Conformal Technicolor: From the Weak Scale To the Planck Scale

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Hierarchy Problem

Standard Model: $\dim(H) = 1$

$\dim(QHt^c) = 4$ $\dim(H^\dagger H) = 2$

Technicolor: $H = \psi\psi^c \Rightarrow \dim(H) = 3$

$\dim(QHt^c) = 6$ $\dim(H^\dagger H) = 6$

Conformal/Walking Technicolor: $\dim(H) = d$

$\dim(QHt^c) = d + 3$ $\dim(H^\dagger H) = \Delta \geq 2d$

Want $d \simeq 1, \;\; \Delta > 4$

Requires strong conformal (scale invariant) dynamics!

LEP vs. SUSY & Technicolor

SUSY

$$m_h > 114 \text{ GeV}$$

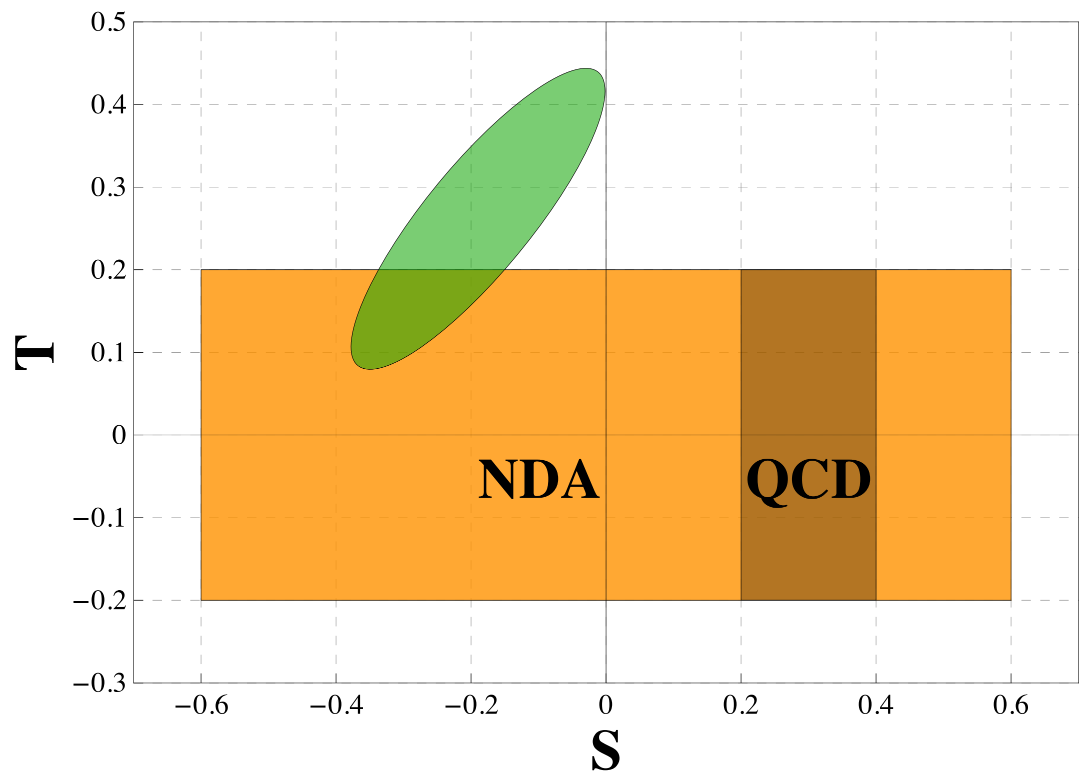
$$m_{h^0}^2 \sim \Delta\lambda\, v^2$$

$$\Delta\lambda \sim \frac{N_c y_t^4}{8\pi^2} \ln \frac{m_{\tilde{t}}^2}{m_h^2}$$

$$\Delta m_H^2 \sim \frac{N_c y_t^2}{8\pi^2} m_{\tilde{t}}^2$$

$$\Rightarrow \text{tuning} \sim \frac{m_Z^2}{\Delta m_H^2} \sim 0.01\, e^{-(m_{h^0}/115\ \text{GeV})^2}$$

Technicolor



Outline

- Conformal technicolor is a plausible solution to the hierarchy problem

  Precision electroweak: composite Higgs
  (or dumb luck?)

