Flavor of a light charged Higgs

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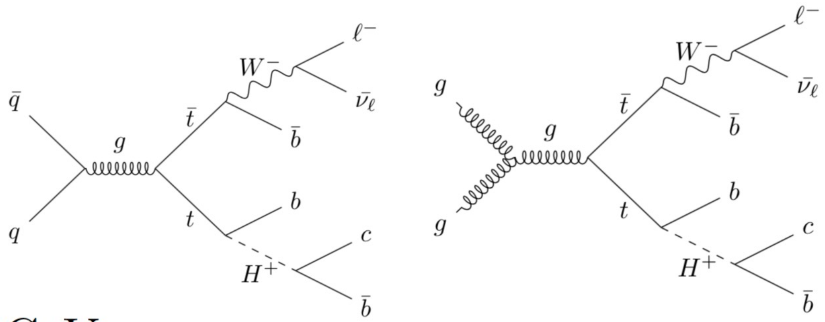
Introduction



- Recent experimental ATLAS result for search for light charged Higgs
- Weaker exclusion limit than expected @ $m_{H^\pm} = 130$ GeV

$$\mathrm{BR}(t \to H^+ b) \times \mathrm{BR}(H^+ \to c\bar{b}) = (1.6 \pm 0.6) \times 10^{-3}$$

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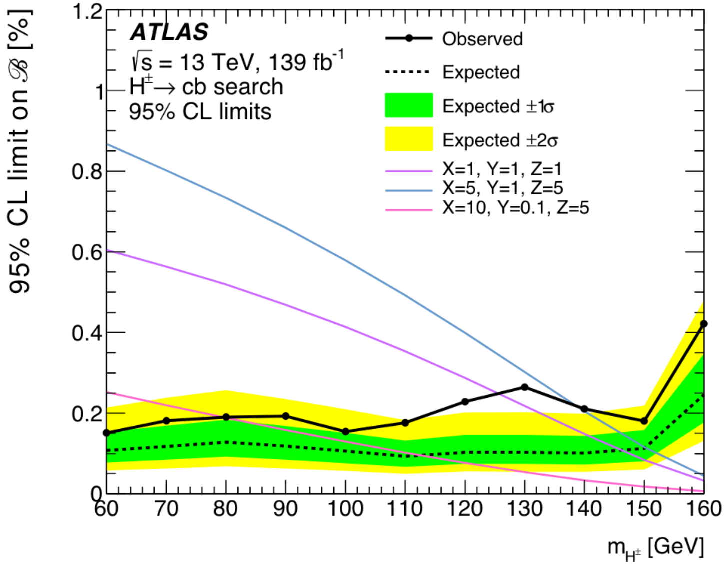


- Assuming this is realized in nature, what are the implications for multi-Higgs doublet models?
- Suppress FCNC via enforcing special flavor structures

Flavor Structures and open questions

- NFC: each fermion sector couples to a single scalar doublet
- MFV: $[U(3)]^5$ global symmetry of the kinetic terms is broken only by the three SM Yukawa matrices
- FN: approximate U(1) symmetry defines the structure of the Yukawa matrices
- A2HDM: each of the three Yukawa matrices is proportional to the corresponding mass matrix

Main questions:

What can we infer of the Yukawa matrices of extra scalars? Which would be the minimal set of Yukawa couplings?

Which experimental signals follow from these Yukawa couplings and could test this further?

What are the implications for the various flavor models ?

2HDM Model and notation

Y_S^F, $S = h$, H, and A — Yukawa matrices of the neutral physical scalars

$$Y_M^F = \frac{\sqrt{2}M^F}{v}, \quad (F = U, D, E)$$

Fermion mass matrices

The charged Higgs couplings are given by the Y_A^F couplings:

$$\mathcal{L}_{H^\pm} = -\overline{D_L} H^- Y_A^U U_R - \overline{U_L} H^+ Y_A^D D_R - \overline{\nu_L} H^+ Y_A^E E_R + \text{h.c.}.$$

