Strong Dynamics via Supersymmetry:

QCD and Beyond

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Work in collaboration with

HEP-TH

Supersymmetry & QCD

F.S. and M. Shifman, 0309252 PRD
P. Merlatti and F.S., 0404251 PRD
A. Feo, P. Merlatti and F.S., 0408214

Supergravity & Supersymmetry

Marotta F.S., 0207163 PLB
Marotta, Pezzella,.. F.S. 0208153 JHEP

HEP-PH

Beyond Standard Model Physics

F.S, K. Tuominen, 0405209
D.K. Hong, S.D. Hsu, F.S., 0406200 PLB
S.D. Hsu and F.S., 0408319

Confinement versus χSB

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Contents

- Part I
- Why are we interested in strong dynamics ?
- New link between SYM and non supersymmetric theories.
- Understanding the QCD vacuum and spectrum via SYM.
- And… from QCD to SYM.

- Part II
- New Strong Dynamics for Electroweak Symmetry Breaking.
- Solving the S-parameter problem and FCNC at once.
- Using supersymmetry to predict a light composite Higgs.

QCD

- Confinement.
- Chiral Symmetry Breaking.
- Vacuum Properties, Spectrum and Dynamics.
- Phase Diagram: temperature, matter density, number of flavors, colors, and masses.

Beyond Standard Model

- New Strong Dynamics.
- Dynamical Electroweak Symmetry Breaking.
- Strong CP Problem.
  (New solutions using only strong dynamics, no axion, Hsu and F.S.)
- Fermion masses.

Part I: New/Old Large N and QCD

Non-Perturbative Tools

Experiments for QCD
Lattice Simulations
Symmetries & Effective Lagrangians
‘t Hooft Anomaly Matching Conditions
Large N
Large masses. Heavy Quark Symmetries
Gauge-Gravity Correspondence
Supersymmetry

`t Hooft - Large N

	$SU(N)$	$U_V(1)$	$U_A(1)$
ψ_c	$\Box$	1	1
$\widetilde{\psi}^c$	$\overline{\Box}$	-1	1
G_μ	Adj	0	0

`t Hooft - Large N

Fermions' corrections are suppressed.

Small number of flavors.

The axial anomaly is suppressed at Large N:

$$m^2_{\eta'} \sim \frac{N_f}{N_c}$$

Corrigan and Ramond `79- Large N

Larks

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{[i,j]}$	$\genfrac{}{}{0pt}{}{\square}{\square}$	1	1
$\widetilde{\psi}^{[i,j]}$	$\overline{\genfrac{}{}{0pt}{}{\square}{\square}}$	-1	1
G_μ	Adj	0	0

Corrigan and Ramond - Large N

Fermion's corrections are not suppressed.

The axial anomaly is not suppressed.

Still small number of flavors. Actually CR thought of considering some fermions in the fundamental and some in the 2-index.

CR also considered models of DESB.

Kiritsis and Papavassiliou '90 provided some large N rules for CR Large N

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{[i,j]}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	1	1
$\tilde{\psi}^{[i,j]}$	$\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	-1	1
G_μ	Adj	0	0

Relation with Super Yang-Mills

S-type

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{\{i,j\}}$	$\Box\Box$	1	1
$\tilde{\psi}^{\{i,j\}}$	$\overline{\Box\Box}$	-1	1
G_μ	Adj	0	0

A-type

	$SU(N)$	$U_V(1)$	$U_A(1)$
$\psi_{[i,j]}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	1	1
$\tilde{\psi}^{[i,j]}$	$\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	-1	1
G_μ	Adj	0	0

Armoni-Shifman-Veneziano

$\downarrow$

	$SU(N)$	$U_A(1)$
λ	Adj	1
G_μ	Adj	0

SYM

Comparing perturbative quantities

	YM
β_0	$\frac{11}{3}N$
β_1	$\frac{17}{3}N^2$
γ	

$$\mu\frac{\partial\alpha}{\partial\mu} \equiv 2\beta(\alpha) = -\frac{\beta_0}{2\pi}\alpha^2 - \frac{\beta_1}{4\pi^2}\alpha^3 + \ldots$$

$$\left(\bar{\Psi}\Psi\right)_Q = \kappa^{\gamma/\beta_0}\left(\bar{\Psi}\Psi\right)_\mu\ , \quad \kappa \equiv \frac{\alpha(\mu)}{\alpha(Q)}\ ,$$

Q and ❍ are the renormalization points.

