Role of the Higgs Sector in the Generation & Flavor Problem

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SLAC Summer Institute 2021,
The Higgs State Fare

August 24, 2021

Outline of the Lectures

1. Part 1 (yesterday)
   - Higgs and Flavor in the Standard Model

     (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)

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2. Part 2 (today)
   - Higgs and Flavor beyond the Standard Model

     (extended Higgs sectors, “flavorful” Higgs bosons, flavor phenomenology, collider phenomenology)

The Standard Model Flavor Puzzle

Why are there three flavors of quarks and leptons?

What is the origin of the hierarchies in the fermion spectrum?

What is the origin of the hierarchies in the quark mixing?

Is lepton mixing anarchic?

Addressing the SM Flavor Puzzle

- Option 1: Electroweak symmetry breaking is as in the SM

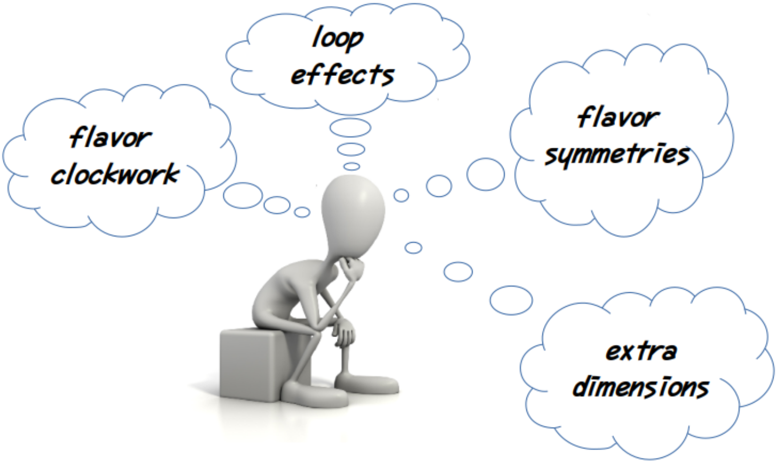
$\rightarrow$ Hierarchical structure of fermion masses and CKM matrix originates solely from the Yukawa couplings

$\rightarrow$ Introduce new physics that gives the Yukawa couplings a hierarchical structure

- Option 2: Extended electroweak symmetry breaking sector

$\rightarrow$ Small quark and lepton masses from a subdominant source of electroweak symmetry breaking

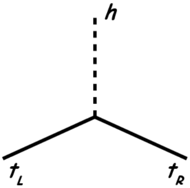
Origin of Hierarchical Yukawa Couplings

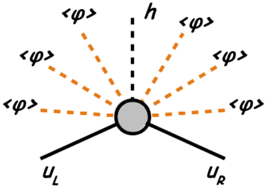


Hierarchy from Symmetry

(Froggatt, Nielsen ’79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry





Simple U(1) model:

$Q(t_L)=Q(t_R)=0$
$Q(u_L)=-Q(u_R)=3$
$Q(h)=0$
$Q(\varphi)=-1$

$h\bar{t}_R t_L$

$$\frac{\varphi^6}{M^6} h\bar{u}_R u_L$$

Hierarchy from Symmetry

mass and mixing hierarchies given by powers of the "spurion" $\langle \varphi \rangle / M$.
in the example from the previous slide we have

$$\frac{m_u}{m_t} \sim \left(\frac{\langle \varphi \rangle}{M} \right)^6 \sim \epsilon^6$$

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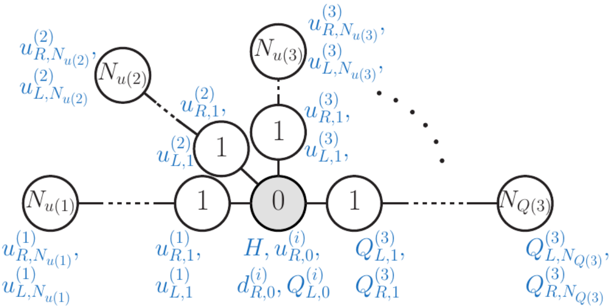
Exercise: Construct a U(1) model with the following hierarchies

$$m_u \sim \epsilon^6 \ , \ \ m_c \sim \epsilon^3 \ , \ \ m_t \sim 1$$

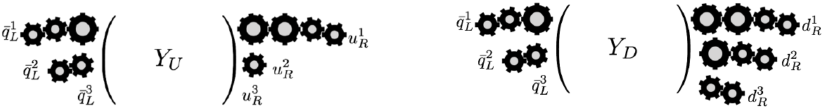
$$m_d \sim \epsilon^5 \ , \ \ m_s \sim \epsilon^4 \ , \ \ m_b \sim \epsilon^2$$

Which predictions does your model make for the CKM hierarchies?

