Stony Brook University

Theories of Enhanced Light Yukawa Couplings

Based mostly on:
1811.00017 (PRL 123.031802),
1908.11376 (PRD 100.115041),
arXiv:2008.XXXXX

Sam Homiller
Stony Brook → Harvard

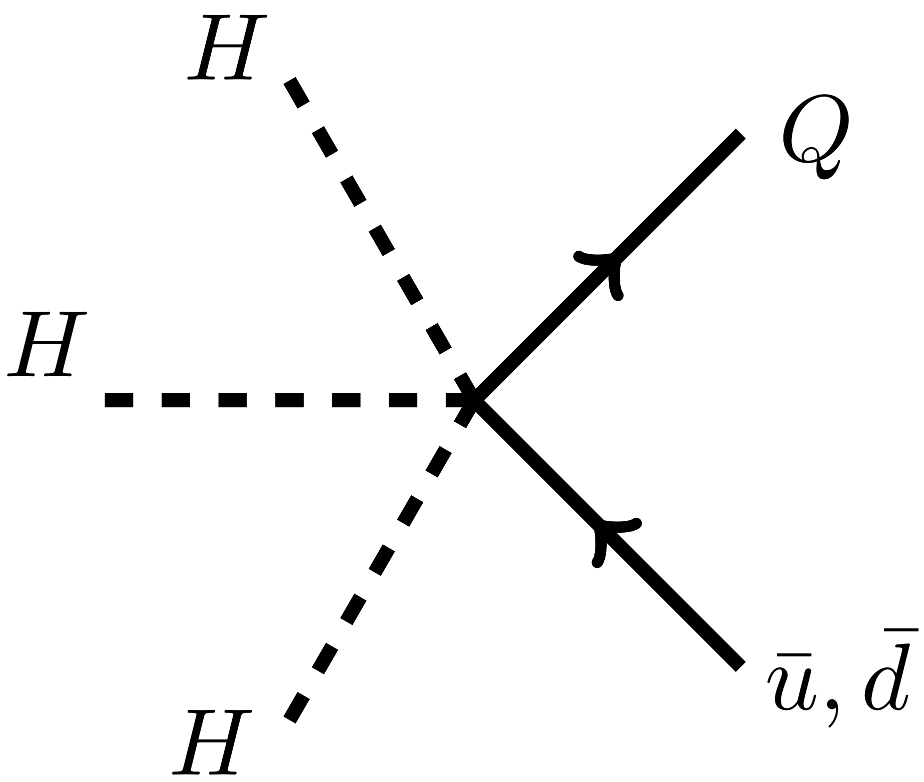
In collaboration with D. Egaña-Ugrinovic and Patrick Meade

EF02 Meeting: Higgs and Flavor

UV Completions for Enhanced Yukawas

EFT Picture: $(H^\dagger H) Q H^c \bar{d},\ (H^\dagger H) Q H \bar{u}$

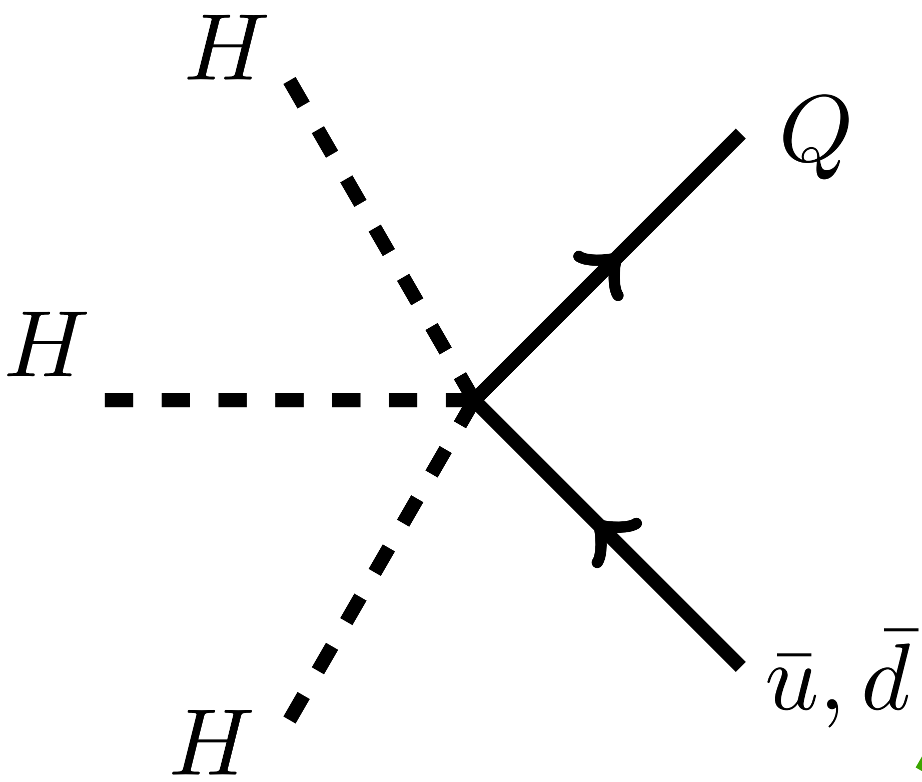
(Alasfar, et al., [1909.05279])

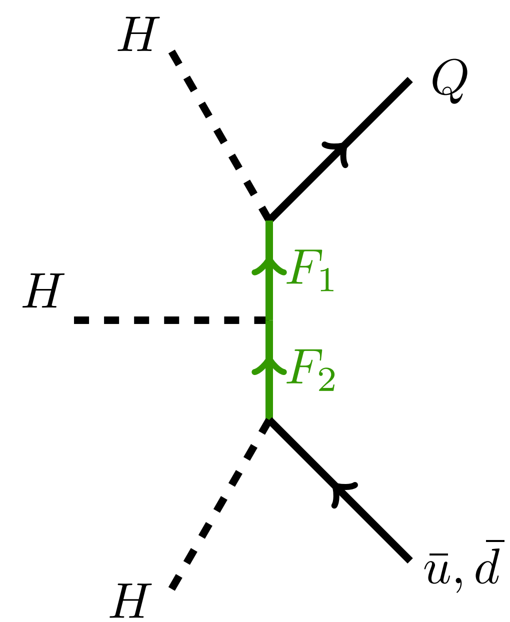


UV Completions for Enhanced Yukawas

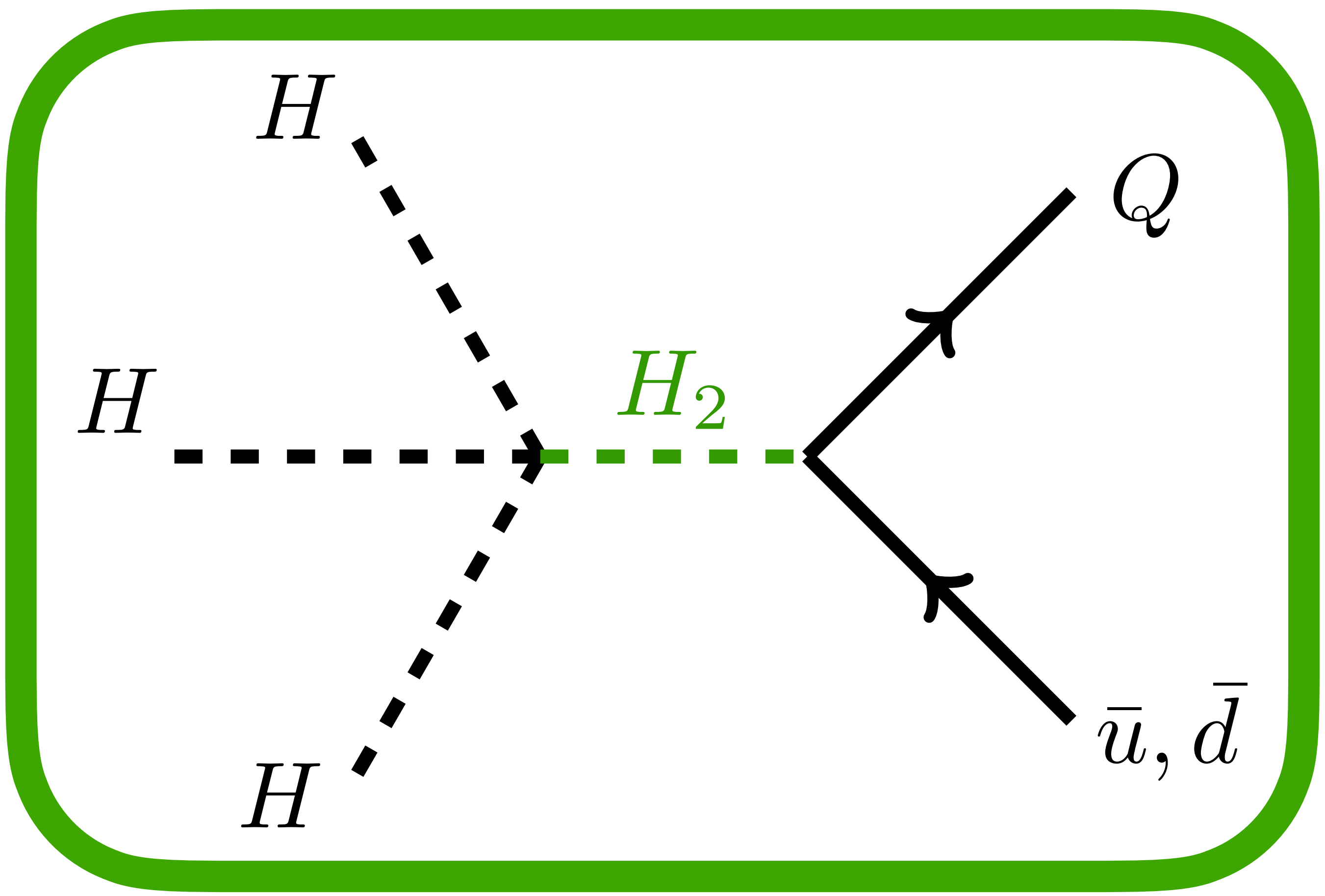
EFT Picture: $(H^\dagger H)QH^c\bar{d},\ (H^\dagger H)QH\bar{u}$

(Alasfar, et al., [1909.05279])





Other, non-minimal UV completions?



Goal of this talk:
What does the phenomenology look like in explicit models leading to this operator?

Flavor-Aligned 2HDMs

arXiv:1811.00017, 1908.11376

General 2HDMs lead to ***large*** flavor-changing neutral currents *at tree-level*

$$\lambda_1^d Q H_1^c \bar{d} + \lambda_1^u Q H_1 \bar{u}$$
$$+ \lambda_2^d Q H_2^c \bar{d} + \lambda_2^u Q H_2 \bar{u}$$

Flavor-Aligned 2HDMs

arXiv:1811.00017, 1908.11376

General 2HDMs lead to ***large*** flavor-changing neutral currents *at tree-level*

$$\lambda_1^d Q H_1^c \bar{d} + \lambda_1^u Q H_1 \bar{u}$$
$$+ \lambda_2^d Q H_2^c \bar{d} + \lambda_2^u Q H_2 \bar{u}$$

Usually remove these via *discrete symmetries* (e.g., Type-I, Type-II 2HDM)

→ retain the SM hierarchies, Yukawas aren't enhanced

Flavor-Aligned 2HDMs

arXiv:1811.00017, 1908.11376

In contrast, can have large light quark Yukawas if they are ***aligned***

Diagonal in the same basis!

$$\begin{array}{c} Y^d Q H_1^c \bar{d} \; - \; V^T Y^u Q H_1 \bar{u} \\ + \; K^d Q H_2^c \bar{d} \; - \; \xi V^T Y^u Q H_2 \bar{u} \end{array}$$

Flavor-Aligned 2HDMs

arXiv:1811.00017, 1908.11376

In contrast, can have large light quark Yukawas if they are ***aligned***

Diagonal in the same basis!

$$Y^d Q H_1^c \bar{d} \;-\; V^T Y^u Q H_1 \bar{u}$$
$$+\, K^d Q H_2^c \bar{d} \;-\; \xi V^T Y^u Q H_2 \bar{u}$$

$$Y^d \equiv \mathrm{diag}(y_d, y_s, y_b) \sim \mathrm{diag}(10^{-5}, 10^{-4}, 10^{-2})$$

$$K^d \equiv \mathrm{diag}(\kappa_d, \kappa_s, \kappa_b)$$

New Yukawa couplings with no relation to the SM quark masses!

