Flavorful 2HDMs at Future Colliders

Based on arxiv:1610.02398 with W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone,

arxiv:1712.01847 with W. Altmannshofer, S. Gori, D. J. Robinson

arxiv:1904.10956 with W. Altmannshofer , B. Maddock

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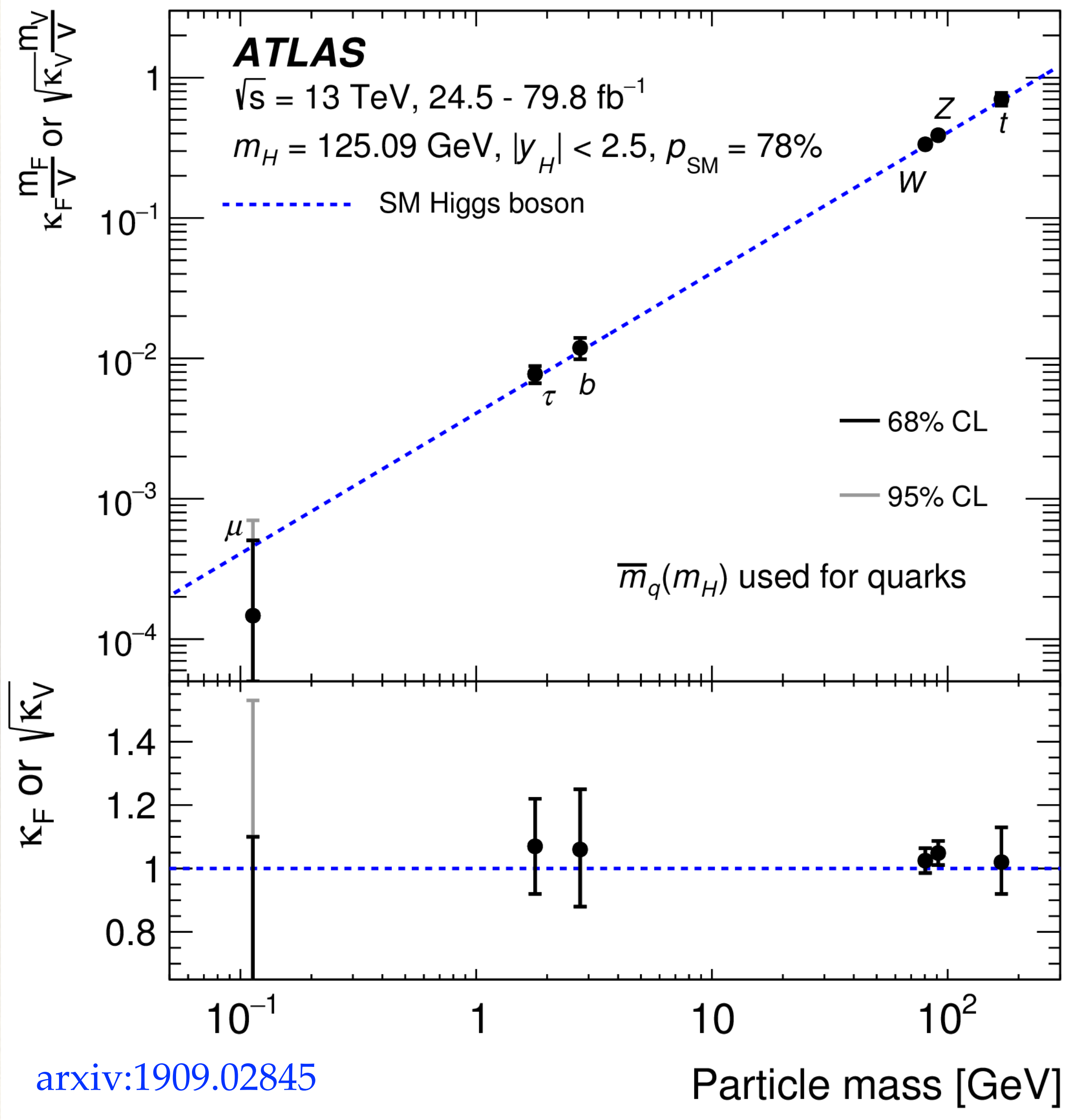
UC Santa Cruz & Fermilab

Snowmass EF02 Meeting
Higgs & Flavor
08/07/2020

The SM Flavor Puzzle

- Experimentally, we know that the 125 GeV Higgs boson couples/gives mass to
  - 3rd generation quarks (t,b) and leptons (tau)
  - Gauge bosons (W,Z)

ATLAS Results



arxiv:1909.02845

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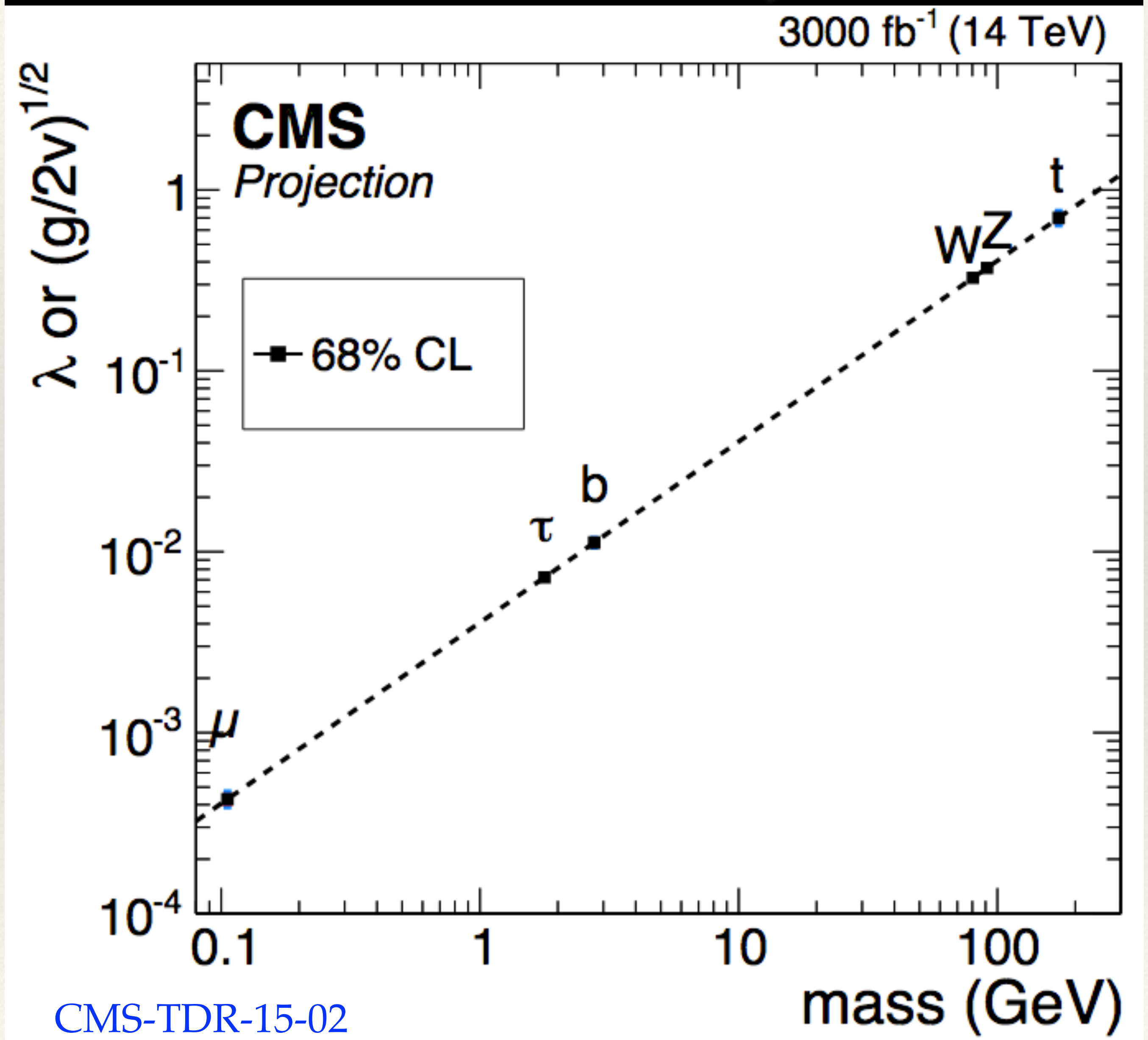
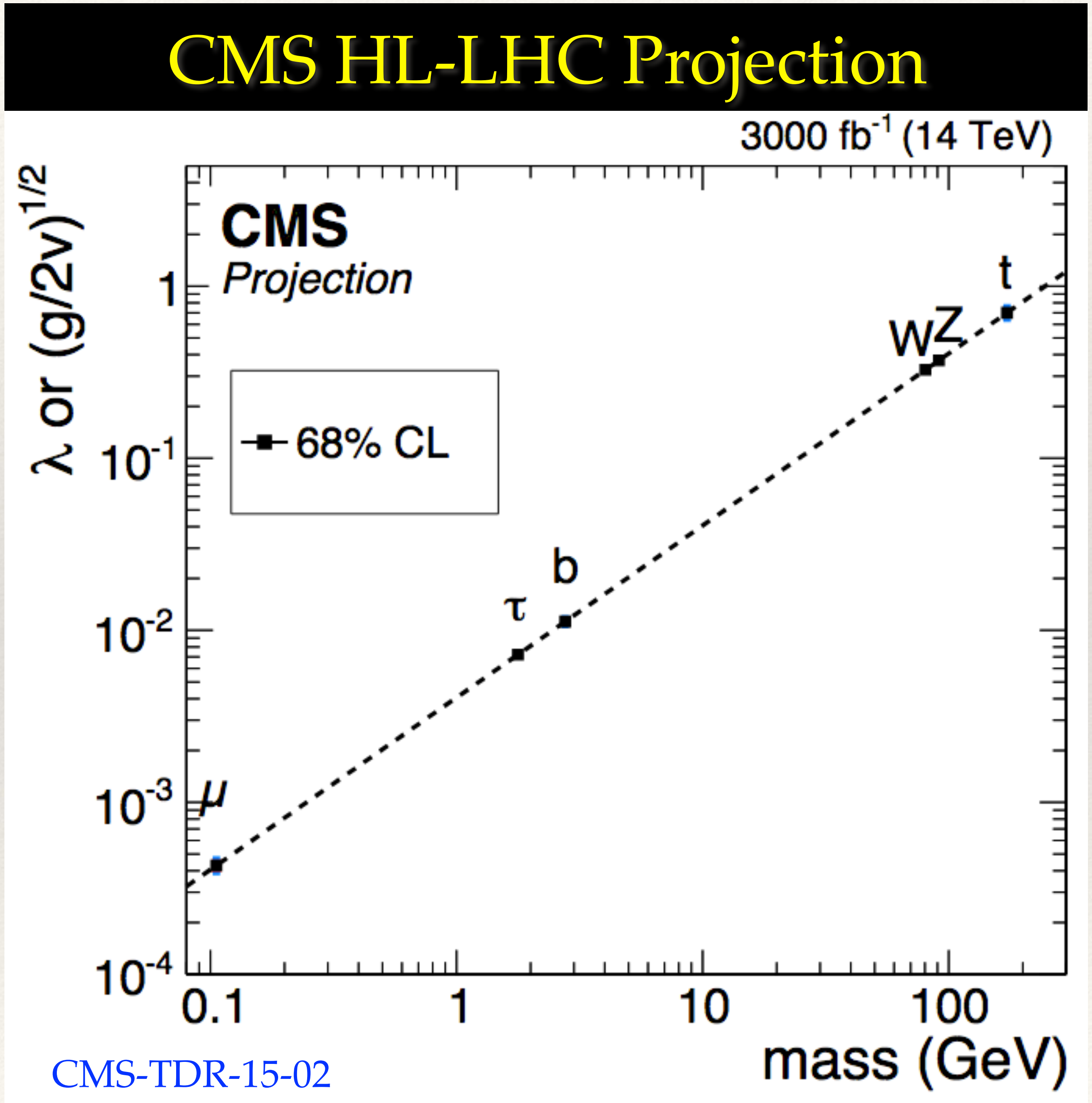
CMS HL-LHC Projection



CMS-TDR-15-02

The SM Flavor Puzzle

- Experimentally, we know that the 125 GeV Higgs boson couples/gives mass to
  - 3rd generation quarks (t,b) and leptons (tau)
  - Gauge bosons (W,Z)
- **<u>What about the Higgs couplings to light fermions?</u>**
  - Charm Yukawa: LHC bounds exist, but this is very challenging!
  - SM couplings to electrons, u, d, s out of reach of LHC



