Dynamical supersymmetry breaking, with Flavor

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Cornell University , November 2009

Based on arXiv: 0911.2467 [Craig, Essig, Franco, Kachru, GT]

and arXiv: 0812.3213 [Essig, Fortin, Sinha, GT, Strassler]

Two central puzzles in particle physics are

a) the hierarchy between the electroweak and the Planck scale
b) the pattern of masses and mixings of the SM fermions

In particular,

- why are most fermions so much lighter than $(t, Z, W^{\pm})$?
- why is the top quark special?
- where does the generational structure come from?
- can the two puzzles be related?

Flavor structure

In the SM, the masses and flavor mixings arise from

$$L_Y = (Y_u)_{ij} Q_i \bar{u}_j H + (Y_d)_{ij} Q_i \bar{d}_j H^* + (Y_l)_{ij} L_i \bar{e}_j H^* \quad (i,j = 1,2,3)$$

Changing to a basis of mass eigenstates $u^0 = V_u u \ldots$ flavor changing interactions appear only in

$$L_{cc} = g \left[u^{0*} \bar{\sigma}_\mu (V_u V_d^\dagger) d^0 \right] W^{\mu +} \Rightarrow \mathbf{V_{CKM}} := \mathbf{V_u V_d^\dagger}$$

Strikingly, at the EW scale we find the flavor hierarchies

- $m_u/m_c \sim 10^{-3}\ ,\ m_u/m_t \sim 10^{-5}$
- $V_{us} \sim V_{cd} \sim 0.22$
- $V_{cb} \sim V_{ts} \sim 10^{-2}$
- $V_{ub} \sim V_{td} \sim 10^{-3}$

Where do these numbers come from? They could be explained by

$$Y \sim \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}, \text{ with } \varepsilon \sim 10^{-1} - 10^{-2}$$

Suppose the SM fermions were secretly composites of some confining gauge theory (with dynamical scale Λ), and that flavor physics is generated at $M_{flavor} > \Lambda$.

- √ Then the Yukawa interactions would be irrelevant, and naturally suppressed by

$$\varepsilon = \frac{\Lambda}{M_{flavor}}$$

- √ The flavor structure would arise simply from different degrees of compositeness. The third generation would be elementary.

Fermions as composites?

The original proposal goes back to 't Hooft. Let's try to understand this idea using QCD...

$SU(3)_C$ confines and gives nucleons that are composite fermions.

However, these baryons are very massive! QCD breaks chiral symmetry, and the proton and neutron acquire masses of order Λ_{QCD}.

$\rightsquigarrow$ If the SM fermions arise as composites of some underlying gauge theory that confines, then the strong dynamics should preserve a chiral symmetry that protects the composites from acquiring large masses.

- √ Explain the SM quantum numbers of the composite fermions: the theory should preserve a large global symmetry G_F and we add spectator gauge fields in

  $$G_{SM} \subset G_F$$

  These have to remain weakly coupled, so that the confining dynamics is not modified.
- √ Spectator fermions may also be needed, either to cancel possible G_F anomalies, or to lift extra (light) nucleons that are not observed in the SM.

Summarizing: we need a gauge theory with confinement and without chiral symmetry breaking, that gives weakly interacting fermionic bound states, and that has a large unbroken flavor group.

Wish-list

$\Rightarrow$ SUSY gauge theories are the natural arena for this!!

The following ingredients have to be combined

1. Confining SUSY gauge theory that generates a composite SSM.
2. Break SUSY spontaneously, to lift the extra light scalars. Can the same confining dynamics do this? $\rightsquigarrow$ Single sector model! [Arkani-Hamed, Luty, Terning]
3. The theory should be calculable: make sure there are no tachyonic sfermion masses.

How far can we get along this direction?

Organization of the talk

The aim of this talk is to present realistic models of flavor + DSB, with only a single sector.

