Fermi National Accelerator Laboratory

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Abstract

We present the results of a search for second generation leptoquarks, $\mathcal{S}_2$, using 19.3 pb^{-1} of data collected at the Collider Detector at Fermilab (CDF) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during the 1992–93 collider run. We have searched for $\mathcal{S}_2\bar{\mathcal{S}}_2$ pairs assuming that each leptoquark decays to a muon+quark with a branching ratio β. We find two candidate events, consistent with an expected background of 1.11 ± 0.48. We obtain upper limits on $\sigma(p\bar{p} \rightarrow \mathcal{S}_2\bar{\mathcal{S}}_2) \times \beta^2$ as a function of $M_{\mathcal{S}_2}$. Using a Monte Carlo prediction for $\mathcal{S}_2\bar{\mathcal{S}}_2$ pair production, we exclude $M_{\mathcal{S}_2} < 131$ GeV/c^2 for $\beta = 1$ and $M_{\mathcal{S}_2} < 96$ GeV/c^2 for $\beta = 0.5$ at 95% CL.

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Leptoquarks are hypothetical color-triplet bosons appearing in many extensions of the standard model [1]. Leptoquarks carry both baryon and lepton quantum numbers, $\pm 1/3$ and ± 1, respectively. Other quantum numbers (e.g., spin, weak isospin, and electric charge Q) are model dependent. In this search we will limit ourselves to scalar leptoquarks of charge $Q = 2/3$ and $-1/3$. A leptoquark decays directly to a quark–lepton pair of the corresponding generation [2]. It is assumed that there are the same number of generations of leptoquarks as of lepton and quark generations.

In this study we search for second generation scalar leptoquarks, $\mathcal{S}_2$, produced in pairs in $p\bar{p}$ collisions. A leptoquark $\mathcal{S}_2$ is assumed to decay to a μq pair with branching ratio β, or to a $\nu_\mu q$ pair with branching ratio $1-\beta$. The quark q must be a second generation quark, and its identity depends on the $\mathcal{S}_2$ charge assignment. There is no previously published limit on the mass of $\mathcal{S}_2$ produced in $p\bar{p}$ collisions. Searches at LEP exclude $M_{\mathcal{S}_2}$, below 44.5 GeV/c^2 at 95% CL for $\mathcal{S}_2\bar{\mathcal{S}}_2$ pair production, independent of β [3], and exclude $M_{\mathcal{S}_2}$ below 73 GeV/c^2 for single $\mathcal{S}_2$ production, assuming that $\beta = 2/3$, charge $-1/3$ and $k = 1$ [4], where k is the Yukawa coupling strength of the quark–lepton–leptoquark vertex expressed in terms of electromagnetic coupling, $g^2/4\pi = k\alpha_{\rm em}$. The limit for single $\mathcal{S}_2$ production will be about 10 GeV/c^2 lower if they use $k = 0.5$ [4], and the studies on FCNC bounds [5,6] show that k should be on the order of 0.1 at the Tevatron energy.

In $p\bar{p}$ collisions, scalar leptoquark pairs would be produced predominantly through $O(\alpha_s^2)$ processes, $q\bar{q}$ annihilation and gluon-gluon fusion. The contributions of k-dependent subprocesses to the $\mathcal{S}_2\bar{\mathcal{S}}_2$ pair production cross-section are negligible [2], and the pair production is expected to dominate the $\mathcal{S}_2$ production in $p\bar{p}$ collisions [2,7]. In our search for $\mathcal{S}_2\bar{\mathcal{S}}_2$ pairs, we choose the decay mode where both leptoquarks decay into μq, thus we look for events with the signature of two oppositely charged muons and two jets. The production rate of this mode is proportional to β^2. This analysis is based on 19.3 ± 0.7 pb^{-1} of data collected with the Collider Detector at Fermilab (CDF) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during the 1992–93 run.

