Fermion Mass Hierarchy and New Physics at the TeV Scale

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S. Nandi, 6/10/09
Talk at SUSY09, Boston
Fermion mass hierarchy

Longstanding problem

- Charged fermion masses vary by 5 orders of magnitude
- Quark mixing angles vary by 2 orders of magnitude

Two main approaches

- Fermion mass hierarchy is caused from physics at high scale (GUT scale or Planck scale): Frogatt- Nielsen mechanism
- Caused by some new physics at the TeV scale

(See talks by Chen, Graham, Toharia and Velasco-sevilla in parallel sessions at this conf)
This Talk

Outline

- Introduction
- Model and Formalism
  - Model
  - Fermion Masses and CKM Mixing
  - Yukawa Interactions, FCNC, Higgs Sector, and Z’
- Phenomenological Implications
  - Constraints from existing Experiments
  - New Physics Signals for the LHC
- TeV Completion
- Conclusions
Introduction

- What are the new physics possibilities at the TeV scale?
  - SUSY: highly motivated
    - new superpartners and Higgs at the TeV scale
  - Extra Dimensions: somewhat motivated
    - new KK Excitations at the TeV Scale
  - Extra U(1): somewhat string motivated
    - new Z’ at the TeV Scale

However, these are all theory motivated.
Introduction

- Experimental Clues so far:
  - Charged fermion masses are highly hierarchical
  - Quark mixing angles are hierarchical
  - FCNC processes are strongly suppressed

- What sort of new physics can explain these, and can be observed at the LHC?

- In this work, we explore one such possibility
Introduction

- In the Standard Model: \( m_{q_i} = y_{q_i} v \)

\[
L_Y = y_{d_i} q_{iL} d_{iR} H + y_{u_i} q_{iL} u_{iR} \tilde{H} + h.c.
\]

- \( m_t \sim 172 \text{ GeV} \Rightarrow y_t \sim 1 \)
- Top quark is directly connected to EW symmetry breaking sector
- Has dimension 4 Yukawa interaction
- Probably not directly connected to EW symmetry breaking sector
- They may be connected via some messenger fields

\( y_b, y_c, y_s, y_d, y_u, y_e, y_\mu, y_\tau \ll 1 \)
Model and Formalism

- Extend SM gauge symmetry by a $U(1)_S$ local symmetry and $U(1)_F$ global flavor symmetry
  - All SM fermions are neutral with respect to $U(1)_S$
  - All SM fermions, except $q_{3L}$ and $u_{3R}$, are charged with respect to $U(1)_F$
- Introduce a complex scalar field $S$
  - $S$ has charge +1 under $U(1)_S$, and neutral under $U(1)_F$
- Introduce a complex flavon field, $F$
  - $F$ is charged under $U(1)_F$, neutral under $U(1)_S$, and SM singlet
- Flavor charges of SM fermions are such that only the top quark has dimension 4 Yukawa interactions
Model (continued)

- S acquires a VEV at the EW scale breaks $U(1)_S$ spontaneously.
- Pseudoscalar component of S is eaten to give mass to $U(1)_S$ gauge boson, $Z'$.
- S acts as the messenger of both flavor sym. breaking as well as EW sym. breaking.
- $U(1)_F$ is broken by the VEV of a flavon scalar, F at the TeV scale.
- There are additional vector-like fermions at the TeV scale, charged under $U(1)_S$ and $U(1)_F$.

The Yukawa interactions of the light fermions, after integrating out heavy vector-like fermions, appear as higher dimension operators.
Model (continued)

- The Yukawa interactions of the light fermions have a hierarchical pattern of the form:

\[
\left( \frac{S^\dagger S}{M^2} \right)^n \left( \frac{F_i}{M} \right)^{n_1} \left( \frac{F_i^\dagger}{M} \right)^{n_2} f_{ij}^d \bar{q}_{iL} d_{jR} H
\]

