Higgs Flavor and Multi-Higgs Production

1811.00017 (PRL 123.031802)
1908.11376 (PRD 100.115041)
2101.04119 (PRD 103.115005)

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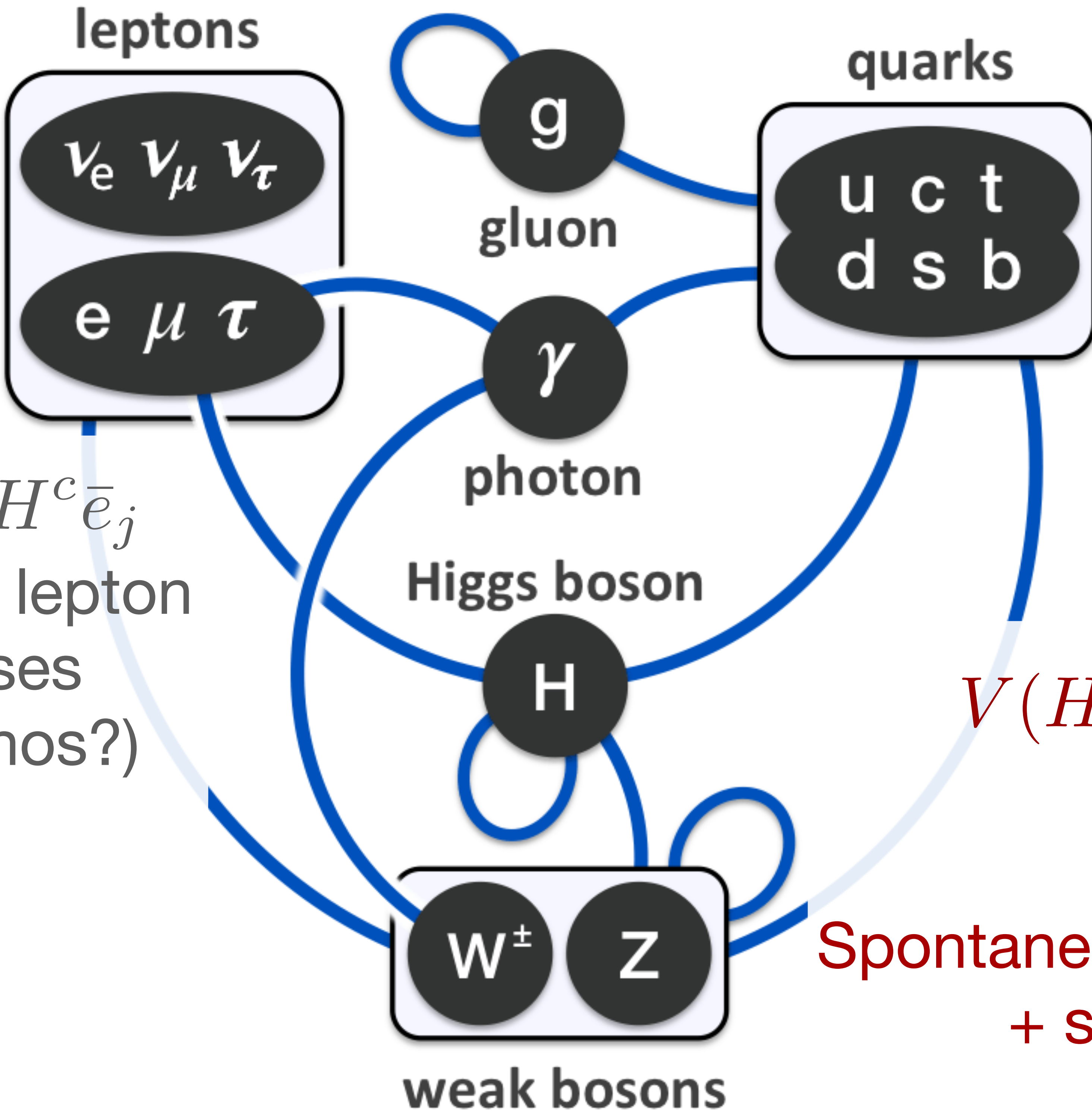
In collaboration with Daniel Egaña-Ugrinovic (Perimeter) and Patrick Meade (Stony Brook)

Oklahoma State University, September 9, 2021

The Higgs is Central to the Standard Model



$$-\lambda^u_{ij} Q_i H \bar{u}_j$$
$$+\lambda^{d\dagger}_{ij} Q_i H^c \bar{d}_j$$

Quark masses
+ *flavor*

$$+\lambda^{\ell\dagger}_{ij} L_i H^c \bar{e}_j$$

Charged lepton masses
(neutrinos?)

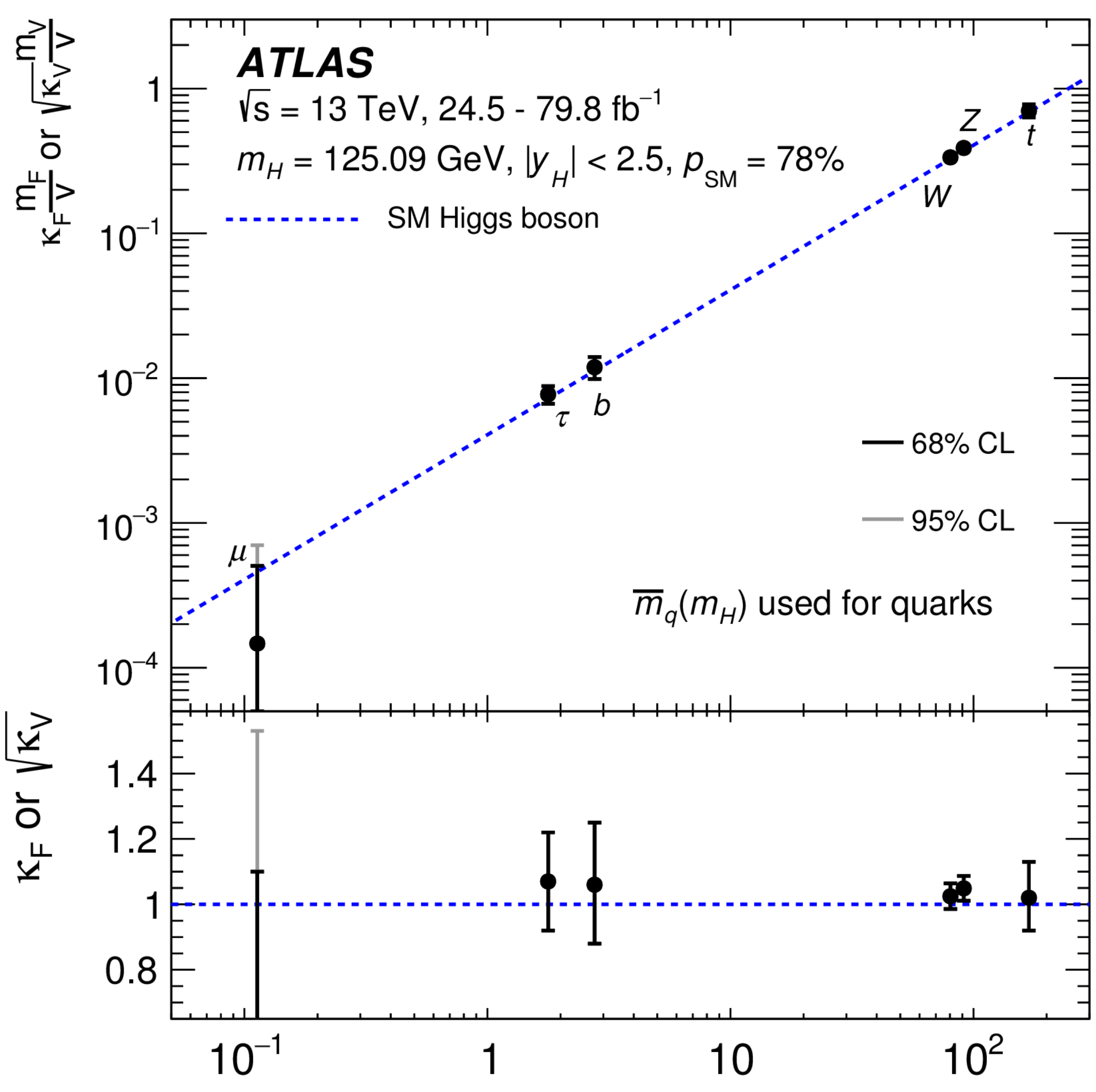
$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Spontaneous Breaking of *SU(2)*
+ self-interactions

The Higgs at the LHC

As of ~2020

arXiv:1909.02845



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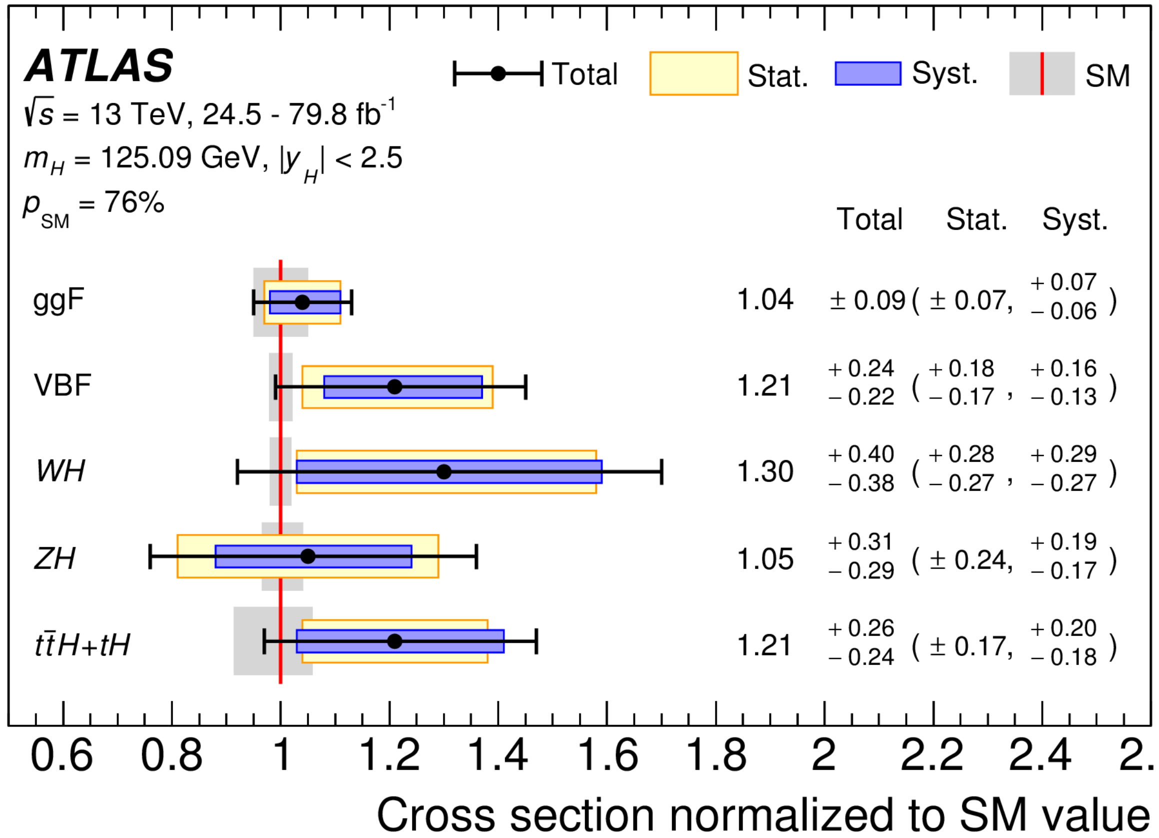
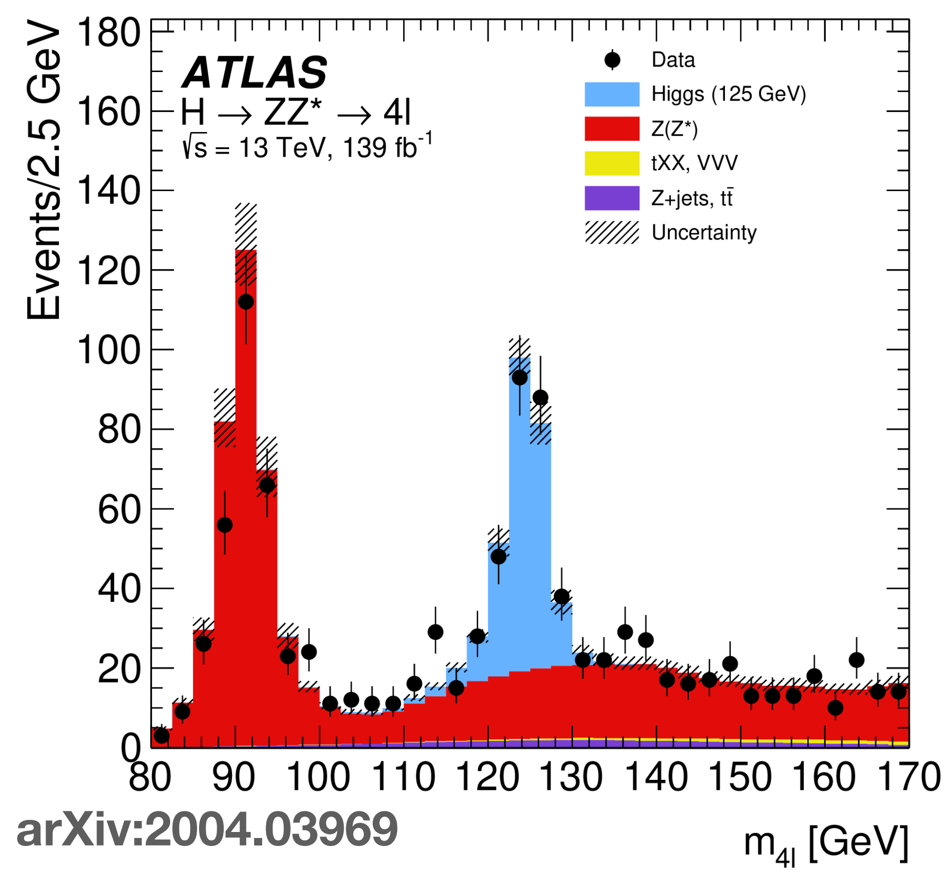


