THE FLAVOR OF FLAVORFUL HIGGS BOSONS

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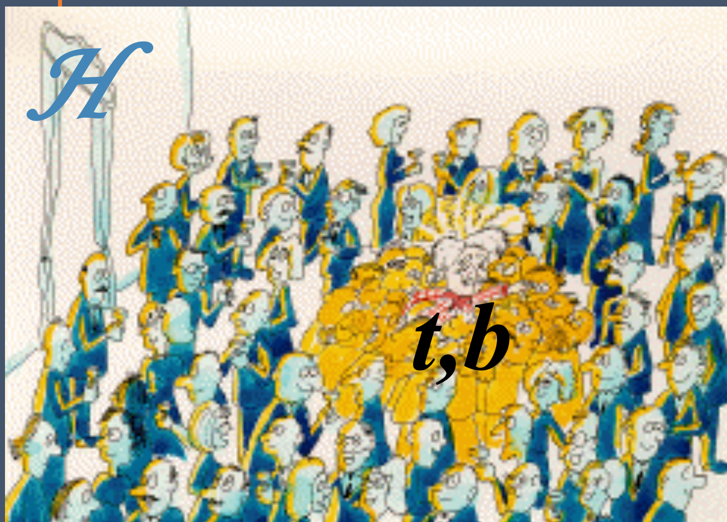
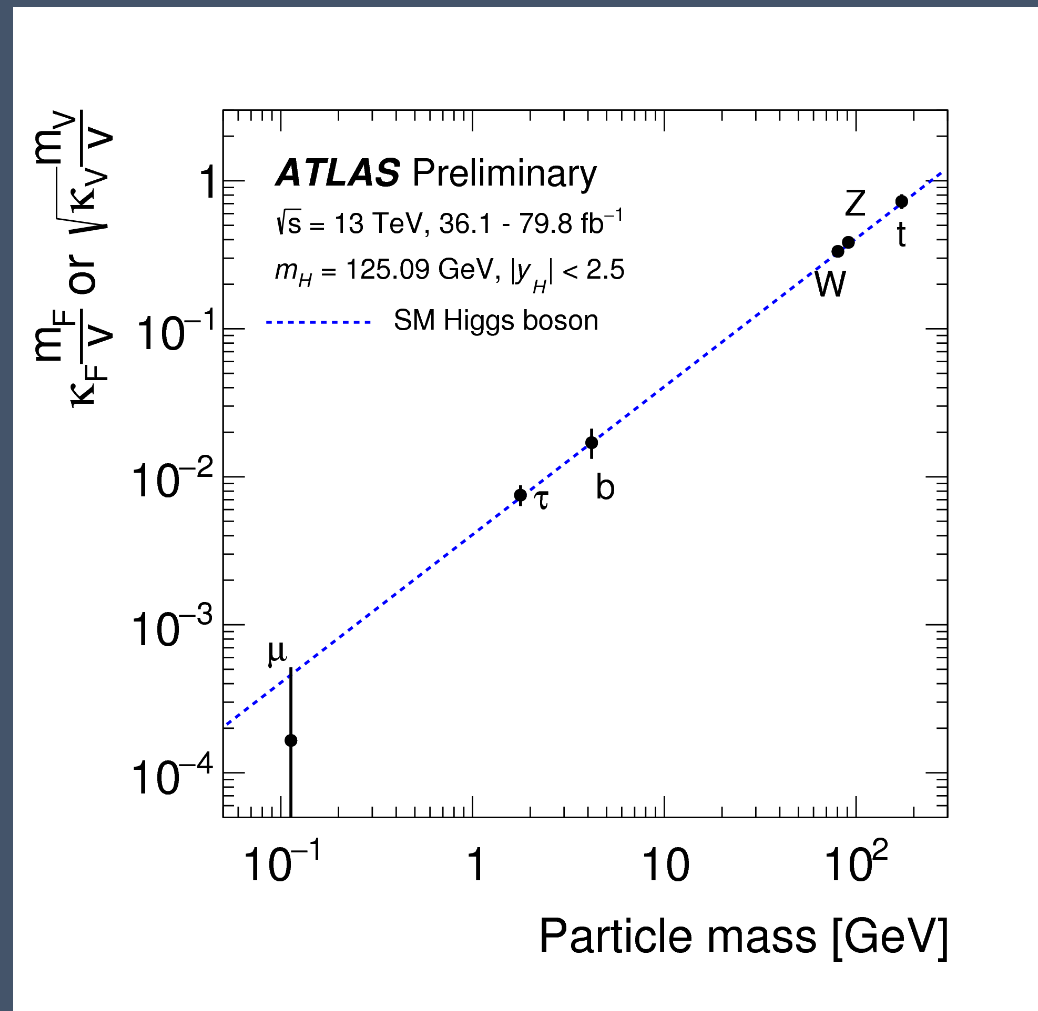
THE SM FLAVOR PUZZLE





