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# THE NEXT HIGGS BOSON(S)

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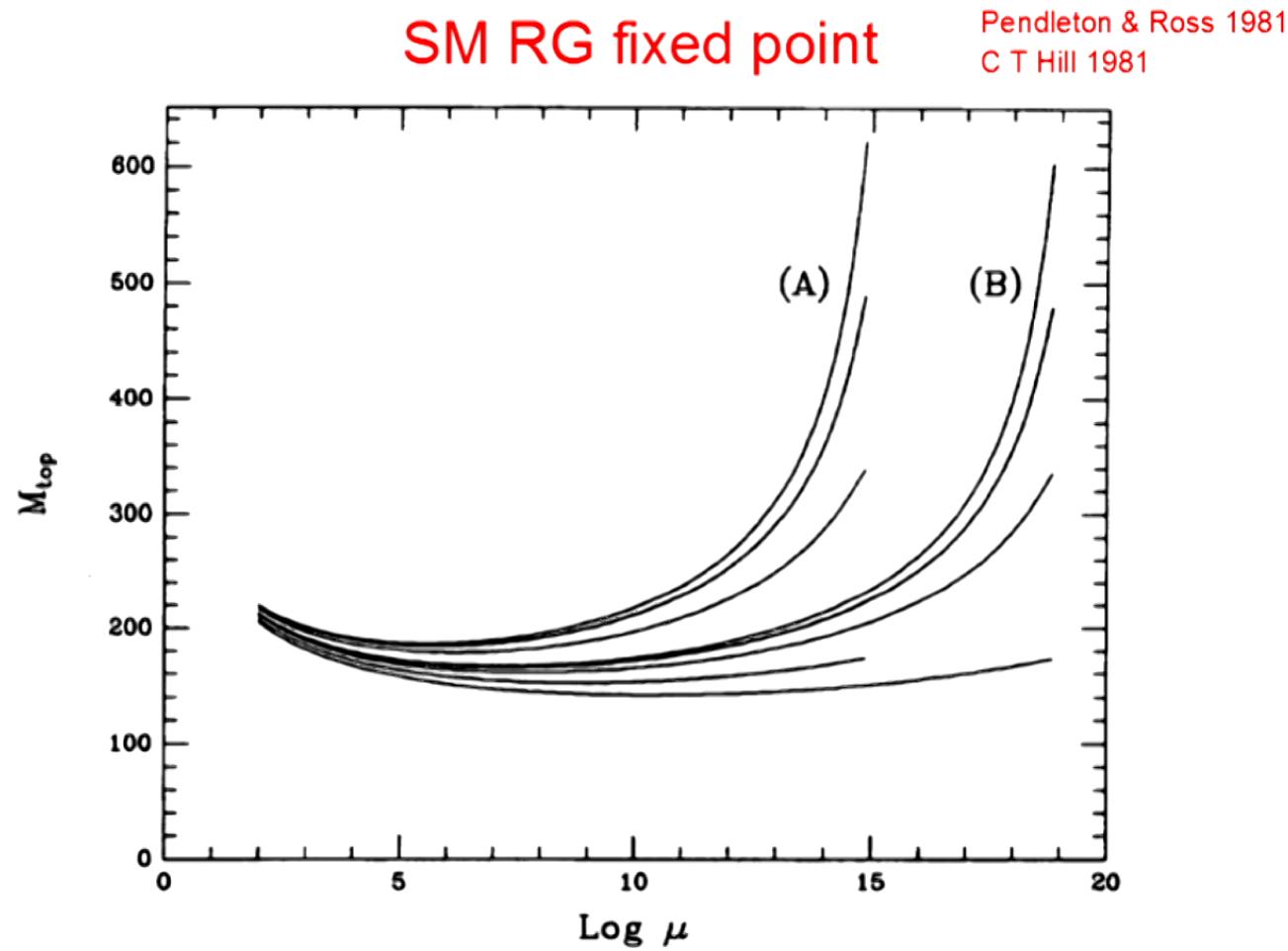
"Simplicity III"  
Perimeter Institute, September, 2019

