Flavorful Higgs Bosons at the LHC

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

Douglas Tuckler
UC Santa Cruz

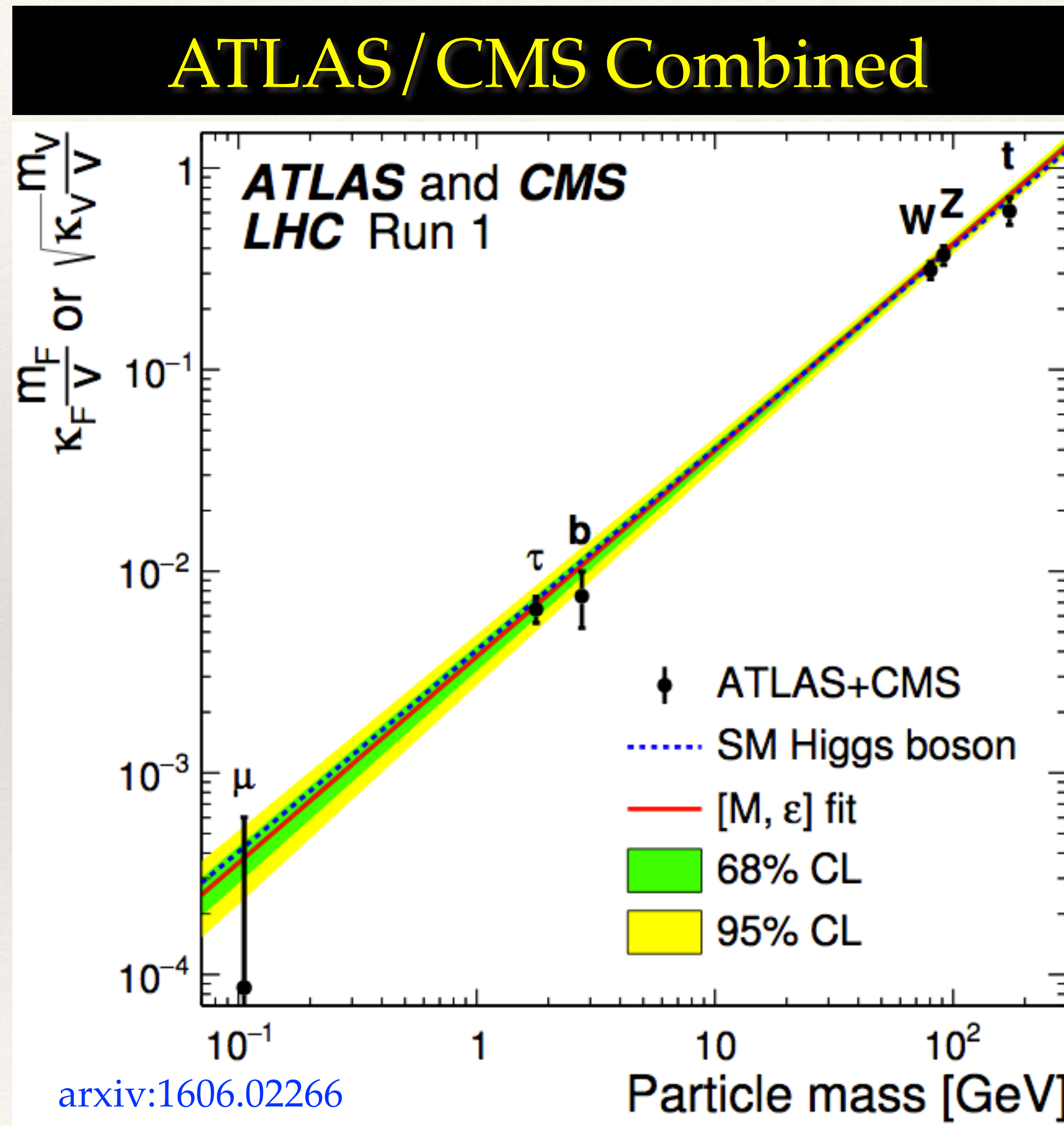
SUSY 2019
05/23/2019

Extended Higgs Sectors

- Motivations:
  1. Why should the scalar sector be so simple?
  2. Hierarchy problem (e.g. SUSY)
  3. Dark matter (e.g. SM+singlet scalar, Inert Doublet Model)
  4. The SM Flavor Puzzle
- Simple extension of the SM with additional Higgs bosons: **Two Higgs Doublet Model** (2HDM)
  - Extra CP-even Higgs (H), CP-odd Higgs (A), and charged Higgs ($H^{\pm}$)

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)



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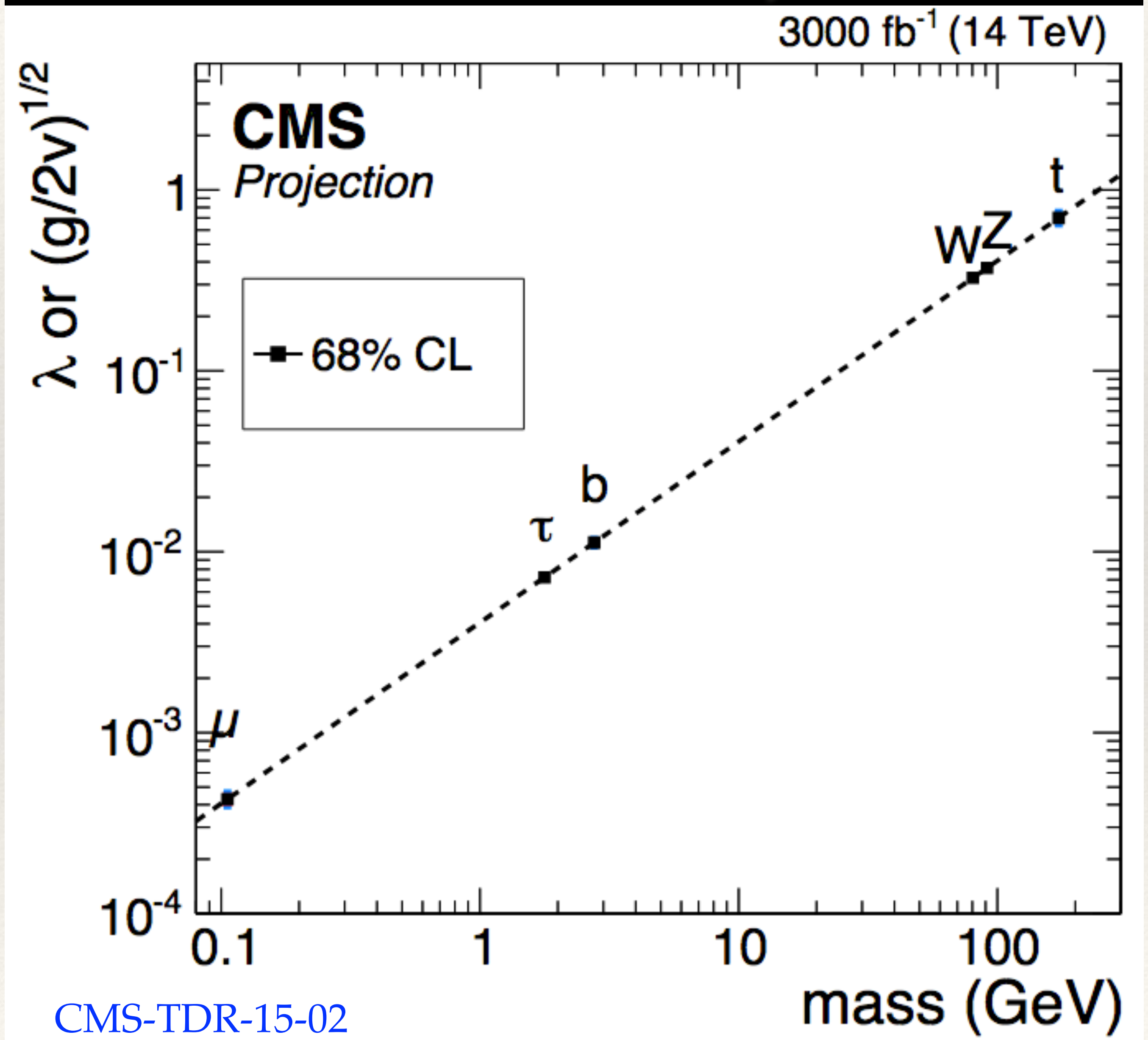
CMS HL-LHC Projection



CMS-TDR-15-02

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  - 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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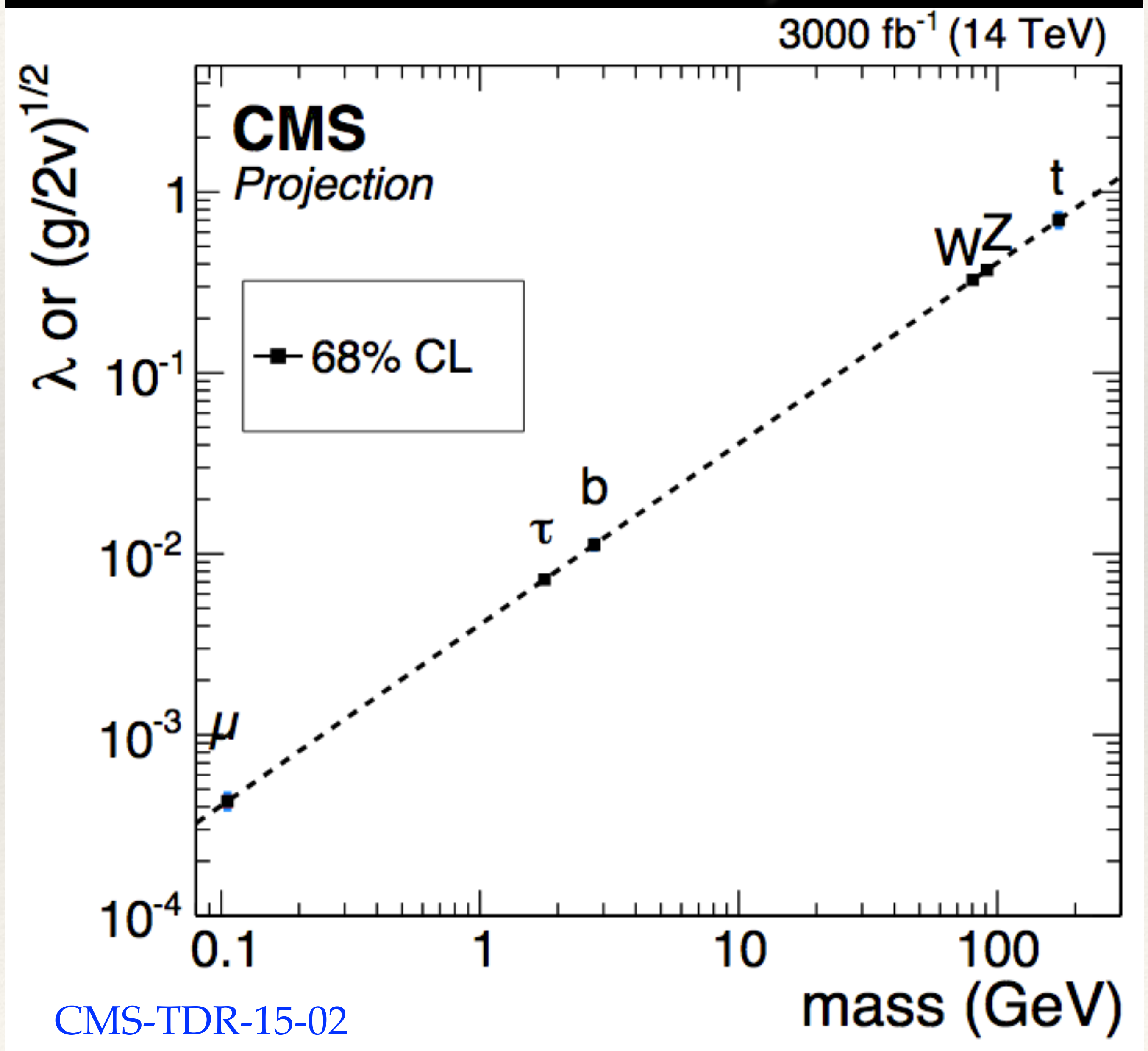

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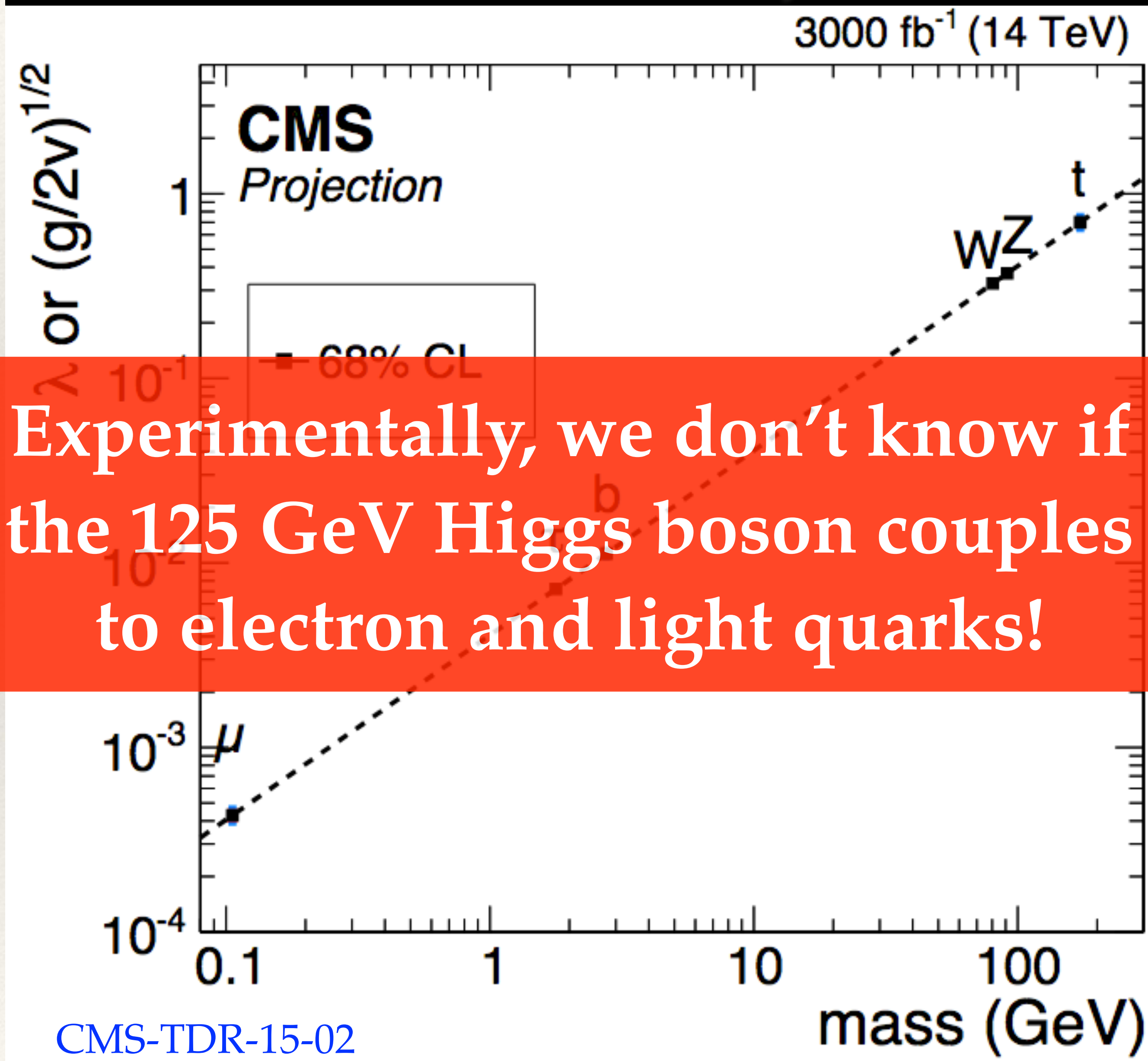

CMS-TDR-15-02

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

Does the 125 GeV Higgs boson give mass to all fermions?

