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Search for Low-Scale Technicolor at the Tevatron

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Abstract

CDF and DØ each have more than $1\,\mathrm{fb}^{-1}$ of data on tape, and their stores are increasing. This should be sufficient to carry out significant searches for low-scale technicolor in $\rho_T \to W\pi_T$ and $\omega_T\,, \rho_T \to \gamma\pi_T$, processes whose cross sections may be as large as several picobarns. In this note we motivate and describe the Technicolor Straw Man framework for these processes and we urge that they be sought soon in the Run 2 data.[1]

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[1] This paper is a contribution to the TeV4LHC Landscapes project.

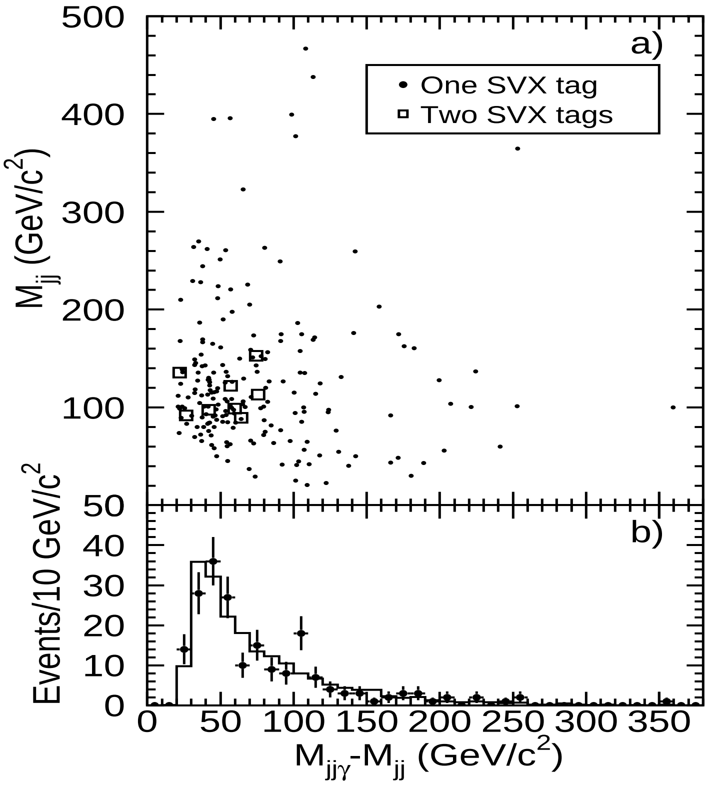

Figure 1: (a) The distribution of M_{jj} vs. $M_{jj\gamma} - M_{jj}$ for events with a photon, b–tagged jet and a second jet. (b) Projection of this data in $M_{jj\gamma} - M_{jj}$; from Ref. [1].

1. Preamble

Take a look at Figs. 1 and 2. Figure 1 is from CDF in Run 1. It shows a search for $\omega_T \to \gamma\pi_T$, with $\pi_T \to b$+jet, based on about $100\,\mathrm{pb}^{-1}$, published in 1999 [1]. Note the $\sim 2\sigma$ excess near $M_{jj\gamma} - M_{jj} = 100\,\mathrm{GeV}$. This search has not been repeated in Run 2.[2] Figure 2 is from CDF in Run 2. It shows results of an unpublished CDF study looking for $\rho_T \to W^\pm\pi_T$.[3] The data were posted in from July 2004 and are based on $162\,\mathrm{pb}^{-1}$. There are small excesses in the dijet and Wjj masses near 110 GeV and 210 GeV, respectively. Assuming $M_{\omega_T} = M_{\rho_T} \simeq 230\,\mathrm{GeV}$, and taking into account losses from semileptonic b-decays, the excesses in Figs. 1 and 2 are in about the right place for $M_{\pi_T} \simeq 120\,\mathrm{GeV}$.

In December 2005, CDF search was reported for WH-production with $W \to \ell\nu$ and $H \to b\bar{b}$ (with a single b-tag), based on $320\,\mathrm{pb}^{-1}$ [3]. The dijet mass spectrum is shown in Fig. 3.[4] There is a 2σ excess at $M_{jj} \simeq 110\,\mathrm{GeV}$. The Wjj spectrum was not reported and is *still* not available. This is puzzling since it requires no additional analysis to do so.

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[2] Both detectors induce jet backgrounds to photons that require much effort to suppress. I hope that effort will be made.

[3] CDF's Run 1 version of this search is published in Ref. [2]

[4] I am grateful to Y.-K. Kim and her CDF collaborators for providing this figure.

