SUSY+beyond

Ryuichiro Kitano (KEK, Sokendai)

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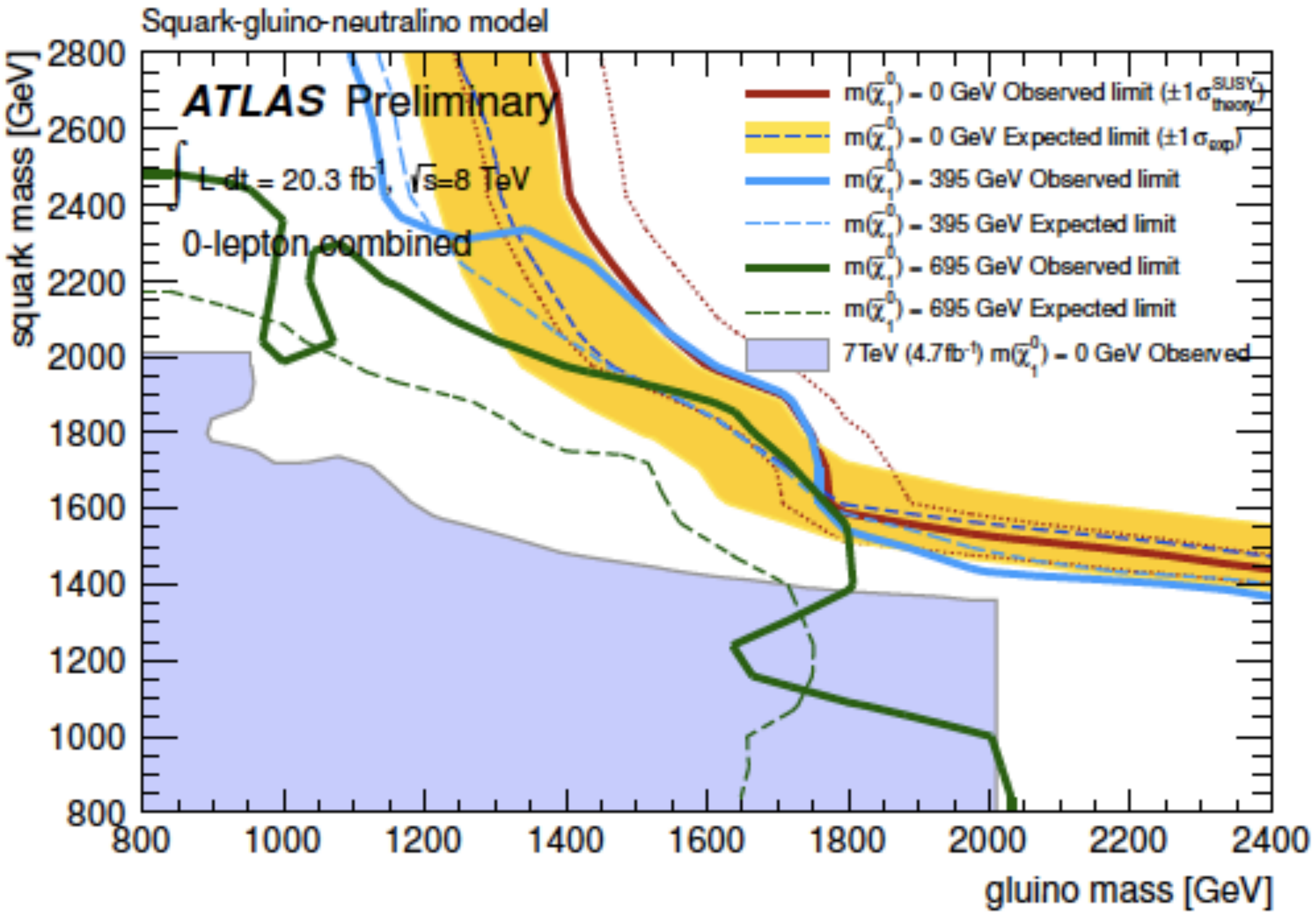
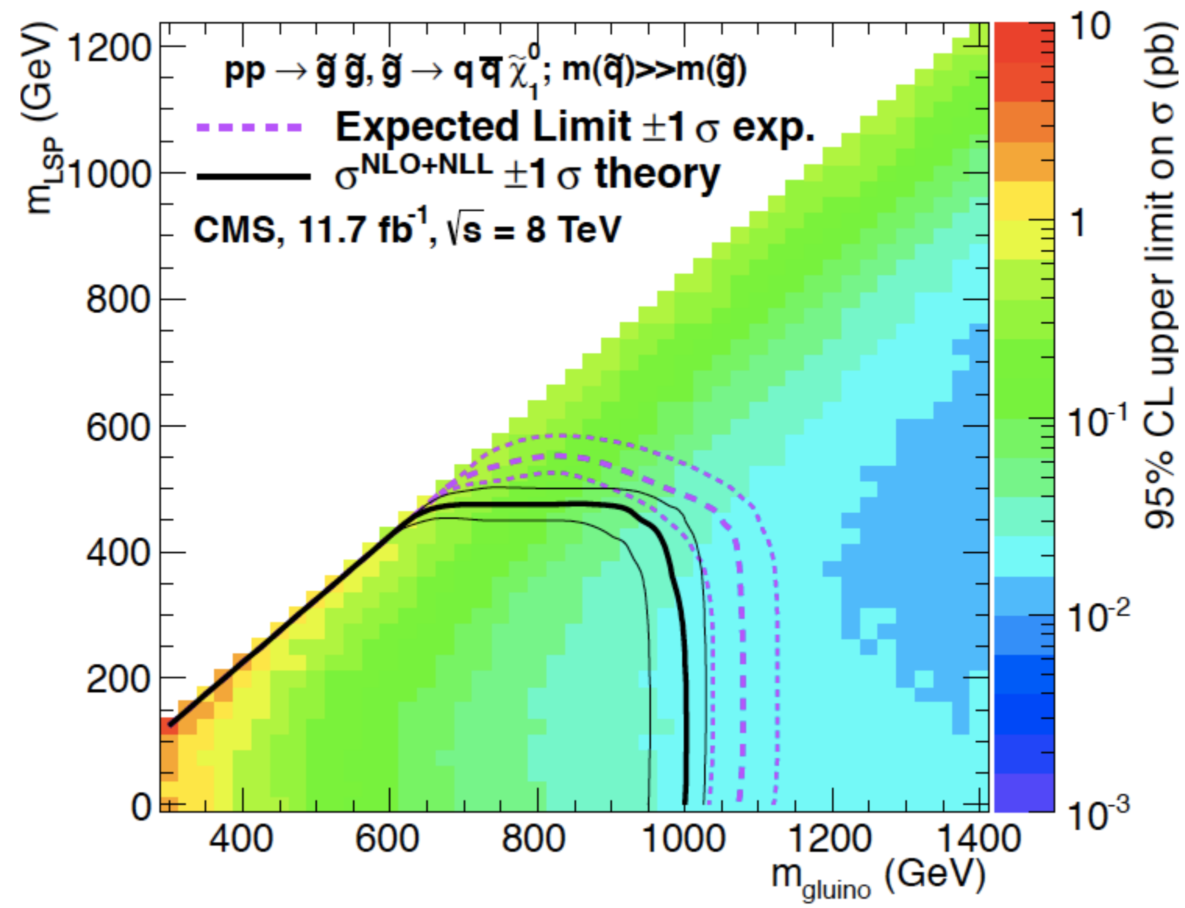
Is SUSY in bad shape?