  Flavor: high scale SUSY

- LHC signals

  Resonant production of W, Z, t

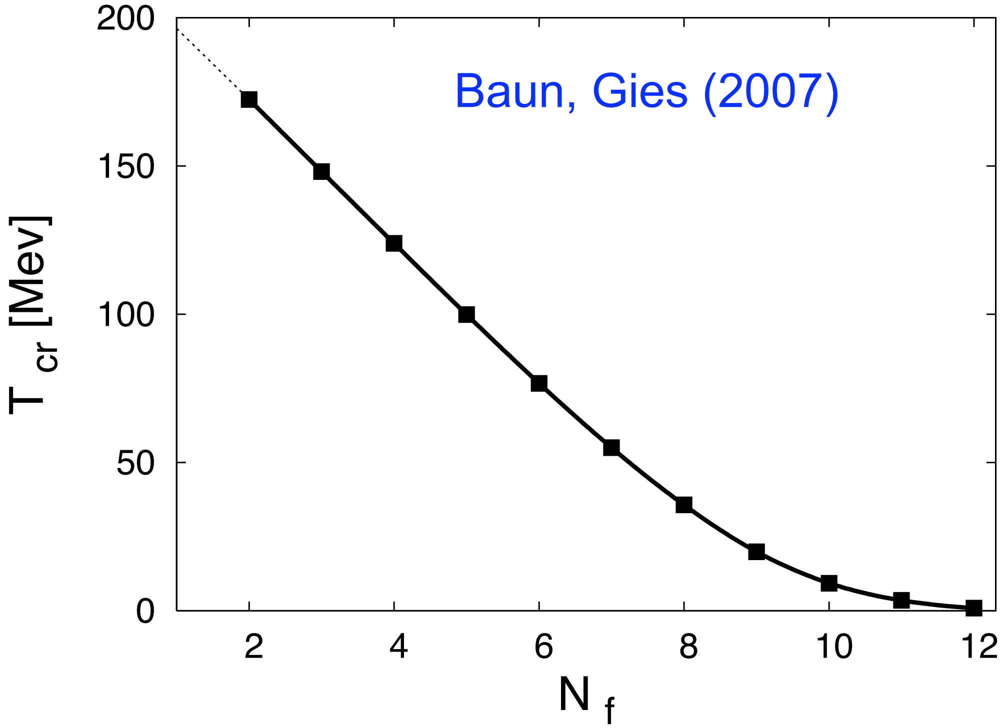
QCD Conformal Window

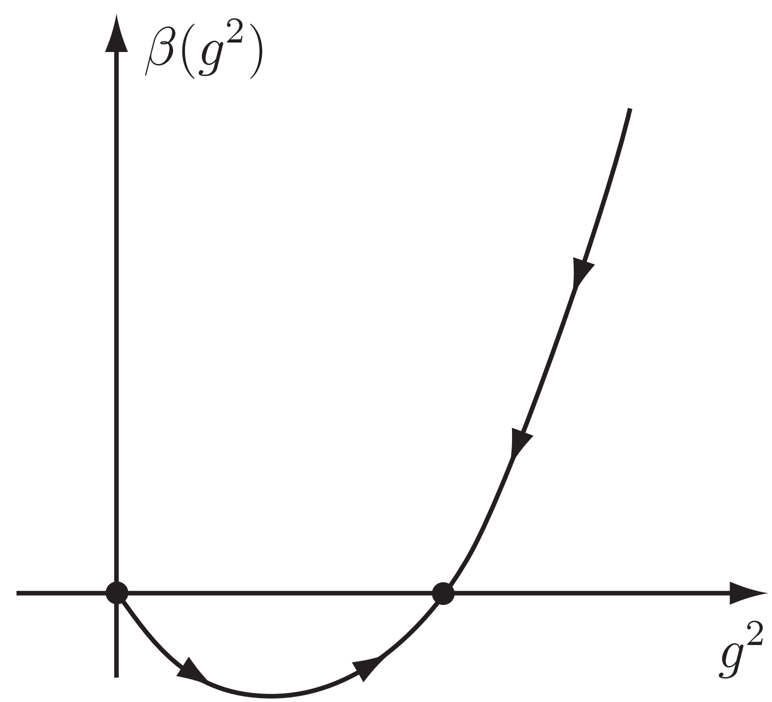
QCD is scale invariant (conformal) for

$$4N_c \lesssim N_f < \frac{11}{2}N_c$$

Lattice, models

Banks-Zaks fixed point





Strong conformal dynamics at end of conformal window

Constraints on Dimensions

(ML, Okui 2004)

- $\dim(H) \to 1 \Rightarrow \dim(H^\dagger H) \to 2$
  (weak coupling limit)

- $\dim(H^\dagger H) = 2\dim(H) + \mathcal{O}(1/N_c)$
  Also applies to RS/AdS/CFT

- Quantitative bounds
  (Rattazzi, Rhychkov, Tonni, Vichi 2007; Rhychkov, Tonni, Vichi 2009)

  $\Delta_{\rm min} = \min\{\dim(H^\dagger H), \dim(H^\dagger \sigma_a H)\}$

  $d > 1.6$ if $\Delta_{\rm min} > 4$

Dimensions on the Lattice

(ML 2008)

Study QCD in conformal window

- $\Delta\mathcal{L} = m\bar{\psi}\psi$ (unavoidable on the lattice)

- Breaks conformal symmetry

  $\Rightarrow \Lambda \propto m^{1/(4-d)}$ $\quad$ $\dim(\bar{\psi}\psi) = d$

- All physical mass scales $\propto \Lambda$

  $\Rightarrow$ use scaling with m to measure d

Simulations starting to appear (DeGrand 2009)

