Supertopcolor

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Introduction

I would say, the MSSM+(soft terms) is an almost perfect model for EWSB.

EWSB by the Higgs mechanism: good with precision measurements

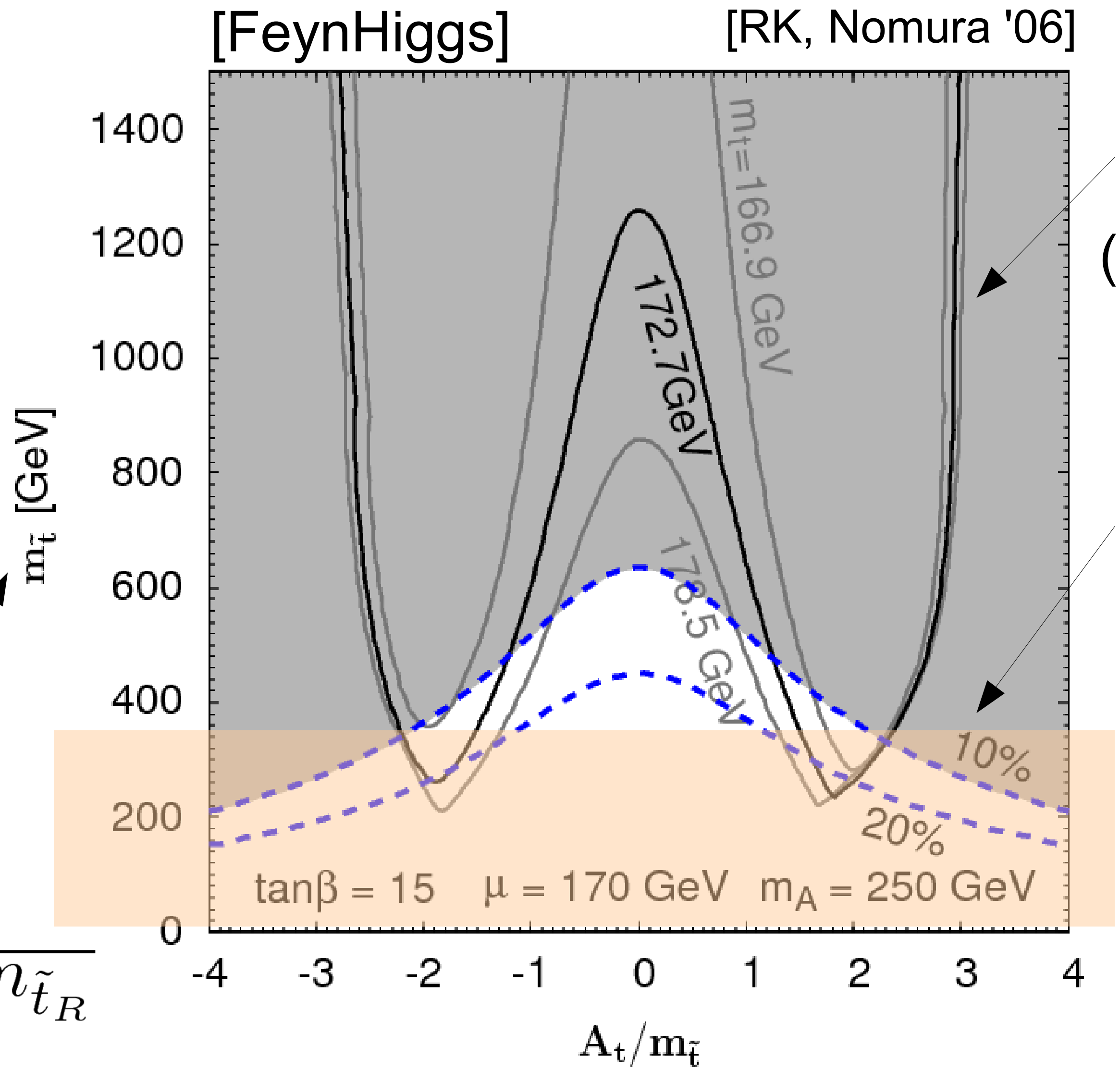
Fermion masses through Yukawa: good with FCNC, CP

