Novel Technicolor Theories:

Dark Matter and Unification

Francesco Sannino

Napoli, February 2007

MARIE CURIE ACTIONS

UNIVERSITY OF SOUTHERN DENMARK

Electroweak Symmetry Breaking

SUSY

Technicolor

Extra Dim.

Curved

Flat

Technicolor

New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

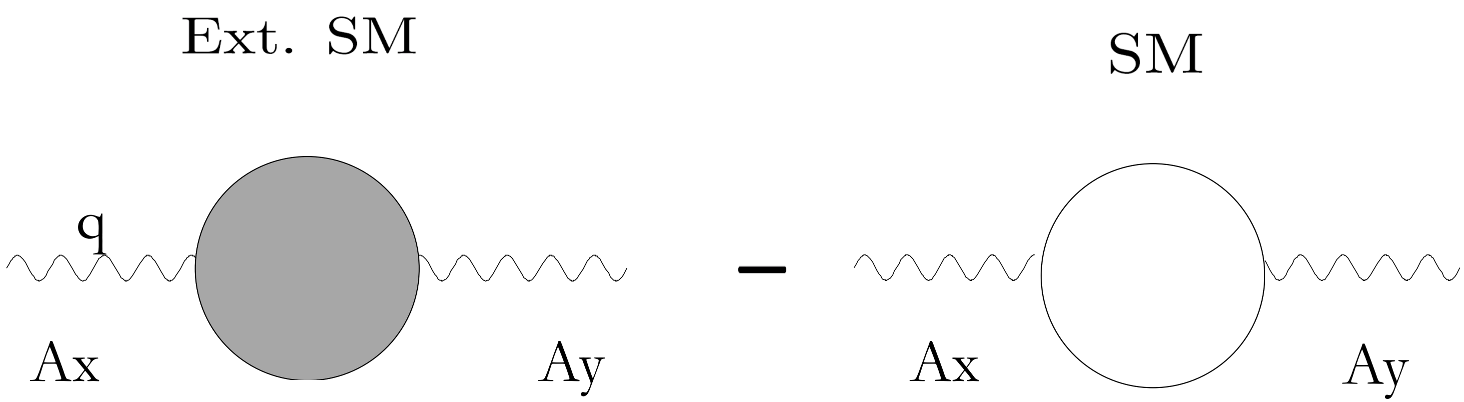
$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 250\ GeV$$

Problems with the Old Models

- At odds with Precision Measurements
- Large Flavor Changing Neutral Currents (FCNC)
- Limited knowledge of strong dynamics!

Electroweak Precision Measurements

Kennedy,Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Bertolini- Sirlin, Marciano-Rosner,..:



$$\Pi^{\mu\nu}_{XY}(q^2) = \Pi_{XY}(q^2) g^{\mu\nu} + \cdots$$

S - T

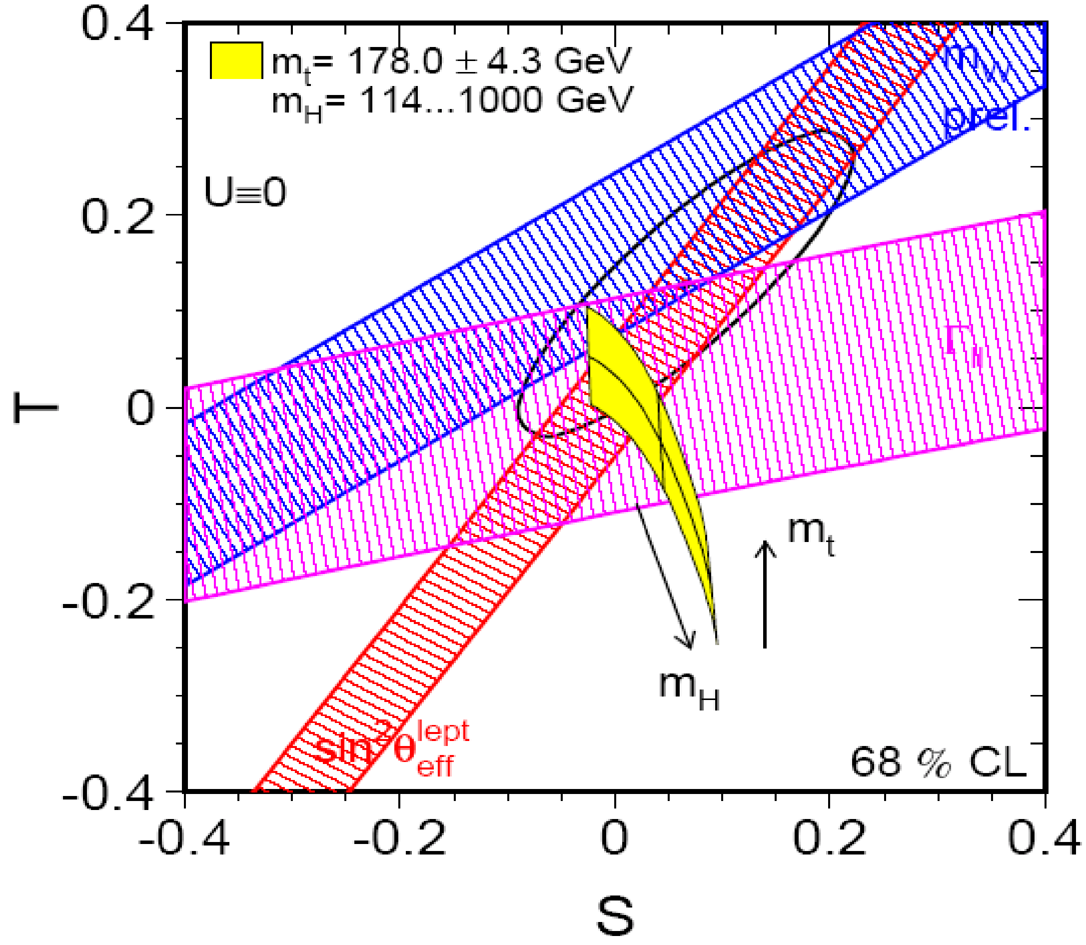
S-measures the left - right type current correlator

$$S = -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2}$$

T-measures deviations from $M_W^2 = \sin^2\theta_w M_Z^2$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}$$

