Flavor in Minimal Conformal Technicolor

Jared A. Evans [1] [2]

jaevans@ucdavis.edu

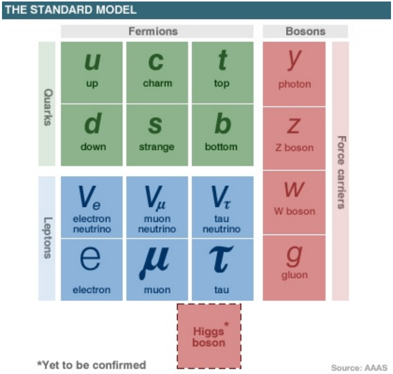
Department of Physics
University of California - Davis

UC Davis

[1] arXiv:1001.1361 – JAE, J. Galloway, M.A.Luty and R.A.Tacchi

[2] In Progess – JAE, J. Galloway, M.A.Luty and R.A.Tacchi

Outline



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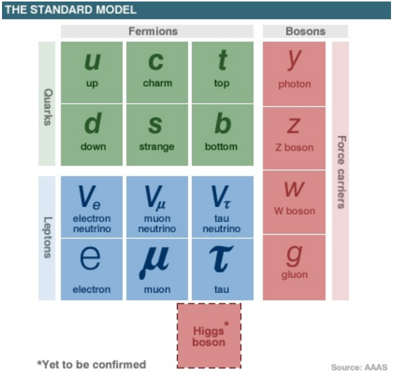

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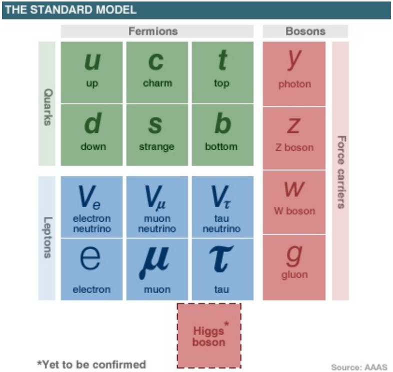

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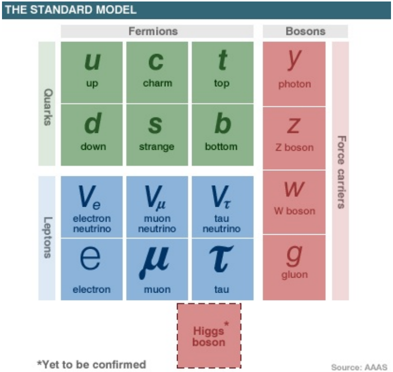

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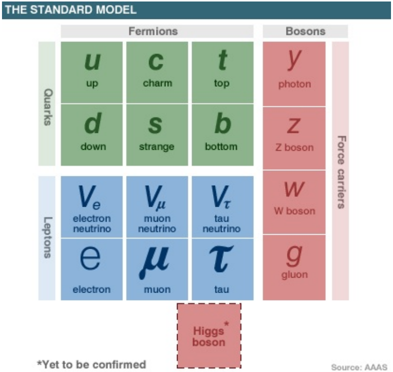

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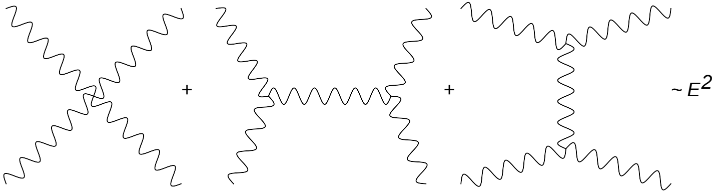
But with a Higgs, *the electroweak scale should be dragged up to* M_{pl}

The Standard Model

The WW Scattering Problem

Sans Higgs contribution there are three WW scattering diagrams:



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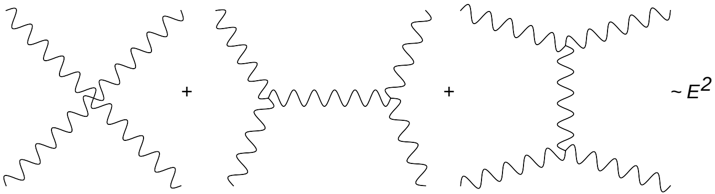

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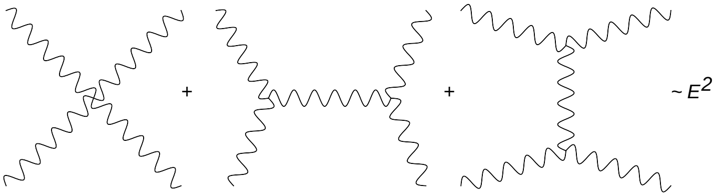

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Standard model Higgs s and t channel diagrams will do exactly that

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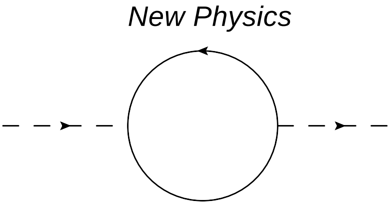
The Hierarchy Problem

Higgs boson receives a mass correction from high scale physics loops



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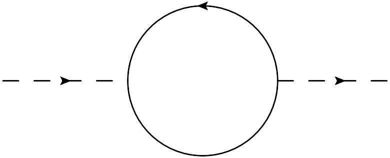
New Physics



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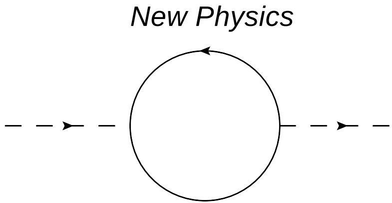

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A very strong suggestion that the SM Higgs is wrong

Technicolor: The Good

One idea is Technicolor!

- $SU(N)$ gauge theories can introduce a *completely natural* hierarchy from the coupling constant running strong –

  $$\text{scale} = \Lambda_{strong} \sim \Lambda_{cutoff}\, e^{-\frac{8\pi^2}{bg^2(\Lambda_{cutoff})}}$$

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- Example Already Exists (sort of): the Standard Model without a Higgs should give a mass to the W and Z bosons (QCD)

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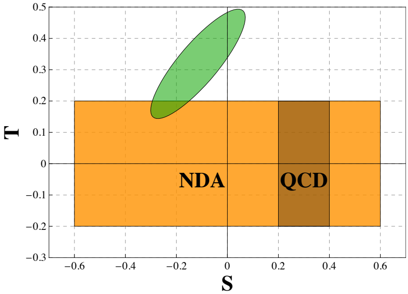

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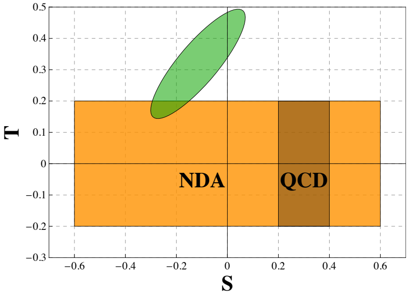

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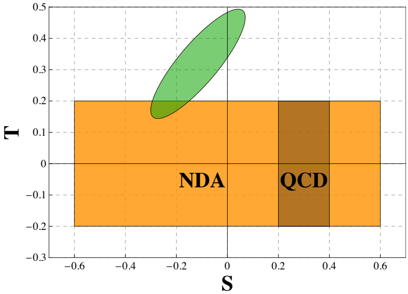

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Even the most generous estimates, put the theory outside of the S-T plane ellipse

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- Extended Technicolor (ETC) can be introduced

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Conformal dynamics:

- Need $d \equiv d\left(\mathcal{H}\right) \lesssim 1.5$ to separate EW scale from flavor scale
- While $\Delta \equiv d\left(\mathcal{H}^\dagger\mathcal{H}\right) \geq 4$ to evade the hierarchy problem

