



Search for second generation scalar leptoquarks in the $\mu\nu jj$ final state with the DØ detector

The DØ Collaboration
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This note describes the search for the pair-production of scalar leptoquarks in $p\bar{p}$ collisions at the Tevatron collider. The analysis is based on the complete 1 fb^{-1} data set collected by the DØ experiment during Run IIa. No evidence for the pair-production of leptoquarks in the final state consisting of a muon, a neutrino and two jets has been found. Upper bounds on the product of cross section times branching fraction are set. This yields a lower limit on the second generation leptoquark mass of $M_{LQ} > 214 \text{ GeV}$ at 95% confidence level for an assumed branching fraction of $\beta = BR(LQ \rightarrow \mu q) = 0.5$ for the leptoquark decaying into a muon and a quark.

Preliminary Results for Winter 2007 Conferences

I. INTRODUCTION

As predicted by numerous extensions of the standard model, leptoquarks are hypothetical bosons allowing lepton-quark transitions [1]. In hadron collisions, the pair-production of scalar leptoquarks is a pure QCD process (see figure 1). Thus its cross section only depends on the leptoquark mass and not on the unknown coupling (λ) between the leptoquark and its associated lepton and quark.

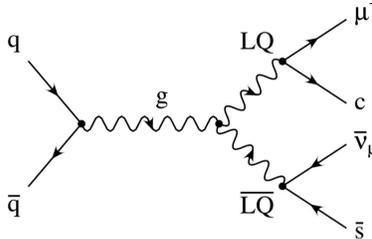


FIG. 1: *Diagram of the pair production of leptoquarks at the Tevatron, followed by their decay in the final state composed by one muon, one neutrino and two quarks.*

The additional contribution due to t-channel lepton exchange with a cross section proportional to λ^2 could actually also be considered, but when adopting the general assumption that the coupling is between the second lepton and second quark generation, this process is further suppressed by vanishing s and c quark parton distribution functions (PDF) at high *Bjorken* x . The contribution of this process is negligible in comparison with the theoretical uncertainties on the cross section.

The analysis presented in this note describes the search for second generation scalar leptoquark pair-production in the channel $LQ_2\overline{LQ}_2 \rightarrow \mu q\nu q$, i.e., a final state consisting of one muon, one neutrino and two second generation quarks that then subsequently hadronize to jets. We define β as the branching ratio for the decay of a leptoquark into a muon and a jet ($\beta = BR(LQ \rightarrow \mu q)$). By assuming $\beta = 0.5$, the branching ratio for the decay of pair-produced leptoquarks to the muon, neutrino and two jets final state is maximized and equal to $BR(LQ\overline{LQ} \rightarrow \mu\nu qq) = 2\beta(1 - \beta) = 0.5$.

II. ANALYSIS SAMPLES

This analysis is based on the data taken at the Fermilab Tevatron collider ($\sqrt{s} = 1.96$ TeV) during RunIIa, which corresponds to the time period between August 2002 and February 2006. The data has been triggered with a collection of 33 single muon triggers and corresponds to a total integrated luminosity of 1.05 fb^{-1} [5]. Signal and background expectations (except QCD multijet production) have been simulated by Monte-Carlo event generators (ALPGEN [2] and PYTHIA [3]). The QCD contribution has been estimated from the data sample.

For the standard model background to the $\mu\nu jj$ final state, we consider Monte-Carlo samples for the decay of the W boson to a lepton, a neutrino, and associated jets; the decay of the Z boson to two muons; and the inclusive decay of pair-produced top quarks (see Table I). W production was simulated using the matrix-elements for the associated production of additional partons as implemented in the ALPGEN event generator. We separately generated samples for partons assumed to be massless (g , u , d , s , and c -quarks) and for $Wb\bar{b}$ production, which is based on massive matrix-element expressions. ALPGEN has been interfaced with PYTHIA for the simulation of jet hadronization, and for initial and final state radiation. The ALPGEN samples for various parton multiplicities are combined using the MLM matching prescription [2].