The fermion mass matrices are given by

$$\mathcal{L}_{\text{mass}} = -\overline{U_L}(v/\sqrt{2}) Y_M^U U_R - \overline{D_L}(v/\sqrt{2}) Y_M^D D_R - \overline{E_L}(v/\sqrt{2}) Y_M^E E_R + \text{h.c.}.$$

2HDM

- Charged Higgs couplings in the mass basis:

$$\mathcal{L}_{H^\pm} = -\overline{D_L^M} H^- V^\dagger \hat{Y}_A^U U_R^M - \overline{U_L^M} H^+ V \hat{Y}_A^D D_R^M - \overline{\nu_L} H^+ \hat{Y}_A^E E_R^M + \mathrm{h.c.},$$

Where

$$\hat{Y}_A^U = V_{uL} Y_A^U V_{uR}^\dagger, \quad \hat{Y}_A^D = V_{dL} Y_A^D V_{dR}^\dagger, \quad \hat{Y}_A^E = V_{eL} Y_A^E V_{eR}^\dagger$$

define

$$\xi_f \equiv (\hat{Y}_A^F)_{ff} / y_f$$

$t \to H^+ b$ decay

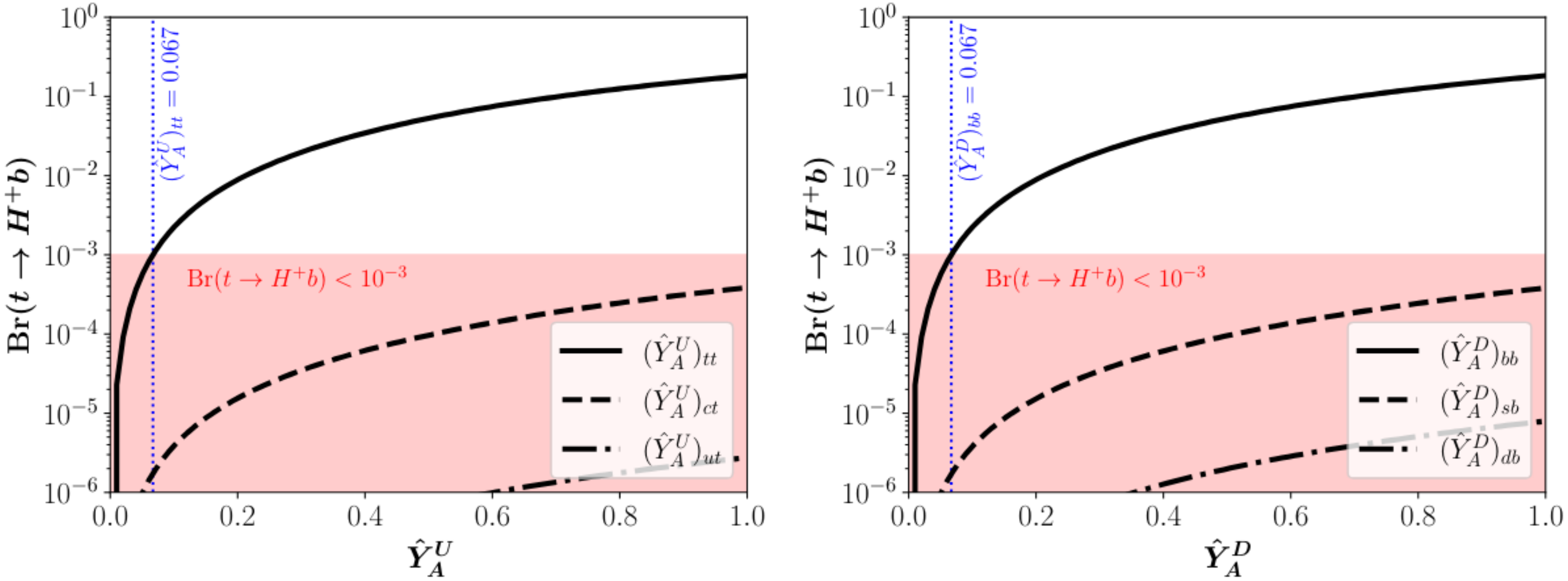
$x_{it} \equiv m_i^2/m_t^2$ and taking $x_{bt} \approx 0$

