Searches for Leptoquarks at Tevatron

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Abstract. We present recent results of searches for leptoquarks with the DØ and CDF detectors at Tevatron. Leptoquarks are exotic bosons which would mediate lepton-quark interactions as predicted in multiple extensions of the Standard Model, among which supersymmetry. The DØ and CDF detectors have recorded about 5 fb$^{-1}$ of proton-antiproton collisions delivered by the Fermilab Tevatron collider. Operating at 1.96 TeV, the Tevatron remains at the energy frontier and is one of the best device to test theories beyond the Standard Model. A summary of the latest searches for leptoquarks with the DØ and CDF experiments is presented in this talk, corresponding to an integrated luminosity from 1 to 2.5 fb$^{-1}$.

1. Introduction
The Standard Model (SM) is believed to be a low-energy approximation of a more general underlying theory. Several possible signatures of new physics could show up in few fb$^{-1}$ of Tevatron data. SUSY is of course a popular candidate, but has not yet been discovered. Nevertheless, there is a rather high probability for a variety of new physics (many non-SUSY) to be at the reach of the Tevatron experiments. Many of these extensions of the SM predict lepton-quark interactions, which would be mediated by leptoquarks. In this article, we will focus on most recent results, obtained with a luminosity of 1 fb$^{-1}$ or more.

2. Phenomenological aspects of Leptoquarks
2.1. General aspects
Leptoquarks (LQs) are predicted by numerous extensions of the SM which connect the quark and lepton sectors [1] such as GUTs, compositeness, RPVing SUSY or extended Technicolor. LQs are color-triplet bosons which carry non-zero lepton L and baryon B numbers [2], a fractional electrical charge (Q=1/3, 2/3, 4/3, 5/3) and a spin 0 (scalar particles) or 1 (vectors). For scalar LQs, Lagrangian and production cross section only depend on the LQ mass and on the center-of-mass collision energy; but for vector LQs, they also depend on anomalous couplings [3].
Leptoquarks couple directly to leptons (either charged $l^{\pm}$ or neutral $\nu$) and quarks, via a Yukawa coupling $\lambda$. They may be dominantly produced in pairs at colliders through SM gauge couplings (dominated by $\alpha_s$: $q\bar{q}$ annihilation, gluon fusion), or singly through Yukawa $l$-$q$-LQ couplings. At Tevatron (and later at LHC), we focus on LQ pair productions. Fig. 1 represents the dominant Feynman diagram (at the leading order LO) for the production of pairs of LQs with a mass greater than 100 GeV/$c^2$ at Tevatron.

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2.2. Experimental considerations

Three generations of LQs are predicted, each one coupling with the fermions from the corresponding generation. Cross-generational couplings are not excluded in theory, but experimentally strongly suppressed (corresponding to flavor changing neutral currents scenarios). As a consequence, we will consider generational couplings only.

Are also excluded the quark-quark-LQ or lepton-lepton-LQ interactions, because in such cases, the proton decay could be allowed. Since there are two decay modes, depending on the charge of the lepton, and for the pair-produced LQs, arise three types of analysis channels: \( LQ LQ \rightarrow l\ell q\bar{q}, LQ LQ \rightarrow l\nu q\bar{q} \) and \( LQ LQ \rightarrow \nu\nu q\bar{q} \). The first two channels benefit from the visible energy of the charged leptons in the detector, and the analysis performance relies on the reconstruction of the isolated deposits in the calorimeters. While in absence of charged leptons, variables such as the topology of events with jets and missing transverse energy in the final state can be preferred in such analyses.

If \( \beta \) denotes the total branching ratio of the LQ into a charged lepton and a quark \( \beta = Br(LQ \rightarrow lq) \), we express the total cross section times branching ratio of the LQs decay in the three channels as:

\[
\sigma \times Br(l^+l^-q\bar{q}) = \beta^2, \quad \sigma \times Br(\nu\nu q\bar{q}) = (1 - \beta)^2, \quad \sigma \times Br(l^+\nu q\bar{q}) = 2\beta(1 - \beta)
\]

3. The DØ and CDF detectors at Tevatron

The Tevatron is the proton-antiproton collider of the Fermi National Accelerator Laboratory, situated near Chicago. It is today the world’s most powerful particle accelerator, with a center-of-mass energy \( \sqrt{s} = 1.96 \) TeV. Associated to its good performances are the DØ and CDF detectors, of which the data taking efficiency is close to 100%.

The DØ and CDF experiments present a usual concentric constitution of multipurpose detectors. The DØ detector \([4]\) comprises three principal elements: a central tracking volume with a silicon microstrip vertex detector and a scintillating fiber tracker located within a 2 T superconducting solenoidal magnet, a uranium/liquid-argon calorimeter, and a surrounding muon system, made of tracking chambers and scintillators before and after toroidal magnets.