Present Data



m_H=150 GeV

hep-ex/0509008

Now: S = 0.07±0.10

Large & Positive S from QCD-like TC

Peskin and Takeuchi, '90

Fermion masses versus FCNC

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \ldots$$

PNG Masses

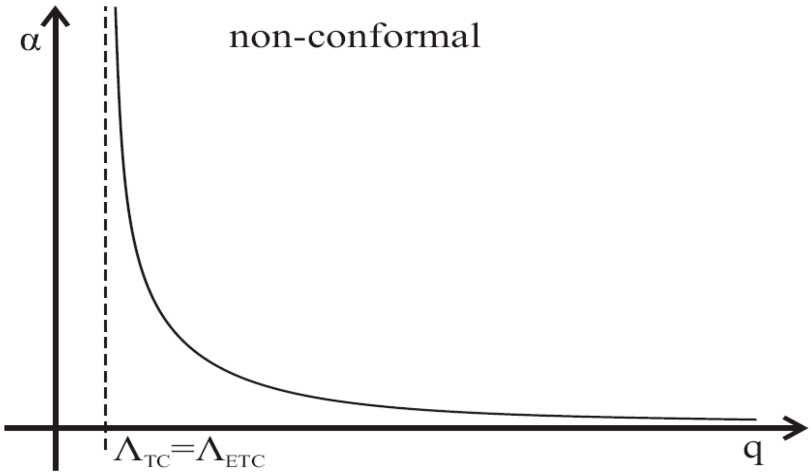
SM-Fermion Masses

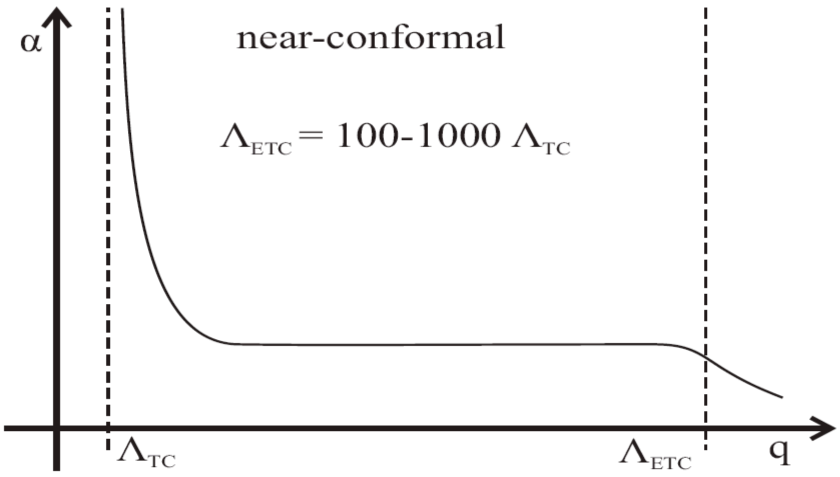
FCNC Operators

Λ_{ETC} should be sufficiently larger than $\Lambda_{TC} \approx 250 GeV$

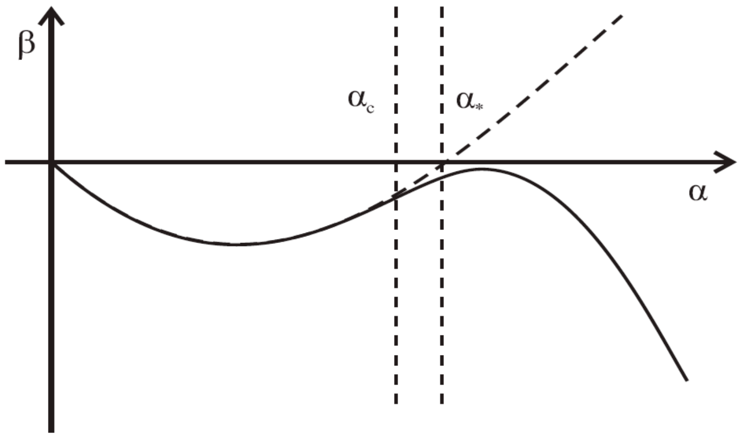
to reduce FCNC.

Near Conformal Properties





Holdom,
Appelquist,Miransky, Yamawaki
Cohen and Georg, Frere...



Why the walking can help ?

$$\langle \bar{Q}Q_{ETC} \rangle = \exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \langle \bar{Q}Q_{TC} \rangle$$

<u>QCD-Like</u>

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \quad \sim \quad (\ln(\Lambda_{ETC}/\Lambda_{TC}))^{\gamma_m}$$

<u>Near the conformal window</u>

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu)) \right) \quad \sim \quad (\Lambda_{ETC}/\Lambda_{TC})^{\gamma_m(\alpha^\star)}$$

S in (Walking) Technicolor

Perturbative Estimate

$$S_{\rm pert} = \frac{1}{6\pi}\frac{N_f}{2}d(R)$$

Non Walking:

$$S_{TC} > S_{\rm pert}$$

Walking:

$$S_{WTC} \leq S_{\rm pert}$$

Sundrum - Hsu 96
Appelquist - F.S. 98

EW Viable Walking Technicolor Models

Minimal Walking Technicolor (MWT)

Higher Dimensional Representations

F.S. & Tuominen 04
Dietrich, F.S., Tuominen 06

Beyond Minimal Walking Technicolor

Partially EW Gauged Technicolor

Split Technicolor

Dietrich, F.S.Tuominen 05
Dietrich, F.S. 06

Additional Fermions in SM

Gudnason, Ryttov, F.S. 06

Progress in Strong Interactions

Phase Diagram of Higher Dimensional Representations.

New Limits for Strongly Interacting Theories

Link between the Confinement and Chiral Symmetry - Phase transitions (Mocsy, F.S., Tuominen)

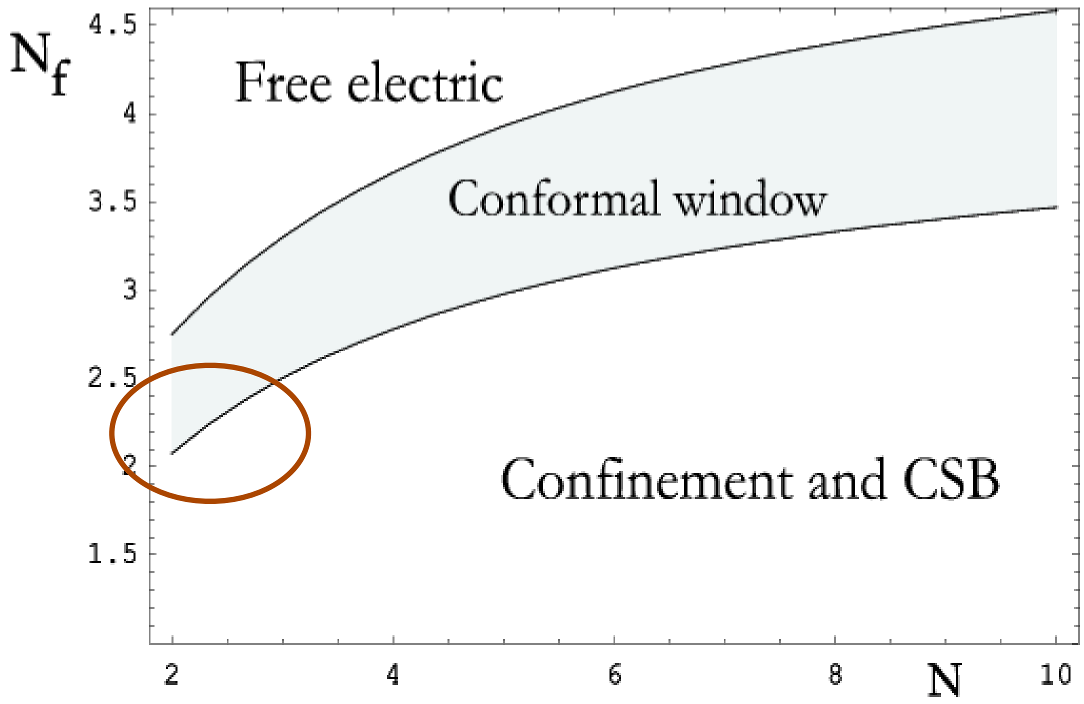
The Model: The Symmetric-Theory

	$SU(N)$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	$U_A(1)$
$Q_{\{ij\}}$	$\square\square$	$\square$	1	1	1
$\widetilde{Q}^{\{ij\}}$	$\overline{\square\square}$	1	$\overline{\square}$	-1	1
G_μ	Adj	0	0	0	0

Here Q and $\widetilde{Q}$ are Weyl fermions.

The A-type is obtained by substituting $\square\square$ with $\begin{smallmatrix}\square\\ \square\end{smallmatrix}$.