1. Basic ingredients in a toy model
2. The model: SQCD with flavors and an adjoint
3. Flavor phenomenology of composite models
4. Future directions

Basic ingredients in a toy model

Let us understand the properties of the conjectured confining gauge theory, in a simple setup.

$\mathbf{SU(N_c)}$ SQCD with $\mathbf{N_f = N_c + 1}$ flavors

Consider super QCD with gauge group $G = SU(N_c)$, and $N_f = N_c + 1$ flavors $(Q_i, \tilde{Q}_i)$.

- √ The flavor symmetry group contains $SU(N_f)_L \times SU(N_f)_R$, acting on Q and $\tilde{Q}$ separately.
- √ There is a moduli space of vacua, parametrized by

$$M_{ij} = Q_i \tilde{Q}_j \quad , \quad B_i = [Q]^{N_c} \quad , \quad \tilde{B}_i = [\tilde{Q}]^{N_c}$$

modulo classical constraints (e.g. $M^{-1}\det M = B\tilde{B}$)

The theory generates a dynamical scale Λ. For energies $E \gg \Lambda$, the *electric description* in terms fundamental quarks is valid. However, at energies $E \lesssim \Lambda$, the theory confines and the electric description breaks down. What happens at low energies?

[Seiberg] There is a dual *magnetic description*, in terms of weakly coupled hadrons $(M, B, \tilde{B})$, with superpotential

$$W = \frac{1}{\Lambda^{2N_c - 1}} \left(B_i M_{ij} \tilde{B}_j - \det M \right)$$

There is a flavor $SU(N_f)_L \times SU(N_f)_R$ symmetry group, as in the electric description.

The superpotential reproduces the classical constraints. Away from the origin, some of the hadrons become massive, and the chiral symmetry is (partly) broken.

Compositeness from SQCD: a toy model

However, near $M = B = \tilde{B} = 0$, the chiral symmetry is preserved and all the hadrons are physical and light!

We have found a very simple SUSY gauge theory with

- $\surd$ confinement without chiral symmetry breaking
- $\surd$ a large unbroken global symmetry $SU(N_f)$
- $\surd$ containing weakly coupled hadrons

All nice features for the compositeness idea!

The next step is to add SM gauge bosons (and gauginos) as spectators. This weakly gauges the subgroup

$$SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(N_f)_D$$

For instance, for $N_f = 11$,

$$SU(5)_{SM} \subset SU(11) \text{ as } Q(11) \sim 5 + \bar{5} + 1 + 1$$

The meson $Q\tilde{Q}$ contains a $\mathbf{10} + \bar{\mathbf{5}}$ SM generation.

If the first two generations are composite, while the third one and Higgs are elementary, then at $M_{flavor} > \Lambda$

$$W_{Yuk} \sim \frac{1}{M_{\rm flavor}^2}(Q\tilde{Q})H(Q\tilde{Q}) + \frac{1}{M_{\rm flavor}}(Q\tilde{Q})H\Psi_3 + \Psi_3 H\Psi_3$$

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$$\rightsquigarrow \quad Y \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \text{, with } \varepsilon = \frac{\Lambda}{M_{flavor}}$$

This is a good starting point for a theory of flavor. [Arkani-Hamed, Luty, Terning; Franco, Kachru]

Dynamical supersymmetry breaking

At this level, there are massless sfermions and gauginos: supersymmetry needs to be broken to make them heavy.

Break susy dynamically using the same confining gauge theory?

