Technicolor at the LHC

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Electroweak symmetry breaking in the Standard Model

- Electromagnetism and the weak force unified in *electroweak* gauge theory.
- Exact electroweak symmetry forbids fermion and gauge boson masses, so it must be (spontaneously) broken.
- In the standard model (SM), this is done by adding a scalar Higgs field by hand, with a potential engineered to produce spontaneous symmetry breaking.

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_3 \end{pmatrix} \qquad\qquad V(\Phi) \sim \lambda\left(\Phi^\dagger\Phi - v^2\right)^2$$

- The SM Higgs mechanism provides all the necessary masses, but has some issues:
  - Sensitive to highest energy scale at which SM is applicable.
    "Unnatural" fine-tuning required to maintain hierarchy.
  - Gives no dynamical explanation of electroweak symmetry breaking.
    Explicitly added by hand, all fermion masses remain free parameters.
  - Theory is "trivial": new physics has to appear by scale Λ or else coupling λ vanishes:

$$\lambda(\mu) \simeq \frac{\lambda(\Lambda)}{1 + (24/16\pi^2)\lambda(\Lambda)\log(\Lambda/\mu)} \Longrightarrow \Lambda \simeq m_h \exp\left(\frac{4\pi^2 v^2}{3m_h^2}\right)$$

$$m_h = 115 \text{ GeV} \Longrightarrow \Lambda \sim 10^{28} \text{ GeV}$$

$$m_h = 700 \text{ GeV} \Longrightarrow \Lambda \sim 1000 \text{ GeV.}$$

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Dynamical electroweak symmetry breaking

- How do other physical examples of spontaneous symmetry breaking deal with these issues?

1. Superconductivity.

2. (Approximate) chiral symmetry breaking in quantum chromo-dynamics (QCD).

- Dynamics naturally explains scale of symmetry breaking.

Speculate:

3. Electroweak symmetry breaking.
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   - (Fun fact: QCD condensate $\langle \overline{q}q \rangle$ breaks electroweak symmetry, giving $m_W = m_Z \cos\theta_W \simeq 34$ MeV.)

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Technicolor

- Such dynamical breaking of electroweak symmetry is technicolor (TC).[1,2,3,4]
- Originally modelled on chiral symmetry breaking in QCD.[5,6,7] Introduce new, unbroken, asymptotically free, nonabelian gauge interaction that becomes strong around the weak scale.
- Electroweak symmetry is broken by "technifermion" condensate $\left\langle \overline{T} T \right\rangle \equiv 4\pi F_T^3 \neq 0$, giving $m_W = m_Z \cos\theta_w \propto F_T$.
- Since TC is unbroken, only technicolor-singlet states (SM particles and "technihadrons") are observable. Three lightest technipions identified as $W_L^{\pm}$ and Z_L.
- Strong interactions $\Longrightarrow$ perturbation theory inapplicable, analytic calculations difficult, generally intractable.
- Can try to use QCD as an "analog computer" for technicolor.

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[1] Martin, 0812.1841.

[2] Shrock, hep-ph/0703050.

[3] Lane, hep-ph/0202255.

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Extending technicolor

- Also need fermion masses – an ambitious goal!
- "Extend" technicolor with even more strong interactions, at an even higher scale, involving both SM- and techni-fermions.[8] Produces fermion masses. . .

  . . . and flavor-changing neutral currents.
- Strong experimental constraints naïvely limit fermion masses $m_f \lesssim 1$ MeV.
- Also tension between experiment and "scaled-up QCD" calculations for precision electroweak observables such as the "S" and "T" parameters.[9]

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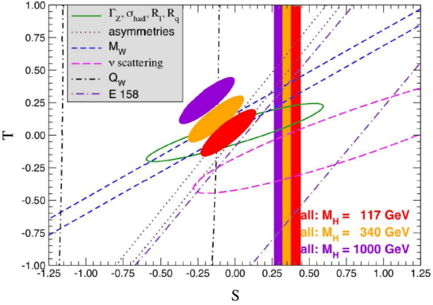

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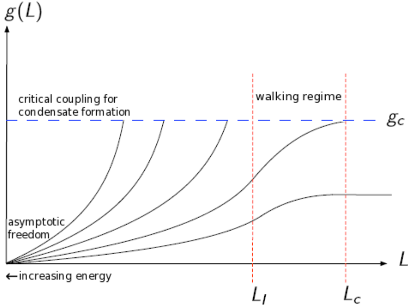
Walking technicolor

- "Walking" behavior can solve some of these problems.[10,11,12,13]
- In walking technicolor (WTC) the TC coupling (interaction strength) changes slowly between electroweak scale and ETC scale – instead of "running", it "walks".



- At a minimum, frees theory from problems of scaled-up QCD (which isn't a walking theory).
- More concretely, allows larger quark and technipion masses, lower TC scale.[14]
- Current work applies extra-dimensional dualities or lattice gauge theory to study walking.

