Second Generation Leptoquark Search

in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We report on a search for second generation leptoquarks with the DØ detector at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV. This search is based on $12.7 \text{ pb}^{-1}$ of data. Second generation leptoquarks are assumed to be produced in pairs and to decay into a muon and quark with branching ratio $\beta$ or to neutrino and quark with branching ratio $(1 - \beta)$. We obtain cross section times branching ratio limits as a function of leptoquark mass and set a lower limit on the leptoquark mass of 111 GeV/c$^2$ for $\beta = 1$ and 89 GeV/c$^2$ for $\beta = 0.5$ at the 95% confidence level.

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Leptoquarks are bosons predicted in many extensions of the Standard Model (SM). They carry both lepton and color quantum numbers and couple to leptons and quarks. In order to satisfy experimental constraints on flavor changing neutral currents and rare pion decays, leptoquarks are required to be left or right handed and couple to only one generation of leptons and quarks. These constraints are required unless leptoquarks are considerably more massive than particles the current Tevatron run can produce.

This paper reports the results of a search for second generation scalar leptoquarks. We assume leptoquarks are produced in pairs by QCD processes. At the Tevatron these QCD processes dominate other production mechanisms which depend on the leptoquark–lepton–quark coupling. Second generation leptoquarks are assumed to decay with branching ratio $\beta$ to a muon and quark and with branching ratio $(1 - \beta)$ to a neutrino and quark. There are three decay signatures for pair produced second generation leptoquarks: two muons plus at least two jets, one muon plus missing transverse energy ($E_T$) and at least two jets, or $E_T$ plus two or more jets. The muons, $E_T$, and jets are expected to be well separated which distinguishes pair produced leptoquarks from $c$-quark and $b$-quark production, and leptoquarks are distinct from $W$ and $Z$ boson backgrounds due the presence of at least two energetic jets. This report gives results for limits on cross section times $\beta^2$ for the dimuon signature and cross section times $2\beta(1 - \beta)$ for the single muon signature. These cross section limits are used to set limits on the second generation leptoquark mass. The data used for this analysis were taken during the Tevatron run between August 1992 and May 1993 and represent an integrated luminosity of 12.7 pb$^{-1}$.

Previous limits from LEP experiments exclude leptoquark masses below 45 GeV/$c^2$. Results from DØ and CDF on first generation scalar leptoquarks have been published. The DØ limits for first generation leptoquarks are 133 GeV/$c^2$ and 120 GeV/$c^2$ for $\beta = 1.0$ and 0.5, and the CDF limits are 113 GeV/$c^2$ and 80 GeV/$c^2$ for $\beta = 1.0$ and 0.5. Experiments at HERA give limits on the mass of first generation leptoquarks where their limits depend on the unknown but constrained leptoquark–electron–quark coupling which they have generally assumed to be at the strength of the electro–weak coupling.
The DØ detector, described in detail elsewhere [8], is composed of three major systems: an inner detector (without a magnetic field) for tracking charged particles within a pseudo-rapidity range $|\eta| < 3.5$, a calorimeter for measuring electromagnetic and hadronic showers within the range $|\eta| < 4.0$, and a muon spectrometer covering the range $|\eta| < 3.3$. The calorimeter has fine segmentation in both $\eta$ and azimuth, $\phi$, and measures electrons with a resolution of $15\%/\sqrt{E}$ and hadrons with a resolution of about $50\%/\sqrt{E}$. Muons are identified and their momentum, $p$, measured with three layers of proportional drift tubes, one before (coming from the interaction region) and two after the magnetized iron toroids. The muon momentum resolution is $\sigma(1/p) = 0.18(p - 2)/p^2 \oplus 0.008$ (with $p$ in GeV/c).

Muons are required to have an impact parameter consistent with coming from the interaction region and to have $|\eta| < 1.7$. Cosmic ray muons are removed by requiring that there are no tracks or pattern of hits back-to-back in $\eta$ and $\phi$. Muons are required to be well isolated to reduce backgrounds from heavy quark production by first requiring that there be no jet with transverse energy ($E_T$) greater than 20 GeV within an angle of 0.7 radians of the muon and, secondly, that the expected deposited energy along the muon track in the calorimeter is not more than about three times that expected from a minimum ionizing particle (about 3 GeV from a MIP for the DØ calorimeter). A further set of requirements is defined for high quality muon identification. This includes requiring energy deposition in the calorimeter consistent with a minimum ionizing particle and a matching track in the tracking chamber. The muon must hit all three layers of the muon system and have timing consistent with originating from the beam crossing. Finally, the muon must traverse a minimum field integral of 1.83 T·m of the toroid magnet.

Jets are measured in the calorimeter. They are defined by a cone algorithm with $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.7$. Jets are corrected for calorimeter response, underlying event, and out-of-cone leakage effects. These corrections amount to about 25% and vary with jet energy and $\eta$. Jets are accepted within $|\eta| < 3.5$.

The $E_T$, representing the transverse energy carried by the neutrino in the single muon signature, is required to be isolated from the jets in $\phi$ by 0.3 radians. Also, the magnitude
of the angular separation in $\phi$ of the muon and $E_T$ cannot be greater than $\pi - 0.2$. These cuts ensure that the $E_T$ is not an artifact of either fluctuations in the jet energy or the muon resolution.