$\rightsquigarrow$ single sector models

The magnetic description has weakly coupled elementary fields (canonically normalized)

$$\Phi = \frac{Q\tilde{Q}}{\Lambda}\ ,\ q = \frac{[Q]^{N_c}}{\Lambda^{N_c-1}}\ ,\ \tilde{q} = \frac{[\tilde{Q}]^{N_c}}{\Lambda^{N_c-1}}$$

To break susy, add a mass term $mQ\tilde{Q}$ for the electric quarks [ISS]

$$W = m\,\mathrm{Tr}\,M + \frac{1}{\Lambda^{2N_c-1}}\,\mathrm{Tr}(BM\tilde{B}) - \frac{1}{\Lambda^{2N_c-1}}\,\det M$$

$$\Rightarrow\;\; W_{mag} = -h\mu^2\,\mathrm{Tr}\,\Phi + h\,\mathrm{Tr}\,q\Phi\tilde{q} \;+\; \text{nonpert.}$$

Focus on the region near the origin of field space, where the nonperturbative piece is negligible.

$$\frac{\partial W}{\partial \Phi_{ij}} = -h\mu^2\,\delta_{\mathbf{ij}} + h\,q_i\tilde{q}_j \neq 0$$

$\rightsquigarrow$ susy is broken because the first term has rank N_c+1, while the second one has only rank 1.

The susy breaking vacuum has

$$\langle q_1 \tilde{q}_1 \rangle = \mu^2 \quad , \quad \Phi_{ij} \text{ “pseudo-modulus” for } i, j \geq 2 \quad , \quad \text{F-term} = h\mu^2$$

This is only the classical story. Take into account:

- perturbative corrections from integrating out the massive nonsupersymmetric fields $(q, \tilde{q})$
- nonperturbative effects from the extra $\det \Phi$ term in the superpotential

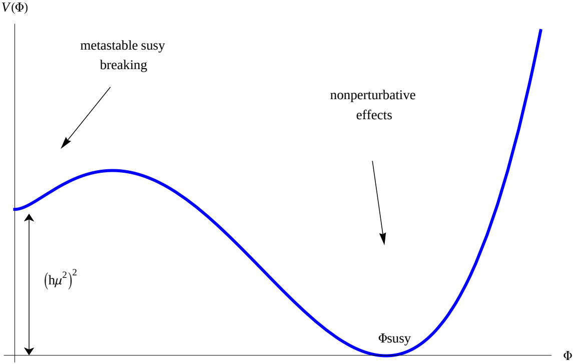
Perturbative one-loop corrections lift the pseudo-flat direction Φ creating a positive curvature at the origin of field space,

$$m^2_{1-loop} \approx \frac{h^2}{8\pi^2} (h\mu)^2$$

For $\Phi \sim \Lambda$, the nonperturbative term dominates, creating susy vacua

$$\langle \Phi_{susy} \rangle^{N_c} \sim \mu^2 \Lambda^{N_c - 2}$$

The susy breaking vacuum is locally stable.



Chiral symmetry breaking

One of the main features of this construction is the presence of an unbroken chiral symmetry protecting the light hadrons. At the same time, this causes phenomenological problems...

For instance, the low energy susy breaking theory has an approximate R-symmetry $[W = \mu^2 \Phi + q \Phi \tilde{q}]$

$$U(1)_R \ : \ R(\Phi) = 2 \ , \ R(q) = R(\tilde{q}) = 0 \, .$$

This forbids Majorana masses for the gauginos!

$\star$ Can we break the R-symmetry in a controllable way, so that the previous construction is still valid, and appreciable gaugino masses are generated? [Essig, Fortin, Sinha, GT, Strassler].

The mechanism is again based on the idea of compositeness. Add a quartic irrelevant deformation to the electric theory

$$\Delta W_{el} = \frac{1}{\Lambda_0}(\tilde{Q}Q)^2 \ , \ \Lambda_0 \gg \Lambda$$

This becomes a mass term in the confined description, but with a naturally small coefficient,

$$\Delta W_{mag} = \frac{\Lambda^2}{\Lambda_0}\,\mathrm{Tr}(\Phi)^2 = \mu_\phi\,\mathrm{Tr}(\Phi)^2 \ , \ \text{where } \Phi = \frac{Q\tilde{Q}}{\Lambda}$$

Near the origin, the effect of this perturbation is to move the metastable vacuum slightly away from the origin.

