

Phenomenology of Sequestered Mass Generation

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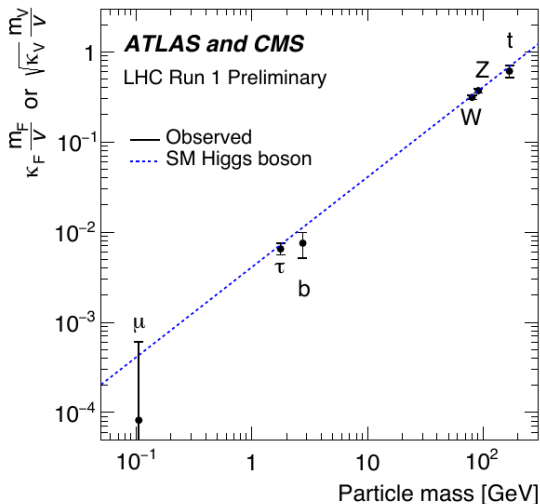
Does the Higgs Give Mass to All Fermions?

Flavor diagonal couplings to
3rd gen. known with
 $\sim 20\% - 30\%$ uncertainty

substantial improvement
at future LHC runs and
at a ILC or FCC-ee

with large enough stats it
will be possible to get
the SM muon coupling
(10% accuracy with $3/\text{ab}$)

What about the rest?



Let's assume the Higgs does *not*
give mass to all fermions.

What are the implications?

“Sequestered” Fermion Masses

a novel setup: two sources of fermion mass

$$\mathcal{M} = \mathcal{M}_0 + \Delta\mathcal{M}$$

- ▶ \mathcal{M}_0 : due to the (main component of the) 125 GeV Higgs provides the bulk of the 3rd generation masses
- ▶ $\Delta\mathcal{M}$: due to some other source mainly responsible for the 1st and 2nd generation masses

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501

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this is a valid setup, given the very limited knowledge of the Higgs coupling to 1st and 2nd generation

what are the testable signatures of such a setup?

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A Simple 2HDM Realization

2 Higgs doublets H and H' with vevs v and v' and Yukawas Y and Y'

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

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2 Higgs doublets H and H' with vevs v and v' and Yukawas Y and Y'

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

fermions receive mass from both Higgs bosons

$$\mathcal{M} = vY + v'Y'$$

invoke some mechanism such that the Yukawa Y is rank 1, while the Yukawa Y' is generic (apart from 1st/2nd generation hierarchy)

$$\mathcal{M}_0 \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} \simeq \begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

(similar in the quark sector)

Phenomenology of the 125 GeV Higgs

Flavor Diagonal Couplings of the 125 GeV Higgs

Compare to other extended Higgs sectors

	W,Z κ_V	up quarks $\kappa_t, \kappa_C, \kappa_U$	down quarks $\kappa_b, \kappa_S, \kappa_d$	leptons $\kappa_\tau, \kappa_\mu, \kappa_e$
2HDM type 1				
2HDM type 2				
sequestered 2HDM				

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2HDM type 2	$S_{\beta-\alpha}$	$\frac{C_\alpha}{S_\beta}$	$\frac{-S_\alpha}{C_\beta}$	$\frac{-S_\alpha}{C_\beta}$
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sequestered 2HDM	$S_{\beta-\alpha}$	$\frac{C_\alpha}{S_\beta}, \frac{-S_\alpha}{C_\beta}, \frac{-S_\alpha}{C_\beta}$	$\frac{C_\alpha}{S_\beta}, \frac{-S_\alpha}{C_\beta}, \frac{-S_\alpha}{C_\beta}$	$\frac{C_\alpha}{S_\beta}, \frac{-S_\alpha}{C_\beta}, \frac{-S_\alpha}{C_\beta}$

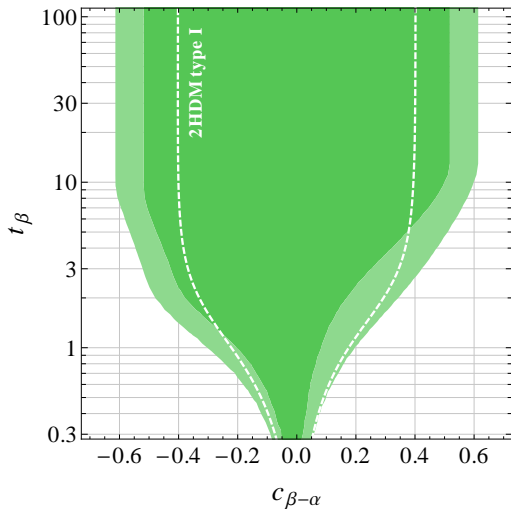
(in the sequestered 2HDM there are additional corrections to the κ 's
of the order of $O(m_C/m_t)$, $O(m_S/m_b)$, $O(m_\mu/m_\tau)$)