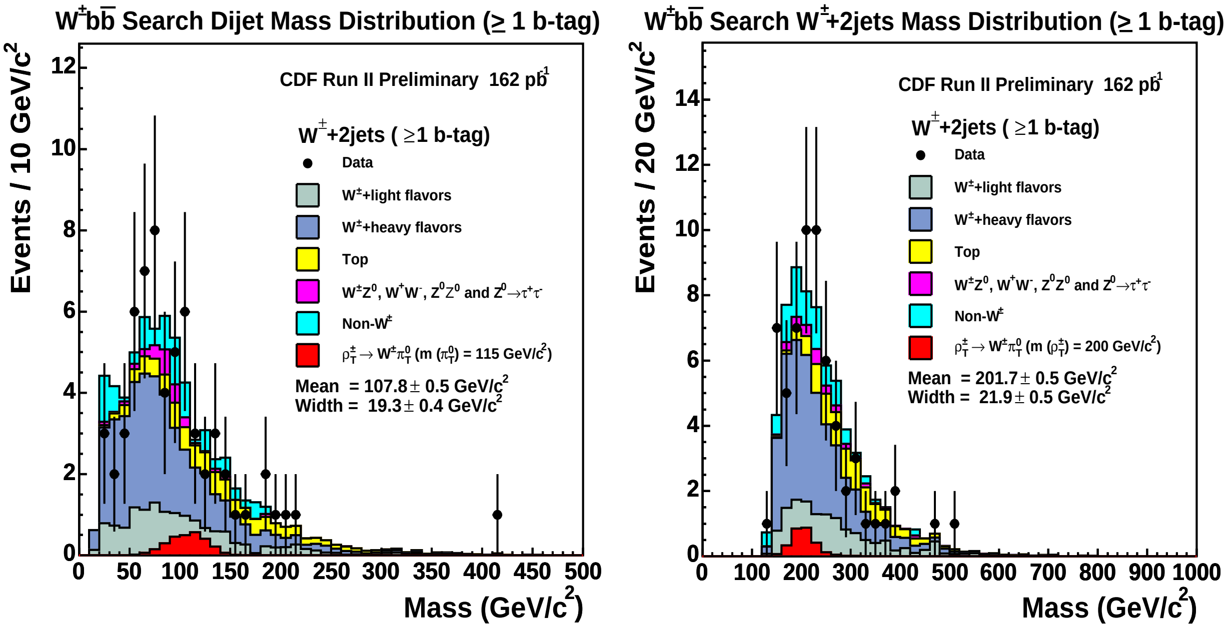

Figure 2: (a) Invariant mass of the dijet system with ≥ 1 b-tagged jets; (b) Invariant mass of the $W+2$ jet system for the $\ell+2$ jet mode with ≥ 1 b-tagged jets. From Run 2 with $162\,\mathrm{pb}^{-1}$; see `http://www-cdf.fnal.gov/physics/exotic/r2a/20040722.lmetbj-wh-tc/`

Never mind that the expected rate for a $\sim 100\,\mathrm{GeV}$ Higgs decaying to $b\bar{b}$ and produced in association with a W is about 0.1 pb. If the excess were real, it would correspond to a total WH cross section of about 5 pb, about 50 times the expected cross section. *Note added:* A DØ search for $WH \to \ell\nu b\bar{b}$ also shows an apparent excess at 110 GeV in the dijet mass distribution in which one jet is b-tagged; see Fig. 10 in Ref. [4].

Now, a little excess here and a little excess there is nothing to write home about. But when the excesses all show up in the same place, it's time to check them out. Both experiments have collected almost $1.5\,\mathrm{fb}^{-1}$. This summer, CDF and DØ will present new results for searches for SUSY and other more recent fads — ADD large extra dimensions, RS gravitons, little Higgs to name a few. They should present the searches for technicolor as well. The most likely processes and search modes are

$$\rho_T^{\pm} \to W^{\pm}\pi_T^0 \to \ell^{\pm}\nu_\ell + b\bar{b} \tag{1}$$

$$\rho_T^0 \to W^{\pm}\pi_T^{\mp} \to \ell^{\pm}\nu_\ell + b\bar{c}\,,\; b\bar{u} \tag{2}$$

$$\omega_T\,,\, \rho_T^0 \to \gamma\pi_T^0\,,\, \gamma\pi_T^{0\prime} \to \gamma b\bar{b} \tag{3}$$

$$\omega_T\,,\, \rho_T^0 \to e^+e^-\;,\; \mu^+\mu^-\;. \tag{4}$$

These processes (and more) are available in PYTHIA [5, 6].

In the rest of this paper, I will motivate low-scale technicolor — that technihadrons may be much lighter than $\sim 1\,\mathrm{TeV}$ and, in fact, may be readily accessible at the Tevatron. Then I will describe the Technicolor Straw Man Model (TCSM) and present some rate estimates

