A Light Scalar as the Messenger of Electroweak and Flavor Symmetry Breaking

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Outline

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Introduction

- What are some new physics possibilities at the TeV scale?
  - SUSY: new superpartners and Higgs at the TeV scale
  - Extra Dimensions: new KK Excitations at the TeV Scale
  - Extra U(1): new Z′ at the TeV Scale
- These are all theory motivated.
- 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 at LHC can explain these?
- In this work, we explore one such possibility

Introduction (SM)

- In the Standard Model: $m_{q_i} = y_{q_i} v/\sqrt{2}$

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

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

- 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 not directly connected to EW symmetry breaking sector
- They may be connected via some messenger fields

Introduction (Model)

- We know FCNC interactions among quarks are highly suppressed:
  - This hints at the existence of some flavor symmetry
- If we let all SM fermions except q_{3L}, u_{3R}, H carry non-zero flavor charges
  - This prevents dimension 4 Yukawa couplings for the light quarks with H
- What sort of additional fields do we need to achieve this scenario?
  - Vector-like quarks and leptons at the TeV scale, and new flavor symmetries, $U(1)_F$
- What are the possible choices for messenger fields?
  - A SM singlet complex Higgs field, S with an extra $U(1)_S$ symmetry
- New Physics -> Q, S, Z'

Model and Formalism

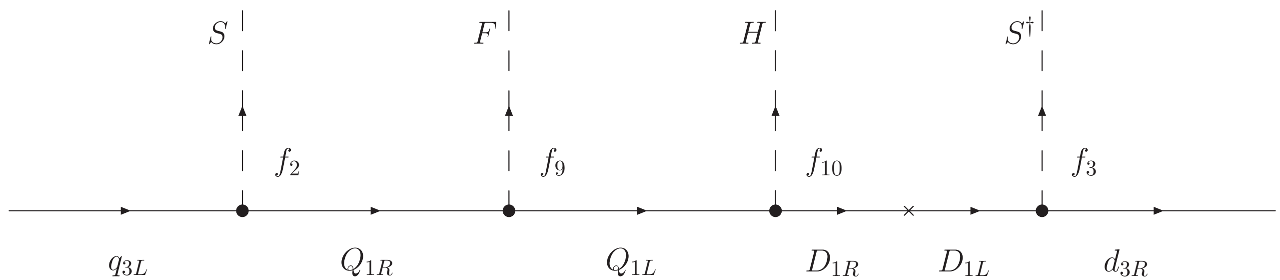
- Extend SM gauge symmetry by a $U(1)_S$ local symmetry and $U(1)_F$ global symmetry
  - All SM fermions are neutral with respect to $U(1)_S$
  - All SM fermions, except q_{3L} and u_{3R}, are charged with respect to $U(1)_F$
- Flavor charges of SM fermions are such that only the top quark has dimension 4 Yukawa interactions
- 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
- There are additional vector-like fermions at the TeV scale, charged under $U(1)_S$ and $U(1)_F$

After integrating out heavy vector-like fermions, the Yukawa interactions of the light fermions, appear as higher dimension operators

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

Model Lagrangian

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

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

Fit to Fermion Masses & CKM mixings

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

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

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

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

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

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

Fit to Fermion Masses & CKM mixings

To leading order in ε:

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

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

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

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

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

$$|V_{ub}| \cong \left| \frac{h_{13}^d}{h_{33}^d} - \frac{h_{12}^u h_{23}^d}{h_{22}^u h_{33}^d} - \frac{h_{13}^u}{h_{23}^d} \right| \varepsilon^2$$