Constraints from Higgs Rates

measurements of
Higgs rates
(3rd generation)
constrain α/β
parameter space

expect constraints similar to
2HDM type 1

difference comes from
 $m^{2\text{nd}}/m^{3\text{rd}}$ suppressed terms



Flavor Violating Couplings of the Higgs

in general the fermion masses and the h couplings cannot be diagonalized simultaneously

$$\text{e.g. } \frac{y_{\mu\tau}}{y_{\mu}^{\text{SM}}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_{\mu}} \frac{\cos(\beta - \alpha)}{\sin\beta \cos\beta}$$

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generic expectations for lepton flavor violating Higgs decays

$$\text{BR}(h \rightarrow \tau\mu) \sim \frac{m_{\mu}^2}{3m_b^2} \sim 10^{-3}$$

$$\text{BR}(h \rightarrow \tau e) \sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}$$

$$\text{BR}(h \rightarrow \mu e) \sim \frac{m_e^2 m_{\mu}^2}{3m_{\tau}^2 m_b^2} \sim 10^{-10}$$

Additional Flavor Violating Signatures

flavor violating
rare top decays with
branching ratios as large as

$$\text{BR}(t \rightarrow ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\text{BR}(t \rightarrow uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

might be in reach of the
high luminosity LHC

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

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lepton flavor violating
rare B meson decays
with sizable branching ratios

$$\text{BR}(B_s \rightarrow \tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \rightarrow K\tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \rightarrow K^*\tau\mu) \sim \text{few} \times 10^{-7}$$

LHCb might be sensitive
to the K^* and K rates

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Phenomenology of the Heavy Scalars

Flavor Diagonal Couplings of the Heavy Scalar

Compare to other extended Higgs sectors

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2HDM type 1				
2HDM type 2				
sequestered 2HDM				

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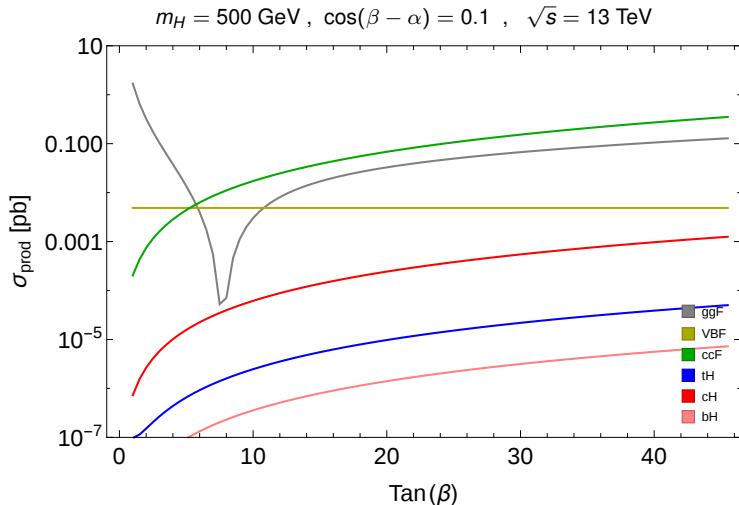
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2HDM type 2	$C_{\beta-\alpha}$	$\frac{1}{t_\beta} \frac{s_\alpha}{c_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$
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2HDM type 2	$C_{\beta-\alpha}$	$\frac{1}{t_\beta} \frac{s_\alpha}{c_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$
sequestered 2HDM	$C_{\beta-\alpha}$	$\frac{1}{t_\beta} \frac{s_\alpha}{c_\beta}, t_\beta \frac{c_\alpha}{s_\beta}, t_\beta \frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta} \frac{s_\alpha}{c_\beta}, t_\beta \frac{c_\alpha}{s_\beta}, t_\beta \frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta} \frac{s_\alpha}{c_\beta}, t_\beta \frac{c_\alpha}{s_\beta}, t_\beta \frac{c_\alpha}{s_\beta}$

(in the sequestered 2HDM there are additional corrections of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$)



