Flavorful Higgs Bosons

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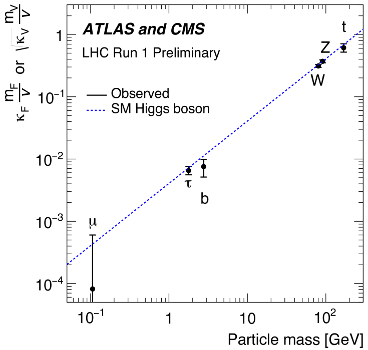
Outine

- Motivation
- Generic 2HDM
- Flavorful 2HDM
  - Yukawa Textures
  - Phenomenology of Heavy Higgs Bosons
- Constraints
  - Direct searches
  - Flavor transitions
- Summary

Discovery of the Higgs Boson

- Discovery of a 125 GeV particle announced on July 4th, 2012
- All evidence tells us that it is the Higgs boson of the SM
    - Gives mass to the W and Z bosons
    - Gives mass to t and b quarks, and τ lepton



ATLAS-CONF-2015-044

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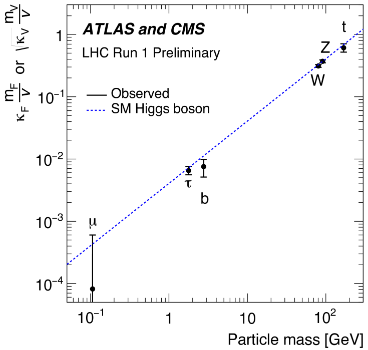
Consistent with SM predictions → 125 GeV particle is the SM Higgs



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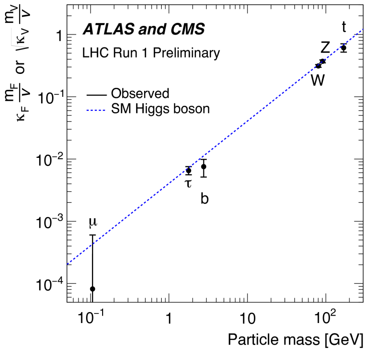
SM Higgs Couplings

- What about the quarks and leptons?
- 3rd generation couplings known with relatively small uncertainties
- Muon coupling is unknown
- Couplings to electron and light quarks are small and challenging to probe

  Altmannshofer et al., 1503.04830; Bodwin et al., 1306.5770; Kagan et al., 1406.1722



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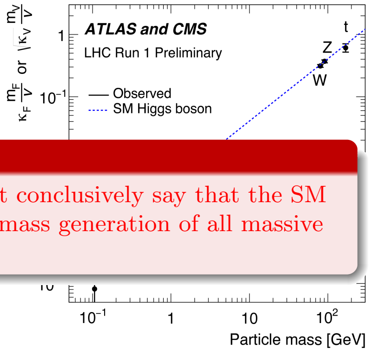

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Conclusion

Experimentally, we can't conclusively say that the SM Higgs is responsible for mass generation of all massive SM particles

Complementary Approach

- We don't know what the Higgs couplings are to lighter generations: What else can we do?

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- Complementary approach: *What if the SM Higgs is not the source of mass for the lighter generations?*

Proposal

The origin of mass of the 1st and 2nd generation fermions is *not* the 125 GeV Higgs but an additional source of EWSB

Generic Two Higgs Doublet Model

- Φ , Φ' with mixing angles α and β giving rise to five physical states
  - Two CP-even scalars, h and H
  - One CP-odd scalar, A
  - Two charged Higgs, $H^{\pm}$
- Most general Yukawa Lagrangian is

$$-\mathcal{L}_Y = \sum_{i,j}\left(\lambda^u_{ij}(\bar{q}_i u_j)\tilde{\Phi} + \lambda^d_{ij}(\bar{q}_i d_j)\Phi + \lambda^e_{ij}(\bar{\ell}_i e_j)\Phi\right) + H.C$$

$$\sum_{i,j}\left(\lambda'^u_{ij}(\bar{q}_i u_j)\tilde{\Phi}' + \lambda'^d_{ij}(\bar{q}_i d_j)\Phi' + \lambda'^e_{ij}(\bar{\ell}_i e_j)\Phi'\right) + H.C$$