- Similarly for the up sector
- The observed fermion mass hierarchy and mixings are reproduced in powers of \( \varepsilon \)

\[
\varepsilon \equiv \frac{\langle S \rangle}{M} \sim \frac{1}{7} \Rightarrow "Little hierarchy"
\]
Model (continued)

\[ L_Y = h_{33}^u \bar{q}_{3L} u_{3R} \tilde{H} \]

\[ + \left( \frac{S^\dagger S}{M^2} \right) \left[ h_{33}^d \bar{q}_{3L} d_{3R} H + h_{22}^u \bar{q}_{2L} u_{2R} \tilde{H} + h_{23}^u \bar{q}_{2L} u_{3R} \tilde{H} + h_{32}^u \bar{q}_{3L} u_{2R} \tilde{H} \right] \]

\[ + \left( \frac{S^\dagger S}{M^2} \right)^2 \left[ h_{22}^d \bar{q}_{2L} d_{2R} H + h_{23}^d \bar{q}_{2L} d_{3R} H + h_{32}^d \bar{q}_{3L} d_{2R} H + h_{12}^u \bar{q}_{1L} u_{2R} \tilde{H} \right. \]

\[ + h_{21}^u \bar{q}_{2L} u_{1R} \tilde{H} + h_{13}^u \bar{q}_{1L} u_{3R} \tilde{H} + h_{31}^u \bar{q}_{3L} u_{1R} \tilde{H} \]

\[ + \left( \frac{S^\dagger S}{M^2} \right)^3 \left[ h_{11}^u \bar{q}_{1L} u_{1R} \tilde{H} + h_{12}^d \bar{q}_{1L} d_{1R} H + h_{13}^d \bar{q}_{1L} d_{3R} H \right. \]

\[ + h_{21}^d \bar{q}_{2L} d_{1R} H + h_{13}^d \bar{q}_{1L} d_{3R} H + h_{31}^d \bar{q}_{3L} d_{1R} H \]

\[ \left. \right] + h.c. \]

All couplings: \( h_{ij}^u, h_{ij}^d \sim O(1) \)
Fit to Fermion Masses & CKM mixings

\[ H = \begin{pmatrix} 0 \\ h/\sqrt{2} + v \end{pmatrix}, \quad S = \begin{pmatrix} s/\sqrt{2} + v_s \end{pmatrix} \]

\[ v \sim 174 \text{ GeV}, \quad \varepsilon \equiv \frac{v_s}{M}, \quad \beta \equiv \frac{v}{M} \]

\[ M_D = \begin{pmatrix} h_{11} \varepsilon^6 & h_{12} \varepsilon^6 & h_{13} \varepsilon^6 \\ h_{21} \varepsilon^6 & h_{22} \varepsilon^4 & h_{23} \varepsilon^4 \\ h_{31} \varepsilon^6 & h_{32} \varepsilon^4 & h_{33} \varepsilon^2 \end{pmatrix} v \]

\[ M_U = \begin{pmatrix} h_{11}^u \varepsilon^6 & h_{12}^u \varepsilon^4 & h_{13}^u \varepsilon^4 \\ h_{21}^u \varepsilon^4 & h_{22}^u \varepsilon^2 & h_{23}^u \varepsilon^2 \\ h_{31}^u \varepsilon^4 & h_{32}^u \varepsilon^2 & h_{33}^u \varepsilon^2 \end{pmatrix} v \]
Fit to Fermion Masses & CKM mixings

To leading order in $\varepsilon$:

$$(m_t, m_c, m_u) \approx \left( \frac{h_{33}^u}{h_{22}^d}, h_{22}^u, h_{11}^u - \frac{h_{12}^u h_{21}^u}{h_{22}^u} \right)^6 \varepsilon v$$

$$(m_b, m_s, m_d) \approx \left( h_{33}^d, h_{22}^d, h_{11}^d \right)^2 \varepsilon^2 v$$

$$(m_\tau, m_\mu, m_e) \approx \left( h_{33}^\ell, h_{22}^\ell, h_{11}^\ell \right)^2 \varepsilon^2 v$$

