

## Technicolor Explanation for the CDF $Wjj$ Excess

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We propose that the  $3.2\sigma$  excess at  $\sim 150$  GeV in the dijet mass spectrum of  $W +$  jets reported by CDF is the technipion  $\pi_T$  of low-scale technicolor. Its relatively large cross section is due to production of a narrow  $Wjj$  resonance, the technirho, which decays to  $W\pi_T$ . We discuss ways to enhance and strengthen the technicolor hypothesis and suggest companion searches at the Tevatron and LHC.

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**Introduction.**—The CDF Collaboration has reported a surprising excess at  $M_{jj} \approx 150$  GeV in the dijet mass distribution of  $W +$  jets events. Fitting the excess to a Gaussian, CDF estimated its production rate to be  $\sim 4$  pb. This is 300 times the standard-model Higgs rate  $\sigma(\bar{p}p \rightarrow WH)B(H \rightarrow \bar{b}b)$ . The Gaussian fit is consistent with a zero-width resonance. Its significance, for a search window of 120–200 GeV and including systematic uncertainties, is  $3.2\sigma$  [1].

In our view, the most plausible new-physics explanation of this excess is resonant production and decay of bound states of technicolor (TC), a new strong interaction at  $\Lambda_{TC} \sim$  several hundred GeV of massless technifermions [2–5]. These technifermions are assumed to belong to complex representations of the TC gauge group and transform as quarks and leptons do under electroweak (EW)  $SU(2) \otimes U(1)$ . Then, the spontaneous breaking of their chiral symmetry breaks EW symmetry down to electromagnetic  $U(1)$  with a massless photon and  $M_W/M_Z \cos\theta_W = 1 + \mathcal{O}(\alpha)$ . We propose that the dijet resonance is the lightest pseudo-Goldstone isovector technipion ( $\pi_T$ ) of the low-scale technicolor scenario. The immediate consequence of this hypothesis is a narrow  $I = 1$  technirho ( $\rho_T$ ) resonance in the  $Wjj$  channel. This accounts for the large  $W\pi_T$  production rate.

In this Letter, we show that a  $\rho_T$  of mass  $\approx 290$  GeV decaying into  $W$  plus  $\pi_T$  of 160 GeV accounts for the CDF dijet excess. The  $\rho_T$  signal sits near the peak of the  $M_{Wjj}$  distribution and will be less obvious than  $\pi_T \rightarrow jj$ . We suggest ways to enhance this signal and tests of the  $\rho_T$ 's presence: (i) The  $\rho_T$ 's narrowness will be reflected in  $Q = M_{Wjj} - M_{jj} - M_W$  [6,7]. The  $M_{jj}$  bins near  $M_{\pi_T}$  will exhibit a sharp increase over background for  $Q \approx Q^* = M_{\rho_T} - M_{\pi_T} - M_W$ . (ii) The  $\rho_T \rightarrow W\pi_T$  angular distribution in the  $\rho_T$  frame will be approximately  $\sin^2\theta$ , indicative of the signal's technicolor origin. We propose further tests of the technicolor hypothesis, including other resonantly produced states which can be discovered at the Tevatron and LHC.

Low-scale technicolor (LSTC) is a phenomenology based on walking technicolor [8–11]. The TC gauge