No quadratic divergence: no hierarchy problem

Renormalizable and weakly coupled: full predictability, UV complete

The μ-problem, the SUSY FCNC/CP problem are the problems in the SUSY breaking/mediation sector, which one may be able to postpone to discuss if we are interested in the dynamics of EWSB.

Almost?



Higgs boson mass bound (LEP-II, 114.4GeV)

level of fine-tuning (with a small log factor ~ 3)

LHC exclusion?

stop mass

$$m_{\tilde{t}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$$

A-term (three point stop-stop-Higgs coupling)

Almost dead?

Maybe we need a little bit more strongly coupled Higgs.

→ Dynamical symmetry breaking in SUSY?

[Luty, Terning, Grant '00][Murayama '03]
[Witten '81][Dine, Fishler, Srednicki '81]
[Dimopoulos, Raby '81]

But I don't want to lose the picture of the Higgs field as an effective degree of freedom since it is data friendly.

→ Look for a dual to the MSSM (like theory).

[Harnik, Kribs, Larson, Murayama '03]
[Delgado, Tait '05]
[Seiberg '94, Maekawa '95, Strassler '96 ...]

But how to give a large mass to the top quark? How to suppress the (s)top loop contribution to the Higgs mass parameter?
Maybe top is also involved in the dynamical sector.

→ Topcolor mechanism in SUSY?

Topcolor model

[Hill '91]

The model is very simple (and I think it's cute!).

Introduce a new strong gauge interaction, $SU(3)_{TC}$.

And replace the color quantum numbers of the top and bottom quarks by topcolor.

$$q_{3L} : (3, 1, 2)_{1/6}$$
$$t^c : (\bar{3}, 1, 1)_{-2/3}$$
$$b^c : (\bar{3}, 1, 1)_{1/3}$$

topcolor

Other fermions have the usual quantum numbers.

No Higgs field. (at least in the original model)

This theory is free from gauge anomaly.

$SU(3)_{TC} \times SU(3)_{C'} \times SU(2)_L \times U(1)_Y$

(In actual model we need more fermions or a U(1) gauge interaction to make the bottom quark lighter.)

Topcolor model (cont'd)

At this stage, this model is the same as two-flavor QCD.

→ Electroweak symmetry breaking by top condensation!

[Miransky, Tanabashi, Yamawaki '89]
[Bardeen, Hill, Lindner '90]

But it is a confining theory → no top quark as asymptotic d.o.f

Therefore it is introduced a Higgs field $\Phi\,(3, \bar{3}, 1)_0$ to break

$$SU(3)_{TC} \times SU(3)_{C'} \longrightarrow SU(3)_C$$

↑ color

Now top quark carries color after this symmetry breaking.

But what about top condensation?

SUSY + topcolor ?

SUSY wants a new interaction for the Higgs and the top quark

⟶ topcolor?

Topcolor wants UV completion ⟶ SUSY?

Supertopcolor

[Fukushima, RK, Yamaguchi '10]
(also a similar model in [Evans, Galloway, Luty, Tacchi '10])

Just a supersymmetric version of the topcolor model

$SU(3)_{TC} \times SU(3)_{C'} \times SU(2)_L \times U(1)_Y$

$$Q = \left(\frac{(1,2)_{1/6}}{(\bar{3},1)_0} \right), \quad \bar{Q} = \left(\frac{\begin{matrix}(1,1)_{-2/3} \\ (1,1)_{1/3}\end{matrix}}{(3,1)_0} \right)$$

q_L

t^C, b^C

Φ

3 under $SU(3)_{TC}$

$\bar{3}$ under $SU(3)_{TC}$

It is an SUSY QCD (SU(3)) with 5 flavors. Properties are well-known.