The CDF detector has been described in detail elsewhere [8]. We give only a brief description of the components relevant to this analysis. The momenta of charged particles are measured in the central tracking chamber, which is surrounded by a 1.4 T superconducting solenoidal magnet. Outside the magnet, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, cover the pseudorapidity region $|\eta| < 4.2$ [9]. The calorimeters are used to identify jets, and the part of the calorimeters in the region $|\eta| < 1.2$ is also used to identify muons. Outside the calorimeters, muon drift chambers in the region $|\eta| < 1.0$ provide muon identification. A three-level trigger selects the inclusive muon events used in this analysis [8].

To select second generation leptoquark candidate events in the dimuon+dijet channel, at least one of the muons is required to be identified by muon chambers within $|\eta| < 0.6$, and to be isolated [8]. The second muon can be a minimum ionizing particle identified by calorimeters within $|\eta| < 1.2$ [8]. Both muons are required to have $p_T > 20$ GeV/c and to have opposite charge. After these cuts, 480 dimuon events remain in the sample. Fig. 1(a) shows the dimuon invariant mass distribution of these events. We further require that the azimuthal angle between the two muons be smaller than 160° to reduce Drell-Yan background. Two jets are required to have $E_T > 20$ GeV and to be in the region of $|\eta| < 3.5$. After these cuts, 7 events are left as shown in Fig. 1(b). To remove background from Z boson production, we reject events with dimuon invariant masses, $M_{\mu\mu}$, in the range of $75 < M_{\mu\mu} < 105$ GeV/c^2 [10]. Five events are consistent with Z boson production.

After removal of the Z candidates, two events remain in the sample. Schematic views in the transverse plane of those events are shown in Fig. 2. Leptoquarks in this figure represent the muon and jet combinations with the smaller difference between the reconstructed leptoquark masses. The reconstructed leptoquark masses are 50.5 GeV/c^2 and 92.2 GeV/c^2 for the first candidate event, and 68.0 GeV/c^2 and 66.2 GeV/c^2 for the second. The resolution of the muon+jet mass reconstructed from Monte Carlo data is about 13 GeV/c^2 for 100 GeV/c^2 leptoquarks. The dimuon invariant masses of the two candidate events are 18.9 GeV/c^2 and 57.9 GeV/c^2, well below the lower Z mass cut.

To determine the signal detection efficiencies, we used the ISAJET [11] Monte Carlo program with CTEQ2pM structure function [12], followed by a CDF detector simulation. Table I shows the overall detection efficiency, $\varepsilon_{\rm LQ}$ (typically, 11.9% for $M_{S_2} = 120$ GeV/c^2), the total fractional systematic uncertainty in the overall detection efficiency, $\delta_{\rm total}$ (14.1% for $M_{S_2} = 120$ GeV/c^2), as a function of leptoquark mass. Table I also includes the uncertainties dominating at low leptoquark mass — the uncertainty due to the limited understanding of gluon radiation, $\delta_{\rm gluon}$, the uncertainty due to the Q^2 scale (factor 4 and 1/4), δ_{Q^2}, and the uncertainty due to the jet energy scale (10%), $\delta_{\rm jet}$. Other uncertainties in the detection efficiency come from the structure function choice (1.2% for $M_{S_2} = 120$ GeV/c^2), Monte Carlo statistics (1.4% for $M_{S_2} = 120$ GeV/c^2), and detector simulation (6%). The uncertainty in the luminosity measurement (3.6%) is also included in the total systematic uncertainty.

Any physical process producing two high p_T muons and two jets with large E_T is a potential source of false leptoquark signatures. The main contributions come from the Drell-Yan production of muon pairs with two jets events (0.73 ± 0.37) and $t\bar{t}$ production in the dimuon channel (0.21 ± 0.09) [13]. Other backgrounds are $Z \rightarrow \tau^+\tau^-$ (0.12 ± 0.03) and hadrons misidentified as muons (0.05 ± 0.04). The backgrounds due to $b\bar{b}$ and WW are negligible. The total expected background is 1.11 ± 0.48 events.

