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Search for Third-Generation Leptoquarks from Technicolor Models in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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Search for Third-Generation Leptoquarks from Technicolor Models in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report the results of a search for technicolor using 110 pb^{-1} of $p\overline{p}$ collisions recorded by the Collider Detector at Fermilab (CDF). In technicolor models containing a technifamily, color-octet technirhos enhance the pair production of color-triplet technipions, which behave as third-generation leptoquarks. From our previously reported search for third-generation leptoquarks, we present constraints on the production of color-triplet technipions and color-octet technirhos as a function of their masses. [S0031-9007(99)08964-4]

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To date, experiments have yet to uncover the mechanism of electroweak symmetry breaking. In the standard model and many extensions to it, the electroweak symmetry is spontaneously broken by introducing fundamental scalar particles into the theory. These are eventually identified with W_L, Z_L, and one or more physical Higgs bosons [1]. Extensive searches for such Higgs bosons are underway [2,3]. Alternatively, the electroweak symmetry may be broken dynamically. This is the hallmark of technicolor (TC) theories [4,5] in which a new strong gauge force (technicolor) and new fermions (technifermions) are introduced. The concept of technicolor is inspired by QCD, with the technifermions being the analogs of ordinary quarks. Technicolor acts between the technifermions to form bound states (technihadrons). In particular, the technipions include the longitudinal weak bosons, W_L and Z_L, as well as the pseudo-Goldstone bosons of dynamical symmetry breaking. Thus the dynamics of the technifermions assume the role of the scalar Higgs fields in theories with spontaneous symmetry breaking.

Particularly interesting from the present experimental point of view [6,7] are TC models containing a technifamily, i.e., a set of technifermions with the same structure and quantum numbers of a complete standard model generation of quarks and leptons, and carrying an additional TC quantum number. By convention, technifermions which are color triplets of ordinary QCD are called techniquarks, and color-singlet technifermions are called technileptons. The particle spectrum of these models includes color-singlet, -triplet, and -octet technipions. The technipions (π_T) decay via extended technicolor (ETC) interactions [8]. Since these are also responsible for the fermion masses, technipions are expected to have Higgs-boson-like couplings to ordinary fermions, i.e., to decay preferentially to third-generation quarks and leptons. In particular, the color-triplet technipions are an example of scalar third-generation leptoquarks (π_{LQ}). In this Letter, we use the results of a search for third-generation leptoquarks in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, previously published by the Collider Detector at Fermilab (CDF) Collaboration [9], in order to constrain TC models containing a technifamily. Other experimental constraints on these models come from precision electroweak measurements at LEP [10,11], and from measurements of the $b \to s\gamma$ decay rate [12].

Here we expand the scope of the previous search [9] to include leptoquarks produced in technicolor models containing a family of color-singlet technileptons and color-triplet techniquarks. In these models, there is a color-octet vector resonance, called technirho (ρ_T), with the quantum numbers of the gluon. Leptoquarks (LQs) are assumed to be pair produced via gluon-gluon fusion and $q\overline{q}$ annihilation. In $q\overline{q}$ and gg collisions, the ρ_T couples to the gluon propagator enhancing s-channel reactions (Fig. 1), analogously to the vector-meson-dominance description of the process $e^+e^- \to \pi^+\pi^-$ [13]. Two decay modes may exist for the technirho [7]: $\rho_T \to q\overline{q}$, gg and $\rho_T \to \pi_T\overline{\pi}_T$. If the ρ_T mass is less than twice the π_T mass, only the $q\overline{q}$, gg decay modes are possible, resulting in resonant dijet production. A search result for the dijet signal of ρ_T has already been reported by the CDF Collaboration. The CDF-measured dijet mass spectrum excludes ρ_T with masses in the range $260 < M(\rho_T) < 480$ GeV/c^2 at the 95% C.L. [14]. If the ρ_T mass is larger than twice the π_T mass, the ρ_T decays preferentially into π_T pairs.