coupling must run very slowly for 100 s of TeV above  $\Lambda_{TC}$  so that extended technicolor (ETC) can generate sizable quark and lepton masses [12] while suppressing flavor-changing neutral current interactions [14]. This may be achieved if technifermions belong to higher-dimensional representations of the TC gauge group. Then, the constraints of Ref. [14] on the number of ETC-fermion representations imply technifermions in the fundamental representation as well. Thus, there are technifermions whose technipions' decay constant  $F_1^2 \ll F_\pi^2 = (246 \text{ GeV})^2$  [15]. Bound states of these technifermions will have masses well below a TeV—greater than the limit  $M_{\rho_T} \gtrsim 250$  GeV [7,16] and probably less than the 600–700 GeV at which “low-scale” TC ceases to make sense. Technifermions in complex TC representations imply a quarkoniumlike spectrum of mesons. The most accessible are the lightest technivectors  $V_T = \rho_T(I^G J^{PC} = 1^+ 1^{--})$ ,  $\omega_T(0^- 1^{--})$ , and  $a_T(1^- 1^{++})$ ; these are produced as  $s$ -channel resonances in the Drell-Yan process in hadron colliders. Technipions  $\pi_T(1^- 0^{-+})$  are accessed in  $V_T$  decays. A central assumption of LSTC is that these technihadrons may be treated in isolation, without significant mixing or other interference from higher-mass states. Also, we expect that (i) the lightest technifermions are  $SU(3)$ -color singlets, (ii) isospin violation is small for  $V_T$  and  $\pi_T$ , (iii)  $M_{\omega_T} \approx M_{\rho_T}$ , and (iv)  $M_{a_T}$  is not far above  $M_{\rho_T}$ . An extensive discussion of LSTC, including these points and precision electroweak constraints, is given in Ref. [17].

Walking technicolor has another important consequence: It enhances  $M_{\pi_T}$  relative to  $M_{\rho_T}$  so that the all- $\pi_T$  decay channels of the  $V_T$  likely are closed [15]. Principal  $V_T$ -decay modes are  $W\pi_T$ ,  $Z\pi_T$ ,  $\gamma\pi_T$ , a pair of EW bosons (including one photon), and fermion-antifermion pairs [17–19]. If allowed by isospin, parity, and angular momentum,  $V_T$  decays to one or more weak bosons involve longitudinally polarized  $W_L/Z_L$ , the technipions absorbed via the Higgs mechanism. These nominally strong decays are suppressed by powers of  $\sin\chi = F_1/F_\pi \ll 1$ . Decays to transversely polarized  $\gamma$ ,  $W_\perp$ , and  $Z_\perp$  are suppressed by  $g$  and  $g'$ . Thus, the  $V_T$  are

very narrow:  $\Gamma(V_T) \lesssim 1$  GeV. These decays provide striking signatures, visible above backgrounds within a limited mass range at the Tevatron and probably up to 600–700 GeV at the LHC [20,21].

*The new dijet resonance at the Tevatron.*—Previous  $\rho_T \rightarrow W\pi_T$  searches at the Tevatron focused on final states with  $W \rightarrow \ell\nu_\ell$  and  $\pi_T \rightarrow \bar{q}q$  where one or both quarks was a tagged  $b$ . This was advocated in Ref. [6] because  $\pi_T$  couplings to standard-model fermions are induced by ETC interactions and are, naively, expected to be largest for the heaviest fermions. Thus,  $\pi_T^+ \rightarrow \bar{b}c$ ,  $\bar{b}u$  and  $\pi_T^0 \rightarrow \bar{b}b$  have been assumed, at least for  $M_{\pi_T} \lesssim m_t$ . While reasonable for  $\pi_T^0$  decays, it is questionable for  $\pi_T^\pm$  because Cabibbo-Kobayashi-Maskawa-like angles may suppress  $\bar{b}q$ . This is important because the inclusive  $\sigma(\bar{u}u, \bar{d}d \rightarrow \rho_T^0) \approx 1.6 \times \sigma(\bar{d}u, \bar{u}d \rightarrow \rho_T^\pm)$  at the Tevatron. If  $\pi_T^+ \rightarrow \bar{b}q$  is turned off in the default model of  $\pi_T$  decays used here [18], up to 40% of the  $\rho_T \rightarrow W\pi_T \rightarrow Wjj$  signal is vetoed by a  $b$  tag. It is notable, therefore, that the CDF observation did not require  $b$ -tagged jets [1].

