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Search for Second and Third Generation Leptoquarks Including Production via Technicolor Interactions in $p\bar{p}$ Collisions at √s = 1.8 TeV

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We report the results of a search for second and third generation leptoquarks using 88 pb^{-1} of data recorded by the Collider Detector at Fermilab. Color triplet technipions, which play the role of scalar leptoquarks, are investigated due to their potential production in decays of strongly coupled color octet technirhos. Events with a signature of two heavy flavor jets and missing energy may indicate the decay of a second (third) generation leptoquark to a charm (bottom) quark and a neutrino. As the data are found to be consistent with standard model expectations, mass limits are determined.

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While limited to interactions via gauge bosons in the standard model, quarks and leptons couple directly in theories with leptoquarks [1–6]. Leptoquarks appear as color triplet bosons allowing for a Yukawa coupling of strength λ between quarks and leptons. The interactions are assumed to conserve baryon and lepton number and are typically assumed to couple to fermions of the same generation in order to suppress flavor changing neutral currents (FCNCs) [7]. The principal mechanisms for leptoquark pair production at the Tevatron are $q\bar{q}$ annihilation and gluon fusion through either direct coupling to the gluon ("continuum") or a technicolor resonance state.

The characteristics of leptoquark production from continuum can be categorized according to spin. For scalar leptoquarks, the production cross section is parameter-free [8] and known to next-to-leading order [9]. Vector leptoquark interactions include anomalous couplings to the gluons denoted as κ_G and λ_G which are related to the anomalous "magnetic" moment and the "electric" quadrupole moment in the color field [10]. Yang-Mills type coupling ($\kappa_G = \lambda_G = 0$) and minimal coupling ($\kappa_G = 1$ and $\lambda_G = 0$) are investigated. At present only leading order processes have been calculated for vector leptoquark pair production [10]. The phenomenological parameter β describes the branching fraction of a leptoquark decaying to a final state which includes a charged lepton. Previous CDF and D0 analyses have determined excluded leptoquark masses at the 95% confidence level (C.L.) for the second and third generations with $\beta = 0$ and $\beta = 1$ [11].

Enhancement of leptoquark pair production occurs through the decay of technicolor resonance states. Obviating the need for elementary scalar bosons, technicolor theories present a dynamical explanation for electroweak symmetry breaking in which quark and lepton chiral symmetries are explicitly broken by gauge interactions including extended technicolor with a coupling constant that evolves slowly to suppress FCNCs [3–5]. In one of the established formulations, a complete family of technifermions composed of an isodoublet of color triplet techniquarks and an isodoublet of color singlet technileptons form a rich spectrum of technimesons [4]. Color octet technirhos, ρ_{T8}, with the same quantum numbers as the gluon are possible, allowing for s-channel coupling. The color triplet and octet technipions, denoted by π_{LQ} and π_{T8}, couple in a Higgs-like fashion to quarks and leptons with the π_{LQ} identified as a scalar leptoquark. The leading-order cross section for leptoquark pair production from technirho resonances is sensitive to the mass difference between color octet technipion and leptoquark, $\Delta M = M(\pi_{T8}) - M(\pi_{LQ})$, $\Delta M = 50\ \mathrm{GeV}/c^2$ expected [5]. Previous CDF studies of the dijet mass spectrum and third generation leptoquarks have set 95% C.L. mass limits for ρ_{T8} [12].

The decay modes to $c\bar{\nu}$ and $b\bar{\nu}$ corresponding to $\beta = 0$ are utilized to search for pair produced leptoquarks in events with two heavy flavor jets, missing transverse energy, and the absence of high transverse momentum leptons. The continuum leptoquarks are assumed to be strictly second and third generation, their decays involving ν_μ and ν_τ, respectively. Of the several potential color triplet technipion decays, the modes $\pi_{LQ} \to c\bar{\nu}_\tau$ and $\pi_{LQ} \to b\bar{\nu}_\tau$ are possible. Although the color triplet technipion decaying to $c\bar{\nu}_\tau$ is a leptoquark of mixed generation, it is considered to be similar to the second generation leptoquark since neutrino types cannot be distinguished in the detector.

