Citation: D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000) (URL: http://pdg.lbl.gov)

Technicolor

DYNAMICAL ELECTROWEAK SYMMETRY BREAKING

Written October 1999 by R.S. Chivukula (Boston Univ.) and J. Womersley (Fermilab).

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. In this note, we review the status of experimental searches for the particles predicted in technicolor, topcolor, and related models.

I. Technicolor

The earliest models [1,2] of dynamical electroweak symmetry breaking [3] include a new non-abelian gauge theory ("technicolor") and additional massless fermions ("technifermions") 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 chiral symmetries in QCD are broken to 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 technipions could be dangerously light [4,5]. The 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 [6].

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 [4,7]. 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 100–500 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 [4]. These force the scale of ETC breaking and the corresponding ETC gauge boson masses to be in the multi-hundred 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" [8]. 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 [3,9]. 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 [10] 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 [11]. 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 [9]. 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.

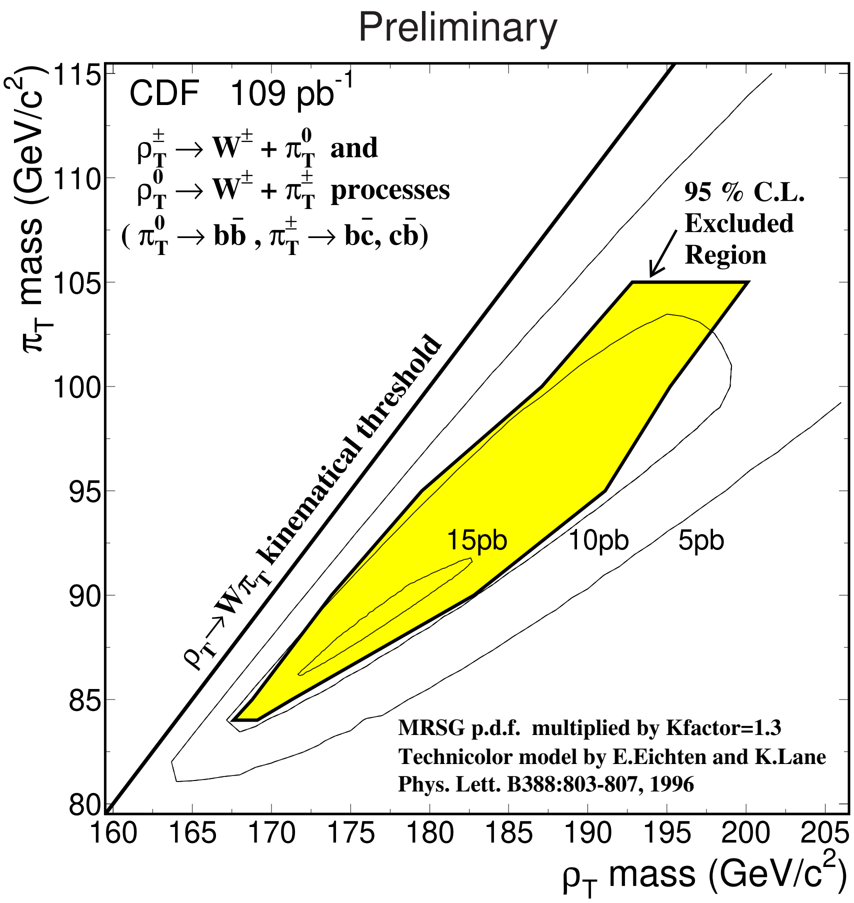

Figure 1: 95% CL exclusion region [13] for light technirho's decaying to $W^\pm$ and a π_T, and in which the π_T decays to two jets including at least one b quark.

