CDF note 7169

Search for Leptoquarks in the Jets and Missing Transverse Energy Topology in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV.

The CDF Collaboration
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We report on a search for the pair production of leptoquarks using 191 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the Tevatron. The leptoquarks are sought via their decay into a neutrino and quark, which yields missing transverse energy and several high transverse energy jets. No evidence for leptoquark production is observed, and limits are set on the cross section times squared branching ratio. Using the next-to-leading order cross section for scalar leptoquark production, we exclude first-generation leptoquarks in the mass interval 78 to 117 GeV/c^2 at the 95% confidence level for 100% branching ratio into neutrino plus quark.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

Leptoquarks are hypothetical color-triplet bosons carrying both lepton and baryon quantum numbers that are predicted in many extensions of the Standard Model (e.g. Grand Unification models, Technicolor, and Supersymmetry with R-parity violation) [1]. The Yukawa coupling of the leptoquark to a lepton and quark, and the branching ratio to a charged lepton, denoted by β, are model dependent. Usually it is assumed that leptoquarks couple to only one generation to avoid flavor-changing neutral currents, which allows one to classify leptoquarks as first-, second-, or third-generation.

In $p\bar{p}$ collisions, leptoquarks can be pair-produced via the strong interaction through gluon-gluon fusion or $q\bar{q}$ annihilation. For Yukawa couplings of electromagnetic strength or less, the contribution to the production rate from direct leptoquark coupling to lepton and quark is less than 1% of the total cross section; so the production rate is essentially determined by the known QCD couplings and leptoquark mass and spin. For scalar leptoquarks (Φ), the production cross section is determined by the coupling between a leptoquark and a gluon and is model independent. The cross section for the pair production of scalar leptoquarks in $p\bar{p}$ collisions has been calculated to next-to-leading order (NLO) in perturbative QCD [2]. On the other hand, vector leptoquark interactions with the gluon field include model-dependent couplings. The NLO cross section for vector leptoquark production has not been calculated, since the possibility of anomalous couplings complicates the situation.

We report on a search for scalar leptoquarks in the jets and missing transverse energy topology, i.e. sensitive to $\beta \approx 0$, using 191 ± 11 pb^{-1} of $p\bar{p}$ collision data at a center-of-mass energy of 1.96 TeV recorded by the Collider Detector at Fermilab (CDF) during the 2002-2003 Tevatron Run II. Limits on leptoquark production from the Tevatron Run I and HERA experiments as of 1999 are summarized in [3]. In particular, both CDF [4] and DØ [5] published limits on first-generation leptoquarks in the $eejj$ channel shortly after the HERA experiments announced [6] an anomalous excess of electron plus jet events in 1997. The combined lower mass limit [7] of 242 GeV/c^2 for scalar leptoquarks with $\beta = 1$ from CDF and DØ ruled out a leptoquark interpretation of the HERA anomaly for large β. CDF has published [8] limits of 123 GeV/c^2 and 148 GeV/c^2 respectively on second- and third-generation leptoquarks in the missing E_{T} plus heavy-flavor jets final state. This analysis extends the previous limit of 98 GeV/c^2 [9] in the $\nu\nu jj$ final state, published by DØ .

CDF is a general purpose detector and is described in detail elsewhere[10]. The components relevant to this analysis are briefly described here. Closest to the beam pipe is the charged-particle tracking system used to reconstruct particle momenta and the collision vertex, which consists of multi-layer silicon detectors and a large open-cell drift chamber covering the pseudorapidity region $|\eta| \leq 1$. The tracking system is enclosed in a superconducting solenoid. It is surrounded by a calorimeter, which is organized into electromagnetic and hadronic sections segmented in projective tower geometry and covers the region $|\eta| \leq 3.6$. The central and plug electromagnetic calorimeters utilize a lead-scintillator sampling technique, whereas the central, wall and plug hadron calorimeters use iron-scintillator technology. Outside the central calorimeter there is a muon detection system, which covers the range $|\eta| < 2$.

II. DATA SAMPLE & EVENT SELECTION

The search for leptoquark pair-production and decay into the $\nu\nu jj$ final state centers on selecting events with large missing E_{T} ($\not\!\!E_{\mathrm{T}}$) and a pair of jets that are acolinear in the transverse plane. The $\not\!\!E_{\mathrm{T}}$ is defined as the energy imbalance in the plane transverse to the beam direction and reconstructed as a vector sum of energy deposited in calorimeter towers. A jet is defined as a localized energy deposition in the calorimeter and is reconstructed using a fixed cone algorithm with a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in $\eta - \phi$ space [11]. An energy correction procedure [11] corrects jet energies and $\not\!\!E_{\mathrm{T}}$ for detector effects.