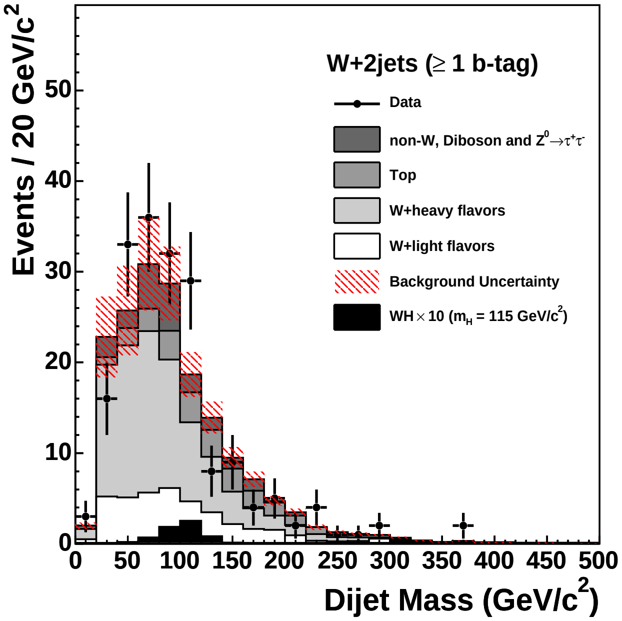

Figure 3: Invariant mass of the $W + 2\,$jet system for the $\ell + 2\,$jet mode with ≥ 1 b-tagged jets; from Run 2 with $320\,\text{pb}^{-1}$; see Ref. [3].

for the most important color-singlet processes. The TCSM is described in more detail in Refs. [7, 8], and much of Sects. 3-4 is lifted from the second of these.

2. Low-Scale Technicolor

Technicolor is the theory of electroweak symmetry breaking (EWSB) by new strong dynamics near 1 TeV [9, 10]. It is the most natural scenario (not to mention the only one with a precedent, namely, QCD) for dealing with the standard model's naturalness problem: it banishes *elementary* scalar particles altogether. Technicolor by itself, however, cannot explain — or even describe in a phenomenological way, as the standard model does — the origin of quark and lepton masses and mixings. The only known way to do that in the dynamical context of technicolor is extended technicolor (ETC) [11].

Two elements of the modern formulation of technicolor (see the reviews and references in Refs. [12, 13]) strongly suggest that its energy scale $\Lambda_{TC} \simeq 4\pi F_T$ — and therefore the masses of technihadrons (ρ_T and ω_T as well as π_T) — are *much* less than several TeV. They are the notions of *walking technicolor* (WTC) [14, 15, 16, 17] and *topcolor-assisted technicolor* (TC2) [18]. Here, F_T is the technipion decay constant. Assuming for simplicity that the technifermions form N_D electroweak doublets, then $F_T \simeq F_\pi/\sqrt{N_D}$, where $F_\pi = 246\,\text{GeV}$. The EWSB condensate is $\langle \bar{T}T \rangle_{TC} \simeq 4\pi F_T^3$.

Extended technicolor inevitably induces flavor-changing neutral current interactions of quarks and leptons. The most problematic of these are the $|\Delta S| = 2$ operators,

$$\mathcal{H}_{|\Delta S|=2} = \frac{g_{ETC}^2}{M_{ETC}^2} \sum_{ij} K_{ij}\, \bar{s}\Gamma_i d\, \bar{s}\Gamma_j d + \text{h.c.}\,, \tag{5}$$

and they require effective ETC gauge boson masses $M_{ETC}/g_{ETC}\sqrt{K_{ij}} \gtrsim 1000\,\text{TeV}$. If TC were a QCD-like gauge theory, one in which asymptotic freedom sets in quickly near Λ_{TC}, the quark and lepton masses $m_{q,l} \simeq g_{ETC}^2 \langle \bar{T}T \rangle_{ETC}/M_{ETC}^2$ generated by such high-scale ETC interactions would be unacceptably small because $\langle \bar{T}T \rangle_{ETC} \simeq \langle \bar{T}T \rangle_{TC}$. This difficulty is cured by walking technicolor. In WTC, the technicolor gauge coupling α_{TC} runs very slowly, i.e., the interaction is close to conformally invariant, and the technifermion condensates $\langle \bar{T}T \rangle_{ETC}$ renormalized at the ETC scale are enhanced relative to $\langle \bar{T}T \rangle_{TC}$ by a factor not much less than M_{ETC}/Λ_{TC}. The small β_{TC}-function required for WTC is readily achieved by having many technidoublets transforming as the fundamental representation of the TC gauge group. Then N_D is large and F_T is small.[5]

Even with the enhancements of walking technicolor, there is no satisfactory way in the context of ETC alone to understand the large mass of the top quark. Either the ETC mass scale generating m_t must be too close to Λ_{TC} or the ETC coupling must be fine-tuned.[6] So far, the most attractive scheme for m_t is that it is produced by the condensation of top quarks, induced at a scale near 1 TeV by new strong topcolor gauge interactions ($SU(3) \otimes U(1)$ in the simplest scheme). This top condensation scheme, topcolor-assisted technicolor, accounts for almost all the top mass, but for only a few percent of EWSB. Realistic models that provide for the TC2 gauge symmetry breaking and for the mixing of the heavy third generation with the two light generations typically require many ($N_D \simeq 10$ (!)) technifermion doublets. Therefore, in the following, we shall assume $F_T \lesssim 100\,\text{GeV}$.[7]

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[5] Walking could in principle be achieved by having a few technidoublets in higher-dimensional TC representations; see Refs. [19] and [20, 21]. It is difficult to see how this could be done without some number of doublets in the fundamental; see Ref. [22]. Another option is to have a large number of technifermions in the fundamental TC representation, but only one doublet of them has electroweak interactions [23].

