

Second Generation Leptoquark Search in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for second generation scalar leptoquarks with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV. This search is based on 12.7 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 β or into a neutrino and quark with branching ratio $1 - \beta$. We obtain cross section times branching ratio limits as a function of leptoquark mass and set lower limits on the leptoquark mass at the 95% confidence level.

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Leptoquarks are bosons predicted [1] 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 [2]. These constraints are required unless leptoquarks are considerably more massive [3] than particles the current Fermilab 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 Fermilab Tevatron these processes dominate other production mechanisms which depend on the leptoquark-lepton-quark coupling. Second generation leptoquarks are assumed to decay with branching ratio β 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 (\cancel{E}_T) and at least two jets, or \cancel{E}_T plus two or more jets. This Letter gives results for limits on cross section times β^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 Fermilab 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 $45 \text{ GeV}/c^2$ [4]. Results from D0 and CDF on first generation scalar leptoquarks have been published [5]. The D0 limits for first generation leptoquarks are 133 and $120 \text{ GeV}/c^2$ for $\beta = 1.0$ and 0.5 , and the CDF limits are 113 and $80 \text{ GeV}/c^2$ for $\beta = 1.0$ and 0.5 . Experiments at HERA [6] give limits on the mass of first generation leptoquarks, where their limits depend on the unknown but constrained [7] leptoquark-electron-quark coupling, which they have generally assumed to be at the strength of the electroweak coupling.

The D0 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 pseudorapidity 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 η and azimuth ϕ 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 η and ϕ . Muons are required to

be well isolated from jets to reduce backgrounds from heavy quark production. A further set of requirements is defined for high quality muon identification. This includes requiring a track consistent with a minimum ionizing particle in the calorimeter and 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 η . Jets are accepted within $|\eta| < 3.5$.

The \cancel{E}_T , representing the transverse energy carried by the neutrino in the single muon signature, is required to be isolated from the jets in ϕ by 0.3 rad . Also, the magnitude of the angular separation in ϕ of the muon and \cancel{E}_T cannot be greater than $\pi - 0.2$. These cuts ensure that the \cancel{E}_T is not an artifact of either fluctuations in the jet energy or the muon resolution. The efficiency for the muon- \cancel{E}_T angle cut for single muon leptoquarks is $(82 \pm 1)\%$ and $(73 \pm 2)\%$ for a W boson plus jet events.

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 $8 \text{ GeV}/c$ and a jet E_T threshold of 15 GeV . Offline, one high quality muon with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 1.0$ is required. The \cancel{E}_T is required to be greater than 25 GeV . The leptoquark signal is enhanced relative to the major physics background (W boson plus jets) by requiring two good jets with $E_T > 25 \text{ GeV}$ and a transverse mass (M_T) of the $\cancel{E}_T + \text{muon} > 95 \text{ GeV}/c^2$. No candidate events are left after these cuts.

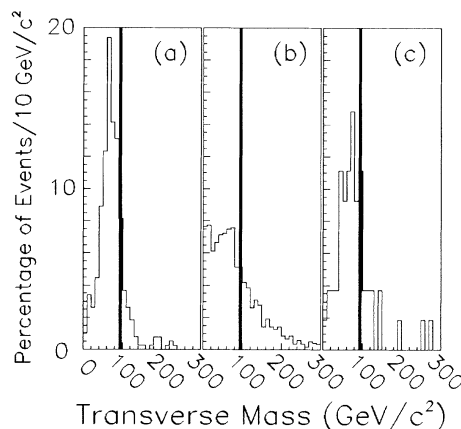


FIG. 1. M_T distributions for (a) a $W \rightarrow \mu\nu$ plus jets Monte Carlo sample, (b) a $100 \text{ GeV}/c^2$ mass second generation leptoquark Monte Carlo sample, and (c) for a data sample obtained by the single muon signature selection with 15 GeV jets. The vertical line shows the M_T cut used in the analysis (see text for details).

TABLE I. The number of single muon events as a function of the 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, $b\bar{b}$, $W \rightarrow cs \rightarrow u$ plus jets, and the total expected backgrounds. The total efficiency for the 100 GeV/c^2 mass leptoquark signal is also given.

M_T	W	$b\bar{b}$	$W \rightarrow cs$	Total bgd.	No. events	ϵ_{LQ}
95	1.4 ± 0.3	0.5 ± 0.2	0.37 ± 0.37	2.4 ± 1.0	0	2.1%
85	2.2 ± 0.5	1.0 ± 0.3	0.37 ± 0.37	3.7 ± 1.3	3	2.4%
75	3.3 ± 0.8	1.4 ± 0.5	0.74 ± 0.54	5.6 ± 2.0	5	2.8%

Figure 1 shows the M_T distribution 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 single muon data. The jet threshold has been dropped to 15 GeV for increased statistics. The vertical line indicates the M_T cut of 95 GeV/c^2 . The fraction of the Monte Carlo W boson sample in Fig. 1(a) surviving the M_T cut is $(16.5 \pm 1.9)\%$ compared to $(34.7 \pm 1.4)\%$ for the leptoquark signal sample shown in Fig. 1(b). The data distribution in Fig. 1(c) is given for a qualitative comparison.

