Electroweak Symmetry Breaking by Strong Dynamics and the Collider Phenomenology*

Conveners:

Timothy L. Barklow†
SLAC
R. Sekhar Chivukula‡
Fermilab
Joel Goldstein§
Department of Physics, Boston University
Tao Han¶
Department of Physics, University of Wisconsin, Madison

Working group members: D. Dominici, S. Godfrey, R. Harris, H.-J. He, P. Kalyniak, W. Kilian, K. Lynch, T. Liu, J. Mizukoshi, M. Narain, T. Ohl, M. Popovic, A. Skuja, T. Tait, W. Walkowiak, J. Womersley

We discuss the possible signatures in the electroweak symmetry breaking sector by new strong dynamics at future hadron colliders such as the Tevatron upgrade, the LHC and VLHC, and e^+e^- linear colliders. Examples include a heavy Higgs-like scalar resonance, a heavy Technicolor-like vector resonance and pseudo-Goldstone states, non-resonance signatures via enhanced gauge-boson scattering and fermion compositeness.

1. Introduction

Particle physics is on the verge of major discovery. General arguments indicate that new physics in the electroweak symmetry breaking sector must show up below the scale of 1 TeV. The experiments at the Tevatron and next generation high energy colliders such as the LHC and a TeV e^+e^- linear collider will fully explore the new physics at the electroweak scale.

In theories of dynamical electroweak symmetry breaking, the electroweak interactions are broken to electromagnetism by the vacuum expectation value of a fermion bilinear. These theories may thereby avoid the introduction of fundamental scalar particles, of which we have no examples in nature thus far. Prominent examples include Technicolor, topcolor, and related models. If the new dynamical scale is somewhat higher than 1 TeV, then the low energy effects or the early signature at collider experiments may be anomalous gauge boson interactions, enhanced WW scattering signals, or contact 4-fermion interactions. In this report, we first briefly introduce the dynamical electroweak symmetry breaking models and parameterization of the anomalous couplings. We then summarize the collider sensitivities to probe the new dynamics at future e^+e^- linear colliders in Sec. II, and at hadron colliders in Sec. III.

1.1. Technicolor

The earliest models [1, 2] of dynamical electroweak symmetry breaking [3, 4] include a new non-Abelian gauge theory ("Technicolor") and additional massless fermions ("technifermions")

*This is the report of the Strong Electroweak Symmetry Breaking Working Group at 2001 Snowmass summer studies.
† timb@slac.stanford.edu
‡ sekhar@bu.edu
§ joelg@fnal.gov
¶ than@pheno.physics.wisc.edu

which feel this new force. The global chiral symmetry of the fermions is spontaneously broken by the formation of a technifermion condensate, just as the approximate chiral $SU(2) \times SU(2)$ symmetry in QCD is broken down to $SU(2)$ isospin by the formation of a quark condensate. If the quantum numbers of the technifermions are chosen correctly (*e.g.* by choosing technifermions in the fundamental representation of an SU(N) Technicolor gauge group, with the left-handed technifermions being weak doublets and the right-handed ones weak singlets) this condensate can break the electroweak interactions down to electromagnetism.

The breaking of the global chiral symmetries implies the existence of Goldstone bosons, the "technipions" (π_T). Through the Higgs mechanism, three of the Goldstone bosons become the longitudinal components of the W and Z, and the weak gauge bosons acquire a mass proportional to the technipion decay constant (the analog of f_π in QCD). The quantum numbers and masses of any remaining technipions are model dependent. There may be technipions which are colored (octets and triplets) as well as those carrying electroweak quantum numbers, and some color-singlet technipions are too light [5, 6] unless additional sources of chiral-symmetry breaking are introduced. The next lightest Technicolor resonances are expected to be the analogs of the vector mesons in QCD. The technivector mesons can also have color and electroweak quantum numbers and, for a theory with a small number of technifermions, are expected to have a mass in the TeV range [7].

While Technicolor chiral symmetry breaking can give mass to the W and Z particles, additional interactions must be introduced to produce the masses of the standard model fermions. The most thoroughly studied mechanism for this invokes "extended Technicolor" (ETC) gauge interactions [5, 8]. In ETC, Technicolor, color and flavor are embedded into a larger gauge group which is broken to Technicolor and color at an energy scale of 100s to 1000s of TeV. The massive gauge bosons associated with this breaking mediate transitions between quarks/leptons and technifermions, giving rise to the couplings necessary to produce fermion masses. The ETC gauge bosons also mediate transitions among technifermions themselves, leading to interactions which can explicitly break unwanted chiral symmetries and raise the masses of any light technipions. The ETC interactions connecting technifermions to quarks/leptons also mediate technipion decays to ordinary fermion pairs. Since these interactions are responsible for fermion masses, one generally expects technipions to decay to the heaviest fermions kinematically allowed (though this need not hold in all models).

In addition to quark masses, ETC interactions must also give rise to quark mixing. One expects, therefore, that there are ETC interactions coupling quarks of the same charge from different generations. A stringent limit on these flavor-changing neutral current interactions comes from K^0–$\overline{K}^0$ mixing [5]. These force the scale of ETC breaking and the corresponding ETC gauge boson masses to be in the 100–1000 TeV range (at least insofar as ETC interactions of first two generations are concerned). To obtain quark and technipion masses that are large enough then requires an enhancement of the technifermion condensate over that expected naively by scaling from QCD. Such an enhancement can occur if the Technicolor gauge coupling runs very slowly, or "walks" [9]. Many technifermions typically are needed to make the TC coupling walk, implying that the Technicolor scale and, in particular, the technivector mesons may be much lighter than 1 TeV [3, 10]. It should also be noted that there is no reliable calculation of electroweak parameters in a walking Technicolor theory, and the values of precisely measured electroweak quantities [11] cannot directly be used to constrain the models.