not necessarily.

I'd like to talk about an optimistic scenario.

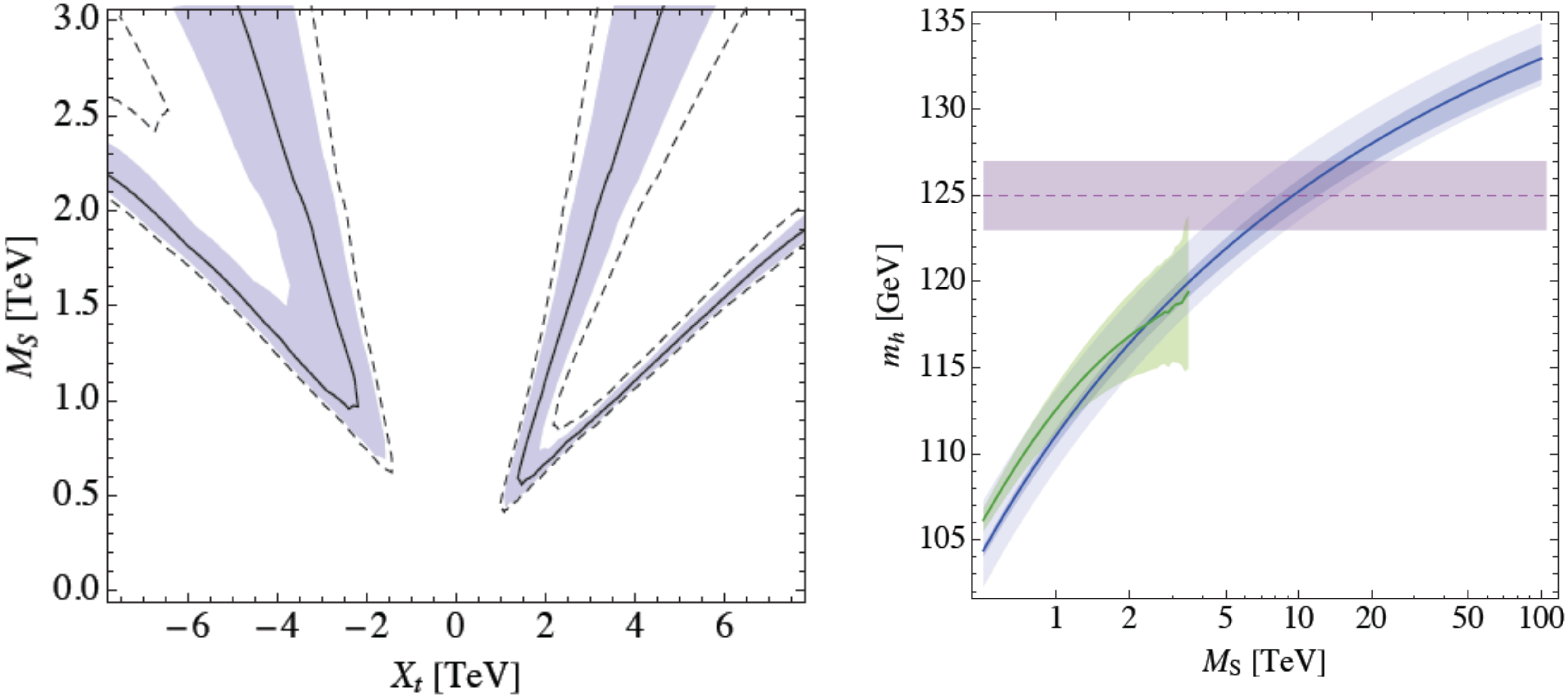
Where are Superparticles?





