Emergent Higgs and Color Confinement

Ryuichiro Kitano (KEK, Sokendai)

seminar@Galileo Galilei Institute, June 19, 2013

126GeV

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)

$\downarrow$ compactification
+ non-perturbative effects
of SM gauge interactions

Standard Model (with Higgs)

"Self-breaking"

[Dobrescu '98][Cheng, Dobrescu, Hill '99][Arkani-Hamed, Dimopoulos '98]
[Arkani-Hamed, Cheng, Dobrescu, Hall '00]

Extra dimensional gauge theory?

5-dimensional gauge theory:

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

$\longrightarrow$ cut-off scale $\Lambda = \dfrac{8\pi^2}{g_5^2}$

large extra dim.

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

= weakly coupled

$\longrightarrow$ We get a weakly coupled theory with KK modes.

$$\frac{1}{g_4^2} = \frac{2\pi R}{g_5^2} = \frac{R\Lambda}{4\pi} \gg \frac{1}{4\pi}$$

small extra dim. or high energy

$$\frac{1}{R} \gg \Lambda \quad \text{or} \quad E \gg \Lambda$$

= strongly coupled

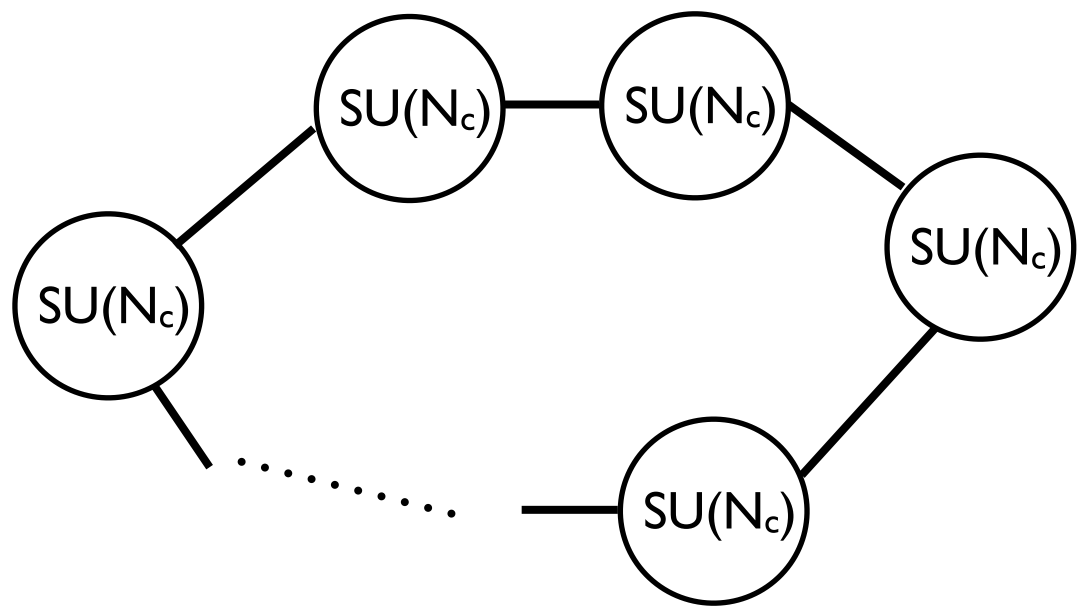
$\longrightarrow$ "???" (non-perturbative)

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: $\frac{1}{R} = \frac{4\pi g v}{N}, \quad \Lambda = \frac{(4\pi)^2 v}{g} \qquad \Lambda_{\rm dec.} \equiv \frac{N}{R} = 4\pi g v$

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

$\downarrow$

The N→∞ limit while fixing R and Λ means

$$g \to \infty\,, \quad v \to \infty$$

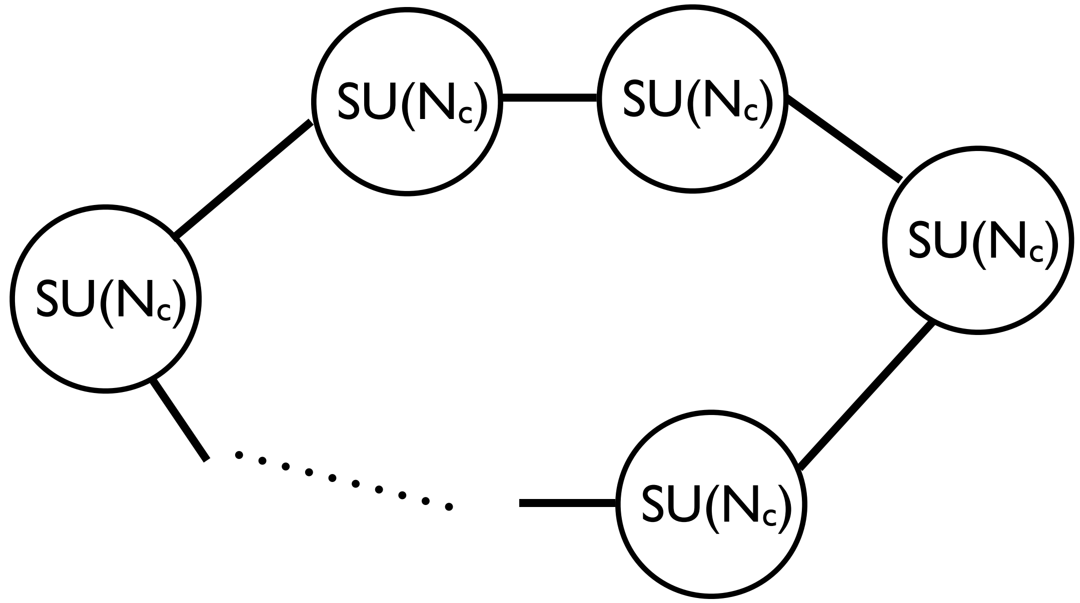
But, we cannot go beyond $g \gg 1$.

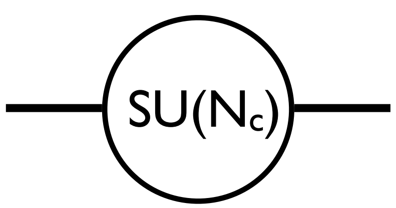
⟶ One cannot take the continuum limit.

