Two Higgs Doublets from Fourth Generation Condensation

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Outline

Introduction and Motivation
Is a Fourth Generation still allowed?
What is it good for?

Two Higgs Doublet Model from Fermion Condensation
Effective Theory
Scalar Spectrum
Phenomenology

Conclusions
Is a Fourth Generation Still Viable?

Higgs must either be:

- Light
  \( m_h < 120 \text{ GeV} \)
- Heavy
  \( m_h > 600 \text{ GeV} \)

Heavy quarks must be \( m_{t'} > 450 \text{ GeV}, m_{b'} > 400 \text{ GeV} \)
Possible Ways Out

- Dynamical explanation for $m_h > 600$ GeV
  - Fermion Condensation with low cutoff $\rightarrow$ Heavy Higgs/No Higgs
  - One Higgs doublet always $m_h > 700$ GeV

- More complicated scalar sector
  - Fermion condensation $\rightarrow$ Two-Higgs doublets at low energy
  - (Mostly) heavy scalar spectrum with different $\sigma \times BR$
Why a Fourth Generation?

Heavy Chiral Fermions: strongly coupled to EWSB sector

- Top quark:
  \[ m_t \simeq v \quad \Rightarrow \quad y_t \sim 1 \]

- If Heavy Fourth Generation \( \Rightarrow y_4 > 1 \)

Higgs sector is strongly coupled

- Natural to assume composite Higgs sector
Why a Fourth Generation?

Other motivation: (Holdom, Hou, Hurth, Mangano, Sultanasoy, Unel '09)

- New CP violation source for baryon asymmetry
- New sources of CPV in meson decays
- ...
Electroweak Symmetry Breaking

Composite EWSB Sector:

- Technicolor: Asymptotically free, unbroken gauge interaction
  \[ \langle \bar{F}_L F_R \rangle \neq 0 \Rightarrow \text{EWSB} \]
  $F$’s are confined fermions, just as quarks in QCD.

- Alternative: gauge interaction spontaneously broken at $\Lambda \sim 1$ TeV
  \[ \Rightarrow F$’s un-confined heavy fermions with EW quantum #’s \]
  (E.g. Bardeen, Hill, Lindner ’90, Hill ’91)
EWSB from Fourth Generation Condensation

**Ingredients:**

- **A Chiral Fourth Generation:** $Q_4, U_{4R}, D_{4R}, L_4, E_{4R}, N_{4R}$

- **New strong interaction at the $O(1)$ TeV scale:**
  - **E.g.** Broken gauge symmetry $M \sim$ TeV
  - Strongly coupled to 4th gen. $\Rightarrow \langle \bar{F}_4 F_4 \rangle \neq 0$
    $\Rightarrow m_4 \simeq (500 - 600)$ GeV

- **Other fermion masses:** higher dimensional operators like

  $$\frac{x_{ij}}{\Lambda^2} \bar{f}_L^i f_R^j \bar{U}_R U_L$$
Models of Fourth Generation Condensation

All ingredients present in $\text{AdS}_5$

(GB, Da Rold '07, GB, Da Rold, Matheus '09)

Extra dimensional theories in compact $\text{AdS}_5$ dual to strongly coupled theories in 4D:

- Naturally results in strongly coupled heavy fermions
- Higher-dimensional operators among light fermions suppressed by large UV scale $\Lambda$
- Build gauge theory in $\text{AdS}_5$ with one extra chiral generation and no Higgs.
- Minimal model: Only up-type 4G quark condenses

$\Rightarrow$ Only 1 Higgs doublet, $m_h \gtrsim 700$ GeV
More general \textit{and} more natural: both up and down type quarks condense

More natural: interaction must be nearly isospin invariant to avoid $T$ parameter constraints

More general: would need to fine tune interaction to avoid one condensation

⇒ Two Higgs doublets at low energy
A Two Higgs Doublet from Fermion Condensation

(Luty '90, Luty, Hill, Paschos '90, GB, Haluch '11)

New fermions

\[ Q^i = \left( \begin{array}{c} U^i \\ D^i \end{array} \right)_L, \quad U^i, D^i \]

with \( i \) gauge index of new interaction.