(or why are the couplings to light fermions so small?)

D. Tuckler

Additional Sources of EWSB

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

W. Altmannshofer, S. Gori, A. Kagan, J. Zupan 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
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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, $H^{\pm}$)

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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

- 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

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

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Leads to flavor violating Higgs couplings to up quarks

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Leads to flavor violating Higgs couplings to up quarks

Down quark sector CKM

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

Leads to flavor violating Higgs couplings to down quarks

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	$c_{\beta-\alpha}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ \frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$

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Type II	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
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1. Non-universal fermion couplings. (Similar pattern for $H^\pm$ and A)

2. **Couplings to third generation are suppressed by tanβ**

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

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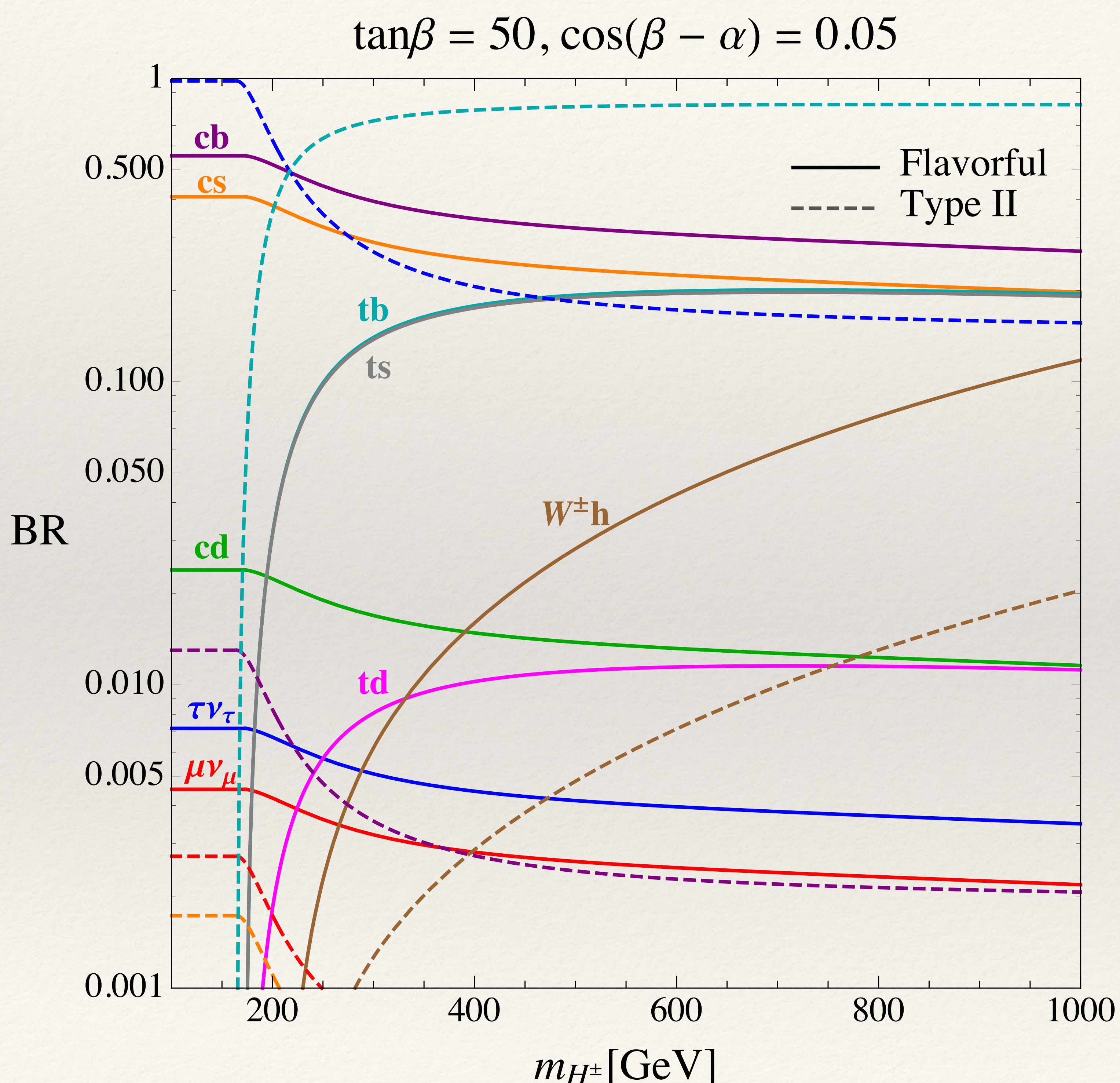
Let's see how this shows up when the the CKM originates in the down quark sector

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



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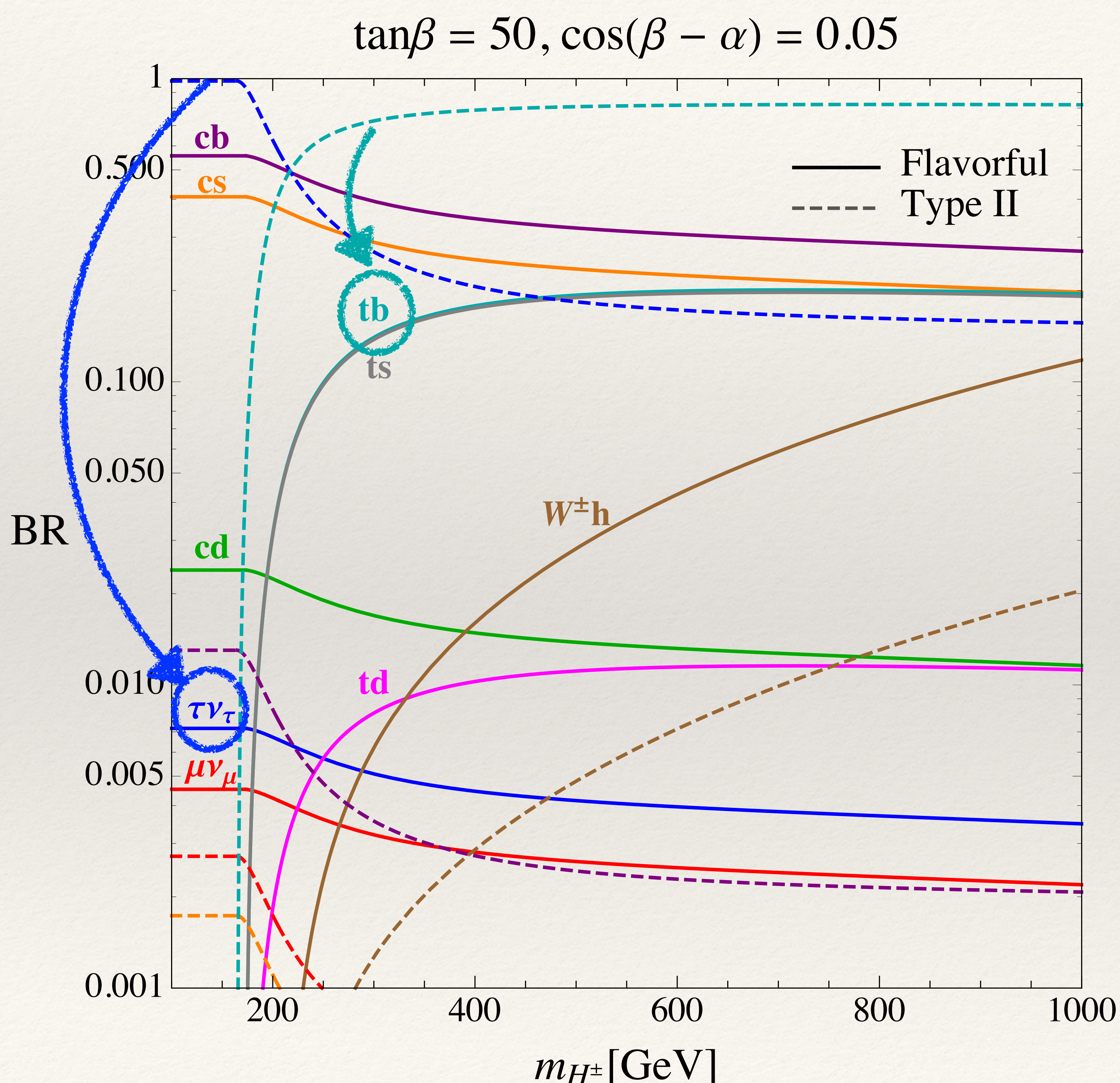