⟶ Equivalent to say that we cannot discuss physics beyond the scale Λ since $\Lambda > \Lambda_{\rm dec.}$

[Arkani-Hamed, Cohen, Kaplan, Karch, Motl '01]

But with N=2 SUSY,





each site is a finite theory.
(N_f=2N_c)

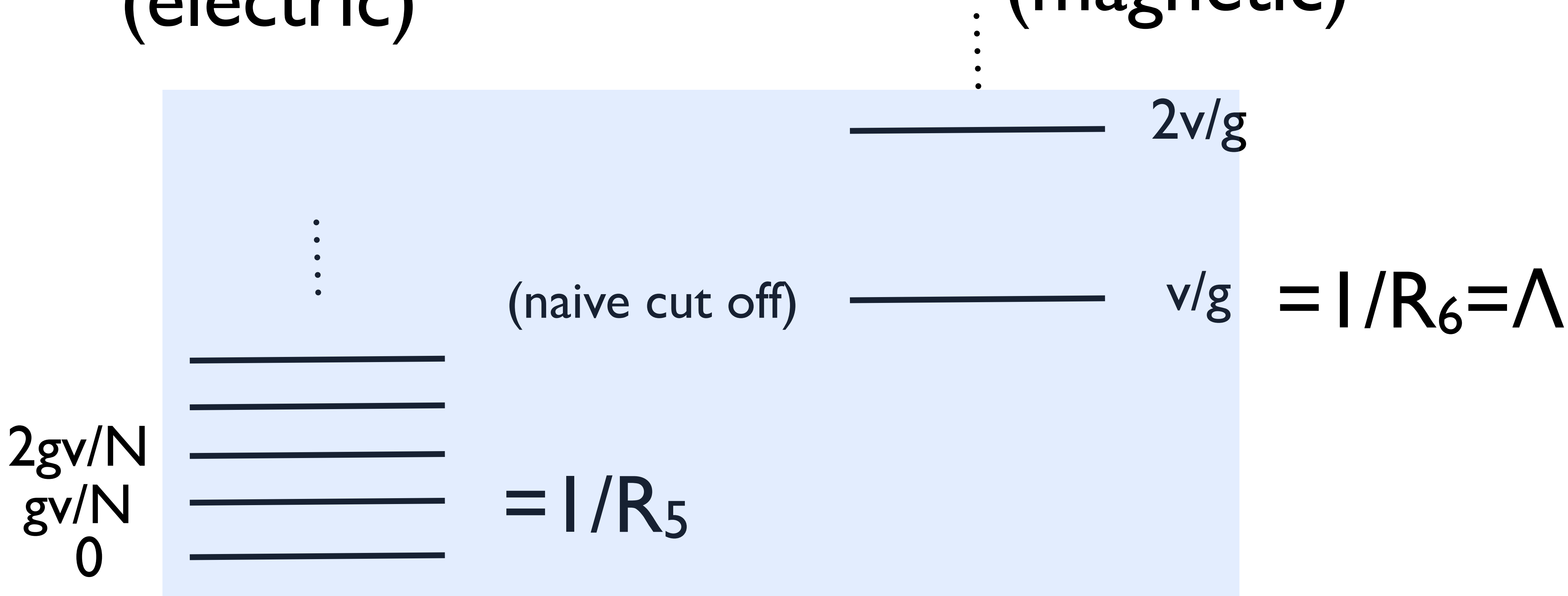
one can just take whatever values of g.

$\longrightarrow$ We can go beyond Λ!!

[Arkani-Hamed, Cohen, Kaplan, Karch, Motl ’01]

6th dimension

KK modes (electric) $\xleftrightarrow{\text{S-dual}}$ another KK tower (magnetic)



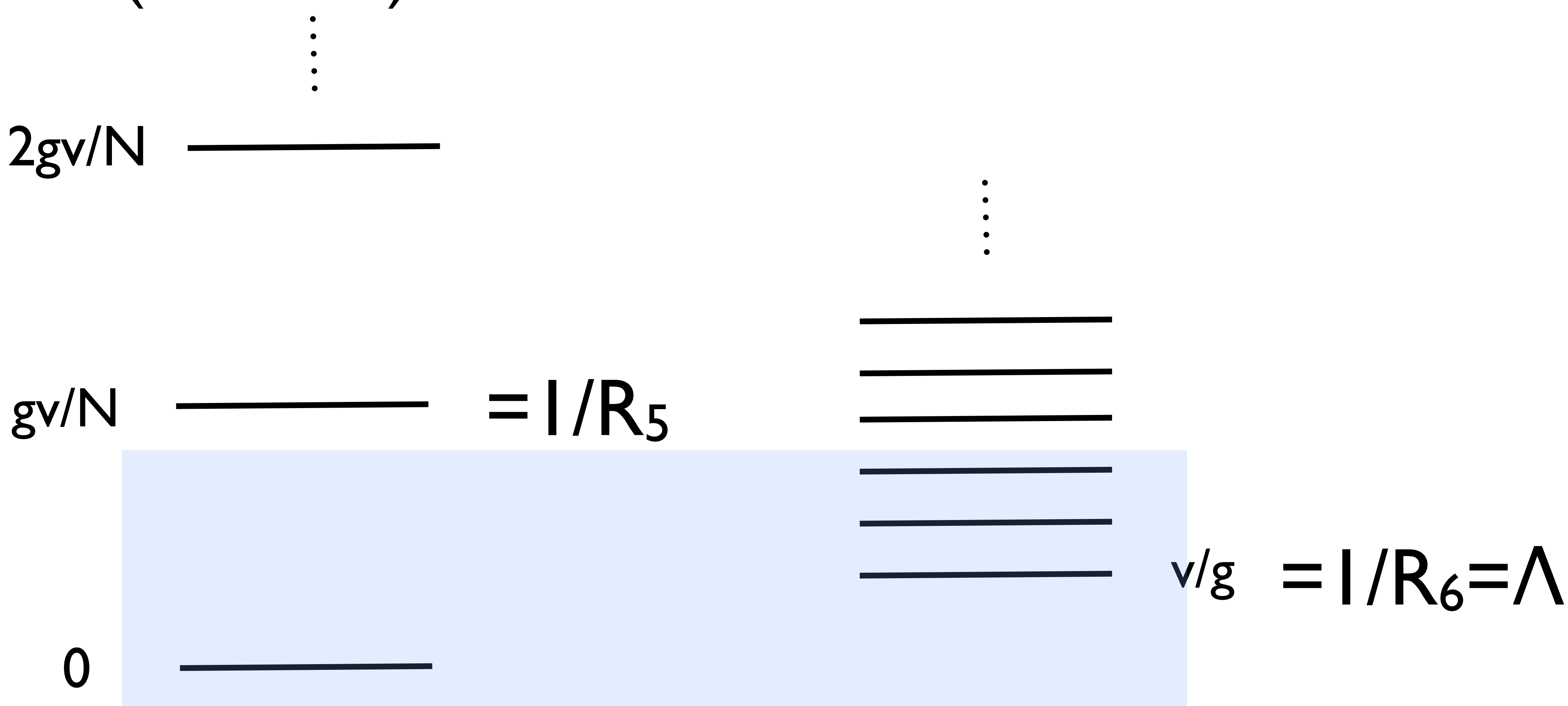
appearance of 6th dimension

Interesting.