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

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

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

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

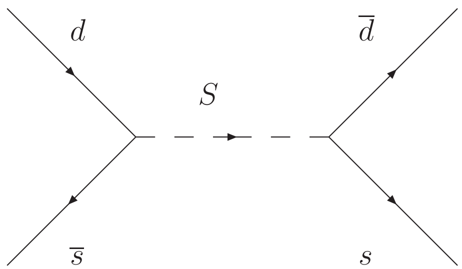
$$|V_{us}| \sim 0.2,$$

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

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

FCNC: K-Kbar and D-Dbar mixing

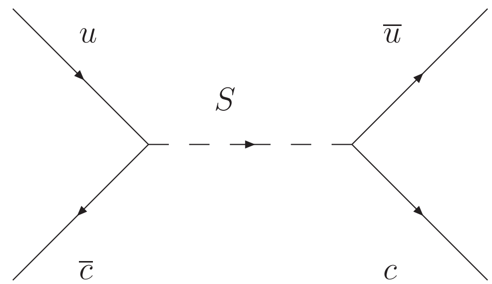
$$K^0 - \overline{K}^0$$



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

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

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



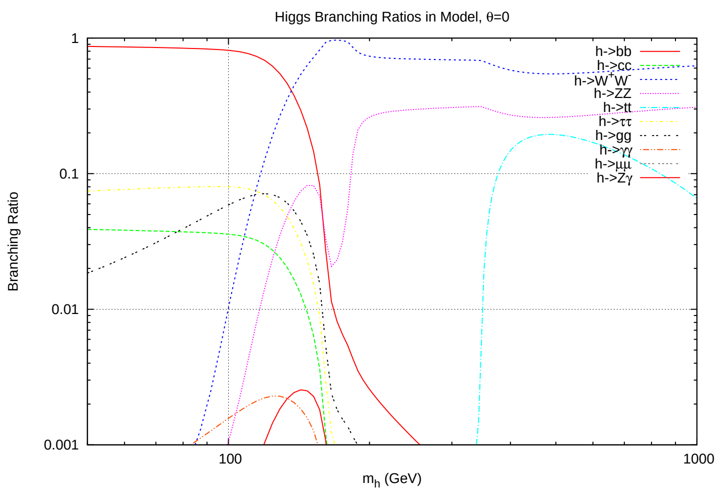
$$\sim h^u_{12} h^u_{21} \beta^2 \epsilon^{6} \sim \epsilon^{8}$$

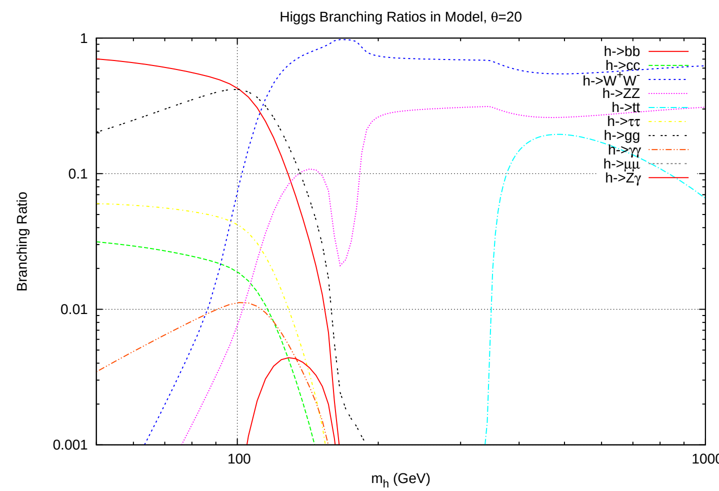
- $\Delta m_D \sim 10^{-14}$ GeV for $m_S \sim 100$ GeV
- $\Delta m_{D(expt)} = 1.6*10^{-14}$ GeV
- β cannot be much larger than ε
- So S cannot be much smaller than 100 GeV