We calculate the 95% confidence level (CL) limits on $\sigma(p\bar{p} \rightarrow S_2\bar{S}_2) \times \beta^2$, including the estimated background and systematic uncertainties [14,15]. The results are shown in Fig. 3 with a theoretical prediction for $\beta = 1$. The prediction is based on ISAJET generation of second generation scalar leptoquarks with its default QCD parameter and scale settings, and with CTEQ2pM structure function [12]. In Fig. 4, we show the limits on the second generation scalar leptoquark mass as a function of β at 95% CL. The 95% CL lower mass limit for $\beta = 1$ is 131 GeV/c^2, and the lower limit for $\beta = 0.5$ is 96 GeV/c^2. These limits are independent of the value of the unknown coupling factor k. The predicted cross-sections and thus the mass limits depend on the choice of the structure functions, the inclusion of the next-to-leading order corrections such as the so-called K-factor [16] and the choice of the Q^2 scale. We find no significant difference in the mass limits derived from the cross-sections calculated using CTEQ2pM [12] and MRS(A) [17] structure functions. The K-factor correction to the cross-section for leptoquark pair production ranges from 1.23 at $M_{S_2} = 40$ GeV/c^2 to 0.987 at $M_{S_2} = 200$ GeV/c^2. With this correction, the mass limits would be 132 GeV/c^2 for $\beta = 1$ and 98 GeV/c^2 for $\beta = 0.5$. If we vary the default Q^2 setting of ISAJET by factors 4 and 1/4, the mass limits become 123 GeV/c^2 for $\beta = 1$ and 89 GeV/c^2 for $\beta = 0.5$, and 139 GeV/c^2 for $\beta = 1$ and 102 GeV/c^2 for $\beta = 0.5$, respectively.

In conclusion, in searches for $S_2\bar{S}_2$ production, we observe two candidate events consistent with the total expected background of 1.11 ± 0.48 events. We set 95% CL lower limits on the mass of a second generation scalar leptoquark of 131 GeV/c^2 for $\beta = 1$ and 96 GeV/c^2 for $\beta = 0.5$, independent of k factor.

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[9] In the CDF coordinate system, θ is the polar angle with respect to the proton beam direction. The pseudorapidity, η, is defined as $-\ln\tan\frac{\theta}{2}$. The transverse momentum of a particle is $p_T = p\sin\theta$. If it is obtained using the calorimeter energy, it becomes the transverse energy, E_T.

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TABLES

TABLE I. Summary of second generation leptoquark acceptance and fractional systematic uncertainties in the acceptance.

$M_{\mathcal{S}_2}$ (GeV/c^2)	40	60	80	100	120	140	160	180	200
$\varepsilon_{\rm LQ}$ (%)	0.8	4.0	7.5	10.2	11.9	13.8	14.8	15.7	16.2
$\delta_{\rm total}$ (%)	69.9	24.8	19.3	16.2	14.1	11.5	10.9	10.1	9.7
$\delta_{\rm gluon}$ (%)	40.1	14.3	12.4	10.2	10.6	7.2	7.5	6.3	5.9
δ_{Q^2} (%)	52.8	12.7	10.5	9.2	4.6	4.3	1.7	2.2	1.3
$\delta_{\rm jet}$ (%)	20.3	13.2	7.2	4.7	3.9	3.1	2.9	2.5	2.4