$$\mathrm{BR}(t \to H^+ b) = \frac{2(1-x_{Ht})^2\left[|(\hat{Y}_A^{U\dagger}V)_{tb}|^2 + |(V\hat{Y}_A^D)_{tb}|^2\right]}{g^2|V_{tb}|^2(1-x_{Wt})\left[1+1/x_{Wt}-2x_{Wt}\right]}$$

$$\mathrm{BR}(t \to H^+ b) \geq 1 \times 10^{-3}$$

Plugging in mass, couplings and matrix element values, we are left with the Yukawa alignment limit of 2HDM, and CKM dependence cancels.

$$\mathrm{BR}(t \to H^+ b) = 0.22 \times \left[|(\hat{Y}_A^{U\dagger}V)_{tb}|^2 + |(V\hat{Y}_A^D)_{tb}|^2\right]$$



For $\mathrm{BR}(H^+ \to c\bar{b}) = 1$

there are upper bounds

$H^+ \to$ cb decay

$$\mathrm{BR}(H^+ \to c\bar{b}) \gtrsim 5 \times 10^{-3}$$

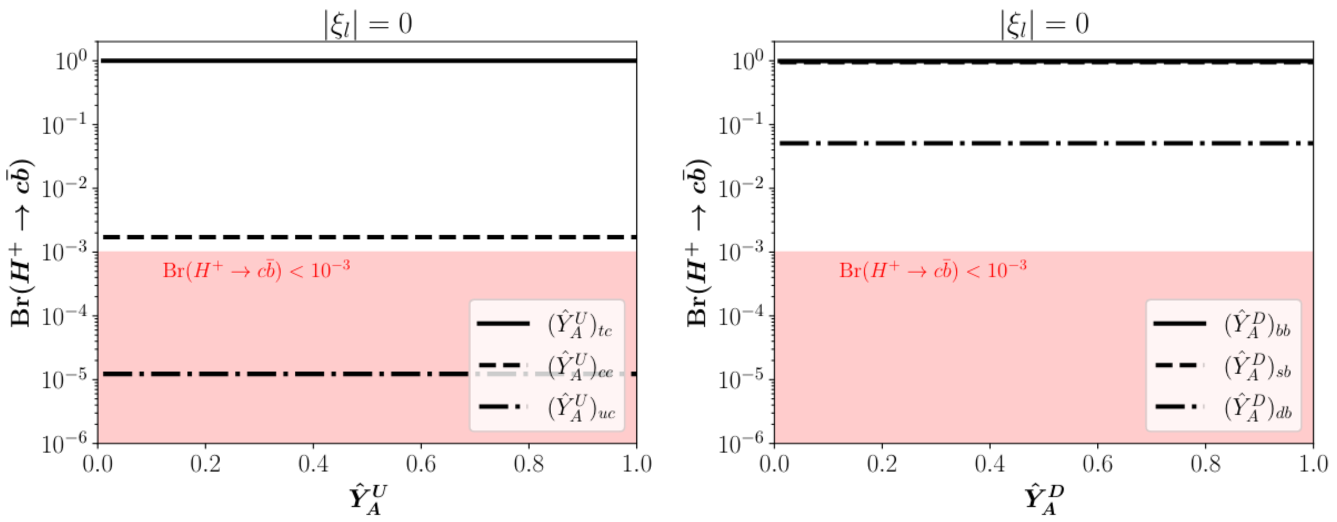
Additional experimental upper bounds on:

$$\mathrm{BR}(t \to H^+ b) \times \mathrm{BR}(H^+ \to c\bar{b} + c\bar{s}) \leq 2.7 \times 10^{-3},$$

$$\mathrm{BR}(t \to H^+ b) \times \mathrm{BR}(H^+ \to \tau^+ \nu_j) \leq 1.5 \times 10^{-3}$$