We also add soft SUSY breaking terms and a mass term for Φ.

In fact, SU(3) 5 flavor theory is in the conformal window:

$$3N_C/2 < N_f < 3N_C$$

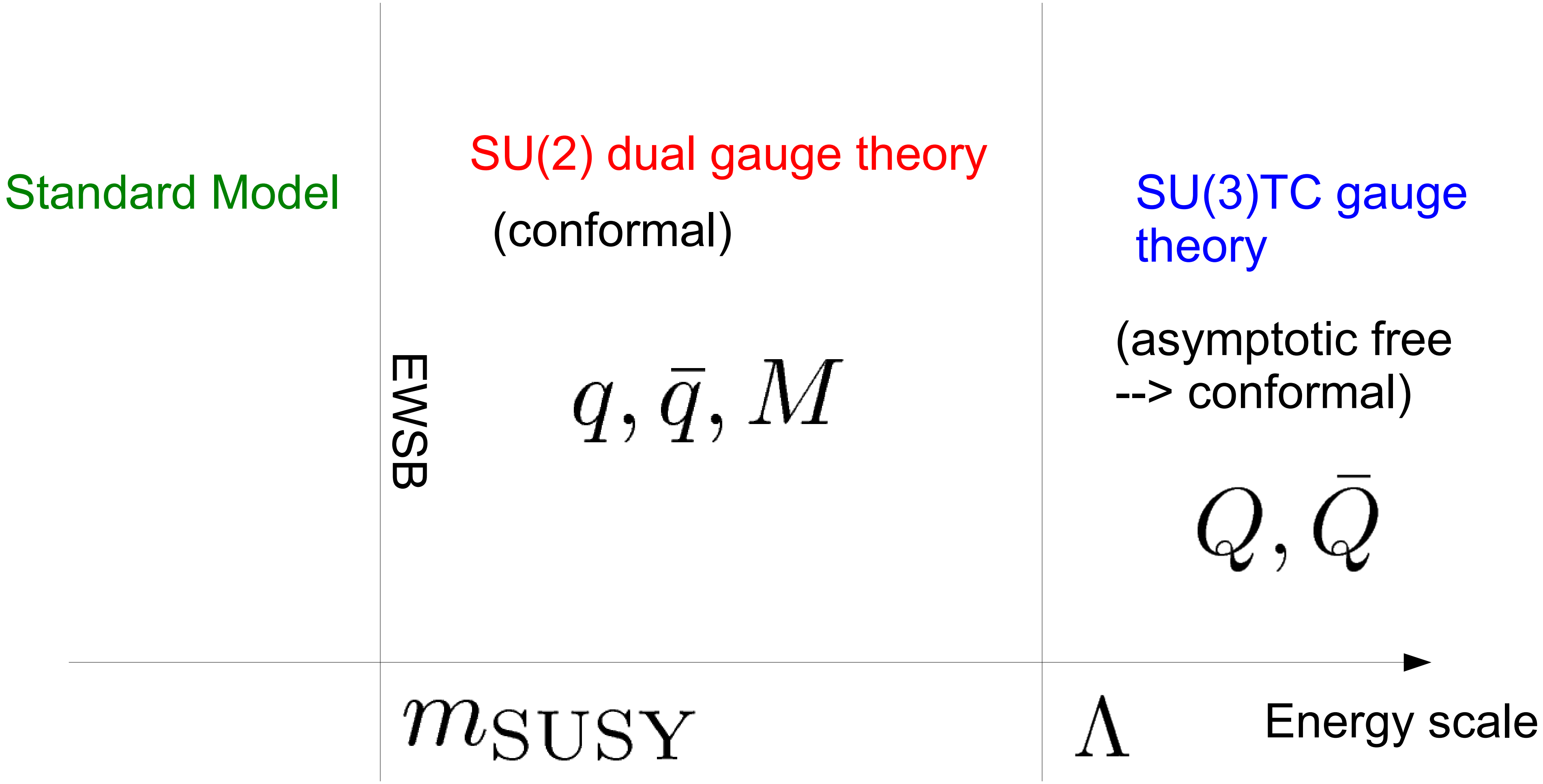
→ $$4.5 < N_f < 9 \quad \text{for} \quad N_c = 3$$

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.