[6] A possible exception to this has been proposed in Ref. [24]. In this model, $N_D = 4$ and F_T is not particularly small. The model is genuinely baroque, but that is probably true of any quasi-realistic ETC model.

[7] The question of the effect of technicolor on precisely measured electroweak quantities such as S, T, and U naturally arises because of the appearance of many technifermion doublets in low-scale technicolor. Calculations that show technicolor to be in conflict with precision measurements have been based on the assumption that technicolor dynamics are just a scaled-up version of QCD. However, because of its walking gauge coupling, this cannot be. In walking technicolor there must be something like a tower of spin-one technihadrons reaching almost to the ETC scale, and these states must contribute significantly to the integrals over spectral functions involved in calculating S, T, and U. Therefore, in the absence of detailed experimental knowledge of this spectrum, including the spacing between states and their coupling to the electroweak currents, it has not yet been possible to estimate these quantities reliably.

3. The Technicolor Straw Man Model

The TCSM provides a simple framework for searching for light technihadrons. Its first and probably most important assumption is that the lowest-lying bound states of the lightest technifermions can be considered *in isolation.* The lightest technifermions are expected to be an isodoublet of color singlets, (T_U, T_D). Color triplets, not considered here, will be heavier because of $SU(3)_C$ contributions to their hard (chiral symmetry breaking) masses. We assume that all technifermions transform under technicolor $SU(N_{TC})$ as fundamentals. This leads us to make — with no little trepidation in a *walking* gauge theory — large-N_{TC} estimates of certain parameters. The electric charges of (T_U, T_D) are Q_U and $Q_D = Q_U - 1$; they are important parameters of the TCSM. The color-singlet bound states we consider are vector and pseudoscalar mesons. The vectors include a spin-one isotriplet $\rho_T^{\pm,0}$ and an isosinglet ω_T. Techni-isospin can be a good approximate symmetry in TC2, so that ρ_T and ω_T are nearly degenerate. Their mixing with each other and the photon and Z^0 is described by a neutral-sector propagator matrix.

The lightest pseudoscalar bound states of (T_U, T_D) are the color-singlet technipions. They also form an isotriplet $\Pi_T^{\pm,0}$ and an isosinglet $\Pi_T^{0\prime}$. However, these are not mass eigenstates. Our second important assumption for the TCSM is that the isovectors may be described as simple *two-state mixtures* of the longitudinal weak bosons $W_L^\pm$, Z_L^0 — the true Goldstone bosons of dynamical electroweak symmetry breaking — and mass-eigenstate pseudo-Goldstone technipions $\pi_T^\pm, \pi_T^0$:

$$|\Pi_T\rangle = \sin\chi \, |W_L\rangle + \cos\chi \, |\pi_T\rangle \, . \tag{6}$$

We assume that $SU(N_{TC})$ gauge interactions dominate the binding of all technifermions into technihadrons. Then the decay constants of color-singlet and nonsinglet π_T are approximately equal, $F_T \simeq F_\pi/\sqrt{N_D}$, and the mixing factor $\sin\chi$ — another important TCSM parameter — is given by

$$\sin\chi \simeq F_T/F_\pi \simeq 1/\sqrt{N_D} \, , \tag{7}$$

so that $\sin^2\chi \ll 1$.

Similarly, $|\Pi_T^{0\prime}\rangle = \cos\chi' \, |\pi_T^{0\prime}\rangle \; + \cdots$, where χ' is another mixing angle and the ellipsis refer to other technipions needed to eliminate the two-technigluon anomaly from the $\Pi_T^{0\prime}$ chiral current. It is unclear whether, like ρ_T and ω_T, these neutral technipions will be degenerate. If π_T^0 and $\pi_T^{0\prime}$ are nearly degenerate *and* if their widths are roughly equal, there may be appreciable π_T^0–$\pi_T^{0\prime}$ mixing and, then, the lightest neutral technipions will be ideally-mixed $\bar{T}_U T_U$ and $\bar{T}_D T_D$ bound states. *Searches for these technipions ought to consider both possibilities: they are nearly degenerate or that* $M_{\pi_T^\pm} = M_{\pi_T^0} \ll M_{\pi_T^{0\prime}}$.

Color-singlet technipion decays are mediated by ETC and (in the case of $\pi_T^{0\prime}$) $SU(3)_C$

interactions. In the TCSM they are taken to be:

$$\begin{aligned}\Gamma(\pi_T \to \bar{f}' f) &= \frac{1}{16\pi F_T^2}\, N_f\, p_f\, C_{1f}^2 (m_f + m_{f'})^2 \\ \Gamma(\pi_T^{0\prime} \to gg) &= \frac{1}{128\pi^3 F_T^2}\, \alpha_C^2\, C_{1g}^2\, N_{TC}^2\, M_{\pi_T^{0\prime}}^{\frac{3}{2}}\,. \end{aligned} \tag{8}$$