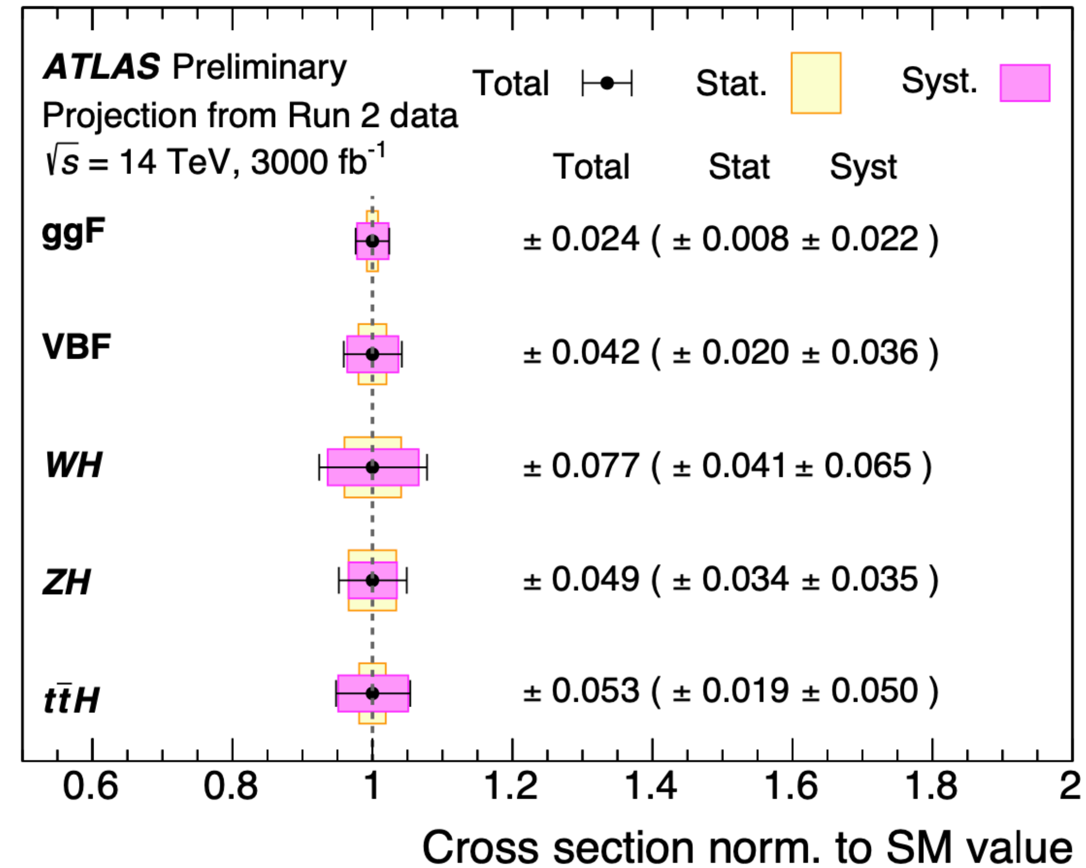


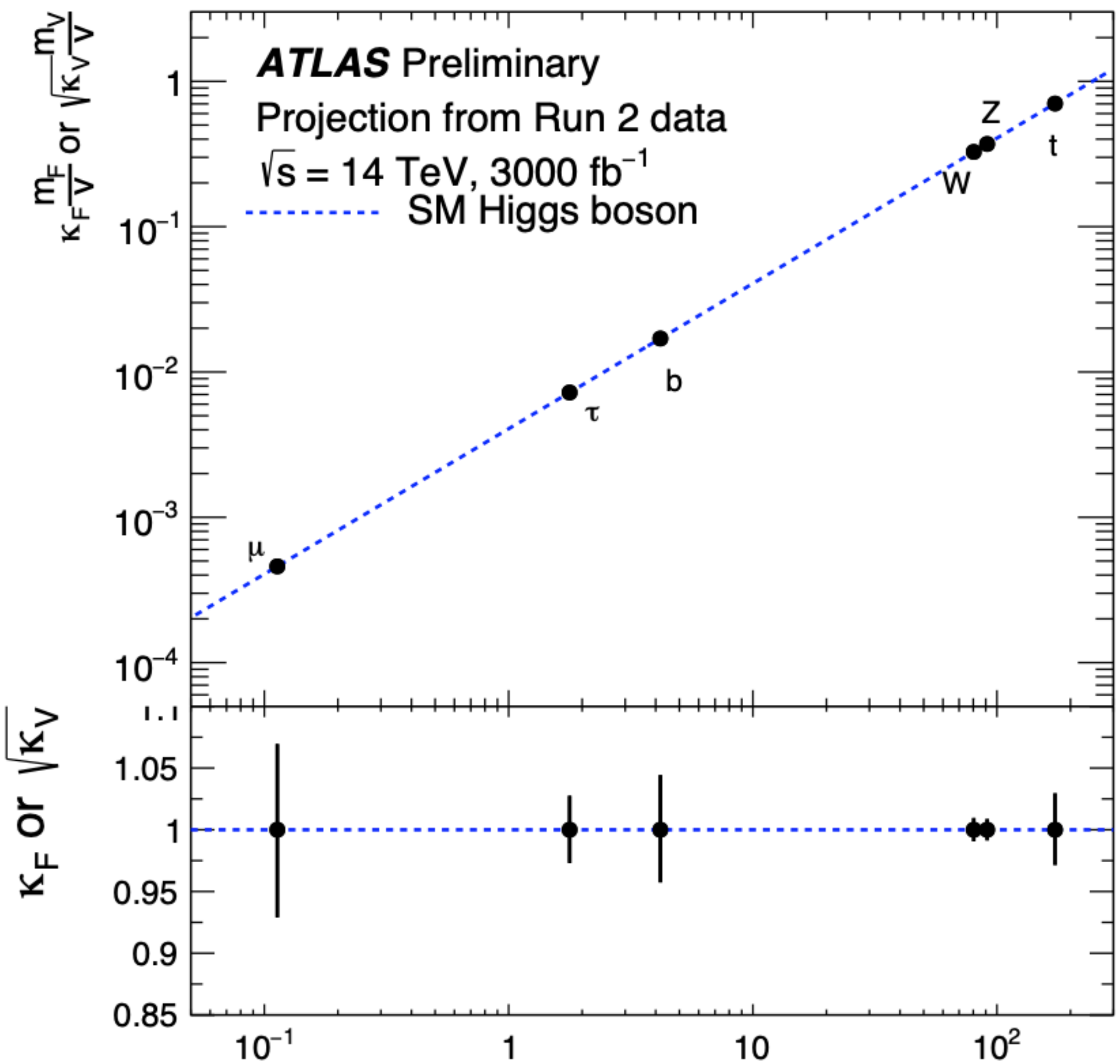
arXiv:2004.03969

The Higgs at the LHC

As of ~2040

ATL-PHYS-PUB-2018-054





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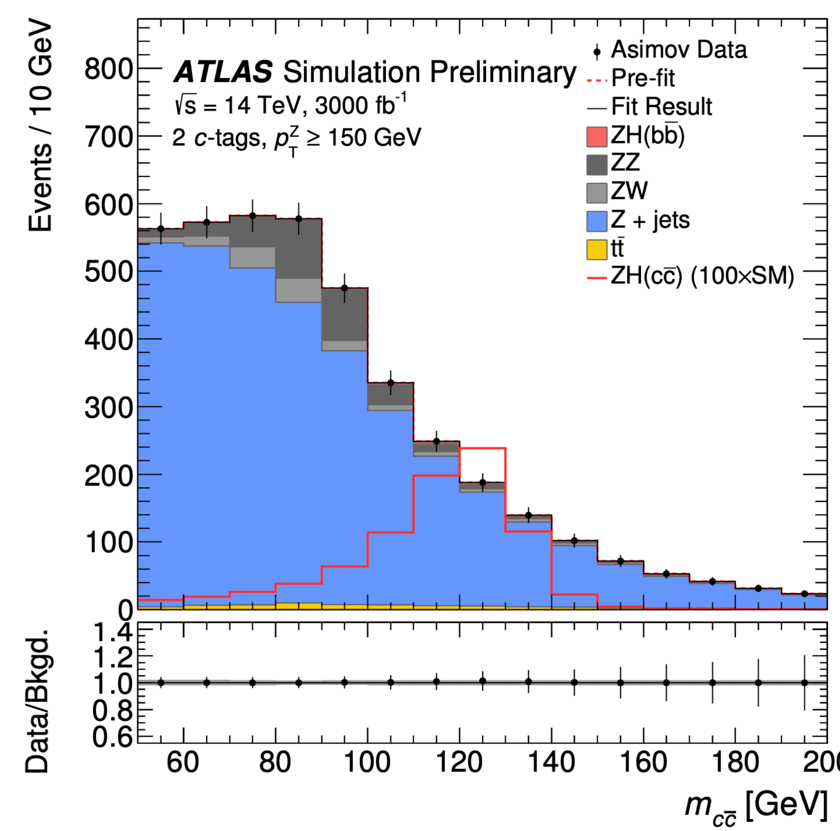

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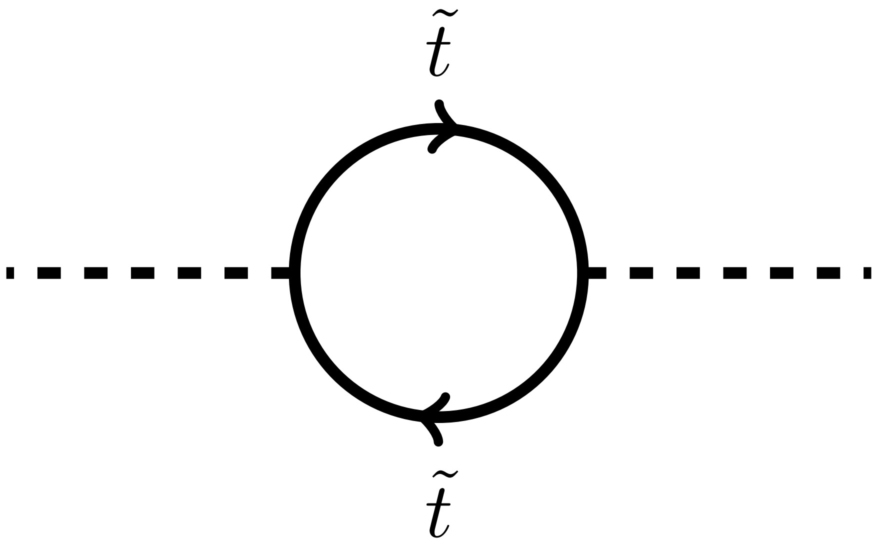
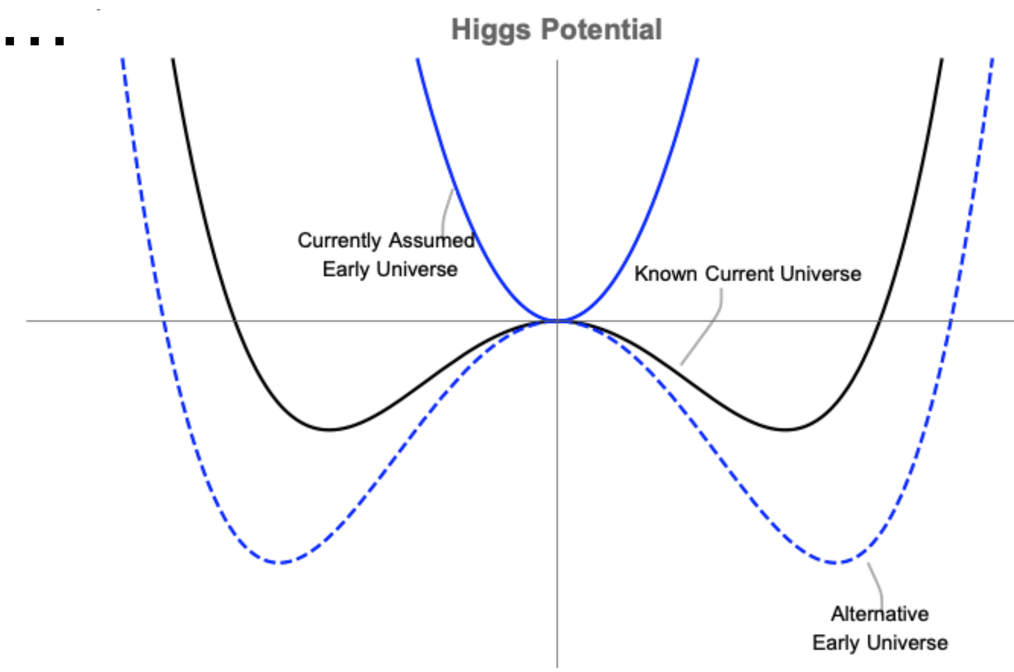
The Higgs is Likely Connected to New Physics

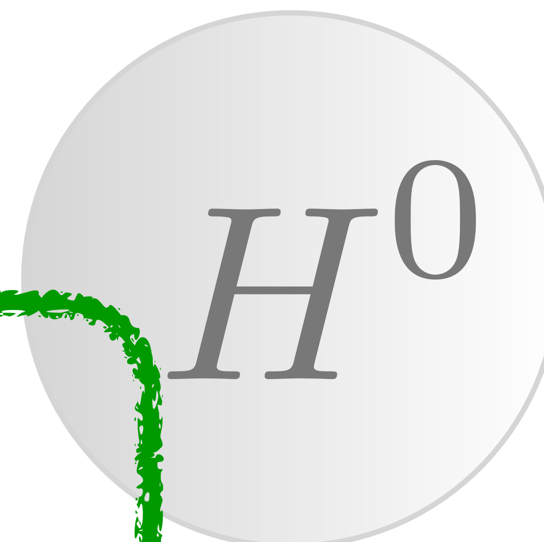


Quadratic Sensitivity to New mass scales

Potential is window into early Universe…



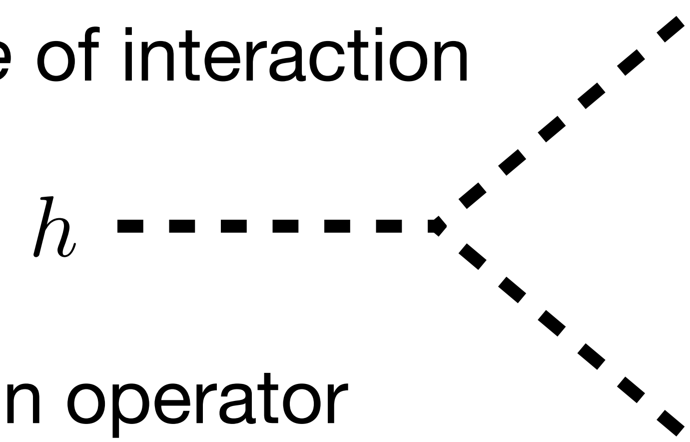
…and stability of our vacuum



$$\mathcal{L} \supset -\lambda^u_{ij} Q_i H \bar{u}_j + \lambda^{d\dagger}_{ij} Q_i H^c \bar{d}_j$$

