut consists in selecting events falling in mass windows defined around several LQ masses. The

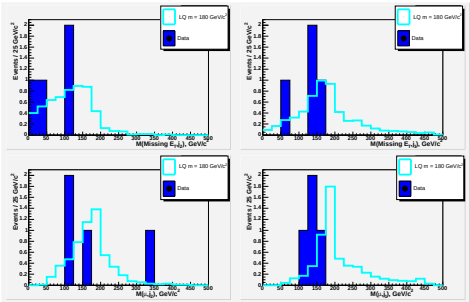

FIG. 1: Fig 1: Final mass distributions (see text) of the surviving events before the mass limit cut compared to the signal distribution for $M_{LQ} = 180$ GeV/c^2

mass window is built as follows. We require that the reconstructed mass combinations of the jets, muon and $\not\!\!E_T$ be consistent with those reconstructed from the leptoquark Monte Carlo. The ambiguity of the jet assignments allows for two different sets of reconstructed leptoquark pairs in each event, from which we build lineshape of mass distributions by matching the reconstructed objects to the generator level objects. The lineshapes are then used with the following selection: $|M(\mu, j_1) - M_{LQ}| < 2\sigma_1$ or $|M(\mu, j_2) - M_{LQ}| < 2\sigma_2$, and $M_T(\not\!\!E_T, j_1) > T_1^{min}$ or $M_T(\not\!\!E_T, j_2) > T_2^{min}$, where M_{LQ} is the mean of the reconstructed leptoquark distribution and $\sigma_{1,2}$ are the width parameterizations. $M(\mu, j_{1,2})$ are the reconstructed muon-jet invariant masses while $M_T(\not\!\!E_T, j_{1,2})$ are the reconstructed transverse invariant masses. For the transverse mass distributions, we have chosen a mass-dependent lower cut denoted by $T_{1,2}^{min}$: $T_1^{min} = 20 + (M_{LQ} - 120)$ GeV/c^2, and $T_2^{min} = 20 + (M_{LQ} - 120)/2$ GeV/c^2. The total efficiency of these cuts for several LQ masses is given in Table I. We checked the simulation prediction of our background sources with data in a control region defined by requiring one muon with $P_T > 25$ GeV/c, $\not\!\!E_T > 35$ GeV/c and 2 jets with $E_T > 30$ GeV/c and observe 203 events to be compared with a prediction of 221 ± 15 from SM sources. In Fig. 1 we plot the mass distributions of the selected events (before the mass limit cut) compared to the signal distribution for $m_{LQ} = 180$ GeV/c^2. The number of events in each mass region, compared with the background expectations is reported in Table II. The efficiency to detect our signal was obtained from MC simulated LQ data (PYTHIA as described above. The following systematic uncertainty is considered when calculating the signal acceptance and the background prediction: i) luminosity: 6% ii) choice of the parton distribution functions: 2.1% iii) statistics of MC $< 1.2\%$; iv) jet energy scale $< 1\%$ v) muon reconstruction 0.3% vi) z_{vertex} cut : 0.5% vii) initial and final state radiation 1.8%.