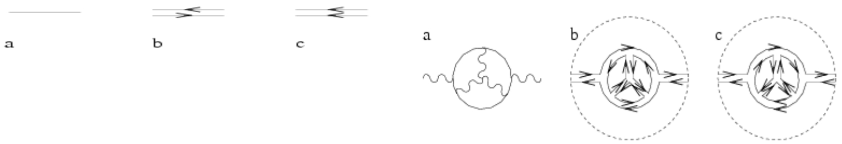
More precisely…

At N→∞ the S/A type theories are non perturbatively equivalent to SYM.

However, only the bosonic part of the infrared spectrum is expected to match SYM ones.

The correspondence has been argued on the base of large N diagrams and wilson line arguments.

Large N arguments



a) The Fermionic propagator and the vertex. A typical Planar Diagram

b) Super Yang Mills.

c) The non susy Theory

<u>Physical Applications</u>

A-type:

QCD vacuum properties and spectrum

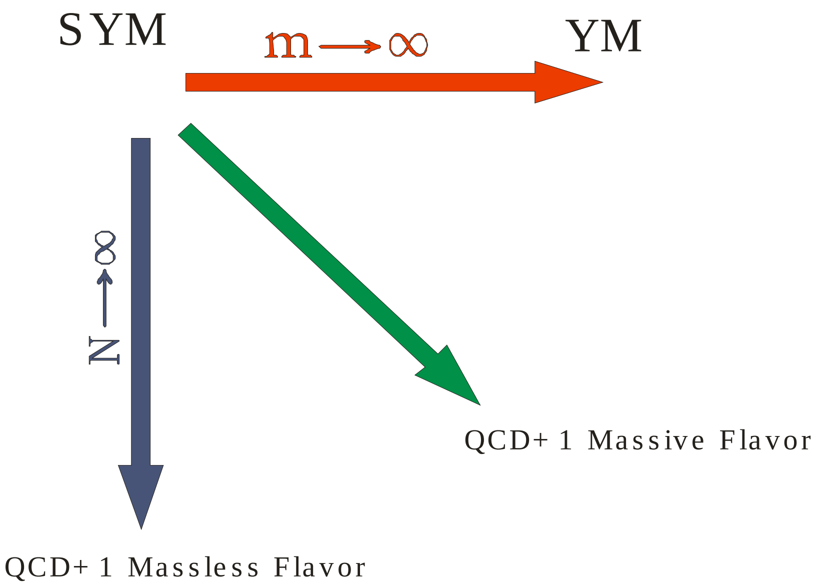
N=1 Supersymmetry-Spectrum

S-type:

Composite Higgs from Higher Representations

Use SUSY to predict a light Higgs 😎

A-Type: QCD & SYM



SYM

$m \longrightarrow \infty$

YM

$N \longrightarrow \infty$

QCD+ 1 Massive Flavor

QCD+ 1 Massless Flavor

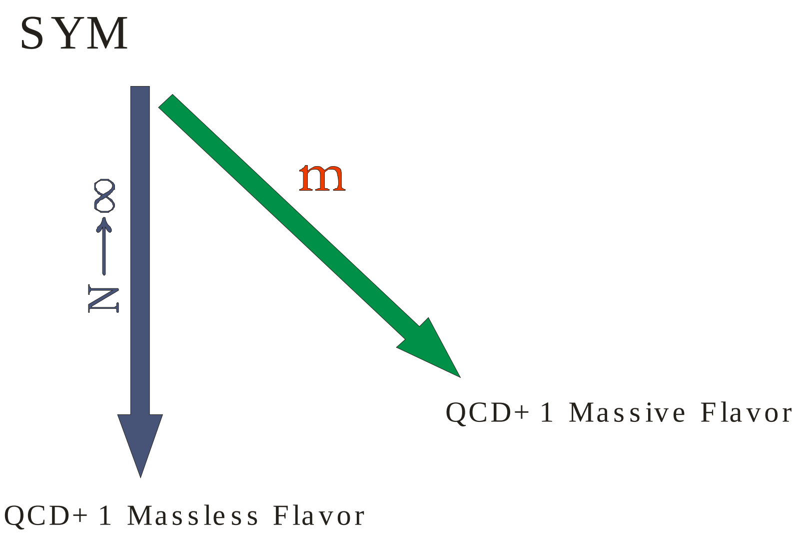
$N = \infty$

Nonzero fermion condensate.

Zero Gluon condensate and Zero vacuum Energy.

Degenerate opposite parity states.

After all we are still far away from QCD.



SYM

QCD+ 1 Massive Flavor

QCD+ 1 Massless Flavor

1/N and small gluino masses

- We construct the effective action saturating the trace and axial anomalies:

$$\partial^\mu J_\mu = [N-2]\frac{1}{16\pi^2}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \qquad \vartheta^\mu_\mu = -3\left[N+\frac{4}{9}\right]\frac{1}{32\pi^2}G^a_{\mu\nu}G^{a,\mu\nu}$$

- At large N we recover the bosonic sector of the Veneziano-Yankielowicz effective action constructed for SYM.
- The spectrum consists of a massive pseudoscalar (eta prime) and the associated scalar fields (sigma). At large N these states are mapped in the pseudoscalar and scalar SYM gluinoball.
- Recently with Merlatti we consistently extended the VY theory to contain supersymmetric glueball states (i.e. R=0 states).

F.S. and Shifman

Predictions for vacuum/spectrum of QCD

F.S. and M. Shifman

Spectrum:

$$\frac{M_{\eta'}}{M_\sigma} = 1 - \frac{22}{9N} - \frac{4}{9}\beta - \frac{m}{\alpha\lambda\Lambda} + O(m^2, N^{-2}, mN^{-1}) < 1$$

Gluon condensate

$$\frac{\langle G^a_{\mu\nu}G^{a,\mu\nu}\rangle}{64\pi^2} = \frac{4\,N\,m}{3\lambda}\Lambda^3 + \frac{8}{27}\alpha\,N\beta\Lambda^4 + O\left(m^2, N^{-1}, mN^0\right)$$

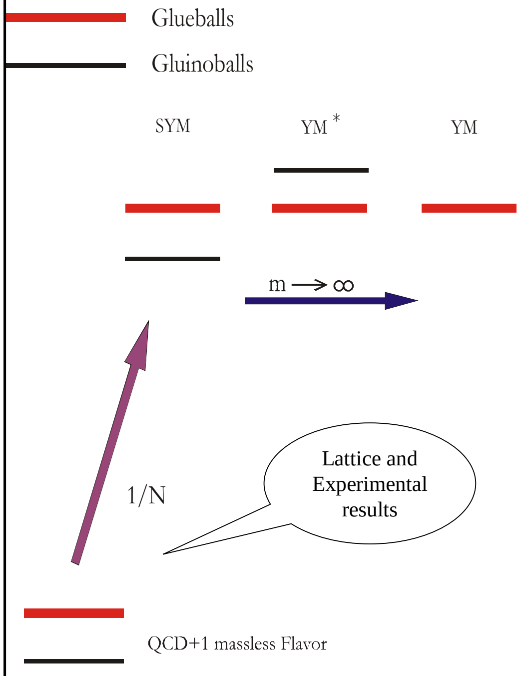
Vacuum Energy and Theta angle

$$\mathcal{E}_{\rm vac} = \frac{8N^2}{3\,\lambda}m\Lambda^3\,\mathrm{min}_k\left\{-\cos\left[\frac{\theta+2\pi\,k}{N-2}\right]\right\} - \frac{4\alpha f}{9}\beta\Lambda^4\ .$$

