NON-SUPERSYMMETRIC EXTENSIONS OF THE STANDARD MODEL

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The motivations for studying dynamical scenarios of electroweak and flavor symmetry breaking are reviewed and the latest ideas, especially topcolor-assisted technicolor, are summarized. Several technicolor signatures at the Tevatron and Large Hadron Collider are described and it is emphasized that all of them are well within the reach of these colliders.

1 Introduction

The title of my talk was chosen by the organizers and, while it was not their intention, they have defined my subject by what it is not. That leaves it for me to define what it is. So, in this talk “non-supersymmetric extensions of the standard model” means Dynamical Electroweak and Flavor Symmetry Breaking. To be specific, I will discuss aspects of technicolor\(^1\) and extended technicolor\(^2,3\). I begin in Sec. 2 by reiterating why it is still important to study scenarios in which electroweak and flavor symmetry are broken by strong dynamics at moderate, accessible energy scales. This is followed in Sec. 3 by a review of technicolor and extended technicolor, focusing on the more modern aspects—walking technicolor, multiscale technicolor, and topcolor-assisted technicolor. In Sec. 4, I will discuss several important signatures of these strong dynamics that can be sought over the next 10-15 years at the upgraded Tevatron Collider and the Large Hadron Collider. For the most part, these signatures involve the production of technihadrons $\rho^T$ and $\omega^T$ and their decay into pairs of technipions, $\pi^T\pi^T$, $W_L\pi^T$ and $Z_L\pi^T$, and possibly dijets. I restrict myself to these hadron colliders not only because they are the only new high-energy machines anywhere near the real axis, \(^4\) but also because they have the greatest reach of all machines under consideration for the unknown physics of the TeV energy scale.

2 Why Study Strong Electroweak and Flavor Dynamics?

The theoretical elements of the standard $SU(3) \otimes SU(2)\otimes U(1)$ gauge model of strong and electroweak interactions have been in place for almost 25 years.\(^5\) In all this time, the standard model has withstood extremely stringent experimental tests, the latest round being described at this conference by Brock, Tipton, and Blondel. \(^6\) Down to distances of at least $10^{-16}$ cm, the basic constituents of matter are known to be spin-\(\frac{1}{2}\) quarks and leptons. These interact via the exchange of spin-one gauge bosons: the massless gluons of QCD and the massless photon and massive $W^\pm$ and $Z^0$ bosons of electroweak interactions. There are six flavors each of quarks and leptons—identical except for mass, charge and color—grouped into three generations.

The fact that the QCD gauge symmetry is exact in both the Lagrangian and the ground state of the theory implies that quarks and gluons are confined at large distances into color-singlet hadrons and that they are almost noninteracting at small distances. However, confinement and asymptotic freedom are not the only dynamical outcomes for gauge theories. Even though gauge bosons necessarily appear in the Lagrangian without mass, interactions can make them heavy. This happens to the $W^\pm$ and $Z^0$ bosons: electroweak gauge symmetry is spontaneously broken in the ground state of the theory, a phenomenon known as the “Higgs mechanism”. \(^7\) Finally, fermions in the standard model also must start out massless. To make quarks and leptons massive, new forces beyond the $SU(3) \otimes SU(2) \otimes U(1)$ gauge interactions are required. These additional interactions explicitly break the fermions' flavor symmetry and communicate electroweak symmetry breaking to them.

Despite this great body of knowledge, the interactions underlying electroweak and flavor symmetry breakdowns remain unknown. The most important element still missing from this description of particle interactions is directly connected to...
electroweak symmetry breaking. This may manifest itself as one or more elementary scalar “Higgs bosons”. This happens in supersymmetry, the scenario for the physics of electroweak symmetry breaking that is by far the most popular. Notwithstanding its popularity, there is no experimental evidence for supersymmetry. We do not know the origin of electroweak symmetry breaking.

If the dynamics of the Higgs mechanism are unknown in detail, those of flavor are completely obscure. We don’t even have a proper name, much less a believable and venerable “mechanism”, for flavor symmetry breaking. Models with elementary Higgs bosons, whether supersymmetric or not, offer no explanation at all for the quark-lepton content of the generations, the number of generations, why they are identical, and why flavor symmetry is broken—the bizarre pattern of quark and lepton masses.

Dynamical electroweak and flavor symmetry breaking—technicolor and extended technicolor—are plausible, attractive, natural, and nontrivial scenarios for this physics that involve new interactions at specified, experimentally accessible energy scales. Technicolor is a strong gauge interaction modeled after QCD. Its characteristic energy is $\lesssim 1$ TeV, so it may be sought in experiments of the coming decade. Extended technicolor (ETC) embeds technicolor, color and flavor into a larger gauge symmetry; this embedding is necessary to produce the nonzero “current-algebraic” or “hard” masses of quarks and leptons. At the same time, ETC offers a simple group-theoretic explanation of flavor in terms of the representation content of fermions. As we explain shortly, the scale at which ETC symmetry is broken down to color $\otimes$ technicolor is $O(100 \text{ TeV})$. Nevertheless, the effects of this interaction are observable at the TeV energy scale in terms of the masses and decay modes of the technihadrons, $\rho_T$ and $\pi_T$, that populate technicolor models.

