Little Flavor:
Composite Higgs theory may explain flavor structure at LHC/ILC

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Spacetime as a topological insulator

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David B. Kaplan, S.S.

Little Flavor

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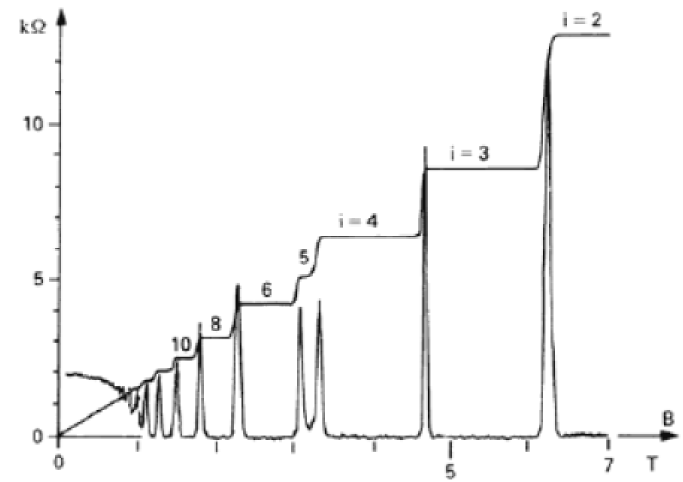
A flavor scenario to give rise three families

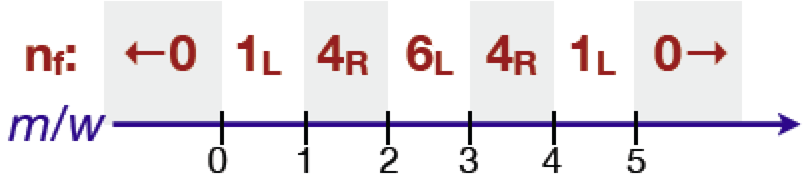
Spacetime as a topological insulator ,David B kaplan and S.S, highlighted in an APS Physics Synopsis.

- "3", fermion generation number as Chern-number
- Same universal physics behind:
  - Domain wall fermion
  - Quantum Hall effect /topological insulator
  - Chiral fermion on the lattice



E.g, d=5 lattice: *lattice derivatives*

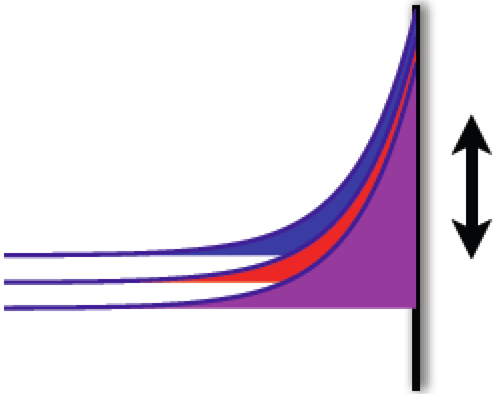
$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi - m \bar{\psi}\psi + w\, \bar{\psi}\partial^2\psi$$



$$\sigma_{xy} = n\frac{e^2}{h}$$

A flavor scenario to give rise three families II

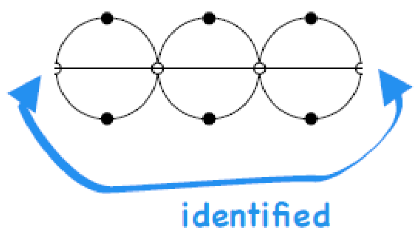
- Three zero mode stuck at one "brane"With different profile.
- Could be implemented into RS. Might having some trouble with gauge field.
- Could also put it on a discretized Z2 orbifold.

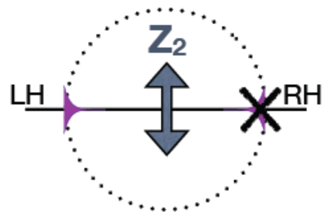


Orbifold projection rather trivial on discretized manifold.
Find index theorem:

\# of LH-RH zeromodes = # fixed points under Z_2

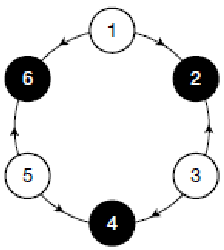
To get 3 families out, need to build in 3 Z_2 fixed pts





For three families led to bizarre multiply-connected extra dimension, reduced to 9 points

Leads to 4d moose diagram:



- white sites = chiral fermions
- black sites = Dirac fermions

Flavor puzzle in standard model:

- hierarchical structure in flavor parameters
  - couplings: gauge ~ Higgs ~ top Yukawa ~ O(1)
    CP violating phase~O(1)
  - angles: $V_{us} \sim 2\times10^{-1}$, $V_{cb} \sim 4\times10^{-2}$, $V_{ub} \sim 2\times10^{-3}$
  - masses: $b/t \sim 5\times10^{-2}$, $c/t \sim 10^{-2}$, $s/t \sim 10^{-3}$, $u/t \sim d/t \sim 10^{-5}$
- flavor changing neutral currents (FCNC)
  - EW higgs sector, dark matter suggest new TeV physics
  - Absence of FCNC *seems* to require much higher scale physics....
- There is another Hierarchical problem in SM, Higgs hierarchy….

Deconstruction Arkani-Hamed, Cohen, Georgi / Hill, Pokorski, Wang (2001)

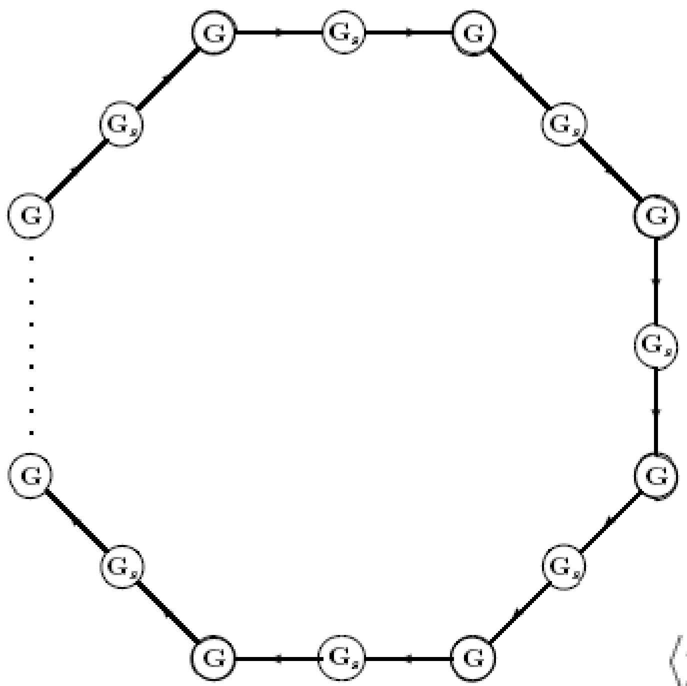
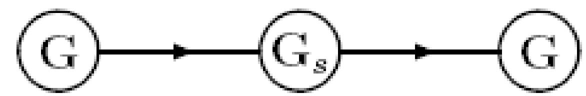


Figure 1: A moose diagram.

$$SU_i(m) \times SU_i(n) \times SU_{i+1}(m)$$



$\chi_{i,i}$ transforming as $(m, \bar{n}, 1)$

$\psi_{i,i+1}$ transforming as $(1, n, \bar{m})$

$$\langle \chi_{i,i}\, \psi_{i,i+1} \rangle \sim 4\pi f_s^3\, U_{i,i+1} \qquad i = 1, \ldots, N$$

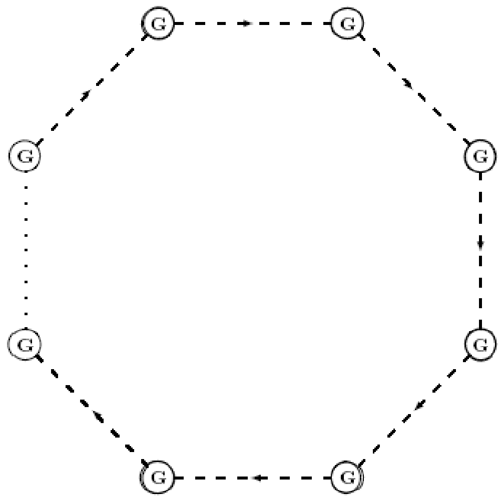


Figure 2: A condensed moose diagram

$$a = \frac{1}{g f_s}, \qquad R = Na \ .$$

$$S = \int d^4x \left(-\frac{1}{2g^2} \sum_{j=1}^{N} \mathrm{tr}\, F_j^2 + f_s^2 \sum_{j=1}^{N} \mathrm{tr} \left[(D_\mu U_{j,j+1})^\dagger D^\mu U_{j,j+1} \right] + \cdots \right)$$

$$D_\mu U_{j,j+1} \equiv \partial_\mu U_{j,j+1} - i A_\mu^j U_{j,j+1} + i U_{j,j+1} A_\mu^{j+1}$$