For the search in the single muon channel, the events in the data sample are required to pass a trigger with a muon transverse momentum ($p_T$) threshold of 8 GeV/c and a jet $E_T$ threshold of 15 GeV. Offline, one high quality muon with $p_T > 20$ GeV/c and $|\eta| < 1.0$ is required. The $E_T$ is required to be greater than 25 GeV. Having applied these kinematic cuts and requiring the two leading jets to have $E_T > 10$ GeV, Fig. 1 shows the transverse mass ($M_T$) of ($E_T + \mu$) versus the absolute difference between the $\phi$ of the $E_T$ and the muon for three event samples: $W$ boson plus jets Monte Carlo, single muon leptoquark Monte Carlo with a mass of 100 GeV/c$^2$, and the data. The two vertical lines indicate the region removed by the muon-$E_T$ back-to-back $\phi$ cut, and the horizontal line indicates a $M_T$ cut where we require that leptoquark candidates have $M_T$ greater than 95 GeV/c$^2$. Since we expect two high $E_T$ jets from leptoquarks, the $E_T$ requirement on the jets is raised to 25 GeV. These jets are also required to have an electromagnetic energy fraction greater than 0.2 to reduce the backgrounds from large jet energy fluctuations or calorimeter noise which may not be correlated with the $E_T$. No candidates remain after the jet $E_T$ cut.

For the single muon signature, the expected backgrounds come from $W$ boson plus jets production, leptonic decays of $b\bar{b}$ pairs, Drell-Yan dimuon plus jets production where one muon is missing, and the decay of $W$ and $Z$ bosons into heavy quarks with semileptonic decays. The number of expected background events for the single muon signature is given in Table 1 for a few values of the $M_T$ cut. The background estimates reasonably account for the data.

For the dimuon signature selection, the candidate events are required to pass the same trigger as the single muon events. In the offline selection for the dimuon sample, both muons are required to be isolated and to have a $p_T$ greater than 25 GeV/c. At least one muon is required to pass the high quality cuts, and at least one is required to have $|\eta| < 1.0$. These cuts leave 15 events in the dimuon sample. For the leptoquark signature, we require
that our candidate events have at least two jets with $E_T$ greater than 25 GeV. This jet cut significantly reduces the Drell-Yan sources of background for this signature. With this last cut no candidate events are left.

The main sources of background for the dimuon signature are Drell-Yan dimuons plus jets and leptonic decays of $b\bar{b}$ pairs. Background estimates are made for different kinematic cuts. In Table II, the background estimates for 15, 20, and 25 GeV cuts on the muons and jets in the dimuon sample are shown with the actual number of events seen. The estimated backgrounds reasonably account for the data.

The efficiencies of the cuts used in the selection for the two signatures are determined from a study of Monte Carlo generated and collider events. The geometric acceptance and kinematic efficiency are taken from leptoquark signal Monte Carlo generated by ISAJET \[9\] and processed with a DØ version of the GEANT \[10\] detector simulator, a simulation of the DØ trigger, and DØ’s standard reconstruction program. The efficiencies for muon identification are determined from the data; they amount to about 21% for the dimuon selection and 32% for the single muon selection. The trigger efficiencies calculated from a study of both the data and the Monte Carlo are $86.2 \pm 0.82\%$ for the dimuon signature and $66.6 \pm 1.6\%$ for the single muon signature. For the dimuon signature, the total efficiency ranges from 0.35% to 8.7% for leptoquark masses between 45 and 200 GeV/$c^2$. For the single muon signature the total efficiency ranges from 0.14% to 5.12% for the same mass range. The relative uncertainty on the total efficiency is 20% for the dimuon signature and 10% for the single muon signature. This uncertainty on the efficiency is dominated by the statistics of the $Z \rightarrow \mu^+\mu^-$ data sample used to calculate the efficiency of the muon quality cuts. The systematic uncertainties vary from 27% to 9% for the dimuon channel for leptoquark masses ranging from 45 to 200 GeV/$c^2$. These systematic uncertainties arise from a 10% jet energy scale uncertainty and a 10% and 25% uncertainty in the first and second terms of the muon $p_T$ resolution. For the single muon signature the systematic uncertainties vary from 16% to 12% for the same mass range. For both signatures the dominant systematic effect comes from the uncertainty in the muon $p_T$ resolution.
The 95% confidence level (CL) limit on cross section times branching ratio factor $\beta^2$ as a function of leptoquark mass for the dimuon signature is given in Fig. 2. This cross section limit takes into account the uncertainty in the integrated luminosity times acceptance \cite{11} taken as the sum in quadrature of the above uncertainties including a 5.4% systematic uncertainty in the integrated luminosity. Also plotted in Fig. 2 is $\beta^2$ times the theoretical cross section based on ISAJET \cite{12} using the Morfin and Tung leading order (MT-LO) parton distribution functions (pdf) \cite{13} for $\beta = 1$. The intersection of these two curves at a leptoquark mass of 111 GeV/c$^2$ gives the 95% CL lower limit on the mass of a second generation leptoquark for $\beta = 1$. The 95% CL lower limit on cross section times branching ratio factor $2\beta(1 - \beta)$ as a function of leptoquark mass for the single muon signature is given in Fig. 3. For $\beta = 0.5$, the single muon limit is 54 GeV/c$^2$.