The CDF detector \([5]\) components relevant to the Leptoquark searches are a charged particle tracking subdetector, located inside a uniform 1.4 T magnetic field, and including a multi-layer silicon microstrip detector system and an open-cell drift chamber that provide position, momentum, and charge information. Electromagnetic (EM) and hadronic calorimeters measure electron, photon and jet energies. In order to identify the electron candidate and help the reconstruction of the EM showers, a set of strip and wire chambers is embedded in the EM calorimeter. Outside the calorimeters, drift chambers and scintillators provide muon candidate identification.
4. Searches for Leptoquarks at Tevatron

The DØ and CDF collaborations have searched for LQs in the three generations and in a large range of final states. We present in this section a review of the most recent results obtained at the two Tevatron experiments.

4.1. Searches for first-generation Leptoquarks

A search for first-generation Leptoquarks in the $eejj$ final state has been performed at DØ, in a data sample corresponding to a luminosity of about 1 fb$^{-1}$. From a previous analysis on 252 pb$^{-1}$ of data, first-generation scalar LQs with a mass below 241 GeV/$c^2$ are ruled out. In the most recent analysis, the main backgrounds are instrumental background (QCD “multijet” events faking leptons in the final state) and electroweak standard processes such as Drell-Yan/$Z \rightarrow ee$ produced in association with jets or $t\bar{t} \rightarrow bW(l\nu)bW(l\nu)$. The electroweak processes are estimated using Monte Carlo simulation, while the QCD background is extracted from data. We select events containing two electrons candidates and two jets, with high transverse energy ($E_T$). The normalization of the simulated background to the data is performed on the dielectron invariant mass $M_{ee}$. The normalization is also controlled on the scalar tranverse energy spectrum $S_T$, which is the sum of the transverse energy of the four objects in the final state. In order to reduce the main background contributions, the cuts on the $M_{ee}$ and $S_T$ variables are optimized so that the expected cross section is minimal. The number of observed events agree with Standard Model expectations and we have set limits on the cross section times branching fraction squared for the production of scalar and vector leptoquark pairs decaying to the $e+\text{jet}$ final state as a function of the leptoquark mass. The limits are interpreted as mass limits and exclude leptoquarks with masses less than 292 GeV/$c^2$ for scalar leptoquarks and from 350 to 458 GeV/$c^2$ for three types of vector leptoquarks, depending on the LQ-$l-\ell$ coupling (Minimal Coupling MC, Yang-Mills YM and Minus-Minus MM). The four results are shown on figure 2.

![Figure 2](image-url)

**Figure 2.** Cross sections at 95% C.L. times branching ratio as a function of the LQ1 mass for the four different couplings considered and with $\beta = 1$. The vector and scalar LQ cross sections are drawn for different values of the renormalization and factorization scale: $M_{LQ}$ (solid line), $M_{LQ}/2$ (dot-dashed line) and $2M_{LQ}$ (dashed line). The horizontal black lines correspond to the expected and observed limit cross section for each coupling.

These results are being combined at DØ with the searches for first-generation LQs in the $evjj$ and $\nu\nujj$ channels. This latter analysis has been published recently [6] and performed on
a 2.5 fb$^{-1}$ dataset. The main physical background in this channel is the $Z \rightarrow \nu\nu +$jets process. Contributions from $W \rightarrow l\nu +$jets processes are suppressed using a veto on isolated leptons. Events are selected so they contain at least two jets with high $E_T$ and missing transverse energy $E_T > 75$ GeV. Cuts are then optimized for a low and high LQ mass. Since no excess of data with respect to the SM predictions is observed, a limit is set on a LQ production cross section interpreted for $\beta = 0$ as a limit on the LQ mass at 214 GeV/c$^2$ (see fig. 3). This analysis also allows to set a limit on T-odd quarks production cross section.

4.2. Searches for second-generation Leptoquarks
The most recent search at DØ for second-generation LQs is a combination of the $\mu\mu jj$ and $\mu\nu jj$ channels, performed on 1 fb$^{-1}$ dataset [7]. For the $\mu\mu jj$ channel, the main background contribution comes from the DY/Z $\rightarrow \mu\mu +$jets. Events are required to have at least two muons and two jets with high $E_T$. Cuts on $S_T$, on the dimuon invariant mass $M_{\mu\mu}$ and on the muon-jet invariant mass $M_{\mu j}$ are used as inputs of a neural network in order to set the limit on the cross section.

For the $\mu\nu jj$ channel, a similar approach is considered. Events are selected so as to contain one muon, two jets and high missing transverse energy. Here again data are found consistent with the SM predictions and a neural network is used to set the limit on the production cross section of a 2$^{nd}$-generation LQ, based on the input variables $S_T$, $M_{\mu\nu}$, $M_{\mu j}$ and $M_{\nu j}$.

Figure 4a represents the cross section as a function of the LQ mass for both channels. The two results are then combined: if $\beta = 1$, second-generation LQs with a mass below 316 GeV/c$^2$ are ruled out. If $\beta = 0.5$, the lower limit on a 2$^{nd}$-generation LQ mass is 270 GeV/c$^2$ (see fig. 4b).