Like elementary Higgs bosons, technipions are *expected* to couple to fermion mass. Thus, C_{1f} is an ETC-model dependent factor of order one *except* that TC2 implies a weak coupling to top quarks, $|C_{1t}| \lesssim m_b/m_t$. Thus, there is no strong preference for technipions to decay to (or radiate from) top quarks. The number of colors of fermion f is N_f. The fermion momentum is p_f. The QCD coupling α_C is evaluated at M_{π_T}; and C_{1g}^2 is a Clebsch of order one. The default values of these and other parameters are tabulated in Ref. [8]. For $M_{\pi_T} < m_t + m_b$, these technipions are expected to decay mainly as follows: $\pi_T^+ \to c\bar{b}$, $u\bar{b}$, $c\bar{s}$ and possibly $\tau^+\nu_\tau$; $\pi_T^0 \to b\bar{b}$ and, perhaps $c\bar{c}$, $\tau^+\tau^-$; and $\pi_T^{0\prime} \to gg$, $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$.

In the limit that the electroweak couplings $g, g' = 0$, the ρ_T and ω_T decay as

$$\begin{aligned}\rho_T &\to \Pi_T\Pi_T = \cos^2\chi\,(\pi_T\pi_T) + 2\sin\chi\,\cos\chi\,(W_L\pi_T) + \sin^2\chi\,(W_L W_L)\,; \\ \\ \omega_T &\to \Pi_T\Pi_T\Pi_T = \cos^3\chi\,(\pi_T\pi_T\pi_T) + \cdots\,. \end{aligned} \tag{9}$$

The ρ_T decay amplitude is

$$\mathcal{M}(\rho_T(q) \to \pi_A(p_1)\pi_B(p_2)) = g_{\rho_T}\, \mathcal{C}_{AB}\, \epsilon(q)\cdot(p_1 - p_2)\,, \tag{10}$$

where $\epsilon(q)$ is the ρ_T polarization vector; $\alpha_{\rho_T} \equiv g_{\rho_T}^2/4\pi = 2.91(3/N_{TC})$ is scaled naively from QCD and the parameter $N_{TC} = 4$ is used in calculations; and

$$\mathcal{C}_{AB} = \begin{cases} \sin^2\chi & \text{for } \; W_L^+ W_L^- \;\text{ or }\; W_L^\pm Z_L^0 \\ \sin\chi\cos\chi & \text{for } \; W_L^\pm \pi_T^\mp\,, \;\text{ or }\; W_L^\pm \pi_T^0\,, Z_L^0 \pi_T^\pm \\ \cos^2\chi & \text{for } \; \pi_T^+\pi_T^- \;\text{ or }\; \pi_T^\pm \pi_T^0\,. \end{cases} \tag{11}$$

The ρ_T decay rate to two technipions is then (for use in cross sections, we quote the energy-dependent width for a ρ_T mass of $\sqrt{\hat{s}}$)

$$\Gamma(\rho_T^0 \to \pi_A^+\pi_B^-) = \Gamma(\rho_T^\pm \to \pi_A^\pm \pi_B^0) = \frac{2\alpha_{\rho_T}\mathcal{C}_{AB}^2}{3}\, \frac{p^3}{\hat{s}}\,, \tag{12}$$

where $p = [(\hat{s} - (M_A + M_B)^2)(\hat{s} - (M_A - M_B)^2)]^{\frac{1}{2}}/2\sqrt{\hat{s}}$ is the π_T momentum in the ρ_T rest frame.

4. Sample TCSM Production Rates at the Tevatron

The $\rho_T \to \Pi_T\Pi_T$ decays are strong transitions, and we might therefore expect the ρ_T to be quite wide. Almost certainly, this is not so. The enhanced technifermion condensate in walking technicolor magnifies technipions' masses much more than it does technivectors' and, so, the channels $\rho_T \to \pi_T\pi_T$, $\omega_T \to \pi_T\pi_T\pi_T$ and even the isospin-violating $\omega_T \to \pi_T\pi_T$ are likely to be closed [19]. A ρ_T^0 of mass 200 GeV may then decay mainly to $W_L^\pm \pi_T^\mp$ or $W_L^+ W_L^-$. These channels are also isospin-forbidden for the ω_T, and so all its important decays are electroweak: $\omega_T \to \gamma\pi_T^0$, $Z^0\pi_T^0$, $W^\pm\pi_T^\mp$, and $\bar{f}f$ — especially e^+e^- and $\mu^+\mu^-$. Here, the Z and W are transversely polarized.[8] Furthermore, since $\sin^2\chi \ll 1$, the electroweak decays of ρ_T to the transverse gauge bosons γ, W, Z plus a technipion may be competitive with the open-channel strong decays. Thus, we expect ρ_T and ω_T to be *very narrow*. For masses accessible at the Tevatron, it turns out that $\Gamma(\rho_T) \sim 1\,\mathrm{GeV}$ and $\Gamma(\omega_T) \lesssim 0.5\,\mathrm{GeV}$.