WA, Eby, Gori, Lotito, Martone, Tuckler, in preparation

2HDM type 1 and type 2

$$\frac{\text{BR}(A/H \rightarrow \mu\mu)}{\text{BR}(A/H \rightarrow \tau\tau)} \simeq \frac{m_\mu^2}{m_\tau^2} \simeq 3 \times 10^{-3}$$

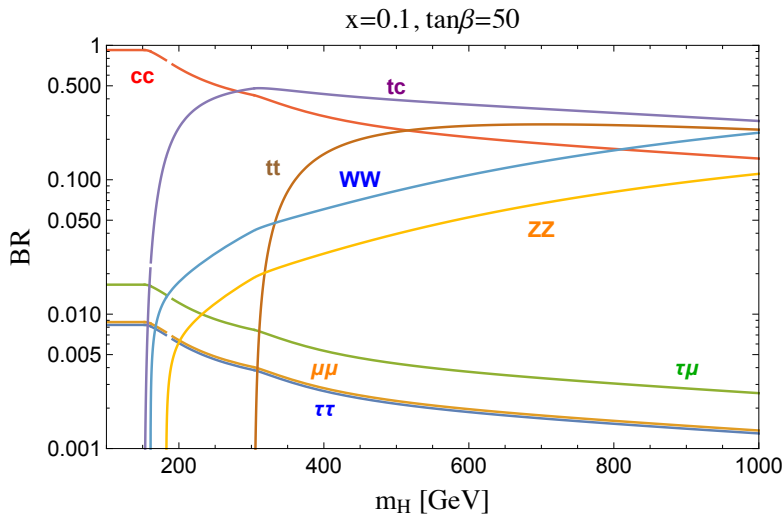
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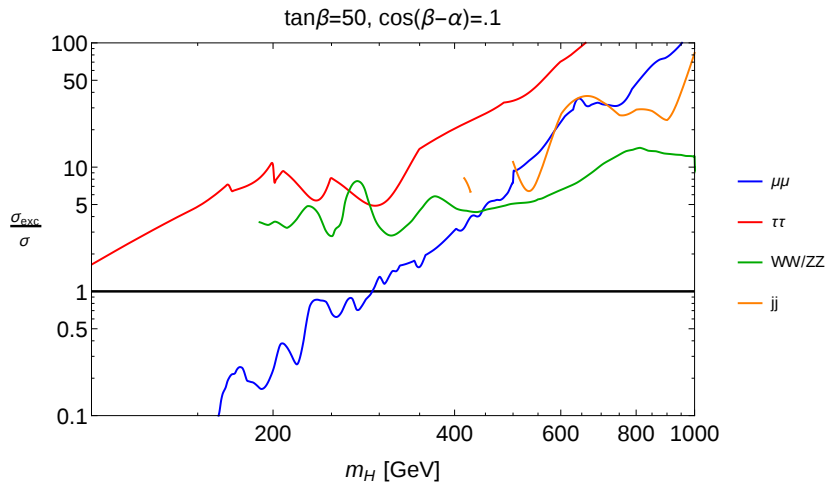
sequestered 2HDM

$$\frac{\text{BR}(A/H \rightarrow \mu\mu)}{\text{BR}(A/H \rightarrow \tau\tau)} \simeq \begin{cases} \frac{m_\mu^2}{m_\tau^2} \times (\tan \beta)^4 & \text{for moderate } \tan \beta \\ m_\mu^2 / |\Delta \mathcal{M}_{\tau\tau}|^2 & \text{for large } \tan \beta \end{cases}$$

branching ratios into 2nd and 3rd generation are generically **comparable**



WA, Eby, Gori, Lotito, Martone, Tuckler, in preparation



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- ▶ We don't know if the Higgs gives mass to the light flavors (and in some cases, we might never know ...)
- ▶ What if there is an additional source of EWSB providing mass to the light flavors?
- ▶ Presented a “flavorful” 2HDM with interesting non-standard low and high energy phenomenology

Back Up

Generation of CKM Mixing

$$\mathcal{M}_0^u \simeq \begin{pmatrix} 0 & 0 \\ 0 & m_t \end{pmatrix}, \quad \Delta\mathcal{M}^u \simeq \begin{pmatrix} m_c & O(m_c) \\ O(m_c) & O(m_c) \end{pmatrix}$$

$$\mathcal{M}_0^d \simeq \begin{pmatrix} 0 & 0 \\ 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M}^d \simeq \begin{pmatrix} m_s & O(m_s) \\ O(m_s) & O(m_s) \end{pmatrix}$$

