Technicolor Returns!

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+ work in progress

Outline

- Constraints on strong electroweak breaking
  $\Rightarrow$ conformal technicolor

- Minimal theory based on QCD-like Lagrangian

- New signals at LHC

Technicolor vs. SUSY

- Both offer compelling solution of "large hierarchy" problem $M_W \ll M_{\rm Planck}$

- Both have problems with phenomenology of electroweak symmetry breaking

SUSY: $m_{h^0} > 114\ \mathrm{GeV} \Rightarrow 1\%$ fine tuning

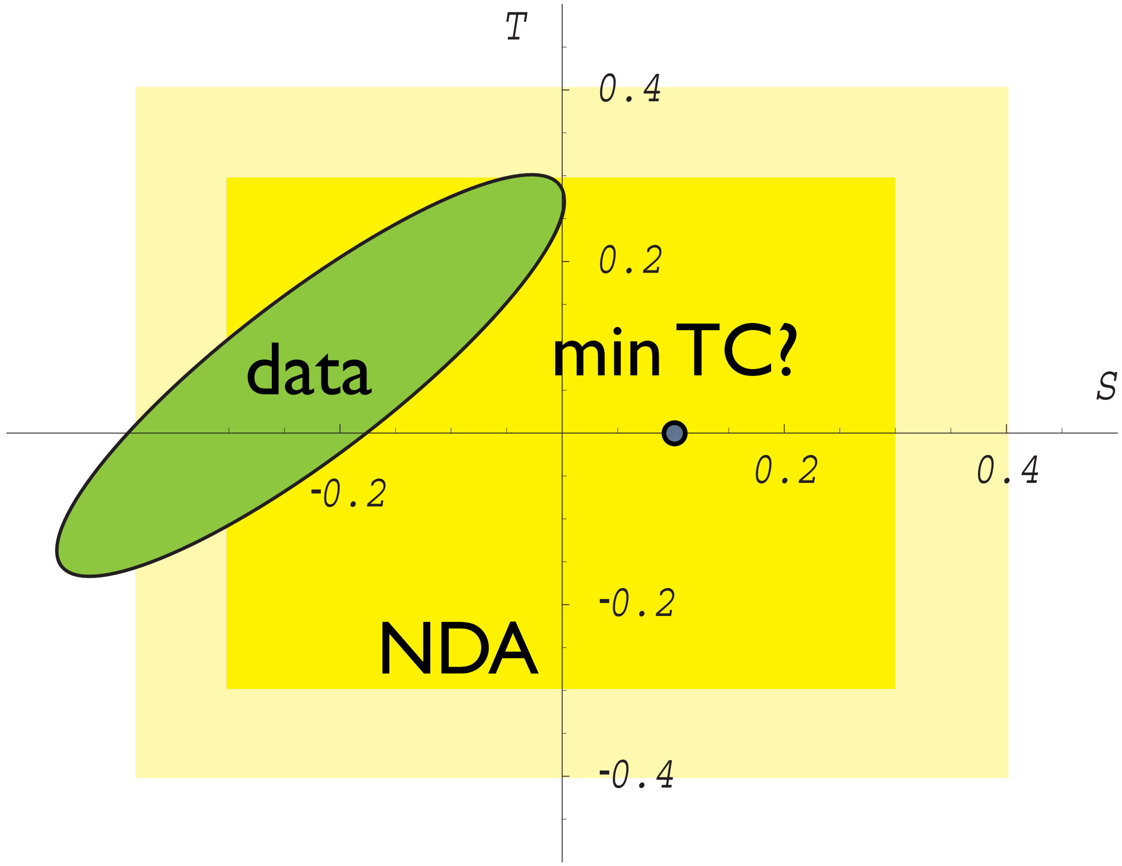
$$\Delta m_H^2 \sim \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2 + \cdots$$

Technicolor: "Let me count the ways..."

Three Strikes Against Technicolor?

