Hadron physics as Seiberg dual of QCD

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Higgs at $125\text{GeV}$

What is this?

Too light for composite, and too heavy for the MSSM?
Examples of symmetry breaking

- from water to ice (EM for ions)
- superconductivity (QED in material)
- chiral symmetry breaking (QCD in vacuum)

There are always some dynamics behind.
Probably,

Electroweak symmetry breaking via the Higgs mechanism is also an effective description of some dynamics,

just like the Ginzburg-Landau model for superconductivity.
In fact, once we have a light Higgs, there is a huge room for new dynamics!

[Ealer, Langacker ’10]
But, why is the Higgs so light?

The naive expectation is $m_h \sim 4\pi v \sim 2\text{TeV}$.

We should look for a dynamics which is very well described as the Higgs mechanism (the linear sigma model).
Higgs mechanism as effective description?

Let’s try to get a hint from QCD.
Quark Confinement

Quarkonium mass spectrum and lattice simulations both support the **Coulomb+linear** potential model for the “static” quark anti-quark system.

\[ V(R) = -\frac{A}{R} + \sigma R. \]
Why?

There is a pretty simple picture. Confinement is dual to Higgs mechanism, and in the dual picture, the quarks are magnetic monopoles.

[Mandelstam ’75, ’t Hooft ’75]
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[Mandelstam ’75, ’t Hooft ’75]
This mechanism provides us with a classical (Higgs) picture for the quark confinement.

\[ V(R) = -\frac{A}{R} + \sigma R. \quad A \sim 0.25 - 0.5, \quad \sqrt{\sigma} \sim 430 \text{ MeV}. \]
If there is such a classical picture,

Where is the magnetic gauge boson in QCD?

There are massive vector mesons $\rho(770), \omega(782)$. 
If there is such a classical picture,

Where is the magnetic Higgs boson in QCD?

There are massive scalar mesons $a_0(980), f_0(980)$. 
Let’s construct a model of $\rho/\omega/f_0/a_0$ system as a Higgsed gauge theory, and compute the quark potential.

model: $$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^{(\omega)} F^{(\omega)\mu\nu} - \frac{1}{4} F_{\mu\nu}^{(\rho)a} F^{(\rho)\mu\nu a}$$

$$+ \frac{f_\pi^2}{2} \text{Tr} \left[ |D_\mu H_L|^2 + |D_\mu H_R|^2 \right]$$

$$- V(H_L, H_R).$$

model parameters are determined by hadron masses and

$$g = \frac{m_\rho^2}{g_\rho} \approx 5.$$
Calculate the energy of the monopole-antimonopole system in the Higgsed vacuum.

$\langle H \rangle \neq 0$

Dirac monopoles with a unit charge. (static quarks)
We could reproduce the QCD potential.

[RK, Nakamura, Yokoi ’12]

\[ V(R) = -\frac{A}{R} + \sigma R. \]

\( N_{\text{flux}} = 1 \)

Numerical results
Cornell potential

\( \kappa = 2.5 \)
\( \kappa = 1.7 \)
\( \kappa = 0.9 \)
\( \kappa = 0.1 \)

\( A = 0.25 \)
\( \sqrt{\sigma} = 400 \text{ MeV} \)

(this line)

(monopole-antimonopole separation)
I think, it is not too crazy to say that,

the low energy hadron physics is

the magnetic picture of QCD!
Can we derive the magnetic model from QCD?

It’s difficult. But I will try here by using electric-magnetic duality in SUSY QCD.
QCD from SQCD

QCD can be obtained by adding soft mass terms for the gaugino and squarks.
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QCD can be obtained by adding soft mass terms for the gaugino and squarks.

- **QCD**
  - Low energy
  - Soft terms

- **SQCD**
  - Low energy
  - soft terms

- **Seiberg dual theory**
  - (free magnetic case)
  - Soft terms

- **Low energy QCD**
  - QCD
The question is the smoothness of this limit. [Aharony, Sonnenschein, Peskin, Yankielowicz ’95]

And unfortunately, it has been shown that it is **not smooth** based on the Vafa-Witten theorem. [Arkani-hamed, Rattazzi ’98]
The problem was the spontaneous $U(1)_B$ breaking due to tachyonic soft masses for the squarks.

Actually, one can easily evade this.
model

auxiliary massive flavors

\[ W = mQ' \bar{Q} ' \]

(mass term for the auxiliary flavors)

\[ \mathcal{L}_{\text{soft}} = -\tilde{m}^2(|Q|^2 + |\bar{Q}|^2 + |Q'|^2 + |\bar{Q}'|^2) - \left( \frac{m_A}{2} \lambda \lambda + \text{h.c.} \right) - (B m Q' \bar{Q}' + \text{h.c.}) \]

(soft SUSY breaking terms)
magnetic picture

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$$L_{\text{soft}} = -\tilde{m}_q^2(|q|^2 + |\bar{q}|^2 + |q'|^2 + |\bar{q}'|^2) - \tilde{m}_M^2(|Y|^2 + |Z|^2 + |\bar{Z}|^2 + |\Phi|^2)$$

$$- \left( \frac{m_\lambda}{2} \tilde{\lambda} \tilde{\lambda} + \tilde{B}m\Lambda Y + Ah \left( q'Y\bar{q}' + q'Z\bar{q} + q\bar{Z}q' + q\Phi\bar{q} \right) + \text{h.c.} \right).$$

$$Y = -\frac{\tilde{B}m\Lambda}{\tilde{m}_M^2}.$$ split into two sectors.
# Hidden Local Symmetry

This sector has the same structure as the HLS.

\[
q = \bar{q} = v1 \neq 0, \quad \Phi = v_{\Phi}1 \neq 0,
\]

break chiral symmetry and give masses to magnetic gauge bosons (\(\rho\) meson) while leaving \(U(1)_B\) symmetry unbroken.

