Technicolor

Status and Prospects

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ANL
OUTLINE

- Motivation for Strong Dynamics
- Overview of Technicolor and variants
- Technicolor Signatures
- Technicolor Production at hadron colliders
  - Searches at CDF
- Technicolor Production at $\mu^+\mu^-$ colliders
- Summary
NEW STRONG DYNAMICS

• Success of the Standard Model has been spectacular!

• But, new physics seems inevitable!
  - the cause for electroweak symmetry breaking and the origin of fermion masses and mixings are unknown

• There are two enticing theoretical approaches to understand EWSB
  - Supersymmetry
    (Elementary scalar bosons)
  - Strong Dynamics
    (composites bound by a new strong interaction)
OVERVIEW OF TECHNICAL COLOR

- Weinberg, Susskind 1979
- Technicolor (TC) is a strong interaction of new fermions (techni-fermions) and gauge bosons at a scale of $\Lambda_{TC} \sim 1$ TeV
- Causes dynamical breaking of electroweak symmetry
  - No Higgs! No elementary scalar bosons
- Inspired by QCD precedent
  - QCD breaks chiral symmetry of massless quarks, leads to pseudo-Goldstone bosons $\pi, k, \eta, \ldots$
  - Would break $SU(2) \times U(1)$ in the absence of Higgs
  - Gives mass to $W$ and $Z$ with correct ratio $m_W/m_Z$, but $m_W^2 = \frac{1}{8} g^2 N_f f_\pi^2$
    \[ f_\pi = 93 \text{ MeV} \]
    \[ m_W \sim 50 \text{ MeV} \]
TECHNICOLOR (contd.)

- TC as scaled up QCD to the TeV scale
  - new technifermions as SU(2) doublet and singlets
  - $m_W = m_Z \cos \theta_W = \frac{1}{2} g F_\pi$
    - $F_\pi = 246$ GeV
  - $3 \pi_T^{\pm,0} \Rightarrow W_L^\pm, Z_L^0$

- $N_D > 1$ technidoublets
  - $\Rightarrow N_D - 4$ extra $\pi_T$

How do they get mass?

How do the SM fermions get mass?
EXTENDED TECHNICOLOR

- Dimopoulos & Susskind; Eichten & Lane, 1979
- TC does not provide for "hard masses."
The SM fermions can acquire masses if they couple to technifermions via additional gauge interactions (ETC)

\[
m_f \approx \frac{g_{ETC}^2}{M_{ETC}^2} \langle T^T \rangle
\]

- Break \( G_{ETC} \rightarrow G_{TC} \otimes G_{QCD} \otimes G_F \)
at some high energy scale, \( \Lambda_{ETC} = \mathcal{O}(100 \text{ TeV}) \)
So,

In the standard Higgs model of EWSB,
- the Higgs potential breaks $SU(2) \times U(1)$
- $V \neq 0$ endows $W^\pm, Z$ with masses
- Quarks and leptons get masses through arbitrary Yukawa couplings to the Higgs field

In the technicolor scenario,
- TC interactions become strong at low energies, forms a techni-fermion condensate that breaks chiral symmetry
- Gives mass to $W^\pm, Z$
- New ETC gauge bosons couple fermions to techni-fermions, allowing the fermions to communicate with the condensate and acquire mass
BUT, TOP QUARK IS HEAVY!

- $m_t = 175.6 \pm 5.5 \text{ GeV}/c^2$ (CDF+DØ)
- "Top quark is a remarkable particle, even for a quark." - Quigg
- Heaviest fundamental particle known
- Top quark is the elementary particle most strongly coupled to the mechanism of mass generation and/or to the dynamics of EWSB  \( G_t = \frac{m_t \sqrt{2}}{v} \)

Top quark may have unique dynamics!!!