4.3. Searches for third-generation Leptoquarks
A search for third-generation Leptoquarks has been published recently [8] by the DØ Collaboration. The final state topology consists of two tau candidates and two b quark jets. One tau lepton is supposed to decay leptonically ($\tau_1 \rightarrow \mu\nu\nu$) and the other hadronically ($\tau_2 \rightarrow h^\pm \nu$). Here, the dominant sources of SM background are due to $W$ or $Z$ bosons produced together with light jets, and top quark production. They are estimated using Monte Carlo simulation. Background contributions from QCD multijet production and light flavor jets misidentified as b-jets are estimated from data. Events are required to have two tau candidates and two jets with high $E_T$. The tau candidates are identified using a neural network based on reconstructed tracks and calorimeter informations. After all cuts, the jets are subjected to a b-tagging algorithm and events divided into two subsamples, one with exactly one tagged b jet and the other with $\geq 2$
Figure 4. Cross sections at 95% C.L. as a function of the LQ2 mass (a). Combination of the LQ2 decay channels in the $(\beta, M_{LQ})$ plane (b).

b jet tags. No excess has been observed above the SM expectations. The $S_T$ spectrum – sum of $E_T(\mu)$, $E_T(\nu)$, $E_T$ of the two leading jets and $E_T$ – is used to set 95% C.L. limits as shown, as a function of the LQ mass, on fig. 5. The limits are interpreted as lower limits on a LQ3 mass at 210 GeV/$c^2$ for $\beta = 1$. When the decay LQ3 $\rightarrow \nu t$ becomes kinematically possible, after including a phase space factor, the cross section times branching ratio for the charge $2/3$ LQ3 $\rightarrow \tau b$ decreases, as indicated with the dashed line in fig. 5 ; in this case, the limit on the LQ3 mass is found at 207 GeV/$c^2$.

Figure 5. Cross sections at 95% C.L. times branching ratio as a function of the LQ3 mass.

The best limits on a vector LQ3 mass to date, have been obtained by the CDF Collaboration [9] from a dataset corresponding to 322 pb$^{-1}$ of integrated luminosity. In this analysis, the pair-produced third-generation vector leptoquarks (VLQ3) are assumed to both decay into a b quark and a tau lepton, and yield two jets from the b quarks, an electron or muon...
from a leptonically decaying tau, and a hadronically decaying tau. Selected events are required to contain at least one electron (or muon) candidate with transverse energy $E_T > 10$ GeV. The backgrounds for this channel come from processes with real electrons or muons in the final state (mainly $\text{DY/Z} \to \tau\tau + \text{jets}$, $t\bar{t} \to bW(l\nu)bW(had\nu)$) and from misidentification of final state particles (such as $t\bar{t} \to bW(had)bW(l\nu)$ where a jet from a hadronic $W$ decay is reconstructed as an electron or a muon, or QCD multijet events). After all selection cuts, the number of data events is in agreement with SM expectations. Assuming Yang-Mills and minimal couplings of the VLQ3 with the fermions, and a branching ratio $\text{BR}(\text{VLQ3} \to b\tau) = 1$, the most stringent upper limits on the VLQ3 pair-production cross section are obtained and interpreted as lower limits at 95% C.L. on a VLQ3 mass for the two couplings at 317 GeV/$c^2$ and 251 GeV/$c^2$ respectively (see fig. 6).

4.4. General search for the three generations at CDF

Many searches for New Phenomena at hadronic colliders are model-driven, based for example on the decay of an exotic particle. Other types of studies concentrate on a final state, for example an exclusive dijet plus $E_T$ event signature, and then interpret the result in terms of cross section limits on a given model.

The analysis described in this section is a generic search for new physics based on 2.0 fb$^{-1}$ of data events fulfilling a high $E_T$ online selection criterion. Events are selected using requirements on the scalar sum of the transverse energies of the two reconstructed jets $H_T$ and on the missing transverse energy $E_T$. Two separate searches are performed in a high and a low kinematic regions, defined by different sets of the $H_T$ and $E_T$ cuts. In both regions, the expected SM backgrounds (mainly $\text{DY/Z} \to \nu\nu + \text{jets}$ and $W \to \tau\nu + \text{jets}$ processes) are compared to observed data and found consistent. Based on this agreement, a limit on the scalar LQ production cross sections is set, considering the three generations of LQs. However, due to a veto on isolated leptons, this analysis is less sensitive to the third-generation LQ signal, and thus the mass limits are slightly lower for LQ3 than for the other two generations. As shown on fig. 7, the limit on the mass of LQ1 and LQ2 with $\beta = 0$ is found at 177 GeV/$c^2$ for the high kinematic region. The limit on the mass of LQ3 with $\beta = 0$ is 167 GeV/$c^2$.

5. Conclusion

An intense search for Leptoquarks of the three generations in all the decay modes has been performed throughout the data taking period at Tevatron, and we presented here the most
recent results from the CDF and DØ Collaborations. No evidence of Leptoquarks, indicating the existence of new physics, has been observed in data samples corresponding to 1 to 2.5 fb$^{-1}$ of integrated luminosity. But with about 5 fb$^{-1}$ now collected at Tevatron and later at LHC, LQ searches, as part of New Phenomena analyses, have indeed a promising future.

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