AVENUES FOR DYNAMICAL SYMMETRY BREAKING

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In this talk I review modern theories of dynamical electroweak symmetry breaking and some of their signatures at Run II of the Tevatron collider.

1 Dynamical Electroweak Symmetry Breaking

1.1 Technicolor

The simplest theory of dynamical electroweak symmetry breaking is technicolor. Consider an $SU(N_{TC})$ gauge theory with fermions in the fundamental representation of the gauge group

$$\Psi_L = \begin{pmatrix} U \\ D \end{pmatrix}_L U_R, D_R.$$ 

The fermion kinetic energy terms for this theory are

$$L = \bar{U}_L i \not\!D U_L + \bar{D}_L i \not\!D D_L + \bar{U}_R i \not\!D U_R + \bar{D}_R i \not\!D D_R,$$

and, like QCD in the $m_u, m_d \to 0$ limit, they have a chiral $SU(2)_L \times SU(2)_R$ symmetry.

As in QCD the exchange of technigluons in the spin zero, isospin zero channel is attractive, causing the formation of a condensate

$$\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0,$$

which dynamically breaks $SU(2)_L \times SU(2)_R \to SU(2)_V$. These broken chiral symmetries imply the existence of three massless Goldstone bosons, the analogs of the pions in QCD.

Now consider gauging $SU(2)_W \times U(1)_Y$ with the left-handed fermions transforming as weak doublets and the right-handed ones as weak singlets. To avoid gauge anomalies, in this one-doublet technicolor model we will take the left-handed technifermions to have hypercharge zero and the right-handed up- and down-technifermions to have hypercharge $\pm 1/2$. The spontaneous breaking of the chiral symmetry breaks the weak-interactions down to electromagnetism. The would-be Goldstone bosons become the longitudinal components of the $W$ and $Z$

$$\pi^\pm, \pi^0 \to W^\pm_L, Z_L,$$

which acquire a mass

$$M_W = \frac{g_{TC}}{2}. $$
Here $F_{TC}$ is the analog of $f_\pi$ in QCD. In order to obtain the experimentally observed masses, we must have that $F_{TC} \approx 246$ GeV and hence this model is essentially QCD scaled up by a factor of \[ \frac{F_{TC}}{f_\pi} \approx 2500. \]

As in QCD, we expect resonances analogous to the vector mesons (the $\rho$ and $\omega$) followed by a tower of higher mass states.

### 1.2 Fermion Masses & ETC Interactions

In order to give rise to masses for the ordinary quarks and leptons, we must introduce interactions which connect the chiral-symmetries of technifermions to those of the ordinary fermions. The most popular choice is to embed technicolor in a larger gauge group, called extended technicolor (ETC), which includes both the unbroken technicolor interactions plus new massive gauge bosons which couple technifermions ($T$) to ordinary fermions ($f$):

\[
\begin{pmatrix}
  f \\
  T \\
  T
\end{pmatrix}
\]

At energies low compared to the ETC gauge-boson mass, $M_{ETC}$, these effects can be treated as local four-fermion interactions

\[
\Psi_U U_L \Psi_{U_R} \Psi_{R_L} \rightarrow \frac{g_{ETC}^2}{M_{ETC}^2} (\Psi_L U_R) (\Psi_R q_L).
\]

After technicolor chiral-symmetry breaking and the formation of a $\langle \bar{U} U \rangle$ condensate, such an interaction gives rise to a mass for an ordinary fermion

\[
m_q \approx \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{U} U \rangle_{ETC},
\]

where $\langle \bar{U} U \rangle_{ETC}$ is the value of the technifermion condensate evaluated at the ETC scale (of order $M_{ETC}$). The condensate renormalized at the ETC scale in can be related to the condensate renormalized at the technicolor scale as follows

\[
\langle \bar{U} U \rangle_{ETC} = \langle \bar{U} U \rangle_{TC} \exp \left( \int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right),
\]

where $\gamma_m(\mu)$ is the anomalous dimension of the fermion mass operator and $\Lambda_{TC}$ is the analog of $\Lambda_{QCD}$ for the technicolor interactions.