Could have…

$$K^d = (1,\ 0,\ 0), \quad (0,\ 1,\ 0), \quad (0.1,\ 0.1,\ 0.1), \ldots$$

Spontaneous Flavor Violation → Alignment

Ansatz: ***All*** quark family number & CP breaking via renormalization of *either* right-handed up- *or* down-type quarks

Spontaneous Flavor Violation → Alignment

Ansatz: ***All*** quark family number & CP breaking via renormalization of *either* right-handed up- *or* down-type quarks

The *only* source of flavor violation

$$\mathcal{L} \supset i\boldsymbol{Z^u_{ij}}\bar{u}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{d}_j + iQ_i^\dagger \bar{\sigma}^\mu D_\mu Q_i$$
$$-\eta^u_{1ij} Q_i H_1 \bar{u}_j + \eta^d_{1ij} Q_i H_1^c \bar{d}_j + \eta^d_{2ij} Q_i H_2^c \bar{d}_j + \ldots$$

$\Longrightarrow$ Couplings to the other sector remain *aligned*

Spontaneous Flavor Violation → Alignment

Ansatz: ***All*** quark family number & CP breaking via renormalization of *either* right-handed up- *or* down-type quarks

The *only* source of flavor violation

$$\mathcal{L} \supset i\boldsymbol{Z^u_{ij}}\bar{u}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{d}_j + iQ_i^\dagger \bar{\sigma}^\mu D_\mu Q_i$$
$$- \eta^u_{1ij} Q_i H_1 \bar{u}_j + \eta^d_{1ij} Q_i H_1^c \bar{d}_j + \eta^d_{2ij} Q_i H_2^c \bar{d}_j + \ldots$$

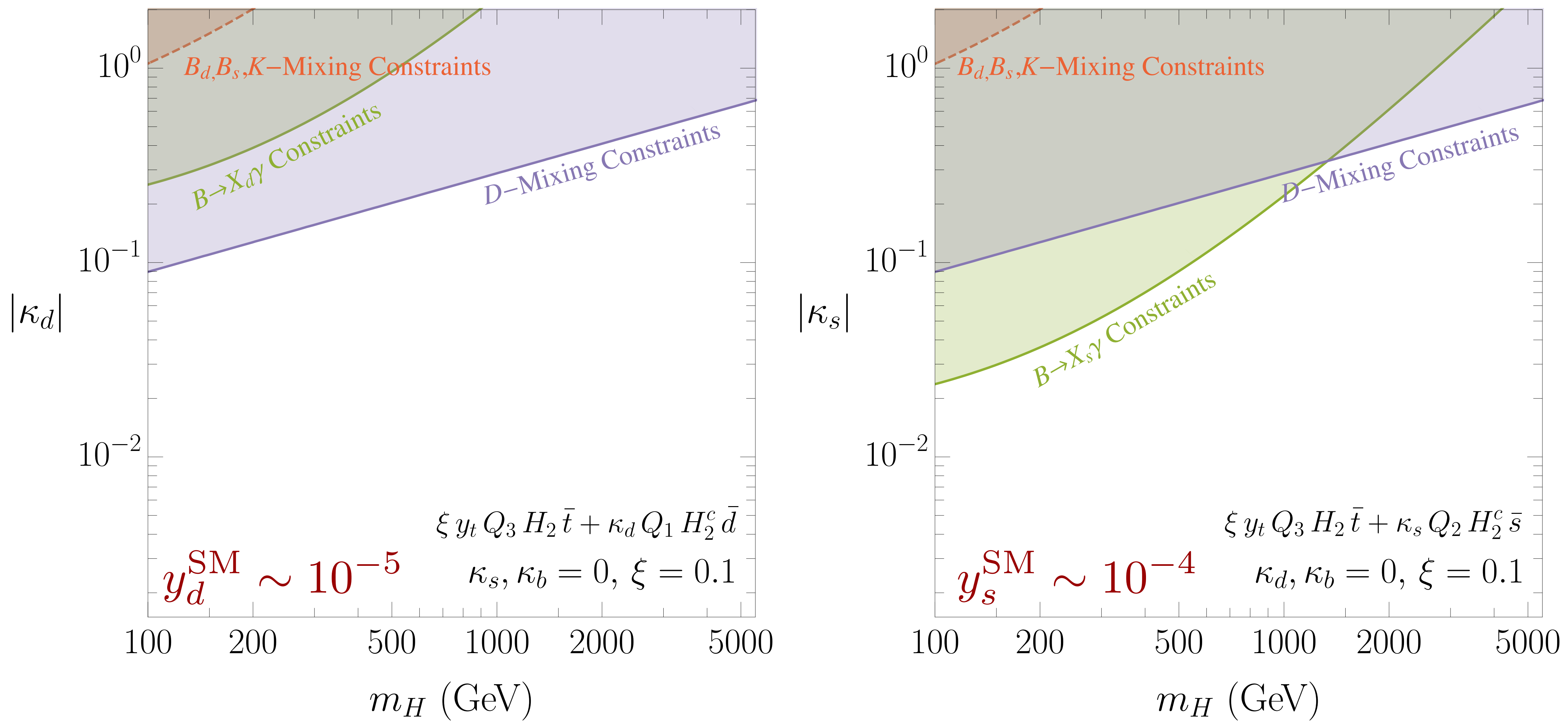
$\Longrightarrow$ Couplings to the other sector remain *aligned*

Canonically normalizing the up-quark fields, and moving to the mass basis, we recover a flavor-aligned 2HDM

Note: two *distinct* theories, with aligned couplings in up *or* down sector

How Large Can 2nd Higgs Yukawas Be?

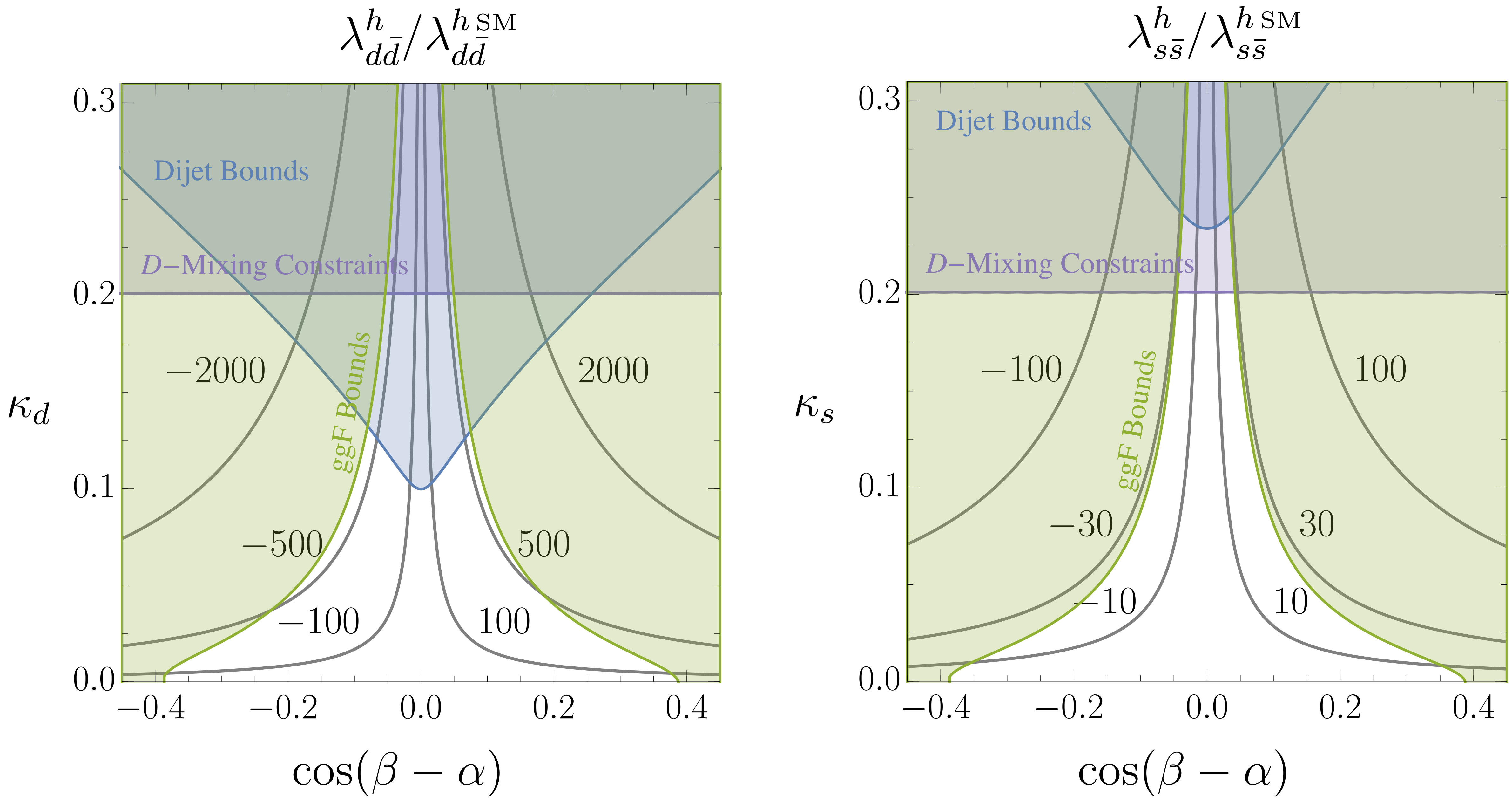
Constraints from Loop-Level FCNCs



Order ~ 0.1 couplings to first and second generation quarks are allowed for a large range of masses!

Enhancements to Higgs Yukawas

$$\lambda^h_{d\bar{d}} = \kappa_d \cos(\beta - \alpha) + y_d \sin(\beta - \alpha)$$