- Fermion mass matrices

$$\mathcal{M}^u = \frac{1}{\sqrt{2}}(v\lambda^u + v'\lambda'^u),\ \mathcal{M}^d = \frac{1}{\sqrt{2}}(v\lambda^d + v'\lambda'^d),\ \mathcal{M}^e = \frac{1}{\sqrt{2}}(v\lambda^e + v'\lambda'^e)$$

- Can not diagonalize mass and Yukawa matrices simultaneously $\rightarrow$ flavor changing neutral Higgs couplings

Yukawa Textures

- So far, everything we've done is completely general and holds in any 2HDM.
- We can consider different Yukawa textures.

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Main Assumption

The main assumption of this setup is that the Yukawa couplings of Φ are rank 1, and provide mass to only one generation of fermions

Yukawa Textures

- Lepton sector

$$\lambda^{\ell} \sim \frac{\sqrt{2}}{v} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \lambda'^{\ell} \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix}$$

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- Quark Sector
  - Must also reproduce the CKM matrix!
  - Assume that the quark mixing is generated from down quark Yukawas → Up quark Yukawa texture analogous to leptons

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$$\lambda^d \sim \frac{\sqrt{2}}{v}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \lambda'^d \sim \frac{\sqrt{2}}{v'}\begin{pmatrix} m_d & \lambda m_s & \lambda^3 m_b \\ m_d & m_s & \lambda^2 m_b \\ m_d & m_s & m_s \end{pmatrix}$$

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This Yukawa texture naturally gives the observed quark and lepton masses

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$v' \ll v$ naturally gives some mass hierarchy between 2nd and 3rd generations

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Off diagonal couplings are naturally suppressed in this model

Phenomenological Consequences

- This Yukawa structure has some interesting phenomenological consequences

	κ_τ	κ_μ	κ_e
h	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$-\frac{s_\alpha}{c_\beta}$
H	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$	$t_\beta \frac{c_\alpha}{s_\beta}$
A	$\frac{1}{t_\beta}$	$-t_\beta$	$-t_\beta$
$H^\pm$	$\frac{1}{t_\beta}$	$-t_\beta$	$-t_\beta$

- $\tan\beta$ enhancement in the couplings of the 1st and 2nd generations
- $\tan\beta$ suppression in the couplings to the 3rd generations

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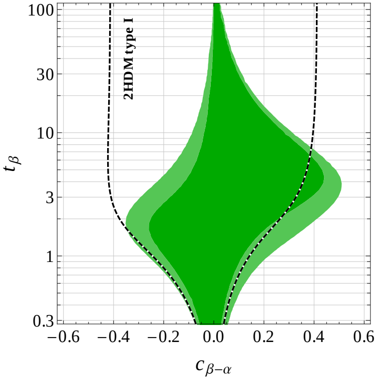
- $\tan\beta$ enhancement in the couplings of the 1st and 2nd generations
- $\tan\beta$ suppression in the couplings to the 3rd generations
- *Decays do not primarily have to be to 3rd generation fermions. Branching ratios involving 2nd generation quarks and leptons can become sizable*
- *Production cross sections involving 2nd generation quarks become sizable*

Constraints from SM Higgs

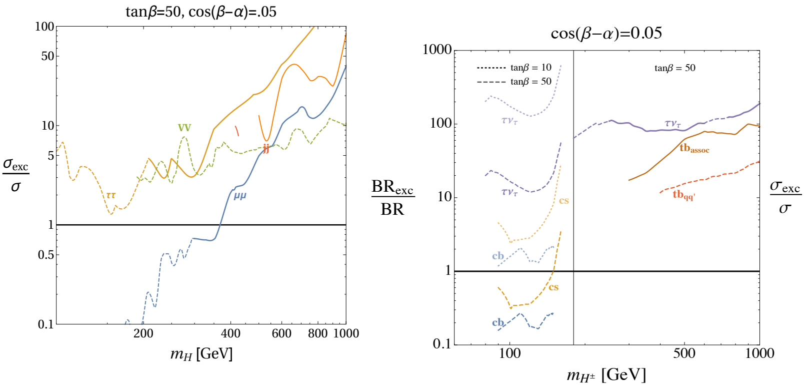
- Combine production mechanisms and branching ratios to construct a χ^2 function: $\Delta\chi^2 = \chi^2 - \chi^2_{SM}$



W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, DT, 1610.02398

Collider Constraints

- In currently studied theories, we expect third generation to be the most constraining. This is not the case in our model.