Standard Model Process	Cross Section \times BR (pb)	Events Generated	MC Generator
$W(+jets) \rightarrow l\nu + jets$	7748	8958k	ALPGEN+PYTHIA
$Z/\gamma^*(+jets) \rightarrow \mu\mu + jets, \frac{M(\mu\mu)}{GeV} \in [60-130]$	256.6	1259k	ALPGEN+PYTHIA
$t\bar{t}$ (inclusive)	6.77	285k	PYTHIA

TABLE I: *List of all the Monte-Carlo samples that have been used to describe the backgrounds. The cross sections for the W and Z samples are NNLO [4], and the one for the $t\bar{t}$ sample is NLO [6].*

The leptoquark signals have been generated with a modified version of PYTHIA in order to allow the pair-produced

leptoquarks to decay into two different final states (muon plus quark and neutrino plus quark). In the simulation we force the leptoquarks to only decay to second generation quarks. As this analysis does not make use of any flavor identification, our results are also valid for the assumption that the leptoquarks couple to the second lepton and the first quark generation. The CTEQ6L1 [7] parton distribution functions have been used. The signal samples have been produced with five different leptoquark masses: 160, 180, 200, 220 and 240 GeV. Approximately 40k events have been generated for each mass. The cross section were calculated at next-to-leading order (NLO) [8], and vary from 0.076 to 1.08 pb for the given mass range.

III. PHYSICS OBJECTS RECONSTRUCTION

The muons are reconstructed offline using hits in the three layers of the muon detector and in the central tracking system. The matched central track is used to measure the value of the transverse momentum of the muon which we further smear in Monte-Carlo events so that the width of the $Z \rightarrow \mu^+ \mu^-$ peak matches that observed in data. Each matched central track must have at least one hit in the SMT tracker, a distance of closest approach to the primary vertex lower than 0.2 cm, and a $\frac{\chi^2}{ndof}$ smaller than 4. The matched track isolation is ensured by requiring the sum of transverse momenta of all other tracks in a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.5$ around the muon to be smaller than 2.5 GeV. The muon isolation is further improved by requiring the energy deposited in the calorimeter in an annulus of radius $0.1 < \Delta R < 0.4$ around the muon to be lower than 2.5 GeV, and by requiring the distance ΔR between a muon and the nearest reconstructed jet to be larger than 0.5. A veto on cosmic muons, based on timing information in the muon system, is applied.

Jets are reconstructed with the RunII cone algorithm [9] with a cone of radius $\Delta R = 0.5$. Each selected jet must fulfill standard quality criteria which include requirements on the electromagnetic and coarse hadronic fractions of the cells energies, a trigger confirmation condition, and an electromagnetic veto. The jet energies have been calibrated as a function of the jet transverse energy and η by balancing the transverse energy in photon plus jet events. Monte-Carlo jets are further smeared and removed in order to match the efficiency and resolution in data.

Neutrinos do not deposit any energy in the detector, but their transverse momentum can be inferred from the vector sum of the transverse momentum of all observed particles and deposited energy. The missing transverse energy (\cancel{E}_T) is estimated by calculating the vector sum of the transverse energies in the calorimeter cell. We correct the \cancel{E}_T by adding the transverse momentum of the muons, and removing the small amount of energy they deposit in the calorimeter.

IV. EVENT SELECTION

Events are required to have exactly one muon found within $|\eta| < 2$ with a transverse momentum exceeding 20 GeV, at least two jets in the region $|\eta| < 2.5$ with transverse energies greater than 25 GeV, and a missing transverse energy larger than 30 GeV. The azimuthal angle ($\Delta\phi$) between the muon and the missing transverse energy is required to be lower than 3 radians, in order to remove events with badly reconstructed muons resulting in an overestimated \cancel{E}_T . The $M_T(\mu\nu)$ transverse mass reconstructed from the four-vector of the muon and the missing transverse energy is required to exceed 50 GeV. The transverse mass of two objects separated in the azimuthal plane by the angle $\Delta\phi$, and of transverse momenta respectively p_{T1} and p_{T2} , is given by: $M_T = \sqrt{2 \times p_{T1} \times p_{T2} \times (1 - \cos \Delta\phi)}$. The motivation for cutting on $M_T(\mu\nu)$ is to remove a large part of the QCD background. All the reconstruction cuts plus the preceding cuts will be referred to as preselection cuts.

