SUSY Breaking in Theories that S-Confine

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John D. Mason
Western State College of Colorado
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Tongyan Lin, JM, Aqil Sajjad , arXiv:1107.2658

Motivation

SUSY breaking is straightforward to arrange by hand:

$$W = X(A^2 - F) + mAY$$

Would like to understand:

1) Dynamical generation of small mass scales.
2) Why certain operators are absent (i.e. origin of the R-symmetry)

Let's see what types of SUSY Breaking superpotentials can emerge from simple strong gauge dynamics

Outline

- $N=1$ $SU(N)$ S-Confining Theories
- Theory 8
- Theory 7
- Conclusions

S-confinement

1) All degrees of freedom in the IR are gauge invariant composites
2) Admits a smooth effective theory in terms of gauge invariants everywhere (i.e. includes the origin)
3) A Dynamical Superpotential gets generated

S = "screening" or "smooth"

Csaki, Schmaltz, Skiba (1997)

N=1 SU(N) S-confining Theories

Theory 1 : $SU(N) \;|\; N+1 \times (\Box + \overline{\Box})$ — Seiberg (1994), ISS (2006)

Theory 2 : $SU(2N) \;|\; \begin{smallmatrix}\Box\\\Box\end{smallmatrix} + 2N\,\overline{\Box} + 4\,\Box$

Theory 3 : $SU(2N+1) \;|\; \begin{smallmatrix}\Box\\\Box\end{smallmatrix} + (2N+1)\,\overline{\Box} + 4\,\Box$

— Murayama (1995), Poppitz, Trivedi (1996), Pouliot (1996)

Theory 4 : $SU(2N) \;|\; \begin{smallmatrix}\Box\\\Box\end{smallmatrix} + \overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}} + 3(\Box + \overline{\Box})$

Theory 5 : $SU(2N+1) \;|\; \begin{smallmatrix}\Box\\\Box\end{smallmatrix} + \overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}} + 3(\Box + \overline{\Box})$

Theory 6 : $SU(6) \;|\; \begin{smallmatrix}\Box\\\Box\\\Box\end{smallmatrix} + 4\,(\Box + \overline{\Box})$

Theory 7 : $SU(5) \;|\; 3\,(\begin{smallmatrix}\Box\\\Box\end{smallmatrix} + \overline{\Box})$

Theory 8 : $SU(5) \;|\; 2\begin{smallmatrix}\Box\\\Box\end{smallmatrix} + 4\,\overline{\Box} + 2\Box$

Theory 9 : $SU(6) \;|\; 2\begin{smallmatrix}\Box\\\Box\end{smallmatrix} + 5\overline{\Box} + \Box$

Theory 10 : $SU(7) \;|\; 2\begin{smallmatrix}\Box\\\Box\end{smallmatrix} + 6\overline{\Box}$

— Csaki, Schmaltz, Skiba (1997)

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Seiberg (1994), ISS (2006)

Shadmi, Shirman (2011)

Murayama (1995)

Poppitz, Trivedi (1996)

Pouliot (1996)

Shadmi (2011)

Csaki, Schmaltz, Skiba (1997)

Veldhuis (1998)

I'll discuss these two

Theory 8 (elementary)

$$SU(5) \mid 2\,\begin{smallmatrix}\square\\\square\end{smallmatrix} + 4\,\overline{\square} + 2\,\square \qquad W = 0$$

	$SU(5)$	$SU(2)$	$SU(4)$	$SU(2)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
A	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\square$	1	1	0	-1	0
$\bar{Q}$	$\overline{\square}$	1	$\square$	1	1	1	$\frac{1}{3}$
Q	$\square$	1	1	$\square$	-2	1	$\frac{1}{3}$

Posseses a considerable amount of global symmetry.
Superpotential is not modified, even non-perturbatively

Theory 8 (S-Confining)

$$P_1,\ P_2,\ X,\ Y,\ Z$$

$$W^{(dyn)} = \frac{1}{\Lambda^9}\left[XYZ + Y^2P_1^2 + YP_2XP_1 + P_2^2Y^2\right]$$

	$SU(5)$	$SU(2)$	$SU(4)$	$SU(2)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
$P_1 = Q\bar{Q}$		1	$\square$	$\square$	-1	2	$\frac{2}{3}$
$X = A\bar{Q}^2$		$\square$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	2	1	$\frac{2}{3}$
$P_2 = A^2Q$		$\square\square$	1	$\square$	-2	-1	$\frac{1}{3}$
$Y = A^3\bar{Q}$		$\square$	$\square$	1	1	-2	$\frac{1}{3}$
$Z = A^2Q^2\bar{Q}$		1	$\square$	1	-3	1	1

Global anomalies match!