- Precision electroweak data
- Light flavor
- Heavy flavor (top quark)

Precision Electroweak Data



- $S \sim N \Rightarrow$ want $N \sim 1$
- $S < 0$ from non-QCD dynamics?
- Adjustable parameters?

Light Flavor

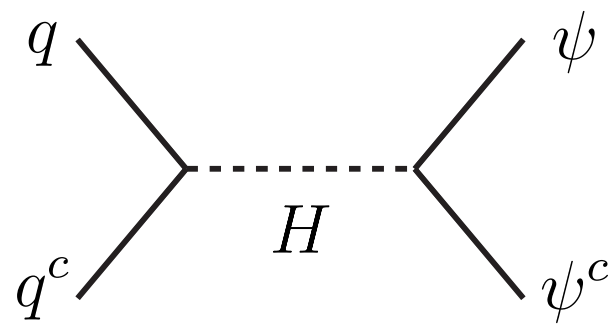
- Electroweak symmetry broken by $\langle \psi^c \psi \rangle \neq 0$

$$\Delta \mathcal{L}_{\text{eff}} \sim \frac{1}{M^2} (\psi^c \psi)(q^c q) \;\Rightarrow\; \text{fermion masses}$$

$$\Delta \mathcal{L}_{\text{eff}} \sim \frac{1}{M^2} (q^c q)^2 \qquad\qquad \Rightarrow\; \text{FCNCs}$$

- "Bosonic Technicolor"

(Kagan, Samuel, Dine 1990)



SUSY broken at ~ 100 TeV

Heavy Higgs exchange gives 4-fermion couplings with GIM suppression of FCNCs

Top Quark

- Top quark coupling to $\psi^c \psi$ gets strong at

$$\Lambda_t \sim \Lambda_{\rm TC} \left(\frac{\Lambda_{\rm TC}}{m_t} \right)^{1/2} \sim 5 \text{ TeV} \qquad \Lambda_{\rm TC} \sim \text{TeV}$$

Motivates "topcolor" (Hill 1995)

- Large anomalous dimension

"Walking" technicolor (Holdom, 1985; Appelquist, Karabali, Wijewardhana 1986)

$$\dim(\psi^c \psi) = d \neq 3$$

$$\Lambda_t \sim \Lambda_{\rm TC} \left(\frac{\Lambda_{\rm TC}}{m_t} \right)^{1/(d-1)} \sim \begin{cases} 10 \text{ TeV} & \text{for } d \simeq 2 \\ 100 \text{ TeV} & \text{for } d \simeq 1.5 \end{cases}$$

How low (in d) can we go?

Conformal Technicolor

(Luty, Okui 2004)

- Conformal (scale invariant) field theory:

  $d = \dim(\mathcal{O}_H) \geq 1$ (e.g. $\mathcal{O}_H = \psi^c \psi$)

- Naturalness: no tuning of "Higgs mass" operator

  $D = \dim(\mathcal{O}_H^\dagger \mathcal{O}_H) > 4$ (irrelevant)