Instead of using the NNLO prediction for the inclusive W cross section, the $W + jets$ background was normalized to data at the preselection level.

QCD events have been estimated from the data sample after all preselection cuts, except those on \cancel{E}_T and $M_T(\mu\nu)$, and by requiring a inverted isolation cut on the muons. Events with a missing transverse energy lower than 10 GeV were used to normalize the QCD sample to data. The normalization is corrected by the estimate of QCD events under the W peak.

In order to enhance the signal contribution and reduce the background (the SM expectation), we consider four additional selection cuts:

- The $M_T(\mu\nu)$ transverse mass, reconstructed from the four-vector of the muon and the \cancel{E}_T , is required to be larger than 160 GeV, in order to remove the bulk of the W contribution.

- The scalar transverse energy ($S_T = p_T^{\mu_1} + p_T^{jet_1} + p_T^{jet_2} + \cancel{E}_T$) should be larger for the signal as the leptoquark decay products are more energetic than those of the backgrounds. We therefore require this quantity to be greater than 350 GeV.
- The $M_T(\nu jet_1)$ transverse mass constructed from the four-vector of the leading jet (with respect to the transverse momentum p_T) and the missing transverse energy is related to the reconstructed leptoquark mass and required to be greater than 150 GeV.
- The invariant mass of the muon-jet combination which is closer to the assumed leptoquark mass, which we refer to as the reconstructed leptoquark invariant mass ($M_{LQ, reco}$), is required to not differ from the assumed leptoquark mass ($M_{LQ, gen}$) by more than 100 GeV: $|M_{LQ, reco} - M_{LQ, gen}| < 100$ GeV.

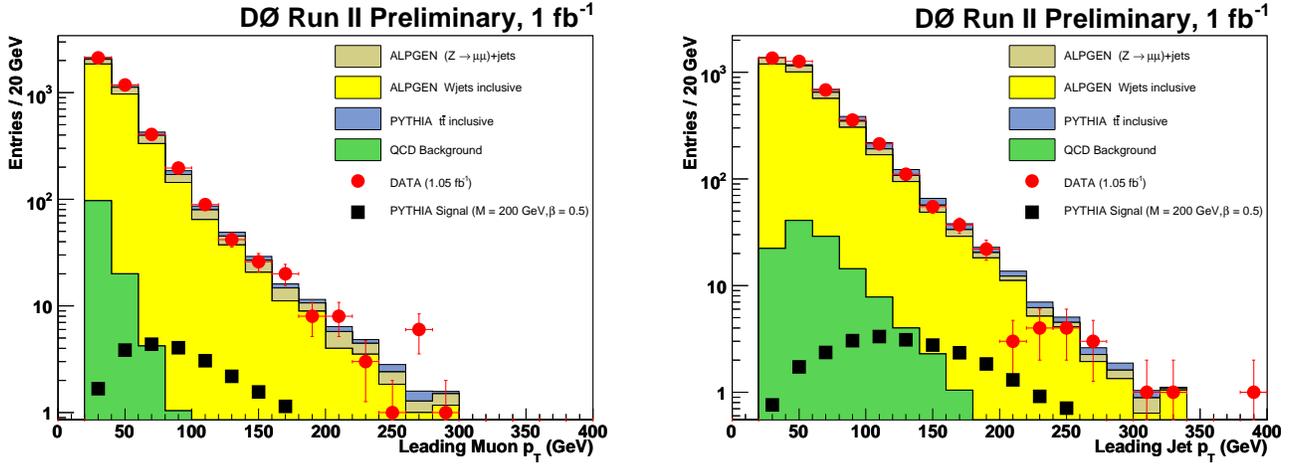


FIG. 2: Comparison, after the preselection cuts, between the data (red dots) and the standard model expectation for the leading muon (left plot) and jet (right plot) transverse momenta. The black squares describe the leptoquark signal, generated assuming $M_{LQ, gen} = 200$ GeV and $\beta = BR(LQ \rightarrow \mu q) = 0.5$.