Dimensions in Conformal Theories

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The arguments of CTC rely on large anomalous dimensions, there exists support from both:

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Lattice:

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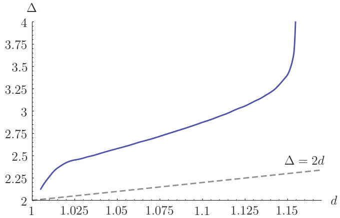
- $\Delta_M \equiv Min\{d(\mathcal{H}^\dagger \tau^a \mathcal{H}), d(\mathcal{H}^\dagger \mathcal{H})\}$ bound is very strong ($\Delta_M > 4 \Rightarrow d \gtrsim 1.6$)
- Bounds on singlet $\mathcal{H}^\dagger \mathcal{H}$ are weak



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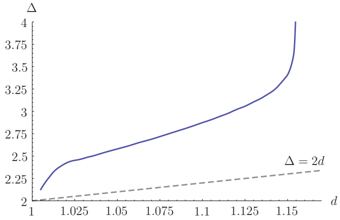

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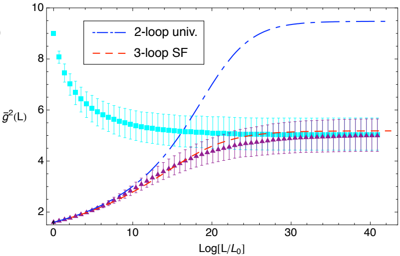
Lattice: (Appelquist, Fleming, Neil 2009; Hasenfratz 2010; Del Debbio, Lucin, Keegan, Pica, Pickup 2010; others. . .)

- Evidence for conformal window $N_c = 3$, $12 \lesssim N_f \leq 16$
- Measure of d (Bursa *et al* 2010) $N_c = 2$, $N_f = 6$, $1.97 \lesssim d \lesssim 2.87$
- S-parameter suppression! (LSD 2010)



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Field Content: $(SU(2)_{CTC}, SU(2)_W)_{U(1)_Y}$

$\psi \sim (2,2)_0$; $\chi \sim (2,1)_{-\frac{1}{2}}$; $\chi' \sim (2,1)_{\frac{1}{2}}$; $\xi \sim (2,1)_0 \times N \sim 8$

$$\begin{aligned}\mathcal{L} &\ni -\kappa\psi\psi - \tilde{\kappa}\chi\chi' - K\xi\xi \\ &+ \frac{g_t^2}{\Lambda_t^{d-1}} (Qt^c)^\dagger (\psi\chi) + \text{h.c.} \\ &+ \frac{g_{4TC}^2}{\Lambda_t^{\Delta-4}} |\psi\chi|^2 + \ldots\end{aligned}$$

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This mass term knocks $SU(2)_{CTC}$ running out of its conformal fixed point

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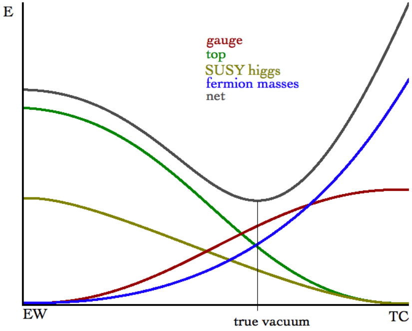
Vacuum alignment

Fermion mass $\propto -\cos\theta$

Top loop, gauge, Higgs $\propto \sin^2\theta$



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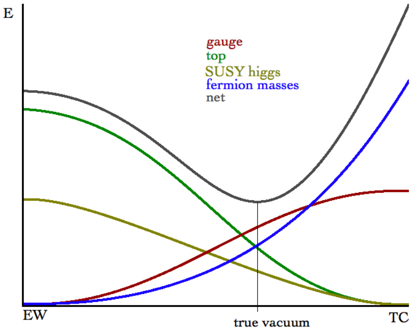

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Minimal Conformal Technicolor

Return of the TC Model

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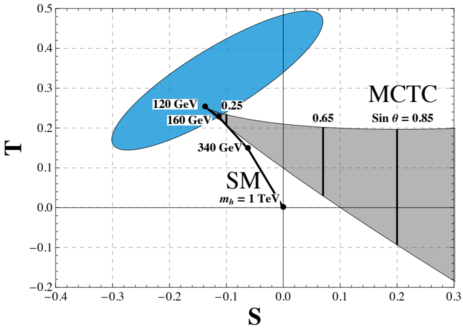
Small enough to fit EW data?

