Composite Higgs and Flavor

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Now, 125GeV Higgs-like particle found

Electroweak symmetry breaking mechanism

Higgs mechanism, a possible solution
Higgs couplings **SM-like**, H-gauge-gauge, H-fermion-fermion

- Should also probe **Higgs self-interactions** to confirm Higgs mechanism
- New physics should contain **SM as an effective theory**, at least for Higgs-gauge, Higgs-fermion interactions, e.g. MSSM
Stabilization of the Fermi scale

- Higgs mass, \( \delta m^2_H \sim \frac{g^2}{16\pi^2} \Lambda^2 \)
- \( \delta m^2_H \sim m^2_H \) indicates \( \Lambda \sim 1 \text{ TeV} \) naturalness

- 3 paths to proceed
- **unnatural theory**, huge fine-tuning of \( O(M_P^2/m_H^2) \), hierarchy problem
- natural theory 1: **supersymmetry**, weakly coupled theory
  MSSM in danger (little hierarchy), NMSSM= MSSM+ singlet
- natural theory 2: **compositeness**, strongly coupled theory
  Higgs as a composite state generated by strong dynamics, similar to \( \pi \) in QCD
  a light Higgs, pseudo-Goldstone boson of a spontaneously broken global symmetry
- common feature of natural theory: light top partners around TeV scale (scalar or fermion)
• Composite Higgs model
  partial compositeness

• Electroweak precision tests
  $S, T, Z\bar{b}_Lb_L$ coupling

• Flavor

• Confront with direct CPV in D decays

• Summary
• massless elementary particle interacts with composite operator with a linear mass term, D. B. Kaplan, 1991, similar to $\gamma - \rho$ mixing in QCD

\[ M_R \lambda_L \bar{u}_L T_R + M_L \lambda_R \bar{u}_R T_L \]

• SM fermion Yukawa matrix, $(\epsilon = \lambda/g_\rho)$

\[
\begin{align*}
y_u &= \epsilon_{u_L} \cdot Y_u \cdot \epsilon_{u_R} \\
y_d &= \epsilon_{d_L} \cdot Y_d \cdot \epsilon_{d_R}
\end{align*}
\]

• same mechanism for weak gauge boson $W^\pm$, $Z$ mass generation

• Higgs as pGB in strong sector of spontaneously broken global symmetry, mass generated via explicitly breaking global symmetry, e.g. heavy top
• the minimal composite Higgs model in $\text{AdS}_5$, Agashe, Contino, Pomarol, 2005

• calculable via AdS/CFT correspondence
Composite Higgs model

- two-sector model with partial compositeness (linear mixing with mass term), Contino, Kramer, Son, Sundrum, 2007

- mass spectra Barbieri, Buttazzo, Sala, Straub, Tesi, 2013
  - simplified assumptions for composite sector: common $g_\rho$, $Y$, $m_\rho$, $m_\psi$
  - $m_\rho \sim 3\text{TeV}$ (spin-1)
  - $m_\psi \sim 1\text{TeV}$ (spin-1/2), LHC direct search bounds around $500 - 600\text{GeV}$
  - $m_H = 125\text{GeV}$ (spin-0), pGB
Electroweak Precision Tests

- **S parameter**
  
  Tree-level contribution \( S = \frac{8\pi v^2}{m_\rho^2} \rightarrow m_\rho \sim 3\text{TeV} \)

- **T parameter**, depend on fermion rep.
  
  Custodial symmetry to protect T parameter \( SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_C \)
  
  \( SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X \) in composite sector

- **\( Z\bar{b}_L b_L \)** coupling precisely measured at LEP, need to be protected,
  
  \( SU(2)_L \otimes SU(2)_R \otimes P_{LR} \), Agashe, Contino, Da Rold, Pomarol, 2006

Choices of rep.

1. \((2, 2)_{2/3(-1/3)} \bigoplus (1, 1)_{2/3(-1/3)} \)
2. \((2, 2)_{2/3} \bigoplus (1, 3)_{2/3} \bigoplus (3, 1)_{2/3} \)

In the former case, left up mixing and left down mixing can be separated, convenient for flavor model.
An example of Composite Higgs model

- elementary sector, $SU(2)_L \otimes U(1)_Y$, massless SM particles $q_L(2)_{1/6}, u_R(1)_{2/3}, d_R(1)_{-1/3}, g, W_\mu^\pm, A_\mu, Z_\mu$

- composite sector, $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$, massive gauge bosons $H(2,2)_0$

\[
Q = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (2,2)_{2/3}, \quad \tilde{T} = (1,1)_{2/3}
\]

\[
Q'_{-1/3} = \begin{bmatrix} B_{-1/3} & T' \\ B_{-4/3} & B' \end{bmatrix} = (2,2)_{-1/3}, \quad \tilde{B} = (1,1)_{-1/3}
\]