Because we are so completely ignorant of electroweak and flavor dynamics, experiments at TeV energies, which for now means those planned for the Tevatron and the LHC, must have the greatest possible discovery potential. They ought to search for technicolor and extended technicolor as well as the standard model Higgs boson, its simple extensions, supersymmetry, and so on. Hadron colliders have powerful reach by virtue of their high energy and luminosity, but extracting clear signals from them can be quite demanding. Thus, detectors should be designed to be sensitive to, and experimenters should be prepared to search for, the signatures of dynamical electroweak and flavor symmetry breaking. So far, there is little indication of this in the large LHC detector collaborations.

## 3 Summary of Technicolor and Extended Technicolor

Technicolor—the strong interaction of fermions and gauge bosons at the scale $\Lambda_{TC} \sim 1$ TeV—describes the breakdown of electroweak symmetry to electromagnetism without elementary scalar bosons. Technicolor has a great precedent in QCD. The chiral symmetry of massless quarks is spontaneously broken by strong QCD interactions, resulting in the appearance of massless Goldstone bosons, $\pi$, $K$, $\eta$. In fact, if there were no Higgs bosons, this chiral symmetry breaking would itself cause the breakdown of electroweak $SU(2) \otimes U(1)$ to electromagnetism. Furthermore, the $W$ and $Z$ masses would be given by $M_W^2 = \cos^2 \theta_W M_Z^2 = g^2 N_F f_\pi^2$, where $g$ is the weak $SU(2)$ coupling, $N_F$ the number of massless quark flavors, and $f_\pi$, the pion decay constant, is only 93 MeV.

In its simplest form, technicolor is a scaled up version of QCD, with massless technifermions whose chiral symmetry is spontaneously broken at $\Lambda_{TC}$. If left and right-handed technifermions are assigned to weak $SU(2)$ doublets and singlets, respectively, then $M_W = \cos \theta_W M_Z = \frac{1}{2} g F_\pi$, where $F_\pi = 246$ GeV is the weak technipion decay constant.

The principal signals in hadron collider experiments of “classical” technicolor were discussed long ago. In the minimal technicolor model, with just one technifermion doublet, the only

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$^6$Those who would cite the apparent unification of the $SU(3) \otimes SU(2) \otimes U(1)$ couplings near $10^{16}$ GeV as evidence now have to incorporate the scenario of supersymmetry breaking mediated by new gauge interactions.

$^c$The hard masses of quarks explicitly break chiral symmetry and give mass to $\pi$, $K$, $\eta$, which are then referred to as pseudo-Goldstone bosons.

$^d$The technipions in minimal technicolor are the linear combinations of massless Goldstone bosons that become, via the Higgs mechanism, the longitudinal components $W_L^\pm$ and $Z_L^0$ of the weak gauge bosons.
prominent collider signals are the modest enhancements in longitudinally-polarized weak boson production. These are the s-channel color-singlet technirho resonances near 1.5–2 TeV: $\rho_T^\pm \to W_L^\pm W_L^-$ and $\rho_T^0 \to W_L^\pm Z_L^0$. The $O(\alpha^2)$ cross sections of these processes are quite small at such masses. This and the difficulty of reconstructing weak-boson pairs with reasonable efficiency make observing these enhancements a challenge.

Nonminimal technicolor models are much more accessible because they have a rich spectrum of lower mass technirho vector mesons and technipion states into which they may decay.\footnote{The technipions of non-minimal technicolor include the longitudinal weak bosons as well as additional Goldstone bosons associated with spontaneous techniﬁeron chiral symmetry breaking. The latter must and do acquire mass—from the extended technicolor interactions discussed below.}

The often-discussed one-family model, contains one isodoublet each of color-triplet techniquarks $(U, D)$ and color-singlet technileptons $(N, E)$. Because the color coupling is weak above 100 GeV, the technifermion chiral symmetry is approximately $SU(8) \otimes SU(8)$. This symmetry and its breakdown to the diagonal $SU(2)$ gives rise to 63 $\rho_T$ and $\pi_T$ which may be classified according to how they transform under ordinary color $SU(3)$ times weak isospin $SU(2)$. The technipions are color singlets $\pi_T^0 \in (1, 1)$; $W_L^\pm, Z_L^0$ and $\pi_T^\pm, \pi_T^0 \in (1, 3)$; color octets $\eta_T \in (8, 1)$ and $\pi_T^8, \pi_T^9 \in (8, 3)$; and color-triplet leptoquarks $\pi_{QL}, \pi_{LQ} \in (3, 3) \oplus (3, 1) \oplus (\bar{3}, 3) \oplus (\bar{3}, 1)$. The $\rho_T$ belong to the same representations.

