Flavor at the TeV Scale and Beyond

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Lecture I

I. The Quark mass + mixing hierarchies
  - what might the mass matrices look lik

II. Solutions to the weak scale hierarchy problem: Different frameworks for Flavor Physics

  A. Supersymmetry
    - The SUSY FCNC problem
    - models with flavor symmetries
    - radiative quark masses

  B. The Little Higgs
    - Speculations about flavor physics

LECTURE II: Signatures of TeV flavor Physics IN B DECAYS

I. The Quark Mass + Mixing Hierarchy

$m_u < m_d$ $\qquad$ $m_c \sim 1.3$ GeV $\qquad$ $m_t \sim 165$ Ge

$m_d \sim 5$ MeV $\qquad$ $m_s \sim 100$ MeV $\qquad$ $m_b \sim 4.2$ Ge

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda = .22 & .003 \\ \lambda & 1 & .04 \\ .003 & .04 & 1 \end{pmatrix}$$

Wolfenstein Parametrization:
- expansion in powers of λ
- assumes unitarity as in SM

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

What might the quark mass matrices look like?

In general can write

$$M^{q=u,d} = m_3^q |h_L^q\rangle\langle h_R^q| + m_2^q |\tilde{h}_L^q\rangle\langle\tilde{h}_R^q| + \delta M^q$$

unitrank contributions arbitrary 3×3 matri

generically (no significant alignment of $|h_{L(R)}\rangle, |\tilde{h}_{L(R)}\rangle$ ..)

$$m_3^d \approx m_b \ , \ m_2^d \sim m_s \ , \ \delta M_{ij}^d \sim m_d$$

$$m_3^u \approx m_t \ , \ m_2^u \sim m_c \ , \ \delta M_{ij}^u \sim m_u$$

- Using perturbation theory, straightforward to solve eigenvalue equations for quark masses, LH and RH mass eigenstates

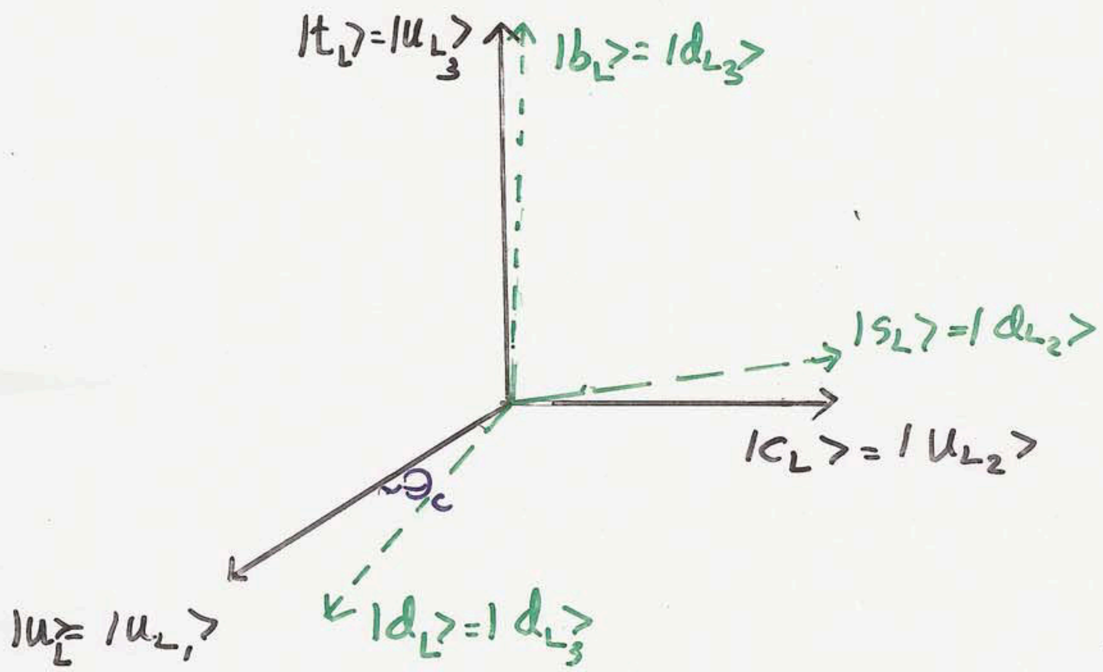
$$M^q M^{q\dagger} |q_{L_i}\rangle = m_i^2 |q_{L_i}\rangle \ , \text{ or}$$

$$M^{q\dagger} M^q |q_{R_i}\rangle = m_i^2 |q_{R_i}\rangle$$

$$\left(M = M^{(0)} + M^{(1)}, \quad M^{(0)} = m_3 |h_L\rangle\langle h_R| \right)$$

• $V_{CKM}^{ij} = \langle u_{i_L} | d_{j_L} \rangle$

Since the mixing angles are small need high degree of alignment between LH up + down mass eigenstates



⟹ (i) $|h_L^u\rangle = |h_L^d\rangle = |h_L\rangle$ so

LH. top, bottom aligned to high accuracy.

(ii) planes spanned by $|h_L\rangle, |\tilde{h}_L^u\rangle$ and $|h_L\rangle, |\tilde{h}_L^d\rangle$ should be parallel to high accuracy

(i) + (ii) necessary to obtain small V_{ub}, V_{cb}

In weak interaction basis

$$M^d \sim \begin{array}{c} \\ \langle 1_L | \\ \langle 2_L | \\ \langle 3_L | \end{array} \begin{array}{c} \begin{array}{ccc} |1_R^d\rangle & |2_R^d\rangle & |3_R^d\rangle \end{array} \\ \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_b \end{pmatrix} \end{array}, \quad M^u \sim \begin{array}{c} \\ \langle 1_L | \\ \langle 2_L | \\ \langle 3_L | \end{array} \begin{array}{c} \begin{array}{ccc} |1_R^u\rangle & |2_R^u\rangle & |3_R^u\rangle \end{array} \\ \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_t \end{pmatrix} \end{array}$$

$|3_L\rangle = |h_L\rangle$, $|2_L\rangle \propto |\tilde{h}_L\rangle - |h_L\rangle\langle h_L|\tilde{h}_L\rangle$,
similarly for $|i_R^u\rangle$, $|i_R^d\rangle$

$$\Longrightarrow \quad m_d = m^d_{11} - \frac{m^d_{12} m^d_{21}}{m_s}, \quad m_s = m^d_{22} - \frac{m^d_{23} m^d_{32}}{m_b}, \quad m_b = m^d_{33}$$

$$|d_{L i}\rangle = X^d_{ij} \, |j_L\rangle, \cdots$$

CKM entries:

$$V_{us} \approx X^d_{21} - X^u_{21} \approx m^d_{12}/m_s$$

$$V_{cb} \approx X^d_{32} - X^u_{32} \approx m^d_{23}/m_b$$

$$V_{ub} \approx X^d_{31} - X^d_{32} X^u_{21} \approx m^d_{13}/m_b$$

- Suggests that its more generic for V_{CKM} to be generated in the down quark sector