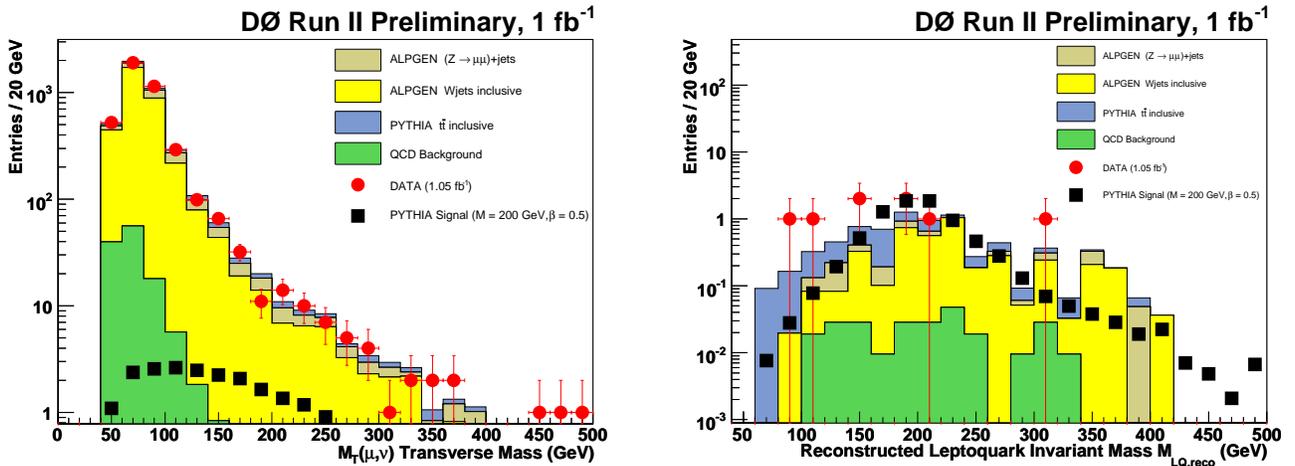


FIG. 3: Left: Comparison between the data (red dots) and the standard model expectation for the $M_T(\mu\nu)$ transverse mass. The black squares describe the leptoquark signal. Right: The reconstructed leptoquark invariant mass is required to not differ from the generated leptoquark mass by more than 100 GeV. The plot shows this variable after the preselection cuts, and the cuts on $M_T(\mu\nu)$, S_T and $M_T(\nu jet_1)$. On both plots, the leptoquark sample is generated assuming $M_{LQ, gen} = 200$ GeV and $\beta = BR(LQ \rightarrow \mu q) = 0.5$.

The 200 GeV leptoquark signal sample has been used to optimize the selection cuts. The same cut values are taken for all assumed leptoquark masses, except for the cut on the reconstructed leptoquark mass, since it depends

on the generated leptoquark mass. As we find the mass limit to be about 200 GeV, this has minimal impact on the sensitivity of the selection. The remaining number of data and background events, as well as the signal efficiency after each selection cut are provided in Table II.

Samples	$\frac{M_T(\mu\nu)}{\text{GeV}} > 160$	$\frac{S_T}{\text{GeV}} > 350$	$\frac{M_T(\nu\text{jet}_1)}{\text{GeV}} > 150$	$\frac{ M_{LQ, reco} - M_{LQ, gen} }{\text{GeV}} < 100$
$W(+jets) \rightarrow l\nu + jets$	$67 \pm 3 \pm 14$	$35 \pm 2 \pm 7$	$4.0 \pm 0.7 \pm 0.8$	$3.2 \pm 0.6 \pm 0.7$
$Z/\gamma^*(+jets) \rightarrow \mu\mu + jets$	$20 \pm 1 \pm 3$	$10 \pm 1 \pm 1$	$0.92 \pm 0.24 \pm 0.12$	$0.68 \pm 0.19 \pm 0.09$
$t\bar{t}$ (inclusive)	$10.0 \pm 0.4 \pm 2.2$	$7.2 \pm 0.4 \pm 1.5$	$2.6 \pm 0.2 \pm 0.6$	$2.3 \pm 0.2 \pm 0.5$
QCD	$0.79 \pm 0.09 \pm 0.16$	$0.52 \pm 0.07 \pm 0.10$	$0.26 \pm 0.05 \pm 0.05$	$0.22 \pm 0.05 \pm 0.04$
Total Background	$98 \pm 3 \pm 14$	$53 \pm 2 \pm 7$	$7.8 \pm 0.8 \pm 0.1$	$6.4 \pm 0.7 \pm 0.8$
Data	94	48	8	6
ϵ_{signal}	$0.130 \pm 0.002 \pm 0.011$	$0.110 \pm 0.002 \pm 0.010$	$0.082 \pm 0.001 \pm 0.007$	$0.079 \pm 0.001 \pm 0.007$