Roughly speaking, gluino needs to be heavier than ~1TeV or more.

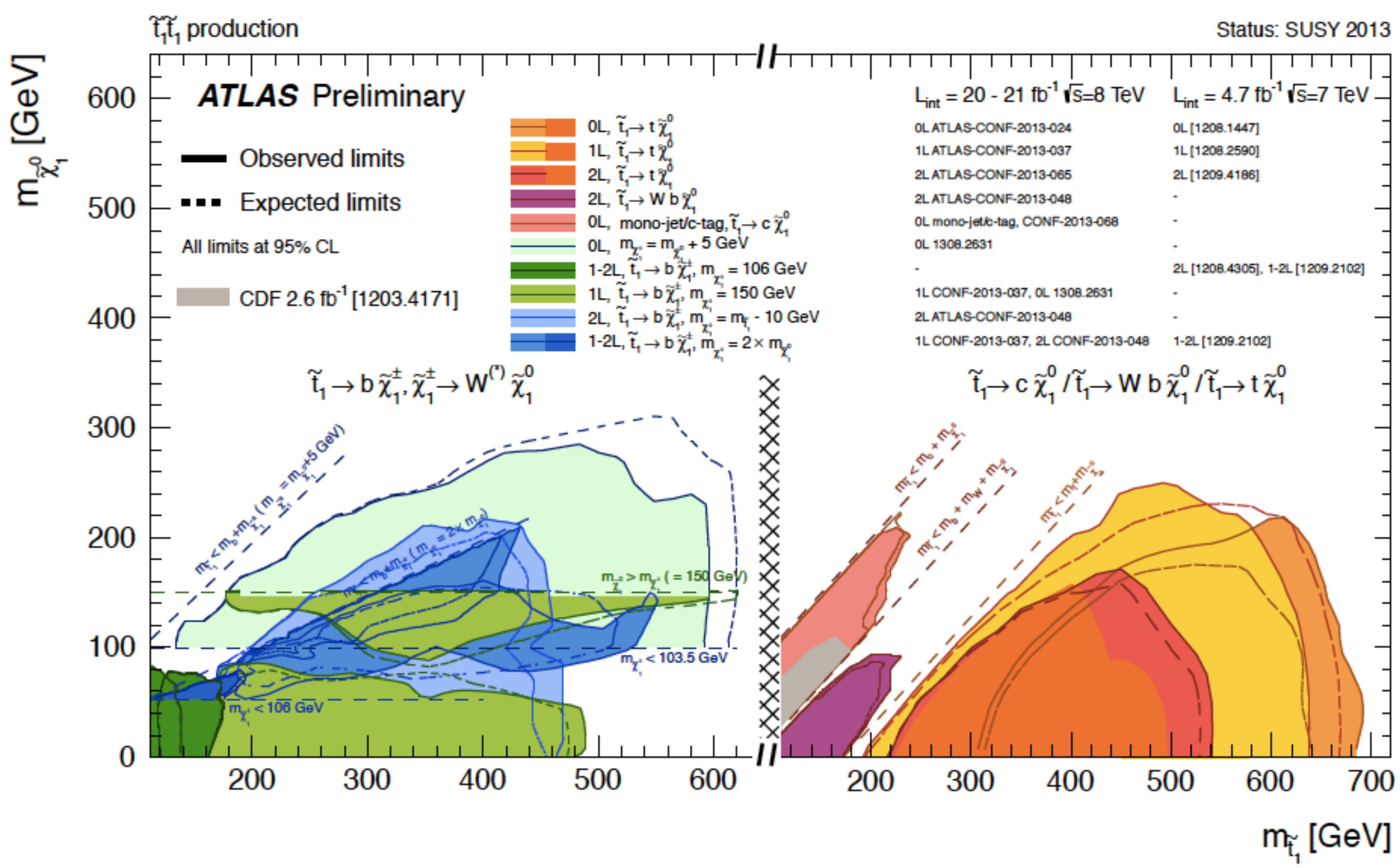
125GeV Higgs boson?