# Standard View of Standard Model



# Present Talk

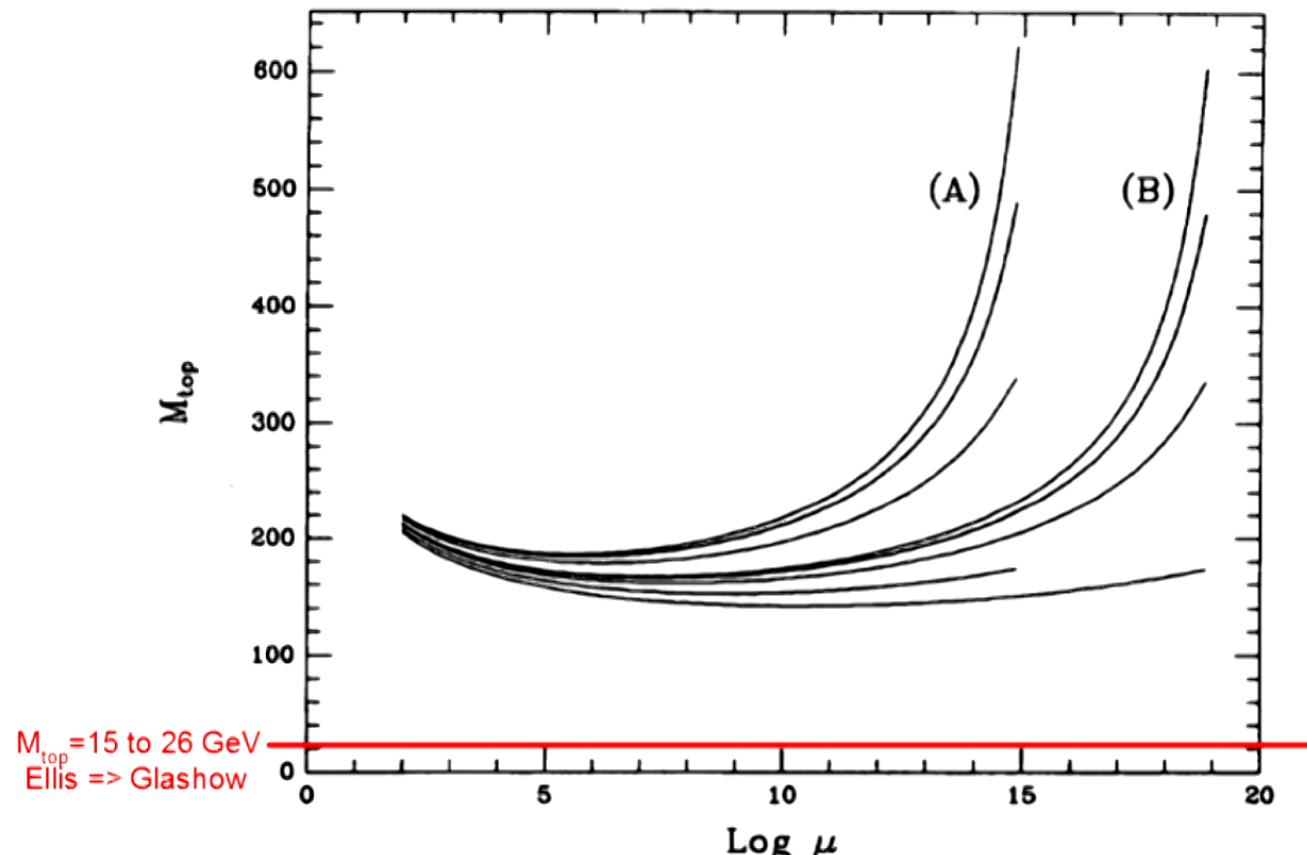




$$16\pi^2 \frac{\partial}{\partial \ln(\mu)} g_{top} = g_{top} \left( \left( N_c + \frac{3}{2} \right) g_{top}^2 - (N_c^2 - 1) g_3^2 - \frac{9}{4} g_2^2 - \frac{17}{12} g_1^2 \right)$$

## SM RG fixed point

Pendleton & Ross 1981  
C T Hill 1981



$$16\pi^2 \frac{\partial}{\partial \ln(\mu)} g_{top} = g_{top} \left( \left( N_c + \frac{3}{2} \right) g_{top}^2 - (N_c^2 - 1) g_3^2 - \frac{9}{4} g_2^2 - \frac{17}{12} g_1^2 \right)$$

## RG fixed point

$$16\pi^2 \frac{\hat{c}}{\hat{c} \ln(\mu)} g_{top} = g_{top} \left( \left( N_c + \frac{3}{2} \right) g_{top}^2 - (N_c^2 - 1) g_3^2 - \frac{9}{4} g_2^2 - \frac{17}{12} g_1^2 \right)$$

$\Lambda(\text{GeV})$	$10^{19}$	$10^{15}$	$10^{11}$	$10^7$	$10^5$
$m_{top}(\text{GeV})$	220	230	250	290	360

Compositeness  $\longleftrightarrow$  RG fixed point

(Top Condensation: Nambu; Bardeen, Hill, Lindner 1990)

$$16\pi^2 \frac{\partial}{\partial \ln(\mu)} g_{top} = g_{top} \left( \left( N_c + \frac{3}{2} \right) g_{top}^2 - (N_c^2 - 1) g_3^2 - \frac{9}{4} g_2^2 - \frac{17}{12} g_1^2 \right)$$

$\Lambda(\text{GeV})$	$10^{19}$	$10^{15}$	$10^{11}$	$10^7$	$10^5$
$m_{top}(\text{GeV})$	220	230	250	290	360

Concordance with observed  
 $m_{top} = 173 \text{ GeV?}$

# $SU(6) \times SU(6)$

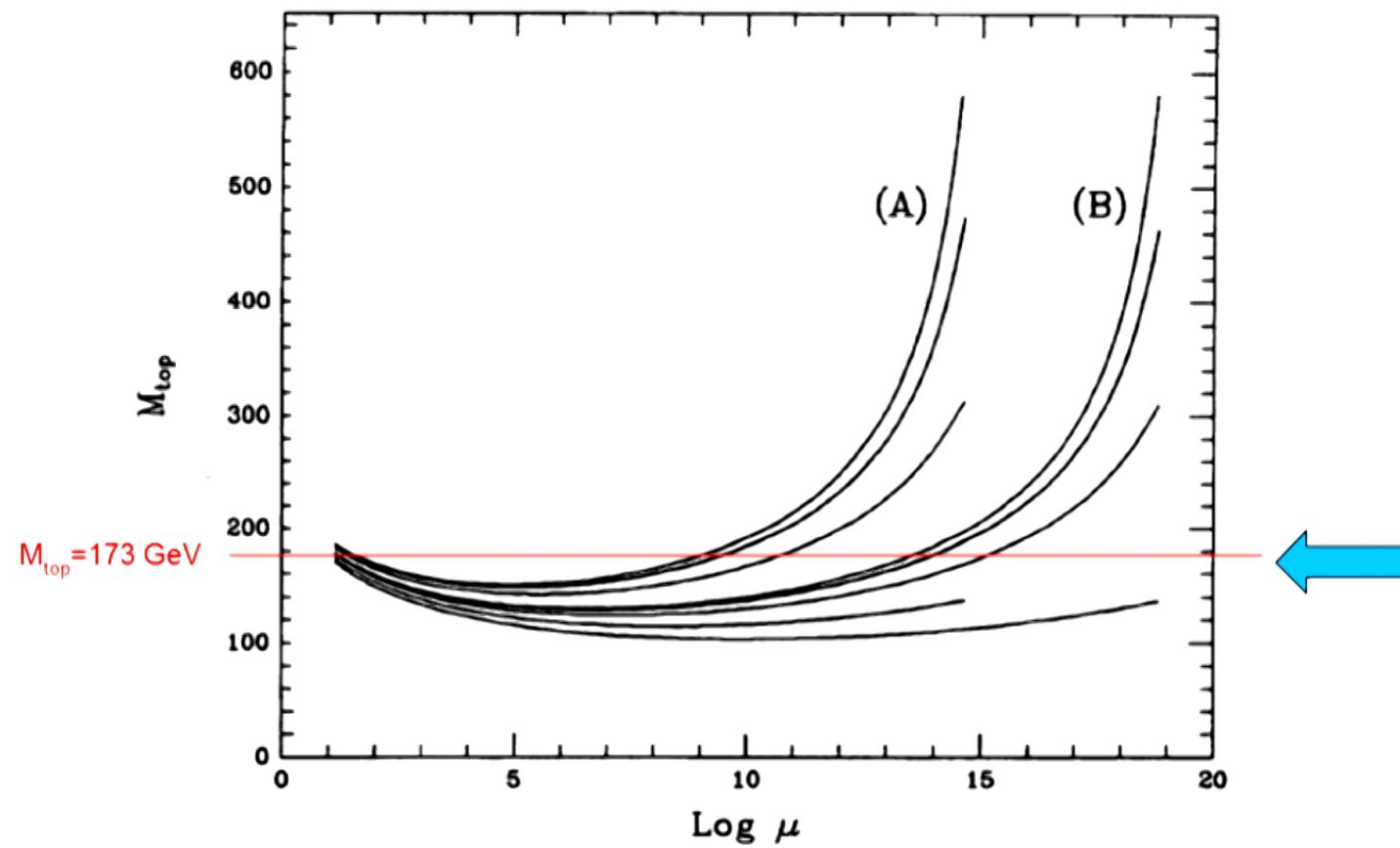
18 heavy doublets in quark sector; universal  $g_{HY}$

$$16\pi^2 \frac{\hat{c}}{\hat{c} \ln(\mu)} g_{top} = g_{top} \left( (N_c + 6)g_{top}^2 - (N_c^2 - 1)g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2 \right)$$