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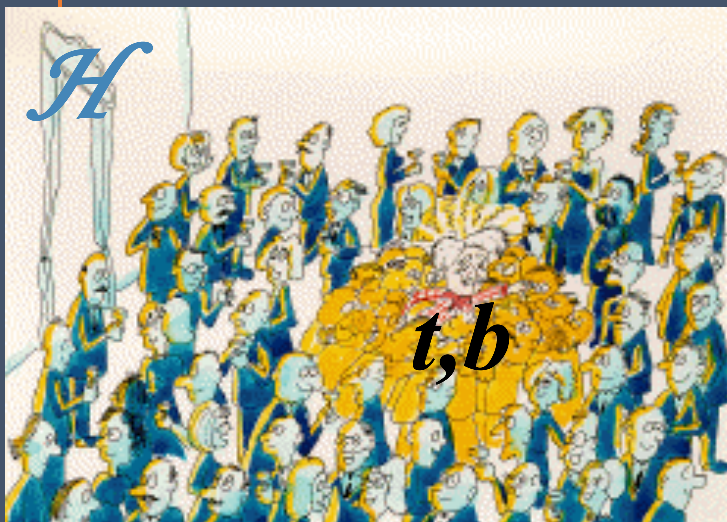

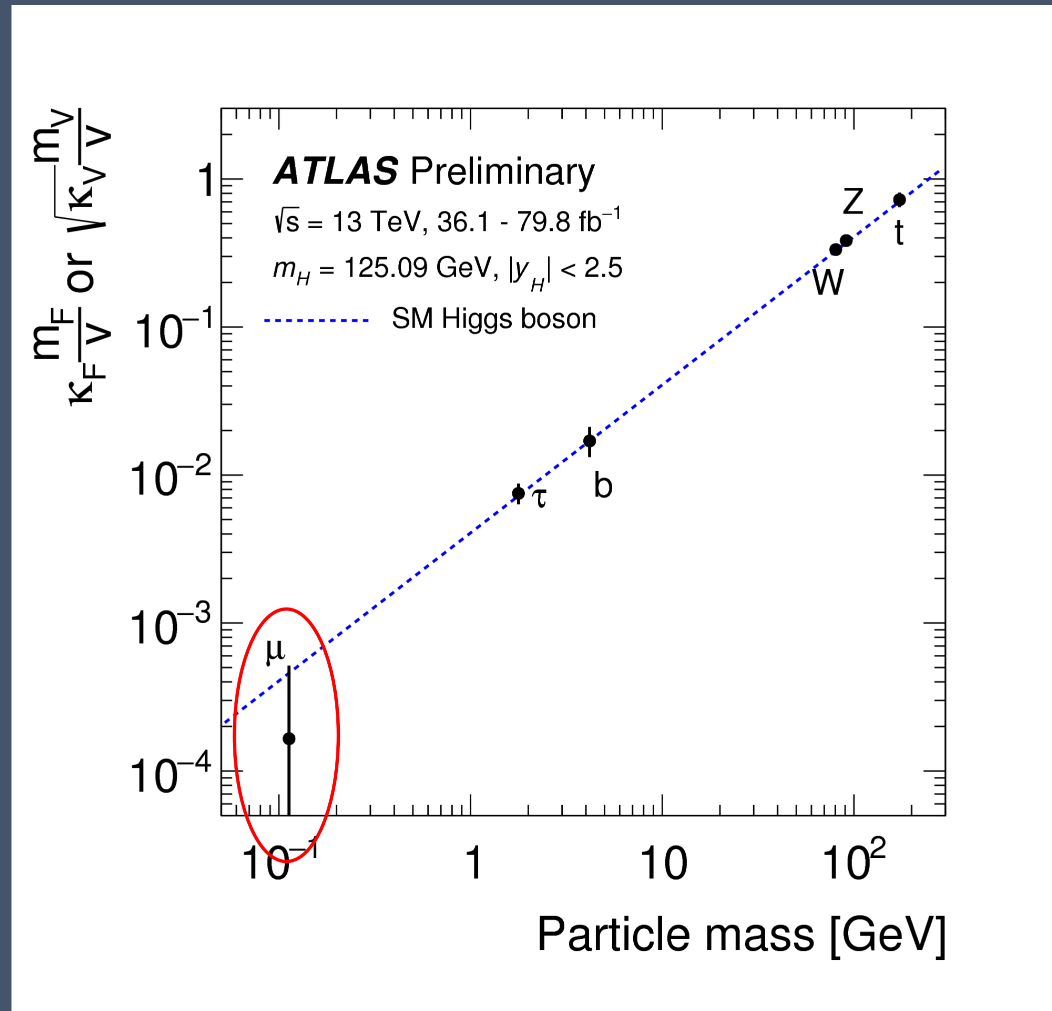

- Measuring the Higgs couplings to electrons, and light quarks (u, c, d, s) is out of reach of current experiments.
- ILC will be able to measure coupling to charm down to a few percent (see arxiv:1710.07621)