But there are examples where quark mixing is necessarily generated in the up sector to avoid FCNC constraints

Requires very special alignment of quark mass contributions

A theory of flavor physics should explain

a) The family mass hierarchy problem. Mechanisms are required to reduce the large range of dimensionless Yukawa couplings $\lambda_{top}/\lambda_{electron} \sim 10^5$ of the SM

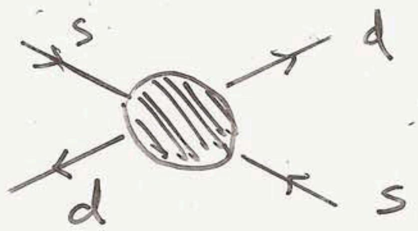
b) The alignment of LH up + down quark mass eigenstates required for reproducing V_{CKM}

In the SM this requires a fine-tuning of the up + down Yukawa coupling matrices λ^u_{ij}, λ^d_{ij} of order 1 part in 20,000!

The most stringent FCNC constraints

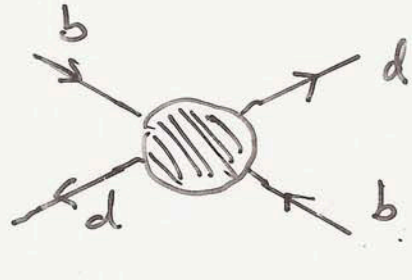
operators

1) $\Delta m_K, \epsilon_K$



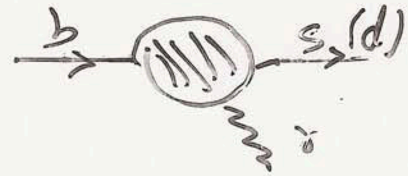
$\frac{\lambda}{M^2}[\bar{d}\, s][\bar{d}\, s]$

2) Δm_{B_d}



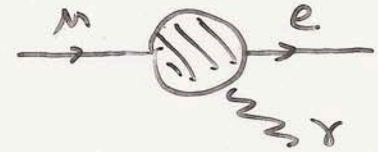
$\frac{\lambda}{M^2}[\bar{d}\, b][\bar{d}\, b]$

3) $b \to s\,(d)\,\gamma$,
$b \to s\,(d)\,l^+ l^-$



$\frac{\lambda}{M} F_{\mu\nu}\, \bar{s}\, \sigma^{\mu\nu} b$

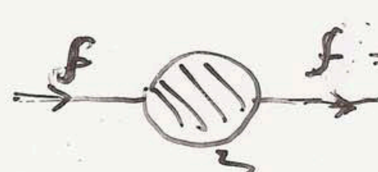
4) $\mu \to e\gamma$



$\frac{\lambda}{M} F_{\mu\nu}\, \bar{e}\, \sigma^{\mu\nu} \mu$

IMPORTANT FLAVOR DIAGONAL CONSTRAINTS:

1) neutron edm, d_n



$f = u, d, s$

electron edm, d_e

CP violating $\frac{\lambda}{M} F_{\mu\nu}\, \bar{f}\, \sigma^{\mu\nu} f$

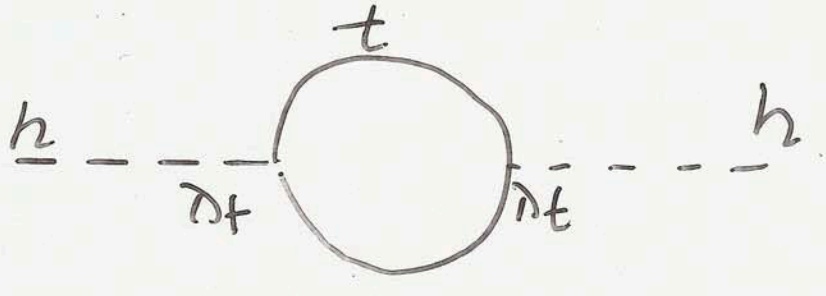
2) muon anomalous magnetic moment, a_μ

CP conserving

II. Solutions to the weak scale hierarchy problem: different frameworks for flavor physics

The hierarchy problem:

Consider top loop contribution to the SM Higgs mass (also scalar, gauge boson loops)



quadratic divergence

$$\delta m_H^2 \approx \frac{-3}{8\pi^2} \lambda_t^2 \Lambda^2$$

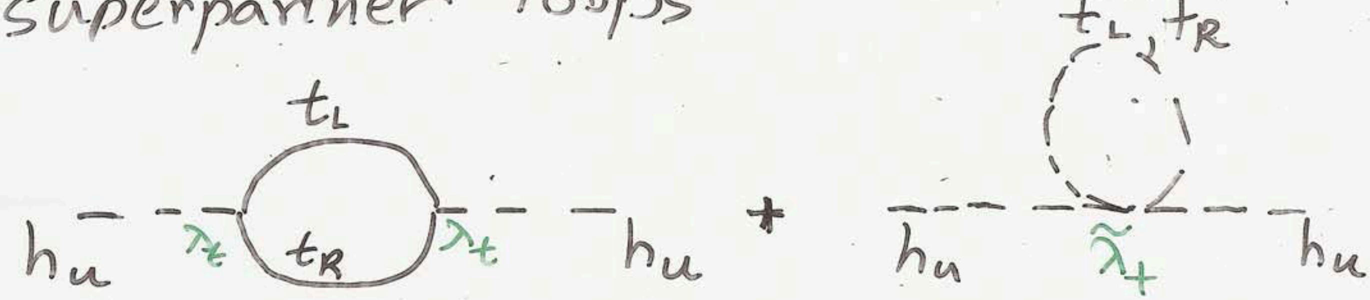
where the cutoff Λ corresponds to scale of New physics

Want $m_h \approx 100-300$ GeV

$\Rightarrow$ New Physics at scale $\Lambda \lesssim 1$ TeV otherwise have to fine tune m_H

A. Supersymmetry

Cancelation of quadratic divergences via superpartner loops



$$\delta m^2_{h_u} = \cancel{-\frac{3\lambda_t^2}{8\pi^2}\Lambda^2} + \cancel{\frac{3\tilde{\lambda}_t}{8\pi^2}\Lambda^2} + \text{Log terms..}$$

