Rare Top Decays as Probes of Flavorful Higgs Bosons

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based on arXiv:1904.10956
with Brian Maddock and Douglas Tuckler

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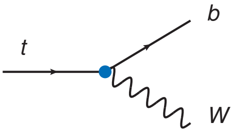
The Challenge

The dominant top decay mode is a
unsuppressed 2 body decay into a W boson and a b quark



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$$\rightarrow \frac{\Gamma_t}{m_t} \simeq 1\%$$

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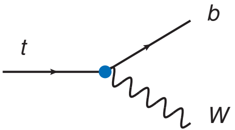

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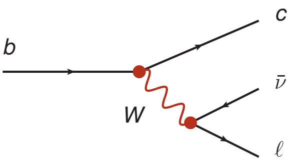
compare to B meson decay: 3 body + CKM suppression

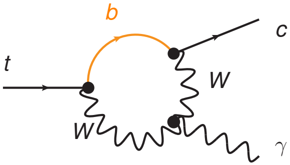


$$\Gamma_{b\to c\ell\nu} \sim \frac{g^4}{384\pi}\frac{1}{16\pi^2}\left(\frac{m_b}{m_W}\right)^4 |V_{cb}|^2 m_b$$

$$\rightarrow \frac{\Gamma_B}{m_B} \simeq 8.2 \times 10^{-13}$$

Top FCNCs in the Standard Model

top FCNCs are 1-loop suppressed, CKM suppressed
and strongly GIM suppressed



$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{m_W^2}V_{tb}V_{cb}^*$$

$$\to \quad \text{BR}(t \to c\gamma)_{\text{SM}} \simeq 5 \times 10^{-14}$$

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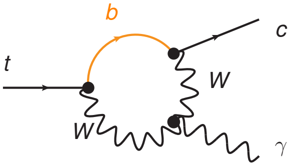

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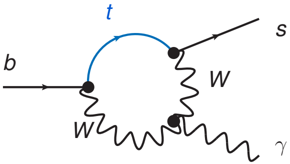
compare to rare B decays: GIM breaking by the large top mass



$$\mathcal{A}_{b\to s\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_t^2}{m_W^2} V_{tb}V_{ts}^*$$

$$\to \quad \text{BR}(B \to X_s\gamma)_{\text{SM}} \simeq 3.15 \times 10^{-4}$$

Standard Model Predictions

(Aguilar-Saavedra hep-ph/0409342)

$$\text{BR}(t \to c\gamma) \simeq 5 \times 10^{-14} \quad , \quad \text{BR}(t \to u\gamma) \simeq 4 \times 10^{-16}$$

$$\text{BR}(t \to cg) \simeq 5 \times 10^{-12} \quad , \quad \text{BR}(t \to ug) \simeq 4 \times 10^{-14}$$

$$\text{BR}(t \to cZ) \simeq 1 \times 10^{-14} \quad , \quad \text{BR}(t \to uZ) \simeq 8 \times 10^{-17}$$

$$\text{BR}(t \to ch) \simeq 3 \times 10^{-15} \quad , \quad \text{BR}(t \to uh) \simeq 2 \times 10^{-17}$$

[side note: these numbers come with large uncertainties from renormalization scale dependence of the bottom mass. In 1904.10956 we did a careful analysis and found

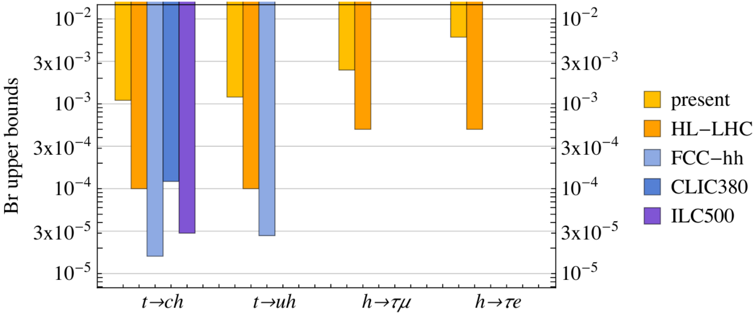
$$\text{BR}(t \to ch) = (4.19^{+1.08}_{-0.80} \pm 0.16) \times 10^{-15}$$

$$\text{BR}(t \to uh) \simeq (3.66^{+0.94}_{-0.70} \pm 0.67) \times 10^{-17} \quad]$$

For practical purposes, the SM predictions are vanishingly small.
Any observation in the foreseeable future
would be a clear sign of New Physics.