Minimal Conformal Technicolor

(ML 2008; Evans, Galloway, ML, Tacchi 2010)

$$SU(2)_{\rm CTC} \times SU(2)_W \times U(1)_Y$$

$$\left.\begin{aligned} \psi &\sim (2,1)_0, \\ U^c &\sim (2,1)_{-\frac{1}{2}}, \\ D^c &\sim (2,1)_{\frac{1}{2}}, \end{aligned}\right\} \text{ minimal technicolor}$$

$$\chi \sim (2,1)_0 \quad \times 12$$

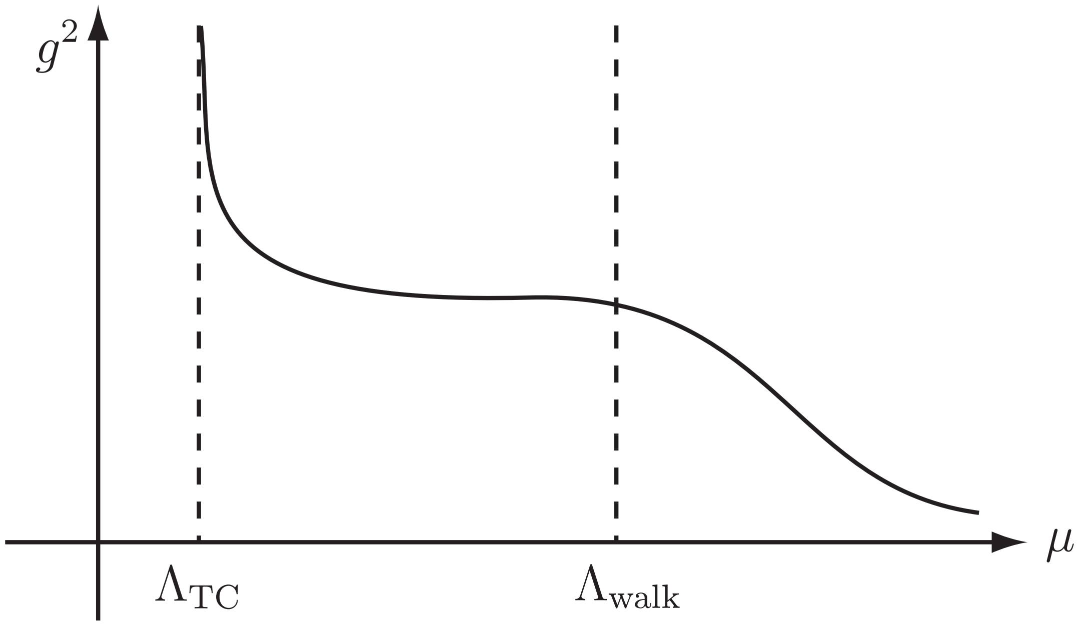
$$\Delta\mathcal{L} = m_\chi \chi\chi$$

Soft breaking of conformal invariance triggers electroweak symmetry breaking

$$\Lambda \sim m_\chi^{1/(d-4)}$$

Walking Technicolor

(Holdom 1985; Appelquist, Karabali, Wijewardhana 1986; Yamawaki, Bando, Matumoto 1986)



Probably requires large N_c

$$\frac{\Lambda_{\rm TC}}{\Lambda_{\rm walk}} \sim e^{-1/N_c}$$

Vacuum Alignment

$$\Psi = \begin{pmatrix} \psi \\ U^c \\ D^c \end{pmatrix} \sim 4 \text{ of } SU(4)$$

$$\langle \Psi^a \Psi^b \rangle = \Lambda^d \Phi^{ab}$$

$$\Rightarrow SU(4) \to Sp(4)$$

$$(\simeq SO(6) \to SO(5))$$

$$\Phi \to \begin{pmatrix} \epsilon & 0 \\ 0 & -\epsilon \end{pmatrix}$$

preserves electroweak symmetry

"electroweak" vacuum

$$\Phi \to \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

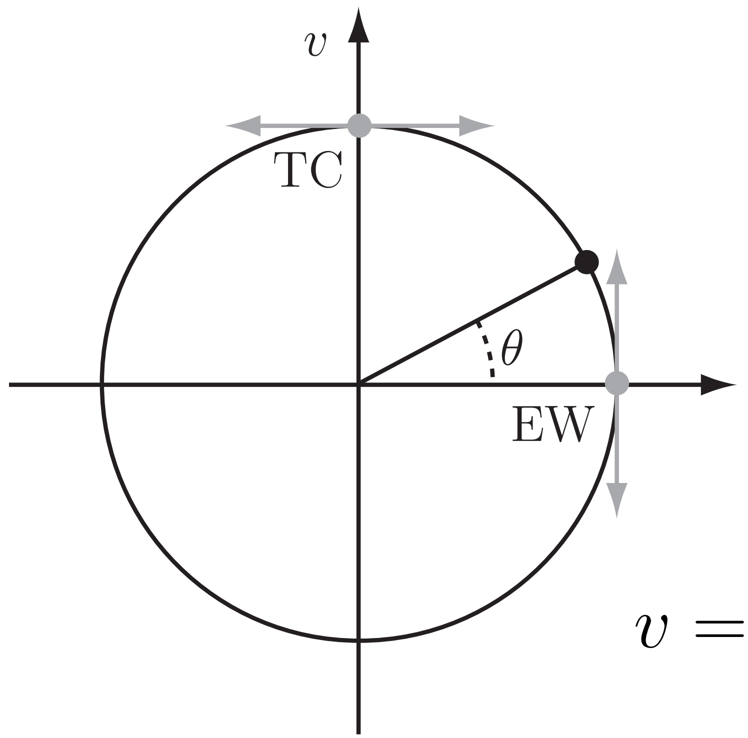
$SU(2)_L \times SU(2)_R \to SU(2)_{\rm cust}$

