Higgs Flavor and Multi-Higgs Production

arXiv:1811.00017 (PRL 123.031802)
arXiv:1908.11376 (PRD 100.115041)
arXiv:2101.04119

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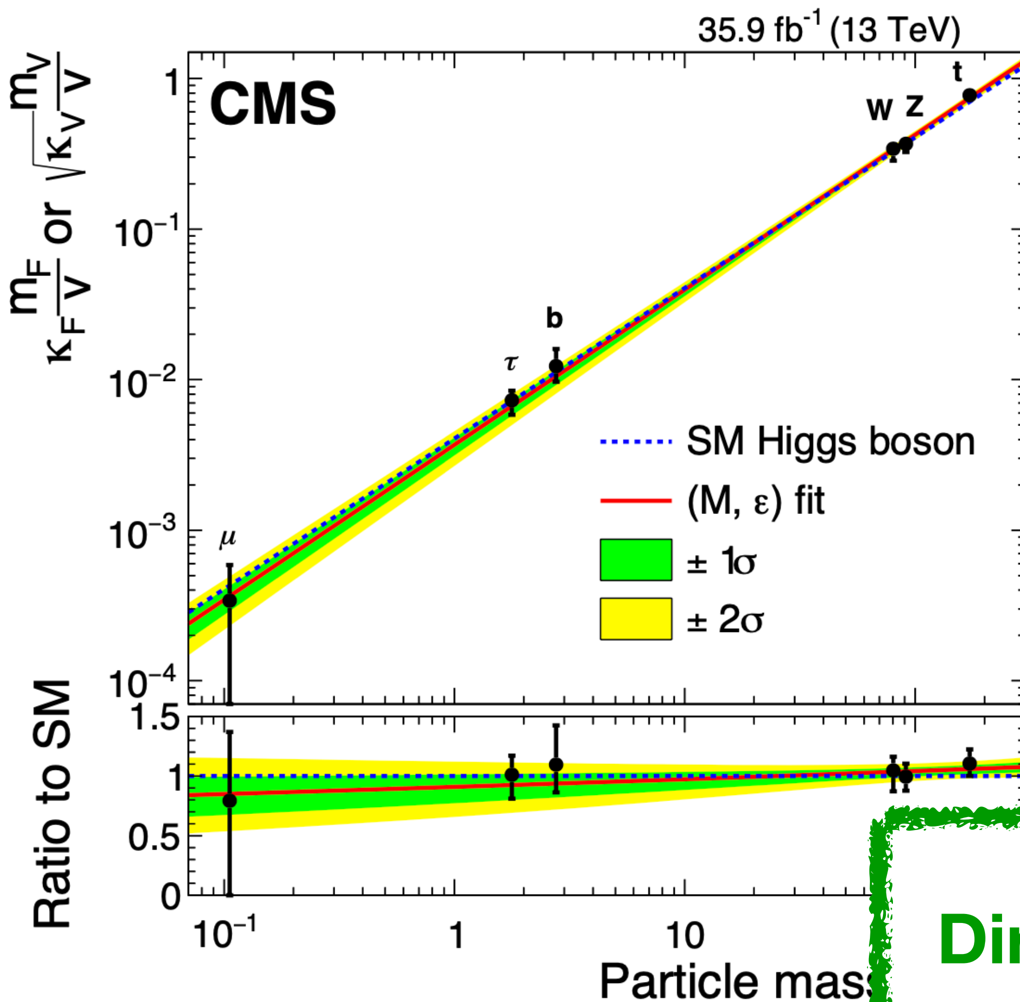
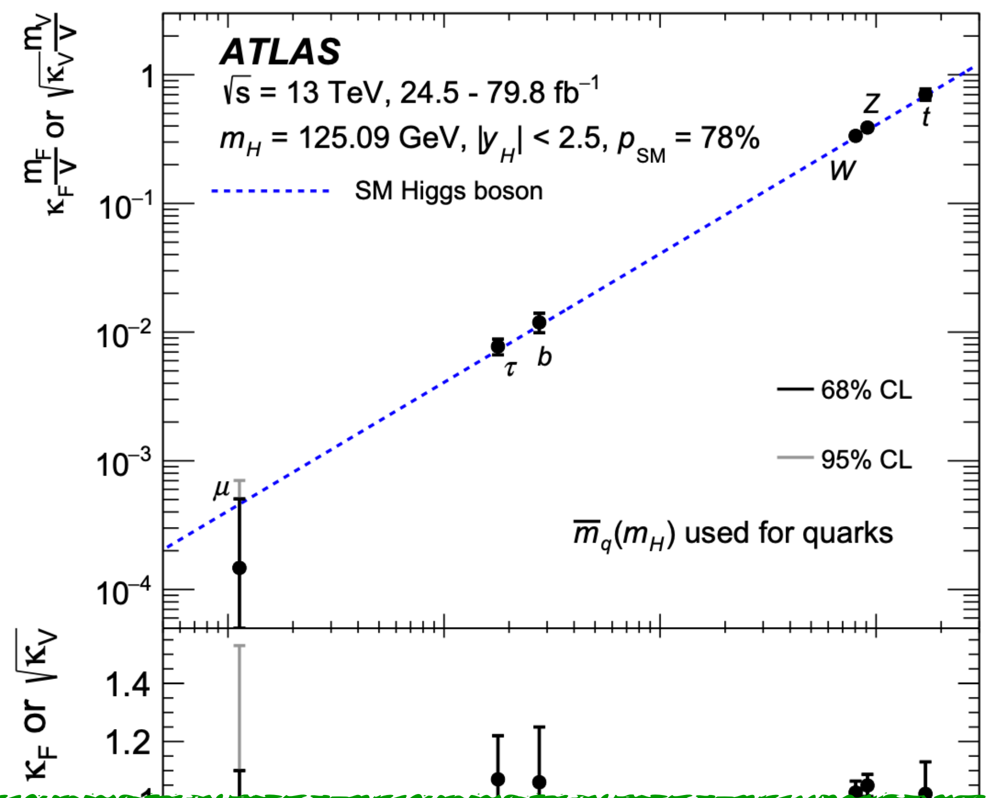
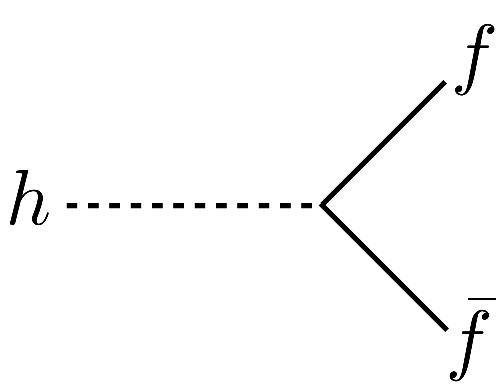
The Higgs is responsible for Flavor

$$\mathcal{L} \supset \lambda_{ij}^{u} Q_i H \bar{u}_j - \lambda_{ij}^{d\dagger} Q_i H^c \bar{d}_j$$







$$\frac{\sqrt{2}m_f}{v}$$

Direct constraints on light Yukawas very weak!

$$y_d \lesssim 500\, y_d^{SM} \sim 0.5 y_b$$

(from fit to Higgs signal strengths)

Multi-Higgs Production Probes Higgs Flavor

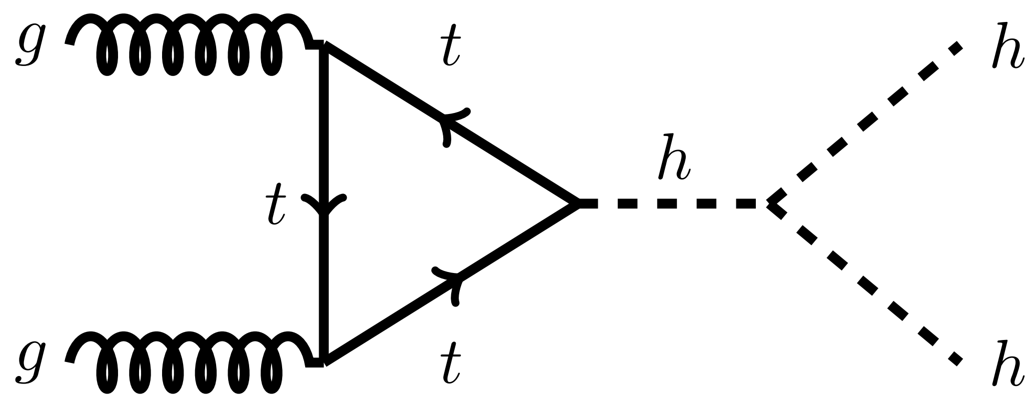
Higgs-quark couplings

2h and (and 3h!) production at the LHC

Multiple Higgs boson production at the LHC is an exquisite probe of the Higgs couplings to quarks (especially 1st gen)

Di-Higgs Production at the LHC

Much interest is because it is the *only* direct test of the Higgs self-coupling



$$\propto \lambda_3 h^3 \supset V(h)$$

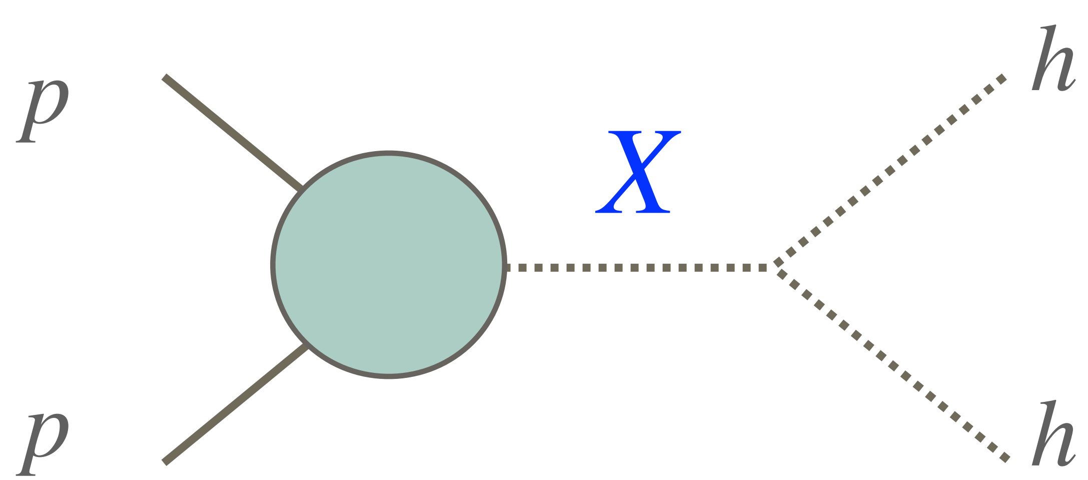
Unfortunately, the LHC *does not* have enough sensitivity to measure this coupling precisely

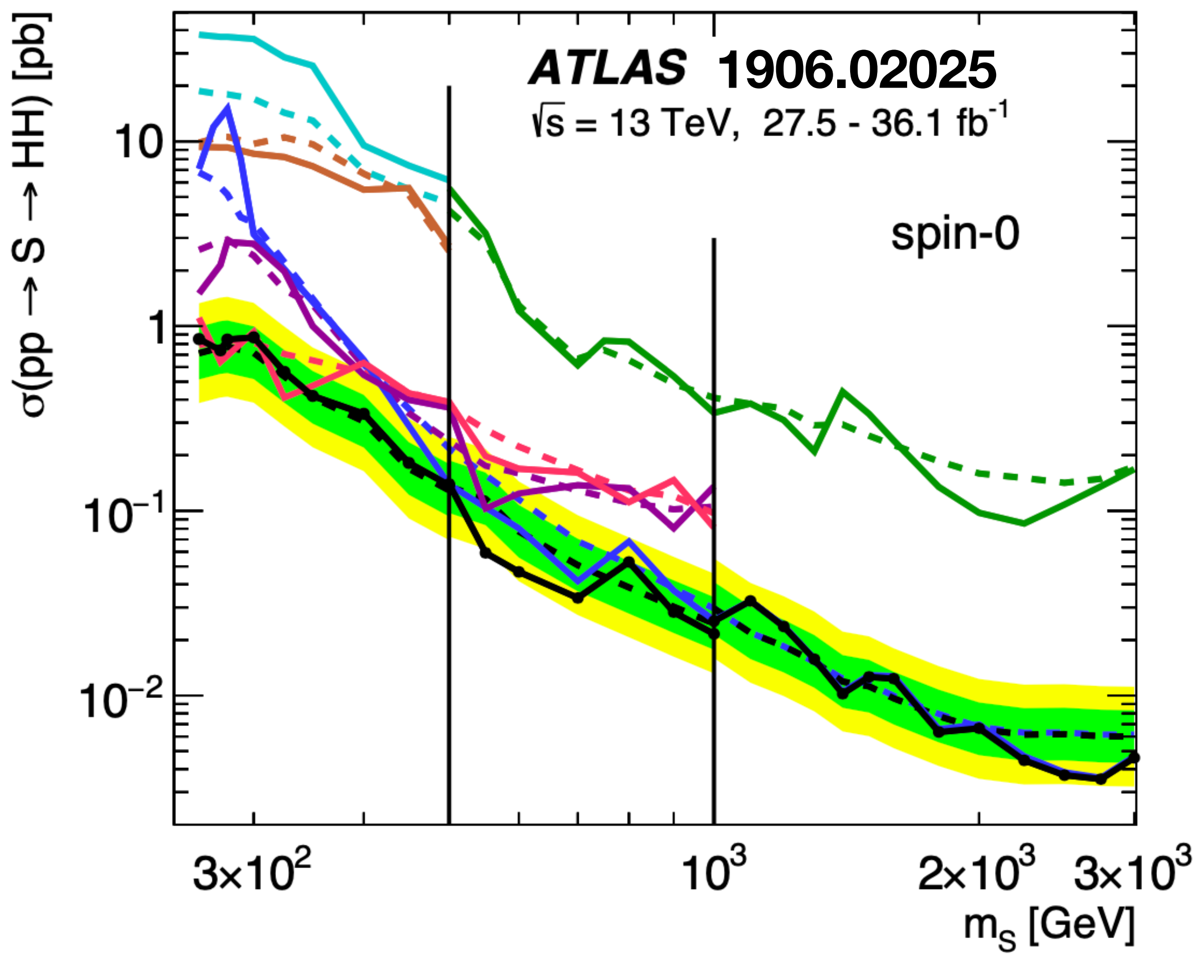
Current bounds: $-3.3 < \lambda/\lambda_{\mathrm{SM}} < 8.5$
CMS-HIG-19-018

HL-LHC Projections: $-0.18 < \lambda/\lambda_{\mathrm{SM}} < 3.6$
arXiv:1910.00012

What is di-Higgs at the LHC Good For?