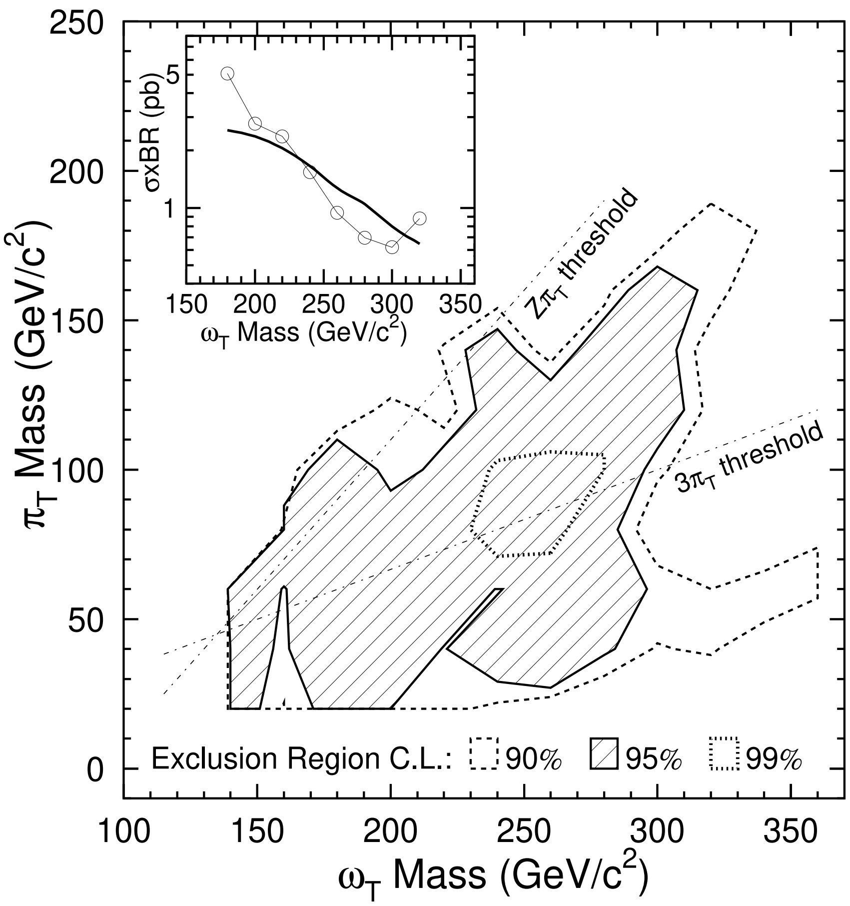

Figure 2: 95% CL exclusion region [15] for light techniomega's decaying to γ and a π_T, and in which the π_T decays to two jets including at least one b quark. (Inset: cross section limit for $m_{\pi_T} = 120$ GeV.)

If the dominant decay mode of the technirho is $W_L \pi_T$, promising signal channels [12] are $\rho_T^{\pm} \to W^{\pm}\pi_T^0$ and $\rho_T^0 \to W^{\pm}\pi_T^{\mp}$. Both channels yield a signal of $W(\ell\nu) + 2$jets, with one or more heavy flavor tags. Recently, the CDF collaboration has carried out a search in this final state [13] based on Run I data and using PYTHIA [14] version 6.1 for the signal simulation. The results are shown in Fig. 1. We see that the search is sensitive to $\sigma \cdot B \gtrsim 10$ pb and that roughly $170 < m_{\rho_T} < 190$ GeV is excluded at the 95% confidence level, for $m_{\pi_T} \approx m_{\rho_T}/2$.

CDF has also searched [15] for the process $\omega_T^0 \to \gamma\pi_T^0$, yielding a signal of a hard photon plus two jets, with one or more heavy flavor tags. The sensitivity to $\sigma \cdot B$ is of order 1 pb. The excluded region is shown in Fig. 2 and is roughly $140 < m_{\omega_T} < 290$ GeV at the 95% level, for $m_{\pi_T} \approx m_{\omega_T}/3$. The analysis assumes four technicolors, $Q_D = Q_U - 1 = \frac{1}{3}$ and $M_T = 100$ GeV$/c^2$. Here Q_U and Q_D are the charges of the lightest technifermion doublet and M_T is a dimensionful parameter, of order 100 GeV$/c^2$, which controls the rate of $\rho_T, \omega_T \to \gamma\pi_T$.

Both DØ [16] and CDF [17] have searched for low-scale technicolor resonances ρ_T and ω_T decaying to dileptons, using inclusive e^+e^- (both experiments) and $\mu^+\mu^-$ (CDF) samples from Run I. In the search, the ρ_T and ω_T are assumed to be degenerate in mass. The absence of structure in the dilepton invariant mass distribution is then used to set limits. Those from DØ are slightly more restrictive. Masses $m_{\rho_T} = m_{\omega_T} <$ 250 GeV are excluded, provided $m_{\rho_T} < m_{\pi_T} + m_W$, or provided $M_T > 300$ GeV. The latter case is shown in Fig. 3. With 2 fb^{-1} of data in Run II, the sensitivity will extend to $m_{\rho_T} = m_{\omega_T} \approx$ 500 GeV.

L3 [18] has reported a search for four topologies: $e^+e^- \to W^+W^-$; $e^+e^- \to W^\pm\pi_T^\mp \to \ell\nu bc$; $e^+e^- \to \pi_T\pi_T \to b\overline{c}\overline{b}c$; $e^+e^- \to \gamma\pi_T \to \gamma b\overline{b}$. All processes proceed through an intermediate ρ_T or ω_T resonance, which are assumed to be degenerate in mass. No excess is seen in any channel, based