## SU(6)xSU(6) RG fixed point

(C. T. Hill, A. Thomsen, prelim)



$SU(6) \times SU(6) \rightarrow 18$  Higgs Doublets

$$16\pi^2 \frac{\partial}{\partial \ln(\mu)} g_{top} = g_{top} \left( (N_c + 6)g_{top}^2 - (N_c^2 - 1)g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2 \right)$$

$\rightarrow$  Universal  $g$

$\Lambda$ (GeV)	$10^{19}$	$10^{15}$	$10^{11}$	$10^7$	$10^5$
$m_{top}$ (GeV)	$156 + \Delta$	$162 + \Delta$	$177 + \Delta$	$205 + \Delta$	$254 + \Delta$

$$\Delta \approx 2.8 \ln(\langle M_H \rangle / 10^2) \text{ GeV} \quad \Delta \approx 2.8 \ln(10^5 / 10^2) \approx 19.342 \text{ GeV}$$

$M_{top} \rightarrow 173$  GeV with  $\langle M_H \rangle$  of order 100 TeV

## Simple counting exercise:

→ SM has 48 Left-handed Weyl fermions

invariants  $\psi_\alpha^i \psi_\beta^j \epsilon^{\alpha\beta} = \psi_\alpha^i \psi^{j\beta}$  symmetric in  $(ij)$

current  $\bar{\psi}_\alpha^k \sigma_\mu^{\dot{\alpha}\beta} \psi_\beta^k$ .

Kinetic term invariant under  $SU(48) \times U(1)$

$$\sum_k i \bar{\psi}_\alpha^k \partial^\mu \sigma_\mu^{\dot{\alpha}\beta} \psi_\beta^k$$

Simple counting exercise:

Introduce scalar couplings:

$$g\Theta_{ij}\psi_\alpha^i\psi_\beta^j\epsilon^{\alpha\beta} + h.c.$$

$\Theta_{ij}$  is the symmetric bilinear representation of  $SU(48)$

$$\frac{1}{2}N(N+1) = \frac{1}{2}48(48+1) = 1176 \text{ cdofs}$$

## Usual Standard Model Notation

$\psi_L^j = 24$  left-handed quarks and leptons  $\subset SU(24)_L$

$\psi_R^j = 24$  right-handed quarks and leptons  $\subset SU(24)_R$

$$g \left( \Phi_{ij} \bar{\psi}_L^i \psi_R^j + \Omega_{ij} \bar{\psi}_L^{Ci} \psi_L^j + \Omega'_{ij} \bar{\psi}_R^{Ci} \psi_R^j + h.c. \right)$$

$\Phi_{ij}$  is the  $(24_L \times 24_R)$  complex scalar field  $24^2 = 576$  cdfs.

$\Omega_{ij}$  and  $\Omega'_{ij}$  are distinct symmetric representations

of  $SU(24)_L$  and  $SU(24)_R$   $\frac{1}{2}N(N+1) = \frac{1}{2}24(24+1) = 300$  cdfs

$$\Phi_{ij}(576) + \Omega_{ij}(300) + \Omega'_{ij}(300) = \Theta_{ij}(1176)$$

$\psi_L^j = 24$  left-handed quarks and leptons  $\subset SU(24)_L$  $\psi_R^j = 24$  right-handed quarks and leptons  $\subset SU(24)_R$ 

$$g \left( \Phi_{ij} \bar{\Psi}_L^i \Psi_R^j + \Omega_{ij} \bar{\Psi}_L^{\text{Ci}} \Psi_L^j + \Omega'_{ij} \bar{\Psi}_R^{\text{Ci}} \Psi_R^j + h.c. \right)$$



Contains Chiral Lagrangian  $SU(24) \times SU(24)$

This contains Higgs scalar isodoublets

$\psi_L^j = 24$  left-handed quarks and leptons  $\subset SU(24)_L$  $\psi_R^j = 24$  right-handed quarks and leptons  $\subset SU(24)_R$ 

$$g \left( \Phi_{ij} \bar{\Psi}_L^i \Psi_R^j + \Omega_{ij} \bar{\Psi}_L^{\text{Ci}} \Psi_L^j + \Omega'_{ij} \bar{\Psi}_R^{\text{Ci}} \Psi_R^j + h.c. \right)$$



Contains Chiral Lagrangian  $SU(24) \times SU(24)$

This contains Higgs scalar isodoublets

**Universal Higgs-Yukawa coupling**

$\psi_L^j = 24$  left-handed quarks and leptons  $\subset SU(24)_L$  $\psi_R^j = 24$  right-handed quarks and leptons  $\subset SU(24)_R$ 

$$g \left( \Phi_{ij} \bar{\Psi}_L^i \Psi_R^j + \Omega_{ij} \bar{\Psi}_L^{\text{Ci}} \Psi_L^j + \Omega'_{ij} \bar{\Psi}_R^{\text{Ci}} \Psi_R^j + h.c. \right)$$



