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

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Abstract

We report the results of a search for technicolor using 110 pb^{-1} of $p\bar{p}$ 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.

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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 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 technicolor force 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 $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, previously published by CDF [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 are assumed to be pair produced via gluon-gluon fusion and $q\bar{q}$ annihilation. In $q\bar{q}$ 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 $e^+e^- \rightarrow \pi^+\pi^-$ [13]. Two decay modes may exist for the technirho [7]: $\rho_T \rightarrow q\bar{q}, gg$ and $\rho_T \rightarrow \pi_T\bar{\pi}_T$. If the ρ_T mass is less than twice the π_T mass, only the $q\bar{q}, gg$ decay modes are possible, resulting in resonant dijet production. A search result for the dijet signal of ρ_T has already been reported by CDF. 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 existence of the ρ_T s-channel resonance would enhance the detection possibilities of third-generation leptoquarks for $M(\rho_T) > 2M(\pi_{LQ})$. The production cross section grows with respect to the continuum case and the detection efficiencies increase due to the extra energy released in the decay $\rho_T \rightarrow \pi_{LQ}\bar{\pi}_{LQ}$. Both effects yield constraints on leptoquark pair production stronger than the ones obtained in the previous analysis [9]. The first effect dominates when $M(\rho_T)$ is near its kinematical threshold of $2M(\pi_{LQ})$. When the difference $M(\rho_T) - 2M(\pi_{LQ})$ grows, the second effect tends to become more important.

The technipion spectrum of the technifamily model was estimated in [15,7]. 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 $\pi_{LQ} \rightarrow \bar{b}\tau^-$ ($\bar{\pi}_{LQ} \rightarrow b\tau^+$) with branching fraction β.

The leading-order leptoquark pair production cross section depends only on the technirho mass ($M(\rho_T)$), the leptoquark mass ($M(\pi_{LQ})$), and the technirho width ($\Gamma(\rho_T)$). $M(\pi_{LQ})$ and $M(\rho_T)$ are treated as independent free parameters. $\Gamma(\rho_T)$ can be calculated as a function of four more basic quantities, $\Gamma(\rho_T) = \Gamma(M(\rho_T), M(\pi_{LQ}), \Delta M, N_{TC})$, where $\Delta M = M(\pi_8) - M(\pi_{LQ})$, and N_{TC} is the number of technicolors. We consider $M(\rho_T)$, $M(\pi_{LQ})$, ΔM, and N_{TC} as the four continuous parameters of the theory. We set limits in the $M(\pi_{LQ}) - M(\rho_T)$ 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 $M(\pi_{LQ})$ are responsible for ΔM, analogously to the QED corrections to $M(\pi^o)$ 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 10° cone 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 leptoquark pair candidate event survives these selection criteria. 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].

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 $p\bar{p}$ 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 $M(\pi_{LQ}) = 100$ GeV/c^2, to 1.8% for $M(\rho_T) = 700$ GeV/c^2 and $M(\pi_{LQ}) = 300$ 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 $M(\pi_{LQ}) = 100$ GeV/c^2 case. The systematic errors in the efficiencies were estimated as described in [9], including uncertainties in the modelling 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 $M(\pi_{LQ}) = 100$ GeV/c^2, to 10% for $M(\pi_{LQ}) \geq 125$ 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, $\sigma_{LQ} \cdot \beta^2$, is given by

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

where ϵ_{LQ} is the total detection efficiency, and $\int \mathcal{L}\, dt = 110 \pm 8$ 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 background estimates [18]. This is accomplished using the following relation with ${\scriptstyle C.L.} = 0.95$

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

where $\mathcal{N}_{obs} = 1$ is the number of candidate events observed, $\mathcal{U}$ is the total systematic uncertainty, $\mu_B = 2.4$ and $\sigma_B = 0.6$ are the background estimate and associated uncertainty, and $G(x; \bar{x}, \sigma)$ is a Gaussian distribution in x, with mean $\bar{x}$ and width σ.

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

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TABLES

TABLE I. Efficiency of the analysis cuts for the $M(\rho_T) = 400$ GeV/c^2 and $M(\pi_{LQ}) = 100$ 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
$\Delta\Phi < 50^o$	59.1 ± 2.9
$N_{jets} \geq 2$	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 $M(\pi_{LQ})$ and $M(\rho_T)$, for $\Delta M = 50$ GeV/c^2. Numbers are given in pb.