$1/R_5 \gg \Lambda$ means,

KK modes
(electric)

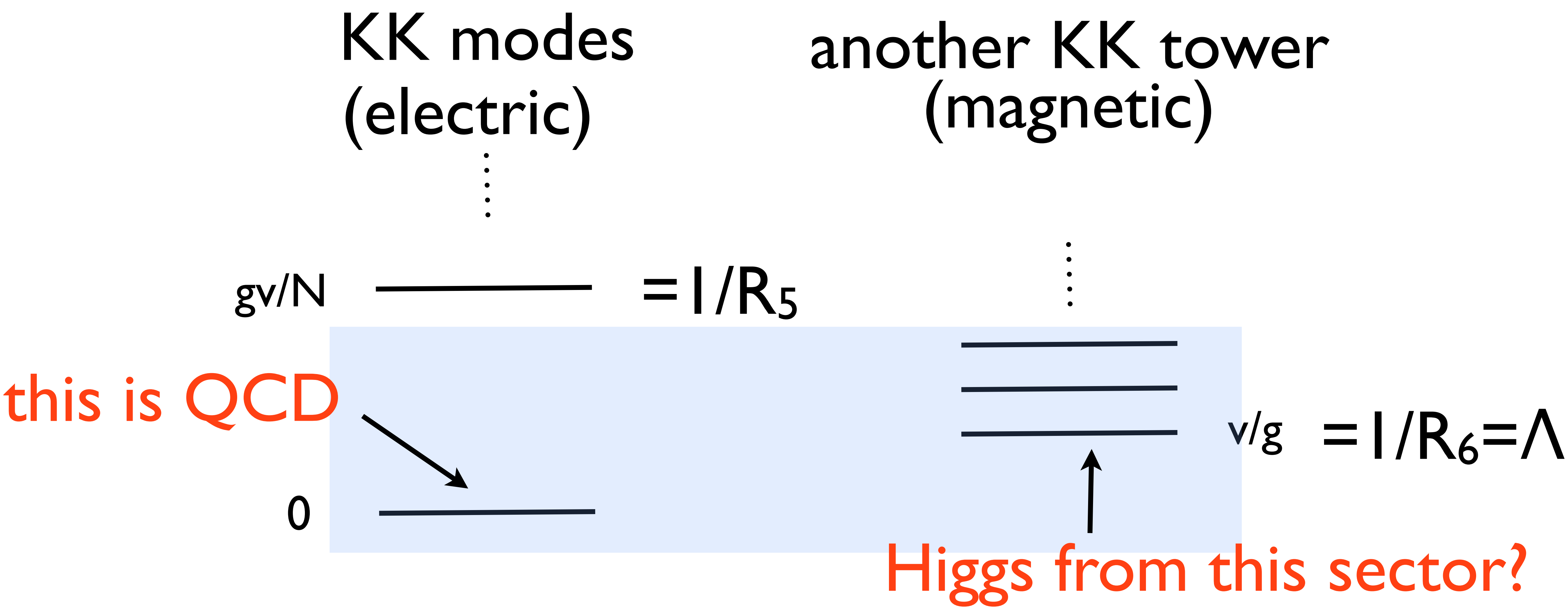
another KK tower
(magnetic)



magnetic picture gets better description.

Emergent Higgs

Higgs may be in the emergent degrees of freedom.

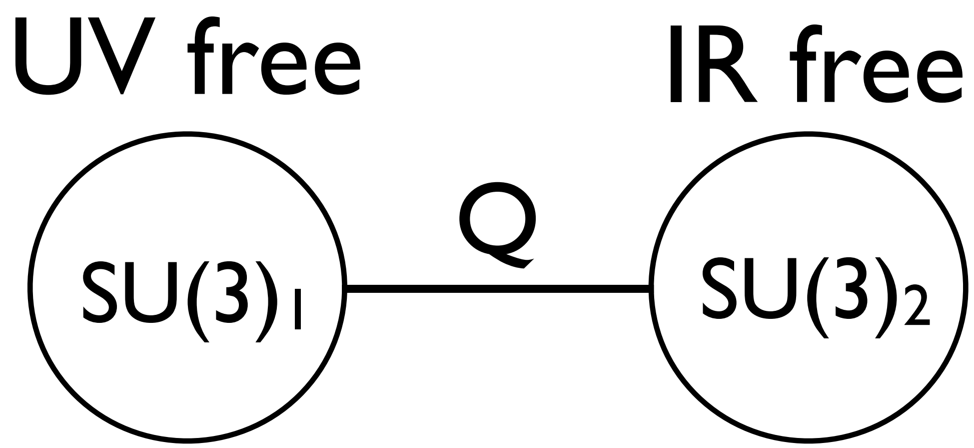


That would be an interesting unification.

a toy model: 2-site model

[RK, Nakai '12]

top/bottom



other quarks
+ top/bottom

N=2
structure

KK modes

	$SU(3)_1$	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
Q	3	$\bar{3}$	1	1_0
$\bar{Q}$	$\bar{3}$	3	-1	1_0
Φ	1	$1+8$	0	1_0
q_1	3	1	1	$2_{1/6}$
t_1^c	$\bar{3}$	1	-1	$1_{-2/3}$
b_1^c	$\bar{3}$	1	-1	$1_{1/3}$
q_2	1	3	0	$2_{1/6}$
t_2^c	1	$\bar{3}$	0	$1_{-2/3}$
b_2^c	1	$\bar{3}$	0	$1_{1/3}$
$\bar{q}_2$	1	$\bar{3}$	0	$\bar{2}_{-1/6}$
$\bar{t}_2^c$	1	3	0	$1_{2/3}$
$\bar{b}_2^c$	1	3	0	$1_{-1/3}$

Topcolor model [Hill '91]
[RK, Fukushima, Yamaguchi '10]
([Craig, Stolarski, Thaler '11][Csaki, Shirman, Terning '11][Cohen, Hook, Torroba '12][Evans, Ibe, Yanagida '12]...)

gauged
(Lagrange multiplier)
(<Q>=v is fixed)

no Higgs field

$$W = \sqrt{2}g\left(q_1\bar{Q}\bar{q}_2 + t_1^c Q\bar{t}_2^c + b_1^c Q\bar{b}_2^c + \bar{Q}\Phi Q - v^2\mathrm{Tr}\Phi + v_q\bar{q}_2 q_2 + v_t\bar{t}_2^c t_2^c + v_b\bar{b}_2^c b_2^c\right).$$

For $\Lambda_1 \ll 4\pi v$ (weak coupling)

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

We get MSSM without Higgs as low energy theory.

Below, we study the case with

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

$\longrightarrow$ we will see that magnetic degrees of freedom appear.