(super)symmetry under transformations between fermionic + bosonic 'superpartners' within 'supermultiplets'

$$\Rightarrow \quad \tilde{\lambda}_t = \lambda_t^2$$

$$\therefore \quad \delta m^2_{h_u} \sim \frac{-3}{8\pi^2}\lambda_t^2\left(2 m^2_{\tilde{t}} \log \Lambda/m_{\tilde{t}} - m_t^2 \log \Lambda/m_t\right)$$
$$+ \dots$$

need superpartner masses $m_S \sim 100\,\text{GeV} - 1\,\text{TeV}$ to avoid fine-tuning of higgs mass

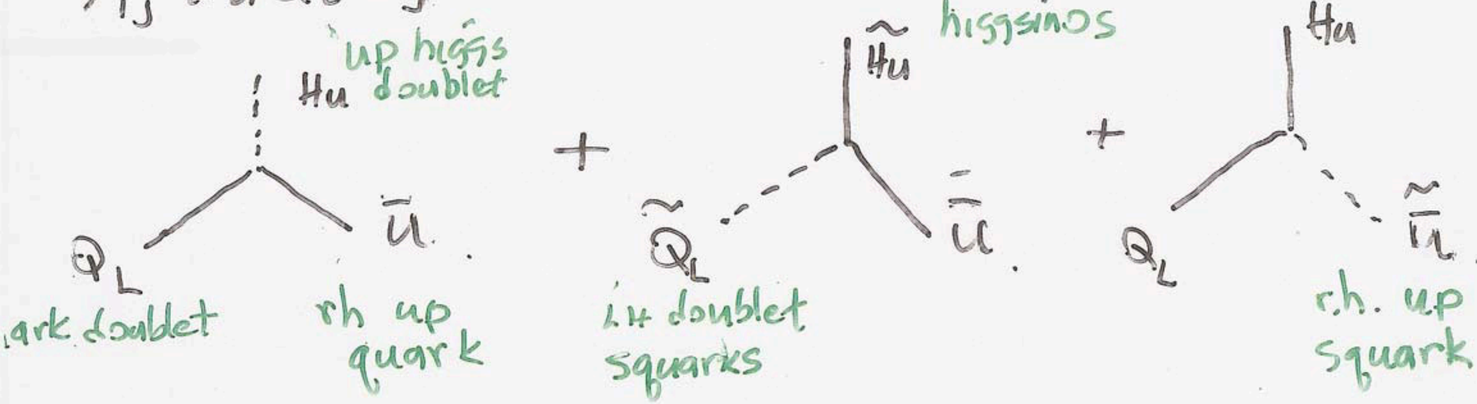
ne supersymmetric flavor problem

superpotential for the supersymmetric SM - MSSM:

$$V = \sum_{i,j} \left(Y^u_{ij} \, H_u Q_{L_i} \bar{U}_{L_j} + Y^d_{ij} H_d Q_{L_i} \bar{D}_{L_j} + Y^l_{ij} H_d L_{L_i} \bar{E}_{L_j} \right) + \mu H_u H_d$$

$H, Q, \bar{U}, \ldots$ are 'LH superfields' containing both SM particles and their superpartners:

$$Y^u_{ij} H_u Q_i \bar{U}_j =$$



soft supersymmetry breaking terms:

$$-\mathcal{L}_{soft} = A^{u}_{ij} H_u \tilde{Q}_i \tilde{\bar{u}}_j + A^{d}_{ij} H_d \tilde{Q}_i \tilde{\bar{d}}_j + \mu B H_u H_d$$
$$+ m^{Q\,2}_{ij} \tilde{Q}^{\dagger}_i \tilde{Q}_i + m^{2\bar{u}}_{ij} \tilde{\bar{u}}^{\dagger}_i \tilde{\bar{u}}_i + m^{2\bar{d}}_{ij} \tilde{\bar{d}}^{\dagger}_i \tilde{\bar{d}}_j$$

+ slepton terms + gaugino masses.

$A^{u}_{ij} H_u \tilde{Q} \tilde{\bar{u}}$ =

scalar trilinear couplings

DOWN SQUARK MASS MATRIX:

$$\begin{array}{c|cccccc}
 & \tilde{d}^*_{L_1} & \tilde{d}^*_{L_2} & \tilde{d}^*_{L_3} & \tilde{\bar{d}}_1 & \tilde{\bar{d}}_2 & \tilde{\bar{d}}_3 \\
\hline
\begin{array}{c}\tilde{d}_{L_1}\\ \tilde{d}_{L_2}\\ \tilde{d}_{L_3}\\ \tilde{\bar{d}}^*_1 \\ \tilde{\bar{d}}^*_2 \\ \tilde{\bar{d}}^*_3\end{array} & \multicolumn{6}{c}{\left(\begin{array}{c|c} M^2_{LL_{ij}} \sim m^{Q\,2}_{ij} & M^2_{LR_{ij}} \sim A_{ij}\langle H_d\rangle + \mu^* Y^d_{ij} \langle H_u^*\rangle \\ \hline M^{2\dagger}_{LR} & M^2_{RR_{ij}} \sim m^{\bar{d}\,2}_{ij} \end{array}\right)}
\end{array}$$

6 down squark mass eigenstates.

In limit $M^2_{LR} << M^2_{LL}, M^2_{RR}$ separate into

3 'LH' + 3 'RH' states $\tilde{D}_{1,2,3}$; $\tilde{\bar{D}}_{1,2,3}$

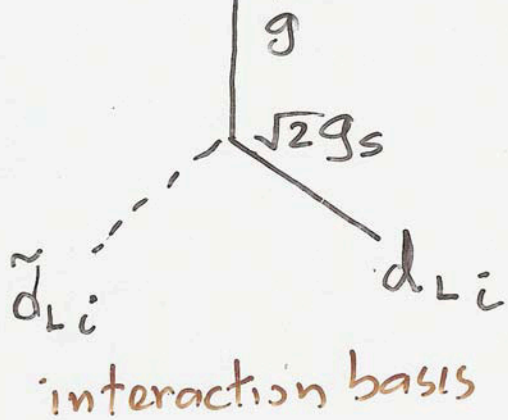
SUSY Flavor Violation

In the SM Yukawa couplings are only source of flavor violation, via V_{CKM}

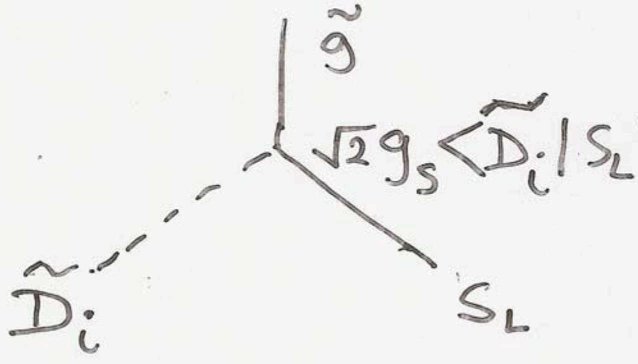
In the MSSM have new source of flavor violation – the squark + slepton masses