At first, it seems unlikely that  $\rho_T \rightarrow W\pi_T$  could be found in untagged dijets because of the large  $W$  + jets background. However, Ref. [22] studied  $\rho_T \rightarrow W\pi_T^0$  without flavor tagging and showed that a  $\pi_T \rightarrow jj$  signal could be extracted. Recently, strong  $W/Z \rightarrow jj$  signals have been observed in  $WW/WZ$  production at the Tevatron [23,24]. So, heavier dijet states resonantly produced with  $W/Z/\gamma$  may indeed be discoverable at the Tevatron.

The CDF dijet excess was enhanced by requiring  $p_T(jj) > 40$  GeV [1]. Such a cut was proposed in Ref. [6]. There it was emphasized that the small  $Q$  value in  $\rho_T \rightarrow W\pi_T$  and the fact that the  $\rho_T$  is approximately at rest in the Tevatron lab frame cause the  $\pi_T$  to be emitted with limited  $p_T$  and its decay jets to be roughly back-to-back in  $\phi$ .

*Simulating  $\rho_T \rightarrow W\pi_T$ .*—PYTHIA 6.4 is used throughout to generate the  $\rho_T \rightarrow W\pi_T$  signal [25]. It employs the default  $\pi_T$ -decay model of Ref. [18] in which  $\pi_T^+ \rightarrow \bar{b}q$  is unhindered. The input masses are  $(M_{\rho_T}, M_{\pi_T}) = (290, 160)$  GeV. This  $M_{\pi_T}$  gives a peak in the simulated  $M_{jj}$  distribution near 150 GeV [26]. This parameter choice is close to case 2(b) of Contribution 8 in Ref. [21].

The signal cross sections [including  $B(\pi_T^0 \rightarrow \bar{q}q) \approx 0.90$ ,  $B(\pi_T^\pm \rightarrow \bar{q}q') \approx 0.95$ , and  $B(W \rightarrow \ell^\pm \nu_\ell) = 0.21$ ] are  $\sigma(W^\pm \pi_T^\pm) = 310$  fb and  $\sigma(W^\pm \pi_T^0) = 175$  fb [27]. Only 20%–30% of these cross sections come from the 320 GeV  $a_T \rightarrow W_\perp \pi_T$ . If  $M_{a_T} = 293$  GeV, they increase slightly to 335 and 205 fb. If  $\pi_T^+ \rightarrow \bar{b}q$  is suppressed, then  $\sigma(W^\pm \pi_T^\pm) = 110$  fb, a decrease of 2/3, for a total  $Wjj$  signal of 285 fb.

Backgrounds come from standard-model  $W/Z$  + jets, including  $b$ ,  $c$ -jets,  $WW/WZ$ ,  $t\bar{t}$ , and multijet QCD. The last two amount to  $\sim 10\%$  at the Tevatron, and we neglect them. The others are generated at the parton level with ALPGENV13 [28] and fed into PYTHIA for showering and

hadronization. The PYTHIA particle-level output is distributed into calorimeter cells of size  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . After isolated leptons (and photons) are removed, all remaining cells with  $E_T > 1$  GeV are used for jet finding. Jets are defined by using a midpoint cone algorithm with  $R = 0.4$ . For simplicity, we did not smear calorimeter energies; this does not significantly broaden our  $M_{jj}$  resolution near  $M_{\pi_T}$ .

In extracting the  $\pi_T$  and  $\rho_T$  signals, we first adopted the cuts used by CDF [1,29]. Our results are in Fig. 1. The data correspond to  $\int \mathcal{L} dt = 4.3$  fb $^{-1}$ . They reproduce the shape and normalization of CDF's  $M_{jj}$  [1] and  $M_{Wjj}$  [30] distributions (except that not smearing calorimeter energies does make our  $W \rightarrow jj$  signal a narrow spike). We obtain  $S/B = 250/1595$  for the dijet signal in the five bins in 120–160 GeV. We find this agreement with CDF's measurement remarkable. Our model inputs are standard defaults, chosen only to match the dijet resonance position and the small  $Q$  value of  $\rho_T \rightarrow W\pi_T$ . The  $\rho_T$  resonance is