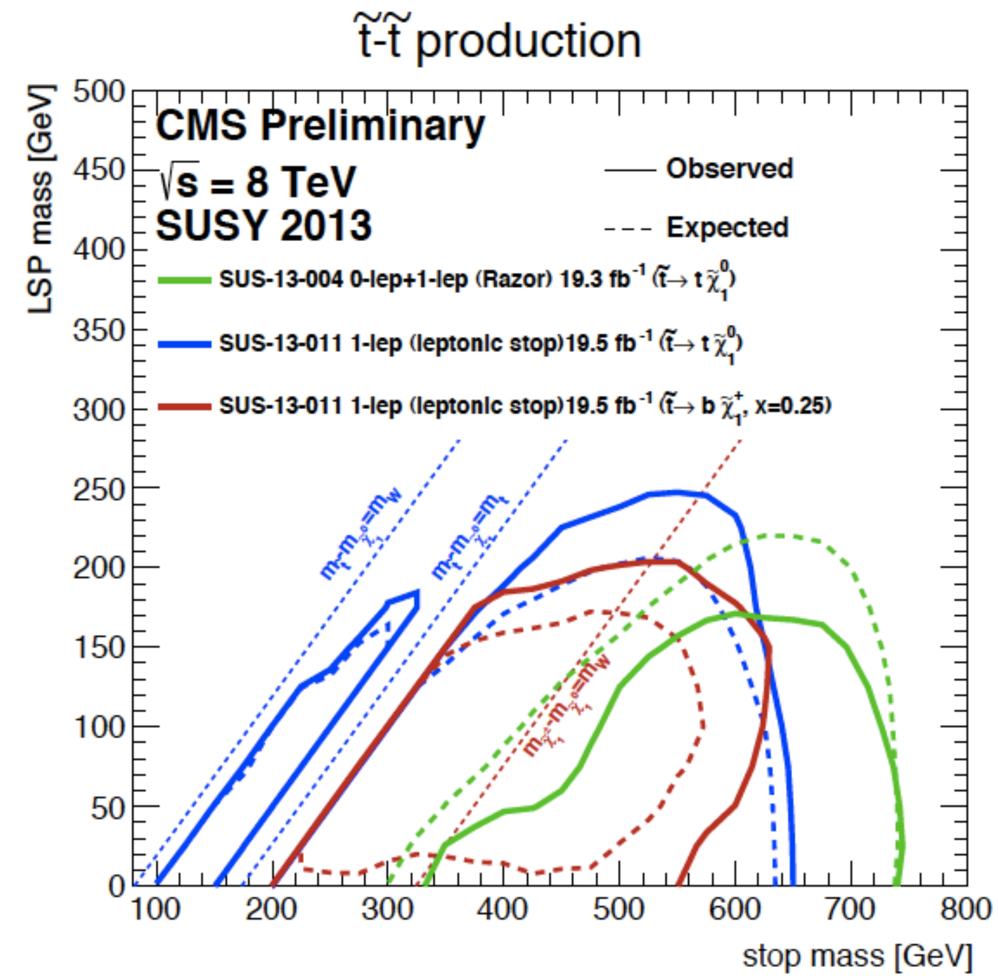


[Draper, Meade, Reece, Shih '11]

In the MSSM, 125GeV Higgs boson requires a heavy stop.

Stop mass bound





not very strong as long as gluino is heavy.

Natural SUSY?

Roughly speaking, we naturally expect

Higgs mass ~ stop mass ~ gluino mass

This is clearly bad...

Natural SUSY?

Considering quantum corrections,
a possible hierarchical pattern one can naturally accommodate is

Higgs mass < stop mass < gluino mass

one-loop (Higgs mass < stop mass) one-loop (stop mass < gluino mass)

The hierarchy cannot be very large when we assume a high scale SUSY breaking scenario. There is a log factor which eliminates the hierarchy.

If the log factor is small, there can be a small hierarchy such as a factor of 3 or 4.

Higgs mass < stop mass < gluino mass
x 3-4 x 3-4

If that is the case,

1. m_h=125GeV indicates $m_{stop} \lesssim 600$GeV.
(experimentally fine, but it is not enough for the MSSM)

2. m_h=125GeV and m_{gluino}>1TeV can be consistent.

Consistent with the LHC data,
but we still need to give up the MSSM.