- "Classic" decay modes (tb, $\tau\nu$) are suppressed

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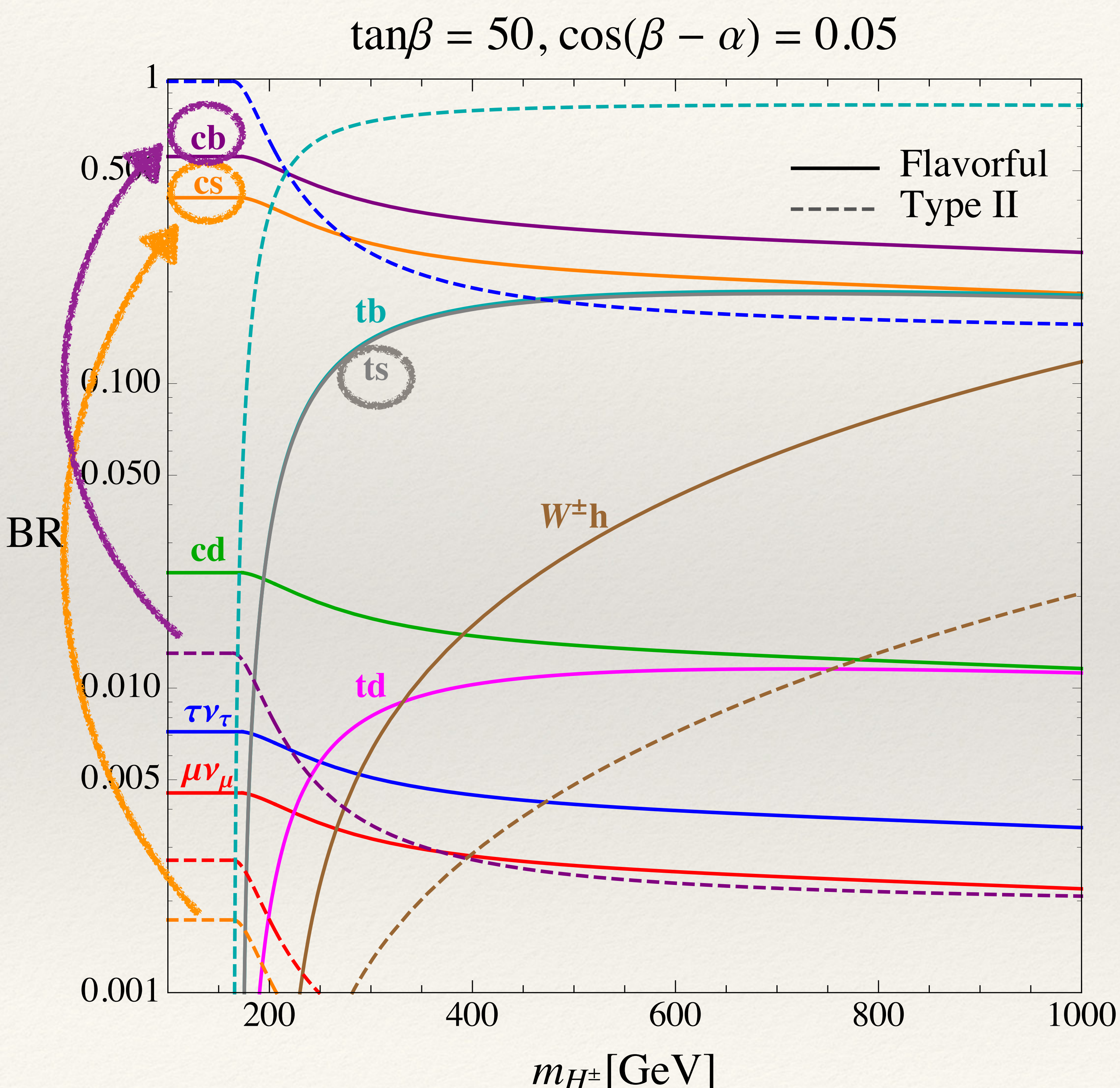
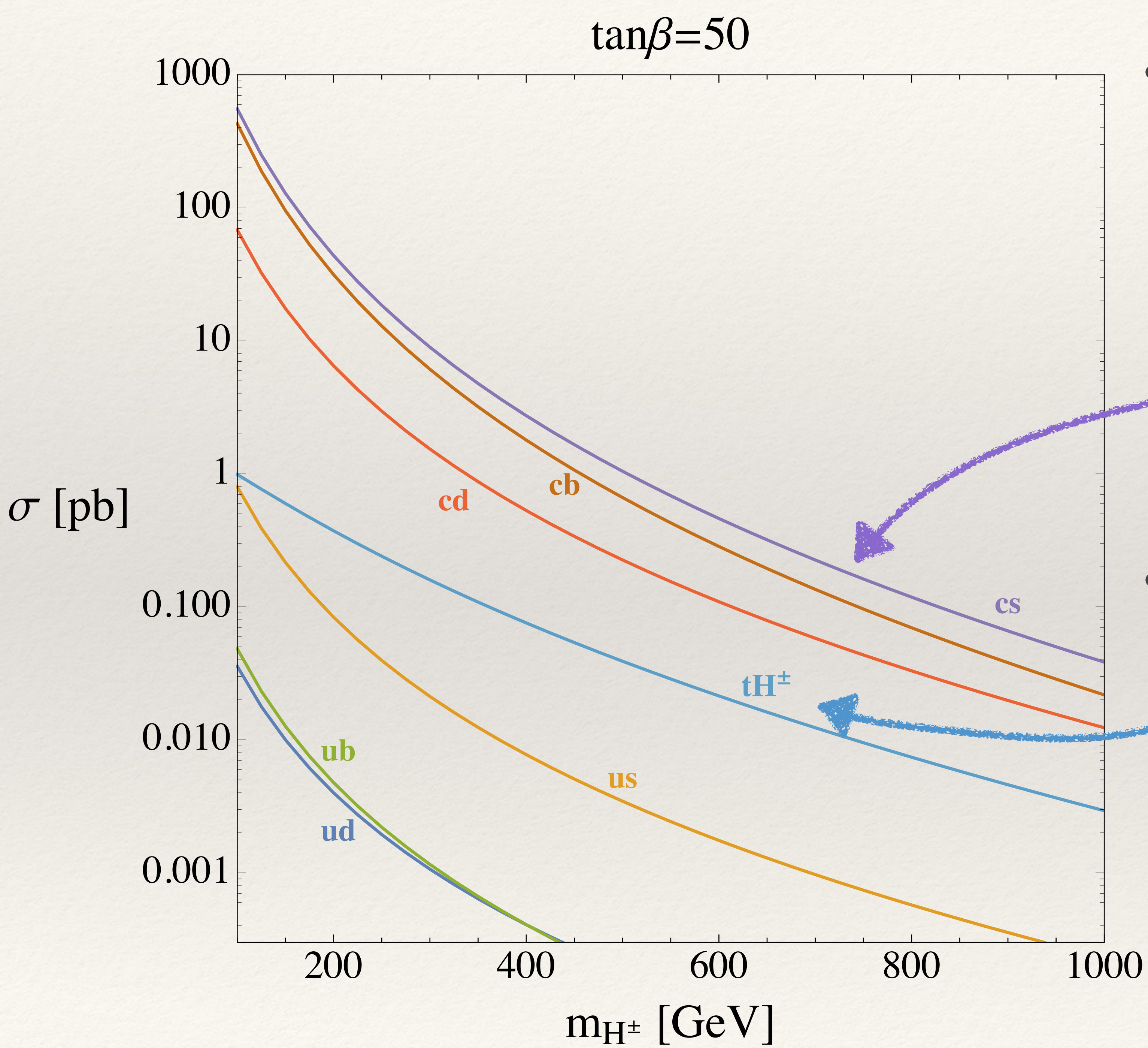
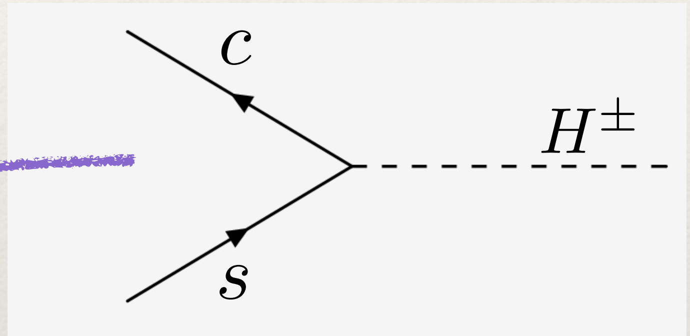


- "Classic" decay modes (tb, τν) are suppressed
- Dominant decay modes are to **charm-strange**, **charm-bottom** — these have only been searched for below the top threshold!
- Decay to **ts** becomes sizeable and of the order of decay to tb

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

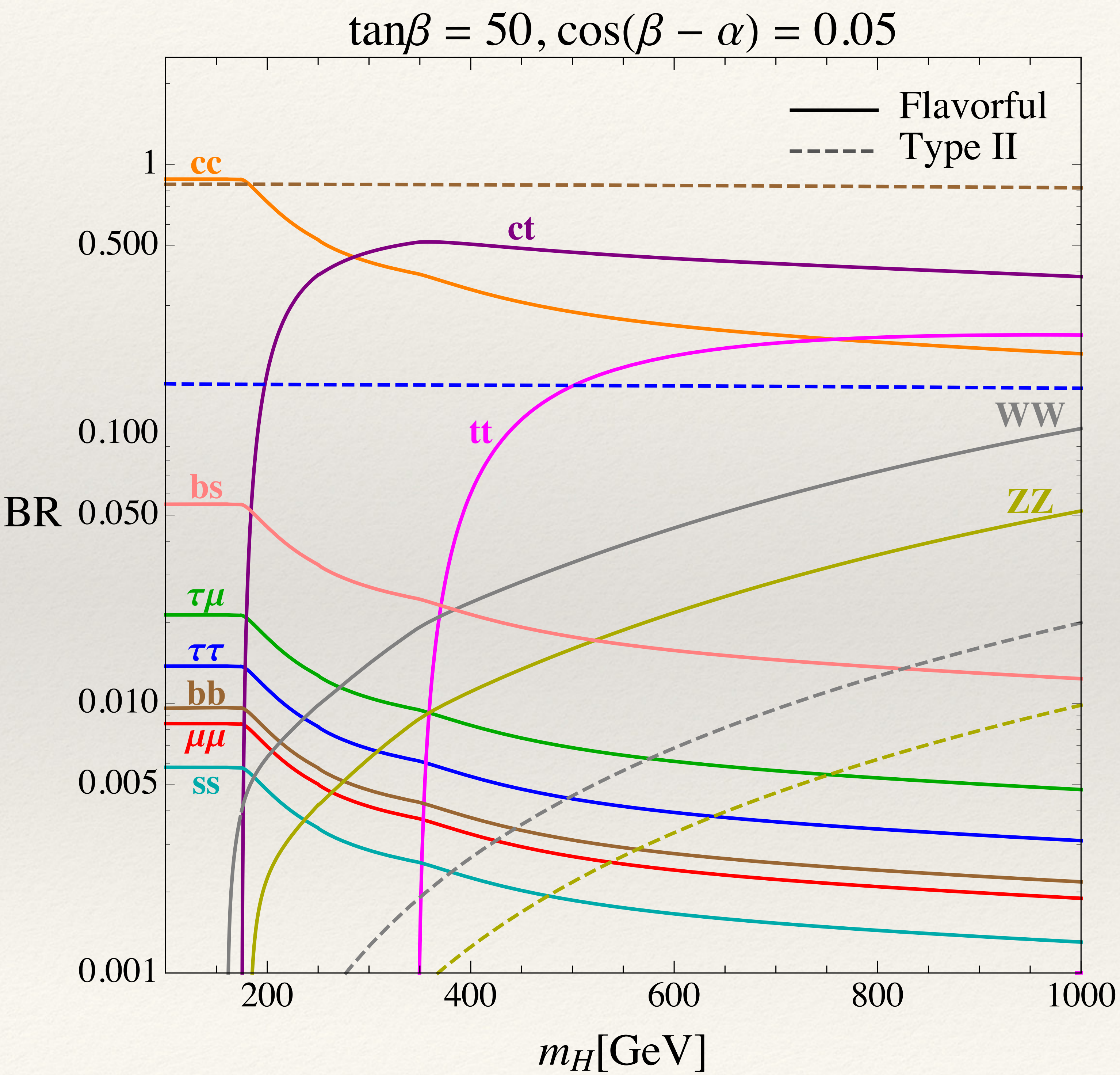


- Dominant production is from s-channel **charm-strange** fusion (2nd generation quarks!)



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

Decays of the Neutral Higgs (H)



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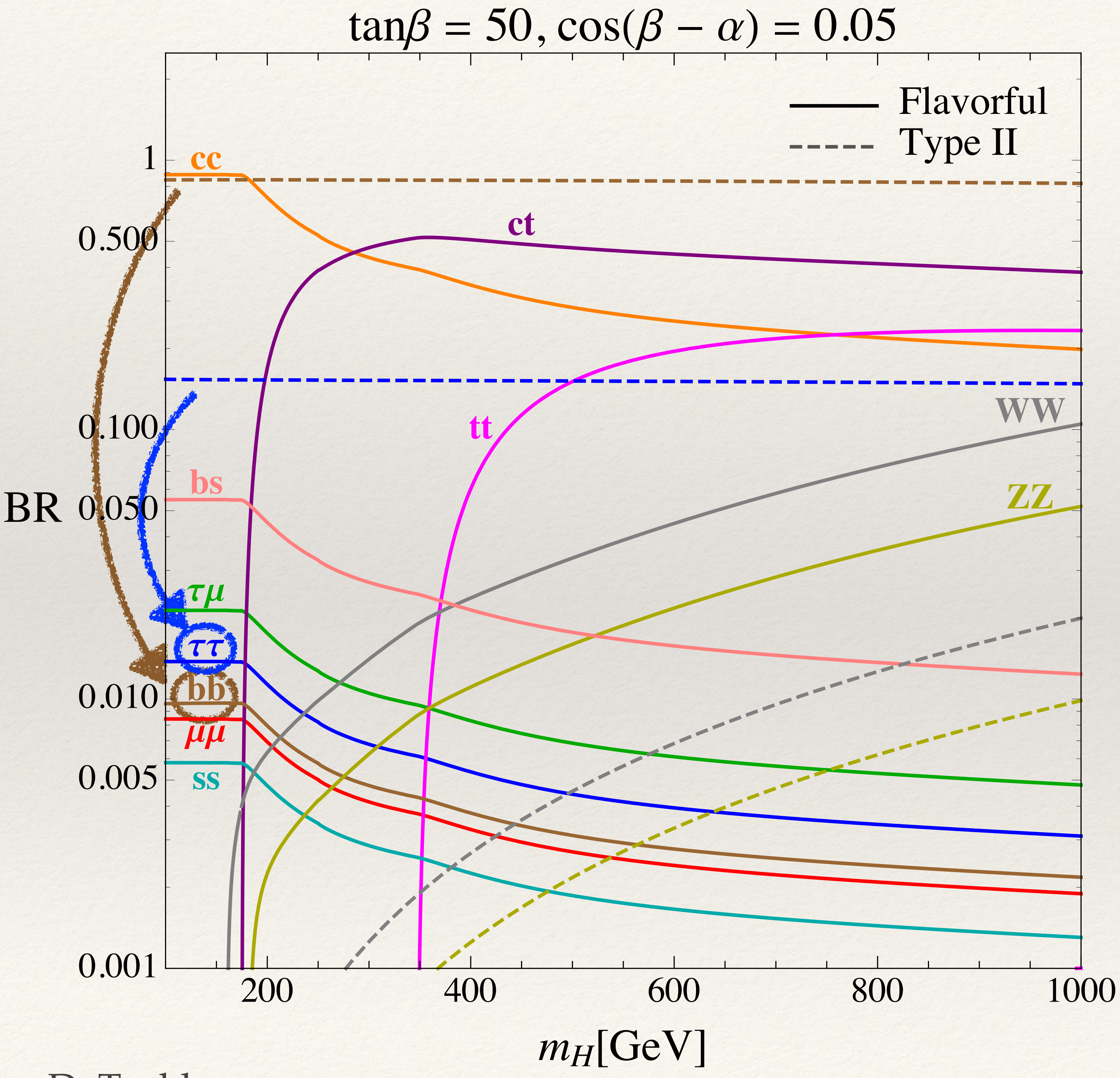