→ One can do perturbative calculation (expansion in terms of $1/N_f$)

Weakly coupled descriptions



The dual theory (for $\Lambda >> m_{SUSY}$, the use of duality is justified.)

The dual theory is $SU(N_f - N_c)$ with N_f flavor. → SU(2) 5 flavor

meson: (SU(2) singlet)

Higgs! Top/bottom!

$$M = \left(\begin{array}{cc|c} H_d & H_u & q_3 = \begin{pmatrix} t \\ b \end{pmatrix} \\ \hline t^c & b^c & X \end{array} \right)$$

Color adjoint + singlet

(looks like the MSSM)

dual quarks: (SU(2) doublet)

$$q = \left(\frac{(1,2)_0}{(3,1)_{1/6}} \right), \quad \bar{q} = \left(\begin{array}{c} (1,1)_{1/2} \\ (1,1)_{-1/2} \\ \hline (\bar{3},1)_{-1/6} \end{array} \right)$$

(looks like a minimal technicolor)

Superpotential: $$W = hqM\bar{q}$$

h is a coupling constant.

One can see that the Higgs and top/bottom are the effective d.o.f.

Soft SUSY breaking terms in SCFT

There are interesting RG behaviors of soft SUSY breaking terms in SCFT.

[Arkani-Hamed, Rattazzi '98][Karch, Kobayashi, Kubo, Zoupanos '98]
[Luty, Rattazzi '99][Abel, Buican, Komargodski '11]

Essentially, all the soft terms vanish at the fixed point except for the D-terms associated with U(1) global symmetries.

$$\tilde{m}^2_{Q_i} = q_i^a D^a$$

This leads sum rules among soft scalar masses for mesons.

$$\tilde{m}^2_{X_1} = \tilde{m}^2_{X_{\rm adj.}},$$

$$\tilde{m}^2_{H_d} - \tilde{m}^2_{H_u} = \tilde{m}^2_{t^c} - \tilde{m}^2_{b^c},$$

$$\tilde{m}^2_{H_d} + \tilde{m}^2_{X_1} = \tilde{m}^2_{q_3} + \tilde{m}^2_{t^c},$$

$$m^2_{H_u} + m^2_{H_d} + 3m^2_{X_1} = 0.$$

No A-terms, no gaugino masses.

Electroweak Symmetry Breaking

We are interested in a vacuum with $\langle M \rangle \neq 0$

→ By superpotential, the dual quarks are massive.

→ Integrate out dual quarks

We get an effective (non-perturbative) superpotential:

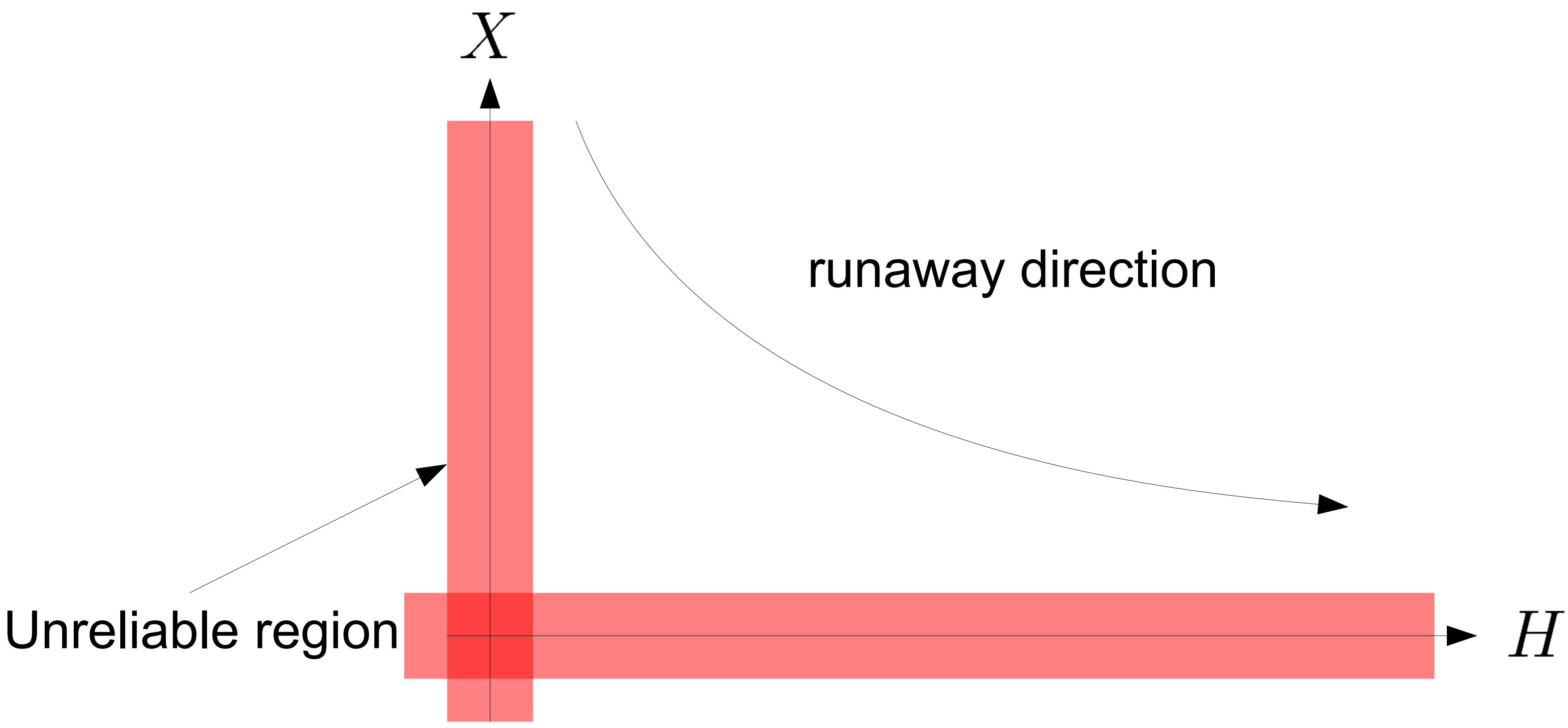
$$W_{\text{eff}} = \kappa N \left(\frac{h^{N_f} \det M}{\Lambda_*^{N_f - 3N}} \right)^{1/N}$$

where $\kappa \equiv e^{-\frac{8\pi^2}{g_*^2 N}} = e^{-N_f/7 + O(1)}$

The use of effective superpotential is valid when

$$h\langle M\rangle \gg m_{\rm SUSY} \,.$$

Now, the effective superpotential gives a runaway potential:



SUSY breaking terms

From the sum rules, the signs of the soft mass^2 are restricted.

By requiring that the stop/sbottom are not tachyonic, we get

$$\tilde{m}_H^2 > 0, \quad \tilde{m}_{X_1}^2 < 0.$$

→ Pulls H to origin, X to infinity

→ Runaway potential is stabilized!

VEVs?

The minimization of the potential gives

$$m_{\rm SUSY} \sim \kappa h^3 v$$

where $v \sim \langle M \rangle$

For a large N (and N_f), κ is exponentially suppressed.

→ SUSY breaking is much smaller than the vev.