With $\varepsilon \approx 1/6.5$, a good fit is obtained for:

$$\left\{ \left| h_{33}^u \right|, \left| h_{22}^u \right|, \left| h_{11}^u - \frac{h_{12}^u h_{21}^u}{h_{22}^u} \right| \right\} = \{0.96, 0.14, 0.95\}$$

$$\left| V_{us} \right| \approx 0.2,$$

$$\left\{ \left| h_{33}^d \right|, \left| h_{22}^d \right|, \left| h_{11}^d \right| \right\} = \{0.68, 0.77, 1.65\}$$

$$\left| V_{cb} \right| \approx 0.04,$$

$$\left\{ \left| h_{33}^\ell \right|, \left| h_{22}^\ell \right|, \left| h_{11}^\ell \right| \right\} = \{0.42, 1.06, 0.21\}$$

$$\left| V_{ub} \right| \approx 0.004$$
Yukawa Interaction and FCNC

\[
\sqrt{2}Y^H_D = \begin{pmatrix}
  h^d_{11} \epsilon^6 & h^d_{12} \epsilon^6 & h^d_{13} \epsilon^6 \\
  h^d_{21} \epsilon^6 & h^d_{22} \epsilon^4 & h^d_{23} \epsilon^4 \\
  h^d_{31} \epsilon^6 & h^d_{32} \epsilon^4 & h^d_{33} \epsilon^2
\end{pmatrix}
\]

\[
\sqrt{2}Y^S_U = \begin{pmatrix}
  6h^u_{11} \epsilon^5 \beta & 4h^u_{12} \epsilon^3 \beta & 4h^u_{13} \epsilon^3 \beta \\
  4h^u_{21} \epsilon^3 \beta & 2h^u_{22} \epsilon \beta & 2h^u_{23} \epsilon \beta \\
  4h^u_{31} \epsilon^3 \beta & 2h^u_{32} \epsilon \beta & 0
\end{pmatrix}
\]

\[
\sqrt{2}Y^H_U = \begin{pmatrix}
  h^u_{11} \epsilon^6 & h^u_{12} \epsilon^4 & h^u_{13} \epsilon^4 \\
  h^u_{21} \epsilon^4 & h^u_{22} \epsilon^2 & h^u_{23} \epsilon^2 \\
  h^u_{31} \epsilon^4 & h^u_{32} \epsilon^2 & h^u_{33}
\end{pmatrix}
\]

\[
\sqrt{2}Y^S_D = \begin{pmatrix}
  6h^d_{11} \epsilon^5 \beta & 6h^d_{12} \epsilon^5 \beta & 6h^d_{13} \epsilon^5 \beta \\
  6h^d_{21} \epsilon^5 \beta & 4h^d_{22} \epsilon^3 \beta & 4h^d_{23} \epsilon^3 \beta \\
  6h^d_{31} \epsilon^5 \beta & 4h^d_{32} \epsilon^3 \beta & 2h^d_{33} \epsilon \beta
\end{pmatrix}
\]

Note: \( Y^H_U \propto M_U, \ Y^H_D \propto M_D \Rightarrow \text{No FCNC mediated by } h^0 \)
Higgs Sector and $Z'$

- Higgs potential invariant under SM and $U(1)_S$

$$V(H, S) = -\mu_H^2 (H^\dagger H) - \mu_S^2 (S^\dagger S) + \lambda_H (H^\dagger H)^2 + \lambda_S (S^\dagger S)^2 + \lambda_{HS} (H^\dagger H)(S^\dagger S)$$

$$M_H^2 = \begin{pmatrix} 2\lambda_H & \lambda_{HS}\alpha \\ \lambda_{HS}\alpha & 2\lambda_S\alpha^2 \end{pmatrix} 2v^2; \quad \alpha \equiv \frac{v_s}{v}$$

$$h^0 = h\cos\theta + s\sin\theta$$

$$s^0 = -h\sin\theta + s\cos\theta$$

- $\theta =$ mixing angle in the Higgs sector
- $Z'$ does not couple to any SM particles directly

$g_E : U(1)_S$ gauge coupling

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Phenomenological Implications

Constraints from existing Experiments

- For $s^0$ the Yukawa interaction matrix $Y$ is **not** proportional to Mass matrix, $M$
  - $S^0$ exchange causes FCNC
  - Coupling of $s^0$ to fermions $\rightarrow$ flavor dependent