With the 25 GeV cuts on the jets, the effect of varying the transverse mass cut is shown in Table I, which gives the number of expected backgrounds, the actual number of surviving events, and the total efficiency for a 100 GeV/c^2 mass leptoquark signal. 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. Not given in the table, but added in the total, is the number of Drell-Yan dimuon plus jets backgrounds which range between 0.10 to 0.17 event with errors equal to the estimates. 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

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 the two jets. Also given is the number of dimuon plus jets events surviving these threshold cuts along with the detection efficiency for a 100 GeV/c^2 mass leptoquark signal.

jet, μ p_T (GeV)	$b\bar{b}$	Drell-Yan	No. events	ϵ_{LQ}
25	0.05 ± 0.02	1.8 ± 0.7	0	4.8%
20	0.23 ± 0.11	3.4 ± 1.0	3	6.5%
15	0.77 ± 0.38	9.9 ± 2.1	12	8.2%

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 total efficiency for the detection of a 100 GeV/c^2 mass dimuon leptoquark signal is also given. 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 D0 version of the GEANT [10] detector simulator, a simulation of the D0 trigger, and D0's standard reconstruction program. 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 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 (C.L.) upper limit on cross section times branching ratio factor β^2 as a function of leptoquark mass for the dimuon signature is given in Fig. 2(a) as the solid line. This cross section limit takes into account [11] the statistical and systematic uncertainties including a 5.4% systematic uncertainty in the integrated luminosity. The dashed line in Fig. 2(a) is β^2 times the theoretical cross section based on ISAJET [12] using the Morfin and Tung leading order (MT-LO) parton distribution func-

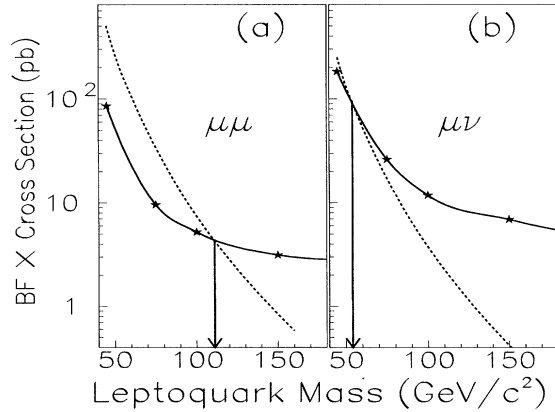


FIG. 2. The 95% C.L. upper limit (solid line) on the cross section as a function of the leptoquark mass for (a) the dimuon signature and (b) the single muon signature. "BF" is the branching ratio factor: β^2 for the dimuon signature and $2\beta(1 - \beta)$ for the single muon signature. Also shown is the theoretical prediction (dashed line).

tions (PDF) [13] for $\beta = 1$. The intersection of these two curves at a leptoquark mass of $111 \text{ GeV}/c^2$ gives the 95% C.L. lower limit on the mass of a second generation leptoquark for $\beta = 1$. The 95% C.L. 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. 2(b) as the solid line. Plotted as the dashed curve is $2\beta(1 - \beta)$ times the theoretical cross section for $\beta = 0.5$. The single muon limit is $54 \text{ GeV}/c^2$.

In Fig. 3 we show the β 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, weighted appropriately by branching fraction, we exclude the additional region indicated by the cross hatched area. The combined mass limit for $\beta = 0.5$ is $89 \text{ GeV}/c^2$. The LEP limit of $45 \text{ GeV}/c^2$ is also given in Fig. 3. Our limit extends to a branching fraction of $\beta = 0.17$ at the LEP mass limit. CDF [14], based on the dimuon channel only, has also set limits on the mass of second generation leptoquarks of 131 and $96 \text{ GeV}/c^2$ for $\beta = 1.0$ and 0.5 using the cross sections from ISAJET v7.06 with CTEQ2pM PDF's. As a direct comparison, we have recomputed our mass limits with the cross sections used by CDF, and we obtain combined mass limits of 119 and $97 \text{ GeV}/c^2$ for $\beta = 1.0$ and 0.5 . This limit is plotted in Fig. 3 as the dashed line. Using this theoretical cross section, we can exclude, compared to CDF, additional β versus mass space starting at $\beta = 0.5$ and extending down to $\beta = 0.16$ at the LEP limit.

More generally, our mass limits change $3.5 \text{ GeV}/c^2$ in the vicinity of $110 \text{ GeV}/c^2$ for every 10% change in the cross section. The variation in the cross section due to choice of PDF's is as large as 20%. Factors of four in the Q^2 scale change the cross section by about 30%. Higher

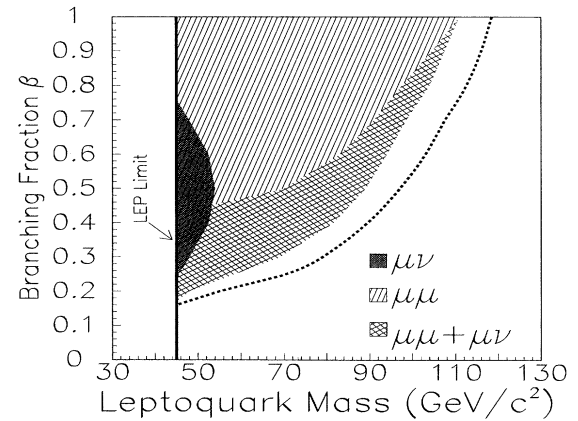


FIG. 3. The 95% C.L. excluded regions for the dimuon, single muon, and combined signatures. The dashed line is the combined limit using cross sections from ISAJET v7.06 with CTEQ2pM from Ref. [14].

order corrections [15] can have about a 10% effect in the $110 \text{ GeV}/c^2$ mass region.

In conclusion, we observe no events from second generation leptoquarks. We have set limits on the mass as a function of β 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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