In existing colliders, technivector mesons are dominantly produced when an off-shell standard model gauge-boson "resonates" into a technivector meson with the same quantum numbers [12]. The technivector mesons may then decay, in analogy with $\rho \to \pi\pi$, to pairs of technipions. However, in walking Technicolor the technipion masses may be increased to the point that the decay of a technirho to pairs of technipions is kinematically forbidden [10]. In this case the decay to a technipion and a longitudinally polarized weak boson (an "eaten" Goldstone boson) may be preferred, and the technivector meson would be very narrow. Alternatively, the technivector may also decay, in analogy with the decay $\rho \to \pi\gamma$, to a technipion plus a photon, gluon, or transversely polarized weak gauge boson. Finally, in analogy with the decay $\rho \to e^+e^-$, the technivector meson may resonate back to an off-shell gluon or electroweak gauge boson, leading to a decay into a pair of leptons, quarks, or gluons.

1.2. Top Condensate and Related Models

The top quark is much heavier than other fermions and must be more strongly coupled to the symmetry-breaking sector. It is natural to consider whether some or all of electroweak-symmetry breaking is due to a condensate of top quarks [3, 13]. Top-quark condensation alone, without additional fermions, seems to produce a top-quark mass larger [14] than observed experimentally, and is therefore not favored. Topcolor assisted Technicolor [15] combines Technicolor and top-condensation. In addition to Technicolor, which provides the bulk of electroweak symmetry breaking, top-condensation and the top quark mass arise predominantly from "topcolor," a new QCD-like interaction which couples strongly to the third generation of quarks. An additional, strong, U(1) interaction (giving rise to a topcolor Z') precludes the formation of a b-quark condensate.

The top-quark seesaw model of electroweak symmetry breaking [16] is a variant of the original top-condensate idea which reconciles top-condensation with a lighter top-quark mass. Such a model can easily be consistent with precision electroweak tests, either because the spectrum includes a light composite Higgs [17, 18] or because additional interactions allow for a heavier Higgs [19, 20]. Such theories may arise naturally from gauge fields propagating in compact extra spatial dimensions [21].

A variant of topcolor-assisted Technicolor is flavor-universal, in which the topcolor SU(3) gauge bosons, called colorons, couple equally to all quarks [22, 23]. Flavor-universal versions of the seesaw model [24, 25] incorporating a gauged flavor symmetry are also possible. In these models *all* left-handed quarks (and possibly leptons as well) participate in electroweak symmetry-breaking condensates with separate (one for each flavor) right-handed weak singlets, and the different fermion masses arise by adjusting the parameters which control the mixing of each fermion with the corresponding condensate. A prediction of these flavor-universal models, is the existence of new heavy gauge bosons, coupling to color or flavor, at relatively low mass scales. A mass limit of between 0.8 and 3.5 TeV is set [26] depending on the coloron-gluon mixing angle. Precision electroweak measurements constrain [27] the masses of these new gauge bosons to be greater than 1–3 TeV in a variety of models, for strong couplings.

1.3. Enhanced gauge-boson couplings and fermion compositeness

If the new strong dynamics scale is somewhat higher than that accessible to the next generation of colliders, the expected signature would be enhanced gauge-boson self-interactions conventionally parameterized by the "anomalous couplings" [28, 29, 30, 31], and the fermion contact interactions the so-called "fermion compositeness" [32] at a scale Λ.

Although the current LEP and Tevatron experiments have put stringent bounds on the anomalous gauge-boson self-interactions, the anticipated size of those couplings due to new strong dynamics may be of order $v^2/\Lambda^2 \sim 1/16\pi^2 < 10^{-3}$, smaller than the current bounds. Experiments at future colliders will reach sensitivity to this level. In particular, high energy scattering of longitudinal gauge-bosons W_L, Z_L as the electroweak Goldstone bosons should be the most direct probe to the electroweak symmetry breaking sector. General arguments such as unitarity [33, 34] indicate that new physics associated with the electroweak symmetry breaking must show up in some form at the scale of TeV, which can be accessible most likely only at higher energy colliders of next generation. Regarding the fermion compositeness, higher sensitivity will be reached at higher energies due to the energy-dependent nature of the dimension 6-operators [32]. In the next two sections, we will summarize the studies of the above physics scenarios at future colliders.

2. Strong Dynamics at e^+e^- Linear Colliders

An e^+e^- linear collider with $\sqrt{s} = 0.5 - 1.5$ TeV and a luminosity of 500–1000 pb^{-1} can be a very effective probe of strong electroweak symmetry breaking. Production mechanisms and backgrounds are limited to electroweak processes, so that signal and background cross sections can be calculated exactly. The initial state is well defined not only in terms of four-momentum, but also in terms of electron (and possibly positron) helicity. Also, complete final state helicity analyses are possible, due to the fact that most if not all of the final state kinematic variables can be reconstructed.

In this section we review the e^+e^- collider phenomenology of strong W^+W^- interactions which appear when there is no light Higgs particle with large couplings to vector gauge bosons. Detection of directly produced narrow-width spinless particles such as technipions [35] and top-pions [36] is straightforward up to the kinematic limit, and will not be discussed further.

2.1. $e^+e^- \to \nu\bar{\nu}W^+W^-$, $\nu\bar{\nu}ZZ$, W^+W^-Z, ZZZ, $\nu\bar{\nu}t\bar{t}$

The first step in studying the reaction $e^+e^- \to \nu\bar{\nu}W^+W^-$ is to separate the scattering of a pair of longitudinally polarized W's, denoted by W_LW_L, from transversely polarized W's and background such as $e^+e^- \to e^+e^-W^+W^-$ and $e^-\bar{\nu}W^+Z$. Studies have shown that simple cuts[37] can be used to achieve this separation in $e^+e^- \to \nu\bar{\nu}W^+W^-$, $\nu\bar{\nu}ZZ$ at $\sqrt{s} = 1000$ GeV, and that the signals[38, 39] are comparable to those obtained at the LHC[40, 41, 42, 43]. Furthermore, by analyzing the gauge boson production and decay angles it is possible to use these reactions to measure chiral Lagrangian parameters with an accuracy greater than that which can be achieved at the LHC [44].