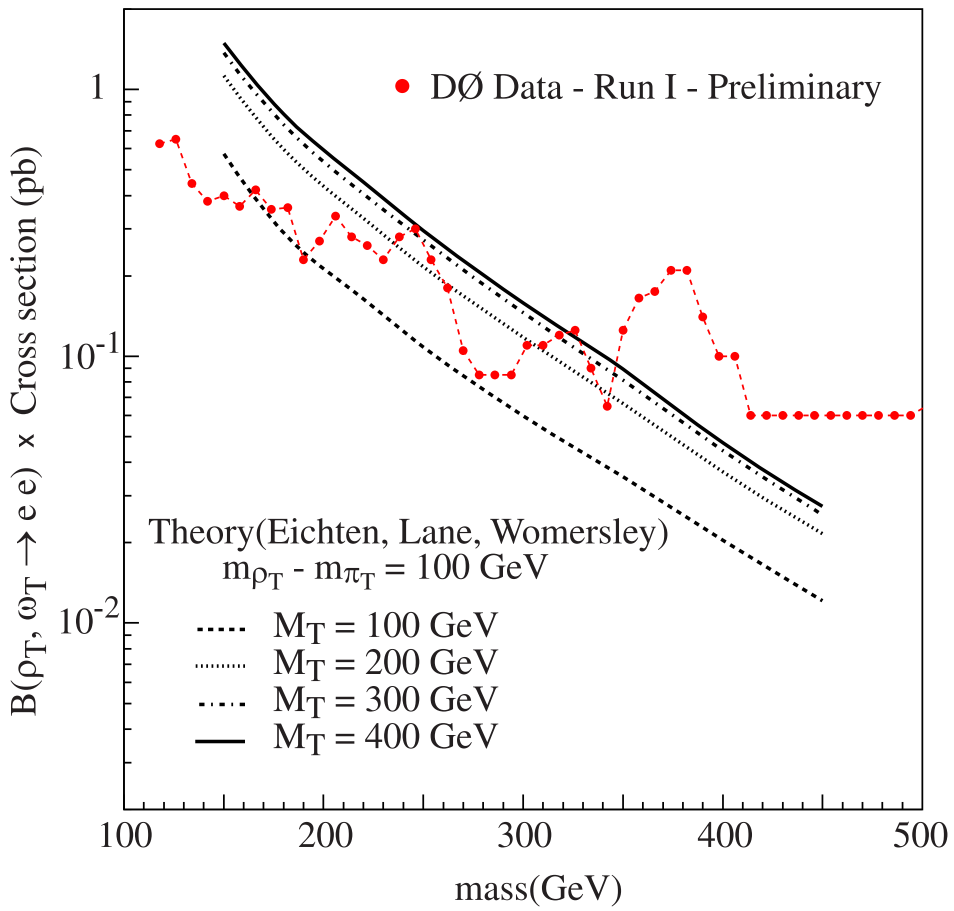

Figure 3: 95% CL cross section limit [16] for light techniomega's and technirho's decaying to $\ell^+\ell^-$.

on 176 pb^{-1} of data taken at an average center of mass energy of 189 GeV. The excluded region in m_{ρ_T}, m_{π_T} parameter space is shown in Fig. 4 and rules out $m_{\rho_T} < 190$ GeV, for all values of m_{π_T}, for the range of parameters considered. This L3 analysis is the only one so far to make use of the latest

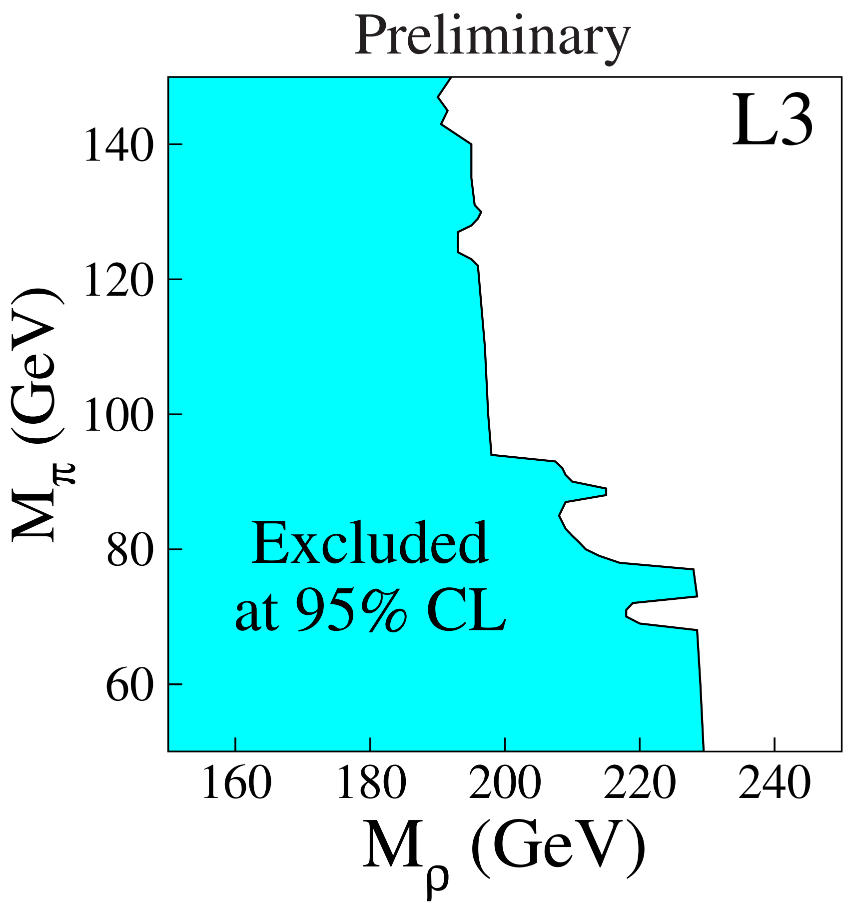

Figure 4: 95% CL exclusion region [18] in the technirho-technipion mass plane obtained from searches by the L3 collaboration at LEP 2.