- "Classic" decays modes (**ττ**, **bb**) are suppressed

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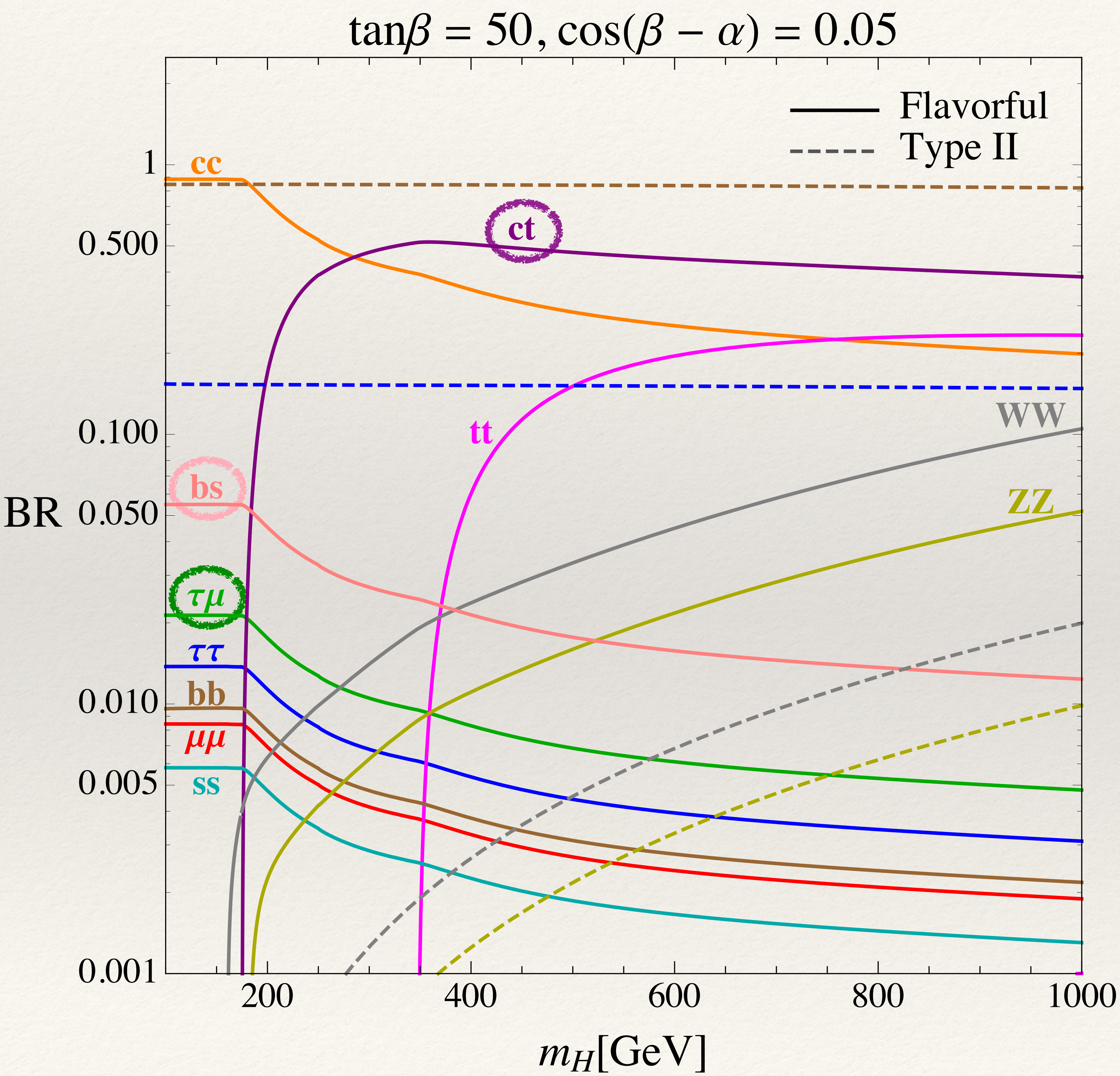

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- Flavor-violating (**ct**, **bs**, **τμ**) decays are now present (compared to Type II)!

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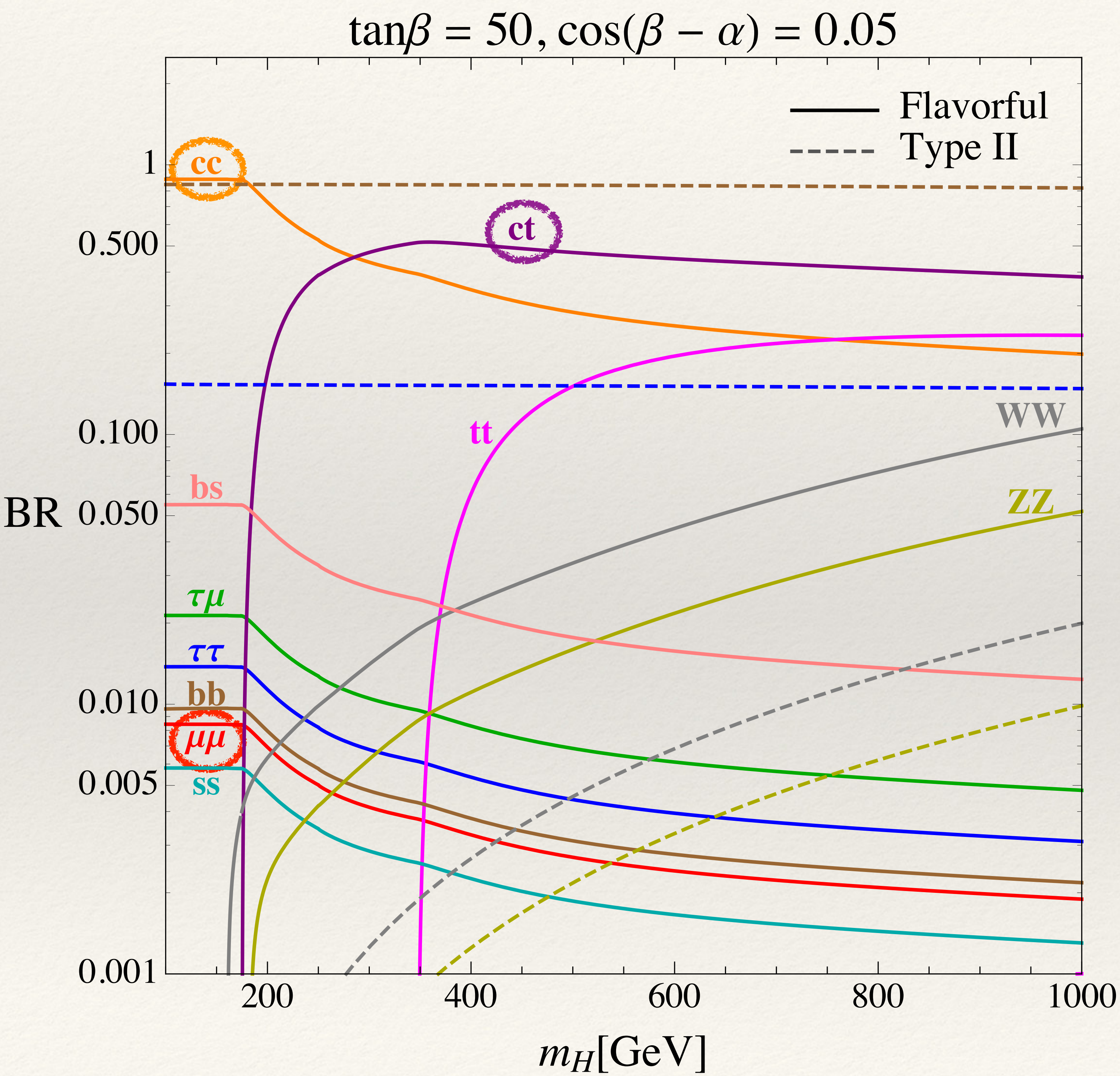
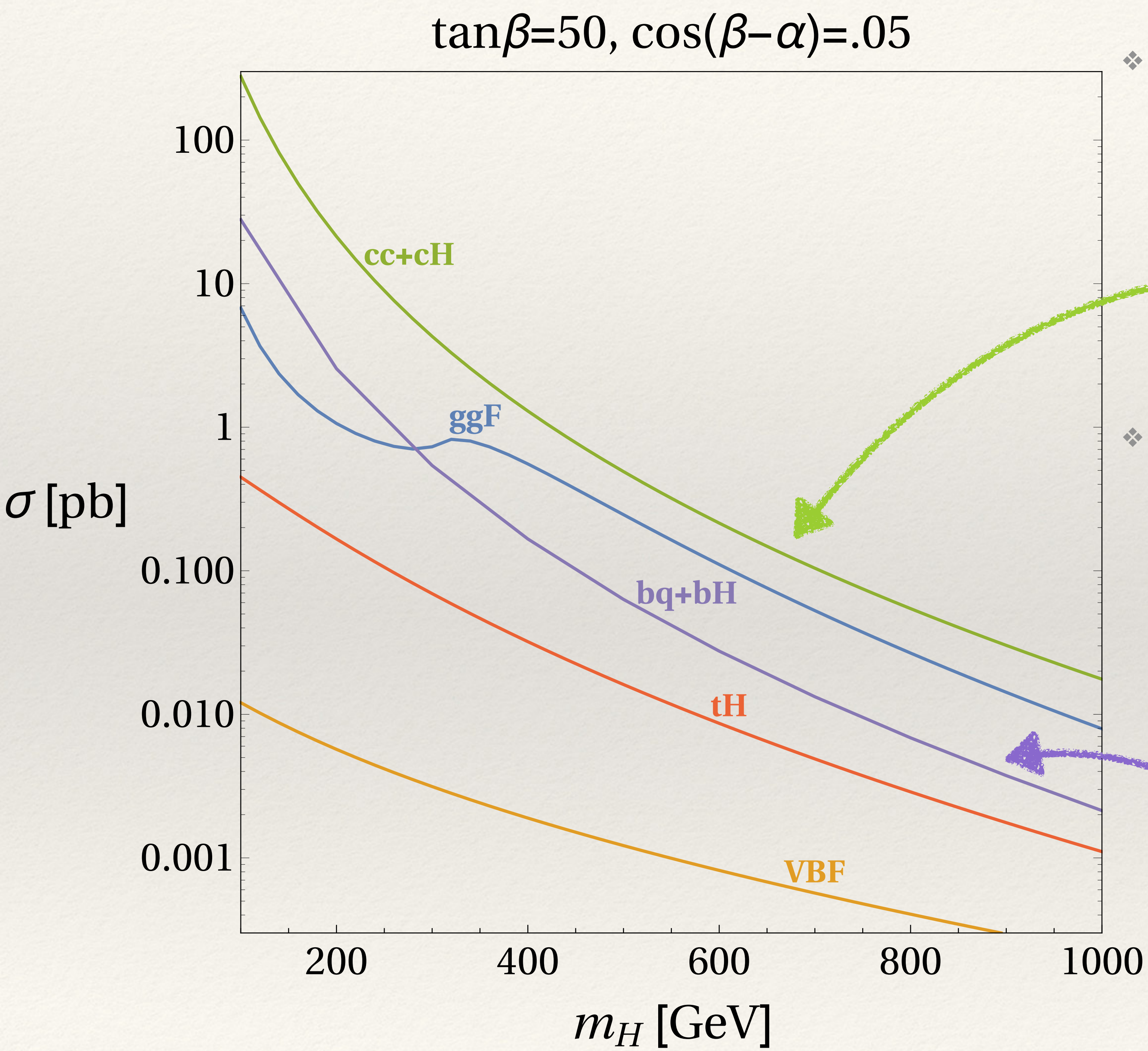
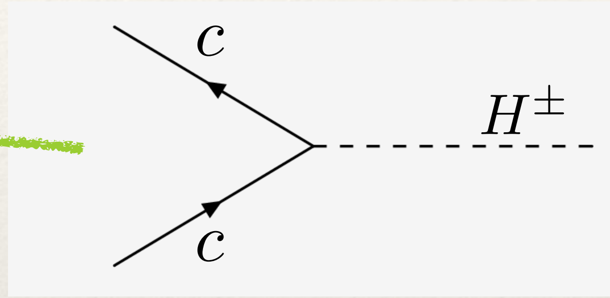


- "Classic" decays modes (**ττ**, **bb**) are suppressed
- Flavor-violating (**ct**, **bs**, **τμ**) decays are now present (compared to Type II)!
- Dominant decay modes are to **charm-charm** and **charm-top**
- Decay to **muons** becomes sizable
  - Inspired an ATLAS search! arxiv:1901.08144

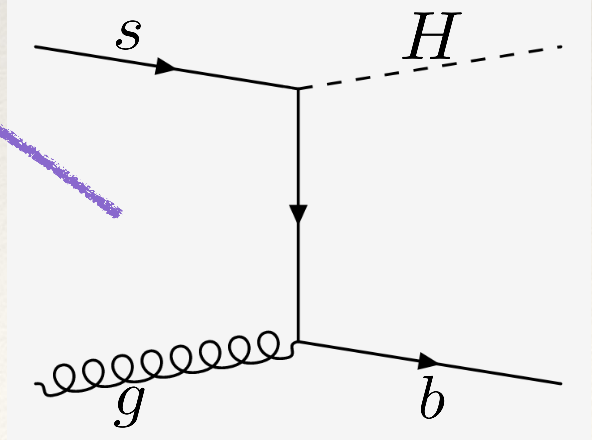
Production of the Neutral Higgs (H)



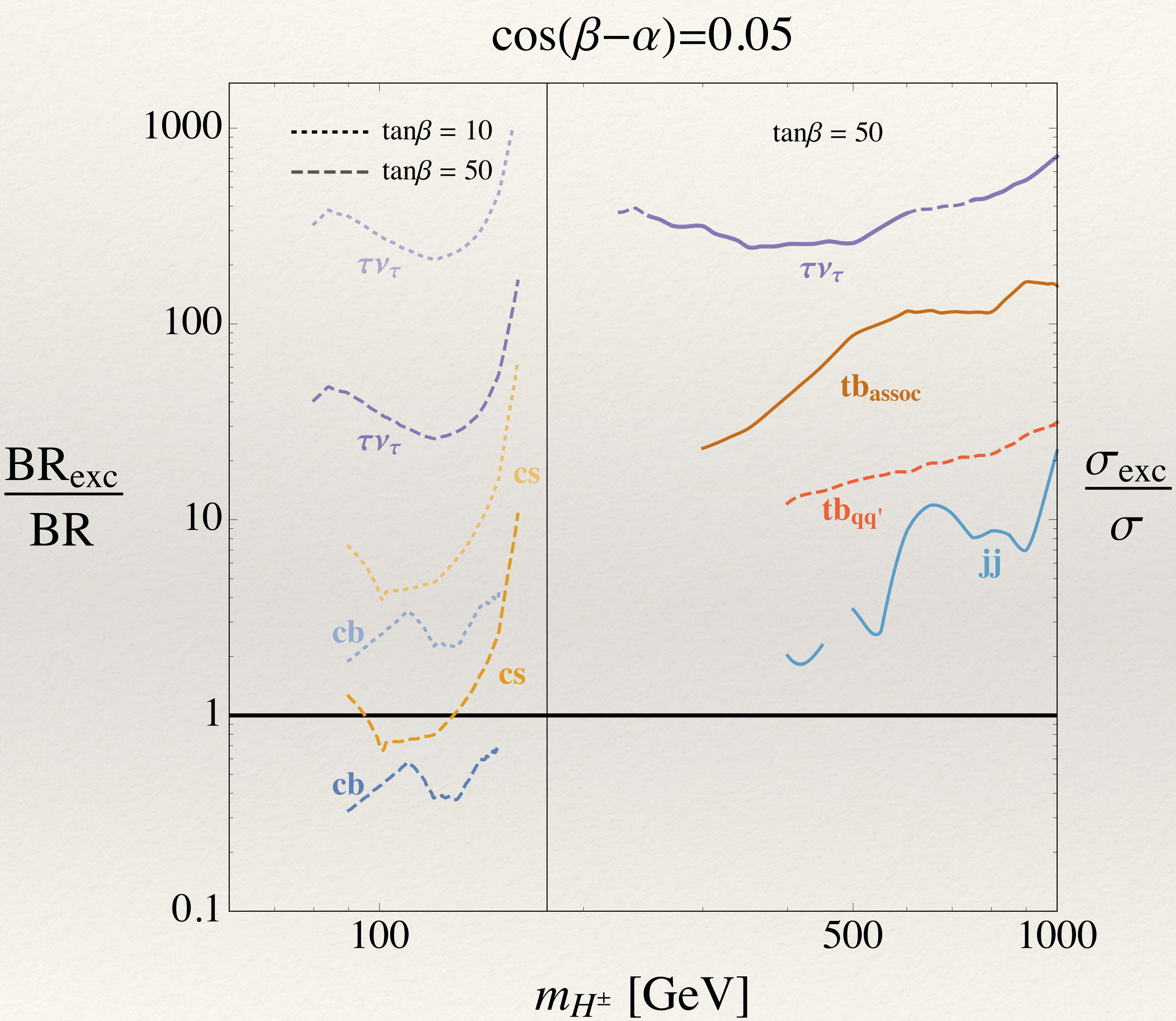
- Dominant production mode is **charm-charm fusion**