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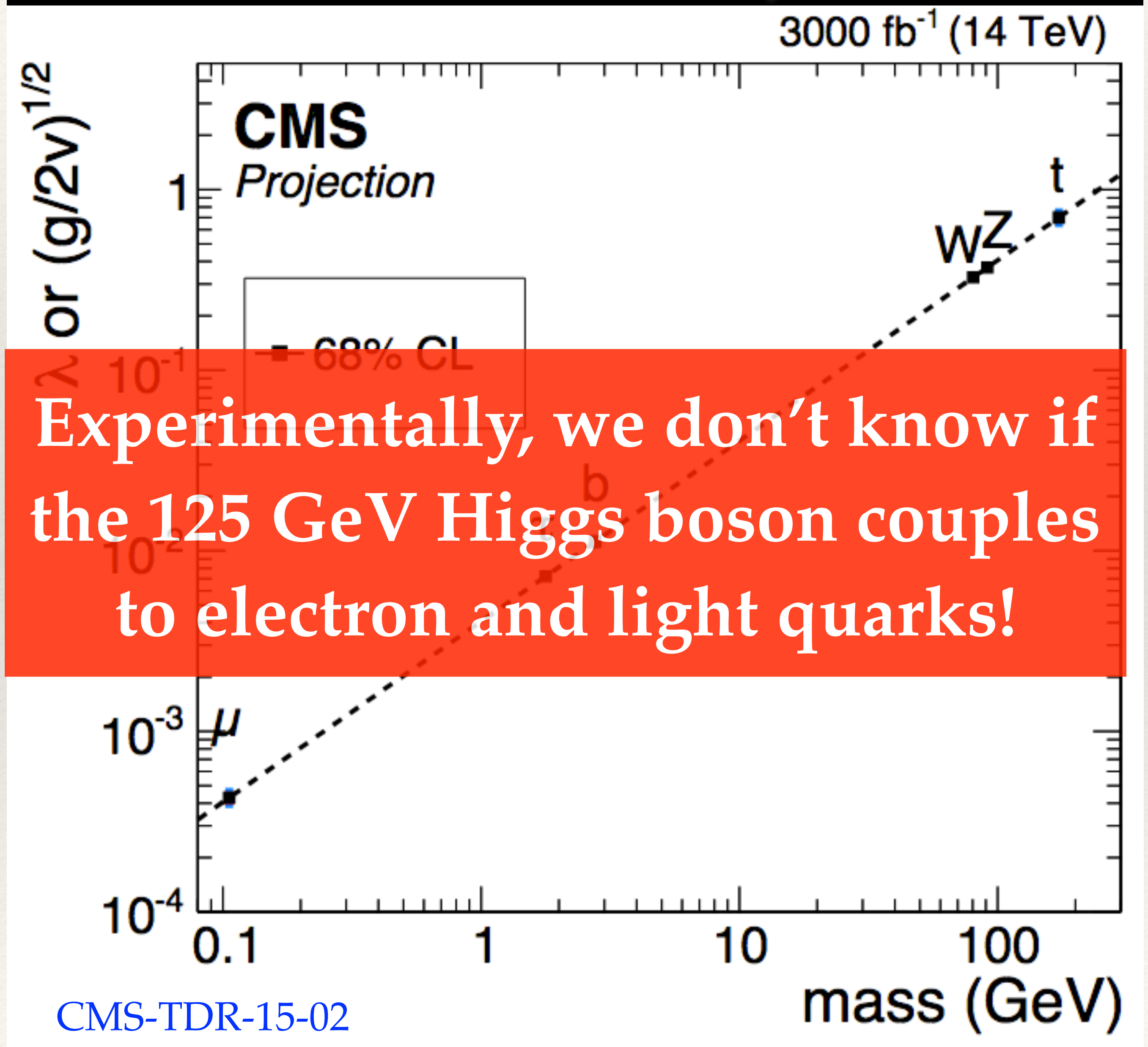


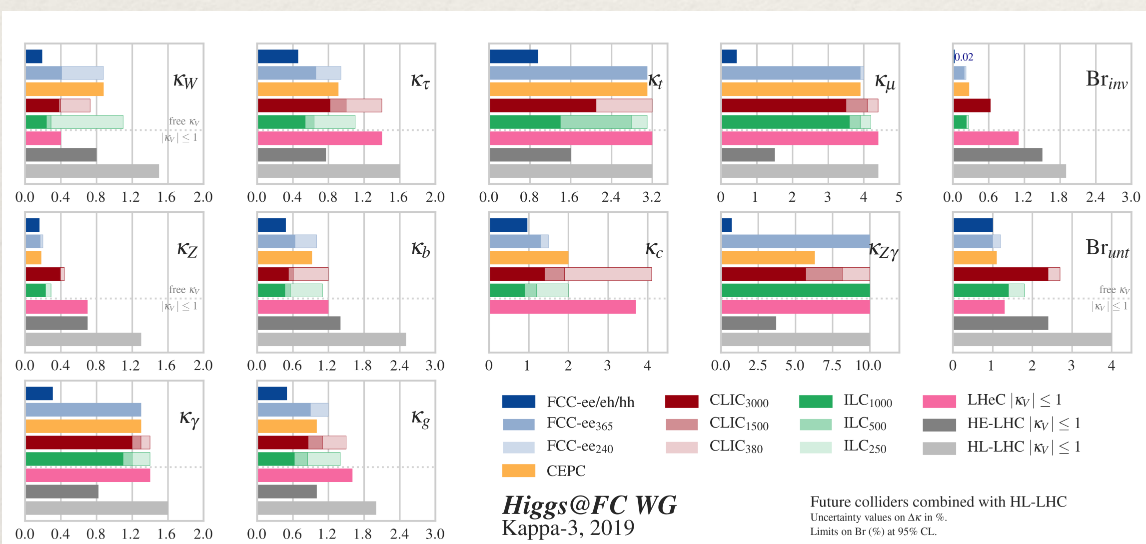
Experimentally, we don't know if the 125 GeV Higgs boson couples to electron and light quarks!

CMS-TDR-15-02

Does the 125 GeV Higgs give mass to all fermions?

Traditional Approach

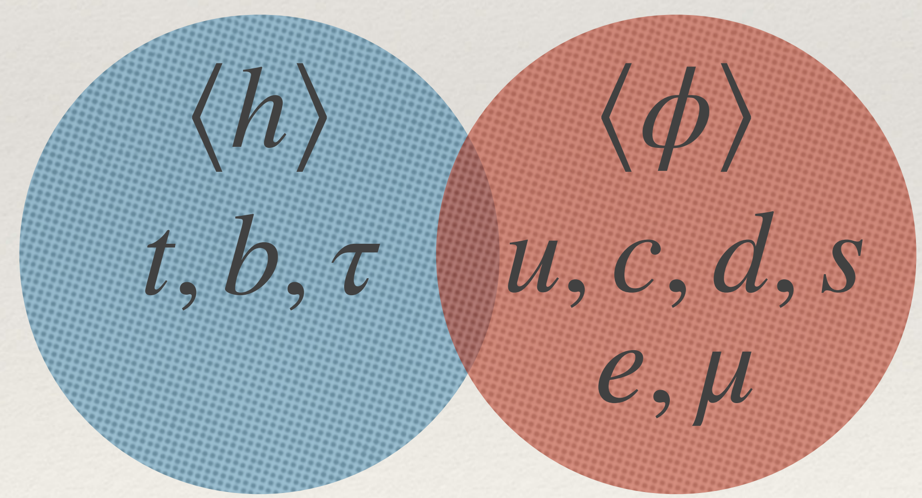
- Yes! The 125 GeV Higgs gives mass to all fermions.
- Continue making improvements to precisely measure Higgs couplings at future colliders



- Study rare decays $h \to MV$, Higgs pT distribution, di-Higgs production, charm/strange tagging.
- *Has the SM flavor puzzle been addressed*? Why are the Higgs couplings to 1st and 2nd gen. fermions so small?

Complimentary Approach

- No! Masses of light fermions are not due to the VEV of the 125 GeV Higgs
- 1st and 2nd generations couple exclusively to an additional source of EWSB



Addresses the SM Flavor puzzle!

Additional Sources of EWSB

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

W. Altmannshofer, S. Gori, A. Kagan, J. Zupan arXiv:1507.07927

- 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 $m_{u,c,d,s,e,\mu}$

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- Simplest realization = Two Higgs Doublet Model (2HDM)

$$\mathcal{L} = Y \bar{f} f \Phi + Y' \bar{f} f \Phi' \longrightarrow \mathcal{M} = vY + v'Y'$$

125 GeV Higgs (h)

Additional Higgs bosons (H, A, H±)

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125 GeV Higgs (h)

Additional Higgs bosons (H, A, $H^\pm$)

Want a flavor structure such that *Y* is rank 1 and *Y'* is generic

Flavorful 2HDMs

(arXiv:1610.02398 W. Almannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, DT)

- Rank 1 SM Higgs couplings → SM Higgs couples dominantly to third generation fermions

$$Y^{u,d} \sim \frac{\sqrt{2}}{v} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_{t,b} \end{pmatrix}, \quad Y'^{u,d} \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_{u,d} & m_{u,d} & m_{u,d} \\ m_{u,d} & m_{c,s} & m_{c,s} \\ m_{u,d} & m_{c,s} & m_{c,s} \end{pmatrix}$$

Analogous flavor structure in the lepton sector

- This Yukawa textures gives the observes fermion masses!
- No discrete symmetries! Flavor changing Higgs couplings are present. FCNCs are suppressed by an approximate U(2) symmetry between the 1st and 2nd generations.
  - Tree level Higgs contributions to meson oscillations are small and may accommodate current data mildly better than the SM (W. Altmannshofer, S. Gori, D. Robinson, DT arXiv:1712.01847)

Naturally explains the fermion mass hierarchy if $v' << v$

Generating the CKM Matrix

- The Yukawa structure of the 2HDM must reproduce the CKM matrix.
- CKM matrix can originate from the rotation matrices that diagonalize the up quark mass matrices OR the down quark mass matrices

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Up quark sector CKM

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & \lambda_c m_c & \lambda_c^3 m_t \\ m_u & m_c & \lambda_c^2 m_t \\ m_u & m_c & m_c \end{pmatrix}$$

$$Y'^d \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix}$$

Down quark sector CKM

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix}$$

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Generating the CKM Matrix

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- CKM matrix can originate from the rotation matrices that diagonalize the up quark mass matrices OR the down quark mass matrices

<u>Up quark sector CKM</u>

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & \lambda_c m_c & \lambda_c^3 m_t \\ m_u & m_c & \lambda_c^2 m_t \\ m_u & m_c & m_c \end{pmatrix}$$

$$Y'^d \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix}$$

Leads to flavor violating Higgs couplings to up quarks

<u>Down quark sector CKM</u>

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix}$$

$$Y'^d \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_d & \lambda_c m_s & \lambda_c^3 m_b \\ m_d & m_s & \lambda_c^2 m_b \\ m_d & m_s & m_s \end{pmatrix}$$

Leads to flavor violating Higgs couplings to down quarks

Generating the CKM Matrix

- The Yukawa structure of the 2HDM must reproduce the CKM matrix.
- CKM matrix can originate from the rotation matrices that diagonalize the up quark mass matrices OR the down quark mass matrices

Up quark sector CKM

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & \lambda_c m_c & \lambda_c^3 m_t \\ m_u & m_c & \lambda_c^2 m_t \\ m_u & m_c & m_c \end{pmatrix}$$

$$Y'^d \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix}$$

Leads to flavor violating Higgs couplings to up quarks

Down quark sector CKM

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix}$$

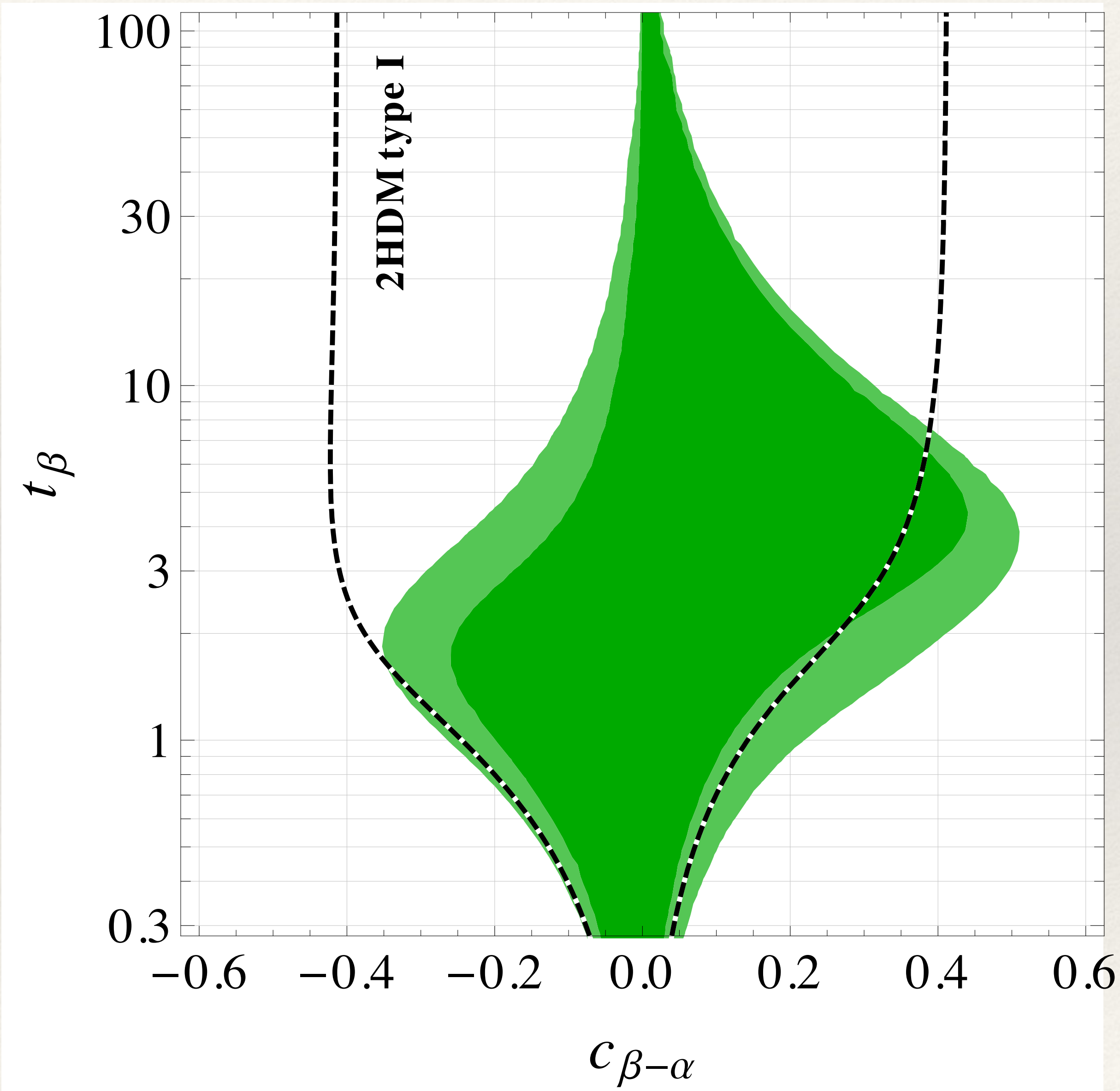
$$Y'^d \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_d & \lambda_c m_s & \lambda_c^3 m_b \\ m_d & m_s & \lambda_c^2 m_b \\ m_d & m_s & m_s \end{pmatrix}$$

Leads to flavor violating Higgs couplings to down quarks

Couplings of additional Higgs boson to 3rd generation fermions are suppressed!