- in general quark + squark mass matrices are not simultaneously diagonalizable, i.e., the squark, quark mass eigenstates not aligned

Example: Flavor violating gluino couplings



interaction basis

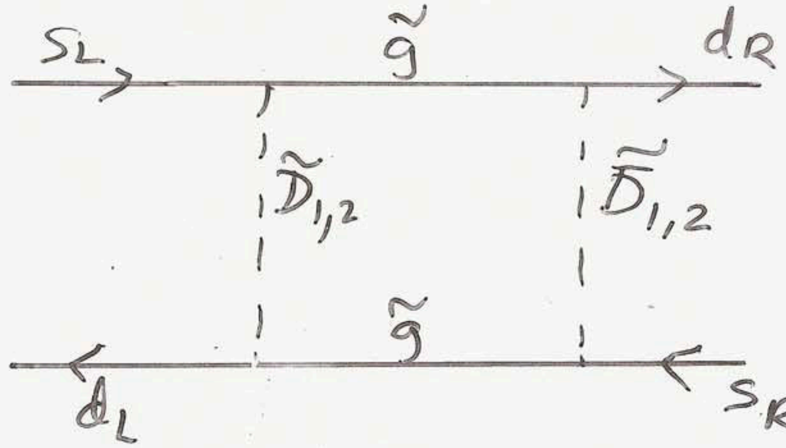


physical basis

The Problem

consider new contributions to Δm_K, ε_K:

(For simplicity consider only 2 generations)



$$\frac{(\Delta m_K)^{susy}}{(\Delta m_K)^{exp}} \sim 10^5 \left(\frac{300\,\text{GeV}}{\tilde{m}}\right)^2 \left(\frac{m^2_{\tilde{D}_2} - m^2_{\tilde{D}_1}}{m^2_{\tilde{D}}}\right)\left(\frac{m^2_{\tilde{\bar{D}}_2} - m^2_{\tilde{\bar{D}}_1}}{m^2_{\tilde{\bar{D}}}}\right)$$

$$\times\ Re\left[\langle s_L|\tilde{D}_1\rangle\langle\tilde{D}_1|d_L\rangle\langle s_R|\tilde{\bar{D}}_1\rangle\langle\tilde{\bar{D}}_1|d_R\rangle\right]$$

$$\frac{(\varepsilon_K)^{susy}}{(\varepsilon_K)^{exp}} \sim 10^7 \quad ''$$

$$\times\ Im\left[\langle s_L|\tilde{D}_1\rangle\langle\tilde{D}_1|d_L\rangle\langle s_R|\tilde{\bar{D}}_1\rangle\langle\tilde{\bar{D}}_1|d_R\rangle\right]$$

generally, $\dfrac{\delta m^2_{\tilde{D},\tilde{\bar{D}}}}{m^2_{\tilde{D},\tilde{\bar{D}}}} \sim \mathcal{O}(1)$; $\langle s_L|\tilde{D}_1\rangle, \ldots \sim \mathcal{O}(1)$

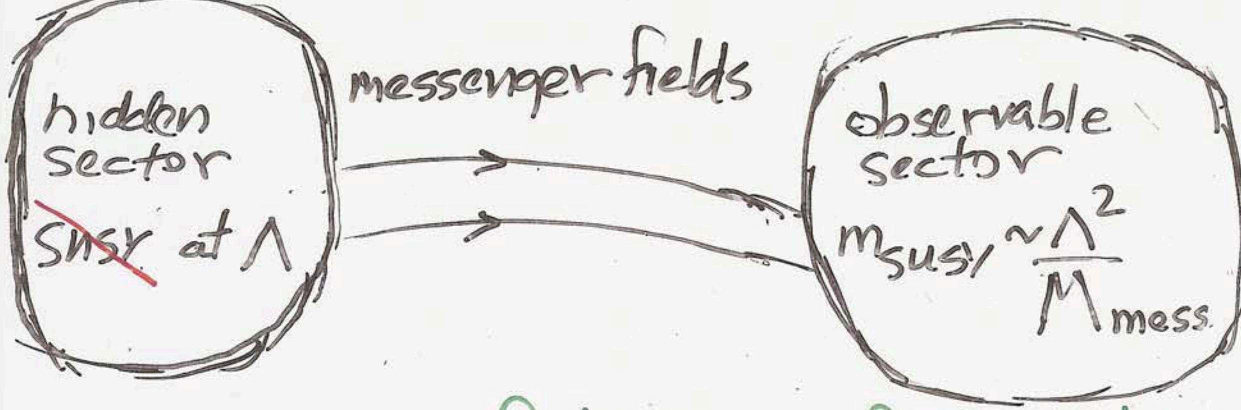
$\Rightarrow$ violate constraints by 5-7 orders of magnitude

Solutions

1) make squark masses degenerate, $\delta m^2_{\tilde D}/m^2_{\tilde D} \ll 1$

susy breaking flavor blind

$\Rightarrow$ no new FCNC, super-GIM



messenger fields are flavor blind

- gauge mediation - intermediate mass messengers ($\gtrsim 100$ TeV) with SM gauge interactions - squarks highly degenera[te]
  Higgs mass tuning?

- messengers near Planck scale
  - In generic supergravity models $\delta \tilde m^2/\tilde m^2 \sim \mathcal{O}$
    need to add flavor symmetries
  - anomaly or gaugino mediated susy breaking

2.) Alignment of LH (RH) quark/squark mass eigenstates

$$\Longrightarrow \langle s_L | \tilde{D}_i \rangle \langle \tilde{D}_i | d_L \rangle \ll 1, \ldots$$

need flavor symmetries

3) Decouple 1st 2 generation squarks, sleptons, eg, $m^2_{\tilde{D}_{1,2}} \sim (100\ \text{TeV})^2$

But in MSSM requirements of color conserving vacuum + no fine-tuning of Higgs mass $\Longrightarrow m^2_{\tilde{D}_{1,2}} < (20\ \text{TeV})^2$

generally insufficient FCNC suppression

will return to this later!