$$\frac{\Gamma(H^+ \to c\bar{b})}{\Gamma(H^+ \to c\bar{s})} = \frac{|(\hat{Y}_A^U)_{ic} V_{ib}|^2 + |V_{ci}(\hat{Y}_A^D)_{ib}|^2}{|(\hat{Y}_A^U)_{ic} V_{is}|^2 + |V_{ci}(\hat{Y}_A^D)_{is}|^2} \gtrsim 0.6,$$

$$\frac{\Gamma(H^+ \to c\bar{b})}{\Gamma(H^+ \to \tau^+ \nu_j)} \approx \frac{3(|(\hat{Y}_A^U)_{ic} V_{ib}|^2 + |V_{ci}(\hat{Y}_A^D)_{ib}|^2)}{|(\hat{Y}_A^E)_{j\tau}|^2} \gtrsim 0.7$$



- $(\hat{Y}_A^U)_{cc}$ and $(\hat{Y}_A^U)_{uc}$ cannot play a dominant role in explaining the experimental result.
- A single entry, $(\hat{Y}_A^D)_{bb} \sim 0.07$, and all other entries in $\hat{Y}_A^U$ and $\hat{Y}_A^D$ negligibly small, can explain the experimental result.
- The experimental result can be explained in the aligned limit, but requires $|(\hat{Y}_A^U)_{cc}/(\hat{Y}_A^D)_{bb}| \lesssim |V_{cb}/V_{cs}| \sim 0.05$ and $|(\hat{Y}_A^E)_{\tau\tau}/(\hat{Y}_A^D)_{bb}| \lesssim 2|V_{cb}| \sim 0.09$.

FCNC constraints

Focus on contributions to FCNC from charged scalars.

- b → sγ and t → cγ: constrain products of $\hat{Y}_A^U$ and $\hat{Y}_A^D$

$$\begin{aligned} \mathrm{BR}(b \to s\gamma)^{H^+}_{E_\gamma > 1.6\ \mathrm{GeV}} &= (0.13 \pm 0.30) \times 10^{-4} \\ &= -1.9 \times 10^{-4} \times \mathcal{R}e(\xi_t \xi_b) \end{aligned}$$

$$-0.22 \lesssim \mathcal{R}e(\xi_t \xi_b) \lesssim +0.09$$

- t → cγ

$$\begin{aligned} \mathrm{BR}(t \to c\gamma) &= \frac{m_t^5}{4\pi\Gamma_t}\left(\frac{5e}{1152\pi^2 m_{H^+}^2}\right)^2 (y_t y_b)^2 |V_{tb} Y_{cb}^*|^2 |\xi_t \xi_b|^2 \\ &\approx 5.7 \times 10^{-7} (y_t y_b)^2 |V_{tb} Y_{cb}^*|^2 |\xi_t \xi_b|^2 \sim 2.6 \times 10^{-13} |\xi_t \xi_b|^2 \end{aligned}$$

Way below experimental sensitivity of ~ 10^{-5}

FCNC constraints

- D meson mixing: contribution when $(\hat{Y}_A^D)_{bb} \neq 0$

Experimental value of the mass splitting between the neutral D-meson mass eigenstates:

$$\Delta m_D/\Gamma_D = (4.1 \pm 0.5) \times 10^{-3}$$

$$\Delta m_D^{H^+}/\Gamma_D \approx 3 \times 10^{-10}\,(\xi_b)^2 + 7.6 \times 10^{-12}\,(\xi_b)^4$$