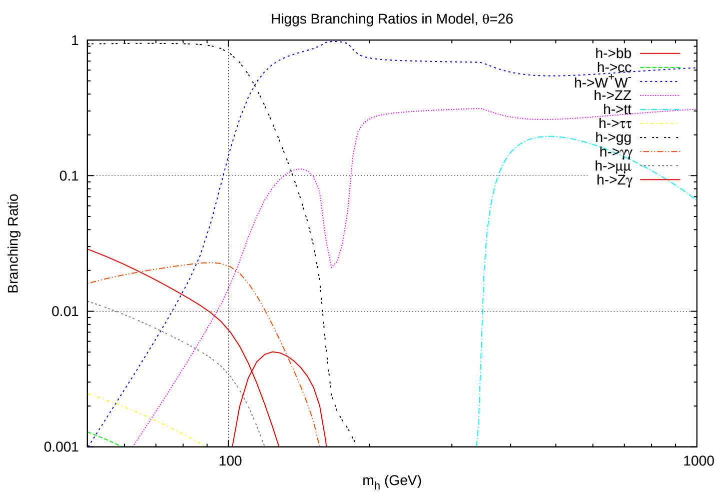
New Physics Signals at the LHC

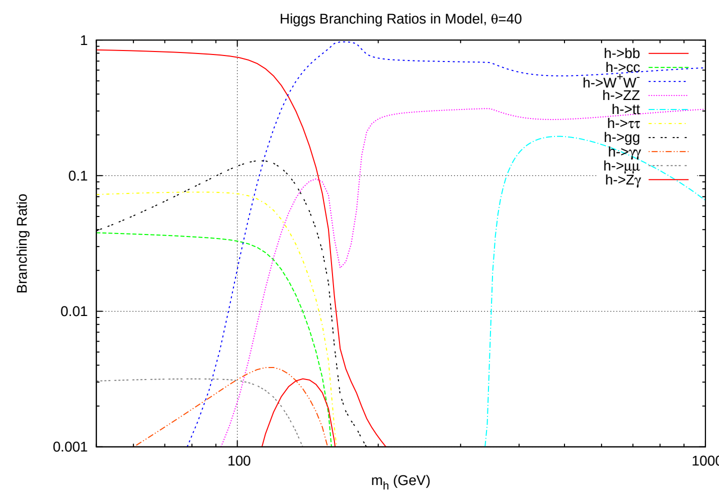
- New particles in the Model:
  - A scalar Higgs, s, m_S>100 GeV
  - An extra gauge boson, Z′, can be very light
  - Heavy vector-like quarks and leptons at the TeV scale
- Without mixing, coupling of h^0 to SM fermions are identical to that in SM
- Higgs Decays:
  - Because of the flavor dependence of the s^0 Yukawa couplings and mixing in the mass eigenstates, BR for h^0 to various final states is altered substantially.
  - BR figures for θ=0°, 20°, 26°, 40°
  - For θ=0°, BR's are the same as in the SM
  - For all plots, m_S=100 GeV and v_s/v=1

h→2x for θ=0°, 20°, 26°, 40°









WW and $\gamma\gamma$ modes

- $h \rightarrow \gamma\gamma$
- For θ=20° and 26°, gg, $\gamma\gamma$ BR's enhanced substantially compared to SM
- 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

- $h \rightarrow WW$
- In SM, $h \rightarrow bb$ and $h \rightarrow WW^*$ crossover occurs at m_h~135 GeV
- In our model for θ=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

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
- Yukawa couplings are all O(1)
- 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

Backup Slides

Yukawa Interaction and FCNC

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

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

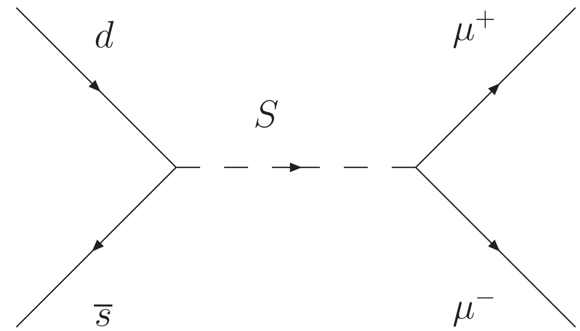
$$\text{note}: \; Y_U^H \propto M_U, \; Y_D^H \propto M_D \Rightarrow \text{No FCNC mediated by } \mathrm{h}^0$$

Yukawa Interactions and FCNC

- Coupling of s^0 to fermions $\Rightarrow$ flavor dependent
- No coupling of s^0 to top; dominant coupling to bottom -> interesting phenomenological implications at the LHC
- For s^0 the Yukawa interaction matrix Y is not proportional to M ->FCNC in s^0 interactions

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:

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

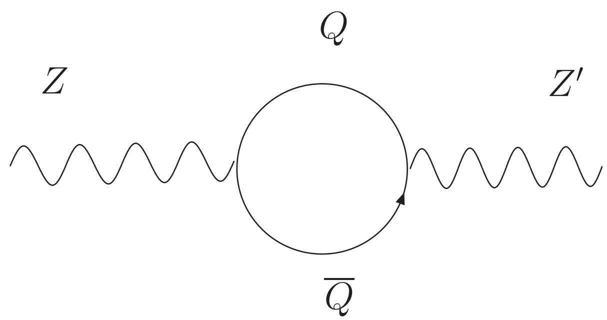
- All orders of magnitude below experimental limits

Constraint on the mass of 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 → $\theta_{Z-Z'} < 10^{-3}$ or smaller for $m_{Z'} < 1$TeV

In our model:



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

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

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]