In the standard model and its extensions, the masses of quarks and leptons are produced by their Yukawa couplings to the Higgs bosons—couplings of arbitrary magnitude and phase that are put in by hand. This option is not available in technicolor because there are no elementary scalars. Instead, quark and lepton chiral symmetries must be broken explicitly by gauge interactions alone. The most economical way to do this is to employ extended technicolor, a group containing flavor, color and technicolor as subgroups. Quarks, leptons and technifermions are combined into the same few large representations of ETC. Then quark and lepton had masses are generated by their coupling (with strength $g_{ETC}$) to technifermions via ETC gauge bosons of generic mass

\[ M_{ETC}: \]

\[ m_q(M_{ETC}) \simeq m_\ell(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{\ell} \ell \rangle_{ETC}, \]

where $\langle \bar{\ell} \ell \rangle_{ETC}$ and $m_\ell(M_{ETC})$ are the technifermion condensate and quark and lepton masses renormalized at the scale $M_{ETC}$.

If technicolor is like QCD, with a running coupling $\alpha_{TC}$ rapidly becoming small above $\Lambda_{TC} \sim 1$ TeV, then $\langle \bar{\ell} \ell \rangle_{ETC} \simeq \langle \bar{\ell} \ell \rangle_{TC} \simeq \Lambda_{TC}^2$. To obtain quark masses of a few GeV thus requires $M_{ETC}/g_{ETC} \lesssim 100$ TeV. This is excluded. Extended technicolor boson exchanges also generate four-quark interactions which, generically, include $|\Delta S| = 2$ and $|\Delta B| = 2$ operators. For these not to be in conflict with $K^0$-$\bar{K}^0$ and $B^0$-$\bar{B}^0$ mixing parameters, $M_{ETC}/g_{ETC}$ must exceed several hundred TeV. This implies quark and lepton masses no larger than a few MeV, and technipion masses no more than a few GeV.

Because of this conflict between constraints on flavor-changing neutral currents and the magnitude of ETC-generated quark, lepton and technifermion masses, classical technicolor was superseded a decade ago by “walking” technicolor. Here, the strong technicolor coupling $\alpha_{TC}$ runs very slowly—walks—for a large range of momenta, possibly all the way up to the ETC scale of several hundred TeV. The slowly-running coupling enhances $\langle \bar{\ell} \ell \rangle_{ETC}/\langle \bar{\ell} \ell \rangle_{TC}$ by almost a factor of $M_{ETC}/\Lambda_{TC}$. This, in turn, allows quark and lepton masses as large as a few GeV and $M_{\pi_T} \gtrsim 100$ GeV to be generated from ETC interactions at $M_{ETC} = O(100$ TeV).

Walking technicolor requires a large number of technifermions in order that $\alpha_{TC}$ runs slowly. These fermions may belong to many copies of the fundamental representation of the technicolor gauge group, to a few higher dimensional representations, or to both. That last possibility inspired “multiscale technicolor” models containing both fundamental and higher representations, and having a very different phenomenology. In multiscale models, there typically are two widely separated scales of electroweak symmetry breaking, with the upper scale set by the weak decay constant, $F_\pi = 246$ GeV. Technihadrons associated with the lower scale may be so light that they are within reach of the Tevatron collider; they are readily produced and detected at the LHC.
An important consequence of walking technicolor is that the large ratio $\langle \bar{T}T \rangle_{ETC}/\langle \bar{t}t \rangle_{TC}$ significantly enhances technipion masses. Thus, $\rho_T \to \pi_T \pi_T$ decay channels may be closed. If this happens, then $\rho_{T1} \to W_L W_L$ or $W_L \pi_T$. The production rates for these color singlets are $5$–$10$ pb at the Tevatron and $25$–$100$ pb at the LHC. If colored technifermions exist, the electrically neutral color-octet technirho, $\rho_{TS}$, may have its $\pi_T \pi_T$ decay channels closed as well. In this case, it appears as a relatively narrow resonance in $\rho_{TS} \to$ dijets. If the $\rho_{T1}$, $\rho_{T8} \to \pi_T \pi_T$ channels are open, they are resonantly produced at large rates, of order 5 pb at the Tevatron and several nanobarns at the LHC. As we describe in more detail below, technipions tend to decay to heavy fermions. Given these large rates and the recent successes and coming advances in heavy flavor detection, many of these technipions should be reconstructable in the hadron collider environment.

Another major development in technicolor was motivated by the recent discovery of the top quark. Theorists have concluded that ETC models cannot explain the top quark’s large mass without running afoul of either experimental constraints from the $\rho$ parameter and the $Z \to b \bar{b}$ decay rate (the ETC mass must be about $1$ TeV; see Eq. (1)) or of cherished notions of naturalness ($M_{ETC}$ may be higher, but the coupling $g_{ETC}$ must be fine-tuned near to a critical value). This state of affairs has led to the proposal of “topcolor-assisted technicolor” (TC2).