Another major turning point:

$\rightarrow$ Topcolor-assisted technicolor

Models

- **Minimal one-doublet**
  - technifermions are (U,D)
  - only low-lying state is $\rho_T \sim 1.5 - 2$ TeV, s-channel resonance in WW, WZ production [see e.g. EHLQ, 1984; ATLAS TP]
TECHNICOLOR SIGNATURES
(Non-minimal)

- The lightest new particles are technipions ($\gtrsim 100$ GeV)

$$\pi_T^0 \rightarrow t\bar{t}, b\bar{b}, c\bar{c}, \tau^+\tau^-$$

$$\pi_T^{0'} \rightarrow g\bar{g}, t\bar{t}, b\bar{b}, ...$$

$$\pi_T^+ \rightarrow c\bar{b}, c\bar{s}, \tau^+\nu_e$$

- Color-singlet technirhoms
  ($m \sim 200-400$ GeV)

$$\rho_T^+ \rightarrow W^+Z, W^+\pi_T^0, Z\pi_T^+, \pi_T^+\pi_T^0$$

$$\rho_T^0 \rightarrow WW, W\pi_T, \pi_T^+\pi_T$$

- Color-octet technirhoms
  ($m \sim 200-600$ GeV)

$$\rho_{T8} \rightarrow \pi_T^+\pi_T^-, gg$$

- Color-singlet techniomega

$$\omega_T \rightarrow \gamma\pi_T^0, Z\pi_T^0, q\bar{q}, l^+l^-$$
<table>
<thead>
<tr>
<th>Process</th>
<th>Sample Mass (GeV)</th>
<th>$\sigma_{\text{TeV}}$(pb)</th>
<th>$\sigma_{\text{LHC}}$(pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho T_1 \to W_L \pi_T$</td>
<td>$220(\rho T_1), 100(\pi_T)$</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>$\rho T_1 \to \pi_T \pi_T$</td>
<td>$220(\rho T_1), 100(\pi_T)$</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>$gg \to \pi_T^0 \to \bar{b}b$</td>
<td>100</td>
<td>$300/5000$</td>
<td>$7000/10^5$</td>
</tr>
<tr>
<td>$gg \to \eta_T \to t\bar{t}$</td>
<td>400</td>
<td>$3/3$</td>
<td>$2000/600$</td>
</tr>
<tr>
<td>$gg \to \pi_T \pi_T$</td>
<td>100</td>
<td>0.2</td>
<td>600</td>
</tr>
<tr>
<td>$\rho T_8 \to \text{jet jet}$</td>
<td>$250(\rho T_8)$</td>
<td>$700/5000$</td>
<td>$1.5 \times 10^4/1.5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>$500(\rho T_8)$</td>
<td>10/40</td>
<td>2000/6000</td>
</tr>
<tr>
<td>$\rho T_8 \to \pi T_8 \pi T_8$</td>
<td>$550(\rho T_8), 250(\pi T_8)$</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>$\rho T_8 \to \pi Q_L \pi L_Q$</td>
<td>$550(\rho T_8), 200(\pi Q_L)$</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>$V_8 \to t\bar{t}$</td>
<td>500</td>
<td>8/3</td>
<td>100/600</td>
</tr>
<tr>
<td>$\Lambda$ reach</td>
<td>$5 \text{ TeV (TeV), 20 TeV (LHC)}$</td>
<td>$10 \text{ fb}^{-1}$</td>
<td>$100 \text{ fb}^{-1}$</td>
</tr>
</tbody>
</table>

Table 1. Sample cross sections for technicolor signatures at the Tevatron and LHC.