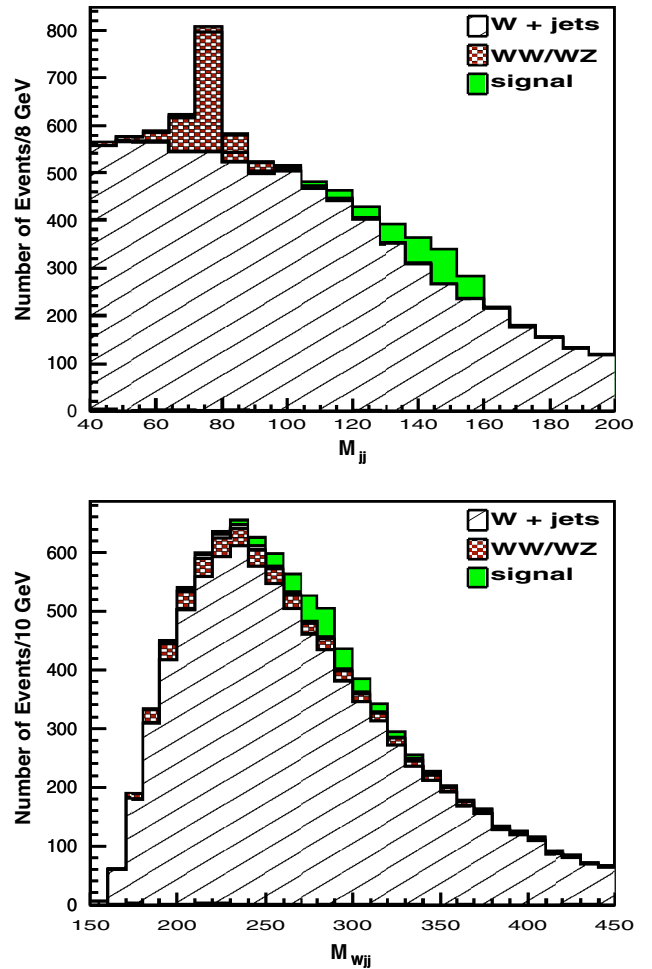


FIG. 1 (color online). The  $M_{jj}$  and  $M_{Wjj}$  distributions in  $\bar{p}p$  collisions at 1.96 TeV for LSTC with  $M_{\rho_T} = 290$  GeV,  $M_{\pi_T} = 160$  GeV, and  $\int \mathcal{L} dt = 4.3$  fb $^{-1}$ . Only the CDF cuts described in the text are used.

near the peak of the  $M_{Wjj}$  distribution [31]. For the six bins in 240–300 GeV, we obtain  $S/B = 235/3390$ .

We then augmented the CDF cuts to enhance the signals. CDF required exactly two jets. We achieved greater acceptance and a modest sharpening of the dijet peak by combining a third jet with one of the two leading jets if it was within  $\Delta R = 1.5$  of either of them. We enhanced the  $\pi_T$  and, especially, the  $\rho_T$  signals by imposing topological cuts taking advantage of the  $\rho_T \rightarrow W\pi_T$  kinematics [6]: (i)  $\Delta\phi(j_1, j_2) > 1.75$  and (ii)  $p_T(W) = |\mathbf{p}_T(\ell) + \mathbf{p}_T(\nu_\ell)| > 60$  GeV. The improvements seen in Fig. 2 are significant. We obtain  $S/B = 200/800$  for  $\pi_T \rightarrow jj$  and  $S/B = 215/1215$  for  $\rho_T \rightarrow Wjj$ . Extracting the  $\rho_T$  signal will require confidence in the background shape.