For QCD-like technicolor (or any theory which is “precociously” asymptotically free), $\gamma_m$ is small over in the range between $\Lambda_{TC}$ and $M_{ETC}$ and using dimensional analysis we find

\[
\langle \bar{U} U \rangle_{ETC} \approx \langle \bar{U} U \rangle_{TC} \approx 4\pi F_{TC}^3.
\]

In this case we find that

\[
\frac{M_{ETC}}{g_{ETC}} \approx 40 \text{ TeV} \left( \frac{F_{TC}}{246 \text{ GeV}} \right)^{\frac{1}{2}} \left( \frac{100 \text{ MeV}}{m_q} \right)^{\frac{1}{2}}.
\]
1.3 Flavor-Changing Neutral-Currents

Perhaps the single biggest obstacle to constructing a realistic ETC model is the potential for flavor-changing neutral currents. Quark mixing implies transitions between different generations: \( q \rightarrow \Psi \rightarrow q' \), where \( q \) and \( q' \) are quarks of the same charge from different generations and \( \Psi \) is a technifermion. Consider the commutator of two ETC gauge currents:

\[
[\gamma \Psi, \gamma q'] \supset \gamma q'.
\]

Hence we expect there are ETC gauge bosons which couple to flavor-changing neutral currents. In fact, this argument is slightly too slick: the same applies to the charged-current weak interactions! However in that case the gauge interactions, \( SU(2)_W \), respect a global \( (SU(5) \times U(1))^5 \) chiral symmetry leading to the usual GIM mechanism.

Unfortunately, the ETC interactions cannot respect GIM exactly; they must distinguish between the various generations in order to give rise to the masses of the different generations. Therefore, flavor-changing neutral-current interactions are (at least at some level) unavoidable.

The most severe constraints come from possible \( |\Delta S| = 2 \) interactions which contribute to the \( K_L - K_S \) mass difference. In particular, we would expect that in order to produce Cabibbo-mixing the same interactions which give rise to the \( s \)-quark mass could cause the flavor-changing interactions which contribute to the neutral kaon mass splitting. Experimentally, we know that \( \Delta M_K < 3.5 \times 10^{-12} \text{ MeV} \). We then calculate, using the vacuum insertion approximation, that

\[
\frac{M_{ETC}}{g_{ETC} \sqrt{\text{Re}(\theta_{sd}^2)}} > 600 \text{ TeV},
\]

where \( \theta_{sd} \) is of order the Cabibbo angle. Using the relation of the ETC gauge-boson mass to the fermion mass, we find that

\[
m_{q,l} \approx \frac{g_{ETC}^2}{M_{ETC}^2} (\langle \langle TT \rangle \rangle_{ETC} \approx 0.5 \text{ MeV} \frac{N_D^{3/2}}{\theta_{sd}^2}),
\]

showing that it will be difficult to produce the \( s \)-quark mass, let alone the \( c \)-quark!

1.4 Walking Technicolor

We must therefore conclude that, to be viable, technicolor dynamics cannot be like QCD! How could it be different? Recall that the estimates given above result from the assumption that \( \gamma_m \approx 0 \), i.e. that the theory is precociously asymptotically free. On the other hand, if \( \beta(\alpha_{TC}) \approx 0 \) all the way from \( \Lambda_{TC} \) to \( M_{ETC} \), then the technicolor coupling remains strong and close to the value required to produce chiral symmetry breaking. That is, the coupling “walks” between the technicolor and extended technicolor scales. If this is the case, it is believed that \( \gamma_m(\mu) \approx 1 \) in this range. We then find

\[
m_{q,l} = \frac{g_{ETC}^2}{M_{ETC}^2} \times \left( \langle TT \rangle_{ETC} \approx \langle TT \rangle_{TC} \frac{M_{ETC}}{\Lambda_{TC}} \right).
\]
Figure 1. 95% Exclusion region for light technirho’s decaying to $W^\pm$ and a $\pi_T$, and in which the $\pi_T$ decays to two jets including at least one $b$-quark.