Within the context of the TCSM (and with plausible assumptions for its parameters), we expect that $\rho_T^{\pm,0}$ and ω_T with masses below about 250 GeV should be accessible in Tevatron Run 2 in one channel or another. Assuming $M_{\rho_T} < 2M_{\pi_T}$, the $\rho_T \to W\pi_T$ cross sections have rates of a few picobarns. An example is shown in Fig. 4, for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$.[9] The parameter M_V against which these rates are plotted is described below; it hardly affects them. These cross sections were computed with EHLQ structure functions [25], and they should be multiplied by a K-factor of about 1.4, typical of Drell-Yan processes such as these. Searches for these modes at the Tevatron require a leptonic decay of the W plus two jets with at least one b-tag.

The parameter M_V appears inversely in the amplitude for $\rho_T, \omega_T \to \gamma\pi_T$. It is a typical TC mass-scale and, for low-scale technicolor, should lie in the range 100–500 GeV. As long as the $\rho_T \to W\pi_T$ channels are open, $\gamma\pi_T^0$ and $\gamma\pi_T^{0\prime}$ production proceeds mainly through the ω_T resonance. Then M_V and the sum of the technifermion charges, $Q_U + Q_D$, control their rates, which are approximately proportional to $(Q_U + Q_D)^2/M_V^2$. Figure 5 shows the $\gamma\pi_T$ cross sections vs. M_V for the favorable case $Q_U + Q_D = \frac{5}{3}$. Again, a K-factor of about 1.4 should be applied. Here, $M_{\pi_T^{0\prime}} = M_{\pi_T^0}$ and about half the rate is $\gamma\pi_T^{0\prime}$. Note that the gg decays of of the $\pi_T^{0\prime}$ will dilute the usefulness of the b-tag for these processes. On the other hand, decays involving b's have two b-jets.

Finally, for large M_V, ω_T decays mainly to $\bar{f}f$ pairs. The most promising modes at the Tevatron (and the LHC) then are e^+e^- and $\mu^+\mu^-$. Figures 6 and 7 show the effect of changing M_V from 100 to 500 GeV on the e^+e^- invariant mass distributions. Note also the ω_T–ρ_T interference effect when their masses are close. This would be lovely to observe! The cross section, for $M_{\omega_T} = M_{\rho_T} = 210\,\mathrm{GeV}$, integrated from 200 to 220 GeV, and including the Drell-Yan background, increases from 0.12 to 0.25 pb when M_V is increased from 100 to 500 GeV. A first search was for $\omega_T, \rho_T \to e^+e^-$ was carried out by DØ in Run 1 and published in Ref. [26]. I look forward to a search based on Run 2 data soon. It shouldn't be difficult to carry out.

So, to sum up, there are nagging little hints of something at $\sim 110\,\mathrm{GeV}$ in dijets with

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[8] Strictly speaking, the identification of W and Z decay products as longitudinal or transverse is approximate, becoming exact in the limit of very large M_{ρ_T,ω_T}.

[9] This figure does not include contributions from transverse weak bosons, which are small for this choice of parameters.

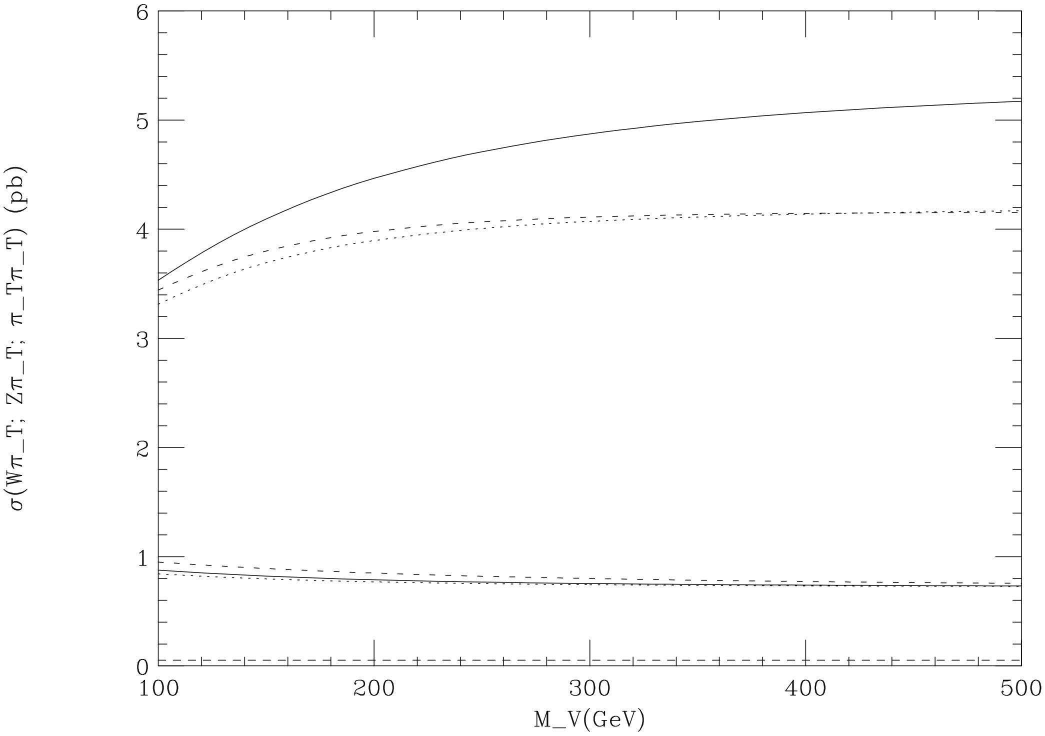

Figure 4: Production rates rates in $p\bar{p}$ collisions at $\sqrt{s} = 2\,\mathrm{TeV}$ for ω_T, ρ_T^0, $\rho_T^\pm \to W\pi_T$ (upper curves) and $Z\pi_T$ (lower curves) versus M_V, for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 200$ (dotted curve), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = \frac{5}{3}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$. Also shown is $\sigma(\rho_T \to \pi_T\pi_T)$ (lowest dashed curve); from Ref. [7].