Seiberg duality [Seiberg '94]

$SU(3)_1$ factor gets strong

$\longrightarrow$ weakly coupled magnetic picture (CFT)

	$SU(3)_1$	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
Q	3	$\overline{3}$	1	1_0
$\bar{Q}$	$\overline{3}$	3	-1	1_0
Φ	1	$1+8$	0	1_0
q_1	3	1	1	$2_{1/6}$
t_1^c	$\overline{3}$	1	-1	$1_{-2/3}$
b_1^c	$\overline{3}$	1	-1	$1_{1/3}$
q_2	1	3	0	$2_{1/6}$
t_2^c	1	$\overline{3}$	0	$1_{-2/3}$
b_2^c	1	$\overline{3}$	0	$1_{1/3}$
$\bar{q}_2$	1	$\overline{3}$	0	$\bar{2}_{-1/6}$
$\bar{t}_2^c$	1	3	0	$1_{2/3}$
$\bar{b}_2^c$	1	3	0	$1_{-1/3}$

$\longrightarrow$

Higgs appeared.

	$SU(2)_1$	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
f	2	1	$3/2$	2_0
$\bar{f}_u$	$\overline{2}$	1	$-3/2$	$1_{1/2}$
$\bar{f}_d$	$\overline{2}$	1	$-3/2$	$1_{-1/2}$
H_u	1	1	0	$2_{1/2}$
H_d	1	1	0	$2_{-1/2}$
f'	2	3	$3/2$	$1_{1/6}$
$\bar{f}'$	$\overline{2}$	$\overline{3}$	$-3/2$	$1_{-1/6}$
q	1	3	0	$2_{1/6}$
t^c	1	$\overline{3}$	0	$1_{-2/3}$
b^c	1	$\overline{3}$	0	$1_{1/3}$

below the dynamical scale Λ_1.

weakly coupled

a-maximization gives [Intriligator, Wecht '03]

$$D(H_d) = 1.03, \quad D(H_u) = 1.13, \quad D(q) = 1.13, \quad D(t^c) = 1.17,$$

$$D(f) = 0.99, \quad D(\bar{f}_u) = 0.99, \quad D(\bar{f}_d) = 0.88, \quad D(f') = 0.84, \quad D(\bar{f}') = 0.88.$$

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

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

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

$$\Lambda_1 \gg 4\pi v \longrightarrow \Lambda' \ll 4\pi v$$ (appearance of light degrees of freedom)

below Λ'

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

$$W = \lambda_d \bar{f}_u H_d f + \lambda_u \bar{f}_d H_u f - \frac{\lambda_q \lambda_t}{\Lambda'} f \bar{f}_u t^c q - \frac{\lambda_q \lambda_b}{\Lambda'} f \bar{f}_d b^c q.$$

SU(2)$_1$ factor confines

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

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

	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
H_u	1	0	$2_{1/2}$
H_d	1	0	$2_{-1/2}$
H'_u	1	0	$2_{1/2}$
H'_d	1	0	$2_{-1/2}$
S	1	3	1
$\bar{S}$	1	-3	1
q	3	0	$2_{1/6}$
t^c	$\bar{3}$	0	$1_{-2/3}$
b^c	$\bar{3}$	0	$1_{1/3}$

gauged

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

<H'> = 0
<S> ≠ 0
at SUSY level.

S is not dynamical
one can integrate them out.

arriving at the MSSM-like model

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

$$K \ni \frac{\Lambda'^\dagger}{\Lambda'} H'_u H'_d + \text{h.c.}$$

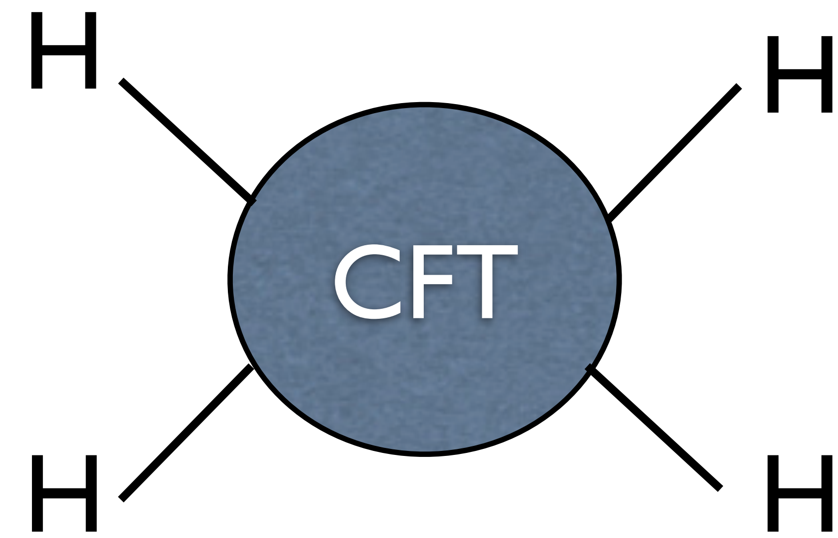
μ-like terms

obtained from kinetic terms for S and $\overline{\text{S}}$.

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



$$V \ni \frac{m_{\rm SUSY}^2}{(4\pi)^2}(|\lambda_u H_u|^2 + \underline{|\lambda_d H_d|^2}) + \frac{1}{(4\pi)^2}(|\lambda_u H_u|^4 + |\lambda_d H_d|^4).$$

$$V \ni m_{\rm SUSY}^2(|H_u'|^2 + |H_d'|^2) + \cdots$$

H_d is the main Higgs direction

$$V \ni m_{\rm SUSY}\left(\frac{\lambda_u \Lambda'}{4\pi} H_u H_d' + \frac{\lambda_d \Lambda'}{4\pi} H_d H_u' + \text{h.c.}\right),$$

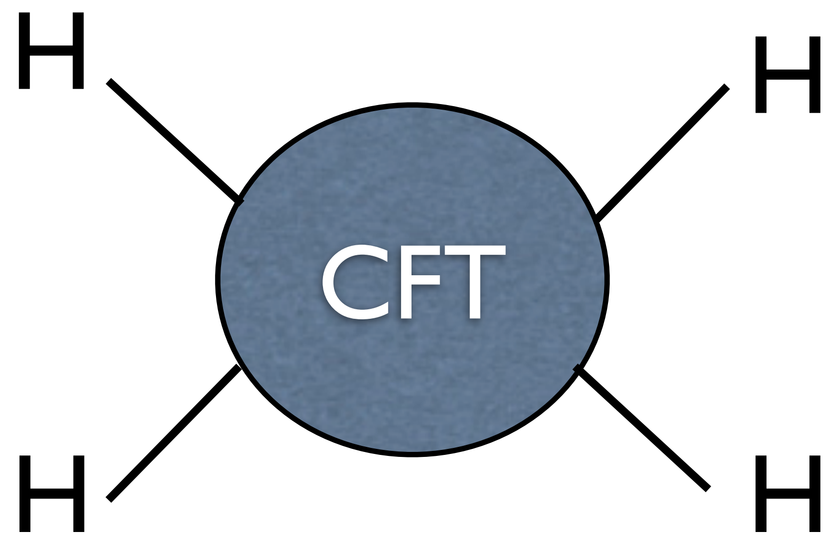
$$W \ni \frac{\Lambda'}{4\pi}(\lambda_u H_u H_d' + \lambda_d H_d H_u') + m_{\rm SUSY} H_u' H_d'.$$