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



Collider Constraints on $H^\pm$



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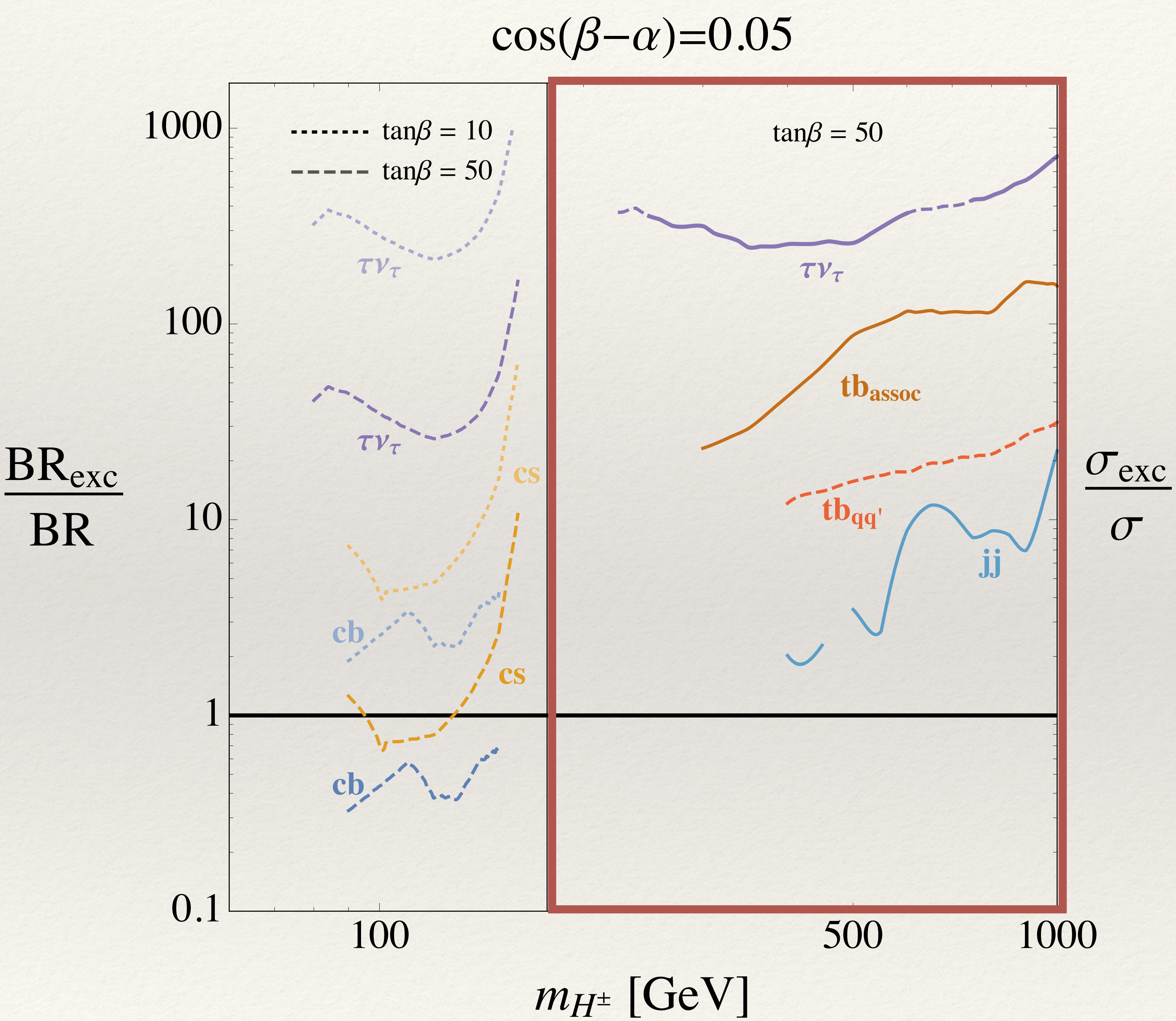

No bound above top threshold!

- Strongest constraints come from di-jet searches
- "Classic" search (tb) probe cross sections that are ~10 times larger than our predictions

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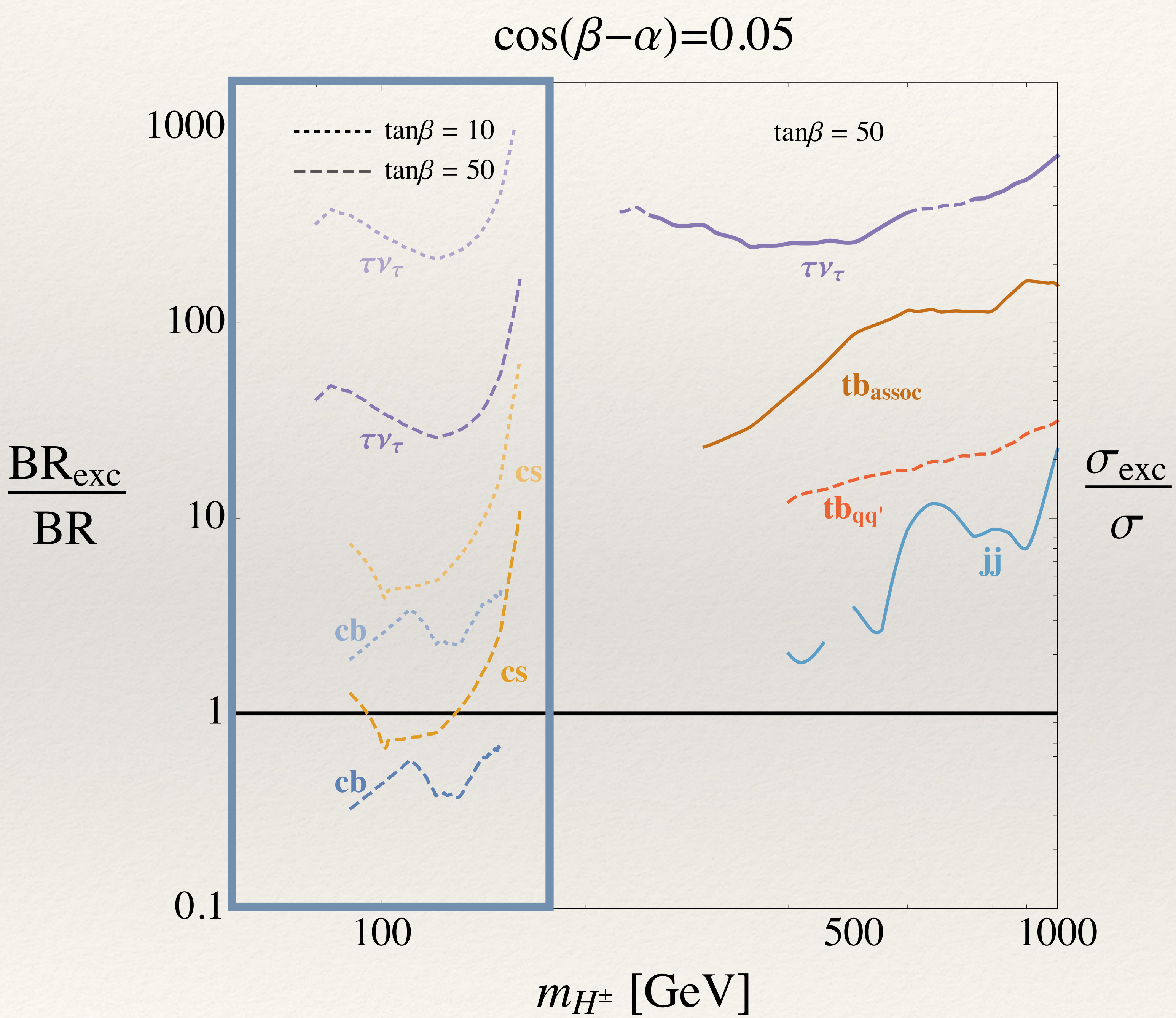

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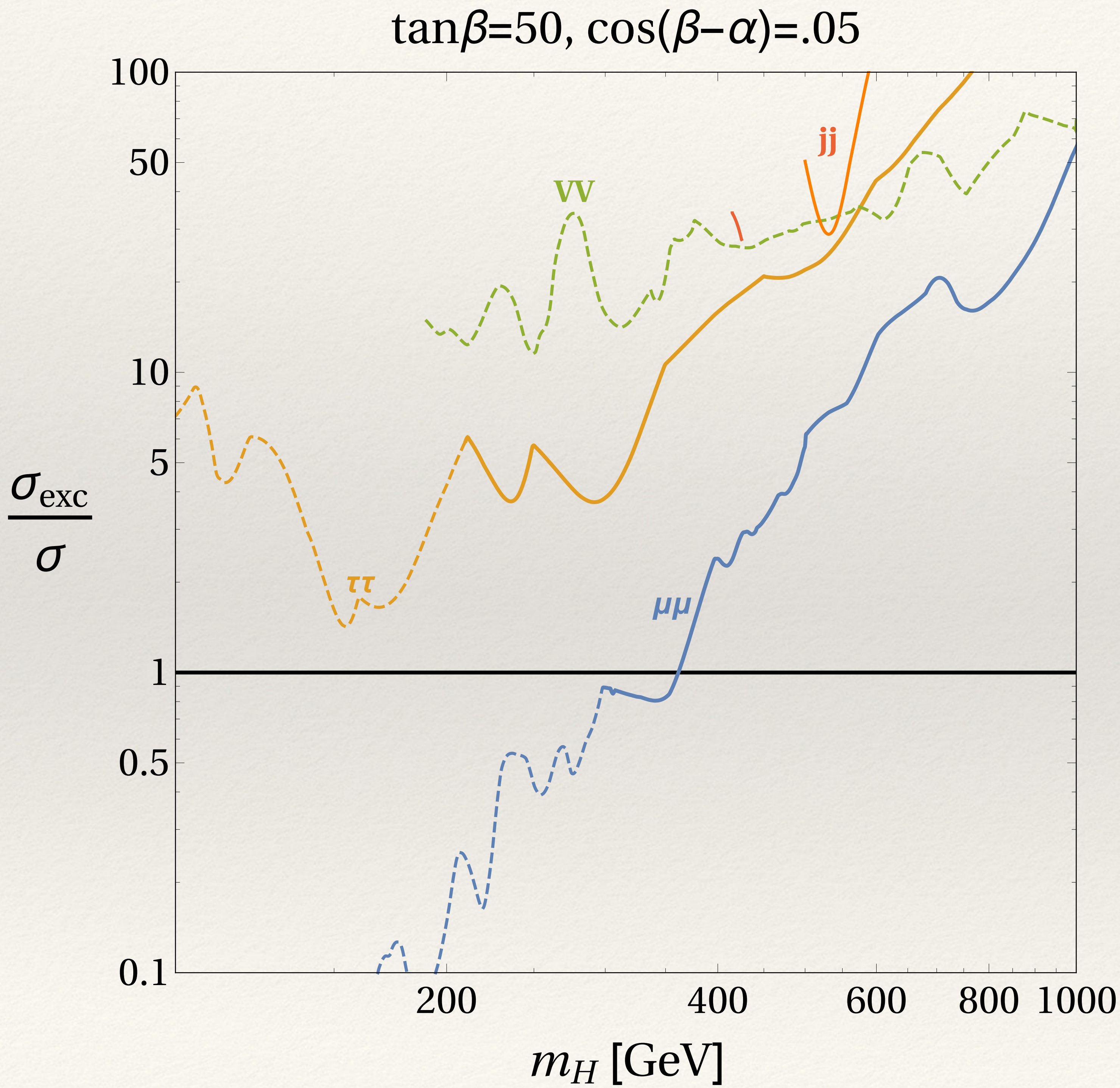
Below top threshold

- "Classic" search (**τν**) probe BRs that are ~20-100 times larger than our predictions, even at large tanβ!
- Strongest constraints are from searches for $H^{\pm}$ decays to **cb**, **cs**

Collider Constraints on H



- Non-standard phenomenology means that the standard searches are not necessarily the most sensitive!
- **Most stringent constraints are from di-muon searches**
  - This is tanβ dependent! Lowering tanβ weakens the constraints.
- "Classic" search (**ττ**) does not yet probe our model!

Novel Collider Signatures

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

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$pp \to tH \to tcc$	

Phenomenology with Up Sector CKM

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

- Similar collider phenomenology to CKM from up quark sector.

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

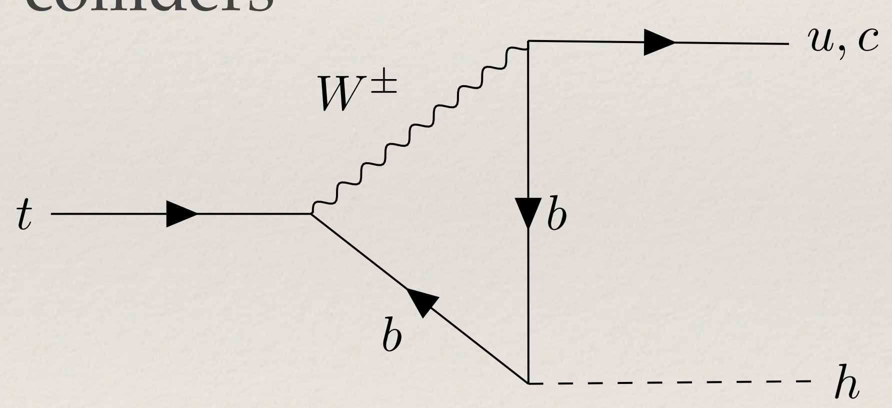
- Flavor constraints from D meson mixing are avoided.
- Strongest constraint from radiative *b* decay *b* —> *s* γ
- Can lead to sizable flavor violating couplings of SM-like Higgs to up quarks
    - New probe: rare top decays!