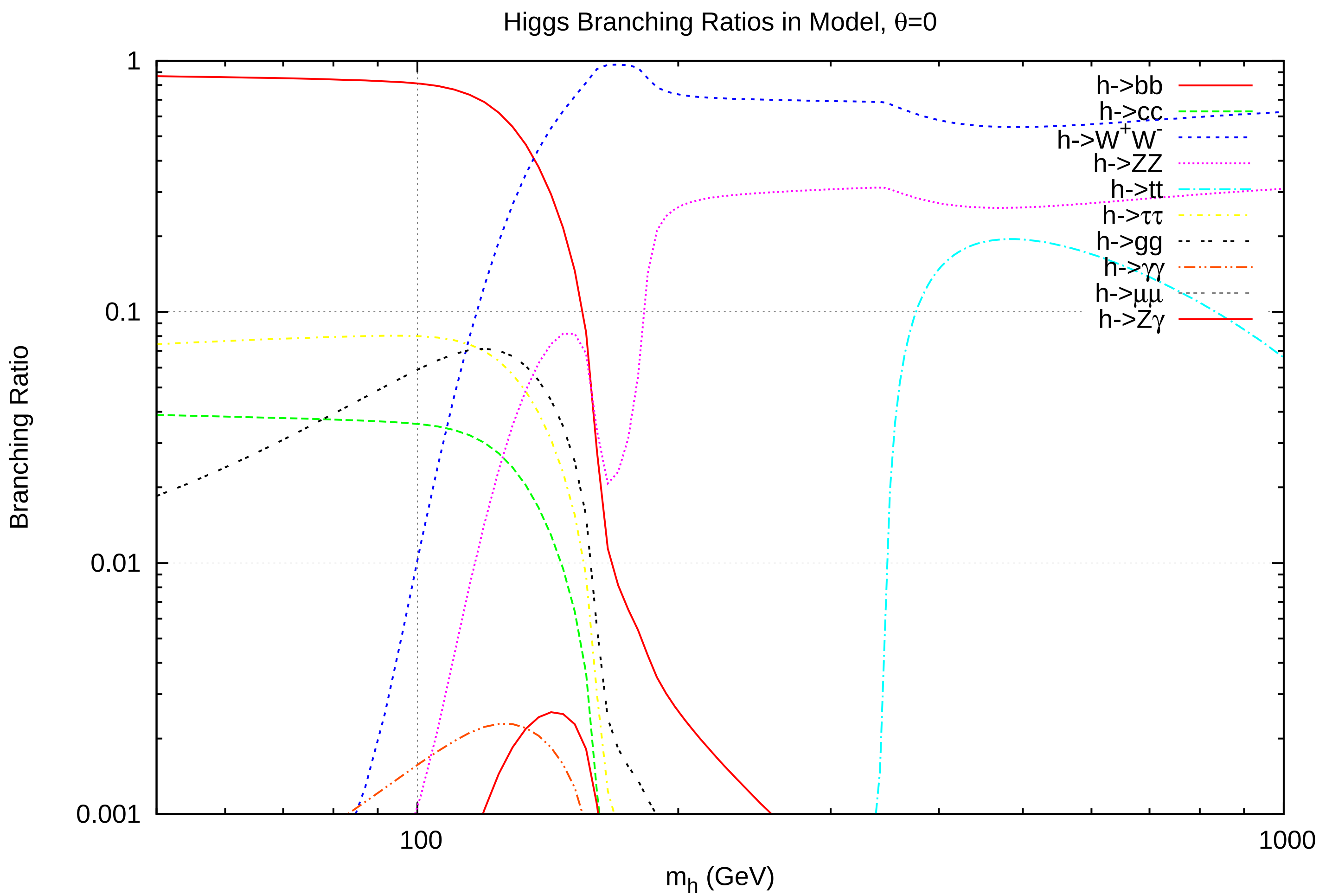
Thus, <u>no</u> significant bound on Z' mass from LEP