These signatures can be employed to conduct a search for leptoquarks at CDF using a total integrated luminosity of $88.0 \pm 3.6\ \mathrm{pb}^{-1}$ collected during the 1994–1995 Tevatron run. Since detailed descriptions of the CDF detector and its components exist [13], only a recapitulation follows. Detector positions are given by a coordinate system with the z axis along the beam line, azimuthal angle, ϕ, in the plane transverse to the z axis, and pseudorapidity, η. Nearest to the interaction point, the silicon vertex detector (SVX′) consists of four layers providing impact parameter measurements with respect to the primary vertex in the plane transverse to the beam direction [14]. The primary vertices along the beam direction are reconstructed by the vertex tracking chamber in the region $|\eta| < 3.25$. Directly inside a 1.4 T superconducting solenoidal magnet encompassing a range $|\eta| < 1.1$ rests the central drift chamber used for precision measurements of charged particles' momenta. The calorimeter consists of electromagnetic and hadronic components covering a range $|\eta| < 4.2$. The muon system covers a range of $|\eta| < 1$. Missing transverse energy, $\not{E}_T$, indicating the presence of neutrinos in the process, is the energy needed in the direction ϕ to balance the raw energy deposited in the calorimeter towers with $|\eta| < 3.6$ in the plane transverse to the beam direction.

Various selection criteria are applied to the data sample collected using a trigger requiring $\not{E}_T > 35$ GeV. Once the irrelevant sources of $\not{E}_T$ originating from accelerator induced and cosmic ray effects are removed, the remaining 304 582 events are dominated by multijet QCD background. Calorimeter information is used to determine jets through a fixed cone algorithm [15] where the cone radius is 0.4 in η-ϕ space. Events characterized by two or three hard jets with $E_T \geq 15$ GeV and $|\eta| \leq 2$ and no additional jets with $E_T > 7$ GeV and $|\eta| \leq 3.6$ are selected. To reduce systematic effects due to the trigger threshold, the $\not\!E_T$ trigger requirement is increased to $\not\!E_T > 40$ GeV. To reduce the effects of jet energy mismeasurement, the angles between $\not\!E_T$ and any jet are restricted to $\Delta\phi(\not\!E_T, j) > 45°$ and between $\not\!E_T$ and the leading E_T jet $\Delta\phi(\not\!E_T, j_1) < 165°$. To further reduce QCD background, the angle between the two highest E_T jets is restricted to $45° < \Delta\phi(j_1, j_2) < 165°$. The number of events passing these selections is 569. The W and Z backgrounds are reduced by rejecting events containing loosely identified, high transverse momentum leptons (excluding tau leptons). Electron candidates are required to have lateral and longitudinal shower profiles consistent with an electron [16], $E_T < 2p_T$ when the momentum measurement is available, and $E_T > 10$ GeV. Muon candidates are determined by matching a charged track to the calorimeter energy deposition compatible with a minimum ionizing particle [16]. If identified in the muon chambers, the muon candidates must have $p_T > 10$ GeV/c, otherwise they must have $p_T > 15$ GeV/c with additional E_T as measured by the calorimeter less than 5 GeV in a 0.4 radius cone around the lepton. Once these criteria are implemented, 396 events remain.

The jet probability algorithm [17] is employed to tag c and b jets. Jet probability, $\mathcal{P}_{\text{jet}}$, uses precision SVX$'$ information and is formed by combining the probabilities that individual tracks come from a primary vertex for tracks associated with a particular jet. Jets arising from primary vertices have a flat $\mathcal{P}_{\text{jet}}$ distribution from 0 to 1, whereas jets from secondary vertices have a peak at 0. Events corresponding to leptoquark decays with a charm quark in the final state use the requirement of at least one taggable jet [18] with $\mathcal{P}_{\text{jet}} \leq 0.05$. For the signatures with a bottom quark, the data sample is further constrained to contain at least one taggable jet with $\mathcal{P}_{\text{jet}} \leq 0.01$. Applying these criteria, 11 observed events for the c and 5 observed events for the b tagged data samples are found. The signal tagging efficiency is approximately 27% for second generation leptoquarks and 49% for third generation leptoquarks.

After the jet probability requirements are satisfied, the predominant background is determined to come from non-QCD sources. Events with W and one jet, where the W decays leptonically to a tau that decays hadronically, compose the largest single background with 7.6 and 3.0 expected background events for $\mathcal{P}_{\text{jet}} \leq 0.05$ and 0.01, respectively. The total expected $W/Z/t\bar{t}$/diboson background for the 0.05 jet probability cut is 11.1 and for the 0.01 cut is 4.5. The QCD background comprises an expected 3.4 events for $\mathcal{P}_{\text{jet}} \leq 0.05$ and 1.3 events for $\mathcal{P}_{\text{jet}} \leq 0.01$. Further discussion concerning backgrounds can be found in Ref. [18].