Phase Diagram for the Symmetric-Theory

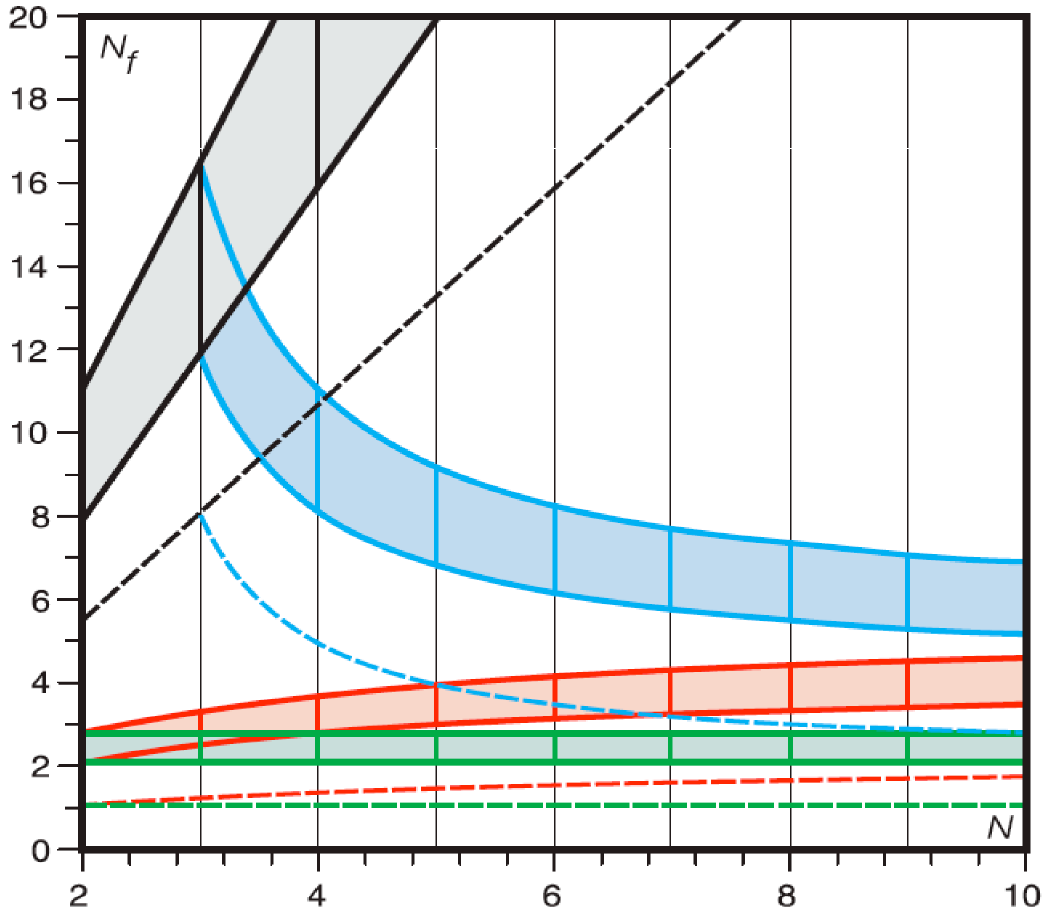


Phase diagram as function of N_f and N. [Sannino-Tuominen]

For N=2,3,4,5 we have that $N_f = 2$

Is it the minimal walking theory?

Universal Phase Diagram for HDRs

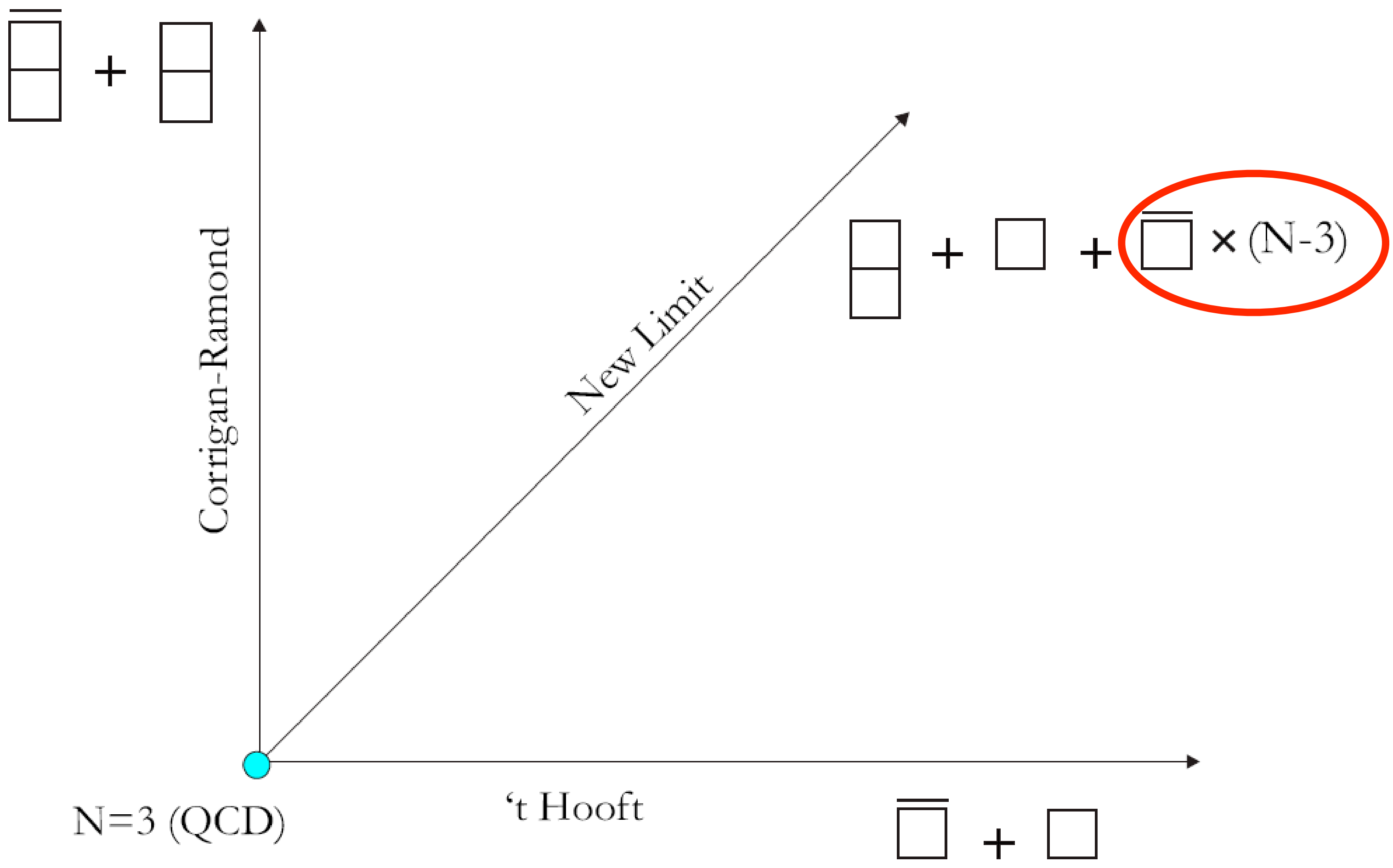


Dietrich-F.S. hep-ph/0611341

Phase diagram for theories with fermions in the Fundamental (Black-gray), 2A (Blue-light blue), 2S (Red-pink), Adjoint (Green - light green).

For N=4, 6 and 8 also the 3-index antisymmetric has a nontrivial phase diagram.

3 Large N Limits



Ryttov and F.S. th/0509130

Minimal Walking Technicolor

Near conformal for, $N_f \sim 2$

Small FCNC + Top mass

OK with precision data.