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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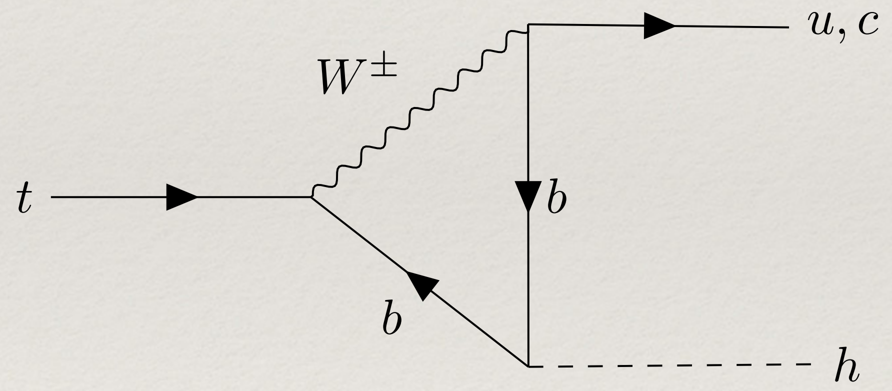

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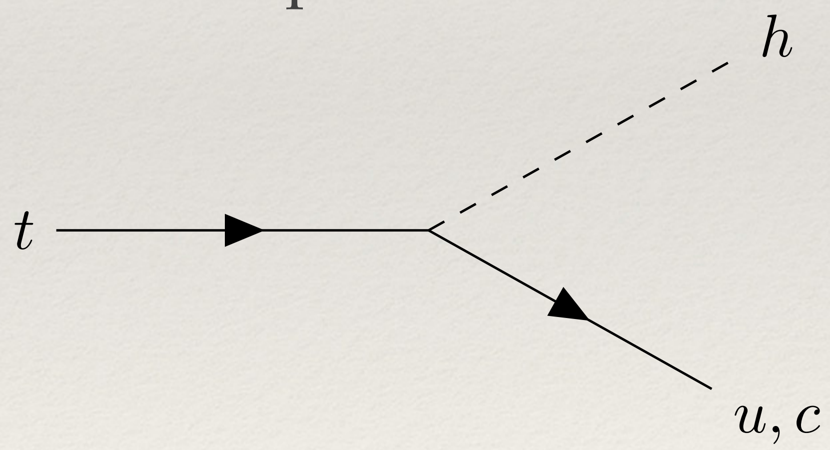
Flavorful 2HDM

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



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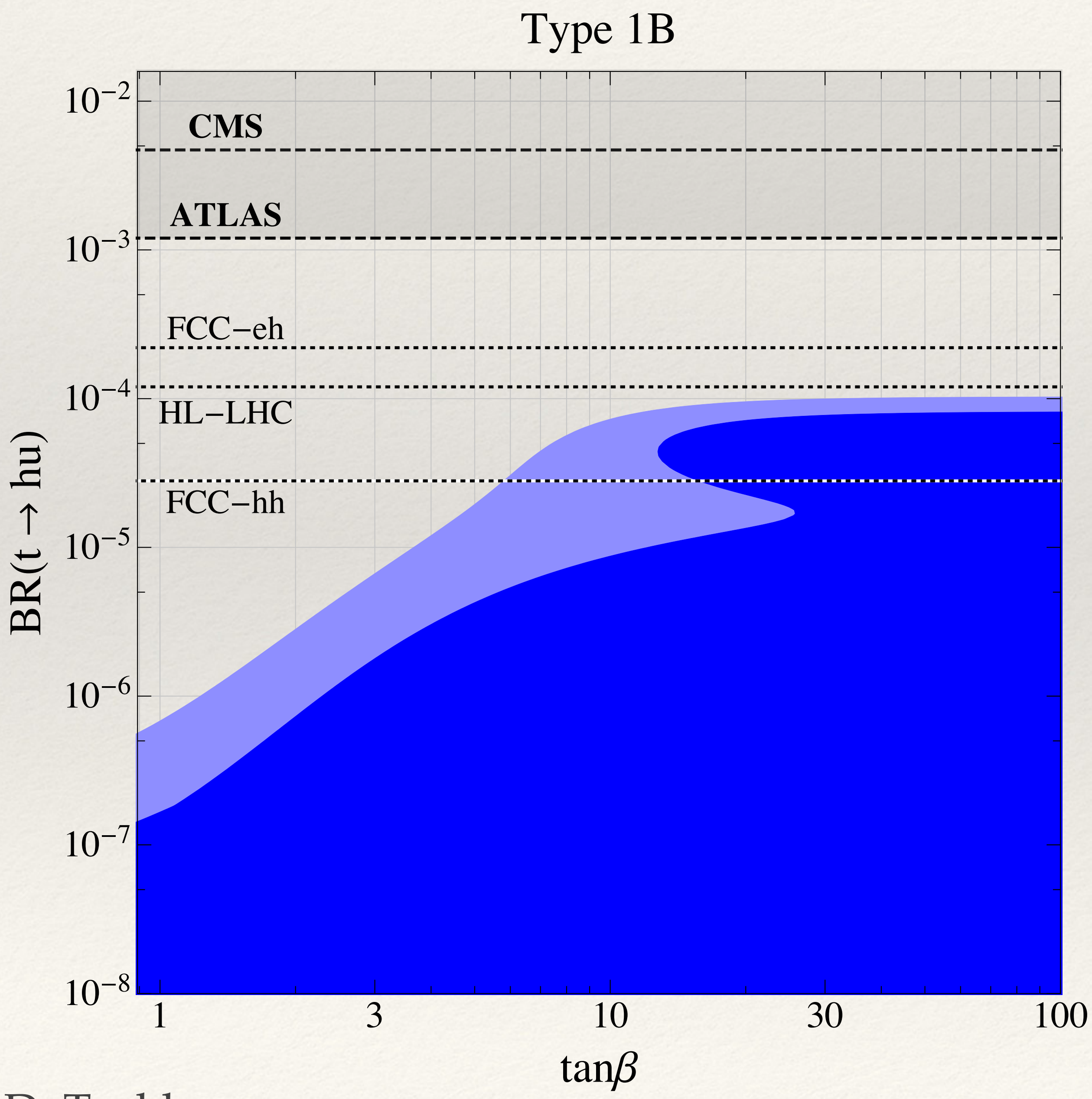

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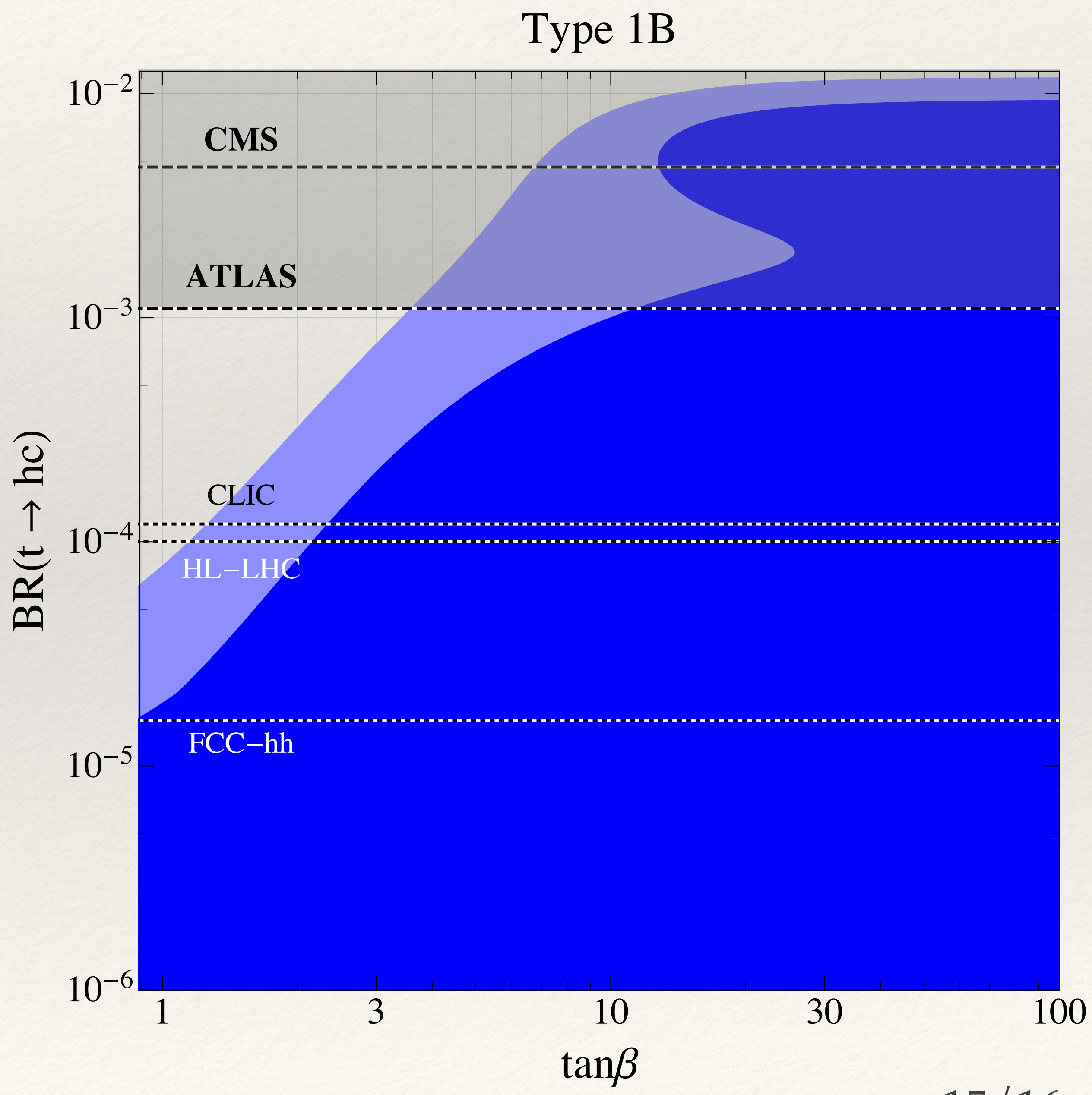

Summary

- 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 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

Current LHC Searches

H

bb	ττ	μμ	γγ	hh	WW	ZZ	tt
bH	gg,bH	gg,bH		gg	all	all	gg, tt

A

bb	ττ	μμ	γγ	Zh	tt
bH	gg,bA	gg,bA		gg,bA	gg, tt

$H^{\pm}$

τν	tb	Wh	cs	μν	cb
(t)$H^{\pm}$ t dec	(t)$H^{\pm}$ t dec	qq fus	t decay	qq fus	t decay

New
since ICHEP 2016

from S. Gori - "(Flavor) gaps
in Heavy Higgs searches"
@ Triggering on New Physics at the HL-LHC

Paradigm Shift?

- Current LHC studies have focused on flavor conserving 2HDMs

Model	u_R^i	d_R^i	e_R^i
Type I	Φ	Φ	Φ
Type II	Φ	Φ'	Φ'
Flipped	Φ	Φ'	Φ
Lepton-specific	Φ	Φ	Φ'

Are we missing interesting signatures by only focusing on these 2HDMs?

Models that break flavor conservation predict very distinct signatures that we miss if we only focus on the 2HDMs above!

They can also provide insight into the SM Flavor Puzzle

Brief Introduction to 2HDMs

- Introduce a second $SU(2)_L$ doublet that mixies with Higgs doublet of the SM

	SM	2HDM
Higgs doublets	Φ	$\Phi,\ \Phi'$
Physical states	h	$h,\ H,\ A,\ H^{\pm}$
Yukawa couplings	Y_{ij}	$Y_{ij},\ Y'_{ij}$

- At the minimum of the potential both Higgs doublets acquire vacuum expectation values: $\langle\Phi\rangle = v,\ \langle\Phi'\rangle = v'$

- Phenomenology of a 2HDM is determined by two parameters:
  - β — mixing angle between imaginary and charged components of the Higgs doublets; parameterized by $\tan\beta = v/v'$
  - α — mixing angle between neutral components of Higgs doublets; parameterized via $\cos(\beta - \alpha)$

Brief Introduction to 2HDMs

- Introduce a second $SU(2)_L$ doublet that mixies with Higgs doublet of the SM

	SM	2HDM
Higgs doublets	Φ	$\Phi,\ \Phi'$
Physical states	h	$h,\ H,\ A,\ H^{\pm}$
Yukawa couplings	Y_{ij}	$Y_{ij},\ Y'_{ij}$

SM: Higgs couplings are flavor diagonal

2HDM: Higgs couplings are not necessarily flavor diagonal!