Several Monte Carlo generators are employed together with a CDF detector simulation package to estimate the backgrounds and the expected signal. The VECBOS program [19] allows for the tree-level calculation of a vector boson plus jets production at the parton level. The partons are then fragmented and hadronized using HERWIG routines [20]. Vector boson pair production and decay are simulated in ISAJET [21]. HERWIG [20] is employed to compute $t\bar{t}$ events. To generate the signal events for scalar leptoquarks from continuum, PYTHIA version 5.7 [22] is used. For vector and technicolor produced leptoquarks, the expected signal is generated by incorporating the appropriate cross sections [5,10] into PYTHIA. The parton distribution function employed in the simulations was CTEQ 4L [23]. The signal efficiency is degraded by a factor of 0.93 to account for the effect of multiple $p\bar{p}$ interactions not present in the simulations [18]. The same search criteria are applied to the Monte Carlo samples as were applied to the data.

The combined systematic uncertainty for tagging efficiency, jet energy scale, trigger, luminosity, and multiple interactions is 18% for both continuum and technicolor produced leptoquarks [18]. The dominant source of systematic uncertainty for continuum leptoquarks comes from gluon radiation in the initial (ISR) and final (FSR) states. The systematic uncertainty is determined to be 31% by comparing efficiencies obtained with ISR or FSR neglected to those where ISR and FSR were included. The effect of different choices of parton distribution function and QCD renormalization scale is found to give a systematic uncertainty in efficiency of 10%. For the leptoquarks generated from technirho decay, the systematic uncertainty due to ISR and FSR is found to be 25%. The choice of parton distribution function and variation of the renormalization scale contribute a 9% and 20% systematic uncertainty, respectively, to both the efficiencies and cross sections. Combining these results, a maximum total systematic

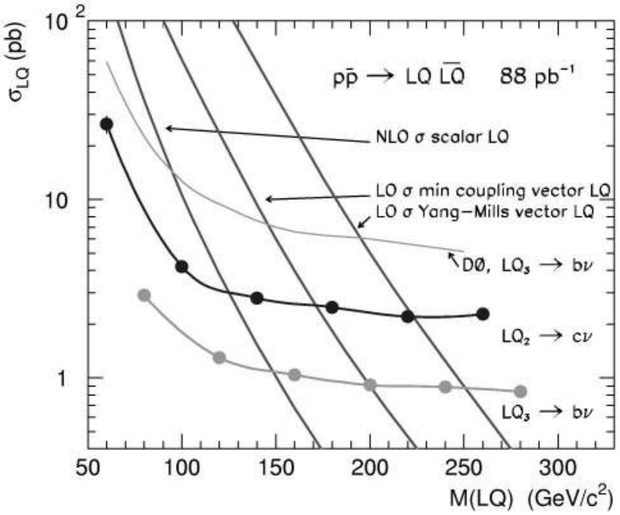

FIG. 1. The 95% C.L. limit for scalar and vector second and third generation leptoquarks assuming $\beta = 0$ compared to theoretical calculations. The D0 Collaboration third generation leptoquark results are also shown [11].

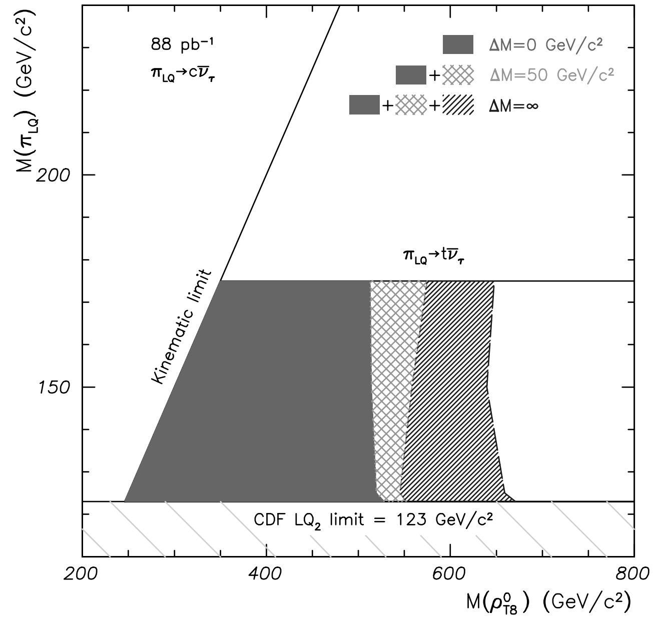

FIG. 2. The 95% C.L. limit for the process $\rho^0_{T8} \rightarrow \pi_{LQ}\bar{\pi}LQ \rightarrow c\bar{c}\nu_\tau\bar{\nu}_\tau$ at $\sqrt{s} = 1.8$ TeV. The solid region corresponds to a mass difference of $\Delta M = 0$ GeV/c^2, the solid and hatched regions to $\Delta M = 50$ GeV/c^2, and all three regions to $\Delta M = \infty$.

uncertainty of 37% is determined for both continuum and technicolor cases.