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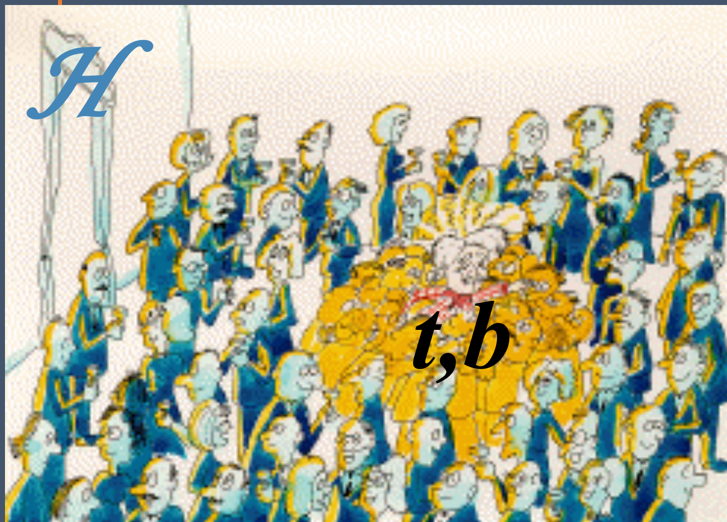

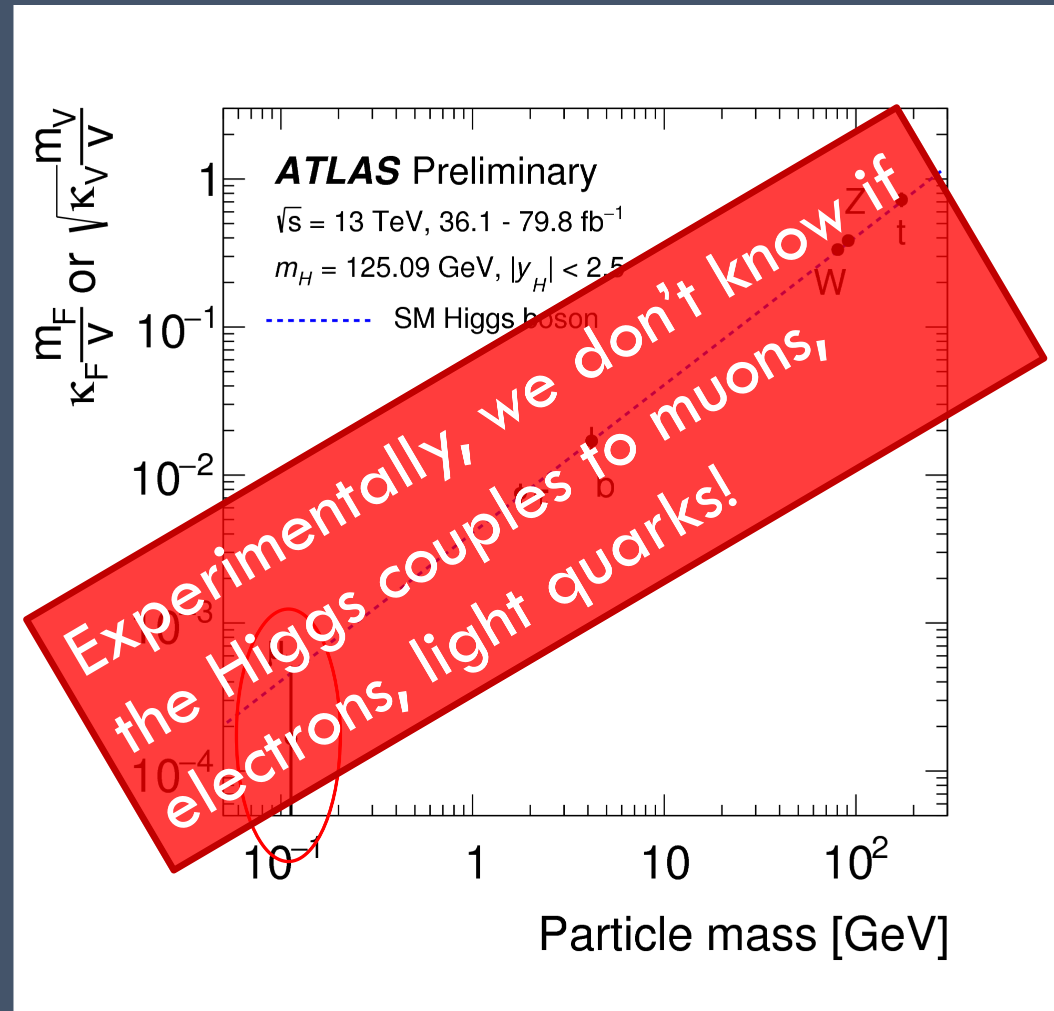