TABLE II: Remaining events after each selection cut. The signal efficiency (cumulative) is also provided. First errors are statistical, second are systematic. The generated leptoquark mass ($M_{LQ, gen}$) is 200 GeV.

After all cuts, the main contributions are from the $W(+jets) \rightarrow l\nu + jets$ and the inclusive $t\bar{t}$ backgrounds.

V. SYSTEMATIC UNCERTAINTIES

The following systematic uncertainties have been considered:

- The global uncertainty on the integrated luminosity is equal to 6.1%.
- For both signal and background a 6% uncertainty is included for the uncertainty on the combined efficiency of the muon triggers, the muon identification, tracking, and isolation.
- The uncertainties on the jet energy scale, the jet energy resolution, and the jet reconstruction efficiency are evaluated after each cut by shifting positively or negatively the central values of these quantities by one sigma. After all cuts, the uncertainty due to the jet energy scale is 11% for the W and Z boson background, 9% for top pair-production, and 3.5% for the leptoquark signal. For all samples a 1% error on the number of selected events after all cuts is estimated to account for uncertainties in the jet energy resolution, and a 1% error to account for uncertainties in the jet reconstruction efficiency.
- For the $W + jets$ background an additional systematic error of 17% is evaluated to account for uncertainties in the correct modeling of the jet p_T shape in $W + jets$ events. This number has been evaluated by comparing the p_T distribution of the first and second leading jet observed in data with the predictions of ALPGEN and PYTHIA in a kinematic region dominated by $W + jets$ production. Furthermore, an error of 1.2% on the $W + jets$ background is added to account for uncertainties in its normalization to data.
- The uncertainty on the QCD multi-jet background is estimated to be 20%, which includes both the uncertainty on the normalization and on the extrapolation of the QCD templates, which are defined using anti-isolation cuts for the reconstructed muon, to the signal region.
- An 18% uncertainty on the theoretical prediction of the $t\bar{t}$ pair-production cross-section is taken into account.
- For the signal efficiency an additional uncertainty of 4% is included to account for uncertainties in the modeling of gluon radiation in the initial and final state and an uncertainty on the acceptance of 4% due to PDF uncertainties is added.

VI. RESULTS

Since no significant excess in data over predicted SM background has been observed, a 95% confidence level limit on the leptoquark pair-production cross section has been set. A Bayesian cross section limit calculator [10] has been used to estimate the observed upper cross section limit on the production of pairs of scalar leptoquarks decaying into the final state composed of a muon, a neutrino and two jets.

The observed upper cross section limit has been calculated for each signal sample, given the luminosity, the signal efficiency after all cuts, the remaining number of background events, and the associated errors (see Table III). The

LQ Mass (GeV)	Signal Efficiency	SM Events	Data Events	$\sigma_{observed}^{95\%CL}$ (pb)	$\sigma_{expected}^{95\%CL}$ (pb)
160	$0.039 \pm 0.001 \pm 0.004$	$6.2 \pm 0.7 \pm 0.8$	7	0.20	0.19
180	$0.057 \pm 0.001 \pm 0.005$	$6.5 \pm 0.7 \pm 0.8$	7	0.13	0.13
200	$0.079 \pm 0.001 \pm 0.007$	$6.4 \pm 0.7 \pm 0.8$	6	0.086	0.093
220	$0.098 \pm 0.001 \pm 0.009$	$6.5 \pm 0.7 \pm 0.8$	6	0.069	0.076
240	$0.110 \pm 0.001 \pm 0.010$	$6.2 \pm 0.7 \pm 0.8$	6	0.061	0.065

