Fermion Mass Hierarchy and New Physics at the TeV Scale

S. Nandi

Oklahoma State University

and Oklahoma Center for High Energy Physics

(Talk at Fermilab, June 8, 2010)

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

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
  - 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: $m_{q_i} = y_{q_i} v$

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

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

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

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

- 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 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)

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

$$\text{All coupings}: \; h_{ij}^u, h_{ij}^d \sim O(1)$$

Fit to Fermion Masses & CKM mixings

$$H=\begin{pmatrix}0\\ h/\sqrt{2}+v\end{pmatrix},\qquad \mathrm{S}=\left(\mathrm{s}/\sqrt{2}+v_s\right)$$

$$v\sim 174\ \mathrm{GeV},\ \ \varepsilon\equiv\frac{v_s}{M},\ \ \beta\equiv\frac{v}{M}$$

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

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

Fit to Fermion Masses & CKM mixings

To leading order in ε:

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

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

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

$$\left|V_{us}\right| \cong \left| \frac{h_{12}^d}{h_{22}^d} - \frac{h_{12}^u}{h_{22}^u} \right| \varepsilon 2$$

$$\left|V_{cb}\right| \cong \left| \frac{h_{23}^d}{h_{33}^d} - \frac{h_{23}^u}{h_{33}^d} \right| \varepsilon 2$$

$$\left|V_{ub}\right| \cong \left| \frac{h_{13}^d}{h_{33}^d} - \frac{h_{12}^u h_{23}^d}{h_{22}^u h_{33}^d} - \frac{h_{13}^u}{h_{23}^d} \right| \varepsilon 4$$

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

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

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

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

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

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

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

Yukawa Interaction and FCNC

$$\sqrt{2}Y_D^H = \begin{pmatrix} h_{11}^d\varepsilon^6 & h_{12}^d\varepsilon^6 & h_{13}^d\varepsilon^6 \\ h_{21}^d\varepsilon^6 & h_{22}^d\varepsilon^4 & h_{23}^d\varepsilon^4 \\ h_{31}^d\varepsilon^6 & h_{32}^d\varepsilon^4 & h_{33}^d\varepsilon^2 \end{pmatrix} \qquad \sqrt{2}Y_U^S = \begin{pmatrix} 6h_{11}^u\varepsilon^5\beta & 4h_{12}^u\varepsilon^3\beta & 4h_{13}^u\varepsilon^3\beta \\ 4h_{21}^u\varepsilon^3\beta & 2h_{22}^u\varepsilon\beta & 2h_{23}^u\varepsilon\beta \\ 4h_{31}^u\varepsilon^3\beta & 2h_{32}^u\varepsilon\beta & 0 \end{pmatrix}$$

$$\sqrt{2}Y_U^H = \begin{pmatrix} h_{11}^u\varepsilon^6 & h_{12}^u\varepsilon^4 & h_{13}^u\varepsilon^4 \\ h_{21}^u\varepsilon^4 & h_{22}^u\varepsilon^2 & h_{23}^u\varepsilon^2 \\ h_{31}^u\varepsilon^4 & h_{32}^u\varepsilon^2 & h_{33}^u \end{pmatrix} \qquad \sqrt{2}Y_D^S = \begin{pmatrix} 6h_{11}^d\varepsilon^5\beta & 6h_{12}^d\varepsilon^5\beta & 6h_{13}^d\varepsilon^5\beta \\ 6h_{21}^d\varepsilon^5\beta & 4h_{22}^d\varepsilon^3\beta & 4h_{23}^d\varepsilon^3\beta \\ 6h_{31}^d\varepsilon^5\beta & 4h_{32}^d\varepsilon^3\beta & 2h_{33}^d\varepsilon\beta \end{pmatrix}$$

$$\text{note}: \; Y_U^H \propto M_U, \; Y_D^H \propto M_D \Rightarrow \text{No FCNC mediated by } \mathrm{h}^0$$

Higgs Sector and Z'

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

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

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

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

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

g_E : $U(1)_S$ gauge coupling

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

Phenomenological Implications

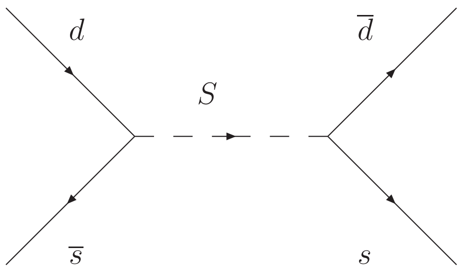
Constraints from existing Experiments

- For s^0 the Yukawa interaction matrix Y is <u>not</u> proportional to Mass matrix, M
  - S^0 exchange causes FCNC
  - Coupling of s^0 to fermions ⇨ flavor dependent