- At the minimum of the potential both Higgs doublets acquire vacuum expectation values: $\langle\Phi\rangle = v,\ \langle\Phi'\rangle = v'$

- Phenomenology of a 2HDM is determined by two parameters:
  - β — mixing angle between imaginary and charged components of the Higgs doublets; parameterized by tanβ = v/v'
  - α — mixing angle between neutral components of Higgs doublets; parameterized via cos(β - α)

Flavor Changing Neutral Currents

- Generic 2HDMs have Yukawa couplings that are not flavor diagonal
  - Can lead to large tree-level Higgs contributions to FCNC (e.g. meson oscillations)
  - How to eliminate flavor changing Higgs couplings? Introduce symmetries!
    - Higgs couples are flavor conserving

Model	u_R^i	d_R^i	e_R^i
Type I	Φ	Φ	Φ
Type II	Φ	Φ'	Φ'
Flipped	Φ	Φ'	Φ
Lepton-specific	Φ	Φ	Φ'

Flavor Changing Neutral Currents

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Motivated by Supersymmetry

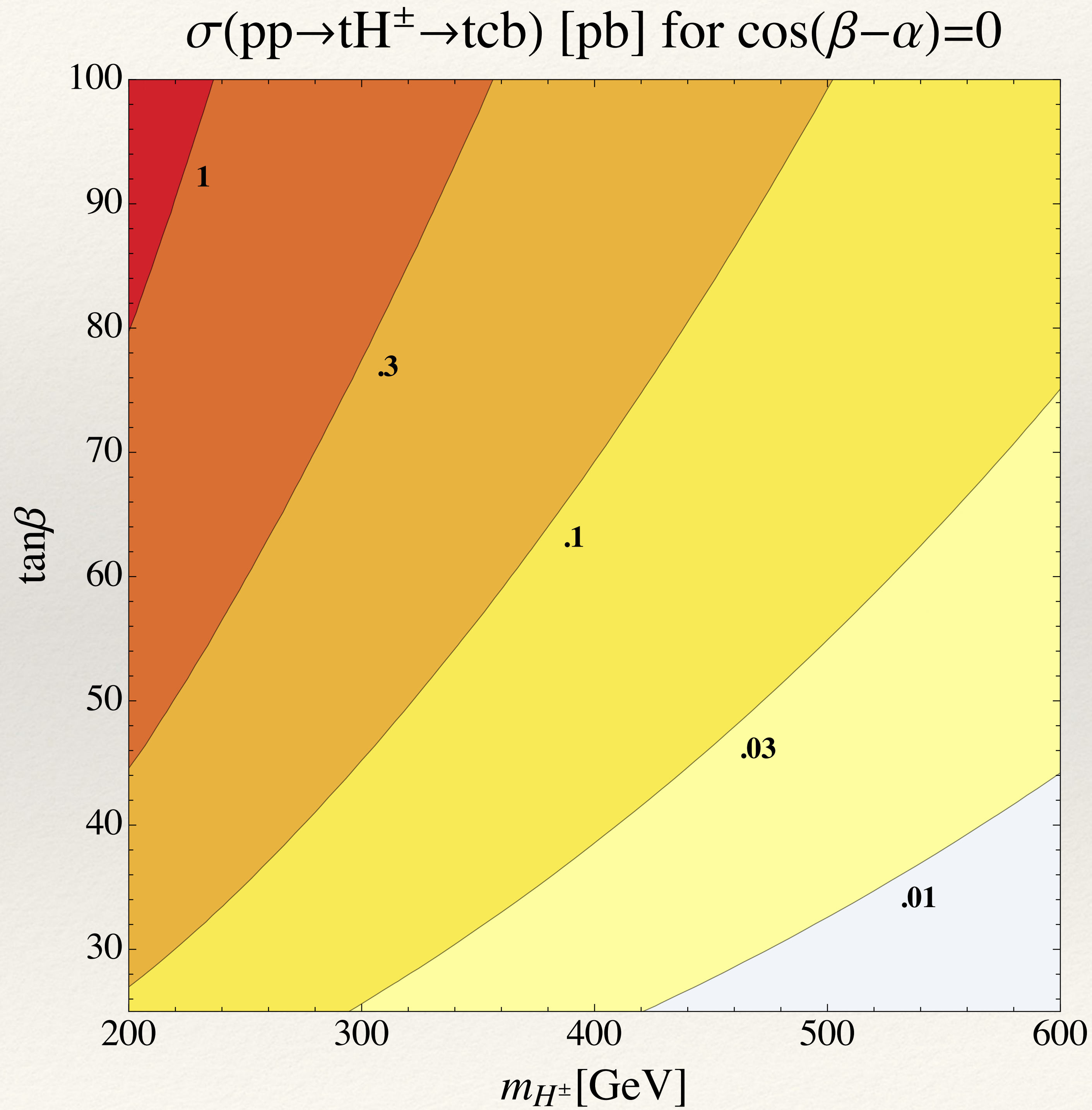
Model	u_R^i	d_R^i	e_R^i
Type I	Φ	Φ	Φ
Type II	Φ	Φ'	Φ'
Flipped	Φ	Φ'	Φ
Lepton-specific	Φ	Φ	Φ'

Supersymmetry has been the driving force behind searches for additional Higgs bosons

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

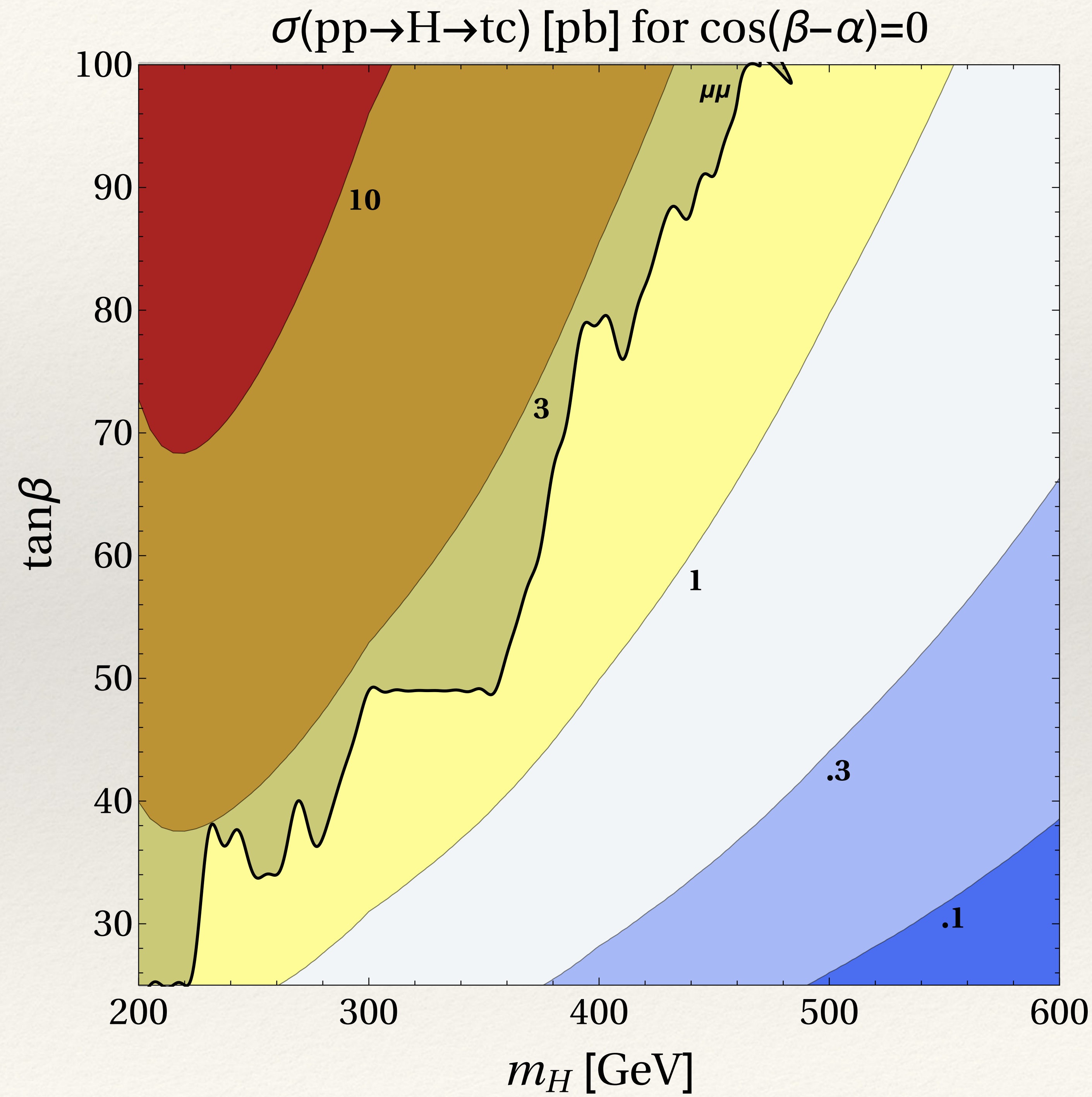


D. Tuckler

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



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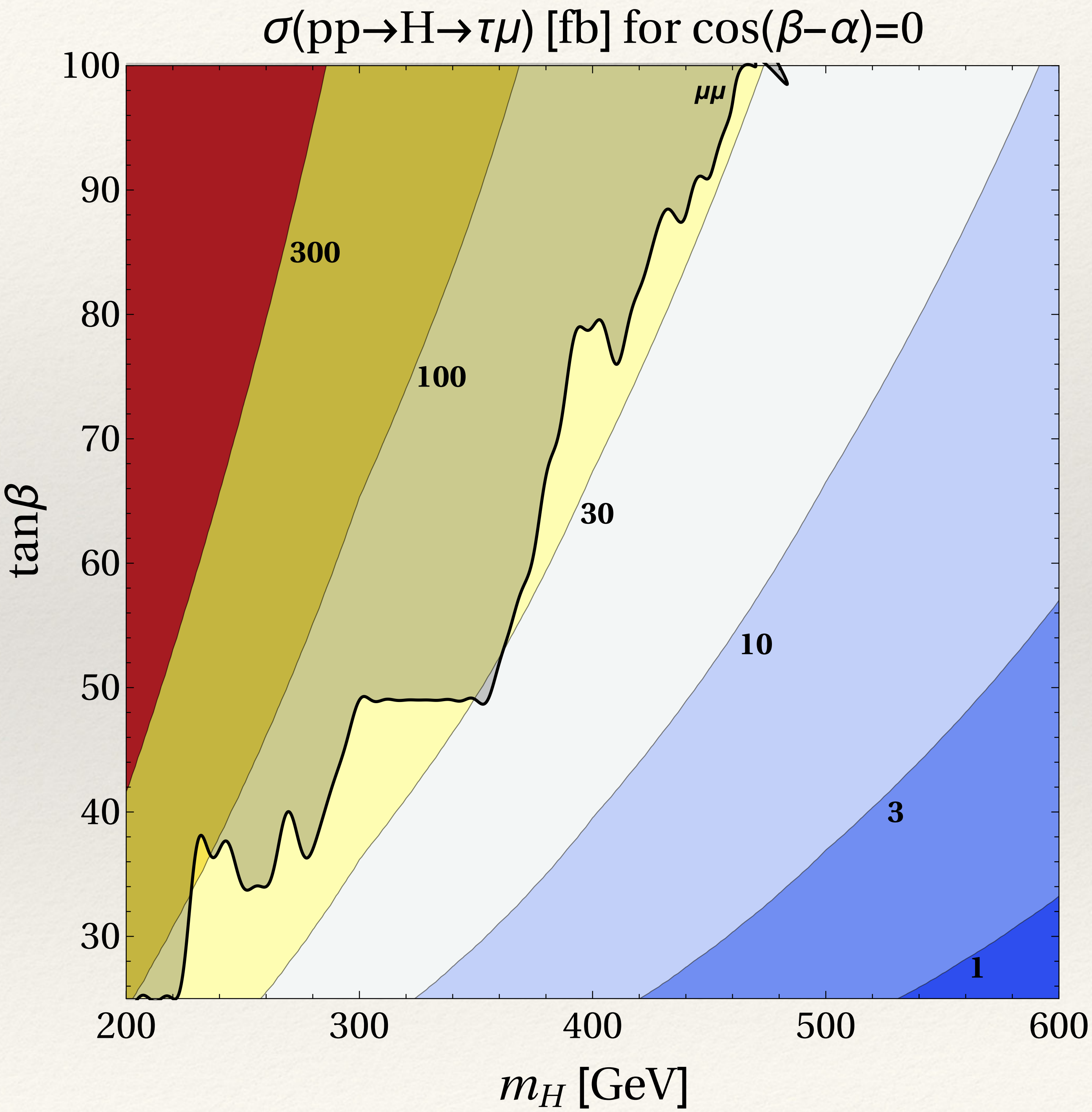
New Signatures for H

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

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



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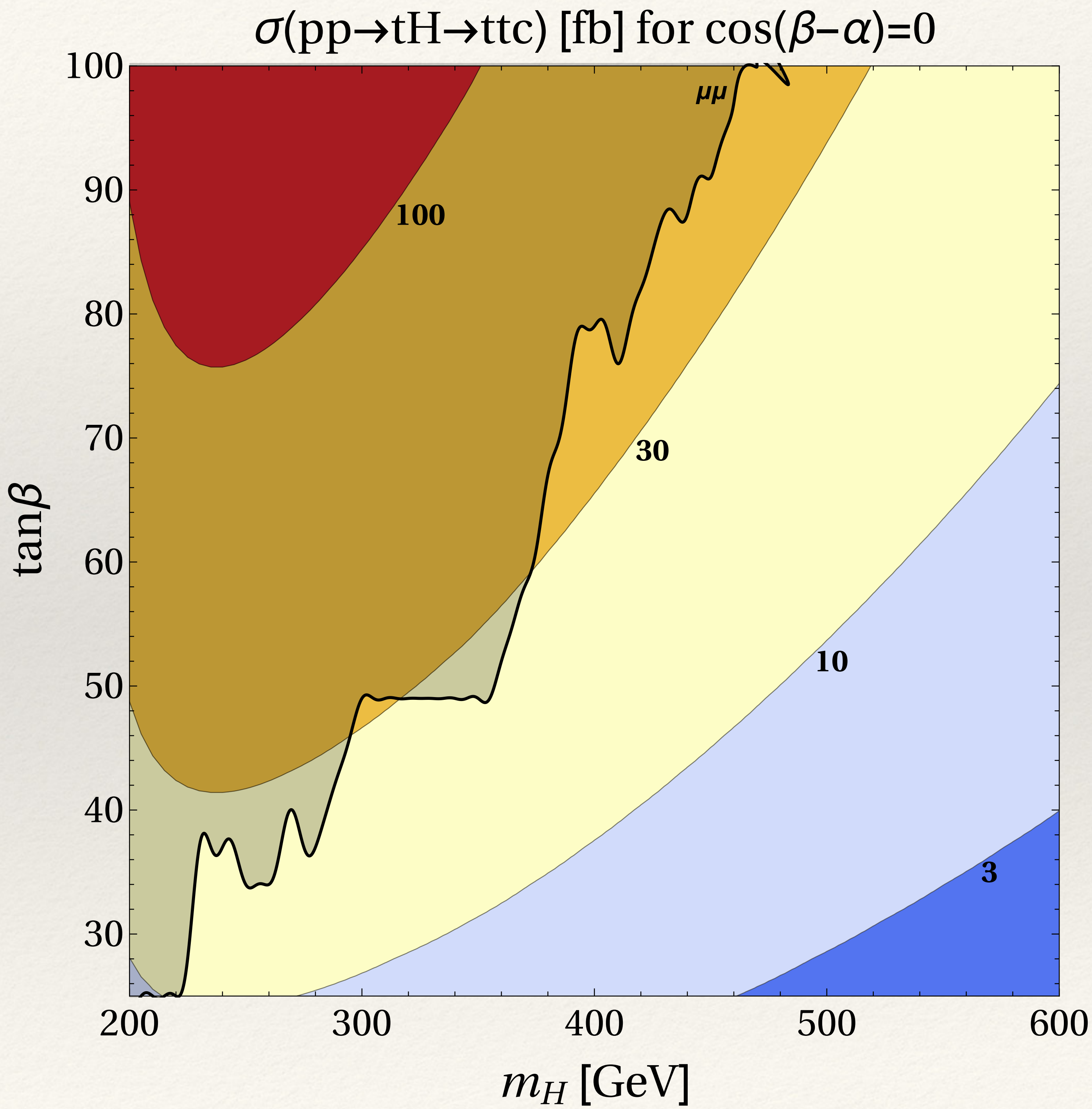
New Signatures for H