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What about flavor?
Meson Oscillations

- FCNCs → Is this model safe from constraints on flavor observables?
- Compute NP contribution to meson mixing using EFT. For B-meson mixing

$$\mathcal{H}_{eff}^{NP} = C_2(\bar{b}_R s_L) + \tilde{C}_2(\bar{b}_L s_R) + C_4(\bar{b}_L s_R)(\bar{b}_R s_L)$$

where

$$C_2 = \frac{(m'_{sb})^2}{2v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c_{\beta-\alpha}^2}{m_h^2} + \frac{s_{\beta-\alpha}^2}{m_H^2} - \frac{1}{m_A^2}\right)$$

$$\tilde{C}_2 = \frac{(m'^*_{bs})^2}{2v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c_{\beta-\alpha}^2}{m_h^2} + \frac{s_{\beta-\alpha}^2}{m_H^2} - \frac{1}{m_A^2}\right)$$

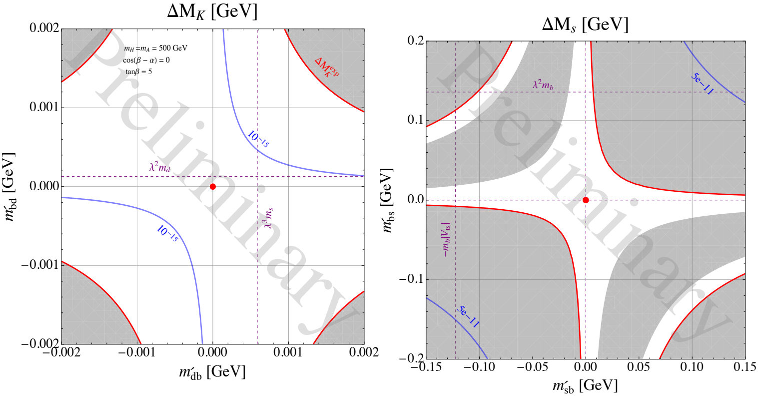
$$C_4 = \frac{(m'_{bs})(m'_{bs})^*}{2v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c_{\beta-\alpha}^2}{m_h^2} + \frac{s_{\beta-\alpha}^2}{m_H^2} - \frac{1}{m_A^2}\right)$$

- For kaon mixing $m'_{sb} \to m'_{ds}, m'_{bs} \to m'_{sd}$.

Meson Oscillations

Meson mixing can be quantified by the mass difference

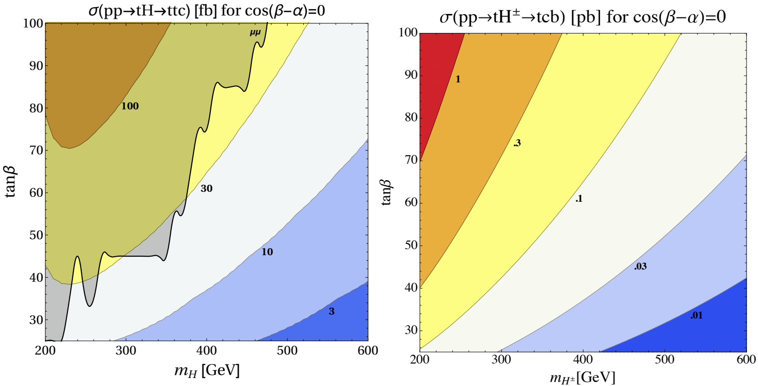
$$\Delta M_K = 2\,\mathrm{Re}\langle \bar{K}^0|\mathcal{H}_{eff}|K^0\rangle, \quad \Delta M_s = 2|\langle \bar{B}_s^0|\mathcal{H}_{eff}|B_s^0\rangle|)$$



W.Altmannshofer, S.Gori, D.Robinson, DT, in preparation.