a b-tag coming from some parent at $\sim 210\,\mathrm{GeV}$. They've been around since Run 1 and it's time now to close the book on them. I urge my experimental colleagues to settle this soon.

Acknowledgments

I am grateful for many conversations with colleagues and friends in CDF and DØ. I again thank Steve Mrenna for putting the TCSM into Pythia. Thanks also to David Rainwater and Bogdan Dobrescu of the TeV4LHC Landscapes project for their patience with me. This research was supported in part by the Department of Energy under Grant No. DE–FG02–91ER40676.

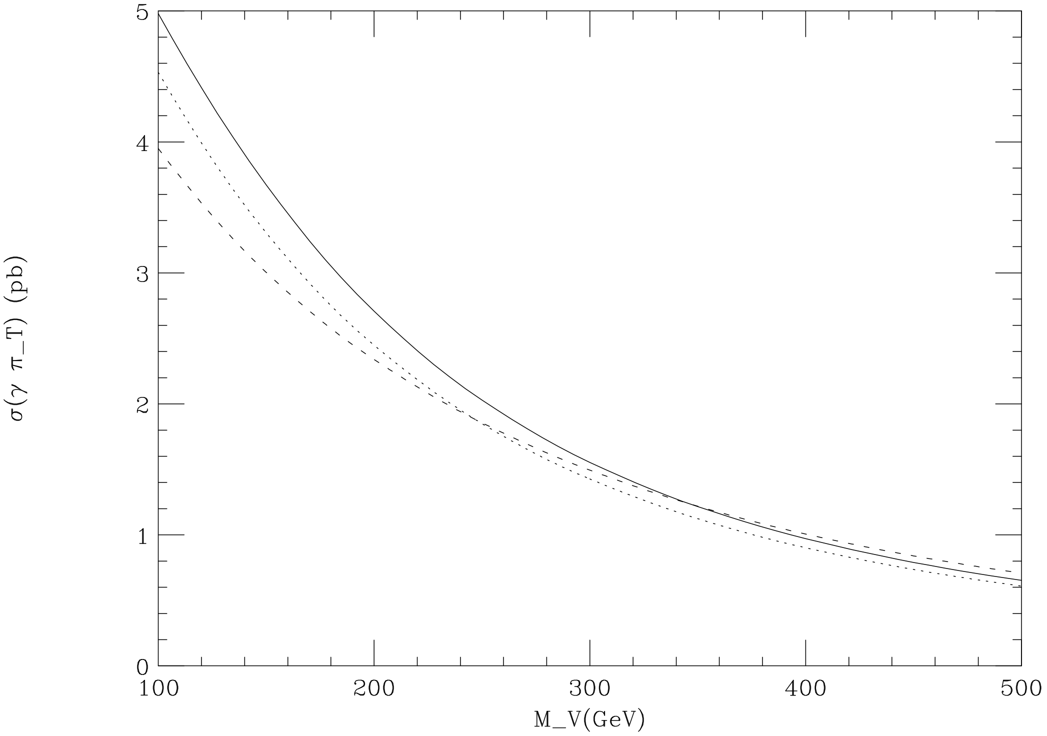

Figure 5: Production rates in $p\bar{p}$ collisions at $\sqrt{s} = 2\,\mathrm{TeV}$ for the sum of ω_T, ρ_T^0, $\rho_T^\pm \to \gamma\pi_T$ and $\gamma\pi_T^{0\prime}$ versus M_V, for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 200$ (dotted curve), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = \frac{5}{3}$, and $M_{\pi_T} = M_{\pi_T^{0\prime}} = 110\,\mathrm{GeV}$; from Ref. [7].