calculations [19] of technihadron production and decay, as implemented in PYTHIA version 6.126 and higher [20]. All the

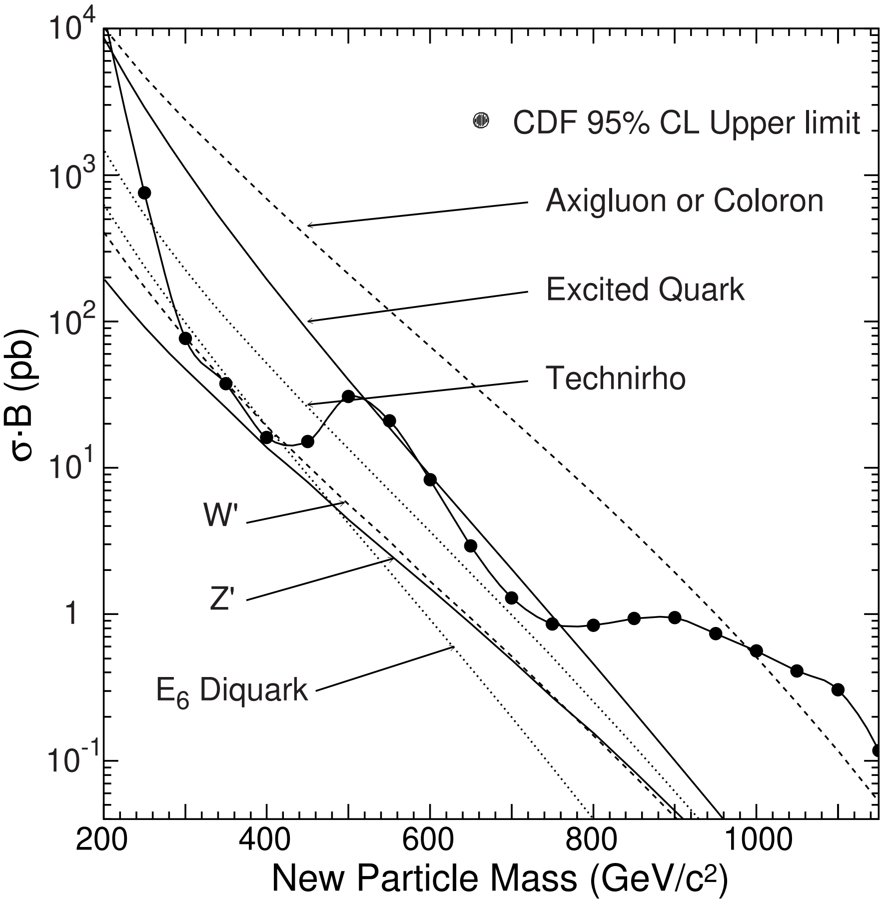

Figure 5: 95% CL cross section limits [22] for technirho's decaying to two jets at the Tevatron.

other analyses described in this review used older versions of PYTHIA and the limits are not directly comparable.

Searches have also been carried out at the Tevatron for colored technihadron resonances [21,22]. CDF has used a search for structure in the dijet invariant mass spectrum to set limits on a color-octet technirho ρ_{T8} produced by an off-shell gluon