In addition to the  $jj$  and  $Wjj$  resonances, the  $Q$  value and the  $\rho_T$ -decay angular distribution are indicative of resonant production of  $W\pi_T$ . The resolution in  $Q = M_{Wjj} - M_{jj} - M_W$  is better than in  $M_{jj}$  and  $M_{Wjj}$  alone because jet measurement errors partially cancel. This is

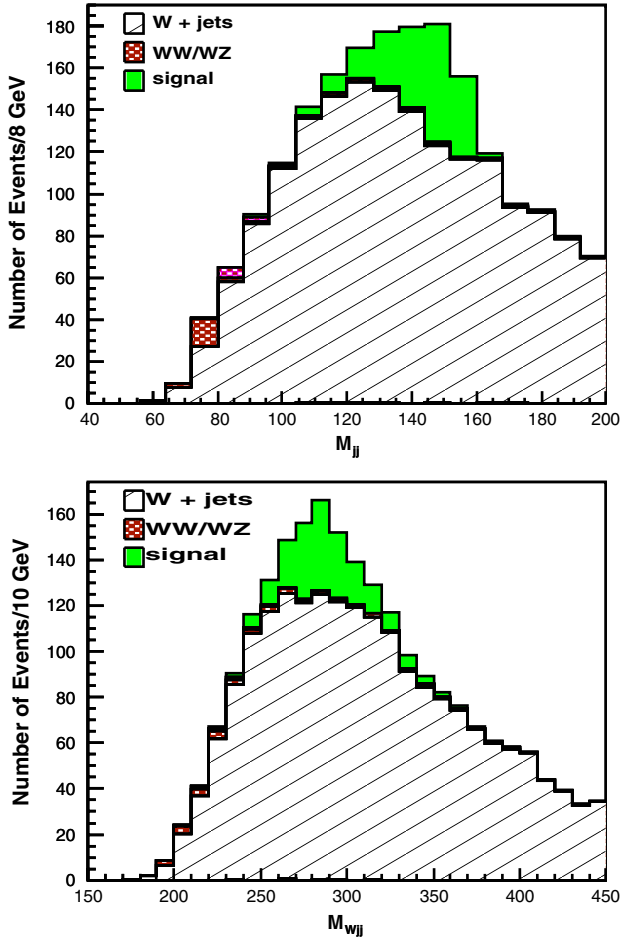


FIG. 2 (color online). The  $M_{jj}$  and  $M_{Wjj}$  distributions in  $\bar{p}p$  collisions at 1.96 TeV for LSTC with  $M_{\rho_T} = 290$  GeV,  $M_{\pi_T} = 160$  GeV, and  $\int \mathcal{L} dt = 4.3 \text{ fb}^{-1}$ . CDF cuts augmented with ours described in the text are used.

seen in Fig. 3, where we plot  $\Delta N(M_{jj}) = N_{\text{observed}}(M_{jj}) - N_{\text{expected}}(M_{jj}) = N_{S+B}(M_{jj}) - N_B(M_{jj})$  for  $Q \leq Q_{\text{max}}$  vs  $Q_{\text{max}}$  for six 16-GeV  $M_{jj}$  bins between 86 and 182 GeV. The sudden increase at  $Q_{\text{max}} \approx 50$  GeV in the three signal bins is clear.

The decay  $\rho_T \rightarrow W\pi_T$  is dominated by  $W_L\pi_T$ . Therefore, the angular distribution of  $q\bar{q} \rightarrow \rho_T \rightarrow W\pi_T$  is approximately  $\sin^2\theta$ , where  $\theta$  is the angle between the incoming quark and the outgoing  $W$  in the  $\rho_T$  frame [19]. The backgrounds are forward-backward peaked. We required  $p_T(W) > 40$  GeV, fit the background in  $250 < M_{Wjj} < 300$  GeV with a quartic in  $\cos\theta$ , and subtracted it from the total. (In reality, of course, one would use sidebands.) The prediction in Fig. 3 matches the normalized  $\sin^2\theta$  well. Verification of this would strongly support the TC origin of the signal.