  - Constraints come from K-Kbar mixing, D-Dbar mixing, $K_L \to \mu^+\mu^-$, $B_S \to \mu^+\mu^-$,…

K-Kbar and D-Dbar mixing

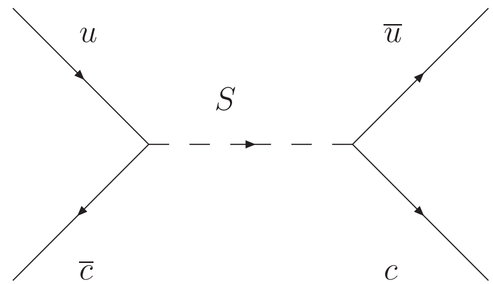
$K^0 - \overline{K}^0$



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

- $\Delta m_K \sim 10^{-16}$-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

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

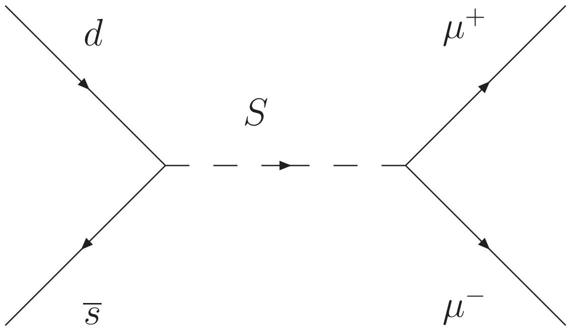


$\sim h^u_{12} h^u_{21} \beta^2 \epsilon^{6} \sim \epsilon^{8}$

- 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

Other Rare processes

$$K_L \to \mu^+ \mu^-$$



$\sim \beta^2 \epsilon^{10}$

- BR~10^{-14} for m_S~100 GeV
- $BR_{expt}=6.9*10^{-9}$
- Similarly, contributions to:

$$K_L \to \mu e, K \to \pi \nu \bar{\nu}, \mu \to e\gamma, \mu \to 3e$$

- All orders of magnitude below experimental limits

Constraint on the mass of S

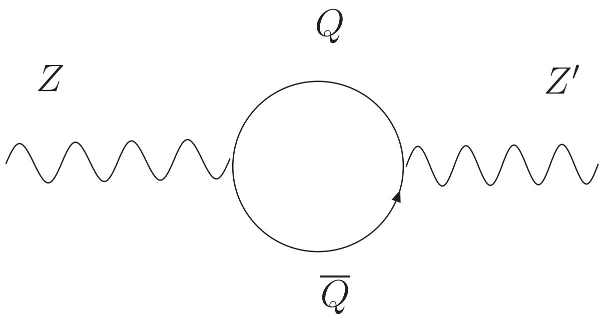
- If mixing exists, for $\sin^2\theta \geq 0.25$, the bound on the SM h, $m_h > 114.4$ GeV also applies to m_s
- S can be lighter if mixing is small

Constraint on the mass of Z'

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

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

In our model:



Q is heavy vector-like fermion at the TeV scale (M)→

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

Thus, <u>no</u> significant bound on Z′ mass from LEP

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]