Searching for new scalar states via *resonant HH production!*



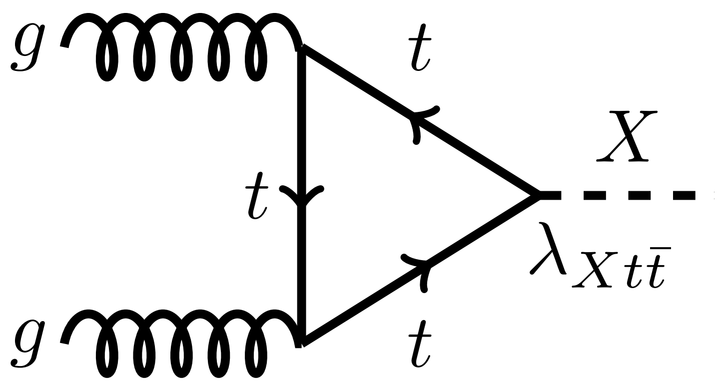


This happens naturally in a *tremendous* variety of theories:

Additional singlets, SUSY, DM Portals, all types of 2HDMs, …

See, e.g., Lewis, Sullivan 1701.08774, DiMiccio et. Al 1910.00012, Englert et. al 1403.7191, and many many more…

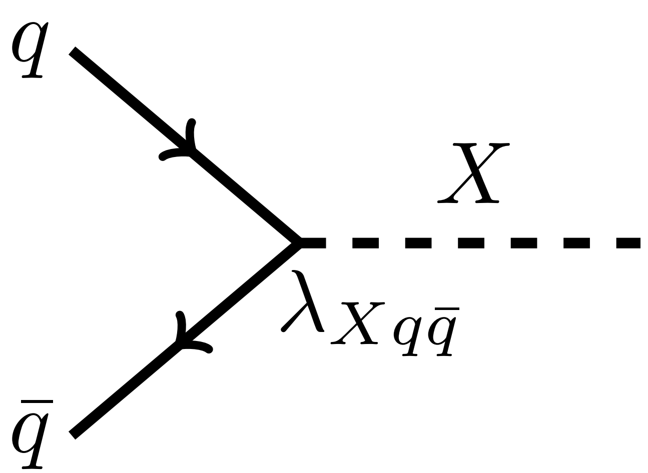
Production of Extra Scalars



Most frequently studied: top coupling

$$\lambda_{Xt\bar{t}} X t \bar{t}$$

(Alternatively: new heavy quarks in the loop)



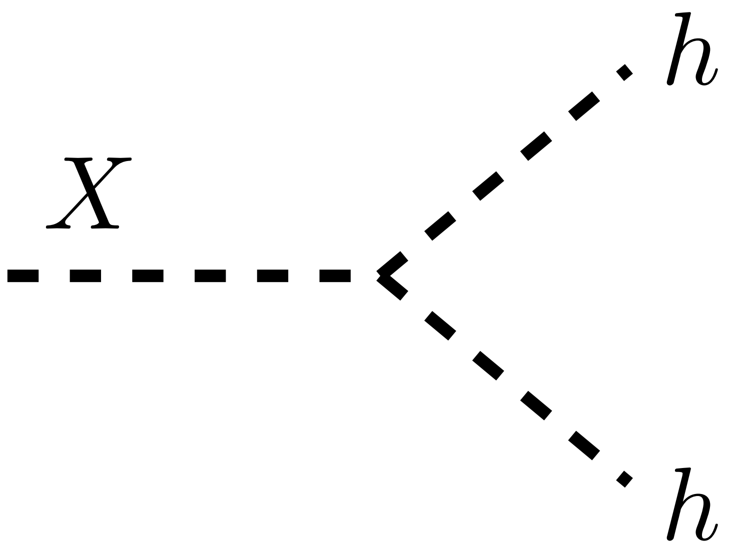
New target: *light quark couplings*

$$\lambda_{Xd\bar{d}} X d \bar{d}$$

$$\lambda_{Xu\bar{u}} X u \bar{u}$$

$$\lambda_{Xs\bar{s}} X s \bar{s}$$

Decays into Higgs Pairs



$$\lambda_6 (H_2^\dagger H_1)(H_1^\dagger H_1)$$

$$\downarrow$$

$$3\lambda v X h h$$

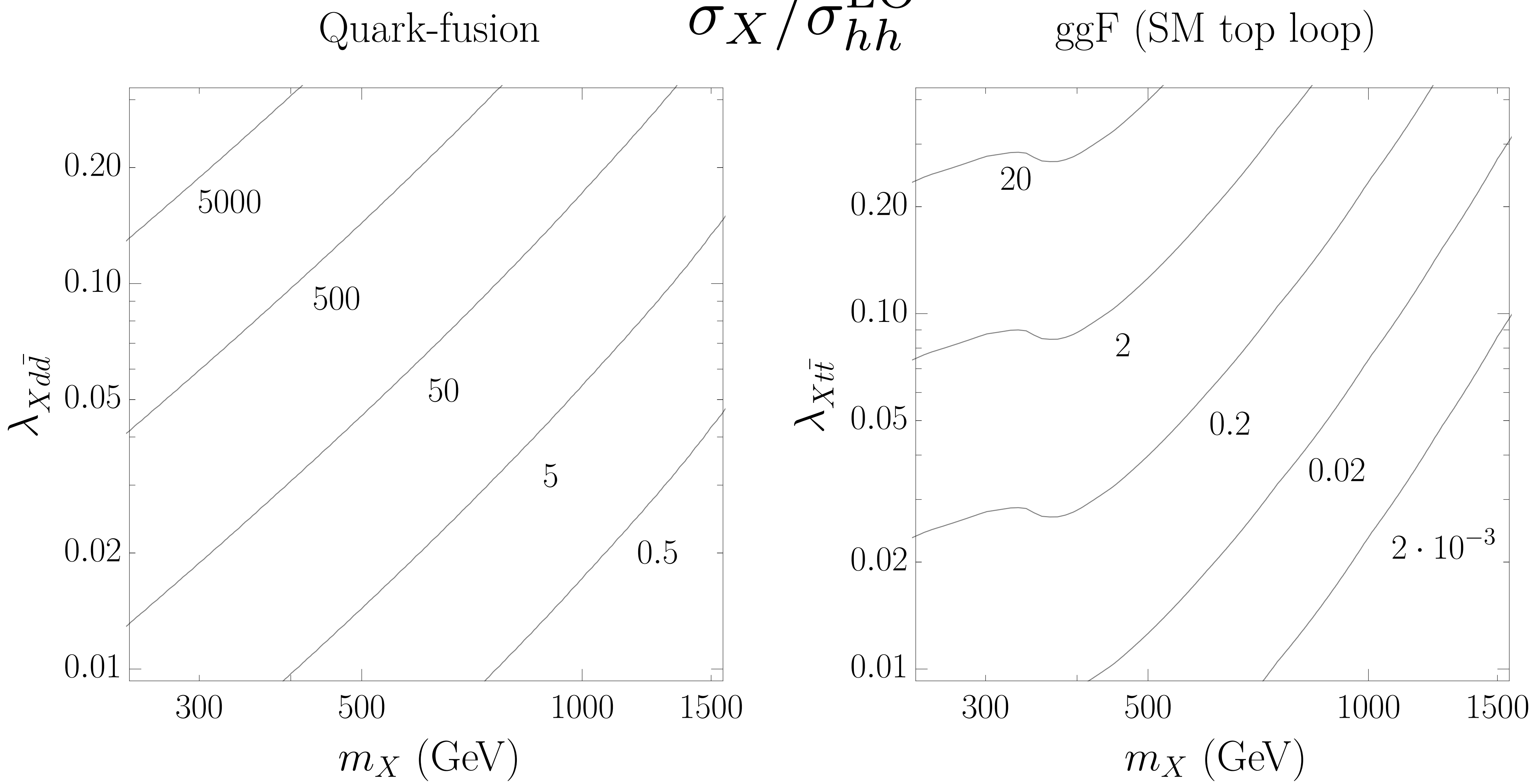
$$v = 246\,\mathrm{GeV}$$

For fun let's assume $\mathrm{Br}(X \to hh) \sim 1$

Typical Cross Sections

$$\sigma_{hh}^{\mathrm{LO}} = 14.5\,\mathrm{fb}$$

$$\sigma_X / \sigma_{hh}^{\mathrm{LO}}$$



The largest cross sections are obtained when extra Higgses couple to light quarks!

What about SM Higgs Yukawas?

Clearly, di-Higgs production is a powerful test of models where extra Higgses couple to light quarks…

…but what does this have to do with the 125 GeV Higgs?

Everything! An ***irreducible*** modification to Higgs couplings arises via mixing:

$$3\lambda v X h h \longrightarrow 3\lambda v^2 X h \longrightarrow X - h \text{ mass mixing}$$

$\longrightarrow$ Di-Higgs production is correlated with modifications of the 125 GeV Higgs couplings to quarks, <u>especially light ones</u>

Models of Enhanced Light Yukawas

arXiv:1811.00017, 1908.11376

$$Y^u = \text{diag}(y_u^{\text{SM}}, y_c^{\text{SM}}, y_t^{\text{SM}})$$
$$Y^d = \text{diag}(y_d^{\text{SM}}, y_s^{\text{SM}}, y_b^{\text{SM}})$$
$$K^d = \text{diag}(\kappa_d, \kappa_s, \kappa_b)$$

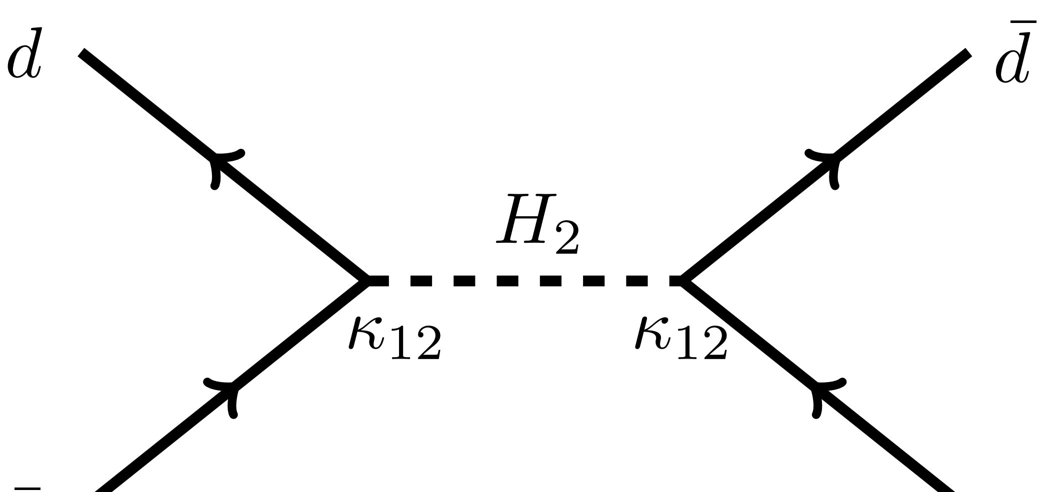
In the quark mass eigenbasis, aligned Yukawas take the form:

Diagonal in the same basis!