- Top loop contribution gives: $m_h \sim \sqrt{3c_t} M_{top}$
- For c_t & $\sin\theta \lesssim \frac{1}{4}$, model in inside the S-T EW ellipse



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$\rightarrow$ sterile technifermions (break $SU(3)_{SCTC}$, get $N_f = 6$ for conformal running)

$\rightarrow$

$\rightarrow$

Consider a supersymmetric theory with the following field content:

$$SU(3)_{SCTC} \times SU(2)_L \times SU(2)_R \supset U(1)_Y$$

$$\begin{aligned}
\Psi &\sim (3,2,1) \\
\Psi^c &\sim (\bar{3},1,2) \\
\Sigma_a &\sim (3,1,1) \\
\Sigma_a^c &\sim (\bar{3},1,1) \\
P &\sim (1,2,1) \\
P^c &\sim (1,1,2) \\
H &\sim (1,2,2) \\
a &= 1,\ldots,4
\end{aligned}$$

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$\rightarrow$

Superconformal Technicolor

Adventures in the UV!!!

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At SUSY breaking scale Σ_4 gets a VEV – $SU(3)_{SCTC} \rightarrow SU(2)_{CTC}$

$$\langle\Sigma\rangle = \langle\Sigma^c\rangle = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & v_\Sigma \end{pmatrix}$$

Superpotential terms $W \ni \Sigma\Sigma^c + (\Sigma\Sigma^c)^2$ break SCTC at the SUSY scale (and gives mass to 3rd SCTC color of Σ terms)

Superconformal Technicolor
Superpotential

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$$\mathcal{L}_{eff} \sim \xi_a \xi_b + \psi\psi + \psi^c\psi^c + |\psi\psi^c|^2 + (\psi\psi^c)^\dagger (Qt^c)$$

where $\Sigma_{1,2,3}, \Sigma^c_{1,2,3} \to \xi_a$ $(a = 1, \ldots, 6)$

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Which is almost the lagrangian for Minimal Conformal Technicolor!

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a-Maximization

Seiberg argued SUSY QCD with $\frac{3}{2}N_c < N_f < 3N_c$ will flow to a SCFT

Strong fixed points expected for $N_f \approx 2N_c$ ($N_f \approx 4N_c$ for non-SUSY)

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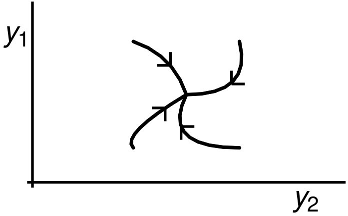
- Fix large Yukawas marginal
- Neglect other superpotential terms
- Apply a-maximization

This will try to construct the theory with Yukawa fixed points



Joint fixed point

Flavor in the UV

That Dastardly Top!

We have: $m_{top} \sim 4\pi v_{ew} \left(\frac{y_{TC}}{4\pi}\right)\left(\frac{y_t}{4\pi}\right)\left(\frac{\Lambda_{TC}}{M_{flavor}}\right)^{d-1}$

$$\Rightarrow \left(\frac{y_{TC}}{4\pi}\right)\left(\frac{y_t}{4\pi}\right)\left(\frac{\Lambda_{TC}}{M_{flavor}}\right)^{d-1} \sim \frac{1}{10}$$

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In SM, $N_c = 3$ and $N_f = 6 \Rightarrow$ No room for fields to do breaking

Two options: $N_c > 3$ or split the quark flavors!