In both the analyses described above the number of events surviving the selection cuts is consistent with the expected number of background events. The conclusion of the two searches is that there is no new signal: we derive an upper limit on the leptoquark production cross section at 95% confidence level. We use a Bayesian approach[13] with a flat prior for the signal cross section and Gaussian priors for acceptance and background uncertainties. The cross section limits are tabulated in Table I and the mass limits are tabulated in Table III. To compare our experimental results with theoretical expectations, we use the next-to-leading order (NLO) cross-section for scalar leptoquark pair production from Ref.[14] with CTEQ4 PDF[15]. The theoretical uncertainties correspond to the variations from $M_{LQ}/2$ to $2M_{LQ}$ of the renormalization scale μ used in the calculalation. To set a limit on the LQ mass we compare our experimental limit to the theoretical cross section for $\mu = 2M_{LQ}$, which is conservative as it corresponds to the lower value of the theoretical cross section. By comparing the 95% CL upper limit on the cross section with the theoretical prediction, we can set a lower limit on the LQ mass. We find lower limits on M(LQ) at 224 GeV/c^2 ($\beta = 1$) and 170 GeV/c^2 ($\beta = 0.5$). To obtain the best result however, we combined the results from the two decay channels just described with the result of a search for leptoquark in the case where the particle decays to neutrino and quark with branching ratio $\beta' = Br(LQ \to \nu q)$ =1.0[5]. A joint likelihood has been formed from the product of the individual channel likelihoods. For each mass we simulated 10K pseudo-experiments, smearing the calculated number of background events and the estimated number of signal events by their respective total uncertainties. The searches in the $\mu\mu jj$ and $\mu\nu jj$ channel use common criteria and sometimes apply the same kind of requirements so the uncertainties in the acceptances have been considered correlated. When calculating the combined limit including the $\nu\nu jj$ channel the uncertainties have been considered uncorrelated. For each β value a limit on the expected number of events is returned for each mass. The resulting cross section limit is then compared with the theoretical production cross section to obtain lower limits on the LQ mass. The combined limit as a function of β is shown in Figure 2, together with the individual channels limits. The combined mass limits are also tabulated

TABLE II: Number of events surviving all cuts in the muon, missing energy and jets topology, compared with background expectations, as function of the LQ mass (in GeV/c^2). The number for the individual contributions have been multiplied by 10.

Mass	Wjj	top	Z jj	multijets	Total	Data
140	9 ± 1	17 ± 2	2 ± 0.1	3 ± 3	3.1 ± 0.3	3
160	14 ± 1	18 ± 2	2 ± 0.2	3 ± 3	3.7 ± 0.4	4
180	14 ± 1	14 ± 2	2 ± 0.1	3 ± 3	3.2 ± 0.3	2
200	16 ± 1	10 ± 4	2 ± 0.1	3 ± 3	3.1 ± 0.3	0
220	16 ± 1	8 ± 3	2 ± 0.1	3 ± 3	2.9 ± 0.3	0

TABLE III: 95% C.L. lower limits on the second generation scalar leptoquark mass (in GeV/c^2), as a function of β.The limit from CDF[4] ($\mu\mu jj$) Run I ($\sim 120pb^{-1}$) is also given.

β	$\mu\mu$ jj	$\mu\nu jj$	$\nu\nu jj$	Combined	CDF Run I
0.01	-	-	114	125	-
0.05	-	-	110	133	-
0.1	-	137	-	143	-
0.2	-	155	-	157	-
0.3	100	162	-	176	-
0.4	152	168	-	200	-
0.5	171	170	-	208	-
0.6	184	168	-	213	-
0.7	196	162	-	217	-
0.8	206	155	-	221	-
0.9	215	137	-	224	-
1.0	224	-	-	226	202

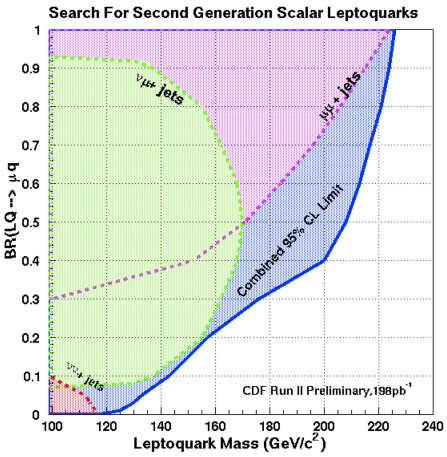

FIG. 2: Leptoquark mass exclusion regions at 95% C.L. as function of Br(LQ$\rightarrow \mu$ q)

in Table III.

In conclusion, we have performed a search for pair production of scalar leptoquarks in the dimuons + jets and muon, missing energy + jets topolgies, using 198 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the TeVatron. We combined these findings with the ones from a search in the $\not\!\!E_T$ + jets topology[5]. No evidence for leptoquarks is observed. Assuming that a leptoquark decays to muon and quark with variable branching ratio β we exclude leptoquarks with masses below 226 GeV/c^2 for $\beta = 1$, 208 GeV/c^2 for $\beta = 0.5$ and 143 GeV/c^2 for $\beta = 0.1$

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