H' are heavy

$$V \ni m_{\rm SUSY}^2 H_u' H_d' + \text{h.c.}$$

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

$$m_h = 126 \text{ GeV}$$



Higgs quartic term:

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

not bad.

tuning:

required size of the Higgs quadratic terms

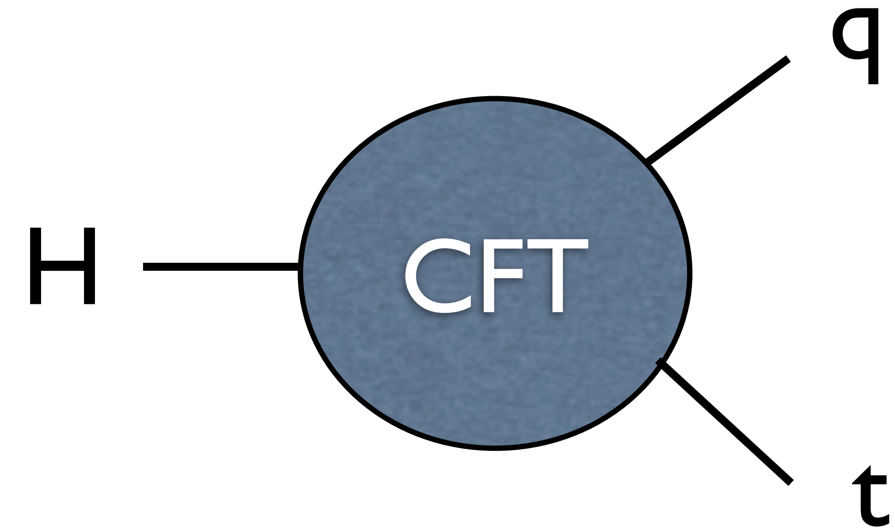
$$\delta = \frac{m_h^2/2}{(\lambda_d m_{\text{SUSY}}/4\pi)^2,} = 20\% \cdot \left(\frac{m_{\text{SUSY}}}{1 \text{ TeV}}\right)^{-2} \left(\frac{\lambda_d/4\pi}{0.2}\right)^{-2}.$$

typical size

not bad.

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

top mass



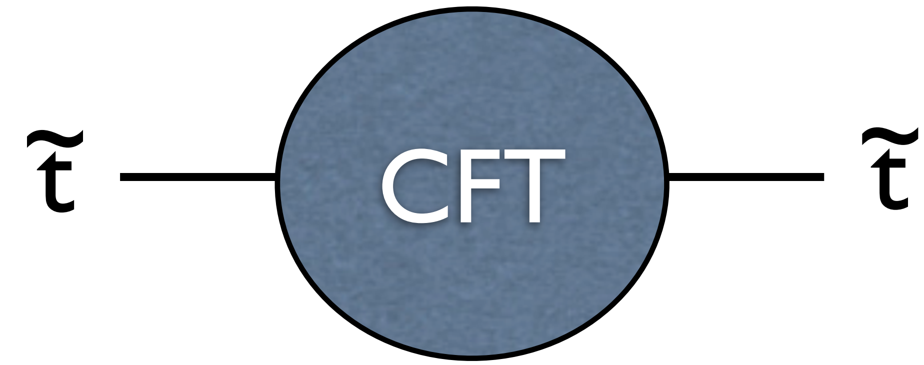
$$K \ni \frac{\lambda_q \lambda_t \lambda_d}{(4\pi)^2} \frac{1}{\Lambda'^\dagger} H_d^\dagger t^c q, \qquad W \ni -\frac{\lambda_q \lambda_t}{4\pi} H_u' t^c q \,.$$

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

not bad.

note: top obtains a mass from H_d

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



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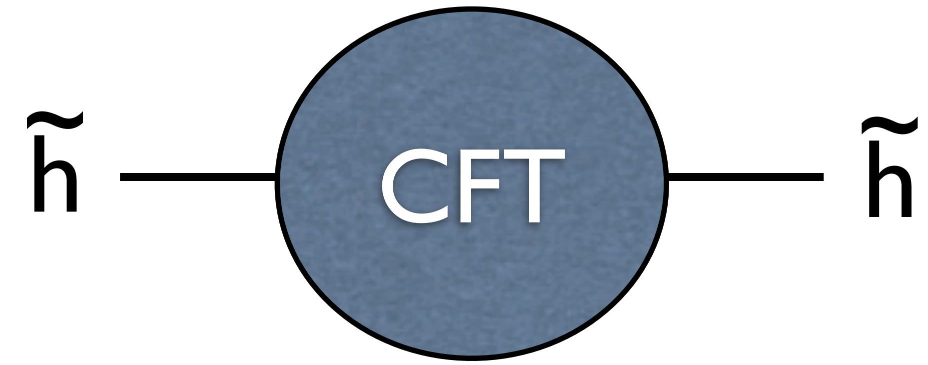
$$m_{\tilde{t}} \sim m_{\tilde{b}} \sim \frac{\lambda_q}{4\pi} m_{\mathrm{SUSY}} \sim 600 \text{ GeV} \cdot \left(\frac{\lambda_q/4\pi}{0.6} \right) \left(\frac{m_{\mathrm{SUSY}}}{1 \text{ TeV}} \right).$$

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

$$m_{\tilde{h}} \sim \frac{\lambda_u \lambda_d}{(4\pi)^2} \frac{\Lambda'^2}{m_{\rm SUSY}} \sim 120 \text{ GeV} \cdot \left(\frac{\lambda_d/4\pi}{0.2}\right) \left(\frac{\lambda_u/4\pi}{0.6}\right) \left(\frac{\Lambda'}{1 \text{ TeV}}\right)^2 \left(\frac{m_{\rm SUSY}}{1 \text{ TeV}}\right)^{-1}.$$

pretty light.

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

dynamical sector

$$\Lambda' \sim 1 \text{ TeV}$$

We can access to UV dynamics of QCD.

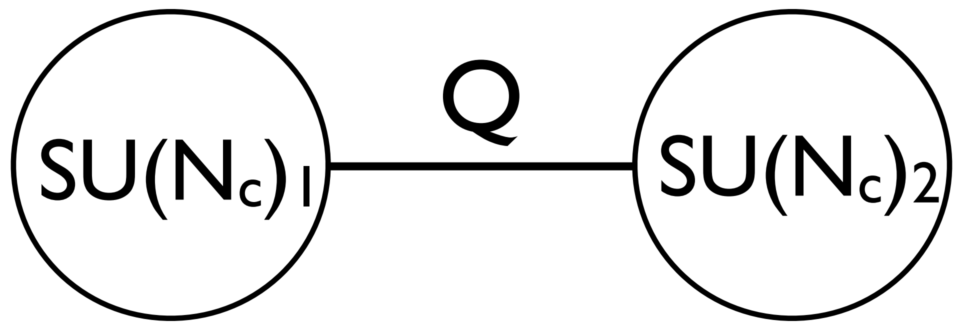
We expect ρ-like resonances (W', Z')

very interesting.