The chiral Lagrangian parameters associated with quartic gauge boson couplings can also be measured with the triple gauge boson production processes $e^+e^- \to W^+W^-Z$ and $e^+e^- \to ZZZ$ [45, 46, 47]. These measurements complement the W^+W^- fusion measurements, and they will play a crucial role in multi-parameter chiral Lagrangian analyses.

The reaction $e^+e^- \to \nu\bar{\nu}t\bar{t}$ provides unique access to $W^+W^- \to t\bar{t}$ since this process is overwhelmed by the background $gg \to t\bar{t}$ at the LHC. Techniques similar to those employed to isolate $W_LW_L \to W^+W^-, ZZ$ can be used to measure the enhancement in $W_LW_L \to t\bar{t}$ production[48, 49, 50, 51]. Even in the absence of a resonance it will be possible to establish a clear signal. The ratio $S/\sqrt{B}$ is expected to be 12 for a linear collider with $\sqrt{s} = 1$ TeV, 1000 fb^{-1} and 80%/0% electron/positron beam polarization, increasing to 22 for the same luminosity and beam polarization at $\sqrt{s} = 1.5$ TeV.

2.2. $e^+e^- \to W^+W^-$

Strong gauge boson interactions induce anomalous triple gauge couplings (TGC's) at tree-level[28, 29, 30, 31]:

$$\begin{aligned}
\kappa_\gamma &= 1 + \frac{e^2}{32\pi^2 s_w^2}(L_{9L} + L_{9R}) \\
\kappa_Z &= 1 + \frac{e^2}{32\pi^2 s_w^2}(L_{9L} - \frac{s_w^2}{c_w^2}L_{9R}) \\
g_1^Z &= 1 + \frac{e^2}{32\pi^2 s_w^2}\frac{L_{9L}}{c_w^2} .
\end{aligned}$$

where κ_γ, κ_Z, and g_1^Z are TGC's, $s_w^2 = \sin^2\theta_w$, $c_w^2 = \cos^2\theta_w$, and L_{9L} and L_{9R} are chiral Lagrangian parameters[52]. Assuming QCD values for L_{9L} and L_{9R}, κ_γ is shifted by $\Delta\kappa_\gamma \sim -3\times10^{-3}$.

Table I contains the estimates of the TGC precision that can be obtained at $\sqrt{s} = 500$ and 1000 GeV for the CP-conserving couplings g_1^V, κ_V, and λ_V [53]. These estimates are derived from one-parameter fits in which all other TGC parameters are kept fixed at their tree-level SM values. The 4×10^{-4} precision for the TGCs κ_γ and κ_Z at $\sqrt{s} = 500$ GeV can be interpreted as a precision of 0.26 for the chiral Lagrangian parameters L_{9L} and L_{9R}. Assuming naive dimensional analysis[54] such a measurement would provide a 8σ (5σ) signal for L_{9L} and L_{9R} if the strong symmetry breaking energy scale were 3 TeV (4 TeV).

When W^+W^- scattering becomes strong the amplitude for $e^+e^- \to W_LW_L$ develops a complex form factor F_T in analogy with the pion form factor in $e^+e^- \to \pi^+\pi^-$[55, 56]. To evaluate the size of this effect the following expression for F_T can be used:

$$F_T = \exp[\frac{1}{\pi}\int_0^\infty ds'\,\delta(s', M_\rho, \Gamma_\rho)\{\frac{1}{s' - s - i\epsilon} - \frac{1}{s'}\}]$$

where

$$\delta(s, M_\rho, \Gamma_\rho) = \frac{1}{96\pi}\frac{s}{v^2} + \frac{3\pi}{8}\left[\tanh(\frac{s - M_\rho^2}{M_\rho\Gamma_\rho}) + 1\right] .$$

	error $\times 10^{-4}$			
	$\sqrt{s}$ = 500 GeV		$\sqrt{s}$ = 1000 GeV	
TGC	Re	Im	Re	Im
g_1^γ	15.5	18.9	12.8	12.5
κ_γ	3.5	9.8	1.2	4.9
λ_γ	5.4	4.1	2.0	1.4
g_1^Z	14.1	15.6	11.0	10.7
κ_Z	3.8	8.1	1.4	4.2
λ_Z	4.5	3.5	1.7	1.2

Table I Expected errors for the real and imaginary parts of CP-conserving TGCs assuming $\sqrt{s}$ = 500 GeV, $\mathcal{L}$ = 500 fb^{-1} and $\sqrt{s}$ = 1000 GeV, $\mathcal{L}$ = 1000 fb^{-1}. The results are for one-parameter fits in which all other TGCs are kept fixed at their SM values.

Here M_ρ, Γ_ρ are the mass and width respectively of a vector resonance in $W_L W_L$ scattering. The term

$$\delta(s) = \frac{1}{96\pi} \frac{s}{v^2}$$

is the Low Energy Theorem (LET) amplitude for $W_L W_L$ scattering at energies below a resonance. Below the resonance, the real part of F_T is proportional to $L_{9L} + L_{9R}$ and can therefore be interpreted as a TGC. The imaginary part, however, is a distinct new effect.

The expected 95% confidence level limits for F_T for $\sqrt{s}$ = 500 GeV and a luminosity of 500 fb^{-1} are shown in Figure 1, along with the predicted values of F_T for various masses M_ρ of a vector resonance in $W_L W_L$ scattering. The signal significances obtained by combining the results for $e^+e^- \to \nu\bar{\nu}W^+W^-$, $\nu\bar{\nu}ZZ$[37, 38] with the F_T analysis of W^+W^- [57] are displayed in Fig. 2 along with the results expected from the LHC[58]. At all values of the center-of-mass energy a linear collider provides a larger direct strong symmetry breaking signal than the LHC for vector resonance masses of 1200, 1600 and 2500 GeV. Only when the vector resonance disappears altogether (the LET case in the lower right-hand plot in Fig. 2) does the direct strong symmetry breaking signal from the $\sqrt{s}$ = 500 GeV linear collider drop below the LHC signal. At higher e^+e^- center-of-mass energies the linear collider signal exceeds the LHC signal.