New Strong Interaction:

- Want un-confined fermions ⇒ spontaneously broken at scale \( M \)
- Massive bosons strongly coupled to \( Q^i, U^i \) and \( D^i \)
- E.g. If \( G^a \) color-octect ⇒ \( i = (1 - 3) \) is color index, \( Q^i, U^i \) and \( D^i \) can be fourth-generation quarks
Electroweak Symmetry Breaking

New strong interactions $\Rightarrow$ four-fermion operators

$$\mathcal{L}_{4f} = \frac{g_L g_u}{M_G^2} \bar{Q} U \bar{U} Q + \frac{g_L g_d}{M_G^2} \bar{Q} D \bar{D} Q$$

with $g_L, g_u, g_d$ gauge couplings. If

$$g_L g_u > \frac{8\pi^2}{N_c} \Rightarrow \langle \bar{Q} U \rangle \neq 0$$
$$g_L g_d > \frac{8\pi^2}{N_c} \Rightarrow \langle \bar{Q} D \rangle \neq 0$$

One doublet condensing $\Rightarrow$ $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$
EWSB and Low Energy Scalar Spectrum

Four-fermion interactions $\leftrightarrow$ Yukawa interactions

$$
\mathcal{L}_{\text{eff.}} = Y_U (\bar{Q} \tilde{Φ}_U U + \text{h.c.}) + Y_D (\bar{Q} Φ_D D + \text{h.c.})
- M_G^2 Φ^\dagger U Φ_U
- M_G^2 Φ^\dagger_D Φ_D
$$

with

$$
Y_U^2 = g_L g_u, \quad Y_D^2 = g_L g_d, \quad \tilde{Φ}_U = -i σ_2 Φ_U^* 
$$

with hypercharges $h_U = -1/2, h_d = 1/2$. 
EWSB and Low Energy Scalar Spectrum

At $\mu < M_G$:

- Scalars develop kinetic terms

\[ \mathcal{L}_{\text{kin.}} = Z_{\Phi_U}(\mu)(D_\mu \Phi_U)\dagger D^\mu \Phi_U + Z_{\Phi_D}(\mu)(D_\mu \Phi_D)\dagger D^\mu \Phi_D \]

with the compositness BCs $Z_{\Phi_U}(M_G), Z_{\Phi_D}(M_G) = 0$.

- They get VEVs if four-fermion couplings super-critical:

\[ \langle QU \rangle \neq 0 \leftrightarrow \langle \Phi_U \rangle \neq 0 \]
\[ \langle QD \rangle \neq 0 \leftrightarrow \langle \Phi_D \rangle \neq 0 \]

- Effective Two-Higgs doublet spectrum at low energy
Low Energy Scalar Spectrum

At $\mu < M_G$ all couplings get renormalized and some generated. E.g.:

$$Y_U \rightarrow \frac{Y_U}{\sqrt{Z_{\Phi_U}}}, \quad Y_D \rightarrow \frac{Y_D}{\sqrt{Z_{\Phi_D}}}$$

$$\mu^2_U = M_G^2 - \frac{g_L g_u N_g}{8\pi^2} (M_G^2 - \mu^2)$$

$$\mu^2_D = M_G^2 - \frac{g_L g_d N_g}{8\pi^2} (M_G^2 - \mu^2)$$

We can see that $m^2_U < 0$ and $m^2_D < 0$ for super-critical couplings

$\Rightarrow V(\Phi_U, \Phi_D)$ with $\langle \Phi_U \rangle = v_U, \langle \Phi_D \rangle = v_D$
Theory is invariant under

\[ Q \rightarrow e^{-i\theta} Q \quad U \rightarrow e^{i\theta} U \quad D \rightarrow e^{i\theta} D \]

\[ \Phi_U \rightarrow e^{2i\theta} \Phi_U \quad \Phi_D \rightarrow e^{-2i\theta} \Phi_D, \]

forbids mixing term \( \mu_{UD}^2 (\Phi_U^\dagger \Phi_D + h.c.) \) in \( V(\Phi_U, \Phi_D) \).

This results in \( M_A = 0 \)
Instantons Induce $M_A$

Fermionic equivalent of mixing term

$$L_{\text{mix}} = G_{UD}(\bar{Q} D \bar{U}^c \tilde{Q} + \text{h.c.}), \quad (\tilde{Q} = -i\sigma_2 Q)$$

But this is generated by 't Hooft fermion determinant (Hill '95)

$$L_{\text{inst.}} = \frac{k}{M_G^2} \text{det} [\bar{Q}_L Q_R]$$

with $k \sim O(1)$.

