Fermion Mass Hierarchy and New Physics at the TeV Scale

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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

This Talk

: Our approach: New physics at the TeV scale

Based on the work by J.D. Lykken, Z. Murdock and S. Nandi,

(Phys Rev D, 2009)

And B. Grossmann, Z. Murdock and S. Nandi (to appear)

Outline

- Introduction
- Model and Formalism
- Phenomenological Implications
  - Constraints from existing Experiments
  - New Physics Signals for the LHC
- TeV Completion
- Conclusions

Introduction

- In the Standard Model: $m_{q_i} = y_{q_i} v$

$$L_Y = y_{d_i} \overline{q}_{iL} d_{iR} H + y_{u_i} \overline{q}_{iL} u_{iR} \widetilde{H} + h.c.$$

$m_t \sim 172\ GeV \;\Rightarrow\; y_t \sim 1$

- Top quark is directly connected to EW symmetry breaking sector
- Has dimension 4 Yukawa interaction

$y_b, y_c, y_s, y_d, y_u, y_e, y_\mu, y_\tau << 1$

- Probably <u>not</u> directly connected to EW symmetry breaking sector
- They may be connected via some messenger fields

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, as well as softly 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:

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

- Similarly for the up sector
- The observed fermion mass hierarchy and mixings are reproduced in powers of ε

$$\varepsilon \equiv \frac{\langle S \rangle}{M} \sim \frac{1}{7} \Rightarrow \text{"Little hierarchy"}$$

Model (continued)

$$L_Y = h^u_{33}\overline{q}_{3L}u_{3R}\widetilde{H}$$
$$+\left(\frac{S^\dagger S}{M^2}\right)\left[h^d_{33}\overline{q}_{3L}d_{3R}H + h^u_{22}\overline{q}_{2L}u_{2R}\widetilde{H} + h^u_{23}\overline{q}_{2L}u_{3R}\widetilde{H} + h^u_{32}\overline{q}_{3L}u_{2R}\widetilde{H}\right]$$
$$+\left(\frac{S^\dagger S}{M^2}\right)^2\left[\begin{array}{l} h^d_{22}\overline{q}_{2L}d_{2R}H + h^d_{23}\overline{q}_{2L}d_{3R}H + h^d_{32}\overline{q}_{3L}d_{2R}H + h^u_{12}\overline{q}_{1L}u_{2R}\widetilde{H} \\ + h^u_{21}\overline{q}_{2L}u_{1R}\widetilde{H} + h^u_{13}\overline{q}_{1L}u_{3R}\widetilde{H} + h^u_{31}\overline{q}_{3L}u_{1R}\widetilde{H} \end{array}\right]$$
$$+\left(\frac{S^\dagger S}{M^2}\right)^3\left[\begin{array}{l} h^u_{11}\overline{q}_{1L}u_{1R}\widetilde{H} + h^d_{11}\overline{q}_{1L}d_{1R}H + h^d_{12}\overline{q}_{1L}d_{2R}H + \\ h^d_{21}\overline{q}_{2L}d_{1R}H + h^d_{13}\overline{q}_{1L}d_{3R}H + h^d_{31}\overline{q}_{3L}d_{1R}H \end{array}\right] + h.c.$$

$$\text{All coupings}: \; h^u_{ij}, h^d_{ij} \sim O(1)$$

Fit to Fermion Masses & CKM mixings

To leading order in ε:

$$\left(m_t, m_c, m_u\right) \cong \left(\left|h^u_{33}\right|, \left|h^u_{22}\right|\varepsilon^2, \left|h^u_{11} - \frac{h^u_{12}h^u_{21}}{h^u_{22}}\right|\varepsilon^6 \right) v$$

$$\left(m_b, m_s, m_d\right) \cong \left(\left|h^d_{33}\right|\varepsilon^2, \left|h^d_{22}\right|\varepsilon^4, \left|h^d_{11}\right|\varepsilon^6 \right) v$$

$$\left(m_\tau, m_\mu, m_e\right) \cong \left(\left|h^\ell_{33}\right|\varepsilon^2, \left|h^\ell_{22}\right|\varepsilon^4, \left|h^\ell_{11}\right|\varepsilon^6 \right) v$$

$$\left|V_{us}\right| \cong \left|\frac{h^d_{12}}{h^d_{22}} - \frac{h^u_{12}}{h^u_{22}}\right| \varepsilon 2$$

$$\left|V_{cb}\right| \cong \left|\frac{h^d_{23}}{h^d_{33}} - \frac{h^u_{23}}{h^d_{33}}\right| \varepsilon 2$$

$$\left|V_{ub}\right| \cong \left|\frac{h^d_{13}}{h^d_{33}} - \frac{h^u_{12}h^d_{23}}{h^u_{22}h^d_{33}} - \frac{h^u_{13}}{h^d_{23}}\right| \varepsilon 4$$