The flavor clockwork mechanism (Giudice, McCullough 1610.07962), is similar to Froggatt-Nielsen with many individual $U(1)$ symmetries for each flavor



(Alonso et al. 1807.09792)



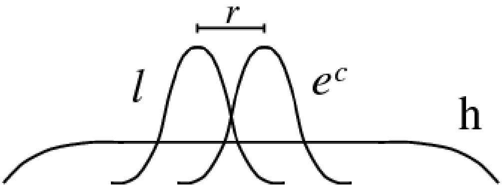
(Alonso et al. 1807.09792)

The numbers of clockwork sites play a similar role as the U(1) charges in the Froggatt-Nielsen setup

$$\frac{m_u}{m_t} \sim \epsilon^{N_{Q_1}+N_{u_1}-N_{Q_3}-N_{u_3}}$$

(Arkani-Hamed, Schmaltz '99; Grossman, Neubert '99; ...)

fermions are localized at different positions in an extra dimension



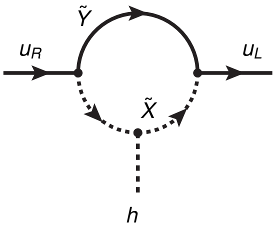
hierarchies from exponentially small wave-function overlap between left-handed and right-handed fermions and the Higgs

$$\frac{m_u}{m_t} \sim e^{-\Delta}$$

Hierarchy from Loops

(Weinberg '72; ...)

light fermion masses arise only from quantum effects



light fermions do not couple
to the higgs directly

couplings are loop-induced
by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2}\right)^n$$

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Extended Higgs Sectors

Strong constraints from the ρ parameter
($I =$ weak isospin, $Y =$ hypercharge, $v =$ vacuum expectation value)

$$\rho = \frac{\sum_i (I_i(I_i+1) - Y_i^2) v_i^2}{\sum_i 2 Y_i^2 v_i^2} = \frac{m_W^2}{m_Z^2 c_W^2} = 1$$

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ρ is automatically 1 for $SU(2)$ singlets and doublets.

(Can be made 1 also for larger $SU(2)$ representations, but in a non-trivial way)

$\rightarrow$ focus on singlets and doublets in the following

Standard Model + Singlet

- Singlet does not contribute to electroweak symmetry breaking
- Singlet does not have renormalizable couplings with SM fermions

$\rightarrow$ not interesting in the context of the flavor puzzle

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- Singlet can mix with the SM Higgs and inherit its couplings
- Couplings of the Higgs mass eigenstate will be universally suppressed by a mixing angle

Two Higgs Doublet Models

the simplest non-trivial extensions of the SM Higgs sector

- two Higgs doublets H_1 and H_2 with hypercharges -1/2 and +1/2 (SUSY convention)

$$H_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v s_\beta + h_2 + i a_2) \end{pmatrix} \quad , \quad H_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v c_\beta + h_1 + i a_1) \\ H_1^- \end{pmatrix}$$

$$v_2 = v \sin\beta = v s_\beta \ , \quad v_1 = v \cos\beta = v c_\beta \ , \quad \tan\beta = t_\beta = v_2 / v_1$$

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- 5 physical degrees of freedom: h and H, A, and $H^\pm$

  assuming CP conservation:

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} H_2^\pm \\ H_1^\pm \end{pmatrix}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_2 \\ h_1 \end{pmatrix} \quad , \quad \begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} a_2 \\ a_1 \end{pmatrix}$$

Couplings to Fermions

both Higgs doublets can couple to the SM fermions

$$\begin{aligned}\mathcal{L} \supset \quad & (y_u)_{ik}\, H_2 \bar{Q}_i U_k + (\tilde{y}_u)_{ik}\, H_1^c \bar{Q}_i U_k \\ & + (y_d)_{ik}\, H_1 \bar{Q}_i D_k + (\tilde{y}_d)_{ik}\, H_2^c \bar{Q}_i D_k \\ & + (y_\ell)_{ik}\, H_1 \bar{L}_i E_k + (\tilde{y}_\ell)_{ik}\, H_2^c \bar{L}_i E_k \quad + \text{h.c.}\end{aligned}$$

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- for generic couplings y and $\tilde{y}$,
  quark masses and Higgs couplings are not aligned, e.g.

$$(m_d)_{ik} = \frac{v}{\sqrt{2}}\Big(c_\beta (y_d)_{ik} + s_\beta (\tilde{y}_d)_{ik}\Big) \,, \quad (g_d^A)_{ik} = \frac{1}{\sqrt{2}}\Big(s_\beta (y_d)_{ik} - c_\beta (\tilde{y}_d)_{ik}\Big)$$

