A Fourth Family and No Higgs
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Why?
A fourth family ...

- sequential fourth family (with a heavy $\nu$) with at least some CKM mixing
- pair production and weak decays of the fourth family quarks

\[ pp \rightarrow t^\prime \bar{t}^\prime \rightarrow W^+W^- b\bar{b} \]

and/or

\[ pp \rightarrow b'\bar{b}' \rightarrow W^+W^- t\bar{t} \]

- since colored fermions are involved, cross sections are decent at the LHC
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... and no light Higgs

- suppose $t'$ and $b'$ masses are in the 600 GeV range
- then the Goldstone bosons of electroweak symmetry breaking couple strongly to these quarks
- strong interactions will unitarize $WW$ scattering
How do experimentalists decide what to focus on?
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Theory Space

most conventional

most conservative
Higgs

- taught to us early as part of ‘standard model’
- perturbative
Higgs

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but not conservative

- elementary scalar field is a theoretical construct
- scalar mass is unstable and unnatural
- another whole layer of complexity is needed
**Most Conventional (2)**

*Supersymmetry*

- great playground for theorists
- many man-years of research (inertia)
- perturbative
**Supersymmetry**
- great playground for theorists
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**but not conservative**
- again a new concept
- no consensus on susy breaking (nonperturbative?)
- origin of flavor is difficult to address
- parameters (lots) replace understanding
- fine-tuning problems still linger
Most Conservative (1)

Technicolor

- nature gives us the example of QCD
- repeat the same story for EWSB
Technicolor
• nature gives us the example of QCD
• repeat the same story for EWSB

but not conventional
• copy of QCD didn’t work (need walking coupling?)
• strong interactions (extra dimension interpretation?)
• origin of flavor is difficult to address
• top mass creates tension
What is a theory of flavor?

- broken gauge interactions connecting different flavors and feeding down mass from heavy to light
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Take this as a hint

• suppose EWSB is also based on a broken gauge interaction
• add a fourth family so its mass can do the job of EWSB
• EWSB is just the last step in the breakdown of flavor symmetries
• no need for unbroken gauge symmetry like technicolor
• new physics scales range from a TeV to a few hundred TeV
Most Conservative (2)

Fourth Family

- allowed by the data
- minimal model of dynamical EWSB
- integrates into some theory of flavor (including top mass)
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- even less so than technicolor
- is the most conservative also the least conventional?
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bonus

- theory of flavor is nearby
  - just from dimensional analysis of effective operators necessary to produce quark and lepton masses
**distinctive features**

- other theories have new vector-like fermions
  - but masses and decay modes are more constrained for a fourth family
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- other theories have new strong interactions
  - but here the effective massive degrees of freedom are fermionic
  - new strong interactions are broken
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EWSB dynamics

- chiral symmetry breaking but not confinement—NJL model is appropriate

\[
\frac{g^2}{\Lambda^2} (\bar{q}'_L q'_R)(\bar{q}'_R q'_L)
\]

\[
v^2 = f^2 \approx \frac{3m^2_{q'}}{4\pi^2} \ln \frac{\Lambda^2}{m^2_{q'}}
\]

- gives our estimate for \(m_{q'}\)
How do gauge symmetries break themselves?

- consider standard model with Higgs removed, and thus no Yukawa couplings
- has exact $SU(3) \times SU(2) \times U(1)$ gauge symmetry
- but this is a chiral gauge symmetry—any mass will break a gauge symmetry
- in fact QCD does produce a dynamical quark mass, $\langle \bar{q}q \rangle \neq 0$
- $W$’s and $Z$ receive mass (too low of course)
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minimal flavor physics

• fermion content is nothing more than standard families
• above the electroweak scale fermion masses are not allowed
• flavor breaking order parameters?
  • right-handed neutrino masses
  • four-fermion operators
What does a ‘potentially’ complete model look like?

\[ U_A(1) \times U_S(2) \times SU_{PS}(4) \times SU_L(2) \times SU_R(2) \]

\[ (+, 2, 4, 2, 1) \]

\[ (−, 2, 4, 1, 2) \]

\[ (−, \bar{2}, 4, 2, 1) \]

\[ (+, \bar{2}, 4, 1, 2) \]

- all possible global symmetries are gauged— but variations of this gauge symmetry is also be possible
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Constraints from $S$ and $T$

- if we remove the light Higgs we have
  \[ 0.25 \lesssim \Delta T \lesssim 0.55 \text{ at 68\% CL} \]
  \[ -0.2 \lesssim \Delta S \lesssim 0.11 \text{ at 68\% CL} \]

- mass splitting in a fermion doublet produces positive $\Delta T$, just like a light Higgs
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- pick the lepton masses $m_{\nu'}$ and $m_{\tau'}$, and then adjust $m_{t'}$ and $m_{b'}$ to satisfy constraints