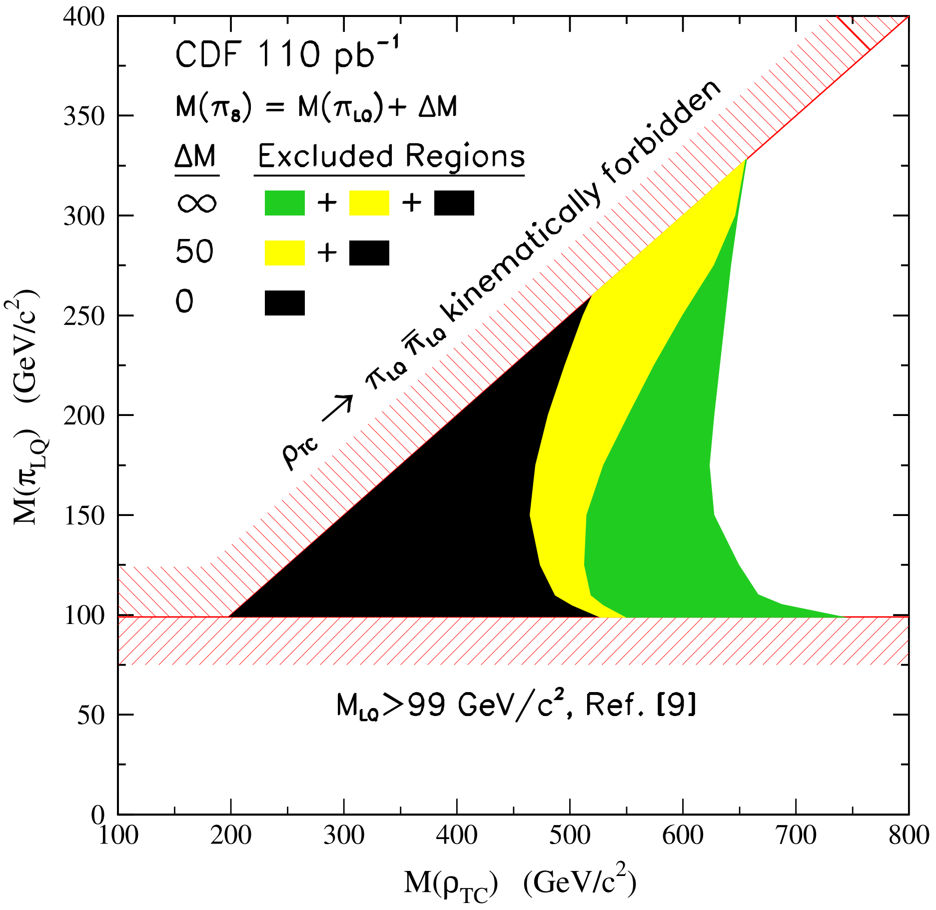

Figure 6: 95% CL exclusion region [24] in the technirho-technipion mass plane for pair produced technipions, with leptoquark couplings, decaying to τq.

and decaying to two real quarks or gluons. As shown in Fig. 5 masses $260 < m_{\rho_{T8}} < 480$ GeV are excluded; in Run II the limits will improve to cover the whole mass range up to about 0.8 TeV [23].

The CDF third-generation leptoquark search [24] has also been interpreted in terms of the complementary ρ_{T8} decay mode: $p\overline{p} \rightarrow \rho_{T8} \rightarrow \pi_{LQ}\pi_{LQ} \rightarrow \tau q \tau q$. Here π_{LQ} denotes a color-triplet technipion carrying both color and lepton number, assumed to decay to τ plus quark. Fig. 6 shows that technirho masses $m_{\rho_{T8}} < 465$ GeV and technipion masses up to $m_{\rho_{T8}}/2$ are excluded in this picture ($m_{\pi_{LQ}} < 99$ GeV already having been ruled out by the standard continuum-production leptoquark searches).

II. 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 [25,3]. Top-quark condensation alone, without additional fermions, seems to produce a top-quark mass larger [26] than observed experimentally, and is therefore not favored. Topcolor assisted technicolor [27] 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 $\langle \overline{b}b \rangle$ condensate.

CDF has searched [28] for the "topgluon," a massive color-octet vector which couples preferentially to the third generation, in the mode $p\overline{p} \rightarrow g_t \rightarrow b\overline{b}$. The results are shown in Fig. 7. As shown, topgluon masses from approximately 0.3 to 0.6 TeV are excluded at 95% confidence level, for topgluon widths in the range $0.3 m_{g_t} < \Gamma < 0.7 m_{g_t}$. Preliminary results have also been reported by CDF [29] on a search for narrow resonances

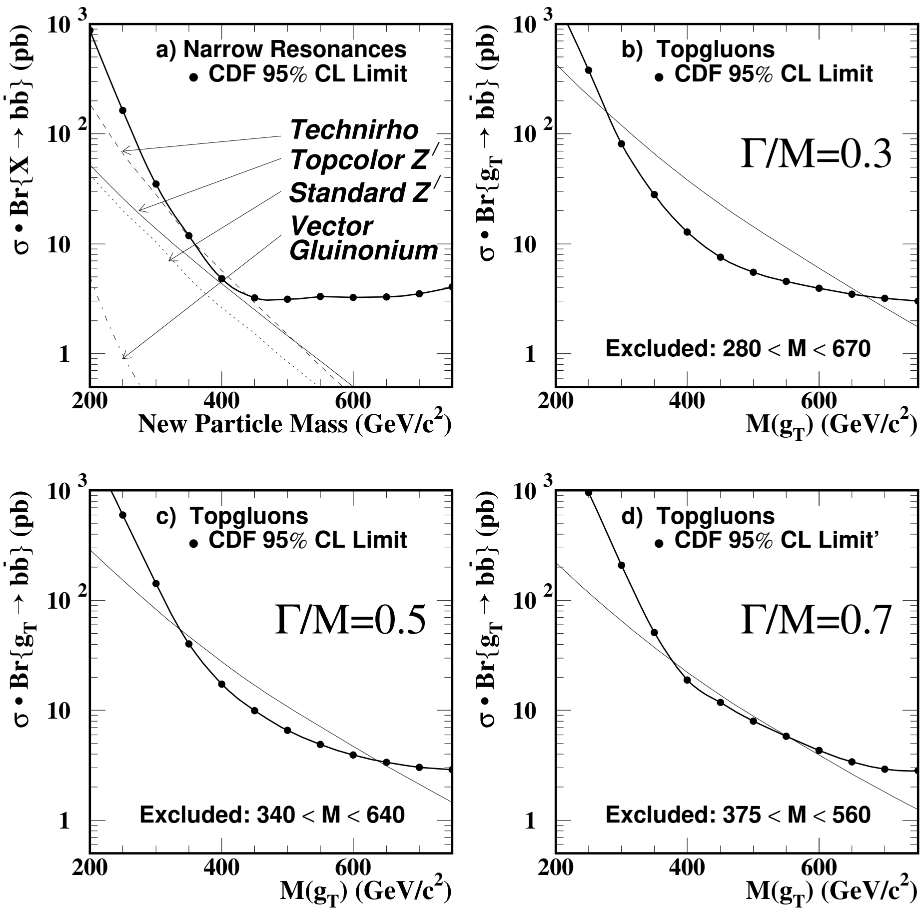

Figure 7: Tevatron limits [28] on new particles decaying to $b\overline{b}$: narrow resonances and topgluons for various widths.