- $d \to 1 \Rightarrow$ free scalar $\Rightarrow D \to 2$

- $N \gg 1 \Rightarrow D = 2d + \mathcal{O}(1/N) \Rightarrow d > 2$

- Want $d = 1 + 1/\text{few}, \ D > 4$

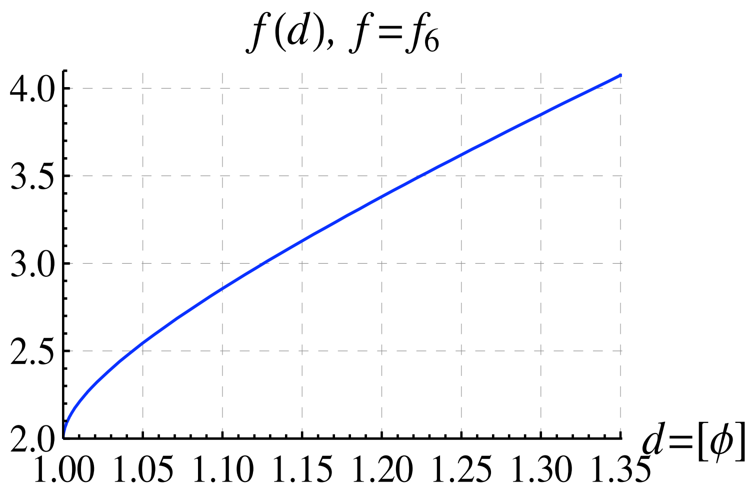
  Does such a theory exist?

Rigorous Bounds

(Rattazzi, Rychkov, Tonni, Vichi 2008)

- Analyzed singlet operator in general CFT, derived model-independent bound

$$D \leq f(d) \qquad d = \dim(\mathcal{O}_1),\ D = \dim(\mathcal{O}_1\mathcal{O}_1)$$



$$\Rightarrow d > 1.34$$

$$(\text{“}\Lambda_t \sim 3000\ \text{TeV”})$$

$$f(1+\epsilon) \sim \epsilon^{1/2}$$

- Bounds for non-singlet operator may be weaker

Conformal QCD

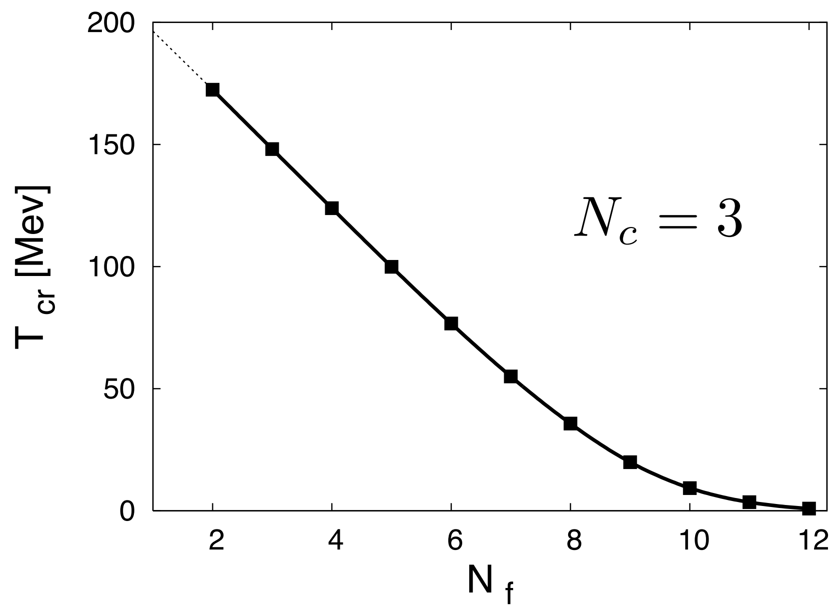
Strong evidence that QCD is conformal for

$$4.4 \lesssim N_f/N_c \lesssim 5.5$$

- $N_f/N_c \simeq 5.5 \Rightarrow$ weakly coupled fixed point at large N_c (Banks, Zaks 1982)
- Analogy to "conformal window" of SUSY QCD (Seiberg 1994)
- Lattice...