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

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

Tree-level FCNCs vanish — *even if diagonal entries are large!*



$$\propto \kappa_{12}^2 = 0$$

Demonstrated in 1811.00017 that alignment can be achieved in a *technically natural*, *UV complete* way

“Spontaneous Flavor Violation”

The only catch is that Yukawas can only be aligned in one quark sector

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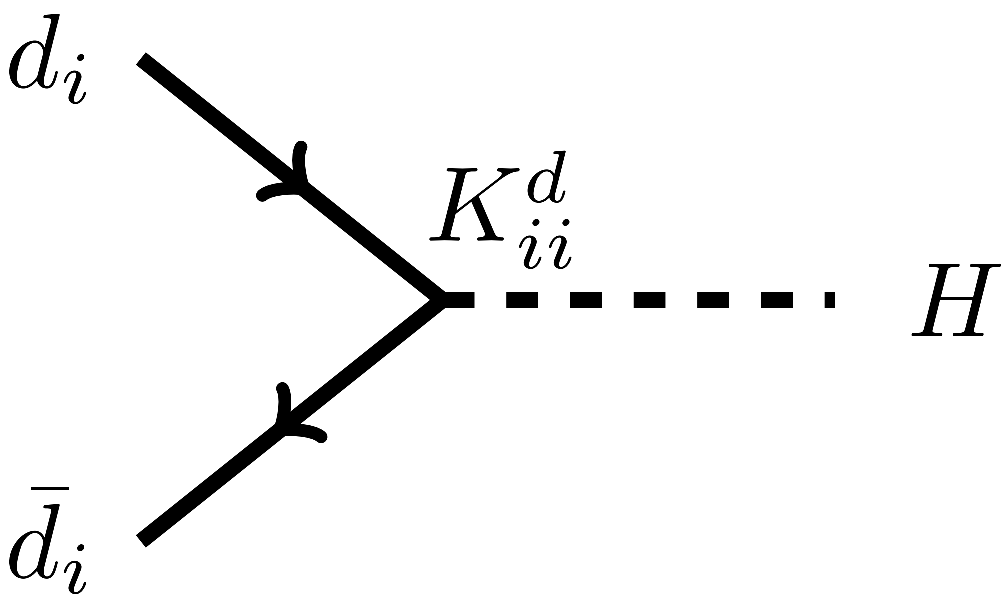

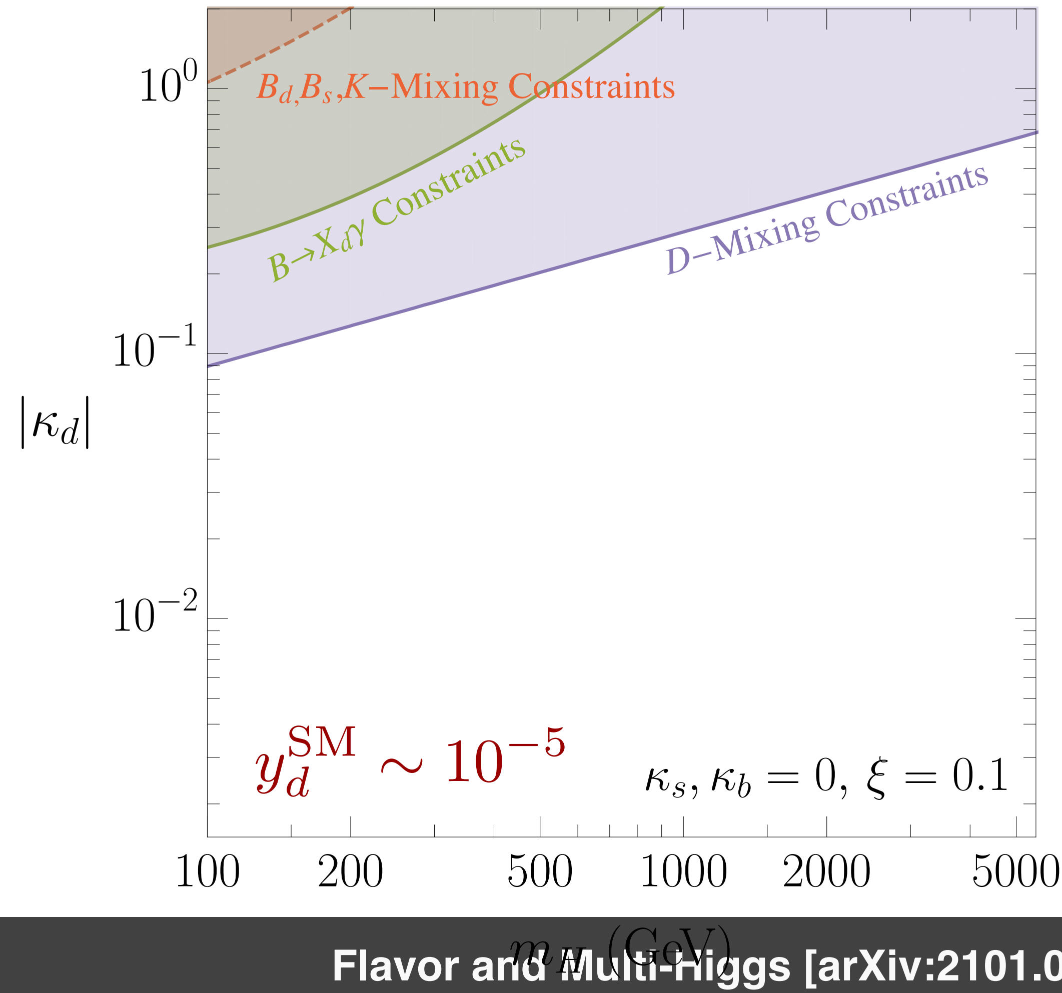

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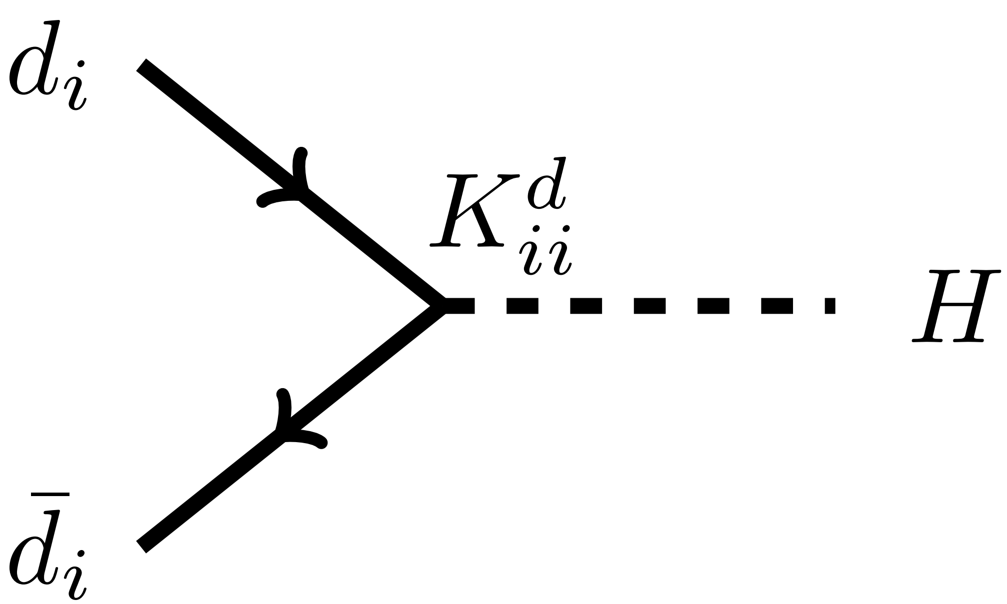
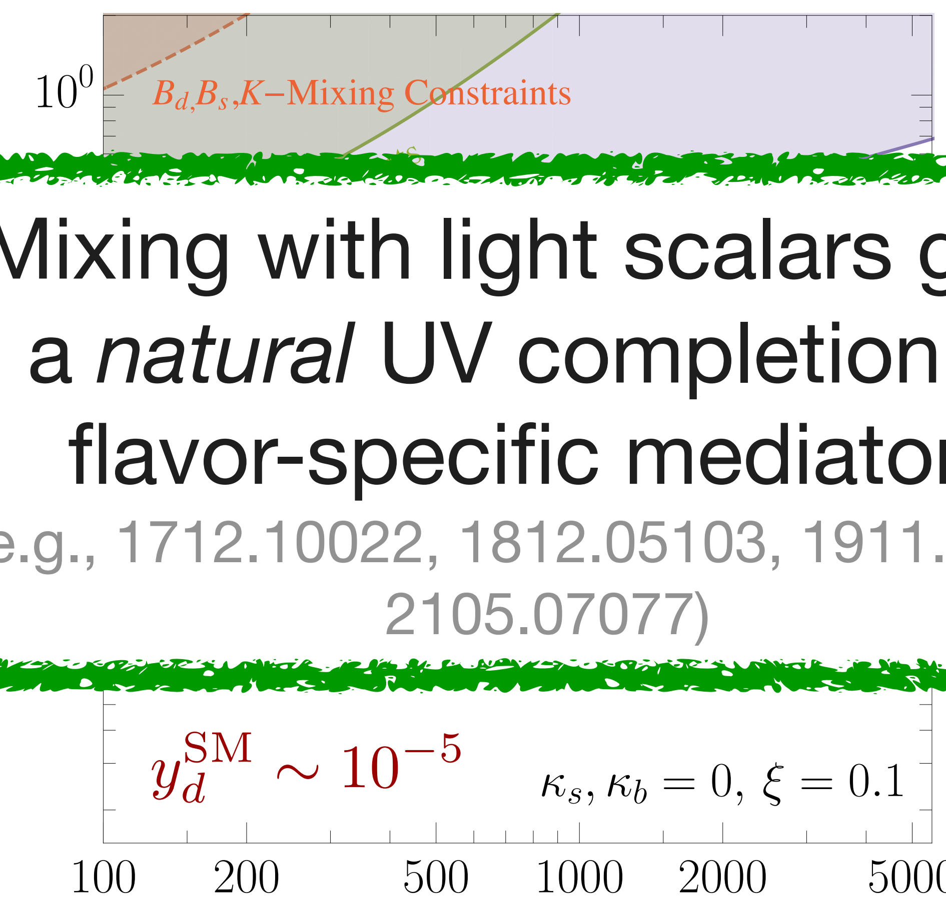
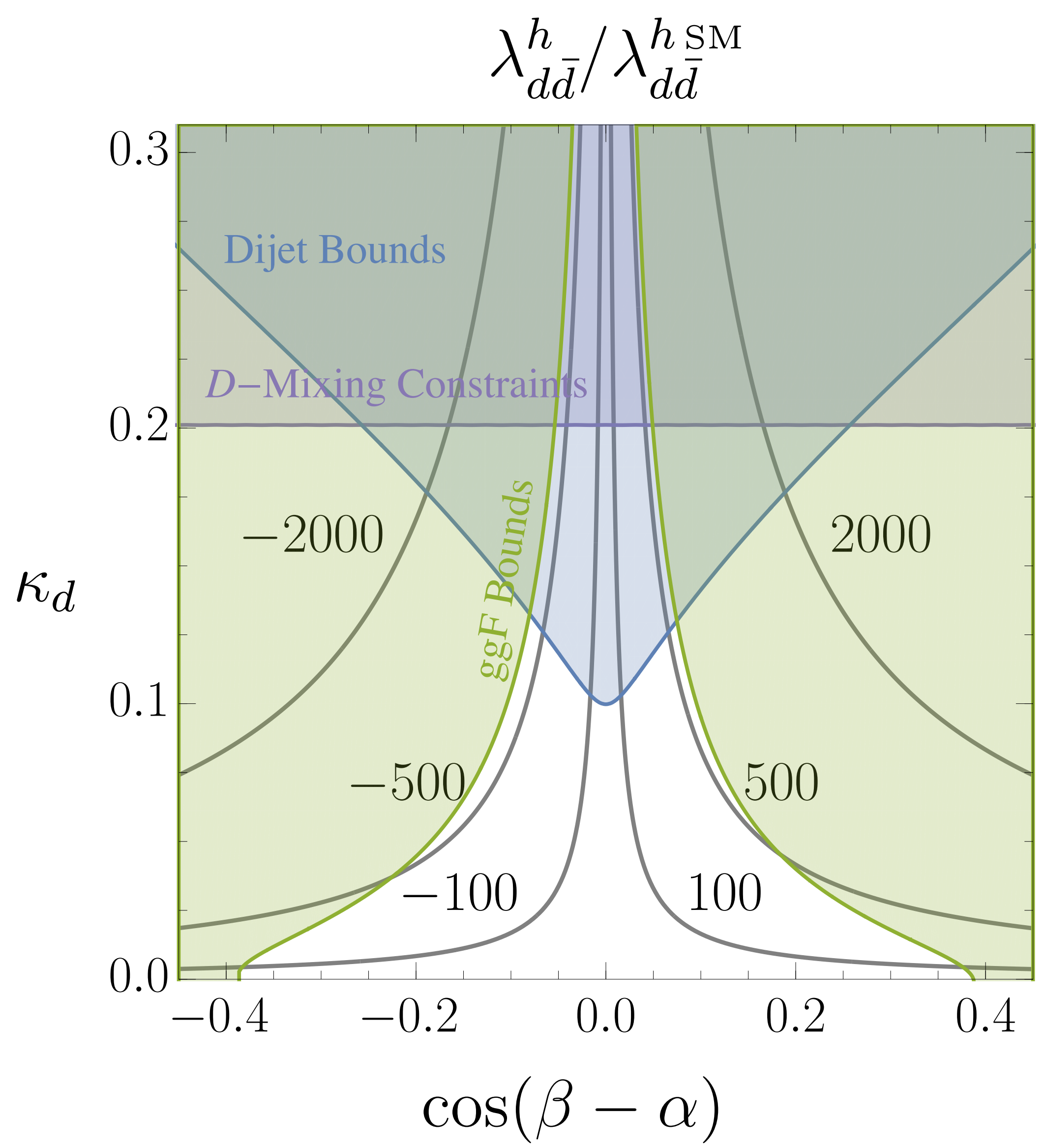