3. Strong Dynamics at Hadron Colliders

Hadron colliders offer exciting possibilities for searches for new particles and other signs of new strong dynamics and compositeness. High luminosity pp and $p\overline{p}$ machines should copiously produce proposed strongly-coupled resonances including technihadrons and excited quarks. They also probe contact interactions and vector boson scattering at extremely high energy scales. In this section we describe the expected physics reach of hadron colliders that exist (the Tevatron), are under construction (the LHC) and are being designed (the VLHC).

3.1. The Tevatron

The Tevatron at Fermilab has taken approximately 100 pb^{-1} of $p\overline{p}$ collision data at $\sqrt{s}$ = 1.8 TeV (Run I). In March 2001 Run II began, with an increased energy ($\sqrt{s}$ = 1.96 TeV) and a planned integrated luminosity of 2 fb^{-1} (Run IIa), followed by extended high luminosity running for a total in excess of 15 fb^{-1} per experiment. In Tables II–V announced results from Run I are tabulated along with extrapolations to RunIIa and a possible 30 fb^{-1} complete RunII.

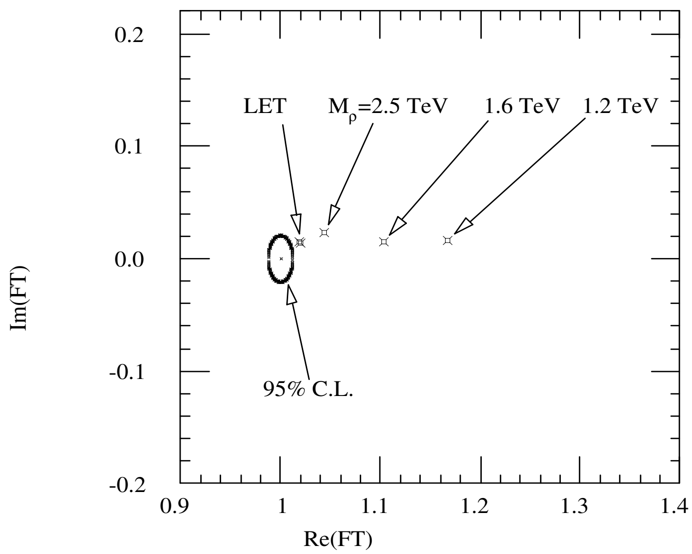

Figure 1: 95% C.L. contour for F_T for $\sqrt{s}$ = 500 GeV and 500 fb^{-1}. Values of F_T for various masses M_ρ of a vector resonance in $W_L W_L$ scattering are also shown. The F_T point "LET" refers to the case where no vector resonance exists at any mass in strong $W_L W_L$ scattering.

Table II **Sensitivity to Technicolor at the Tevatron**

Channel	Run I (100 pb^{-1}) (GeV at 95% CL)	Run IIa (2 fb^{-1}) (GeV at 95% CL)	Run II (30 fb^{-1}) (GeV at 95% CL)
$\rho_{T1} \to W\pi_T \to l\nu b\bar{b}$	$170 < M_\rho < 200$[59] (for $M_\pi \approx M\rho/2$)	$160 < M_\rho < 240$[60] (for $M_\pi \approx M\rho/2$)	$M\rho < 350 - 450$[61]
$\omega_{T1} \to \gamma\pi_T \to \gamma b\bar{b}$	$240 < M_\omega < 310$ ($M_\pi = 120$) $140 < M_\omega < 290$ ($M_\pi = 60$)[62]	-	-
$\rho_{T1}, \omega_{T1} \to e^+e^-$ (If $W\pi$ and $\gamma\pi$ forbidden)	$M < 225$[63]	$M < 410$[64]	-
$\rho_{T8} \to qq, gg \to jj$ ($M_\pi > M_\rho/2$) $\to b\bar{b}$	$260 < M < 480$[65] $350 < M < 440$[67]	$M < 770$[66]	$M < 900$[66]
$\rho_{T8} \to \pi_{LQ}\pi_{LQ} \to b\nu b\nu$	$M < 600$[68]	$M < 850$[69]	-
($M_\pi < M_\rho/2$) $\to c\nu c\nu$	$M < 510$[68]	-	-
$\to b\tau b\tau$	$M < 470$[70]	-	-

3.2. The LHC

Despite the challenge at hadron colliders in the search for new strong dynamics at the TeV scale, much theoretical work has been performed at the LHC[40, 41, 42, 43]. Many studies of strong EWSB at ATLAS and CMS have been performed and summarized in several places[86, 87, 88, 89]. An expected "low luminosity" period will collect 30 fb^{-1} of data at $\sqrt{s}$ = 14 TeV over the first three years of operation, and will be followed by a similar "high luminosity" period collecting up to 300 fb^{-1}. High luminosity running (up to 10^{34} cm^{-2}s^{-1}) presents many experimental challenges with an average of 20 collisions per beam crossing, degrading tracking and electron identification capabilities particularly in the forward region.