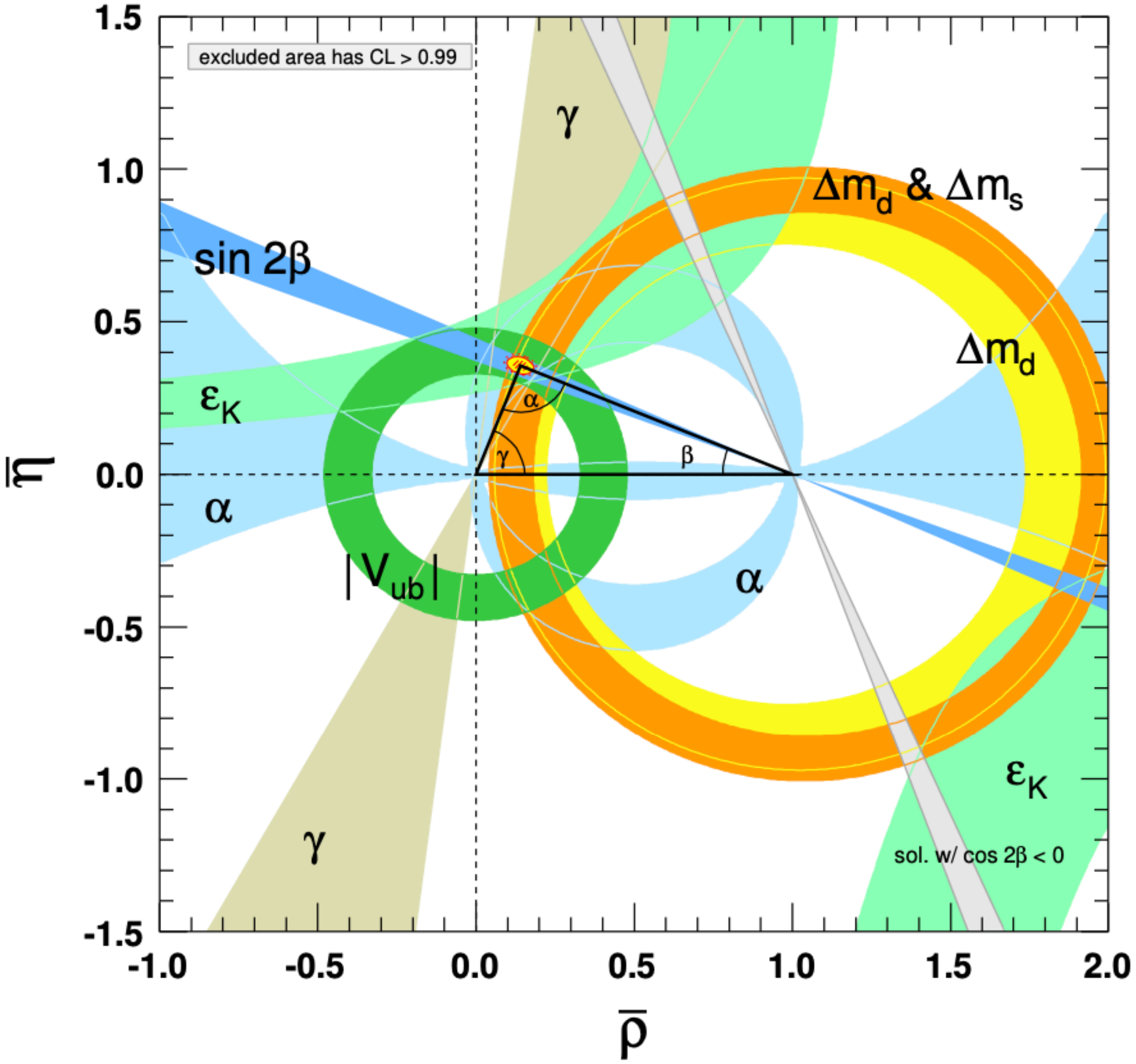
Source of all *flavor* in the SM

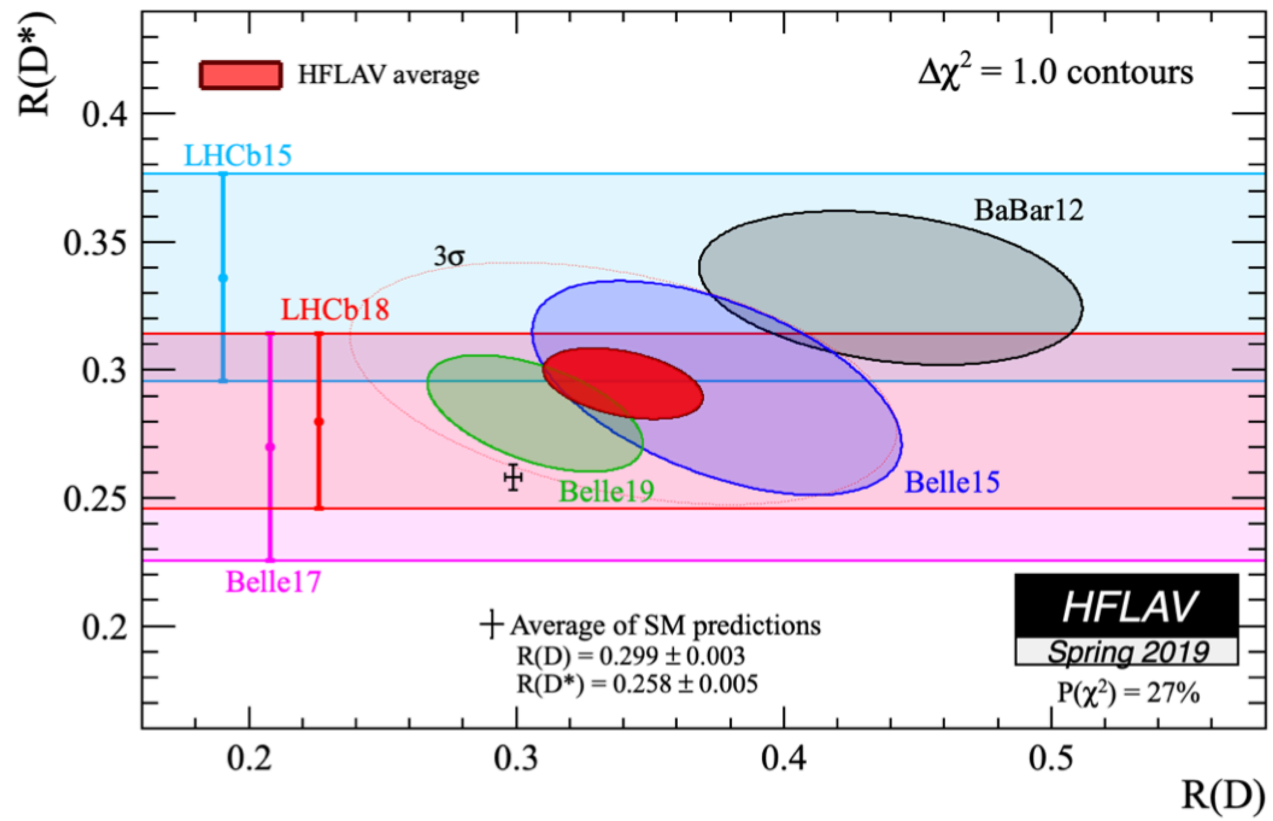
New *type* of interaction

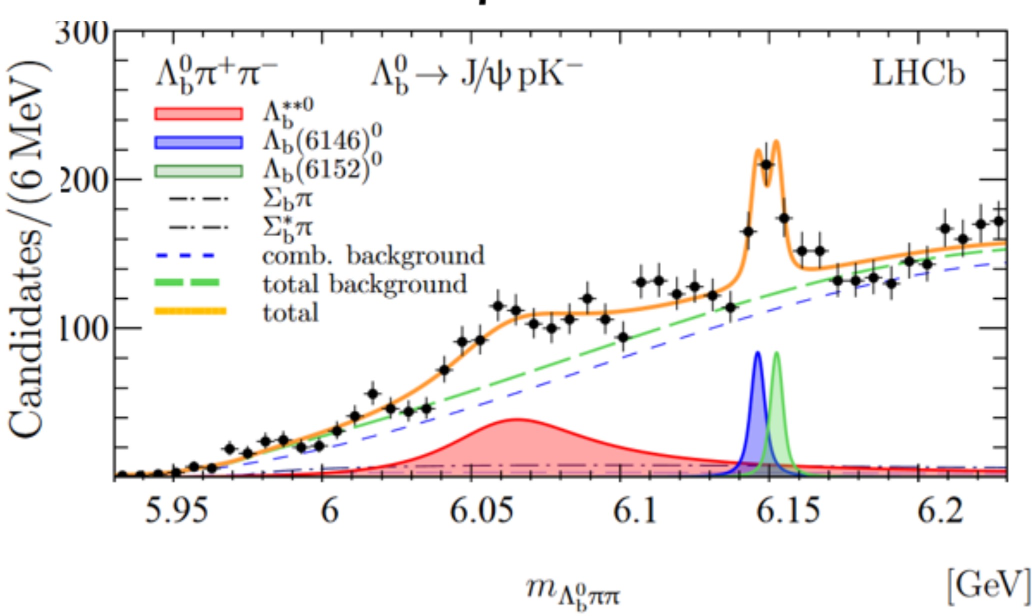


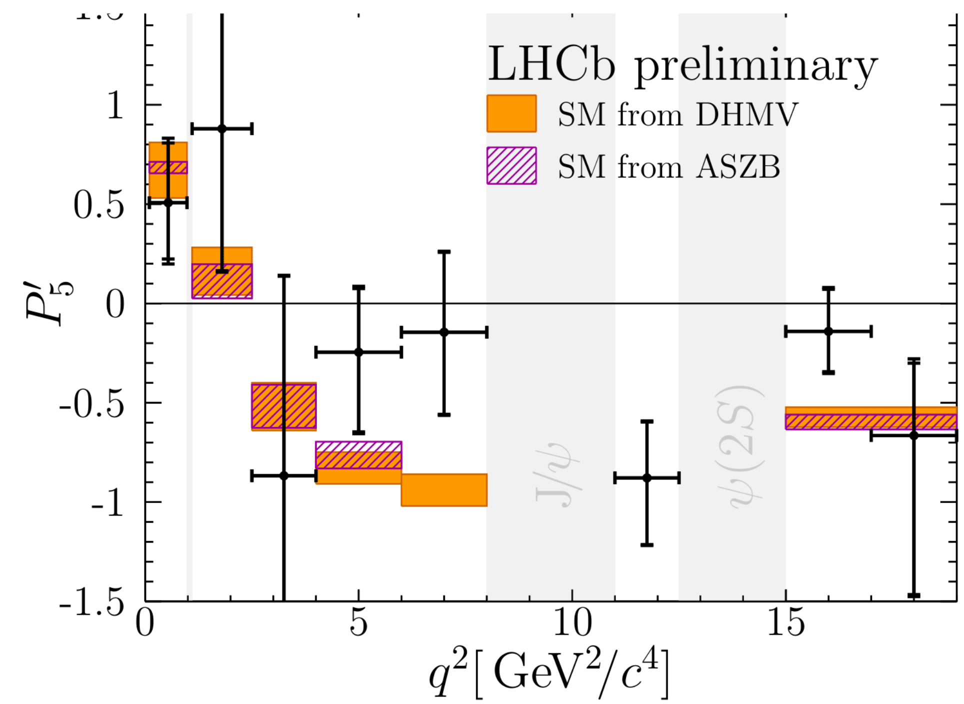
Lowest dimension operator — Higgs portal couplings

