Emergent Higgs and Color Confinement

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What is the microscopic physics behind the Higgs mechanism?
We know that

- EWSB happened twice: one by Higgs and another by QCD (chiral symmetry breaking).
- We probably need more spatial dimensions for the quantization of gravity.
Scenario

Standard Model in extra dim. (no Higgs)

\[\text{compactification} + \text{non-perturbative effects of SM gauge interactions}\]

Standard Model (with Higgs)

"Self-breaking"
Extra dimensional gauge theory?

5-dimensional gauge theory:

- two parameters: $g_5, R$
- $\dim(g_5) = -1/2$

$\longrightarrow$ cut-off scale

$$\Lambda = \frac{8\pi^2}{g_5^2}$$

large extra dim.

$$\frac{1}{R} \ll \Lambda$$

= weakly coupled

We get a weakly coupled theory with KK modes.

$$\frac{1}{g_4^2} = \frac{2\pi R}{g_5^2} = \frac{R\Lambda}{4\pi} \gg \frac{1}{4\pi}$$
We need a definition of the theory to discuss this region.

We can hope “???” is going to be our Higgs.

We need a **definition** of the theory to discuss this region.

(results depend on how we cut off the theory..)
A (possible) definition

It has been proposed that

provides a UV completion.

[Arkani-Hamed, Cohen, Georgi ’01]
[Hill, Pokorski, Wang ’01][Cheng, Hill, Pokorski, Wang ’01]
**Usual story:** mimics extra-dimension only at low energy

N-site model:

\[
\frac{1}{R} = \frac{4\pi gv}{N}, \quad \Lambda = \frac{(4\pi)^2 v}{g}, \quad \Lambda_{\text{dec.}} \equiv \frac{N}{R} = 4\pi gv
\]

g: gauge coupling at each site, v: vev of the link fields

\[
\text{The } N \to \infty \text{ limit while fixing } R \text{ and } \Lambda \text{ means}
\]

\[
g \to \infty, \quad v \to \infty
\]

But, we cannot go beyond \( g \gg 1 \).

→ One cannot take the continuum limit.

→ Equivalent to say that we cannot discuss physics beyond the scale \( \Lambda \) since \( \Lambda > \Lambda_{\text{dec.}} \).
But with $N=2$ SUSY,

\[ \text{SU}(N_c) \rightarrow \text{SU}(N_c) \rightarrow \cdots \rightarrow \text{SU}(N_c) \]

each site is a finite theory.

$(N_f=2N_c)$

one can just take whatever values of $g$.

\[ \rightarrow \quad \text{We can go beyond } \Lambda!! \]
6th dimension

KK modes
(electric)

S-dual

another KK tower
(magnetic)

\[
\begin{align*}
2gv/N &= 1/R_5 \\
gv/N &= 1/R_6 = \Lambda \\
0 &= \text{(naive cut off)}
\end{align*}
\]

appearance of 6th dimension

Interesting.
$\frac{1}{R_5} \gg \Lambda$ means,

- **KK modes (electric)**
  - $2gv/N$
  - $\vdots$
  - $gv/N = \frac{1}{R_5}$
  - $0$

- **another KK tower (magnetic)**
  - $\vdots$

The magnetic picture gets better description.
Emergent Higgs

Higgs may be in the emergent degrees of freedom.

$K K$ modes (electric)  another $K K$ tower (magnetic)

\[ g v / N = 1 / R_5 \]

\[ v / g = 1 / R_6 = \Lambda \]

this is $QCD$

Higgs from this sector?

That would be an interesting unification.
a toy model: 2-site model

\[ W = \sqrt{2}g (q_1 \bar{Q} q_2 + t_1^c Q \bar{t}_2^c + b_1^c Q \bar{b}_2^c + \bar{Q} \Phi Q - v^2 \text{Tr} \Phi + v q \bar{q}_2 q_2 + v t \bar{t}_2 t_2 + v b \bar{b}_2 b_2) . \]
For $\Lambda_1 \ll 4\pi v$ (weak coupling)

$$\text{SU}(3)_1 \times \text{SU}(3)_2 \rightarrow \text{SU}(3)_{1+2}$$

We get MSSM without Higgs as low energy theory.