The data sample for this analysis was collected using an inclusive $\not\!\!E_{\mathrm{T}}$ trigger, which is distributed across 3 levels of online event selection. The Level-1 $\not\!\!E_{\mathrm{T}}$ is required to be greater than 25 GeV and is calculated by summing over trigger towers with transverse energies above 1 GeV. Level-2 automatically accepts all events that passed the Level-1 $\not\!\!E_{\mathrm{T}}$ selection. At Level-3 $\not\!\!E_{\mathrm{T}}$ is required to be greater than 45 GeV and it is recalculated using full calorimeter information, and a tower energy threshold of 100 MeV. We use events from the inclusive high p_{T} lepton samples to measure trigger efficiency directly from data.

Event electromagnetic fraction (F_{em}) and event charged fraction (F_{ch}) [12] are used to remove events associated with beam halo and cosmic ray sources. We reject events that contain little energy in the electromagnetic section of the calorimeter or that have mostly neutral jets, by requiring $F_{em} > 0.1$ and $F_{ch} > 0.1$. Furthermore, to reduce systematic effects associated with trigger threshold we select events with $\not\!\!E_{\mathrm{T}} > 60$ GeV. There are 148,462 events in our analysis sample after the initial selection.

The dominant backgrounds to the leptoquark search in the jets and $\not\!\!E_{\mathrm{T}}$ signature are QCD multi-jet production, W and Z boson production in association with one or more jets, and top quark pair production. The ALPGEN generator [13] was used for the simulation of the W and Z boson plus parton production, with Herwig [14] used to model parton showers. Herwig was also used to estimate the contribution from $t\bar{t}$ production.

Leptoquark selection cuts were chosen to maximize the statistical significance of the signal over background events using simulated samples before the signal region data were examined. The signal region is defined by requiring $\not\!\!E_{\rm T} \geq 60$ GeV, the opening angle in the transverse plane between the two highest $E_{\rm T}$ jets $80^\circ < \Delta\phi(j_1, j_2) < 165^\circ$, and zero identified leptons (e or μ). In addition, we require that the two highest $E_{\rm T}$ jets ($E_{{\rm T}j_1} > 40$ GeV, $E_{{\rm T}j_2} > 25$ GeV) be in the central region $|\eta| < 1$. A third jet with $E_{\rm T} > 15$ GeV and $|\eta| < 2.5$ is allowed, and we veto events with any additional jets (mostly soft jets) with $E_{\rm T} > 15$ GeV and $|\eta| < 3.6$. To reject events with $\not\!\!E_{\rm T}$ resulting from jet energy mismeasurement, we require that the $\not\!\!E_{\rm T}$ direction is not parallel to any of the jets ($30^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 135^\circ$) and is not antiparallel to the leading $E_{\rm T}$ jet ($100^\circ < \Delta\phi(j_1,\not\!\!E_{\rm T}) < 165^\circ$). These cuts reject most of the QCD multi-jet background events. To reduce the background contribution from $W/Z+$ jets and $t\bar{t}$ production containing leptons, we reject events with one or more identified leptons with $E_{\rm T} > 10$ GeV (electrons) or $P_{\rm T} > 10$ GeV/c (muons). To further reduce this background we require each jet not to be purely electromagnetic (jet electromagnetic fraction $f_{em} < 0.9$) and to have 4 or more associated tracks for central jets ($|\eta| < 1$).

III. BACKGROUNDS

The $Z+$ jets and $W+$ jets simulation predictions are normalized to the exclusive $Z \to ee\ +1$ jet cross section measured in our data.

Two methods are employed to estimate the QCD multi-jet contribution in the signal region directly from the inclusive $\not\!\!E_{\rm T}$ data sample. Among all the offline analysis selection cuts, most of the QCD multi-jet events are removed by the azimuthal angular separation cut between the $\not\!\!E_{\rm T}$ vector and a jet. Therefore, for the first method we define a region which is rich in QCD multi-jet events by requiring that a mismeasured jet is close to the $\not\!\!E_{\rm T}$ direction ($20^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 27^\circ$). Studies on simulated QCD multi-jet samples show that the shape of the $\not\!\!E_{\rm T}$ distribution in this region is similar to the $\not\!\!E_{\rm T}$ distribution in the signal region. These two regions defined by the $\Delta\phi(j,\not\!\!E_{\rm T})$ cuts are further sub-divided into four kinematic regions:

A) $50 < \not\!\!E_{\rm T} < 57$ GeV $20^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 27^\circ$.

