Bosonic See-Saw Mechanism for Electroweak Symmetry Breaking

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SUSY 05

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Introduction

- Electroweak Symmetry Breaking
- Bosonic See-Saw
- Supersymmetry
- Technicolor

How is $SU(2) \times U(1)$ broken?

hep-ph/0501059; work in progress

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- LHC will tell us.
- The most urgent question we should address now.

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- QCD (chiral symmetry breaking)
  $\langle \bar{q} q \rangle \neq 0$
  Global $SU(2)_L \times SU(2)_R \to SU(2)_D$
  Tiny electroweak symmetry breaking
  $(\Lambda_{\rm QCD} \sim 1{\rm GeV} \ll M_W \sim 100$ GeV$)$
  QCD alone can not explain the EWSB
  Pions are massless

Scalars in the SM

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- If H in $(1,2)_{\frac{1}{2}}$ is the only scalar in the SM, there is no color/charge breaking.

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- Higgs is a composite
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- Conformality

Common problems

- Top Yukawa couplings should be large
  $\lambda_t H \psi_Q \psi_{t^c}$ where $Q = \begin{pmatrix} t \\ b \end{pmatrix}$
  $m_t = \lambda_t \frac{v}{\sqrt{2}} \sim 180$ GeV $\rightarrow \lambda_t \sim \mathcal{O}(1)$
  pGB idea can not explain small m^2 and large λ_t simultaneously. (exception : little Higgs)

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- Flavor changing neutral currects
  $\delta m_K \sim 10^{-12}$ MeV
  $\frac{1}{\Lambda^2} \bar{\psi}_s \psi_d \bar{\psi}_d \psi_s \rightarrow \Lambda > 10^5$ TeV is needed for the ETC scale.

Weak Scale Supersymmetry

Radiative Electroweak Symmetry Breaking

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  $\rightarrow m_{\tilde{t}} \geq 500$ GeV
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- $\frac{M_Z^2}{2} \sim -m_{H_u}^2 - |\mu|^2$
  Fine tuning of $1 \sim 2\%$

Mediation of supersymmetry breaking

- Gravity Mediation
  $K \supset c_{ij} \frac{X^\dagger}{M_P} \frac{X}{M_P} \phi_i^\dagger \phi_j$
  $\longrightarrow$
  $m_{ij}^2 = c_{ij} \left| \frac{F}{M_P} \right|^2$

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- Universality ($c_{ij} = c$) is a very special assumption which is not easily justified. Therefore, FCNC appears as a serious problem.

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- Fine tuning of $2 \sim 3\%$

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- Yukawa Mediation
  Chacko and Ponton 2002
  From messenger-Higgs mixing, we get loop corrrections proportional to Yukawa couplings since messenger couples directly to the quarks and leptons.

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- Analytic continuation into superspace
  Giudice and Rattazzi 1998

$$m_Q^2 = -\frac{1}{4}\left[\sum_\lambda \left(\frac{d\Delta\gamma}{d\lambda}\beta_>(\lambda) - \frac{d\gamma_<}{d\lambda}\Delta\beta_>(\lambda)\right)\right]\left|\frac{F}{M}\right|^2$$

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- There is an instability along D-flat direction due to the absence of quartic couplings

See-Saw Mechanism

$$
\begin{aligned}
L &= \begin{pmatrix} \nu \\ e \end{pmatrix}, , N, H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \\
-\mathcal{L} &= \lambda_\nu H_u L N + \frac{1}{2} M N N
\end{aligned}
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M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}
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- Mixing angle: $\frac{m_D}{M}$

Bosonic See-Saw Mechanism

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- Two options : couple it to H_u or H_d

$$
\begin{aligned}
W &= X H_u H_d' + M H_u' H_d' \\
-\mathcal{L} &= F H_u H_d' + \mathrm{h.c.} + |M|^2 (|H_u|^2 + |H_d|^2)
\end{aligned}
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Bosonic See-Saw Mechanism

- Det M_H^2 is negative definite for $\langle X \rangle = 0$.

$$M_H^2 = \begin{pmatrix} 0 & F^* \\ F & |M|^2 \end{pmatrix} \begin{pmatrix} H_u \\ H_d'^* \end{pmatrix}$$

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- SUSY Breaking $\Longrightarrow$ Electroweak Symmetry Breaking
  For $\sqrt{F} \ll M$,

$$m_{H_u}^2 = -\left|\frac{F}{M}\right|^2$$

Bosonic See-Saw Mechanism: Mixing

- General consideration of the scalar VEV : $\langle X \rangle \neq 0$
  We can redefine X, H_u and H_u' to make $\langle X \rangle = 0$.

$$\begin{aligned}
\tilde{X} &= X - \langle X \rangle \\
\tilde{H}_u &= H_u \cos\alpha - H_u' \sin\alpha \\
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- As a consequence, new term is generated.

$$W = \cos\alpha \tilde{X} \tilde{H}_u H'_d + \sin\alpha \tilde{X} \tilde{H}'_u H'_d + M \sec\alpha \tilde{H}'_u H'_d$$

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- $\to$ potential unbounded from below

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- Considering μ from 0 to 1 TeV, the right parameter space giving EWSB is 1%.
- NMSSM is an easy way to reduce fine tuning.