$\alpha \sim N^0$ $\quad \beta = O(1/N)$ $\quad f(N) \to N^2$ at $N \to \infty$ $\quad \lambda \equiv \frac{g^2 N}{8\pi^2}$ $\quad M = 2\alpha\,\Lambda/3$

From QCD to SYM

- Although we have a great number of *exact* results for supersymmetric theories we cannot yet confront them with data!
- However having established a relation between SYM and QCD we can now use also known facts about QCD to make predictions for SYM.
- What are the lightest states in SYM ?
- Old Lattice simulations suggest the glueballs to be lighter than the gluinoballs.



a) Using QCD results + correspondence we deduce:

Gluinoballs are the lightest states in SYM

b) Using the newly VY extended effective Lagrangian we can show that the mixing between the glueballs (i.e. R=0 states) and the gluinoballs (R=2) is small.

c) Lattice results were qualitatively/quantitatively away from the SUSY limit.

Feo, Merlatti and F.S.

Conclusions and Outlook I

- We introduced the CR large N limit.
- Link QCD with 1 flavor to SYM.
- New information on the vacuum/spectrum structure of QCD.
- Used QCD results to deduce information on SYM.
- We extended the VY theory to include ordinary glueballs.
- We constructed the VY type theory for S/A-theory.
- Results can be tested by Lattice simulations or experiments!
- One can imagine a number of string theory applications.

Part II: New Strong Interactions

S-Type: Composite Higgs

- **SM extremely successful**

Gauge structure is well tested.

Flavor structures are well measured: 3 generations.

- **How to explain hierarchy between weak and Planck scales?**

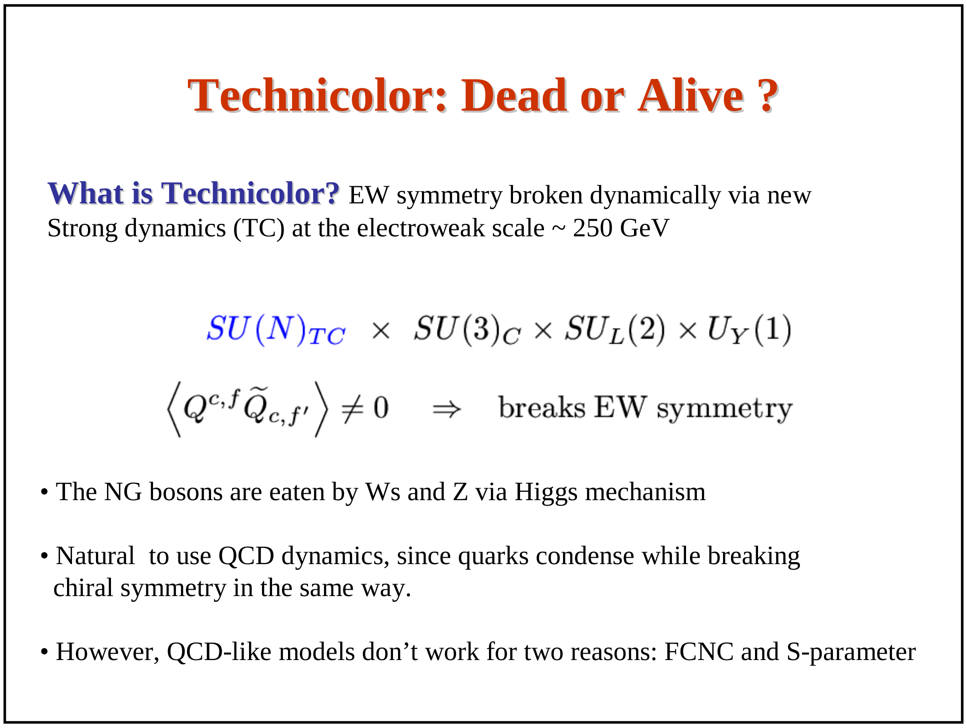
SUSY, Dynamical SB, Extra-dims..

