Search for Charge 1/3 Third Generation Leptoquarks in $p\bar{p}$ Collisions at $\sqrt{s}$ =1.8 TeV

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We report on a search for charge 1/3 third generation leptoquarks (LQ) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at Fermilab. Third generation leptoquarks are assumed to be produced in pairs and to decay to a tau neutrino and a b quark with branching fraction B. We place upper limits on $\sigma(p\bar{p} \to LQ\ \overline{LQ}) \cdot B^2$ as a function of the leptoquark mass M_{LQ}. Assuming $B = 1$, we exclude at the 95% confidence level third generation scalar leptoquarks with $M_{LQ} < 94$ GeV/c^2, and third generation vector leptoquarks with $M_{LQ} < 216$ GeV/c^2 ($M_{LQ} < 148$ GeV/c^2) assuming Yang-Mills (anomalous) coupling.

Leptoquarks (LQ) are bosons predicted in many extensions to the standard model [1]. They carry both lepton and color quantum numbers, couple to leptons and quarks, and decay via $LQ \rightarrow l + q$. To satisfy experimental constraints on flavor changing neutral currents, leptoquarks of mass accessible to current collider experiments are constrained to couple to only one generation of leptons and quarks [2]. Therefore, only leptoquarks which couple within a single generation are considered here.

This Letter reports the results of a search for charge 1/3 third generation leptoquarks produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We assume that leptoquarks are produced in pairs by QCD processes such as $p\bar{p} \rightarrow g \rightarrow LQ\ \overline{LQ} + X$. This process dominates over other production mechanisms which depend on the unknown leptoquark-lepton-quark coupling λ under the standard condition $\lambda \leq \sqrt{4\pi\alpha_{EM}}$. We search for the decay signature where both leptoquarks decay via $LQ \rightarrow \nu_\tau + b$ resulting in a $\nu_\tau\bar{\nu}_\tau b\bar{b}$ final state. For a leptoquark mass (M_{LQ}) smaller than the mass of the top quark (m_t), the decay $LQ \rightarrow \tau + t$ is forbidden, and the branching fraction for the $\nu_\tau b$ mode, B, is unity [3]. For $M_{LQ} > m_t$, phase space factors suppress τt decays relative to the $\nu_\tau b$ channel. In this paper we give limits on the pair production cross section times B^2 ($\sigma \cdot B^2$) for M_{LQ} between 50 GeV/c^2 and 300 GeV/c^2. Limits on the cross section are used to set limits on the third generation leptoquark mass for scalar and vector leptoquarks. Previous limits from the LEP e^+e^- collider exclude all third generation leptoquarks with masses below 45 GeV/c^2 [4], while the CDF Collaboration has set limits for pair produced charge 2/3 or 4/3 third generation leptoquarks decaying via $LQ \rightarrow \tau + b$ [5].

The data used for this analysis were collected by the DØ detector [6] operating at the Fermilab Tevatron Collider during the 1993–1996 period. The DØ detector is composed of three major systems: an inner detector for tracking charged particles, a uranium/liquid argon calorimeter for measuring electromagnetic and hadronic showers, and a muon spectrometer consisting of a magnetized iron toroid and three layers of drift tubes. The detector measures jets with an energy resolution of approximately $\sigma/E = 0.8/\sqrt{E}$ (E in GeV) and muons with a momentum resolution of $\sigma/p = [(\frac{0.18(p-2)}{p})^2 + (0.003p)^2]^{1/2}$ (p in GeV/c). Missing transverse energy ($\not\!\!E_T$) is determined by summing the calorimeter and muon transverse energies, and is measured with a resolution of $\sigma = 1.08$ GeV + $0.019 \cdot (\Sigma|E_T|)$ (E_T in GeV).

The decay of a b quark is indicated by the presence of a muon associated with a jet. We use three triggers to collect candidate leptoquark events, each requiring one or two muons [7]. A dimuon trigger required two muons with transverse momentum $p_T^\mu > 3.0$ GeV/c. One single muon trigger required a muon with $p_T^\mu > 1.0$ GeV/c and a jet with $E_T^j > 10$ GeV. The other single muon trigger required a muon with $p_T^\mu > 10$ GeV/c in the trigger and $p_T^\mu > 15$ GeV/c during offline analysis, and a jet with $E_T^j > 15$ GeV. Integrated luminosities of 60.1 pb^{-1}, 19.5 pb^{-1}, and 92.4 pb^{-1} respectively were collected using these three triggers.