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  $\Sigma : (1,3)_0$ is a weak triplet
- u-parity can forbid the usual μ term
  $P_u(H_u, u^c, \Sigma) = -(H_u, u^c, \Sigma)$

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- $T \sim 0.5$ is marginally consistent

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- Stop soft mass is too large compared to selectron mass

Origins of fine tunings in MSSM

- H_u soft masses are too much negative
- Stop soft mass is too large compared to selectron mass
- Σ soft mass should be heavy in 0μSSM

Yukawa Mediation

$$\begin{aligned} W &= y_t H_u Q u^c + H_u \Sigma(\lambda_{\Sigma_1} H_d + \lambda_{\Sigma_2} H'_d) \\ &\quad + X H'_u(\lambda_1 H_d + \lambda_2 H'_d) + M H'_u H'_d \end{aligned}$$

$$\begin{aligned} \Delta m^2_{H_u} &= \left[\frac{3}{\pi^2}\alpha^2_{\Sigma_2} + \frac{1}{\pi^2}\alpha_{\Sigma_2}\alpha_{\lambda_2}\right]\frac{1}{4}\left|\frac{F}{M}\right|^2 \\ \Delta m^2_{H_d} &= \left[-\frac{2}{\pi^2}\alpha_{\Sigma_1}\alpha_{\Sigma_2}\right]\frac{1}{4}\left|\frac{F}{M}\right|^2 \\ \Delta m^2_{Q,u^c} &= \left[-\frac{1}{2\pi^2}\alpha_t\alpha_{\Sigma_2}\right]\frac{1}{4}\left|\frac{F}{M}\right|^2 \\ \Delta m^2_{\Sigma} &= \left[\frac{3}{\pi^2}\alpha_t\alpha_{\Sigma_2} + \frac{3}{\pi^2}\alpha^2_{\Sigma_2} + \frac{1}{\pi^2}\alpha_{\Sigma_2}\alpha_{\lambda_2} - \frac{5}{\pi^2}\alpha\alpha_{\Sigma_2}\right]\frac{1}{4}\left|\frac{F}{M}\right|^2, \end{aligned}$$

Fundamental + Composite

- Composite Higgs

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Composite Higgs

Kaplan and Georgi 1984

$$\psi = \begin{pmatrix} \psi_U \\ \psi_D \end{pmatrix}, \psi_{U^c}, \psi_{D^c}, H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \tag{1}$$

- H is fundamental.

$$-\mathcal{L} = M^2|H|^2 + \psi H \psi_{U^c} + \psi H^\dagger \psi_{D^c} + \text{h.c.}$$

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- $f = \frac{\Lambda}{4\pi}$ is the decay constant of techni-pion.

$$M_H^2 = \begin{pmatrix} M^2 & f\Lambda \\ f\Lambda & \Lambda^2 \end{pmatrix} \begin{pmatrix} H \\ \phi \end{pmatrix}$$

$$-\mathcal{L} = |\phi|^4$$

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- Depending on the relative size of M^2 and $f^2\Lambda^2/\Lambda^2$, H can obtain a VEV.

Ultracolor

K. Choi and J. E. Kim 1985

- Technicolor condensates at the EW scale
  H is a fundamental scalar, ϕ is a techni-meson.

$$M_H^2 = \begin{pmatrix} M^2 & f\Lambda \\ f\Lambda & -\Lambda^2 \end{pmatrix} \begin{pmatrix} H \\ \phi \end{pmatrix}$$

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  $\langle \phi \rangle = \Lambda$

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- ϕ develops a VEV
  $\langle \phi \rangle = \Lambda$
- Tadpole for H appears
  $\langle H \rangle = \frac{f\Lambda^2}{M^2} \simeq \frac{\Lambda^3}{4\pi M^2}$

Bosonic Technicolor

Simmons 1989; Samuel 1990; Haba, Kitazawa and Okada 2005

Technicolor + Fundamental scalar (EW doublet)

- Suppose $M = 0$ for H.

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- Bosonic See-Saw mechanism applies.

$$M_H^2 = -f^2 \simeq -(\frac{\Lambda}{4\pi})^2$$

Now $f \sim 200$ GeV and $\Lambda = 4\pi f \sim 2TeV$ and we can raise the scale of strong coupling physics. Perfectly consistent with current data

Lessons

There is no single model for the electroweak symmetry breaking which is unanimously accepted.
The answer from LHC might not be among what we already have.
We still have 3 or 4 more years before LHC pins down the model and should try harder than now to get a satisfactory model.

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