In Fig. 4 we show the $\beta$ versus mass excluded region for the dimuon signature as the area covered by the diagonal lines. The area covered by the solid shading is the region excluded for the single muon signature. By combining the acceptance for the single muon and dimuon signatures, we exclude the additional region indicated by the cross hatched area. The combined mass limit for $\beta = 0.5$ is 89 GeV/c$^2$. The LEP limit of 45 GeV/c$^2$ is also given in Fig. 4. Our limit extends to a branching fraction of $\beta = 0.17$ at the LEP mass limit. CDF \cite{14}, based on the dimuon channel only, has also set limits on the mass of second generation leptoquarks of 131 and 96 GeV/c$^2$ for $\beta = 1.0$ and 0.5. The mass limits depend somewhat on the choice of pdf, momentum transfer scale (we have assumed $Q^2 = \hat{s}$ for this analysis), and higher order effects \cite{15} which we have chosen not to include. Using the same theoretical cross section and choice of pdf (CTEQ2pM) as quoted by CDF in Ref. \cite{14}, our combined mass limits become 119 and 97 GeV/c$^2$ for $\beta = 1.0$ and 0.5. Using this theoretical cross section we can exclude, compared to CDF, additional $\beta$ vs mass space starting at $\beta = 0.5$ and extending down to $\beta = 0.17$ at the LEP limit.

In conclusion we observe no events from second generation leptoquarks. We have set limits on the mass as a function of $\beta$ for the pair production of second generation leptoquarks where the cross section for their production is independent of the coupling strength of the
leptoquark to a second generation lepton and quark.

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TABLE I. The number of single muon events is given in this table as a function of $M_T$ (GeV/c$^2$) cut. All other cuts are kept the same as given in the text. Also given is the number of events expected from $W \rightarrow \mu\nu$ plus jets, $b\bar{b}$, $Z \rightarrow \mu^+\mu^-$ plus jets where one muon is missing, $W \rightarrow c\bar{s}$ plus jets and the total expected backgrounds. Note that the uncertainty in the $Z$ background is 100%.

| $M_T$ (GeV) | $W$ (events) | $b\bar{b}$ (events) | $Z$ (events) | $W \rightarrow c\bar{s}$ (events) | Total bkgd. (events) | # events |
|------------|--------------|----------------------|--------------|-----------------------------------|---------------------|----------|
| 95         | 1.4±0.3      | 0.5±0.2              | 0.10         | 0.37±0.37                         | 2.4±1.0             | 0        |
| 85         | 2.2±0.5      | 1.0±0.3              | 0.13         | 0.37±0.37                         | 3.7±1.3             | 3        |
| 75         | 3.3±0.8      | 1.4±0.5              | 0.17         | 0.74±0.54                         | 5.6±2.0             | 5        |

TABLE II. Estimates of background contributions to the dimuon sample from Drell-Yan $\mu^+\mu^-$ with jets (including $Z \rightarrow \mu^+\mu^-$) and leptonic $b\bar{b}$ decays for the indicated threshold cuts on both the two muons and two jets. Also given is the number of dimuon plus jets events surviving these threshold cuts.

| $\mu$ $p_T$, jet $E_T$ (GeV) | Drell-Yan (events) | $b\bar{b}$ (events) | # events |
|-----------------------------|---------------------|----------------------|----------|
| 25                          | 1.8±0.7             | 0.05±0.02            | 0        |
| 20                          | 3.4±1.0             | 0.23±0.11            | 3        |
| 15                          | 9.9±2.1             | 0.77±0.38            | 12       |
FIG. 1. $M_T$ versus the absolute difference in $\phi$ between the muon and $E_T$ for (a) a $W \rightarrow \mu \nu$ plus jets Monte Carlo sample, (b) a 100 GeV/c$^2$ mass second generation leptoquark Monte Carlo sample, and (c) for a data sample obtained by the single muon signature selection with 10 GeV jets. The horizontal and vertical lines show cuts used in the analysis (see text for details). The number of events in (a), (b), and (c) are not normalized to the same integrated luminosity.
FIG. 2. The 95% CL upper limit obtained by DØ on the cross section times $\beta^2$ for the dimuon signature, as a function of the leptoquark mass. Also shown is the ISAJET prediction times $\beta^2$ for $\beta=1.0$. 

Experimental upper limit on cross section at 95% CL

Theoretical Cross Section $\times \beta^2$; $\beta=1.0$
FIG. 3. The 95% CL upper limit on the cross section times $2\beta(1-\beta)$ for the single muon signature, as a function of the leptoquark mass. Also shown is the ISAJET prediction times $2\beta(1-\beta)$ for $\beta=0.5$. 
FIG. 4. The 95% CL excluded regions for the dimuon, single muon, and combined signatures.