We have previously estimated that flavor-changing neutral current requirements imply that the ETC scale associated with the second generation must be greater than of order 100 to 1000 TeV. The walking technicolor enhancement of the technifermion condensate implies that

$$m_{q,l} \simeq \frac{50 - 500 \text{ MeV}}{N_D^3 g^2_{sd}},$$

arguably enough to accommodate the strange and charm quarks.

2 Low-Scale Technicolor at the Tevatron

How can $\beta(\alpha_{TC}) \simeq 0$? The gauge contributions to the $\beta$ function are always negative; therefore these must be canceled by fermions. To cancel the gauge contribution entirely one must introduce either many fermions, or fermions in higher representations of the gauge group (or possibly both).

Increasing the number of fermions enlarges the chiral symmetries which are present. If the chiral symmetry is larger than $SU(2)_L \times SU(2)_R$, there will be additional (pseudo-)Goldstone bosons ($\pi_T$) which are not “eaten” by the $W$ and $Z$. In general, such nonminimal models will contain several sets of electroweak doublets. The $F$-constant associated with each sector is analogous to the vacuum expectation values $v_i$ of the different Higgs scalars in a multi-Higgs model. The lower the value of the $F$-constant, the lower the masses of the corresponding resonances.

These considerations lead to the possibility of discovering signals of a low-scale technicolor sector at the Tevatron. The extended symmetry breaking sector could give rise to potentially light resonances, such as a technirho in the few-100 GeV range. It might be expected, in analogy with QCD, that such a technirho would
decay dominantly to technipions. However, in walking technicolor the effects of “small” chiral-symmetry breaking interactions are likely to be enhanced. It is then possible that $\rho_T \rightarrow \pi_T \pi_T$ is closed. In this case the dominant decay mode is $\rho_T \rightarrow W_L \pi_T$, and the technirho can be very narrow. As in the case of extra Higgs scalars in multihiggs models, we expect the technipions to decay to the heaviest fermions, $\pi_T^0 \rightarrow b\bar{b}$ & $\pi_T^\pm \rightarrow c\bar{b}$. Hence, we consider the overall signal $\rho_T^\pm \rightarrow W^\pm \pi_T^0 \rightarrow \ell \nu(jj)_b$.

Simulations at the Tevatron yield a potentially observable cross section: $\sigma \rho_T \cdot BR = 5.3$ pb.

Recently, a search has been done in this channel by the CDF collaboration based on Run I data. These results are shown in figure I, and we see that $\sigma \cdot BR \geq 15$ pb is already excluded at the 95% confidence level. We expect in Run II, with twenty times as much data, the sensitivity will reach the predicted level.

3 Topcolor-Assisted Technicolor (TC2)

The top-quark is much heavier than other fermions. It must therefore be more strongly coupled to the symmetry-breaking sector. Perhaps all or some of electroweak-symmetry breaking is due to a condensate of top-quarks, $\langle \bar{t}t \rangle \neq 0$.

Recently, Chris Hill has proposed a theory which combines technicolor and top-condensation. Features of this type of model include technicolor dynamics at 1 TeV, which dynamically generates most of electroweak symmetry breaking, and extended technicolor dynamics at scales much higher than 1 TeV, which generates the light quark and lepton masses, as well as small contributions to the third generation masses $(m_{t,b,\tau}^{ETC})$ of order 1 GeV. The top quark mass arises predominantly from “topcolor,” a new QCD-like interaction which couples preferentially to the third generation of quarks, at a scale of order 1 TeV and which generates $\langle \bar{t}t \rangle \neq 0$ and $m_t \sim 175$ GeV.

Hill’s Simplest TC2 Scheme

The simplest scheme which realizes these features has the following structure:

$$G_{TC} \times SU(2)_{EW} \times SU(3)_{Lc} \times SU(3) \times U(1)_H \times U(1)_L$$
$$\downarrow M \gtrsim 1 \text{ TeV}$$
$$G_{TC} \times SU(3)_{C} \times SU(2)_{EW} \times U(1)_Y$$
$$\downarrow \Lambda_{TC} \sim 1 \text{ TeV}$$
$$SU(3)_{C} \times U(1)_{EM}$$