SM Higgs Coupling Modifications

- Modify SM-like Higgs couplings to 1st and 2nd gen. fermions.
  - At large $\tan\beta$ couplings to charm and muons can be strongly enhanced
- Measurements of the 125 GeV Higgs production and decay rates constrain values of α, β
  - At low $\tan\beta$ constraints are similar to Type I 2HDM



Phenomenology of Flavorful Higgs Bosons

(arXiv:1610.02398 W. Almannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, DT)

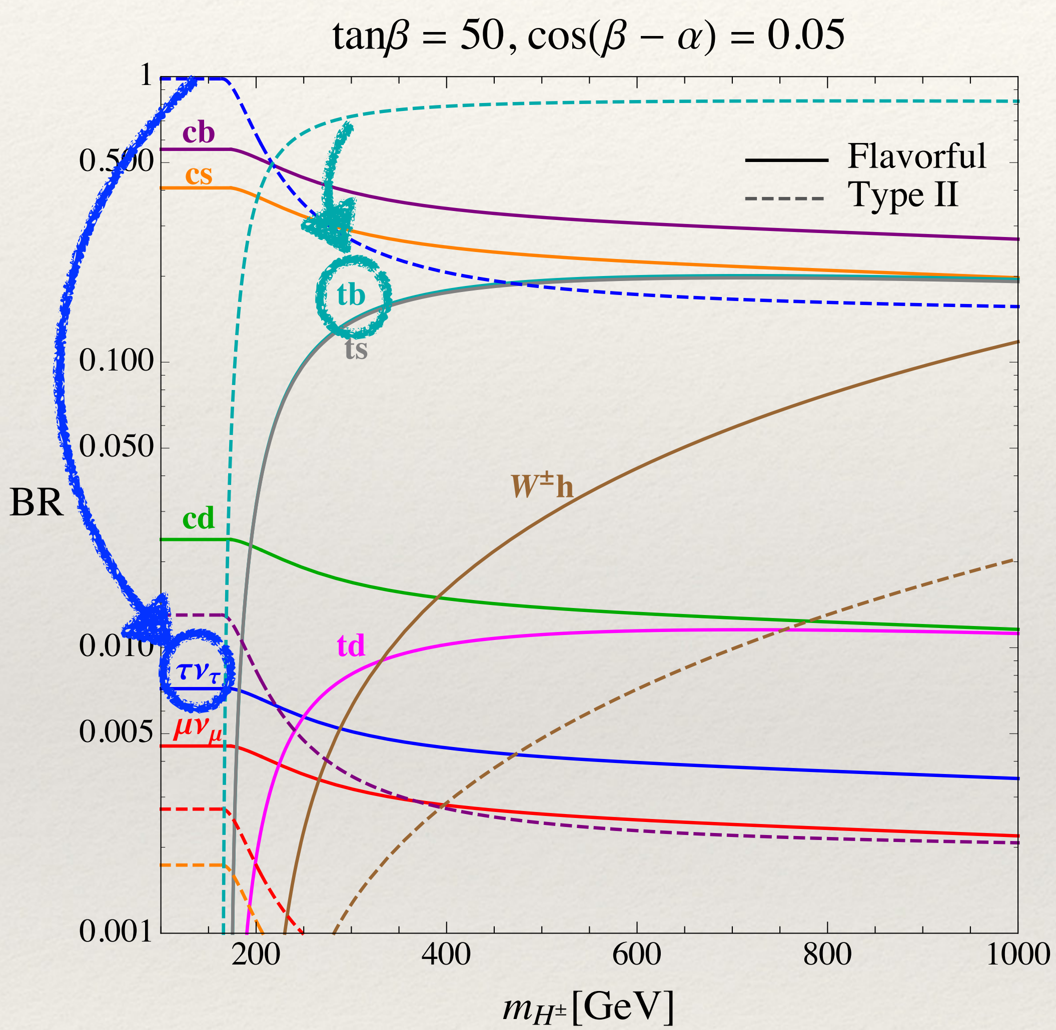
Main results:

1. Additional Higgs bosons can decay dominantly to 2nd generation quark and leptons
2. Collider signatures are distinct from typically studied 2HDMs (e.g. Type I, II)
3. Weak collider constraints

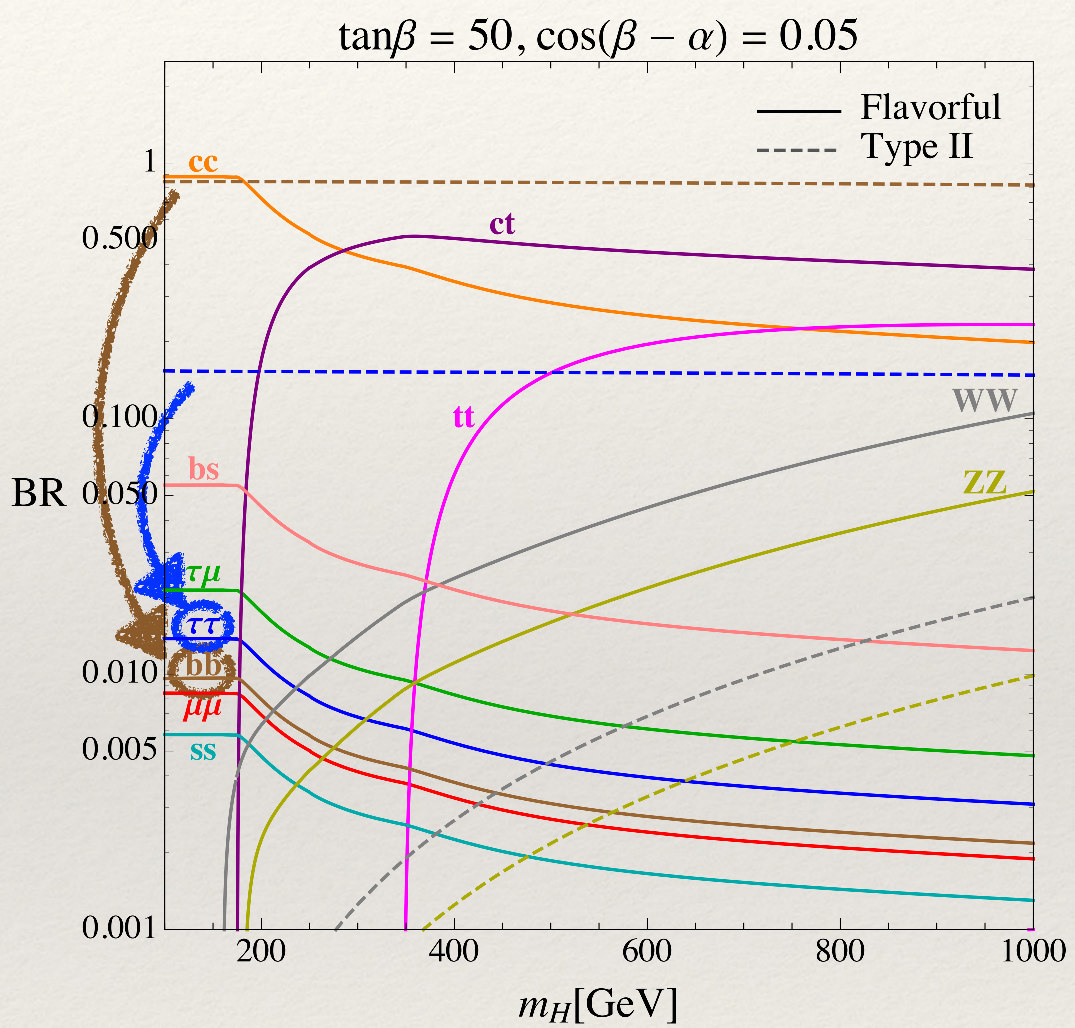
Let's see how this shows up when the the CKM originates in the down quark sector

Decays of the Heavy Higgs Bosons

Charged Higgs



Neutral Higgs



"Classic" decay modes ($H^\pm \to$ tb, τν, $H \to$ **ττ**, **bb**) are suppressed!

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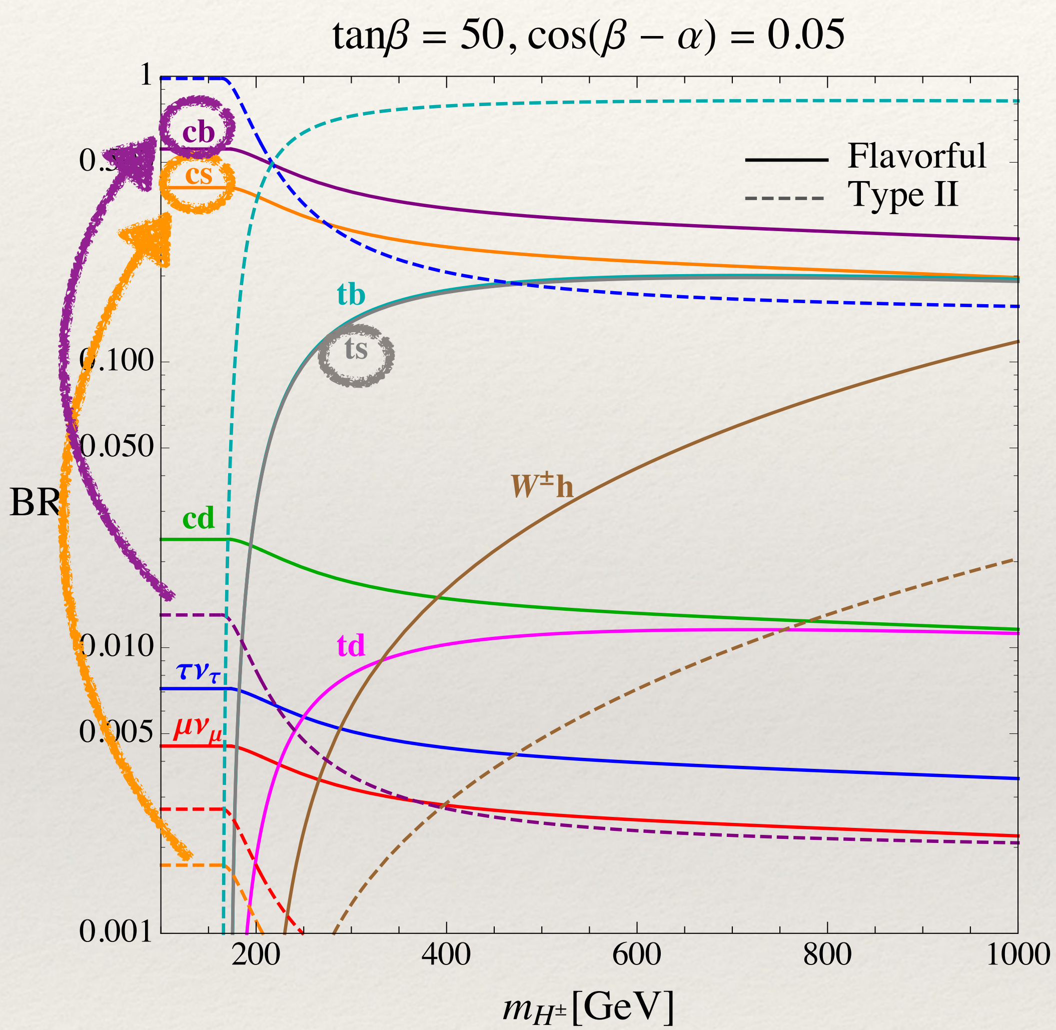
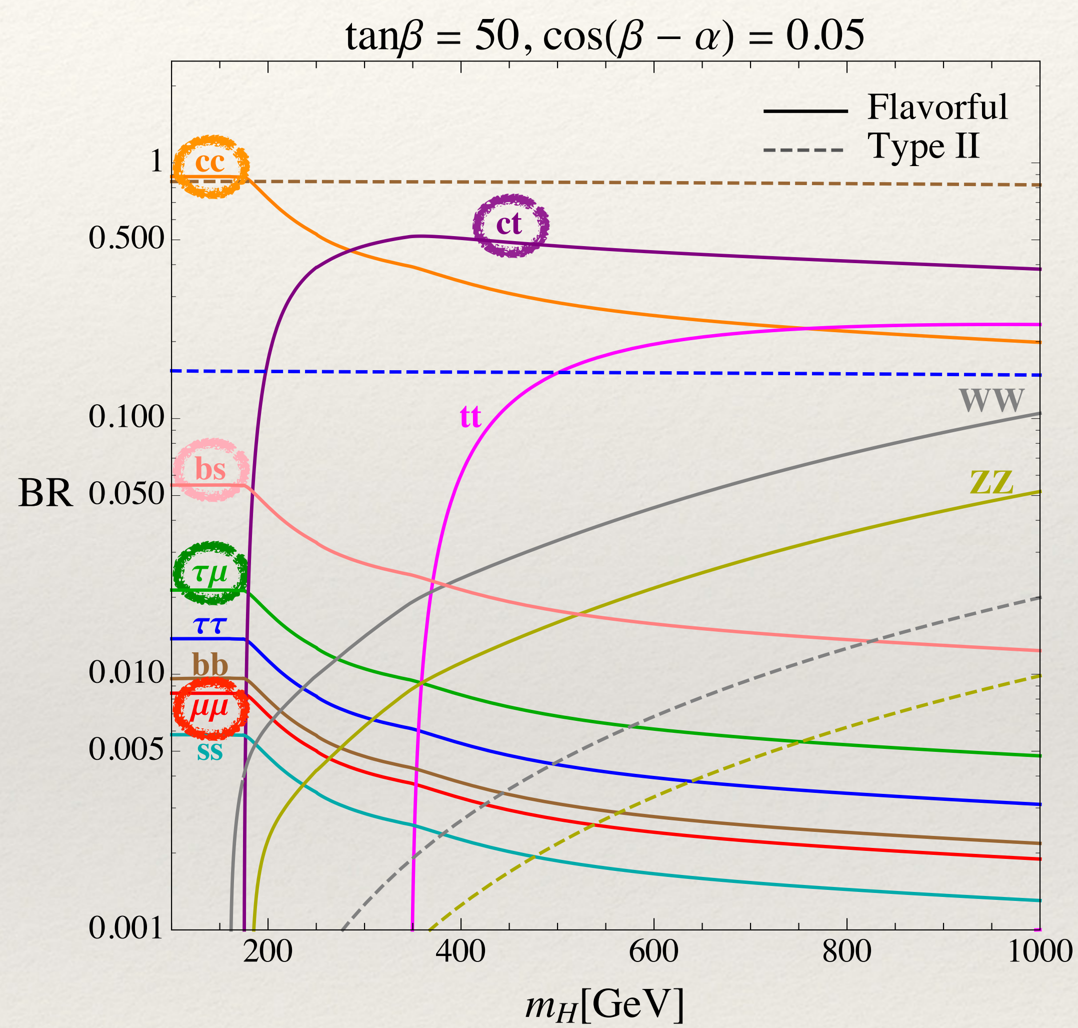