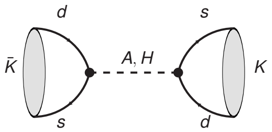
$$(g_d^h)_{ik} = \frac{v}{\sqrt{2}}\Big(-s_\alpha (y_d)_{ik} + c_\alpha (\tilde{y}_d)_{ik}\Big) \,, \quad (g_d^H)_{ik} = \frac{1}{\sqrt{2}}\Big(c_\alpha (y_d)_{ik} + s_\alpha (\tilde{y}_d)_{ik}\Big)$$

$\Rightarrow$ FCNCs at tree level!

Constraints from Meson Mixing

tree level FCNCs

$\rightarrow$ very strong constraints from meson mixing



$$M_{12}^K \sim f_K^2 \frac{m_K^2}{m_s^2} \left(\frac{g_{sd}^h g_{ds}^h}{m_h^2} + \frac{g_{sd}^H g_{ds}^H}{m_H^2} + \frac{g_{sd}^A g_{ds}^A}{m_A^2} \right)$$

Constraints from Meson Mixing

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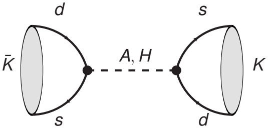

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- The SM Higgs contributions are absent in the Higgs alignment limit $\beta - \alpha = \pi/2$.

  In that case the couplings of h and the fermion mass matrices are propotional to each other.

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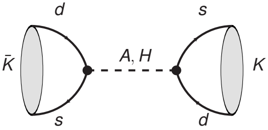

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- Still need to deal with the H and A contributions.
- For generic complex $O(1)$ flavor changing couplings, m_A and m_H have to be extremely heavy $\gtrsim 10^5$ TeV to avoid constraints from CP violation in Kaon mixing.

The New Physics Flavor Puzzle

Low energy flavor observables are sensitive to
New Physics far beyond the TeV scale

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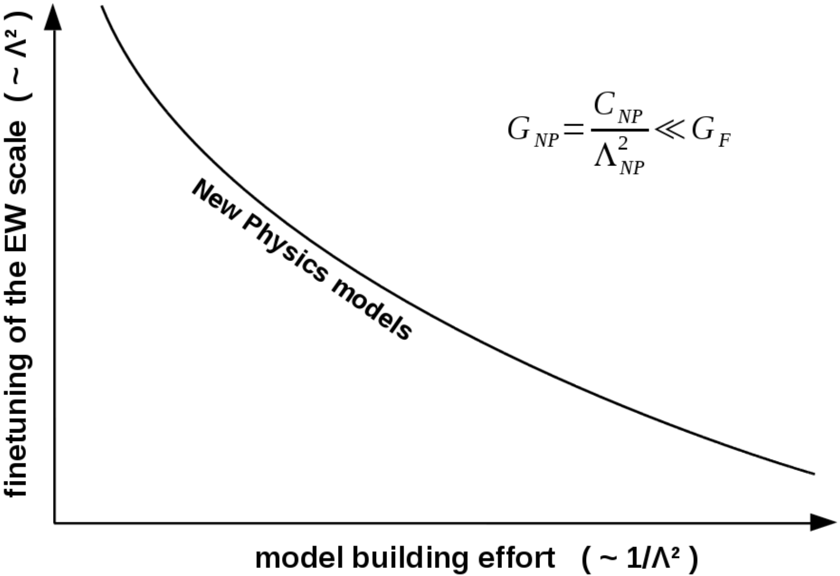
If there is New Physics at the TeV scale, why have we not seen it yet in flavor observables?

Reactions to the New Physics Flavor Puzzle



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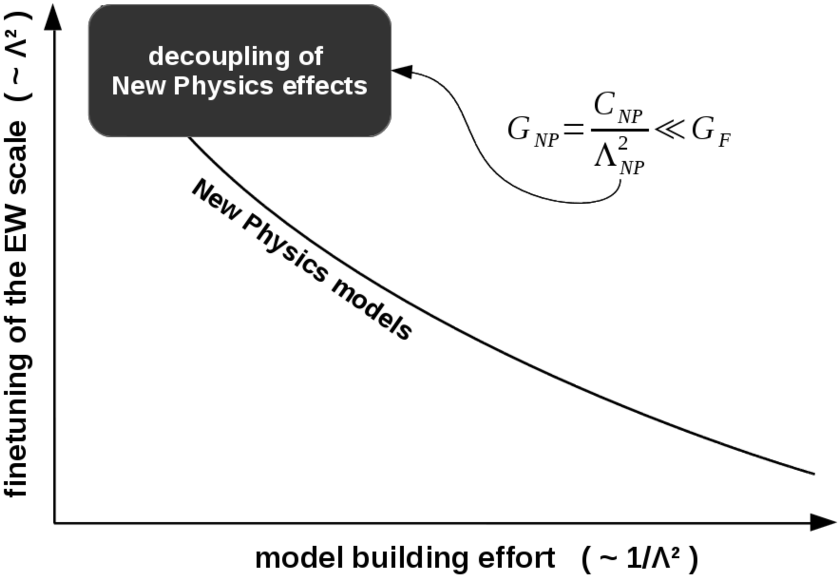