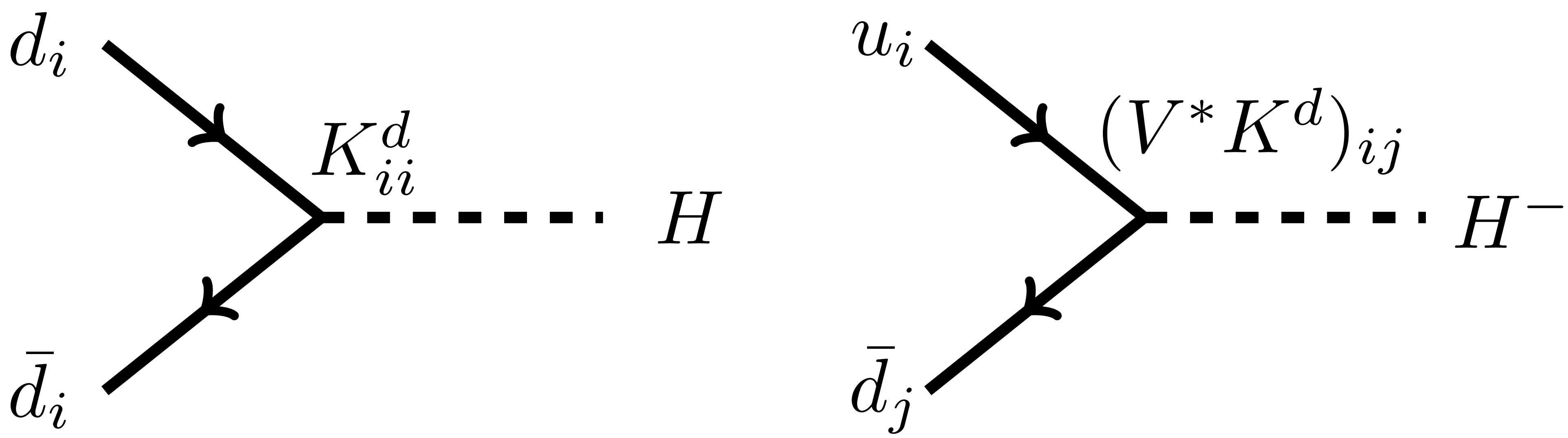


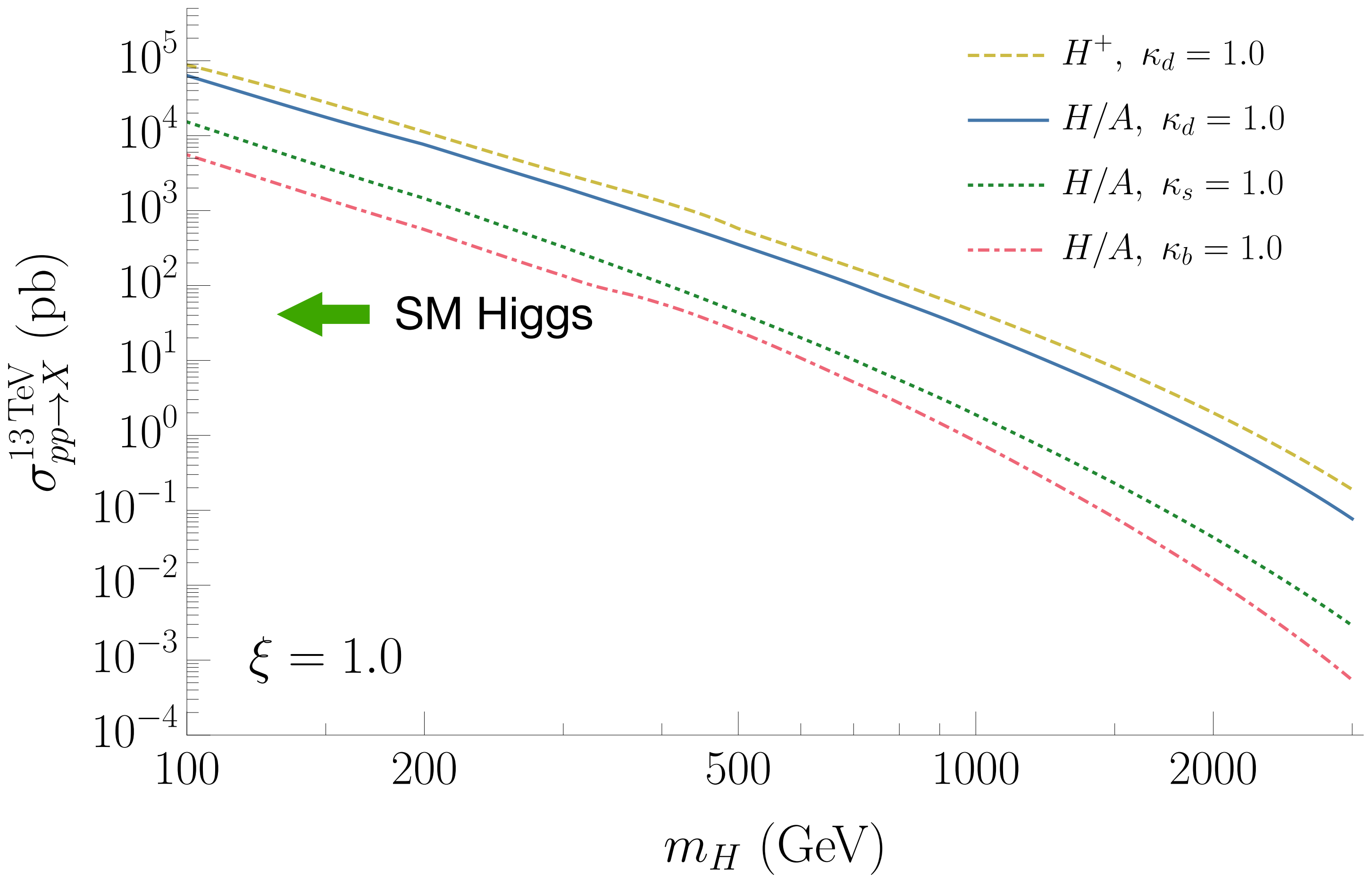
Targets for quark-flavor taggers or enhanced Yukawa searches!

e.g., Nakai et al., [2003.09517] (later today!)

New Higgses → New Signals

Additional heavy Higgs states will have large production rates!



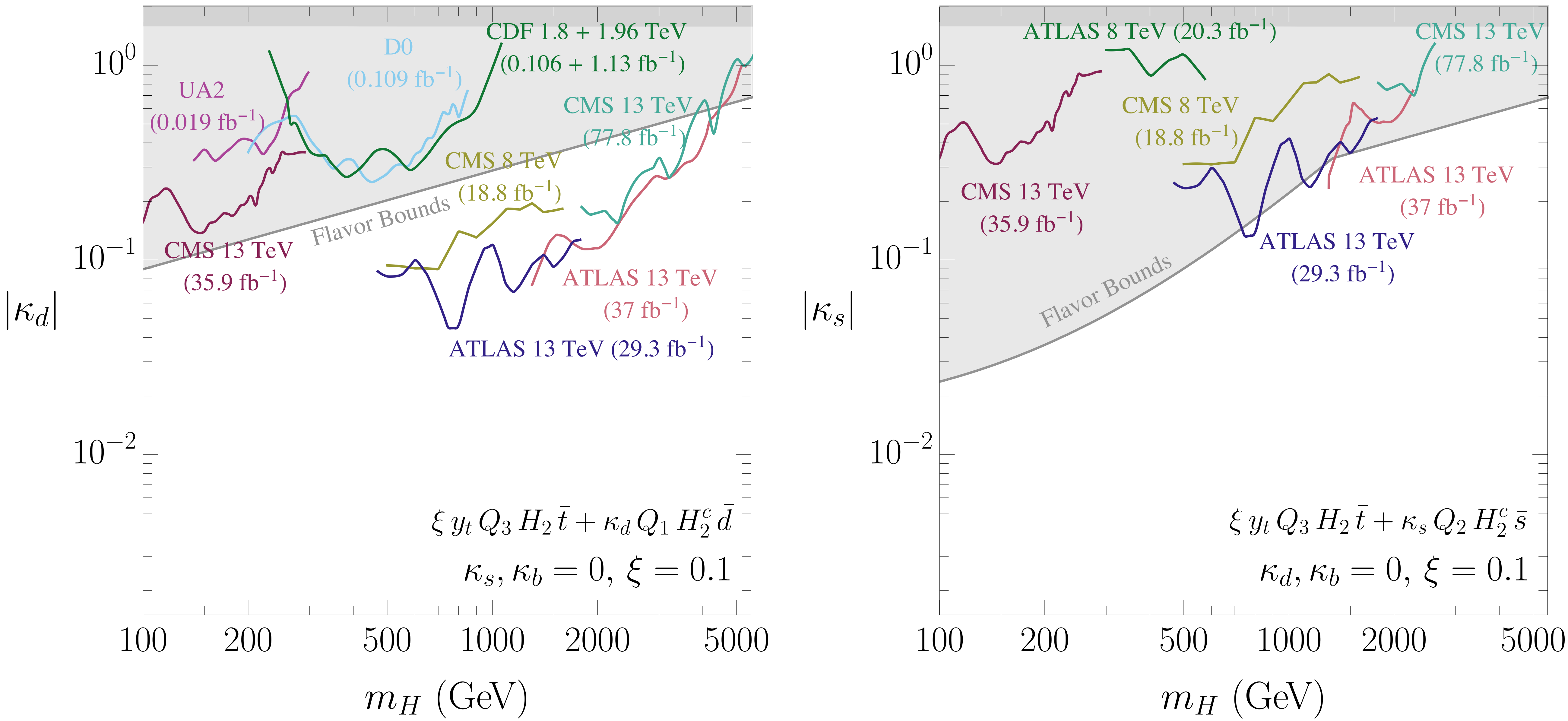


Enhanced Yukawa couplings requires $\cos(\beta - \alpha)$ not too small

→ states likely within reach of the LHC!

e.g., for $\cos(\beta - \alpha) = 0.1$, perturbativity requires $m_H \lesssim 1500\,\mathrm{GeV}$

Limits from Di-jet Searches



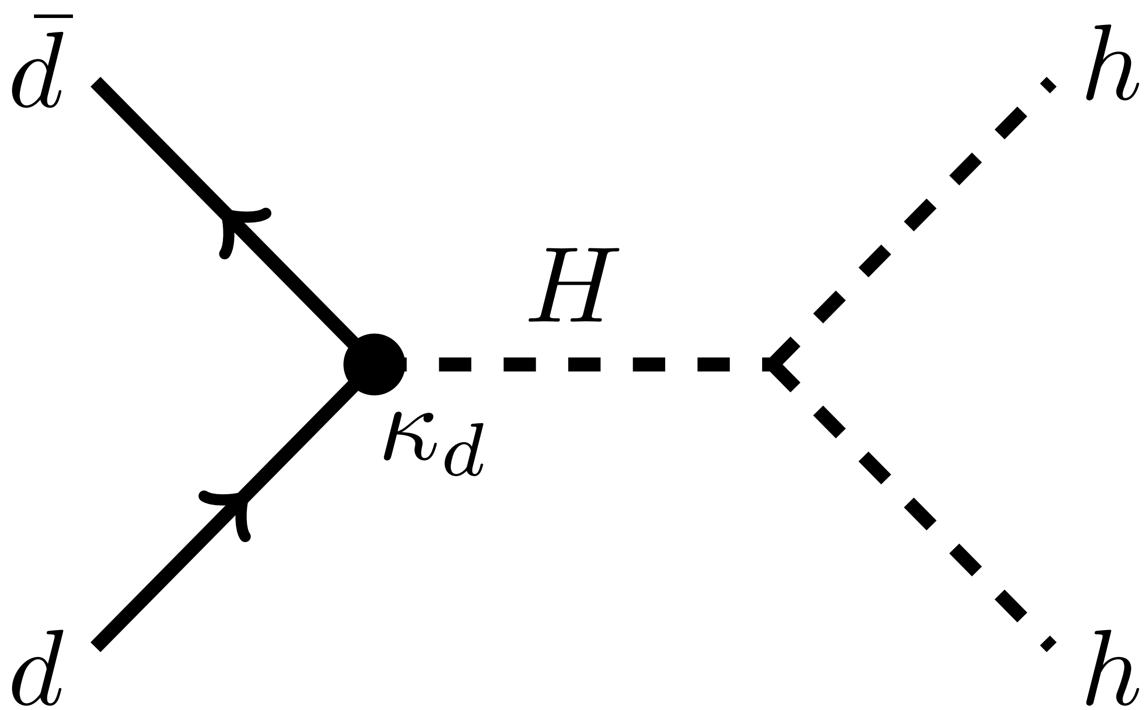
Much of the parameter space is more efficiently probed with colliders — even for O(100 GeV) new Higgses!