New Signatures

- We have some constraints, but parameter space is still available. What new searches can be performed?



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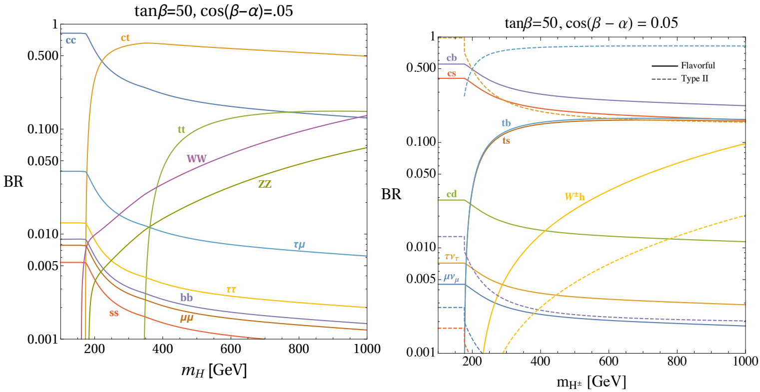
- Many other interesting signatures
  - $pp \to H/A \to \tau\nu$, $pp \to tcH/A, H/A \to \tau\nu$
  - $pp \to tH^\pm, H^\pm \to cs$, $pp \to tH^\pm, H^\pm \to \mu\nu$,

Summary

- Experimentally, we don't know if the Higgs gives mass to all massive particles.
- Complimentary approach: the 125 GeV Higgs is not the main source of mass for the 1st and 2nd generation quarks and leptons
  - 2HDM with non-standard Yukawa texture
- Results in interesting phenomenology
  - Couplings of heavy Higgses to 1st and 2nd generation are enhanced → distinct production and decay modes of heavy Higgses
- Constraints:
  - High energy: 2nd generation quarks and leptons for both H and $H^{\pm}$; relatively weak constraints.
  - Low energy: Stronger constraints from B_s meson mixing on Yukawa matrices. Parameter space is still available!
- New signatures can have sizable cross sections and can be searched for in colliders

Thank you!

Backup Slides



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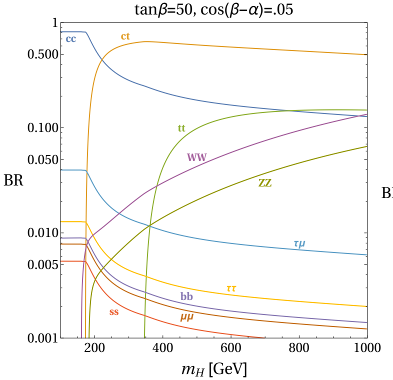
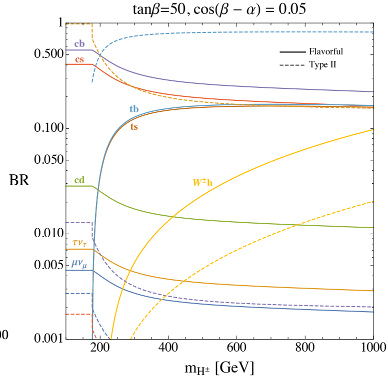
Phenomenology

Decays





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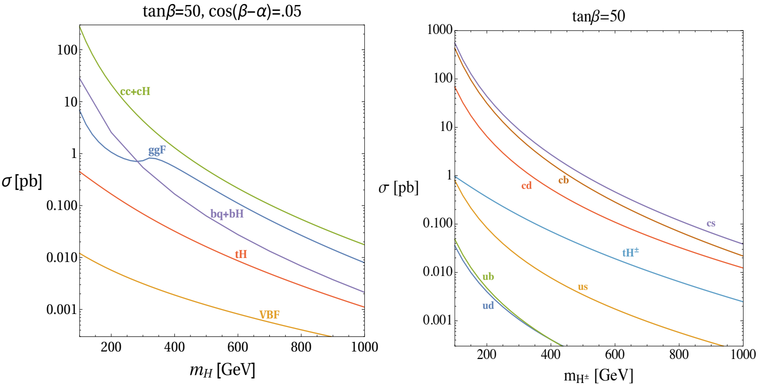
Decay modes involving second generation quarks can be dominant!