Light Composite Higgs

Dark Matter

Unification

Nf=2 & N=2: Minimal-Walking/Working-Theory

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \qquad U_R^a, \qquad D_R^a \qquad a = 1,2,3$$

$$Y(Q_L) = \frac{y}{2} \qquad\qquad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2} \right)$$

$$\mathcal{L}_L = \begin{pmatrix} N \\ E \end{pmatrix}_L \qquad N_R \qquad E_R$$

$$Y(\mathcal{L}_L) = -\,3\frac{y}{2} \qquad\qquad Y(N_R, E_R) = \left(\frac{-3y+1}{2}, \frac{-3y-1}{2} \right)$$

$\mathcal{N} = 4$ super Yang-Mills

S-parameter

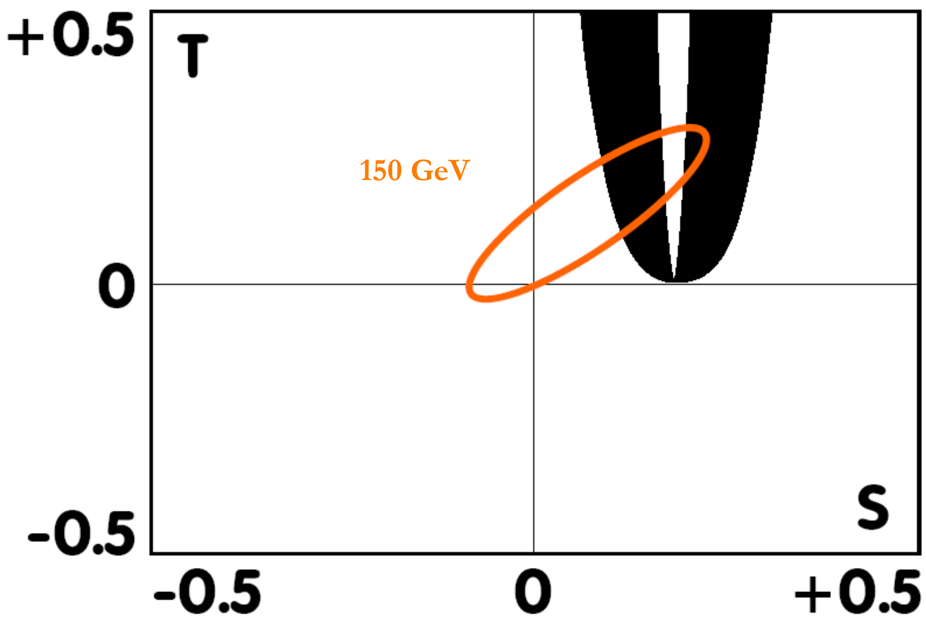
$$S = \left(\frac{1}{6\pi} - \delta\right) \frac{N(N+1)}{2} \cdot \frac{N_f}{2}$$

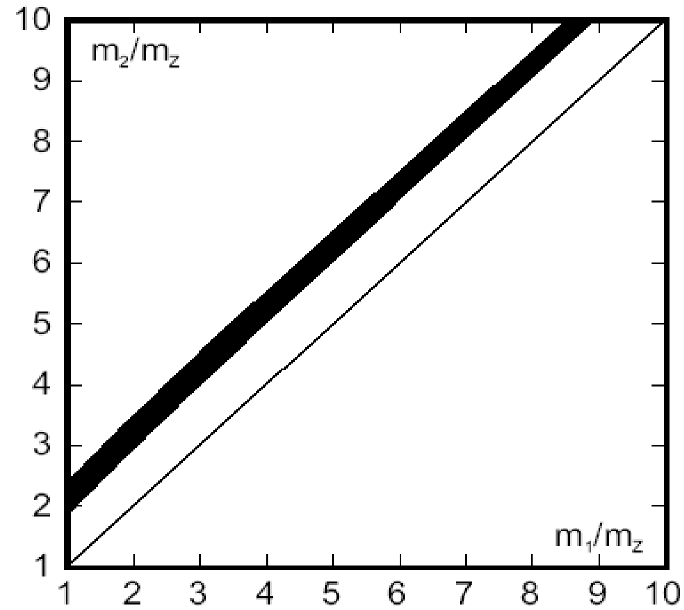
- $\delta \sim 0.013$ due to near conformal dynamics [Sundrum-Hsu, Appelquist-Sannino].

$$S(N=2, N_f=2) \simeq 0.1$$

- The estimate for **S** in the S-type model is:

Model versus EWPData





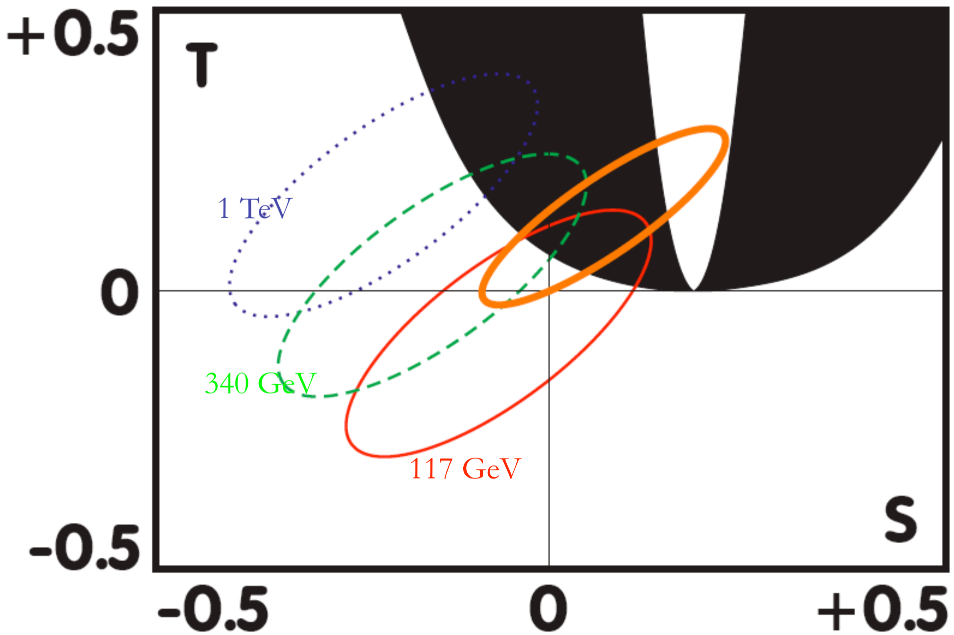
68% contour

4th Lepton Family

Electron (m2) and Neutrino (m1) Dirac masses.

Standard Hypercharge Assignment

Exotic Hypercharge Assignment



Non Standard Hypercharge Assignment.

The new Electron now is doubly electrically charged, while the would be neutrino is singly charged.

Spectrum and Effective Theory

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix},$$

$$\langle Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} \rangle = -2 \langle \overline{U}_R U_L + \overline{D}_R D_L \rangle \ ,$$

Gudnason, Kouvaris & F.S. 06

$$E = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

Goldstone-Spectrum

Techni-Mesons

$$\overline{D}_R U_L \;, \qquad \overline{U}_R D_L \;, \qquad \frac{1}{\sqrt{2}}(\overline{U}_R U_L - \overline{D}_R D_L)$$

Techni-Baryons

Electric Charge

$$U_L U_L \;, \quad D_L D_L \;, \quad U_L D_L \;, \qquad y+1 \;, \quad y-1 \;, \quad y \;,$$

The Low Energy Effective Theory

$$U = \exp\left(i\frac{\Pi^a X^a}{F}\right) E \ ,$$

$$L = \frac{F^2}{2}\mathrm{Tr}\left[D_\mu U D^\mu U^\dagger\right] - \frac{1}{2}\Pi_a (M^2_{\mathrm{ETC}})^{ab}\Pi_b$$

$$D_\mu U = \partial_\mu U - i\,g\left[G_\mu U + U G_\mu^T\right]$$

$$G_\mu = \begin{pmatrix} W_\mu & 0 \\ 0 & -\frac{g'}{g}B_\mu^T \end{pmatrix} + \frac{y}{2}\frac{g'}{g}B_\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Spectrum of Heavy States via QCD