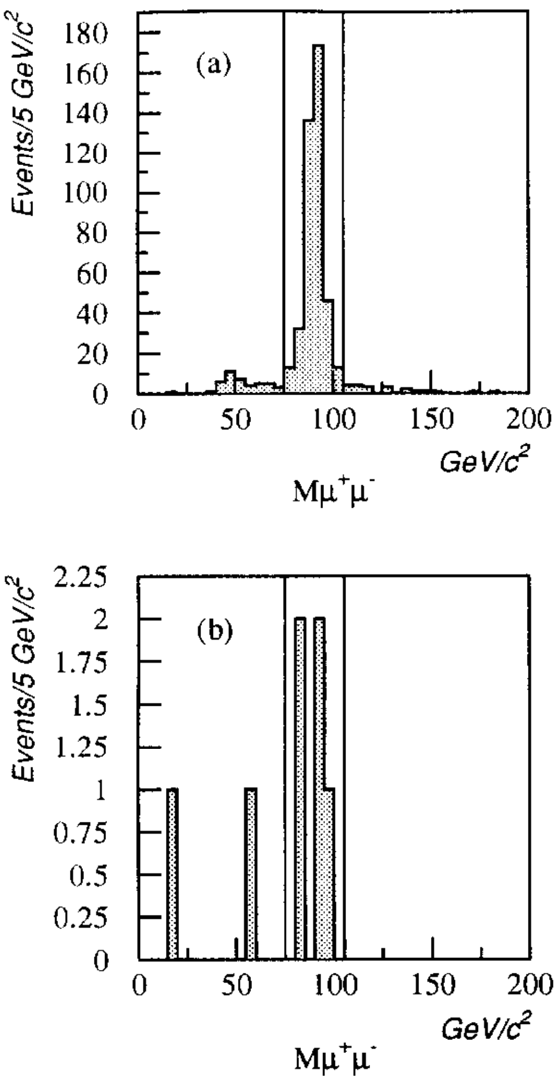

FIG. 1. Dimuon invariant mass distributions. Vertical lines indicate Z mass window. (a) Muon identification, p_T and opposite charge cuts are applied. (b) Two jet and angle cuts are applied as well as the cuts for (a).

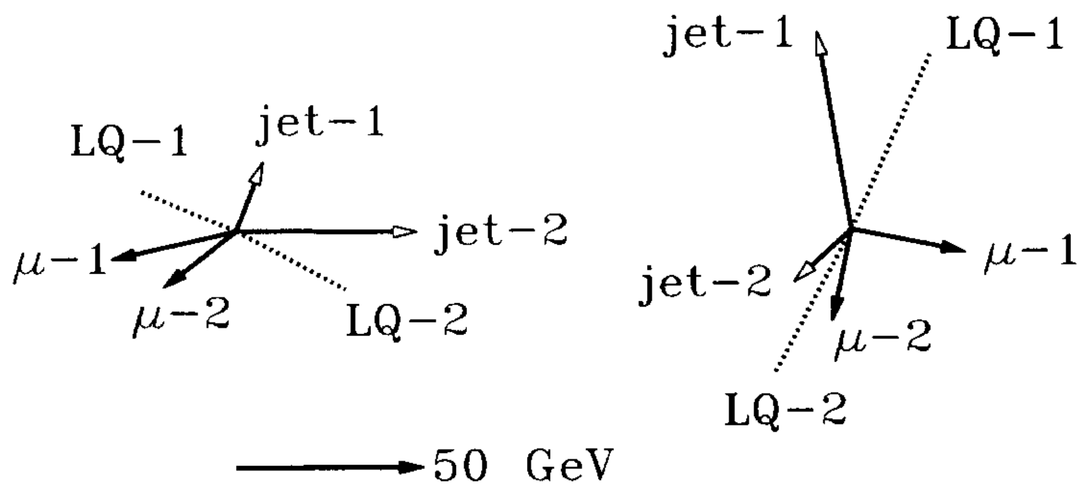

FIG. 2. Display of kinematics of two candidate events. The lines show momentum vectors of the decay particles in a view transverse to the beam. The length of a vector is proportional to the momentum of a particle. A 50 GeV/c vector line is shown at the bottom to set the scale.