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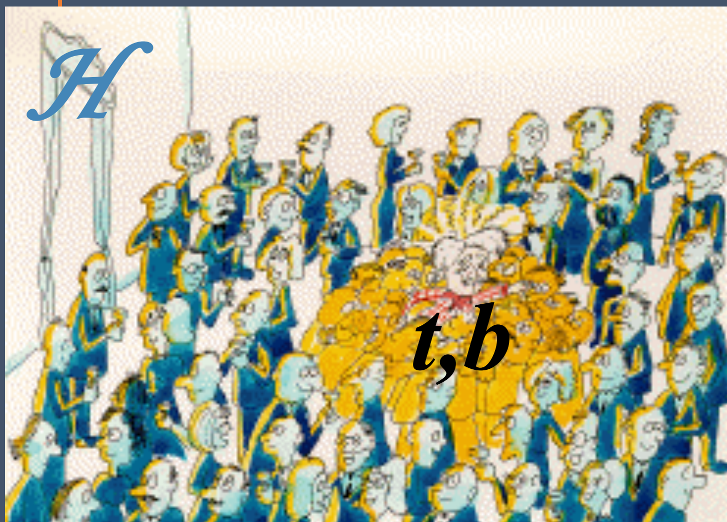
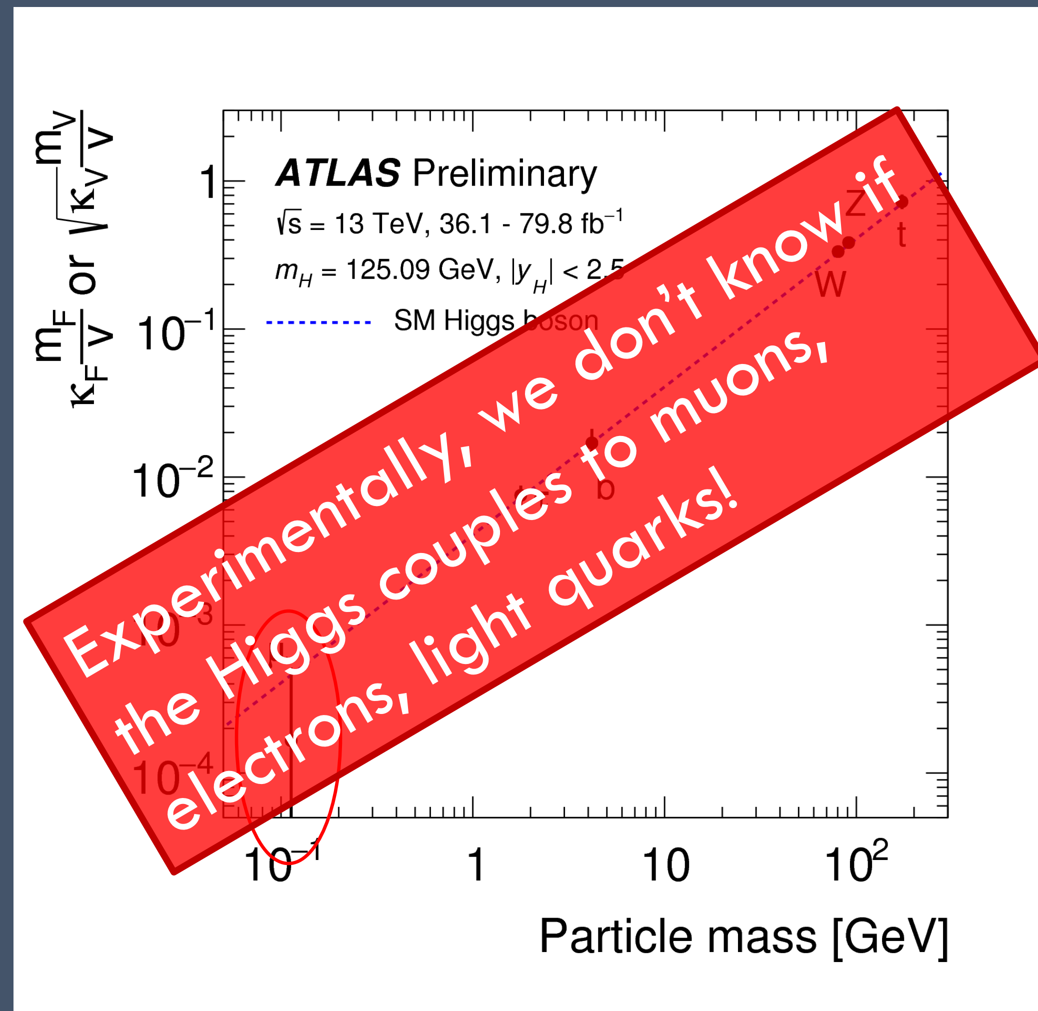