As an example of a Technicolor resonance search, ATLAS have considered the production of 500 GeV technirho in a multiscale Technicolor model and its signal in the channel $\rho_T^\pm \to WZ \to l^\pm \nu l^+ l^-$ [86]. This study assumes the 30 fb^{-1} of low luminosity data and hence the full lepton ID and tracking capabilities of the detector. The expected signal significance is strongly dependent on the input model parameters: a narrow resonance (Γ_{ρ_T} = 1.1 GeV) which is not allowed to decay

Table III **Sensitivity to Topgluons at the Tevatron**

Channel	Width Γ/M	Run I (100 pb^{-1}) (GeV at 95% CL)	Run IIa (2 fb^{-1}) (GeV for 5σ signal)	Run II (30 fb^{-1}) (GeV for 5σ signal)
$g_T \to b\bar{b}$	0.3	$280 < M < 670$	$M < 950$	$M < 1200$
	0.5	$340 < M < 640$[71]	$M < 860$[72]	$M < 1100$[72]
	0.7	$375 < M < 560$	$M < 770$	$M < 1000$
$g_T \to t\bar{t} \to l\nu + jets$	0.3	-	$M < 1110$	$M < 1400$
	0.5	-	$M < 1040$[73]	$M < 1350$[73]
	0.7	-	$M < 970$	$M < 1290$
$g_T \to t\bar{t} \to 6\ jets$	0.3	-	$M < 1000$	$M < 1200$
	0.5	-	$M < 900$[74]	$M < 1130$[74]
	0.7	-	$M < 800$	$M < 1100$

Table IV **Sensitivity to Topcolor Z' and h_b at the Tevatron**

Channel	Width Γ/M	Run I (100 pb^{-1}) (GeV at 95% CL)	Run IIa (2 fb^{-1}) (GeV for 5σ signal)	Run II (30 fb^{-1}) (GeV for 5σ signal)
Z' Model I[a] $\to t\bar{t} \to l\nu + jets$	0.02	-	-	$M < 830$[74]
	0.04	-	-	$M < 670$
Z' Model II $\to t\bar{t} \to l\nu + jets$	0.02	-	$M < 720$[74]	$M < 980$[74]
	0.04	-	$M < 950$	$M < 1200$
Z' Model III $\to t\bar{t} \to l\nu + jets$	0.02	-	$M < 600$[74]	$M < 910$[74]
	0.04	-	$M < 800$	$M < 1000$
Z' Model IV $\to t\bar{t} \to l\nu + jets$	0.012	$M < 480$	-	-
	0.02	$M < 650$[76]	$M < 980$[74]	$M < 1200$[74]
	0.04	$M < 780$	$M < 1100$	$M < 1300$
			(GeV at 95% CL)	(GeV at 95% CL)
$b\bar{b}h_b \to b\bar{b}b\bar{b}$		-	$M < 270$[b]	$M < 380$

[a] Z' models described in [75]
[b] Using $y_b/y_b^{SM} = 72$ in Fig 8b of [77]

Table V **Sensitivity to Compositeness at the Tevatron.** In each channel, Λ^+ is the upper entry and Λ^- the lower.

Channel	Run I (100 pb^{-1}) (TeV at 95% CL)	Run IIa (2 fb^{-1}) (TeV at 95% CL)	Run II (30 fb^{-1}) (TeV at 95% CL)
$\Lambda^\pm(qq \to qq)$	2.7[78]	-	-
	2.4	-	-
$\Lambda^\pm(qq \to ee)$	3.3[79]	6.5[80]	14[80]
	4.2	10	2 0
$\Lambda^\pm(qq \to \mu\mu)$	2.9[81]	-	-
	4.2	-	-
$\Lambda^\pm(qq \to \gamma\gamma)$	-	0.75[80, 82]	0.9[80, 82]
	-	0.71	-
$q^* \to q\gamma, qW$	0.54[a][83]	0.91[66]	1.18[66]
		(TeV for 5σ signal)	(TeV for 5σ signal)
$q^* \to qg$	0.76[b]	0.94[85]	1.1[85]

[a] 25 pb^{-1}
[b] D0 q^* search (Bertram) combined with [84]