*Other LSTC tests at the Tevatron and LHC.*—(i) It is important to find the  $\omega_T$  and  $a_T$  states, expected to be close to  $\rho_T$ , near 300 GeV. At the Tevatron, the largest production rates involve  $\omega_T \rightarrow \gamma\pi_T^0$  and  $a_T^\pm \rightarrow \gamma\pi_T^\pm$ . For our input parameters, these are 80 and 185 fb, respectively. Their existence, masses, and production rates critically test the technifermions' TC representation structure and the strength of the dimension-five operators inducing these decays. In addition, recent papers from D0 [32] and CDF [33] suggest that the  $e^+e^-$  channel is promising. The

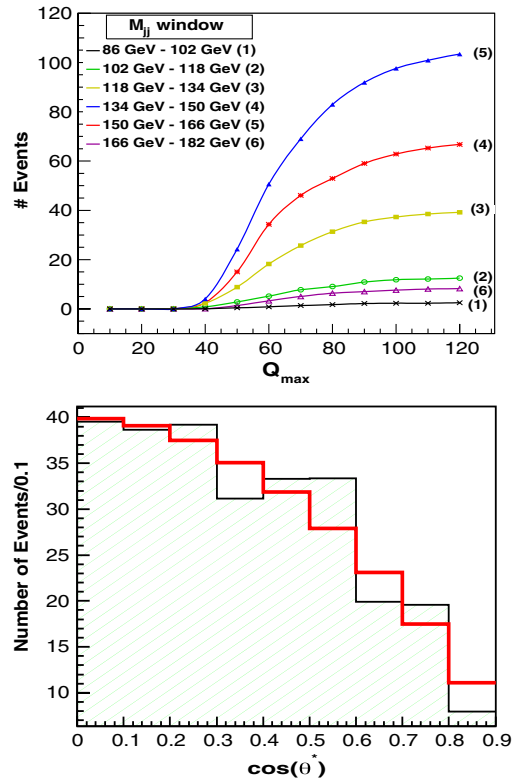


FIG. 3 (color online). Top:  $\Delta N(M_{jj})$  vs  $Q_{\text{max}}$  as described in the text for the indicated  $M_{jj}$  bins. Bottom: The background-subtracted  $W$ -dijet angular distribution, compared to  $\sin^2\theta$  (red).

excess (signal) cross sections for our parameters are  $\sigma(\omega_T, \rho_T^0 \rightarrow e^+e^-) = 12$  fb and  $\sigma(a_T^0 \rightarrow e^+e^-) = 7$  fb. (ii) Finding these LSTC signatures at the LHC is complicated by  $\bar{t}t$  and other multijet backgrounds. The likely discovery and study channels at the LHC are the nonhadronic final states of  $\rho_T^\pm \rightarrow W^\pm Z^0$ ,  $\rho_T^\pm, a_T^\pm \rightarrow \gamma W^\pm$ , and  $\rho_T^0, \omega_T, a_T^0 \rightarrow \ell^+\ell^-$  [20,21]. The dilepton channel may well be the earliest target of opportunity. (iii) The  $b$  and  $\tau$  fractions of  $\pi_T$  decays should be determined as well as possible. They probe the ETC couplings of quarks and leptons to technifermions, a key part of the flavor physics of dynamical electroweak symmetry breaking [14].

If experiments at the Tevatron and LHC reveal a spectrum resembling these predictions, it could well be that low-scale technicolor is the key to electroweak symmetry breaking, for it will then be possible to know its dynamical origin and discern the character of its basic constituents, the technifermions. The masses and quantum numbers of their bound states will provide stringent experimental benchmarks for the theoretical studies of the strong dynamics of walking technicolor just now getting started; see, e.g., [34].

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*Note added in proof.*—An important corroboration of the  $\rho_T \rightarrow W^\pm \pi_T \rightarrow \ell^\pm \nu_\ell jj$  signal is its isospin partner (suppressed by phase space and branching ratios)  $\rho_T^\pm \rightarrow Z^0 \pi_T^\pm \rightarrow \ell^+ \ell^- jj$ . We predict cross sections of 38 fb at the Tevatron and 155 fb at the 7-TeV LHC for  $\ell = e$  and  $\mu$ .

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