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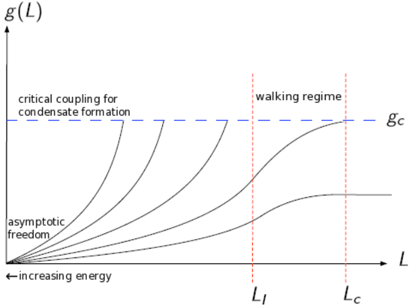

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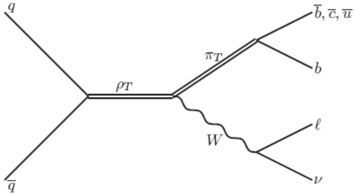
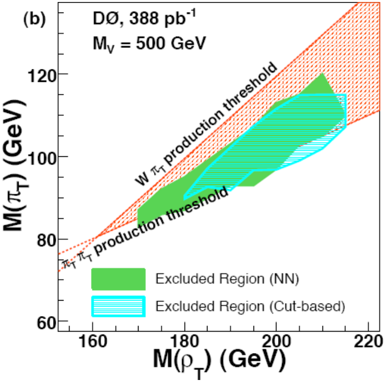
Searching for technicolor in collider experiments

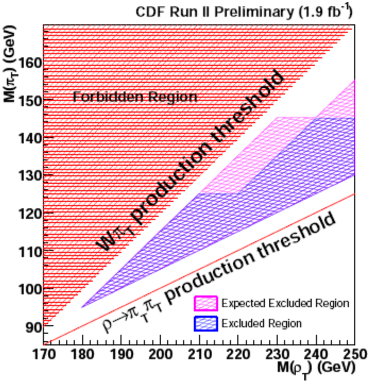
- Since technicolor involves new strong dynamics, will not see individual technifermions.
- Look for bound states, analogous to the π, ρ, ω of QCD.
- Technivector resonances (ρ_T, a_T, ω_T) expected to be relatively narrow and easy to see.
- Main discovery channel at the Tevatron is $\rho_T \rightarrow W^{\pm}\pi_T \rightarrow \ell^{\pm}\nu_\ell bj$.



Current limits

- Results from DØ and CDF: $M_{\pi_T} \gtrsim 125$ GeV, $M_{\rho_T} \gtrsim 215$ GeV at 95% CL.[15,16,17]





- Run II expected to probe up to $M_{\rho_T} \simeq 400$ GeV,[18] should be able to discover or rule out $M_{\rho_T} \lesssim 250$ GeV, $M_{\pi_T} \lesssim 150$ GeV with data collected as of mid-2008.[19]

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[15] DØ, PRL 98:221801 (2007) hep-ex/0612013.

[16] CDF, Public Note 9302 (2008).

[17] Nagai, Masubuchi, Kim and Yao, 0808.0226 (2008).

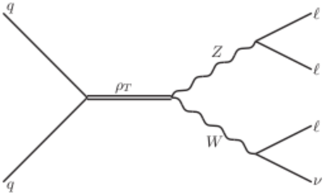
[18] Lane, PRD 60:075007 (1999) hep-ph/9903369.

[19] Eichten and Lane, PLB 669:235 (2008) 0706.2339.

LHC discovery channels

- At the LHC the $\rho_T \to W^{\pm}\pi_T$ channel will be swamped by $t\bar{t}$ and $W+$ heavy flavor backgrounds.
- Best discovery channels are diboson decays of vector resonances, with leptons in the final state: clean signals and relatively low backgrounds.

$$\rho_T \to WZ \to 3\ell + \nu \qquad a_T \to \gamma W \to \ell\nu\gamma \qquad \omega_T \to \gamma Z \to \ell\ell\gamma$$



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$$t\bar{t} \to 2\ell 2\nu b\bar{b} \qquad WZ \to 3\ell + \nu \qquad ZZ \to 4\ell \qquad Zb\bar{b} \to 2\ell b\bar{b}$$

- Backgrounds have larger cross sections, but can be removed by cutting on $\left|M(\ell^+\ell^-) - m_Z\right|$, $|\eta(Z) - \eta(W)|$, and $p_T(W)$, $p_T(Z)$, and $\not{E}_T$.
- Should be able to see signal up to 600 GeV with $\mathcal{O}$(1-10) fb^{-1}.[20]

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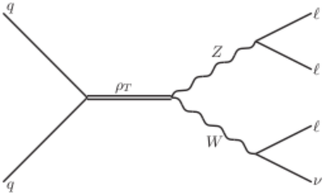

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From signal to theory

- Should we see some signal, how do we decide it's actually technicolor?
- Distinctive angular distributions of W and Z show that they come from decay of spin-one resonance. Would need $\mathcal{O}$(10-100) fb^{-1} to check.
- The patterns of masses and widths of resonances can also provide (more model-dependent) evidence.
- Direct observation of technipions (besides $W_L^{\pm}$ and Z_L) in addition to vector resonances could be especially conclusive (if it doesn't trick people into thinking they've found a Higgs...)
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Take-away messages

- Technicolor is a long-standing, viable, ambitious and attractive *concept*, for which no fully realistic model has yet been developed.
- Technicolor involves strong interactions, which are tough to work with.
- Technicolor will be stringently tested at the LHC.
- Much remains to be done in collider studies of technicolor.
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