Signal over background rates shown as S/B
$\rho_T \rightarrow q\bar{q}, gg \rightarrow \text{jets}$

$\sqrt{s} = 1.8 \text{ TeV}$

$\rho\bar{\rho}$

100%/$\sqrt{E}$

Ideal

Mass reach $\sim 800-900 \text{ GeV}$ with $2 \text{ fb}^{-1}$
Techniomega production

\( qq' \rightarrow Z^* \rightarrow \omega_T \rightarrow \gamma T \)

- Signal is photon + 2 b-jets:
  - \( \sigma \cdot B = 2.6 \text{ pb} \)
  - \( \sigma \cdot B = 740 \text{ pb} (p_T^\gamma > 45 \text{ GeV}) \)
- Dominant background is \( \gamma + \text{jets} \):
  - \( p_T^\gamma > 50 \text{ GeV}/c, |\eta| < 1.1 \)
- Require a high \( p_T \) photon
- Require two jets
- \( E_T > 20 \text{ GeV}, |\eta| < 2.0, \Delta R > 0.7 \text{ from } \gamma \)
- Topological cuts
- \( \Delta \phi_{ij} > 90^\circ \)
- \( h \)-tagging as before
$W + 2$ jet with SVX $b$-tag

Dots: Background Distribution (22 fb$^{-1}$)
Circle: DATA (109 pb$^{-1}$)
200 events observed, $131\pm30\pm29$ expected:

![Graph showing M(γ,b,jet) - M(b,jet) vs. M(b,jet)](image)

- Signal would be "spot" on plane
projections of previous plot:

CDF Preliminary 85pb⁻¹ γ,b,jet Data

- Data
- Background (norm. to data)
- Technicolor x 4

ω₁ → γπ₁ → γbb

Events/10 GeV/c²

M(b,jet) (GeV/c²)

45
35
30
25
20
15
10
5

Events/5 GeV/c²

M(γ,b,jet)-M(b,jet) (GeV/c²)
cross section limits for particular mass choice:

\[ \omega_T \rightarrow \gamma \pi_T \rightarrow \gamma b \bar{b} \]

\[ M(\pi_T) = 120 \text{ GeV/c}^2 \]

- Data 95% C.L. Limits

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\[ N_{Tc} = 4, \quad Q_D = Q_U - 1/3, \quad M_T = 100 \text{ GeV/c}^2, \quad \text{CTEQ4L, K-factor = 1.3} \]
TOPCOLOR SIGNATURES

• All the previous technicolor signatures plus:

• Isotriplet of "top-pions" $\pi_t$
  from breakdown of $SU(3) \times U(1)$
  $$\pi_t \rightarrow t\bar{b} \text{ or } t \rightarrow \pi_t b$$

• "Top-rho" $\rho_t$ ($m \sim 2m_t - 1 \text{ TeV}$)
  $$\rho_t \rightarrow \pi_t \pi_t', \ t\bar{t}, \ b\bar{b}$$

• Color-octet gauge bosons - colorons or topgluons
  ($m \sim 0.5 - 2 \text{ TeV}, \ \Gamma/m \sim 0.5$)
  - resonances in $b\bar{b}, \ t\bar{t}$ production
  - $\sigma \sim 1 - 10 \text{ pb (Tevatron)}, \ 100\text{ pb} - 1 \text{ nb (LHC)}$
  $$\sqrt{s}/B \rightarrow b\bar{b}, \ t\bar{t}$$

• Topcolor $Z'_t$
  $$Z'_t \rightarrow t\bar{t}$$
Topcolor \( Z' \) associated with breakdown of \( U(1)_3 \)

\[ Z' \rightarrow t \bar{t} \]

Resonance in \( t \bar{t} \)

Min \( \sigma \cdot B(X \rightarrow tt) \) for a resonance to be observed at the 5\( \sigma \) level.

\begin{align*}
\sigma \cdot B (pb) & \frac{1}{fb^{-1}} \\
& 10 fb^{-1} \\
& 100 fb^{-1} \\
& 1 fb^{-1}
\end{align*}

\begin{align*}
M_{tt} \text{ GeV/c}^2 & 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000 \\
\end{align*}

- Tevatron
  - \( \Delta \) TopColor \( Z' \), \( \Gamma = 1.2\% \)
  - \( \Box \) TopColor \( Z' \), \( \Gamma = 10\% \)
A large ongoing effort is being devoted to assessing the feasibility of building a high-energy muon collider. Initial results from the machine design studies are encouraging. The First Muon Collider (FMC) is envisaged as a machine producing $\mu^+\mu^-$ collisions at a center-of-mass energy in the range from $m_Z$ up to above the $t\bar{t}$ threshold. This would provide a step towards a very high energy collider (a 4 TeV muon collider, for example). In addition to the collider ring, the FMC requires a very intense muon source that provides a variety of additional physics possibilities. The FMC accelerator complex would evolve within the following parameter ranges:

- An intense low energy proton source delivering initially $6 \times 10^{20}$ protons/year and ultimately $1.5 \times 10^{22}$ protons/year at 8 GeV/c or above.