When we usually think about flavor…



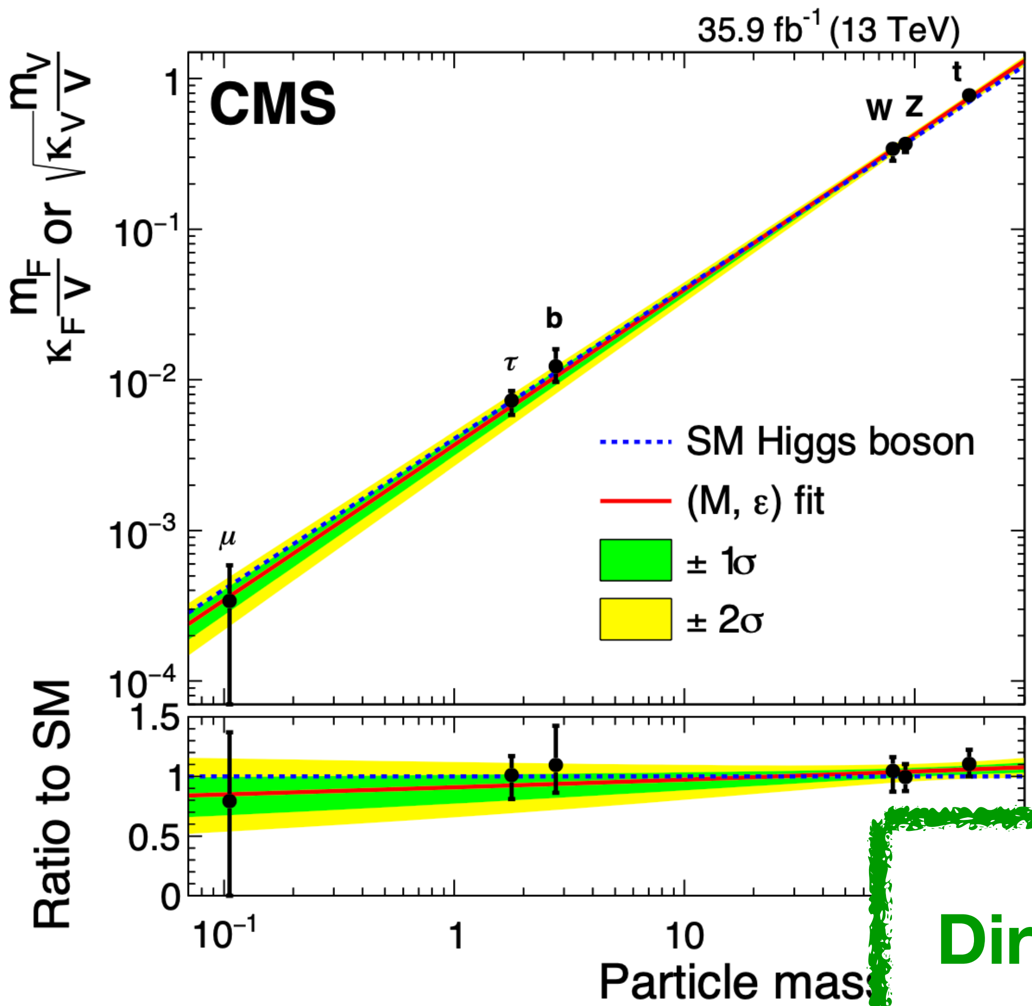


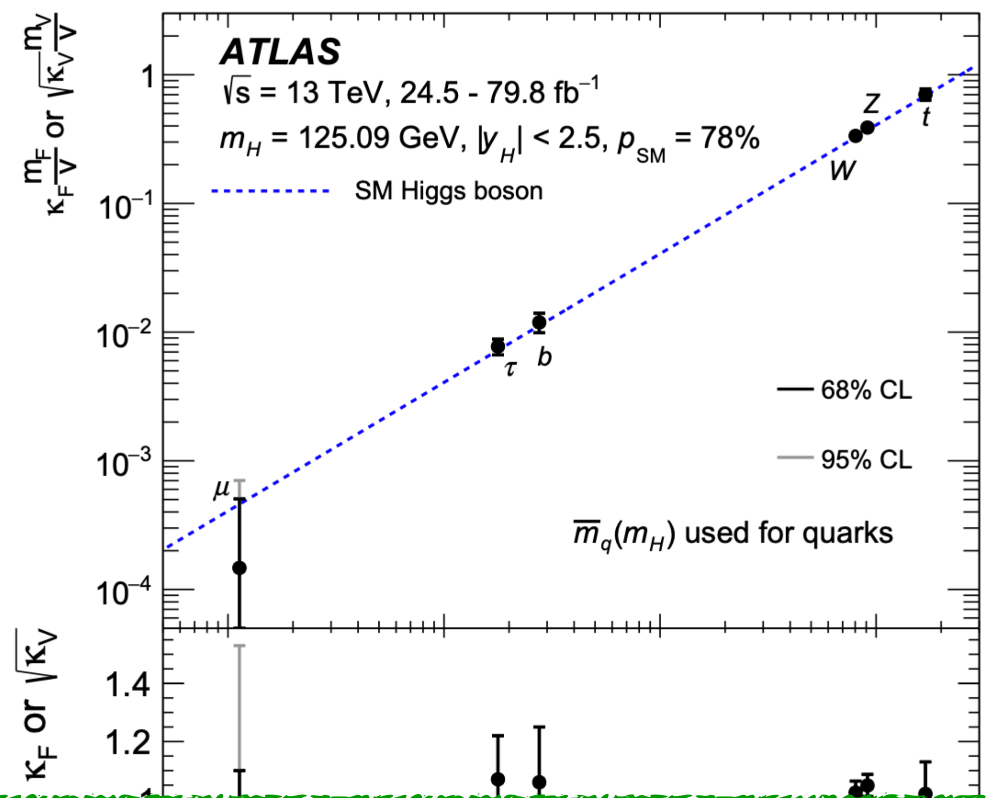


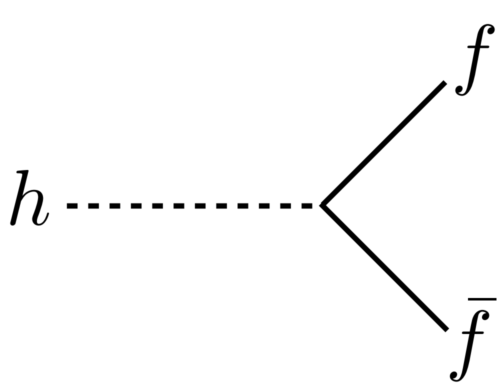


The Higgs is responsible for Flavor

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







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

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)

Outline:

I. Di-Higgs production at the LHC: what physics are we testing?

II. Models of Higgses with large couplings to light quarks

III. Bounds on Higgs-quark couplings from multi-Higgs production

IV. Future Directions

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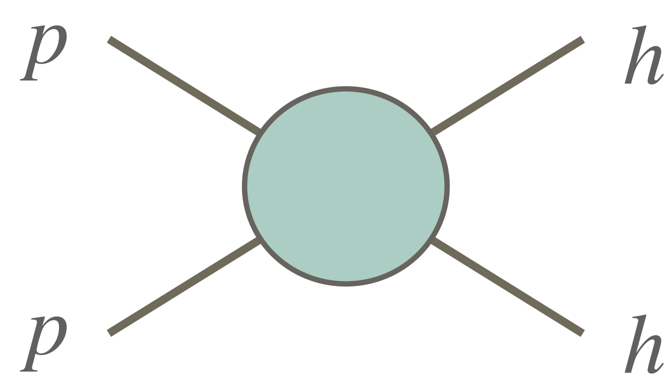
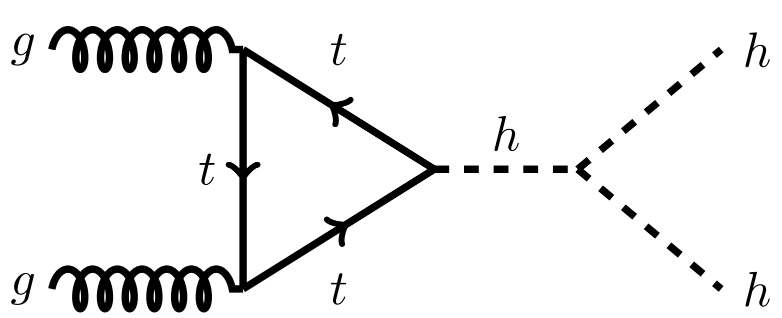
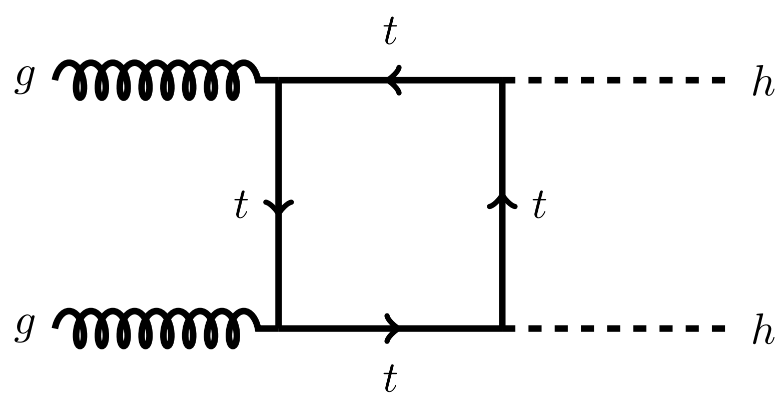
Di-Higgs Production at the LHC

Di-Higgs production is one of the most important targets of the HL-LHC



In the Standard Model:



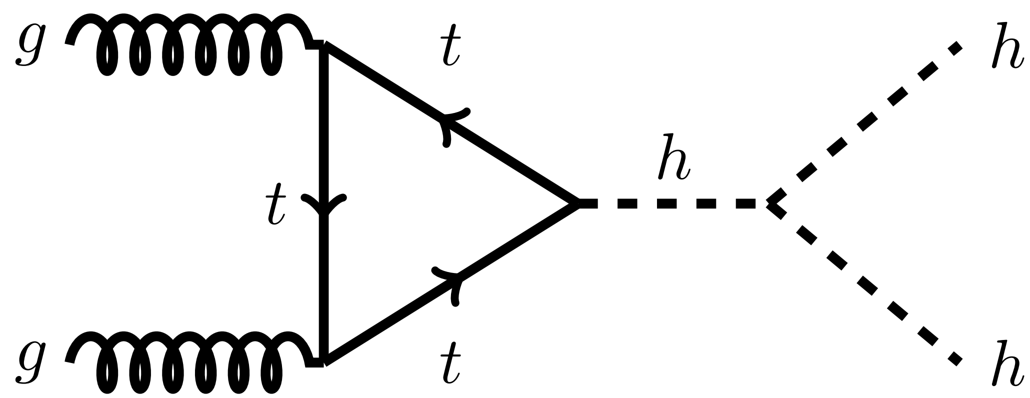


$$\sigma_{hh}^{SM} = 31\ \text{fb}$$

(> 4000 pairs already created, but hiding in backgrounds)

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

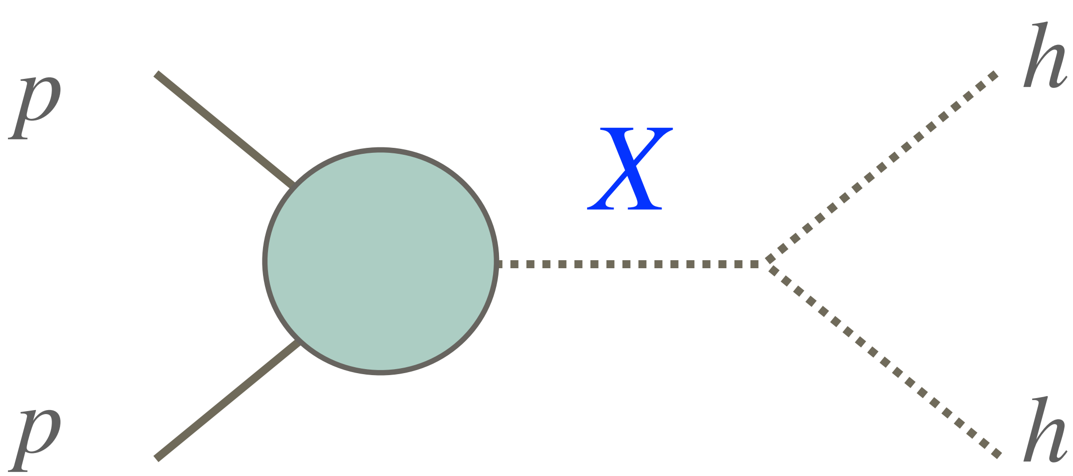
Current bounds: $-3.3 < \lambda/\lambda_{\rm SM} < 8.5$
CMS-HIG-19-018

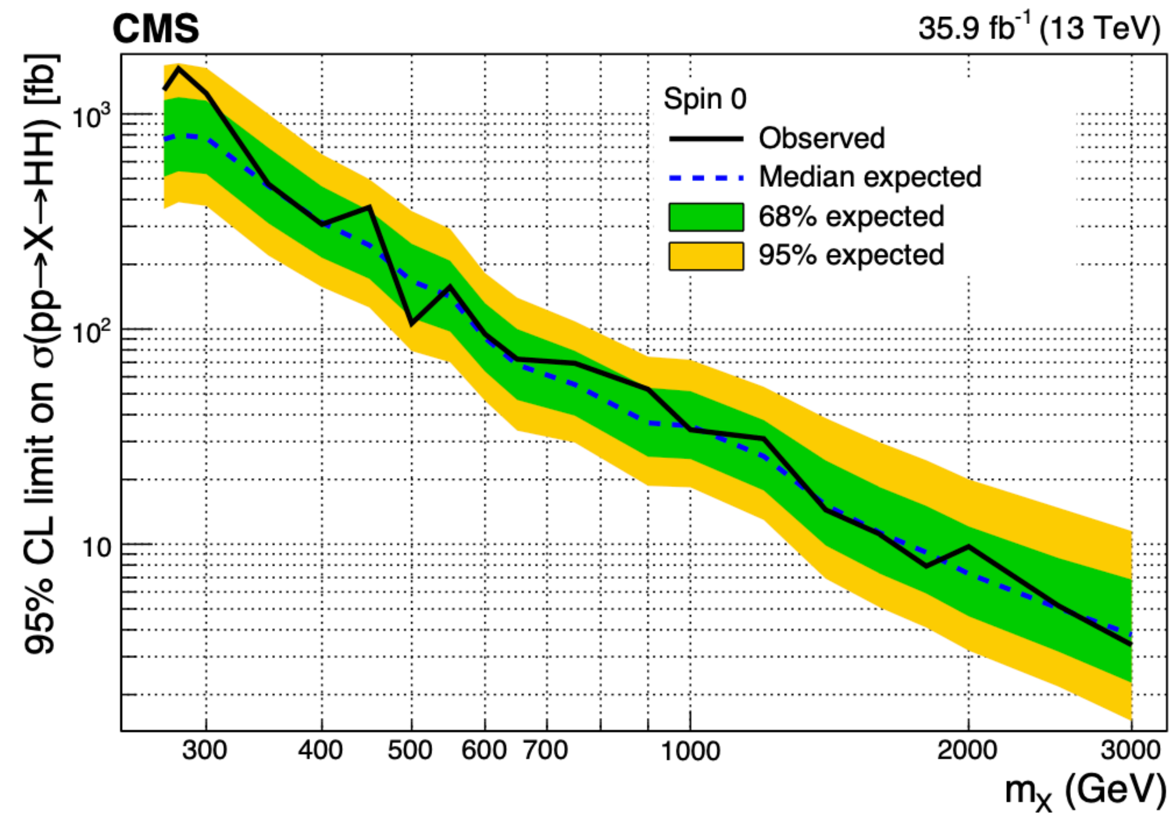
HL-LHC Projections: $-0.18 < \lambda/\lambda_{\rm SM} < 3.6$
arXiv:1910.00012

Di-Higgs Production at the LHC

But it's also useful to search for extra scalars!

Resonant di-Higgs production!



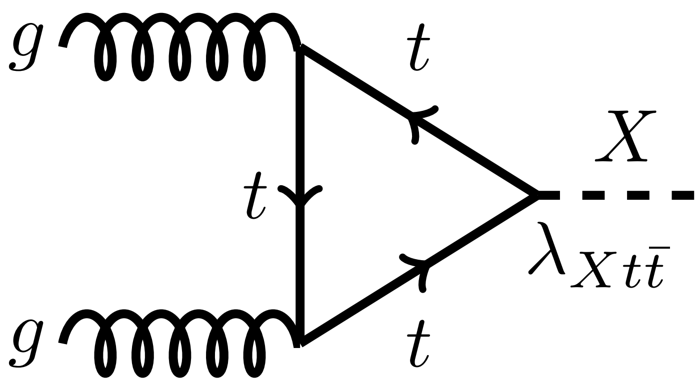


This happens naturally in a *tremendous* variety of theories:

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…

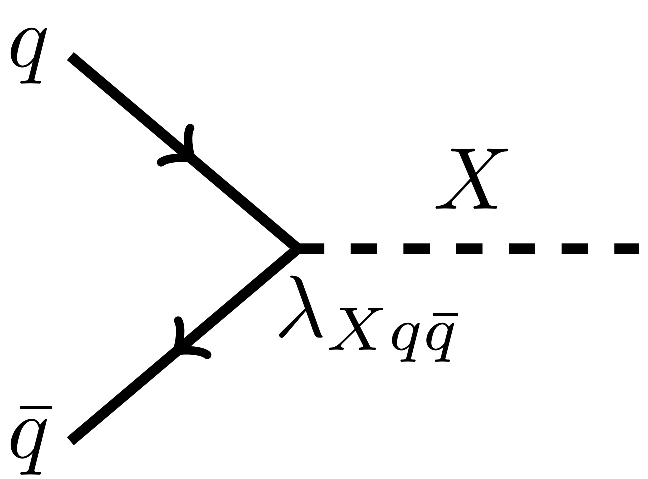
Production of Extra Scalars



Most frequently studied: top coupling

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

(Alternatively: new heavy quarks in the loop)