[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: θ, $v_s/v = \alpha$

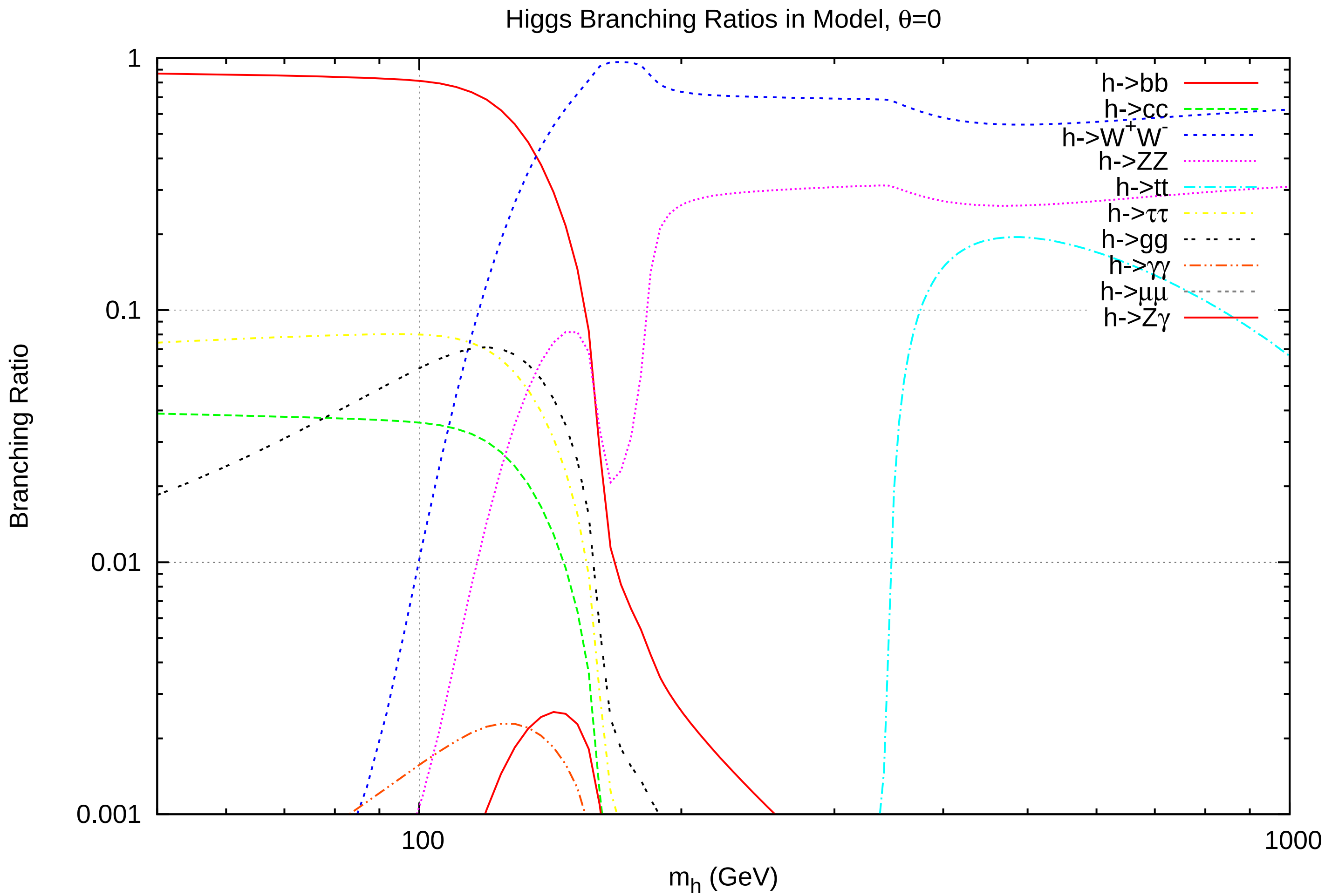
Yukawa and Gauge Couplings (with mixing)