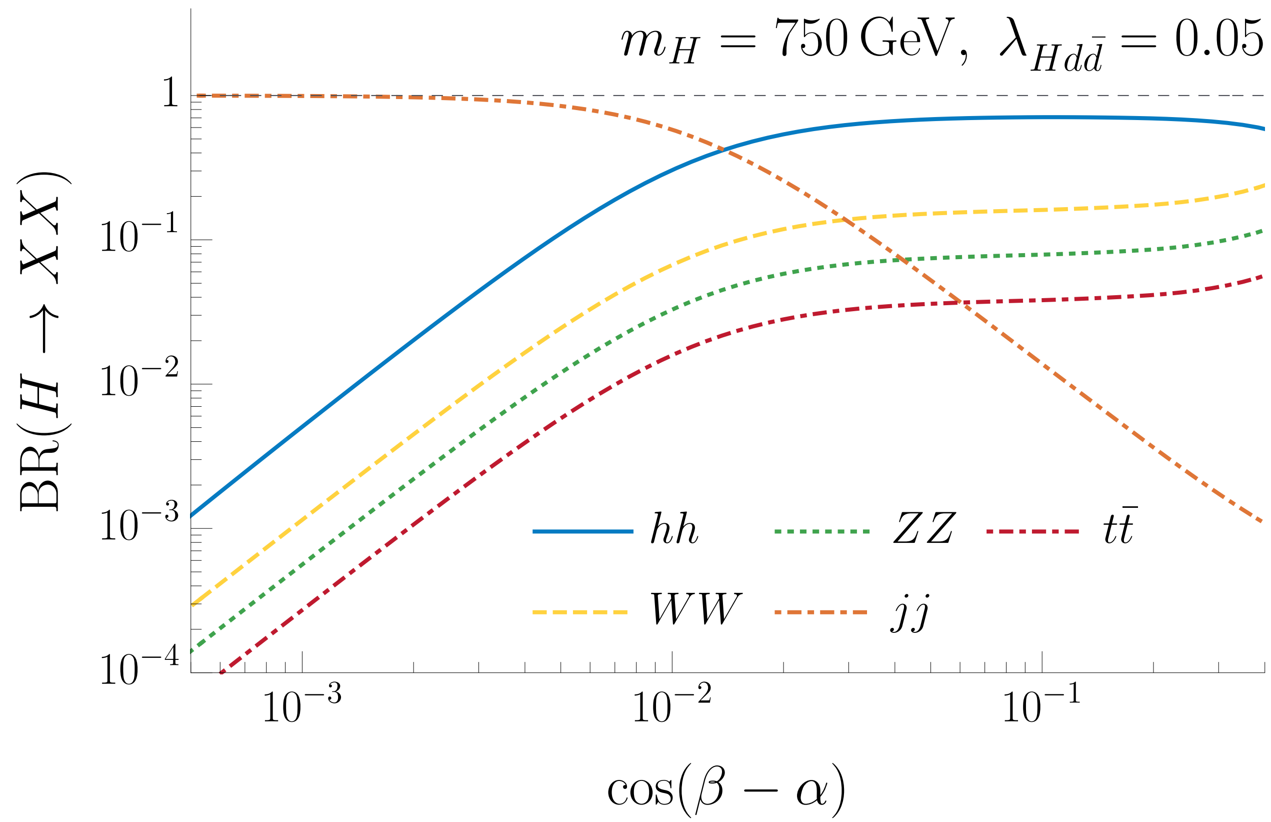
~10^8 new Higgses at 100 GeV hiding at LHC!

Resonant di-Higgs Production

(Work in Progress — arXiv:2008.XXXX)

Extra Higgs states could decay predominantly to SM Higgs pairs



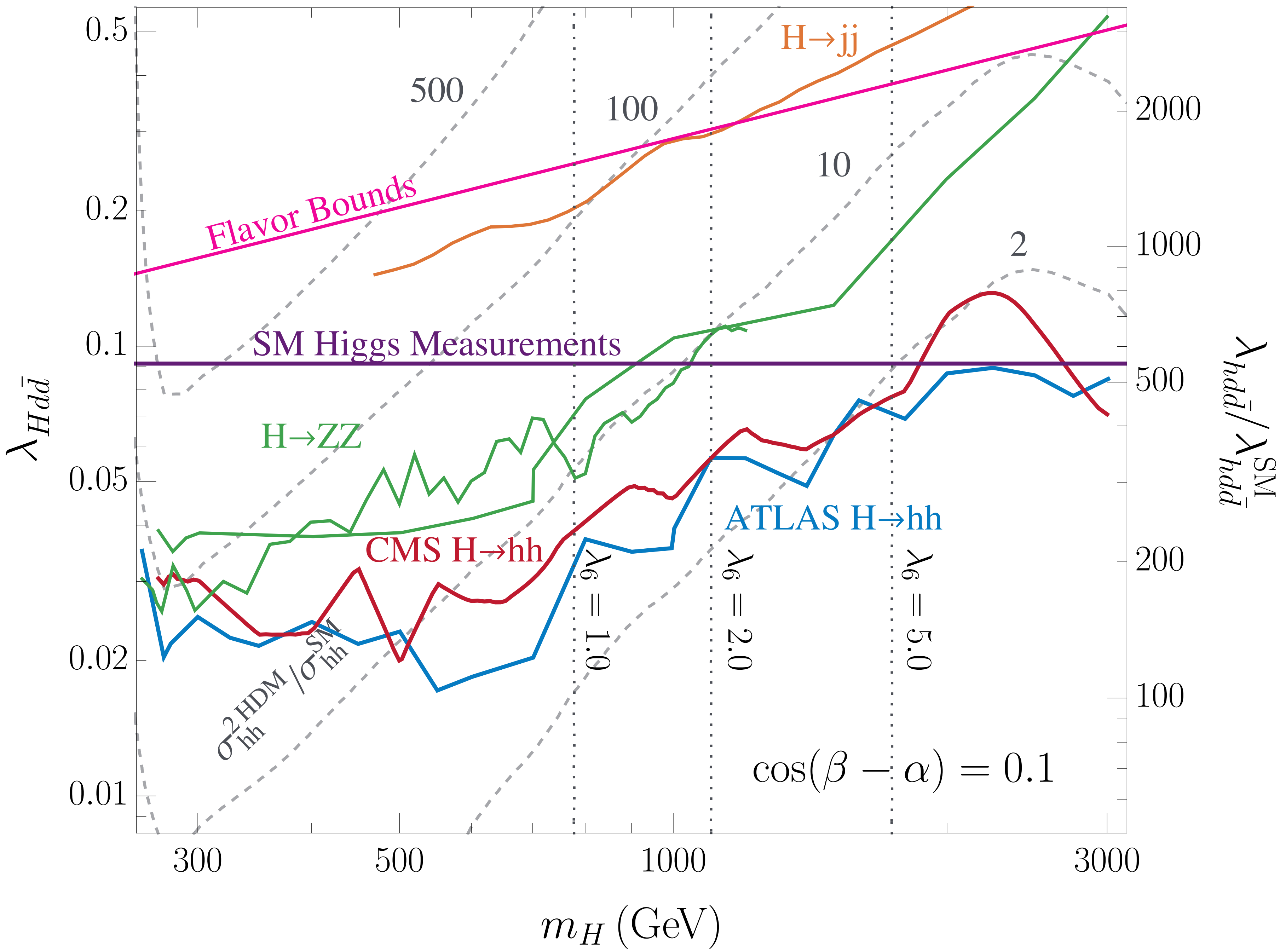


Large rates observable at the LHC, produced via *quark-fusion*

See also Alasfar, Lopez, Gröber, [1909.05279]

Current Di-Higgs Limits

(Work in Progress — arXiv:2008.XXXX)



Di-Higgs limits at the LHC are ***testing the flavor structure of extended Higgs sectors***

In this scenario, Higgs pair production is the ***strongest*** probe of enhanced Yukawa couplings

Potential improvement with *hh* final states including jets?

Conclusions

- Extended Higgs Sectors can naturally lead to enhanced Yukawas if they have non-minimal flavor structure
    - SFV provides a motivated, robust Ansatz for this!
- These models typically have ***other*** LHC phenomenology, very different than standard signals!
    - Huge production rates for heavy Higgs
    - Gigantic di-Higgs rates
    - Large branching ratios of SM Higgs to jets

Conclusions

- Extended Higgs Sectors can naturally lead to enhanced Yukawas if they have non-minimal flavor structure
    - SFV provides a motivated, robust Ansatz for this!
- These models typically have ***other*** LHC phenomenology, very different than standard signals!
    - Huge production rates for heavy Higgs
    - Gigantic di-Higgs rates
    - Large branching ratios of SM Higgs to jets

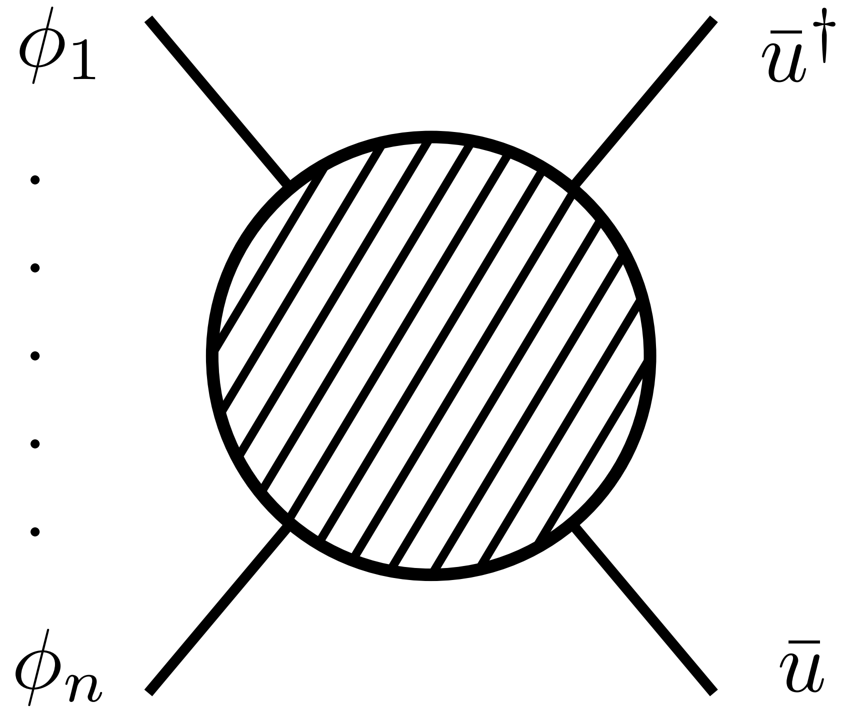
Looking forward:

- What does the phenomenology look like in other models leading to Yukawa enhancement operator?
- Are there other, dedicated searches which can do better?

Backup

A UV Completion for Flavor Alignment

Mixing with Spontaneously Broken Flavor Vacuum



$$\Longrightarrow \quad iZ^u_{ij}\, \bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j$$

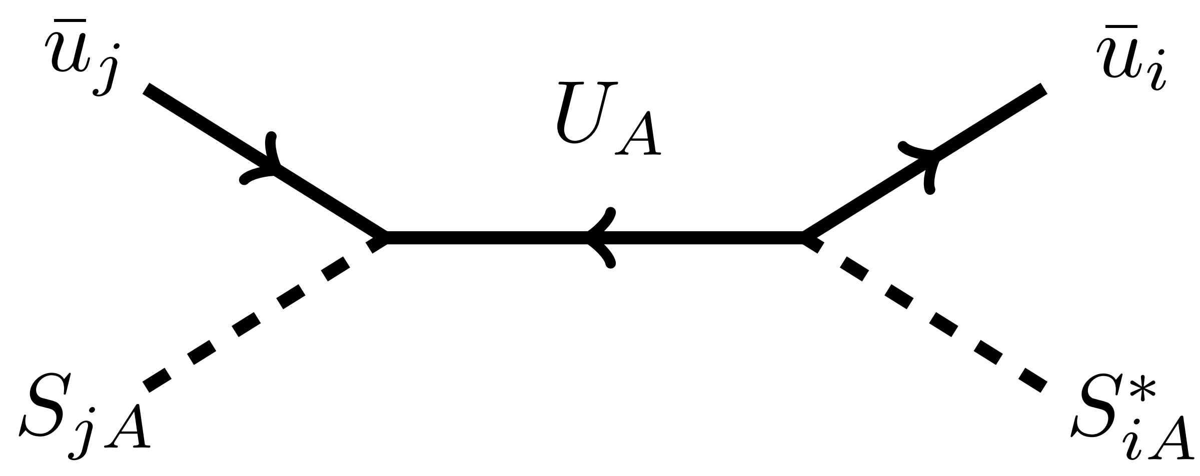
$$\mathcal{L} \supset iZ^u_{ij}\, \bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}^\dagger_i \bar{\sigma}^\mu \bar{d}_i + iQ^\dagger_i \bar{\sigma}^\mu D_\mu Q_i + \ldots$$

Could have done the same thing with RH down-quarks

$\Longrightarrow$ Two distinct theories: up- and down-type SFV

UV Completion = Nelson-Barr Model

Example: SM quarks mix with heavy vector-like quarks



$\implies$ This is just a Nelson-Barr model!