Natural SUSY after the first run of LHC

To be consistent with the LHC data naturally, one needs

1. a small log factor in the one-loop corrections.

$$\log \frac{\Lambda}{\mathrm{TeV}} \sim 1 \longrightarrow \text{TeV new physics}$$

2. additional contribution to the Higgs boson mass

$\longrightarrow$ TeV new physics!

LHC data may be suggesting..

SUSY + TeV scale new dynamics!

this is actually a rather conventional scenario which we somehow gave up.

[Witten '81, Dine, Fischler, Srednicki '81, Dimopoulos, Raby '81...]
[Luty, Terning, Grant '01, Harnik, Kribs, Larson, Murayama '03...]

EWSB by TeV dynamics and elementary Higgs for fermion masses. SUSY protects the Higgs mass.

It sounds nothing is wrong!

What kind of dynamics at TeV?

There is a very interesting class of possibility which addresses the origin of the Higgs field.

Higgs as magnetic degree of freedom.

(EWSB is dual to confinement of some TeV scale force.)

[Seiberg '95, Maekawa'96, Strassler '96, ..., Fukushima, RK, Yamaguchi '10
Craig, Stolarsky, Thaler '11, Csaki, Shirman, Terning '11, Csaki, Randall, Terning '11,
RK, Nakai '12]

emergent Higgs field!

In fact, one can find such a picture in QCD.

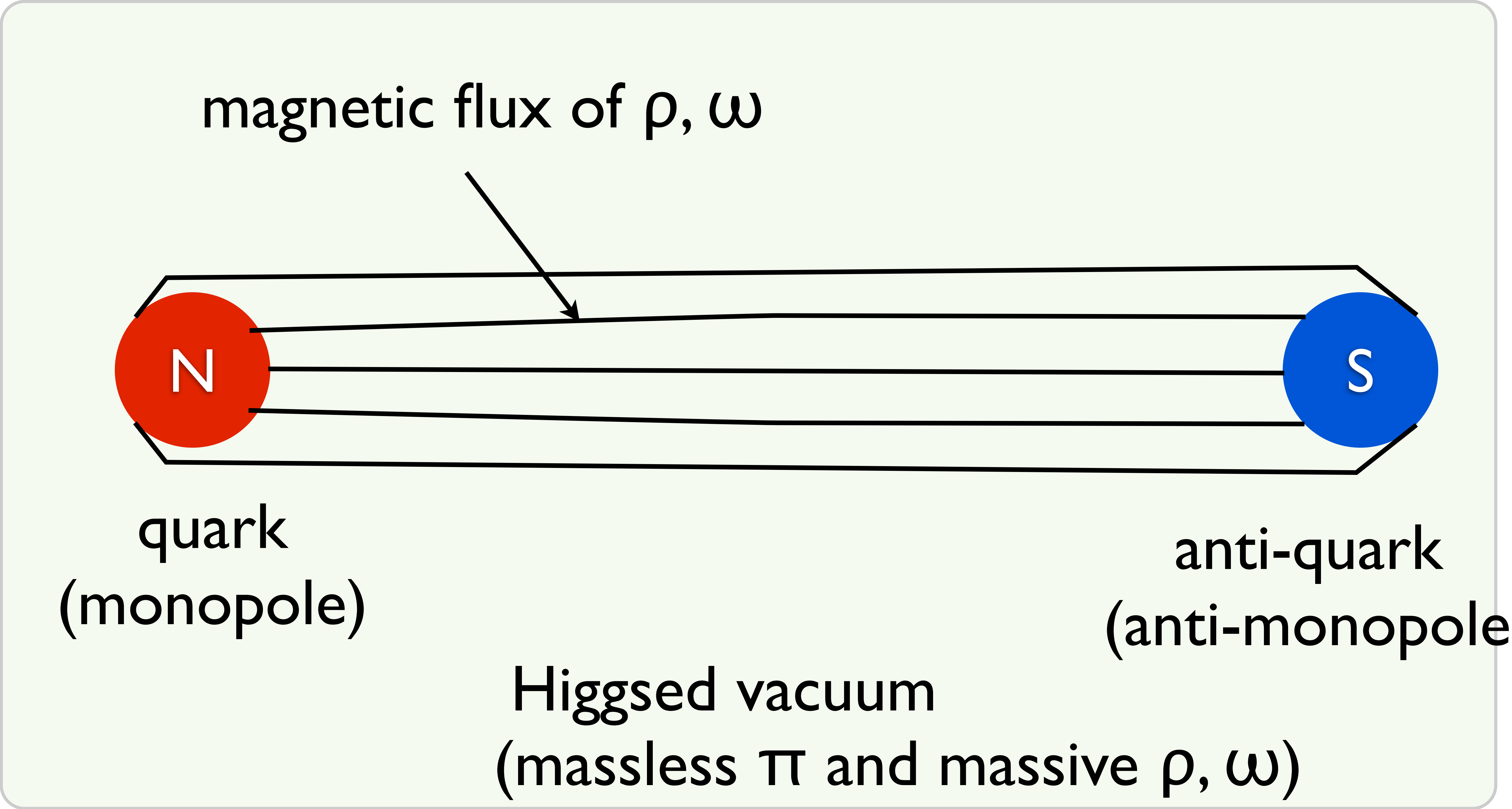
One can try to identify light hadrons
as magnetic degrees of freedom.