- Dominant decay modes are to **charm-strange**, **charm-bottom** — these have only been searched for below the top threshold.
- Decay to **ts** becomes sizeable and of the order of decay to tb

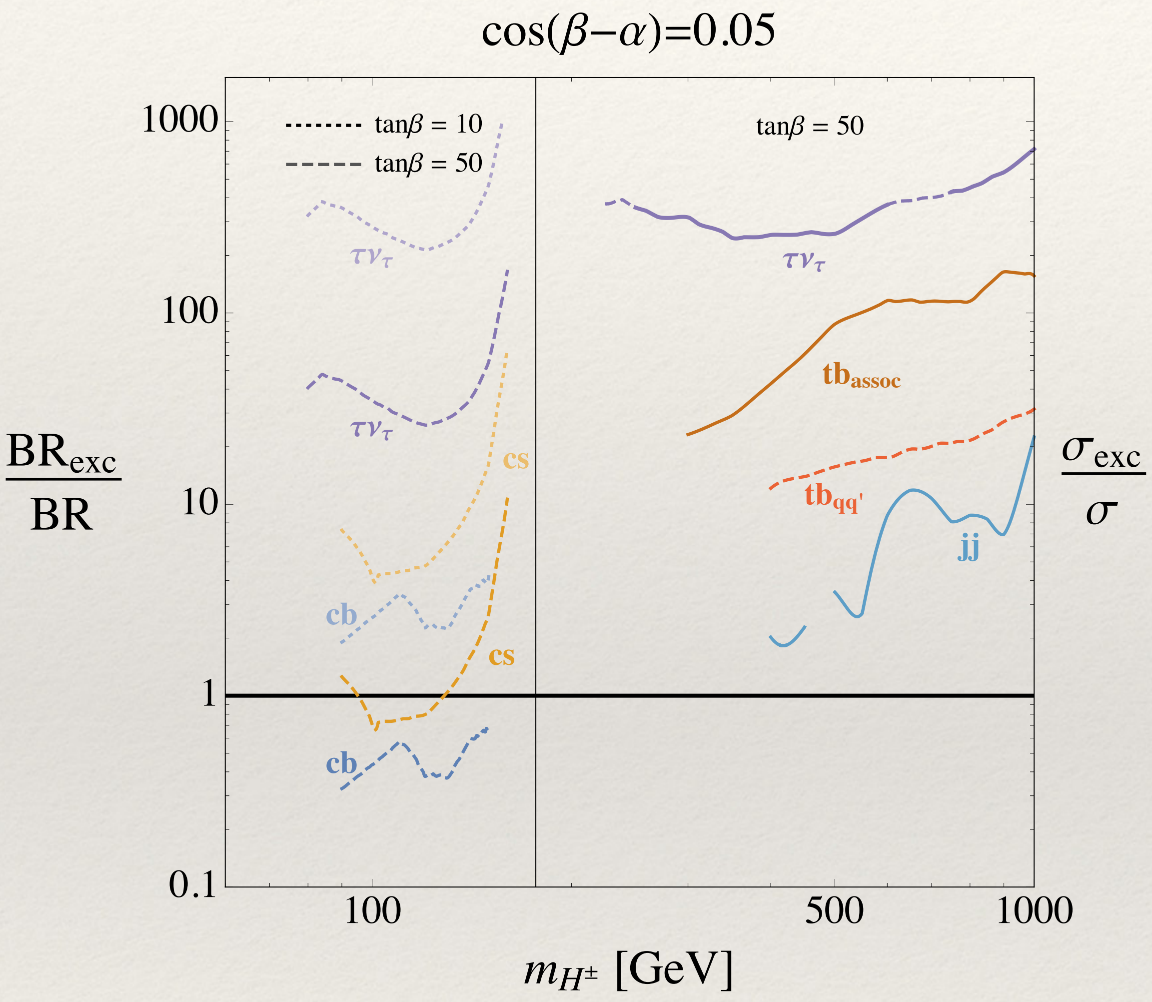
Neutral Higgs



- Flavor-violating (**ct**, **bs**, **τμ**) decays are now present (compared to Type II)! Dominant decay modes are to **charm-charm** and **charm-top**
- Decay to **muons** becomes sizable. Inspired an ATLAS search! arxiv:1901.08144

Exclusion Limits

Charged Higgs



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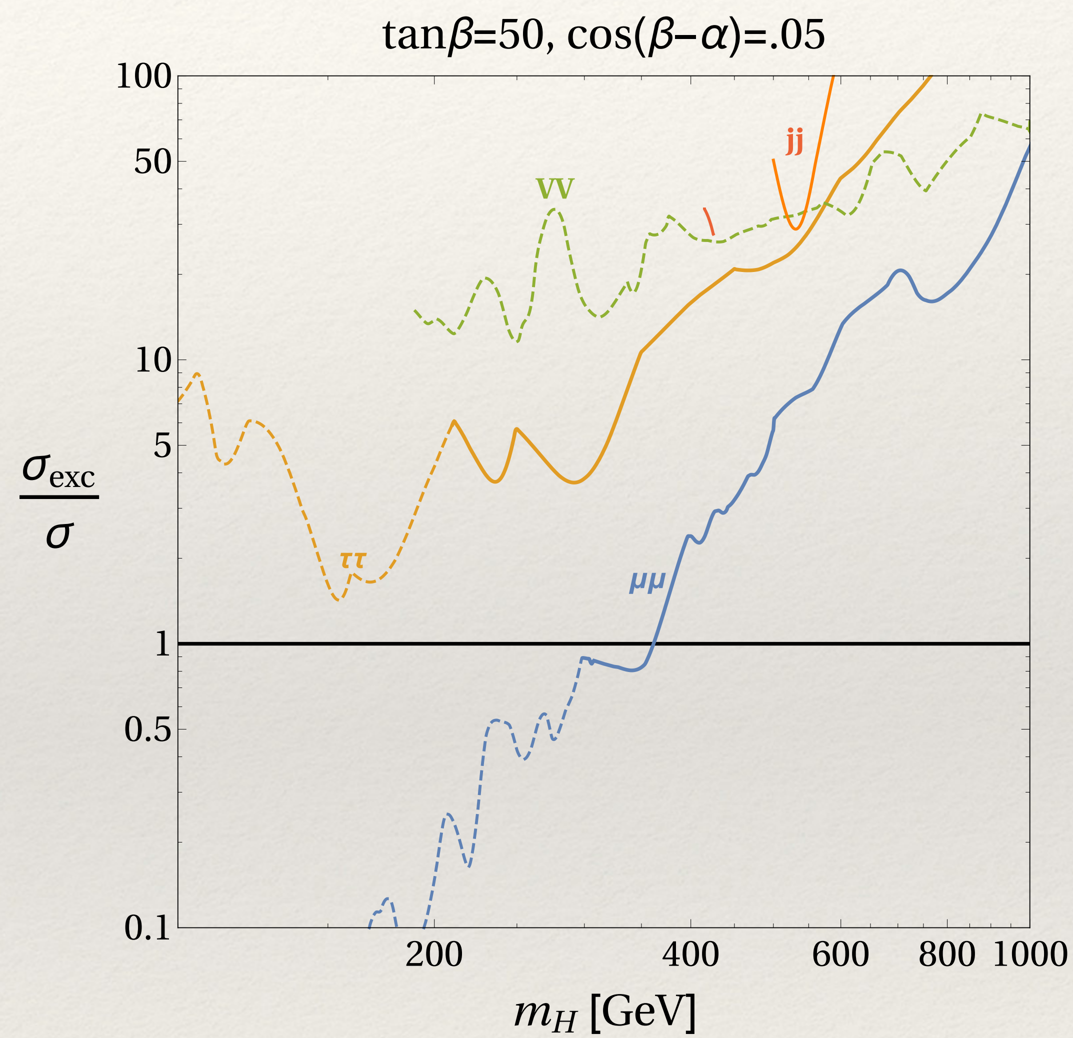


Strongest bounds from di-muon and dijet searches, not searches for decays to 3rd generation!

Novel Collider Signatures

Neutral Higgs (H)	Charged Higgs ($H^\pm$)
$pp \to H \to tc$	$pp \to tH^\pm \to tcb$
$pp \to H \to \tau\mu$	$pp \to H^\pm \to cs$
$pp \to tH \to ttc$	$pp \to tH^\pm \to tcs, tts$
$pp \to H \to cc$	$pp \to tH^\pm \to t\mu\nu_\mu$
$pp \to tH \to tcc$	

Phenomenology with Up Sector CKM

(arXiv:1904.10956 W. Almannshofer, B. Maddock, DT)

- Similar collider phenomenology to CKM from up quark sector.

$$Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix} \to Y'^u \sim \frac{\sqrt{2}}{v'} \begin{pmatrix} m_u & \lambda_c m_c & \lambda_c^3 m_t \\ m_u & m_c & \lambda_c^2 m_t \\ m_u & m_c & m_c \end{pmatrix}$$

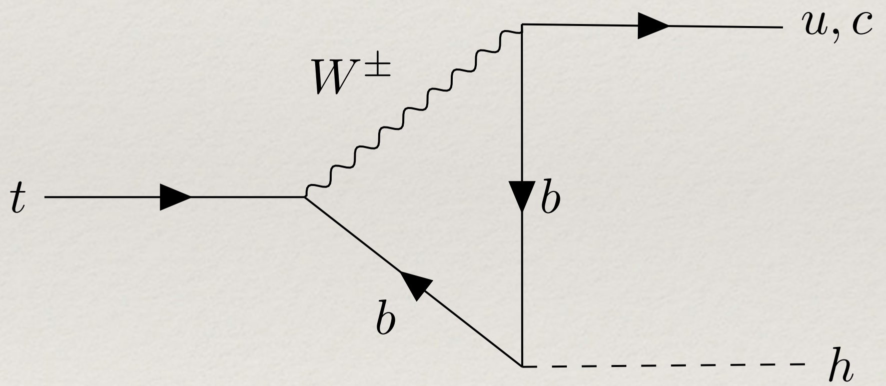
- Flavor constraints from D meson mixing are avoided.
- Strongest constraint from radiative b decay $b \to s\gamma$
- Can lead to sizable flavor violating couplings of SM-like Higgs to up quarks
  - New probe: rare top decays!

Rare Top Decays

(arXiv:1904.10956 W. Almannshofer, B. Maddock, DT)

Rare Top Decays in the SM

- Loop suppressed
- GIM suppressed
- Unobservable at the LHC or future colliders



	SM Prediction	Experiment
$t \to hu$	$(3.66^{+0.94}_{-0.70} \pm 0.67) \times 10^{-17}$	$< 0.12\%$
$t \to hc$	$(4.19^{+1.08}_{-0.80} \pm 0.16) \times 10^{-15}$	$< 0.11\%$

ATLAS arXiv:1812.11568

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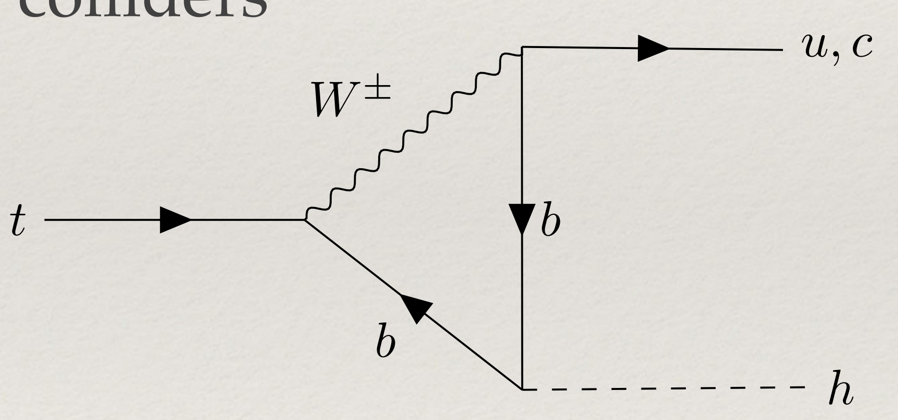

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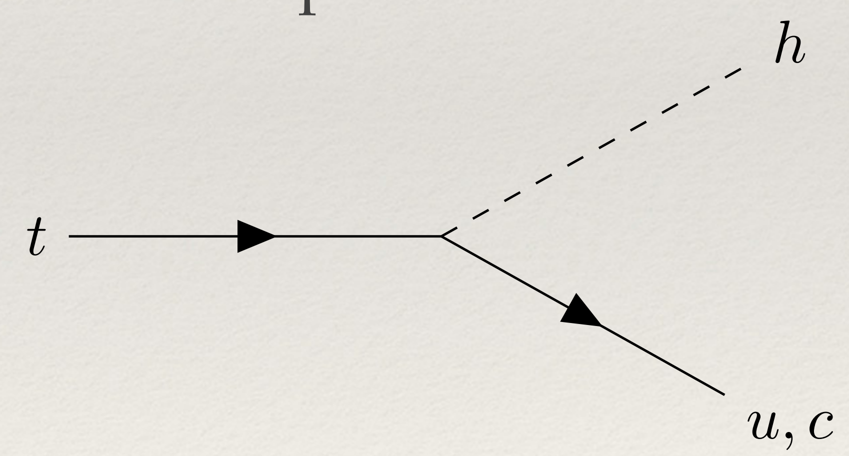
Flavorful 2HDM

- Flavor-violating SM Higgs couplings
- Tree level contribution
- Can experimental searches test the parameter space?