→ Analysis is reliable

$h\langle M \rangle \gg m_{\rm SUSY}$ implies $N_f \gg 10$

....

Well..., at least with a large value of N, we could find a vacuum where SU(2)xU(1) is dynamically broken.

The actual model is N_f=5, where we don't have a control from SUSY.

→ But from the discussion in the large Nf limit, we are encouraged to assume that a similar vacuum exists for N=2 at

$$m_{\rm SUSY} \sim \langle H \rangle .$$

(whereas NDA gives 4π<H>.)

It is also true that the meson fields are weakly coupled in the sense that the loop-expansion parameter is O(1/5) (anomalous dimension is 1/5).

→ It's good to treat mesons (Higgs and top/bottom) as effective degrees of freedom.

The Higgs boson mass

We saw that the Higgs potential is “stabilized” by SUSY breaking.

(rather than “destabilized” by SUSY breaking and “stabilized” by the gauge interaction.)

→ Higgs mass is unrelated to the Z boson mass.

→ No tension from LEP-II bound on the Higgs boson mass.

No SUSY fine-tuning problem(!?)

(I cannot calculate the mass though...)

Top quark mass

Let's go back to a large Nf theory so that one can do perturbative calculation.

The fermion masses are generated through the non-perturbative superptential.

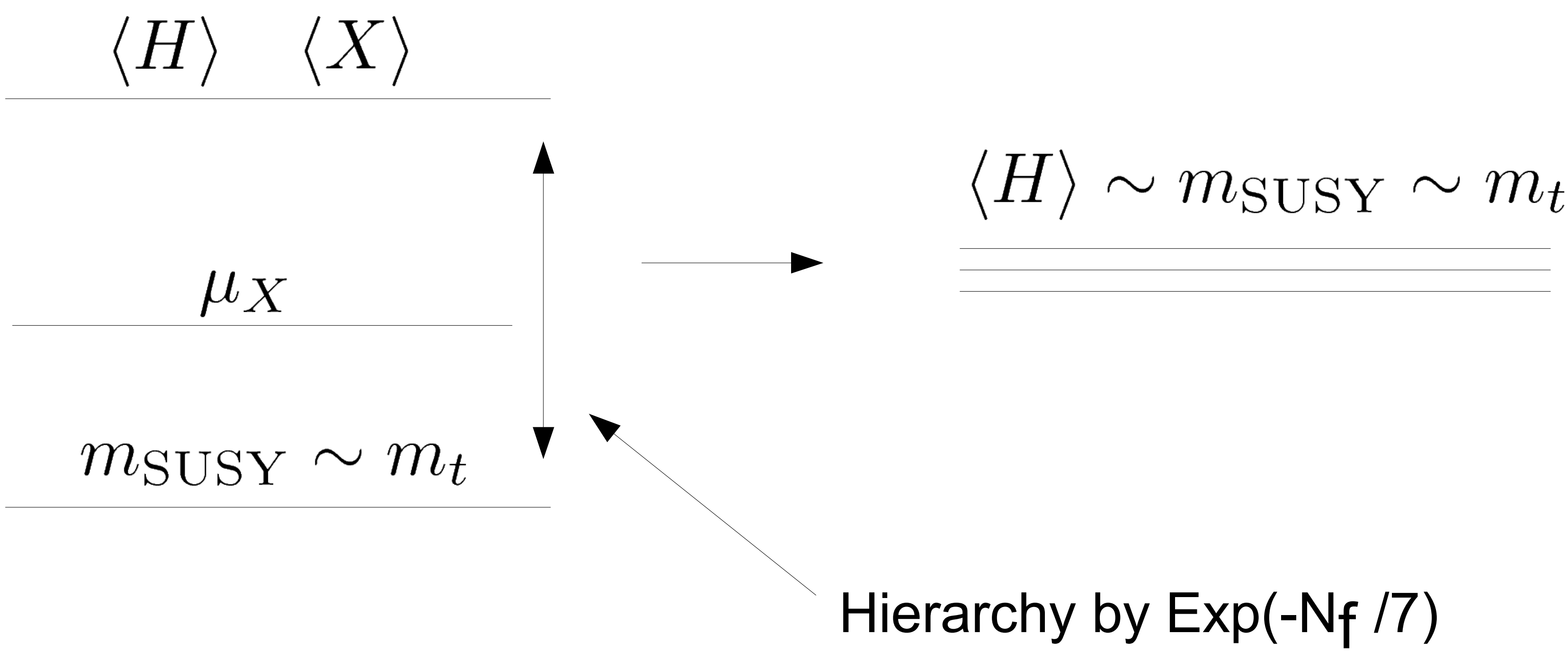
$$m_F^{ij,kl} = \frac{\partial^2 W_{\rm eff}}{\partial M_{ij} \partial M_{kl}} = \kappa h^3 (\det M)^{3/N_f} \left(\frac{1}{N} (M^{-1})_{ji} (M^{-1})_{lk} - (M^{-1})_{li} (M^{-1})_{jk} \right)$$