Interaction	Coupling	Interaction	Coupling
$s \to u\bar{u}$	$\frac{m_u}{v\sqrt{2}}\left(\sin\theta + \frac{6\cos\theta}{\alpha}\right)$	$h \to u\bar{u}$	$\frac{m_u}{v\sqrt{2}}\left(\cos\theta - \frac{6\sin\theta}{\alpha}\right)$
$s \to d\bar{d}$	$\frac{m_d}{v\sqrt{2}}\left(\sin\theta + \frac{6\cos\theta}{\alpha}\right)$	$h \to d\bar{d}$	$\frac{m_d}{v\sqrt{2}}\left(\cos\theta - \frac{6\sin\theta}{\alpha}\right)$
$s \to \mu^+\mu^-$	$\frac{m_\mu}{v\sqrt{2}}\left(\sin\theta + \frac{4\cos\theta}{\alpha}\right)$	$h \to \mu^+\mu^-$	$\frac{m_\mu}{v\sqrt{2}}\left(\cos\theta - \frac{4\sin\theta}{\alpha}\right)$
$s \to s\bar{s}$	$\frac{m_s}{v\sqrt{2}}\left(\sin\theta + \frac{4\cos\theta}{\alpha}\right)$	$h \to s\bar{s}$	$\frac{m_s}{v\sqrt{2}}\left(\cos\theta - \frac{4\sin\theta}{\alpha}\right)$
$s \to \tau^+\tau^-$	$\frac{m_\tau}{v\sqrt{2}}\left(\sin\theta + \frac{2\cos\theta}{\alpha}\right)$	$h \to \tau^+\tau^-$	$\frac{m_\tau}{v\sqrt{2}}\left(\cos\theta - \frac{2\sin\theta}{\alpha}\right)$
$s \to c\bar{c}$	$\frac{m_c}{v\sqrt{2}}\left(\sin\theta + \frac{2\cos\theta}{\alpha}\right)$	$h \to c\bar{c}$	$\frac{m_c}{v\sqrt{2}}\left(\cos\theta - \frac{2\sin\theta}{\alpha}\right)$
$s \to b\bar{b}$	$\frac{m_b}{v\sqrt{2}}\left(\sin\theta + \frac{2\cos\theta}{\alpha}\right)$	$h \to b\bar{b}$	$\frac{m_b}{v\sqrt{2}}\left(\cos\theta - \frac{2\sin\theta}{\alpha}\right)$
$s \to t\bar{t}$	$\frac{m_t}{v\sqrt{2}}\sin\theta$	$h \to t\bar{t}$	$\frac{m_t}{v\sqrt{2}}\cos\theta$
$s \to ZZ$	$\frac{m_Z^2}{v\sqrt{2}}\sin\theta$	$h \to ZZ$	$\frac{m_Z^2}{v\sqrt{2}}\cos\theta$
$s \to Z'Z'$	$\frac{m_{Z'}^2}{v\sqrt{2}}\cos\theta$	$h \to Z'Z'$	$\frac{m_{Z'}^2}{v\sqrt{2}}\sin\theta$
$s \to W^+W^-$	$\frac{m_W^2}{v\sqrt{2}}\sin\theta$	$h \to W^+W^-$	$\frac{m_W^2}{v\sqrt{2}}\cos\theta$
		$h \to ss$	λ_{hss}

Higgs Decays:

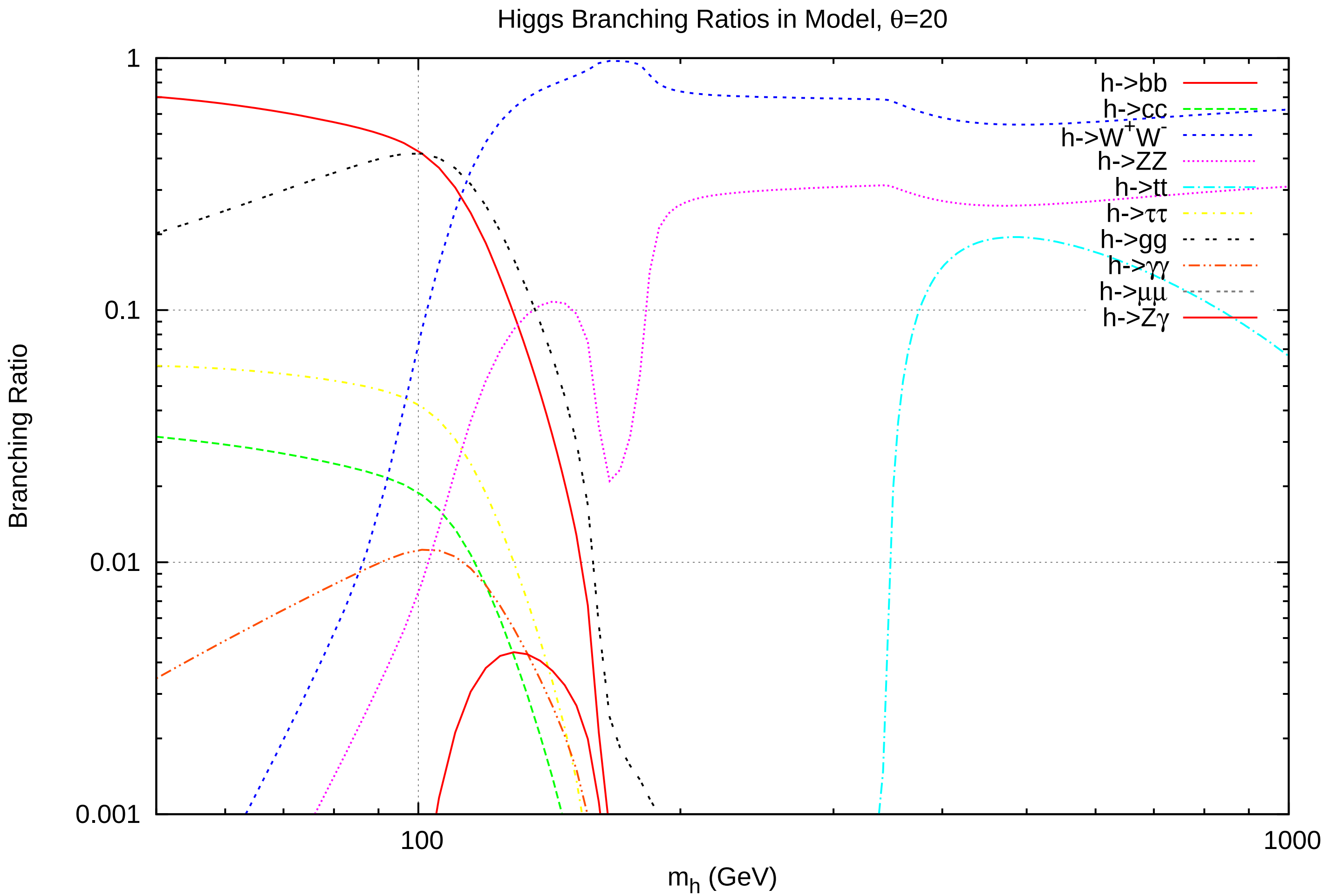
- Because of Flavor dependence of the Yukawa couplings of s^0 and mixing, BR for H to various final states is <u>altered</u> substantially.
- BR figures for $\theta=0°$, $20°$, $26°$, $40°$
- For $\theta=0°$, BR's are the same as in the SM
- For all plots, $m_S=100$ GeV and $\alpha=1$