- Constraints come from K-Kbar mixing, D-Dbar mixing, $K_L \rightarrow \mu^+ \mu^-$, $B_S \rightarrow \mu^+ \mu^-$,...
K-Kbar and D-Dbar mixing

\[ K^0 - \bar{K}^0 \]
\[ D^0 - \bar{D}^0 \]

- $\Delta m_K \sim 10^{-16}$-$10^{-17}$ GeV for $m_S \sim 100$ GeV
- $\Delta m_{K_{\text{expt}}} = 3.5 \times 10^{-15}$
- Diagram goes as $1/m_s^4$
- So $S$ cannot be much smaller than 100 GeV

- Enhanced compared to K-Kbar
- $\Delta m_D \sim 10^{-14}$ GeV for $m_S \sim 100$ GeV
- $\Delta m_{D_{\text{expt}}} = 1.6 \times 10^{-14}$
- $\beta$ cannot be much larger than $\varepsilon$
- So $S$ cannot be much smaller than 100 GeV

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Other Rare processes

\[ K_L \rightarrow \mu^+ \mu^- \]

- BR\(\sim10^{-14}\) for \(m_S\sim100\) GeV
- \(\text{BR}_{\text{expt}}=6.9\times10^{-9}\)
- Similarly, contributions to:
  
  \[ K_L \rightarrow \mu e, K \rightarrow \pi v \bar{v}, \mu \rightarrow e \gamma, \mu \rightarrow 3e \]

- All orders of magnitude below experimental limits
Constraint on the mass of S

- If mixing exists, for $\sin^2 \theta \geq 0.25$, the bound on the SM $h$, $m_h > 114.4$ GeV also applies to $m_S$
- $S$ can be lighter if mixing is small
Constraint on the mass of $Z'$

$$m_{Z'}^2 = 2g_E^2\nu_s^2$$

- $\nu_s \sim \nu$, but $g_E$ unknown and hence $m_{Z'}$ is not determined in our model.
- Accurate measurements of $Z$-properties at LEP → $\theta_{Z-Z'} < 10^{-3}$ or smaller for $m_{Z'} < 1$ TeV

$Z'$ can couple to SM fermions via 6 dimensional operators

$$L = \frac{1}{M^2} \bar{\psi}_L \sigma^{\mu\nu} \psi_R H Z'_{\mu\nu}$$

If $M$ is in TeV scale, the $Z'$ can be very light\(^1\)

In our model:

\[ \theta_{Z-Z'} \sim \frac{g_z g_{Z'}}{16\pi^2} \left( \frac{m_Z}{M} \right)^2 \sim 10^{-4} \]

Thus, no significant bound on $Z'$ mass from LEP

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\(^1\)Dobrescu, Phys.Rev.Lett.94:151802,2005
New Physics Signals at the LHC

- New particles in the Model:
  - A scalar Higgs, $s$, $m_s > 100$ GeV
  - An extra gauge boson, $Z'$, can be very light
  - Heavy vector-like quarks and leptons at the TeV scale
- Without mixing, coupling of $h^0$ to SM fermions are identical to that in SM
- And coupling of $s^0$ to SM fermions are flavor dependent:
  - $(t,b,\tau;c,s,\mu;u,d,e) = (0,2,2;2,4,4;6,6,6)$
  - These involve 2 parameters: $\theta$, $v_s/v = \alpha$
# Yukawa and Gauge Couplings (with mixing)