In TC2, as in top-condensate models of electroweak symmetry breaking, almost all of the top quark mass arises from a new strong “topcolor” interaction. To maintain electroweak symmetry between (left-handed) top and bottom quarks and yet not generate $m_b \simeq m_t$, the topcolor gauge group under which $(t, b)$ transform is usually taken to be $SU(3) \otimes U(1)$. The $U(1)$ provides the difference that causes only top quarks to condense. Then, in order that topcolor interactions be natural—i.e., that their energy scale not be far above $m_t$—without introducing large weak isospin violation, it is necessary that electroweak symmetry breaking remain due mostly to technicolor interactions.

In TC2 models, ETC interactions are still needed to generate the light and bottom quark masses, contribute a few GeV to $m_t$, and give mass to the technipions. The scale of ETC interactions still must be hundreds of TeV to suppress flavor-changing neutral currents and, so, the technicolor coupling still must walk. Early steps in the development of the TC2 scenario have been taken in two recent papers. Although the phenomenology of TC2 is in its infancy, it is expected to share general features with multiscale technicolor: many technihadron states, some carrying ordinary color, some within range of the Tevatron, and almost all easily produced and detected at the LHC at moderate luminosities.

I assume throughout this talk that the technicolor gauge group is $SU(N_{TC})$ and that its gauge coupling walks. A minimal, one-doublet model can have a walking $\alpha_{TC}$ only if the technifermions belong to a large non-fundamental representation. For nonminimal models, I generally consider the phenomenology of only the lighter technifermions. These transform according to the fundamental ($N_{TC}$) representation. Some of them may also be ordinary color triplets. Finally, in TC2, there is no need for large technifermion isospin splitting associated with the top-bottom mass difference. This simplifies our discussion greatly.

The decays of technipions are induced mainly by ETC interactions which couple them to quarks and leptons. These couplings are Higgs-like, and so technipions are expected to decay into heavy fermion pairs. For the color-singlets, e.g.,

$$
\begin{align*}
\pi_T^0 & \to \begin{cases} 
bb & \text{if } M_{\pi_T} < 2m_t \\
t\bar{t} & \text{if } M_{\pi_T} > 2m_t
\end{cases} \\
\pi_T^+ & \to \begin{cases} 
\bar{c}b, c\bar{s}, \tau^+\nu_\tau & \text{if } M_{\pi_T} < m_t + m_b \\
\bar{t}b & \text{if } M_{\pi_T} > m_t + m_b
\end{cases}
\end{align*}
$$

(2)

An important exception to this rule occurs in TC2 models. There, only a few GeV of the top mass arises from ETC interactions. The $\bar{b}b$ mode of a heavy $\pi_T^0$ then competes with $t\bar{t}$; $\bar{c}b$ or $c\bar{s}$ compete with $\bar{t}b$ for $\pi_T^+$. Note that, since the decay $t \to \pi_T^+b$ is strongly suppressed in TC2 models, the $\pi_T^+$ can be much lighter than the top quark.

In almost all respects, walking technicolor models are very different from QCD with a few fundamental $SU(3)$ representations. One example of this is that integrals of weak-current spec-
tral functions and their moments converge much more slowly than they do in QCD. Consequently, simple dominance of spectral integrals by a few resonances cannot be correct. This and other calculational tools based on naive scaling from QCD and on large-\(N_{TC}\) arguments are suspect. Thus, it is not yet possible to predict with confidence the influence of technicolor degrees of freedom on precisely-measured electroweak quantities—the \(S, T, U\) parameters to name the most discussed example.\\footnote{These comments respond to a question from Graham Ross regarding the effects of technicolor on precision electroweak tests. I thank him for the opportunity to reiterate them.}

4 Technicolor Signatures at Hadron Colliders

4.1 Color-Singlet Technipion Production

The \(\rho_{T1} \rightarrow W_L^+ W_L^-\) and \(W_L^\pm Z_L^0\) signatures of the minimal technicolor model were discussed long ago. If there is to be just one technifermion doublet, it must belong to a higher dimensional representation of \(SU(N_{TC})\) so that \(\alpha_{TC}\) walks. The main phenomenological consequence of this is that it is questionable to use the \(\rho_{T1} \rightarrow \pi_T \pi_T\) coupling \(\alpha_{\rho_T}\) obtained by naive scaling from QCD,

\[
\alpha_{\rho_T} = 2.91 \left( \frac{3}{N_{TC}} \right). \tag{3}
\]

This coupling may be smaller than Eq. (3) indicates, leading to a narrower \(\rho_{T1}\). There is also the possibility that, because of its large mass (naively, 1.5–2 TeV), the \(\rho_{T1}\) has a sizable branching ratio to four-weak-boson final states. To my knowledge, neither of these possibilities has been investigated.