Experimental resolution, long awaited: LHC

- **New physics beyond SM**

Neutrino Oscillations

Dark Matter and Energy



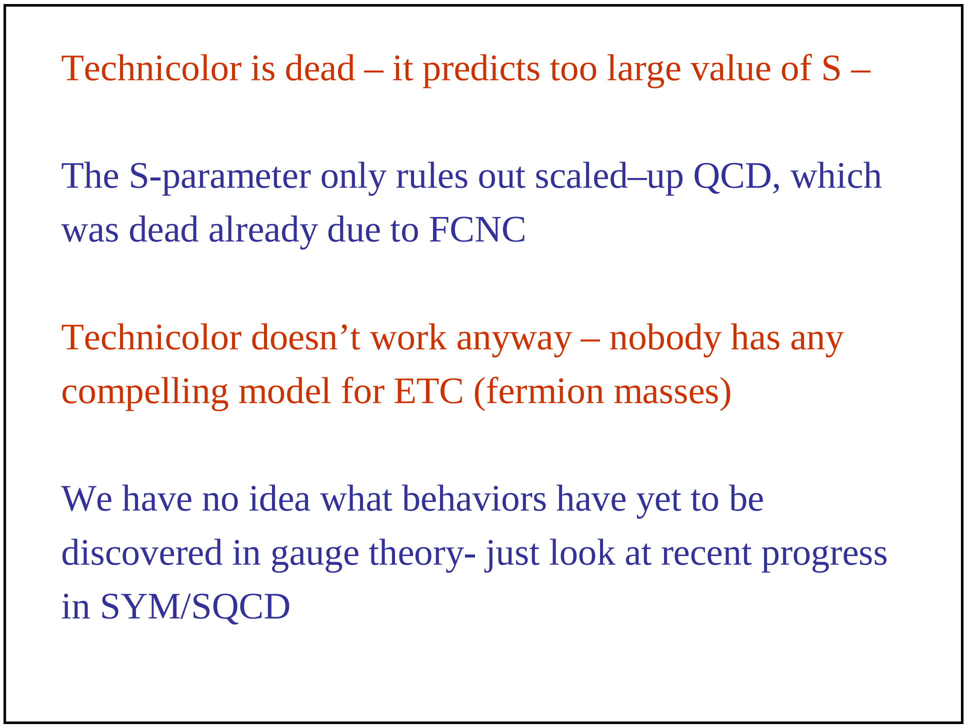
Technicolor: Dead or Alive ?

What is Technicolor? EW symmetry broken dynamically via new Strong dynamics (TC) at the electroweak scale ~ 250 GeV

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

$$\left\langle Q^{c,f}\widetilde{Q}_{c,f'}\right\rangle \neq 0 \quad \Rightarrow \quad \text{breaks EW symmetry}$$

- The NG bosons are eaten by Ws and Z via Higgs mechanism
- Natural to use QCD dynamics, since quarks condense while breaking chiral symmetry in the same way.
- However, QCD-like models don't work for two reasons: FCNC and S-parameter



Technicolor is dead – it predicts too large value of S –

The S-parameter only rules out scaled–up QCD, which was dead already due to FCNC

Technicolor doesn't work anyway – nobody has any compelling model for ETC (fermion masses)

We have no idea what behaviors have yet to be discovered in gauge theory- just look at recent progress in SYM/SQCD

Problems with the old models

- When extended to account for fermion masses, one usually generates large Flavor Changing Neutral Currents (FCNC)
- Precision EW tests: S-parameter is too large.
- Very heavy Higgs ~ 1 TeV.
- Generally have a large number of NG bosons uneaten by the Ws and Z.
- The most sever problem is our limited knowledge about strong dynamics!