With ε ~ 1/6.5, a good fit is obtained for:

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

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

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

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

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

$$\left|V_{ub}\right| \sim 0.004$$

Higgs Sector and Z’

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

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

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

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

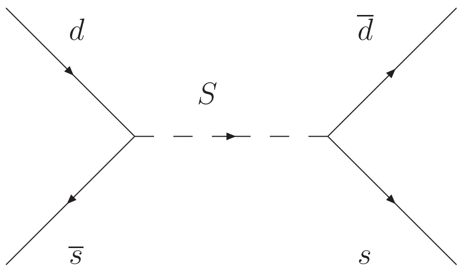
$$m_{Z'}^2 = 2g_E^2 v_s^2$$

g_E : $U(1)_S$ gauge coupling

- θ= mixing angle in the Higgs sector
- Z’ does not couple to any SM particles directly

K-Kbar and D-Dbar mixing

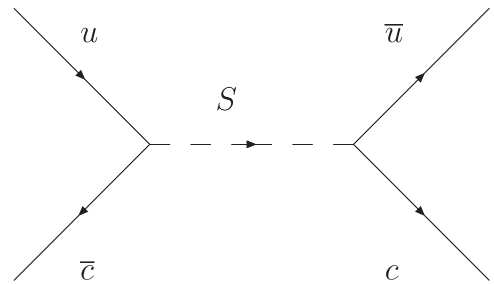
$$K^0 - \overline{K}^0$$



$$\sim h^d_{12} h^d_{21} \beta^2 \epsilon^{10} \sim \epsilon^{12}$$

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

$$D^0 - \overline{D}^0$$



$$\sim h^u_{12} h^u_{21} \beta^2 \epsilon^{6} \sim \epsilon^{8}$$

- Enhanced compared to K-Kbar
- $\Delta m_D \sim 10^{-14}$ GeV for $m_S \sim 100$ GeV
- $\Delta m_{D(expt)} = 1.6*10^{-14}$
- β cannot be much larger than ε
- So S cannot be much smaller than 100 GeV