$$Z^u_{ij} = \delta_{ij} + \frac{\xi^* \xi}{M^*_A M_A} S^*_{iA} S_{jA}$$

$$\mathcal{L} \supset i Z^u_{ij}\, \bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j + i \bar{d}^\dagger_i \bar{\sigma}^\mu \bar{d}_i + i Q^\dagger_i \bar{\sigma}^\mu D_\mu Q_i + \ldots$$

In fact: *any UV realization of SFV automatically solves the strong CP problem*

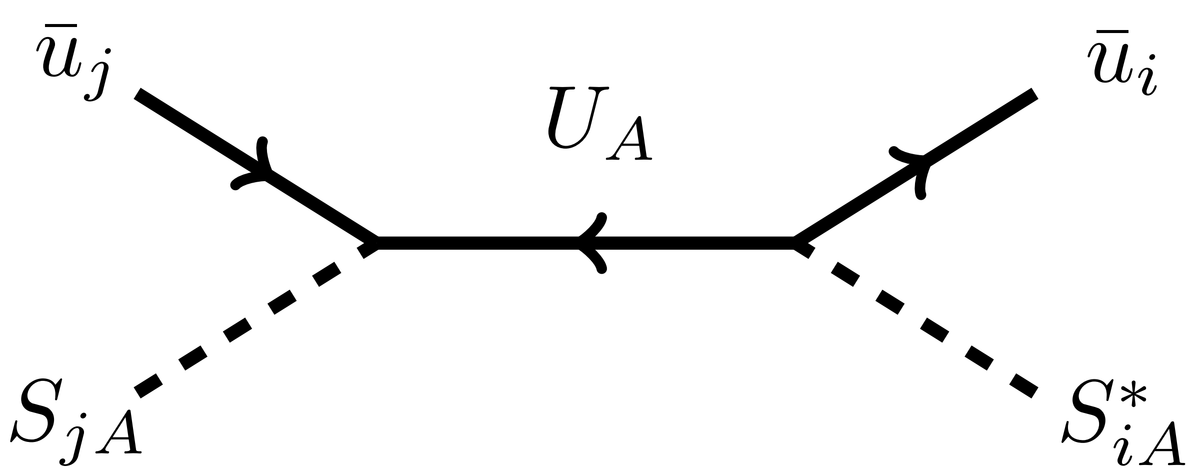
Backup: Details of the UV Completion

$$\mathscr{L} \supset M_{AB}\, U_A\, \bar{U}_B + \xi\, S_{iA}\, \bar{u}_i\, U_A$$
$$- \left[\eta^u_{ij}\, Q_i\, H\, \bar{u}_j - \eta^d_{ij}\, Q_i\, H^c\, \bar{d}_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}}$$

No additional spurions/fields transforming under $U(3)_{\bar{u}}$

Introduce mixing between up-quark and heavy VLQs in a flavor breaking vacuum

	$U(3)_U$	$U(3)_{\bar{U}}$	$U(3)_{\bar{u}}$	$U(1)_B$	$\mathbb{Z}_2$
U	3			$1/3$	-1
$\bar{U}$		3		$-1/3$	-1
S	$\bar{3}$		$\bar{3}$		-1

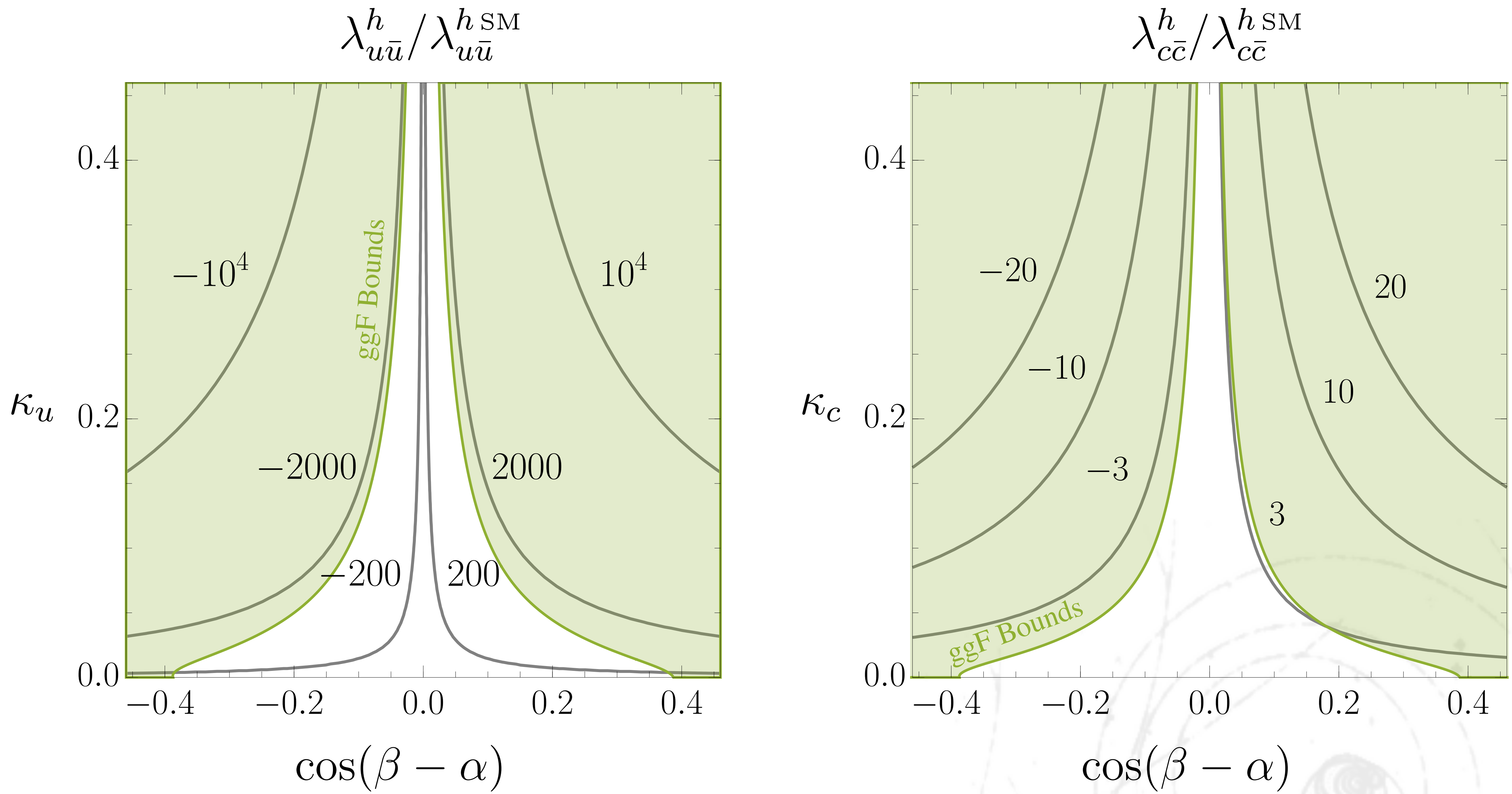


Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

$$Z^u_{ij} = \delta_{ij} + \frac{\xi^* \xi}{M^*_A M_A} S^*_{iA} S_{jA}$$

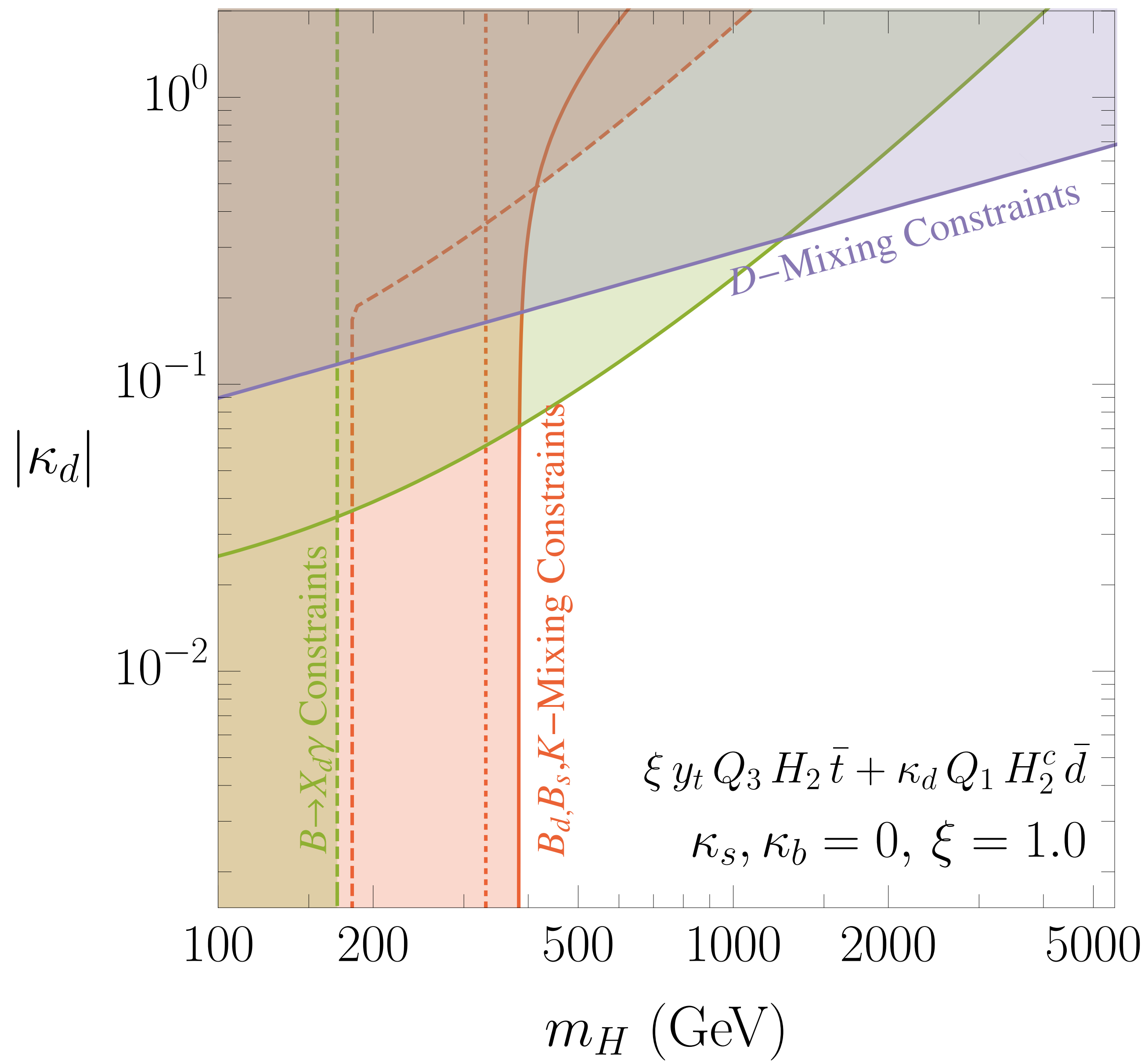
The source of all flavor-breaking!
CKM matrix arises from returning to canonical basis