More concretely,

$$V \approx \mu^2 \, \mu_\phi \Phi + \frac{\mu^2}{8\pi^2} \, \Phi^2 \;\Rightarrow\; \langle \Phi \rangle_{DSB} \approx 8\pi^2 \, \mu_\phi$$

There is a large spontaneous breaking of the R-symmetry, that gives realistic masses to the gauginos.

The perturbation does not alter the essential DSB+flavor properties of the theory. There are still very light fermions from Φ, protected by the remaining unbroken flavor symmetry [Essig, Fortin, Sinha, GT, Strassler].

It is possible to combine the previous points into consistent single sector models of DSB+flavor. [Franco, Kachru; & Craig, Essig, GT]

The model: SQCD with flavors and an adjoint

Summarizing what we have learned so far,

1. $SU(N_c)$ SQCD with $N_c + 1$ flavors has a large flavor symmetry group with light mesons that are good candidates for SM composites;
2. mesons which are neutral under the SM gauge group can generate a metastable supersymmetry breaking vacuum;
3. it is possible to break the chiral symmetry in a controllable way, generating gaugino masses.

To obtain a realistic flavor structure, we will add a gauge group adjoint U, so that at low energies confinement produces dimension 3 and 2 mesons $QU\tilde{Q}$, $Q\tilde{Q}$.

SM fields:

- first SM generation: dim 3 meson $QU\tilde{Q}$
- second SM generation: dim 2 meson $Q\tilde{Q}$
- elementary fields: third generation Ψ_3, Higgs H_u, H_d.

The Yukawa interactions generated at a scale $M_{flavor} > \Lambda$ are

$$W_{Yuk} \sim \frac{1}{M^4_{\rm flavor}}(QU\tilde{Q})H(QU\tilde{Q}) + \frac{1}{M^2_{\rm flavor}}(Q\tilde{Q})H(Q\tilde{Q}) + \Psi_3 H \Psi_3 + \ldots$$

$\rightsquigarrow$ explains naturally $Y \sim \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}$, with $\varepsilon = \dfrac{\Lambda}{M_{flavor}}$

The electric theory

Consider $SU(N_c)$ SQCD with N_f quarks $(Q, \tilde{Q})$ and an adjoint field U, with generic renormalizable superpotential [Kutasov, Schwimmer, Seiberg]

$$W_{el} = g_U \,\mathrm{Tr}\, U^3 + m_U \,\mathrm{Tr}\, U^2$$

Restrict to $2N_f = N_c + 1$ (the analog of $N_f = N_c + 1$ before).

Classical space of vacua parametrized by

- mesons $\Phi = \dfrac{Q\tilde{Q}}{\Lambda}$, $\Phi_U = \dfrac{QU\tilde{Q}}{\Lambda^2}$
- baryons $q = \dfrac{(UQ)^{N_f} Q^{N_f-1}}{\Lambda^{N_c-1}}$, $\tilde{q} = \dfrac{(U\tilde{Q})^{N_f} \tilde{Q}^{N_f-1}}{\Lambda^{N_c-1}}$

The magnetic theory

The magnetic dual is a theory of weakly coupled hadrons $(\Phi, \Phi_U, q, \tilde{q})$ with superpotential

$$W_{mag} = h\,\mathrm{Tr}(q\Phi_U\tilde{q}) + h_1\,\frac{m_U}{\Lambda}\,\mathrm{Tr}(q\Phi\tilde{q}) + (nonpert)$$

and a flavor symmetry $SU(N_f)_L \times SU(N_f)_R \times U(1)_R$.