- the Lagrangian, Vignaroli, 2012

\[
\mathcal{L} = \bar{q}_L^i \not{q}_L^i + \bar{u}_R^i \not{u}_R^i + \bar{d}_R^i \not{d}_R^i + Tr \left\{ \bar{Q} (i \not{\partial} - M_{Q^*_i}) Q \right\} + \tilde{T} (i \not{\partial} - M_{\tilde{T}^*_i}) \tilde{T} + Y_{U} Tr \left\{ \bar{Q} \mathcal{H} \right\} \tilde{T} + Tr \left\{ \bar{Q}' (i \not{\partial} - M_{Q'^*_i}) Q' \right\} + \tilde{B} (i \not{\partial} - M_{\tilde{B}^*_i}) \tilde{B} + Y_{D} Tr \left\{ \bar{Q}' \mathcal{H} \right\} \tilde{B} - \Delta_{L1} \bar{q}_L^3 (T, B) - \Delta_{R1} \bar{t}_R \tilde{T} - \Delta_{L2} \bar{q}_L^3 (T', B') - \Delta_{R2} \bar{b}_R \tilde{B} + h.c.
\]
• **Anarchy**, yukawa couplings

\[
y_u = \epsilon_{u_L} \cdot Y_u \cdot \epsilon_{u_R}
\]

\[
y_d = \epsilon_{d_L} \cdot Y_d \cdot \epsilon_{d_R}
\]

$Y_{u,d}$ are anarchic, light fermion with small yukawa coupling from small mixing

• light quarks are elementary, top strongly composite

• tree-level FCNC, but suppressed by light quark mass

• Flavor changing $Z$ Couplings, $K_L(B_S) \rightarrow \mu^+\mu^-$

• not enough for Kaon, from $Q_S^{LR}$, $m_{\rho} > 10 \text{TeV}$

• need flavor symmetry, e.g. $SU(3)$, $SU(2)$
Flavor symmetry

- Yukawa couplings
  
  \[ y_u = \epsilon_u L \cdot Y_u \cdot \epsilon_u R \]
  \[ y_d = \epsilon_d L \cdot Y_d \cdot \epsilon_d R \]

- \( SU(3) \)

- large compositeness of light generation due to heavy top
  Collider constraint, composite \( u, d \) quark within proton

- MFV setup, no flavor problem

- \( SU(2) \)

- heavy top not connected to light quarks

- tree-level FCNC, e.g. \( Z \) exchange, heavy gauge boson exchange

- Redi, Weiler, 2011; Redi, 2012; Barbieri, Buttazzo, Sala, Straub, 2012; Barbieri, Buttazzo, Sala, Straub, Tesi, 2013
Direct CPV in D decays

- Direct CPV in $\Delta C = 1$ $c \rightarrow u$ transition processes
  
  $$D^0 \rightarrow K^- K^+(\pi^- \pi^+)$$

- $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+)$

- World average (HFAG) by LHCb, CDF, Belle, BaBar before 2013
  
  $$\Delta A_{CP} = [-0.678 \pm 0.147] \%$$

- LHCb pion tagged analysis, LHCb-CONF-2013-003
  
  $$\Delta A_{CP} = [-0.34 \pm 0.15 \pm 0.10] \%$$

- LHCb muon-tagged analysis, 1303.2614
  
  $$\Delta A_{CP} = [+0.49 \pm 0.30 \pm 0.14] \%$$

- Discussion in SM or NP, from QCD chromomagnetic operator $O_{8g}$ in NP
  
  $$O_{8g} = \frac{g_s}{8\pi^2} m_c [\bar{u}\sigma_{\mu\nu} T^a (1 + \gamma^5) c] G^a_{\mu\nu}$$


- Discussion in a 2HDM and SUSY version, Chao-Shang Huang, Tianjun Li, Xiao-Chuan Wang, XHW, 2013
Direct CPV in D decays, cont’d

- Contribution from 4-fermion QCD operators
  \[ O_{4,6}' = (\bar{u}_\alpha c_\beta)V + A \sum_q (\bar{q}_\beta q_\alpha)V^\pm A \]

- \[ a_{K+K^-} \sim 0.1\% \times C_4'(m_c), \text{ with} \]
  \[ C_4'(m_c) \sim \frac{\sqrt{2}}{G_F \lambda b m_\rho^2} \epsilon_{u_R} \epsilon_{c_R} \epsilon_{s_R}^2 \sim 1.8 \times 10^4 \frac{g_\rho^2}{16\pi^2} \frac{(3\text{TeV})^2}{m_\rho^2} \epsilon_{u_R} \epsilon_{c_R} \epsilon_{s_R}^2 \]

- To accommodate \( \Delta A_{CP} \), \( u_R, c_R, s_R \) (or \( d_R \)) should be largely composite

- Constraints from \( \Delta c = 2 \) process \( D^0 - \bar{D}^0 \) mixing
  \[ \epsilon_{u_R} \epsilon_{c_R} \leq 2 \times 10^{-4} \]

- \( s_R \) (or \( d_R \)) should be fully composite for \( \Delta A_{CP} \)

- a viable model in progress \( \text{XHW 2013} \)
Summary

• Composite Higgs model is a natural theory beyond the SM.

• With proper choices of fermion rep. to survive EWPT and flavor symmetry to survive flavor constraints, e.g. $B$, $K$

• Interesting phenomenology in up-type quark sector.
Thank you for your attention!