Fixed Points on the Lattice

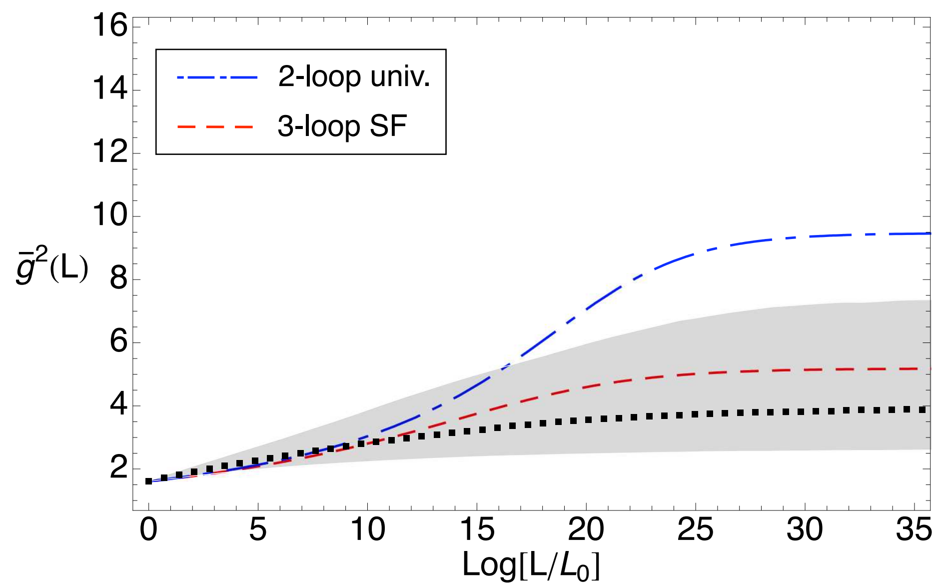
- Deconfinement transition as function of N_f



(Braun, Gies 2007)

- Schrödinger functional for $N_f = 12$

(Appelquist, Fleming, Neil 2008)



Dimensions from the Lattice

(Luty 2008)

- Add mass term for all flavors

  $\Delta\mathcal{L} = m\psi^c\psi \;\Rightarrow$ mass gap

- Confinement:

  $$m_\pi \propto m^{1/2}$$
  $$m_\rho \propto m^0$$

- Conformal fixed point:

  $$m_\pi, m_\rho \propto m^{1/(4-d)} \qquad d = \dim(\psi^c\psi)$$

- Measure scaling of hadron masses with m

Model Building

$$G_{\text{gauge}} = SU(N)_{\text{CTC}} \times SU(2)_W \times U(1)_Y$$

$$\left.\begin{aligned} \psi &\sim (N,2)_0 \\ \chi^c &\sim (\bar{N},1)_{+\frac{1}{2}} \\ \chi'^c &\sim (\bar{N},1)_{-\frac{1}{2}} \end{aligned}\right\} \text{ Minimal technicolor}$$

$$\left.\begin{aligned} \xi &\sim (N,1)_0, \\ \xi^c &\sim (\bar{N},1)_0 \end{aligned}\right\} \text{ Sterile techniquarks } (\times K)$$

$$\Delta\mathcal{L} = m_\xi \xi \xi^c$$

- Conformal invariance explicitly broken
- Chiral symmetry breaking at conformal breaking scale

Large Hierarchy Problem

- Technicolor (including walking technicolor):

$$\Lambda_{\mathrm{TC}} \sim M e^{1/\alpha(M)} \sim \mathrm{TeV}$$

- SUSY: Explicit (soft) breaking of $\underbrace{\text{SUSY}}_{\text{spacetime symmetry}}$

  Soft breaking may have deeper origin
  (e.g. dynamical SUSY breaking)

- Conformal technicolor:
  Explicit (soft) breaking of $\underbrace{\text{conformal invariance}}_{\text{spacetime symmetry}}$

  ...may have deeper origin

Minimal Conformal Technicolor

(Evans, Galloway, Luty, Tacchi, in progress)

$$N = 2 \Rightarrow \bar{2} \simeq 2$$

$$G_{\text{gauge}} = SU(2)_{\text{CTC}} \times SU(2)_W \times U(1)_Y$$

$$\begin{aligned} \psi &\sim (2,2)_0 \\ \chi &\sim (2,1)_{-\frac{1}{2}} \\ \chi' &\sim (2,1)_{+\frac{1}{2}} \\ \xi &\sim (2,1)_0 \qquad (\times 2K) \end{aligned}$$