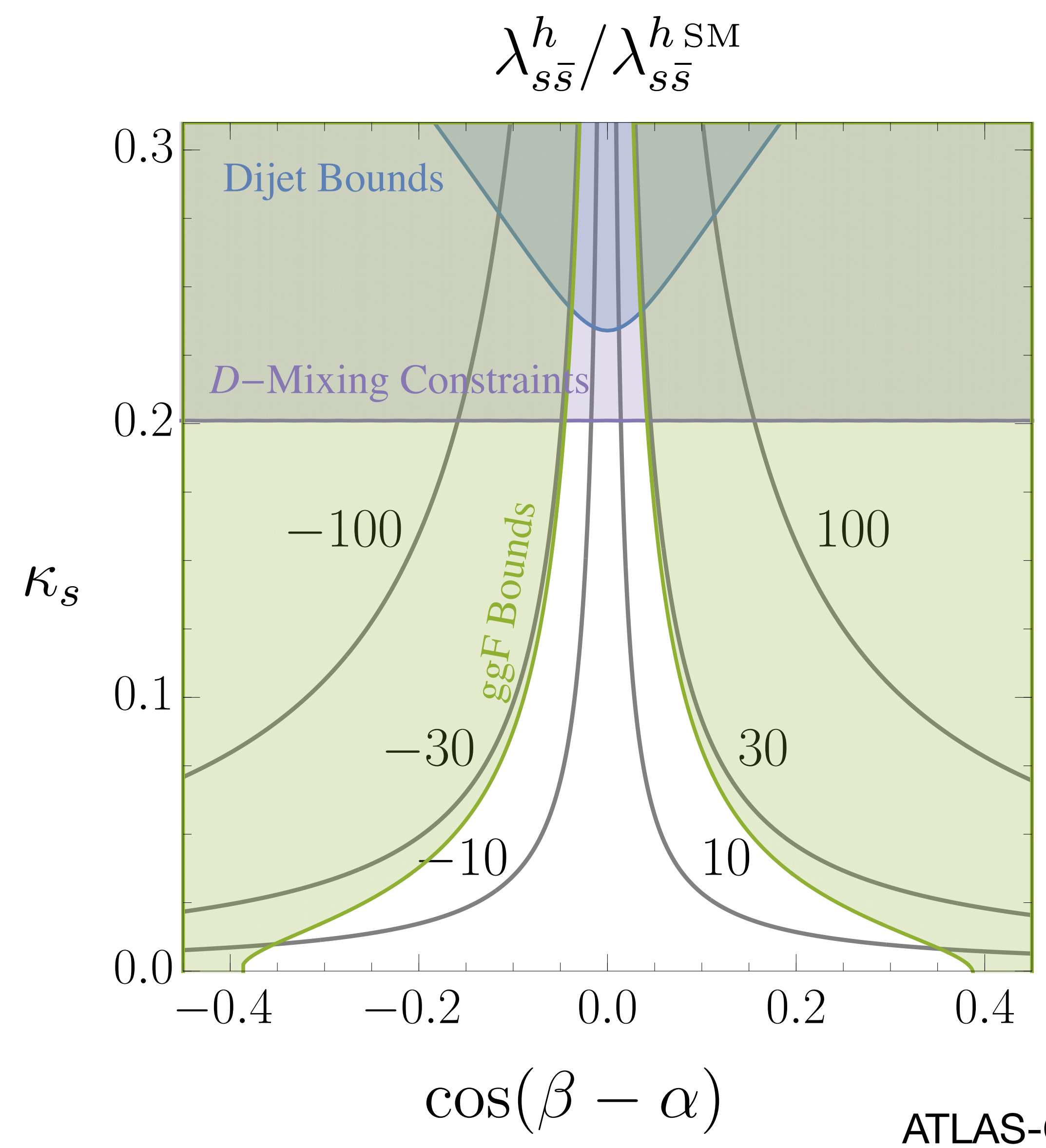


Mixing with light scalars gives a *natural* UV completion for flavor-specific mediators!

(e.g., 1712.10022, 1812.05103, 1911.10203, 2105.07077)

Enhancement of SM Higgs Yukawas





See also.
ILC TDR 1306.6352
Kagan et. Al 1406.1722
Perez et. Al 1505.06689
Zhou 1505.06369
Brivio et. Al 1507.02916
Bishara et.Al 1606.09253
Soreq et.al 1606.09621
Duarte et.Al. 1811.09636
Coyle et.Al 1905.09360

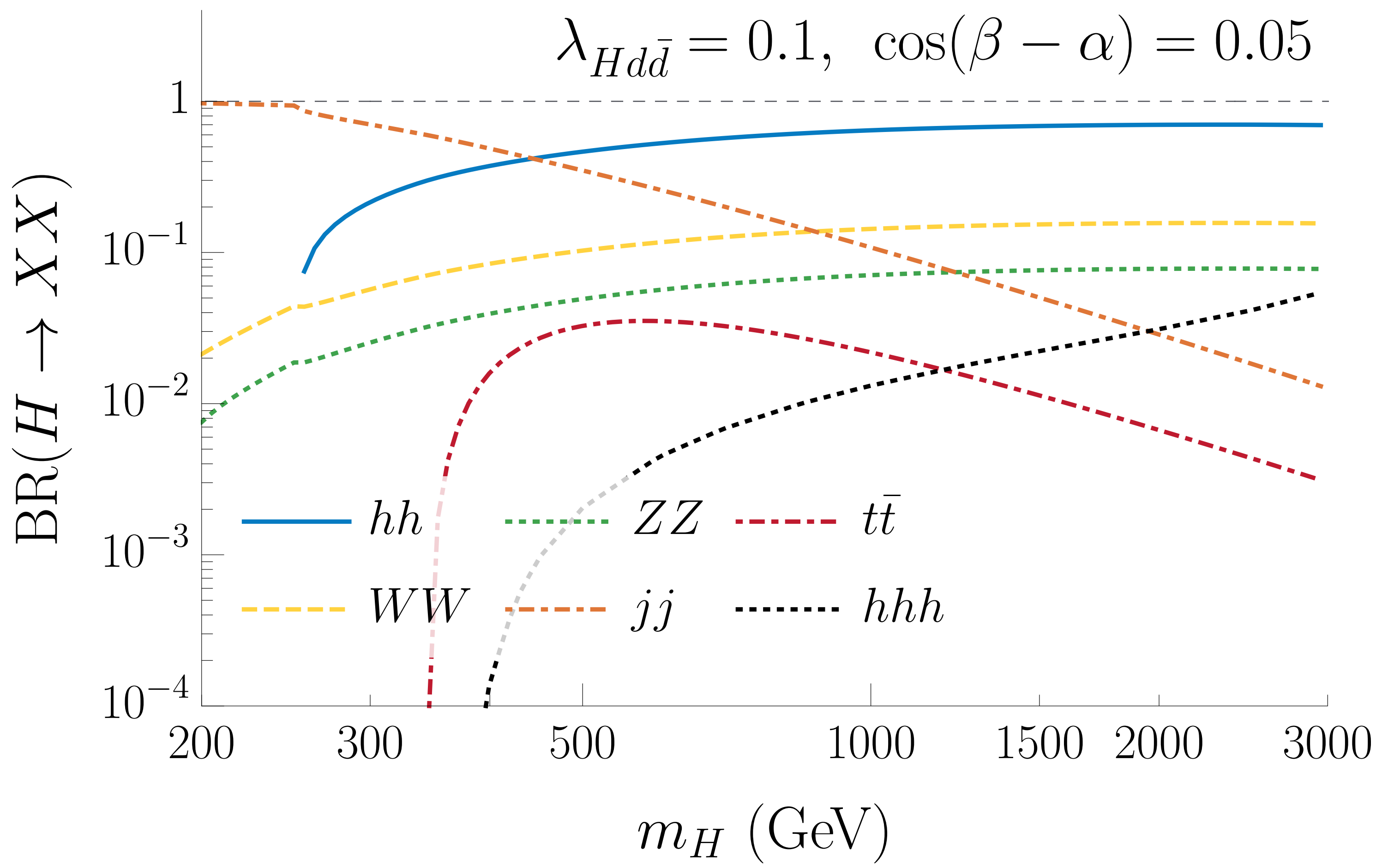
LHC fits from
ATLAS-CONF-2019-005, 80 fb^-1.
* also see 1905.09360.

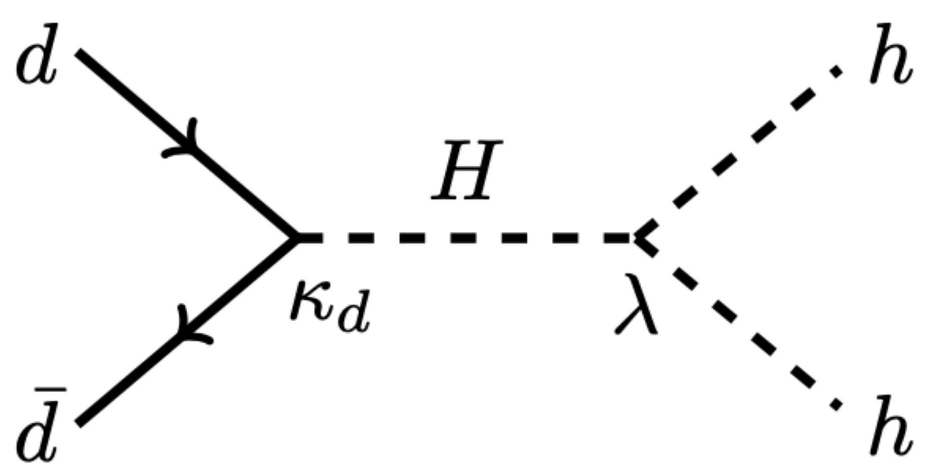
It is important to study the viability of enhanced Higgs Yukawas within full UV completions!

Tree-Level Di-Higgs Production

Resonant di-Higgs production from decays of new neutral Higgs

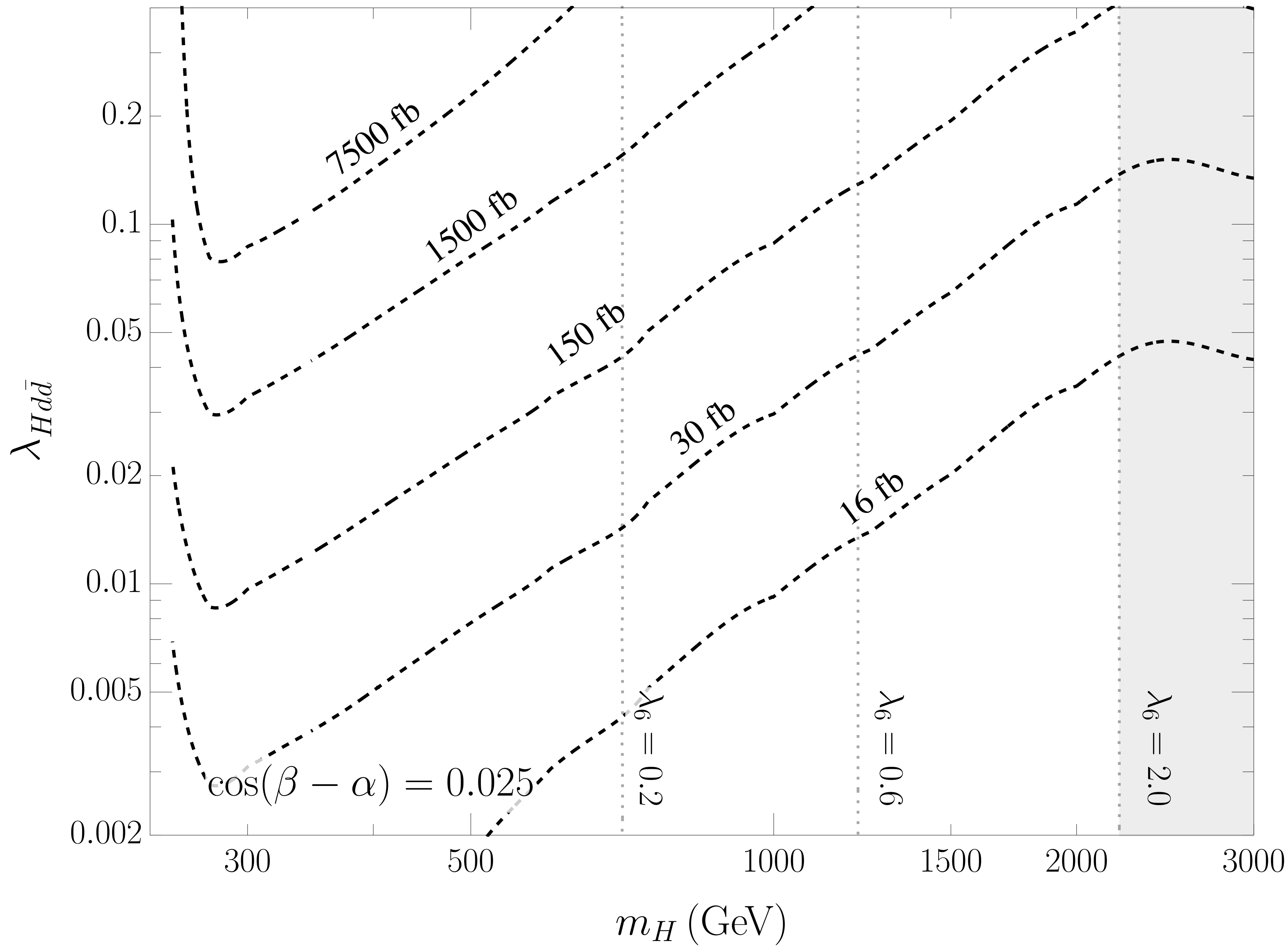
$$\lambda_6 H_2^\dagger H_1 H_1^\dagger H_1 \to \lambda_6 v(H h^2)$$