"technicolor" vacuum

Vacuum Angle

General vacuum up to EW gauge transformations:

$$\Phi = \begin{pmatrix} \cos\theta\,\epsilon & \sin\theta \\ -\sin\theta & -\cos\theta\,\epsilon \end{pmatrix} \qquad 0 \le \theta \le \pi$$



$$v = f \sin\theta$$

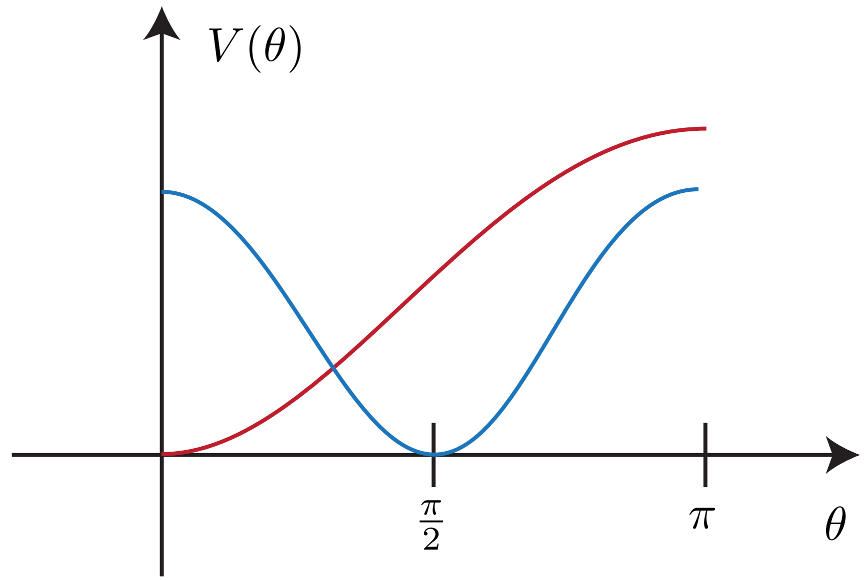
Minimal technicolor automatically has PNGB Higgs

Good for precision electroweak fit...

PNGB Potential

$SU(4)$ breaking from

- Top, electroweak loops
- $\Delta\mathcal{L} = m\psi\psi + \tilde{m}U^cD^c + \text{h.c.}$