[RK, Yokoi in progress]

by-product
(confinement by CFL)

N_f quarks

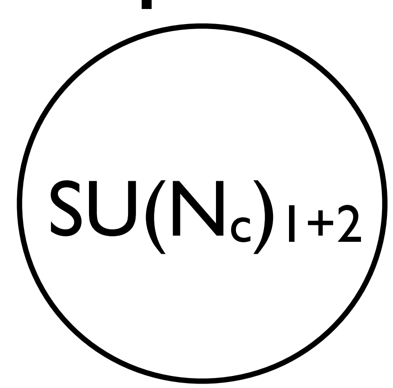


$(N_f < N_c)$

This provides an interesting deformation of QCD.

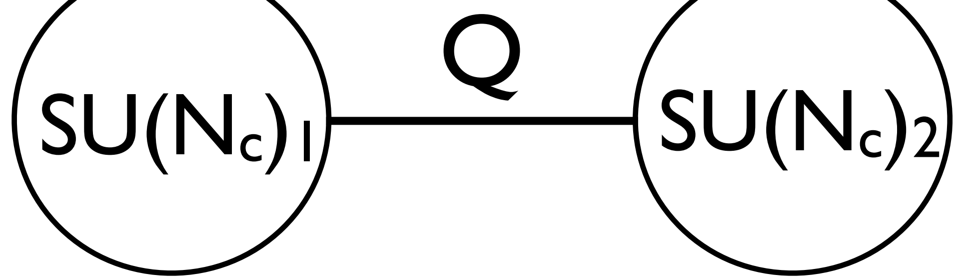
For $v \gg \Lambda_1, \Lambda_2$, this is just QCD.

N_f quarks



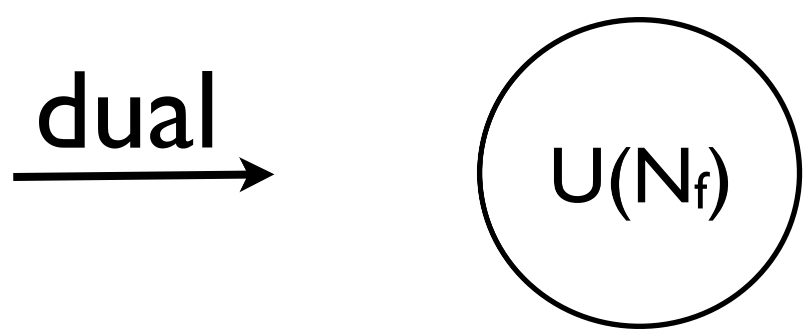
$$\Lambda_1 \gg \Lambda_2 \gg v$$

N_f quarks



Starting with N=2 SUSY and
adding a small breaking of N=2 SUSY to N=1

N_f dual quarks

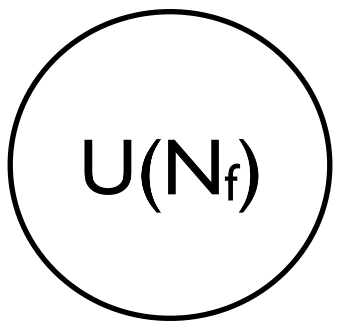


magnetic picture

color-flavor locking

[See also Shifman and Yung '07, ...]

N_f dual quarks



turning on v

$$\langle q \rangle = \langle \bar{q} \rangle = \begin{pmatrix} v/\sqrt{N_c} & & \\ & \ddots & \\ & & v/\sqrt{N_c} \end{pmatrix}$$

magnetic gauge bosons of U(N_f) behave as vector mesons ρ and ω.

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

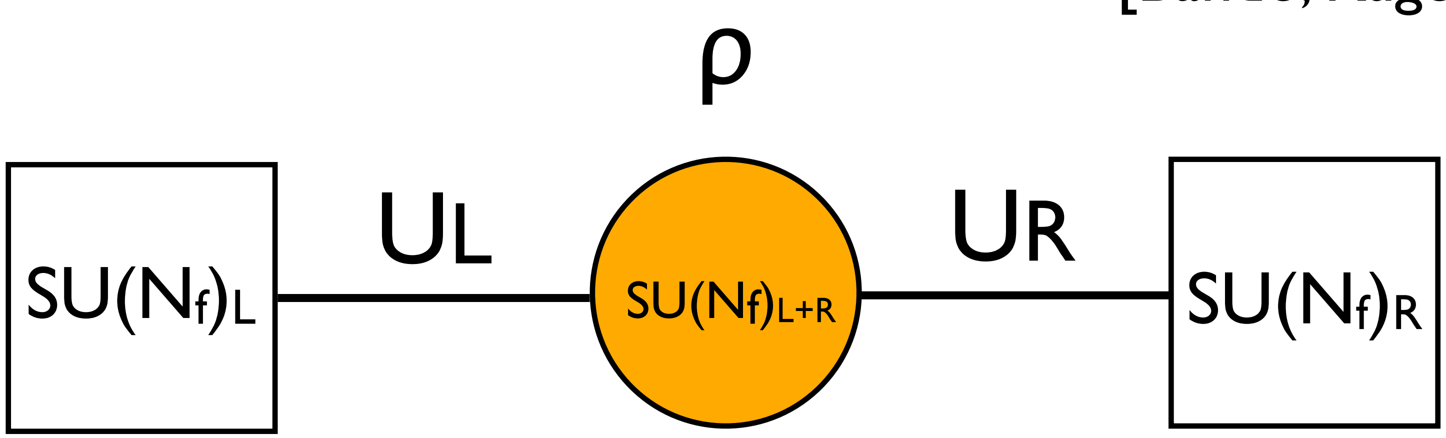
[Mandelstam '75, 't Hooft '75]

low energy QCD as magnetic picture?