Scalar couplings typically dominate — natural to have large BRs to lighter Higgs

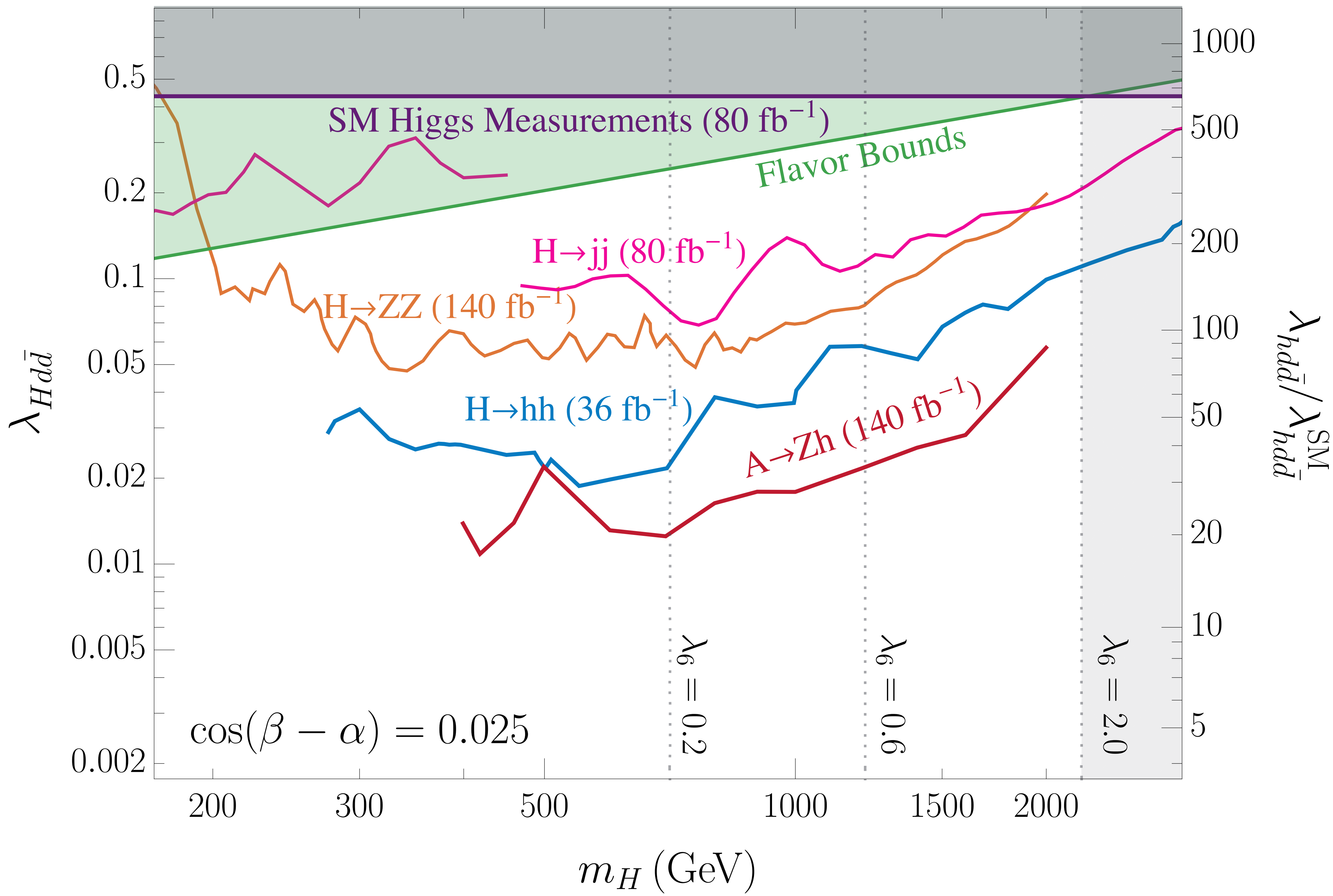
Tree-Level Di-Higgs Production



$$\sigma_{hh}^{\mathrm{SM}} = 31 \text{ fb}$$

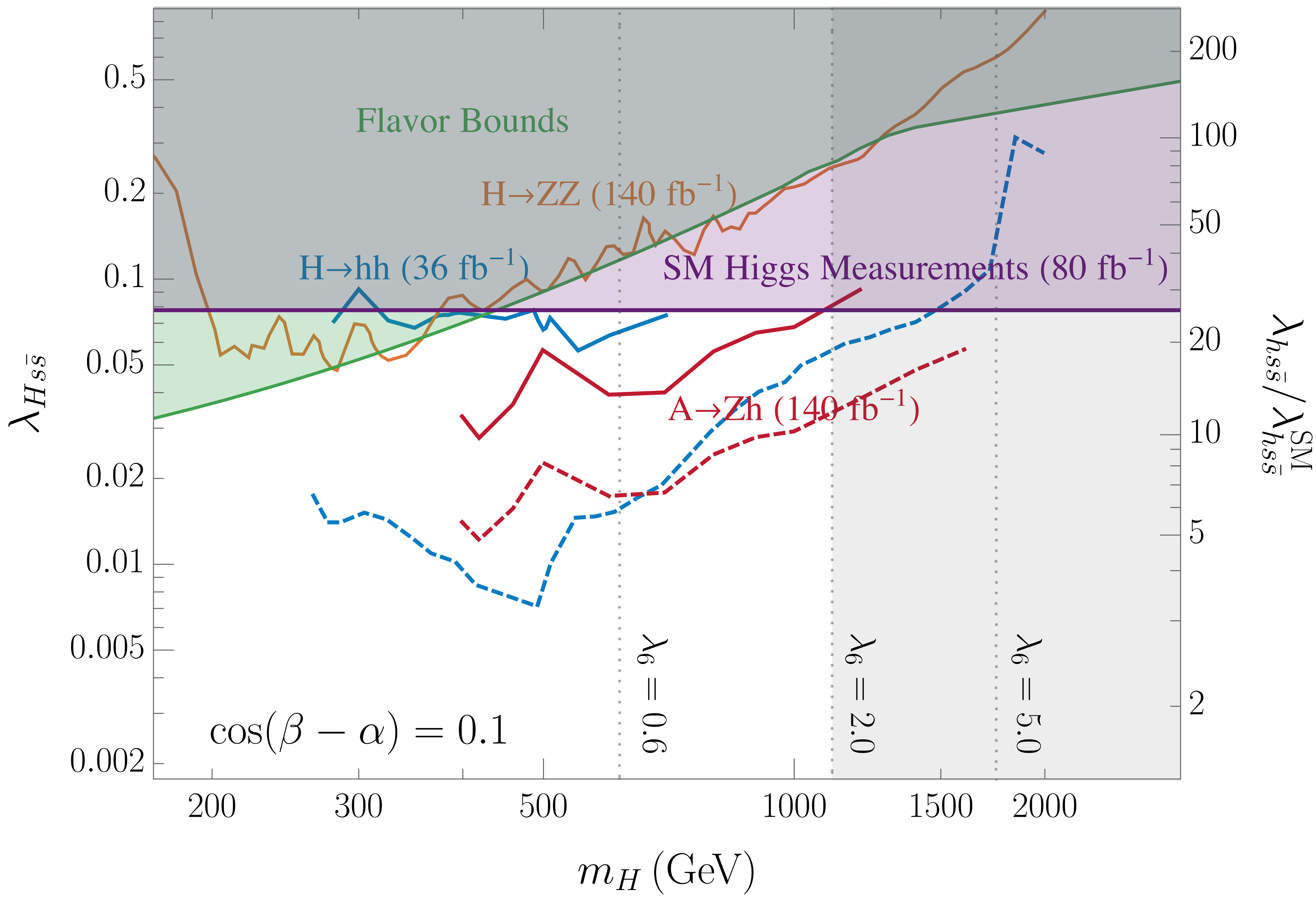
Down Quark Couplings Bounds

Di-Higgs Production is a Stringent Test of the 125 GeV Higgs Couplings!



Strange Quark Coupling Bounds

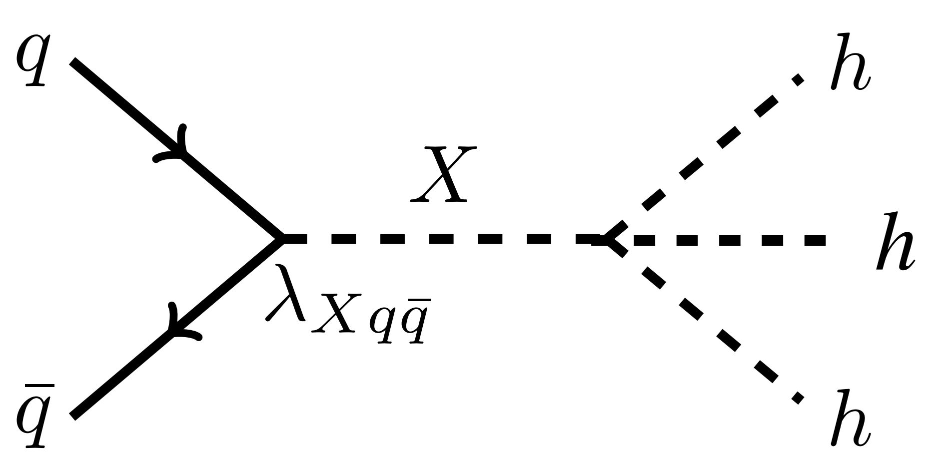
hh starting to bound strange Yukawa — will improve at HL-LHC