For $m_U \ll \Lambda$, the dimension 2 meson Φ approximately decouples from the rest of the fields. Then consider perturbing the electric theory by marginal and irrelevant interactions

$$\Delta W_{el} \sim QU\tilde{Q} + \frac{1}{\Lambda_0^3}\,(QU\tilde{Q})^2$$

Metastable susy breaking

These operators become relevant in the IR, giving,

$$W_{mag} = -h\mu^2 \,\mathrm{Tr}\,\Phi_U + h\,\mathrm{Tr}(q\Phi_U\tilde{q}) + h^2\mu_\phi\,\mathrm{Tr}\,(\Phi_U)^2 + h_1\,\frac{m_U}{\Lambda}\,\mathrm{Tr}(q\Phi\tilde{q})$$

This is almost the same long-distance theory as we studied before!

- √ For $\mu_\phi = 0$, supersymmetry is broken by the linear Φ_U term (plus rank condition). Φ_U is stabilized at the origin by one-loop effects.
- √ For μ_ϕ small, the metastable vacuum is displaced from the origin by $8\pi^2\mu_\phi$. R-sym is broken and gaugino masses are generated.
- √ Important differences: the susy breaking field Φ_U is dim. 3 in the UV, and there is an extra meson Φ almost decoupled.

Flavor phenomenology of composite models

Finally we are ready to build a realistic theory of flavor. Recall that the $SU(N_f)$ flavor symmetry acting on $(q_i, \tilde{q}_i, \Phi_{U,\,ij})$ is broken:

$$SU(N_f) \to SU(N_f - 1) \;\text{ by }\; \langle q_1 \tilde{q}_1 \rangle = \mu^2$$

Take e.g. $N_f = 12$, $SU(5)_{SM}$: $Q \sim \mathbf{1} + (\mathbf{1} + \mathbf{5} + \overline{\mathbf{5}})$.
The SQCD dynamics gives

- a singlet $\mathrm{tr}\,\Phi_U$ responsible for susy and R-sym breaking
- composite "messengers" $(q_i, \Phi_{U,1i})$ for $i > 1$, in $(\mathbf{5} + \overline{\mathbf{5}})$'s
- two composite SM generations $\mathbf{10} + \overline{\mathbf{5}}$ (from Φ_U and Φ)
- extra matter in $\mathbf{24} + \mathbf{15} \ldots$ from the mesons. Need spectators to lift them, $W = S_{1,\overline{R}}(Q\tilde{Q})_R + (1/\Lambda_0) S_{2,\overline{R}}(QU\tilde{Q})_R$.

Flowing towards the MSSM

$asymp.\ \ free\ \ SQCD\ \ with\ \ (Q, \tilde{Q}, U)$

$M_{flavor} \sim 10^{17}\ \ GeV$

* elementary H and third generation
* Yukawa couplings given by dimensional hierarchy

$\Lambda \sim 10^{16}\ \ GeV$

* confinement
* magnetic description in terms of baryons and mesons

$$q\ ,\ \tilde{q}\ ,\ \Phi = \frac{Q\tilde{Q}}{\Lambda}\ ,\ \Phi_U = \frac{QU\tilde{Q}}{\Lambda}$$

$$flavor\ \ hierarchies\ \ explained\ \ by\ \ \epsilon = \frac{\Lambda}{M_{flavor}}$$

$\mu \sim 200\ \ TeV$

* weakly coupled O'R model. SUSY broken
* direct mediation, composite “messengers” in **5+5***

$$W = \mu^2\ \Phi_U + \mu_\phi\ \Phi_U^2 + q\,\Phi_U\,\tilde{q}$$

$\mu_\phi \sim 1\ \ TeV$

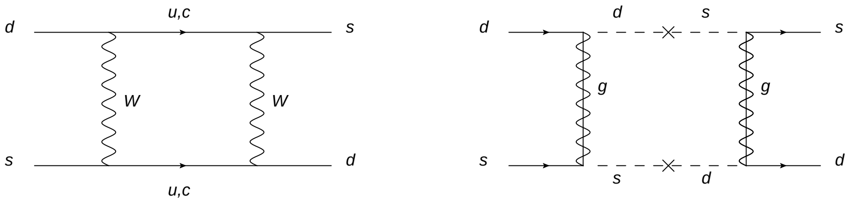
* R-symmetry breaking
* gauge mediated masses for gauginos and sfermions

$MSSM$

Constraints from FCNCs

What type of realistic models can we get? The strongest constraints come from FCNCs, e.g. $K^0 - \overline{K}^0$ mixing.