$$pp \to tH \to ttc$$

- 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



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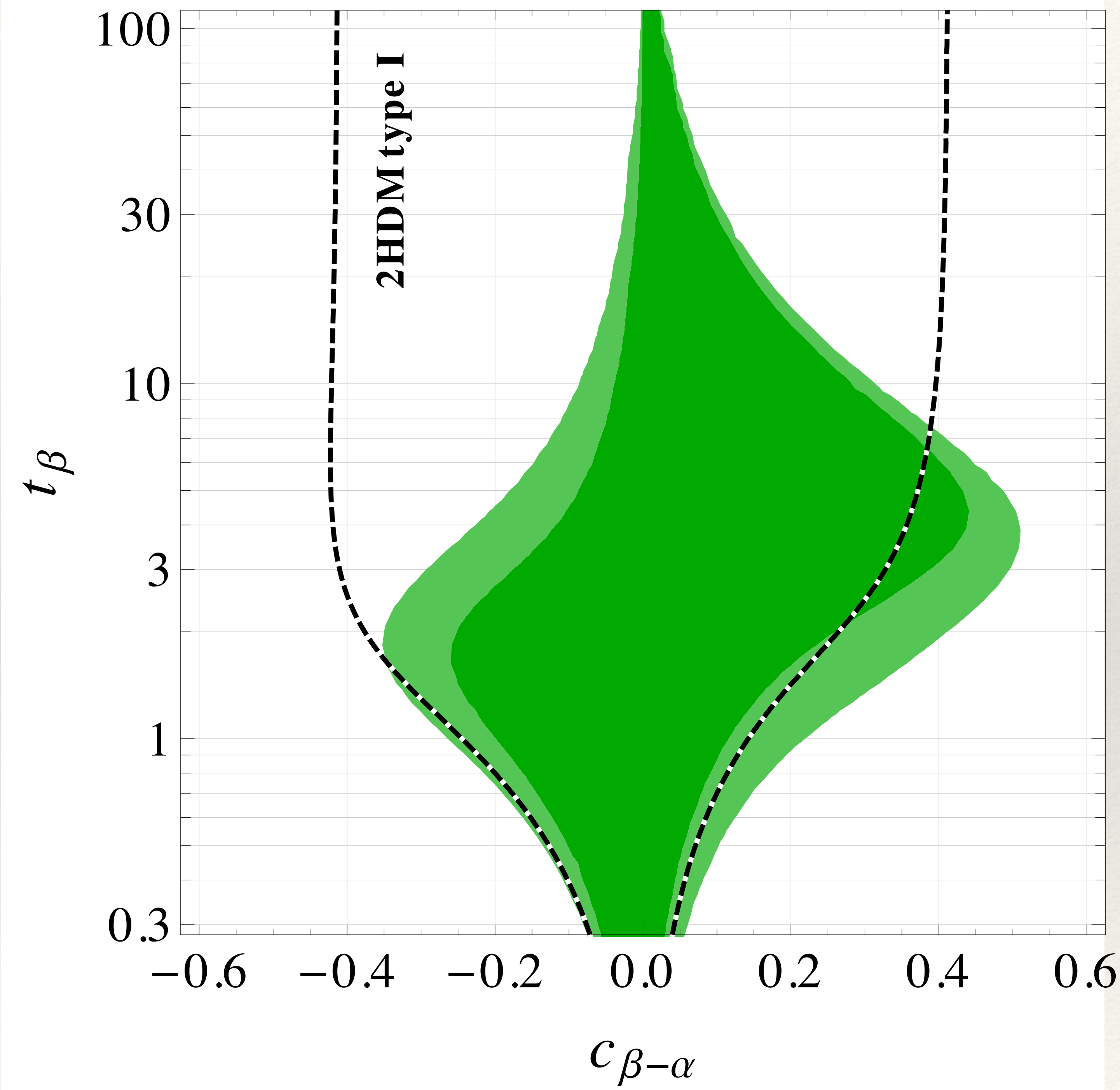
Constraints from 125 GeV Higgs

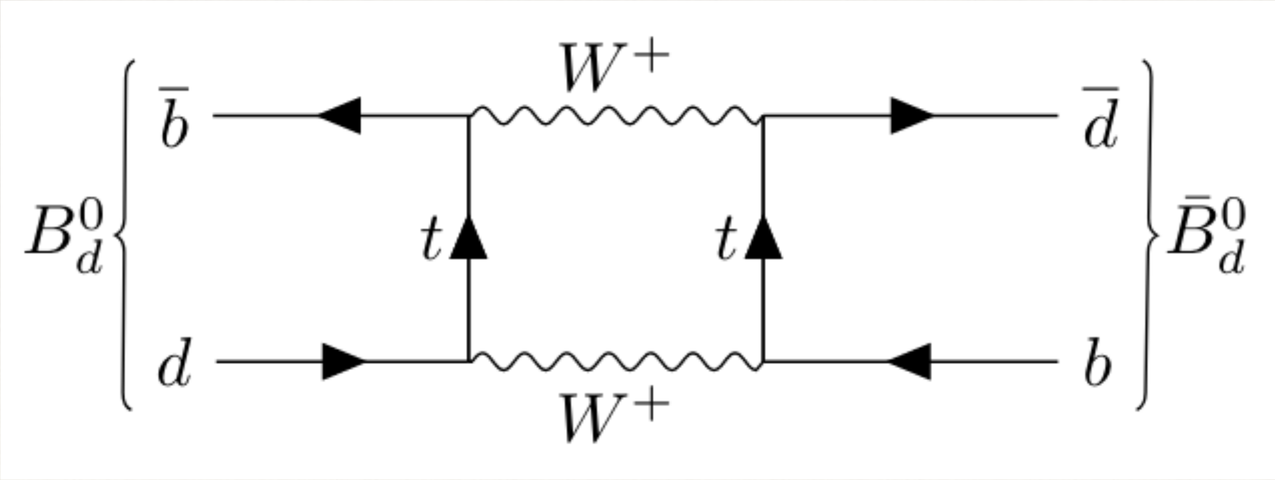


Flavor Constraints on Down Sector CKM

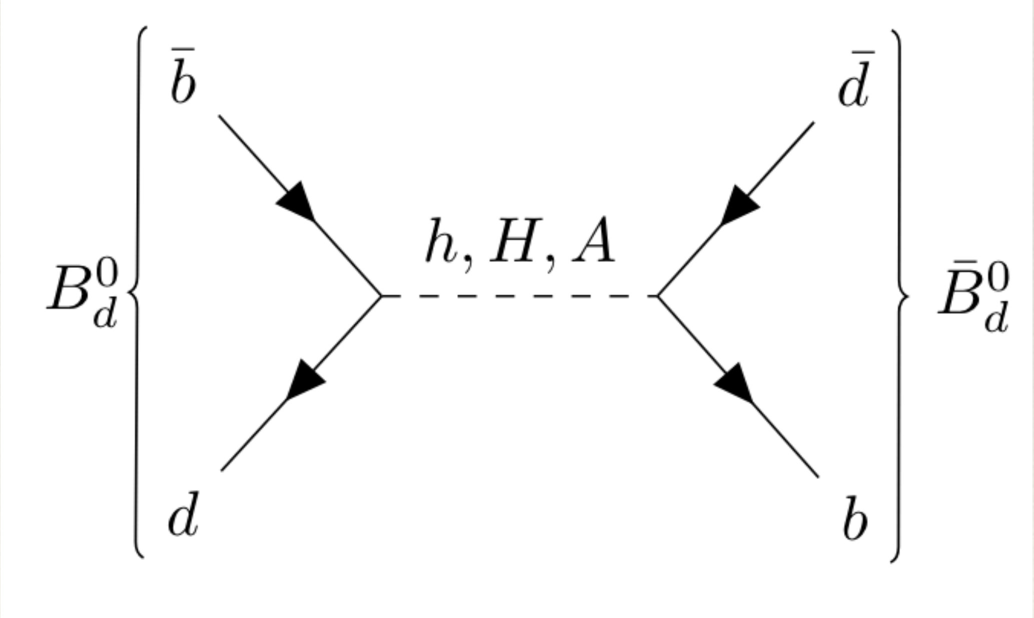
(arxiv:1712.01847 W. Altmannshofer, S. Gori, D. Robinson, DT)

- 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



Flavor Constraints on Down Sector CKM

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

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

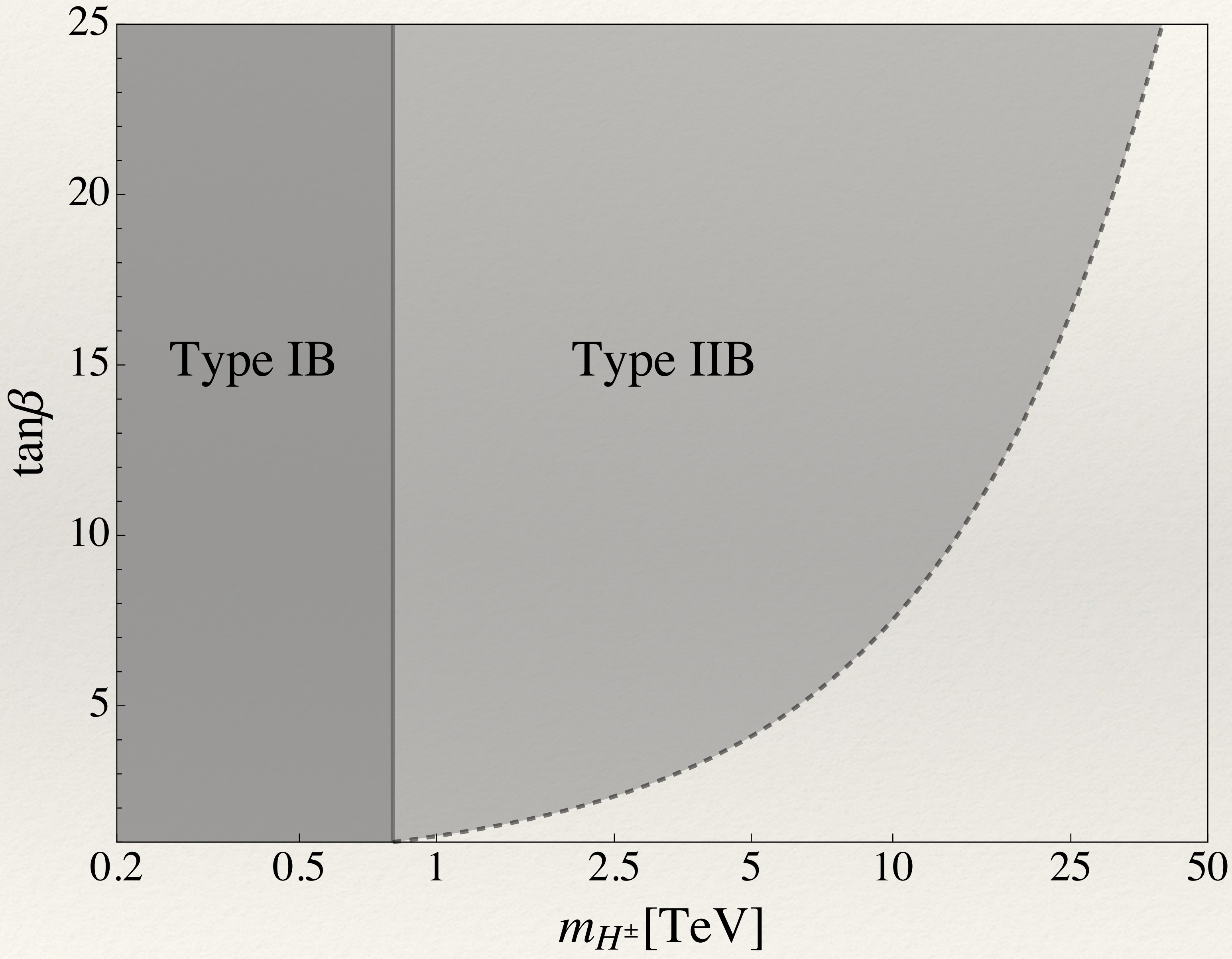
	Data	SM Prediction	NP Contribution
ΔM_K	$(5.294 \pm 0.002) \times 10^{-3}$ ps^{-1}	$(4.7 \pm 1.8) \times 10^{-3}$ ps^{-1}	$\simeq -2 \times 10^{-6}$ ps^{-1}
ΔM_{B_d}	0.5055 ± 0.0020 ps^{-1}	0.63 ± 0.07 ps^{-1}	$\simeq 0.01$ ps^{-1}
ΔM_{B_s}	17.757 ± 0.021 ps^{-1}	19.6 ± 1.3 ps^{-1}	$\simeq -1.8$ ps^{-1}
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: $X^2_{\text{loop}}(\text{SM}) \sim 10.8$, $X^2_{\text{loop}} \sim 7.1$

Flavor Constraints on Up Sector CKM



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