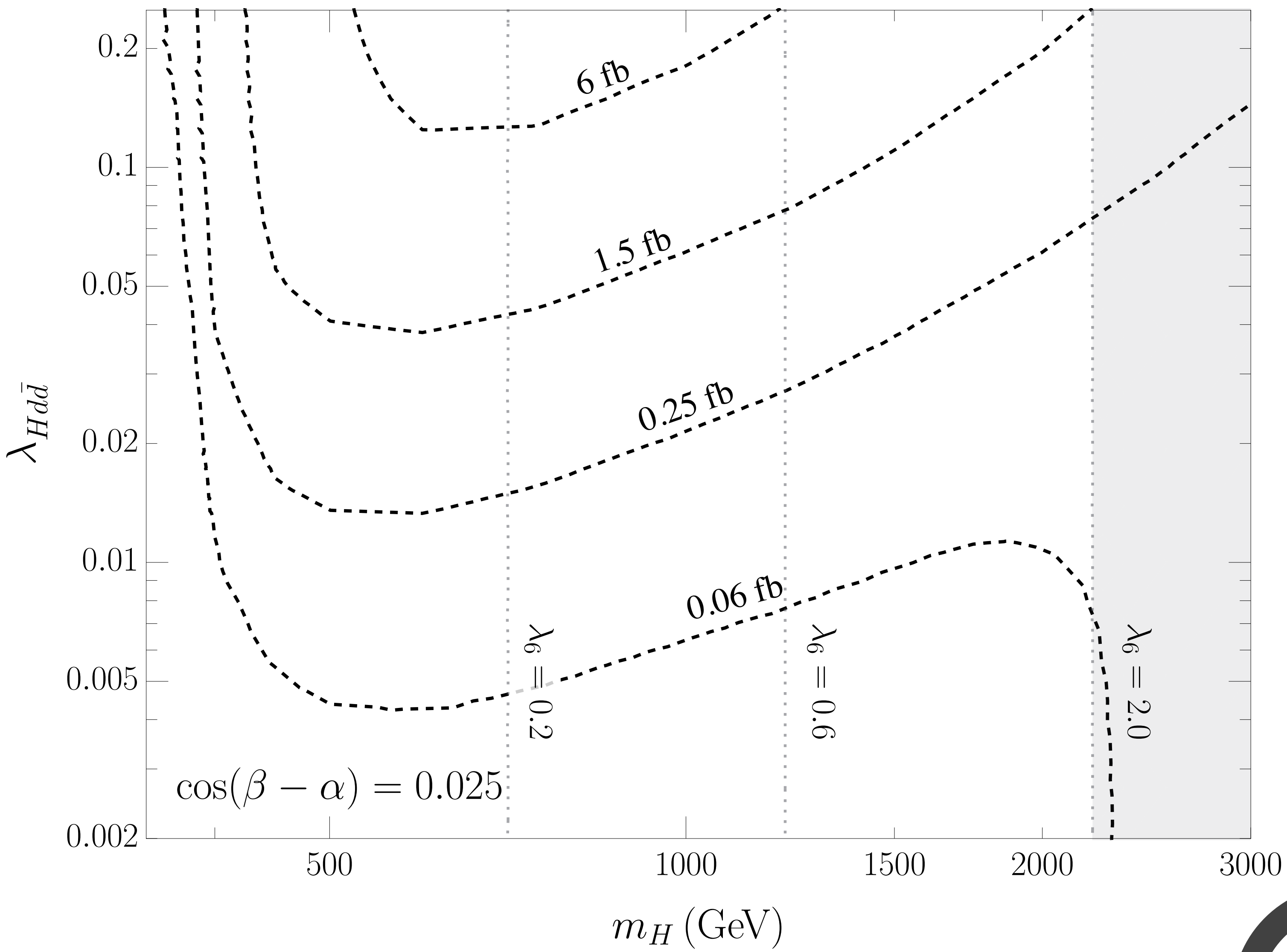


Triple-Higgs Production?

Tri-Higgs production at the LHC, even in BSM theories, has not been explored (thought to be out of reach?)

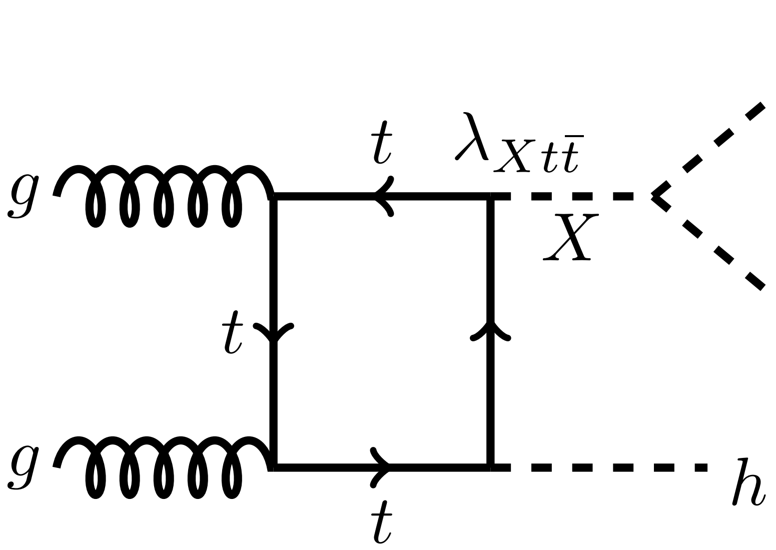
But if production of additional scalars is large, rates are significant!



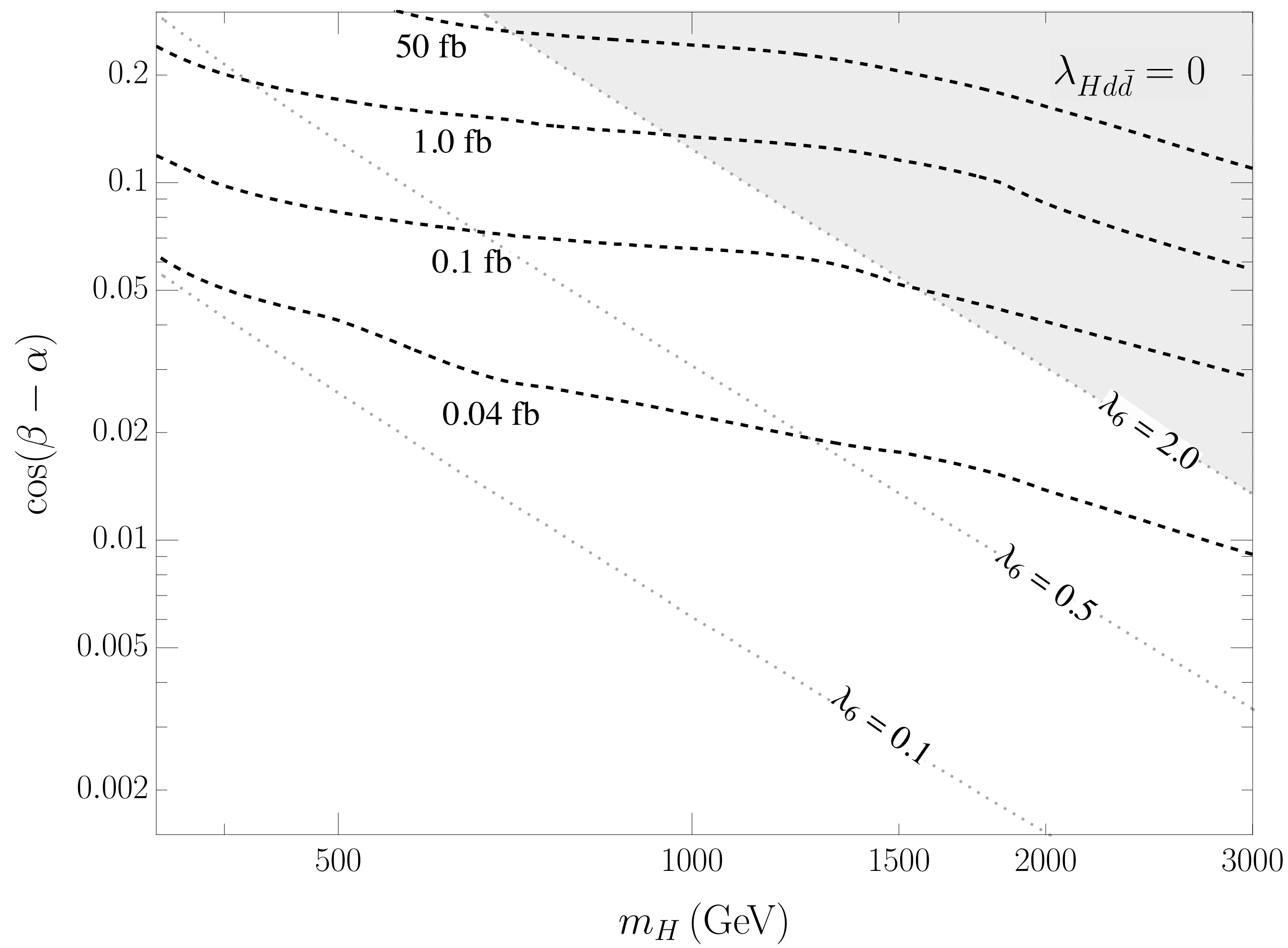


Triple-Higgs Production?

Large rates can be achieved even in models with preferential couplings to the top (e.g., the famous types I-IV 2HDMs)



Here, couplings of X to top only via mixing with the Higgs, and still, large rates!



Could be useful in parts of parameter space due to distinctive final state, semi-resonant topology — need detailed studies

Summary

- Di-Higgs production is a very sensitive probe of enhanced Higgs couplings to light quarks
- Currently, it gives the best bounds on the couplings to the down quark within 2HDMs, over wide regions of parameter space
- Several future directions to pursue:
    - Triple Higgs production
    - Gaps remain with extra Higgs masses below the di-Higgs threshold
    - Other models (vector-like quarks?) Couplings to light leptons?

Thank you!

SFV Bilinears

$$d\,(\,V^T Y_u^2 V^*\,)\,d^\dagger\ ,\ d\,(\,V^T Y_u^2 V^*\,)\,Y^d\,\bar{d}\ ,\ \bar{d}^\dagger\,Y^d(\,V^T Y_u^2 V^*\,)Y^d\,\bar{d}$$

$$u\,(\,V^* Y_d^2 V^T\,)u^\dagger\ ,\ u\,(\,V^* Y_d^2 V^T\,)\,Y_u\bar{u}$$

SFV Can Be Applied to *Any* BSM Model

- The SFV flavor Ansatz can be applied to any of your favorite BSM models, or even to the Standard Model EFT.
- The results is a strong suppression of flavor bounds.
- It can be shown that in the SFV Ansatz, all FCNCs are CKM and Yukawa suppressed.

Example:
A theory with any BSM field and only one new flavor breaking spurion

Operator	SFV factor
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	$C_D^1 = (V^* K_d^2 V^T)_{12}^2$ $C_K^1 = (V^T Y_u^2 V^*)_{12}^2$
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	$\Big[(V^T Y_u^2 V^* K^d)_{12}$ $(V^T Y_u^2 V^* K^d)_{21}^*\Big]$
$Q_2 H^c \sigma^{\mu\nu} \bar{d}_3 F_{\mu\nu}$	$\left[(V^T Y_u^2 V^*) K^d\right]_{23}$

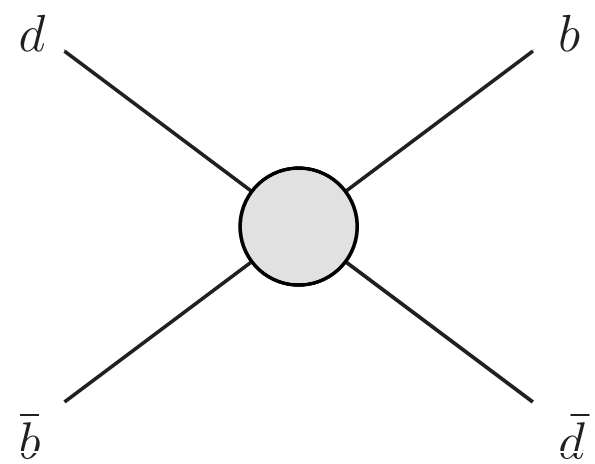
SFV Strongly Suppresses FCNCs

- Even if you allow for *any imaginable FCNC operator*, new physics close to the EW scale may preferentially couple to light quarks without being excluded by flavor bounds

Operator	$\Lambda_{\rm NP}^{\rm anarchic}$ [TeV]	$\Lambda_{\rm NP}^{\rm SFV}$ [TeV]	$\Lambda_{\rm NP}^{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar\sigma^\mu Q_2)^2$	1.5×10^4 (Im)	$262.7\,\lvert\kappa_d^2 - \kappa_s^2\rvert$	5.1
$(Q_1 \bar d_3)(Q_3^\dagger \bar d_1^\dagger)$	2.1×10^3 (Abs)	$19.3\sqrt{\lvert\kappa_d \kappa_b\rvert}$	—
$(Q_1 \bar d_2)(Q_2^\dagger \bar d_1^\dagger)$	2.4×10^5 (Im)	$72.7\sqrt{\lvert\kappa_d \kappa_s\rvert}$	—
$2eH\sigma^{\mu\nu} Q_2\, \bar d_3\, F_{\mu\nu}$	276.3 (Re)	$54.3\sqrt{\lvert\kappa_b\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar d_2\, F_{\mu\nu}$	276.3 (Re)	$54.3\sqrt{\lvert\kappa_s\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar d_1\, F_{\mu\nu}$	140.5 (Abs)	$13.2\sqrt{\lvert\kappa_d\rvert}$	7.0