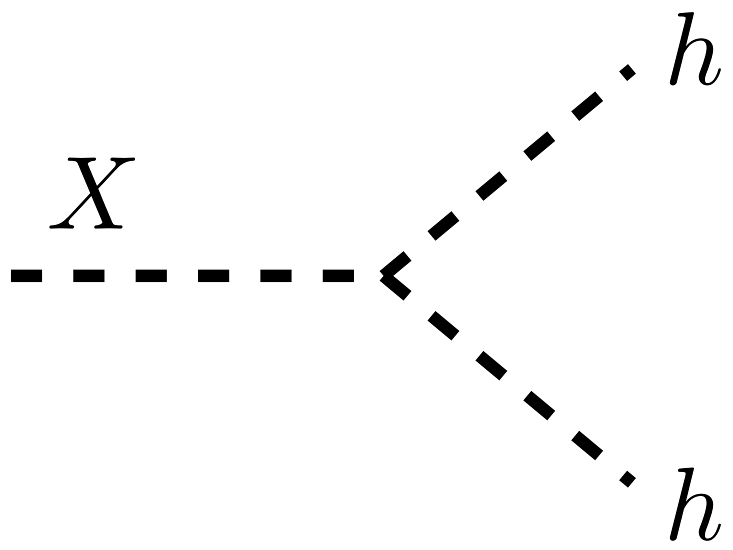
New target: *light quark couplings*

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

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

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

Decays into Higgs Pairs



$$\overset{X}{\downarrow}\qquad\overset{h}{\downarrow}$$

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

$$\downarrow$$

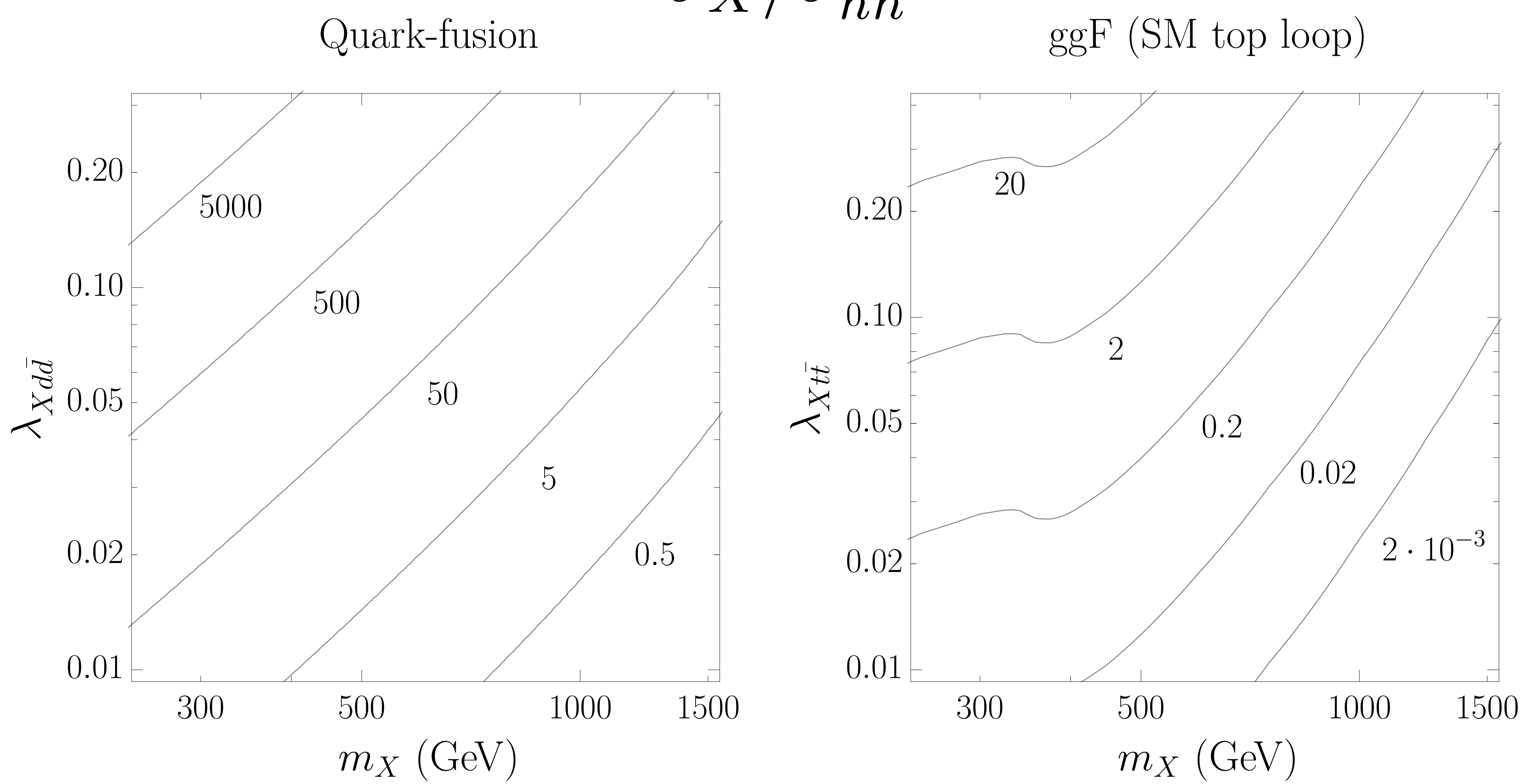
$$3\lambda v X h h$$

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

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

Typical Cross Sections

$$\sigma_X/\sigma_{hh}^{\rm LO} \qquad \sigma_{hh}^{\rm LO} = 14.5\,\text{fb}$$



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

How does this test the 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:

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

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

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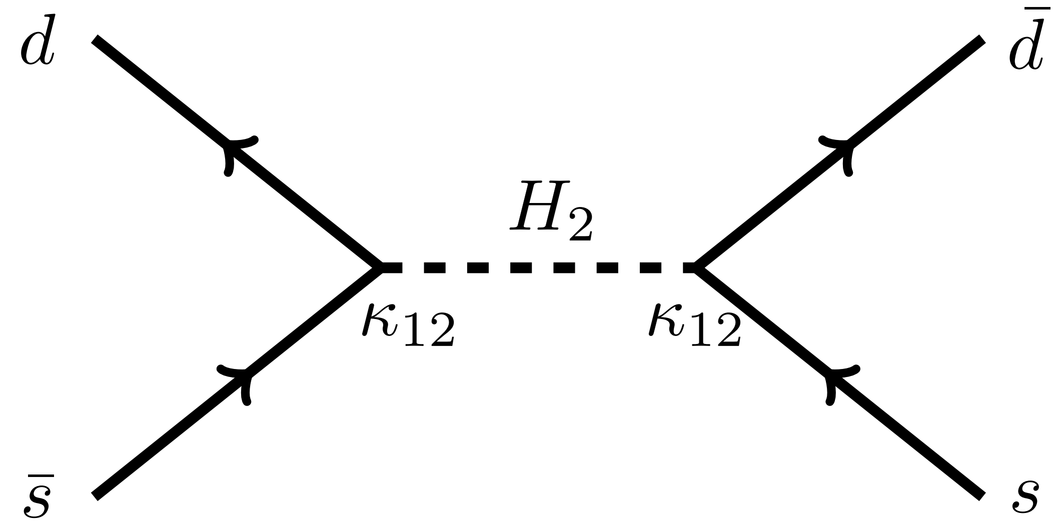
FCNCs in Extended Higgs Sectors

Most important question in theories with extended Higgs sectors:
How do we avoid FCNCs?

$$\kappa^d_{ij} Q_i {H_2}^c \bar{d}_j$$

Potential source of flavor violation!



$$\frac{1}{\Lambda^2} s\bar{d}s\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}$$

Need a *symmetry* based argument to suppress these contributions and allow new states at the TeV scale

Typical Extended Higgs Sectors

The most popular way of doing this: "Natural Flavor Conservation"
i.e., the "Glashow-Weinberg conditions"

$$\lambda_1^d Q \Phi_1^c \bar{d} + \lambda_1^u Q \Phi_1 \bar{u}$$
$$+ \lambda_2^d Q \Phi_2^c \bar{d} + \lambda_2^u Q \Phi_2 \bar{u}$$

$$\tan\beta \equiv \langle \phi_1 \rangle / \langle \phi_2 \rangle$$

$$y^u = \frac{\sqrt{2} m^u}{v \cos\beta} \qquad y^d = \frac{\sqrt{2} m^d}{v \sin\beta}$$

Forbid problematic FCNCs by imposing a discrete symmetry!

Glashow,Weinberg, PRD 15 (1977) 1958

➔ retain the SM hierarchies, couple predominantly to 3rd generation

Beyond the Type I-IV 2HDMs?

Has become lore that there are only four types of 2HDMs…

Effective Field Theory*†‡

Howard Georgi

Unfortunately, perhaps because the authors are two of the greatest physicists of the last third of the 20th century, too many readers of the Glashow-Weinberg paper mistook the Glashow-Weinberg condition as a necessary condition on theories with more than one scalar doublet. The common

Alternative: Flavor Alignment

Seiberg, Nir hep-ph/9304307

Rotate to the basis where H_1 breaks electroweak symmetry

the "Higgs basis" (Georgi, Nanopoulos Phys. Lett B **82** (1979) 95-96)

➔ All flavor violation due to H_2

If H_2 Yukawas are *diagonal in the same basis* as H_1, no FCNCs!

More generally: if flavor breaking spurions are **simultaneously diagonal**, there are no FCNCs at tree level

Now just need to impose this alignment in a technically natural way

(e.g., "Horizontal Symmetries")

Flavor-Aligned 2HDMs

arXiv:1811.00017, 1908.11376

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

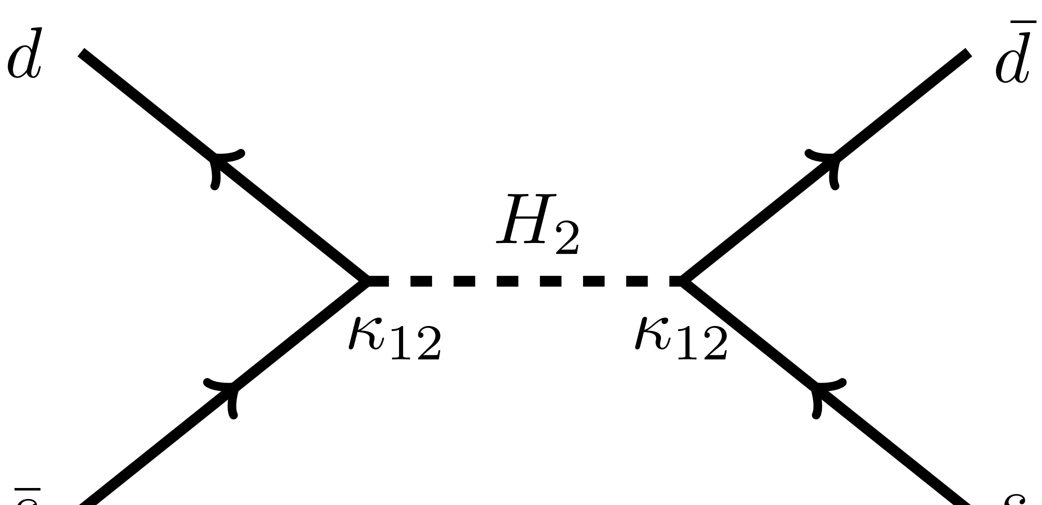
New Yukawa couplings with no relation to the SM quark masses!

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

Diagonal in the same basis!

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

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



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

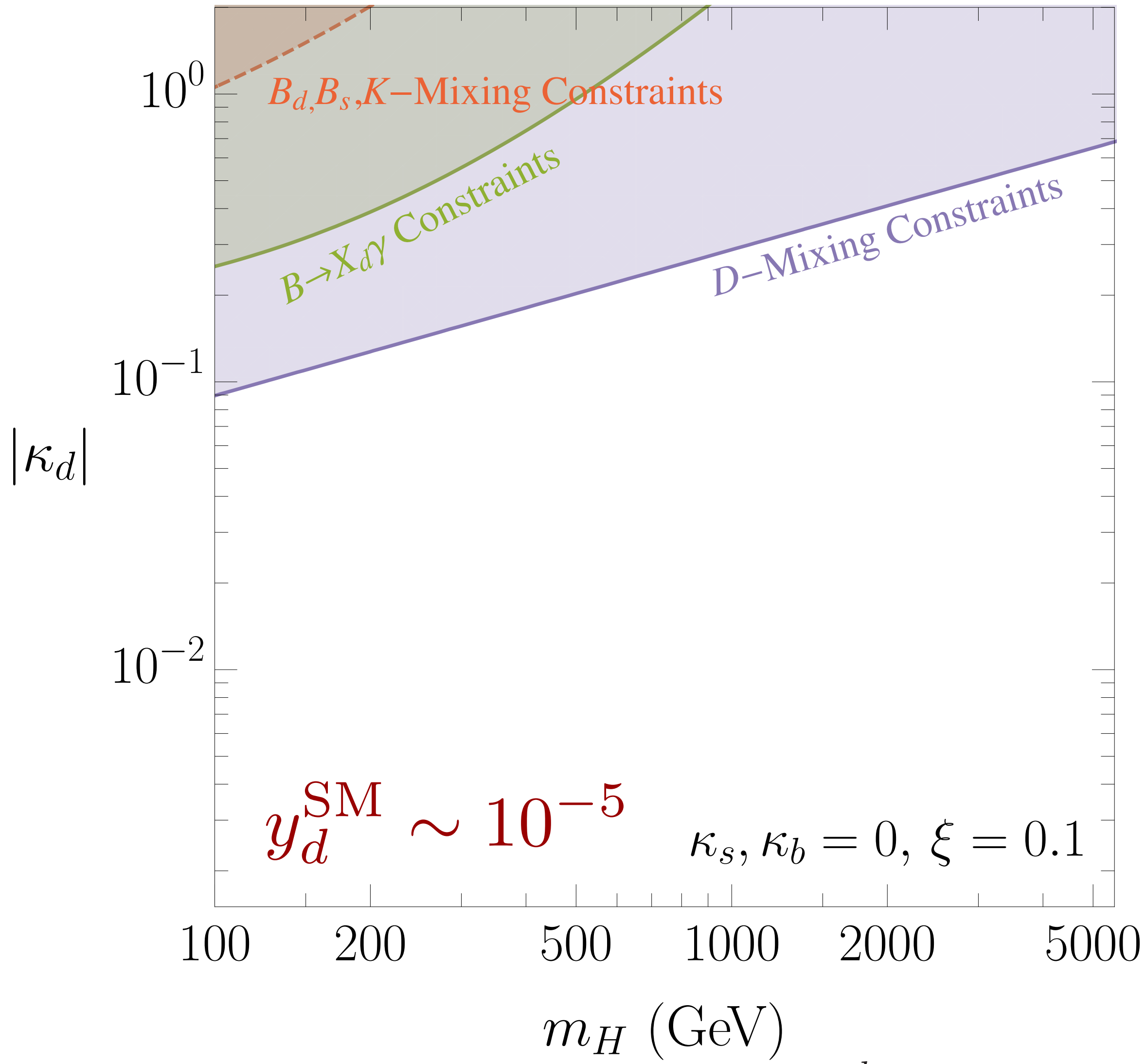
Demonstrated in 1811.00017 that alignment can be achieved in a *technically natural*, *UV complete* way