For $m_{H^+} = 130$ GeV,

$$\xi_b \lesssim 90.$$

- B meson mixing: contribution when

$(\hat{Y}_A^U)_{tt} \neq 0$

Exp. Value: $\Delta m_B/\Gamma_B = 0.769 \pm 0.004.$

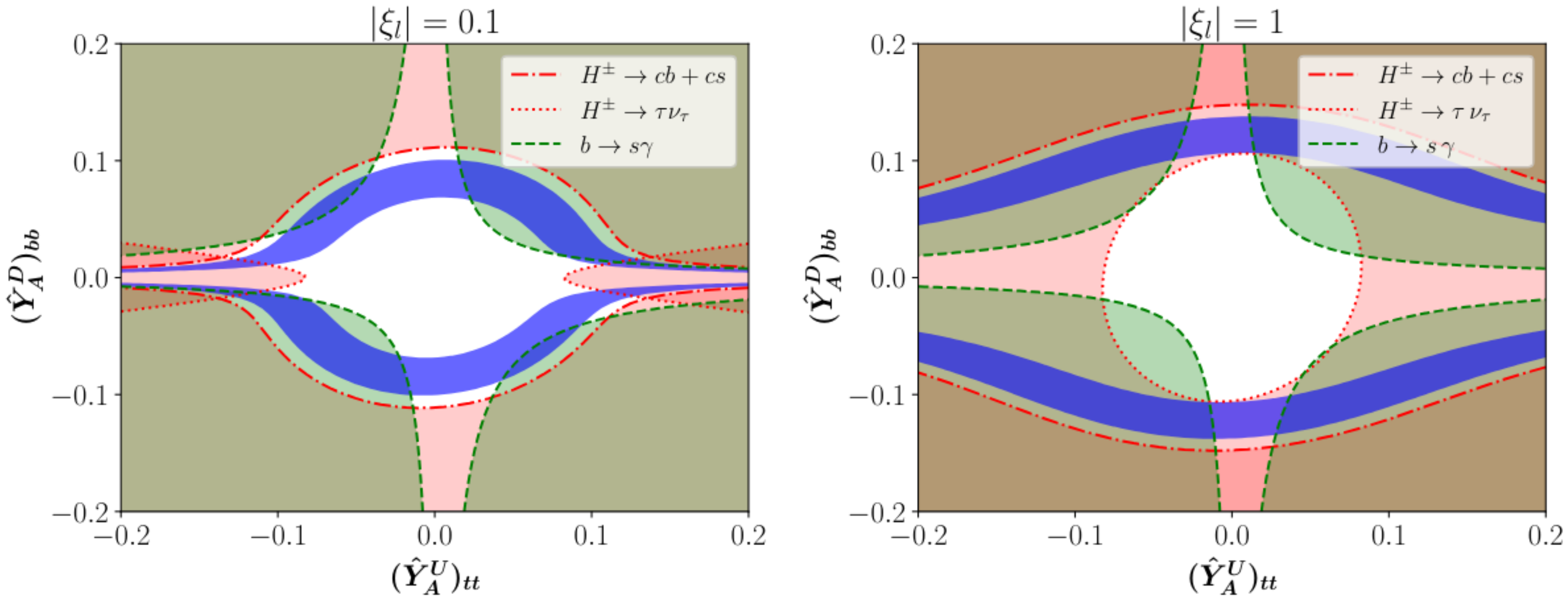
$$\Delta m_B^{H^+}/\Gamma_B \approx 3.0\,(\xi_t)^2 + 0.26\,(\xi_t)^4$$

For $m_{H^+} = 130$ GeV,

$$\xi_t \lesssim 0.2.$$

Summary of constraints

Most significant constraints considering only third generation fermions summed up in these plots.



Flavor models

- 2HDM with NFC

$$\mathcal{L}_Y = \overline{Q}\widetilde{\Phi}_u Y^U U + \overline{Q}\Phi_d Y^D D + \overline{L}\Phi_e Y^E E$$

$$\hat{Y}_A^F = \xi_F \hat{Y}_M^F,$$

Charged Higgs contributions to some observables are independent of ξ_F for certain NFC models

- Type I: $\xi_U = \xi_D = -\xi_E$.
- Type II: $\xi_U = 1/\xi_D = 1/\xi_E$.
- Type III: $\xi_U = -\xi_D = 1/\xi_E$.
- Type IV: $\xi_U = 1/\xi_D = -\xi_E$.

$$\mathrm{BR}(b \to s\gamma)^{H^+ t}_{E_\gamma > 1.6\ \mathrm{GeV}} = -1.9 \times 10^{-4} \quad \text{(Type II and Type IV)}$$