Flavor with $N_c > 3$

Field Content of the Flavor Sector

$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

$$\begin{aligned}
\Phi &\sim (6, \bar{3}, 1, 1)_0 \\
\Phi^c &\sim (\bar{6}, 3, 1, 1)_0 \\
\Delta &\sim (6, 1, \bar{3}, 1)_0 \\
\Delta^c &\sim (\bar{6}, 1, 3, 1)_0 \\
Q_i &\sim (6, 1, 1, 2)_{1/6} \\
U_i^c &\sim (\bar{6}, 1, 1, 1)_{-2/3} \\
D_i^c &\sim (\bar{6}, 1, 1, 1)_{1/3} \\
\tilde{q}_i &\sim (1, 1, \bar{3}, 2)_{-1/6} \\
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\tilde{d}_i^c &\sim (1, 1, 3, 1)_{-1/3}
\end{aligned}$$

$$\begin{aligned}
W &\ni y^u_{ij} Q_i H_u U^c_j + y^d_{ij} Q_i H_d D^c_j \\
&+ x^u_{ij} \tilde{q}_i H_d \tilde{u}^c_j + x^d_{ij} \tilde{q}_i H_u \tilde{d}^c_j \\
&+ z^Q_{ij} Q_i \Delta^c \tilde{q}_j + z^u_{ij} U_i \Delta \tilde{u}_j + z^Q_{ij} D_i \Delta \tilde{d}_j
\end{aligned}$$

$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

These fields get VEVs:

$$\langle \Phi \rangle = \langle \Phi^c \rangle \propto \begin{pmatrix} \mathbf{1}_3 \\ \mathbf{0}_3 \end{pmatrix}$$

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Flavor with $N_c > 3$

Field Content of the Flavor Sector

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These break:

$$SU(6)_{SC} \times SU(3)_A \times SU(3)_B \rightarrow SU(3)_C \times SU(3)_{C'}$$

$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

These fields contain the SM quarks

$$\begin{aligned}
\Phi &\sim \left(6, \bar{3}, 1, 1\right)_0 \\
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\end{aligned}$$

These fields contain the SM quarks

They will be separated into:
$Q_i^{(1,\ldots,6)} \to Q_i^{(1,2,3)} + Q_i^{(4,5,6)} \equiv q_i + q_i'$

q_i are the SM quarks

$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

q'_i partners with the $\tilde{q}_i$ fields to create new quarks at a higher scale through interactions of the form:

$$W \ni z^Q_{ij} Q_i \Delta^c \tilde{q}_j$$

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Flavor with $N_c > 3$

Field Content of the Flavor Sector

$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

q'_i partners with the $\tilde{q}_i$ fields to create new quarks at a higher scale through interactions of the form:

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There are twelve new quarks under $SU(3)_{C'}$

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$$(SU(6)_{SC} \times SU(3)_A \times SU(3)_B \times SU(2)_L)_{U(1)_Y}$$

$$\begin{aligned} W \ni \; & y^u_{ij} Q_i H_u U^c_j + y^d_{ij} Q_i H_d D^c_j \\ + \; & x^u_{ij} \tilde{q}_i H_d \tilde{u}^c_j + x^d_{ij} \tilde{q}_i H_u \tilde{d}^c_j \\ + \; & z^Q_{ij} Q_i \Delta^c \tilde{q}_j + z^u_{ij} U_i \Delta \tilde{u}_j + z^Q_{ij} D_i \Delta \tilde{d}_j \end{aligned}$$