Fermion masses, FCNC and 'Walking' TC

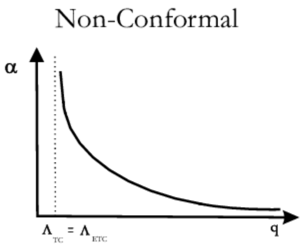
Fermion masses arise from ETC interactions: $\frac{<QQ>}{\Lambda^2_{ETC}}qq$

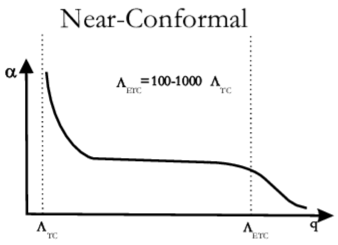
Since $< QQ >\sim 250\ \mathrm{GeV}$, Λ_{ETC} cannot be too large and still account for top quark mass. But, a small ETC scale leads to FCNC

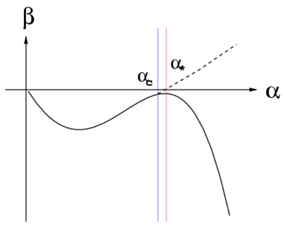
Solution: Near conformal dynamics – i.e.Walking TC – allows for large anomalous dimensions ($\gamma\sim1$) of the technifermion bilinear due to nearly constant gauge coupling (nearly vanishing beta-function).

(Eichten & Lane, Georgi & Cohen, Appelquist et al., Yamawaki et al.)

Near Conformal Properties





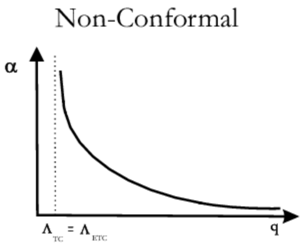


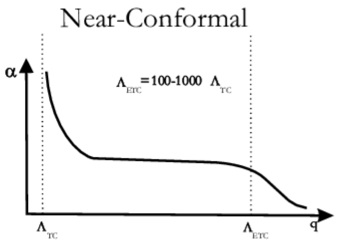
Critical Number of techniflavors

For fermions in the fundamental representation near conformal means:

$$N_f^c \sim 4\,N$$

The number of techndoublets is $N_D = N_f/2$





OK FCNC but large S-parameter

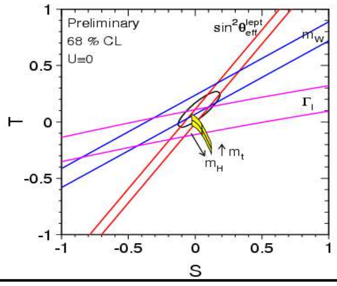
The S-parameter for fermions in ③ is

$$S = \frac{N_f\, N}{12\pi} - \bullet$$

For N=2 we have Nf/2=4 which yields:

$$S_{pert.} = 4/3\pi \sim 0.42$$

Experimentally S = −0.03±0.11



A New Model for Technicolor

F.S. and K. Tuominen, hep-ph/0405209
D.K.Hong, S.D. Hsu, F. S., PLB597 (2004) 90 [hep-ph/0406200]

New features:

Near conformal window with small number of flavors, N_f 🕓 2

No FCNC problem and small S parameter.

SUSY-aided calculations (F.S. – Shifman)

The New Model solves many of these problems

- It is near the conformal window to avoid FCNC
- It is consistent with EW precision data, since N_f and N_{TC} are small.
- It has no uneaten Nambu-Goldstone bosons.
- It has a light Higgs: m_H=200 ~ 500 GeV.
- Some reliable estimates are possible in the non perturbative regime.