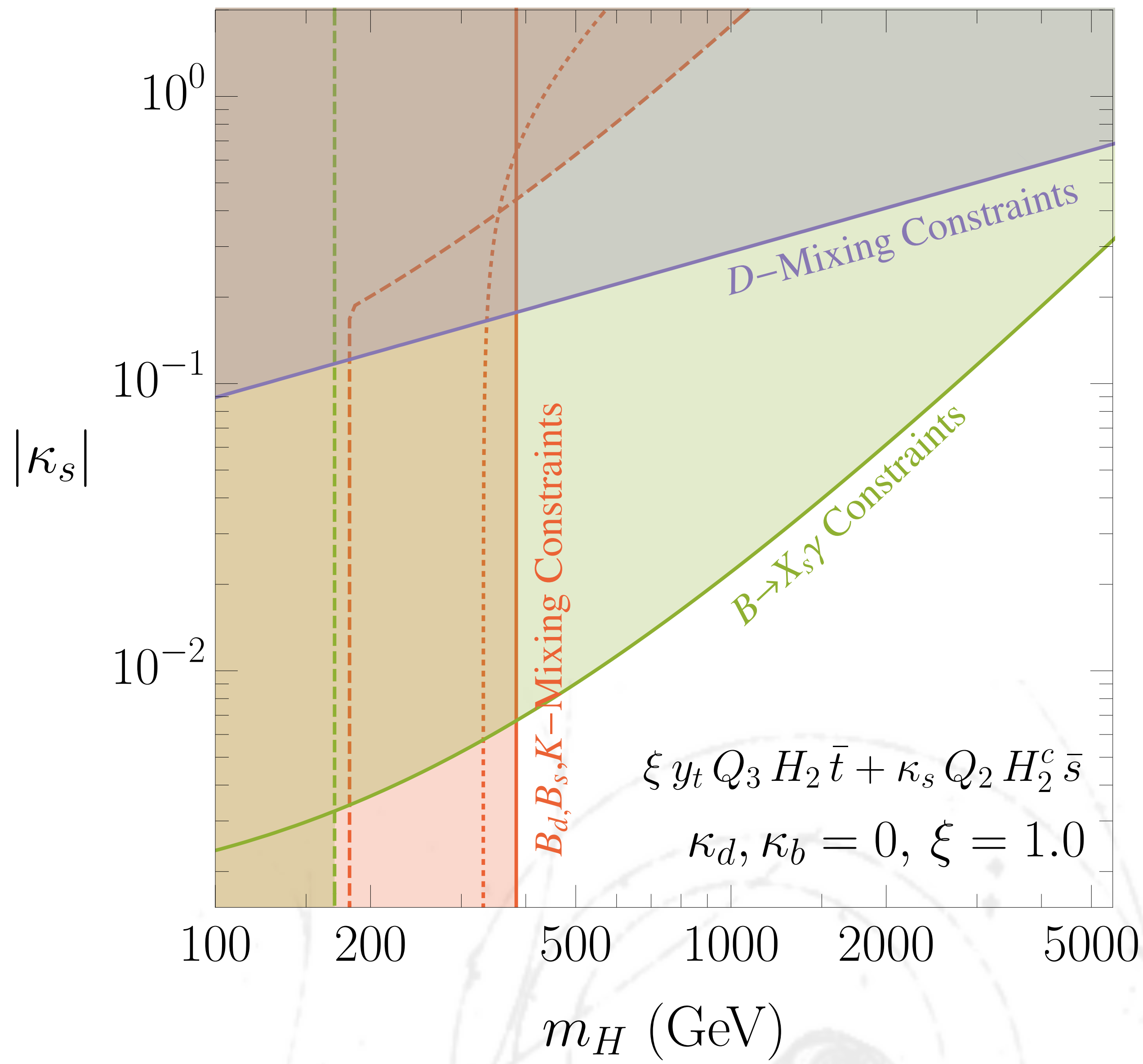
Backup: Up-type Yukawa Enhancements



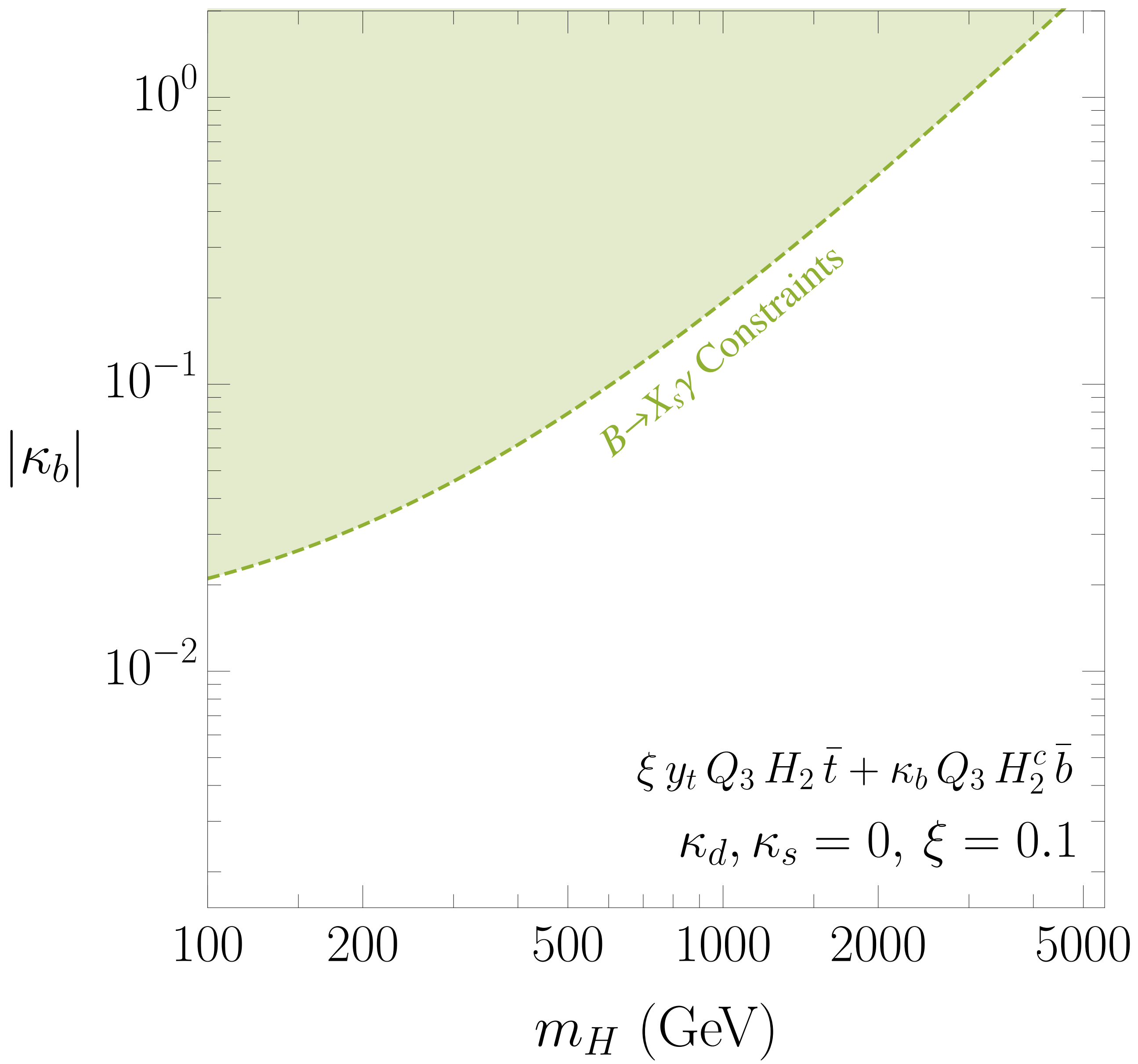
Targets for quark-flavor taggers!