These give mass to the SM fermions through H communicating with the technisector

$$\begin{aligned} \Phi &\sim (6, \bar{3}, 1, 1)_0 \\ \Phi^c &\sim (\bar{6}, 3, 1, 1)_0 \\ \Delta &\sim (6, 1, \bar{3}, 1)_0 \\ \Delta^c &\sim (\bar{6}, 1, 3, 1)_0 \\ Q_i &\sim (6, 1, 1, 2)_{1/6} \\ U^c_i &\sim (\bar{6}, 1, 1, 1)_{-2/3} \\ D^c_i &\sim (\bar{6}, 1, 1, 1)_{1/3} \\ \tilde{q}_i &\sim (1, 1, \bar{3}, 2)_{-1/6} \\ \tilde{u}^c_i &\sim (1, 1, 3, 1)_{2/3} \\ \tilde{d}^c_i &\sim (1, 1, 3, 1)_{-1/3} \end{aligned}$$

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$$\begin{aligned} W &\ni y^u_{ij} Q_i H_u U^c_j + y^d_{ij} Q_i H_d D^c_j \\ &+ x^u_{ij} \tilde{q}_i H_d \tilde{u}^c_j + x^d_{ij} \tilde{q}_i H_u \tilde{d}^c_j \\ &+ z^Q_{ij} Q_i \Delta^c \tilde{q}_j + z^u_{ij} U_i \Delta \tilde{u}_j + z^Q_{ij} D_i \Delta \tilde{d}_j \end{aligned}$$

$$\begin{aligned} \Phi &\sim (6, \bar{3}, 1, 1)_0 \\ \Phi^c &\sim (\bar{6}, 3, 1, 1)_0 \\ \Delta &\sim (6, 1, \bar{3}, 1)_0 \\ \Delta^c &\sim (\bar{6}, 1, 3, 1)_0 \\ Q_i &\sim (6, 1, 1, 2)_{1/6} \\ U^c_i &\sim (\bar{6}, 1, 1, 1)_{-2/3} \\ D^c_i &\sim (\bar{6}, 1, 1, 1)_{1/3} \\ \tilde{q}_i &\sim (1, 1, \bar{3}, 2)_{-1/6} \\ \tilde{u}^c_i &\sim (1, 1, 3, 1)_{2/3} \\ \tilde{d}^c_i &\sim (1, 1, 3, 1)_{-1/3} \end{aligned}$$

These give mass to the SM fermions through H communicating with the technisector

The give an $\mathcal{O}(M_{SUSY})$ mass to the 12 $SU(3)_{C'}$ quarks

Flavor

looks

disastrous!

+

Suppressing Flavor Violation

Flavor

looks

disastrous!

$+$

Set $M^X_{ij} \equiv z^X_{ij}\,\langle\Delta\rangle$

and $\tilde{m}^X_{ij} \equiv x^X_{ij}\,v$

$$
\begin{array}{c} \\ u'_1 \\ u'_2 \\ u'_3 \\ \tilde{u}^c_1 \\ \tilde{u}^c_2 \\ \tilde{u}^c_3 \end{array}
\begin{array}{c}
\begin{array}{cccccc} u'^c_1 & u'^c_2 & u'^c_3 & \tilde{u}_1 & \tilde{u}_2 & \tilde{u}_3 \end{array} \\
\left(\begin{array}{ccc|ccc}
m_u & 0 & 0 & M^Q_{11} & M^Q_{21} & M^Q_{31} \\
0 & m_c & 0 & M^Q_{12} & M^Q_{22} & M^Q_{32} \\
0 & 0 & m_t & M^Q_{13} & M^Q_{23} & M^Q_{33} \\
\hline
M^U_{11} & M^U_{21} & M^U_{31} & \tilde{m}^U_{11} & \tilde{m}^U_{21} & \tilde{m}^U_{31} \\
M^U_{12} & M^U_{22} & M^U_{32} & \tilde{m}^U_{12} & \tilde{m}^U_{22} & \tilde{m}^U_{32} \\
M^U_{13} & M^U_{23} & M^U_{33} & \tilde{m}^U_{13} & \tilde{m}^U_{23} & \tilde{m}^U_{33}
\end{array}\right)
\end{array}
$$

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\end{array}\right)
\end{array}
$$