Why are the couplings of the 125 GeV Higgs boson to the 1st and 2nd generations so small?



ADDITIONAL SOURCE OF EWSB (ARXIV:1507.07927 WOLFGANG ALTMANNSHOFER, STEFANIA GORI, ALEXANDER L. KAGAN, LUCA SILVESTRINI, JURE ZUPAN)

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

- Due to the Higgs boson of the SM
- Gives the bulk of $m_{t,b,\tau}$

- Due to some extra source of mass
- Gives the bulk of $m_{u,d,c,s,e,\mu}$

Simplest realization = Two Higgs Doublet Model

$$\mathcal{L} = Y_{ij}\bar{f}_i f_j \Phi + Y'_{ij}\bar{f}_i f_j \Phi'$$

The Yukawa matrix Y is rank 1, while Y' has a generic structure that preserves an approximate U(2) symmetry between the first and second generations – “flavorful” 2HDM

$$\mathcal{M}_0^{u,d} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_{t,b} \end{pmatrix}, \quad \Delta\mathcal{M}^{u,d} \sim \begin{pmatrix} m_{u,d} & m_{u,d} & m_{u,d} \\ m_{u,d} & m_{c,s} & m_{c,s} \\ m_{u,d} & m_{c,s} & m_{c,s} \end{pmatrix}$$

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Does this reproduce the CKM matrix?

ORIGIN OF THE CKM MATRIX

The Yukawa structure of the 2HDM must reproduce the CKM matrix. This can be generated in the up quark or down quark sector

Down quark sector:

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

$$\mathcal{M}_0^d \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M}^d \sim \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix} \sim \begin{pmatrix} m_d & \lambda m_s & \lambda^3 m_b \\ m_d & m_s & \lambda^2 m_b \\ m_d & m_s & m_s \end{pmatrix}$$

Up quark sector:

$$\mathcal{M}_0^u \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix}, \quad \Delta\mathcal{M}^u \sim \begin{pmatrix} m_u & m_u & m_c \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix} \sim \begin{pmatrix} m_u & \lambda m_c & \lambda^3 m_t \\ m_u & m_c & \lambda^2 m_t \\ m_u & m_c & m_c \end{pmatrix}$$

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Can lead to sizable flavor changing couplings

$$\mathcal{M}_0^d \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M}^d \sim \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix} \sim \begin{pmatrix} m_d & \lambda m_s & \lambda^3 m_b \\ m_d & m_s & \lambda^2 m_b \\ m_d & m_s & m_s \end{pmatrix}$$

Up quark sector:

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DOWN SECTOR CKM: PHENOMENOLOGY

(ARXIV: 1610.02398 WOLFGANG ATLMANNSHOFER, JOSH EBY, STEFANIA GORI, MATTEO LOTITO, MARIO MARTONE, DT)

Generic features:

1. Goes beyond Natural Flavor Conservation and Minimal Flavor Violation
2. Heavy Higgs bosons can couple dominantly to 2nd generation quarks
3. Novel signatures different than typically studied 2HDMs e.g. Type I, II, Flipped, Lepton-specific
4. Weak collider constraints