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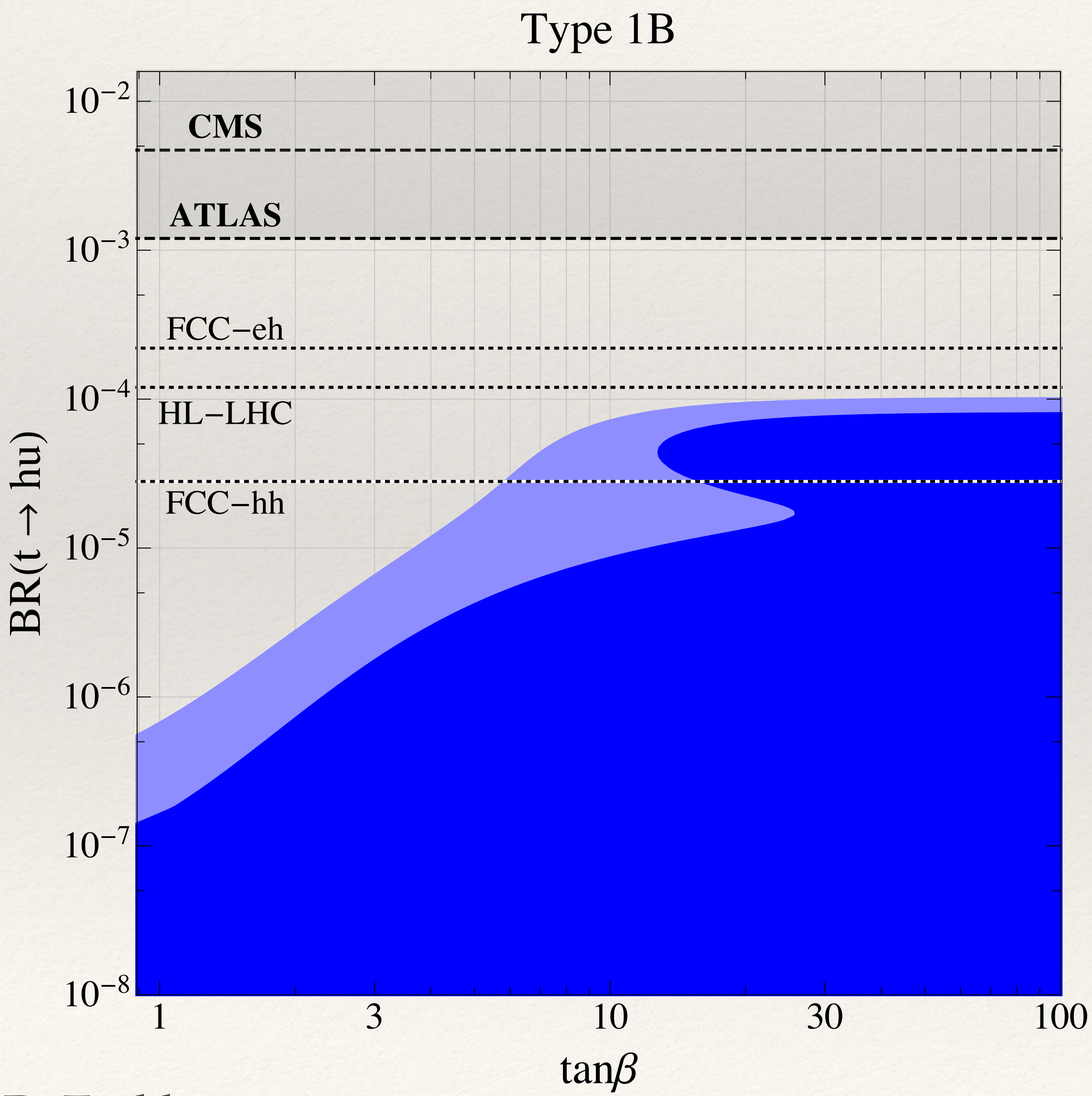

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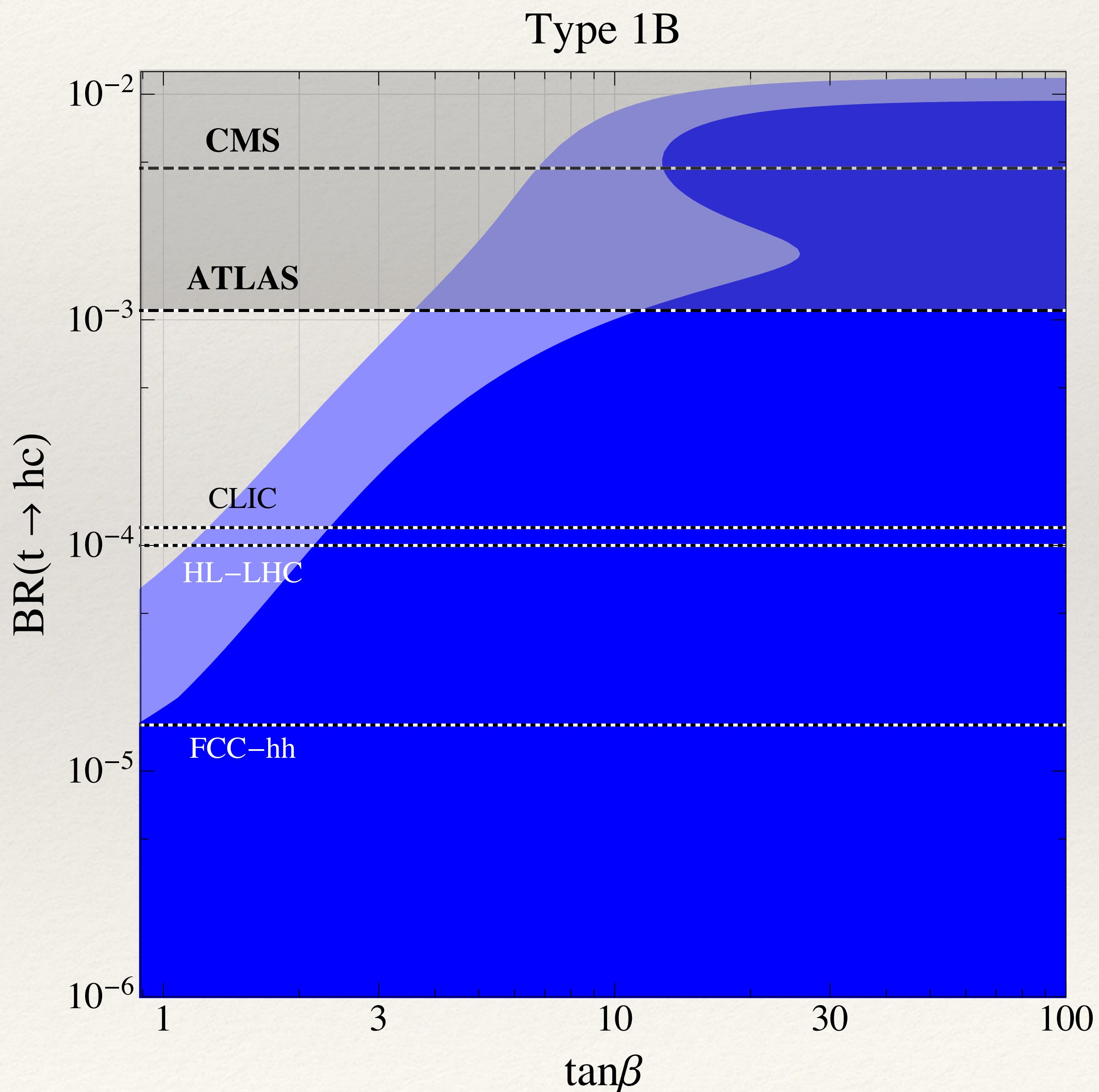
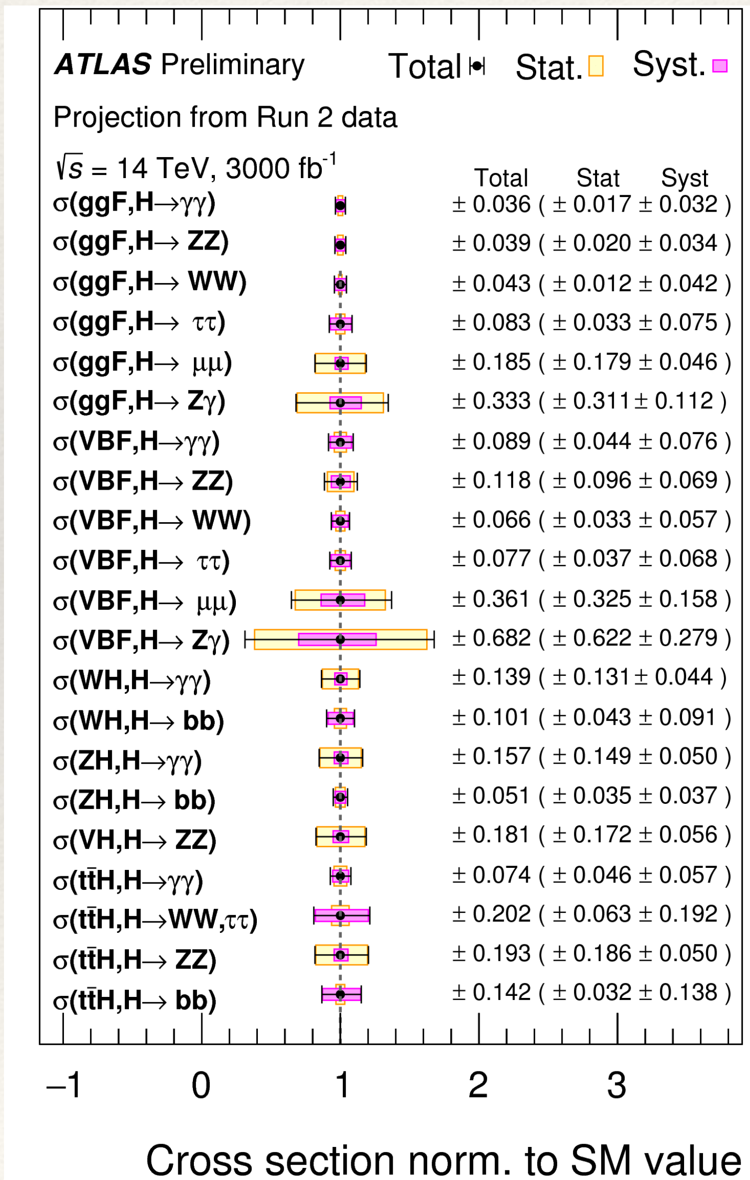
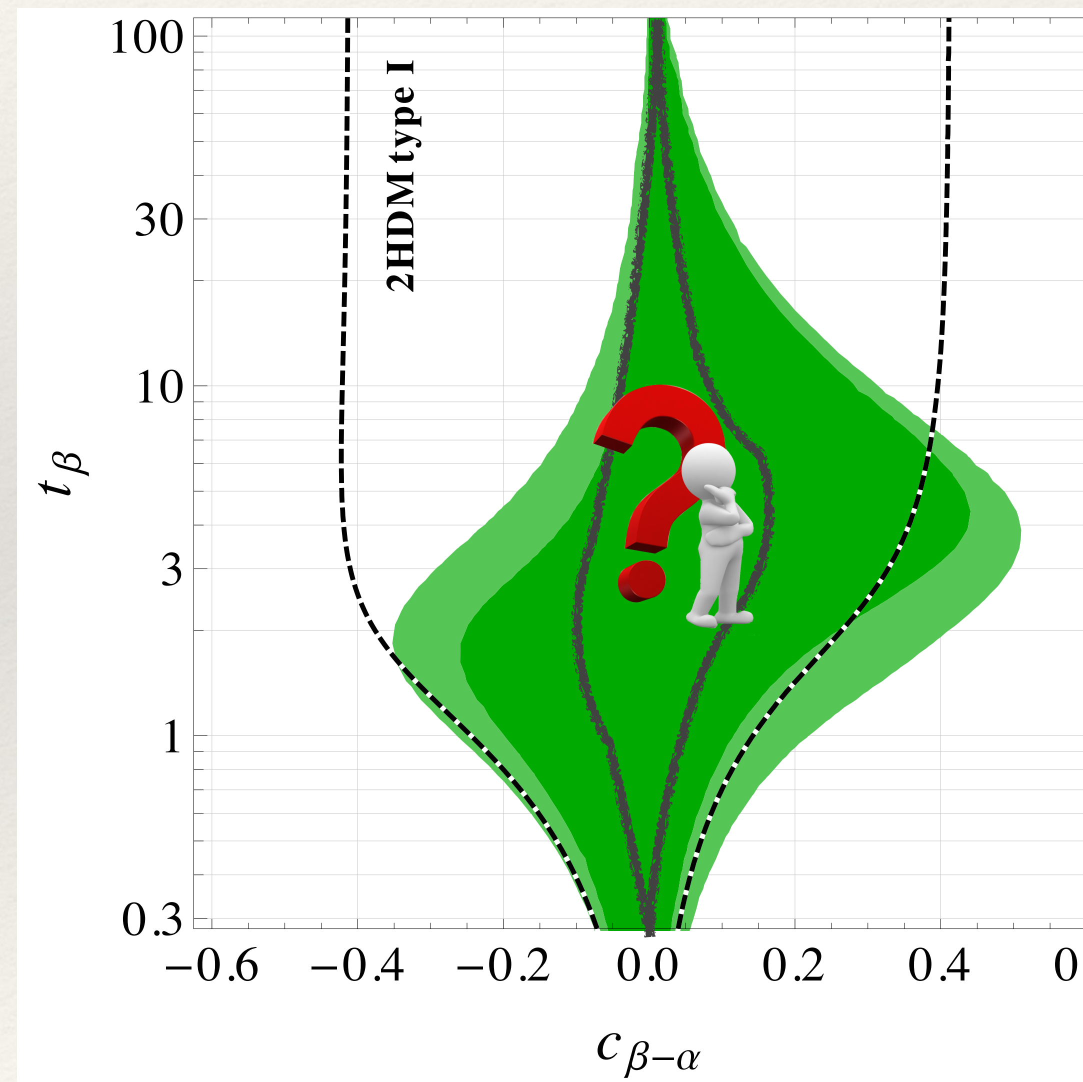