$$\Delta\mathcal{L} = m_\xi \xi^2$$

Vacuum Alignment

$SU(4) \simeq SO(6)$ global symmetry $\quad \Psi = \begin{pmatrix} \psi \\ \chi \\ \chi' \end{pmatrix}$

spontaneously broken by $C^{ab} = \langle \Psi^a \Psi^b \rangle \neq 0$

$C^{ab} = -C^{ba} \Rightarrow$ unbroken subgroup is $Sp(4) \simeq SO(5)$

$C = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}$ $\quad SU(2)_W \times U(1)_Y \to U(1)_{\mathrm{EM}}$

"Technicolor vacuum"

$C = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix}$ $\quad SU(2)_W \times U(1)_Y$ unbroken

"Electroweak vacuum"

Vacuum Alignment

$SU(4)$ explicitly broken by perturbative interactions
Determines vacuum alignment

- Higgs exchange from SUSY at 100 TeV

$$\Delta\mathcal{L}_{\text{eff}} = +\frac{y^2}{m_H^2}|\psi\chi|^2 + \frac{y'^2}{m_{H'}^2}|\psi\chi'|^2 \qquad (B\mu \to 0)$$

$m_H^2, m_{H'}^2 > 0 \Rightarrow$ favors $\langle\psi\chi\rangle, \langle\psi\chi'\rangle \neq 0$

Enhanced at low energy

$$\dim(\psi\chi) = \dim(\psi\chi') = 1 + 1/\text{few}$$

$$\Rightarrow \dim(|\psi\chi|^2) = \dim(|\psi\chi'|^2) \simeq 4$$

Vacuum Alignment

- Technifermion mass terms

$$\Delta\mathcal{L} = m_\psi \psi\psi + m_\chi \chi\chi'$$ (unique to minimal technicolor)

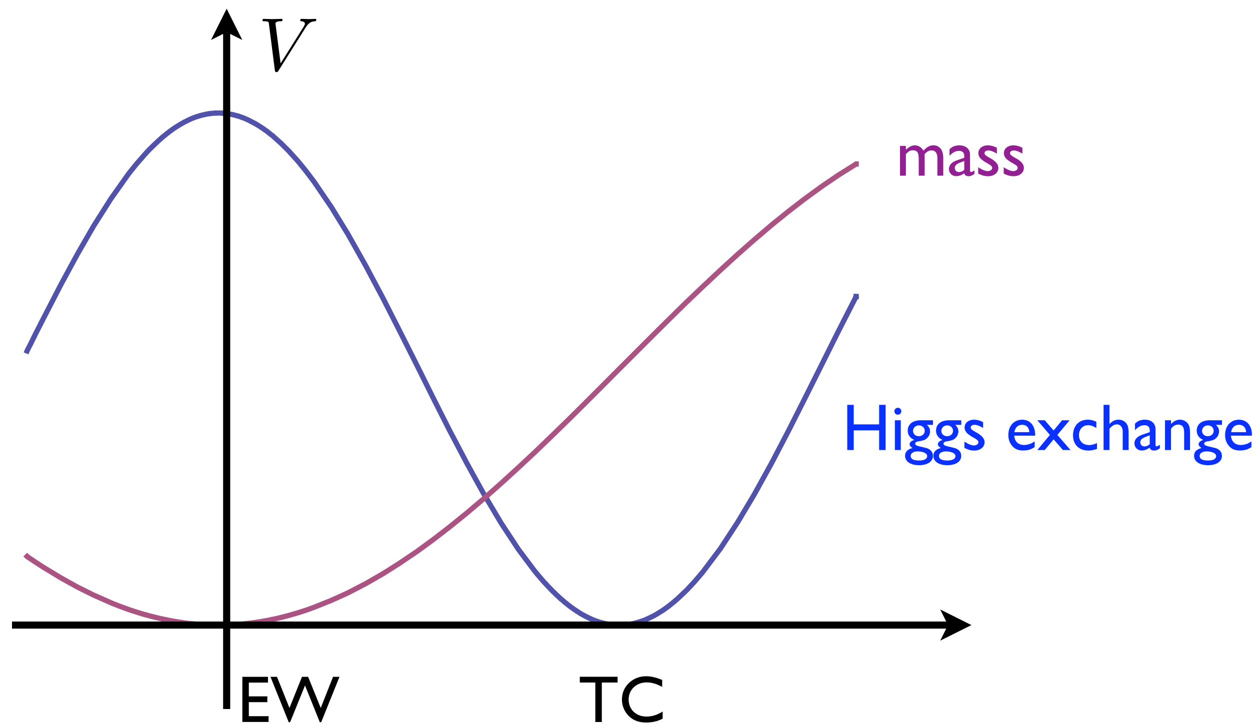
TeV scale set by similar mass term $\Delta\mathcal{L} = m_\xi \xi\xi$