Simultaneous Solutions to fermion mass + FCNC problems

- USE FLAVOR SYMMETRY GROUP G_f, G_f commutes with SUSY
- In G_f symmetric limit:
  - high degree of flavor conservation in squark mass matrices
  - quarks of 1st 2 generations, and possibly bottom are massless
- Hierarchical breaking of G_f by VEVs of 'flavon' fields $\langle \phi_i \rangle = v_i$
  - light quark masses suppressed by powers of $\epsilon_i = v_i / M_f$, M_f is flavor mass scale

    eg, $\bar{\psi} H \psi \left(\langle \phi \rangle / M_f \right)^n$ ← n depends on quark G_f charges
  - flavor violating corrections to squark mass matrices also suppressed by ϵ_i^n !

How do powers $\left(\langle\phi\rangle/M_f\right)^n$ arise?

Froggat - Nielsen mechanism:

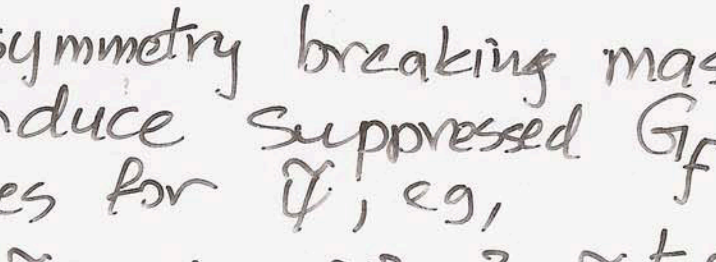
- introduce heavy vector-like quark pairs $\chi_i, \bar{\chi}_i$ with masses $M_f\, \chi \bar{\chi}$ which couple to light quarks ψ, higgs h and flavon fields, eg,

$$\bar{\chi}\left(M_f\, \chi + \phi\, \psi\right) + \chi\, h\, \psi$$

- $\langle\phi\rangle \neq 0$ induces effective low energy ($\mu \ll M_f$) coupli

$$\langle\phi\rangle/M\ \psi h \psi = \epsilon\, \psi h \psi$$

- Diagramatically (like see-saw)



- Supersymmetry breaking masses for $\tilde{\chi}$ induce suppressed G_f breaking masses for $\tilde{\psi}$, eg,

$$\tilde{m}^2\, \tilde{\chi}^\dagger \tilde{\chi} \Longrightarrow \tilde{m}^2 \epsilon^2\, \tilde{\psi}^\dagger \tilde{\psi}$$

NON-ABELIAN G_f

- minimal choice is $G_f = U(2)$ Dine Leigh AK, Barbieri, Hall ⋮
  - 1st+2nd generations are doublets, 3rd generatio is singlet

$Q_a = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}$, $\bar{u}_a = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$, $\bar{d}_a = \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$, q_3, $\bar{d}_3$, $\bar{u}_3$.

  - Higgs doublets H_u, H_d are singlets
- In G_f symmetric limit:
  - 1st 2 generation squarks are degenerate
  - only $Q_3 \bar{u}_3 H_u$, $Q_3 \bar{d}_3 H_d$ Yuk couplings

Additional building blocks:

Flavons ϕ^a - doublet of $U(2)$
A^{ab} - antisymmetric tensor
S^{ab} - symmetric tensor

Vectorlike Quarks χ^a, $\bar{\chi}^a$ (doublets); χ, $\bar{\chi}$ (singlets

At Low scales, can obtain effective couplings:

$Q_3 \bar{d}^a H_d \phi^a / M_f$, $Q^a \bar{d}^b H_d A_{ab} / M_f$, ...

Two small numbers $\epsilon \equiv \langle \phi^2 \rangle / M_f \gg \epsilon' \equiv \langle A^{12} \rangle / M$

- An interesting alternative uses Hall + Murayama; Carone, Hall, Murayama

$$G_f = S_3^Q \times S_3^u \times S_3^D \ , \quad \text{where}$$

S_3 is group of rotations in 3-dim which leave equilateral triangle invariant.
It contains doublet + singlet representations

- in non-abelian models V_{CKM} generated in down sector
  ⟹ Even though SUSY FCNC satisfy bounds from $\Delta m_K, \epsilon_K, \Delta m_B$,

  Interesting SUSY FCNC signatures are possible in B decays

$U(2)$: time dependent CP asymmetries in $B_s \to J/\psi\, \phi$, $B_d \to J/\psi\, K_S$; Δm_{B_S};
CP asymmetries in $b \to sg$, $b \to sq\bar{q}$ mediated processes Masiero, Romanino, Piai, Silvestrini

S_3^3: $BR(B \to X_d \gamma)$, $A_{CP}(B \to X_d \gamma)$ Ko + Park

ABELIAN FLAVOR SYMMETRIES

Leurer, Nir, Seiberg; Nir, Seiberg

$G_f = U(1)_1 \times U(1)_2$: Can't impose squark mass degeneracy $\Rightarrow$ solve FCNC problem via quark/squark alignment

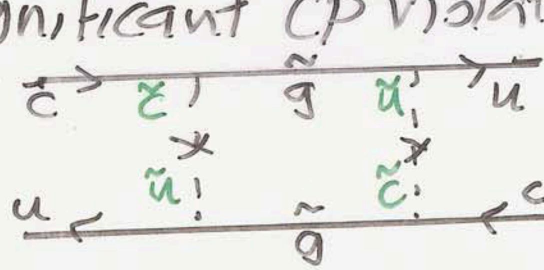
- VEVs of $U(1)_i$ breaking Flavons $\langle \phi_i \rangle$ suppress off-diagonal entries in quark, squark mass matrices

$$Q_i \bar{d}_j H_d \left(\langle \phi \rangle / M_f \right)^{n_{ij}} , \quad \tilde{m}^2 \tilde{Q}_i^\dagger \tilde{Q}_j \left(\langle \phi \rangle / M_f \right.$$

- naive quark/squark alignment $\langle s_L | \tilde{d}_L \rangle \sim \theta$ far short of what is required for $\epsilon_K, \Delta m_K$
  - must pick $U(1)$ charges so that $\langle s_L | \tilde{d}_L \rangle \sim \theta_c^7$, $\langle s_R | \tilde{d}_R \rangle \sim \theta_c^7$

