# 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 $\sim \mathcal{O}(1)$

$V_{us} \sim \mathcal{O}(2 \times 10^{-1})$

$V_{cb} \sim \mathcal{O}(4 \times 10^{-2})$

$V_{ub} \sim \mathcal{O}(4 \times 10^{-3})$

$$\frac{m_c}{m_t} \sim \mathcal{O}(10^{-2})$$

$$\frac{m_b}{m_t} \sim \mathcal{O}(5 \times 10^{-2})$$

$$\frac{m_s}{m_t} \sim \mathcal{O}(10^{-3})$$

$$\frac{m_u}{m_t} \sim \mathcal{O}(10^{-5})$$

$$\frac{m_d}{m_t} \sim \mathcal{O}(10^{-5})$$

# 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:

$$\frac{c_{sd}}{\Lambda^2_{NP}}(\bar{s}\gamma_\mu d)^2 \qquad \frac{c_{bd}}{\Lambda^2_{NP}}(\bar{b}\gamma_\mu d)^2 \qquad \frac{c_{uc}}{\Lambda^2_{NP}}(\bar{c}\gamma_\mu u)^2$$

$c_{ij}$'s~ *O(1)?* loop factor?

Neutral meson mixing constraints:

$$\Im c_{sd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^4) TeV \qquad \Re c_{sd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^3) TeV$$

$$\Re c_{uc} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^3) TeV \qquad c_{bd} \sim 1 \rightarrow \Lambda_{NP} > \mathcal{O}(10^2) TeV$$

# 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 ~TeV for solution to hierarchy problem
- cutoff ~ 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

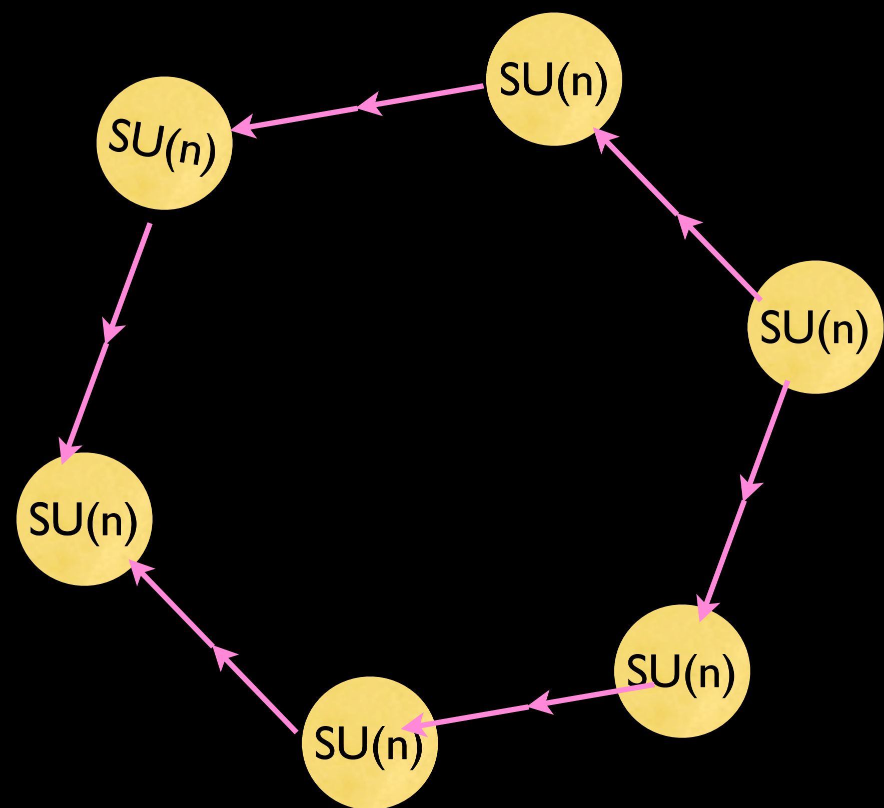
# Deconstruction and new dimensions

*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$^2$ ~ $g^4 f^2/(16 \pi^2)$ 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

site + link diagrams




Dimensional deconstruction:
site =gauge group
link=nonlinear sigma model field

sites=symmetry group SU(n)