<table>
<thead>
<tr>
<th>Interaction</th>
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<tbody>
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<td>$s \rightarrow u\bar{u}$</td>
<td>$\frac{m_u}{v\sqrt{2}} \sin \theta + \frac{\cos \theta}{\alpha}$</td>
<td>$h \rightarrow u\bar{u}$</td>
<td>$\frac{m_u}{v\sqrt{2}} \left( \cos \theta - \frac{6 \sin \theta}{\alpha} \right)$</td>
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<td>$s \rightarrow d\bar{d}$</td>
<td>$\frac{m_d}{v\sqrt{2}} \sin \theta + \frac{\cos \theta}{\alpha}$</td>
<td>$h \rightarrow d\bar{d}$</td>
<td>$\frac{m_d}{v\sqrt{2}} \left( \cos \theta - \frac{6 \sin \theta}{\alpha} \right)$</td>
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<td>$s \rightarrow \mu^+\mu^-$</td>
<td>$\frac{m_\mu}{v\sqrt{2}} \sin \theta + \frac{4 \cos \theta}{\alpha}$</td>
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<td>$s \rightarrow \tau^+\tau^-$</td>
<td>$\frac{m_\tau}{v\sqrt{2}} \sin \theta + \frac{2 \cos \theta}{\alpha}$</td>
<td>$h \rightarrow \tau^+\tau^-$</td>
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<td>$s \rightarrow c\bar{c}$</td>
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<td>$s \rightarrow \tilde{t}\tilde{t}$</td>
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<td>$\frac{m_t}{v\sqrt{2}} \cos \theta$</td>
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<td>$s \rightarrow Z'Z'$</td>
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<td>$h \rightarrow ss$</td>
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Higgs Decays:

- Because of Flavor dependence of the Yukawa couplings of $s^0$ and mixing, BR for H to various final states is altered substantially.
- BR figures for $\theta=0^\circ, 20^\circ, 26^\circ, 40^\circ$
- For $\theta=0^\circ$, BR’s are the same as in the SM
- For all plots, $m_S=100$ GeV and $\alpha=1$
h→2x for θ=0°

Higgs Branching Ratios in Model, θ=0
$h \rightarrow 2x$ for $\theta = 20^\circ$

Higgs Branching Ratios in Model, $\theta=20$

Branching Ratio vs. $m_h$ (GeV)
h→2x for θ=26°

Higgs Branching Ratios in Model, θ=26
$h \rightarrow \gamma\gamma$ mode

- For $\theta=20^\circ$ and $26^\circ$, gg, $\gamma\gamma$ BR’s enhanced substantially compared to SM
- The effect is most dramatic for $\theta=26^\circ$
- For a light Higgs, $m_h \sim 115$ GeV, the usually dominant $bb$ mode is highly suppressed
- $\gamma\gamma$ mode is enhanced by a factor of 10 compared to SM
- Potential discovery of the Higgs via this mode at the LHC
h → WW mode

- In SM, $h \rightarrow bb$ and $h \rightarrow WW^*$ crossover occurs at $m_h \sim 135$ GeV
- In our model for $\theta = 20^\circ$ (for example) this crossover takes place sooner ($\sim 110$ GeV).
- As a result, Tevatron experiments will be more sensitive to a lower mass range of Higgs than in SM.
For $m_h > 200$ GeV the golden mode of discovery is $h \rightarrow ZZ$

In our model, $h$ and $s$ both decay via this mode with substantial BR’s

As a result it will be hard to tell whether we are seeing $h$ or $s$

Accurate measurement of $\sigma \ast BR$ will be needed to tell
Prediction for rare decays

- **Rare top decays**
  - $t \rightarrow ch$, BR~$10^{-3}$ for $m_h$~150 GeV
  - BR for SM ~ $10^{-14}$
    - with $\sigma_t \bar{t}$~800 fb, this decay will be observable, and can be a significant mode for Higgs production.

- **Rare B decays**
  - $B_s \rightarrow \mu^+ \mu^-$, BR ~ $10^{-9}$
  - Current limit from Tevatron: BR < 4.5 x $10^{-8}$

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Production and Decay of Heavy Vector-Like Fermions

- Our framework requires heavy vector-like quarks and leptons: $Q_L, Q_R, U_L, U_R, D_L, D_R, E_L, E_R$, at the TeV scale
- At LHC, $\sigma_{QQ\text{-bar}} \sim 60$ fb for $m_Q=1$ TeV
- We need several such vector-like quarks
- $\sigma_{\text{total}} \sim$ few hundred fb
- $Q \rightarrow qs$, $Q \rightarrow qh$, $h \rightarrow ZZ$, $s \rightarrow ZZ$ or $Z'Z'$
- Signal: 2 high pT jets + 4Z or 4Z’ bosons
TeV Completion (2 Generation)