B) $\not\!\!E_{\rm T} > 60$ GeV, $20^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 27^\circ$.

C) $50 < \not\!\!E_{\rm T} < 57$ GeV, $30^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 135^\circ$.

D) $\not\!\!E_{\rm T} > 60$ GeV, $30^\circ < \Delta\phi(j,\not\!\!E_{\rm T}) < 135^\circ$.

The QCD multi-jet contribution in the signal region (D) is estimated by: $N_D = \frac{N_B}{N_A} N_C$, where N_A, N_B, and N_C are the remaining number of events in regions A, B, and C, after the W/Z plus jets and $t\bar{t}$ contributions have been subtracted. For the second method, the combined selection cut efficiency is measured as a function of $\not\!\!E_{\rm T}$ in an independent inclusive jet sample, and is then applied to the high $\not\!\!E_{\rm T}$ subsample preselected with looser analysis cuts. The number of multi-jet events predicted by both methods agree within statistical and systematic uncertainties. We take the uncertainty weighted average of the two methods as an estimate of the mutli-jet background events in the signal region.

We check the simulation predictions for vector boson plus jets with data in a control region, which is defined by requiring, in addition to 2 or 3 jets, $\not\!\!E_{\rm T} > 60$ GeV and at least one electron or muon. We observe 144 events in our inclusive $\not\!\!E_{\rm T}$ sample, which is in excellent agreement with 154.3 ± 27.9 events predicted from Standard Model processes.

IV. SIGNAL ACCEPTANCE AND SYSTEMATIC UNCERTAINTIES

The total detection efficiency (ϵ_{Φ_1}) for the first-generation scalar leptoquark (Φ_1) signal is estimated using the Pythia event generator[15], and the CDF detector simulation program. The Pythia underlying event simulation was tuned to reproduce CDF data [16]. The samples were generated using the CTEQ5L [17] parton distribution functions (PDF), with the renormalization and factorization scales set to $\mu = m_{\Phi_1}$. Table I lists the total detection efficiency ϵ_{Φ_1}, the corresponding total fractional uncertainty δ_{tot}, and the expected NLO cross section $\sigma_{\rm NLO}$ for various leptoquark masses. The systematic uncertainty on the signal acceptance includes the uncertainties due to modeling gluon radiation from the initial state (ISR) or final state partons (FSR) (10%) and the choice of the PDF (4%). The finite statistics of the leptoquark simulation samples give a 3% statistical error. On the experimental side, the signal acceptance uncertainty due to the jet energy scale varies from 4% to 26%, and the uncertainty on the luminosity is 6%.

TABLE I: Summary of the first-generation scalar leptoquark detection efficiency (ϵ_{Φ_1}), relative error on detection efficiency ($\delta_{\rm tot}$), and next-to-leading order cross section ($\sigma_{\rm NLO}$) using CTEQ5L and $\mu = m_{\Phi_1}$ as a function of leptoquark mass.

m_{Φ_1} (GeV/c^2)	ϵ_{Φ_1}	$\delta_{\rm tot}$ (%)	$\sigma_{\rm NLO}$ (pb)
75	0.0073	29	69.4
80	0.0113	26	49.2
90	0.0187	23	26.0
100	0.0300	20	14.6
110	0.0431	16	8.4
115	0.0482	15	6.7
125	0.0590	15	4.2
150	0.0828	13	1.4
175	0.1010	12	0.57

The uncertainty on the trigger efficiency is 1%. The theoretical uncertainties on the renormalization and factorization scales are not included here, since we conservatively choose the NLO cross section for $\mu = 2m_\Phi$, which is found to reduce the cross section by 15% relative to $\mu = m_\Phi$ [2].

V. RESULTS

In the signal region, we expect 118.3 ± 14.5 events from Standard Model processes and observe 124 events. The predicted backgrounds from Standard Model processes are summarized in Table II. In Figure 1 the predicted $\not\!\!E_{\rm T}$

TABLE II: The number of expected events from various Standard Model sources in the leptoquark signal region. The simulation statistical uncertainty is the first one shown, and the systematic uncertainty is the second one.