Theory 8 (perturbed)

$$\delta W = \lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} A^i \bar{Q}^\alpha \bar{Q}^\beta$$

$$\lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} = \lambda \left[\begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \right]$$

$$i : \; SU(2)$$

$$\alpha, \; \beta : \; SU(4)$$

	$SU(5)$	$\#$	$Sp(4)$	$SU(2)$	$U(1)$	$U(1)_R$
A	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	2	1	1	2	0
$\bar{Q}$	$\overline{\square}$	1	$\square$	1	-1	1
Q	$\square$	1	1	$\square$	-4	-1

Some symmetry is explicitly broken

Theory 8 (perturbed and confined)

$$\delta W = \lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} A^i \bar{Q}^\alpha \bar{Q}^\beta$$

→

$$\delta W = F^{\bar{i}}_{\bar{\alpha}\bar{\beta}} X^{\alpha\beta}_i$$

$$W = XYZ + \frac{Y^2 P_1^2}{\Lambda^5} + \frac{Y P_2 X P_1}{\Lambda^5} + \frac{P_2^2 Y^2}{\Lambda^5}$$

$$\lambda \ll 1 \to F \sim \lambda\Lambda^2 << \Lambda^2$$

Theory 8 (perturbed and confined)

$$\delta W = \lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} A^i \bar{Q}^\alpha \bar{Q}^\beta$$

$$\delta W = F^{\bar{i}}_{\bar{\alpha}\bar{\beta}} X_i^{\alpha\beta}$$

$$W = XYZ + \frac{Y^2 P_1^2}{\Lambda^5} + \frac{Y P_2 X P_1}{\Lambda^5} + \frac{P_2^2 Y^2}{\Lambda^5}$$

Irrelevant couplings

$$W = hXYZ + FX$$

$$F = \lambda \Lambda^2$$

More specifically ...

	$SU(5)$	$\#$	$Sp(4)$	$SU(2)$	$U(1)$	$U(1)_R$
P_1		1	$\square$	$\square$	-5	0
X		2	$\begin{array}{c}\square\\\square\end{array}$	1	0	2
P_2		3	1	$\square$	0	-1
Y		2	$\square$	1	5	1
Z		1	$\square$	1	-5	-1

$$W = \lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} X^{\alpha\beta}_i + \epsilon_{\alpha\beta\delta\gamma}\epsilon^{ij} X^{\alpha\beta}_i Y^{\delta}_j Z^{\gamma}$$

$$\Rightarrow \quad F^{\bar{i}}_{\bar{\alpha}\bar{\beta}} - (Y^{\bar{i}} Z)_{\bar{\alpha}\bar{\beta}} = 0$$

These F-term equations have no solution. It is essentially a rank breaking condition, but is not solved because of a 2x4x4 tensor rank.

Theory 8 (recap)

$$SU(5) \mid 2\,\begin{smallmatrix}\square\\ \square\end{smallmatrix} + 4\,\overline{\square} + 2\,\square \qquad \delta W = \lambda^{\bar{i}}_{\bar{\alpha}\bar{\beta}} A^i \bar{Q}^\alpha \bar{Q}^\beta$$

SUSY is broken by tree-level perturbation and s-confining dynamics. Vacuum is stable and calculable after a U(1) is gauged. All mass scales are dynamically generated and are the same order of magnitude: $|F|$.

Theory 7 (elementary)

$$SU(5)\ \big|\ 3\left(\begin{array}{c}\square\\[-2pt]\square\end{array}+\overline{\square}\right)\qquad W=0$$

	$SU(5)$	$SU(3)$	$SU(3)$	$U(1)$	$U(1)_R$
A	$\begin{array}{c}\square\\[-2pt]\square\end{array}$	$\square$	1	1	0
$\bar{Q}$	$\overline{\square}$	1	$\square$	-3	$\frac{2}{3}$

This is just the Grand Unified Superymmetric Standard Model without Higgs doublets. W = 0 is exact, even non-perturbatively.

Theory 7 (confined)

$X,\ Y,\ Z$

	$SU(5)$	$SU(3)$	$SU(3)$	$U(1)$	$U(1)_R$
$X = A\bar{Q}^2$		$\square$	$\overline{\square}$	-5	$\frac{4}{3}$
$Y = A^3\bar{Q}$		$\yng(2,1)$	$\square$	0	$\frac{2}{3}$
$Z = A^5$		$\yng(2)$	1	5	0

$$W = XYZ + Y^3$$

Note that there no terms higher than cubic order.

Theory 7 (results)

$$SU(5) \mid 3\ \left(\begin{array}{|c|}\hline \\ \hline \\ \hline \end{array} + \overline{\Box} \right)$$

$$\delta W = \lambda A \bar{Q}^2 + \frac{A^3 \bar{Q}}{M_p} + \frac{A^5}{M_p^2}$$

1) SUSY Breaking
2) R-symmetry Breaking
3) Not Calculable

Conclusions

S-Confining Theories have rich gauge dynamics that can be used to generate O'R models from the balance of a tree-level interaction and the confining superpotential.

All mass scales can be dynamically generated.

Theory 8 has a vacuum near the origin with SUSY Breaking and no R-symmetry Breaking.