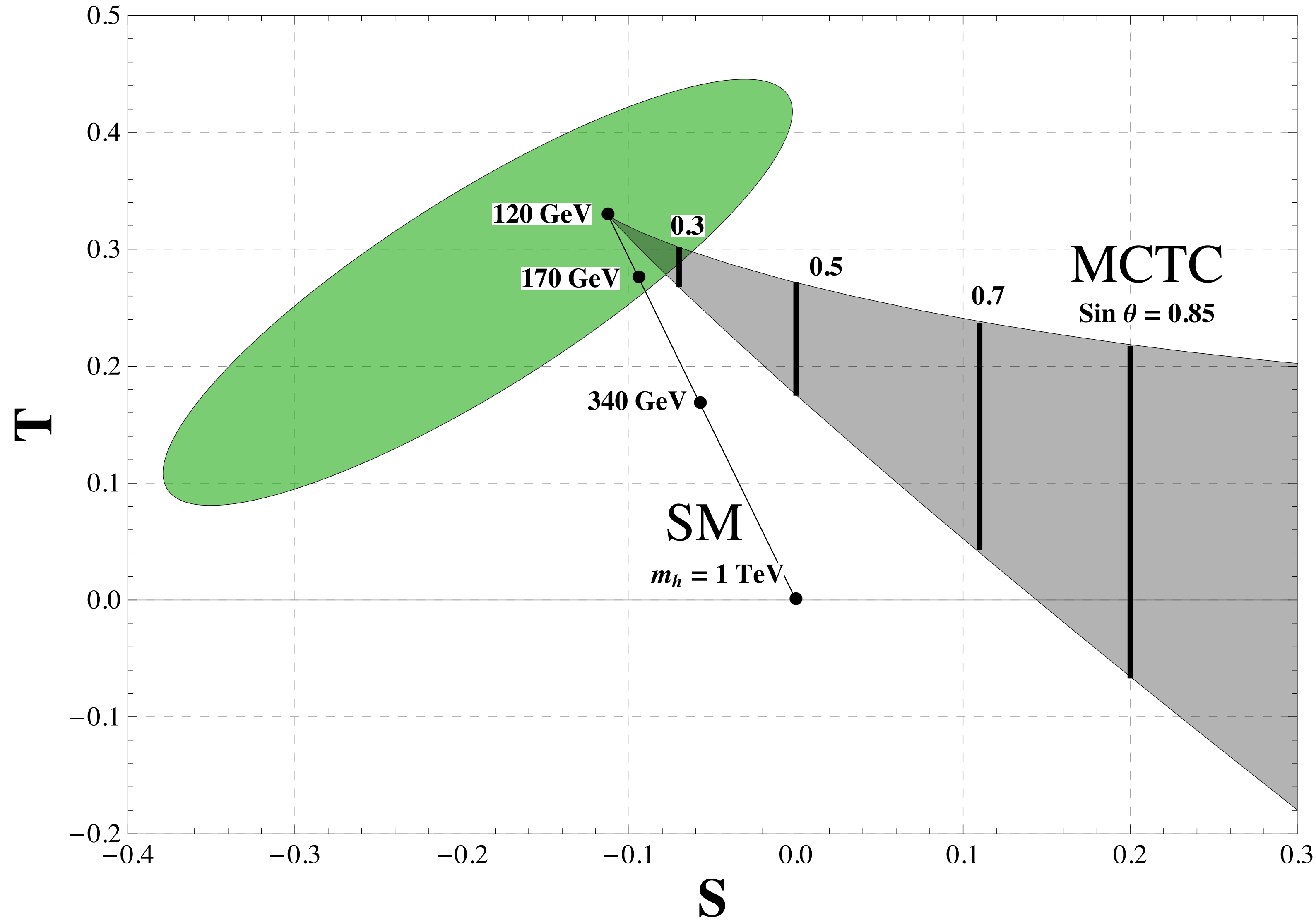


$$V(\theta) = -\tfrac{1}{2}\underbrace{(C_t - C_{\text{EW}})}_{>0}\sin^2\theta - \underbrace{C_m}_{>0}\cos\theta$$

$$m_{h^0}^2 = c_t N_c m_t^2 \qquad c_t \sim 1$$

$$m_A^2 = \frac{m_{h^0}^2}{\sin^2\theta}$$

Precision Electroweak Fit



$\sin\theta \lesssim 0.3 \quad \Rightarrow$ tuning $\sim 10\%$

Top Flavor Scale

$$\Delta\mathcal{L} = \frac{c_t}{\Lambda_t^{d-1}} Q t^c H + \text{h.c.}$$ gets strong at scale Λ_t

$$\Rightarrow m_t \sim \frac{4\pi v}{\sin\theta}\left(\frac{4\pi v}{\Lambda_t}\right)^{1/(d-1)}$$

$$d = 3 : \Lambda_t \sim 30 \text{ TeV}$$

$$d = 2 : \Lambda_t \sim 100 \text{ TeV} \qquad (\sin\theta = 0.25)$$

$$d = 1.5 : \Lambda_t \sim 1000 \text{ TeV}$$

How small does d have to be?

Need UV completion...

UV Completion

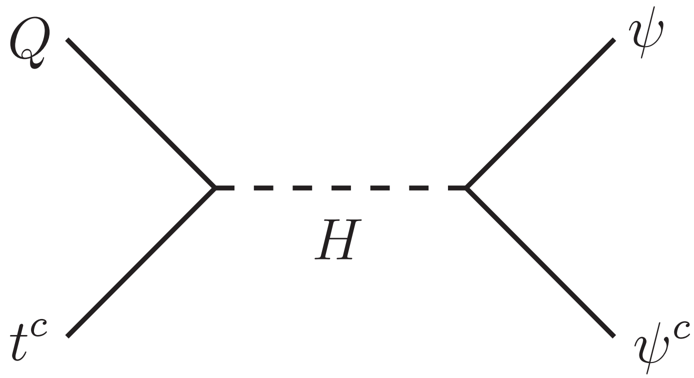
- Is there a plausible theory of flavor?
- How small does $\dim(\psi\psi^c)$ have to be?
- Observable consequences?

(Evans, Galloway, ML, Tacchi, under construction)

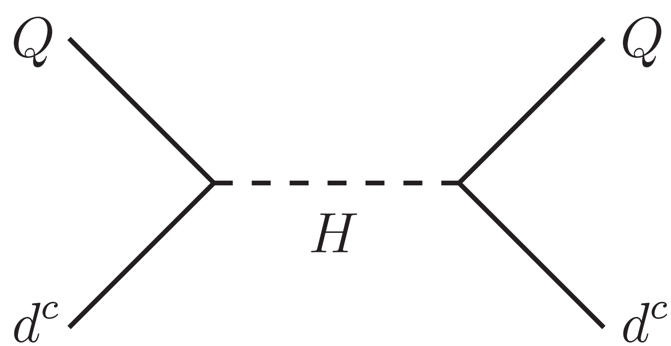
Bosonic Technicolor

(Dine, Kagan, Samuel 1990)

Generate 4-femion couplings from heavy Higgs exchange



$$\longrightarrow \quad y_t y^*_{\mathrm{TC}} (Q t^c)(\psi \psi^c)^\dagger + \text{h.c.}$$



$$\longrightarrow \quad \underbrace{(y_d)_i{}^j (y_d^*)^k{}_\ell}_{\text{diagonal in mass basis}} (Q^i d^c_j)(Q^k d^c_\ell) + \text{h.c.}$$

Requires SUSY broken at high scale with $\langle H_{u,d} \rangle = 0$

$M_{\mathrm{SUSY}} \gtrsim 10\ \mathrm{TeV} \Rightarrow$ no SUSY flavor problem

Superconformal Technicolor

$$m_t \sim \text{TeV} \underbrace{\left(\frac{y_t}{4\pi}\right)\left(\frac{y_{\text{TC}}}{4\pi}\right)\left(\frac{\text{TeV}/\sin\theta}{M_{\text{SUSY}}}\right)^{1/(d-1)}}_{\sim \frac{1}{10}}$$