Questions for the Future

- How will future 125 GeV Higgs rates/coupling measurements constrain α, β?





Questions for the Future

- What are the expected sensitivities of future experiments like HL/HE-LHC and FCC?
  - Sensitivities based on 3rd generation fermions are not the strongest. Need a dedicated analysis.
- Need dedicated searches for extended Higgs sectors that decay dominantly to second generation fermions!
  - How will improvements in light quark tagging help in searching for signatures of our model (e.g $pp \to tH \to ttc$, $pp \to tH^{\pm} \to tts$)?
  - Generally, the community should begin taking seriously well-motivated scenarios that predict signatures that are very different from the standard searches.

Summary

- The SM flavor puzzle can be addressed in a **Flavorful 2HDM** with rank-1 structure for the SM-like Higgs boson
    - Theory of flavor needs a UV completion! Can use the *"flavor-locking" mechanism* for down quark CKM (see arXiv:1507.00009 and arXiv:1712.01847 for details) or *Froggatt-Nielsen* for up quark CKM (see arXiv:1904.10956 for implementation).
- "Clever" flavor structures to suppress large FCNCs (but still have off-diagonal couplings!)
    - **Distinct production and decays modes involving 2nd gen. fermions**
    - Weak collider constraints
    - New collider signatures that can be looked for at the LHC
    - Complimentary approach in **rare top decays**
- Several benchmarks for the Flavorful 2HDM have been delivered to experimentalists, and have inspired searches already! See link below:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Flavorful2HDM

Thanks!

Questions?

Back up Slides

SM Higgs Coupling Modifications

	κ_V^h	$\kappa_u^h,\ \kappa_c^h,\ \kappa_t^h$	$\kappa_d^h,\ \kappa_s^h,\ \kappa_b^h$	$\kappa_e^h,\ \kappa_\mu^h,\ \kappa_\tau^h$
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	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta},\ \frac{-s_\alpha}{c_\beta},\ \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta},\ \frac{-s_\alpha}{c_\beta},\ \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta},\ \frac{-s_\alpha}{c_\beta},\ \frac{-s_\alpha}{c_\beta}$

Heavy Higgs Coupling Modifications

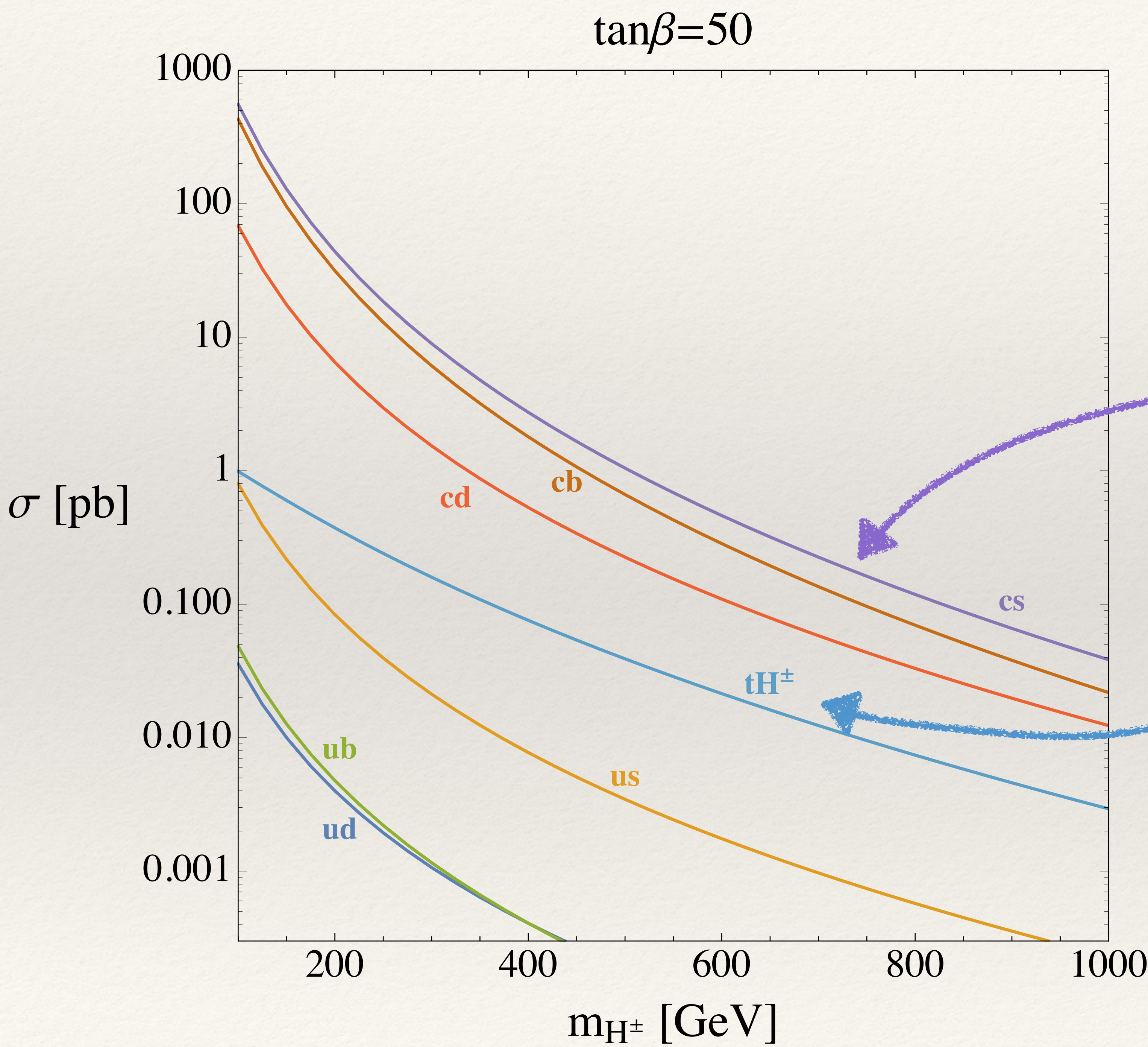
	κ_V^H	$\kappa_u^H,\ \kappa_c^H,\ \kappa_t^H$	$\kappa_d^H,\ \kappa_s^H,\ \kappa_b^H$	$\kappa_e^H,\ \kappa_\mu^H,\ \kappa_\tau^H$
Type I	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
Type II	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful	$c_{\beta-\alpha}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$

Coupling Modifications

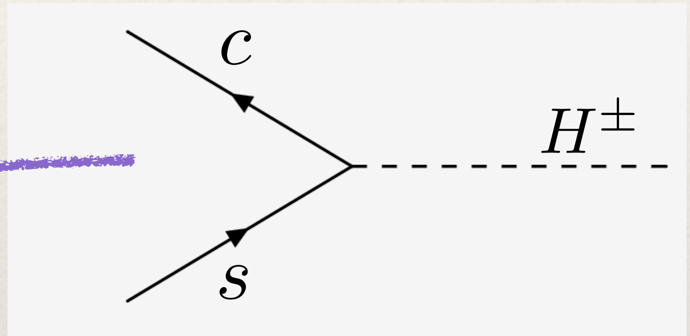
	κ_V^H	$\kappa_u^H,\ \kappa_c^H,\ \kappa_t^H$	$\kappa_d^H,\ \kappa_s^H,\ \kappa_b^H$	$\kappa_e^H,\ \kappa_\mu^H,\ \kappa_\tau^H$
Type I	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
Type II	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful	$c_{\beta-\alpha}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$

1. **Non-universal fermion couplings.** (Similar pattern for $H^\pm, A$)
2. **Couplings to third generation are suppressed by $\tan\beta$**

Production of the Charged Higgs ($H^{\pm}$)



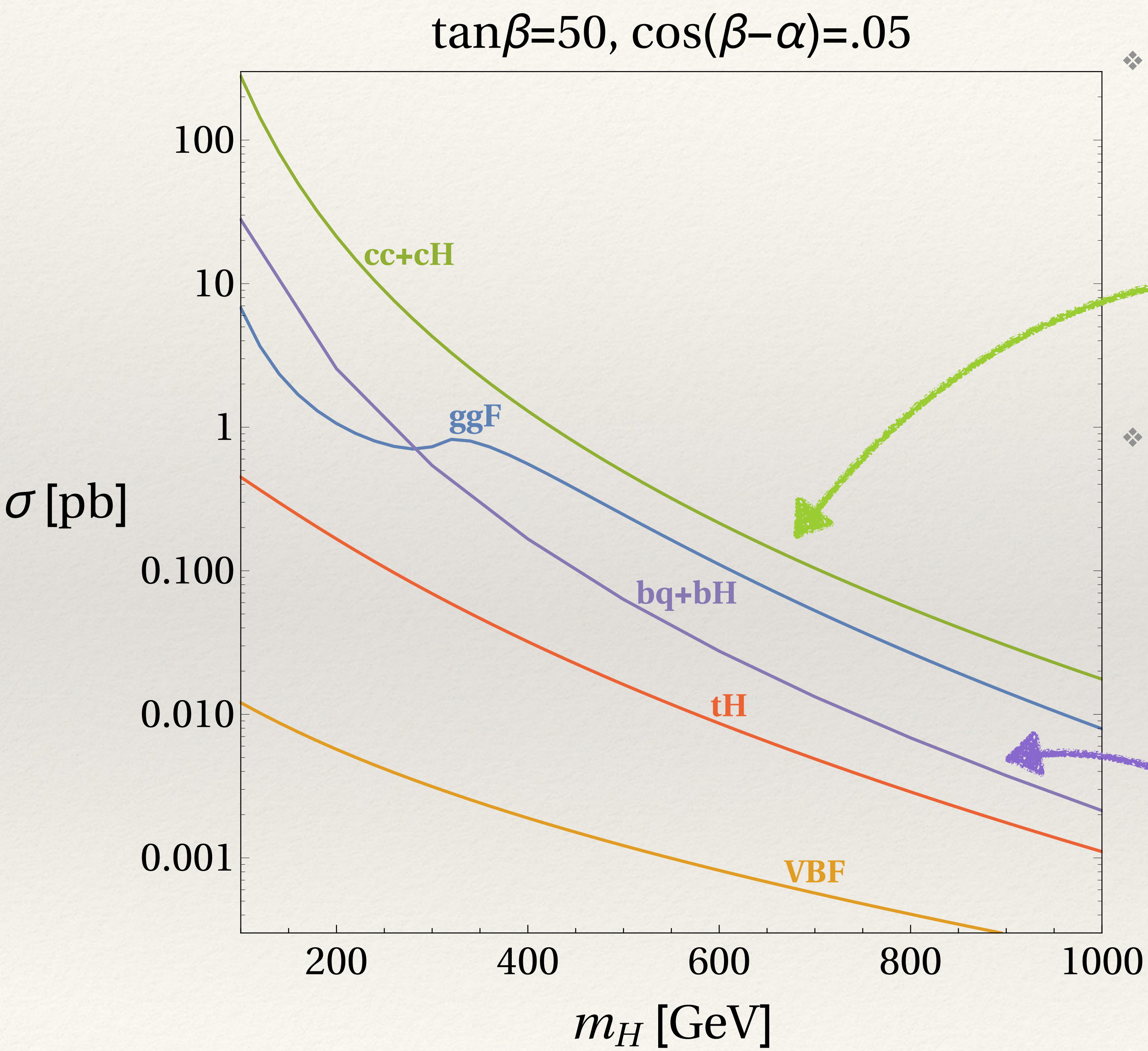
- Dominant production is from s-channel **charm-strange** fusion (2nd generation quarks!)