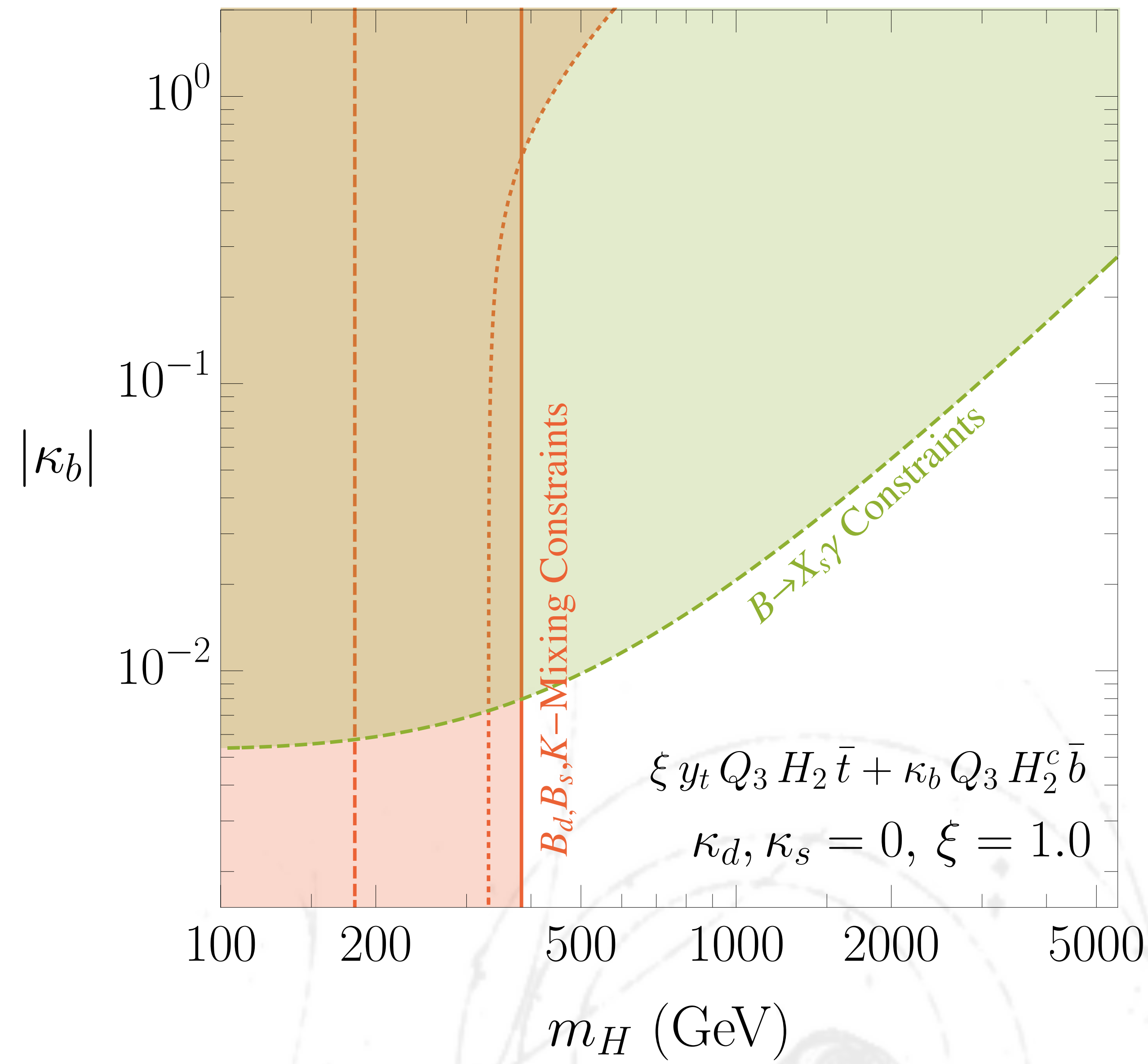
Backup: Additional Flavor Bounds



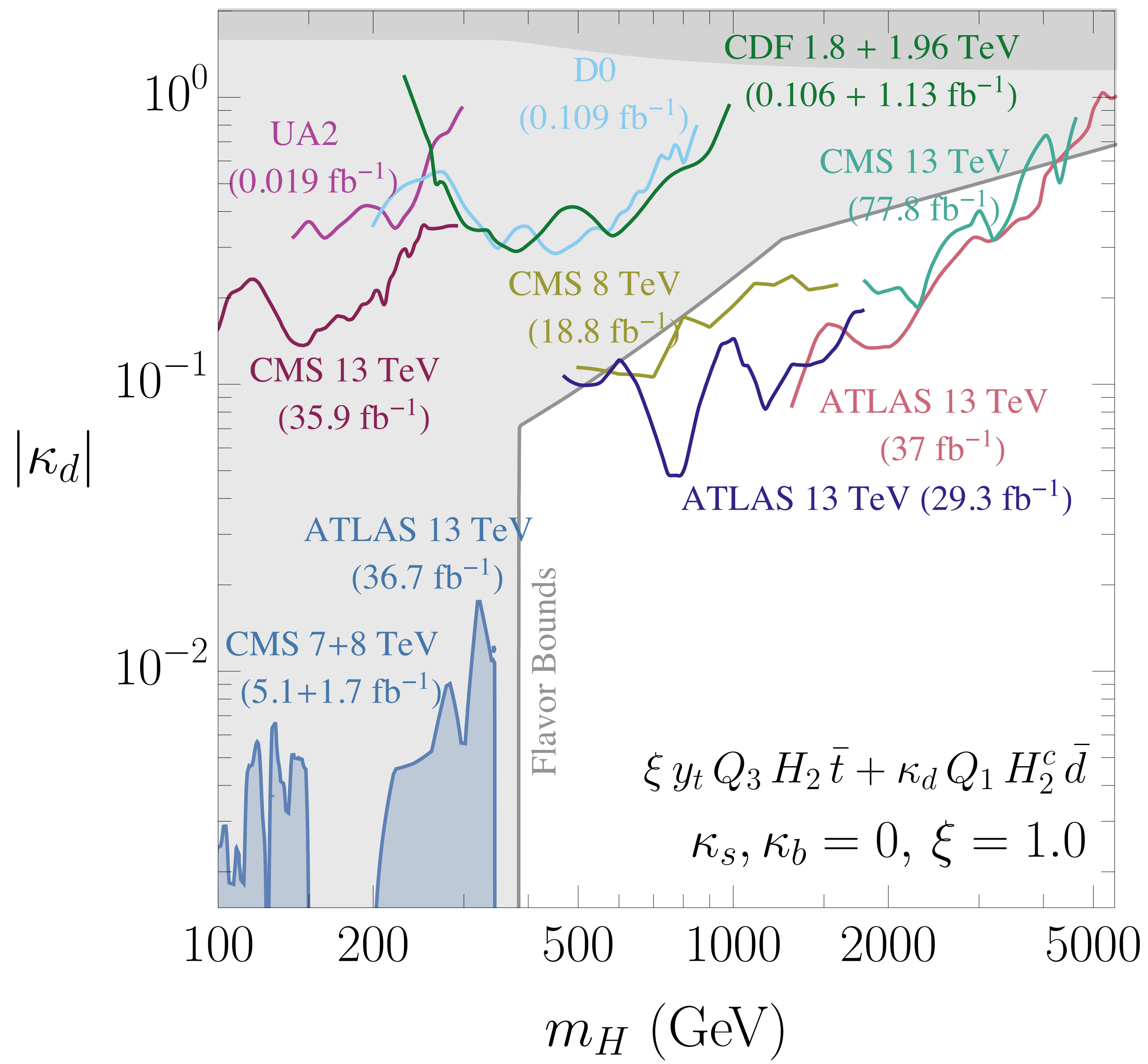


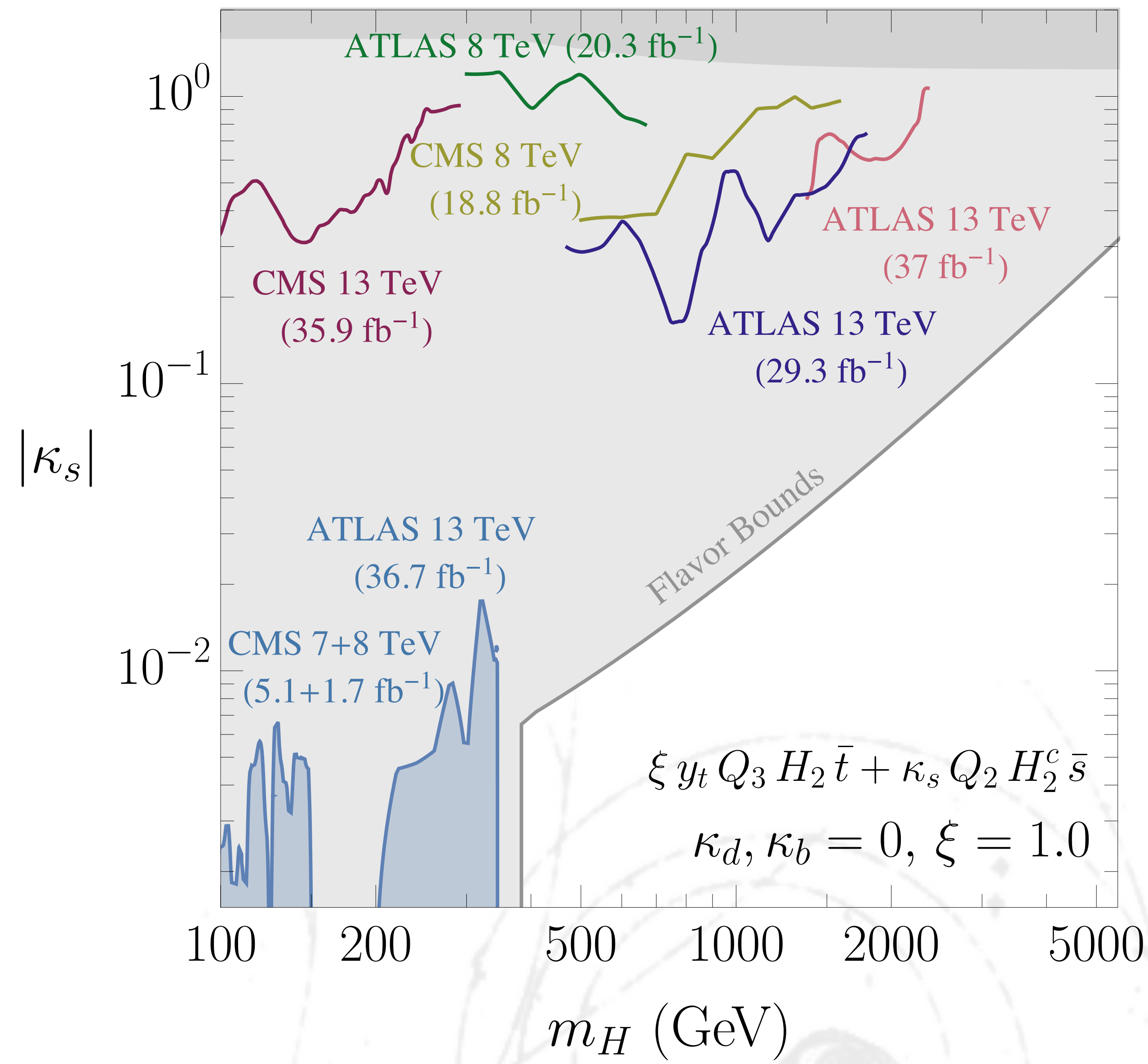
Backup: Additional Flavor Bounds



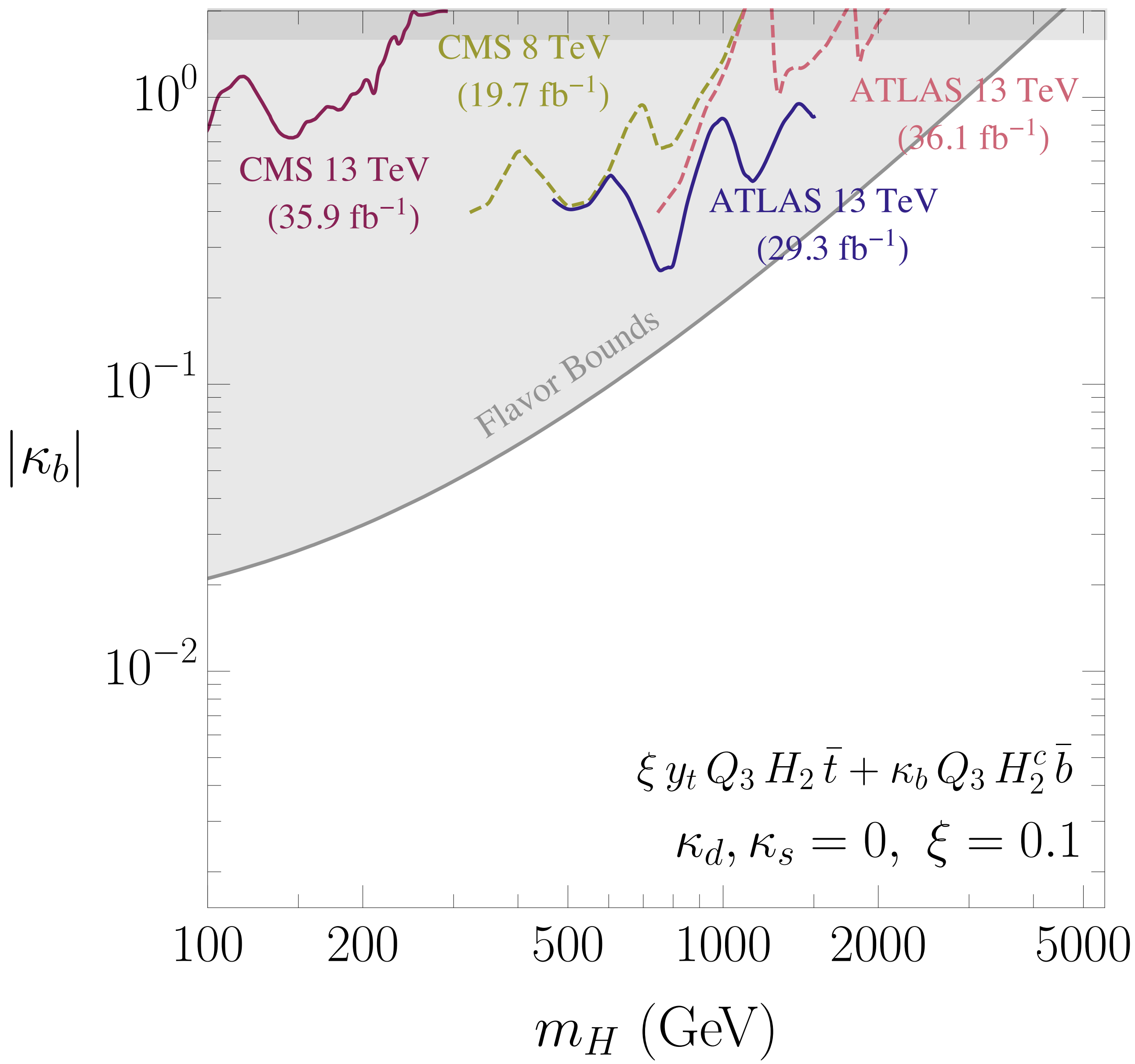


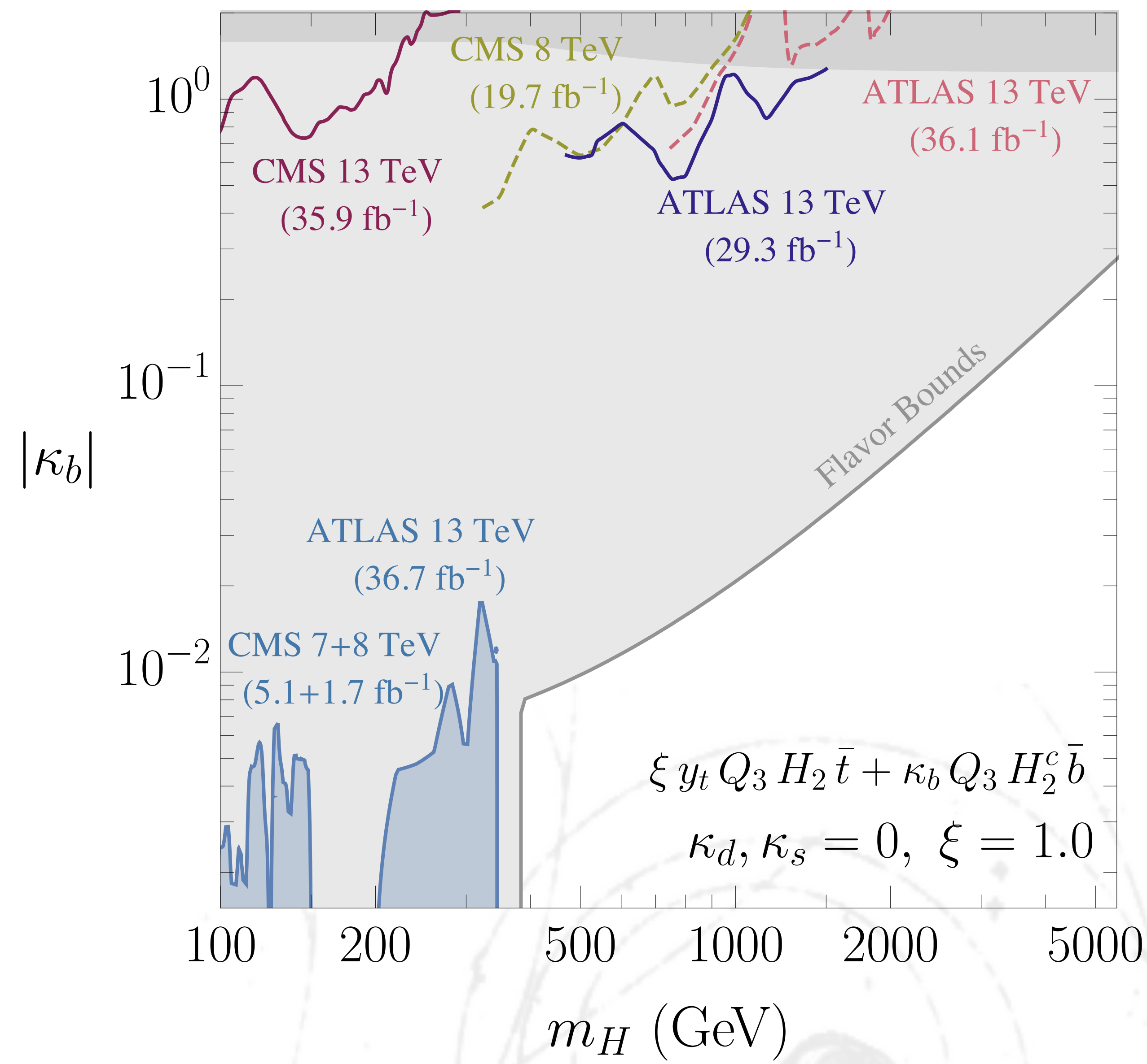
Backup: Additional Collider Bounds





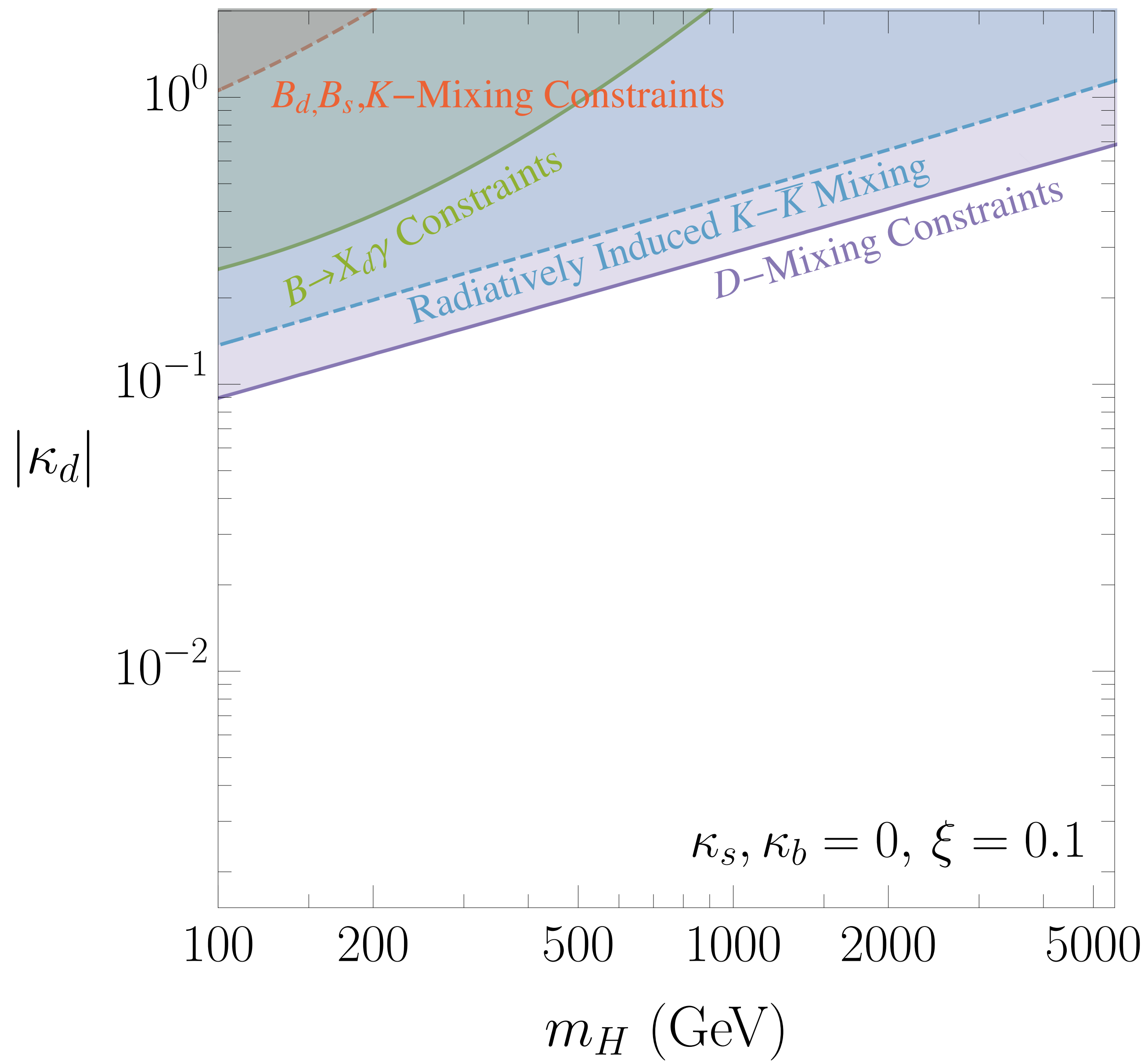
Backup: Additional Collider Bounds