Contains Sterile neutrinos: Seesaw mechanism

## SM decomposition of the 576 $\Phi_{ij}$ (color, isospin, Y) “Scalar Democracy” Hill,Machado,Thomsen,Turner

- $9 \times (\mathbf{1}, \mathbf{2}, \frac{1}{2}) \sim \overline{Q}_L U_R$ ;  $3^2 \times 1 \times 2 = 18$  complex degrees of freedom (DoFs),
- $9 \times (\mathbf{1}, \mathbf{2}, -\frac{1}{2}) \sim \overline{Q}_L D_R$ ;  $3^2 \times 1 \times 2 = 18$  complex DoFs,
- $9 \times (\mathbf{1}, \mathbf{2}, \frac{1}{2}) \sim \overline{L}_L N_R$  leptonic;  $3^2 \times 1 \times 2 = 18$  complex DoFs,
- $9 \times (\mathbf{1}, \mathbf{2}, -\frac{1}{2}) \sim \overline{L}_L E_R$  leptonic;  $3^2 \times 1 \times 2 = 18$  complex DoFs,
- $9 \times (\mathbf{8}, \mathbf{2}, \pm \frac{1}{2}) \sim \overline{Q}_L \lambda^a U_R [D_R]$ ;  $3^2 \times 8 \times 2 \times 2 = 288$  complex DoFs,
- $9 \times (\mathbf{3}, \mathbf{2}, \frac{1}{6}[-\frac{5}{6}]) \sim \overline{L}_L U_R [D_R]$ ;  $3^2 \times 3 \times 2 \times 2 = 108$  complex DoFs,
- $9 \times (\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}[-\frac{7}{6}]) \sim \overline{Q}_L N_R [E_R]$ ;  $3^2 \times 3 \times 2 \times 2 = 108$  complex DoFs,

We may have already seen  
one of these scalars:

The Higgs boson

The SM Higgs couples to 72  
of the 1176 bilinears.  
Mostly to  $t\bar{t}$

# The Higgs structure of quarks is an SU(6)xSU(6) Sigma Model

$$g \begin{pmatrix} t \\ b \\ c \\ s \\ u \\ d \end{pmatrix}_L \left( \Sigma \right) \begin{pmatrix} t \\ b \\ c \\ s \\ u \\ d \end{pmatrix}_R$$

$$T = \begin{pmatrix} t \\ b \end{pmatrix} \quad C = \begin{pmatrix} c \\ s \end{pmatrix} \quad U = \begin{pmatrix} u \\ d \end{pmatrix} \quad g \begin{pmatrix} T \\ C \\ U \end{pmatrix}_L \begin{pmatrix} \Sigma_t & \Sigma_{tc} & \Sigma_{tu} \\ \Sigma_{ct} & \Sigma_c & \Sigma_{cu} \\ \Sigma_{ut} & \Sigma_{uc} & \Sigma_u \end{pmatrix} \begin{pmatrix} T \\ C \\ U \end{pmatrix}_R$$

Similar for the leptons

$$\left( \bar{P} \right)_L \left( \sum_i \right) \left( \begin{matrix} P \\ n \end{matrix} \right)_R$$
$$\left( \bar{\psi} \right)_L \left( \sum_i \right) \left( \begin{matrix} t \\ b \end{matrix} \right)_R$$

$\varepsilon > \frac{m}{n}$

$$\Sigma = \left( t_{D_1}^1, \varepsilon t_{D_1}^1 \right)$$

$$t_{D_1} = \varepsilon t_{D_1} \times \hat{N}$$
$$t_{D_1} > \varepsilon t_{D_1} \hat{N}$$

# Scalar Democracy

Hill Machado Thomsen Turner  
(Private Higgs) Porto Zee

$$g \begin{pmatrix} t \\ b \\ c \\ s \\ u \\ d \end{pmatrix}_L \sum \begin{pmatrix} t \\ b \\ c \\ s \\ u \\ d \end{pmatrix}_R$$

$$T = \begin{pmatrix} t \\ b \end{pmatrix} \quad C = \begin{pmatrix} c \\ s \end{pmatrix} \quad U = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\mathbf{g} \begin{pmatrix} T \\ C \\ U \end{pmatrix}_L \begin{pmatrix} \Sigma_t & \Sigma_{tc} & \Sigma_{tu} \\ \Sigma_{ct} & \Sigma_c & \Sigma_{cu} \\ \Sigma_{ut} & \Sigma_{uc} & \Sigma_u \end{pmatrix} \begin{pmatrix} T \\ C \\ U \end{pmatrix}_R$$



Universal Higgs-Yukawa Coupling

Technical naturalness protects small HY couplings  
eg,  $y_b = 0.024$ ,  $y_e = 2.9 \times 10^{-6}$

Cannot be perturbatively generated because of  
technical naturalness

Small  $y$ 's must be power law suppressed,  
originating from something large, ie  $O(1)$ :

$$y_b \sim g_b (\mu^2 / M_b^2) \quad g_b = O(1)$$

Many Higgses can explain origin  
of small HY couplings

A full theory of Scalar Democracy  
requires understanding Higgs masses/mixings:

Introduce  $d=2$  soft symmetry breaking  
of  $SU(48)$ ,  $SU(24) \times SU(24)$

Symmetry Breaking terms are technically natural

Requires fine tuning only of singlet mass term:  $M^2 \text{Tr} \theta \theta^*$   
=> Analogue of SM Higgs mass.

No less technically natural than the  
standard model

CKM mixing and hierarchies?

# A No CKM mixing:

“Scalar Democracy” Hill, Machado, Thomsen, Turner

Higgs field	Fermion mass	Case (1) [TeV]	Case (2) [TeV]
$H'_0 = v + \frac{h}{\sqrt{2}}$	$m_t = gv = 175 \text{ GeV}$	$m_H = 0.125$	$m_H = 0.125$
$H'_b = v \frac{\mu^2}{M_b^2} + H_b$	$m_b = gv \frac{\mu^2}{M_b^2} = 4.5 \text{ GeV}$	$M_b = 3.9$	$M_b = 0.620$
$H'_\tau = v \frac{\mu^2}{M_\tau^2} + H_\tau$	$m_\tau = g_\ell v \frac{\mu^2}{M_\tau^2} = 1.8 \text{ GeV}$	$M_\tau = 6.8$	$M_\tau = 0.825$
$H'_e = v \frac{\mu^2}{M_e^2} + H_e$	$m_e = g_\ell v \frac{\mu^2}{M_e^2} = 1.3 \text{ GeV}$	$M_e = 13.5$	$M_e = 1.2$
$H'_\mu = v \frac{\mu^2}{M_\mu^2} + H_\mu$	$m_\mu = g_\ell v \frac{\mu^2}{M_\mu^2} = 106 \text{ MeV}$	$M_\mu = 1.2 \times 10^2$	$M_\mu = 3.4$
$H'_s = v \frac{\mu^2}{M_s^2} + H_s$	$m_s = gv \frac{\mu^2}{M_s^2} = 95 \text{ MeV}$	$M_s = 1.8 \times 10^2$	$M_s = 4.3$
$H'_d = v \frac{\mu^2}{M_d^2} + H_d$	$m_d = gv \frac{\mu^2}{M_d^2} = 4.8 \text{ MeV}$	$M_d = 3.6 \times 10^3$	$M_d = 19$
$H'_u = v \frac{\mu^2}{M_u^2} + H_u$	$m_u = gv \frac{\mu^2}{M_u^2} = 2.3 \text{ MeV}$	$M_u = 7.6 \times 10^3$	$M_u = 27$
$H'_e = v \frac{\mu^2}{M_e^2} + H_e$	$m_e = g_\ell v \frac{\mu^2}{M_e^2} = 0.5 \text{ MeV}$	$M_e = 2.45 \times 10^4$	$M_e = 49$