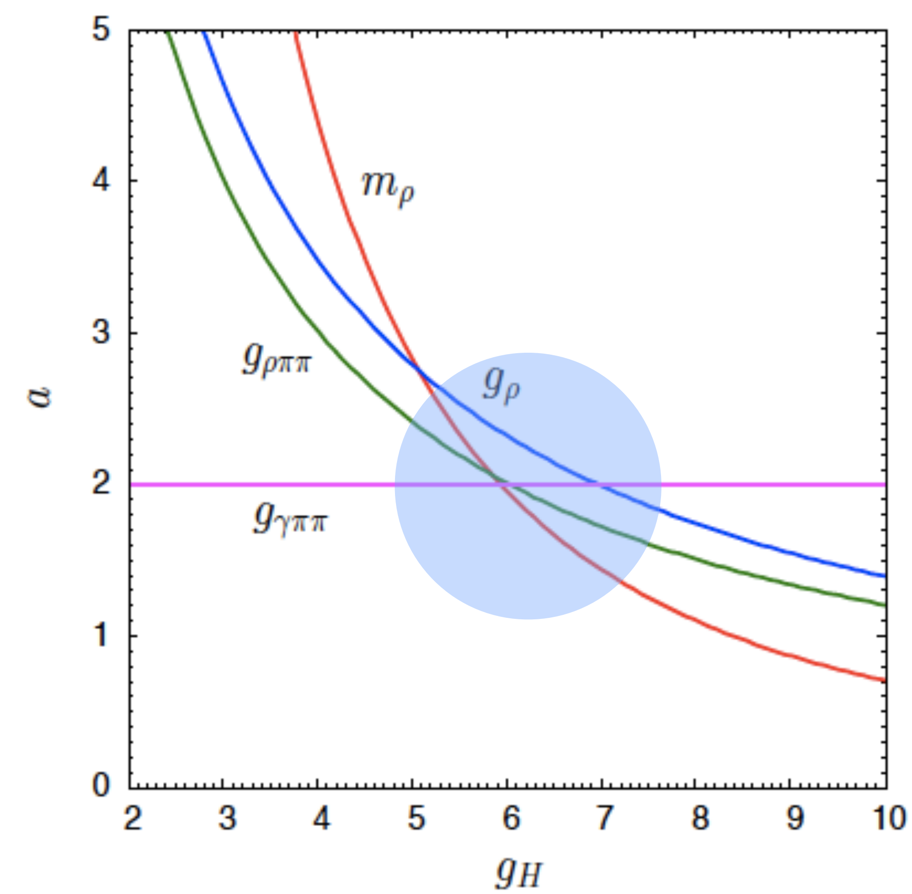
May not be totally crazy.

Hidden Local Symmetry

[Bando, Kugo, Uehara, Yamawaki, Yanagida '85]



$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4g_H^2} F^a_{\mu\nu} F^{a\mu\nu} \\
& + \frac{a f_\pi^2}{2} \mathrm{tr}\left[|D_\mu U_L|^2 + |D_\mu U_R|^2 \right] \\
& + \frac{(1-a) f_\pi^2}{4} \mathrm{tr}\left[|\partial_\mu (U_L U_R)|^2 \right].
\end{aligned}
$$



We see such a picture in the real world.

Quiver deformation provides us with
an understanding of HLS as
the magnetic gauge theory.

large v $\longleftrightarrow$ small v

QCD

HLS as
magnetic theory

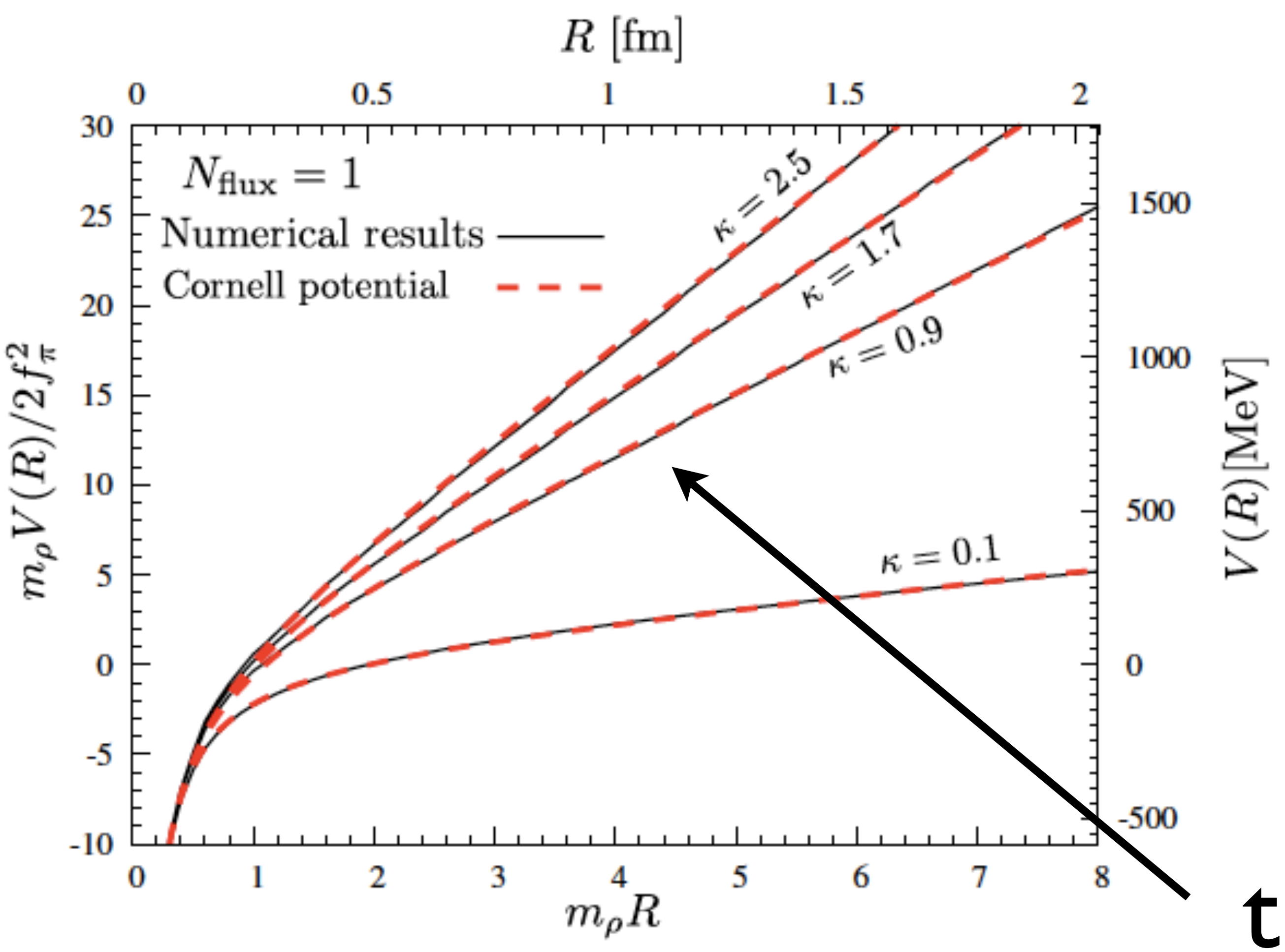
See also

[Seiberg '95, Harada, Yamawaki '99, Komargodski '10, RK '11, Abel, Barnard '12]

[RK, Nakamura, Yokoi '12]

Moreover,

one can construct a string configuration made of ρ, ω, and f_0 and calculate an energy.