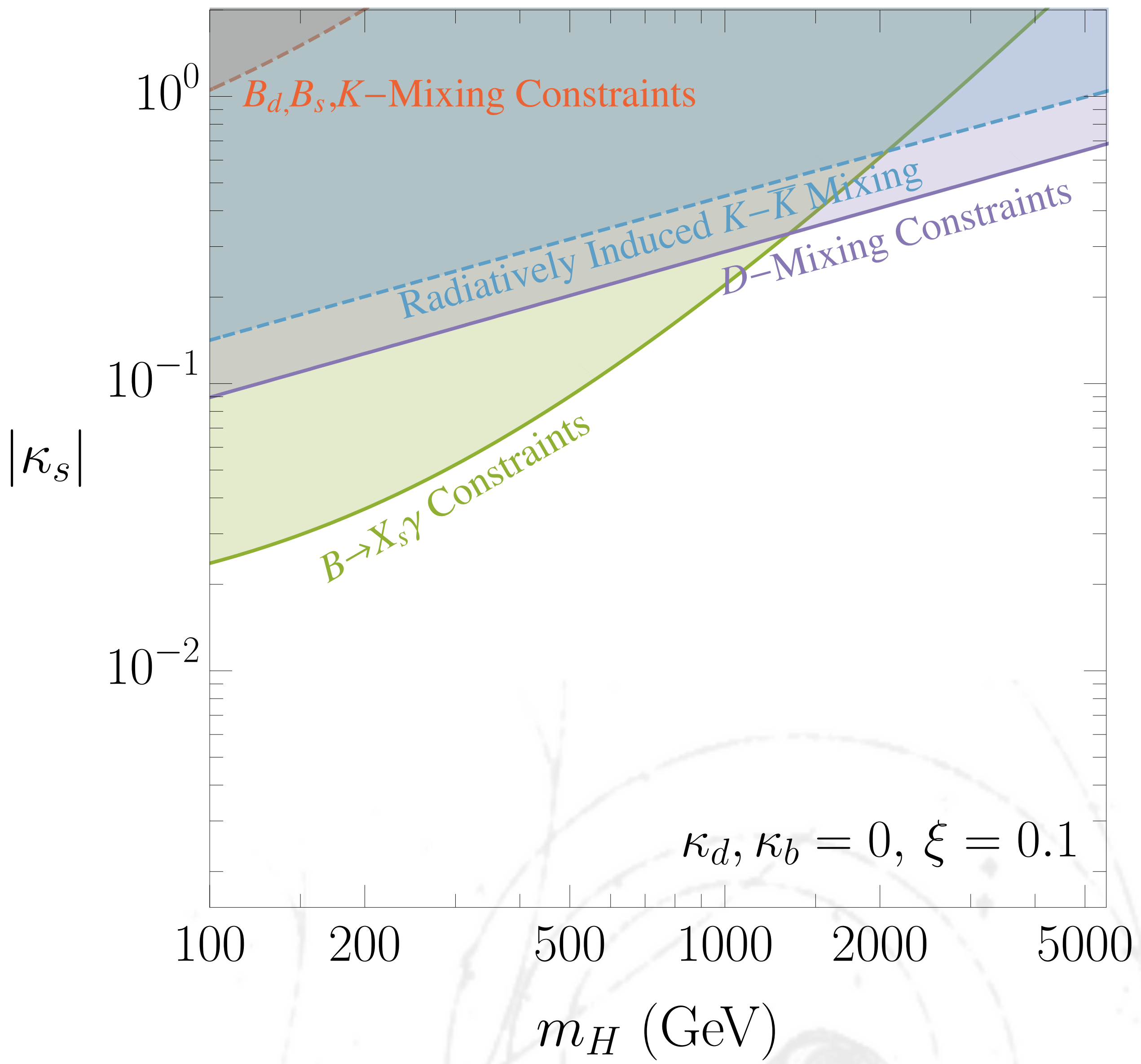




Backup: Radiative Corrections to SFV

Assuming SFV is Imposed at 100 TeV

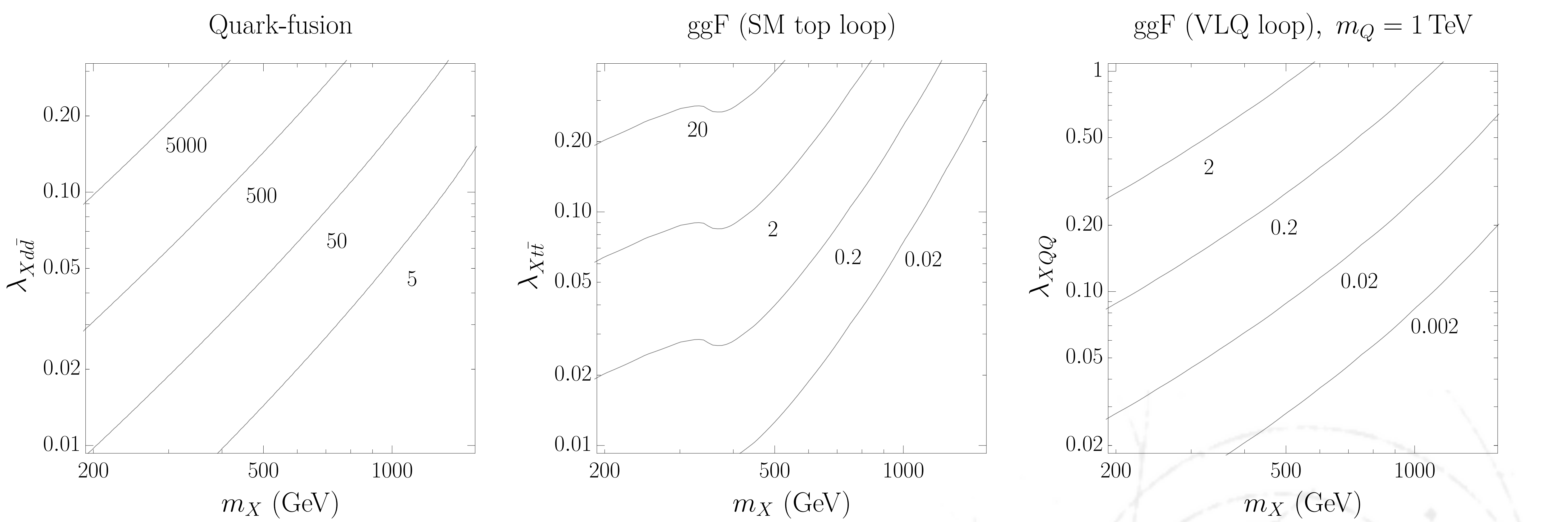




Backup: Resonant Di-Higgs Production

Simplified Models of Resonant Di-Higgs Productio

Contours of the enhancment to di-Higgs produc



Clearly the largest rates are if new physics couples at tree-level to the proton