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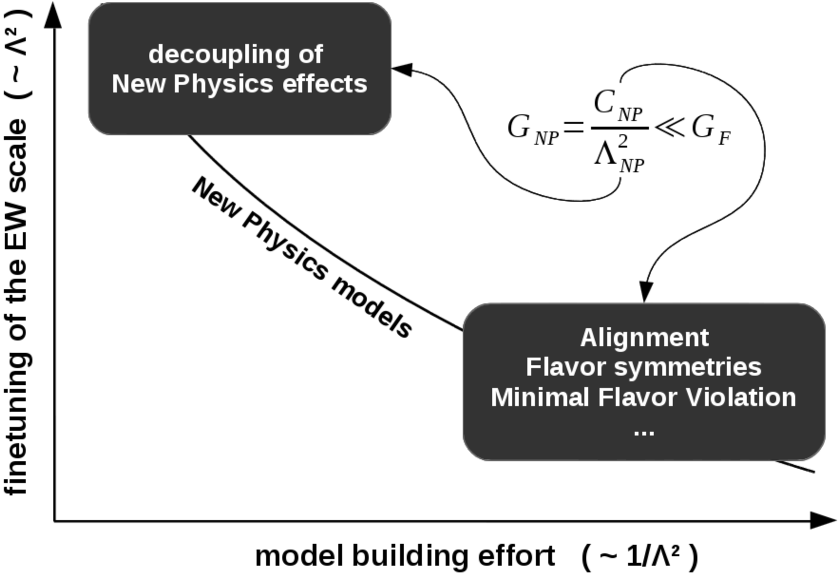

2HDMs with Natural Flavor Conservation

- Usual (radical?) approach: get completely rid of tree level FCNCs
- Natural Flavor Conservation: no tree level FCNCs if all types of fermions couple only to one Higgs doublet (Glashow, Weinberg '77)
- Can be enforced by:
  (softly broken) continuous symmetries (Peccei-Quinn)
  or discrete symmetries (Z_2)

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- 4 possibilities: $(y_u)_{ik}\ H_2 \bar{Q}_i U_k + (\tilde{y}_d)_{ik}\ H_2^c \bar{Q}_i D_k + (\tilde{y}_\ell)_{ik}\ H_2^c \bar{L}_i E_k$

	type I
up quarks	H_2
down quarks	H_2
leptons	H_2

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	type I	type II
up quarks	H_2	H_2
down quarks	H_2	H_1
leptons	H_2	H_1

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	type I	type II	lepton specific
up quarks	H_2	H_2	H_2
down quarks	H_2	H_1	H_2
leptons	H_2	H_1	H_1

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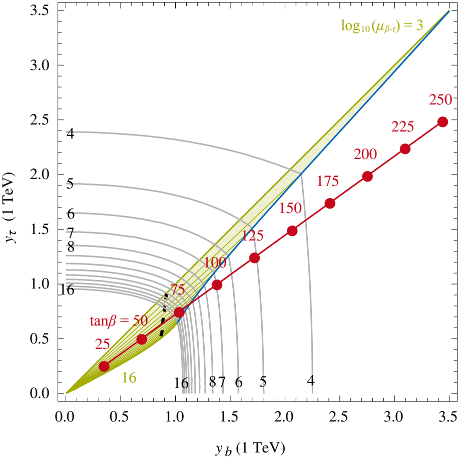
	type I	type II	lepton specific	flipped
up quarks	H_2	H_2	H_2	H_2
down quarks	H_2	H_1	H_2	H_1
leptons	H_2	H_1	H_1	H_2

Connection to the SM Flavor Puzzle

- In a 2HDM type II, the smallness of m_b, m_τ compared to m_t could be explained by a small vacuum expectation value v_1
- Points to values of $\tan\beta = v_2/v_1 \sim m_t/m_{b,\tau}$
- Possible to achieve third generation Yukawa unification