Table I. The non-mixing estimates for heavy dormant Higgs bosons masses assuming (1) the level-repulsion feedback on the Higgs mass term is limited to  $(100 \text{ GeV})^2$  for each of the quarks and leptons, hence  $M_q = (100 \text{ GeV})(m_t/m_q)$  and  $M_\ell = (100 \text{ GeV})(g_\ell m_t/m_\ell)$ . (2)  $\mu = 100 \text{ GeV}$  for all mixings, hence  $M_q = \mu(m_t/m_q)^{1/2}$  and  $M_\ell = \mu(m_\ell g_\ell/gm_q)^{1/2}$ . Here  $g = 1$ ,  $g_\ell = 0.7$  and  $v = 175 \text{ GeV}$ . The scalar spectrum relevant to the neutrino mass generation is discussed in more detail in Sec. V A.

# CKM mixing limit:

“Scalar Democracy” HMTT

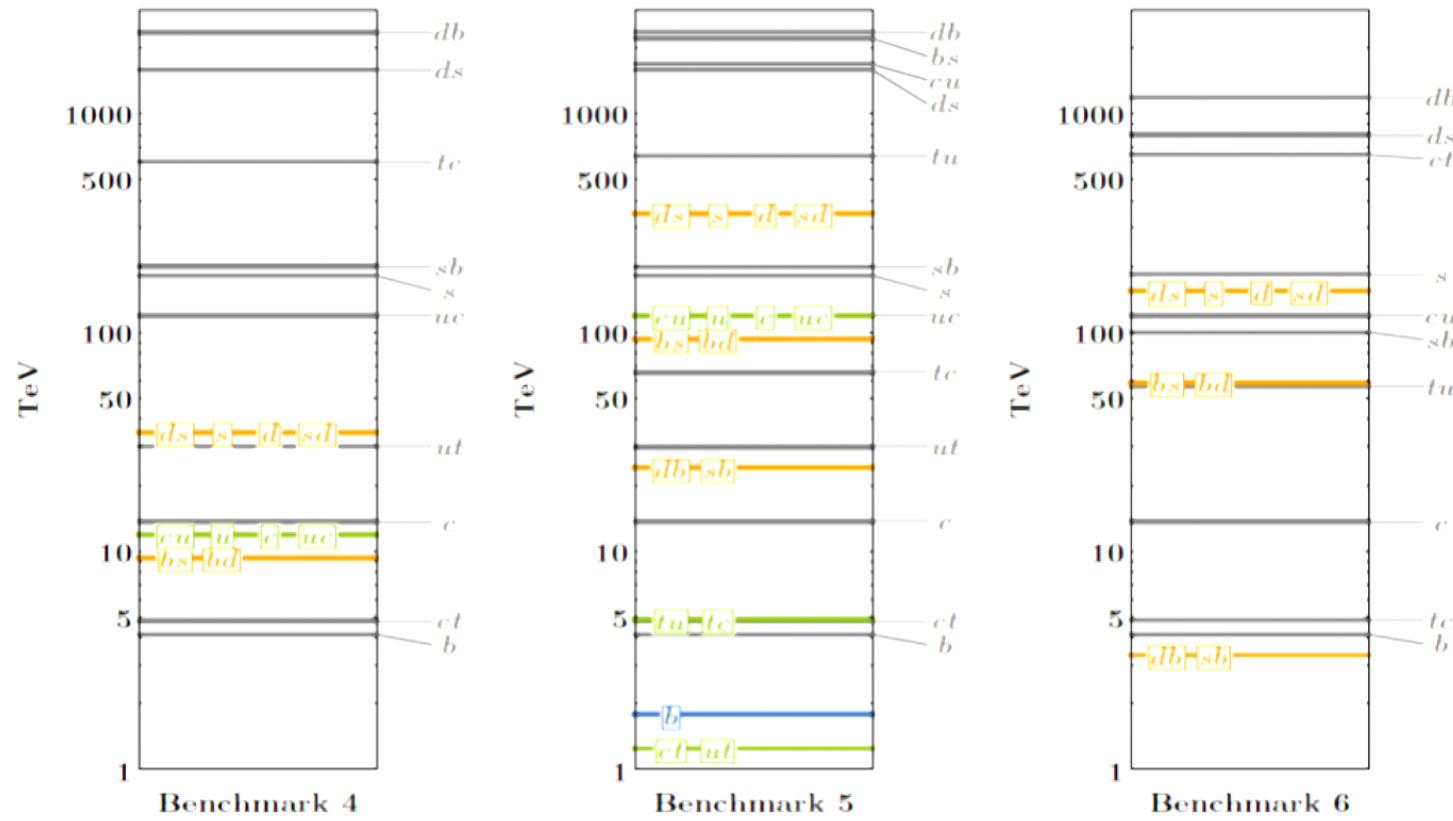


Figure 5. Experimental constraints and mass estimates for the dormant Higgses in the quark sector in six different benchmarks (see text); the labels denote the indices of the corresponding Higgs. The gray lines are the mass estimates. The colored lines correspond to the most stringent experimental lower bound on each of the Higgs masses; if the constraint is from  $D_0$  mixing, from  $K_0$  and blue from  $B_s$ . If a mass-estimate entry is not shown, it is above the scale of the plot. Similarly if a mass bound is not shown it is below the scale of the plot.

What might convince us of  
scalar democracy?