Phenomenology
Production



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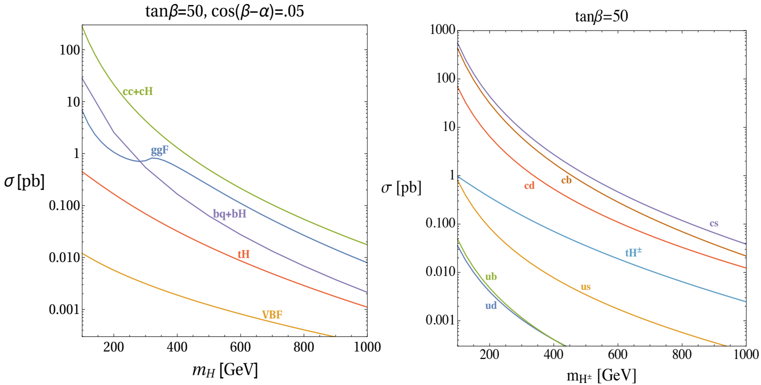

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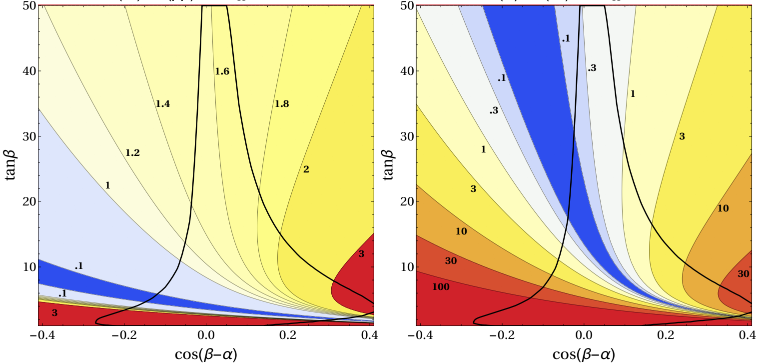
Production modes involving second generation quarks can be dominant!

Heavy Neutral Higgs

Decays

BR($\tau\tau$)/BR($\mu\mu$) for m_H=500 GeV — BR(tt)/BR(cc) for m_H=500 GeV



W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, DT, in preparation

Generic Two Higgs Doublet Model

- Consider two Higgs doublets Φ and Φ'

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \phi + ia) \end{pmatrix}, \Phi' = \begin{pmatrix} \phi'^+ \\ \frac{1}{\sqrt{2}}(v' + \phi' + ia') \end{pmatrix}$$

- $v^2 + v'^2 = v_W^2 = (246 \text{ GeV})^2$ and $t_\beta = \frac{v}{v'}$
- The most generic potential can be written as

$$\begin{aligned} V = \ & m_\Phi^2 \Phi^\dagger \Phi + m_{\Phi'}^2 \Phi'^\dagger \Phi' + \lambda_1 \left(\Phi^\dagger \Phi\right)^2 + \lambda_2 \left(\Phi'^\dagger \Phi'\right)^2 + \lambda_3 \left(\Phi^\dagger \Phi\right)\left(\Phi'^\dagger \Phi'\right) \\ & + \lambda_4 \left(\Phi'^\dagger \Phi\right)\left(\Phi^\dagger \Phi'\right) + \Bigg(- \mu^2 \left(\Phi^\dagger \Phi'\right) + \frac{\lambda_5}{2} \left(\Phi^\dagger \Phi'\right)^2 + \lambda_6 \left(\Phi^\dagger \Phi'\right)\left(\Phi^\dagger \Phi\right) \\ & + \lambda_7 \left(\Phi^\dagger \Phi'\right)\left(\Phi'^\dagger \Phi'\right) + H.c \Bigg). \end{aligned}$$