New Signatures:

$$pp \to tH^{\pm},\ H^{\pm} \to cb$$

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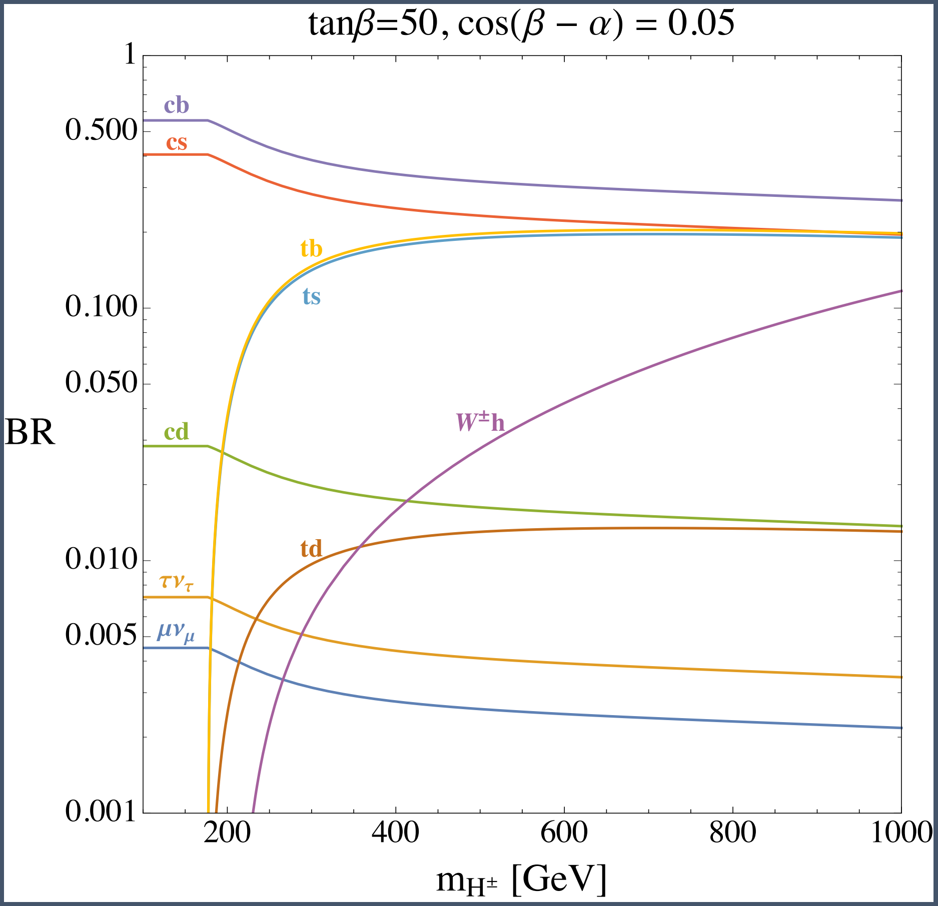

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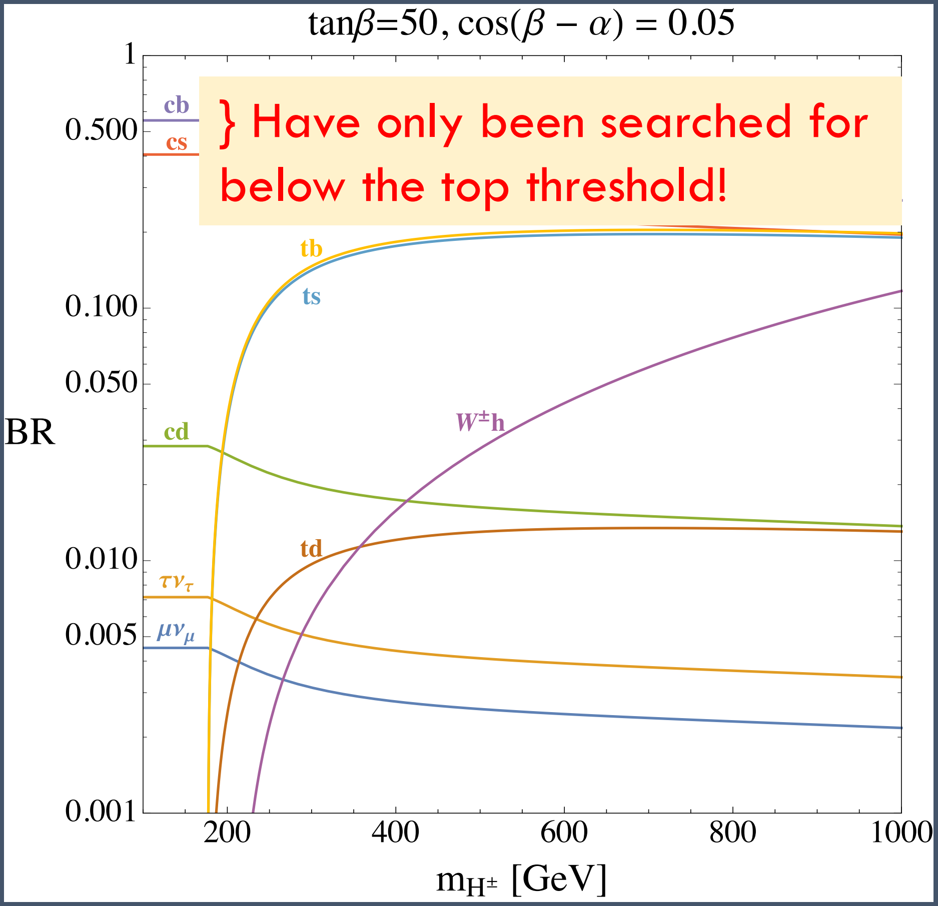