The first new sequential  
Higgs with  $g = 1$  :

$$H_b$$

Focus on the top-bottom subsystem

$$V_{HY} = \bar{g} \overline{\Psi}_L \Sigma \Psi_R + hc \quad \text{where: } \Psi = \begin{pmatrix} t \\ b \end{pmatrix}$$

Standard Model HY couplings form a chiral Lagrangian (top-bottom subsystem):

$$V_{HY} = g \overline{\Psi}_L \Sigma \Psi_R + hc \quad \text{where: } \Psi = \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\Sigma = (H_0, H_b^c) \quad Y = I_{3R} + (B - L)/2$$

where  $H^c = i\sigma_2 H^*$ , and  $H \rightarrow U_L H$ ,  $H^c \rightarrow U_L H^c$

$$V_{HY} = \overline{g \begin{pmatrix} t \\ b \end{pmatrix}_L} H_0 t_R + \overline{g \begin{pmatrix} t \\ b \end{pmatrix}_L} H_b^c b_R$$

## = Minimal Approximate Symmetry extension of the Standard Model

$$G = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \times \mathrm{U}(1)_A$$

By “approximately” we mean that, if we turn off the electroweak gauging  $(g_1, g_2) \rightarrow 0$ , the global symmetry  $G$  is exact in the  $d = 4$  operators (kinetic terms, Higgs-Yukawa couplings, and potential terms). The Standard Model (SM) gauging is the usual,  $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ , and is a subgroup of  $G$ , where the  $\mathrm{U}(1)_Y$  generator is now  $I_{3R} + (B - L)/2$ . This electroweak gauging weakly breaks the symmetry  $\mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \rightarrow \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$ , however, the  $\mathrm{SU}(2)_R$  remains as an approximate global symmetry of the  $d = 4$  operators. In addition, a global  $\mathrm{U}(1)_A$  arises as well.

$$V = M_1^2 \operatorname{Tr}(\Sigma^\dagger \Sigma) - M_2^2 \operatorname{Tr}(\Sigma^\dagger \Sigma \sigma_3) \\ + \mu^2 (e^{i\theta} \det \Sigma + \text{h.c.}) + \frac{\lambda_1}{2} \operatorname{Tr}(\Sigma^\dagger \Sigma)^2 + \lambda_2 |\det \Sigma|^2$$

analogue of SM Higgs mass

breaks  $SU(2)_R$  to  $U(1)$

$$V = M_1^2 \text{Tr}(\Sigma^\dagger \Sigma) - M_2^2 \text{Tr}(\Sigma^\dagger \Sigma \sigma_3) + \mu^2 (e^{i\theta} \det \Sigma + \text{h.c.}) + \frac{\lambda_1}{2} \text{Tr}(\Sigma^\dagger \Sigma)^2 + \lambda_2 |\det \Sigma|^2$$

breaks  $U(1)_A$

$SU(2)_R \times SU(2)_R \times U(1) \times U(1)$

$e^{i\alpha} (\det \Sigma) \text{Tr}(\Sigma^\dagger \Sigma)$ ,  $e^{i\alpha'} (\det \Sigma)^2$ , etc., are forbidden.

$$(\text{Tr}(\Sigma^\dagger \Sigma))^2 = \text{Tr}(\Sigma^\dagger \Sigma)^2 + 2 \det \Sigma^\dagger \Sigma$$

$\lambda \sim 0.25$ , contribute negligibly small effects.

$$V \rightarrow M_H^2 H_0^\dagger H_0 + M_b^2 H_b^\dagger H_b + \mu^2 \left( e^{i\theta} H_0^\dagger H_b + \text{h.c.} \right)$$

Substituting back into  $V$  we recover the SMH potential

$$V = M_0^2 H_0^\dagger H_0 + \frac{\lambda}{2} (H_0^\dagger H_0)^2 + O\left(\frac{\mu^2}{M_b^2}\right),$$

$$M_0^2 = M_H^2 - \frac{\mu^4}{M_b^2}.$$

$$M_0^2 \simeq -(88.4) \text{ GeV}^2$$

$$\lambda \simeq 0.25.$$

## Tachyonic instability from level repulsion

Substituting back into  $V$  we recover the SMH potential

$$V = M_0^2 H_0^\dagger H_0 + \frac{\lambda}{2} (H_0^\dagger H_0)^2 + O\left(\frac{\mu^2}{M_b^2}\right), \quad (10)$$

$$M_0^2 = M_H^2 - \frac{\mu^4}{M_b^2}. \quad M_0^2 \simeq -(88.4) \text{ GeV}^2 \\ \lambda \simeq 0.25.$$



$$H_0 = \begin{pmatrix} v + \frac{1}{\sqrt{2}}h \\ 0 \end{pmatrix}, \quad v = 174 \text{ GeV},$$

$$v^2 = -M_0^2/\lambda, \quad m_h = \sqrt{2}|M_0| = 125 \text{ GeV},$$

$$H_b \rightarrow H_b - \frac{\mu^2}{M_b^2} \begin{pmatrix} v + \frac{1}{\sqrt{2}}h \\ 0 \end{pmatrix},$$

## b-quark mass

$$V_{HY} = g \overline{\begin{pmatrix} t \\ b \end{pmatrix}}_L H_0 t_R + g \overline{\begin{pmatrix} t \\ b \end{pmatrix}}_L H_b^c b_R$$

$$m_b = g_b(m_b) v \frac{\mu^2}{M_b^2} = m_t \frac{g_b(m_b) \mu^2}{g_t(m_t) M_b^2},$$

$$R_b = \frac{g_b(m_b)}{g_t(m_t)} \simeq 1.5.$$

## b-quark mass

In the case that the Higgs mass,  $M_0^2$ , is due entirely to the level repulsion by  $H_b$ , *i.e.*  $M_H^2 = 0$ , and using Eqs. (11),

$$m_b = 4.18 \text{ GeV}, \quad m_t = 173 \text{ GeV}.$$



$$M_b = \frac{m_t}{m_b} R_b |M_0| \simeq 5.5 \text{ TeV}$$

## b-quark mass

$$m_b = 4.18 \text{ GeV}, m_t = 173 \text{ GeV}$$



$$M_b = \frac{m_t}{m_b} R_b |M_0| \simeq 5.5 \text{ TeV}$$

$M_H^2$  nonzero  $\rightarrow$  Require no fine tuning  $\rightarrow M_b \lesssim 5.5 \text{ TeV}$