Same origin $\Rightarrow m_\psi, m_\chi \lesssim m_\xi$ natural

Pushes condensate away from "technicolor" vacuum

Also solves domain wall problem $Z_4 \to Z_2$

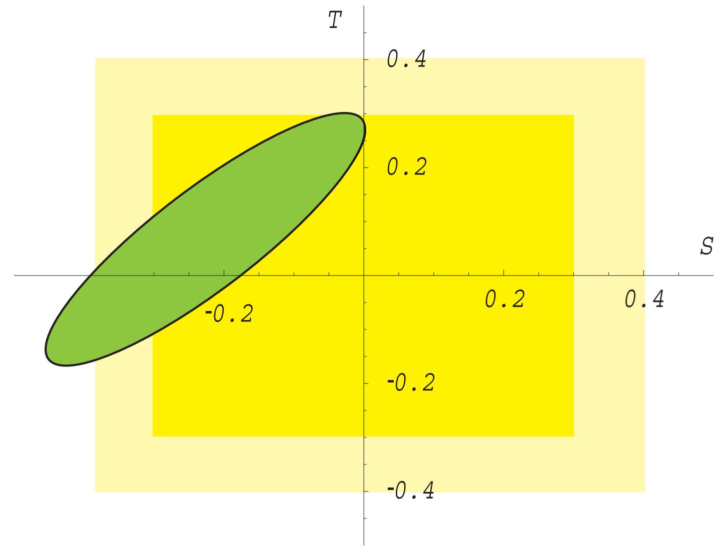
Vacuum Alignment



Other contributions smaller

- Electroweak gauge boson loops
- Top quark loops

"In Between" Vacuum

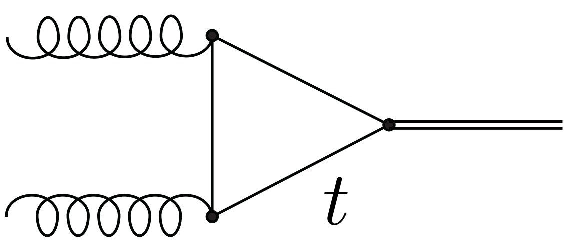


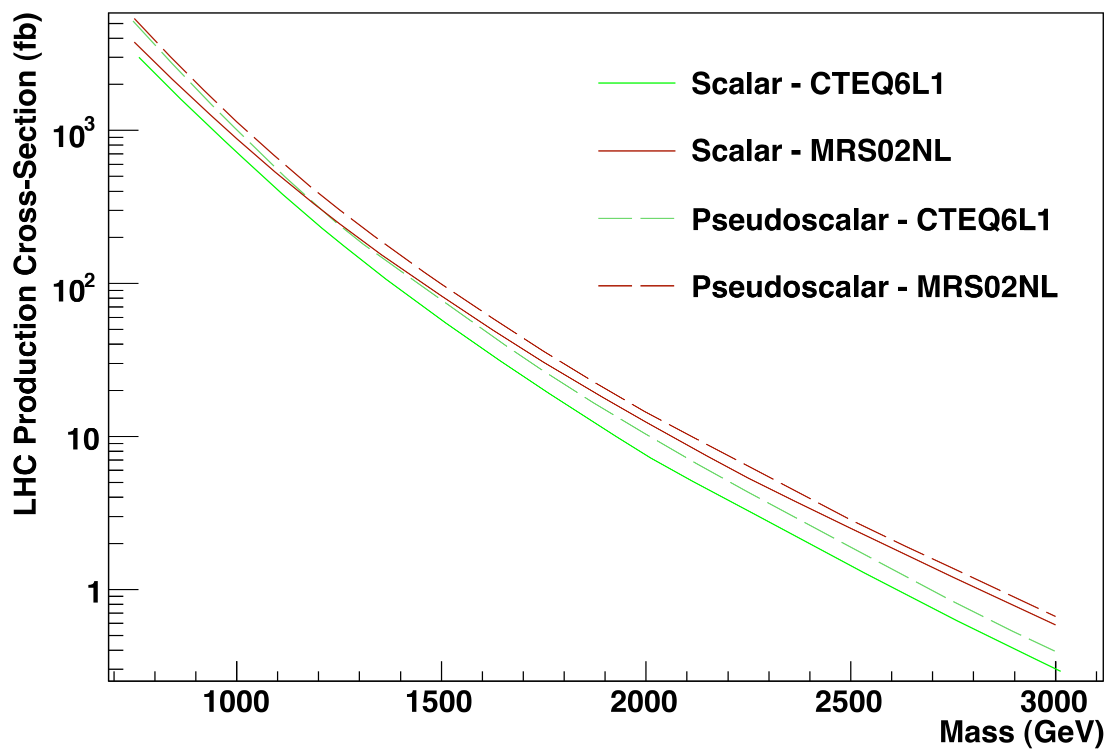
- Custodial symmetry OK
- $S_{\mathrm{had}} \sim \frac{1}{2} S_{\mathrm{TC}}$
- Higgs-like scalar ~ 100 GeV
  $\Rightarrow$ additional negative contribution to S
- Light pseudoscalar
- Light scalar has Higgs-like couplings
  expect suppression compared to SM Higgs

TeV Phenomenology

Top coupling $\Delta\mathcal{L} = c_t(Qt^c)(\psi\chi')$

$$(\psi\chi')|0\rangle = |\text{scalar}\rangle + |\text{pseudoscalar}\rangle$$





Techniscalars

Good symmetries: $Sp(4) \times CP$

- $\sigma = 1_+$

  $\sigma \to \pi\pi \Rightarrow$ broad $\quad (\pi^\pm = W_L,\ \pi^0 = Z_L)$

  TeV Higgs search applies

- $\eta = 1_-$

  Only allowed strong decays are

  $\eta \to \pi\pi\pi\pi,\ \eta \to \rho\pi\pi\ (\rho \to \pi\pi)$

  $$\frac{\Gamma(\eta \to \bar{t}t)}{m_\eta} \sim 10^{-1} \qquad \frac{\Gamma(\eta \to \rho\pi\pi)}{m_\eta} \sim 10^{-2}$$

  $\Rightarrow \eta \to WWWW$ 10% of the time!

Conclusions

• Conformal technicolor gives a plausible mechanism to combine the top quark with strong electroweak symmetry breaking

• Dynamical assumptions can be tested on the lattice

• Minimal conformal technicolor may give a good fit to precision electroweak data