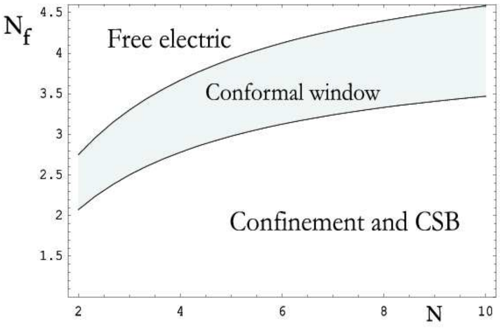
The Model: The generalized S-Theory

	$SU(N)$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	$U_A(1)$
$Q_{\{ij\}}$	$\square\square$	$\square$	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 $\begin{smallmatrix}\square\\\square\end{smallmatrix}$.

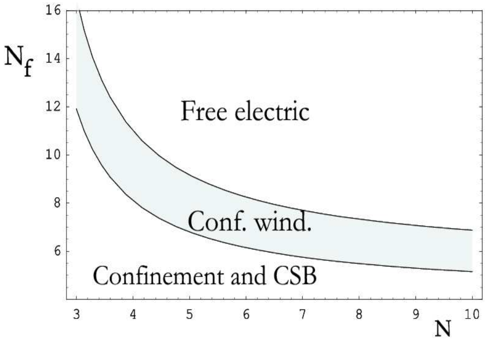
Phase Diagram for the S-Theory



Phase diagram as function of Nf and N for S-type theory. (F.S. & Tuominen)

For N=2,3,4,5 we have that Nf=2 is already the highest possible number of flavors Before entering the conformal window.

Phase Diagram for the A-Theory



Phase diagram as function of Nf and N for A-type theory. (F.S. & Tuominen)

For any N we have that Nf must be >5.

FCNC and S-parameter

FCNC: Near the conformal window we compute

$$\Lambda_{ETC} \geq 300\,\Lambda_{TC}$$

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

- δ ~ 0.013 due to near conformal dynamics (Sundrum-Hsu, Appelquist-Sannino).
- The best estimate for **S** in the S-type model is:

$$S(N=3, N_D = N_f/2 = 1) \simeq 0.2$$

Which is within the 68% confidence ellipse in the S-T plane.

Light Higgs from Higher Representations

QCD-like TC: Scaling up suggests (Di-Vecchia - Veneziano):

$$m_H \sim 4\pi F_\pi \;, \qquad F_\pi \sim \frac{250}{\sqrt{2}}\ \mathrm{GeV}$$

For S/A-type theories with Nf=1:

$$\lim_{N\to\infty} \mathrm{S/A-type} \Longrightarrow \mathrm{Super\ Yang-Mills}$$

Using the large N limit (valid only for Nf=1!!) we relate the masses of the lightest fermion-antifermion states (i.e. Higgs and the technieta) to the fermion condensate:

$$\left\langle \widetilde{Q} Q \right\rangle \equiv \left\langle \widetilde{Q}^{\{i,j\}} Q_{\{i,j\}} \right\rangle$$

- The common scalar (Higgs) and technieta masses at large N:

$$M = \frac{2\,\alpha}{3}\left[\frac{3\left\langle \tilde{Q}Q\right\rangle}{32\pi^2\, N}\right]^{\frac{1}{3}} = \frac{2\hat{\alpha}}{3}\Lambda\ ,$$

with

$$\left\langle \tilde{Q}Q \right\rangle = 3N\Lambda^3 \qquad \text{and} \qquad \hat{\alpha} = \alpha\left[\frac{9}{32\pi^2}\right]^{\frac{1}{3}} \sim O(1)$$

At large N $$\Lambda^3 = \mu^3\left(\frac{16\pi^2}{3Ng^2(\mu)}\right)\exp\left[\frac{-8\pi^2}{Ng^2(\mu^2)}\right]$$

- We then estimate with $\Lambda = \Lambda_{TC} \sim 250\ GeV$

$m_H = M \simeq 170 - 500\ GeV$ for $\hat{\alpha} \sim 1 - 3$

What about 1/N corrections ?