The top/bottom, Higgsinos obtain masses at the vacuum.

$$m_t \sim \kappa h^3 v \sim m_{\rm SUSY}$$

This is a desired relation.

Large N | Not so large N
Theoretically under control → Phenomenologically viable?



What we could show is that if we generalize the model to a large N_f (while $3N-N_f$ fixed), there is a vacuum where

Electroweak symmetry breaking

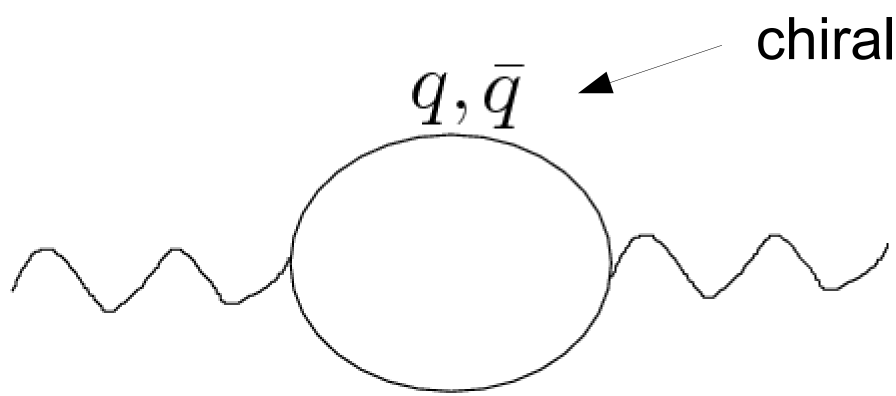
and

Top quark mass generation

are both achieved through the non-perturbative effect of the dual gauge theory.

S,T parameters?

In the large N theory, new contributions other than the SM particles are the loop of dual (s)quarks.



At leading order in 1/N (again 3N-Nf fixed to be 1)

$$\Delta S = \frac{N}{6\pi}.$$

$$\Delta T = 0.15 \left(\frac{5}{N_f} \right) \quad (\tan\beta = 1.1),$$

$$\Delta T = 0.57 \left(\frac{5}{N_f} \right) \quad (\tan\beta = 1.2).$$

Looks OK for N=2 and tanβ~1 together with a not-so-heavy Higgs boson.

LHC?

This model has a rich structure.

It includes MSSM + technicolor.

LHC will find both SUSY and technicolor.

Also, there is X which is color adjoint+singlet. It can be resonantly produced and decays into tt or bb.

Summary

SUSY + topcolor looks like a good combination.

(Although we still need to consider bottom mass etc.)

Dynamical EWSB + Dynamcial top mass generation can be seen at least at a large N extension of the theory.

LHC will find many new particles.