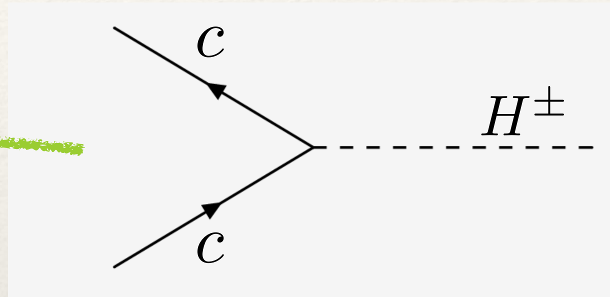
- "Classic" production mode (associated production with top quark) is suppressed.

D. Tuckler

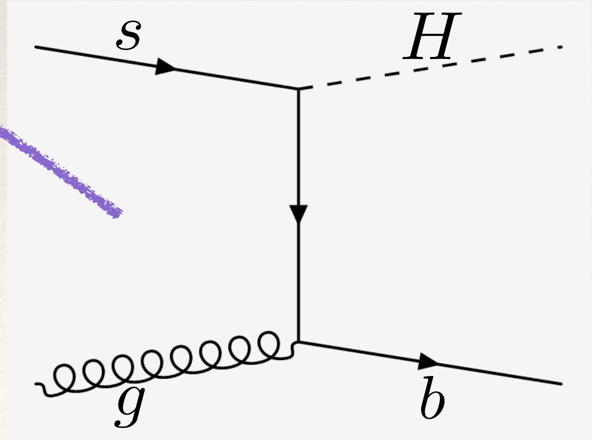
Production of the Neutral Higgs (H)



- Dominant production mode is **charm-charm fusion**



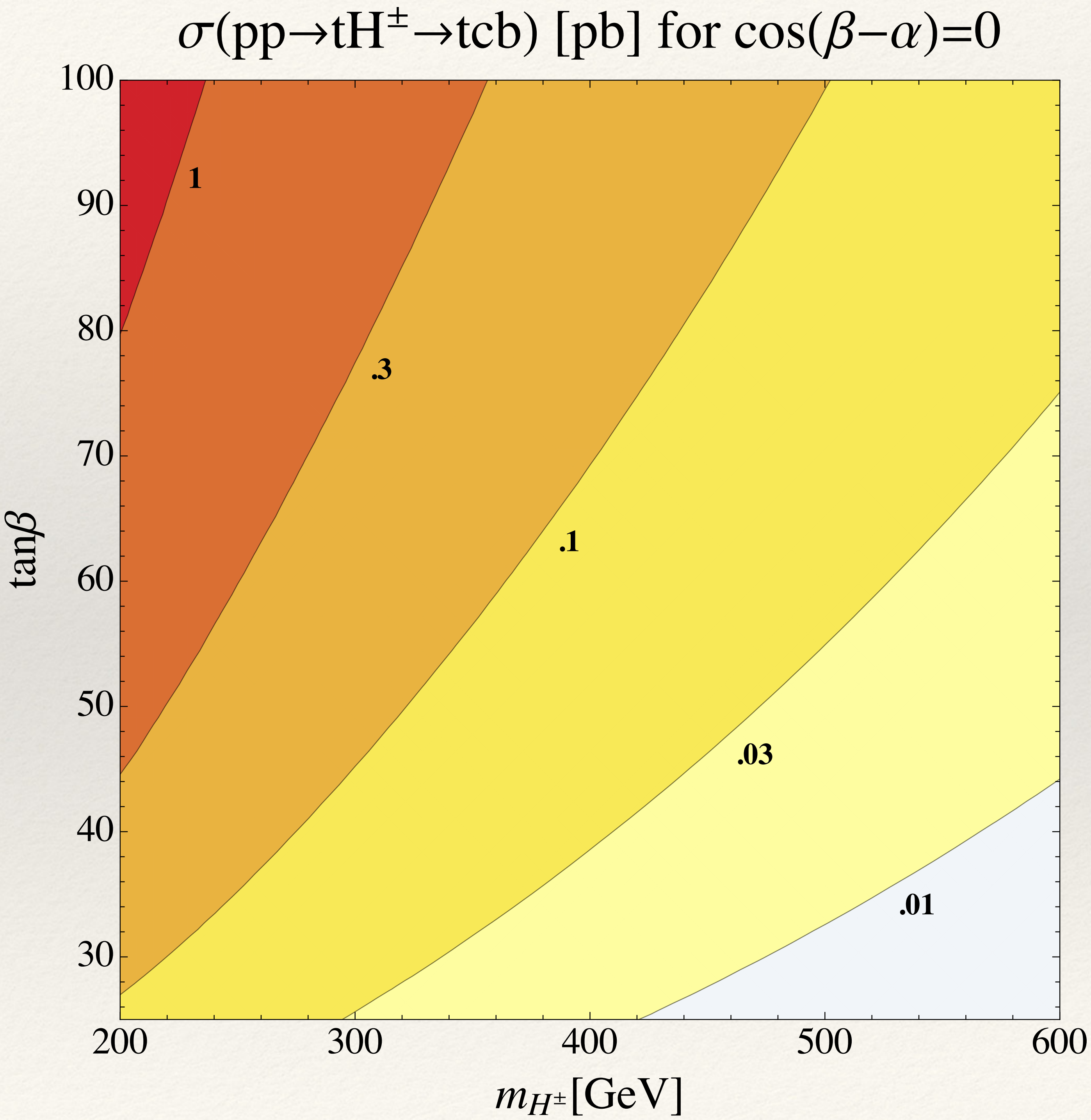
- Associated production with a b quark is generically suppressed compared to Type II 2HDM
  - Dominant contribution is from strange quark initiated process!



New Signatures for $H^{\pm}$

$$pp \to tH^{\pm} \to tcb$$

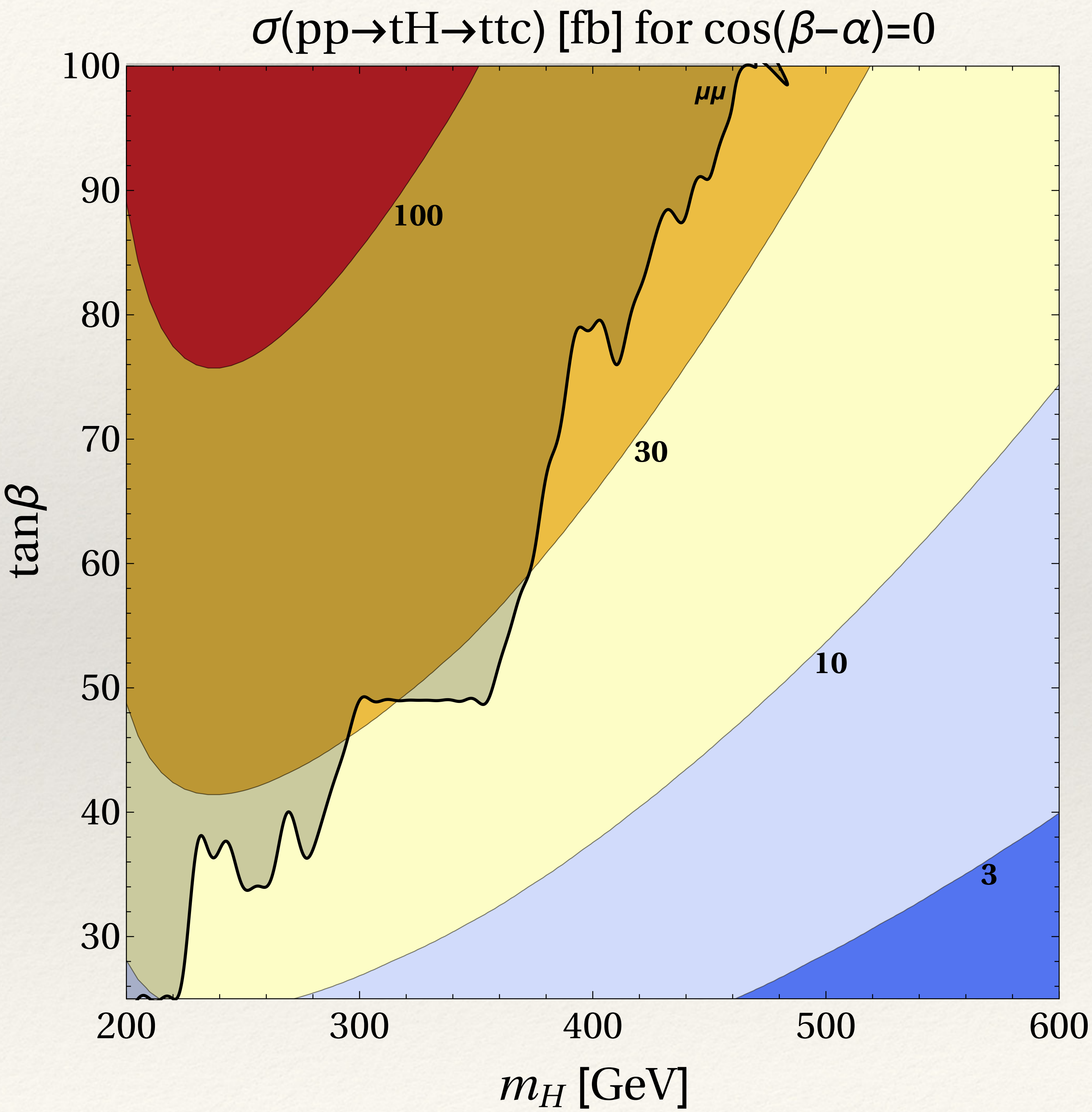
- Charged Higgs-top associated production
- Di-jet resonance + top quark
- Sizable σ × BR of a few hundred of fb - pb
- Unconstrained by current LHC searches



New Signatures for *H*

$$pp \to tH \to ttc$$

- Higgs-top associated production
- Look for **same-sign top quarks**
    - Two same sign final state leptons
- Sizable σ × BR of a few to tens of fb

