The Fourth Generation in Extensions of the Standard Model

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- Motivation for the Fourth Generation
- Extensions
  - Randall-Sundrum geometry
  - Two Higgs Doublet Model
    - Model I,II
    - Model III
  - MSSM
Are 4 families allowed?

• History:
  • late 70’s. 3rd family discovered...why not?
  • 1990: Z-width measurements show that there are 3 light neutrinos. Interest fades.
  • late 90’s: neutrinos have mass. Possibility of a 4th generation neutrino (with mass > 45 GeV) is revived.
  • early 00’s: precision electroweak fits
“A fourth generation of ordinary fermions is excluded to 99.999% CL on the basis of the S parameter alone”----PDG2006

“This conclusion is wrong”-----Graham Kribs, 2007

PDG claim was based on the work of Erler and Langacker. The Erler-Langacker analysis was correct, but they explicitly made the above statement under the condition that the fourth generation masses are all degenerate. They aren’t.

Kribs, Plehn, Spannowsky and Tait reanalyzed the precision electroweak bounds in 2007
For example, if the average mass is 350 GeV and the splitting is 50 GeV, the contributions to $S$ and $T$ are each 0.15, within the one sigma ellipse.
Advantages

• CP violation is much larger (the Jarlskog invariant is larger by a factor of $10^{14}$) making baryogenesis easier.

• Many more possibilities for dynamical electroweak symmetry breaking.

• Higgs production cross section is much bigger.
Warped Extra Dimensions (Randall-Sundrum)

\[ ds^2 = e^{-2k|y|} \eta_{\mu\nu} \, dx_\mu dx_\nu - dy^2 \]

Compactified on \( S_1/Z_2 \) with \( L = \pi R \)

Generates hierarchy
\[ \Lambda_{\text{TeV}} \sim M_{\text{Pl}} \, e^{-kL} \sim M_{\text{Pl}} \, e^{-k\pi R} \]
for \( kR \sim 11-12 \)

If fermions propagate in the bulk, and the Higgs is on the TeV brane, then fermions localized near the TeV brane are heavy and fermions localized near the Planck brane are light. Can easily get a large fermion mass hierarchy.

So the flavor hierarchy is determined by fermion geography
The KK gauge bosons are localized near the TeV brane. Thus fermions near the TeV brane (i.e. heavy fermions) will have large couplings to the KK gauge bosons.

The KK gauge bosons will mix with the standard model gauge bosons.
• In the three generation case, the top and bottom couple more strongly to the KK-Z.
• Since the KK-Z mixes with the Z, this leads to modifications in the interaction of the top and bottom with the Z.
• Since the Zbb coupling is measured accurately, one must keep the b away from the TeV brane.
• Then the $t_L$ must also be away from the TeV brane. This gives a tension between the large top mass and corrections to the Zbb coupling.

See papers by Agashe et al, Rizzo et al, Huber
Agashe, Perez and Soni point out that the basis in which the 5-D mass terms are diagonal is not the same as the 4-D mass basis.

(See also Burdman et al, Huber and others)

Thus one expects flavor changing couplings to the Z, which are bigger for heavier quarks, and they find that $t \rightarrow c \ Z$ will have a branching ratio of $10^{-5}$ for a KK-Z mass of 3 TeV.

In 4 generation models, there are no precision EW constraints, so one can get very large FCNC
ATLAS claims a bound of $10^{-5}$ can be reached in $100 \text{ fb}^{-1}$ for $t \rightarrow c \ Z$.

Scaling by the production cross section, a sensitivity of $10^{-3}$ can be reached for $t' \rightarrow t \ Z$. 

*Typical branching ratios of $O(10^{-3}-10^{-2})$*
Two Higgs Doublet Models

Model II---most popular

\[ u, c, t, t' \] couple to \( \Phi_1 \)  \quad \[ d, s, b, b' \] couple to \( \Phi_2 \)

With \( \tan \beta \equiv v_2/v_1 \):

Yukawa coupling of \( t' \) is \( \sim m/v_1 \sim (m/v)/\cos \beta \)

Yukawa coupling of \( b' \) is \( \sim m/v_2 \sim (m/v)/\sin \beta \)

For \( m \geq 280 \text{ GeV} \), \( \alpha_{Yuk} < 1 \Rightarrow \)

\[ 1/2 < \tan \beta < 2 \]

Model I has all fermions coupling only to \( \Phi_1 \), so upper limit vanishes
Effect of larger Yukawas:

Can have large rate for $t' \rightarrow H^+ b$, suppressing the branching ratio for $t' \rightarrow W^+ b$

Not a huge effect, suppression of the rate by a factor of 2-3 at most.

However, much more interesting effect in Model III
Model III

No discrete symmetries
All fermions couple to both Higgs doublets
Gives tree level FCNC of the form $\lambda_{ij} \bar{\Psi}_i \Psi_j \Phi$
where $i \neq j$ and $\Phi$ is $h, H, A$ (scalars or pseudoscalar)
Cheng and MS (1987) showed that a wide variety of mass matrices lead to $\lambda_{ij}^2 = O((h_{Yuk})_i (h_{Yuk})_j)$

In this case, the FCNC $\bar{t'} t \Phi$ coupling will be huge.

Note that $\Phi$ is either A (the pseudoscalar) or the combination of $h, H$ that is orthogonal to the Higgs boson.
If kinematically allowed, the decay $t' \to t \Phi$ will dominate, with typically well over 95% branching ratio.

For 400 GeV, the production rate for $t'$ pairs is 15 picobarns (for 14 TeV). In this case, one would see $p p \to \bar{t}' t' \to (\bar{t} \Phi)(t \Phi)$, where $\Phi$ is the lightest scalar or the pseudoscalar, at a huge rate (several milliHertz).

Detailed analysis is currently underway.
MSSM and four generations

most recent analysis is by Fok and Kribs

Major impact on the mass of the lightest Higgs

still have $1/2 < \tan \beta < 2$, so the tree level mass is negligible

Gives a lightest Higgs mass of

$$m_h^2 = \sum_f \frac{3m_f^4}{2\pi^2 v^2} \ln \left(\frac{m_f^2}{m_l^2}\right)$$

This can be much larger than the 3 family case
Assumes squark masses are equal, $\tan \beta = 1$, for $t'$ squark mass = (1.2, 1.1, 1.0, 0.95) $t'$ mass (top to bottom)

With a higher production cross section (factor of 9 or so) and a much larger Higgs mass, the possibility of a large rate at the Tevatron or the LHC for the “golden mode” should be analyzed.

Much more work on the phenomenology needed
Summary

• A fourth generation is allowed by EWPT

• In R-S geometry, the decay $t' \rightarrow t \, Z$ will have a large branching ratio

• In 2HDM Models I,II, the $t' \rightarrow b \, W$ decay will be suppressed, but in Model III, the decay $t' \rightarrow t \, \Phi$ could be the dominant decay with a huge cross section.

• In the MSSM, the Higgs mass can be well above the golden mode threshold with a much larger cross section than the SM.