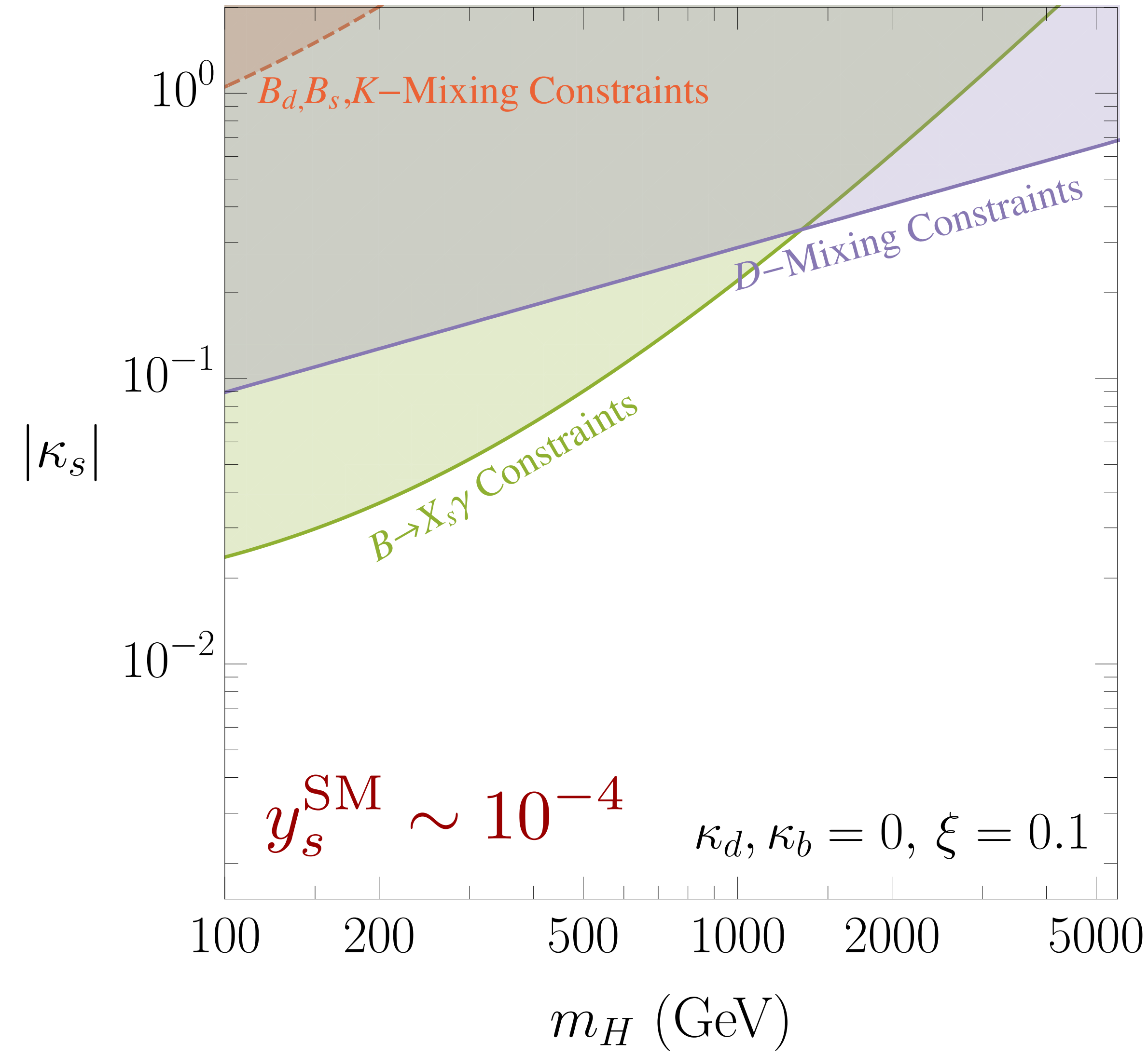
"Spontaneous Flavor Violation"

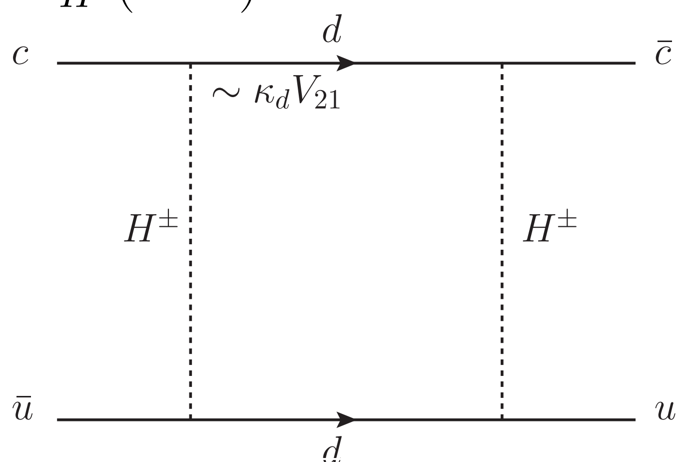
The only catch is that Yukawas can only be aligned in one quark sector

Down-Sector Alignment

Couplings ~ 0.1 are perfectly allowed!







1-loop FCNCs
still GIM/CKM suppressed

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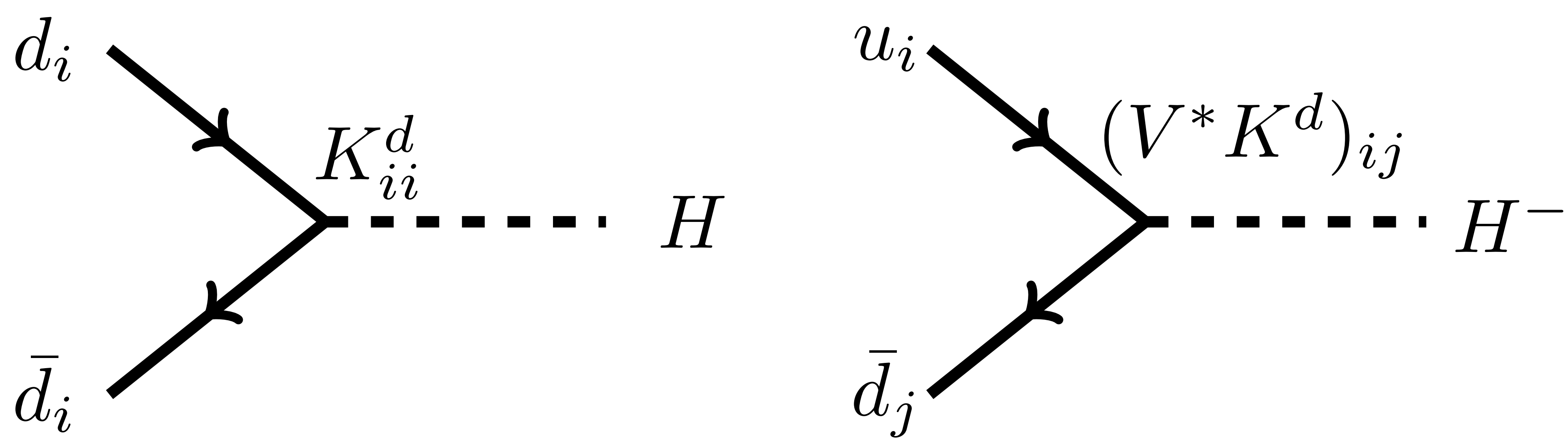
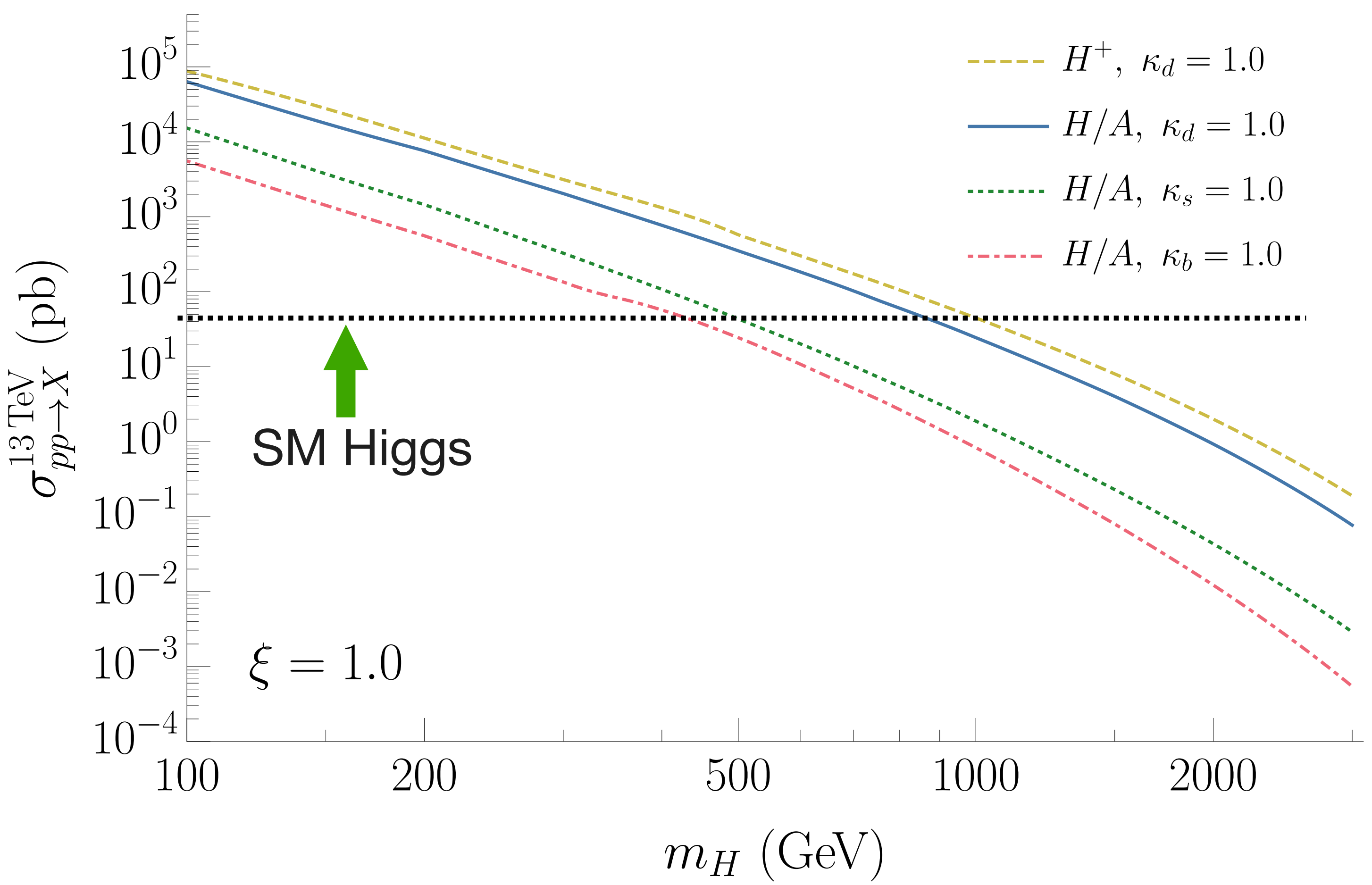
New Higgses → New Signals

Additional heavy Higgs states will have large production rates!





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

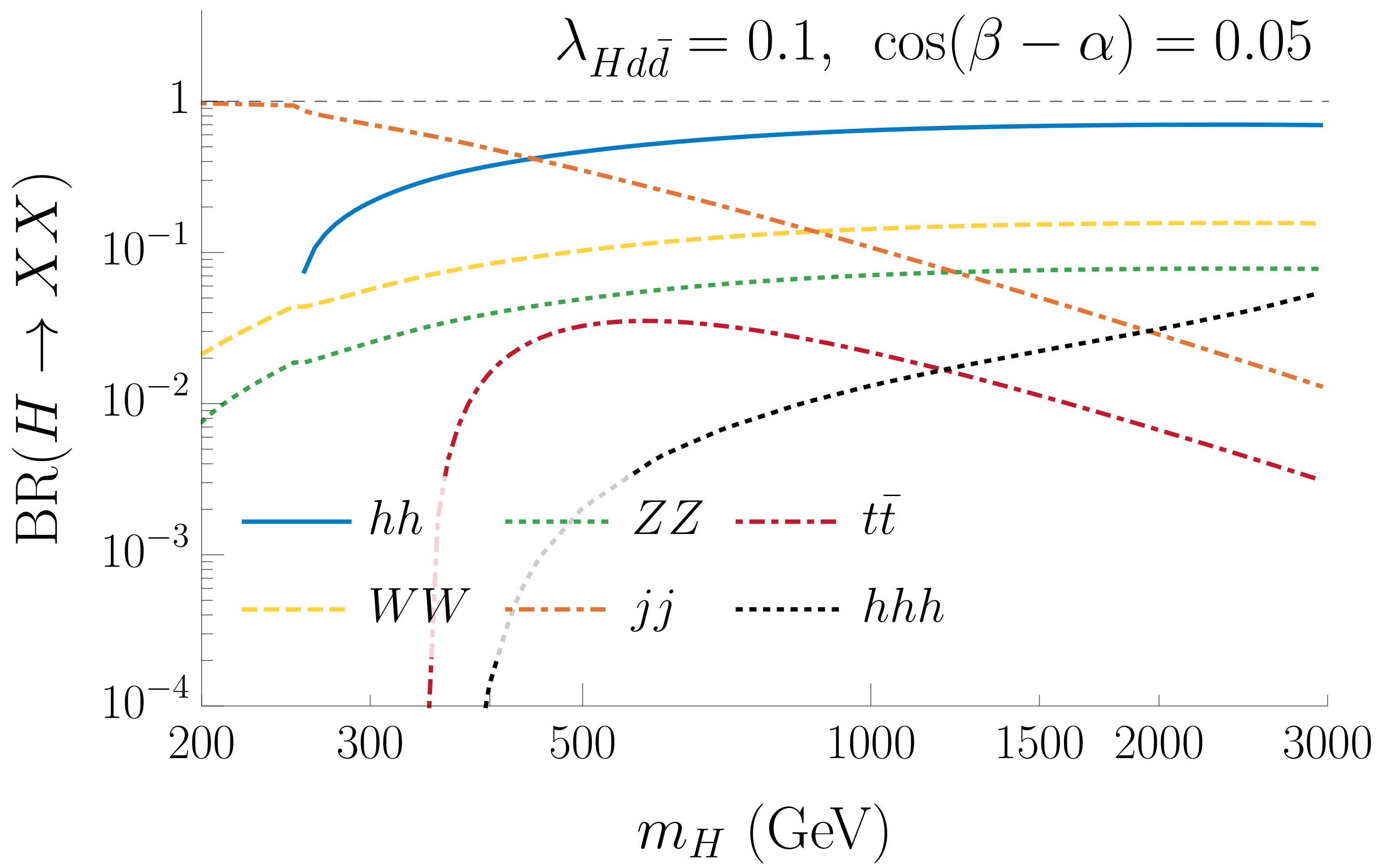
→ states likely within reach of the LHC!