Theory 7 has a vacuum in the incalculable regime with SUSY Breaking and R-symmetry Breaking.

Theory 7 (perturbed)

$$\delta W = \lambda A\bar{Q}^2 + \frac{A^3\bar{Q}}{M_p} + \frac{A^5}{M_p^2}$$

$$W = XYZ + Y^3 + \lambda\Lambda^2 X + \left(\frac{\Lambda}{M_p}\right)\Lambda^2 Y + \left(\frac{\Lambda}{M_p}\right)^2 \Lambda^2 Z$$

$$\epsilon = \frac{\Lambda}{M_p} \quad F = \lambda\Lambda^2 \quad \epsilon \ll \lambda \ll 1$$

Only keep leading term for now.

$$W = XYZ + Y^3 + FX$$

Theory 7 (more specifically)

$$\delta W = \lambda_{\bar{i}\alpha} \epsilon^{\alpha\beta\gamma} A^i \bar{Q}_\alpha \bar{Q}_\beta \qquad \lambda^{\bar{i}}_{\bar{\alpha}} = \lambda \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$W = X^{i\bar{\alpha}} Y^{a\alpha} T^a_{j\bar{k}} Z^{kl} \epsilon_{ijl} + \epsilon_{\alpha\beta\gamma} f^{abc} Y^{a\alpha} Y^{b\beta} Y^{c\gamma} + F_{\bar{i}\alpha} X^{i\bar{\alpha}}$$

This theory breaks supersymmetry but at a point on moduli space that is incalculable.

Theory 7 (at large VEVs)

$$\delta W = \lambda A \bar{Q}^2 + \frac{A^3 \bar{Q}}{M_p} + \frac{A^5}{M_p^2}$$

If all flat directions can be lifted then:

1) Near the origin the confined description indicates that the potential slopes away from the origin.
2) Far from the origin the elementary dof description yields a rising potential.
3) The theory must stabilize in-between. SUSY and R-symmetry are broken but not calculable.

Thank you!

Theory 8 (pick a vacuum)

$$X = 0$$

$$Y_\alpha^{(1)} = \left(0,\ 0,\ 0,\ \frac{1}{2^{1/4}}\right)\sqrt{F}$$

$$Y_\alpha^{(2)} = \left(0,\ 0,\ 0,\ -\frac{1}{2^{1/4}}\right)\sqrt{F}$$

$$Z_\alpha = \left(0,\ 0,\ 0,\ 2^{1/4}\right)\sqrt{F}$$

$Sp(4) \times U(1) \to SU(2) \times U(1)$ ⇒ <u>7 Goldstone Bosons</u>

Theory 8 (calculate masses)

At Tree level there are 20 dof in X, Y and Z that are massless
At one-loop level only 7 remain massless.
These are the goldstones. All others have mass:

$$m^2_{tree} = (8,4) \times h^2|F|$$

$$m^2_{loop} = (8,4,4,4,4,2,2,2,2,1,1,1,1) \times h^4|F|\frac{(\log 4 - 1)}{\pi^2}$$

$P_1, \ P_2$ ➡ "Higgsing pseudo-moduli" Intriligator , Shih, Sudano (2009)

Gauging a combination of any of 4 anomaly free U(1)s will stabilize these at 2-loop w/ positive masses.

$$m^2_{P_1,P_2} \sim \frac{g^2 h^4}{(16\pi^2)^2}|F|$$

Theory 7 (perturbed and confined)

$$W = XYZ + Y^3 + \lambda\Lambda^2 X + \frac{\Lambda}{M_p} Y + \frac{\Lambda}{M_p^2} Z$$

$$\delta W = \lambda_{\bar{i}\alpha} \epsilon^{\alpha\beta\gamma} A^i \bar{Q}_\alpha \bar{Q}_\beta$$ → $$\delta W = \lambda_{\bar{i}\alpha} X^{i\bar{\alpha}}$$

$$W = XYZ + Y^3 + FX$$

$$\lambda \ll 1 \rightarrow F \sim \lambda\Lambda^2 << \Lambda^2$$

Theory 7 (more specifically)

$$\delta W = \lambda_{\bar{i}\alpha}\epsilon^{\alpha\beta\gamma}A^i\bar{Q}_\alpha\bar{Q}_\beta \qquad \lambda^{\bar{i}}_{\bar{\alpha}} = \lambda\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$W = X^{i\bar{\alpha}}Y^{a\alpha}T^a_{j\bar{k}}Z^{kl}\epsilon_{ijl} + \epsilon_{\alpha\beta\gamma}f^{abc}Y^{a\alpha}Y^{b\beta}Y^{c\gamma} + F_{\bar{i}\alpha}X^{i\bar{\alpha}}$$

This theory has a runaway direction:

$$X = 0, \quad Y \to 0, \quad Z \to \infty$$

At large Z VEVs the gauge group is Higgsed and we can use the higgsed description.