Set $M^X_{ij} \equiv z^X_{ij} \langle \Delta \rangle$
and $\tilde{m}^X_{ij} \equiv x^X_{ij} v$

Since $M \gg m, \tilde{m}$, to suppress FCNCs we need $M^X_{ij} = M^X \delta_{ij}$

Supersymmetric Conformal Technicolor with Topcolor

The Audience: Okay, now you are just messing with us...

$$\left(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\right)_{U(1)_Y}$$

$$
\begin{aligned}
W &\ni y_t H_u q_3 t^c + y_b H_d q_3 b^c \\
&+ (y_u)_{ij} H_u q_i u^c_j + (y_d)_{ij} H_d q_i d^c_j \\
&+ z_t \Phi t^c U + z_t \Phi b^c D \\
&+ (z_u)_i q_i H_u U^c + (z_d)_i q_i H_d D^c \\
&+ \mu_u U U^c + \mu_d D D^c
\end{aligned}
$$

$$
\begin{aligned}
\Phi &\sim \left(3, \bar{3}, 1\right)_0 \\
\Phi^c &\sim \left(\bar{3}, 3, 1\right)_0 \\
q_3 &\sim (3, 1, 2)_{1/6} \\
t^c &\sim \left(\bar{3}, 1, 1\right)_{-2/3} \\
b^c &\sim \left(\bar{3}, 1, 1\right)_{1/3} \\
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D^c &\sim \left(1, \bar{3}, 1\right)_{1/3}
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These fields get VEVs $\mathcal{O}\left(M_{SUSY}\right)$:

$$\langle\Phi\rangle = \langle\Phi^c\rangle \propto \mathbf{1}_3$$

$$\begin{aligned}
\Phi &\sim (3, \bar{3}, 1)_0 \\
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q_3 &\sim (3, 1, 2)_{1/6} \\
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q_i &\sim (1, 3, 2)_{1/6} \\
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d_i^c &\sim (1, \bar{3}, 1)_{1/3} \\
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Supersymmetric Conformal Technicolor with Topcolor

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$$\left(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\right)_{U(1)_Y}$$

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\Phi & \sim & (3, \bar{3}, 1)_0 \\
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q_3 & \sim & (3, 1, 2)_{1/6} \\
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u_i^c & \sim & (1, \bar{3}, 1)_{-2/3} \\
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U^c & \sim & (1, \bar{3}, 1)_{-2/3} \\
D & \sim & (1, 3, 1)_{-1/3} \\
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\end{array}$$

These fields get VEVs $\mathcal{O}\left(M_{SUSY}\right)$:

$$\langle \Phi \rangle = \langle \Phi^c \rangle \propto \mathbf{1}_3$$

Which break $SU(3)_{tC} \times SU(3)_{\bar{C}} \rightarrow SU(3)_C$

Supersymmetric Conformal Technicolor with Topcolor

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$$\big(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\big)_{U(1)_Y}$$

These are the third generation quarks charged under topcolor

$$
\begin{aligned}
\Phi &\sim (3, \bar{3}, 1)_0 \\
\Phi^c &\sim (\bar{3}, 3, 1)_0 \\
q_3 &\sim (3, 1, 2)_{1/6} \\
t^c &\sim (\bar{3}, 1, 1)_{-2/3} \\
b^c &\sim (\bar{3}, 1, 1)_{1/3} \\
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\end{aligned}
$$

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$$\left(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\right)_{U(1)_Y}$$

These are the first two generations of quarks ($i = 1, 2$)

$$\begin{aligned}
\Phi &\sim \left(3, \bar{3}, 1\right)_0 \\
\Phi^c &\sim \left(\bar{3}, 3, 1\right)_0 \\
q_3 &\sim (3, 1, 2)_{1/6} \\
t^c &\sim \left(\bar{3}, 1, 1\right)_{-2/3} \\
b^c &\sim \left(\bar{3}, 1, 1\right)_{1/3} \\
q_i &\sim (1, 3, 2)_{1/6} \\
u_i^c &\sim \left(1, \bar{3}, 1\right)_{-2/3} \\
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U &\sim (1, 3, 1)_{2/3} \\
U^c &\sim \left(1, \bar{3}, 1\right)_{-2/3} \\
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Supersymmetric Conformal Technicolor with Topcolor