$\Rightarrow V_{CKM}$ must be generated in up-sector

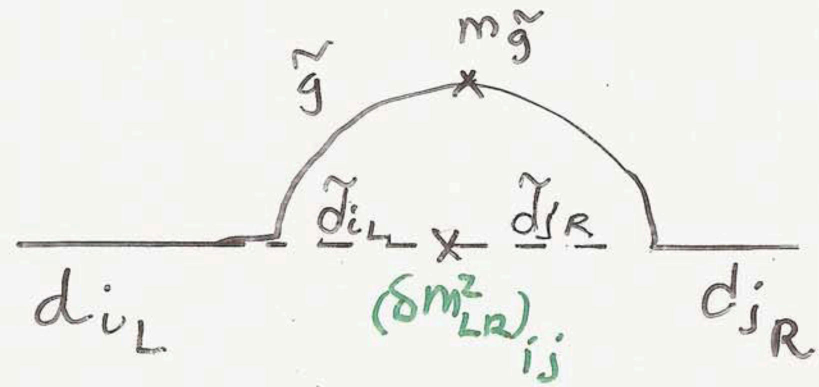
$\therefore$ most likely signals are Δm_D close to present bound, significant CP violation in $D-\bar{D}$ mixing



radiative masses + mixing angles

- an old idea is to generate light quark masses, CKM angles via loop suppression

SUSY EXAMPLE   del Aguila et al; Banks; Albright + AK; Ma, ..



$$(\delta m^2_{LR})_{ij} = \begin{cases} A_{ij} \langle H_d \rangle \tilde d_{i_L} \tilde d_{j_R} \\ \quad\text{or} \\ A'_{ij} \langle H_u^{+} \rangle \tilde d_{i_L} \tilde d_{j_R} \end{cases}$$

$$m^d_{ij} \sim \frac{1}{16\pi^2} \frac{A^{(\prime)}_{ij}}{\tilde m_{susy}} \langle H_{d(u)} \rangle$$

$$\sim \frac{A^{(\prime)}_{ij}}{\tilde m_{susy}} (.1 - 1 \text{ GeV})$$

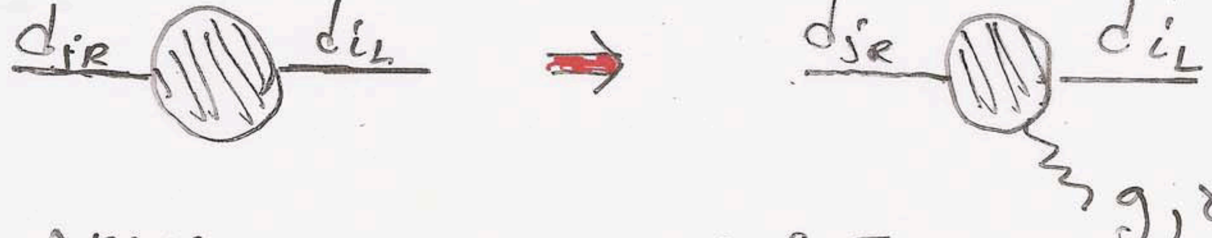
$\Rightarrow$ can generate m_d, θ_c, V_{ub} and m_s, V_{cb} if $\frac{A^{(\prime)}_{ij}}{\tilde m_{susy}} \lesssim 1$

- Its possible to generate $A_{ij}^{(\prime)}$ in this range <u>without</u> having Yukawa couplings $\lambda_{ij} H_d Q_i \bar{d}_j$, using flavor symmetries

Borzumati, Farrar, Polonsky, Thomas

- In general, radiatively generated CKM mixing at TeV scales has interesting implications for phenomenology

eg



Δm_{ij}

$$\begin{cases} C^g_{ij}\, \bar{d}_{iL} \sigma^{\mu\nu} T^a d_{jR} G^a_{\mu\nu} \\ C^\gamma_{ij}\, \bar{d}_{iL} \sigma^{\mu\nu} d_{jR} F_{\mu\nu} \end{cases}$$

dimensional analysis $\Rightarrow$ $C_{ij} \sim \Delta m_{ij}/M^2$ ← heavy scale in loop

- If $M \sim \frac{1}{2} - 2$ TeV correlations between V_{ub} (Δm_{13}) + $C_{d_L b_R}$ or V_{cb} (Δm_{23}) + $C_{s_L b_R}$ $\Rightarrow$ interesting contributions to $b \to d g(\gamma)$, $b \to s g(\gamma)$

Little Higgs

Arkani-Hamed, Cohen, Georgi,
Wacker, Gregoire, Katz, Nelson,
Low, Skiba, Smith,
Chivukula, Evans, Simmons, Lane

B. LITTLE HIGGS - A NEW FRAMEWORK FOR EWK SYM BREAKING + THEORIES OF FLAVOR

- PRECISION EWK MEASUREMENTS REMARKABLY CONSISTENT WITH PERTURBATIVE SM CALCULATIONS AND A LIGHT HIGGS OF MASS ~ 100 - 300 GeV

- HIGGS MASS QUADRATIC DIVERGENCES NEED TO BE CUT-OFF BY NEW PHYSICS AT SCALES $\lesssim$ 1 TEV

  - PRECISION EWK MEASUREMENTS SUGGEST THAT THIS NEW PHYSICS SHOULD BE PERTURBATIVE

  - UNTIL RECENTLY SUSY THE ONLY POSSIBILITY

BUT POTENTIAL PROBLEMS FOR LOW SCALE ($\lesssim$ TeV) SUSY:

- FCNC - WOULD BE NICE IF SUSY MASSES COULD BE > 10 TeV (1st 2 gen squarks > 100 TeV)
  could lead to simpler solutions for fermion mass hierarchy