Requires y_t, y_{TC} strong at M_{SUSY}

Natural in strong superconformal theories

Technicolor Sector

$$SU(3)_{\mathrm{CTC}} \times SU(2)_W \times U(1)_Y$$

$$\left.\begin{aligned} \Psi &\sim (3,2)_0, \\ \bar{U} &\sim (\bar{3},1)_{-\frac{1}{2}}, \\ \bar{D} &\sim (\bar{3},1)_{\frac{1}{2}}, \end{aligned}\right\} \quad \text{technifermion multiplets}$$

$$\left.\begin{aligned} \Sigma_{1,2,3,4} &\sim (3,1)_0, \\ \bar{\Sigma}_{1,2,3,4} &\sim (\bar{3},1)_0. \end{aligned}\right\} \quad \text{sterile technifermion multiplets}$$

$SU(3)_{\mathrm{CTC}}$ has 6 flavors

$\Rightarrow$ strong (self-dual) conformal fixed point

Higgs-Technicolor Couplings

$$W \supset y_{\bar{U}}(\Psi\bar{U})H_u + y_{\bar{D}}(\Psi\bar{D})H_d$$

$y_{\bar{U}}, y_{\bar{D}} =$ relevant couplings (dimension $+\frac{1}{2}$)

- Can get strong at $M_{\rm SUSY}$ due to analog of Giudice-Masiero mechanism:

$$\langle Y\rangle \sim M_{\rm int} \sim (M_{\rm P}M_{\rm SUSY})^{1/2}, \quad \langle F_{\rm Y}\rangle \lesssim M_{\rm int}M_{\rm SUSY}$$

Occurs naturally in simple hidden sectors

- Strong fixed point for Yukawa couplings

Evidence from a maximization: (Intriligator, Wecht 2003)

$$\dim(\Psi\bar{U}) = \dim(\Psi\bar{D}) = 1.67, \qquad \dim(H_{u,d}) = 1.33$$

SUSY Breaking

- Strong conformal dynamics suppresses gaugino masses, universal scalar masses
- Scalar masses proportional to symmetry generators are protected

$\Rightarrow$ some $m_i^2 \sim -M_{\rm SUSY}^2$

$$\langle \Sigma_4 \rangle, \langle \bar{\Sigma}_4 \rangle \neq 0 \;\Rightarrow SU(3)_{\rm CTC} \to SU(2)_{\rm CTC}$$

- Massless technifermions: $\Psi, \bar{U}, \bar{D}, \Sigma_{1,2,3}, \bar{\Sigma}_{1,2,3}, \lambda_2$

$\Rightarrow SU(2)_{\rm CTC}$ has $N_f^{\rm eff} = 7$

Consistent with strong conformal dynamics

Strong Top Sector

$$\underbrace{SU(3)_{C1}}_{\text{strong conformal}} \times \underbrace{SU(3)_{C2}}_{\text{weak}} \rightarrow \underbrace{SU(3)_{C}}_{\text{weak}}$$

3rd generation charged under $SU(3)_{C1}$

$$W \supset y_t Q_3 t^c H_u$$

y_t at strong fixed point

...to the TeV Scale

$SU(2)_{\mathrm{CTC}}$ technifermion masses from

$$W \supset \Sigma_4 \Psi\Psi + \bar{\Sigma}_4 \bar{U}\bar{D}$$
$$+\Sigma_4 \Sigma\Sigma + \bar{\Sigma}_4 \bar{\Sigma}\bar{\Sigma}$$

$SU(2)_{\mathrm{CTC}}$ gaugino mass exponentially suppressed

may be essentially massless

$$SU(4) \times U(1)_\lambda \to Sp(4)$$

$\Rightarrow$ additional PNGB

Summary

- SUSY allows Yukawa couplings

  $\Rightarrow$ origin of flavor can be at Planck scale

- High scale SUSY breaking

  $\Rightarrow$ no SUSY flavor problem,
  simple solution of μ problem (Giudice-Masiero)

- $M_{\rm SUSY}$ is natural scale of symmetry breaking

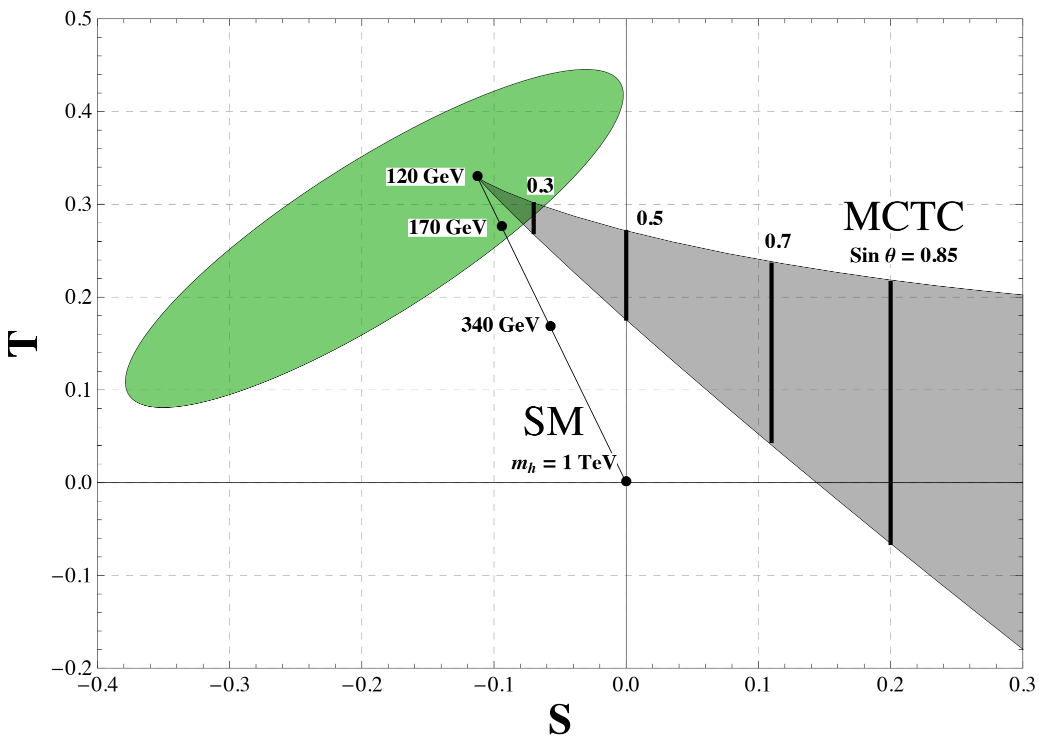
  Allows strong SUSY CFT $\rightarrow$ conformal technicolor