The total production cross section (σ_T) and detection efficiency (ϵ_T) can be expressed as integrals over the invariant mass of the underlying partonic interactions as

$$\sigma_T = \int_{4M(\pi_T)^2}^{s} \frac{d\sigma}{d\hat{s}}\, d\hat{s}\,,$$

$$\epsilon_T = \frac{1}{\sigma_T} \int_{4M(\pi_T)^2}^{s} \frac{d\sigma}{d\hat{s}}\, \hat{\epsilon}(\hat{s})\, d\hat{s}\,.$$

The existence of the ρ_T resonance modifies the normalization and shape of the $d\sigma/d\hat{s}$ spectrum, affecting σ_T and ϵ_T. σ_T grows with respect to the continuum case. For a given technipion mass, the function $\hat{\epsilon}(\hat{s})$ is a monotonically increasing function of $\hat{s}$. Therefore, the integrated efficiency ϵ_T simply reflects the shape of the $d\sigma/d\hat{s}$ distribution. Three cases should be discussed depending on the value of the ρ_T mass. First, when $M(\rho_T)$ is near its kinematical threshold of $2M(\pi_T)$, the resonance Breit-Wigner is partially cut and the resulting $d\sigma/d\hat{s}$ distribution is softer than in the continuum case. The 95% C.L. limits are expected to degrade accordingly. In the normal case, the resonance is fully contained, and the technipion pairs are formed in collisions with higher average $\hat{s}$. The efficiency is enhanced yielding constraints on leptoquark pair production stronger

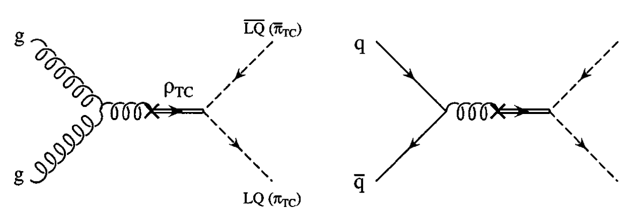

FIG. 1. The resonant production of leptoquark (technipion) pairs. The technirho couples directly to the gluon via vector-meson-dominance enhancing the s-channel production of LQ pairs.

than the ones obtained in the previous analysis [9]. Finally, when $M(\rho_T) \gg 2M(\pi_{\mathrm{LQ}})$ the relative size of the resonant part of $d\sigma/d\hat{s}$ decreases, representing a small perturbation of the continuum spectrum. In this region ϵ_T is expected to reach asymptotically its continuum value.

The technipion spectrum of the technifamily model was estimated in [7,15]. It contains color-singlet, -triplet, and -octet (π_8) technipions. The octets are heavier than the triplets, and these are heavier than the singlets. We make the simplifying assumption that there is no mass splitting among the different octet and triplet technipions. As pointed out in the introduction, color-triplet technipions are scalar third-generation leptoquarks. We consider the class of leptoquarks decaying via $\pi_{\mathrm{LQ}} \to \overline{b}\tau^-$ ($\overline{\pi}_{\mathrm{LQ}} \to b\tau^+$) with branching fraction β.

The leading-order leptoquark pair production cross section depends only on the technirho mass $(M(\rho_T))$, the leptoquark mass $(M(\pi_{\mathrm{LQ}}))$, and the technirho width $(\Gamma(\rho_T))$. $M(\pi_{\mathrm{LQ}})$ and $M(\rho_T)$ are treated as independent free parameters. $\Gamma(\rho_T)$ can be calculated as a function of four more basic quantities, $\Gamma(\rho_T) = \Gamma(M(\rho_T), M(\pi_{\mathrm{LQ}}), \Delta M, N_{TC})$, where $\Delta M = M(\pi_8) - M(\pi_{\mathrm{LQ}})$, and N_{TC} is the number of technicolors. We consider $M(\rho_T)$, $M(\pi_{\mathrm{LQ}})$, ΔM, and N_{TC} as the four continuous parameters of the theory. We set limits in the $M(\pi_{\mathrm{LQ}}) - M(\rho_T)$ plane. We probe the dependence of the production cross section on $\Gamma(\rho_T)$ by fixing $N_{TC} = 4$, while allowing ΔM to take one expected and two limiting values. ETC and QCD corrections to $M(\pi_8)$ and $M(\pi_{\mathrm{LQ}})$ are responsible for ΔM, analogously to the QED corrections to $M(\pi^0)$ and $M(\pi^\pm)$. ΔM is expected to be around 50 GeV$/c^2$ [7]. We take $\Delta M = 0$ and $\Delta M = \infty$ as two extreme values. The resulting variation in $\Gamma(\rho_T)$ could also have been obtained changing N_{TC} by a factor of 4, for a fixed $\Delta M = 50$ GeV$/c^2$.