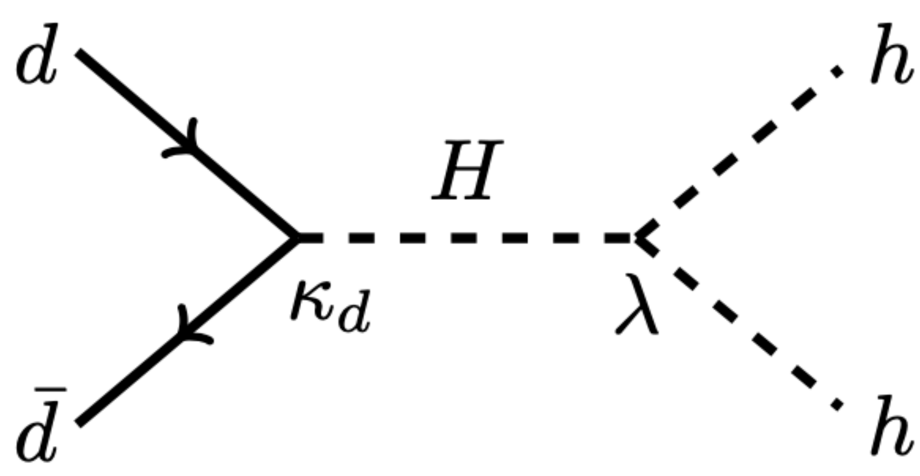
e.g., for $\cos(\beta - \alpha) = 0.1$, perturbativity requires $m_H \lesssim 1500\,\mathrm{GeV}$

Tree-Level Di-Higgs Production

Resonant di-Higgs production from decays of new neutral Higgs

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

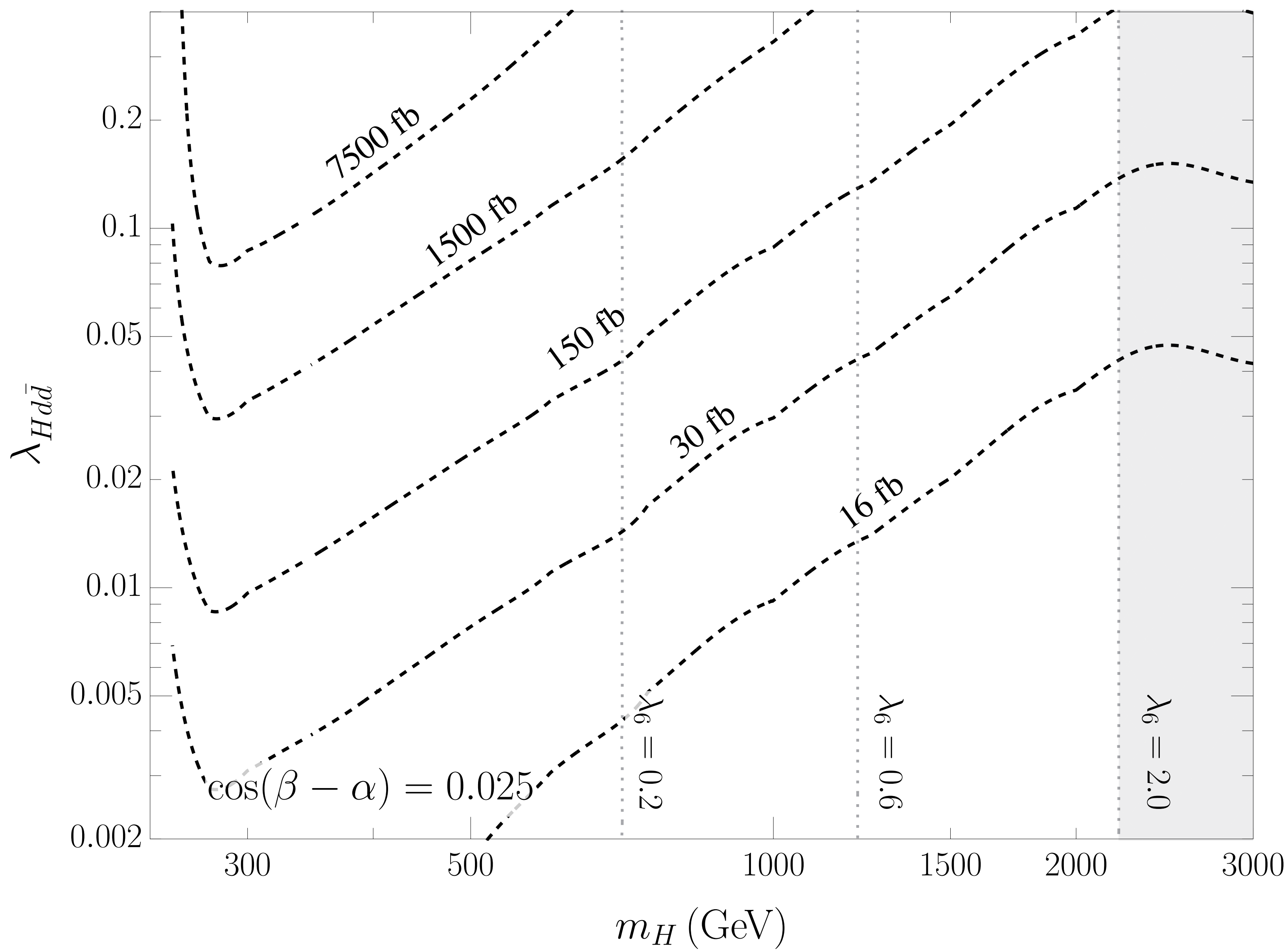




Scalar couplings typically dominate — natural to have large BRs to lighter Higgs

Di-Higgs Rates

Enormous resonant di-Higgs cross sections are naturally obtained in these models



$$\sigma_{hh}^{\rm SM} = 31\ {\rm fb}$$

Mixing and 125 GeV Higgs Couplings

Mixing in 2HDM dictated by:

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

$$\cos(\beta - \alpha) \sim \lambda_6 \frac{v^2}{m_H^2}$$

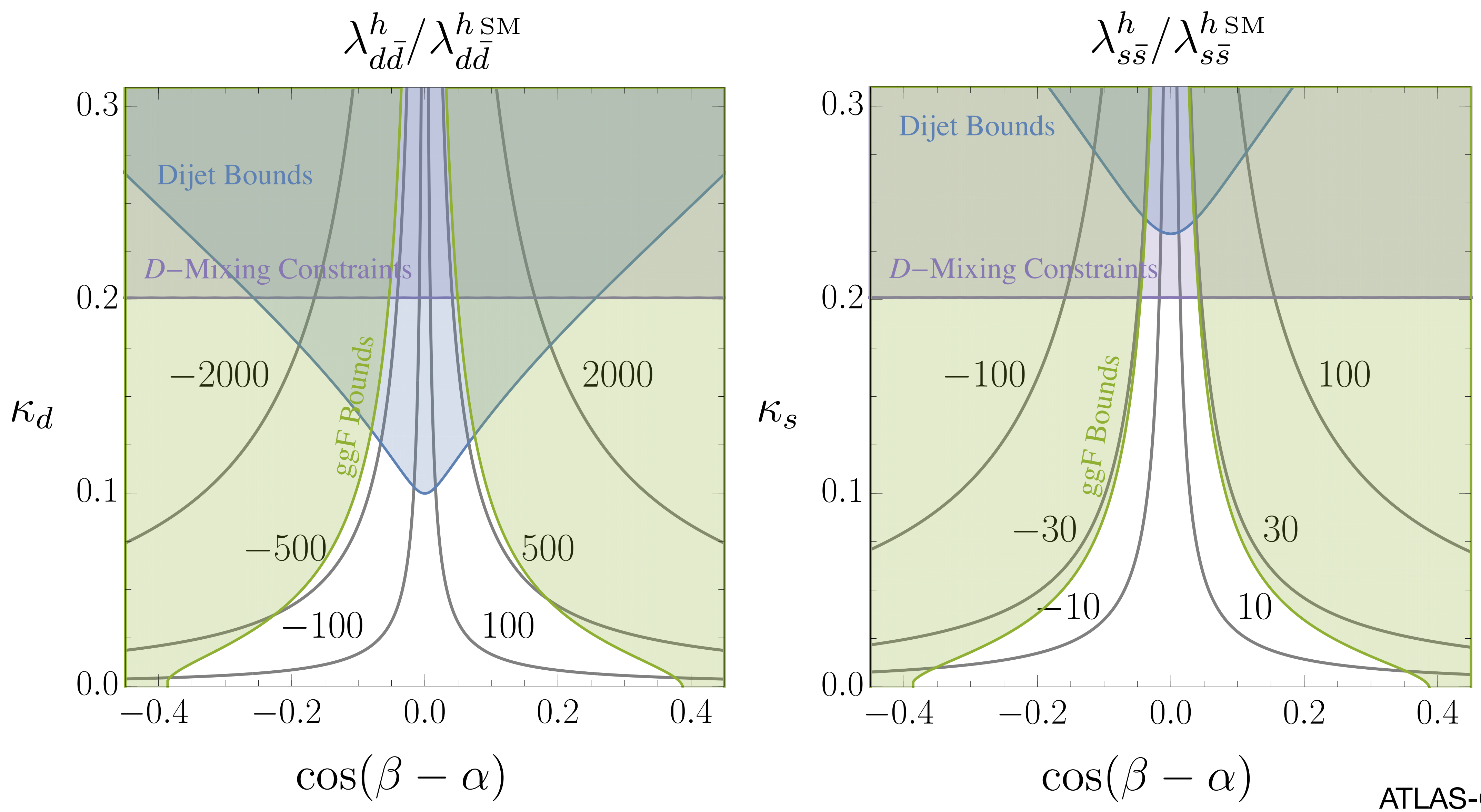
Note: for large mixing, can't be too heavy!
(problematic for EFT approach…)

The 125 GeV Higgs Yukawas are given by:

$$\lambda_{hd\bar{d}} = y_d^{\rm SM} + \cos(\beta - \alpha)\kappa_d$$

BIG!

Dramatic Enhancements of Yukawas:



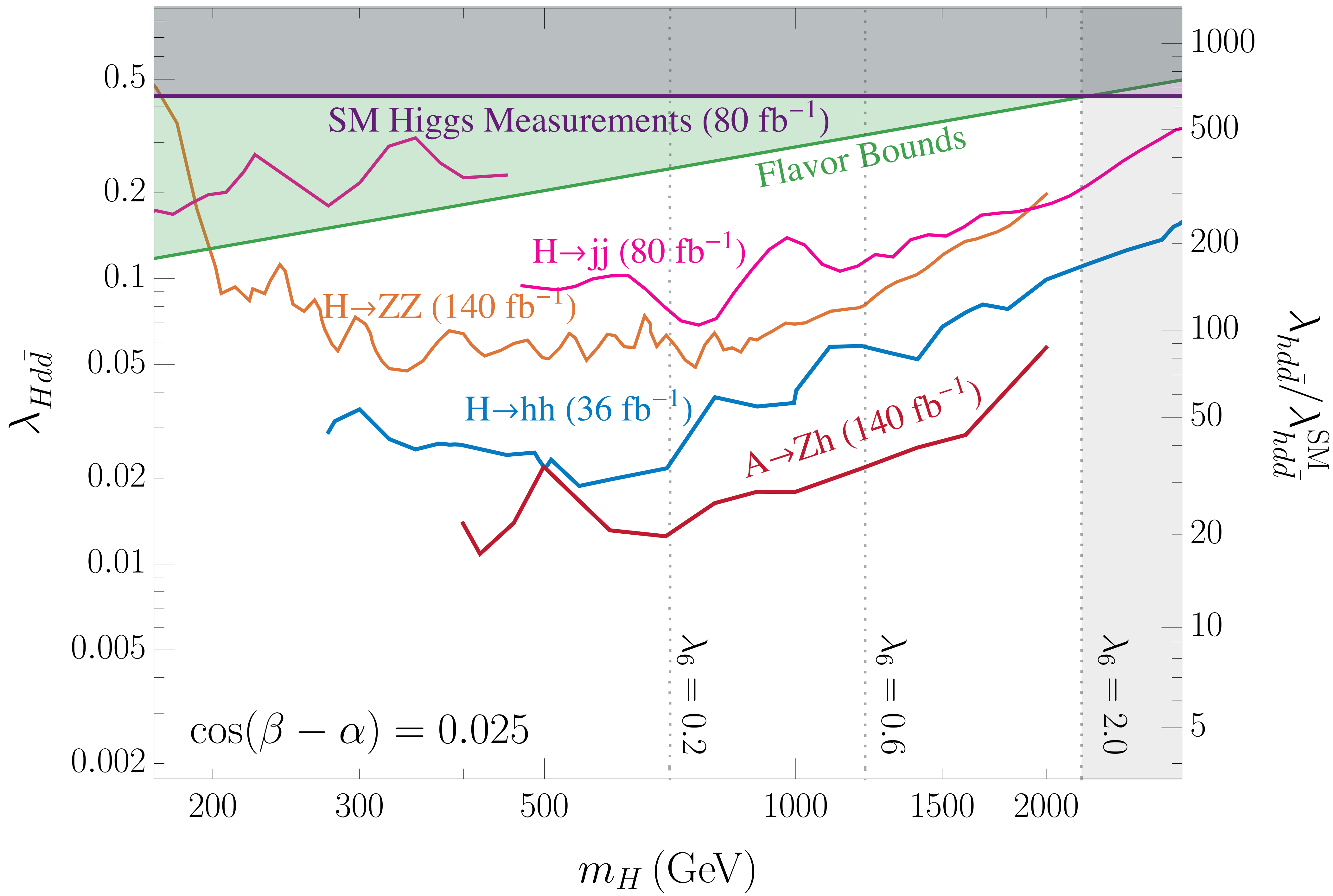
See also.
ILC TDR 1306.6352
Kagan et. Al 1406.1722
Perez et. Al 1505.06689
Zhou 1505.06369
Brivio et. Al 1507.02916
Bishara et.Al 1606.09253
Soreq et.al 1606.09621
Duarte et.Al. 1811.09636
Coyle et.Al 1905.09360

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!