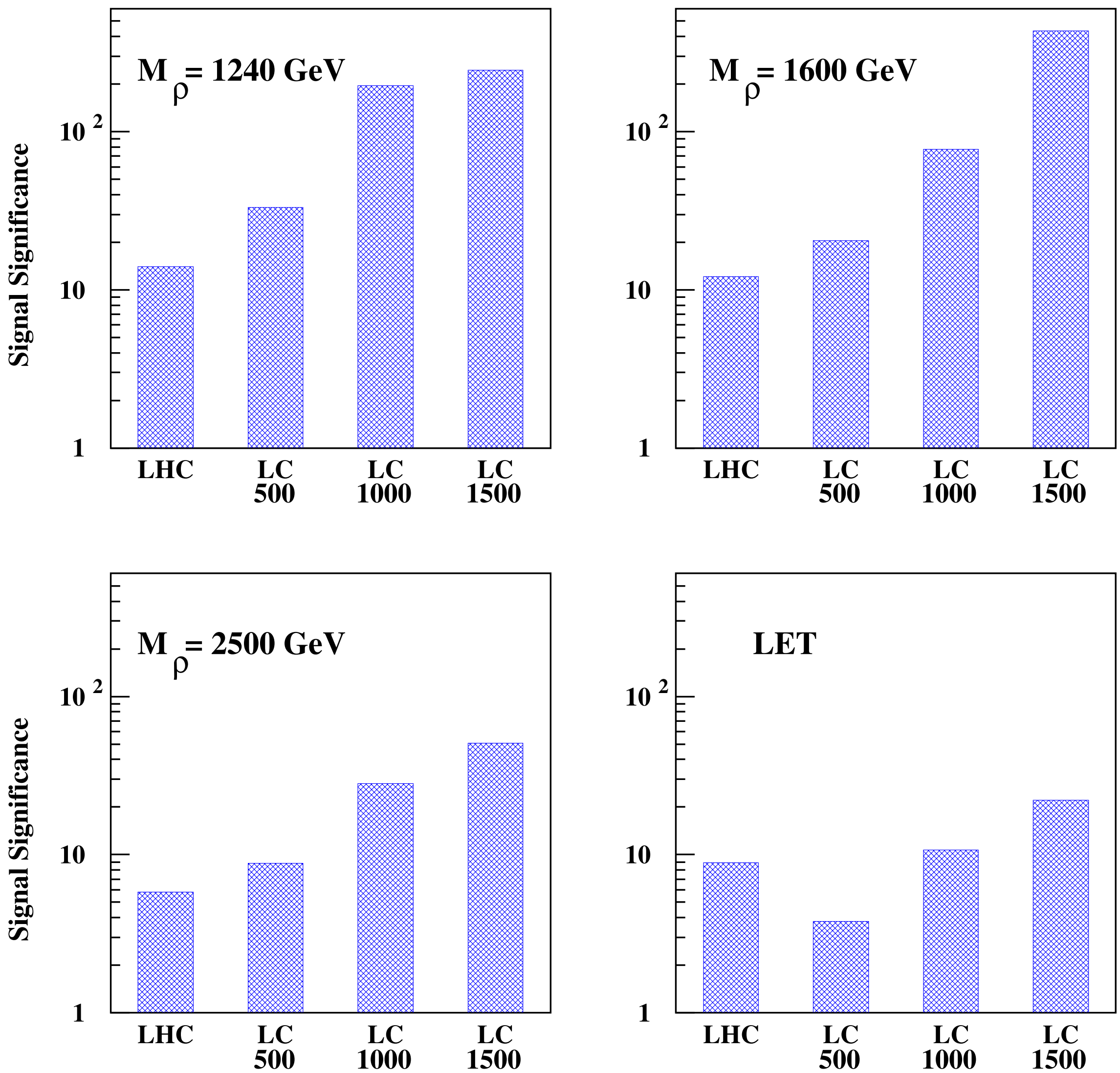

Figure 2: Direct strong symmetry breaking signal significance in σ's for various masses M_ρ of a vector resonance in $W_L W_L$ scattering. The numbers below the "LC" labels refer to the center-of-mass energy of the linear collider in GeV. The luminosity of the LHC is assumed to be 300 fb^{-1}, while the luminosities of the linear colliders are assumed to be 500, 1000, and 1000 fb^{-1} for $\sqrt{s}$=500, 1000, and 1500 GeV respectively. The lower right hand plot "LET" refers to the case where no vector resonance exists at any mass in strong $W_L W_L$ scattering.

to $\pi_T \pi_T$ ($m_{\pi_T} > m_{\rho_T}/2$) could have $S/\sqrt{B} \approx 80$; but for $\Gamma_{\rho_T} = 110$ GeV and $m_{\pi_T} = 110$ GeV this would drop to an indiscernable $S/\sqrt{B} \approx 0.3$.

The masses of observable resonances at the LHC are expected to be 5-10× those at the Tevatron. A Z' with couplings similar to those of the Standard Model Z should be observable up to $m_{Z'} \approx$ 5 TeV and direct observation of excited quarks of $m_{q^*} \approx 6$ TeV is possible[85]. The reach for compositeness scales is similarly enhanced, with 300 fb^{-1} of dijet data being sensitive to $\Lambda \approx$ 40 TeV.

A further possibility at the LHC is that as $\sqrt{\hat{s}}$ begins to exceed 1 TeV, strong interaction effects in WW scattering could become detectable. If jets can be reliably tagged in the forward region at high luminosities, a signal should be observable with the full 300 fb^{-1}.

3.3. The Super-LHC

There has been some discussion of upgrading the LHC in luminosity and energy after the 300 fb^{-1} run is complete. A possible (though unlikely) doubling of the energy has been considered along with a tenfold increase in instantaneous luminosity. Since the LHC detectors were not designed for these conditions only jet and muon information is likely to be usefull. Such an upgrade could double the reach for a Z' ($m_{Z'} \approx 10$ TeV) and compositeness ($\Lambda \approx 80$ TeV), and significantly increase the sensitivity for excited quarks ($m_{q^*} \approx 9$ TeV) and the scale of WW scattering available ($\sqrt{\hat{s}} \approx 1.5$ TeV, assuming that forward jet tagging is still possible). Unfortunately, most of these gains come from the energy increase, which is less plausible than a simple luminosity upgrade.

3.4. The VLHC

A staged 40-175 TeV $p\overline{p}$ collider operating at luminosities comparable to the LHC (1-2$\times 10^{34}$ cm^{-2}s^{-1}) has been proposed[90]. Studies of such a machine's physics reach are in progress (see also the E4 Working Group report), but the direct reach for excited quark resonances is expected to be $m_{q^*} \approx 25$ TeV for 10 fb^{-1} at $\sqrt{s} = 100$ TeV[85], and WW scattering could be probed at the scale of $2-3$ TeV.

New signatures could become detectable at such high center-of-mass energies. For example, in topcolor models, direct χ pair production and subsequent decays $\chi \to ht \to t\bar{t}t$ could occur[20], with a $6t$ final state. Such a heavy state may only be copiously produced. The cross section for this process with $m_\chi = 1$ TeV would be ~ 10 pb, as shown in Fig. 3.

In interactions with $\sqrt{\hat{s}} \gg \Lambda_{TC}$, it is possible (in analogy with QCD) that asymptotically free techniquarks could be produced that subsequently hadronize into technijets consisting of weak vector bosons and technihadrons. A technijet would manifest itself as an extremely massive but significantly boosted (and hence not necessarily wide) jet in a VLHC detector. The production rate for such a process can be significant: For $m_{Q_T} = 400$ GeV with $\sqrt{s} = 100$ TeV the dijet differential cross section for technijets exceeds that for $t\bar{t}$ for dijet masses > 900 GeV. Exploration of technijets could provide the ultimate determination of the TC dynamics. As shown in Fig. 4, a representative techni-quark may decay subsequently into multiple jets and the separation between any two jets may be small enough so that experimental signature would be a very massive (but not too fat) jet.