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

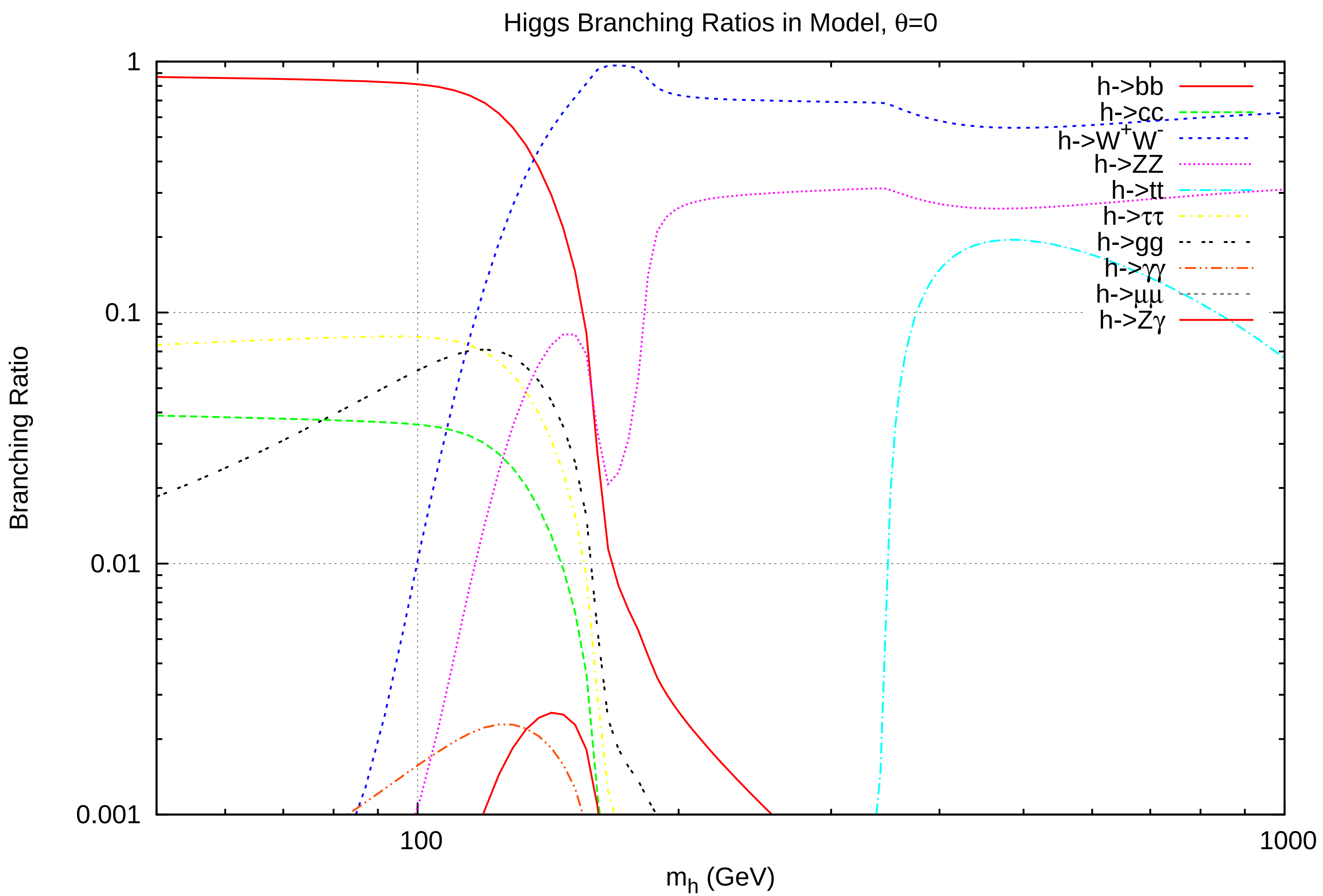
- Without mixing, coupling of h^0 to SM fermions are identical to that in SM

- 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: θ, $v_s/v = \alpha$

Higgs Decays:

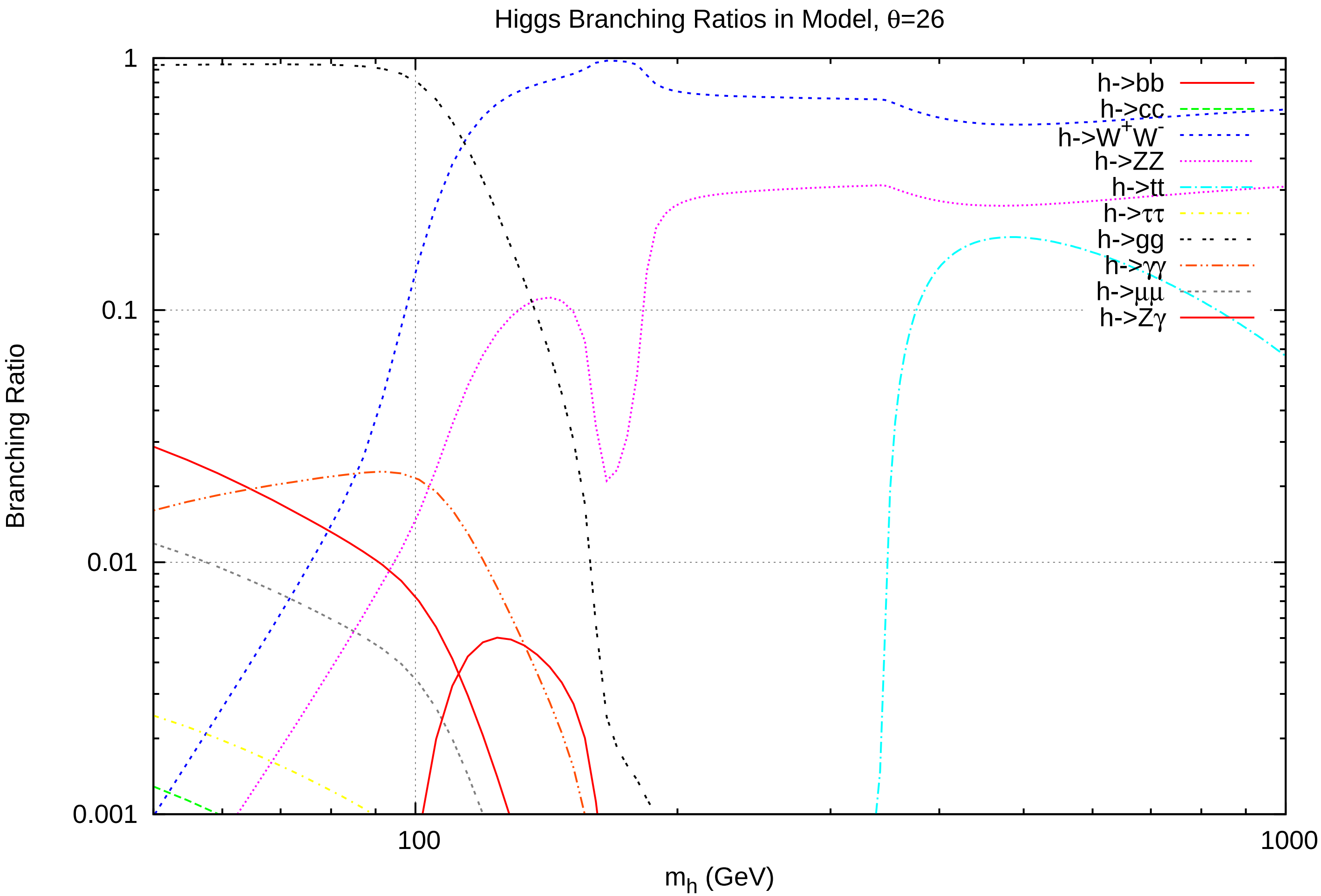
- Because of Flavor dependence of the Yukawa couplings of s^0 and mixing, BR for H to various final states is altered substantially.
- BR figures for $\theta=0°$, $26°$
- For $\theta=0°$, BR's are the same as in the SM
- For all plots, $m_S=100$ GeV and $\alpha=1$

h→2x for θ=0°



Higgs Branching Ratios in Model, θ=0
Branching Ratio
1
0.1
0.01
0.001
100
1000
m_h (GeV)
h->bb
h->cc
h->W+W-
h->ZZ
h->tt
h->ττ
h->gg
h->γγ
h->μμ
h->Zγ

h→2x for θ=26°



Higgs Branching Ratios in Model, θ=26
Branching Ratio
m_h (GeV)
1
0.1
0.01
0.001
100
1000
h->bb
h->cc
h->W+W-
h->ZZ
h->tt
h->ττ
h->gg
h->γγ
h->μμ
h->Zγ

$h \rightarrow \gamma\gamma$ mode

- For θ=20° and 26°, gg, $\gamma\gamma$ BR's enhanced substantially compared to SM
- The effect is most dramatic for θ=26°
- For a light Higgs, m_h~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

$h \to WW$ mode

- In SM, $h \to bb$ and $h \to WW^*$ crossover occurs at $m_h \sim 135$ GeV
- In our model for $\theta = 20°$ (for example) this crossover takes place sooner (~ 110 GeV).
- As a result, Tevatron experiments will be more sensitive to a lower mass range of Higgs than in SM

Prediction for rare decays

Rare top decays

- $t \rightarrow ch$, BR~10^{-3} for m_h~150 GeV
- BR for SM ~ 10^{-14}

with $\sigma_{t\ t\text{-}bar}$~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 < 4.5×10^{-8}

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, $\sigma_{QQ\text{-bar}}$ ~60 fb for m_Q=1 TeV
- We need several such vector-like quarks
- σ_{total} ~ 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: SM + $U(1)_S$+$U(1)_F$
  - $U(1)_S$ is local, broken at EW scale, <S>
  - $U(1)_F$ broken at TeV scale, <F>. 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: $Q_{iL,R}$, $D_{iL,R}$, $U_{iL,R}$