- PUSHING ALL SUPERPARTNER MASSES ABOVE CURRENT BOUNDS ALREADY REQUIRES SOME TUNING IN MANY MODELS OF SUSY

LITTLE HIGGS

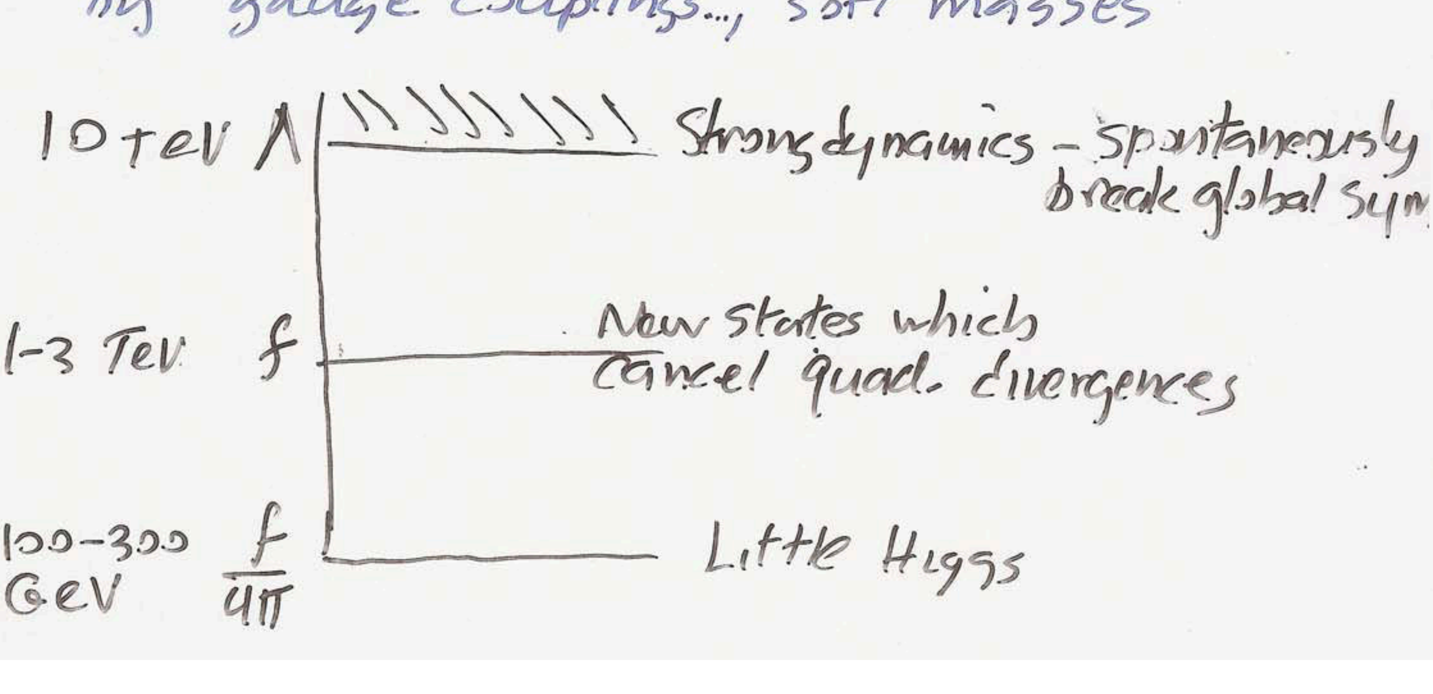
in this framework higgs is a pseudo-goldstone boson $\Sigma = \exp(i\sigma/f)$

- $f \sim 1$ TeV is the decay constant (f_π analog)
- The strong interaction scale $\Lambda \sim 4\pi f \sim 10$ TeV (Λ_{QCD} analog)

- approximate global, chiral symmetries under which $\Sigma \to L \Sigma R^{+}$

$\Rightarrow$ light higgs $m_h^2 \ll \Lambda^2$

The global symmetries are broken by gauge couplings..., soft masses



Example

- Gauge group $(SU(2) \times U(1))_1 \times SU(3)_2$
- 4 bifundamental non-linear sigma model fields $X_i = e^{i X_i / f}$

  under gauge transformations $X_i \to g_{2,1} X_i g_{1,2}^{-1}$
- turning off all couplings
  $\Rightarrow$ large $SU(3)^8$ global sym

  broken to $SU(3)^4$
- Strong interactions at scale Λ spontaneously break $SU(3)_2 \times (SU(2) \times U(1))_1 \to [SU(2) \times U(1)]_{Di}$

  SM gauge grp

  $\Rightarrow$ 8 massive gauge bosons

  $SU(3)$ $\quad 8 \to 3_0 + 1_0 + 2_{\frac{1}{2}}$ $\quad SU(2) \times U(1)$

  $W, \; B, \; V \quad m \sim g f$

  3 massless EWK gauge bosons W, B
- Arrange potential for X_i 3 have

  $8 \to 3_0 + 1_0 + 2_{1/2}$

tree level $\to$ 2 sets of <u>massless</u> scalars $\quad 2\varphi, \; 2\eta, \; 2h$ higgs do

1 set of massive scalars $\quad \varphi, \; \eta, \; h \sim$

Top Yukawa + cancelation of divergences

- need to add vectorlike pair of up quarks
  χ, $\bar{\chi}$ ($SU(2)_L$ singlets)

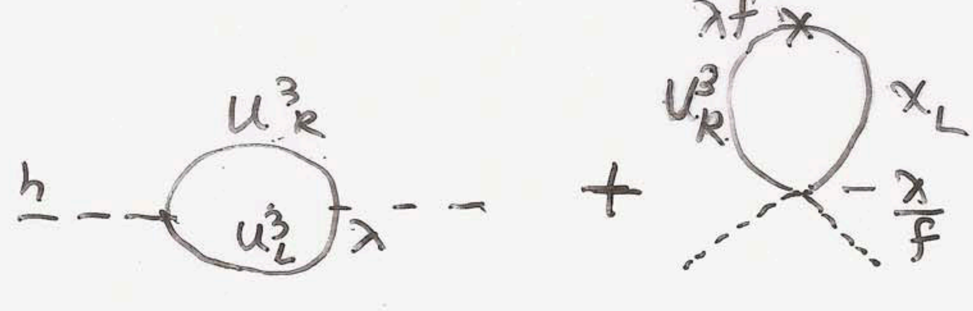
$$\mathcal{L}_t = \lambda f (0\ \ 0\ \ \bar{u}^3_R)\, e^{\frac{i}{f}\begin{pmatrix}\phi+\eta & h \\ h^+ & -2\eta\end{pmatrix}} \begin{pmatrix} u^3_L \\ d^3_L \\ \chi_L\end{pmatrix} + \lambda' f\, \bar{\chi}_R \chi_L$$

soft SU(3) breaking

addition of χ promotes quark doublet $\rightarrow$ quark triplet $\Rightarrow$ global $SU(3)_L$

insures cancelation of top loop quad div !

$$\mathcal{L}_t \Rightarrow \lambda f\, \bar{u}^3_R \chi_L + i \lambda\, \bar{u}^3_R h^+ u^3_L - \frac{\lambda}{2f} h^+ h\, \bar{u}^3_R \chi_L + h.$$



$\Rightarrow \delta m_h^2 \sim \frac{\lambda^2 f^2}{16\pi^2}$

$$\approx -\frac{\lambda^2}{16\pi^2}\Lambda^2 + \frac{\lambda}{f}\cdot\frac{\lambda f}{16\pi^2}\Lambda^2$$

$\because f \sim 1$ TeV, $\Lambda \sim 4\pi f \sim 10$ TeV

- Cancelation of quad divergence between fermion loops!
- Similarly, global symmetries insure cancelation between light and heavy gauge boson loops, light and heavy scalar loops