- link field could be parameterized as below, protected by large globe symmetry:

$$X_j = \exp(2i x_j / f) \qquad x = \begin{pmatrix} \varphi_x + \eta_x & h_x \\ h_x^\dagger & -2\eta_x \end{pmatrix}$$

Deconstruction and Little Higgs

- Composite Higgs Kaplan, Georgi, (1984)
- Deconstruction Arkani-Hamed, Cohen, Georgi / Hill, Pokorski, Wang (2001)
- Little Higgs Arkani-Hamed, Cohen, Katz, Gregoire, A.N., Wacker (2002)
- A latticized, compact new dimension= 4D model with non linear sigma model + product gauge group G×G×..
- 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^4f^2/(16π^2), instead typical g^2f^2

Combining little higgs with flavor model?

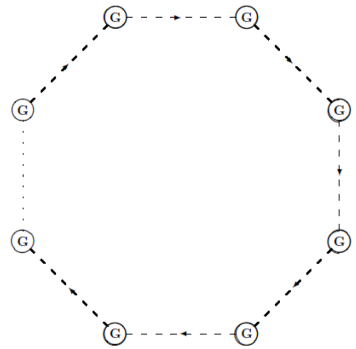
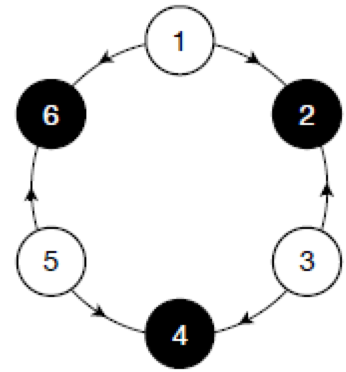


Figure 2: A condensed moose diagram



- white sites = chiral fermions
- black sites = Dirac fermions

Little Higgs:

(Arkani-Hamed, Cohen, Georgi (2001); Arkani-Hamed, Cohen, Katz, Nelson (2002))

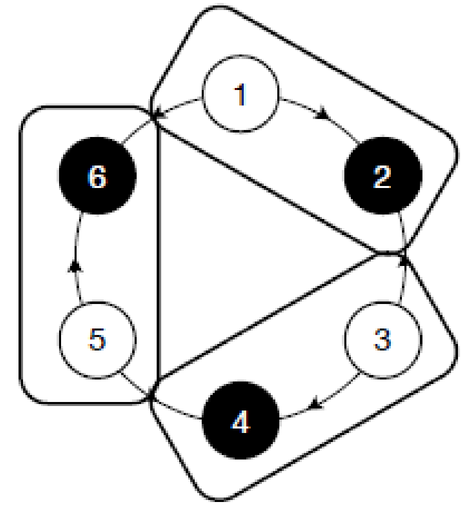
large symmetry group + sparse symmetry breaking spurions
= unusually large natural hierarchy between EW scale and UV (eg $1/\alpha^2$)

Flavor models:

(e.g.: Frogatt-Nielsen (1979))

large flavor symmetry group + sparse symmetry breaking spurions
= natural hierarchy between quark masses & mixing angles

The model (for quarks)



- 3 cells
- on each **black** site:
  - gauge group $G_b = SU(2) \times U(1)$
  - 4 **Dirac** fermions:

$$\Psi = \begin{pmatrix} u \\ d \\ U \\ D \end{pmatrix}$$

SU(2) doublet (u, d)

SU(2) singlets (U, D)

- on each **white** site:
  - gauge group $G_w = SU(2) \times U(1)$
  - 4 **Chiral** fermions:

$$\psi_L = \begin{pmatrix} u \\ d \\ 0 \\ 0 \end{pmatrix}_L \qquad \psi_R = \begin{pmatrix} 0 \\ 0 \\ U \\ D \end{pmatrix}_R$$