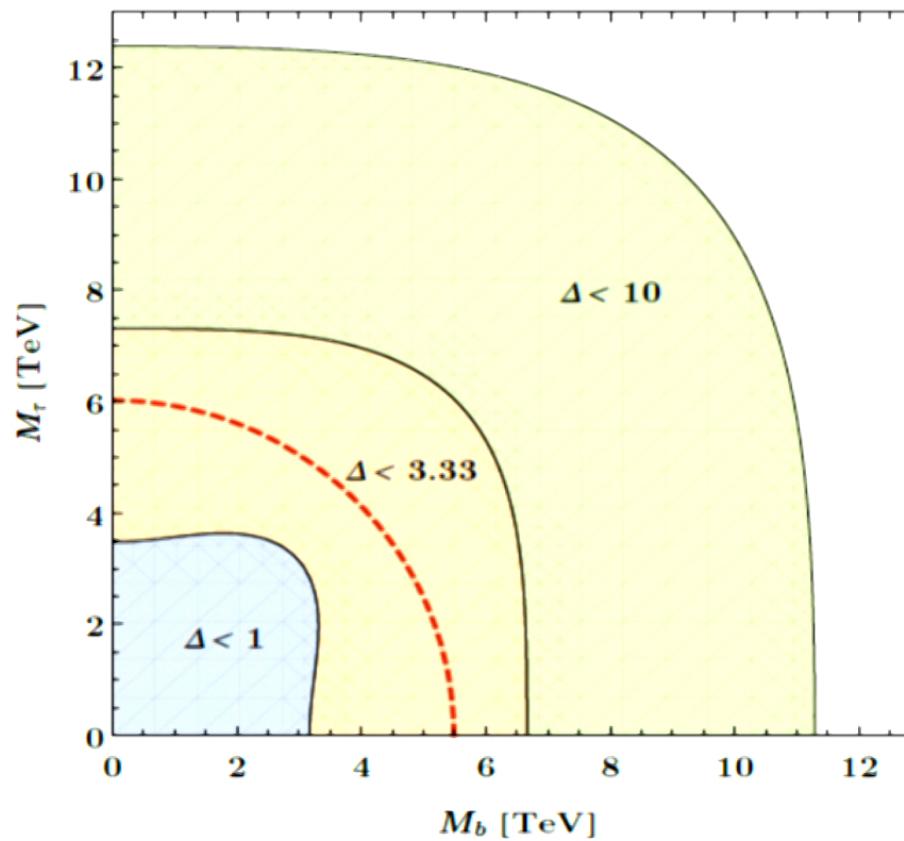


Figure 1. The fine tuning associated with different values of the  $M_b$  and  $M_\tau$  parameters. The remaining three parameters  $\mu_b$ ,  $\mu_\tau$ , and  $M_H$  are fixed by the physical choices of fermion masses and Higgs vev. The red dashed line corresponds to  $M_H^2 = 0$ , and the origin to  $M_H^2 = -|M_0^2|$ .

$$M_0^2 + M_H^2 = \frac{m_b^2 M_b^2}{m_t^2 R_b^2} + \frac{m_\tau^2 M_\tau^2}{m_t^2 R_\tau^2},$$

$H_b$  and  $H_\tau$  contribute equally to the SMH mass,

$$M_b \simeq 3.6 \text{ TeV}, \quad M_\tau \simeq 4.2 \text{ TeV}.$$

The  $H_\tau$  mixes directly to the SMH through the  $V'_2$  term.  $H_\tau$  then acquires a VEV, and feeds back upon the Higgs mass as

$$H_\tau = -\frac{\mu_2^2}{M_\tau^2} H_0, \quad \delta M_0^2 = -\frac{\mu_2^4}{M_\tau^2}. \quad (30)$$

$$R_\tau = \frac{g_\tau(m_\tau)}{g_t(m_t)} \simeq 0.7. \quad m_\tau = m_t R_\tau \frac{\mu_2^2}{M_\tau^2}.$$

We observe that  $H_\tau$  and  $H_b$  now simultaneously contribute to the SMH mass

$$-M_0^2 = M_H^2 - \frac{\mu_b^4}{M_b^2} - \frac{\mu_2^4}{M_\tau^2}. \quad (33)$$

$$M_0^2 + M_H^2 = \frac{m_b^2 M_b^2}{m_t^2 R_b^2} + \frac{m_\tau^2 M_\tau^2}{m_t^2 R_\tau^2},$$