WA, Straub 1004.1993



- modified properties of the 125 GeV Higgs
- direct searches for the additional Higgs bosons
  at high energy colliders
- looking for indirect effects of the additional Higgs bosons
  in low energy observables

Modified $h(125)$ Couplings

	W,Z κ_V	up quarks κ_t, κ_c, κ_u	down quarks κ_b, κ_s, κ_d	leptons κ_τ, κ_μ, κ_e
mixing with singlet				
2HDM type 1				
2HDM type 2				
lepton specific				
flipped				

Modified $h(125)$ Couplings

	W,Z κ_V	up quarks $\kappa_t, \kappa_c, \kappa_u$	down quarks $\kappa_b, \kappa_s, \kappa_d$	leptons $\kappa_\tau, \kappa_\mu, \kappa_e$
mixing with singlet	c_α	c_α	c_α	c_α
2HDM type 1				
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2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2				
lepton specific				
flipped				

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2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
lepton specific				
flipped				

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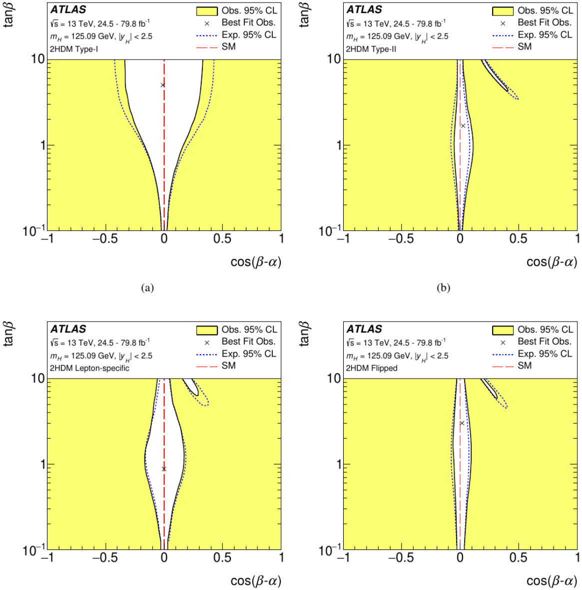
2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
lepton specific	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$
flipped	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$



ATLAS 1909.02845

Heavy Higgs Couplings

	W,Z κ_V	up quarks κ_t, κ_c, κ_u	down quarks κ_b, κ_s, κ_d	leptons κ_τ, κ_μ, κ_e
mixing with singlet				
2HDM type 1				
2HDM type 2				
lepton specific				
flipped				

(in the Higgs alignment limit $\cos(\beta - \alpha) = 0$)

Heavy Higgs Couplings

	W,Z κ_V	up quarks $\kappa_t, \kappa_c, \kappa_u$	down quarks $\kappa_b, \kappa_s, \kappa_d$	leptons $\kappa_\tau, \kappa_\mu, \kappa_e$
mixing with singlet	s_α	s_α	s_α	s_α
2HDM type 1				
2HDM type 2				
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flipped				

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Heavy Higgs Couplings

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mixing with singlet	s_α	s_α	s_α	s_α
2HDM type 1	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
2HDM type 2				
lepton specific				
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mixing with singlet	s_α	s_α	s_α	s_α
2HDM type 1	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
2HDM type 2	0	$\frac{1}{t_\beta}$	t_β	t_β
lepton specific				
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2HDM type 1	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
2HDM type 2	0	$\frac{1}{t_\beta}$	t_β	t_β
lepton specific	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	t_β
flipped	0	$\frac{1}{t_\beta}$	t_β	$\frac{1}{t_\beta}$

(in the Higgs alignment limit $\cos(\beta - \alpha) = 0$)

Standard Search Strategies

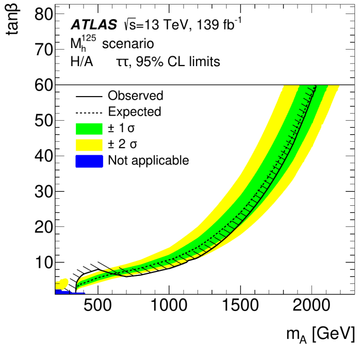
Focus on third generation fermions
top for small $\tan\beta$, bottom/tau for large $\tan\beta$

Production in association with bottom or top
Decay to top/bottom/tau

e.g. searches for MSSM Higgs bosons in large $\tan\beta$ regime:

$$pp \to bbH \to bb\tau\tau$$
$$pp \to H \to \tau\tau$$

ATLAS 2002.12223



Flavor Change from the Charged Higgs

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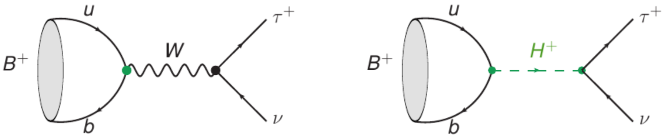