For the second generation leptoquark search, 11 observed events are found and a background of 14.5 ± 4.2 events is estimated. In the case of third generation leptoquarks, 5 observed events are found and a background of 5.8 ± 1.8 events is estimated. Since no excess of observed events over standard model background is found, 95% C.L. limits are determined through a background subtraction method [24].

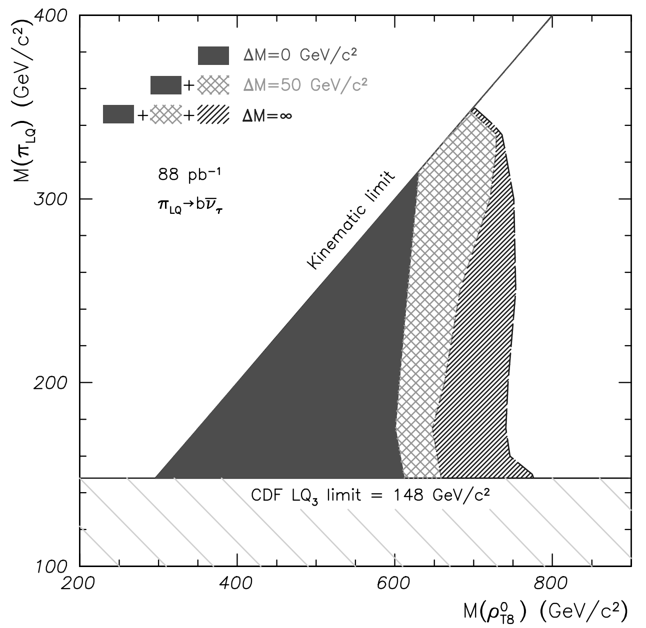

FIG. 3. The 95% C.L. limit for the process $\rho^0_{T8} \rightarrow \pi_{LQ}\bar{\pi}LQ \rightarrow b\bar{b}\nu_\tau\bar{\nu}_\tau$ at $\sqrt{s} = 1.8$ TeV. The solid region corresponds to a mass difference of $\Delta M = 0$ GeV/c^2, the solid and hatched regions to $\Delta M = 50$ GeV/c^2, and all three regions to $\Delta M = \infty$.

The 95% C.L. limits on continuum leptoquark production cross sections are determined and compared to the corresponding theoretical cross sections [9,10]. The results are shown in Fig. 1. In the case of second generation leptoquarks, scalar leptoquarks with $M < 123$ GeV/c^2, minimally coupled vector leptoquarks with $M < 171$ GeV/c^2, and Yang-Mills vector leptoquarks with $M < 222$ GeV/c^2 are excluded. For third generation leptoquarks, scalar leptoquarks with $M < 148$ GeV/c^2, minimally coupled vector leptoquarks with $M < 199$ GeV/c^2, and Yang-Mills vector leptoquarks with $M < 250$ GeV/c^2 are excluded.

The 95% C.L. exclusion regions in the $M(\rho_{T8}) - M(\pi_{LQ})$ plane for $\Delta M = 0$, 50 GeV/c^2, and ∞ shown as shaded areas in Figs. 2 and 3 are determined by comparing the 95% C.L. cross section limit for production of leptoquarks which decay to quarks and neutrinos to theoretical predictions [5]. The kinematically forbidden region is given by $M(\rho_{T8}) < 2M(\pi_{LQ})$. In Fig. 2, the decay of the leptoquark to $c\bar{\nu}_\tau$ is limited by the top quark mass, above which the leptoquark will decay preferentially to $t\bar{\nu}_\tau$. When $\Delta M = 0$, $M(\rho_{T8}) < 510$ GeV/c^2 for the second generation and $M(\rho_{T8}) < 600$ GeV/c^2 for the third generation are excluded at 95% C.L.

This analysis reports on the search for leptoquarks produced from continuum and color octet technirho decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using 88 pb^{-1} of data. Events with two or three jets, substantial missing energy, and no high transverse momentum leptons are subjected to the jet probability requirement indicating at least one jet being consistent with originating from a heavy flavor. No excess of events above standard model predictions are found, and therefore 95% C.L. limits are determined.

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