Search for Second Generation Leptoquark Pairs Decaying to $\mu + \text{jets}$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for second generation leptoquarks (LQ) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at Fermilab. Second generation leptoquarks are assumed to be produced in pairs and to decay to either $\mu$ or $\nu$ and either a strange or a charm quark ($q$). Limits are placed on $\sigma(p\bar{p} \rightarrow LQ \rightarrow \mu \nu + \text{jets})$ as a function of the mass of the leptoquark. For equal branching ratios to $\mu q$ and $\nu q$, second generation scalar leptoquarks with a mass below 160 GeV/$c^2$, vector leptoquarks with anomalous minimal vector coupling s with a mass below 240 GeV/$c^2$, and vector leptoquarks with Yang-Mills couplings with a mass below 290 GeV/$c^2$, are excluded at the 95% confidence level.
Leptoquarks (LQ) are hypothetical particles that carry color, fractional electric charge, and both lepton and baryon number. They appear in several extended gauge theories and composite models beyond the standard model [3]. Leptoquarks with universal couplings to all lepton flavors would give rise to flavor-changing neutral currents, and are therefore tightly constrained by experimental data [4]. To satisfy experimental constraints on flavor-changing neutral currents, leptoquarks that couple only to second generation leptons and quarks are considered.

This Letter reports on a search for second generation leptoquark pairs produced in $p\bar{p}$ interactions at a center-of-mass energy $\sqrt{s} = 1.8$ TeV. They are assumed to be produced dominantly via the strong interaction, $p\bar{p} \to g + X \to LQ\bar{LQ} + X$. The search is conducted for the signature where one of the leptoquarks decays via $LQ \to$ muon + quark and the other via $LQ \to$ neutrino + quark, where the quark may be either a strange or a charm quark. The corresponding experimental cross section is $2\beta(1-\beta) \times \sigma(p\bar{p} \to LQ\bar{LQ})$ with $\beta$ the unknown branching fraction to a charged lepton ($e, \mu, \tau$) and a quark ($j$) and $(1-\beta)$ the branching fraction to a neutrino ($\nu$) and a jet. The search considers leptoquarks with scalar or vector couplings in the $\mu + j$ final state. Additional details on this analysis may be found in reference [3].

The DØ detector consists of three major components: 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. Jets are measured in the calorimeters and are reconstructed using a cone algorithm with a radius $R = 0.5$ ($R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$). Jets must be produced within $|\eta| < 2.0$, and have $E_T > 15$ GeV; with the most energetic jet in each event required to have $|\eta| < 1.5$.

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The transverse energy of the neutrino is not directly measured, but is inferred from the energy imbalance in the calorimeters and the momentum of the reconstructed muon. Events are required to have missing transverse energy $E_T > 30$ GeV. To ensure that $E_T$ is not dominated by mismeasurement of the muon $p_T$, events having $E_T$ within $\pi \pm 0.1$ radians of the muon track in azimuth are rejected.

To provide further rejection against dimuon events in which one of the muons was not identified in the spectrometer, muons are identified by a pattern of isolated energy deposited in the longitudinal segments of the hadronic calorimeter. Any event where such deposited energy lies along a track originating from the interaction vertex in the region $|\eta| < 1.7$ and is within 0.25 radians in azimuth of the direction of the $E_T$ vector is rejected.

Each candidate event is required to pass a selection based on the expected LQ event topology. Since the decay products of the LQ are $\mu\bar{\nu}$ or $\nu\bar{\nu}$, the muon and neutrino in LQ pair decays come from different parent particles nearly at rest and are therefore uncorrelated. For the primary background events (e.g. $W + j$ets), the two leptons have the same parent. Similar reasoning holds for the jets. Correlated backgrounds are rejected with the requirement of significant separation between the muon and $E_T$ ($|\Delta\phi(\mu, E_T)| > 0.3$) and between the two leading jets ($|\Delta R(j_1, j_2)| > 1.4$).