  Allows strong Yukawa couplings for technifermions and 3rd generation quarks

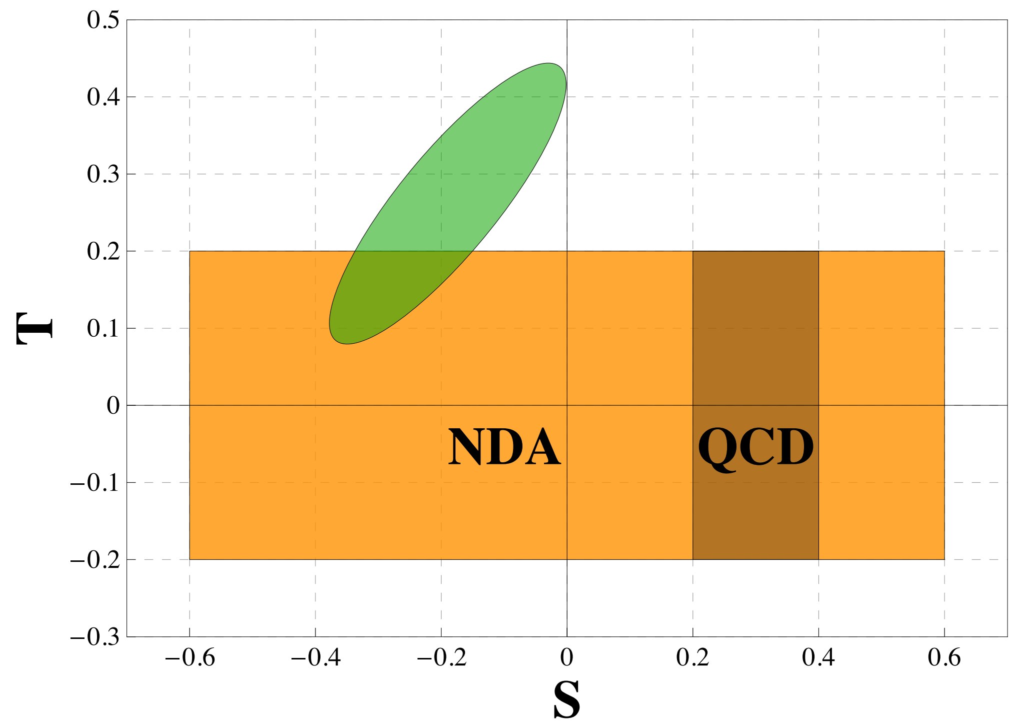
LHC Phenomenology

Two stories for precision electroweak constraints:

PNGB Higgs



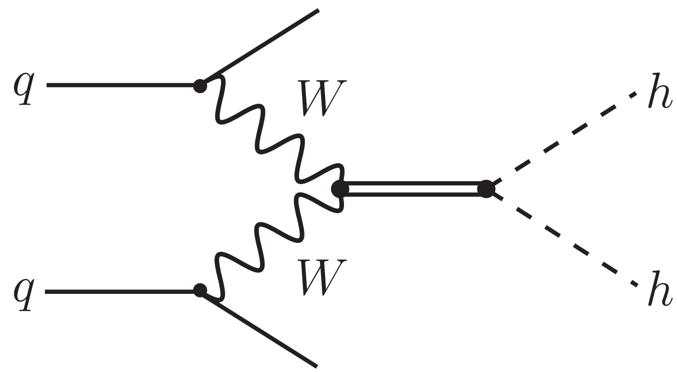
$S < 0$



PNGB Higgs Phenomenology

Smoking gun signal: double Higgs production

(Contino, Grojean, Moretti, Piccinini, Rattazzi, 2010)



