Little Flavor

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Based on work in progress with
David B. Kaplan and Sichun Sun
Thanks

- to Howie for teaching me so much about supersymmetry and the Higgs
- to Michael for being willing to collaborate on crazy complicated models of supersymmetry breaking at a time when model building was unfashionable
- to both for intellectual honesty and always taking problems with their favorite models seriously
this talk

• brief review of flavor issues
• brief review of little Higgs
• brief intro to mooses
• brief review of flavor from new dimensions
• introduction to “little flavor models”
  • flavor physics at few TeV scale
  • experimentally acceptable FCNC
Flavor Puzzle(s)
Flavor Puzzle #1

- Why 3 generations of quark and leptons?
  - new symmetries?
  - new dimensions?
  - new dynamics?
Flavor Puzzle #2

Why so much hierarchical structure in flavor parameters?

SM gauge couplings $\sim \mathcal{O}(1)$
Higgs self coupling $\sim \mathcal{O}(1)$
top Yukawa coupling $\sim \mathcal{O}(1)$
CP violating phase $\sim \mathcal{O}(1)$

\begin{align*}
\frac{m_c}{m_t} &\sim \mathcal{O}(10^{-2}) \\
\frac{m_b}{m_t} &\sim \mathcal{O}(5 \times 10^{-2}) \\
\frac{m_s}{m_t} &\sim \mathcal{O}(10^{-3}) \\
\frac{m_u}{m_t} &\sim \mathcal{O}(10^{-5}) \\
\frac{m_d}{m_t} &\sim \mathcal{O}(10^{-5})
\end{align*}

\(V_{us} \sim \mathcal{O}(2 \times 10^{-1})\)
\(V_{cb} \sim \mathcal{O}(4 \times 10^{-2})\)
\(V_{ub} \sim \mathcal{O}(4 \times 10^{-3})\)
Flavor Puzzle #3

Where are the Flavor Changing Neutral Currents (FCNC)?

Absence of $s \rightarrow d$ transitions key to prediction of charm quark ([GIM, Gaillard and Lee])

Hierarchy problem of electroweak scale, dark matter puzzle suggest new physics (NP) scale $\Lambda_{NP} \sim 1$ TeV

Generic effect of NP at low energy: higher dimension operators that give FCNC
Dimension 6 operators and FCNC

some allowed dimension 6 operators:

\[ \frac{c_{sd}}{\Lambda_{NP}^2} (\bar{s}\gamma_\mu d)^2 \quad \frac{c_{bd}}{\Lambda_{NP}^2} (\bar{b}\gamma_\mu d)^2 \quad \frac{c_{uc}}{\Lambda_{NP}^2} (\bar{c}\gamma_\mu u)^2 \]

\( c_{ij}'s \sim O(1) \) ? loop factor?

Neutral meson mixing constraints:

\[ \Im c_{sd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^4) \text{TeV} \quad \Re c_{sd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^3) \text{TeV} \]

\[ \Re c_{uc} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^3) \text{TeV} \quad c_{bd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^2) \text{TeV} \]
Absence of non standard FCNC =constraint on NP for LHC

• TeV scale physics respects flavor symmetry ?
• TeV scale physics very weakly coupled to fermions (except maybe right handed top)?
• TeV scale physics is not “generic” (but neither is flavor structure of standard model)
flavor problem(s) in SUSY

- fcnc flavor problem from susy breaking terms--unless first two sfermion generations nearly degenerate or very heavy (beyond LHC) $\Delta m_K$ and/or $\Delta m_D$ is too big, $\varepsilon_K$ generically too big

- technically natural to assume no fcnc problem
  - “minimal flavor violation”
  - can solve fcnc problem in several ways, e.g.
    - addressing flavor hierarchies at high scale
    - mediate susy breaking at lower scale
flavor problem in composite/little Higgs

• higgs compositeness scale \( \sim \) TeV for solution to hierarchy problem

• cutoff \( \sim \) 10 TeV

• potential FCNC from cutoff scale physics and below

• technically natural to assume no fcnc problem “minimal flavor violation”
General features of most flavor hierarchy models which avoid the fcnc problem:

- Origin of flavor hierarchy involves high scales
- Sequestration of flavor hierarchy physics from LHC scale physics
- “Little Flavor” (model to be presented here) will be a counter example.
Little Higgs
Deconstruction and new dimensions

Arkani-Hamed, Cohen, Georgi / Hill, Pokorski, Wang

- A latticized, compact new dimension= 4D model with non-linear sigma model + product gauge group G×G×….

- *ACG*: Higgs models with no n-loop quadratic divergences

- n arbitrarily large, although n=1 is “good enough” since there is a cutoff at scale \( \Lambda \sim 4 \pi f \)

- Higgs can be a “Little” pseudo Nambu-Goldstone Boson with mass\(^2 \sim g^4 f^2/(16 \pi^2) \) instead of typical \( g^2 f^2 \)

- quadratic divergences in Higgs mass\(^2 \) cancelled by *same spin* “partners” with mass naturally heavier than Higgs by \( \sim 4 \pi/g \)
“Moose” (or quiver) notation

- Sites = symmetry group $\text{SU}(n)$
- Links = something in bilinear representation $(n, \bar{n})$

Dimensional deconstruction:
- Site = gauge group
- Link = nonlinear sigma model field
Essential features of little Higgs
Arkani-Hamed, Cohen, Katz, Gregoire, A.N., Wacker