in the $t\overline{t}$ invariant mass distribution. The cross section limit is shown in Fig. 8 and excludes a topcolor Z' with masses less than 650 GeV/c^2, for the case where its width $\Gamma = 0.012\,m_{Z'}$. This choice of width maximizes the cross section. A broad topgluon could also be detected in the same final state, though

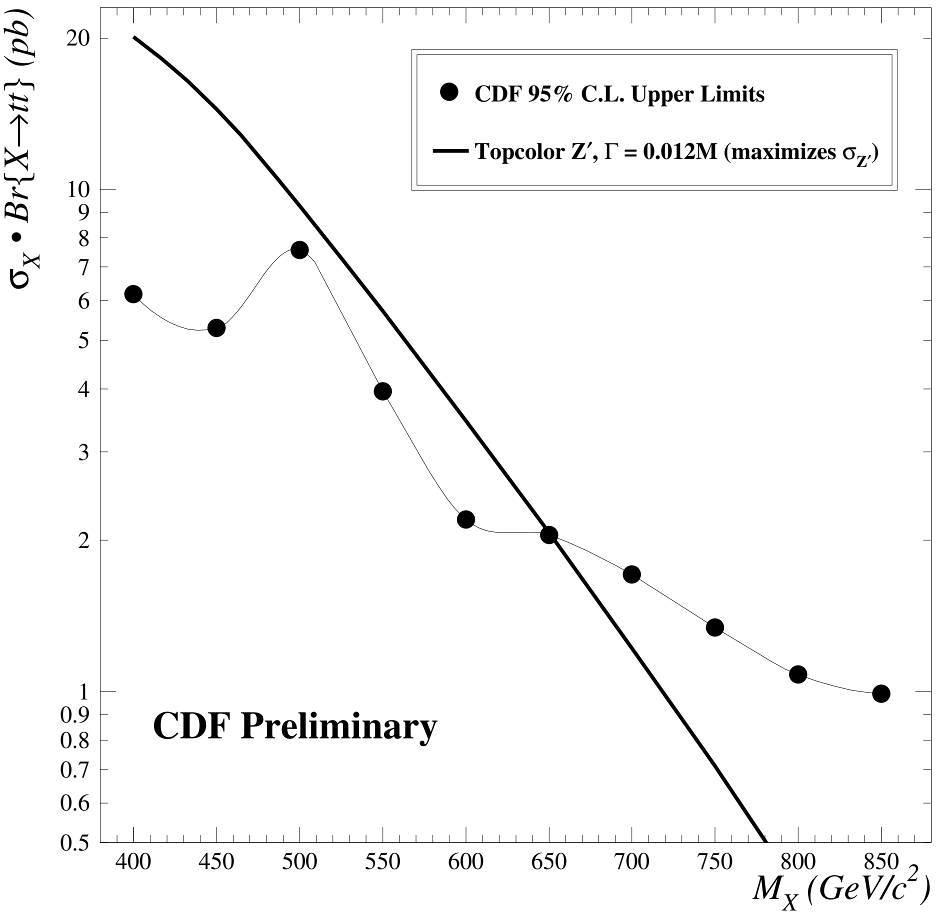

Figure 8: Cross section limits for a narrow resonance decaying to $t\overline{t}$ [29] and expected cross section for a topcolor Z' boson.

no results are yet available. In Run II, the Tevatron [23] should be sensitive to topgluon and topcolor Z' masses up to of order 1 TeV in $b\overline{b}$ and $t\overline{t}$ final states.

The top-quark seesaw model of electroweak symmetry breaking [30] 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 [31] or because additional interactions allow for a heavier Higgs [32]. The unique role of the top quark is, in a sense, lost in seesaw models. By adjusting parameters in the theory, it is possible to generate *any* required fermion mass.

Flavor-universal versions of the seesaw model [33] are possible in which *all* left-handed quarks (and possibly leptons as well) participate in the electroweak symmetry-breaking condensate with separate (one for each flavor) right-handed weak singlets.

A universal prediction of these models, is the existence of new heavy gauge bosons, coupling to color or flavor, at relatively low mass scales. The absence of an excess of high-E_T jets in DØ data [34] has been used to constrain strongly-coupled flavor-universal colorons (massive color-octet bosons coupling to all quarks). A mass limit of between 0.8 and 3.5 TeV is set [35] depending on the coloron-gluon mixing angle. Precision electroweak measurements constrain [36] the masses of these new gauge bosons to be greater than 1–3 TeV in a variety of models, for strong couplings. These limits are all summarized in Table 1.