$H^+ \to c\bar{b} + c\bar{s}$:

$$\frac{\Gamma(H^+ \to c\bar{b})}{\Gamma(H^+ \to c\bar{s})} \approx \left|\frac{V_{cb}}{V_{cs}}\right|^2 \frac{m_b^2}{m_c^2} \sim 0.09 \quad \text{(Type I and Type III)}$$

$H^+ \to \tau^+\nu_\tau$:

$$\frac{\Gamma(H^+ \to c\bar{b})}{\Gamma(H^+ \to \tau^+\nu_\tau)} \approx 3|V_{cb}|^2 \frac{m_b^2}{m_\tau^2} \sim 0.013 \quad \text{(Type I and Type II)}$$

Thus all four types of NFC would be excluded.

See also 2202.03522

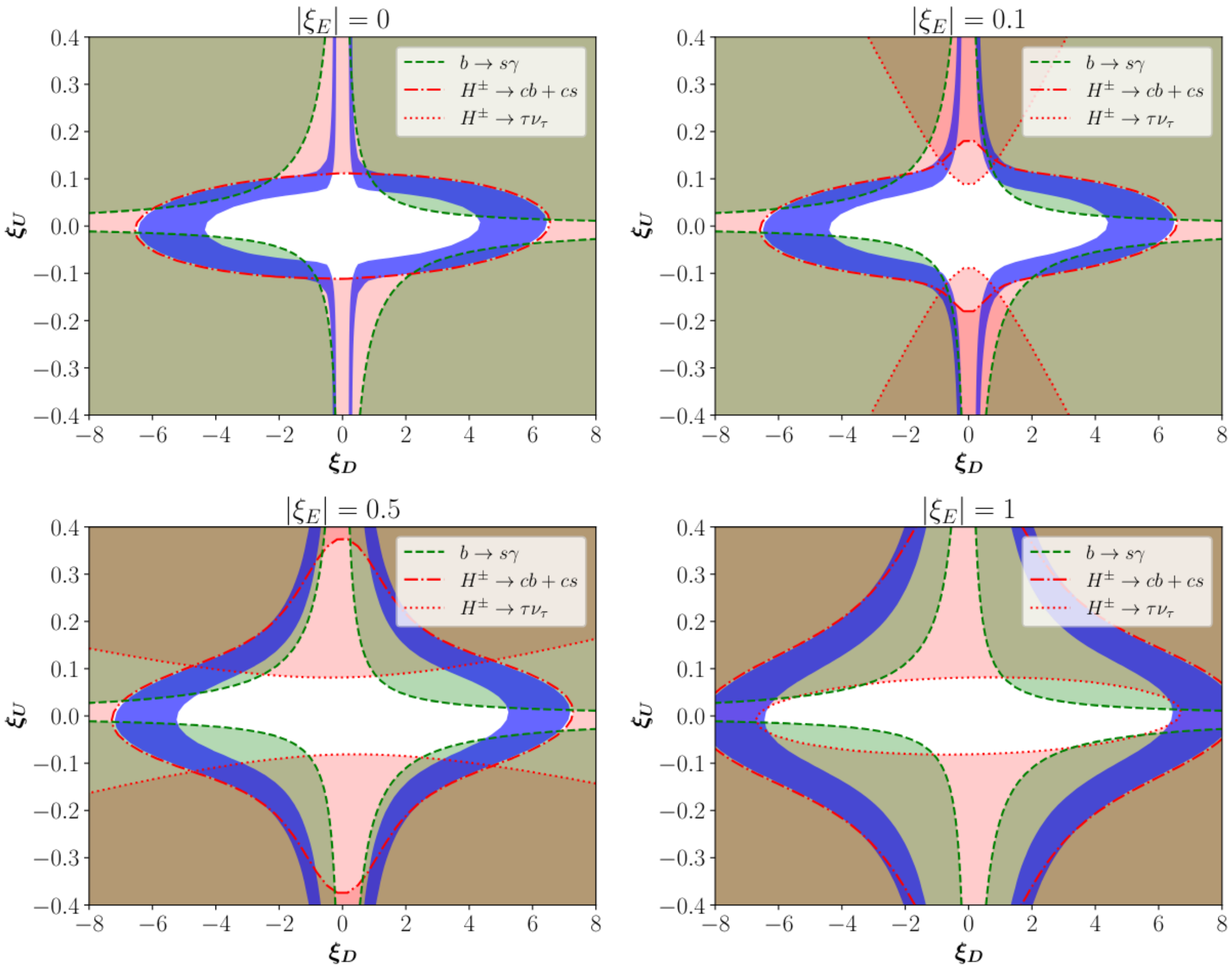
Flavor models

Consider now a 3HDM with NFC, such that

ξ_U, ξ_D and ξ_E are three independent parameters

Testable prediction in this case:

$$\frac{\Gamma(H^+ \to c\bar{s})}{\Gamma(H^+ \to c\bar{b})} = \left(\left|\frac{V_{cs}}{V_{cb}}\right| \frac{m_s}{m_b}\right)^2 \times \frac{1 + |(\xi_U/\xi_D)(m_c/m_s)|^2}{1 + |(\xi_U/\xi_D)(m_c/m_b)|^2} \gtrsim 0.22$$



MFV and FN

$$\hat{Y}_A^U = (\xi_U + \xi_U^{uu}\hat{Y}_M^U\hat{Y}_M^{U\dagger} + \xi_U^{dd}V\hat{Y}_M^D\hat{Y}_M^{D\dagger}V^\dagger)\hat{Y}_M^U$$
$$\hat{Y}_A^D = (\xi_D + \xi_D^{dd}\hat{Y}_M^D\hat{Y}_M^{D\dagger} + \xi_D^{uu}V^\dagger\hat{Y}_M^U\hat{Y}_M^{U\dagger}V)\hat{Y}_M^D$$
$$\hat{Y}_A^E = (\xi_E + \xi_E^{ee}\hat{Y}_M^E\hat{Y}_M^{E\dagger})\hat{Y}_M^E,$$

Linear terms give same effect as the 3HDM-NFC

ξ_U^{dd} and ξ_D^{uu} lead to off-diagonal $\hat{Y}_A^F$, can contribute to $t \to H^+ b$ decay and $H^+ \to c\bar{s}$, but are negligible