- After EWSB, Φ and Φ' mix

$$\begin{pmatrix} \phi^+ \\ \phi'^+ \end{pmatrix} = \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & -\sin\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix},$$

$$\begin{pmatrix} a \\ a' \end{pmatrix} = \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & -\sin\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix},$$

$$\begin{pmatrix} \phi \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}.$$

- G^0, $G^\pm$ are eaten up by the Z and $W^\pm$ gauge bosons (as in the SM).
- Remaining physical states
  - Two CP-even scalars, h and H
  - One CP-odd scalar, A
  - Two charged Higgs, $H^\pm$

- Most general Yukawa Lagrangian is

$$-\mathcal{L}_Y = \sum_{i,j}\left(\lambda^u_{ij}(\bar{q}_i u_j)\tilde{\Phi} + \lambda^d_{ij}(\bar{q}_i d_j)\Phi + \lambda^e_{ij}(\bar{\ell}_i e_j)\Phi\right) + H.C$$
$$\sum_{i,j}\left(\lambda'^u_{ij}(\bar{q}_i u_j)\tilde{\Phi}' + \lambda'^d_{ij}(\bar{q}_i d_j)\Phi' + \lambda'^e_{ij}(\bar{\ell}_i e_j)\Phi'\right) + H.C$$

- Fermion mass matrices

$$\mathcal{M}^u = \frac{1}{\sqrt{2}}(v\lambda^u + v'\lambda'^u),\ \mathcal{M}^d = \frac{1}{\sqrt{2}}(v\lambda^d + v'\lambda'^d),\ \mathcal{M}^e = \frac{1}{\sqrt{2}}(v\lambda^e + v'\lambda'^e)$$

Yukawa Interactions
Physical Higgs boson

Rotate to physical Higgses, fermion mass eigenstate basis

$$
\begin{aligned}
\mathcal{L}_Y = &- \sum_{i,j} (\bar{u}_i P_R u_k)(h(Y_h^u)_{ij} + H(Y_H^u)_{ij} + iA(Y_A^u)_{ij}) \\
&- \sum_{i,j} (\bar{d}_i P_R d_j)(h(Y_h^d)_{ij} + H(Y_H^d)_i j + iA(Y_A^d)_{ij}) \\
&- \sum_{i,j} (\bar{\ell}_i P_R \ell_j)(h(Y_h^\ell)_{ij} + H(Y_H^\ell)_{ij} + iA(Y_A^\ell)_{ij}) \\
&- \sum_{i,j} \sqrt{2}\big((\bar{d}_i P_R u_j) H^-(Y_\pm^u))ij + (\bar{u}_i P_R d_j) H^-(Y_\pm^d))ij \\
&\qquad + (\bar{\nu}_i P_R \ell_j) H^-(Y_\pm^\ell) ij\big) + h.c
\end{aligned}
$$

Yukawa Couplings

Some notation

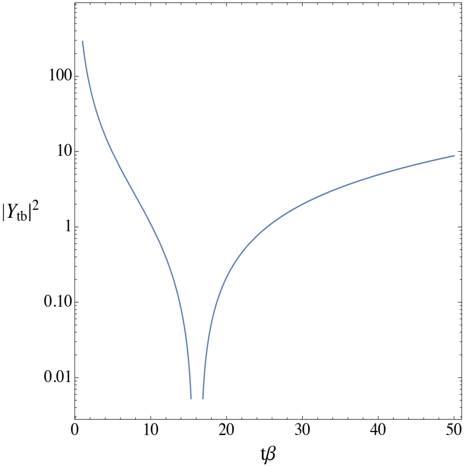
$$m'_{qq'} = \langle q_L | \mathcal{M}^u_{\Phi'} | q'_R \rangle, \quad \text{for } q, q' \in \{u, c, t\}$$
$$m'_{qq'} = \langle q_L | \mathcal{M}^d_{\Phi} | q'_R \rangle, \quad \text{for } q, q' \in \{d, s, b\}$$
$$m'_{\ell\ell'} = \langle \ell_L | \mathcal{M}^\ell_{\Phi'} | \ell'_R \rangle, \quad \text{for} \ell, \ell' \in \{e, \mu, \tau\}.$$