- An extremely intense very low energy muon source producing, for example, initially $8 \times 10^{19}$ muons/year, and ultimately $2 \times 10^{21}$ muons/year at $\sim$100 MeV/c.

- A muon accelerator complex producing muon beams with energies up to a maximum of, for example, 200 GeV, and the accompanying neutrino beams.
TECHNICOLOR AT
THE MUON COLLIDER

- The low energy techni-hadrons can be probed at the FMC with $\sqrt{s} = 100-500 \text{GeV}$.

- Specifically, neutral technipions and technivectors are very narrow and can be produced as $s$-channel resonances.

- Coupling to $\mu^+\mu^- \sim m_\mu/\nu$, $\nu \approx 246 \text{GeV}$
  
  So, $\sigma \propto m_\mu^2$  
  
  $= 10^4$ times better than at $e^+e^-$  
  
  $\sim 0.1-10 \text{ nb}$

Also, $\delta p/p \sim 10^{-3}$ to $10^{-5}$

$\Rightarrow \mu^+\mu^-$ Collider will be  
  a remarkable facility
$\mu^+\mu^- \rightarrow \rho_T$

$m_\rho = 400 \text{ GeV}\\
m_{\pi_T} = 150 \text{ GeV}$

$10^4 \text{ events/yr @ } L = 10^{32}$
$\mu \mu \rightarrow \omega \tau$

$m_\omega = 210$ GeV

$m_\tau = 110$ GeV

$10^4$ pb

$\Rightarrow 10^7$ events/year

@ $L = 10^{32}$
$\mu \rightarrow \pi \pi \pi$ isovector $\pi^0 \rightarrow b\bar{b}$
$\mu^+\mu^- \rightarrow \text{ISOSCALAR } \pi^0 \rightarrow b\bar{b}, \gamma\gamma$

$\sigma(\mu^+\mu^-)$

$10^3$

$10^2$

$10^1$

$10^0$

$\sqrt{s} \text{ (GeV)}$

$109.8$ $109.9$ $110$ $110.1$ $110.2$

$\pi^0 \rightarrow \gamma\gamma$

$\pi^0 \rightarrow b\bar{b}$

TOTAL
\( \mu^+ \mu^- \rightarrow \rho_T, \omega_T \rightarrow e^+ e^- \)

A small non-zero isospin splitting between \( \rho_T \) and \( \omega_T \) can produce dramatic interference in \( \mu^+ \mu^- \rightarrow f\bar{f} \).
AT THE FMC

• Technicolor low enough in mass to be produced at the FMC will have been discovered at the Tevatron—certainly at the LHC

• So, precision measurements would be the goal

• FMC can be a technipion factory

• Sit on the resonance and study all decays and BR's of the $\rho$'s, $\omega$'s and $\pi$'s (all-hadronic modes are hard at the hadron colliders)

• Explore the full spectrum of hadrons

• Study $(\rho, \omega)$ interference
SUMMARY

- Technicolor is an intuitively attractive and ambitious ansatz for dynamical Electroweak symmetry Breaking.

- Several low energy signatures are accessible at the Tevatron and LHC.

- Searches are underway at the Tevatron. Rates \( \sim 10 \) larger at LHC. So, TC signatures should be easily observable.

- Muon collider would be a remarkable facility to study technicolor. Spectacular narrow resonances are expected.

- We don't know how nature has chosen to break Electroweak symmetry and flavor symmetry. We should be open-minde