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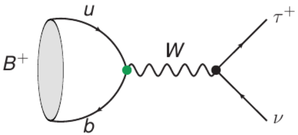
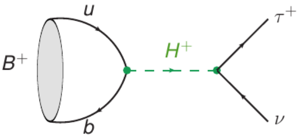
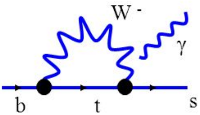
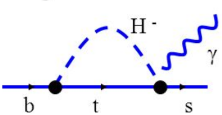
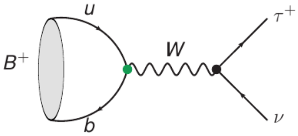


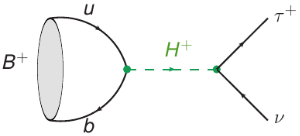


- Leads e.g. to 1-loop contributions to radiative B decays



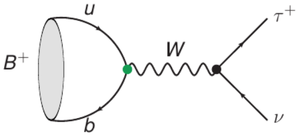


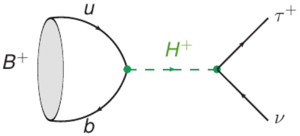




$$\frac{BR(B^+ \to \tau^+\nu)}{BR(B^+ \to \tau^+\nu)_{\text{SM}}} = \begin{cases} \left(1 - \frac{m_{B^+}^2}{m_{H^+}^2} \tan^2\beta\right)^2 & \text{type II} \\ \left(1 - \frac{m_{B^+}^2}{m_{H^+}^2}\right)^2 & \text{lepton specific and flipped} \\ \left(1 - \frac{m_{B^+}^2}{m_{H^+}^2} \cot^2\beta\right)^2 & \text{type I} \end{cases}$$

Constraints from $B \to \tau\nu$





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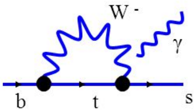
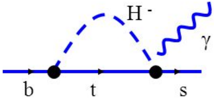
$$BR(B^+ \to \tau^+\nu)_{\text{SM}} = (0.851^{+0.039}_{-0.038}) \times 10^{-4} \quad \text{CKMfitter}$$

$$BR(B^+ \to \tau^+\nu)_{\text{exp}} = (1.06 \pm 0.19) \times 10^{-4} \quad \text{HFLAV}$$





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f_1 and f_2 are ratios of loop functions that depend on m_t^2, $m_{H^+}^2$, m_W^2

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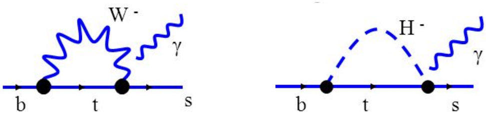

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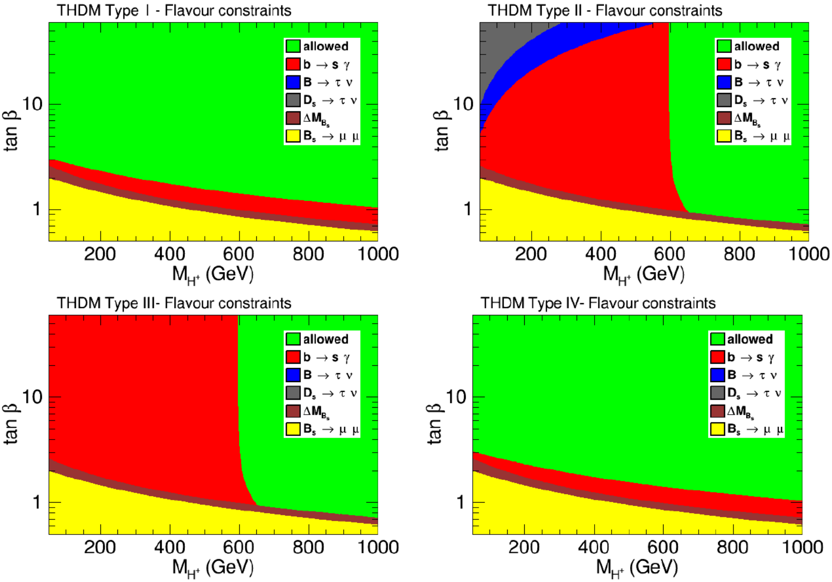
f_1 and f_2 are ratios of loop functions that depend on m_t^2, $m_{H^+}^2$, m_W^2

Gives a very strong constraint in the type II and flipped model:

$m_{H^+} \gtrsim 800$ GeV , Misiak et al. 2002.01548

(but experimental uncertainties might be underestimated, see Bernlochner et al. 2007.04320)

Summary of Charged Higgs Flavor Constraints



Arbey et al. 1706.07414

Alternatives to Natural Flavor Conservation

- the Yukawa couplings y and $\tilde{y}$ are proportional to each other

$\Rightarrow$ no tree level FCNCs, as all linear combinations of y and $\tilde{y}$ are simultaneously diagonal (Pich, Tuzon 0908.1554)

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- Yukawa couplings y and $\tilde{y}$ preserve an approximate $SU(2)^5$ symmetry acting of the first two genertions

$\Rightarrow$ tree-level FCNCs exist, but most stringent constraints avoided
(WA, Gori, Kagan, Silvestrini, Zupan 1507.07927)

Minimal Flavor Violation

recall from the first lecture that without the Yukawa couplings, the SM has a large global flavor symmetry

$$SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E \times U(1)^5$$

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The $SU(3)^5$ symmetry can be formally restored if one promotes the Yukawa couplings to “spurions” that transform in the following way

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the Yukawa interactions are now formally flavor invariant

$$\mathcal{L} \supset H^c(\bar{Q} Y_u U) \ + \ H(\bar{Q} Y_d D) \ + \ H(\bar{L} Y_\ell E)$$

Minimal Flavor Violation

the SM Yukawas remain the only sources of flavor breaking
also in theories beyond the SM

Chivukula, Georgi '87; D'Ambrosio et al. '02

2HDMs with Minimal Flavor Violation

- expansion of the "wrong" Higgs couplings

$$\begin{aligned}
\tilde{y}_u &= \epsilon_u y_u + \epsilon'_u y_u y_u^\dagger y_u + \epsilon''_u y_d y_d^\dagger y_u + \ldots \\
\tilde{y}_d &= \epsilon_d y_d + \epsilon'_d y_d y_d^\dagger y_d + \epsilon''_d y_u y_u^\dagger y_d + \ldots \\
\tilde{y}_\ell &= \epsilon_\ell y_\ell + \epsilon'_\ell y_\ell y_\ell^\dagger y_\ell + \ldots
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- still Flavor Changing Neutral Currents at tree level, but controlled by small Yukawas and CKM elements

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Exercise part 1:
demonstrate that these terms are formally invariant under the flavor group

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$$

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Exercise part 1:
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Exercise part 2:
rotate into the quark mass eigenstate basis and show that off-diagonal entries in $\tilde{y}_u$ and $\tilde{y}_d$ are suppressed by small CKM elements

Coming Back to the SM Flavor Puzzle

Maybe the first and second generation are light, because they get their mass from a subdominant source of electroweak symmetry breaking

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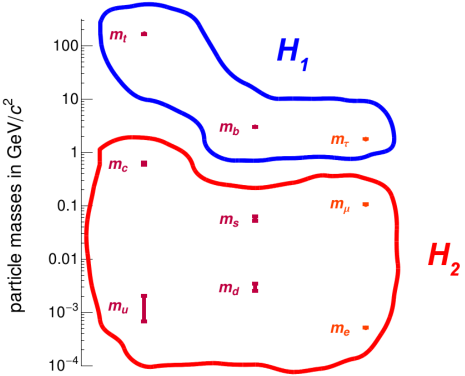
simple realization in the context of 2HDMs



one Higgs is responsible for the masses of the heaviest flavors

a second Higgs gives mass to the light flavors and is responsible for flavor mixing

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Flavor Constraints

The strongest flavor constraints typically come from transitions between the second and first generation

$$s \leftrightarrow d \;:\quad \text{Kaon mixing}$$

$$d \leftrightarrow u \;:\quad \text{D meson mixing}$$

$$\mu \leftrightarrow e \;:\quad \mu \to e\gamma \;,\;\; \mu \to e \text{ conversion}$$

Models with an $SU(2)^5$ flavor symmetry acting on the first two generations tend to be largely safe from flavor constraints

$SU(2)^5$ in a 2HDM Context

$$\lambda_{u_{1,2}} \sim \frac{\sqrt{2}}{v_{u_{1,2}}} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix} , \qquad \lambda_{u_3} \sim \frac{\sqrt{2}}{v_{u_3}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$\lambda_{d_{1,2}} \sim \frac{\sqrt{2}}{v_{d_{1,2}}} \begin{pmatrix} m_d & \lambda m_s & \lambda^3 m_b \\ m_d & m_s & \lambda^2 m_b \\ m_d & m_s & m_s \end{pmatrix} , \quad \lambda_{d_3} \sim \frac{\sqrt{2}}{v_{d_3}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

$$\lambda_{\ell_{1,2}} \sim \frac{\sqrt{2}}{v_{\ell_{1,2}}} \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix} , \qquad \lambda_{\ell_3} \sim \frac{\sqrt{2}}{v_{\ell_3}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