π, $a_0(980)$, $f_0(980)$: dual scalar quarks (Higgs)
$\rho(770)$, $\omega(782)$: magnetic gauge bosons

construct a linear sigma model for them.

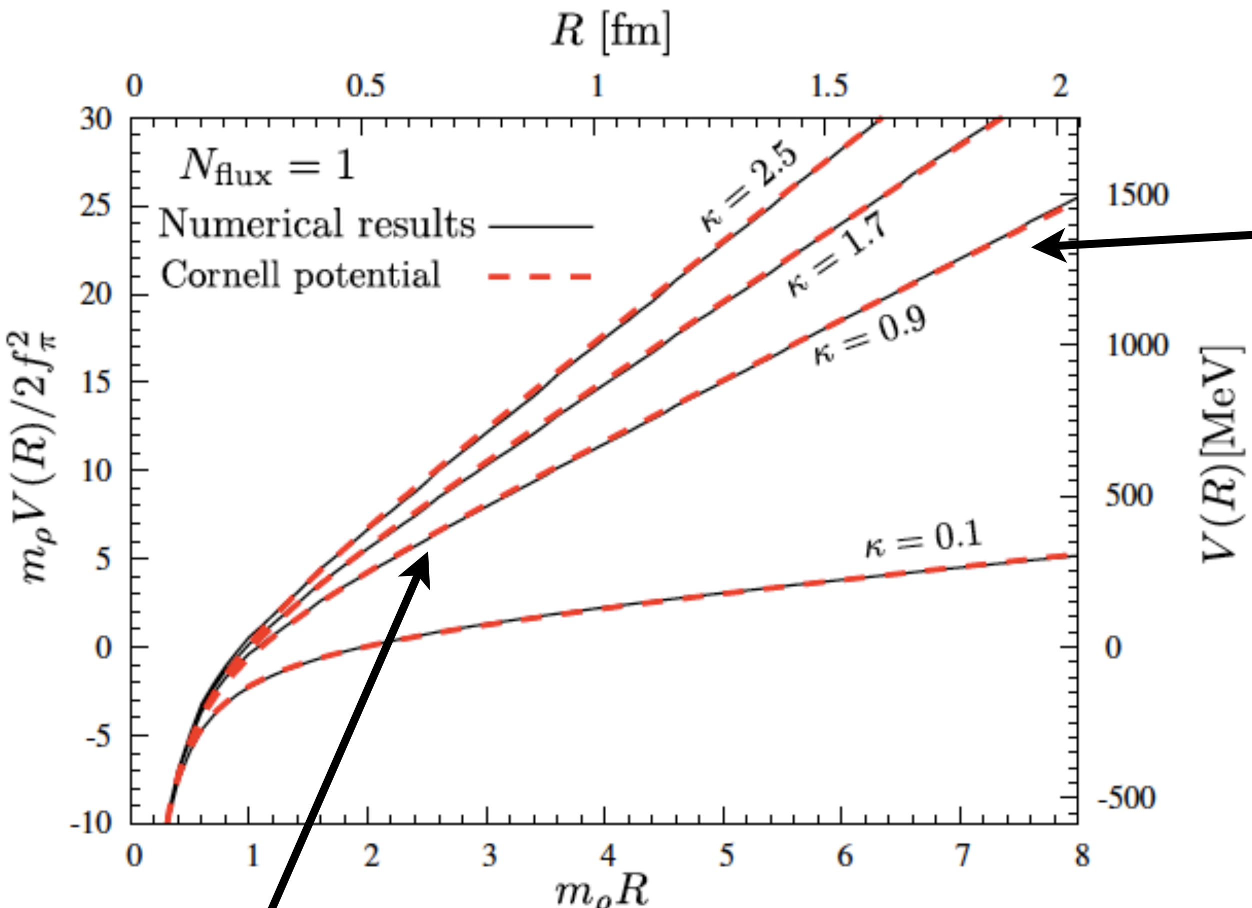
→ Hidden Local Symmetry (linearly realized version)
which is known to be a very successful framework.

string made of mesons



This model even reproduces the QCD potential.