[1]Dobrescu, **Phys.Rev.Lett.94:151802,2005**

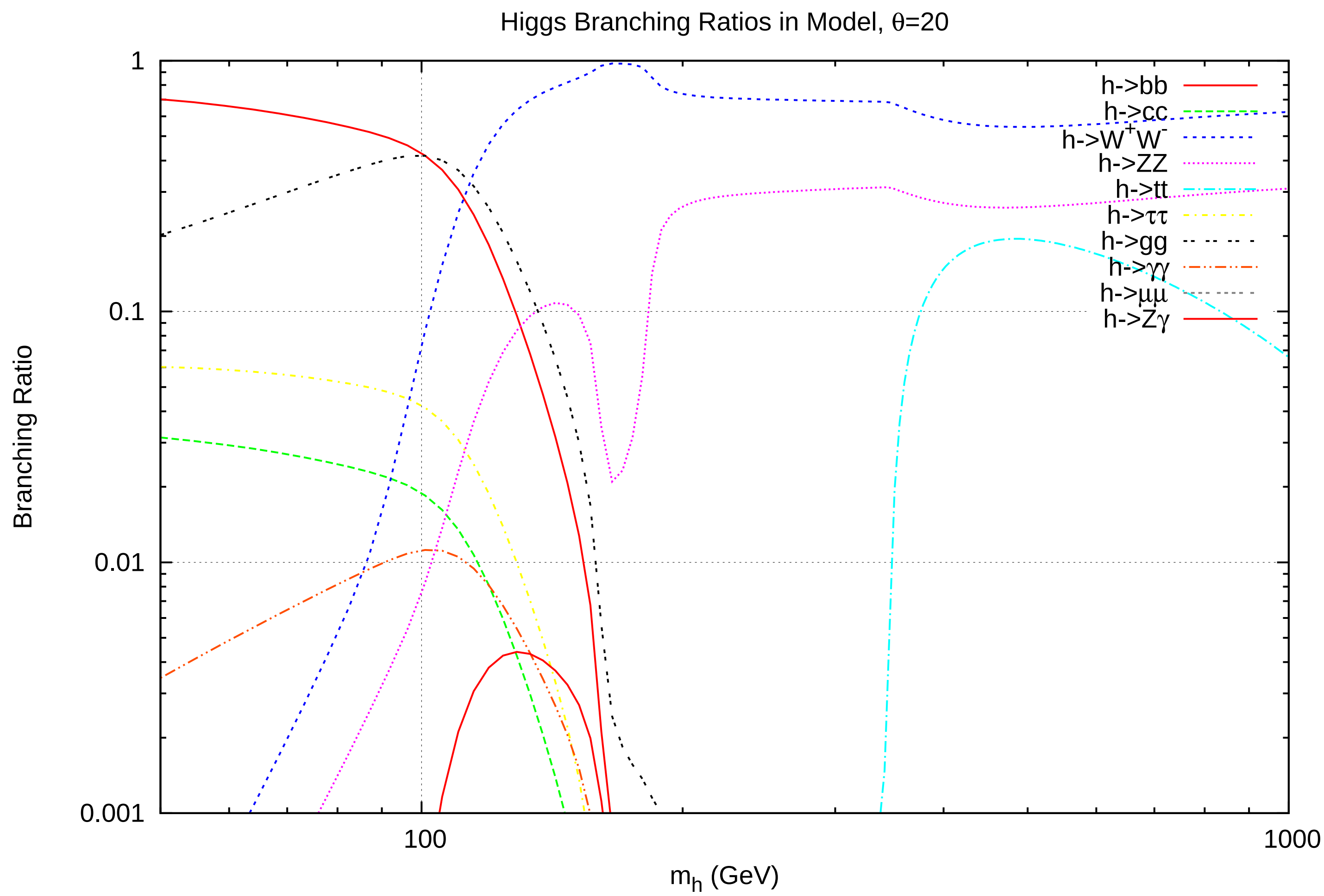
Yukawa and Gauge Couplings (with mixing)