Below, we study the case with

$$\Lambda_1 \gg 4\pi v$$ (strongly coupled region)

$$\rightarrow$$ we will see that magnetic degrees of freedom appear.
Seiberg duality [Seiberg '94]

SU(3) \_1 factor gets strong

\[ \text{weakly coupled magnetic picture (CFT)} \]

Higgs appeared.

below the dynamical scale $\Lambda_1$.‌
weakly coupled

\[ D(H_d) = 1.03, \quad D(H_u) = 1.13, \quad D(q) = 1.13, \quad D(t^c) = 1.17, \]
\[ D(f) = 0.99, \quad D(\bar{f}_u) = 0.99, \quad D(\bar{f}_d) = 0.88, \quad D(f') = 0.84, \quad D(\bar{f}') = 0.88. \]

\[ \frac{\tilde{g}}{4\pi} \sim 0.41, \quad \frac{\lambda_d}{4\pi} \sim 0.11, \quad \frac{\lambda_u}{4\pi} \sim 0.26, \quad \frac{\lambda_t}{4\pi} \sim 0.29, \quad \frac{\lambda_q}{4\pi} \sim 0.26, \]

(we assumed \( \lambda_b \ll 4\pi \) by taking small \( v_b \))

\[ W = \lambda_d \bar{f}_u H_d f + \lambda_u \bar{f}_d H_u f + \lambda_t \bar{f}_u t^c f' + \lambda_b \bar{f}_d b^c f' + \lambda_q \bar{f}' q f + \frac{(4\pi v)^2}{\Lambda_1} \bar{f}' f', \]
\[ = \Lambda' \]

\( \Lambda_1 \gg 4\pi v \quad \rightarrow \quad \Lambda' \ll 4\pi v \)

(appearance of light degrees of freedom)
SU(2)$_1$ factor confines

\[ W = \lambda_d f_u H_d f + \lambda_u f_d H_u f - \frac{\lambda_q \lambda_t}{\Lambda'} f f_u t^c q - \frac{\lambda_q \lambda_b}{\Lambda'} f f_d b^c q. \]

(note: at this stage, \( \lambda \)'s get renormalized by \( O(1) \) factors.)

\[ <H'> = 0 \]

\[ <S> \neq 0 \]

Partially composite Higgs \[ [RK, Luty, Nakai '12] \]

\[ \frac{\lambda_u \Lambda'}{4\pi} H_u H'_d + \frac{\lambda_d \Lambda'}{4\pi} H_d H'_u - \frac{\lambda_q \lambda_t}{4\pi} H'_u t^c q - \frac{\lambda_q \lambda_b}{4\pi} H'_d b^c q. \]

\[ (H'_u H'_d - S \bar{S}) = \frac{\Lambda'^2}{(4\pi)^2}. \]

\[ <H'> = 0 \]

\[ <S> \neq 0 \]

S is not dynamical

one can integrate them out.
arriving at the MSSM-like model

\[ W = \frac{\lambda_u \Lambda'}{4\pi} H_u H'_d + \frac{\lambda_d \Lambda'}{4\pi} H_d H'_u - \frac{\lambda_q \lambda_t}{4\pi} H'_u t^c q - \frac{\lambda_q \lambda_b}{4\pi} H'_d b^c q. \]

\[ K \supset \frac{\Lambda'}{\Lambda'} H'_u H'_d + \text{h.c.} \]

\( \mu \)-like terms

obtained from kinetic terms for S and \( \bar{S} \).