The SIAJET [4] Monte Carlo event generator is used to simulate the scalar leptoquark ($S_{LQ}$) signal, and PYTHIA [11] is used for the vector leptoquark ($V_{LQ}$) signal. The efficiencies for $V_{LQ}$ and $S_{LQ}$ are consistent within differences due to the choice of generator. This is verified by choosing a test point at which both scalar and vector Monte Carlo events from the same generator are compared. Therefore, efficiencies obtained from the two simulations are not distinguished. In addition, the efficiencies for vector leptoquarks are insensitive to differences between minimal vector ($\kappa = 1; \lambda = 0$) and Yang–Mills ($\kappa = 0; \lambda = 0$) couplings at large mass ($M_{V_{LQ}} > 200$ GeV/$c^2$). The leptoquark production cross sections used for the $S_{LQ}$ are from next-to-leading order (NLO) calculations [13] with a renormalization scale $\mu = M_{S_{LQ}}$ and uncertainties determined from variation of the renormalization/factorization scales from $2M_{S_{LQ}}$ to $\frac{1}{2}M_{S_{LQ}}$. The $V_{LQ}$ cross sections are leading order (LO) calculations at a scale $\mu = M_{V_{LQ}}$ [12].
The dominant backgrounds, from $W + jets$ and $Z + jets$, are simulated using VECTBOS \cite{14} for parton level generation and HERWIG \cite{15} for parton fragmentation. Background due to $WW$ production is simulated with PYTHIA \cite{16}. Additional background from $t\bar{t}$ decays into one or more muons and two or more jets, is simulated using the HERWIG Monte Carlo program for a top quark mass of 170 GeV/$c^2$. Monte Carlo samples are processed through a detector simulation program based on the GEANT \cite{17} package.

With the initial data selection described above, there are 107 events, consistent with a background of 106±30 events (see Fig. 1). The dominant background is $W + jets$ with 100±30 events. Other backgrounds are 2.7±0.7 ($Z + jets$), 2.4±0.8 $t\bar{t}$, and 1.5±0.6 ($WW$). The uncertainty in the background is dominated by the statistical uncertainty in the $W + jets$ simulation and the systematic uncertainty in the $W + jets$ cross section. The expected signal for 160 GeV/$c^2$ scalar leptoquarks is 4.8±0.7 events. Signal estimations are shown for a $S_{LQ}$ mass of 160 GeV/$c^2$ using the NLO cross section with a scale of 2$M_{LQ}$.

To separate any possible signal from the backgrounds, a neural network (NN) \cite{18} with inputs: $E_T^{\mu}$, $E_T^{\tau}$, $p_T^{\mu}$ and $E_T$, and nine nodes in a single hidden layer is used. The network is trained on a mixture of $W + jets$, $Z + jets$ and $t\bar{t}$ background Monte Carlo events, and an independently generated signal Monte Carlo sample at a mass of 160 GeV/$c^2$. Figure 1 shows distributions of the four input quantities and Fig. 2 the network output (referred to as the discriminant, $D_{NN}$). No evidence of a signal is observed in either the discriminant distribution or any of the kinematic distributions. For setting limits, the selection on $D_{NN}$ is optimized by maximizing a measure of sensitivity \cite{19} defined by

$$S(D_{NN}) = \sum_{k=0}^{n} P(k, b) M_{A}^{95\%}(k, b, s(M_{LQ}))$$

where $P(k, b) = e^{-b} b^k / k!$ is a Poisson coefficient with $k$ being any possible number of observable events, $b$ the expected mean number of background events, and $s(M_{LQ})$ the expected signal for a given leptoquark mass. $M_{A}^{95\%}$ is an approximate \cite{20} mass limit at the 95% confidence level for a given $k$, $s$ and $b$. $S(D_{NN})$ is the sum of the approximate mass limits, weighted by the probability of observing $k = 0, 1, 2, \ldots, n(P(n, b) < 0.05)$ events for a particular choice of the $D_{NN}$ selection criterion.

By maximizing the value of $S(D_{NN})$ a discriminant selection of $D_{NN} > 0.9$ is obtained. With this selection, no events remain in the data, which is consistent with an expected background of 0.7±0.9 events. The remaining background is dominated by $t\bar{t}$ (0.6±0.2 events). The uncertainty on the total background is dominated by the statistical and systematic uncertainties from $W + jets$.