$M(\pi_{LQ})$	$M(\rho_T)$ (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

FIGURES

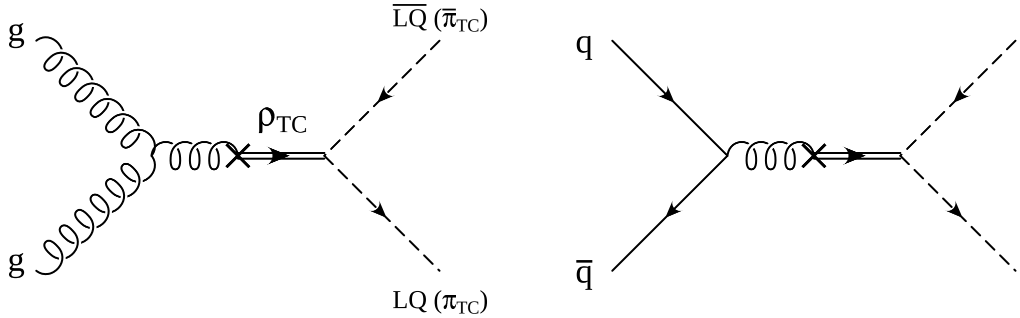

FIG. 1. The resonant production of leptoquark (technipion) pairs. The technirho couples directly to the gluon via vector-meson-dominance enhancing the s-channel production of LQ pairs.

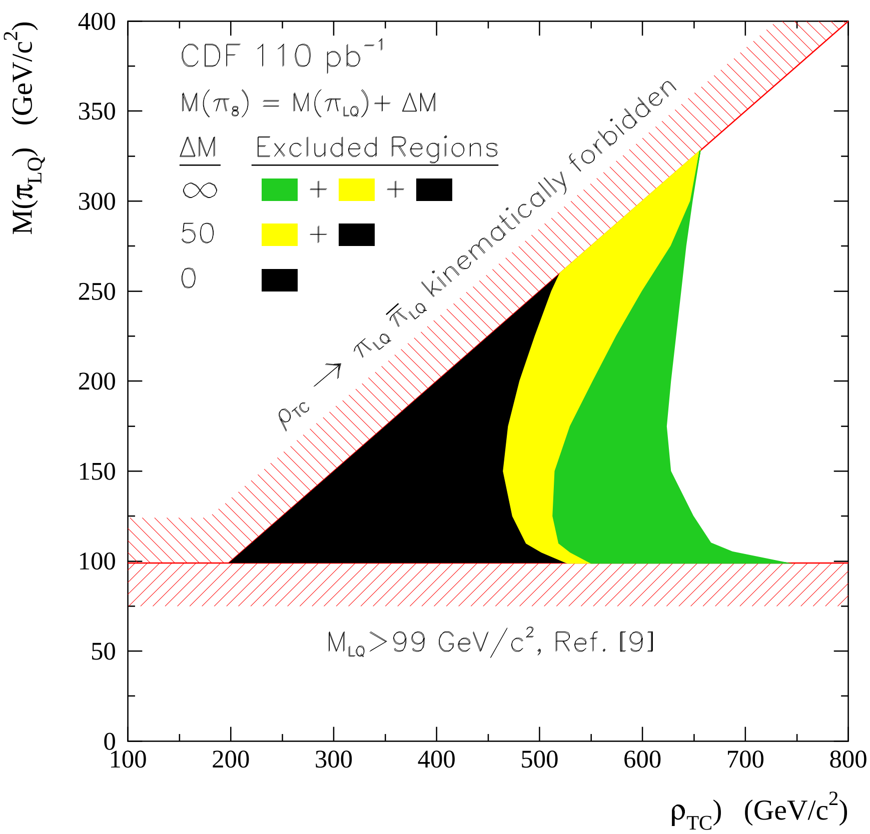

FIG. 2. The 95% C.L. exclusion regions in the $M(\pi_{LQ}) - M(\rho_T)$ plane. The three shaded areas correspond (from left to right) to technipion mass splitting values of 0, 50 GeV$/c^2$ and ∞, respectively.