We consider SUSY breaking by turning on

\( \Lambda'(1 + m_{\text{SUSY}} \theta^2) \) with \( m_{\text{SUSY}} \sim \Lambda' \sim 1 \text{ TeV} \)
Higgs potential

\[ V \supset \frac{m_{\text{SUSY}}^2}{(4\pi)^2} (|\lambda_u H_u|^2 + |\lambda_d H_d|^2) + \frac{1}{(4\pi)^2} (|\lambda_u H_u|^4 + |\lambda_d H_d|^4). \]

\[ V \supset m_{\text{SUSY}}^2 (|H'_u|^2 + |H'_d|^2) + \cdots \]

\[ V \supset m_{\text{SUSY}} \left( \frac{\lambda_u \Lambda'}{4\pi} H_u H'_d + \frac{\lambda_d \Lambda'}{4\pi} H_d H'_u + \text{h.c.} \right), \]

\[ W \supset \frac{\Lambda'}{4\pi} (\lambda_u H_u H'_d + \lambda_d H_d H'_u) + m_{\text{SUSY}} H'_u H'_d. \]

\[ V \supset m_{\text{SUSY}}^2 H'_u H'_d + \text{h.c.} \]

H\(_d\) is the main Higgs direction

H\('\) are heavy

Partially composite Higgs

[RK, Luty, Nakai ’12]
$m_h = 126$ GeV

Higgs quartic term:

$$\frac{\lambda_d^4}{(4\pi)^2} + \frac{g_L^2 + g_Y^2}{2} \sim \frac{m_h^2}{\langle H \rangle^2} \sim 0.5, \quad \frac{\lambda_d}{4\pi} \sim 0.2.$$ 

not bad.

required size of the Higgs quadratic terms

$$\delta = \frac{m_h^2/2}{(\lambda_d m_{\text{SUSY}}/4\pi)^2} = 20\% \cdot \left(\frac{m_{\text{SUSY}}}{1 \text{ TeV}}\right)^{-2} \left(\frac{\lambda_d/4\pi}{0.2}\right)^{-2}.$$ 

typical size

not bad.

fixed point values: $\frac{g}{4\pi} \sim 0.41$, $\frac{\lambda_d}{4\pi} \sim 0.11$, $\frac{\lambda_u}{4\pi} \sim 0.26$, $\frac{\lambda_t}{4\pi} \sim 0.29$, $\frac{\lambda_q}{4\pi} \sim 0.26$. 
top mass

\[ K \equiv \frac{\lambda_q \lambda_t \lambda_d}{(4\pi)^2} \frac{1}{\Lambda_{t}^{\ast}} H_d^t t^e q, \quad W \equiv -\frac{\lambda_q \lambda_t}{4\pi} H_u^t t^e q. \]

\[ m_t \sim \frac{\lambda_q \lambda_t \lambda_d}{(4\pi)^2} \langle H_d \rangle \sim 160 \text{ GeV} \cdot \left( \frac{\lambda_d/4\pi}{0.2} \right) \left( \frac{\lambda_q/4\pi}{0.6} \right) \left( \frac{\lambda_t/4\pi}{0.6} \right). \]

not bad.

note: top obtains a mass from \( H_d \)

fixed point values: \( \frac{\tilde{g}}{4\pi} \sim 0.41, \quad \frac{\lambda_d}{4\pi} \sim 0.11, \quad \frac{\lambda_u}{4\pi} \sim 0.26, \quad \frac{\lambda_t}{4\pi} \sim 0.29, \quad \frac{\lambda_q}{4\pi} \sim 0.26, \)
stop/sbottom

\[ m_{\tilde{t}} \sim m_{\tilde{b}} \sim \frac{\lambda_q}{4\pi} m_{\text{SUSY}} \sim 600 \text{ GeV} \cdot \left( \frac{\lambda_q/4\pi}{0.6} \right) \left( \frac{m_{\text{SUSY}}}{1 \text{ TeV}} \right). \]

should be observed soon!
(should have been observed?)