FCNC Suppression due to Pattern of Flavor Breaking

- Such suppression can be easily seen from symmetries



$$(d_i \; c_{ij} \; d_j^\dagger)^2 \qquad i = 1, j = 3$$

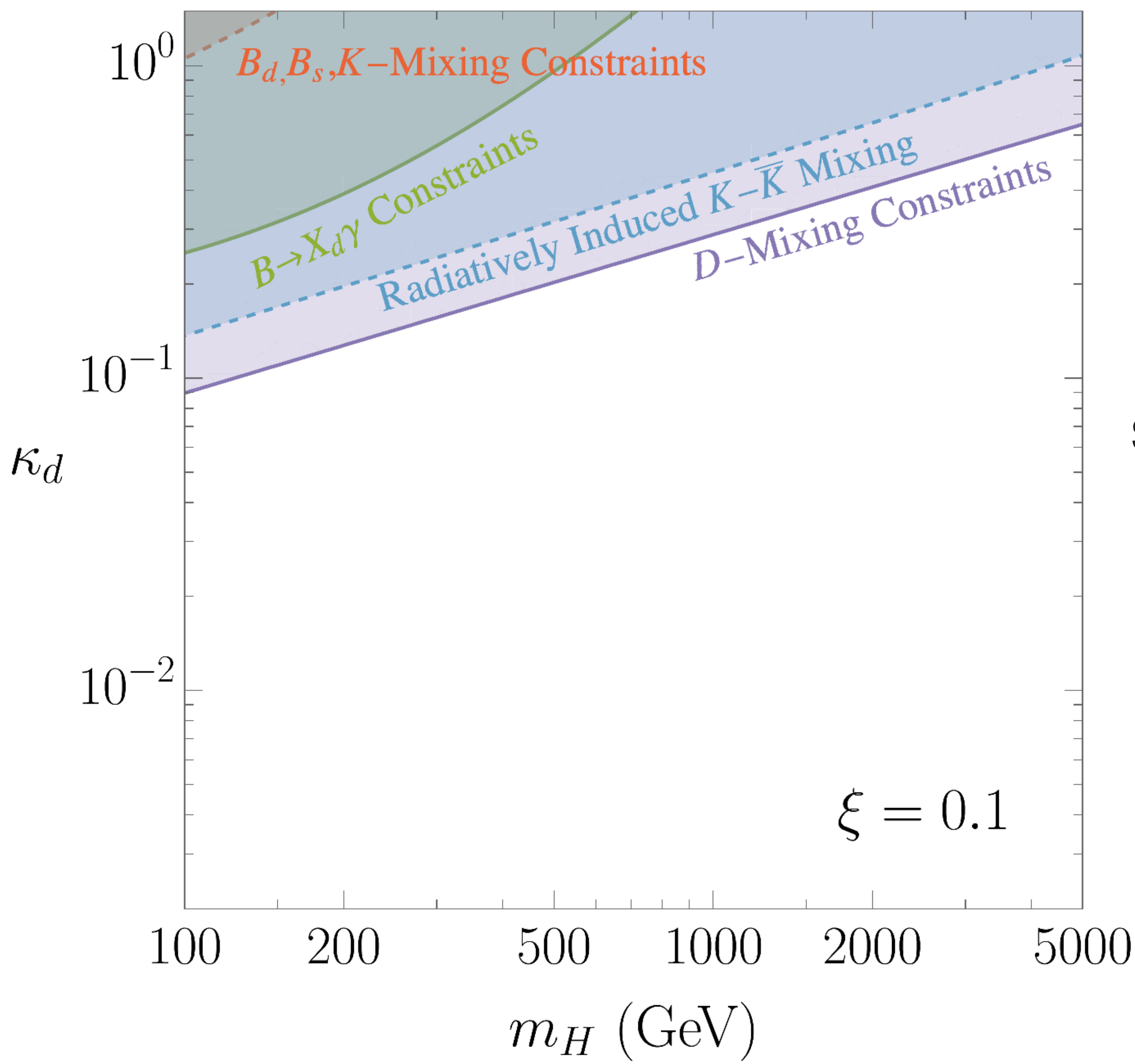
$$\downarrow$$

$$d_i \; (\lambda_u \lambda_u^\dagger)_{ij} \; d_j^\dagger$$

$$\begin{aligned} d_1 \; (\lambda_u \lambda_u^\dagger)_{12} \, d_2^\dagger &= d_1 \, (\, V^T Y_u^2 V^* \,)_{12} \, d_2^\dagger \\ &= d_1 \left(y_t^2 V_{31} V_{32}^* + y_c^2 V_{21} V_{22}^* + \ldots \right) d_2^\dagger \end{aligned}$$

Yukawa, GIM and CKM suppression of FCNCs!

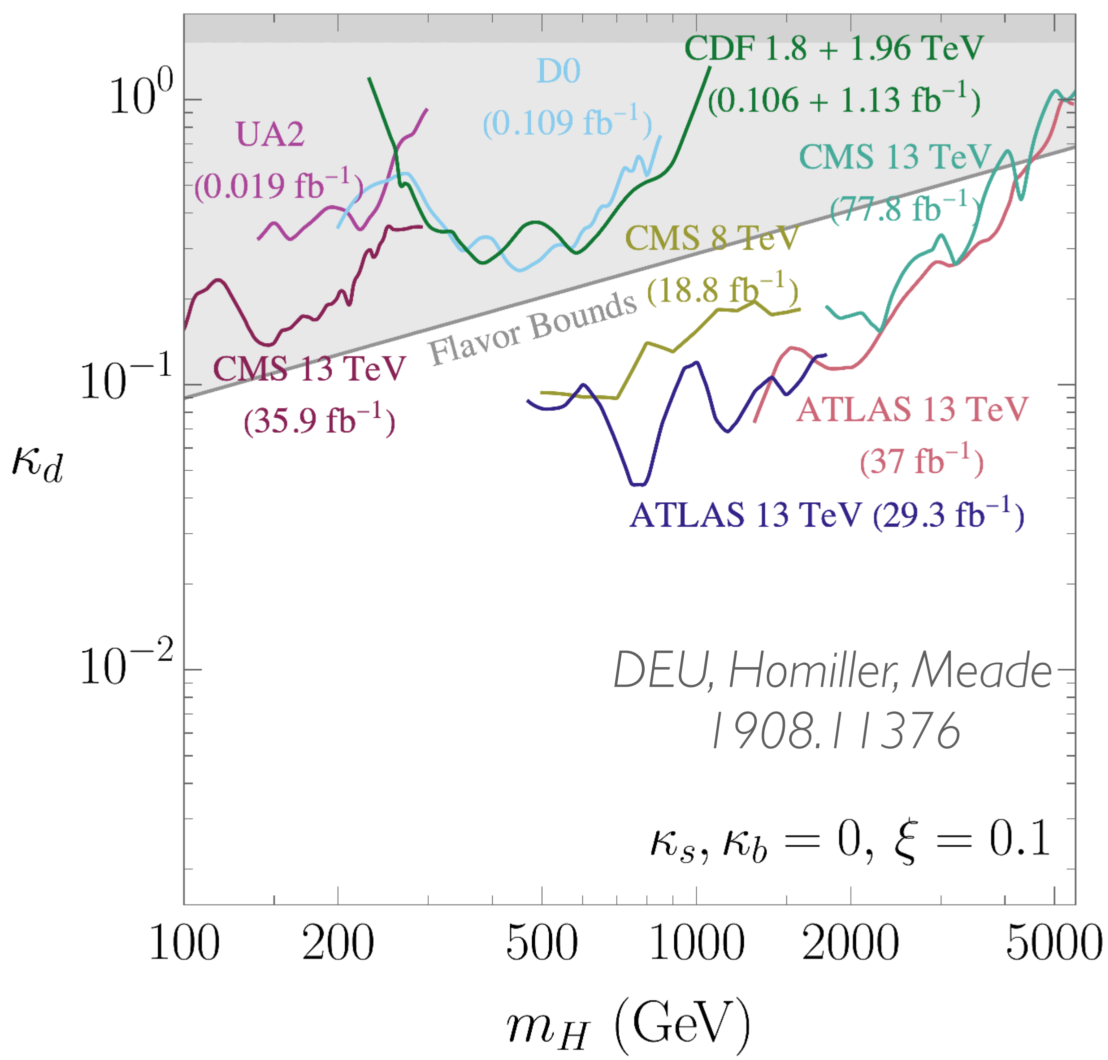
Radiatively Induced FCNCs

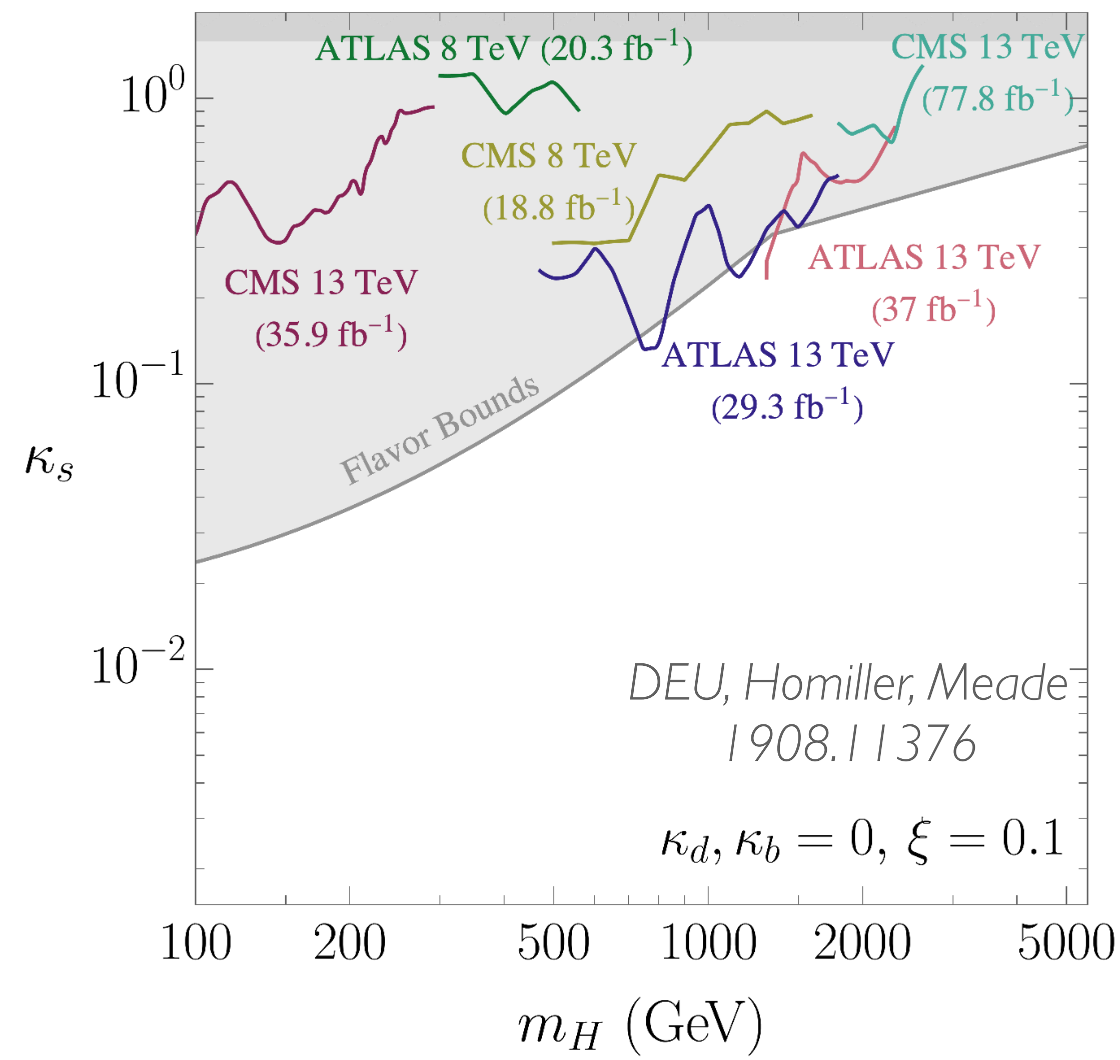


UV SFV scale set at 100 TeV

Limits from Dijet Searches

- SFV Higgses are copiously produced and decay to dijets





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

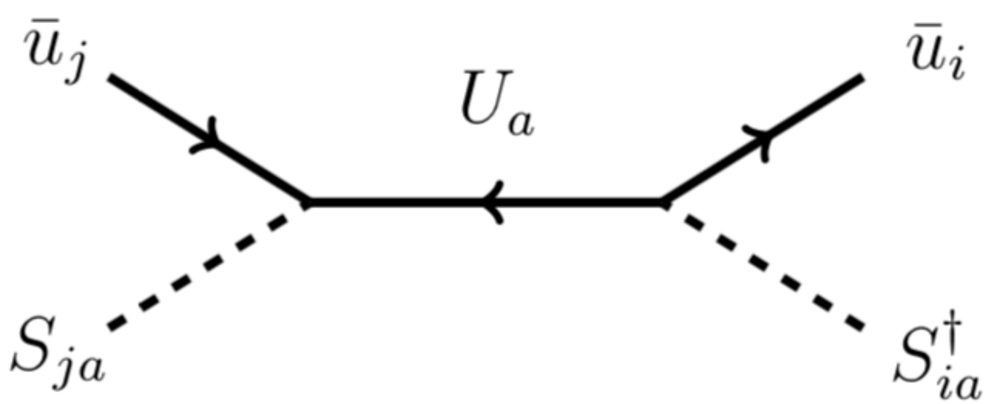
E.g. Fraser, Schwartz, 1803.08066
Duarte el.Al. 1811.09636
Nakai et.Al 2003.09517
(strange tagging)

UV Completion for Flavor Alignment

Assume we start with a completely flavor symmetric SM:

Flavor-preserving SM + BSM+

$$M_{AB} U_A \bar{U}_B + \zeta S_{iA} U_A \bar{u}_i \qquad M_{AB} > 100\,\mathrm{TeV}$$



$$\sim Z^u_{ij} \bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j$$

In the context of extra dimensions, see Csaki et.al. 0709.1714

This is nothing more than a Nelson-Barr model.
In fact the strong CP problem is automatically solved in all SFV realizations!