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}

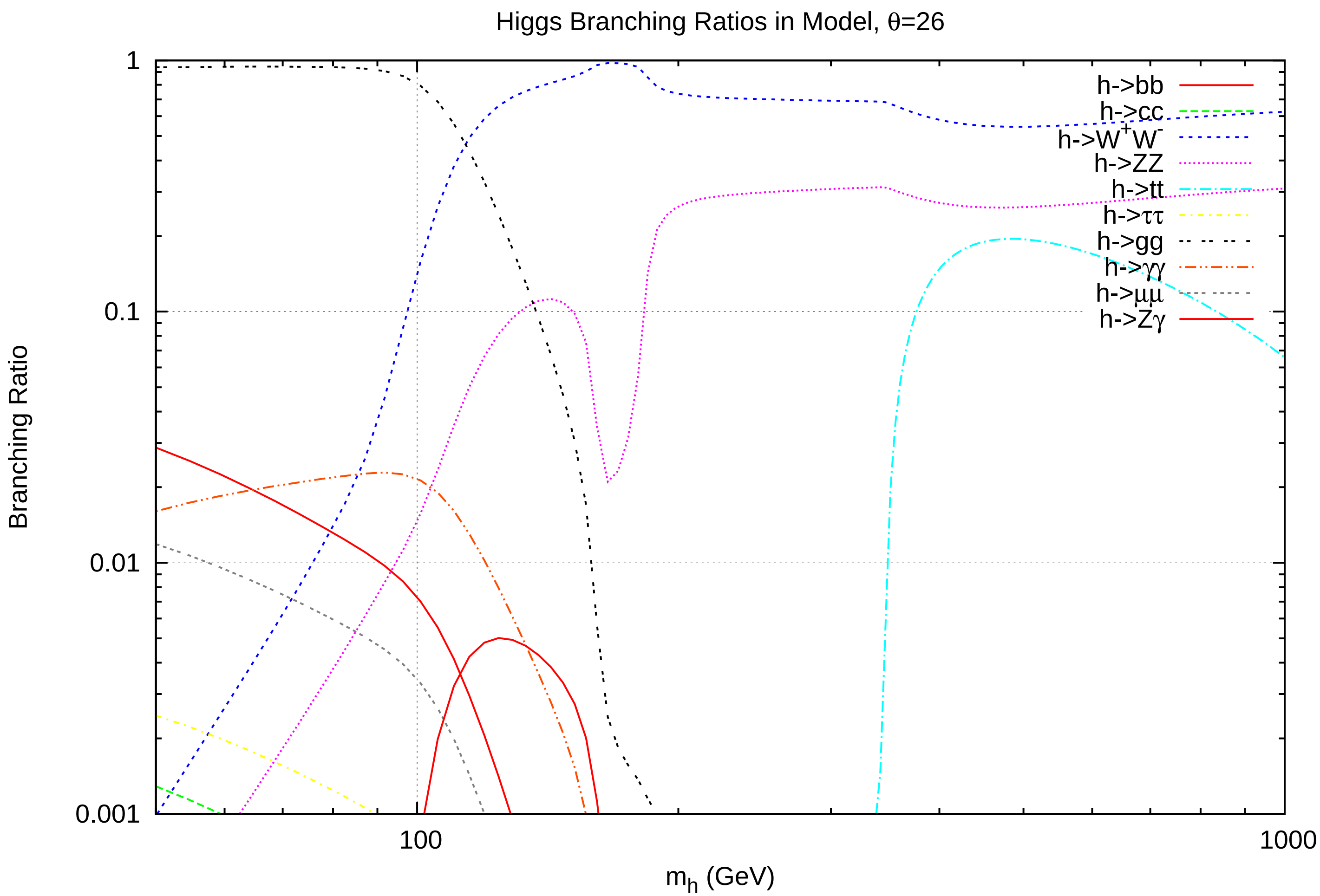
h→2x for θ=0°


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

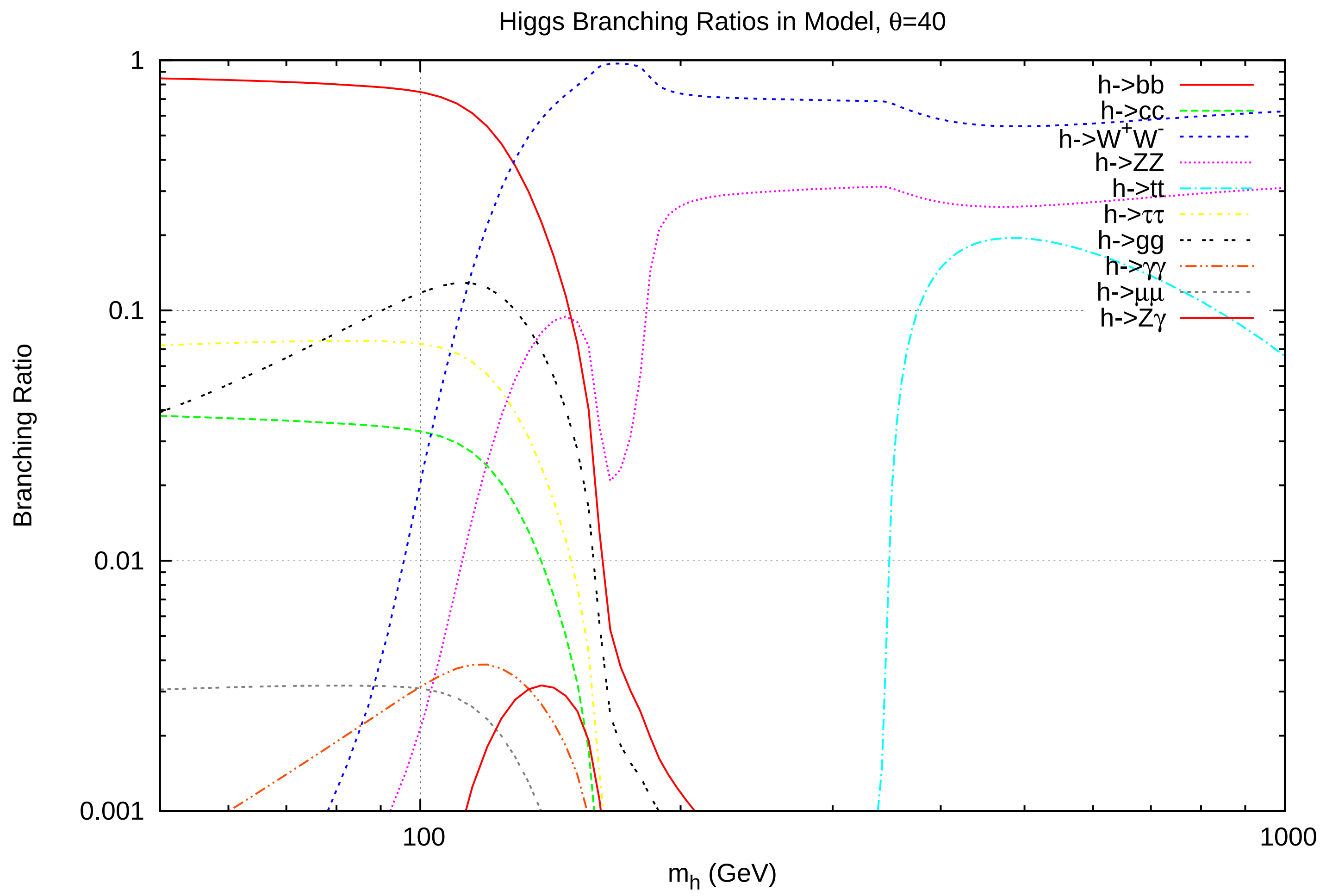
h→2x for θ=20°