FLAVOR CONSTRAINTS (ARXIV: 1712.01847 WOLFGANG ALTMANNSHOFER, STEFANIA GORI, DEAN ROBINSON, DT)

We don't impose NFC or MFV to control flavor changing couplings which may lead to large FCNCs. Let's explore how large these contributions can be to Kaon and $B_{d,s}$ mixing.

- Neutral Higgs bosons h, H, A will give tree level contributions to meson mixing amplitudes

- Based on a UV completion of the flavorful 2HDM – flavor locking mechanism (see D. Robinson and S. Knapen arxiv:1507.00009)
- Benchmark point: $m_A = m_H = 500$ GeV, $\tan\beta = 5$, $\beta - \alpha = \pi/2$

	Data	SM Prediction	NP Contribution
ΔM_K	$(5.294 \pm 0.002) \times 10^{-3}$ ps^{-1}	$(4.7 \pm 1.8) \times 10^{-3}$ ps^{-1}	$\simeq -2 \times 10^{-6}$ ps^{-1}
ΔM_{B_d}	0.5055 ± 0.0020 ps^{-1}	0.63 ± 0.07 ps^{-1}	$\simeq 0.01$ ps^{-1}
ΔM_{B_s}	17.757 ± 0.021 ps^{-1}	19.6 ± 1.3 ps^{-1}	$\simeq -1.8$ ps^{-1}
ϵ_K	$(2.288 \pm 0.011) \times 10^{-3}$	$(1.81 \pm 0.28) \times 10^{-3}$	$\simeq 0.025 \times 10^{-3}$
ϕ_d	$43.7 \pm 2.4^\circ$	$47.5 \pm 2.0^\circ$	$\simeq -2.4^\circ$
ϕ_s	$-1.2 \pm 1.8^\circ$	$-2.12 \pm 0.04^\circ$	$\simeq 0.26^\circ$

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- Quantify the goodness of the model by constructing a χ^2-like function
- Loop observables: ΔM_K, ΔM_d, ΔM_s, ϕ_d, ϕ_s, ε_K
- Compare to SM: $X^2_{loop} \sim 7.1$, $X^2_{loop}(SM) \sim 10.8$

$$X^2_{\text{loop}} = \sum_i \left[\frac{(\mathcal{O}_i^{\text{NP}} - \mathcal{O}_i^{\text{exp-SM}})^2}{(\sigma_{\mathcal{O}_i^{\text{exp}}})^2 + (\sigma_{\mathcal{O}_i^{\text{SM}}})^2} \right]$$