Yukawa Couplings

	Y_ℓ	Y_q	$Y_{\ell\ell'}$	$Y_{qq'}$
h	$\frac{m_\ell}{v_W}\left(\frac{c_\alpha}{s_\beta} - \frac{m'_{\ell\ell}}{m_\ell}\frac{c_{\beta-\alpha}}{s_\beta c_\beta}\right)$	$\frac{m_q}{v_W}\left(\frac{c_\alpha}{s_\beta} - \frac{m_{qq'}}{m_q}\frac{c_{\beta-\alpha}}{s_\beta c_\beta}\right)$	$-\frac{m'_{\ell\ell'}}{v_W}\frac{c_{\beta-\alpha}}{s_\beta c_\beta}$	$-\frac{m'_{qq'}}{v_W}\frac{c_{\beta-\alpha}}{s_\beta c_\beta}$
H	$\frac{m_\ell}{v_W}\left(\frac{s_\alpha}{s_\beta} + \frac{m'_{\ell\ell}}{m_\ell}\frac{s_{\beta-\alpha}}{s_\beta c_\beta}\right)$	$\frac{m_q}{v_W}\left(\frac{s_\alpha}{s_\beta} + \frac{m'_{qq}}{m_q}\frac{s_{\beta-\alpha}}{s_\beta c_\beta}\right)$	$+\frac{m'_{\ell\ell'}}{v_W}\frac{s_{\beta-\alpha}}{s_\beta c_\beta}$	$+\frac{m'_{qq'}}{v_W}\frac{s_{\beta-\alpha}}{s_\beta c_\beta}$
A	$\frac{m_\ell}{v_W}\left(\frac{1}{t_\beta} - \frac{m'_{\ell\ell}}{m_\ell}\frac{1}{s_\beta c_\beta}\right)$	$\frac{m_q}{v_W}\left(\frac{1}{t_\beta} - \frac{m'_{qq}}{m_q}\frac{1}{s_\beta c_\beta}\right)$	$-\frac{m'_{\ell\ell'}}{v_W}\frac{1}{s_\beta c_\beta}$	$-\frac{m'_{qq'}}{v_W}\frac{1}{s_\beta c_\beta}$
$H^\pm$	$\frac{m_\ell}{v_W}\left(\frac{1}{t_\beta} - \frac{m'_{\ell\ell}}{m_\ell}\frac{1}{s_\beta c_\beta}\right)$		$\frac{m_{q'}}{v_W}\left(\frac{V^*_{qq'}}{t_\beta} - \sum_{x=d,s,b}\frac{m'_{xq'}}{m_{q'}}\frac{V_{qx}}{s_\beta c_\beta}\right)$ for $q \in$ {u,c,t} and $q' \in$ {d,s,b}	$\frac{m_{q'}}{v_W}\left(\frac{V^*_{q'q}}{t_\beta} - \sum_{x=u,c,t}\frac{m'_{xq'}}{m_{q'}}\frac{V_{xq}}{s_\beta c_\beta}\right)$ for $q \in$ {d,s,b} and $q' \in$ {u,c,t}

Yukawa Couplings

- Behavior of Yukawa couplings as a function of t_β



Comparison with Other 2HDMs

- These couplings are different than other 2HDMs. For example, define $\kappa_i \equiv \frac{Y_i}{Y_i^{SM}}$. Then, for the SM-like Higgs we have the following:

	W,Z κ_V	Up Quarks $\kappa_t, \kappa_c, \kappa_u$	Down Quarks $\kappa_b, \kappa_s, \kappa_d$	Leptons $\kappa_\tau, \kappa_\mu, \kappa_e$
Type I	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Type II	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
Flavorful	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$

- In general, the couplings in this model are not universal, as compared with 2HDMs with natural flavor conservation or flavor alignment.