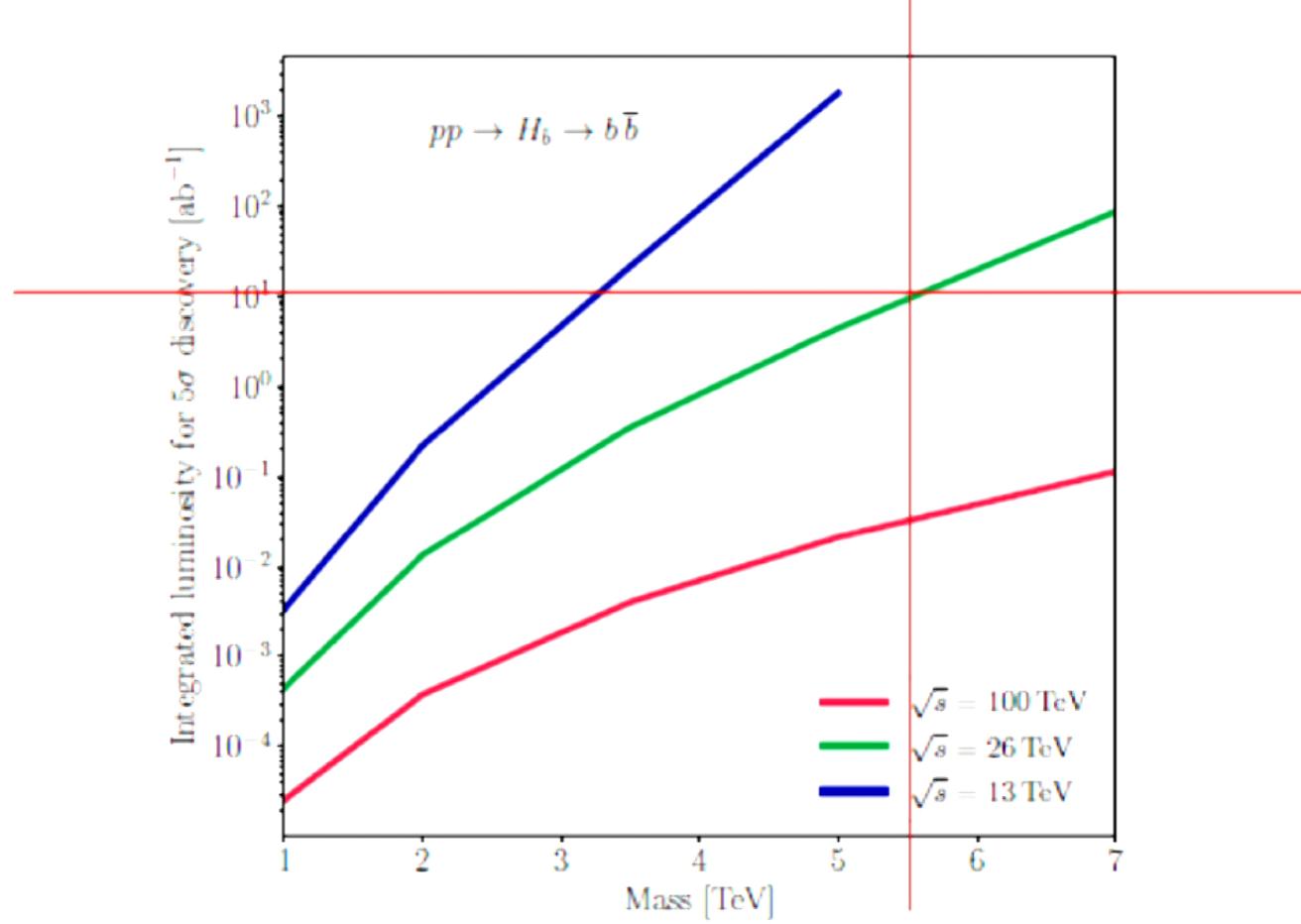
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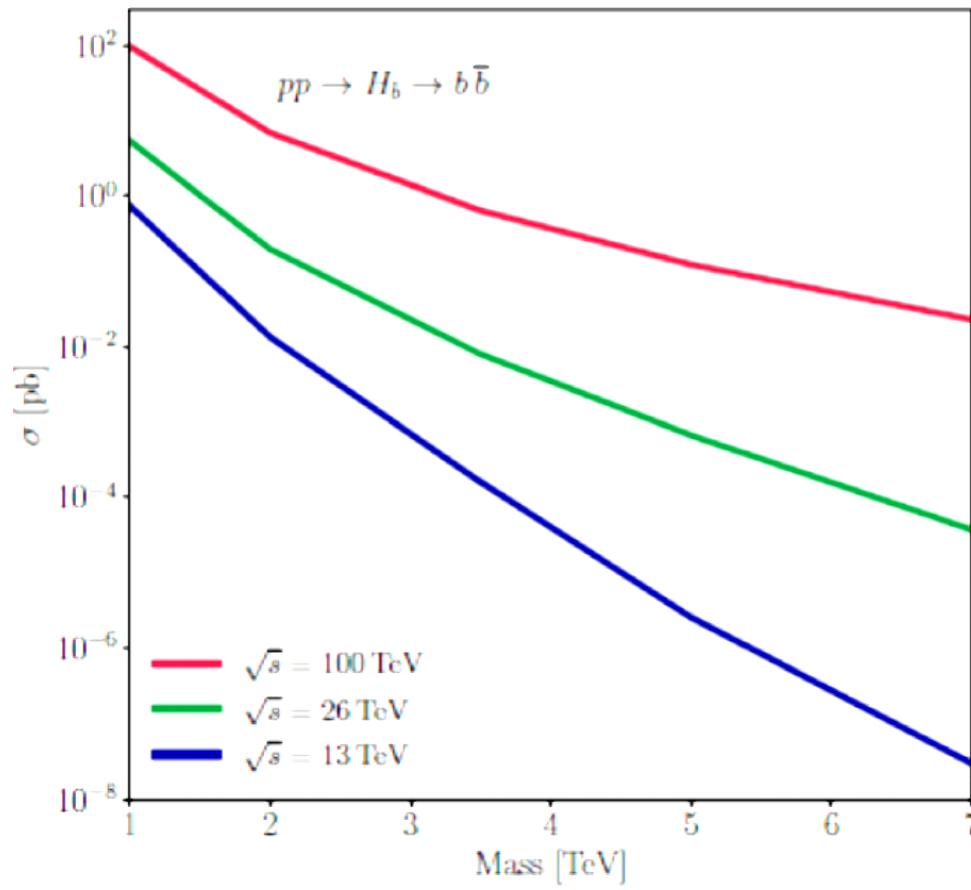
$$M_0^2 + M_H^2 = \frac{m_b^2 M_b^2}{m_t^2 R_b^2} + \frac{m_\tau^2 M_\tau^2}{m_t^2 R_\tau^2} + \frac{m_{D\nu}^2 M_\nu^2}{m_t^2 R_\nu^2}$$

With additional light Higgs fields, the elliptical constraint forces all of the Higgs masses to smaller values. We emphasize that the mass bounds of Fig. (1) should be viewed as upper limits on the Higgs mass spectrum that could be explored at the LHC.

## Production and Detection



## Production and Detection



## Production and Detection

Remarkably, the  $h_\tau^0$  (and  $h_\nu^0$ ), neutral components of the associated iso-doublets,  $H_\tau$  and  $H_\nu$ , may also be singly produced because they can mix with  $H_b$  through the  $\mu_1^2$  and  $\mu_2^2$  terms of Eq. (24) and (27) respectively. This implies a total cross section

$$\sigma(h_\tau^0, h_\nu^0) \sim \theta^2 \sigma(h_b^0), \quad (43)$$

for the mixing angle,  $\theta$ , between either the states  $h_\tau^0$  or  $h_\nu^0$  and  $h_b^0$ . Although  $\theta$  is unknown it could easily be large,  $\theta \sim 0.3$ . The  $h_\tau^0 \rightarrow \bar{\tau}\tau$  is visible with  $\tau$ -tagging, and the background is also slightly suppressed since the peak is narrower by a factor of  $(g_\tau^2/3g_b^2) \sim 0.16$ . Hence at the 26 TeV LHC discovery is in principle possible for a 3.5 TeV state with integrated luminosity of order  $2 \text{ ab}^{-1}$ .

We note that the LHC *already has* the capability of ruling out an  $H_b$  of mass  $\sim 1$  TeV, with  $\sim 200 \text{ fb}^{-1}$ . The main point is that  $g_b \simeq 1$  significantly enhances access to these states, and we are unaware of any limits for these in the literature to date. We think it is important for the collaborations to develop an analysis strategy for these states.

I believe the  $H_b$  exists

Can be discovered at  
Energy Doubled LHC @  $10 \text{ ab}^{-1}$

It would explain  $y_b$  and  
with  $g=1$  would lend credibility  
to universality/compositeness/  
Scalar democracy

## A Deeper View of Standard Model



Universal compositeness:  
How?

$$\frac{\Psi_{\alpha_1 \alpha_2} \Psi_{\beta_1 \beta_2}}{\Lambda^2} \left( \bar{\psi}_L \psi_R \right) \left( \bar{\psi}_R \psi_L \right)$$