From now on, I consider only nonminimal models which, I believe, are much more likely to lead to a satisfactory walking model. They have a rich phenomenology with many diverse, relatively accessible signals. The masses of technipions in these models arise from broken ETC and ordinary color interactions. In walking models that have been studied, they lie in the range 100–600 GeV; technirho vector meson masses are expected to lie between 200 and 1000 GeV. Multiscale and topcolor-assisted models of technicolor tend to have so many technifermions that the characteristic scale of these models, set by the technipion decay constant \(F_T\), is small. Consequently, it is plausible that technihadrons \(\pi_T\) and \(\rho_T\) have masses at the lower end of these ranges. I should not have to point out that such low-scale technihadrons are accessible at the Tevatron.

Color-singlet technipions, including the longitudinal \(W_L\) and \(Z_L\), are pair-produced via the Drell-Yan process in hadron collisions. The \(O(\alpha^2)\) signal rates at the Tevatron and LHC are probably unobservably small compared to backgrounds unless there are fairly strong color-singlet technirho resonances, \(\rho_T^{+\pm,0}\) not far above threshold. To parameterize the cross sections, we consider a simple model containing two isotriplets of technipions which are mixtures of \(W_L^\pm, Z_L^0\) and an isotriplet of mass-eigenstate technipions \(\pi_T\). The lighter isotriplet \(\rho_{T1}\) is assumed to decay dominantly into pairs of the mixed state \(|\Pi_T\rangle = \sin \chi |W_L\rangle + \cos \chi |\pi_T\rangle\), leading to the processes

\[
\begin{align*}
q\bar{q}' &\rightarrow W_L^\pm \rightarrow \rho_{T1}^\pm \rightarrow \begin{cases} W_L^\pm Z_L^0, & \text{if } \pi_T^0 \rightarrow \pi_T^\pm \pi_T^- \\
W_L^\pm \pi_T^0, & \text{if } \pi_T^0 \rightarrow \pi_T^\pm \pi_T^- \end{cases} \\
q\bar{q} &\rightarrow \gamma, Z^0 \rightarrow \rho_{T1}^0 \rightarrow \begin{cases} W_L^+ W_L^-, & \text{if } \pi_T^0 \rightarrow \pi_T^+ \pi_T^- \\
W_L^\pm \pi_T^0, & \text{if } \pi_T^0 \rightarrow \pi_T^+ \pi_T^- \end{cases}
\end{align*}
\tag{4}
\]

The mixing angle \(\chi\) is specified by \(\sin \chi = F_T/F_\pi\), where \(F_T\) is the \(\Pi_T\) decay constant and \(F_\pi = 246\) GeV. Although this mixing usually is quite small, walking technicolor enhancements of technipion masses suppress or even close the \(\rho_{T1} \rightarrow \pi_T^+ \pi_T^-\) channels. Thus, the \(\rho_{T1}\) should be quite narrow and any of the decay modes in Eq. (4) may be important. This is seen in Fig. 1 where the production rates of individual channels are calculated for the Tevatron as a function of \(M_{\rho_{T1}}\), for \(M_{\pi_T} = 110\) GeV and \(\sin \chi = \frac{1}{4}\). Such low mass technipions are expected to decay to \(b\bar{b}\) or \(c\bar{c}\). Furthermore, some scheme such as TC2 which results in a small coupling \(m_{TC}^{ETC}/F_T\) of technipions to the top quark is required to suppress the unseen mode \(t \rightarrow \pi_T^\pm b\). Heavy-flavor tagging and kinematical selection techniques are useful to extract the signals. Figure 1 illustrates several important general points.
point depends to some extent on the suppression factor $\tan \chi$, but it should not be much different from this. A search for the $\pi_T^+ \pi_T^0$ channel will be rewarding, even if it is negative.

Since the isospin of technifermions is approximately conserved, the $\rho_{T1}$ is expected to be nearly degenerate with its isoscalar partner $\omega_T$. The walking technicolor enhancement of technipion masses almost certainly closes off the isospin-conserving decay $\omega_T \rightarrow \Pi_T^+ \Pi_T^- \Pi_T^0$. Even the triply-suppressed mode $W_T^+ W_L^- Z_L$ has little or no phase space for $M_{\omega_T} \lesssim 300 \text{ GeV}$. Thus, the main decays are expected to be $\omega_T \rightarrow \gamma \Pi_T^0$, $Z \Pi_T^0$, and $\Pi_T^+ \Pi_T^-$. In terms of mass eigenstates, these modes are $\omega_T \rightarrow \gamma \pi_T^0, \gamma Z_L, \pi_T^0, Z \pi_T^0, Z \pi_T^0, Z \pi_T^0; \gamma \pi_T^0, \gamma \pi_T^0, \gamma \pi_T^0$. It is not possible to estimate the relative magnitudes of the decay amplitudes without an explicit model of the $\omega_T$’s constituent technifermions. Judging from the decays of the ordinary $\omega$, we expect $\omega_T \rightarrow Z \pi_T^0 (\pi_T^0)$, $\gamma \pi_T^0 (\pi_T^0)$ to dominate, with the latter mode favored by phase space.