The experimental signature considered is $\tau^+\tau^-$ plus two jets in the final state, in the case where one τ decays leptonically and the other decays hadronically. The analysis selects a 110 pb^{-1} data set containing an isolated electron or muon in the region $|\eta| < 1$ with $p_T > 20$ GeV$/c$ [16], and an isolated, highly collimated hadronic jet consistent with a hadronic tau decay. Hadronic τ candidates (τ jets) are selected from jets that have an uncorrected total transverse energy of $E_T > 15$ GeV in the region $|\eta| < 1$. The associated charged particles with $p_T > 1$ GeV$/c$ in a cone of angular radius 10° around the jet direction must satisfy the following requirements: (i) the τ jet must have one or three charged particles; (ii) if there are three, the scalar sum p_T must exceed 20 GeV$/c$ and the invariant mass must be smaller than 2 GeV$/c^2$; and (iii) the leading charged particle must have $p_T > 10$ GeV$/c$ and must point to an instrumented region of the calorimeter. The efficiency of the τ-jet identification criteria grows from 32% for τ jets in the range $15 < E_T < 20$ GeV to a plateau value of 59% for $E_T > 40$ GeV. Isolated τ jets must have no charged particles with $p_T > 1$ GeV$/c$ in the annulus between 10° and 30° around the jet axis. Events where the high-p_T lepton is consistent with originating from a $Z \to ee$ or $Z \to \mu\mu$ decay are removed. In addition, the analysis uses the missing transverse energy characteristic of neutrinos from tau decays. The requirement $\Delta\Phi < 50°$, where $\Delta\Phi$ is the azimuthal separation between the directions of the missing transverse energy $\not{E}_T$ and the lepton, distinguishes $\tau^+\tau^-$ events from backgrounds such as W + jets. Finally, two or more jets with $E_T > 10$ GeV and $|\eta| < 4.2$, assumed to originate from b quark hadronization, are required. One opposite-sign leptoquark pair candidate event survives these selection criteria, but no same-sign event survives. The observed yield is consistent with the $2.4^{+1.2}_{-0.6}$ expected background events from standard model processes, dominated by $Z \to \tau\tau$ + jets production (2.1 ± 0.6) with the remainder from diboson and $t\bar{t}$ production [9]. Fake backgrounds are estimated by the number of same-sign events (0^{+1}_{-0}).

The detection efficiencies for the signal are determined using a full leading-order matrix element calculation for technipion pair production [7] and embedded in the PYTHIA Monte Carlo program [17] to model the full $p\overline{p}$ event structure. The generated events are passed through a detector simulation program and subjected to the same search requirements as the data. The total efficiency increases from 0.3% for $M(\rho_T) =$ 200 GeV$/c^2$ and $M(\pi_{\mathrm{LQ}}) = 100$ GeV$/c^2$, to 1.8% for $M(\rho_T) = 700$ GeV$/c^2$ and $M(\pi_{\mathrm{LQ}}) = 300$ GeV$/c^2$. The efficiencies of the different analysis cuts are detailed in Table I, for the $M(\rho_T) = 400$ GeV$/c^2$ and $M(\pi_{\mathrm{LQ}}) = 100$ GeV$/c^2$ case. The systematic errors in the efficiencies were estimated as described in [9], including uncertainties in the modeling of gluon radiation, in the calorimeter energy scale, in the dependence on renormalization scales, and in the luminosity measurement. They range from 15% for $M(\rho_T) = 200$ GeV$/c^2$ and $M(\pi_{\mathrm{LQ}}) = 100$ GeV$/c^2$, to 10% for $M(\pi_{\mathrm{LQ}}) \geq 125$ GeV$/c^2$.