Table I shows the signal detection efficiencies and upper limits \cite{21} on the cross section at the 95% confidence level as a function of the leptoquark mass. The dominant systematic uncertainty on the signal efficiency is due to the simulation, (initial and final state radiation, parton distribution function, renormalization scale, choice of generator) with a 10% uncertainty. The systematic uncertainties shown include approximately equal contributions from uncertainty in the jet energy scale \cite{22} and
the trigger efficiency/spectrometer resolution for high $p_T$ muons (6.6% and 6.4% respectively). The overall systematic uncertainty for the signal efficiency is 15%.

The limits on the observed cross section are shown in Fig. 3, and are compared with the theoretical cross section times branching ratio for scalar and vector leptoquark production for $\beta = \frac{1}{2}$. Mass limits of 160 GeV/$c^2$ for scalar leptoquarks and 290 (240) GeV/$c^2$ for vector leptoquarks with Yang-Mills (minimal vector) couplings, are obtained at the 95% confidence level.

In conclusion, we have performed a search for second generation leptoquarks in the $\mu + jets$ decay channel using $94 \pm 5$ pb$^{-1}$ of data collected with the DØ detector at the Fermilab Tevatron. No evidence for a signal is seen and limits are set at the 95% confidence level on the mass of second generation leptoquarks. For equal branching fractions to $\mu q$ and $\nu q$ ($\beta = \frac{1}{2}$) limits of 160 GeV/$c^2$, 240 GeV/$c^2$, and 290 GeV/$c^2$ for $S_{LQ}$, minimal vector, and Yang-Mills vector couplings, respectively, are obtained.

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\begin{table}
\begin{tabular}{|c|c|c|c|c|}
\hline
$S_{LQ}$ Mass (GeV/$c^2$) & $\sigma_{25}\%$ & $\sigma_{S_{LQ}}$ & $\sigma_{MV}$ & $\sigma_{Y_{LM}}$ \\
\hline
100 & 3.7$\pm$0.2$\pm$0.6 & 0.94 & 2.8 & 53 & 430 \\
120 & 5.0$\pm$0.2$\pm$0.7 & 0.72 & 2.2 & 23 & 150 \\
140 & 7.2$\pm$0.3$\pm$1.1 & 0.47 & 0.75 & 10 & 50 \\
160 & 10.3$\pm$0.3$\pm$1.5 & 0.33 & 0.34 & 4.0 & 25 \\
180 & 12.2$\pm$0.3$\pm$1.8 & 0.27 & 0.16 & 2.0 & 10 \\
200 & 13.4$\pm$0.3$\pm$2.0 & 0.25 & 0.08 & 1.0 & 5.0 \\
220 & 14.1$\pm$0.3$\pm$2.1 & 0.24 & 0.04 & 0.45 & 2.5 \\
240 & 15.2$\pm$0.3$\pm$2.3 & 0.23 & 0.02 & 0.23 & 1.3 \\
260 & 15.5$\pm$0.3$\pm$2.3 & 0.22 & 0.01 & 0.13 & 0.60 \\
280 & 16.3$\pm$0.4$\pm$2.4 & 0.21 & 0.06 & 0.30 \\
300 & 15.7$\pm$0.4$\pm$2.3 & 0.22 & 0.03 & 0.18 \\
350 & 16.4$\pm$0.4$\pm$2.4 & 0.21 & 0.03 \\
400 & 17.2$\pm$0.4$\pm$2.6 & 0.20 \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Cross section limits in the $\mu + jets$ channel. The $V_{LQ}$ cross sections are leading order,[12] calculated at a scale $\mu = M_{S_{LQ}}$. The $S_{LQ}$ cross sections are next-to-leading order,[13]. The calculation is done at a renormalization scale $\mu = M_{S_{LQ}}$ with uncertainties obtained from variation of the renormalization/factorization scale from $M_{S_{LQ}}$ to $\frac{1}{3}M_{S_{LQ}}$. For the $S_{LQ}$ the limit is obtained at the intersection of the experimental curve with the theoretical curve for $\mu = 2M_{S_{LQ}}$.}
\end{figure}

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[19] The approximation used in $M^A_{95\%}$ is that uncertainties are not included. The difference between $S(0.9)$ calculated using $M^A_{95\%}$ and $S(0.9)$ using an exact calculation is approximately 1%.

[20] Limits are calculated using a Bayesian approach with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on the efficiencies, the integrated luminosity, and the background estimation are included in the calculation (assuming Gaussian prior distributions).

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