The $\omega_T$ is produced in hadron collisions just as the $\rho_{T1}^0$ is, via its vector-meson-dominance coupling to $\gamma$ and $Z$. For $M_{\omega_T} \simeq M_{\rho_{T1}}$, the $\omega_T$ production cross section should be approximately $|Q_U + Q_D|^2$ times the $\rho_{T1}^0$ rate, where $Q_{U,D}$ are the electric charges of the $\omega_T$’s constituent technifermions. The principal signatures for $\omega_T$ production, then, are $\ell^+\ell^-$ (or $\nu\bar{\nu}$) $+b\bar{b}$ and $\gamma + b\bar{b}$, with $M_{b\bar{b}} = M_{\omega_T}$. A search for the $Z \pi_T$ mode will use the same strategies as for $\rho_{T1} \rightarrow Z \pi_T$ and $W_L \pi_T$. The search for $\omega_T \rightarrow \gamma \pi_T^0$ in hadron collider experiments is under study.\[^{24}\]

4.2 Color-Octet Technirho Production and Decay to Jets and Technipions

Models with an electroweak doublet of color-triplet techniquarks ($U, D$) have an octet of $I = 0$ technirhos, $\rho_{TS}$, with the same quantum numbers as the gluon. The $\rho_{TS}$ is produced strongly in $\bar{q}q$ and $gg$ collisions. Assuming the one-family model for simplicity, the 63 technipions listed in Sec. \[^{2}\] were considered by Chivukula and Golden for a one-doublet technicolor model.\[^{3}\] Our estimates of the branching ratios for the isospin-violating decays $\rho_{T1} \rightarrow \gamma \pi_T^0, Z \pi_T^0$ suggest that they are negligible unless the mixing angle $\chi$ is very small.

\[^{24}\]the modes \(\omega_T \rightarrow \gamma Z_L, Z \pi_T\) were considered by Chivukula and Golden for a one-doublet technicolor model.

\[^{3}\]Our estimates of the branching ratios for the isospin-violating decays $\rho_{T1} \rightarrow \gamma \pi_T^0, Z \pi_T^0$ suggest that they are negligible unless the mixing angle $\chi$ is very small.
Figure 2: Dijet cross sections at the Tevatron ($\bar{p}p$ collisions at 1.8 TeV) including the effect of octet technirho vector mesons at 250 and 500 GeV. The solid curve assumes perfect jet energy resolution while the dashed curve assumes resolution $\sigma(E)/E = 100\%E^{1/2}$ (GeV). Jet angles and rapidities were limited by $\cos \theta^* < \frac{2}{3}$ and $|\eta_j| < 2.0$.

also occur. There are two possibilities for $\rho_T$ decays:

In the first, walking technicolor enhancements of the technipion masses close off the $\pi_T \pi_T$ channels. Then the octet technirho’s coupling to the gluon mediates $\rho_T \rightarrow \bar{q}q, gg \rightarrow$ jets. The $O(\alpha_S^2)$ dijet cross sections including the $\rho_T$ enhancement are illustrated for the Tevatron and the LHC in Figs. 2 and 3. For $M_{\rho_T} = 250$ GeV, the signal-to-background rates is estimated to be 0.70 nb/5.0 nb at the Tevatron and 15 nb/150 nb at the LHC. For $M_{\rho_T} = 500$ GeV, the $S/B$ rates in these figures are 10 pb/40 pb and 2.0 nb/6.0 nb, respectively. Searches for the dijet signal of $\rho_T$ have been carried out by the CDF Collaboration. Using 103 pb$^{-1}$ of data from Tevatron Collider Run I, CDF has excluded the range $250 \text{ GeV} < M_{\rho_T} < 500 \text{ GeV}$ for the model A parameters used in the second paper of Ref. 15.

The second possibility is that technirho decay channels are open, in which case $\rho_T \rightarrow \pi_T \pi_T \bar{q}q$ and $\pi_{Q\bar{Q}} \pi_{L\bar{L}}$ dominates the dijet modes. The color octet technipions are expected to decay into heavy quark pairs, as do the color-singlets in Eq. 3.

The caveat regarding technipion decays to top quarks in TC2 models still applies. Technipion pair production rates, per channel, are expected to lie in the range 1–10 pb at the Tevatron and 1–10 nb at the LHC. Detailed rate estimates depend on $\rho_T$ and $\pi_T$ masses and other model parameters. The LHC rate estimates are so high that color octet and triplet technipions cannot fail to be discovered there—if they exist and if they have not already been detected in Run II of the Tevatron.