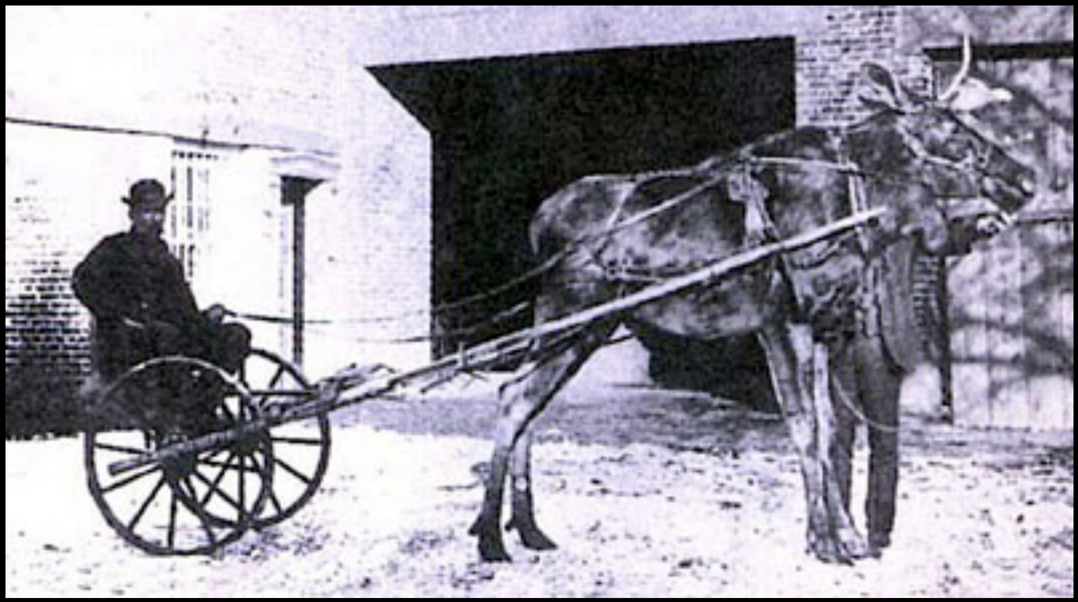
links=something in bilinear representation $(n,\bar{n})$

# 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

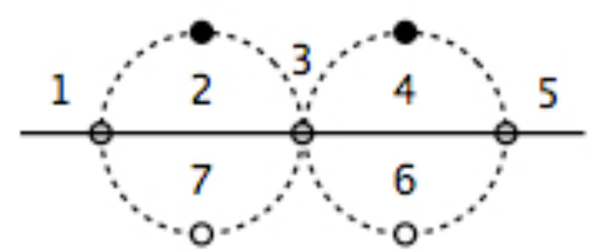
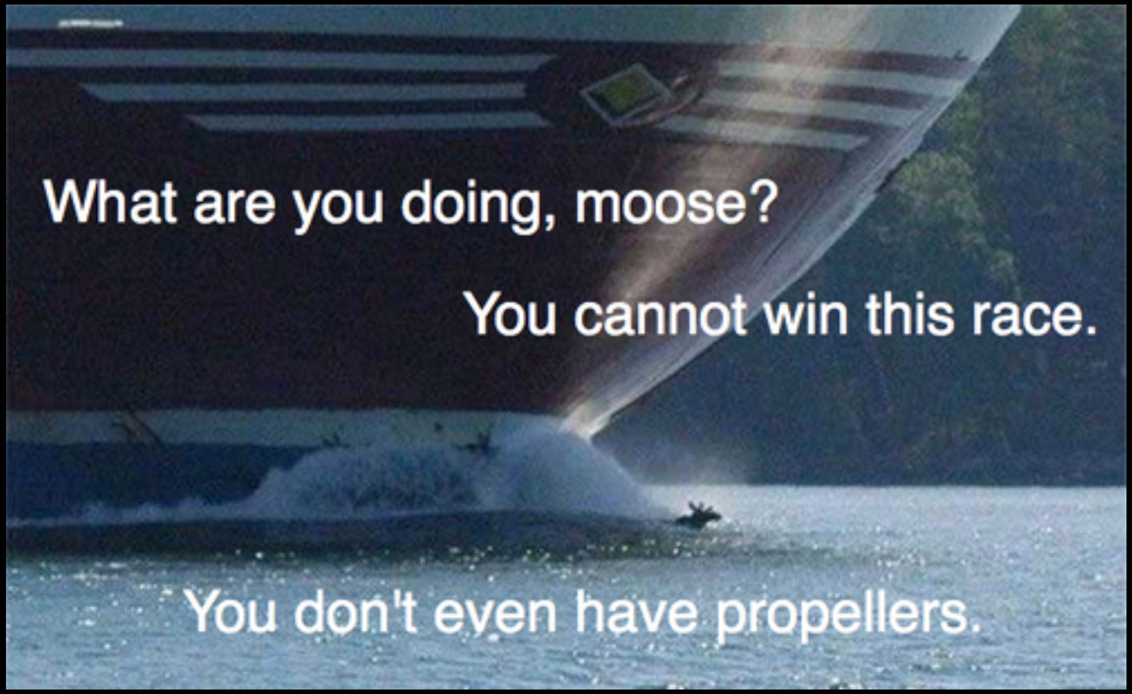