The offline analysis uses muons in the pseudorapidity range $|\eta_\mu| < 1.0$ with $p_T^\mu > 3.5$ GeV/c. The muon trajectories are required to be consistent with the reconstructed vertex position and have associated energy in the calorimeter. For events from either single muon trigger additional requirements are imposed: the presence of hits in all three muon detector layers, a matching track in the central detector, and a good fit [8] when these elements are combined. For the dimuon trigger events, at least one of the two muons must satisfy each of these additional requirements. Jets are reconstructed using only calorimeter energy with a cone algorithm of radius $R = 0.7$ where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ about the jet's centroid and ϕ is the azimuthal angle. Each jet is required to have $E_T^j > 10$ GeV and to satisfy reconstruction quality criteria [9]. For the dimuon trigger, events with dimuon invariant mass greater than 8 GeV/c^2 are selected to eliminate backgrounds from low mass resonances and each muon must be associated with a different jet with $\Delta R_{\mu-jet} < 0.5$ to increase b quark purity [10]. For the single muon triggers, we require a jet associated with the muon with the same ΔR requirement plus an additional jet with $E_T^j > 25$ GeV and $|\eta_j| < 1.5$.

We use $\not\!\!E_T$ to identify neutrinos. To help eliminate events with poorly measured $\not\!\!E_T$, we reject events where the azimuthal angular separation, $\Delta\phi$, between the missing energy and the nearest jet is less than 0.7 radians. In some events, the source of the measured $\not\!\!E_T$ is not mismeasured jets, but rather noise in individual calorimeter cells or from cells activated by the background generated by the Main Ring accelerator, which passes through the calorimeter. Such events are removed if the vector sum of the transverse energies in the jets and muons is consistent with zero.

Data from the two single muon triggers with large $\not\!\!E_T$ have contributions from $W+ \geq 2$ jet events where $W \rightarrow \mu\nu$ and the muon overlaps a jet. We use two variables, Z_μ and F_μ, for events passing those triggers to reduce the W boson acceptance. We define $Z_\mu \equiv p_T^\mu / H_T^{\mu j}$, where $H_T^{\mu j}$ is the scalar sum of the E_T of the jets and muons in the event. In Fig. 1 we compare the Z_μ distributions of data events that pass the low-p_T single muon trigger to Monte Carlo (MC) samples [11] satisfying a simulation of the trigger. There, for illustrative purposes, we select events with $\not\!\!E_T > 30$ GeV and $\Delta\phi > 0.6$ so that the data shown have roughly equal contributions from W boson and hadronic multijet events. Also shown are MC distributions of equal numbers of multijet events (which are b quark-dominated due to their muon content) and

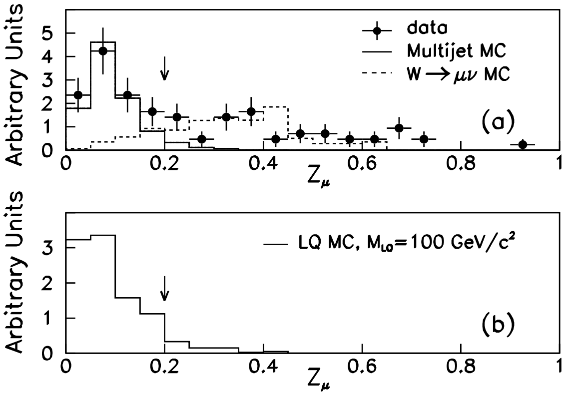

FIG. 1. The Z_μ distribution for events with $\not\!\!E_T > 30$ GeV and $\Delta\phi > 0.6$ from (a) data compared to MC events from multiple jet (solid) and $W \to \mu\nu$ (dashed) processes and (b) leptoquark events with $M_{LQ} = 100$ GeV/c^2. The arrow indicates the requirement $Z_\mu < 0.20$ used in this analysis.

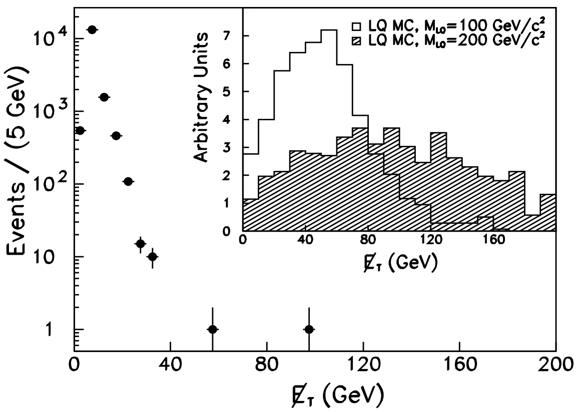

FIG. 2. The distributions of $\not\!\!E_T$ for data events after all other selection requirements have been applied. Shown in the insert are $\not\!\!E_T$ distributions for MC leptoquark events with leptoquark mass of 100 GeV/c^2 and 200 GeV/c^2.