h→2x for θ=0°



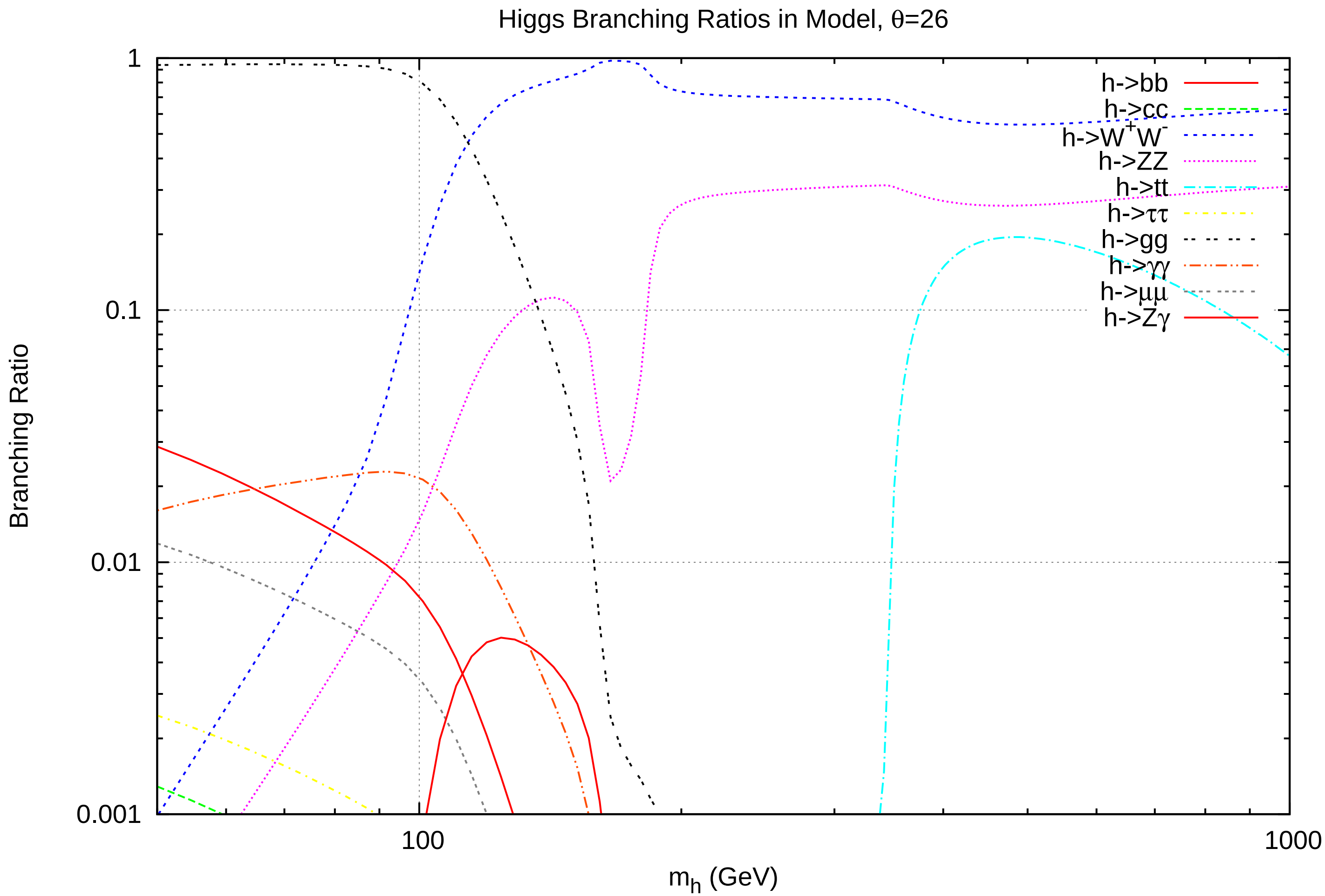
Higgs Branching Ratios in Model, θ=0
Branching Ratio
m_h (GeV)
1
0.1
0.01
0.001
100
1000
h->bb
h->cc
h->W+W-
h->ZZ
h->tt
h->ττ
h->gg
h->γγ
h->μμ
h->Zγ