- Large approximate, nonlinearly realized, global symmetry
- Higgs transforms nonlinearly in multiple ways
- Sparse structure of symmetry breaking spurions
- Higgs coupling arises from “collective symmetry breaking”
- No single coupling breaks all the nonlinearly realized symmetries protecting the Higgs mass
- Symmetry breaking is “soft” and UV insensitive
- Higgs potential calculable
Challenges for Little Higgs:
precision electroweak
UV completion
Unification

• “Fully realistic constructions are situated somewhere between late baroque and early rococco.” Resonaances (Adam Falkowski)
Origin of fermion generations from new dimensions

*Kaplan, Sun*

- “surface modes” of a 5D theory compactified on orbifold, #orbifold fixed points=#chiral fermions
- Deconstructed model is a moose
- “Black sites”: vector fermions
- other 3 sites: chiral fermions
- wave function in extra dimensions deconstructs to which linear combinations of sites light fermions live on

*FIG. 1: A discretized $Z_2$ orbifold with three zero modes; $\mathcal{R}$ reflects about the horizontal axis.*
Little Flavor
Why young physicists are great

- They do things that senior physicists think can't work or are not worth doing
- and sometimes discover something new
- Sichun Sun: “why not flavor moose= little Higgs moose?”

What are you doing, moose?
You cannot win this race.

You don't even have propellers.
Basic idea of little flavor

• Little Higgs models have large approximate flavor symmetries and sparse symmetry breaking

• LH global symmetries=flavor symmetries?

• Potential issues
  • flavor hierarchy?
  • fcnc?
The original Moose

SU(4)$^6$ approximate global symmetry

SU(2) × U(1) subgroup of each SU(4) is gauged
chiral fermions on white sites
Vector-like fermions on black sites

Sigma fields break SU(4)$^6$ to SU(4)
The reduced Moose

SU(2) × U(1) subgroup of each SU(4) is gauged

3 generations of chiral fermions on white site

3 generations of vector-like fermions on black site
The pseudo NGB’s

\[ \Sigma = \xi \Sigma_H \xi \]
\[ \Sigma_H = \exp \left[ \left( \frac{i \sqrt{2}}{f} \right) \left( \begin{array}{cc} 0 & \Phi^\dagger \\ \Phi & 0 \end{array} \right) \right] \]
\[ \Phi = \begin{pmatrix} H_u^T \\ H_d^T \end{pmatrix} \]
\[ \xi = \exp \left[ \left( \frac{i}{2f} \right) \begin{pmatrix} \tilde{\pi}' \cdot \tilde{\sigma} + \eta/\sqrt{2} & 0 \\ 0 & \tilde{\pi} \cdot \tilde{\sigma} - \eta/\sqrt{2} \end{pmatrix} \right] \]

- even with only 1 \( \Sigma \) field, mechanism similar to one used in “Littlest Higgs” model can give Higgs quartic, \( \eta, \pi^{\pm} \) masses \( \sim f \)
- \( \pi^0 \) and \( \pi^{\pm,0'} \) are eaten to give mass \( \sim f \) to heavier \( \text{SU}(2) \times \text{U}(1) \) bosons
- 2 little Higgs doublets, \( H_u \) and \( H_d \), vevs determined by vacuum alignment, give mass to W and Z
Quarks (leptons are similar)

\[ Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix} = (3, 2)_{1/6}, \quad U_i = (3, 1)_{2/3}, \quad D_i = (3, 1)_{-1/3}, \quad i = 2, 4, 6 \]

\[
\begin{pmatrix} Q_i \\ U_i \\ D_i \end{pmatrix} = \begin{pmatrix} u_i \\ d_i \\ U_i \\ D_i \end{pmatrix}, \quad i = 2, 4, 6
\]

- black site has vector-like fermions in complete SU(4) multiplets. Couplings to \( \Sigma \) on black site preserve SU(4)

\[ Q_{iL} = \begin{pmatrix} u_i_L \\ d_i_L \end{pmatrix} = (3, 2)_{1/6}, \quad U_{iR} = (3, 1)_{2/3}, \quad D_{iR} = (3, 1)_{-1/3}, \quad i = 1, 3, 5 \]

- white site has chiral fermions in incomplete multiplets whose couplings to \( \Sigma \) break SU(4)
Quark masses

- In limit of unbroken SU(4) on black sites, alignment of $\Sigma$ does not affect quark masses
- 3 massless generations even after electroweak symmetry breaking
- approximate global $SU(4)^3 \times \mathbb{Z}_3$ (one $SU(4)$ for each generation) $\times SU(4)^2$ ($\Sigma$ transformation)
- Add small $SU(4)$ breaking Dirac mass terms (spurions) to black site quarks to give quark masses
- little Higgs mechanism is preserved-no quadratic divergences in Higgs potential
Quark mass, mixing hierarchy

- computer search through random black site spurions to fit CKM parameters, quark masses.
- good fit with hierarchical, nearly diagonal spurions in mass matrix
- large global symmetry group + small spurions suppresses dangerous 4 fermi terms
- very small ($10^{-5}$) off diagonal Z couplings from mixing with heavy fermions
- sufficiently small off diagonal couplings to heavy neutral gauge bosons
Lepton masses

- similar to quark masses
- could have Dirac neutrinos
- could have TeV scale seesaw for neutrinos
- so far only ad hoc explanation of why neutrino masses small (small spurions)
Flavor physics at LHC?

- “Little flavor” gives existence proof that flavor physics at few TeV scale is not inconsistent with absence of new FCNC at low energy!

- Key ingredient is large approximate global symmetry and small sparse symmetry breaking spurions

- spurion structure accounts for fermion mass hierarchy and mixing angle structure

- suppresses fcnc

- also key ingredient of little Higgs