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$$\left(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\right)_{U(1)_Y}$$

These are new high scale quarks

$$\begin{aligned}
\Phi &\sim \left(3, \bar{3}, 1\right)_0 \\
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q_3 &\sim (3, 1, 2)_{1/6} \\
t^c &\sim \left(\bar{3}, 1, 1\right)_{-2/3} \\
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D^c &\sim \left(1, \bar{3}, 1\right)_{1/3}
\end{aligned}$$

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$$\left(SU(3)_{tC} \times SU(3)_{\bar{C}} \times SU(2)_L\right)_{U(1)_Y}$$

These are new high scale quarks

They have dirac masses of $\mathcal{O}\left(M_{SUSY}\right)$

$$\begin{aligned}
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These are new high scale quarks

They have dirac masses of $\mathcal{O}\left(M_{SUSY}\right)$

Through interactions with t^c and b^c, they communicate mixing between the 3rd and first two generations of quarks

$$\begin{aligned}
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$$\begin{aligned} W \ni \;& y_t H_u q_3 t^c + y_b H_d q_3 b^c \\ +\;& (y_u)_{ij} H_u q_i u^c_j + (y_d)_{ij} H_d q_i d^c_j \\ +\;& z_t \Phi t^c U + z_t \Phi b^c D \\ +\;& (z_u)_i q_i H_u U^c + (z_d)_i q_i H_d D^c \\ +\;& \mu_u U U^c + \mu_d D D^c \end{aligned}$$

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&+ (z_u)_i q_i H_u U^c + (z_d)_i q_i H_d D^c \\
&+ \mu_u U U^c + \mu_d D D^c
\end{aligned}$$

after VEVs this reduces to:

$$\begin{aligned}
\mathcal{L} &\ni (m_u)_{ij} u_i u^c_j + m_t t t^c + (\delta_u)_i u_i U^c \\
&+ \Delta_u t^c U + \mu_u U U^c + \text{down-type terms}
\end{aligned}$$

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\end{aligned}$$

We have then a mass matrix of:

$$M_u = \begin{pmatrix} u \\ t \\ U \end{pmatrix}^T \begin{pmatrix} m_u & 0 & \delta_u \\ 0 & m_t & 0 \\ 0 & \Delta_u & \mu_u \end{pmatrix} \begin{pmatrix} u^c \\ t^c \\ U^c \end{pmatrix}$$

Flavor in SCTC w/ tC

or Supersymmetric Walking/Conformal Topcolor-assisted Technicolor

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Diagonalization of $M_u^\dagger M_u$ and $M_d^\dagger M_d$ can give the correct CKM matrix elements for very reasonable parameter choices

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Still, the strongly interacting tC gluon exchange puts the SUSY scale bound into the 10s of TeV range

Finding MCTC at the LHC

Detection of this model at the LHC is difficult, but not impossible!

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We will have light $SU(2)_{CTC}$ gauginos, our global symmetry structure is

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- For good S-parameter, it needs to be light (120 GeV)
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η is a new state which is also very weakly coupled to the SM

- Similar story to a, but much lighter ... but unfortunately

This is most likely physics for the 14 TeV LHC

Conclusion

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Conclusion

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- Both are natural, UV-complete models for conformal technicolor
- These models are partially intended as “existence proofs”
- Recent developments from both theory and lattice support CTC, the superconformal symmetry is essential to the model
- This is a relatively young idea with much need for model building
- The phenomenology needs to be developed more thoroughly, but there is definitely interesting new physics there
- Much more work is in progress

The Thank You Slide

Thank you!