Search for First Generation Leptoquarks at D0

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1. Introduction

Because of the limitations of the standard model (SM), several extensions have been proposed, among them supersymmetry (SUSY), grand unified theories, and string theory. Many of these extensions predict the existence of particles that directly connect the lepton and quark sectors. By combining leptons and quarks in multiplets of a larger symmetry group, they are expected to interact through new mediating bosons called leptoquarks (LQ) [1, 2]. Leptoquarks can either be scalar or vector fields. The analysis presented focuses on the search for scalar leptoquarks [3]. This search is independent of specific extensions of the SM because effective models are assumed for experimental searches for leptoquarks. In $p\bar{p}$ collisions such as at the Tevatron collider, leptoquarks can be produced in leptoquark-antileptoquark pairs. Leptoquark pair production can occur via both, quark-antiquark annihilation and gluon-gluon fusion, although quark-antiquark annihilation dominates. The production cross section for scalar leptoquarks depends only on the strong coupling constant and on the leptoquark mass, and is known at next-to-leading order (NLO). Once produced, leptoquarks can decay to two final states: $\ell q$ and $vq'$ (where $\ell = e$, $\mu$, or $\tau$). It is assumed that in the low energy limit there is no intergenerational mixing. For first generation LQ pairs the final state will contain a pair of leptons ($e$ or $\nu_e$) and a pair of quarks ($u$ or $d$). The analysis presented considers the case in which one leptoquark decays into a $eq$ and the other to $v_eq'$. We define $\beta$ as the branching ratio of a first generation leptoquark to decay to $eq$. Then the probability for a leptoquark to decay to $v_eq'$ is $(1 - \beta)$, and the probability for a leptoquark pair to decay to the final state $eqv_eq'$ is $\text{BR}(LQLQ \rightarrow eqv_eq') = 2\beta(1 - \beta)$. Therefore the probability to obtain $eqv_eq'$ in the final state becomes maximal for $\beta = 0.5$.

2. Experimental Setup and Simulation

The analysis is based on 5.4 fb$^{-1}$ of $p\bar{p}$ collision recorded by the D0 detector during Run II at the Tevatron collider. The center of mass energy of the collider was $\sqrt{s} = 1.96$ TeV. The D0 detector is an all-purpose detector with a tracking system consisting of a silicon vertex detector and a fiber tracker in a 2 T magnetic field, a liquid argon calorimeter with a coverage up to $\eta = 4.2$ and a muon system with very high purity. A three level trigger system allows to select events of interested in which then lepton, quarks and missing energy are reconstructed. Details to detector and reconstruction can be found in [4]. Events must satisfy at least one trigger from the single-electron and electron plus jet trigger sets. For all data samples, trigger objects are required to match the reconstructed objects. The trigger efficiencies are measured in data and parametrized for specific lepton and jet identification criteria.

Scalar leptoquark pair Monte Carlo (MC) samples are generated using PYTHIA and are produced for different LQ masses between 200 and 360 GeV. Diboson ($WW$, $WZ$ and $ZZ$) background processes are produced with PYTHIA as well, whereas $t\bar{t}$ and $V+\text{jets}$ samples (with $V=W$, $Z$) are produced using the ALPGEN generator and then interfaced in PYTHIA for parton showering and hadronization. Single top production is simulated using COMPHEP. Signal and diboson production cross section processes are calculated with next-to-leading-order (NLO) accuracy and $V+\text{jets}$ and $t\bar{t}$ at next-to-next-to-leading-order (NNLO) [5]. Instrumental background from QCD multijet production is estimated from data. The generated transverse momenta spectrum $p_T$ of the Z boson is
corrected according to the spectrum measured in data. The \( p_T \) spectrum of the \( W \) boson is corrected considering the differences between \( Z \) and \( W \) boson \( p_T \) spectra at NNLO.

3. Analysis

In the \( eq\nuq' \) final state one does not know a priori how to assign the jets to the leptoquark decaying to \( eq \) or \( veq' \). Therefore, to reconstruct the properties such as mass and \( p_T \) of the leptoquarks from the final products, an algorithm is needed to choose the best pairing. Although no requirement is placed on the jet multiplicity per event only the two highest momentum jets are used for the two possible combination of the leading jet either pairing with the electron or the neutrino. There are various ways to pair the objects, it has been found that it is most effective to minimize the difference between the transverse masses, \( M_T = \sqrt{E_T^2 - \vec{p}_T^2} \). Here \( E_T \) and \( \vec{p}_T \) are transverse energy and transverse momentum of the two leptoquarks. This pairing algorithm is 75% effective in finding the correct pairing assignment. Events are required to be consistent with the \( LQ \rightarrow eq\nuq' \) process by selecting one electron, large missing energy (\( E_T \)) and at least two jets. The electron has to exceed a minimum transverse momentum \( p_T > 15 \) GeV and to be within the central calorimeter region \( |\eta| < 1.1, E_T > 15 \) GeV, and at least two jets with \( p_T > 20 \) GeV and \( |\eta_{\text{jet}}| < 2.5 \). Multijet (MJ) and instrumental background is suppressed by requiring \( E_T / 50 + M_T^{\nuq'}/70 \geq 1 \). Here \( M_T^{\nuq'} \) is the transverse mass between the electron and neutrino in GeV.