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Magnetic picture:

$SU(N_f)_L \rightarrow SU(N_f) \rightarrow SU(N_f)_R$

$\bar{Z}$ $q$ $q'$ $\bar{q}$ $\bar{q}'$ $Z$

$\Phi$

$Z$ and $q'$ have quantum numbers of quarks. They get masses from chiral symmetry breaking.

Pretty similar to low energy QCD!
Indeed,

one can find such a vacuum is realized in a large region of the parameter space.
Theory space

SQCD (electric)  QCD  large N QCD?

SQCD + extra Nc flavors  Hidden Local Symmetry

SQCD (magnetic)  QCD (hadron world)  5d gravity?
I think SQCD is smoothly connected to QCD through the mass deformed $N_f+N_c$ flavor theory.

If that’s the case, chiral symmetry breaking = magnetic Higgs mechanism = confinement

$\rho$ meson is the magnetic gauge boson!

[Seiberg ’95, Harada, Yamawaki ’99, Komargodski ’10, RK ’11, Abel, Barnard ’12]
Electroweak symmetry breaking may be similar. Namely, the SM may be the magnetic picture of some fundamental theory.

[Seiberg ’95, Maekawa’96, Strassler ’96, ..., RK, Fukushima, Yamaguchi ’10 Craig, Stolarsky, Thaler ’11, Csaki, Shirman, Terning ’11, Csaki, Randall, Terning ’11]

I think it is very important to look for a magnetic gauge boson (vector resonance) next at the LHC!
electroweak physics is similar?

Higgs = composite field

= Magnetic degree of freedom?

= dual to some dynamical system

But we know that theories too similar to QCD will not be good, since that’s just the QCD-like technicolor paradigm.

We need a light Higgs boson!
The SQCD model we studied for QCD has two limits.

1. non-SUSY limit: it’s supposed to be QCD.

   \[\rightarrow\text{technicolor}\]

2. SUSY limit: \textcolor{red}{massless} Higgs fields.

   \[\rightarrow\text{MSSM-like}\]

In between two limits, one can obtain a theory with partially composite Higgs.
As the first trial, I consider the very same model as the one used for QCD.

\[ W = mQ' \bar{Q}' \]

\[ \mathcal{L}_{\text{soft}} = -\tilde{m}^2(|Q|^2 + |\bar{Q}|^2 + |Q'|^2 + |\bar{Q}'|^2) - \left( \frac{m_\lambda}{2} \lambda \lambda + \text{h.c.} \right) - (BmQ' \bar{Q}' + \text{h.c.}) \]
model

\[ N_c = 3, \quad N_f = 2 \]

embed \[ SU(2)_L \times U(1)_Y \]

anomalous?
model

$N_c=3, N_f=2$

embed $SU(2)_L \times U(1)_Y$

embed $SU(3)_c$

anomalous?

Subtract top+bottom (and Higgs) from the MSSM
This is the super-topcolor model.

[RK, Fukushima, Yamaguchi '10]
In fact, SU(3) 5 flavor theory is in the conformal window:

\[ \frac{3N_C}{2} < N_f < 3N_C \]

\[ \rightarrow \quad 4.5 < N_f < 9 \quad \text{for} \quad N_c = 3 \]

\( N_f = 5 \) is at the most strongly coupled point in the conformal window.

This means the Seiberg dual theory is at the most weakly coupled point in the conformal window.

\[ \rightarrow \quad \text{One can do perturbative calculation (expansion in terms of } 1/N_f) \]

\( \text{(particle picture in the dual theory)} \)
Weakly coupled descriptions

Standard Model

SU(2) dual gauge theory (conformal)

$q, \bar{q}, M$

SU(3)TC gauge theory

(asymptotic free --> conformal)

$Q, \bar{Q}$

$m_{SUSY}$

$\Lambda$

Energy scale
We obtain the MSSM coupled to weakly coupled CFT.

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Magnetic picture:

Hidden local symmetry

\[ SU(N_f)_L \quad SU(N_f) \quad SU(N_f)_R \]

Higgs fields

\[ \Phi \]

\[ Z \quad q \quad q' \quad \bar{q} \]

Z and q’ are top/bottom quarks!

MSSM-like model as magnetic picture!
Sketch

• Higgs mass can be enhanced by a coupling to the CFT sector. [Fukushima, RK, Yamaguchi ’10, Gherghetta, Pomarol ’11, Heckman, Kumar, Vafa, Wecht ’11, Evans, Ibe, Yanagida ’12, RK, Nakai, Luty ’12]

• stop mass has IR fixed point at zero when we ignore the gluino mass and D-terms. The stop is naturally light, and it is good for naturalness. [Fukushima, RK, Yamaguchi ’10, Csaki, Randall, Terning ’11]
Summary

• A possible smooth path from SQCD to QCD is found.

• The $\rho$ meson can be interpreted as the magnetic gauge boson.

• The Higgs mechanism in the SM may also be the magnetic picture.

• I think it is very important to look for a vector resonance!