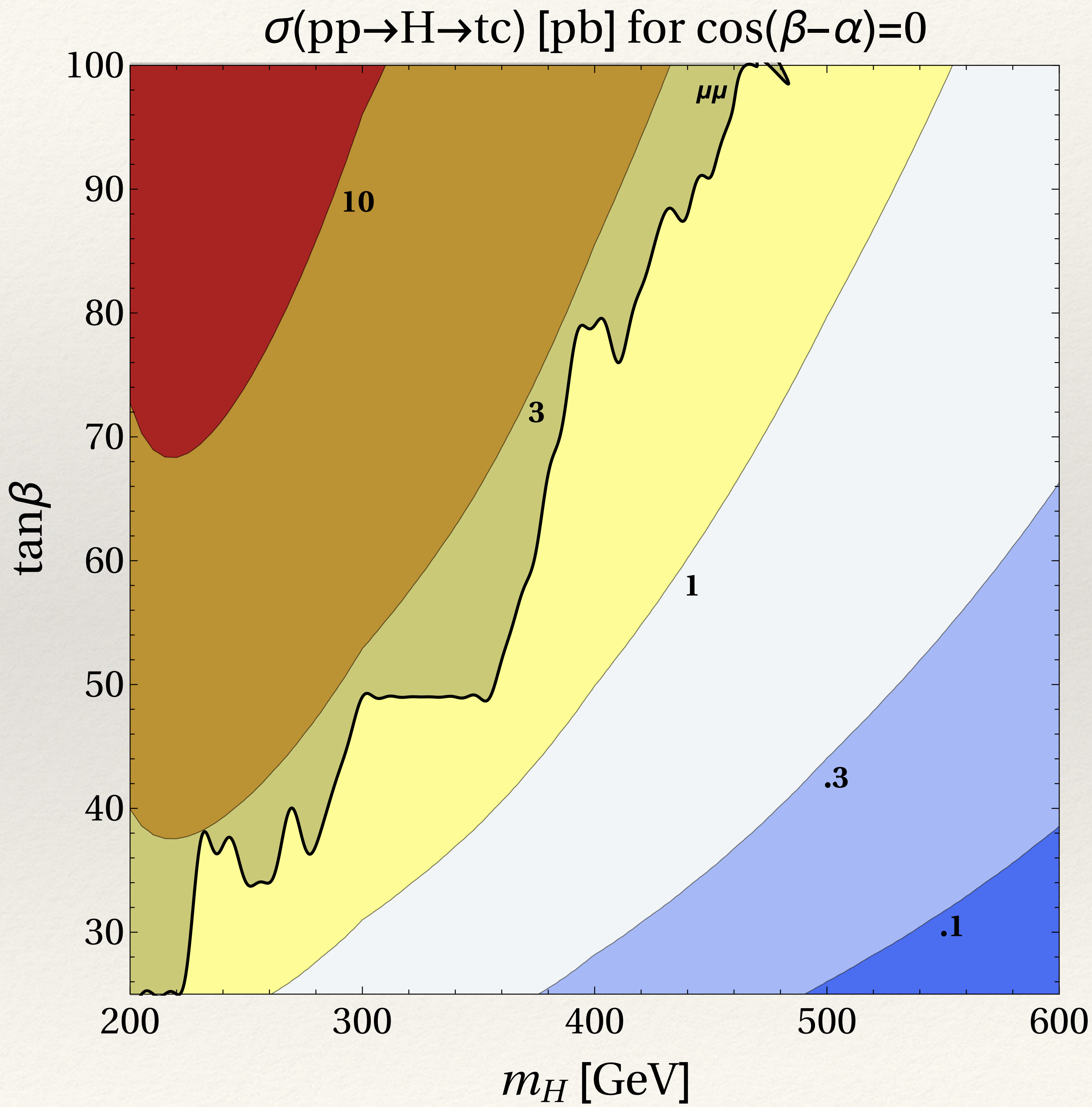


D. Tuckler

New Signatures for H

$$pp \to H \to tc$$

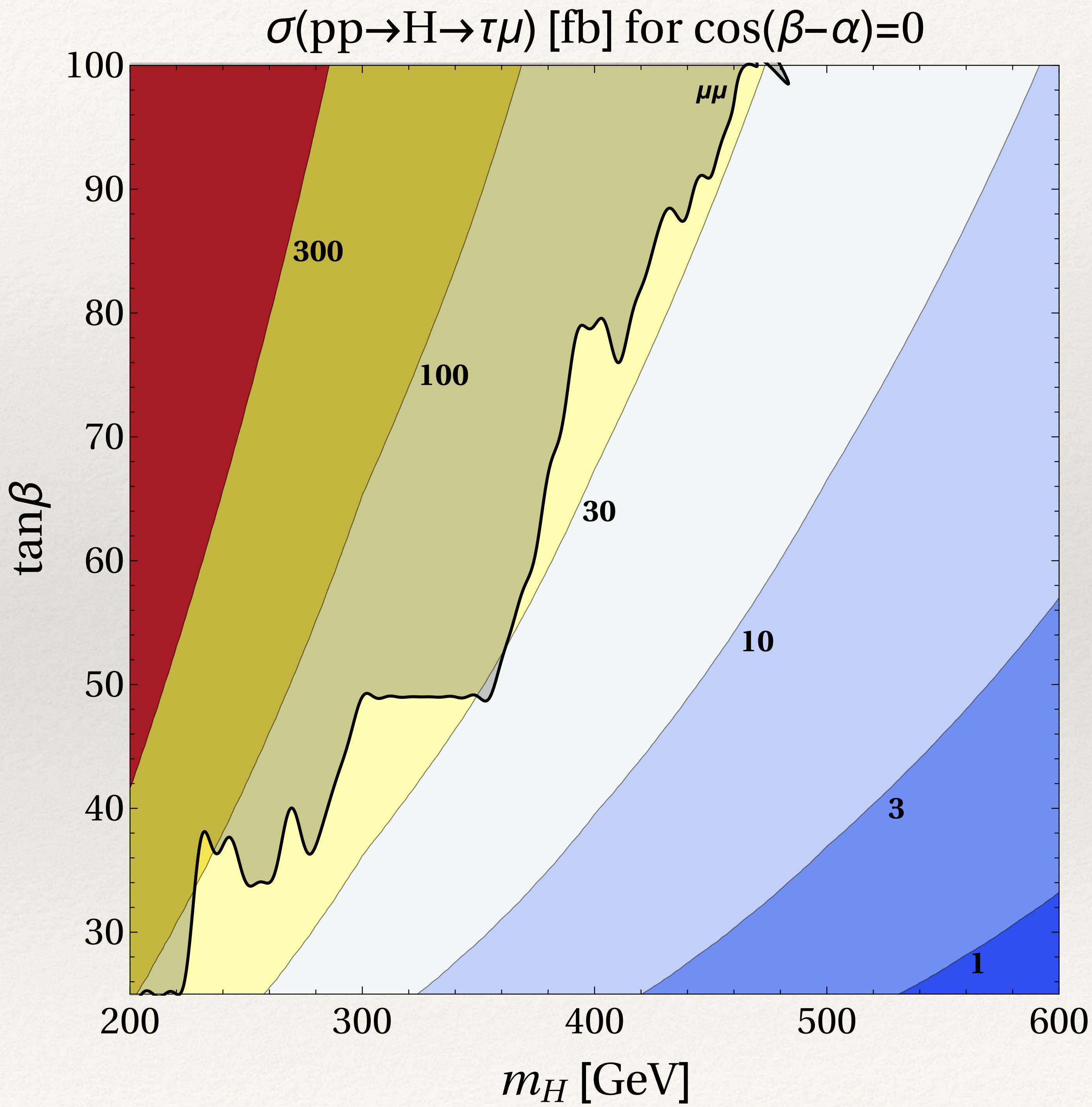
- Quark-quark fusion production
- Top-charm resonances
  - Use leptonically decaying top quark as a trigger
- Sizable σ × BR of hundreds of fb to a few pb
- Shaded region = constraints from di-muon searches



New Signatures for H

$$pp \to H \to \tau\mu$$

- Quark-quark fusion production
- τμ resonance
- Sizable σ × BR of a few to tens of fb



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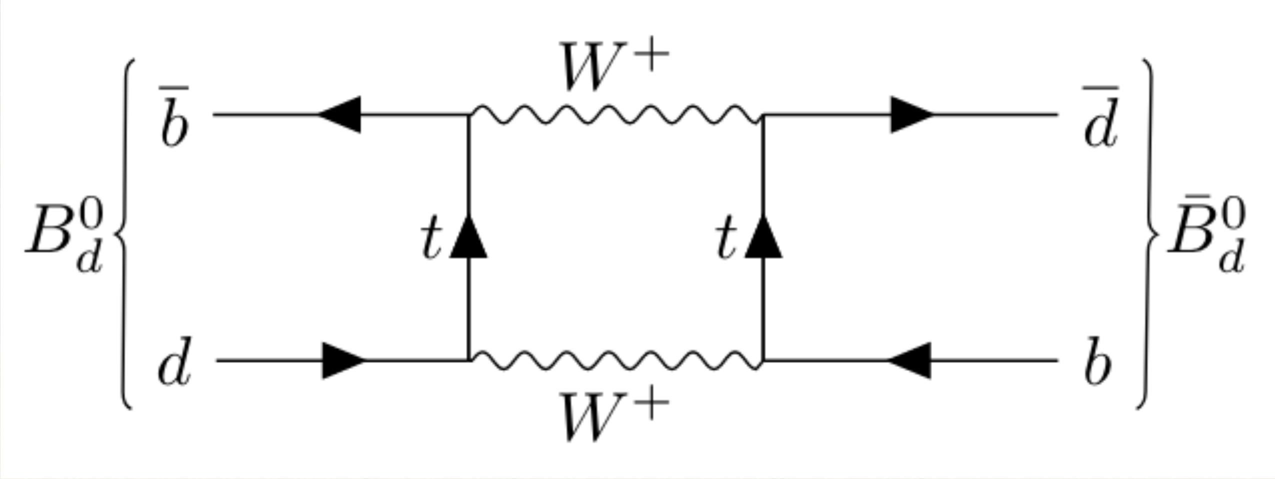
Flavor Constraints on Down Sector CKM

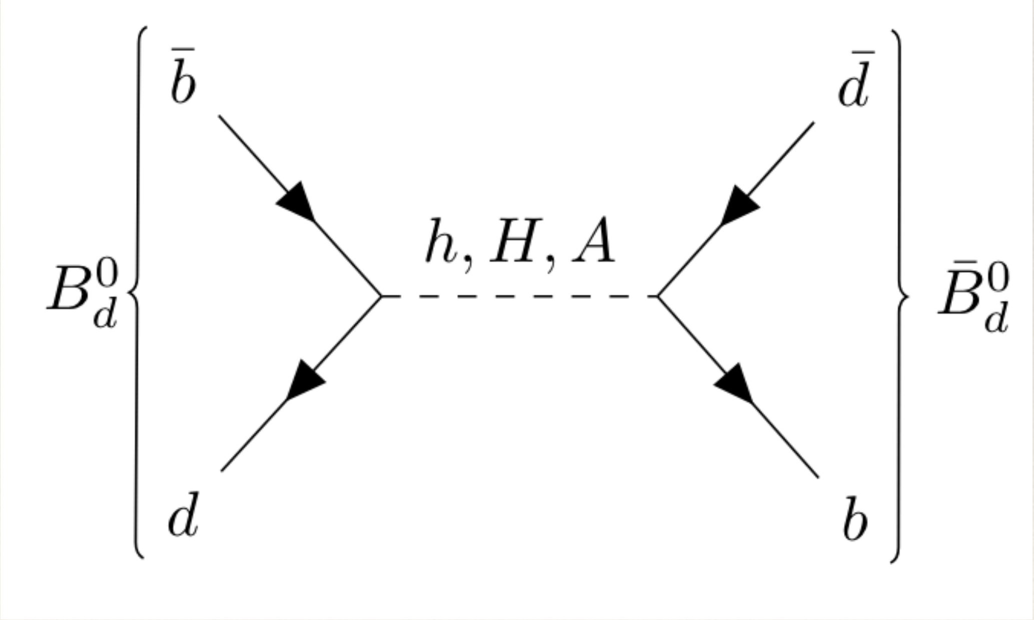
(arxiv:1712.01847 W. Altmannshofer, S. Gori, D. Robinson, DT)

- Flavor changing Higgs couplings generate tree level contributions to meson oscillation
- There are mild tensions between SM predictions and experimental measurements. Our model can accommodate current date slightly better than the SM.

SM



Flavorful 2HDM



Meson Mixing Constraints on Down Sector CKM

(arxiv:1712.01847 W. Altmannshofer, S. Gori, D. Robinson, DT)

- Benchmark point: $m_A = m_H = 500$ GeV, $\tan\beta = 5$, $\cos(\beta-\alpha) = 0$
- Observables that are sensitive to Higgs bosons: $\Delta M_K,\ \Delta M_{B_{d,s}},\ \epsilon_K,\ \phi_{d,s}$

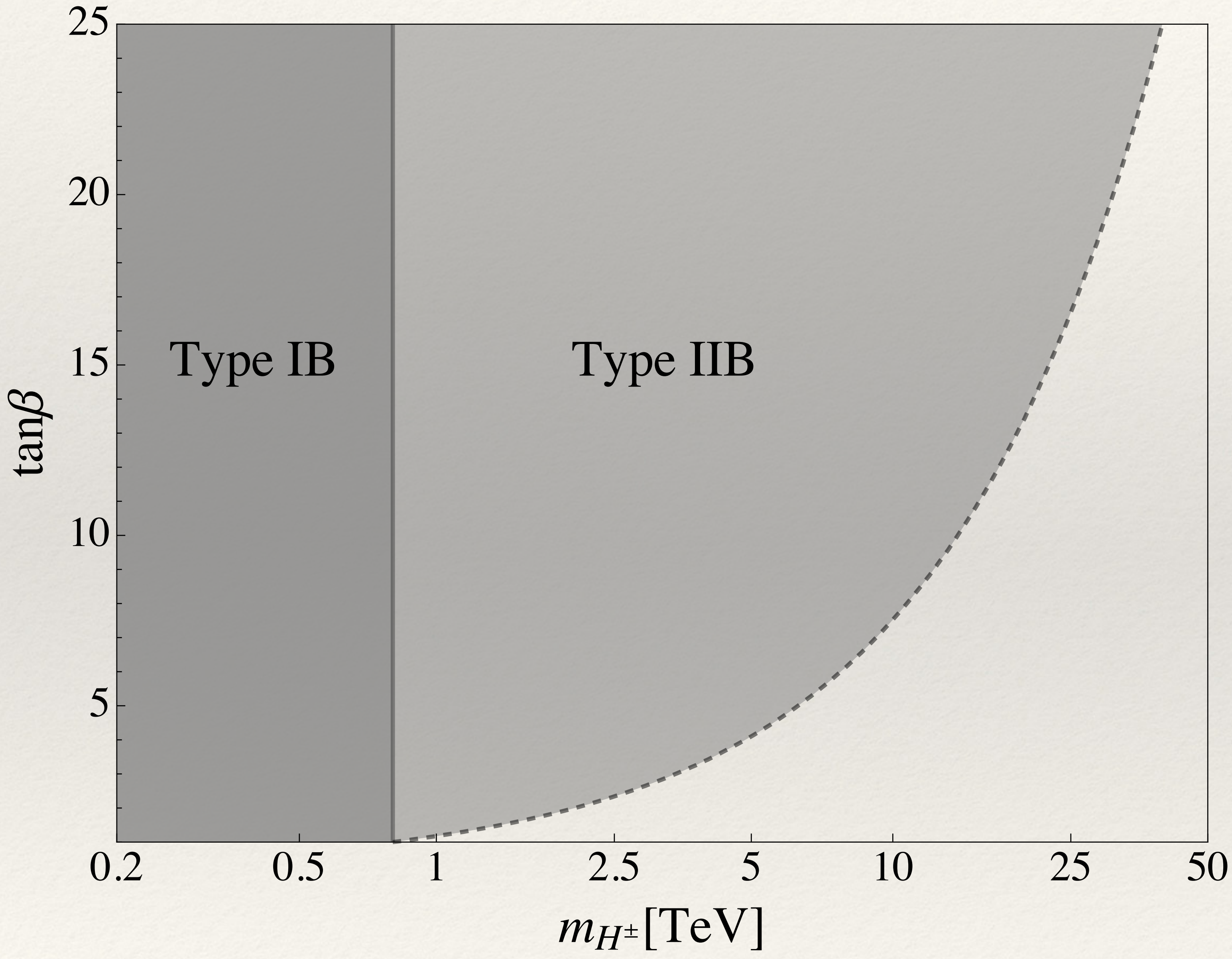
	Data	SM Prediction	NP Contribution
ΔM_K	$(5.294 \pm 0.002) \times 10^{-3}$ ps^{-1}	$(4.7 \pm 1.8) \times 10^{-3}$ ps^{-1}	$\simeq -2 \times 10^{-6}$ ps^{-1}
ΔM_{B_d}	0.5055 ± 0.0020 ps^{-1}	0.63 ± 0.07 ps^{-1}	$\simeq 0.01$ ps^{-1}
ΔM_{B_s}	17.757 ± 0.021 ps^{-1}	19.6 ± 1.3 ps^{-1}	$\simeq -1.8$ ps^{-1}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

- Quantify the goodness of the model by constructing a χ^2-like function
- Observables that are sensitive to Higgs bosons:

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

- Zero means that the model perfectly reproduces the experimental data
- Compare to SM: $X^2_{\text{loop}}(\text{SM}) \sim 10.8,$ $X^2_{\text{loop}} \sim 7.1$

Constraints from $b \to s\gamma$ on Up Sector CKM



- Large contribution from charged Higgs in the loop
- Restrict charged Higgs mass to be above 800 GeV