SU(2) doublet

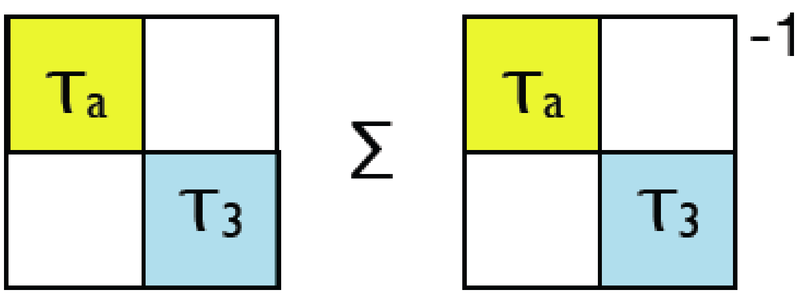
SU(2) singlets

- on each **link:**
  - *SU(4)xSU(4)/SU(4)* nonlinear sigma field

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

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

- G_w x G_b = $[SU(2) \times U(1)]^2$ gauge group is embedded in *SU(4) x SU(4)*



G_w=*SU(2)xU(1)* G_b=*SU(2)xU(1)*

- diagonal *SU(2) x U(1)* will be SM gauge group
- π'=*SU(2)* triplet
- $\pi^\pm$, π^0, η = *SU(2)* singlets
- H_u, H_d = Higgs doublets

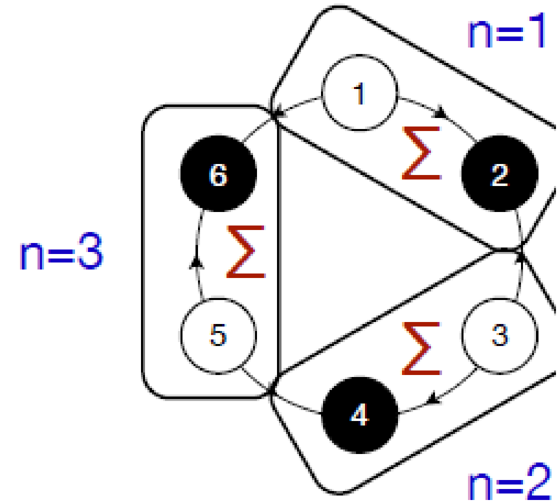
Fermion mass and Yukawa interactions:

U(3) x SU(4) symmetric terms

$$\Psi = \begin{pmatrix} u \\ d \\ \hdashline U \\ D \end{pmatrix} \qquad \psi_L = \begin{pmatrix} u \\ d \\ \hdashline 0 \\ 0 \end{pmatrix}_L \qquad \psi_R = \begin{pmatrix} 0 \\ 0 \\ \hdashline U \\ D \end{pmatrix}_R$$

SU(2) doublet

SU(2) singlets



$$\mathcal{L}_{\rm sym} = \sum_{n=1}^{3} \left[M \bar{\Psi}_n \Psi_n + \lambda f \left(\bar{\psi}_{L,n} \Sigma \Psi_{R,n} - \bar{\Psi}_{L,n} \Sigma^\dagger \psi_{R,n} \right) \right]$$

- Gives a mass M~5 TeV to black Dirac fermions
- Σ (including Higgs) couples black Dirac fermions to white chiral fermions; f~ 1.5 TeV
- exact U(3) symmetry (acts on index n)
- exact SU(4) symmetry (acts on black Dirac fermions and Σ)

Fermion mass and Yukawa interactions:

add U(3) x SU(4) symmetry breaking terms

$$\mathcal{L}_{\text{asym}} = \sum_{m,n=1}^{3} \bar{\Psi}_{m,L} \left(M^u X_u + M^d X_d\right)_{mn} \Psi_{n,R} + h.c.$$

$$\Psi = \begin{pmatrix} u \\ d \\ U \\ D \end{pmatrix}$$

SU(2) doublet (u, d)

SU(2) singlets (U, D)

- Acts only on black-site Dirac fermions
- M^u, M^d break the U(3) symmetry ⇒ $U(1)_B$ *(particular texture chosen)*

$$M^u = \begin{pmatrix} \mathcal{M}^u_{11} & \mathcal{M}^u_{12} & 0 \\ 0 & \mathcal{M}^u_{22} & 0 \\ \mathcal{M}^u_{31} & 0 & \mathcal{M}^u_{33} \end{pmatrix} \quad , \qquad M^d = \begin{pmatrix} \mathcal{M}^d_{11} & 0 & 0 \\ \mathcal{M}^d_{21} & \mathcal{M}^d_{22} & 0 \\ 0 & \mathcal{M}^d_{32} & \mathcal{M}^d_{33} \end{pmatrix}$$

- X_u, X_d break the SU(4) symmetry ⇒ different $SU(3)$ subgroups

$$X_u = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & -3 & \\ & & & 1 \end{pmatrix} , \qquad X_d = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix}$$

Normal "little Higgs" Mechanism
Plus different generations mainly live on different cells, to explain flavor.