TABLE I. Third generation scalar leptoquark acceptances for the three trigger channels and 95% C.L. limits on $\sigma \cdot B^2$ for different M_{LQ}.

	Acceptance ($\times 10^{-3}$)			
LQ mass (GeV/c^2)	dimuon	one muon low-p_T	one muon high-p_T	$\sigma \cdot B^2$ limit (pb)
50	0.04	0.95	0.14	144
60	0.08	2.4	0.35	59
80	0.29	6.0	0.93	22.6
100	0.40	9.7	1.9	12.7
125	0.59	14	2.8	8.9
150	1.2	18	3.2	7.0
200	1.3	24	3.1	6.0
250	1.9	27	3.7	5.1
300	1.8	31	2.2	5.4

$W \to \mu\nu$ events. The data (normalized to the total number of MC events) are consistent with the sum of these sources. Also shown is the same distribution for a leptoquark MC sample with $M_{LQ} = 100$ GeV/c^2 satisfying the same criteria. Since the leptoquark Z_μ distribution is determined by b quark decay kinematics, it is similar to the multijet distribution. Requiring $Z_\mu < 0.20$ eliminates about 90% of the remaining $W \to \mu\nu$ background while maintaining a signal efficiency of 82% for $M_{LQ} = 100$ GeV/c^2. The second variable, F_μ, is the ratio of calorimeter energy within a cone of 0.4 centered on the muon's direction to that within a cone of 0.6: $F_\mu \equiv E(R_\mu \leq 0.4)/E(R_\mu \leq 0.6)$. Most hadronic energy in higher E_T direct b quark decays is spatially close to the muon. Requiring $F_\mu > 0.80$ removes about 84% of the $W \to \mu\nu$ background with a leptoquark signal efficiency of 82%. MC studies indicate that Z_μ and F_μ have little correlation.

The data from the high-p_T muon trigger include a significant contribution from top quark pair production ($t\bar{t}$) events. The scalar sum of jet E_T, H_T^j, was used to identify the top quark in Ref. [12]. In this analysis, we require $H_T^{\mu j} < 240$ GeV for those events satisfying the high-p_T single muon trigger to reduce the $t\bar{t}$ contribution. Similarly, since the low-p_T single muon trigger has a larger contribution from multijet events, we reject events with six or more jets ($E_T^j > 10$ GeV) for that trigger.

The resulting $\not\!\!E_T$ distribution for data from all three triggers after all selection criteria have been applied is given in Fig. 2. Also shown are the $\not\!\!E_T$ distributions for MC events with $M_{LQ} = 100$ and 200 GeV/c^2. Requiring $\not\!\!E_T > 35$ GeV leaves two events.

We consider background contributions from $t\bar{t}$, intermediate vector boson, and multijet production of $b\bar{b}$ and $c\bar{c}$. Top quark events have multiple b quarks and $\not\!\!E_T$, but with additional, energetic jets. We use MC and our measured $t\bar{t}$ production cross section [13] to estimate that there are 1.4 ± 0.5 $t\bar{t}$ events in our sample. Intermediate vector boson events have $\not\!\!E_T$ from $W \to l\nu$ or $Z \to \nu\bar{\nu}$ and muons near jets mimicking b quark decays when either a prompt muon overlaps a jet or a jet fragments into a muon via c quark or a π/K decay. Using our measured W and Z boson production cross sections [14] yields 1.0 ± 0.4 W boson events and 0.1 ± 0.1 Z boson events in this sample. Hadronically-produced $b\bar{b}$ and $c\bar{c}$ events do not have energetic neutrinos and are effectively eliminated by the $\not\!\!E_T$ and $\Delta\phi$ cuts. Estimates of their contribution using data and MC are consistent with zero, and we conservatively assume this in our limit calculation. Therefore, the total background is estimated to be 2.5 ± 0.6 events.

We calculate the detection efficiency for scalar leptoquark signals using MC acceptances multiplied by muon trigger and reconstruction efficiencies obtained from data samples collected using test triggers. The acceptances for

TABLE II. Summary of systematic errors in terms of % error on the acceptance.

Channel	dimuon	one muon low-p_T	one muon high-p_T
trigger	6.5	5.1	5.1
reconstruction	5.1	5.7	4.2
muon momentum resolution	1	1	10
jet energy scale	4	4	2
F_μ cut	NA	10	6
$b \to \mu$ fraction	12	6	6

different leptoquark masses are summarized in Table I. The use of a muon to tag b quark decays limits the acceptance to values under 3.5%. Factors contributing to this limited acceptance for the low-p_T single muon channel with $M_{LQ} = 100$ GeV/c^2 include the muon branching fraction (0.35), muon and jet kinematic requirements (0.35), and muon trigger and reconstruction efficiency (0.25). The requirements used to reduce the background ($\not{E}_T$, $\Delta\phi$, Z_μ, F_μ) retain $\approx 40\%$ of the leptoquark signal.