Using ‘t Hooft Large N and Unitarity in Pion-Pion Scattering in QCD

Vector Meson is a quark-antiquark state: $\rho(770)$

Broad Sigma of multiquark nature $f_0(600)$

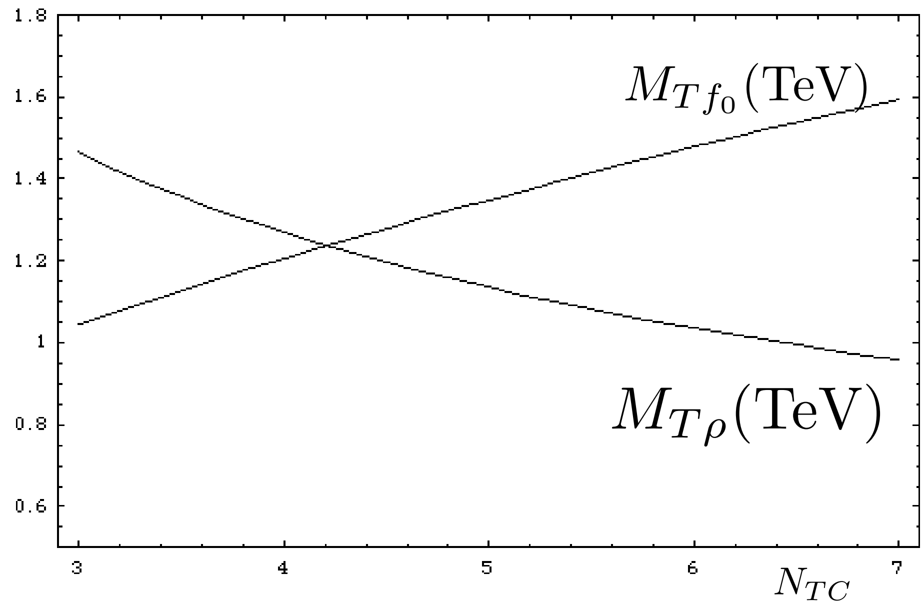
F.S. & Schechter, 95
Harada, F.S. and Schechter, 03
F.S. and Schechter, 07

Higgsless: QCD-like TC Spectrum via QCD

$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi}\frac{\sqrt{3}}{\sqrt{N_D N_{TC}}}m_\rho \qquad v_0 \sim 250\text{GeV}$$

$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi\sqrt{N_D}}\left(\frac{N_{TC}}{\sqrt{3}}\right)^{\frac{p-1}{2}} m_{f_0} \qquad p > 0$$

$N_D = 2$



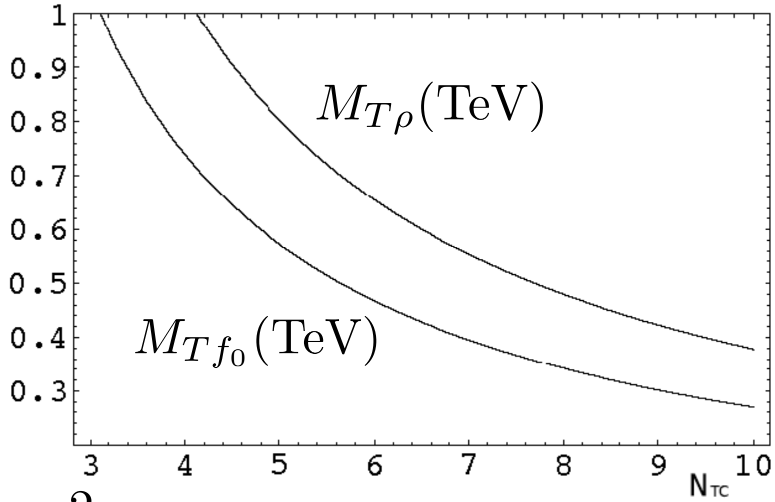
Light Higgs in Two Index Theories

$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi}\frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D\, N_{TC}(N_{TC}\mp 1)}}m_\rho$$

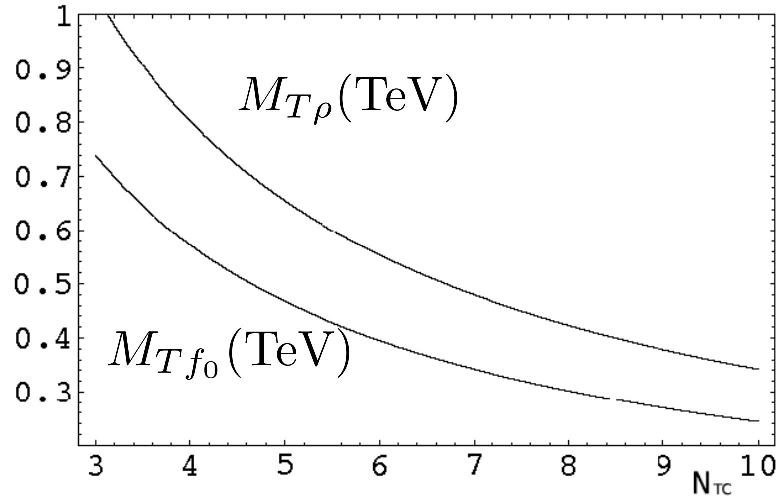
$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi}\frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D\, N_{TC}(N_{TC}\mp 1)}}m_{f_0}$$

F.S. 07

Antisymmetric



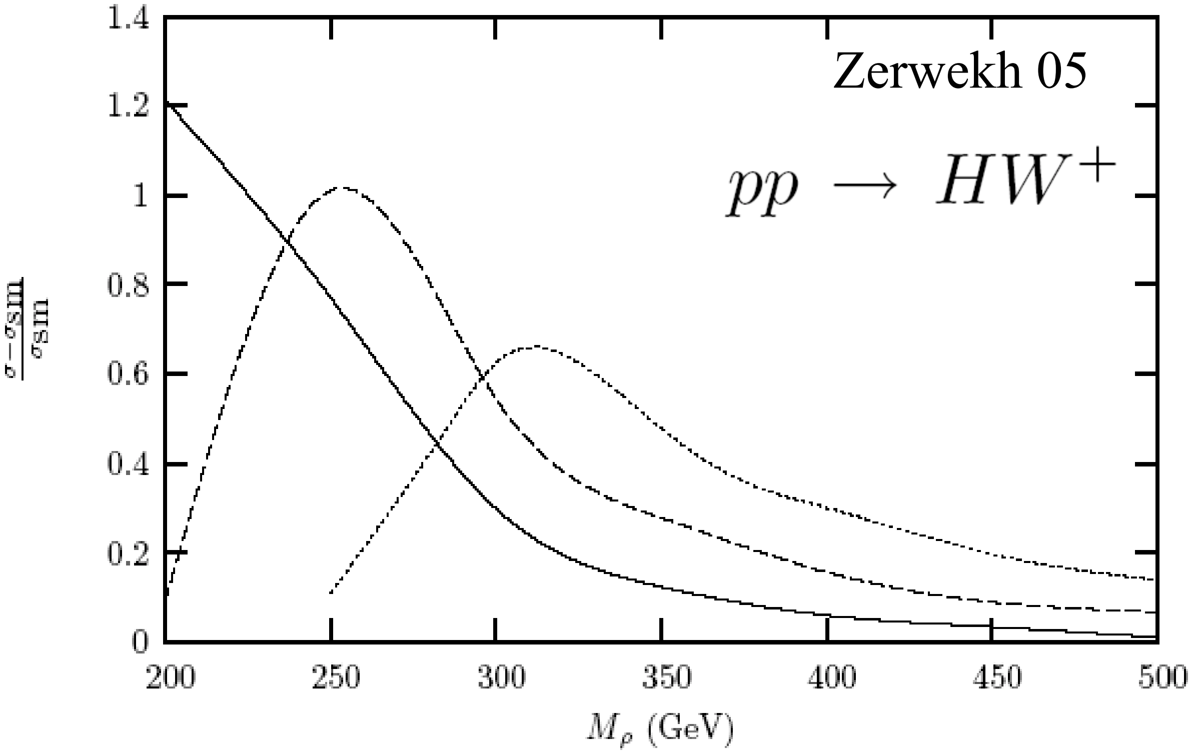
Symmetric



$N_D = 2$

One Light Composite Higgs Signature:

Large Production at Tevatron and CERN



M_H = 115 GeV (solid line), 150 GeV (dashed line) and 200 GeV (dotted line)

Technibaryon as DM

Nussinov,
Barr, Chivukula and Farhi
Gudnason, Kouvaris, F.S.

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \ ,$$

m_{TB} is the mass of the LTB

For TeV scale Technibarions the previous ratio is of Order 1!