[RK, Nakamura, Yokoi ’12]



(monopole-antimonopole separation)

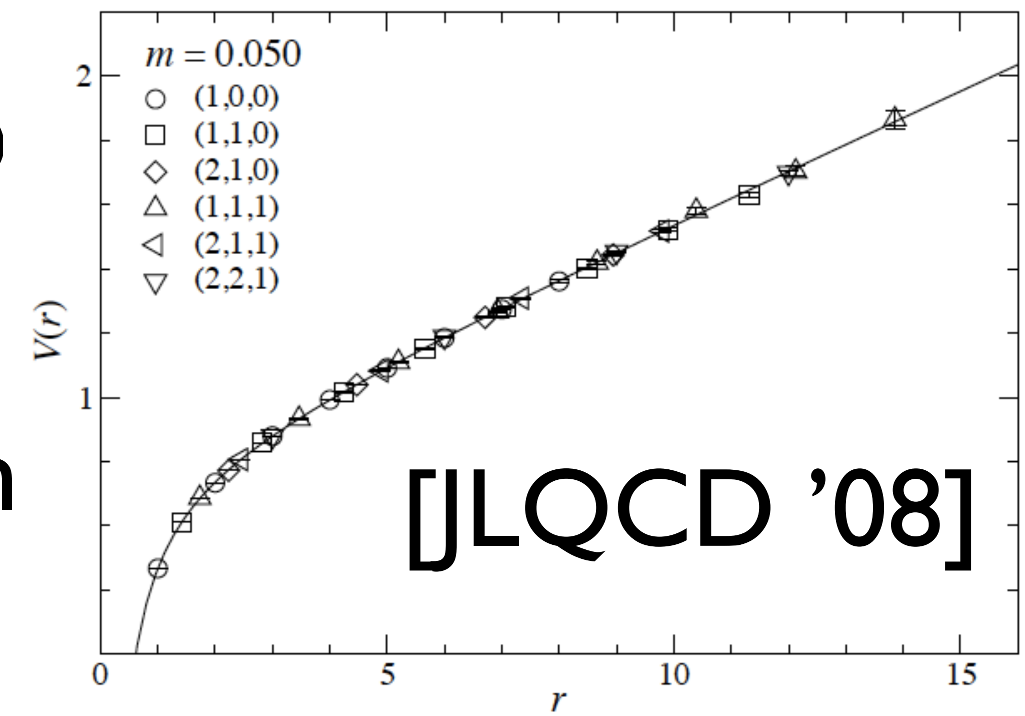
this line

$$V(R) = -\frac{A}{R} + \sigma R. \qquad A = 0.25$$

$$\sqrt{\sigma} = 400 \text{ MeV}$$

energy of the vortex configuration between Dirac monopoles.

lattice QCD



[JLQCD ’08]

Interesting...

chiral symmetry breaking = magnetic Higgs mechanism

= confinement

[Nambu ’74, Mandelstam ’76, ‘t Hooft ’81]

[Carlino, Konishi, Murayama ’99 ...]

As is well-known,

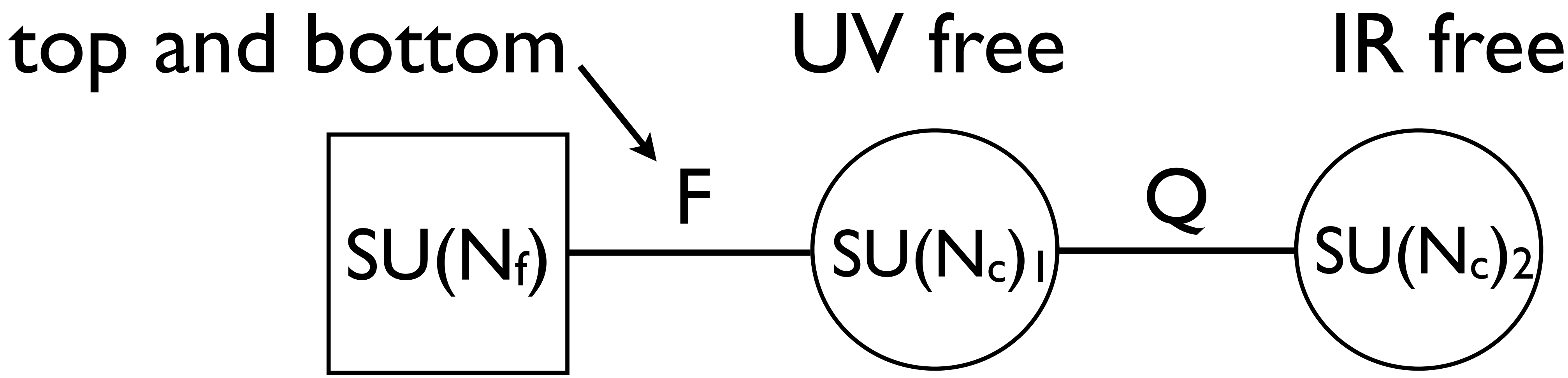
the symmetry breaking pattern of QCD

is the **same** as EWSB.

The Higgs mechanism in the EWSB may be magnetic picture of some dynamics?

A topcolor-like SUSY model:

[Fukushima, RK, Yamaguchi '10]
[RK, Nakai '12]



	$SU(3)_1$	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
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	$1_{-1/3}$

other quarks
+ top/bottom

gauged
(Lagrange multiplier)

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 $\Lambda \ll 4\pi v,$ (classical level)

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

We get MSSM without Higgs as low energy theory.

not interesting.