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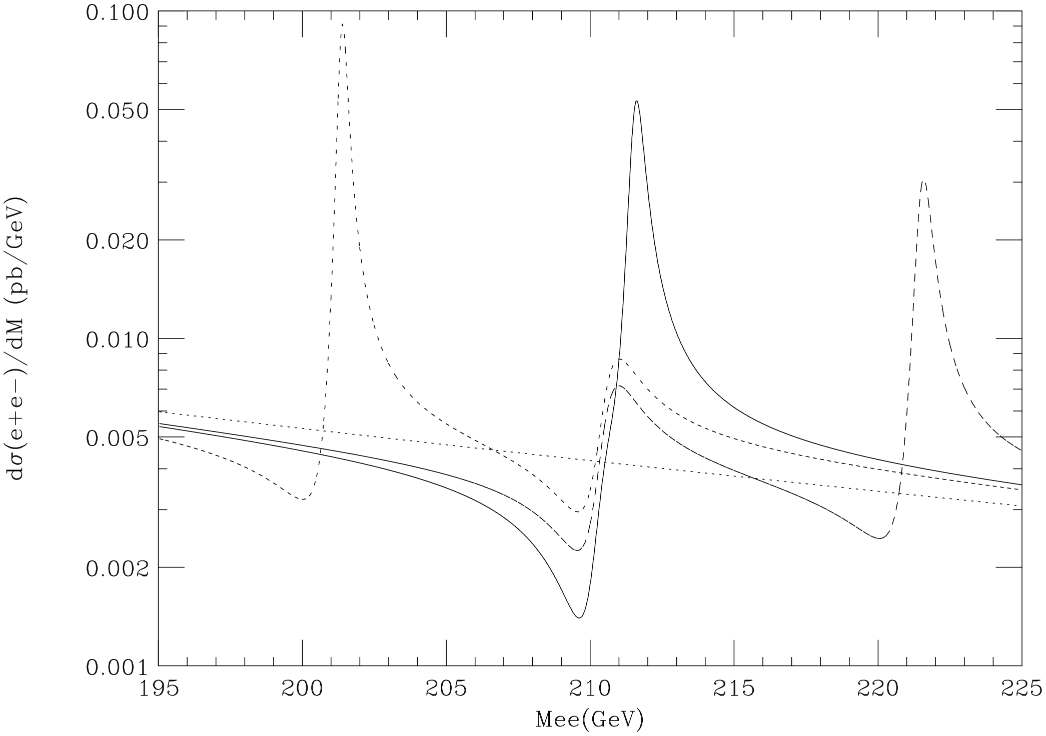

Figure 6: Invariant mass distributions in $p\bar{p}$ collisions at $\sqrt{s} = 2\,\mathrm{TeV}$ for ω_T, $\rho_T^0 \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 100\,\mathrm{GeV}$. The standard model background is the sloping dotted line. $Q_U + Q_D = \frac{5}{3}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$; from Ref. [7].

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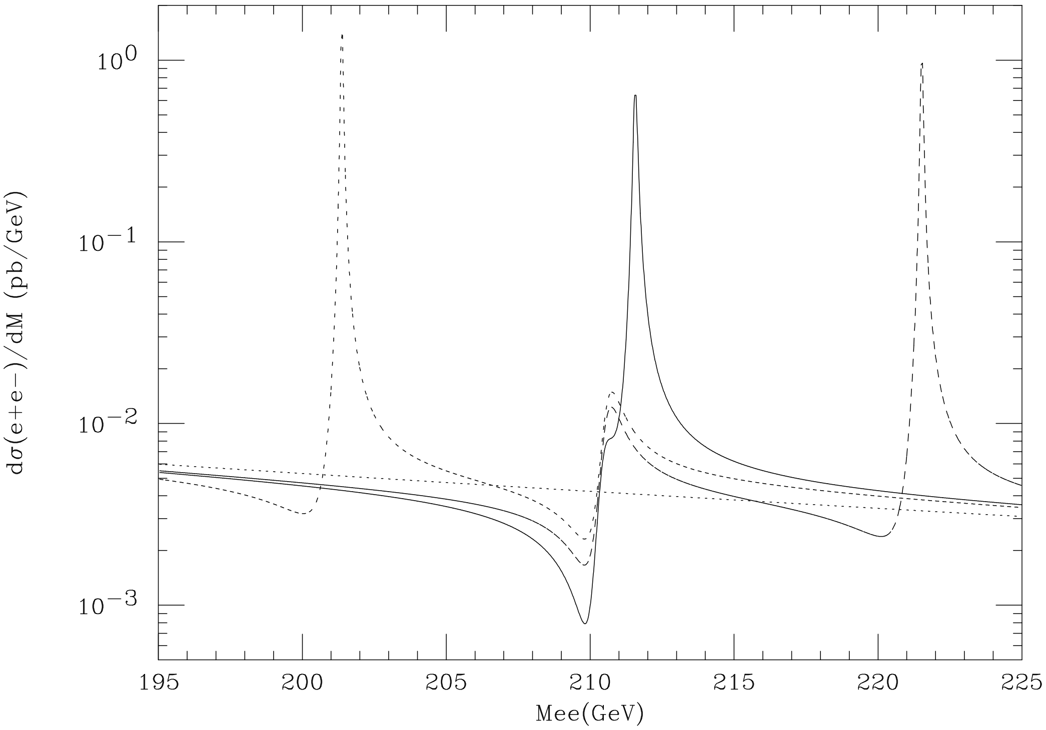

Figure 7: Invariant mass distributions in $p\bar{p}$ collisions at $\sqrt{s} = 2\,\mathrm{TeV}$ for ω_T, $\rho_T^0 \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 500\,\mathrm{GeV}$. The standard model background is the sloping dotted line. $Q_U + Q_D = \frac{5}{3}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$; from Ref. [7].

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