TABLE III: Remaining number of background events, data events, and signal efficiencies, after all the cuts, and for all the leptoquarks samples (first error is statistical, and second is systematic). The corresponding 95% upper cross section limits (observed and expected) have been calculated with a Bayesian calculator. The variations of the data remaining events and the standard model expectations between the different leptoquark samples are due to the last cut ($|M_{LQ, reco} - M_{LQ, gen}| < 100$ GeV) which depends on the assumed leptoquark mass.

upper cross section bounds are compared to the NLO prediction of the leptoquark pair-production cross section, reduced by its uncertainty. We thus derive a lower limit on the leptoquark mass, assuming $\beta = 0.5$. The uncertainty on the cross section includes the scale uncertainty (varied between $\frac{1}{2}M_{LQ}$ and $2M_{LQ}$) and the PDF uncertainty (evaluated using the CTEQ6.1M error PDF sets). As shown in Figure 4, an observed mass limit of 214 GeV (corresponding to an upper bound on the production cross section equal to 0.074 pb^{-1}) and an expected mass limit of 210 GeV (corresponding to an upper bound on the production cross section equal to 0.085 pb^{-1}) have been obtained at 95% confidence level for leptoquarks decaying into a muon and a quark with a branching ratio of $\beta = 0.5$.

This measurement significantly improves over previous mass limits for scalar second generation leptoquarks. Previous best limits at $\beta = 0.5$ obtained in the $\mu\nu jj$ channel are $M_{LQ} > 170$ GeV (CDF, Run II [11]) and $M_{LQ} > 160$ GeV (DØ, Run I [12]), respectively. The previous best mass limits derived by combining the $\mu\nu jj$ selection with both the $\mu\mu jj$ and $\nu\nu jj$ channels are $M_{LQ} > 208$ GeV (CDF, Run II [11]) and $M_{LQ} > 204$ GeV (DØ, Run II [13]), respectively.

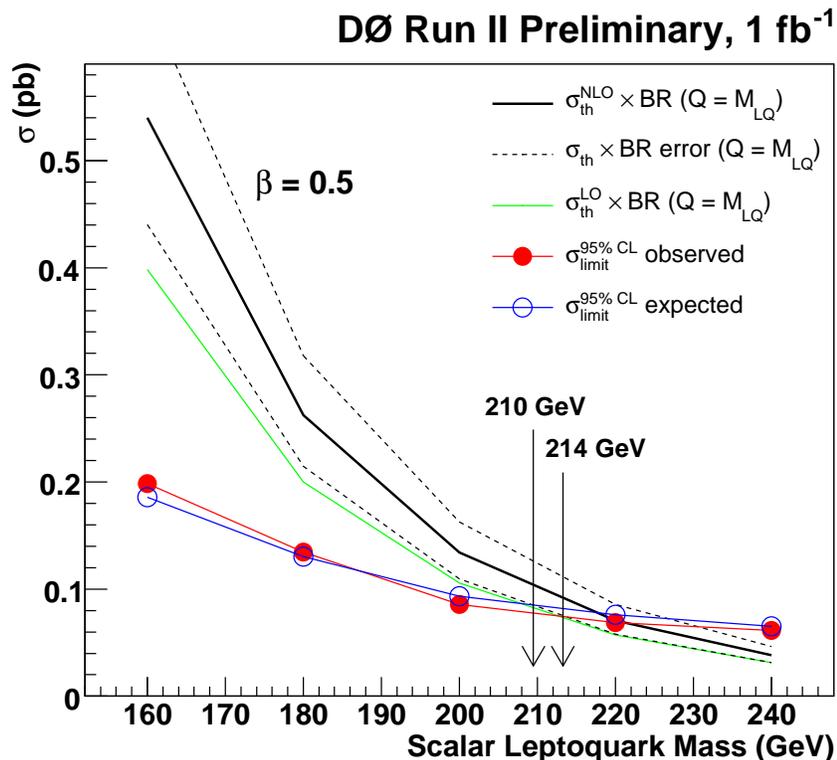


FIG. 4: Comparison of the 95% upper cross-section limit with the theoretical prediction (LO and NLO). By considering the lower errors of the NLO prediction, we can conclude that the mass of a leptoquark decaying to a muon and a quark can be ruled out up to 214 GeV. The expected mass limit is 210 GeV.

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