Below, we study the case with

$\Lambda \gg 4\pi v,$ (strongly coupled region)

$\longrightarrow$ magnetic description gets better.

Seiberg duality

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.

$SU(2)_1$ factor gets strong at a scale Λ'.

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

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

	$SU(3)_2$	$U(1)_B$	$SU(2)_L \times U(1)_Y$
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

<S> $\longrightarrow$ S is not dynamical

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 $\overline{S}$.

We consider SUSY breaking by turning on

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

Turn on SUSY breaking

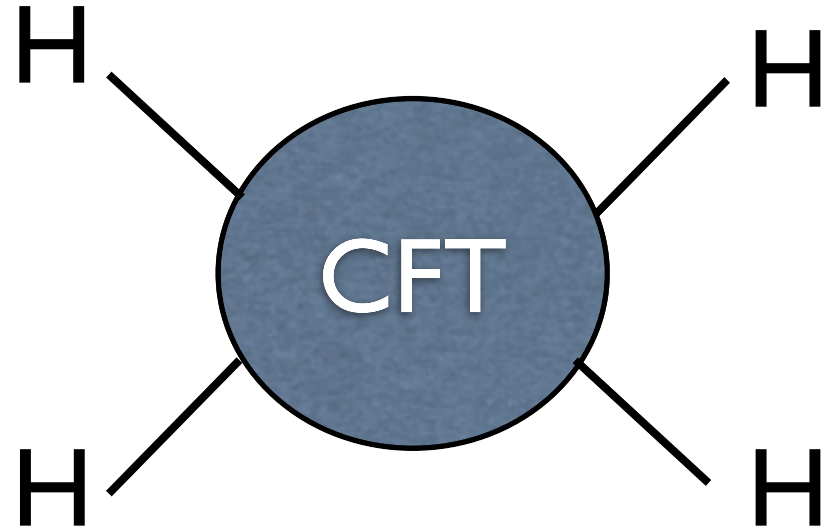
$\longrightarrow$ H' fields decouple

~TeV scale masses

Below TeV,

we arrive at the MSSM.

Higgs potential



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

Extra quartic terms from SUSY breaking

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

Higgsino mass matrix

$$m_h = 125\ \text{GeV}$$

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:

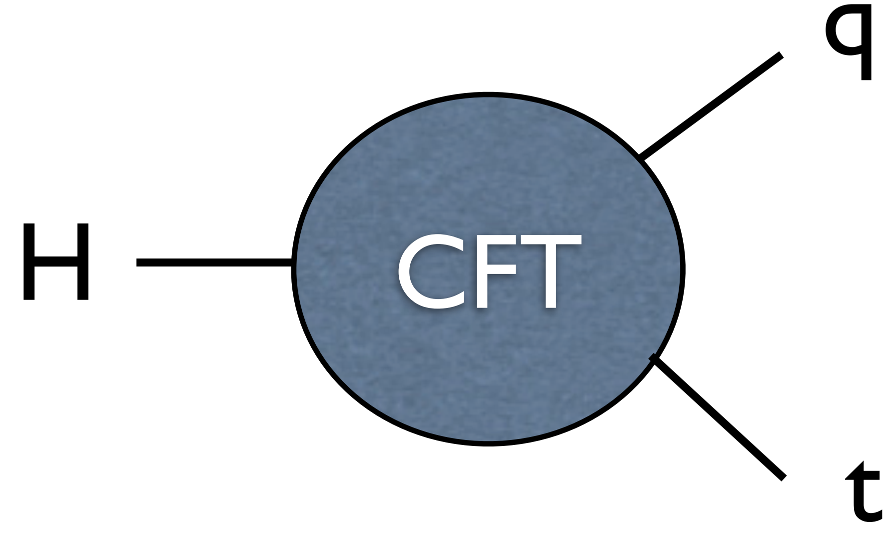
required size of the Higgs quadratic terms

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

typical size

not bad.

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 mass from H_d

stop/sbottom

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

should be observed soon!

(should have been observed?)

dynamical sector

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

We may access to UV dynamics of QCD.

We expect ρ-like resonances (W', Z')

very interesting.

looks fine...

- enhanced Higgs boson mass via new interactions [Fukushima, RK, Yamaguchi '10, Gherghetta, Pomarol '11, Heckman, Kumar, Vafa, Wecht '11, Evans, Ibe, Yanagida '12, RK, Nakai, Luty '12]
- completely unconventional pattern of SUSY breaking parameters (IR fixed point structure) [Fukushima, RK, Yamaguchi '10, Csaki, Randall, Terning '11]
- maintaining elementary Higgs picture by weakly coupled CFT.

Summary

the current situation may be indicating physics beyond the MSSM.

- stop should be light. We should find it soon.
- There may be many resonances waiting for us around TeV scale.
- Higgsino should be light. Discovery at ILC?

I hope that's the case! Thank you.