Experimental Status

European Strategy Physics Briefing Book 1910.11775



- Current constraint: BR($t \to qh$) $\lesssim 10^{-3}$.
- Can be improved by an order of magnitude at HL-LHC.
- A bit better for the other types of rare top decays, but not much.

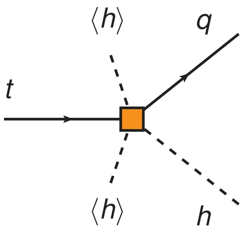
SMEFT Interpretation

- One can interprete the constraints on the $t \to ch$ and $t \to uh$ branching ratios as constraints on flavor changing Higgs couplings
- or, equivalently, on SMEFT operators that give flavor changing Higgs couplings

"Higgs penguin operators"

$$\frac{1}{\Lambda^2}(H^\dagger H)(\bar{c}_R Q_3)H^c$$

$$\frac{1}{\Lambda^2}(H^\dagger H)(\bar{Q}_2 t_R)H$$



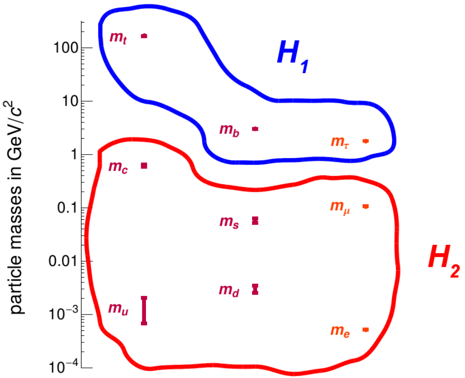
$$\frac{\text{BR}(t \to qh)}{\text{BR}(t \to bW)} \sim \frac{v^4}{\Lambda^4} \quad \Rightarrow \quad \Lambda \gtrsim 1\ \text{TeV}$$

Question for the Rest of the Talk

Is there a (not entirely unmotivated) model that gives flavor changing Higgs couplings saturating the constraints?

Flavorful Higgs Bosons I

Consider a 2HDM with non-trivial flavor structure



one Higgs is responsible for the masses of the heaviest flavors

(we assume it has rank-1 Yukawa couplings)

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

(could have rank-2 or rank-3 Yukawas)

WA, Gori, Kagan, Silvestrini, Zupan, PRD 93 (2016) no.3, 031301

Flavorful Higgs Bosons II

- The setup can address part of the hierarchies in the fermion masses $m_{1\text{st}}, m_{2\text{nd}} \ll m_{3\text{rd}}$ if $\tan\beta = v_1/v_2 \gg 1$

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- The setup goes beyond “natural flavor conservation” $\Rightarrow$ expect flavor changing neutral currents at tree level.
- The most constraining flavor probes are transitions between the first and second generation, e.g. $K^0 - \bar{K}^0$ mixing, or $\mu \to e\gamma$.
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- There are several variations of viable flavor structures.
- Main distinction: is the CKM matrix generated (mainly) in the up-sector or in the down-sector?

Example of an "Up-Sector Model"

WA, Maddock, Tuckler 1904.10956

Arguably the simplest choice to get rank-1 Yukawas for H_1:
charge H_1 and the 3 generation of LH quarks under a $U(1)$ symmetry.

Introduce a second $U(1)$ flavor symmetry to model
the remaining mass and mixing hierarchies

$$v\lambda_u \sim v_{\rm w} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \epsilon^{|a|} & \epsilon^1 & 1 \end{pmatrix}, \qquad v'\lambda'_u \sim v_{\rm w} \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^{|b|} & \epsilon^3 & \epsilon^2 \\ 0 & 0 & 0 \end{pmatrix},$$

$$v\lambda_d \sim v_{\rm w} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \epsilon^3 \end{pmatrix}, \qquad v'\lambda'_d \sim v_{\rm w} \begin{pmatrix} \epsilon^7 & \epsilon^6 & 0 \\ \epsilon^{|c|} & \epsilon^5 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

(Yukawas are uniquely determined up to a few discrete choices for the parameters a, b, c)

Predictions for Top Flavor Violation

- The resulting model turns out to be highly predictive.
- Flavor violating Higgs couplings are given by CKM matrix elements and quark mass ratios.
- Rare top branching ratios only depend on two parameters:

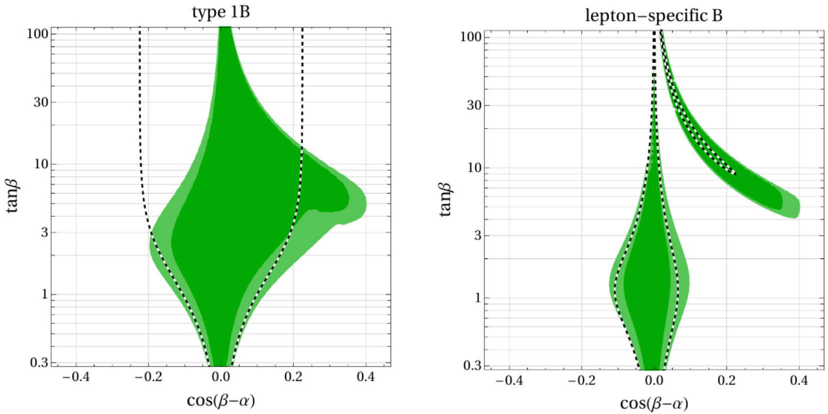
  tan β (ratio of the two vevs)
  α (mixing angle of the scalar Higgs bosons *h* and *H*)

$$\mathrm{BR}(t \to hq) \simeq 2|V_{qb}|^2 \frac{\cos^2(\beta-\alpha)}{\sin^2\beta\cos^2\beta} \frac{\left(1 - m_h^2/m_{t,\,\mathrm{pole}}^2\right)^2}{\left(1 - m_W^2/m_{t,\,\mathrm{pole}}^2\right)^2\left(1 + 2m_W^2/m_{t,\,\mathrm{pole}}^2\right)}$$

$$\simeq \frac{\cos^2(\beta-\alpha)}{\sin^2\beta\cos^2\beta} \times \begin{cases} 9.2 \times 10^{-4} & \text{for} \quad t \to hc \; , \\ 8.0 \times 10^{-6} & \text{for} \quad t \to hu \; . \end{cases}$$

Contraints from Higgs Precision Program

Precision measurements of Higgs production and decays
constrain the parameters $\tan\beta$ and α



WA, Maddock, Tuckler 1904.10956

(note: plots are 4 years old; current constraints will be somewhat more stringent.)

Rare Top Decays

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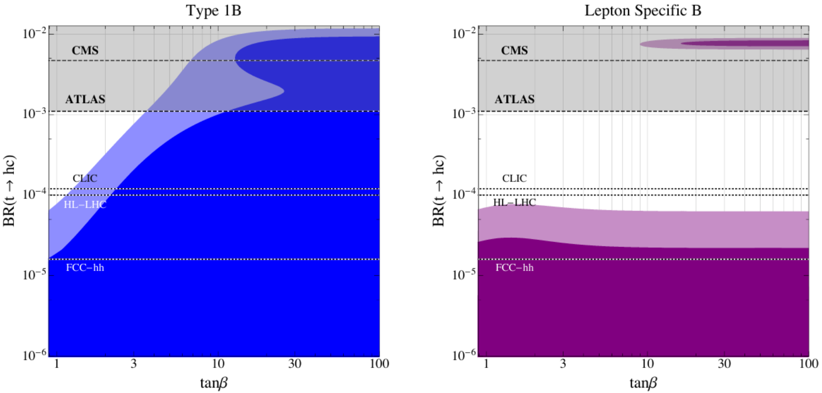
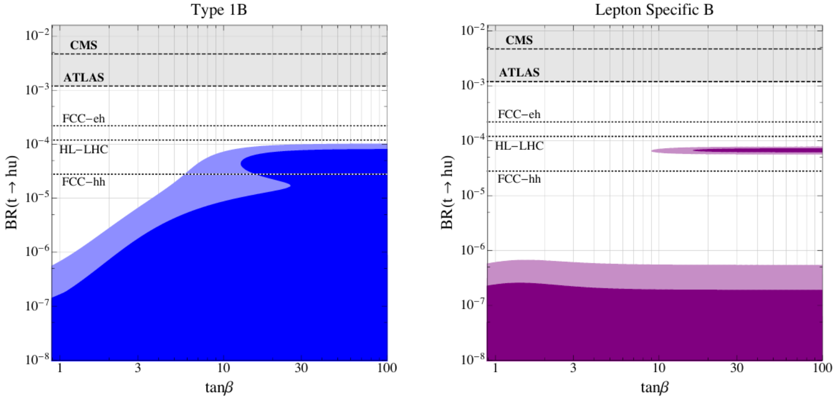


current LHC constraints on $t \to hc$ already probe parameter space.

WA, Maddock, Tuckler 1904.10956



$t \to hu$ likely out of reach at the LHC and future colliders.

Summary

- Observation of rare top decays would be a clear sign of new physics.
- Current limits on $t \to ch$ and $t \to uh$ probe generic new physics scales of $\Lambda \sim 1$ TeV.
- In models of "flavorful Higgs bosons" one can saturate the current limits on $t \to ch$.