Suppression of FCNCs

$$\mathcal{M}_0^u \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix} ~,~~ \mathcal{M}_0^d \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix} ~,~~ \mathcal{M}_0^\ell \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

The rank 1 Yukawa couplings preserve a $SU(2)^5$ flavor symmetry for the light two generations of quarks and leptons

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The rank 1 Yukawa couplings preserve a $SU(2)^5$ flavor symmetry for the light two generations of quarks and leptons

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

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

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

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

generic expectations for lepton flavor violating Higgs decays

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

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

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

Additional Flavor Violating Signatures

flavor violating
rare top decays with
branching ratios as large as

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

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

might be in reach of the
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lepton flavor violating rare B meson decays with sizable branching ratios

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

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

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

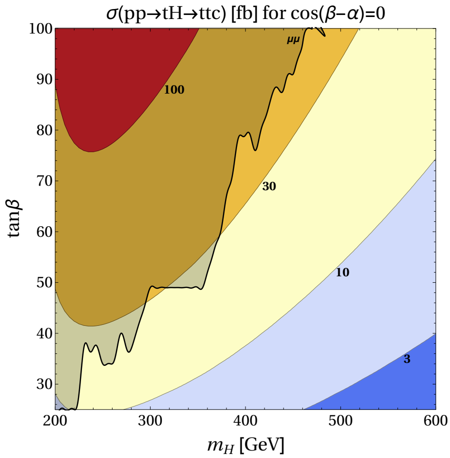
LHCb might be sensitive to the K^* and K rates

Couplings of the Heavy Higgses

Compare heavy Higgs couplings 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 $\kappa_\tau, \kappa_\mu, \kappa_e$
mixing with singlet	s_α	s_α	s_α	s_α
2HDM type 1	0	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
2HDM type 2	0	$\frac{1}{t_\beta}$	t_β	t_β
flavorful 2HDM	0	$\frac{1}{t_\beta}, t_\beta, t_\beta$	$\frac{1}{t_\beta}, t_\beta, t_\beta$	$\frac{1}{t_\beta}, t_\beta, t_\beta$

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



current most stringent constraint:
di-muon resonance searches
$pp \to H/A \to \mu^+\mu^-$
(gray shaded region)

Interesting signatures include:

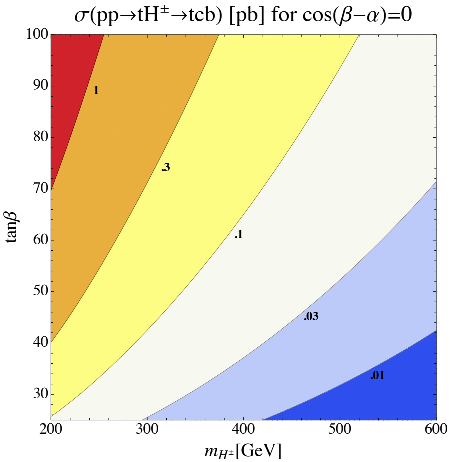
same sign tops
$pp \to tH/A \to tt\bar{c}$

di-jet resonances that are produced in association with a top
$pp \to tH/A \to tc\bar{c}$

flavor violating heavy Higgses
$pp \to H/A \to \tau\mu$
(also Sher, Thrasher 1601.03973; Buschmann et al. 1601.02616)

WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Non-Standard Collider Signatures for Charged Higgs



di-jet resonance searches
$pp \to H^\pm \to jj$
are currently only sensitive for very large $\tan\beta > 100$

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$pp \to tH^\pm \to tcb$
$pp \to tH^\pm \to tcs$

WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Other Ideas to Address the SM Flavor Puzzle

- "Private Higgs" (Porto, Zee 0712.0448),
  "Scalar Democracy" (Hill et al. 1902.07214)

  Each fermion gets its own Higgs; all hierarchies in the fermion masses are explained by hierarchies in the Higgs vev's.

- TeV scale Froggatt-Nielsen in 2HDM (Bauer, Carena, Gemmler 1506.01719)

  the two Higgs doublets jointly act as the flavon

  light fermion masses from higher dimensional operators; cut-off scale at few TeV.

- ...

Summary

Higgs Physics and Flavor Physics
are tightly connected
in the Standard Model and beyond.

It is very worthwhile to
continue exploring their interplay!