Resonances at scale

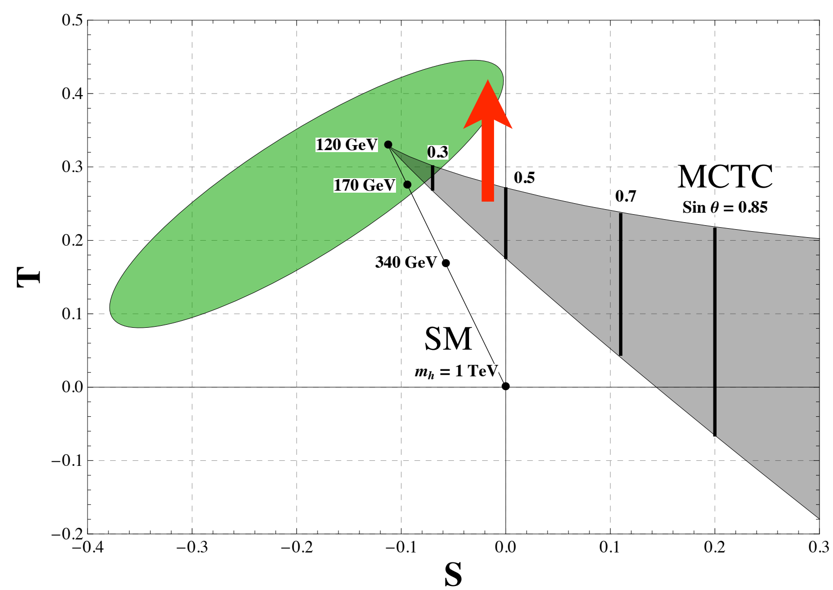
$$\Lambda \sim \frac{2\ \mathrm{TeV}}{\sin\theta}$$

Tuning $\sim \sin^2\theta$

suggests $\sin\theta \sim 0.5$

($\Delta T > 0$ e.g. from 4-fermion couplings)

$\Rightarrow \Lambda$ accessible at LHC?



PNGB Phenomenology

Strong gauge dynamics does not naturally give minimal breaking pattern $SO(5) \to SO(4)$

$\Rightarrow$ additional PNGBs

Pair production at comparable rate to Higgs, but decays may give more spectacular signals

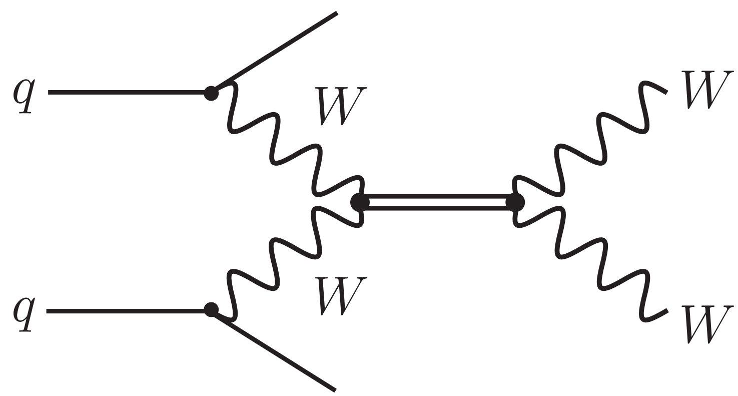
E.g. in minimal conformal technicolor,

$A \to \bar{f}f$ suppressed by $Sp(4)$ custodial symmetry

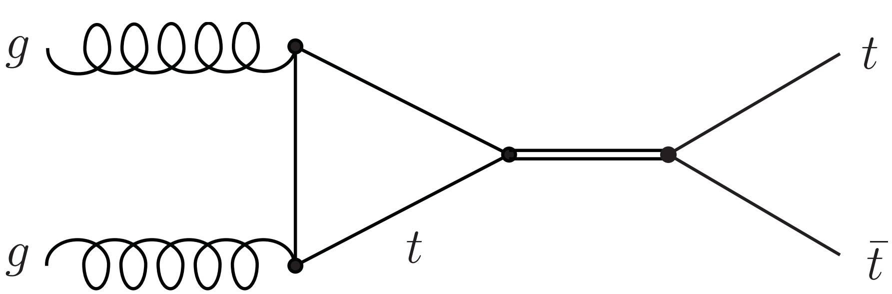
$A \to W^+W^-,\ ZZ,\ Z\gamma$ (but not $\gamma\gamma$) for $m_A < 2m_t$

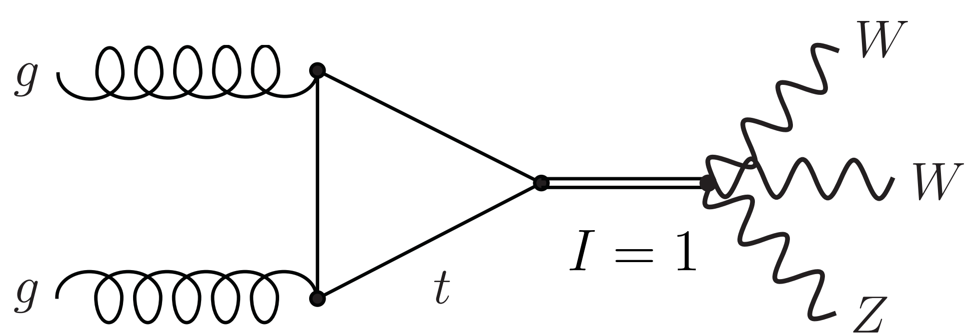
General Strong Signals

- No theorem that $S > 0$ (even in QCD!)
- Precision electrowdo not probe
  the symmetry breaking sector alone



but also





(Evans, ML 2009 + work in progress)

Conclusion

"The rumors of the death of technicolor have been greatly exaggerated."

Experiment will Decide...