We combine the three trigger channels to set limits. Errors on the acceptance are shown in Table II. Errors on trigger and reconstruction efficiencies are due to the statistical errors of the data used to calculate their values. Muon momentum resolution and jet energy scale errors are obtained from data and their impact on the acceptance is determined using MC with $M_{LQ} = 100$ GeV/c^2. The error on the F_μ cut efficiency is estimated by comparing data events without $\not{E}_T$ requirements to MC multijet events. The three trigger channels have different systematic errors since their selection criteria and average muon p_T differ, but most errors are correlated. The total systematic error, including correlations and MC statistics, on the combined acceptance varies between 12.5% and 13.6% for different leptoquark masses.

The 95% confidence level (C.L.) upper limits on $\sigma \cdot B^2$ include the systematic acceptance uncertainty and a 5.3% uncertainty in the integrated luminosity. The resulting upper limits for scalar leptoquark pair production as a function of leptoquark mass are given in Table I and shown in Fig. 3. Also shown in Fig. 3 are theoretical cross sections for the production of scalar and vector leptoquarks. The calculation of the scalar leptoquark cross section includes next-to-leading order diagrams and uses CTEQ4M parton distribution functions [15]. The theory band shown in the figure is determined using a renormalization factor of $\mu = M_{LQ}$ for the central value and $\mu = 2M_{LQ}$ and $M_{LQ}/2$ for the lower and upper bounds, respectively. The intersection of our limit curve with the lower edge of the theory band is at 94 GeV/c^2. This is our 95% C.L. lower limit on the mass of a charge 1/3 third generation scalar leptoquark (taking $B = 1$ since $M_{LQ} < m_t$).

Similarly, we set limits for the mass of vector leptoquarks [16]. The vector leptoquark cross section has been calculated in the leading order approximation using CTEQ4M parton distribution functions and $\mu = M_{LQ}$ [17]. Vector leptoquarks are assumed to be either fundamental gauge bosons with Yang-Mills coupling or composite particles with anomalous coupling. For Yang-Mills type coupling, a mass limit of 216 GeV/c^2 is obtained for $B = 1$. If $M_{LQ} > m_t$ the τt mode is allowed. We consider the case in which the branching fraction to $\nu_\tau b$ and τt each would be 0.5 if the fermion masses could be neglected relative to M_{LQ}. Taking into account phase space suppression factors [18], we determine that $M_{LQ} > 209$ GeV/c^2 for Yang-Mills type vector leptoquarks for this $B < 1$ case. For anomalous coupling, we choose the coupling which yields the minimum pair production cross section. The intersection of our limit on $\sigma \cdot B^2$ with the theory curve gives $M_{LQ} > 148$ GeV/c^2 for minimal anomalous vector coupling.

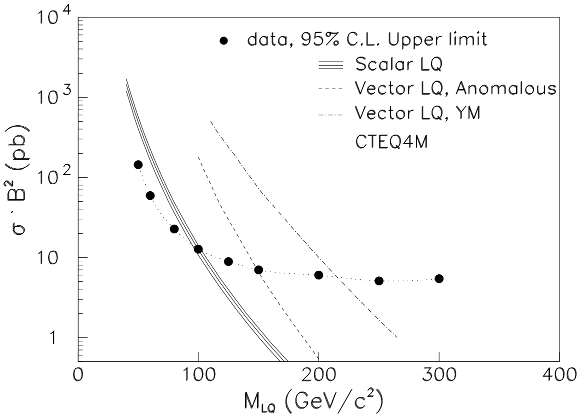

FIG. 3. The 95% C.L. limit on $\sigma \cdot B^2$ (●) compared to theoretical predictions. The prediction for scalar leptoquarks (solid) use $\mu = 2M_{LQ}$, M_{LQ} and $M_{LQ}/2$, while vector leptoquarks with minimal anomalous (dashed) or Yang-Mills (dot-dashed) coupling use $\mu = M_{LQ}$.

In conclusion, we observe two events consistent with the final state $\nu\bar{\nu}b\bar{b}$ compared to an expected 2.5 ± 0.6 events from $t\bar{t}$ and W and Z boson production. We set limits on the mass of a charge 1/3 scalar or vector leptoquark. This result is independent of the coupling strength of a leptoquark to a third generation lepton and quark.

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