fixed point values: \[ \frac{\tilde{g}}{4\pi} \sim 0.41, \quad \frac{\lambda_d}{4\pi} \sim 0.11, \quad \frac{\lambda_u}{4\pi} \sim 0.26, \quad \frac{\lambda_t}{4\pi} \sim 0.29, \quad \frac{\lambda_q}{4\pi} \sim 0.26, \]
Higgsino

\[ m_{\tilde{h}} \sim \frac{\lambda_u \lambda_d}{(4\pi)^2} \frac{\Lambda'^2}{m_{\text{SUSY}}} \sim 120 \text{ GeV} \cdot \left( \frac{\lambda_d}{4\pi} \right) \left( \frac{\lambda_u}{4\pi} \right) \left( \frac{\Lambda'}{1 \text{ TeV}} \right)^2 \left( \frac{m_{\text{SUSY}}}{1 \text{ TeV}} \right)^{-1}. \]

pretty light.

fixed point values: \[ \frac{\hat{g}}{4\pi} \sim 0.41, \quad \frac{\lambda_d}{4\pi} \sim 0.11, \quad \frac{\lambda_u}{4\pi} \sim 0.26, \quad \frac{\lambda_t}{4\pi} \sim 0.29, \quad \frac{\lambda_q}{4\pi} \sim 0.26, \]
dynamical sector

\[ \Lambda' \sim 1 \text{ TeV} \]

We can access to UV dynamics of QCD.

We expect \( \rho \)-like resonances (\( W' \), \( Z' \))

very interesting.
by-product
(confinement by CFL)

This provides an interesting deformation of QCD.
For $v \gg \Lambda_1, \Lambda_2$, this is just QCD.
Starting with $N=2$ SUSY and adding a small breaking of $N=2$ SUSY to $N=1$

$\Lambda_1 \gg \Lambda_2 \gg \nu$

$N_f$ quarks

$\text{SU}(N_c)_1 \quad Q \quad \text{SU}(N_c)_2$

$N_f$ dual quarks

dual

$U(N_f)$

magnetic picture
color-flavor locking

$N_f$ dual quarks turning on $v$

$$\langle q \rangle = \langle \bar{q} \rangle = \left( \begin{array}{c} \frac{v}{\sqrt{N_c}} \\ \vdots \\ \frac{v}{\sqrt{N_c}} \end{array} \right)$$

magnetic gauge bosons of $U(N_f)$ behave as vector mesons $\rho$ and $\omega$.

string formation from $U(1)$ breaking $\rightarrow$ confinement

[Shifman and Yung '07, ...]

low energy QCD as magnetic picture?

[See also Mandelstam '75, 't Hooft '75]
May not be totally crazy.

Hidden Local Symmetry
[Bando, Kugo, Uehara, Yamawaki, Yanagida '85]

\[ \mathcal{L} = -\frac{1}{4g_H^2} F_{\mu\nu}^a F^{a\mu\nu} + \frac{a f_\pi^2}{2} \text{tr} \left[ |D_\mu U_L|^2 + |D_\mu U_R|^2 \right] + \frac{(1 - a) f_\pi^2}{4} \text{tr} \left[ |\partial_\mu (U_L U_R)|^2 \right]. \]

We see such a picture in the real world.
Quiver deformation provides us with an understanding of HLS as the magnetic gauge theory.

See also
[Seiberg '95, Harada, Yamawaki '99, Komargodski '10, RK '11, Abel, Barnard '12]
Moreover, one can construct a string configuration made of $\rho, \omega,$ and $f_0$ and calculate an energy.

$$g_\rho = (340 \text{ MeV})^2,$$
$$m_\rho = 770 \text{ MeV},$$
$$\sim m_\omega$$
$$m_S = m_A = 980 \text{ MeV},$$
(scalar meson masses)

this line

$$V(R) = -\frac{A}{R} + \sigma R.$$  
$$A = 0.25 \quad \sqrt{\sigma} = 400 \text{ MeV}$$
Comparing to lattice QCD

pretty consistent.

confining string = hadron vortex
Summary

• We studied a quiver model for EWSB. The Higgs fields emerge as magnetic degrees of freedom. By adding SUSY breaking terms, EWSB can occur while 125GeV Higgs boson is naturally explained.

• By using a similar model, we see that the color confinement can be understood as the magnetic color-flavor locking.