Universe Electric Neutrality

Chemical Equilibrium

Sphaleron Processes

Dark Matter in MWT

a) Technibaryon, DD is neutral for y=1

Gudnason, Kouvaris, F.S. ph/0608055

b) Neutrino for y=1/3.

Kainulainen, Tuominen, Virkajärvi. ph/0612247

c) Dark Majorana

Kouvaris ph/0703266

1st Order

$$-\frac{TB}{B} = \sigma_{DD} \frac{22 + \sigma_{\nu'}}{9(22 + 2\sigma_{DD} + \sigma_{\nu'})} \left[3 + \frac{L}{B} + \frac{1}{\sigma_{\nu'}} \frac{L'}{B} \right]$$

$$\sigma_i = \begin{cases} 6\mathscr{F}\left(\frac{m_i}{T^*}\right) & \text{for fermions ,} \\ 6\mathscr{G}\left(\frac{m_i}{T^*}\right) & \text{for bosons ,} \end{cases}$$

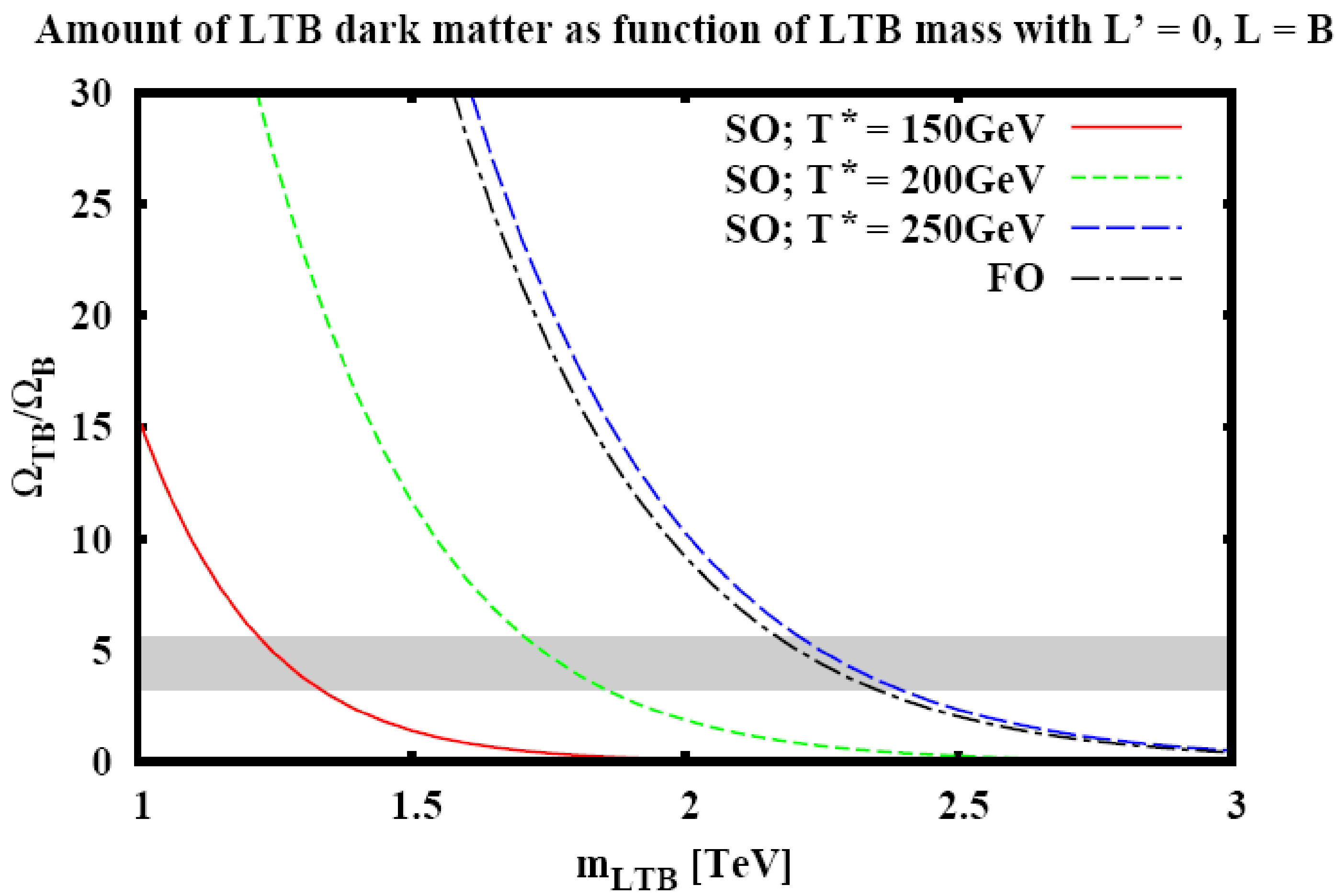
$$\mathscr{F}(z) = \frac{1}{4\pi^2} \int_0^\infty dx\, x^2 \cosh^{-2}\left(\frac{1}{2} \sqrt{x^2 + z^2} \right)$$

$$\mathscr{G}(z) = \frac{1}{4\pi^2} \int_0^\infty dx\, x^2 \sinh^{-2}\left(\frac{1}{2} \sqrt{x^2 + z^2} \right)$$

2nd Order

$$-\frac{TB}{B} = \frac{\sigma_{DD}}{3(18+\sigma_{\nu'})}\left[(17+\sigma_{\nu'}) + \frac{(21+\sigma_{\nu'})}{3}\frac{L}{B} + \frac{2}{3}\frac{(9+5\sigma_{\nu'})}{\sigma_{\nu'}}\frac{L'}{B}\right]$$

Technibaryon as DM



Technibaryon, DD

Gudnason, Kouvaris and F.S. ph/0608055

Unification

Technicolor assisted Unification

Gudnason, Ryttov, F.S. ph/0612230

1 - loop running for SU(n)

$$\alpha_n^{-1}(\mu) = \alpha_n^{-1}(M_Z) - \frac{b_n}{2\pi} \ln\left(\frac{\mu}{M_Z}\right)$$

Degree of SU(3)xSU(2)xU(1) Unification

$$B_{Th} \leftarrow \frac{b_3 - b_2}{b_2 - b_1} \quad = \quad \frac{\alpha_3^{-1} - \alpha^{-1}\sin^2\theta_w}{(1+c^2)\alpha^{-1}\sin^2\theta_w - c^2\alpha^{-1}} \rightarrow B_{Exp}$$

Unification Scale

$$M_{GUT} = M_Z \exp\left[2\pi \frac{\alpha_2^{-1}(M_Z) - \alpha_1^{-1}(M_Z)}{b_2 - b_1}\right]$$

Standard Model

$$b_3 = \frac{4}{3}N_g - 11$$

$$b_2 = \frac{4}{3}N_g - \frac{22}{3} + \underbrace{\frac{1}{6}}_{\text{Higgs}}$$

$$b_1 = \frac{3}{5}\left(\frac{20}{9}N_g + \frac{1}{6}\right) = \frac{4}{3}N_g + \underbrace{\frac{1}{10}}_{\text{Higgs}}$$