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In addition to quark masses need also to reproduce **CKM mixing**

$$|V_{ts}| \simeq \left| \frac{(\Delta\mathcal{M}^d)_{sb}}{m_b} - \frac{(\Delta\mathcal{M}^u)_{ct}}{m_t} \right| \simeq \frac{O(m_s)}{m_b}$$

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works pretty well, given the measured values

$$|V_{ts}| \simeq 4 \times 10^{-2}, \quad \frac{m_s}{m_b} \simeq 2 \times 10^{-2}$$

Extension to Three Generations

require structure in the Y' Yukawa couplings to explain the hierarchy between the first and second generation masses

$$\mathcal{M}_0^u \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix}, \quad \Delta\mathcal{M}^u \simeq \begin{pmatrix} m_u & O(m_u) & O(m_u) \\ O(m_u) & m_c & O(m_c) \\ O(m_u) & O(m_c) & O(m_c) \end{pmatrix}$$

$$\mathcal{M}_0^d \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M}^d \simeq \begin{pmatrix} m_d & O(m_d) & O(m_d) \\ O(m_d) & m_s & O(m_s) \\ O(m_d) & O(m_s) & O(m_s) \end{pmatrix}$$

$$\mathcal{M}_0^\ell \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M}^\ell \simeq \begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

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$$\mathcal{M}_0^d \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M}^d \simeq \begin{pmatrix} m_d & V_{cd}m_s & V_{td}m_b \\ O(m_d) & m_s & V_{ts}m_b \\ O(m_d) & O(m_s) & O(m_s) \end{pmatrix}$$

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need to stretch a bit to get correct CKM entries

$$|V_{cd}| \simeq 0.23 \quad \text{vs.} \quad m_d/m_s \simeq 0.05$$

$$|V_{td}| \simeq 8 \times 10^{-3} \quad \text{vs.} \quad m_d/m_b \simeq 1 \times 10^{-3}$$

An Approximate $SU(2)^5$ symmetry

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flavor violating transitions between 1st and 2nd generation are protected

$$\begin{pmatrix} m_u & O(m_u) & O(m_u) \\ O(m_u) & m_c & O(m_c) \\ O(m_u) & O(m_c) & O(m_c) \end{pmatrix} \xrightarrow[\text{basis}]{\text{mass eigenstate}} \begin{pmatrix} m_u & O\left(\frac{m_u m_c}{m_t}\right) & O(m_u) \\ O\left(\frac{m_u m_c}{m_t}\right) & m_c & O(m_c) \\ O(m_u) & O(m_c) & O(m_c) \end{pmatrix}$$

$$\begin{pmatrix} m_d & V_{cd} m_s & V_{td} m_b \\ O(m_d) & m_s & V_{ts} m_b \\ O(m_d) & O(m_s) & O(m_s) \end{pmatrix} \xrightarrow[\text{basis}]{\text{mass eigenstate}} \begin{pmatrix} m_d & O(m_s V_{td}) & m_b V_{td} \\ O(m_d V_{ts}) & m_s & m_b V_{ts} \\ O(m_d) & O(m_s) & O(m_s) \end{pmatrix}$$

$$\begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix} \xrightarrow[\text{basis}]{\text{mass eigenstate}} \begin{pmatrix} m_e & O\left(\frac{m_e m_\mu}{m_\tau}\right) & O(m_e) \\ O\left(\frac{m_e m_\mu}{m_\tau}\right) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

Constraints from Low Energy Observables

due to the $SU(2)^5$ flavor symmetry
flavor and CP violating low energy processes are largely under control

- ▶ $\mu \rightarrow e\gamma$ ✓
- ▶ electron EDM ✓
- ▶ $D^0 - \bar{D}^0$ oscillations ✓

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Kaon oscillations, B_d and B_s meson oscillations
give additional constraints on the down quark Yukawa

$$\begin{pmatrix} m_d & V_{cd}m_s & V_{td}m_b \\ O(m_d) & m_s & V_{ts}m_b \\ O(m_d) & O(m_s) & O(m_s) \end{pmatrix} \xrightarrow[\text{constraints}]{\text{low energy}} \begin{pmatrix} m_d & V_{cd}m_s & V_{td}m_b \\ \lesssim m_d/10 & m_s & V_{ts}m_b \\ \lesssim m_d & \lesssim m_s/6 & O(m_s) \end{pmatrix}$$