• No domain wall problem

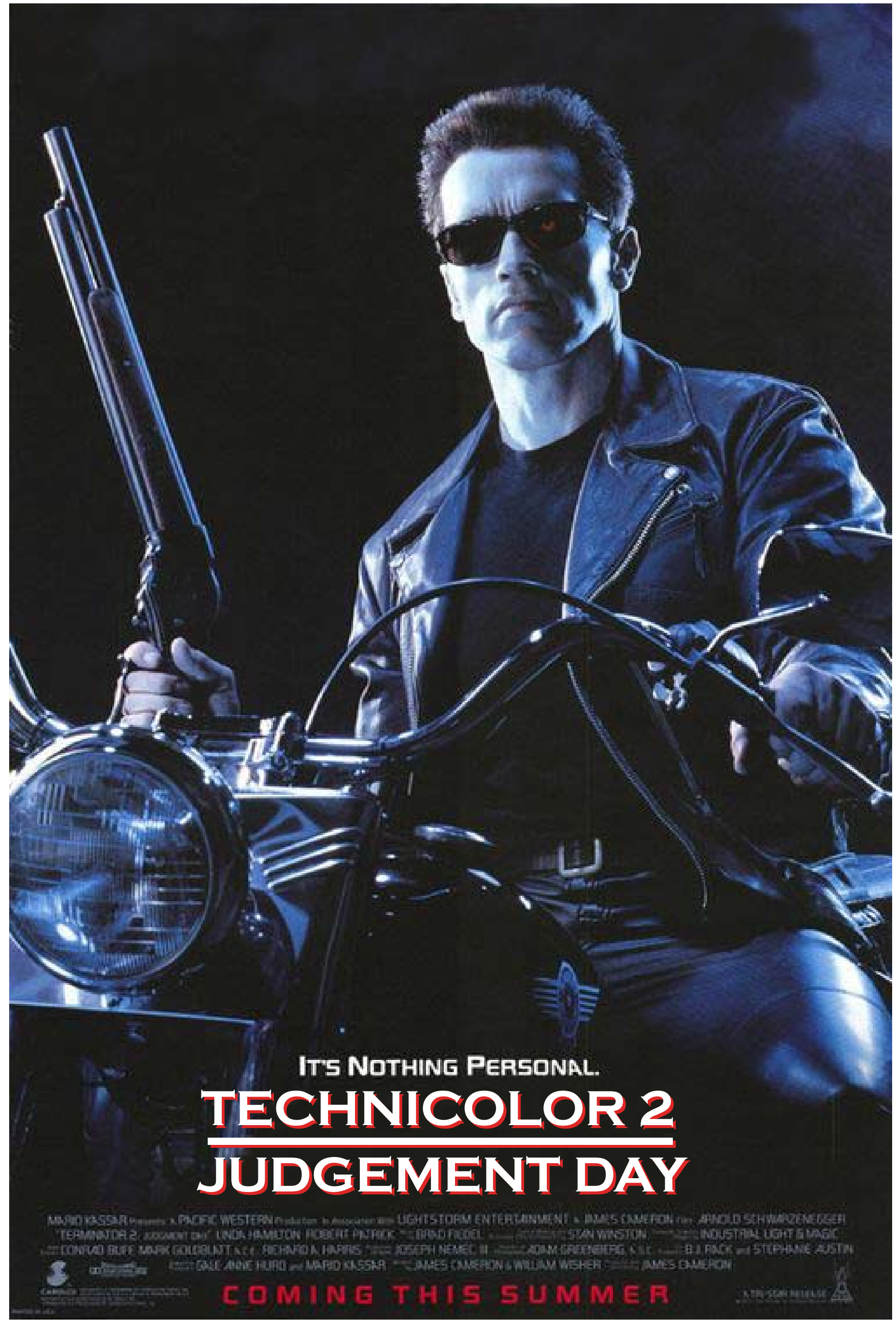
Conclusions

- New signals for strong electroweak breaking
  - Light scalar and pseudoscalars with Higgs-like couplings
  - Broad Higgs-like resonance at TeV
  - Narrow pseudoscalar resonance decaying to $\bar{t}t,\ WWWW$

Technicolor is back!

Is it here to stay?

Experiment will decide...



Experiment will decide...