Acknowledgments

We would like to thank the participants in the Strong Electroweak Symmetry Breaking Working group for the contribution during the Snowmass workshop, on which the materials summarized in this report are based. T.L.B. was supported by Department of Energy contract DE-AC03-76SF00515. R.S.C. was supported in part by a DOE grant DE-FG02-91ER40676. T.H. was supported in part by a DOE grant No. DE-FG02-95ER40896 and in part by the Wisconsin Alumni Research Foundation.

References

[1] S. Weinberg, Phys. Rev. D **20**, 1277 (1979).
[2] L. Susskind, Phys. Rev. D **20**, 2619 (1979).
[3] K. Lane, hep-ph/0007304.
[4] (2001), hep-ph/0110196.
[5] E. Eichten and K. Lane, Phys. Lett. **90B**, 125 (1981).

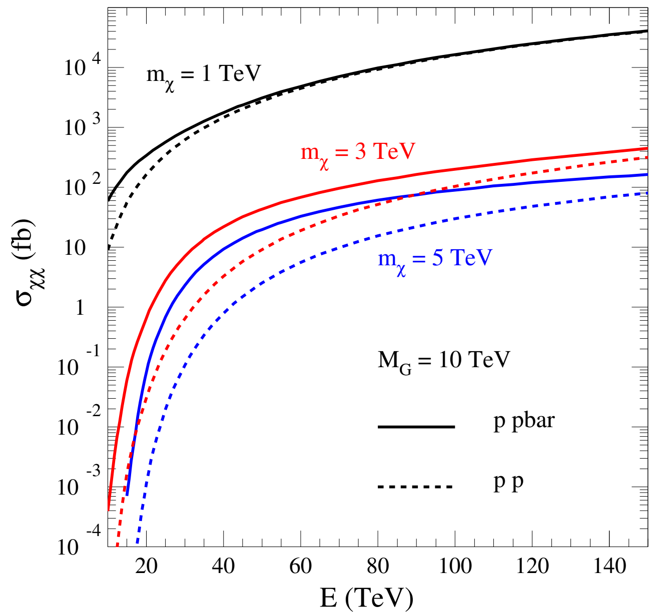

Figure 3: χ-pair production in top-color models at high energy hadron colliders leading to 6-top events.

[6] E. Farhi and L. Susskind, Phys. Rev. **74**, 277 (1981).
[7] S. Dimopoulos, S. Raby, and G. Kane, Nucl. Phys. B **182**, 77 (1981).
[8] S. Dimopoulos and L. Susskind, Nucl. Phys. B **155**, 237 (1979).
[9] B. Holdom, Phys. Rev. D **24**, 1441 (1981).
[10] E. Eichten and K. Lane, Phys. Lett. B **222**, 274 (1989).
[11] Langacker and Erler, see review in this volume.
[12] E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).
[13] V. Miransky, M. Tanabashi, and K. Yamawaki, Phys. Lett. B **221**, 177 (1989).
[14] W. Bardeen, C. Hill, and M. Lindner, Phys. Rev. D **41**, 1647 (1990).
[15] C. Hill, Phys. Lett. B **345**, 483 (1995).
[16] B. Dobrescu and C. Hill, Phys. Rev. Lett. **81**, 2634 (1998).
[17] R. S. Chivukula *et al.*, Phys. Rev. D **59**, 075003 (1999).
[18] (2001), hep-ph/0110214.
[19] H. Collins, A. Grant, and H. Georgi, hep-ph/9908330.
[20] (2001), hep-ph/0108041.
[21] B. Dobrescu, Phys. Lett. B **461**, 99 (1999).
[22] R. S. Chivukula, A. G. Cohen, and E. H. Simmons, Phys. Lett. **B380**, 92 (1996), hep-ph/9603311.
[23] M. B. Popovic and E. H. Simmons, Phys. Rev. **D58**, 095007 (1998), hep-ph/9806287.
[24] E. Simmons, Nucl. Phys. B **324**, 315 (1989).
[25] G. Burdman and N. Evans, Phys. Rev. D **59**, 115005 (1999).
[26] I. Bertram and E. Simmons, Phys. Lett. B **443**, 347 (1998).
[27] G. Burdman, R. Chivukula, and N. Evans, Phys. Rev. D **61**, 035009 (2000).
[28] K. Hagiwara, R. Peccei, D. Zeppenfeld, and K. Hikasa, Nucl. Phys. B **282**, 253 (1987).
[29] S. Dawson and G. Valencia, Nucl. Phys. B **352**, 27 (1991).
[30] A. Dobado, M. Herrero, and J. Terron, Z. Phys. C **50**, 205 (1991).
[31] T. Appelquist and G.-H. Wu, Phys. Rev. D **48**, 3235 (1993).
[32] E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
[33] B. Lee, C. Quigg, and H. Thacher, Phys. Rev. D **16**, 1519 (1977).
[34] M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261**, 379 (1985).

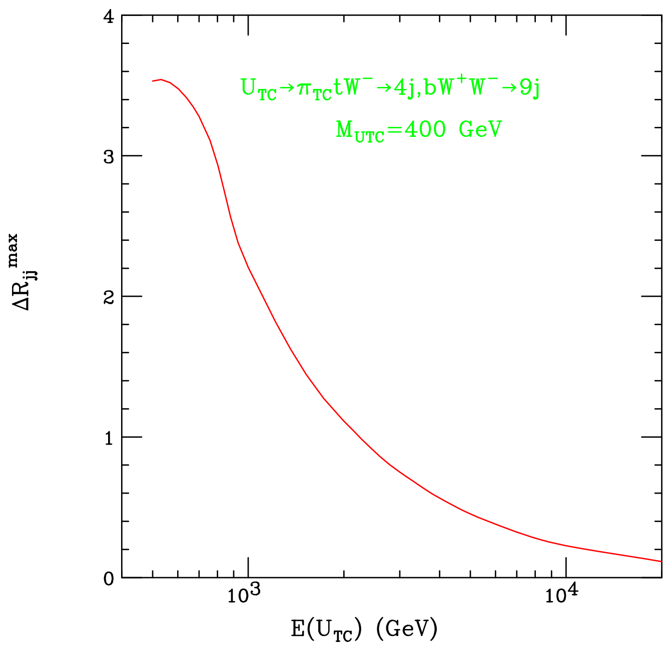

Figure 4: Maximum separation in ΔR distribution among the jets from a heavy techni-quark decay.