- Fortunately these corrections were computed (Sannino-Shifman) and differ for theories of type S and A.

$$\frac{m_H(S)}{M} = 1 - \frac{4}{9N} + \frac{1}{8N}\frac{\langle G^a_{\mu\nu}G^{a\mu\nu}\rangle}{\hat{\alpha}\,\Lambda^4} + O(N^{-2}) \quad < 1$$

since we expect the technigluon condensate $\langle G^a_{\mu\nu}G^{a\mu\nu}\rangle \sim \Lambda^4$ term to be small.

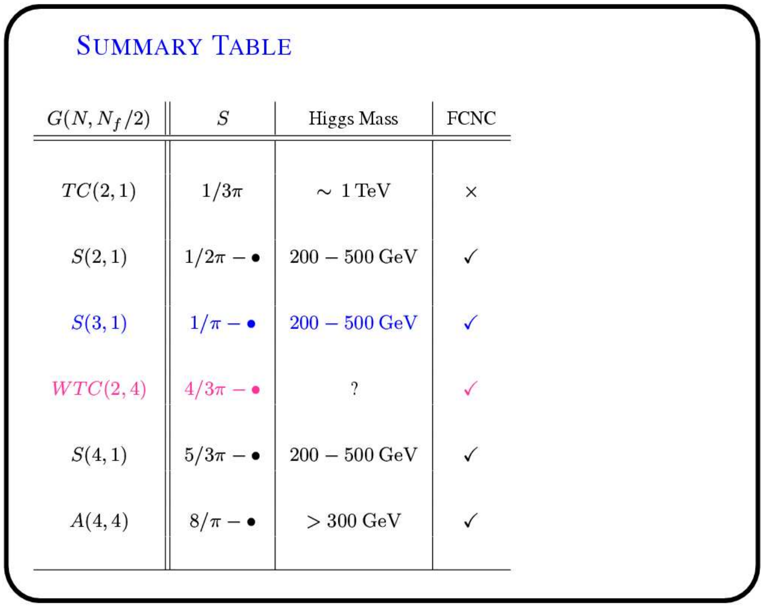
- Our calculations suggest that the favorite S-type models *naturally* yield *light* composite Higgs bosons.

- To reassure ourserlves we estimate $\hat{\alpha}$ via the A-type relation with supersymmetry at large N. We deduce:

$$\hat{\alpha} \sim \frac{\sqrt{3}}{2}\frac{m_{\eta'}}{\Lambda} \sim 3.2\,\frac{\sqrt{3}}{2} \sim 2.8$$

Here $m_{\eta'} = 958\ MeV$ is the ordinary 3-flavor QCD mass for the η' and $\Lambda \sim 300\ MeV$ is identified with the characteristic QCD invariant scale.

- Current Lattice simulations are able to provide better estimates for the Higgs.



SUMMARY TABLE

$G(N, N_f/2)$	S	Higgs Mass	FCNC
$TC(2,1)$	$1/3\pi$	$\sim$ 1 TeV	×
$S(2,1)$	$1/2\pi - \bullet$	200 – 500 GeV	✓
$S(3,1)$	$1/\pi - \bullet$	200 – 500 GeV	✓
$WTC(2,4)$	$4/3\pi - \bullet$	?	✓
$S(4,1)$	$5/3\pi - \bullet$	200 – 500 GeV	✓
$A(4,4)$	$8/\pi - \bullet$	> 300 GeV	✓

Conclusions and Outlook II

- DESB models from higher representations lie close to the conformal window and are free from the FCNC problem despite the small number of flavors and colors.
- The **S** parameter is small and not excluded by precision data.
- Due to the large N equivalence (for one flavor) to SYM, we can make quantitative estimates of the Higgs mass, which turns to be surprisingly light and narrow: m_H=200 – 500 GeV.
- Signatures at LHC or in cosmology are expected.
- Lattice simulations/String Theory can provide further insight on near conformal strongly interacting dynamics.