$H^+ \to c\bar{b}$ decay

$(\hat{Y}_A^D)_{sb}$ coupling might contribute comparably to $(\hat{Y}_A^D)_{bb}$

For generation diagonal processes MFV essentially like 3HDM-NFC, for generation off-diagonal processes can be O(1) deviations from 3HDM-NFC case.

MFV can accommodate signal in parameter space like that of the 3HDM-NFC.

MFV and FN

2HDM with a FN symmetry (2DHM-FN), $\epsilon_{\rm FN} \lesssim 10^{-3}$ is required. To zeroth order in $\epsilon_{\rm FN}$, the FN mechanism results in NFC-like Yukawa matrices

2HDM-FN cannot explain experimental result

For 3HDM with FN symmetry, to first order in $\epsilon_{\rm FN}$,

$$(\hat{Y}_A^F)_{ii} = \xi_F y_i (1 + \epsilon_{\rm FN} \xi_i),$$
$$(\hat{Y}_A^F)_{ij} \sim \epsilon_{\rm FN}\ y_j V_{ij} \quad (j > i),$$
$$(\hat{Y}_A^F)_{ij} \sim \epsilon_{\rm FN}\ y_j / V_{ji} \quad (j < i).$$

Off diagonal couplings do not dominate the decays:

$$t \to H^+ b$$
$$H^+ \to c\bar{b}$$
$$H^+ \to c\bar{s}$$

3HDM-FN gives similar results to 3HDM-NFC

Minimal scenarios

A. Single coupling $(\hat{Y}_A^D)_{bb}$ coupling dominates both $t \to H^+ b$ and $H^+ \to c\bar{b}$

$$0.067 \lesssim (\hat{Y}_A^D)_{bb} \lesssim 0.10,$$

$$4 \lesssim \xi_b \lesssim 6$$

"*Nightmare scenario*", as there are no other unavoidable constraints:

- charmless H+ decay has a very small BR
- D meson mixing is very suppressed
- no contribution to FCNC decays

Implications for neutral scalars:

- no strong constraints from ggF production of A and H decaying into a pair of b quarks
- tree level bbA and bbH production, upper bound on ξ_b way above the allowed value

Next to minimal scenario

Two $\hat{Y}_A^U$ couplings:

- the $(\hat{Y}_A^U)_{tt}$ coupling accounts for $t \to H^+ b$
- the $(\hat{Y}_A^U)_{tc}$ dominates $H^+ \to c\bar{b}$.

With $\mathrm{BR}(t \to H^+ b) = (1.6 \pm 0.6) \times 10^{-3}$, while $\mathrm{BR}(H^+ \to c\bar{b}) \simeq 1$.

$$0.067 \lesssim (\hat{Y}_A^U)_{tt} \lesssim 0.10,$$

$(\hat{Y}_A^U)_{tc}$ coupling can assume any value

- The bottomless H^+ decay has a very small branching ratio:

$$\mathrm{BR}(H^+ \to c\bar{s}) \simeq |V_{ts}/V_{tb}|^2 \sim 2.5 \times 10^{-3}$$

- The bottomless top decay into H^+ has a negligibly small branching ratio:

$$\mathrm{BR}(t \to H^+ s) \simeq |V_{ts}/V_{tb}|^2 \mathrm{BR}(t \to H^+ b) \sim 5 \times 10^{-6}$$

- The H^+ contribution to $B^0 - \overline{B}^0$ mixing is of order $\Delta m_B^{H^+}/\Gamma_B \sim 0.013 - 0.03$, a factor of a few below the current upper bound.
- With $\xi_{b,s,d} \simeq 0$, there is no contribution to the radiative decays $b \to s\gamma$, $t \to c\gamma$ and $c \to u\gamma$.

Implications for neutral scalars A and H:

- dominant production mode ggF but suppresed compared to h

Relevant decay modes of the heavy neutral CP-odd scalar A and heavy neutral CP-even scalar H are $t\bar{t}$ and $t\bar{c} + c\bar{t}$.
Searches in the range $m_{A,H} = 400 - 750$ GeV, upper bounds on ξ_t of order $0.6 - 1$ are obtained, well above the required value.

- ttA and ttH production

For $m_{A,H} = 0.4 - 1$ TeV, upper bounds on ξ_t of order $0.7 - 1.6$

Conclusions

- If signal is established, then in a 2HDM, NFC, MFV and FN flavor structures are excluded.
- For 3HDM-NFC there is a lower bound $\frac{\Gamma(H^+ \to c\bar{s})}{\Gamma(H^+ \to c\bar{b})} \gtrsim 0.22$
- Minimal scenario:
  - has a single coupling dominating both decays, with value 4-6 times the SM bottom quark Yukawa coupling y_b.
  - heavy neutral scalars should be produced via pp → bbA and pp → bbH at rates which could reach at most a factor 10 below current bounds. The effects on FCNC processes, such as D0 − D0 mixing and t → cγ decay, are negligibly small.
- Next to minimal scenario:
  - constrains $(\hat{Y}_A^U)_{tt}$ = (0.067 − 0.1)y_t, while second coupling is not significantly constrained.
  - heavy neutral scalars should be produced via pp → ttA and pp → ttH at rates that could be at most a factor of 50 below current bounds.
  - For $m_{A,H}$ within the range (m_t+m_c, 2m_t), A and H appear as tc resonances.
  - For $m_{A,H} < m_t$, the top decays t → (A, H)c can be observable.
  - The charged Higgs contribution to B0 − B0 mixing is non-negligible and can be signaled by a deviation of order 2 − 5 percent from the SM prediction for Δm_B

Backup