FIG. 1: A discretized $Z_2$ orbifold with three zero modes; $\mathcal{R}$ reflects about the horizontal axis.

# Little Flavor

# Why young physicists are great

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

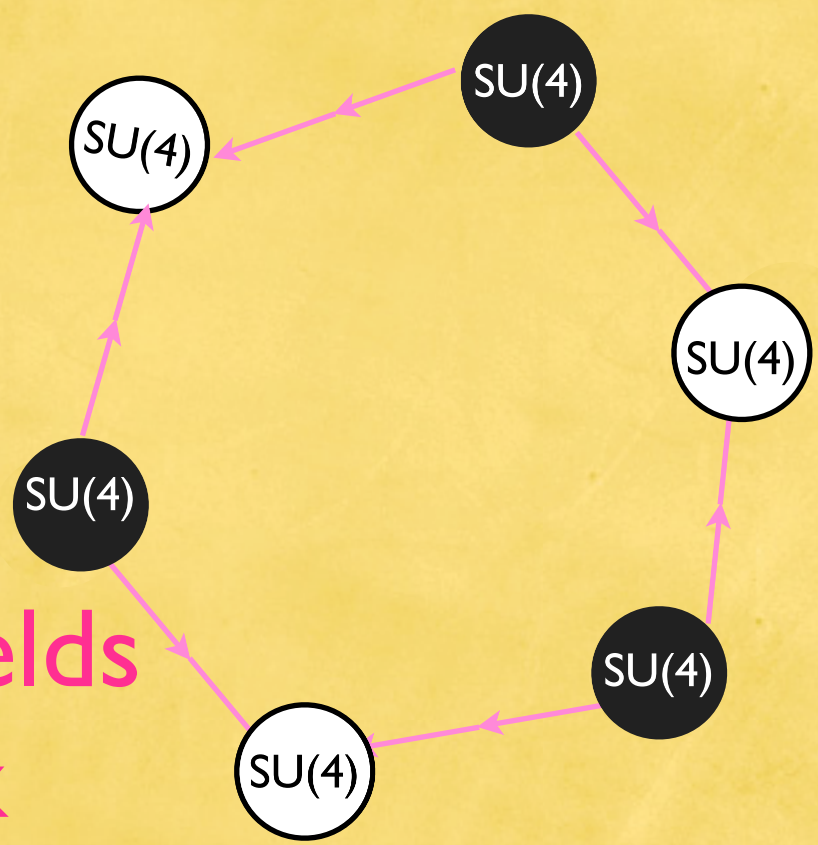


# Basic idea of little flavor

- 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



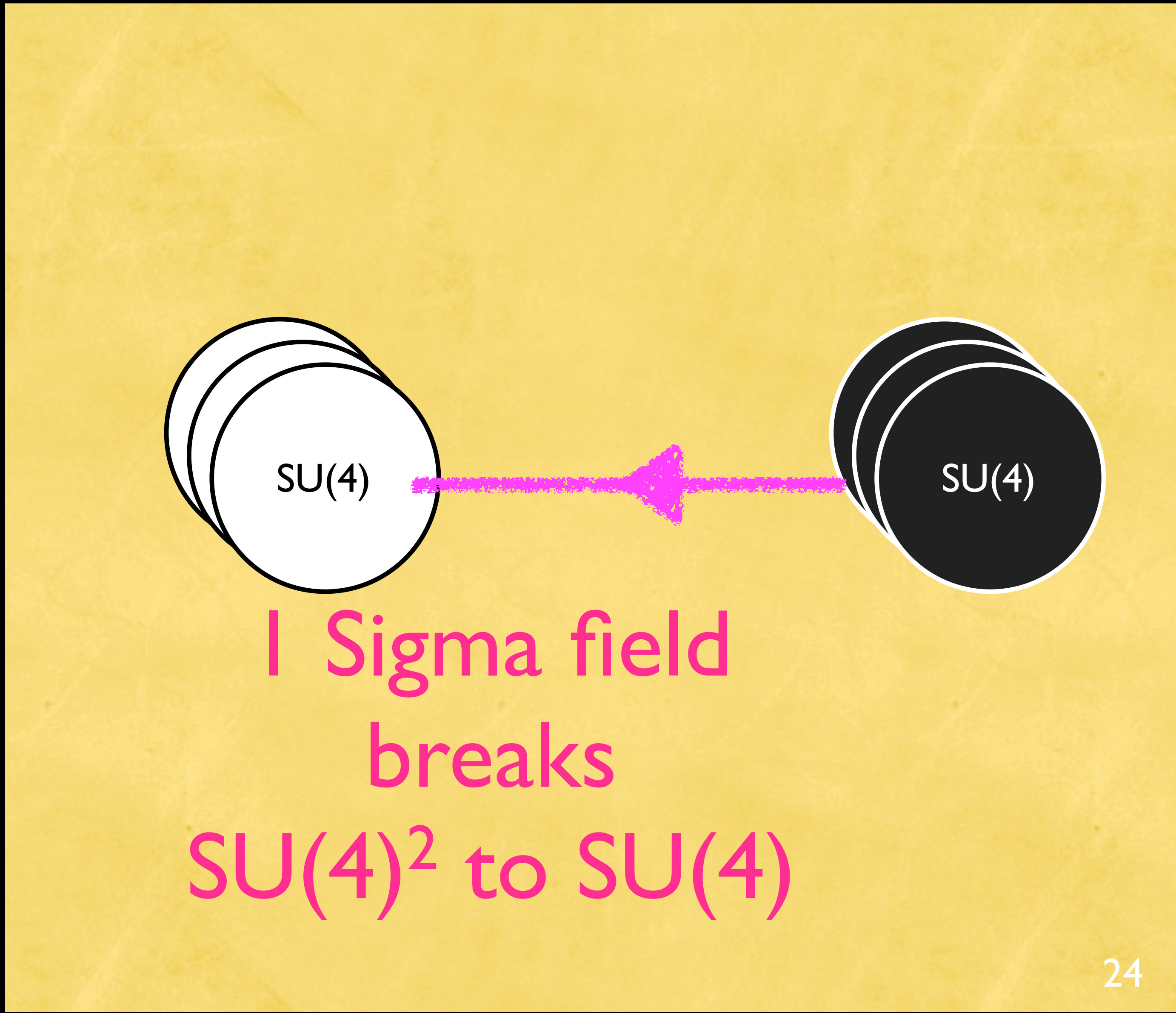

Sigma fields break $SU(4)^6$ to $SU(4)$

$SU(2) \times U(1)$ subgroup of each $SU(4)$ is gauged

chiral fermions on white sites

Vector-like fermions on black sites

# 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

$$\Sigma = \xi \Sigma_H \xi \qquad \Sigma_H = \exp\left[\left(\frac{i\sqrt{2}}{f}\right)\begin{pmatrix} 0 & \Phi^\dagger \\ \Phi & 0 \end{pmatrix}\right]$$

$$\Phi = \begin{pmatrix} H_u^T \\ H_d^T \end{pmatrix} \qquad \xi = \exp\left[(i/2f)\begin{pmatrix} \vec{\pi}\,' \cdot \vec{\sigma} + \eta/\sqrt{2} & 0 \\ 0 & \vec{\pi} \cdot \vec{\sigma} - \eta/\sqrt{2} \end{pmatrix}\right]$$

- even with only 1 $\Sigma$ field, mechanism similar to one used in "Littlest Higgs" model can give Higgs quartic, $\eta$, $\pi^{\pm}$ masses~$f$
- $\pi^0$ and $\pi^{\pm,0\prime}$ are eaten to give mass $\sim f$ to heavier SU(2)×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)

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

$$\begin{pmatrix} Q_i \\ U_i \\ D_i \end{pmatrix} = \begin{pmatrix} u_i \\ d_i \\ U_i \\ D_i \end{pmatrix} \ , \qquad i = 2,4,6$$

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

$$Q_{iL} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L = (3,2)_{1/6} \ , \qquad U_{iR} = (3,1)_{2/3} \ , \qquad D_{iR} = (3,1)_{-1/3} \ , \qquad i = 1,3,5$$

- 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 $SU(4)^3 \times \mathbf{Z_3}$ (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