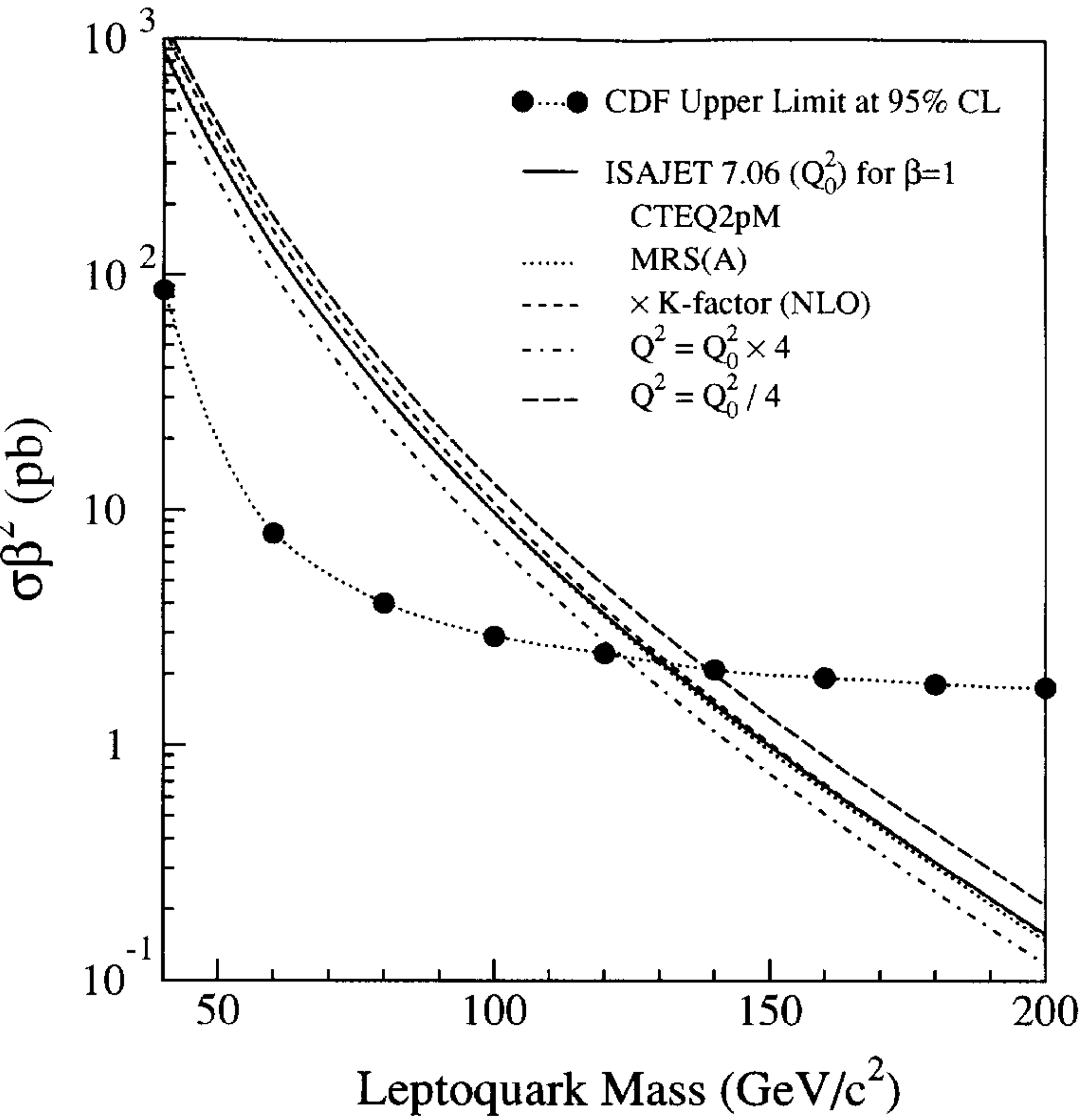

FIG. 3. 95% CL upper limits on $\sigma(p\bar{p} \rightarrow S_2\bar{S}_2) \times \beta^2$ for the signature of two muons plus two jets as a function of leptoquark mass. The theoretical cross-section prediction shown as a solid curve is derived using ISAJET with the CTEQ2pM structure function and $\beta = 1$. The dot curve is for the MRS(A) structure function, and the short dash curve for the higher order K-factor correction. The dot-dash and long dash curves are for the Q^2 change by the factors 4 and 1/4, respectively.