SM contribution, suppressed by GIM mechanism *MSSM contribution (large?!)*



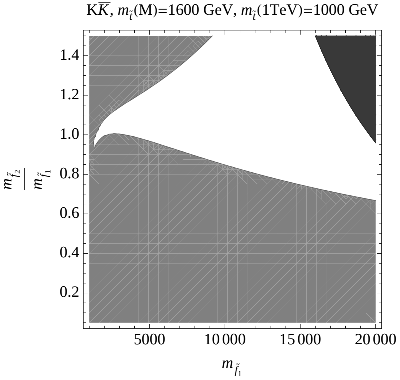
Gives upper bound on sfermion mass mixings [Gabbiani et al]

$$\frac{(\Delta m_{12})^2}{m_{\tilde{f}_1} m_{\tilde{f}_2}} \lesssim 10^{-3} \frac{\sqrt{m_{\tilde{f}_1} m_{\tilde{f}_2}}}{500\ GeV} \quad \text{for} \quad m_{\tilde{g}}^2 \approx 0.3\, m_{\tilde{f}_1} m_{\tilde{f}_2}$$

These ratios are calculable and depend on the parameters of the microscopic electric theory. Low energy flavor properties give us a window into very high energy physics!

Example: exclusion plot,

- light gray region ruled out by K-K mixing
- dark gray region ruled out by tachyonic stops
- white region allowed



Possible microscopic models

Three patterns of susy breaking masses, all possible in SQCD + adjoint:

1. one composite participating in susy breaking, the other decoupled (small h)

$$m_{\tilde{f}_1} \sim m_{1-loop} \approx \frac{h^2}{4\pi}\,\mu \quad , \quad m_{\tilde{f}_2} \sim m_{\tilde{f}_3} = m_{gauge-mediated} \approx \frac{g_{SM}^2}{16\pi^2}\,\mu$$

2. both composites participating in susy breaking (small g_U)

$$m_{\tilde{f}_1} \sim m_{\tilde{f}_2} \sim m_{1-loop} \quad , \quad m_{\tilde{f}_3} = m_{gauge-mediated}$$

3. both composites acquiring only gauge-mediated masses ($W = U^4$)

$$m_{\tilde{f}_1} = m_{\tilde{f}_2} = m_{\tilde{f}_3} = m_{gauge-mediated}$$

Phenomenology

These models can be made consistent with flavor bounds, and lead to realistic spectra.

Some of them realize a "more minimal SSM" [Dimopoulos, Cohen, ...]

Examples:

	sfermions	messengers	extra matter at	unification
class 1)	approx. universal	$4 \times (\mathbf{5} + \bar{\mathbf{5}})$	$\sim 10^{-1}\,\Lambda$	possible
class 2)	$\sim$ 2, 15, 20 TeV	$6 \times (\mathbf{5} + \bar{\mathbf{5}})$	$\sim 10^{-1}\,\Lambda$	no
class 3)	universal	$4 \times (\mathbf{5} + \bar{\mathbf{5}})$	$\sim 10^{-2}\,\Lambda$	?

Future directions

We have proposed that the intricate structure of the (M)SSM can emerge from rather simple microscopic gauge theories.

Our models are fully calculable and the same confining dynamics explains the flavor hierarchies and breaks supersymmetry dynamically.

Some future directions:

- Main point to improve: find models with less extra matter.
- Build a realistic GUT with perturbative unification.
- Explore the range of soft spectra and pheno signatures from this class of models.