We place limits on the leptoquark pair production cross section times branching ratio squared within the framework of the technicolor model described above. The 95% confidence level (C.L.) upper limit, $\sigma_{\mathrm{LQ}}\beta^2$, is

TABLE I. Efficiency of the analysis cuts for the $M(\rho_T) =$ 400 GeV$/c^2$ and $M(\pi_{\mathrm{LQ}}) = 100$ GeV$/c^2$ case. Errors reflect the finite statistics of the Monte Carlo simulation.

Cut	Efficiency (%)
Lepton + τ-jet selection	3.23 ± 0.10
Lepton isolation	72.0 ± 1.5
τ-jet isolation	70.0 ± 1.8
Z removal	63.7 ± 2.2
$\Delta\Phi < 50°$	59.1 ± 2.9
$N_{\mathrm{jets}} \geq 2$	88.6 ± 2.4
Total	0.52 ± 0.02

TABLE II. The 95% confidence level upper limits on the leptoquark (color-triplet technipion) production cross section times branching ratio squared as a function of $M(\pi_{\mathrm{LQ}})$ and $M(\rho_T)$, for $\Delta M = 50\ \mathrm{GeV}/c^2$. Numbers are given in pb.

$M(\pi_{\mathrm{LQ}})$	$M(\rho_T)$ (GeV/c^2)										
(GeV/c^2)	200	250	300	350	400	450	500	550	600	650	700
100	12.7	9.8	8.2	7.4	7.2	7.7	8.5	9.4	9.8	10.0	10.2
125		6.4	5.3	4.6	4.1	3.9	3.9	4.1	4.5	4.8	5.0
150			4.7	4.1	3.6	3.3	3.1	3.0	3.1	3.2	3.5
175				3.7	3.3	3.1	2.9	2.7	2.6	2.6	2.7
200					3.4	3.0	2.8	2.5	2.3	2.2	2.1
225						2.9	2.7	2.5	2.3	2.2	2.1
250							2.8	2.5	2.3	2.2	2.1
275								2.5	2.3	2.2	2.0
300									2.3	2.2	2.0

given by

$$\sigma_{\mathrm{LQ}}\beta^2 = \frac{N_{95\%}}{\epsilon_{\mathrm{LQ}} \int \mathcal{L}\, dt},$$

where ϵ_{LQ} is the total detection efficiency, and $\int \mathcal{L}\, dt = 110 \pm 8\ \mathrm{pb}^{-1}$ is the integrated luminosity. $N_{95\%}$ represents the 95% C.L. upper limit on the number of leptoquark events observed and is determined using a background subtraction method which takes into account the systematic uncertainties in both the signal efficiency and the background estimates [18]. This is accomplished using the following relation with C.L. $= 0.95$

$$1 - \mathrm{C.L.} = \frac{\int_0^\infty dz\, \int_0^\infty dx \int_0^\infty dy\, G(x; N_{95\%}, \mathcal{U} \cdot N_{95\%}) G(y; \mu_B, \sigma_B) \sum_{n=0}^{\mathcal{N}_{\mathrm{obs}}^{OS}} \frac{(x+y+z)^n}{n!} e^{-(x+y+z)} \sum_{m=0}^{\mathcal{N}_{\mathrm{obs}}^{SS}} \frac{z^m}{m!} e^{-z}}{\int_0^\infty dz\, \int_0^\infty dy\, G(y; \mu_B, \sigma_B) \sum_{n=0}^{\mathcal{N}_{\mathrm{obs}}^{OS}} \frac{(y+z)^n}{n!} e^{-(y+z)} \sum_{m=0}^{\mathcal{N}_{\mathrm{obs}}^{SS}} \frac{z^m}{m!} e^{-z}},$$