Implications for flavor physics?

top mass matrix:
$$\begin{array}{c|cc} & u^3_L & \chi_L \\ \hline \chi_R & 0 & \lambda' f \\ u^3_R & \lambda v & \lambda f \end{array}$$

$v \equiv \langle h \rangle$

$\Rightarrow$ $m_t \sim \frac{\lambda\lambda'}{\sqrt{\lambda^2+\lambda'^2}} v$, $m_\chi \sim \sqrt{\lambda^2+\lambda'^2} f$

and $|t_L\rangle \approx |u^3_L\rangle - \frac{\lambda^2}{\lambda^2+\lambda'^2} v/f \, |\chi_L\rangle$

significant admixture with isosinglet quark

$\Rightarrow$ potentially interesting Zct coupling, $t \to cZ$?

bottom quark: (model-dependent) could add vectorlike pair of down quarks $\chi_d, \bar{\chi}_d$ with similar Yukawa lagrangian as $\mathcal{L}_t$

$\Rightarrow$ significant admixture of b_L w/ isosinglet possible

- could saturate (Zsb) bound from $b \to s\ell$

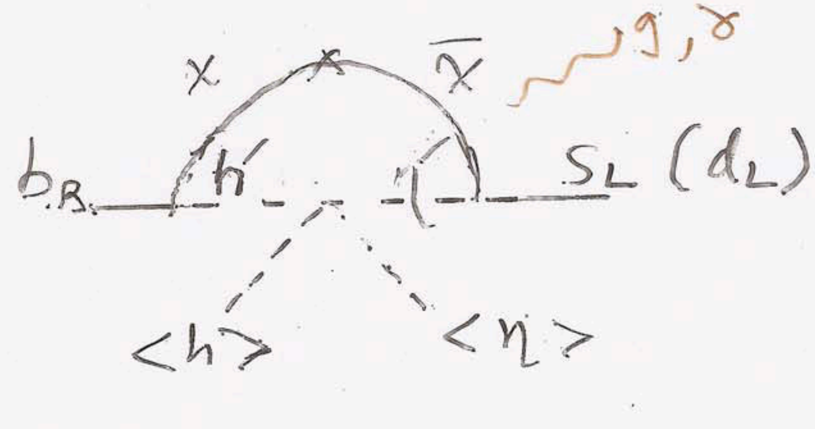
interesting implications for rare decays:

naively $(Zsb) \lesssim \frac{v^2}{f^2} V_{cb} \sim 10^{-3}$

$\Rightarrow$ significant effects in $B \to \phi K, K\pi, s\ell^+\ell^-, K^*\ell^+\ell^-$

- loops containing the vectorlike quarks, heavy scalars h', η', with large couplings to light quarks? (model-dependent)

e.g



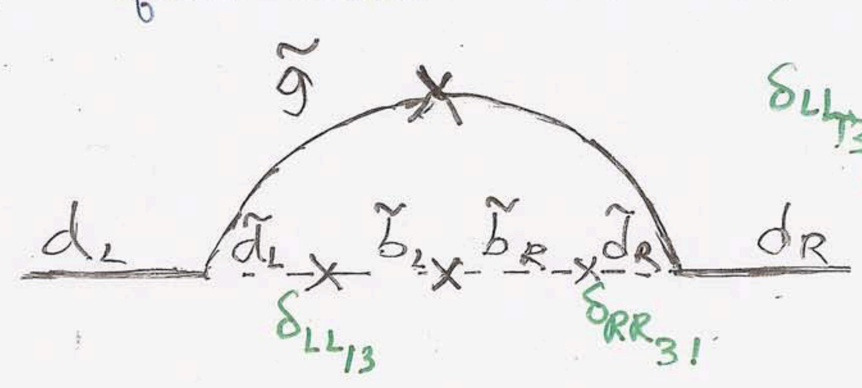
radiative masse

$b \to s(d)\gamma$, $b \to s$ [illegible]

- if the little higgs exists in a supersymmetric framework 'UV completion', then $\mathcal{O}(10-100)$ TeV squark masses

$\Longrightarrow$ new radiative squark/gluino loops for quark masses consistent with FCNC bound

eg m_d



$\delta_{LL_{13}}, \delta_{RR_{13}} \sim 1$ consistent w/ Δm_B

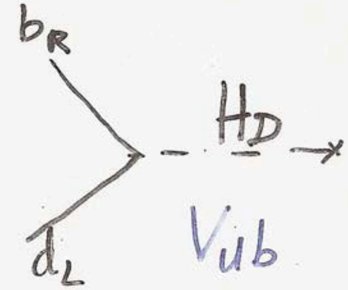
$$m_d \sim \frac{1}{16\pi^2} \underbrace{\frac{\delta m^2_{\tilde{d}_L \tilde{b}_L}}{\tilde{m}^2}}_{\delta_{LL_{13}}} \underbrace{\frac{\delta m^2_{\tilde{d}_R \tilde{b}_R}}{\tilde{m}^2}}_{\delta_{RR_{13}}} m_b$$

SUSY FRAMEWORK CONTINUED:

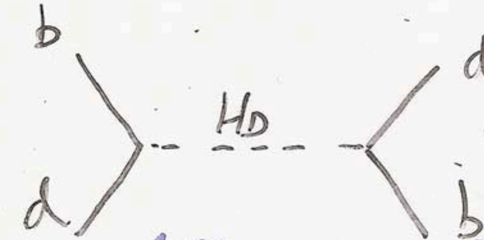
- Also, additional $\mathcal{O}(10\text{-}100)$ TeV Higgs doublets well motivated.

Suppressed VEVs could generate light quark masses, or mixing angles, but corresponding tree-level FCNC would be consistent w/ bounds

eg



$\Rightarrow$



$\sim \frac{1}{m^2_{H_D}}$

$\Delta m_B < \Delta m_B^{EXP}$

Conclusion

- Have reviewed some old ideas for attacking the flavor hierarchy problem in SUSY framework

  interesting FCNC effects in B decays, D physics associated with superpartner exchange

- new idea - Little Higgs - a perturbative theory for Higgs which does not use SUSY partners to cancel quad divergences.

- An alternative set of particles at $\mathcal{O}(1\text{ TeV})$ does the job
- theory valid to scales $\Lambda \sim 10$ TeV
- Can embed in SUSY framework with SUSY masses $\sim 10-100$ TeV - nice solution to SUSY FCNC problem
- interesting implications for flavor physics due to $\mathcal{O}(1\text{TeV})$ particles possible