Acknowledgments

We thank Tom Appelquist, Robert Harris, Chris Hill, Greg Landsberg, Kenneth Lane, and Elizabeth Simmons for help in the preparation of this article. *This work was supported in part by the Department of Energy under grant DE-FG02-91ER40676.*

References

1. S. Weinberg, Phys. Rev. **D19**, 1277 (1979).
2. L. Susskind, Phys. Rev. **D20**, 2619 (1979).

Table 1: Summary of the mass limits. Symbols are defined in the text.

Process	Excluded mass range	Decay channels	Ref.
$p\overline{p} \to \rho_T \to W\pi_T$	$170 < m_{\rho_T} < 190$ GeV for $m_{\pi_T} \approx m_{\rho_T}/2$	$\rho_T \to W\pi_T$ $\pi_T^0 \to b\overline{b}$ $\pi_T^\pm \to b\overline{c}$	[13]*
$p\overline{p} \to \omega_T \to \gamma\pi_T$	$140 < m_{\omega_T} < 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ and $M_T = 100$ GeV	$\omega_T \to \gamma\pi_T$ $\pi_T^0 \to b\overline{b}$ $\pi_T^\pm \to b\overline{c}$	[15]
$p\overline{p} \to \omega_T/\rho_T$	$m_{\omega_T} = m_{\rho_T} < 250$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 300$ GeV	$\omega_T/\rho_T \to \ell^+\ell^-$	[16]*
$e^+e^- \to \omega_T/\rho_T$	$m_{\omega_T} = m_{\rho_T} < 190$ GeV	$\rho_T \to WW$, $W\pi_T$, $\pi_T\pi_T$ $\omega_T \to \gamma\pi_T$ $\pi_T^0 \to b\overline{b}$ $\pi_T^\pm \to b\overline{c}$	[18]*
$p\overline{p} \to \rho_{T8}$	$260 < m_{\rho_{T8}} < 480$ GeV	$\rho_{T8} \to q\overline{q}$, gg	[22]
$p\overline{p} \to \rho_{T8}$	$m_{\rho_{T8}} < 465$ GeV	$\rho_{T8} \to \pi_{LQ}\pi_{LQ}$ $\pi_{LQ} \to \tau q$	[24]
$p\overline{p} \to g_t$	$0.3 < m_{g_t} < 0.6$ TeV for $0.3m_{g_t} < \Gamma < 0.7m_{g_t}$	$g_t \to b\overline{b}$	[28]
$p\overline{p} \to Z'$	$m_{Z'} < 650$ GeV for $\Gamma = 0.012m_{Z'}$	$Z' \to t\overline{t}$	[29]*

*Preliminary, not yet published.

3. For a recent review, see R.S. Chivukula, `hep-ph/9803219`.
4. E. Eichten and K. Lane, Phys. Lett. **90B**, 125 (1980).
5. For reviews, see E. Farhi and L. Susskind, Phys. Reports **74**, 277 (1981);
   R.K. Kaul, Rev. Mod. Phys. **55**, 449 (1983);
   R.S. Chivukula *et al.*, `hep-ph/9503202`.
6. S. Dimopoulos, S. Raby, and G. L. Kane, Nucl. Phys. **B182**, 77 (1981).

7. S. Dimopoulos and L. Susskind, Nucl. Phys. **B155**, 237 (1979).
8. B. Holdom, Phys. Rev. **D24**, 1441 (1981) and Phys. Lett. **150B**, 301 (1985);
   K. Yamawaki, M. Bando, and K. Matumoto, Phys. Rev. Lett. **56**, 1335 (1986);
   T.W. Appelquist, D. Karabali, and L.C.R. Wijewardhana, Phys. Rev. Lett. **57**, 957 (1986);
   T. Appelquist and L.C.R. Wijewardhana, Phys. Rev. **D35**, 774 (1987) and Phys. Rev. **D36**, 586 (1987).
9. E. Eichten and K. Lane, Phys. Lett. **B388**, 803 (1996).
10. See the review on "Electroweak Model and Constraints on New Physics" by Langacker and Erler in this *Review*.
11. E. Eichten *et al.*, Rev. Mod. Phys. **56**, 579 (1984) and Phys. Rev. **D34**, 1547 (1986).
12. E. Eichten, K. Lane, and J. Womersley, Phys. Lett. **B405**, 305 (1997).
13. F. Abe *et al.*, FERMILAB-PUB-99/141-E.
14. T. Sjostrand, Comp. Phys. Commun. **82**,74 (1994).
15. F. Abe *et al.*, Phys. Rev. Lett. **83**, 3124 (1999).
16. DØ: M. Narain, presented at the Workshop on New Strong Dynamics at Run II (Fermilab, October 1998).
17. CDF: K. Maeshima, presented at the Workshop on New Strong Dynamics at Run II (Fermilab, October 1998).
18. L3: Search for technicolour production at lep, L3 Note 2428, June 1999, submitted to the International Europhysics Conference on High Energy Physics (Tampere, Finland, July 1999).
19. K. Lane, Phys. Rev. **D60**, 075007 (1999), `hep-ph/9903372`.
20. S. Mrenna, Phys. Lett. **B461**, 352 (1999).
21. K. Lane and M. V. Ramana, Phys. Rev. **D44**, 2678 (1991).
22. CDF: F. Abe *et al.*, Phys. Rev. **D55**, R5263 (1997).
23. K. Cheung and R.M.Harris, `hep-ph/9610382`.
24. CDF: F. Abe *et al.*, Phys. Rev. Lett. **82**, 3206 (1999).