[35] R. Casalbuoni *et al.*, Nucl. Phys. **B555**, 3 (1999), hep-ph/9809523.
[36] C.-X. Yue, G.-R. Lu, J.-J. Cao, J.-T. Li, and G. Liu, Phys. Lett. **B496**, 93 (2000), hep-ph/0011112.
[37] V. D. Barger, K. Cheung, T. Han, and R. J. N. Phillips, Phys. Rev. **D52**, 3815 (1995), hep-ph/9501379.
[38] E. Boos *et al.*, Phys. Rev. **D57**, 1553 (1998), hep-ph/9708310.
[39] E. Boos *et al.*, Phys. Rev. **D61**, 077901 (2000), hep-ph/9908409.
[40] V. Barger *et al.*, Phys. Rev. D **42**, 3052 (1990).
[41] J. Bagger *et al.*, Phys. Rev. D **49**, 1246 (1994).
[42] M. S. Chanowitz and W. Kilgore, Phys. Lett. **B322**, 147 (1994), hep-ph/9311336.
[43] J. Bagger *et al.*, Phys. Rev. D **52**, 3878 (1995).
[44] (2001), LC-PHSM-2001-038, `http://www.desy.de/~lcnotes`.
[45] V. D. Barger and T. Han, Phys. Lett. **B212**, 117 (1988).
[46] V. D. Barger, T. Han, and R. J. N. Phillips, Phys. Rev. **D39**, 146 (1989).
[47] T. Han, H.-J. He, and C. P. Yuan, Phys. Lett. **B422**, 294 (1998), hep-ph/9711429.
[48] (1996), prepared for 1996 DPF / DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, Colorado, 25 Jun - 12 Jul 1996.
[49] F. Larios, T. M. P. Tait, and C. P. Yuan, Phys. Rev. D **57**, 3106 (1998).
[50] (1999), hep-ph/9909383.
[51] T. Han, Y. J. Kim, A. Likhoded, and G. Valencia, Nucl. Phys. **B593**, 415 (2001), hep-ph/0005306.
[52] J. Bagger, S. Dawson, and G. Valencia, Nucl. Phys. **B399**, 364 (1993), hep-ph/9204211.
[53] (2001), resource book for Snowmass 2001, 30 Jun - 21 Jul 2001, Snowmass, Colorado.
[54] A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).
[55] (1984), presented at Physics in Collision IV Conf., Santa Cruz, CA, Aug 22-24, 1984.
[56] F. Iddir, A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Rev. **D41**, 22 (1990).
[57] (2000), presented at 5th International Linear Collider Workshop (LCWS2000), Batavia, IL, October 24-28, 2000.
[58] (1999), CERN-LHCC-99-15.
[59] CDF, Phys. Rev. Lett. **84**, 1110 (2000).
[60] K. Lane, hep-ph/0006143 (2000).
[61] G. Landsberg, *Private communication.*
[62] CDF, Phys. Rev. Lett. **83**, 3124 (1999).
[63] D0, hep-ex/0005020 (2000).

[64] K. Lane, hep-ph/0006143 (2000).
[65] CDF, Phys. Rev. D **55**, R5263 (1997).
[66] *Tev2000 report*, Fermilab-Pub-96/08 (1996).
[67] CDF, Phys. Rev. Lett. **82**, 2038 (1999).
[68] CDF, Phys. Rev. Lett. **85**, 2056 (2000).
[69] Haas, *Strong dynamics workshop*, http://runiicomputing.fnal.gov/strongdynamics/tex/strongdynamics.ps (2001).
[70] CDF, Phys. Rev. Lett. **82**, 3206 (1999).
[71] CDF, Phys. Rev. Lett. **82**, 2038 (1999).
[72] R. Harris, *Snowmass 96*, hep-ph/9609316 (1996).
[73] R. Harris, *Snowmass 96*, hep-ph/9609318 (1996).
[74] R. Harris, *Strong dynamics workshop*, http://runiicomputing.fnal.gov/strongdynamics/tex/strongdynamics.ps (2001).
[75] Harris, Hill, and Parke, hep-ph/9911288 (1999).
[76] CDF, Phys. Rev. Lett. **85**, 2062 (2000).
[77] C. Balaza, J. Diaz-Cruz, H.-J. He, T. Tait, and C.-P. Yuan, Phys. Rev. D **59**, 055016 (1999).
[78] D0, Phys. Rev. Lett. **82**, 2457 (1999).
[79] D0, Phys. Rev. Lett. **82**, 4769 (1999).
[80] K. Cheung and R. Harris, *Snowmass 96*, hep-ph/9610382 (1996).
[81] CDF, Phys. Rev. Lett. **79**, 2198 (1997).
[82] T. Rizzo, Phys. Rev. D **51**, 1994 (1994).
[83] CDF, Phys. Rev. Lett. **72**, 3004 (1994).
[84] CDF, Phys. Rev. D **55**, R5263 (1997).
[85] R. Harris, *Snowmass 96*, hep-ph/9609319 (1996).
[86] ATLAS, *ATLAS Detector and Physics Performance: TDR*, Grey book, CERN (1999).
[87] ATLAS and CMS, *High transverse momentum physics at the lhc*, http://www-theory.lbl.gov/ ianh/lhc/ (2001).
[88] *CERN Workshop on Standard Model Physics (and more) at the LHC*, no. 2000-004. CERN (1999).
[89] J. Butterworth, B. Cox, and J. Forshaw, hep-ph/0201098.
[90] V. D. S. Group, *Design Study for a Staged Very Large Hadron Collider*, Tech. Rep. TM-2149, Fermilab (2001).