4. Analysis

Additional cuts are applied to reduce SM background processes. To minimize \( V + \text{jets} \) processes \( M_T^{\nuq'} > 110 \) GeV is required. Because the longitudinal component of the neutrino momentum \( p_z \) is not measurable, we reconstruct only the visible mass \( m_{\text{vis}} \) of the decay \( LQ \rightarrow veq' \) as \( M_{LQ} = M(\text{jet} + \nu_{\text{vis}}) \). The four vector of \( \nu_{\text{vis}} \) is given as \( (\vec{p}_x, \vec{p}_y, 0, E_T) \). \( \sum M_{LQ} \) is the sum of the invariant mass of the decay \( LQ \rightarrow eq \) and the visible mass of the decay \( LQ \rightarrow veq' \). By requiring \( \sum M_{LQ} > 350 \) GeV SM backgrounds are further suppressed. A third and last selection requirement is formed by applying a selection of \( S_T > 450 \) GeV. \( S_T \) is the scalar sum of the \( p_T \) of the electron, \( E_T \) and the \( p_T \) of the two leading jets. All selection criteria have been optimized to achieve best expected sensitivity for \( M_{LQ} = 260 \) GeV. After each selection the number of expected and observed events agree reasonably well and are given along with the expected signal for \( M_{LQ} = 260 \) GeV in Tab. 1.

<table>
<thead>
<tr>
<th>Selection Requirement</th>
<th>Data (events)</th>
<th>Total Background (events)</th>
<th>Signal (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>65992</td>
<td>65703 ± 5958</td>
<td>50 ± 7</td>
</tr>
<tr>
<td>( M_T^{\nuq'} &gt; 110 ) GeV</td>
<td>990</td>
<td>986 ± 82</td>
<td>43 ± 5</td>
</tr>
<tr>
<td>( \sum M_{LQ} &gt; 350 ) GeV</td>
<td>64</td>
<td>55 ± 4</td>
<td>27 ± 4</td>
</tr>
<tr>
<td>( S_T &gt; 450 ) GeV</td>
<td>15</td>
<td>15 ± 1</td>
<td>24 ± 3</td>
</tr>
</tbody>
</table>

Table 1: Numbers of events for data and contributing processes after each selection requirement for \( M_{LQ} = 260 \) GeV and \( \beta = 0.5 \). Uncertainties include statistical contributions. The only.
Systematic uncertainties affecting only the normalization of the background and the signal efficiency include uncertainties on cross sections of signal (10%) and background (6% – 10%) processes, normalization of the MJ background (20%), integrated luminosity (6.1%), and lepton trigger and identification (4%). Uncertainties which also affect the differential distribution of $S_T$ which is the quantity used to set the limits on $LQ$ are due to the jet energy resolution and scale, jet identification efficiency, parton distribution functions, and the modeling of the jet $p_T$ distribution of the dominant $W +$ jets background. Their impacts are evaluated by repeating the analysis with values varied by ±1 standard deviation (SD). Uncertainties on the jet $p_T$ modeling. The $Z$-boson $p_T$ distribution is modeled to match the distribution observed in data, taking into account the dependence on the number of reconstructed jets. To reproduce the $W$-boson $p_T$ distribution in simulated events, the product of the measured $Z$-boson $p_T$ spectrum and the ratio of $W$ to $Z$-boson $p_T$ distributions at NLO is used as correction [6, 7]. The difference between these distributions before and after corrections are taken as ±1 SD bands.

The distribution of $S_T$ after all selection requirements is used as a discriminant to set an upper limit on $LQ$ pair production cross section in the $e\nu_L Q$ final state. For each generated leptoquark mass the limit is calculated as 95% confidence level (C.L.) using the semifrequentist $CL_s$ method.

**Figure 1:** (a) $M_T^{W}$ distribution after preselection (b) $\Sigma M_{LQ}$ for $M_T^{W} > 110$ GeV (c) $S_T$ for $M_T^{W} > 110$ and $\Sigma M_{LQ} > 350$ GeV (d) $S_T$ after final selection as used to set upper limits on $LQ$ pair production.
based on a Poisson log-likelihood test statistic [8]. Signal and background normalizations and shape variations due to systematic uncertainties are incorporated assuming Gaussian priors. The best fit to the background distributions is evaluated by minimizing a profile likelihood function with respect to the observed data and various sources of uncertainty, maintaining all correlations among systematic uncertainties [9]. Limits on the cross section multiplied by the branching fraction and the theoretical $LQ$ cross section for $\beta = 0.6$ are shown in Fig. 2 a). The limit on the $LQ$ mass as a function of $\beta$ is determined as shown in Fig. 2 b), and compared to the previous measurements from D0 [10], CMS [11, 12] and Atlas [13].

![Figure 2](image_url)

**Figure 2:** (a) Expected and observed upper limits calculated at the 95% C.L. on the $LQ$ cross section as a function of $M_{LQ}$ for a scalar leptoquark compared with the NLO prediction for $\beta = 0.5$. The NLO cross section is shown for different choices of the renormalization and factorization scales, $\mu = M_{LQ}$, $\mu = 2 \times M_{LQ}$, $\mu = 0.5 \times M_{LQ}$. (b) 95% C.L. observed limit for $\mu = M_{LQ}$ on the leptoquark mass as a function of $\beta$ compared with the previous D0, CMS and Atlas results.

5. Summary

A search for scalar leptoquark pair production in the $eq'\bar{q}'$ final state in 5.4 fb$^{-1}$ of integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV has been performed. No signal has been observed and the production of first generation leptoquarks with $M_{LQ} < 326$ GeV of $\beta = 0.5$ are excluded at 95% C.L.

References

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