Table of Charge Assignments

Field	$U(1)_Y$	$U(1)_S$	$U(1)_F$	Field	$U(1)_Y$	$U(1)_S$	$U(1)_F$
H	$1/2$	0	0	Q_{3L}	$1/6$	-1	3
S	0	1	0	Q_{3R}	$1/6$	-1	2
F	0	0	1	Q_{4L}	$1/6$	2	2
q_{3L}	$1/6$	0	0	Q_{4R}	$1/6$	2	1
q_{2L}	$1/6$	0	2	U_{1L}	$2/3$	1	0
u_{3R}	$2/3$	0	0	U_{1R}	$2/3$	1	1
u_{2R}	$2/3$	0	3	U_{2L}	$2/3$	-1	3
d_{3R}	$-1/3$	0	-1	U_{2R}	$2/3$	-1	3
d_{2R}	$-1/3$	0	3	D_{1L}	$-1/3$	-1	-1
Q_{1L}	$1/6$	-1	-1	D_{1R}	$-1/3$	-1	-1
Q_{1R}	$1/6$	-1	0	D_{2L}	$-1/3$	2	3
Q_{2L}	$1/6$	1	1	D_{2R}	$-1/3$	2	2
Q_{2R}	$1/6$	1	2	$D_{3L,R}$	$-1/3$	1	3

UV Completion

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

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

- f_i's are dimensionless couplings ~1
- Only top quark has direct EW sym breaking connection
- Other couplings involve S, but <u>not</u> H or F
- EW sym breaking is communicated to lighter quarks or leptons <u>by S</u>.

UV Completion

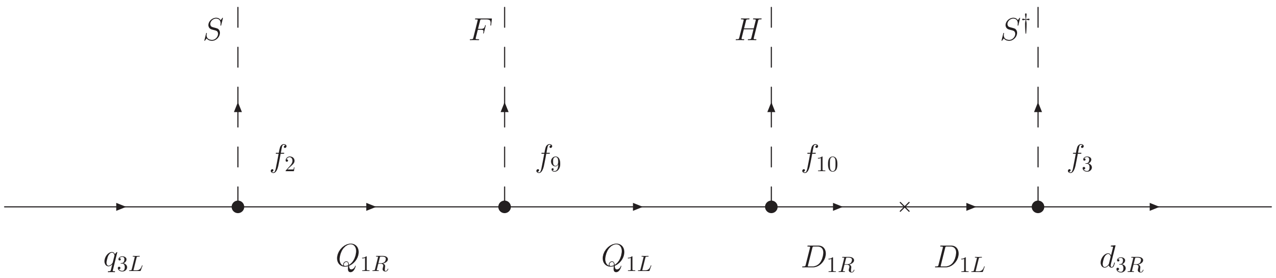
Dimension 4 couplings involving just the heavy vector-like fermions are:

$$
\begin{aligned}
L_Y = {} & f_9 \overline{Q}_{1R} Q_{1L} F + f_{10} \overline{Q}_{1L} D_{1R} H + f_{11} \overline{Q}_{2R} Q_{2L} F + f_{12} \overline{Q}_{2L} U_{1R} \tilde{H} + \\
& f_{13} \overline{U}_{1R} U_{1L} F + f_{14} \overline{Q}_{3R} Q_{3L} F^{\dagger} + f_{15} \overline{Q}_{3L} U_{2R} \tilde{H} + f_{16} \overline{Q}_{2L} Q_{4R} S^{\dagger} + \\
& f_{17} \overline{Q}_{4L} Q_{2R} S + f_{18} \overline{Q}_{4R} Q_{4L} F^{\dagger} + f_{19} \overline{Q}_{4L} D_{2R} H + f_{20} \overline{D}_{2R} D_{2L} F^{\dagger} + \\
& f_{21} \overline{D}_{2L} D_{3R} S + M \overline{D}_{1R} D_{1L} + M \overline{D}_{3L} D_{3R} + M \overline{U}_{2R} U_{2L} + h.c.
\end{aligned}
$$

UV Completion

Integrating out the heavy fermions in the tree level diagram composed from the couplings:

$$f_2 \overline{q}_{3L} Q_{1R} S + f_9 \overline{Q}_{1R} Q_{1L} F + f_{10} \overline{Q}_{1L} D_{1R} H + M \overline{D}_{1R} D_{1L} + f_3 \overline{D}_{1L} d_{3R} S^\dagger$$



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

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