where $\mathcal{N}_{\mathrm{obs}}^{OS} = 1$ and $\mathcal{N}_{\mathrm{obs}}^{SS} = 0$ are the observed numbers of opposite-sign candidates and same-sign fake events, respectively. $\mathcal{U}$ is the total systematic uncertainty, $\mu_B = 2.4$ and $\sigma_B = 0.6$ are the real $\tau^+\tau^-$ background estimate and associated uncertainty, and $G(x; \bar{x}, \sigma)$ is a Gaussian distribution in x, with mean $\bar{x}$ and width σ.

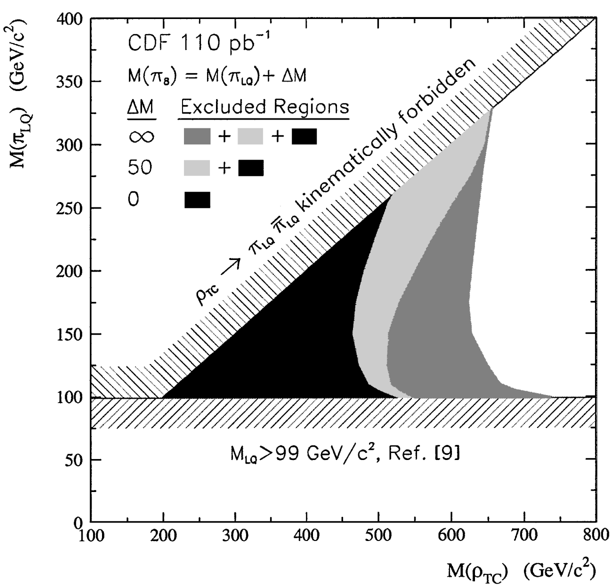

FIG. 2. The 95% C.L. exclusion regions in the $M(\pi_{\mathrm{LQ}}) - M(\rho_T)$ plane. The three shaded areas correspond (from left to right) to technipion mass splitting values of 0, 50 GeV/c^2, and ∞, respectively.

Table II lists the leptoquark 95% confidence level upper limits on the production cross section times branching ratio squared as a function of $M(\pi_{\mathrm{LQ}})$ and $M(\rho_T)$ for $\Delta M = 50\ \mathrm{GeV}/c^2$. These numbers differ by at most 1 pb from the corresponding limits for $\Delta M = 0$ and $\Delta M = \infty$ when $M(\pi_{\mathrm{LQ}}) < 175\ \mathrm{GeV}/c^2$. For larger values of $M(\pi_{\mathrm{LQ}})$ the differences are negligible. Assuming $\beta = 1$, and comparing to the theoretical expectations for $\sigma(p\bar{p} \to \pi_{\mathrm{LQ}}\bar{\pi}_{\mathrm{LQ}})$, we place bounds in the $M(\pi_{\mathrm{LQ}}) - M(\rho_T)$ plane. Figure 2 shows the 95% C.L. mass exclusion regions calculated using the CTEQ-2L parton distribution functions [19]. The upper part of the plot corresponds to the kinematically forbidden region where $M(\rho_T) < 2M(\pi_{\mathrm{LQ}})$. The bottom region is the exclusion area from the continuum leptoquark analysis, $M(\pi_{\mathrm{LQ}}) \geq 99\ \mathrm{GeV}/c^2$ [9]. The three shaded areas from left to right correspond to technipion mass splitting values of $\Delta M = 0$, $50\ \mathrm{GeV}/c^2$, and ∞, respectively. Although more information is presented in Fig. 2, it is useful to summarize our technirho excluded region using a single number. For $\Delta M = 0$ and $M(\pi_{\mathrm{LQ}}) < M(\rho_T)/2$, we exclude color-octet technirhos with mass less than $465\ \mathrm{GeV}/c^2$ at 95% confidence level.

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