h→2x for θ=20°



Higgs Branching Ratios in Model, θ=20
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
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

$h \to \gamma\gamma$ 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

h→ZZ mode

- For m_h>200 GeV the golden mode of discovery is h→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 σ*BR will be needed to tell

Prediction for rare decays

Rare top decays

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

with $\sigma_{t\ t\text{-}bar} \sim 800$ fb, this decay will be observable, and can be a significant mode for Higgs production.

Rare B decays

- $B_s \rightarrow \mu^+ \mu^-$, $BR \sim 10^{-9}$
- Current limit from Tevatron: $BR < 4.5 \times 10^{-8}$

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, $\langle S \rangle$
  - $U(1)_F$ 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

$Field$	$U(1)_Y$	$U(1)_S$	$U(1)_F$	$Field$	$U(1)_Y$	$U(1)_S$	$U(1)_F$
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:

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

- f_i's are dimensionless couplings ~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:

$$L_Y = f_9 \overline{Q}_{1R} Q_{1L} F + f_{10} \overline{Q}_{1L} D_{1R} H + f_{11} \overline{Q}_{2R} Q_{2L} F + f_{12} \overline{Q}_{2L} U_{1R} \tilde{H} +$$

$$f_{13} \overline{U}_{1R} U_{1L} F + f_{14} \overline{Q}_{3R} Q_{3L} F^{\dagger} + f_{15} \overline{Q}_{3L} U_{2R} \tilde{H} + f_{16} \overline{Q}_{2L} Q_{4R} S^{\dagger} +$$

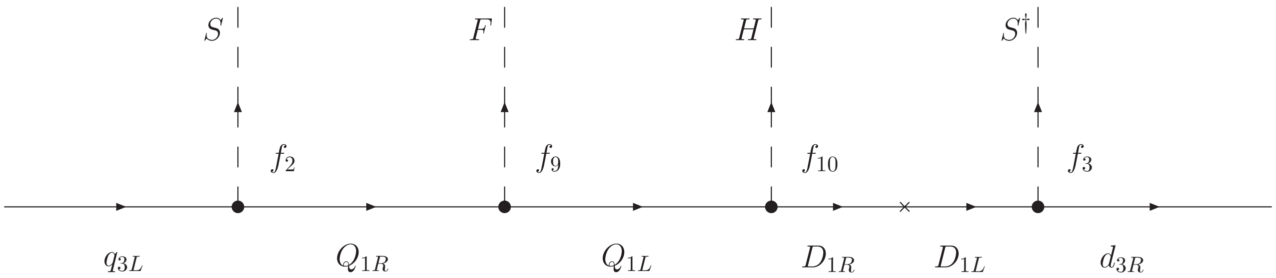
$$f_{17} \overline{Q}_{4L} Q_{2R} S + f_{18} \overline{Q}_{4R} Q_{4L} F^{\dagger} + f_{19} \overline{Q}_{4L} D_{2R} H + f_{20} \overline{D}_{2R} D_{2L} F^{\dagger} +$$