At this conference, K. Maeshima of CDF reported on a search for color-triplet leptoquarks decaying into $\tau + \text{jet}$. The limit obtained, $M_{\pi_{QL}} > 100 \text{ GeV}$ assumes only pure-QCD production of the leptoquark pair. A somewhat more stringent (and more model-dependent) limit would result if it is assumed that the leptoquarks are resonantly produced.

color-triplet leptoquarks decay as

$$
\begin{align*}
\pi_{U\bar{N}} & \rightarrow \begin{cases} 
c\bar{\nu}_\tau & \text{if } M_{\pi_T} < m_t \\
 t\bar{u}_\tau & \text{if } M_{\pi_T} > m_t 
\end{cases} \\
\pi_{U\bar{E}} & \rightarrow \begin{cases} 
c\tau^+ & \text{if } M_{\pi_T} < m_t \\
 t\tau^+ & \text{if } M_{\pi_T} > m_t 
\end{cases} \\
\pi_{D\bar{N}} & \rightarrow b\bar{\nu}_\tau \\
\pi_{D\bar{E}} & \rightarrow b\tau^+ .
\end{align*}
$$

(5)
4.3 Signatures of Topcolor-Assisted Technicolor

Topcolor and topcolor-assisted technicolor (TC2) were reviewed at this conference by D. Kominis. The development of TC2 is still at an early stage and, so, its phenomenology is not fully formed. Nevertheless, in addition to the color-singlet and nonsinglet technihadrons already discussed, there are three TC2 signatures that are likely to be present in any surviving model: 18, 23, 34, 28

- The isotriplet of color-singlet “top-pions” \( \pi_t \) arising from spontaneous breakdown of the top quark’s \( SU(2) \otimes U(1) \) chiral symmetry.
- The color-octet of vector bosons \( V_8 \), called “colorons”, associated with breakdown of the top quark’s strong \( SU(3) \) interaction to ordinary color.
- The \( Z' \) vector boson associated with breakdown of the top quark’s strong \( U(1) \) interaction to ordinary weak hypercharge.

The three top-pions are nearly degenerate. They couple to the top quark with strength \( m_t / F_t \), where \( m_t \) is the part of the top-quark mass induced by topcolor—expected to be within a few GeV of its total mass—and \( F_t \simeq 70 \text{ GeV} \) is the \( \pi_t \) decay constant. If the top-pion is lighter than the top quark, then

\[
\Gamma(t \rightarrow \pi_t^+ b) \simeq \frac{(m_t^2 - M_{\pi_t}^2)^2}{16\pi m_t F_t^2}.
\]

The standard top-decay mode branching ratio \( B(t \rightarrow W^+ b) = 0.87^{+0.13}_{-0.11} \) (stat.) \( ^{+0.13}_{-0.11} \) (syst.) was reported a year ago. At the 1\( \sigma \) level, then, \( M_{\pi_t} \gtrsim 150 \text{ GeV} \). At the 2\( \sigma \) level, the lower bound is 100 GeV, but such a small branching ratio for \( t \rightarrow W^+ b \) would require \( \sigma(p\bar{p} \rightarrow t\bar{t}) \) at the Tevatron about 4 times the standard QCD value of 4.75 \( ^{+0.63}_{-0.68} \) pb. The \( t \rightarrow \pi_t^+ b \) decay mode can be sought in high-luminosity runs at the Tevatron and with moderate luminosity at the LHC. If \( M_{\pi_t} < m_t \), then \( \pi_t^+ \rightarrow e^+ b \) through \( t-c \) mixing. It is also possible, though unlikely, that \( \pi_t^+ \rightarrow t\bar{s} \) through \( b-s \) mixing.

If \( M_{\pi_t} > m_t \), then \( \pi_t^+ \rightarrow t\bar{b} \) and \( \pi_t^0 \rightarrow \bar{t}t \) or \( \bar{c}c \), depending on whether the neutral top-pion is heavier or lighter than 2\( m_t \). The main hope for discovering top-pions heavier than the top quark seems to rest on the isotriplet of top-rho vector mesons, \( \rho_t^{3/2} \). It is hard to estimate \( M_{\rho_t} \); it may lie near \( 2m_t \) or closer to \( \Lambda_t = O(1 \text{ TeV}) \). The \( \rho_t \) are produced in hadron collisions just as the corresponding color-singlet technirhos discussed above. The conventional expectation is that they decay as \( \rho_t^{3/2} \rightarrow \pi_t^+ \pi_t^0, \pi_t^+ \pi_t^- \). The rates are not likely to be large, but the distinctive decays of top-pions help suppress standard model backgrounds.

It is also plausible that, because topcolor is broken near \( \Lambda_t \), the \( \rho_t \) are not completely analogous to the \( \rho \)-mesons of QCD and technicolor. For distance scales between \( \Lambda_t^{-1} \) and 1 GeV\(^{-1} \), top and bottom quarks do not experience a growing confining force. Instead of \( \rho_t \rightarrow \pi_t \pi_t \), the \( \rho_t^{3/2} \) may fall apart into their constituents \( b\bar{b}, b\bar{f} \) and \( t\bar{t} \). The \( \rho_t^{3/2} \) resonance may be visible as a significant increase in \( t\bar{b} \) production, but \( \rho_t^{1/2} \) won’t be seen in \( t\bar{t} \).