ADDITIONAL FLAVOR STRUCTURES

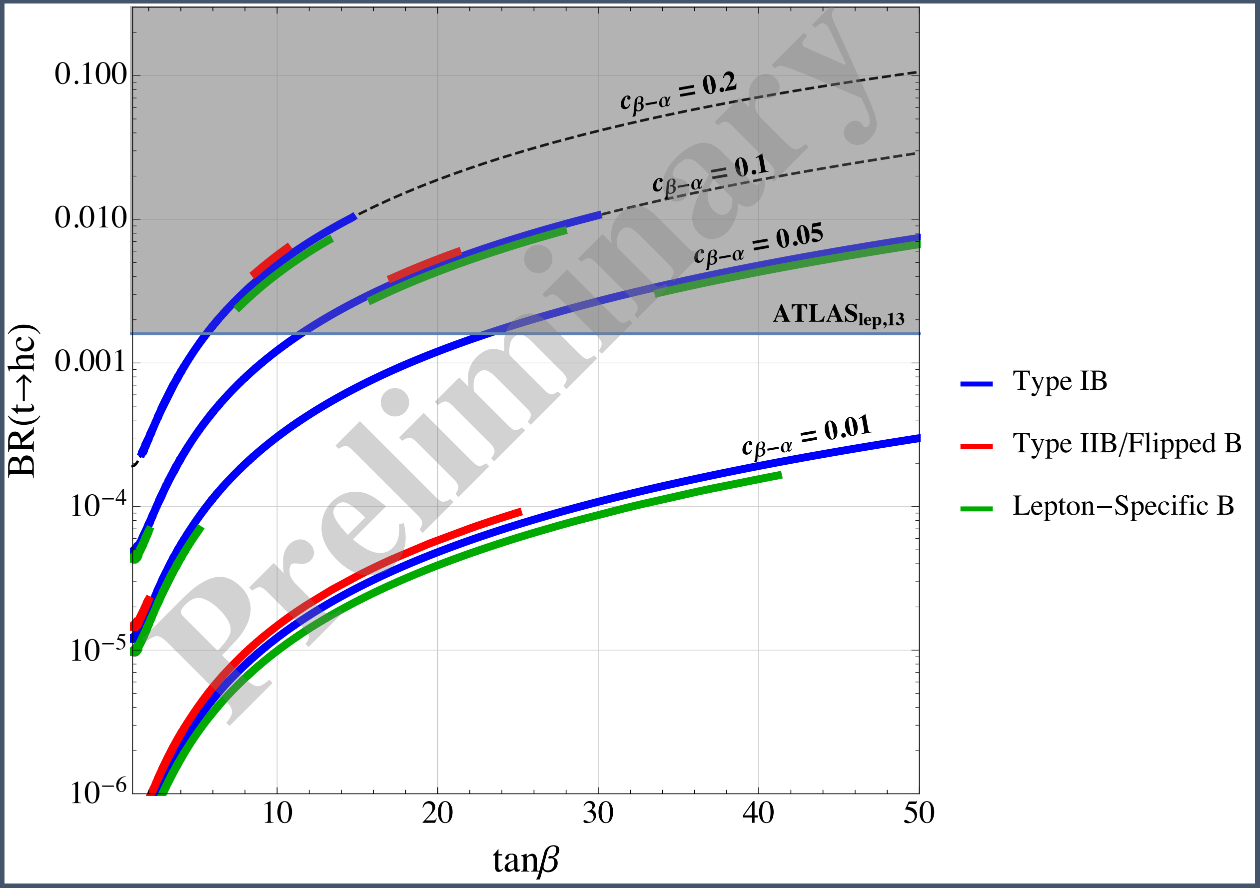
- There are four well studied 2HDMs: Type I, Type II, Flipped, and Lepton Specific (Label these“type A” 2HDMs)
- In each of these types, switch the Higgs doublet to which the first and second generations couple to compared to the third generation. (Label these“type B” 2HDMs)
- Phenomenology of these models with CKM generated in the down quark sector explored in arxiv:1805.08659, Wolfgang Altmannshofer and Brian Maddock

Model	$u_{1,2}$	u_3	$d_{1,2}$	d_3	$e_{1,2}$	e_3
Type IA	Φ	Φ	Φ	Φ	Φ	Φ
Type IB	Φ'	Φ	Φ'	Φ	Φ'	Φ
Type IIA	Φ	Φ	Φ'	Φ'	Φ'	Φ'
Type IIB	Φ'	Φ	Φ	Φ'	Φ	Φ'
Flipped A	Φ	Φ	Φ'	Φ'	Φ	Φ
Flipped B	Φ'	Φ	Φ	Φ'	Φ'	Φ
Lepton-Specific A	Φ	Φ	Φ	Φ	Φ'	Φ'
Lepton-Specific B	Φ'	Φ	Φ'	Φ	Φ	Φ'

UP SECTOR CKM FOR TYPE B 2HDMS

(ARXIV 1810.XXXX WOLFGANG ALTMANNSHOFER, BRIAN MADDOCK, DT)

- For the "type B" 2HDMs, generate the CKM matrix in the up quark sector
- Enhance off diagonal SM-like Higgs couplings h-t-c and h-t-u
- Predict branching ratios for rare top decays that can be within reach of the LHC, motivating continued searches for these processes.



SUMMARY

- The SM flavor puzzle can be addressed in a two Higgs doublet model where the third generation couples to a different Higgs doublet than the first and second generations
- These kinds of "flavorful" 2HDMs have interesting/novel phenomenology compared to typically studied 2HDMs
  - Depends on whether the CKM matrix is generated in the up or down quark sector
- Constraints from meson mixing are not too stringent
  - There is parameter space where this model does better than the SM!!
- Predict rates for processes that are <u>currently</u> accessible at the LHC, motivating continued searches
  - Heavy Higgs production and decays
  - Rare top decays
- There are interesting UV completions of these models
  - Flavor-Locking mechanism for down quark CKM
  - Froggatt-Nielsen mechanism for up quark CKM

THANK YOU!

QUESTIONS?