Here $U(1)_H$ and $U(1)_L$ are $U(1)$ gauge groups coupled to the (standard model) hypercharges of the third-generation and first-two generation fermions respectively.
Below $M$, this leads to the effective interactions:

$$\frac{-4\pi\kappa_{tc}}{M^2} \left[ \frac{\lambda^a}{2} \frac{\psi^\dagger \gamma^\mu \Psi}{2} \right]^2,$$

from topgluon exchange and the isospin-violating interactions

$$\frac{-4\pi\kappa_1}{M^2} \left[ \frac{1}{3} \frac{R_L \gamma_\mu \Psi_L}{3} + \frac{4}{3} \frac{R_R \gamma_\mu \Psi_R}{3} - \frac{2}{3} \frac{b_R \gamma_\mu b_R}{3} \right]^2,$$

from exchange of the “heavy-hypercharge” ($Z'$) gauge boson.

The interactions above are attractive in the $\bar{t}t$ channel, but repulsive in the $\bar{b}b$ channel and the couplings $\kappa_{tc}$ and $\kappa_1$ can be chosen to produce $\langle \bar{t}t \rangle \neq 0$ and a large $m_t$, but leave $\langle \bar{b}b \rangle = 0$.

4 Topgluon Searches at the Tevatron

The topgluon is a massive color-octet vector which couples preferentially to the third generation. It has been searched for by CDF in the mode $p\bar{p} \rightarrow g_{TC} + X \rightarrow \bar{b}b + X$. The results are shown in figure 2. As shown, topgluon masses from approximately 300 to 600 GeV are excluded at 95% confidence level, depending on the width of the topgluon. Furthermore, as shown in figure 3 for the mode $g_{TC} \rightarrow \bar{t}t$, the Tevatron should be sensitive to topgluons up to masses of order 1 TeV in Run II.
5 All Symmetry Breaking is Dynamical...

The models presented above may seem rather complicated, especially in contrast to the one Higgs doublet standard model. However, the standard model itself must have some underlying dynamics which gives rise to symmetry breaking! In quantum field theory, the vacuum acts as a polarizable medium: all couplings are a function of the momentum scale at which they are measured. In the symmetry breaking sector of the standard one-doublet higgs model, the relevant coupling is the self-coupling of the Higgs boson. The dependence of this coupling as a function of momentum scale is determined by the $\beta$ function. To lowest-order in perturbation theory, we find

$$\beta \equiv \frac{3\lambda^2}{2\pi^2} > 0 .$$

Integrating this positive $\beta$ function, we find that the effective coupling becomes infinite at a finite momentum scale. Conversely if we require the theory make sense to arbitrarily high momentum scales, i.e. that it is truly fundamental, the renormalized coupling at low-energies is zero! That is, if we try to take the continuum limit the theory becomes free (and is hence trivial), and could not result in the observed symmetry breaking. The argument given here relies on perturbation theory, at least, the presence of these interactions does not qualitatively change the features of the higgs sector.

For convenience, we ignore the corrections due to the weak gauge interactions. In perturbation theory, at least, the presence of these interactions does not qualitatively change the features of the higgs sector.
theory, but non-perturbative investigations confirm the triviality of the standard higgs model.

The triviality of the scalar sector of the standard one-doublet Higgs model implies that this theory is only an effective low-energy theory valid below some cutoff scale $\Lambda$. Physically this scale marks the appearance of new strongly-interacting symmetry-breaking dynamics. Examples of such high-energy theories include “top-mode” standard models and composite Higgs models.

In this sense, all symmetry breaking is dynamical! A light Higgs boson, such as occurs in the minimal supersymmetric model, arises from a dynamical theory at high $\Lambda$. However, a heavy Higgs requires a large low-energy self-coupling, and therefore arises from an underlying strongly-interacting theory at relatively low $\Lambda$.

6 Conclusions

Technicolor, topcolor, and related models provide an avenue for constructing theories in which electroweak symmetry breaking is natural and has a dynamical origin. Unfortunately, no complete and consistent model of this type exist. This is not surprising, since such a theory must also be a theory of flavor. If electroweak symmetry breaking is due to strong dynamics at energy scales of order a TeV, experimental direction will be crucial to construct the correct theory. With luck, the necessary clues will begin to appear at the Tevatron in Run II!

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