- Symmetries: $\text{SM} + U(1)_S + U(1)_F$
  - $U(1)_S$ is local, broken at EW scale, $\langle S \rangle$
  - $U(1)_F$ broken at TeV scale, $\langle F \rangle$. This global Symmetry is also broken softly by the Higgs pot.
  - 3 Generation model adds 3 $U(1)_F$
- $q_{3L}, u_{3R}$ have no $U(1)_F$ charge
- All other quarks carry $U(1)_F$ charges
- Heavy vector-like quarks are introduced: $Q_{iL,R}, D_{iL,R}, U_{iL,R}$
  - Direct Dirac mass terms for $Q, U, D$ only if L and R carry same $U(1)_F$ charge
Table of Charge Assignments

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<tr>
<th>Field</th>
<th>$U(1)_Y$</th>
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<td>$1$</td>
<td>$1$</td>
<td>$D_{2R}$</td>
<td>$-1/3$</td>
<td>$2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$Q_{2R}$</td>
<td>$1/6$</td>
<td>$1$</td>
<td>$2$</td>
<td>$D_{3L,R}$</td>
<td>$-1/3$</td>
<td>$1$</td>
<td>$3$</td>
</tr>
</tbody>
</table>
UV Completion

With these charge assignments, only the following dimension 4 interactions involving SM particles are allowed:

\[
L_Y = f_1 \bar{q}_{3L} u_{3R} \tilde{H} \\
+ f_2 \bar{q}_{3L} Q_{1R} S + f_3 \bar{D}_{1L} d_{3R} S^\dagger + f_4 \bar{q}_{2L} Q_{2R} S^\dagger + f_5 \bar{U}_{1L} u_{3R} S \\
+ f_6 \bar{q}_{2L} Q_{3R} S + f_7 \bar{U}_{2L} u_{2R} S^\dagger + f_8 \bar{D}_{3L} d_{2R} S + h.c.
\]

- \( f_i \)'s are dimensionless couplings \( \sim 1 \)
- Only top quark has direct EW sym breaking connection
- Other couplings involve S, but not H or F
- EW sym breaking is communicated to lighter quarks or leptons by S.
UV Completion

Dimension 4 couplings involving just the heavy vector-like fermions are:

\[ L_Y = f_9 \overline{Q}_{1R} Q_{1L} F + f_{10} \overline{Q}_{1L} D_{1R} H + f_{11} \overline{Q}_{2R} Q_{2L} F + f_{12} \overline{Q}_{2L} U_{1R} \tilde{H} + f_{13} \overline{U}_{1R} U_{1L} F + f_{14} \overline{Q}_{3R} Q_{3L} F^\dagger + f_{15} \overline{Q}_{4L} U_{2R} \tilde{H} + f_{16} \overline{Q}_{2L} Q_{4R} S^\dagger + f_{17} \overline{Q}_{4L} Q_{2R} S + f_{18} \overline{Q}_{4R} Q_{4L} F^\dagger + f_{19} \overline{Q}_{4L} D_{2R} H + f_{20} \overline{D}_{2R} D_{2L} F^\dagger + f_{21} \overline{D}_{2L} D_{3R} S + M\overline{D}_{1R} D_{1L} + M\overline{D}_{3L} D_{3R} + M\overline{U}_{2R} U_{2L} + h.c. \]
Integrating out the heavy fermions in the tree level diagram composed from the couplings:

\[
L_Y^{\text{eff}} = f_2 f_3 f_9 f_{10} \left( \frac{F}{M} \right) \left( \frac{S^\dagger S}{M^2} \right) \bar{q}_{3L} d_{3R} H + \text{h.c.}
\]

Similarly for other interactions.
Conclusions

- Presented a TeV scale model of flavor
- Only top quark directly participates in EW symmetry breaking
- All lighter quarks participate via a messenger field, a complex scalar, $S$
- Fermion masses and mixings are reproduced by breaking of a flavor symmetry at the TeV scale
- $S$ also acts a messenger for EW symmetry breaking
- New Physics:
  - A singlet scalar $S$, light $Z'$, and vector-like fermions (TeV)
  - Observable new signals at the LHC for Higgs discovery, $Z'$ and TeV scale vector-like fermions