  - for what region in $m_{\nu'}$-$m_{\tau'}$ space is this possible?
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- use constituent mass type approximation (with $f = 246$ GeV)

$$S = \frac{4}{6\pi} - \frac{1}{12\pi} - \frac{1}{3\pi} \ln\left(\frac{m_{\tau'}}{m_{\nu'}}\right)$$

$$\alpha f^2 T = \frac{1}{16\pi^2} (3g(m_{t'}, m_{b'}) + g(m_{\nu'}, m_{\tau'})) - \frac{m_{\nu'}^2}{4\pi^2} \ln\left(\frac{\Lambda_{\nu'}}{m_{\nu'}}\right)$$

$$g(m_1, m_2) = m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2} \ln\left(\frac{m_1}{m_2}\right)$$
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- mass splitting in a fermion doublet produces positive $\Delta T'$, just like a light Higgs

- four fermion masses replace one Higgs mass

- pick the lepton masses $m_{\nu'}$ and $m_{\tau'}$, and then adjust $m_{t'}$ and $m_{b'}$ to satisfy constraints

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- use constituent mass type approximation (with $f = 246$ GeV)

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g(m_1, m_2) = m_1^2 + m_2^2 - \frac{4m_1^2m_2^2}{m_1^2 - m_2^2} \ln\left(\frac{m_1}{m_2}\right)
\]
black contours: $T$

- lower edge: leptons provide all of $T = 0.55$
- contributions from leptons decrease by $\Delta T = -1$ on successive contours (quark contributions $\Delta T = 1$)
- $\Delta T = 1$ corresponds to 130 GeV quark mass splitting

red contours: $S$

- from lower to upper: $S = 0$, $S = 0.11$ and $S = 0.22$
- plausible that:
  
  $m_{\nu'} \approx 150-300$ GeV
  
  $m_{\tau'} \approx 400-600$ GeV
Model building?

- effective 4-fermion interactions
- identify approximate symmetries
- can achieve suppression of
  a) $Zb\bar{b}$ vertex correction
  b) $t'-b'$ mass splitting
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  a) $Zb\bar{b}$ vertex correction
  b) $t'-b'$ mass splitting

* $t$ mass operator feeds back on the $b'$ mass!
* this is the origin of the prediction $m_{b'} > m_{t'}$
the main issue: t mass

- approximate symmetries on \((q'_L, q'_R, q_L, q_R)\) with \(q' = (t', b')\) and \(q = (t, b)\)

\[ Q: (+, -, -, +) \text{ and } \tilde{Q}: (+, -, +, -) \]
the main issue: t mass

- approximate symmetries on \((q'_L, q'_R, q_L, q_R)\) with \(q' = (t', b')\) and \(q = (t, b)\)
- \(Q: (+, -, -, +)\) and \(\tilde{Q}: (+, -, +, -)\)

1) \(\bar{t}'_L t'_R \bar{t}'_R t'_L \quad \bar{b}'_L b'_R \bar{b}'_R b'_L\) (neutral under both charges)
   - \(t'\) and \(b'\) masses
   - due to gauge exchange

2) \(\bar{t}'_L t'_R \bar{t}_R t_L \quad \bar{b}'_L b'_R \bar{b}_R b_L\) (charged under \(Q\))
   - in ETC type models these are generated by gauge exchange
   - related gauge exchanges gave dangerous operators
   - \(t\) mass in tension with \(t'-b'\) mass splitting and \(Z b \bar{b}\) corrections

3) \(\bar{b}'_L b'_R \bar{t}_L t_R \quad \bar{t}'_L t'_R \bar{b}_L b_R\) (charged under \(\tilde{Q}\))
   - \(t\) mass, assuming \(\tilde{Q}\) is more badly broken than \(Q\)
   - this dynamics must badly break SU(2)\(R\)
**leptons**

- story for $\tau'$ and $\tau$ is similar to story for $b'$ and $b$

- right-handed neutrinos have flavor scale masses (flavor breaking order parameters)

- $\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}$ masses
  - there is also a large zoo of six fermion operators that can contribute to these masses
  - they are naturally in the sub-eV range

- $\nu'_{L\tau}$ mass comes from $\ell'_L \ell'_L (\ell'_L \ell'_L)^\dagger$
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- $\nu_{L\tau}$ mass—this is very different than the $t$ mass
  - there is no $Q$-invariant 4-fermion operator that can feed mass to $\nu_{L\tau}$
  - need $Q$-violating operator $\ell'_{L} \ell'_{L} (\ell_{L} \ell_{L})^\dagger$—thus $Q$ must be very good symmetry in the neutrino sector
lepton signals

• pair production of Majorana mass neutrinos

\[ Z \rightarrow \nu'_\tau \bar{\nu}'_\tau \rightarrow 4\ell + E \]
\[ 3\ell + 2j + E \]  (similar to SUSY)
\[ 2\ell + 4j \]  (including same sign)

• but \( \nu'_\tau \) could be stable enough to escape the detector
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**vector-like quarks are different**

- don’t need associated leptons
- masses unconstrained by EWSB—could be above a TeV
- more decay modes due to mixing with the top
  
  \[ t' \rightarrow t + Z, \quad t' \rightarrow t + h \]

- compatible with Higgs
  
  - only a lighter fourth family is consistent with a Higgs
“For decades theorists have sought a description of electroweak symmetry breaking that is somehow perturbative, ...”
Do perturbative theories offer anything more than a parameterization of our ignorance?