$B_{\text{Th}} \sim 0.53$ $\quad$ $B_{\text{Exp}} \sim 0.72$

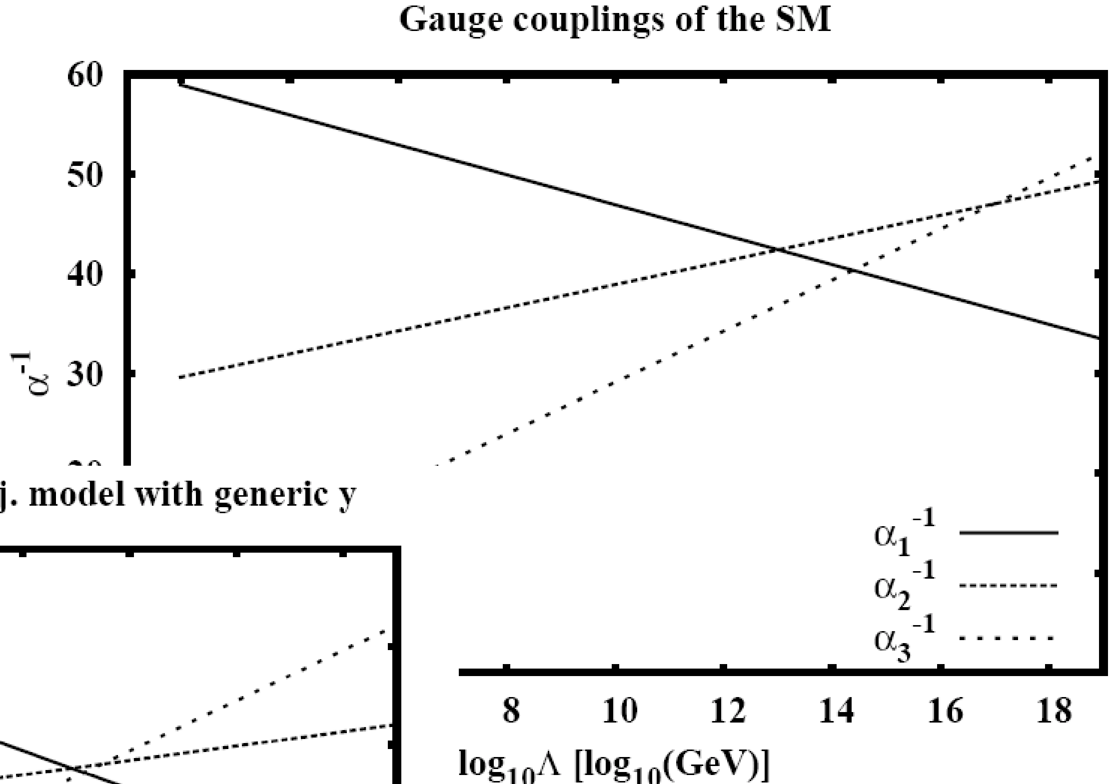
Minimal Walking Technicolor

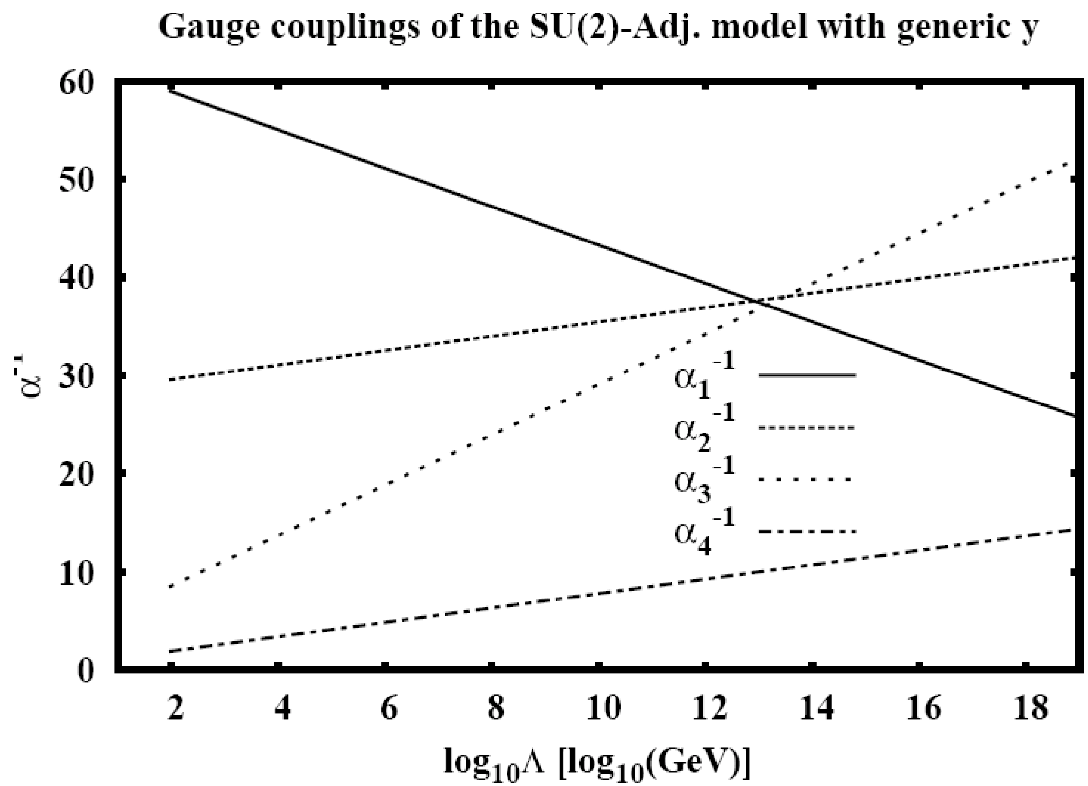
$$b_3 = \frac{4}{3}N_g - 11$$

$$b_2 = \frac{4}{3}N_g - \frac{22}{3} + \frac{2}{3}\frac{1}{2}\left(\frac{2(2+1)}{2} + 1\right) = \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3}$$

$$b_1 = \frac{3}{5}\left(\frac{20}{9}N_g + \frac{20}{9}\right) = \frac{4}{3}\left(N_g + 1\right)$$

$B_{\text{Th}} \sim 0.68$ $\quad$ $B_{\text{Exp}} \sim 0.72$


Gauge couplings of the SM
60
50
40
30
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]


Gauge couplings of the SU(2)-Adj. model with generic y
60
50
40
30
20
10
0
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_4^{-1}
2
4
6
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]