$\Rightarrow$ Instantons of new strong interactions responsible for $M_A$
Scalar potential generated by fermion loops

\[ V(\Phi_U, \Phi_D) = \mu_U^2 |\Phi_U|^2 + \mu_D^2 |\Phi_D|^2 + \mu_{UD}^2 (\Phi_U^\dagger \Phi_D + \text{h.c.}) \]
\[ + \frac{\lambda_1}{2} |\Phi_U|^4 + \frac{\lambda_2}{2} |\Phi_D|^4 + \lambda_3 |\Phi_U|^2 |\Phi_D|^2 + \lambda_4 |\Phi_U^\dagger \Phi_D|^2 \]

Couplings \( Y_U, Y_D, \lambda_i, \mu_U, \mu_D, \mu_{UD} \) run down by using RGEs

\[ \Rightarrow \text{scalar spectrum} \]
Running to Low Energies

Solutions for $\lambda_1(\mu)$ for $M_G = 2, 3, 4$ TeV
Scalar Spectrum

\[ A = \sqrt{2} \left( \text{Im}[\Phi_D^0] \cos \beta - \text{Im}[\Phi_U^0] \sin \beta \right) \]

\[ h = \sqrt{2} \left( -\text{Re}[\Phi_U^0] \sin \gamma + \text{Re}[\Phi_D^0] \cos \gamma \right) \]

\[ H = \sqrt{2} \left( \text{Re}[\Phi_U^0] \cos \gamma + \text{Re}[\Phi_D^0] \sin \gamma \right) \]

\[ H^\pm = \Phi_D^\pm \cos \beta - \Phi_U^\pm \sin \beta \]

\[ \tan \beta = \frac{v_U}{v_D} \simeq 1. \text{ The CP-even mixing is} \]

\[ \tan 2\gamma = \frac{\mu_{UD}^2 + (\lambda_3 + \lambda_4)v^2 \sin 2\beta/2}{\mu_{UD}^2 + \lambda_4 v^2 \cos 2\beta/2} \]
Scalar Masses

E.g.: Pseudo-scalar mass

$$\mu_{UD}^2 = \frac{k \, v^2}{2 M_G^2} \left[ 1 - k v^2 (\lambda_1 \cos^2 \beta \cot \beta + \lambda_2 \sin^2 \beta \tan \beta) / (2 M_G^2) \right]$$

and the pseudo-scalar mass is

$$M_A^2 = -2 \frac{\mu_{UD}^2}{\sin 2\beta}$$
Scalar Masses

For $k = (0.1 - 1)$

<table>
<thead>
<tr>
<th></th>
<th>$M_G = 2$ TeV</th>
<th>$M_G = 3$ TeV</th>
<th>$M_G = 4$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_h$</td>
<td>(548-580) GeV</td>
<td>(459-467) GeV</td>
<td>(422-425) GeV</td>
</tr>
<tr>
<td>$M_H$</td>
<td>(651-732) GeV</td>
<td>(530-537) GeV</td>
<td>(482-585) GeV</td>
</tr>
<tr>
<td>$M_{H^\pm}$</td>
<td>(603-719) GeV</td>
<td>(495-512) GeV</td>
<td>(453-459) GeV</td>
</tr>
</tbody>
</table>

- Heavy $(h, H, H^\pm) \simeq (400 - 700)$ GeV depending on $(k, M_G)$
- Light $A \simeq (10 - 120)$ GeV
Phenomenology

- Usual $h, H$ decay channels suppressed in favor of $AA, A, Z$

- If condensing fermions carry color (4G quarks) $\rightarrow \sigma_{\text{prod.}}(gg \rightarrow (h, H, A)) \approx (6 - 7)$ SM values

- If new fermion colorless, no enhancement of $\sigma_{\text{prod.}}$. But scalar spectrum still same.
Electroweak Precision Constraints

Constraints in the S-T plot (68% and 95% C.L. contours)
Parameter space of scalar sector $(k, M_G)$ + fourth generation
Flavor

- Dynamics at the high scale introduce higher dimensional operators such as
  \[ \frac{x_{ij}}{\Lambda^2} \bar{f}_i f_j \bar{U}_R U_L \]

- Can always accommodate \( \Phi_U \) only couples to up-type quarks, \( \Phi_D \) only to down-type quarks and charged leptons

- PQ symmetry softly broken \( \Rightarrow \) mixing does not induce FCNCs at tree level

- Loop effects: \( H^{\pm} \) too heavy to give important effects in \( b \to s\gamma \), etc.
Summary/Outlook

- 4th Generation still not excluded by Higgs searches
- Composite 2HDM with light $A$ and heavy ($h, H, H^\pm$) is a natural consequence of fermion condensation
- If new fermions carry color:
  - We will see them soon ($m_{t'} > 450$ GeV)
  - $\sigma(h, H, A)$ larger than in standard 2HDM
  - But preferred decay channels are ($h, H$) $\rightarrow$ ($A, A$), ($A, Z$)
- If new fermions colorless, unusual scalar spectrum still hint of fermion condensation