The \( V_8 \) colorons of broken \( SU(3) \) topcolor are readily produced in hadron collisions. They are expected to have a mass of 0.5–1 TeV. Colorons couple with strength \( -g_S \cot \xi \) to quarks of the two light generations and with strength \( g_S \tan \xi \) to top and bottom quarks, where \( \tan \xi \gg 1 \).

Their decay rate is

\[
\Gamma_{V_8} = \frac{1}{4} \alpha_S M_{V_8} \left\{ 4 \cot^2 \xi + \frac{\tan^2 \xi (1 + \beta_t(1 - m_t^2/M_{V_8}^2))}{1 - 4m_t^2/M_{V_8}^2} \right\},
\]

where \( \beta_t = \sqrt{1 - 4m_t^2/M_{V_8}^2} \). Colorons may then appear as resonances in \( bb \) and \( t\bar{t} \) production. R. Harris has studied the limits on masses and couplings of colorons decaying to \( bb \) and \( t\bar{t} \) that may be set at the Tevatron in Run II \( (\int dt = 20 \text{ fb}^{-1}) \) and at the high-luminosity TeV33 upgrade \( (\int dt = 30 \text{ fb}^{-1}) \). He found that nearly the entire interesting range, \( M_{V_8} \lesssim 1.3 \text{ TeV} \), can be probed. 13

Colorons have little effect on the standard dijet production rate. The situation may be very different for the \( Z' \) boson of the broken strong \( U(1) \) interaction. In some TC2 models, it is natural that \( Z' \) couples strongly to the fermions of the first two generations as well as those of the third. The \( Z' \) in these models is heavier than the colorons, roughly \( M_{Z'} = 1–3 \text{ TeV} \). Thus, at subprocess energies well below \( M_{Z'} \), the interaction of \( Z' \) with all quarks is described by a contact interaction, just like what is expected for quarks with sub-
structure at a scale of a few TeV. This leads to an excess of jets at high $E_T$ and invariant mass. An excess in the jet-$E_T$ spectrum consistent with $\Lambda \simeq 1600$ GeV has been reported by the CDF Collaboration. It remains to be seen whether it is due to topcolor or any other new physics. As with quark substructure, the angular and rapidity distributions of the high-$E_T$ jets induced by $Z'$ should be more central than predicted by QCD. The $Z'$ may also produce an excess of high invariant mass $\ell^+\ell^-$. It will be interesting to compare limits on contact interactions in the Drell-Yan process with those obtained from jet production.

If the $Z'$ is strongly coupled to light fermions it will be produced directly in $\bar{q}q$ annihilation in LHC experiments. Because it may be strongly coupled to so many fermions, including technifermions in the LHC’s energy range, it is likely to be very broad. This possibility should be taken into account in forming strategies to look for the topcolor $Z'$ at the LHC. I reiterate, however, that it is too early to predict the $Z'$ couplings, width and branching fractions with confidence. I hope for progress on these questions in the coming year.

5 Conclusions

In this talk, I have tried to emphasize the importance of searching for signatures of dynamical as well as weakly-coupled scenarios for electroweak and flavor physics. We cannot be reminded too often how unaware we remain of TeV-scale physics and that only experiment will remove our ignorance. A young woman in Amherst, Massachusetts, said it best over a century ago:

“Faith” is a fine invention
When Gentlemen can see —
But Microscopes are prudent
In an Emergency.

— Emily Dickinson, 1860

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Questions

David J. Miller, University College, London:
SUSY has the attraction that she [sic] offers us a dark matter candidate. Does your technicolor theory?

K. Lane:
The topcolor-assisted technicolor models I have been investigating tend to have stable technibaryons. Whether or not they are electrically charged and, hence, ruled out is a model-dependent question.

Bernd Kniel, Max Planck Institute, Munich:
Technifermions have gauge couplings and introduce thresholds in the beta functions of the gauge couplings. In addition, there is a new gauge coupling introduced by technicolor. Will these couplings meet at some grand unification scale as they do in supersymmetry?

K. Lane:
There already is a “petit unification”—at the extended technicolor scale of several hundred TeV where technicolor, color, and flavor gauge symmetries are rejoined. I have no idea whether technicolor will involve grand unification at some very high scale, although the attractiveness of that possibility is undeniable. I remind you that the modern gauge-mediated scenarios of supersymmetry breaking introduce new gauge couplings and, so, also imperil the grand unification claimed for the $SU(3) \otimes SU(2) \otimes U(1)$ couplings. In view of the recent developments in duality, I would not be surprised in ten years time to find supersymmetry and technicolor united into a strong-dynamical theory of electroweak and flavor symmetry breaking, with quarks and leptons as composite entities at some scale.