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°

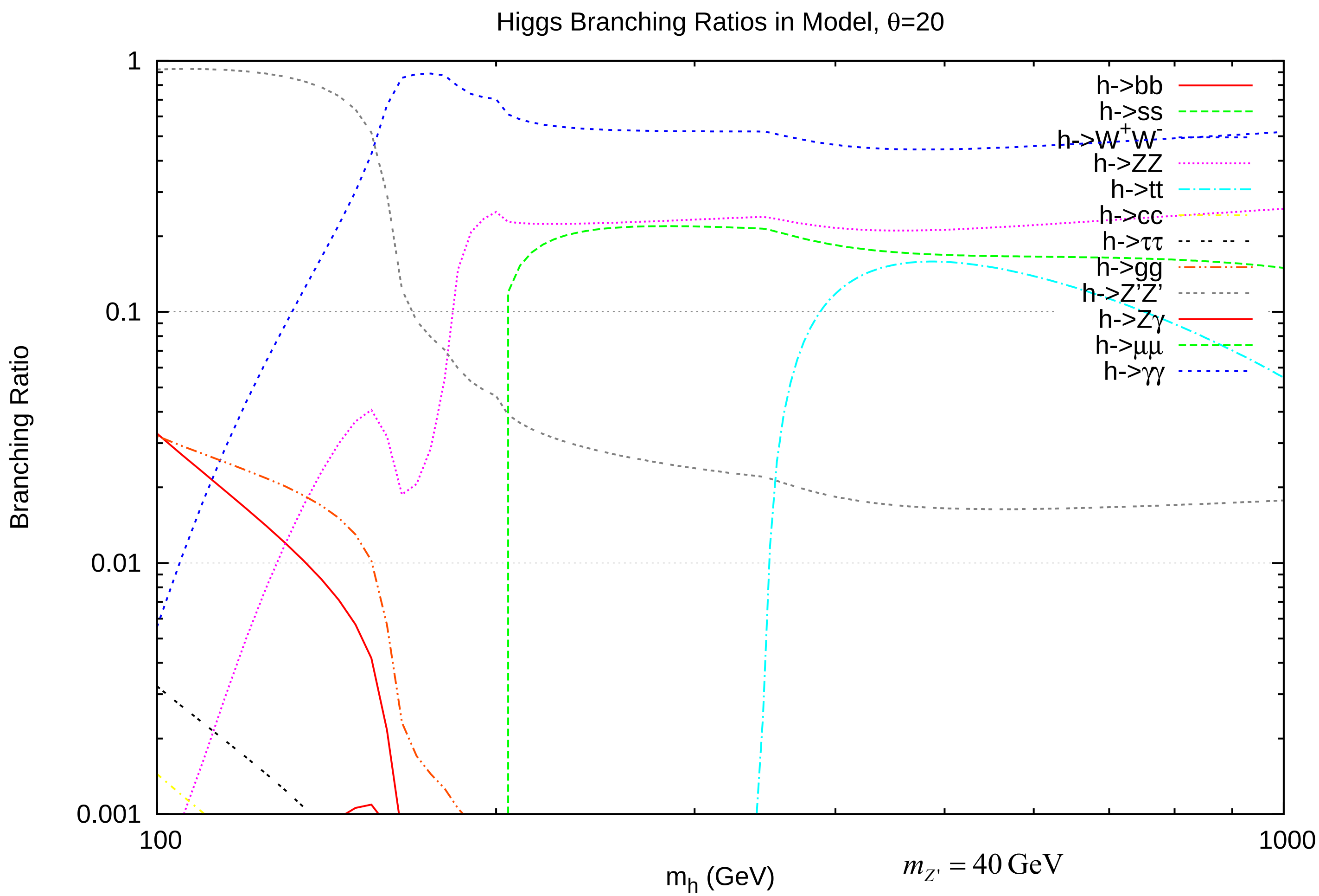

Higgs Branching Ratios in Model, θ=26
Branching Ratio
1
0.1
0.01
0.001
100
1000
m_h (GeV)
h->bb
h->cc
h->W+W-
h->ZZ
h->tt
h->ττ
h->gg
h->γγ
h->μμ
h->Zγ