- $<\Sigma>$ breaks $(SU(2)\times U(1))^2$ to diagonal $SU(2)\times U(1)$
  - Identify diagonal $SU(2)\times U(1)$ as SM gauge group
  - symmetry breaking scale is $f\sim$ 1.5 TeV
  - $g\,f\sim$ new gauge boson masses
  - Orientation of Σ parameterized by pNGB s
  - π', π^0 are eaten by heavy "axial" $SU(2)\times U(1)$ bosons
  - H doublets can act as Higgs to further break SM $SU(2)\times U(1) \Rightarrow U(1)$ electromagnetic

What do FCNC look like in a phenomenological fit to quark masses (RG scaled to 1 TeV) and CKM angles?

$$M = 5000 \text{ GeV} , \qquad f = 1500 \text{ GeV} , \qquad \tan\beta = \frac{v_u}{v_d} = 1$$

$$\lambda = 1.49794$$

$$M^u = \begin{pmatrix} 1189.54 & 15.4904 & 0 \\ 0 & 6.96490 & 0 \\ 3.50799 e^{-i1.224428} & 0 & 0.01441071 \end{pmatrix} , \qquad M^d = \begin{pmatrix} 45.7769 & 0 & 0 \\ -1.60269 & 0.600984 & 0 \\ 0 & 0.137582 & 0.0336607 \end{pmatrix} \quad \text{(GeV)}$$

Yields quark masses

$$m_t = 153.2 \qquad m_c = 5.32 \times 10^{-1} \qquad m_u = 1.10 \times 10^{-3}$$
$$m_b = 2.45 \qquad m_s = 4.69 \times 10^{-2} \qquad m_d = 2.50 \times 10^{-3} \qquad \text{(GeV)}$$

and angles:

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.974 & 0.226 & 0.00385 \\ 0.226 & 0.973 & 0.0423 \\ 0.00892 & 0.0415 & 0.998 \end{pmatrix} \qquad \sin(2\alpha) = 0.052 , \qquad \sin(2\beta) = 0.72 , \qquad \sin(2\gamma) = 0.68$$

New exotic particles and couplings:

- *W* (80 GeV):
  RH current ~ LH current *x* 10^{-3}

- *W'*(1.4 TeV):
  LH current: *W* x 0.05
  RH current: *W* x 2

- *Z'*(750 GeV), *Z''*(1.4 TeV) ... (next slide)

- heavy quark partners:
  lightest is top partner at 2.6 TeV
  (7% fine-tuning for 126 GeV Higgs)

- Other heavy u, d quarks: 5.4-6.6 TeV

- 3 exotic pseudo-scalars η, $\pi^{\pm}$

Flavor dependence of neutral gauge boson couplings (Z, Z', Z")

$$M_{Z'} = 750 \text{ GeV} , \qquad M_{Z''} = 1400 \text{ GeV}$$

$$|\mathcal{L}_Z^u| = \begin{pmatrix} 2.6\times10^{-1} & 0 & 1.9\times10^{-6} \\ 0 & 2.6\times10^{-1} & 9.7\times10^{-6} \\ 1.9\times10^{-6} & 9.7\times10^{-6} & 2.6\times10^{-1} \end{pmatrix} , \qquad |\mathcal{R}_Z^u| = \begin{pmatrix} 1.1\times10^{-1} & 0 & 2.3\times10^{-6} \\ 0 & 1.1\times10^{-1} & 1.0\times10^{-5} \\ 2.3\times10^{-6} & 1.0\times10^{-5} & 1.1\times10^{-1} \end{pmatrix} ,$$

$$|\mathcal{L}_Z^d| = \begin{pmatrix} 3.2\times10^{-1} & 1.0\times10^{-6} & 5.0\times10^{-6} \\ 1.0\times10^{-6} & 3.2\times10^{-1} & 2.3\times10^{-5} \\ 5.0\times10^{-6} & 2.3\times10^{-5} & 3.2\times10^{-1} \end{pmatrix} , \qquad |\mathcal{R}_Z^d| = \begin{pmatrix} 5.5\times10^{-2} & 0 & 0 \\ 0 & 5.5\times10^{-2} & 3.6\times10^{-6} \\ 0 & 3.6\times10^{-6} & 5.5\times10^{-2} \end{pmatrix} ,$$