$$f_{21} \overline{D}_{2L} D_{3R} S + M \overline{D}_{1R} D_{1L} + M \overline{D}_{3L} D_{3R} + M \overline{U}_{2R} U_{2L} + h.c.$$

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

More on model building

Effective Lagrangians

- Restrict mass terms of the same order to have the same higher dimensional coefficient
- 24 possible Lagrangians for the Yukawa couplings

$$
\begin{aligned}
\mathcal{L}^{\text{Yuk}} = {} & h_u^{33}\overline{q}_{L3}u_{R3}\tilde{H} \\
& + \left(\frac{H^\dagger H}{M^2}\right)^{n_1}\left(\frac{S^\dagger S}{M^2}\right)^{m_1}\left(h_d^{33}\overline{q}_{L3}d_{R3}H + h_u^{22}\overline{q}_{L2}u_{R2}\tilde{H} + \cdots\right) \\
& + \left(\frac{H^\dagger H}{M^2}\right)^{n_2}\left(\frac{S^\dagger S}{M^2}\right)^{m_2}\left(h_d^{22}\overline{q}_{L2}d_{R2}H + h_d^{23}\overline{q}_{L2}d_{R3}H + \cdots\right) \\
& + \left(\frac{H^\dagger H}{M^2}\right)^{n_3}\left(\frac{S^\dagger S}{M^2}\right)^{m_3}\left(h_u^{11}\overline{q}_{L1}u_{R1}\tilde{H} + h_d^{11}\overline{q}_{L1}d_{R1}H + \cdots\right) \\
& + h.c.
\end{aligned}
$$

- $n_i + m_i = i$

More on model building

Higgs Decay ($h \to b\bar{b}$)

- SM low mass range (90–125 GeV) dominated by $h \to b\bar{b}$
  - Branching ratio almost 100%
  - Difficult to distinguish from QCD background
- In 12 of the 24 models (with $S^\dagger S$ in the Lagrangian)

$$h_d^{33}(\alpha \cos\theta - 2\sin\theta)\epsilon^2\alpha/\sqrt{2}$$

  - If $\theta \sim 0°$; Higgs decays almost indistinguishable from SM
  - If $\theta \sim 26°$, $\alpha \sim 1$; coupling is reduced
    - $h \to \gamma\gamma$ signal enhanced ~ 10 times

More on model building

Higgs Decay ($h \to b\bar{b}$)

- SM low mass range (90–125 GeV) dominated by $h \to b\bar{b}$
  - Branching ratio almost 100%
  - Difficult to distinguish from QCD background
- In the other 12 models (with $H^\dagger H$ in the Lagrangian)

$$3h_d^{33}\epsilon^2\cos\theta$$

  - $h \to \gamma\gamma$ signal mostly unchanged.
  - $h \to b\bar{b}$ signal enhanced by $9\cos^2\theta$
    - Relative signal of $\gamma\gamma$ mode is reduced by a factor of 9

More on model building

Flavor Changing Neutral Currents

- $t \to cH$ is controlled by $S^\dagger S$ or $H^\dagger H$

$$S^\dagger S : h_u^{23}\sqrt{2}\alpha\epsilon^2 \sin\theta \qquad H^\dagger H : h_u^{23}\sqrt{2}\epsilon^2 \cos\theta$$

- $t \to cS$ is controlled by $S^\dagger S$ or $H^\dagger H$

$$S^\dagger S : h_u^{23}\sqrt{2}\alpha\epsilon^2 \cos\theta \qquad H^\dagger H : h_u^{23}\sqrt{2}\epsilon^2 \sin\theta$$

- In all models, the coupling is proportional to $\epsilon^2\sqrt{2}$
  - The BR is enhanced $\sim 8 \times 10^{-4}$
  - SM BR$\sim 10^{-14}$

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