Source	Events expected
$W \to e\nu+$ jets	$6.1 \pm 1.4 \pm 1.5$
$W \to \mu\nu+$ jets	$21.7 \pm 2.3 \pm 2.8$
$W \to \tau\nu+$ jets	$28.4 \pm 3.8 \pm 4.1$
$Z \to \mu\mu+$ jets	$1.1 \pm 0.2 \pm 0.2$
$Z \to \tau\tau+$ jets	$0.9 \pm 0.2 \pm 0.2$
$Z \to \nu\nu+$ jets	$39.1 \pm 2.8 \pm 3.6$
$t\bar{t}$	$4.3 \pm 0.4 \pm 0.3$
QCD	16.7 ± 6.7 (total)
Total Events	118.3 ± 14.5(total)

distribution is compared with the distribution observed in data. No evidence for leptoquark production is observed. We calculate the upper limit on the possible number of signal events at 95% confidence level (C.L.) using a Bayesian approach with a flat prior for the signal cross section and Gaussian priors for acceptance and background uncertainties. The upper limit on the cross section times squared branching ratio is shown in Figure 2 and is compared with the theoretical cross sections [2]. The theoretical cross sections for the scalar leptoquark production have been calculated to NLO using CTEQ5M [17] PDFs.

In conclusion, we performed a search for leptoquarks in the jets and $\not\!\!E_{\rm T}$ topology using 191 pb^{-1} of CDF Run II data. No evidence for leptoquarks is observed; therefore, we set an upper limit on the production cross section at the 95% C.L. Assuming a leptoquark decays into a neutrino and quark with 100% branching ratio, we exclude the mass interval from 78 to 117 GeV/c^2 for first generation scalar leptoquarks. This extends the previous limit of 98 GeV/c^2 [9].

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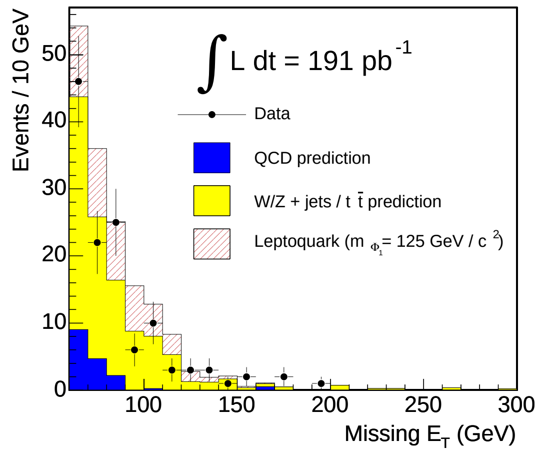

FIG. 1: The $\not\!\!E_{\rm T}$ distribution in the leptoquark signal region for data (solid points) compared to Standard Model background (shaded histogram). Also shown is the expected distribution arising from leptoquark production and decay at a mass of 125 GeV/c^2 (hatched histograms).

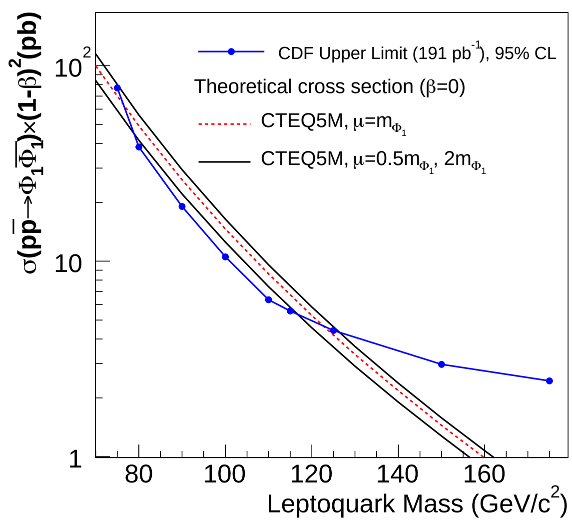

FIG. 2: The upper limit on the cross section times squared branching ratio for scalar leptoquark production in jets and $\not\!\!E_{\rm T}$ topology. Also shown is the NLO cross section for $\beta = 0$ for 3 choices of the factorization/renormalization scale: $\mu = m_{\Phi_1}$, $\mu = 2\ m_{\Phi_1}$, and $\mu = 0.5\ m_{\Phi_1}$.

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