$$g_\rho = (340\ \text{MeV})^2,$$

$$m_\rho = 770\ \text{MeV},$$

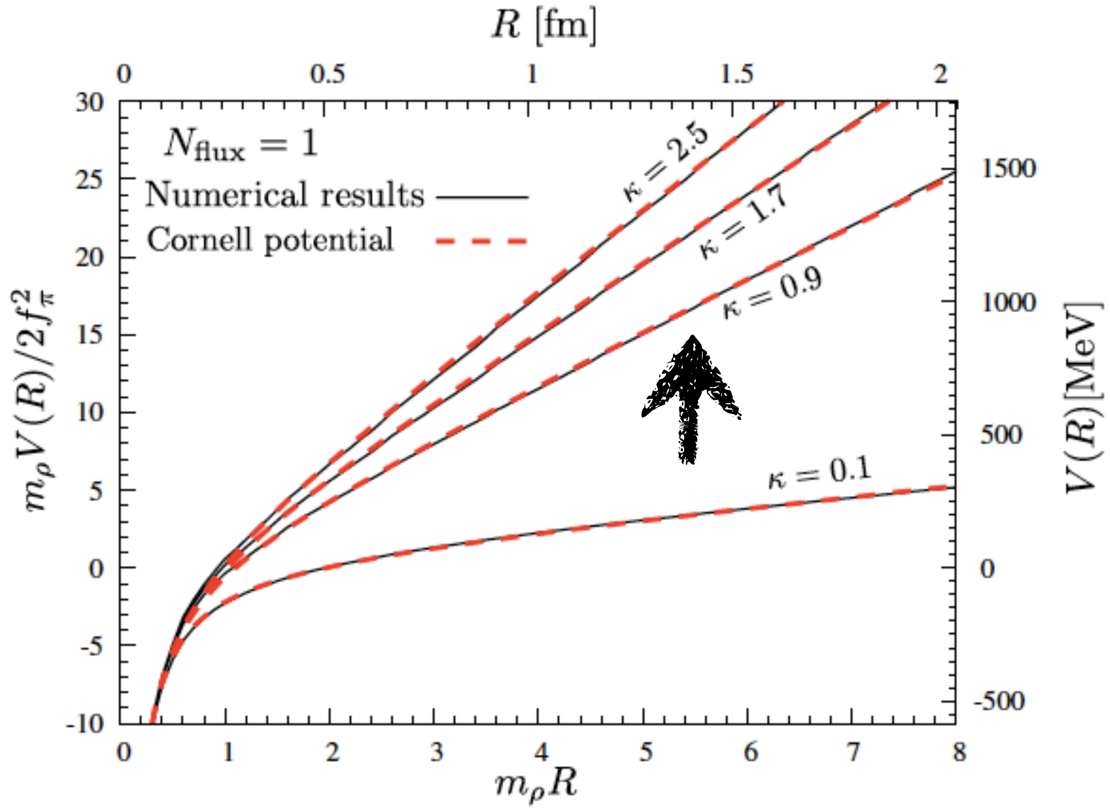
~ m_ω

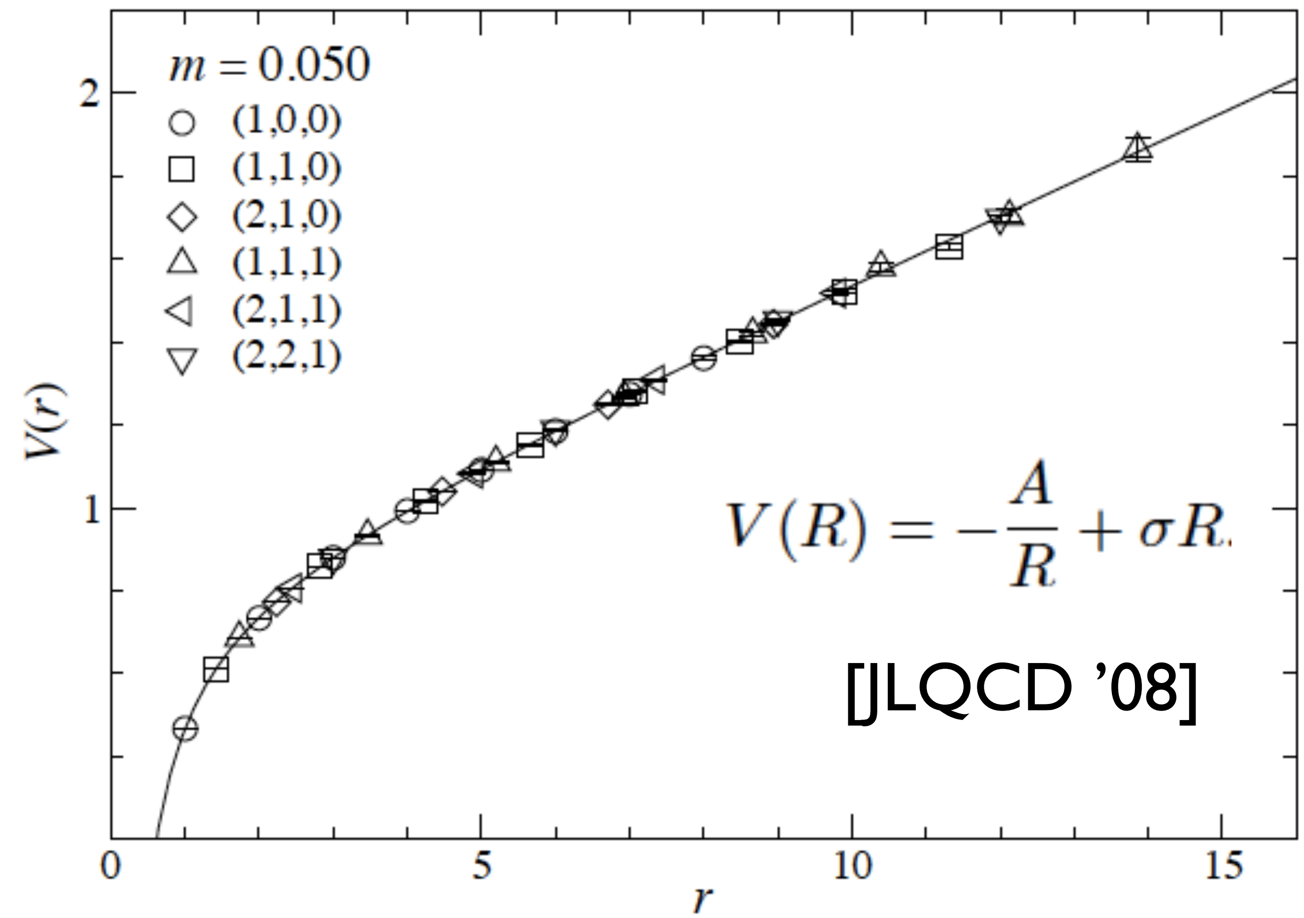
$$m_S = m_A = 980\ \text{MeV},$$

(scalar meson masses)

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

Comparing to lattice QCD





$A = 0.25 \qquad \sqrt{\sigma} = 400 \text{ MeV}$

$A \sim 0.25 - 0.5, \quad \sqrt{\sigma} \sim 430 \text{ MeV}.$

pretty consistent.

confining string $\stackrel{?}{=}$ 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.