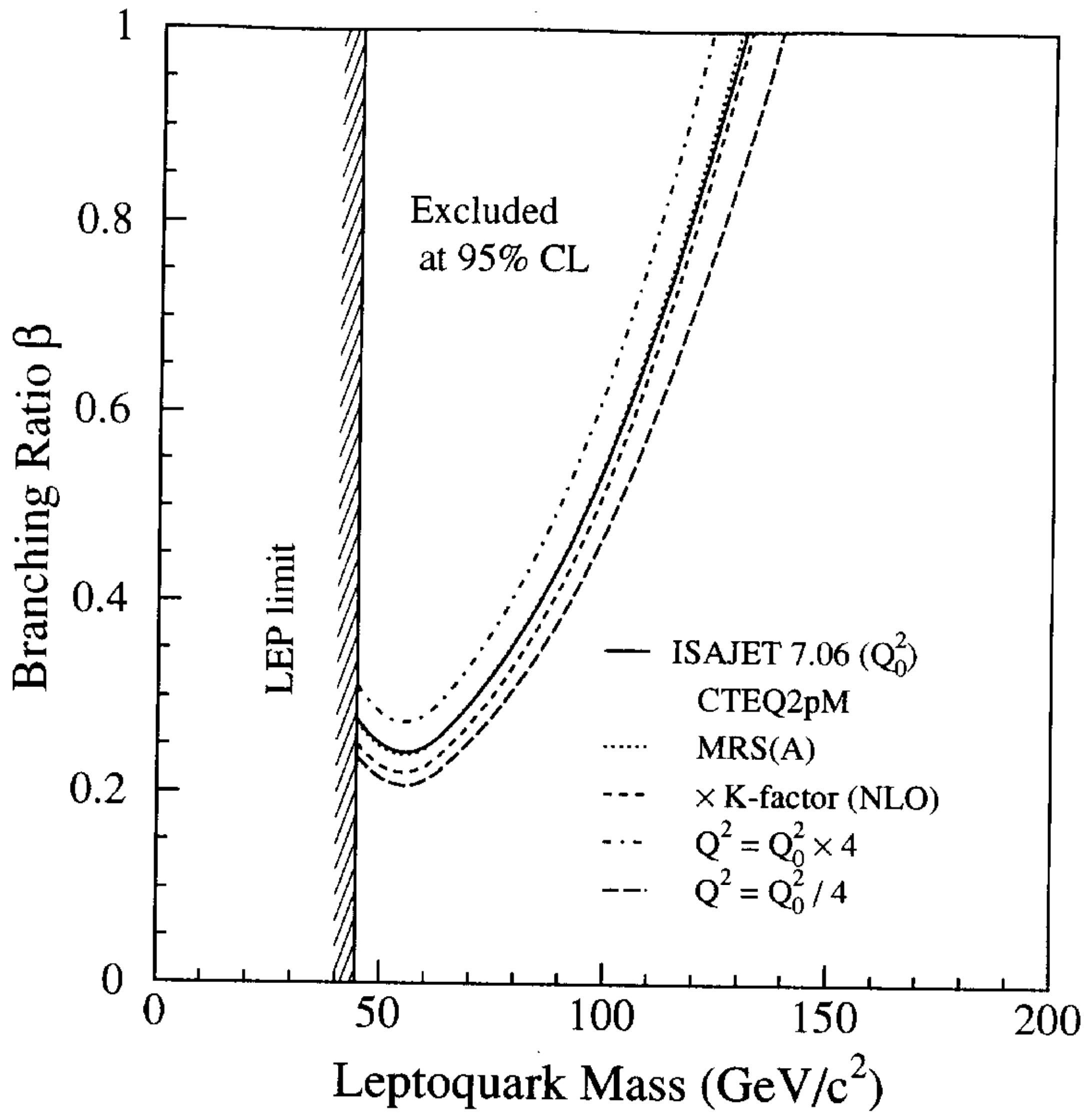

FIG. 4. 95% CL lower limits on β as a function of second generation leptoquark mass. The limits are derived using the theoretical predictions in Fig. 3.