25. V.A. Miransky, M. Tanabashi, and K. Yamawaki, Phys. Lett. **221B**, 177 (1989) and Mod. Phys. Lett. **4**, 1043 (1989);
Y. Nambu, EFI-89-08 (1989);
W.J. Marciano, Phys. Rev. Lett. **62**, 2793 (1989).
26. W.A. Bardeen, C.T. Hill, and M. Lindner, Phys. Rev. **D41**, 1647 (1990).
27. C.T. Hill, Phys. Lett. **B345**, 483 (1995); see also Phys. Lett. **266B**, 419 (1991).
28. CDF: F. Abe *et al.*, Phys. Rev. Lett. **82**, 2038 (1999).
29. CDF Collaboration, presented by P. Koehn at the International Europhysics Conference on High Energy Physics (Tampere, Finland, July 1999).
30. B.A. Dobrescu and C.T. Hill, Phys. Rev. Lett. **81**, 2634 (1998).
31. R.S. Chivukula *et al.*, Phys. Rev. **D59**, 075003 (1999).
32. H. Collins, A. Grant, and H. Georgi, Phys. Rev. **D61**, 055002 (2000).
33. G. Burdman and N. Evans, Phys. Rev. **D59**, 115005 (1999);
E.H. Simmons, Nucl. Phys. **B324**, 315 (1989).
34. DØ: B. Abbott *et al.*, Phys. Rev. Lett. **82**, 2457 (1999).
35. I. Bertram and E.H. Simmons, Phys. Lett. **B443**, 347 (1998).
36. G. Burdman, R.S. Chivukula, and N. Evans, Phys. Rev. **D61**, 035009 (2000).

MASS LIMITS for Resonances in Models of Dynamical Electroweak Symmetry Breaking

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 350–440	95	[1] ABE	99F	CDF	color-octet techni-ρ, $\rho_T \rightarrow b\overline{b}$
>465	95	[2] ABE	99H	CDF	color-octet techni-ρ, $\rho_T \rightarrow 2\pi_T$
		[3] ABE	99N	CDF	color-octet techni-ω, $\omega_T \rightarrow \gamma b\overline{b}$
none 260–480	95	[4] ABE	97G	CDF	color-octet techni-ρ, $\rho_T \rightarrow$ 2 jets

none 320–480	95	[5] ABE	95N	CDF	color-octet techni-ρ, $\rho_T \rightarrow$ 2 jets

[1] ABE 99F search for a new particle X decaying into $b\overline{b}$ in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. See Fig. 7 in the above Note on "Dynamical Electroweak Symmetry Breaking" for the upper limit on $\sigma(p\overline{p} \rightarrow X)\times$B$(X \rightarrow b\overline{b})$. ABE 99F also exclude top gluons of width Γ=0.3M in the mass interval 280 $<M<$ 670 GeV, of width Γ=0.5M in the mass interval 340 $<M<$ 640 GeV, and of width Γ=0.7M in the mass interval 375 $<M<$ 560 GeV.

[2] ABE 99H search for the color-octet techni-ρ decaying into a pair of color-triplet technipions which subsequently decay into $\tau+$ jet. See Fig. 6 in the above Note on "Dynamical Electroweak Symmetry Breaking" for the exclusion plot in the $M_{\rho_T}-M_{\pi_T}$ plane.

[3] ABE 99H search for the techni-ω decaying into $\gamma\pi_T$. The technipion is assumed to decay $\pi_T \rightarrow b\overline{b}$. See Fig. 2 in the above Note on "Dynamical Electroweak Symmetry Breaking" for the exclusion plot in the $M_{\omega_T}-M_{\pi_T}$ plane.

[4] ABE 97G search for a new particle X decaying into dijets in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. See Fig. 5 in the above Note on "Dynamical Electroweak Symmetry Breaking" for the upper limit on $\sigma(p\overline{p} \rightarrow X)\times$B$(X \rightarrow 2j)$.

[5] ABE 95N search for a new particle decaying into dijets in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV.

REFERENCES FOR Technicolor

ABE	99F	PRL 82 2038	F. Abe *et al.*	(CDF Collab.)
ABE	99H	PRL 82 3206	F. Abe *et al.*	(CDF Collab.)
ABE	99N	PRL 83 3124	F. Abe *et al.*	(CDF Collab.)
ABE	97G	PR D55 R5263	F. Abe *et al.*	(CDF Collab.)
ABE	95N	PRL 74 3538	F. Abe *et al.*	(CDF Collab.)