Improving on Unification

Adding New Fermions in the SM

Gudnason, Ryttov, F.S. ph/0612230

Minimal Walking Technicolor + SM Adjoint Matter

Colored Octet of Majorana Particles

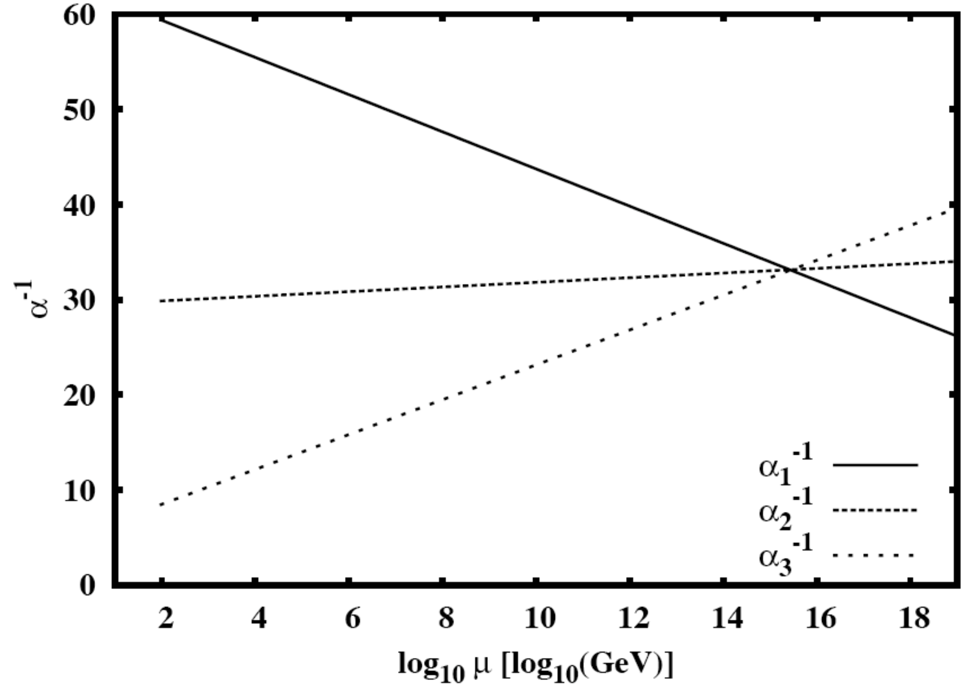
Weak Triplet of Majorana Fermions

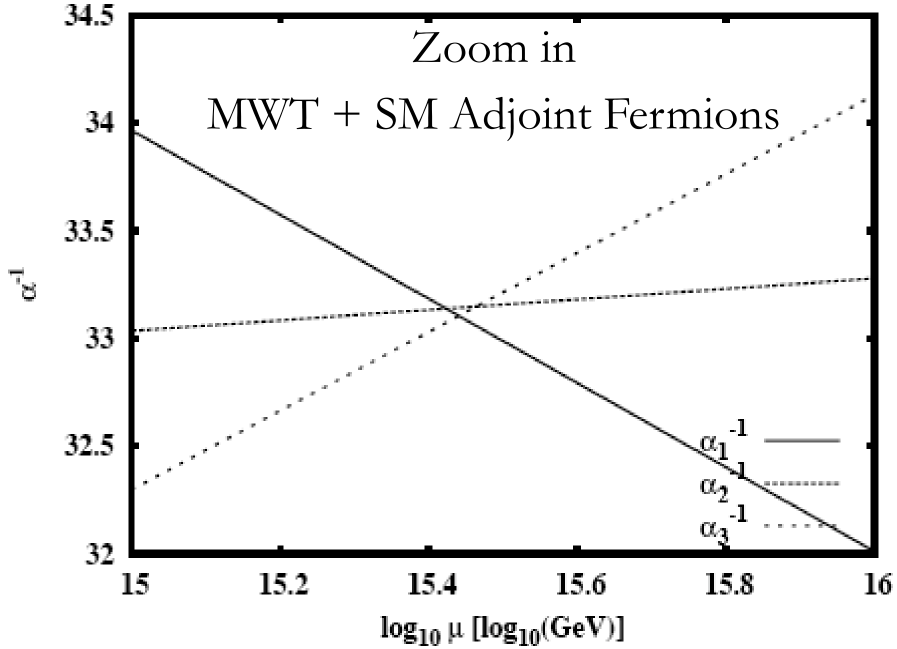
Extra SM Weyl Singlet

$$
\begin{aligned}
b_3 &= \frac{4}{3}N_g - 11 + 2 \\
b_2 &= \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3} + \frac{4}{3} \\
b_1 &= \frac{4}{3}\left(N_g + 1\right)
\end{aligned}
$$

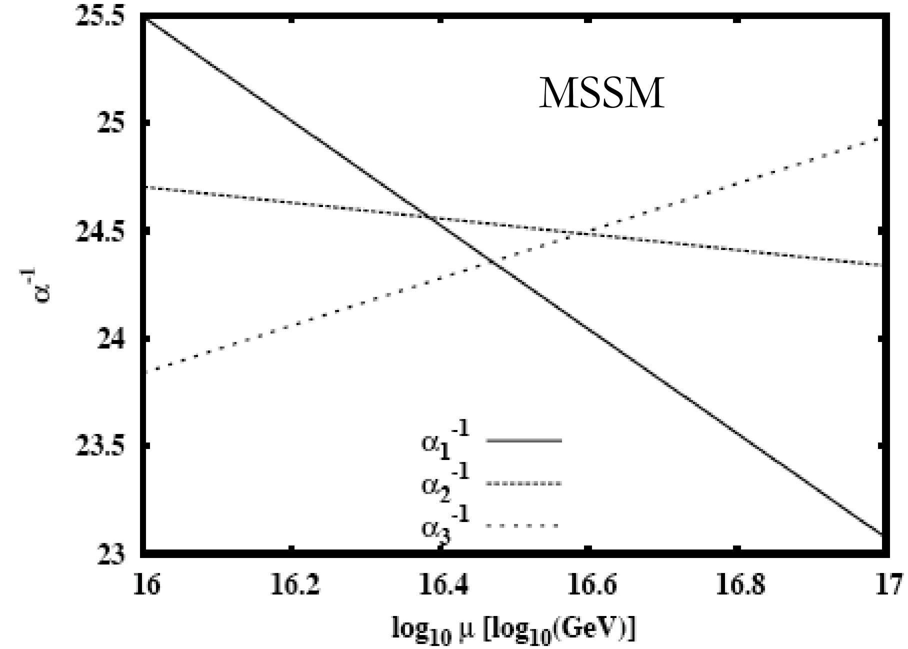
$$B_{\rm Th} = 13/18 = 0.72(2) \quad \text{versus} \quad B_{\rm Exp} \simeq 0.72$$

MWT + SM Adjoint Fermions



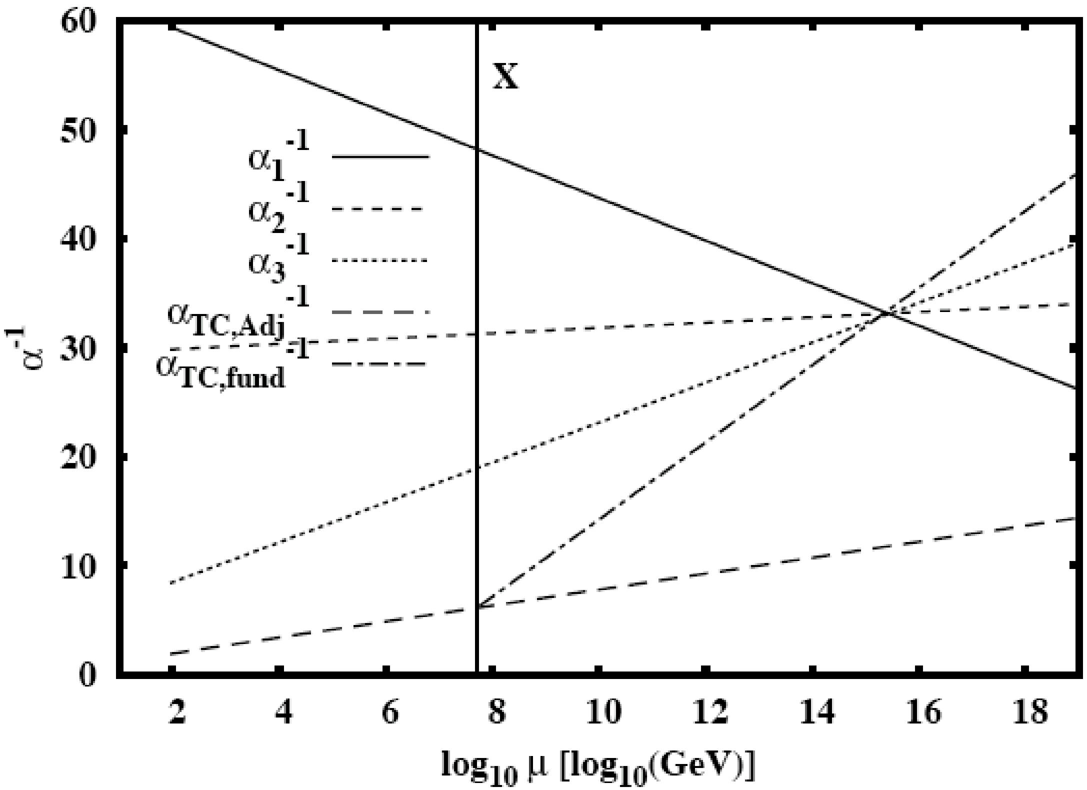


Zoom in
MWT + SM Adjoint Fermions
34.5
34
33.5
33
32.5
32
15
15.2
15.4
15.6
15.8
16
α^{-1}
$\log_{10}\mu$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}



MSSM
25.5
25
24.5
24
23.5
23
16
16.2
16.4
16.6
16.8
17
α^{-1}
$\log_{10}\mu$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}

Unifying also TC
Cartoon!



Summary

- Introduced different types of viable technicolor theories
- Phase diagram of Higher Dimensional Representations
- Presented Minimal Walking Technicolor
- Minimal Walking Technicolor + Adjoint Matter
- Dark Matter as a technibaryon
- Unification