h→2x for θ=40°



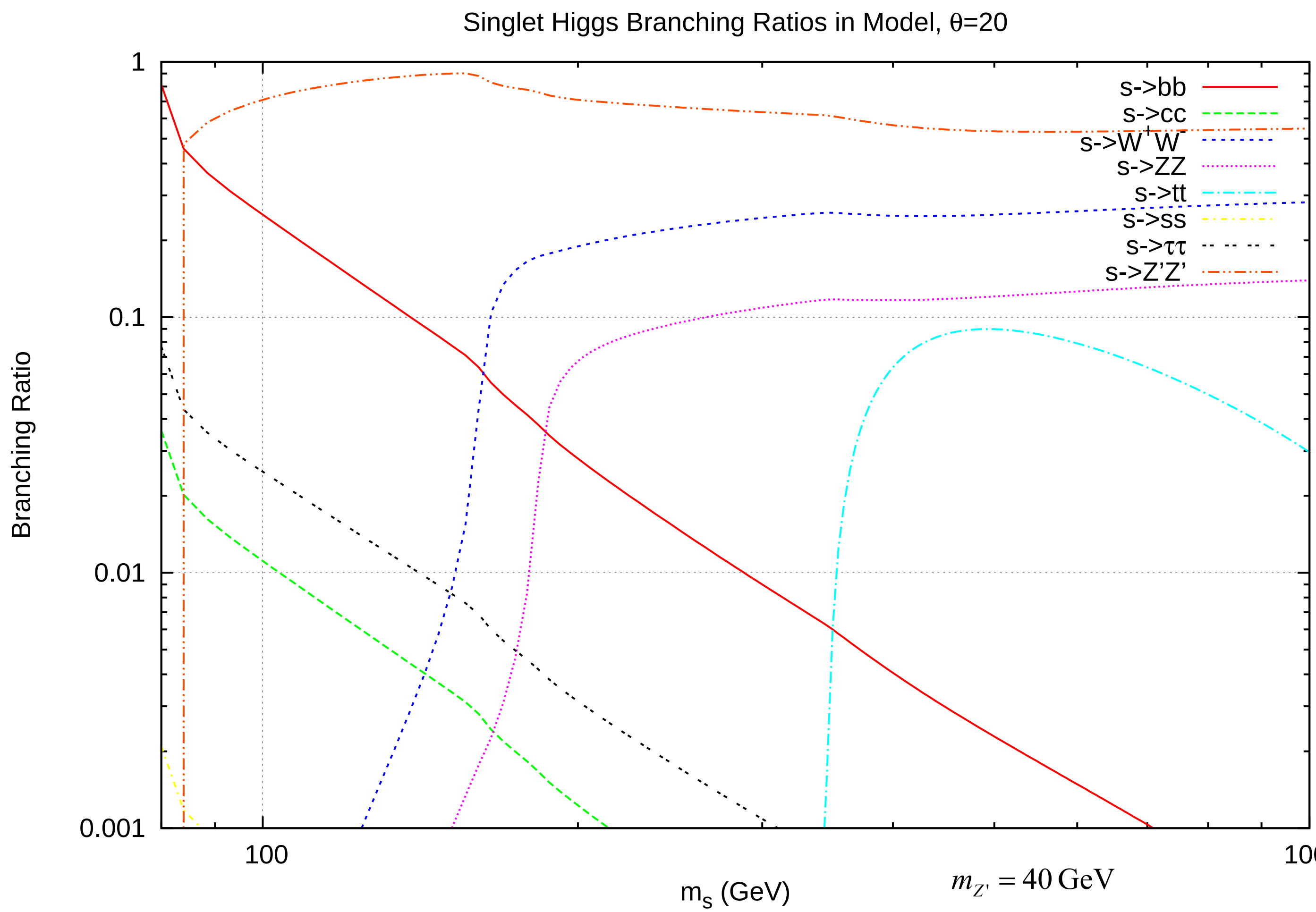
Higgs Branching Ratios in Model, θ=40
Branching Ratio
1
0.1
0.01
0.001
100
1000
m_h (GeV)
h->bb
h->cc
h->W+W-
h->ZZ
h->tt
h->ττ
h->gg
h->γγ
h->μμ
h->Zγ

h→2x including h→ss and z'z'



$m_{Z'} = 40\,\mathrm{GeV}$

s→2x



$m_{Z'} = 40\,\mathrm{GeV}$

UV Completion (2 Generation)

- Symmetries: SM + $U(1)_S + U(1)_F$
  - $U(1)_S$ broken at EW scale, $\langle S \rangle$
  - $U(1)_F$ broken at TeV scale, $\langle F \rangle$
  - 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:

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

- 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:

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