UV Completion for Flavor 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

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

Couplings to the other sector remain ***aligned***

$$\bar{u} \rightarrow \sqrt{Z^u}^{-1} \bar{u} \implies$$ Recover the CKM matrix

CKM via Wave-Function Renormalization

$$\bar{u}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{u}_i$$

$$+\left[Y_{ij}^u Q_i H \bar{u}_j - Y_{ij}^d Q_i H \bar{d}_j - \alpha Y_{ij}^u Q_i H_2 \bar{u}_j - \kappa_{ij}^d Q_i H_2 \bar{d}_j\right]$$

• •

$$\tilde{Y}^u \to \tilde{Y}^u \sqrt{Z}^{-1} = \lambda^u = V_{\text{CKM}}^T Y^u$$

Y^d , κ^d Remain real-diagonal and aligned

In the context of extra dimensions, see Csaki et.al. 0709.1714

The Catch: Alignment in *One* Sector

- Assume we also introduce a generic Yukawa for the up-sector

$$Z^u_{ij}\bar{u}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{u}_j$$

$$+\left[\tilde{Y}^u_{ij}Q_iH\bar{u}_j - Y^d_{ij}Q_iH\bar{d}_j + \kappa^u_{ij}Q_iH_2\bar{u}_j - \kappa^d_{ij}Q_iH_2\bar{d}_j\right]$$

Real-diagonal

- After WF renormalization, large misalignment is introduced

$$\tilde{Y}^u \to \tilde{Y}^u\sqrt{Z}^{-1} = \lambda^u = V^T_{\text{CKM}}Y^u$$

$$\kappa^u \to \kappa^u\sqrt{Z}^{-1}$$

Not simultaneously diagonalizable, unless $\kappa^u \propto \tilde{Y}^u$

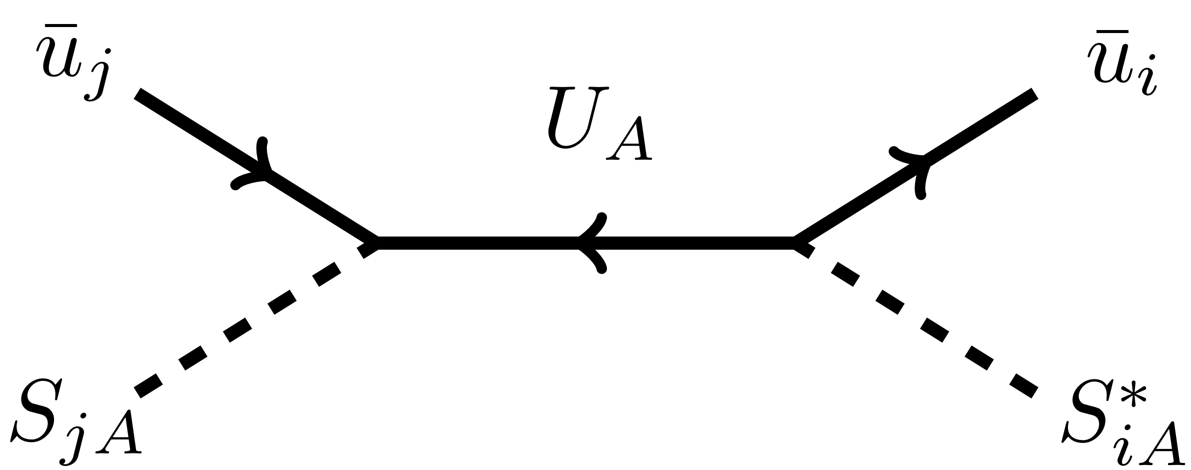
More Details on the UV Completion

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

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



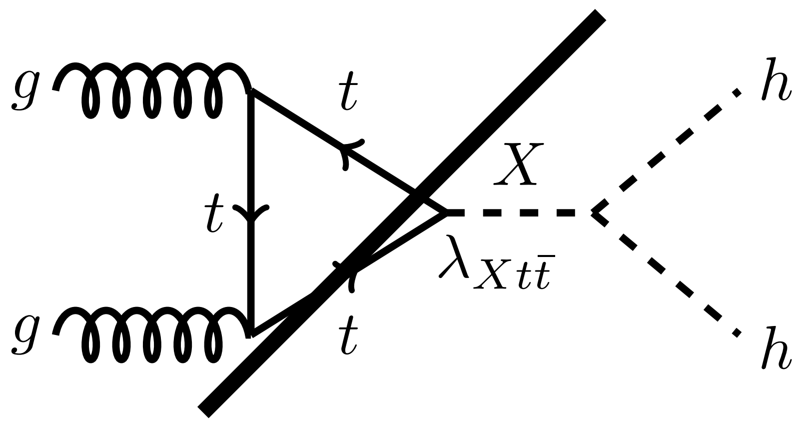
Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

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

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

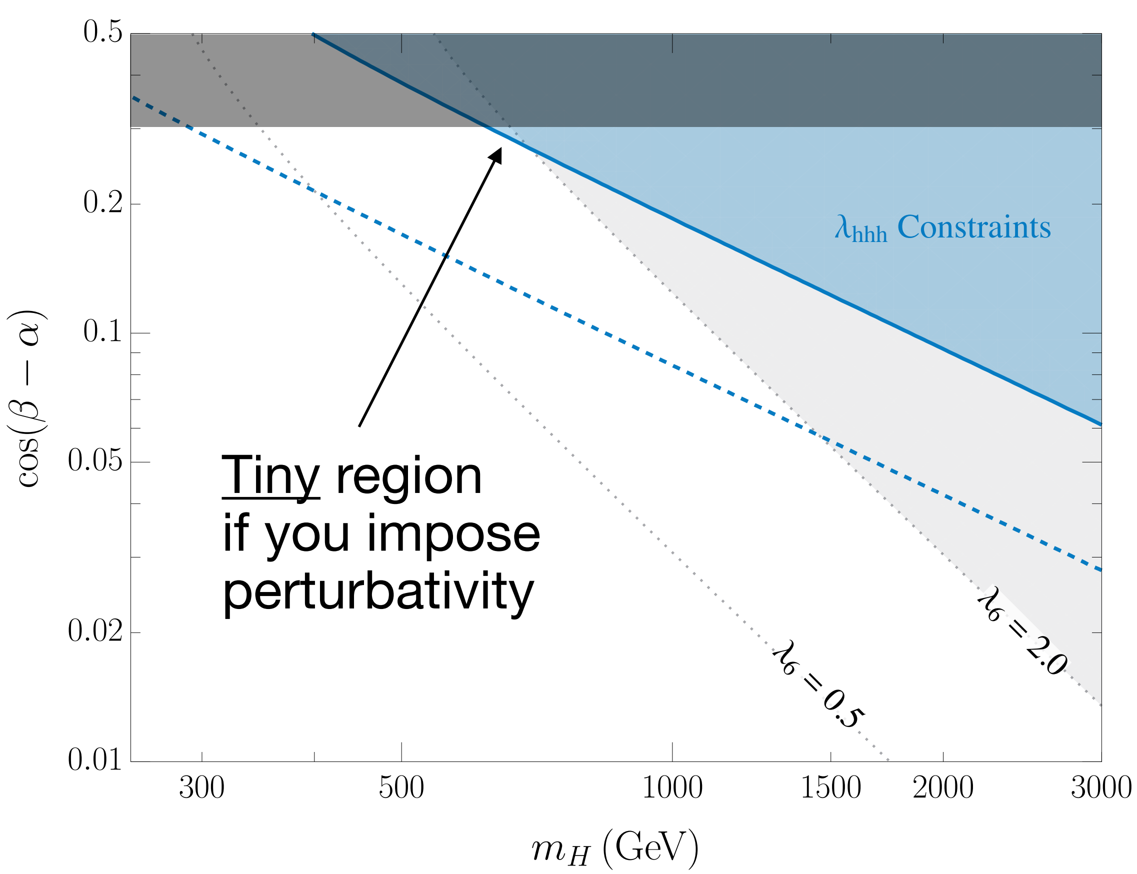
Is Non-Resonant Di-Higgs Ever Important?

Yes, but <u>barely</u>, and only in *production blind-spots.*



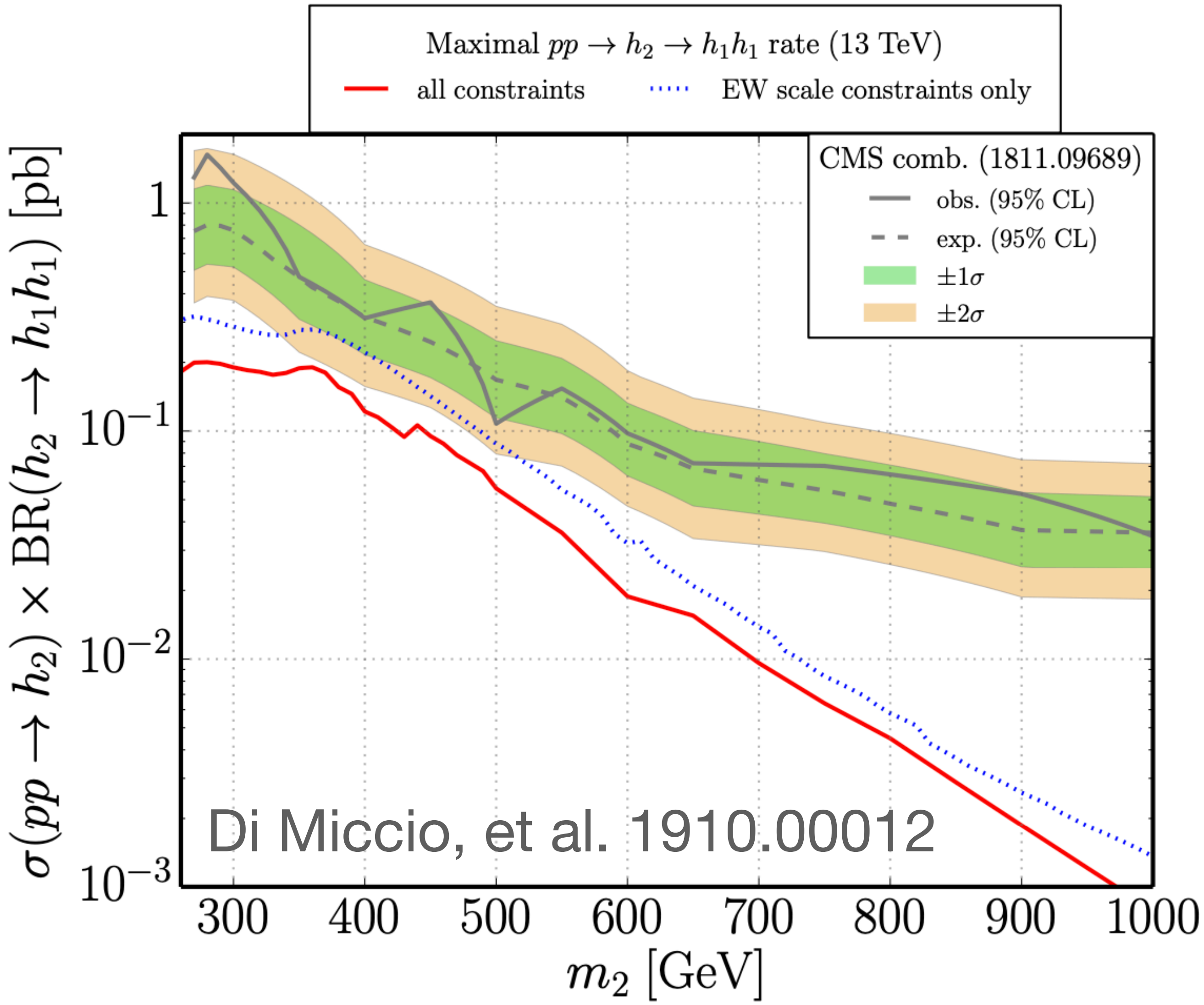
Tune resonant production to zero.

Then only effect left is modification of Higgs cubic



Di-Higgs Has Limited Reach for Top-Coupled Models

e.g., Singlet-extended SM



Di-Higgs cannot yet test even the simplest models with couplings to the top, but there is reach to other top-coupled models

Figure 3.1: Maximal allowed $pp \to h_2 \to h_1 h_1$ signal rate at the 13 TeV LHC in the softly-broken Z_2-symmetric case. Shown are values after applying (red solid) all constraints and (blue dotted) only constraints at the EW scale. The corresponding $\mathrm{BR}_{\max}^{h_2 \to h_1 h_1}$ values are given in Table 3.1. For comparison we include the current strongest cross section limit (at 95% CL), obtained from the combination of various CMS $h_2 \to h_1 h_1$ searches at 13 TeV with up to 36 fb^{-1} of data [63].