$$|\mathcal{L}_{Z'}^u| = \begin{pmatrix} 2.6\times10^{-3} & 0 & 0 \\ 0 & 2.6\times10^{-3} & 3.4\times10^{-5} \\ 0 & 3.4\times10^{-5} & 3.8\times10^{-3} \end{pmatrix} , \qquad |\mathcal{R}_{Z'}^u| = \begin{pmatrix} 1.4\times10^{-2} & 0 & 4.0\times10^{-4} \\ 0 & 1.5\times10^{-2} & 1.7\times10^{-3} \\ 4.0\times10^{-4} & 1.7\times10^{-3} & 3.7\times10^{-1} \end{pmatrix}$$

$$|\mathcal{L}_{Z'}^d| = \begin{pmatrix} 5.\times10^{-3} & 1.9\times10^{-5} & 8.9\times10^{-5} \\ 1.9\times10^{-5} & 4.9\times10^{-3} & 4.1\times10^{-4} \\ 8.9\times10^{-5} & 4.1\times10^{-4} & 3.7\times10^{-3} \end{pmatrix} , \qquad |\mathcal{R}_{Z'}^d| = \begin{pmatrix} 6.7\times10^{-3} & 0 & 2.6\times10^{-5} \\ 0 & 6.6\times10^{-3} & 2.0\times10^{-4} \\ 2.6\times10^{-5} & 2.0\times10^{-4} & 8.8\times10^{-3} \end{pmatrix}$$

$$|\mathcal{L}_{Z''}^u| = \begin{pmatrix} 1.9\times10^{-2} & 0 & 7.9\times10^{-5} \\ 0 & 1.9\times10^{-2} & 2.8\times10^{-4} \\ 7.9\times10^{-5} & 2.8\times10^{-4} & 2.9\times10^{-2} \end{pmatrix} , \qquad |\mathcal{R}_{Z''}^u| = \begin{pmatrix} 1.4\times10^{-3} & 0 & 0 \\ 0 & 1.4\times10^{-3} & 0 \\ 0 & 0 & 1.3\times10^{-3} \end{pmatrix}$$

$$|\mathcal{L}_{Z''}^d| = \begin{pmatrix} 2.0\times10^{-2} & 1.0\times10^{-4} & 5.0\times10^{-4} \\ 1.0\times10^{-4} & 1.9\times10^{-2} & 2.3\times10^{-3} \\ 5.0\times10^{-4} & 2.3\times10^{-3} & 2.9\times10^{-2} \end{pmatrix} , \qquad |\mathcal{R}_{Z''}^d| = \begin{pmatrix} 1.6\times10^{-3} & 0 & 0 \\ 0 & 1.6\times10^{-3} & 0 \\ 0 & 0 & 9.7\times10^{-4} \end{pmatrix}$$

Can read off ΔS = 2 dim 6 operators from Z, Z', Z" exchange:

$$\frac{1\times 10^{-12}}{M_Z^2} \simeq \frac{1}{(10^5\ \mathrm{TeV})^2}\,, \qquad \frac{4\times 10^{-10}}{M_{Z'}^2} \simeq \frac{1}{(4\times 10^4\ \mathrm{TeV})^2}\,, \qquad \frac{1\times 10^{-8}}{M_{Z''}^2} \simeq \frac{1}{(1.3\times 10^4\ \mathrm{TeV})^2}$$

...all safe from FCNC, even though:

- flavor physics is at the few TeV scale
- full theory does not have a $U(3)^3$ approximate chiral symmetry (for Q,U,D), such as found in minimal flavor violation models, where all flavor symmetry breaking is due to quark mass matrix (Chivukula, Georgi, 1987)

Direct detection of Z'(750 GeV) or Z"(1.4 TeV)?

- Production rate of Z' is down by 10-3 compared to Z-like couplings
- Production rate of Z" is down by 5 x10-3 compared to Z-like couplings
- Leptonic partial width not computable in this model (working in progress), which is more relevant for ILC
- Likely not ruled out presently

RH W coupling give rise to 4% correction to b->sgamma matrix element.