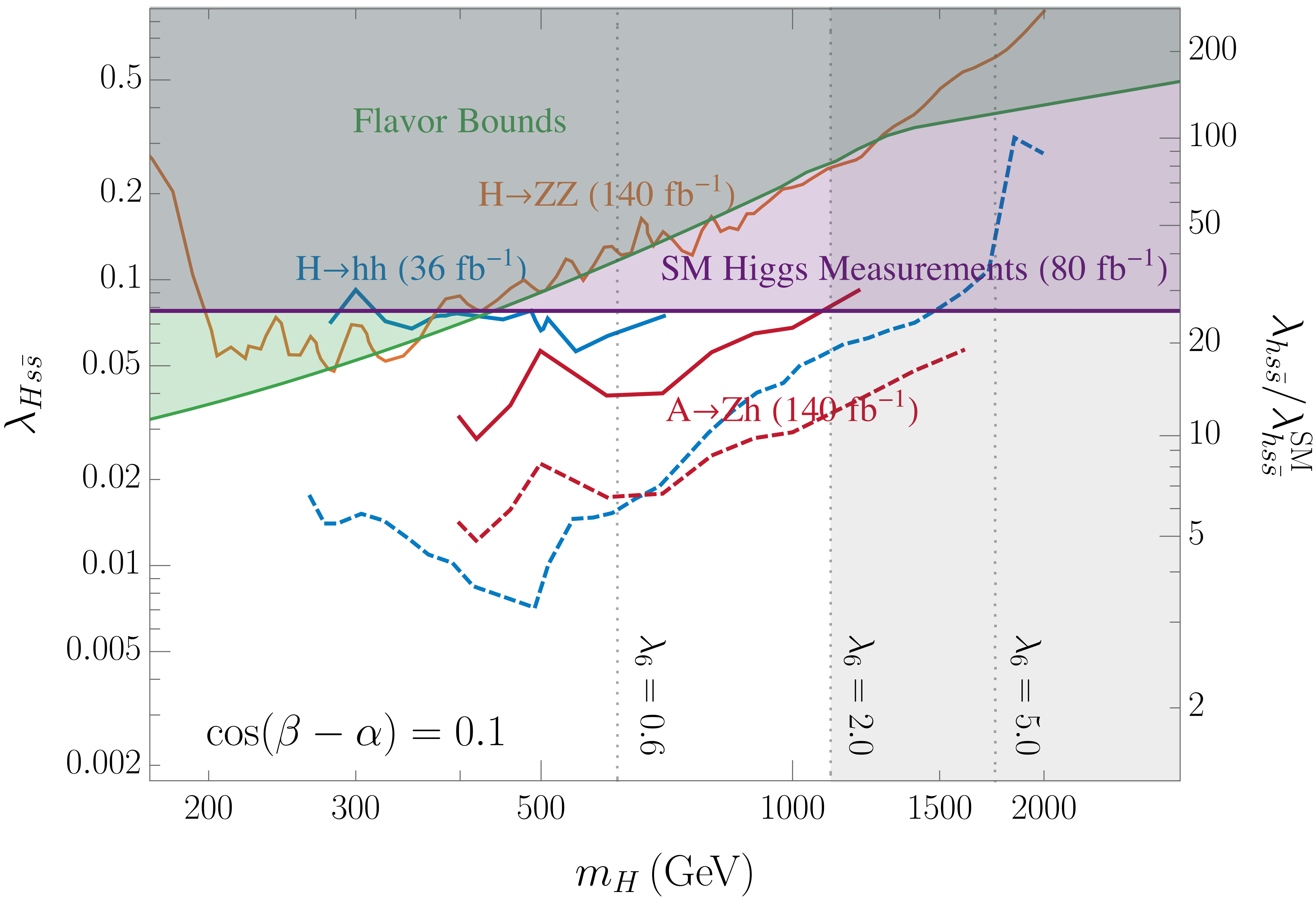
Bounds on Couplings to the Down Quark

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



Bounds on Couplings to the Strange Quark

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



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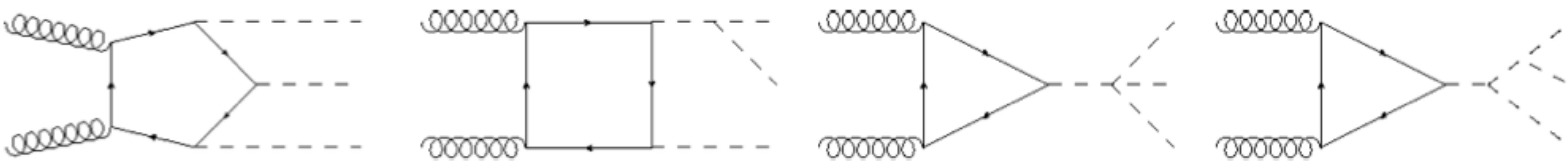
Triple Higgs Production in the SM

Triple Higgs production has received far less attention:

$$\sigma_{hhh}^{\text{NNLO, SM}} = \begin{array}{c} 0.1\,\text{fb at } 14\,\text{TeV} \\ 5.6\,\text{fb at } 100\,\text{TeV} \end{array}$$

(de Florian, et al., 1912.02760)

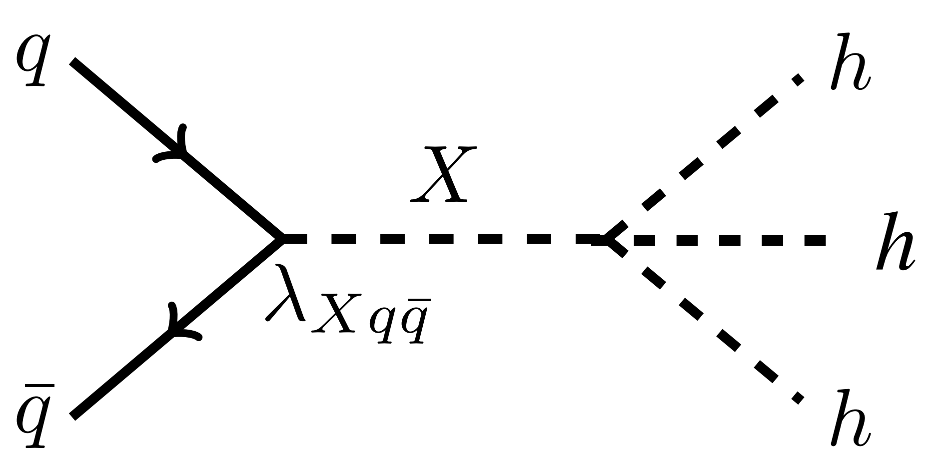


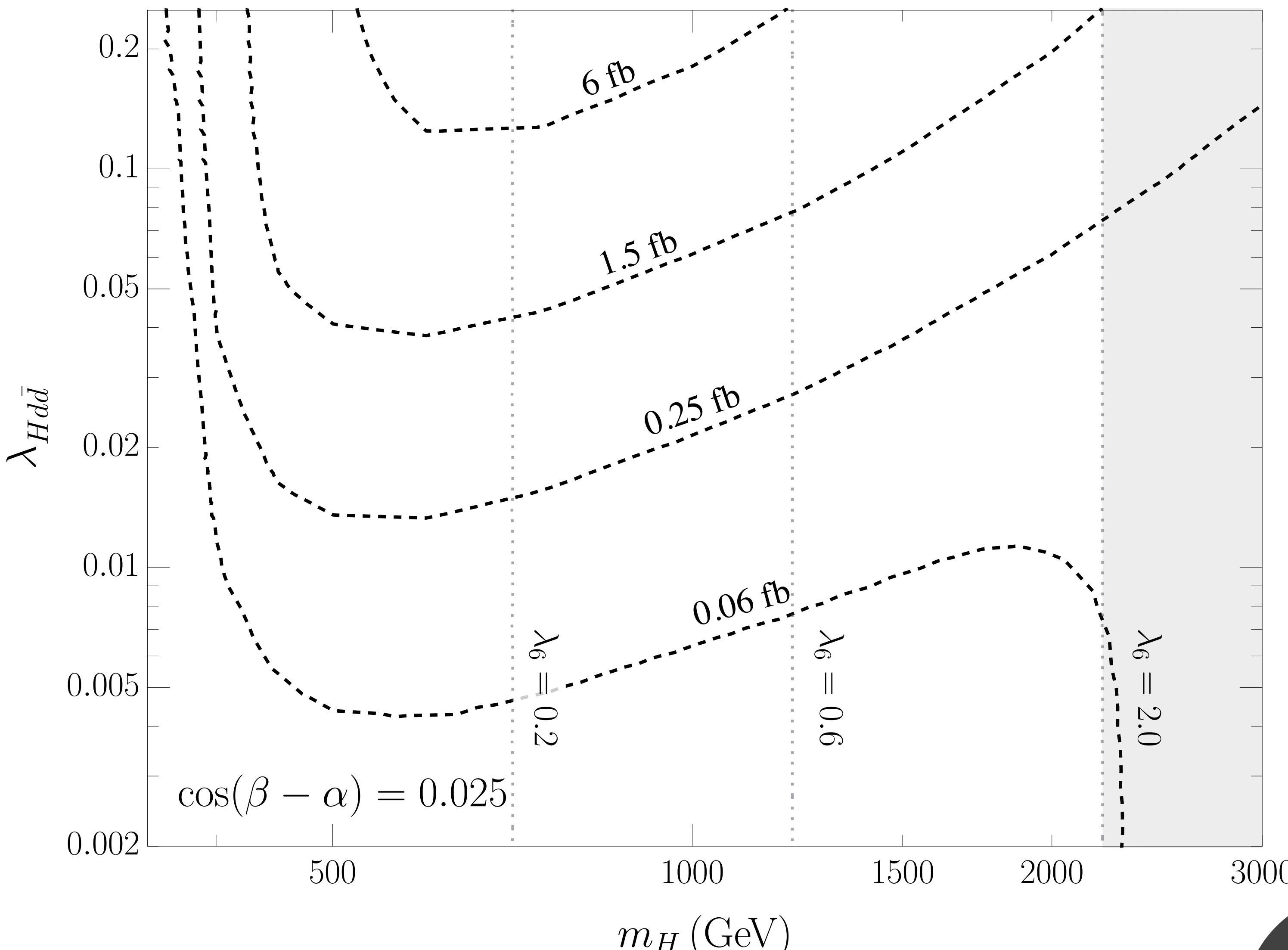
Also less interesting theoretically — self-coupling already probed by *hh* production…

Resonant Production Could be Visible!

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

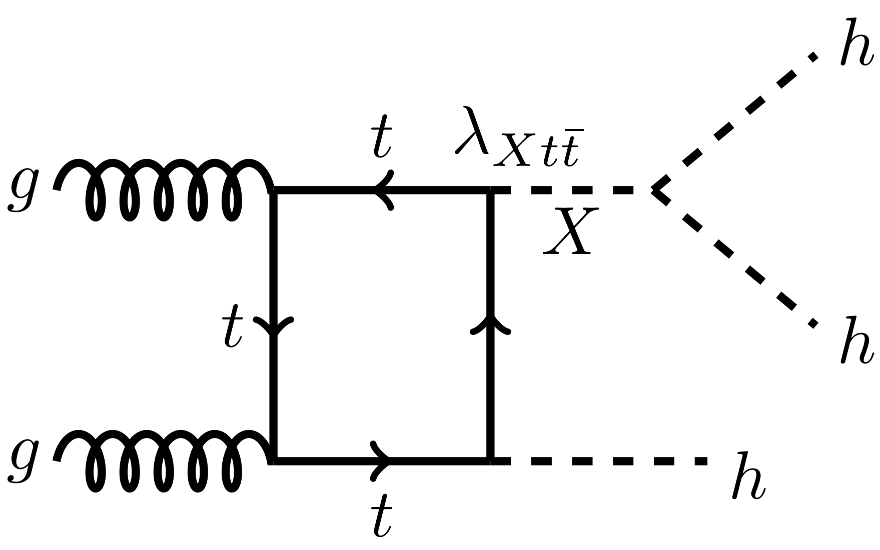
But if production of additional scalars is large, rates are significant!



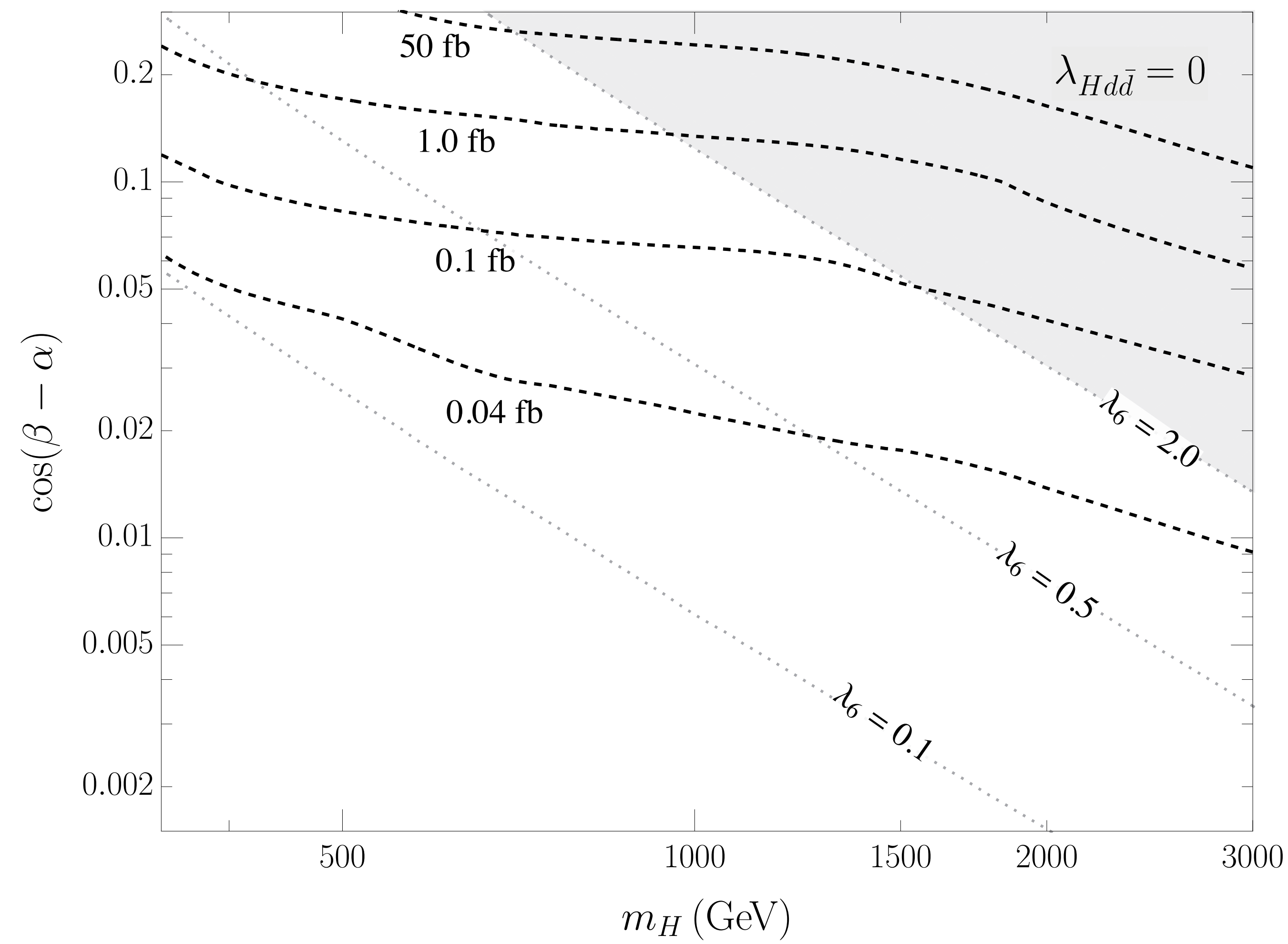


Useful in Typical 2HDMs?

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

Open Questions Regarding *hhh*

hhh has particular kinematic features that could substantially reduce the (already small) backgrounds:

- 3 Higgs resonances
- Semi-resonant topology, two Higgs at high pT?

Open question: Will the reach to extended Higgs sectors from 3h production be complementary to the reach from di-Higgs searches at the HL-LHC?
(at least in some regions of parameter space)

More Thoughts for the Future

- Two more quarks to go (u,c): we need to explore them all.

- Other models of enhanced Yukawas besides 2HDM? Clearly this can't be treated in the SM EFT (at least with perturbative UV completions) — counterexamples?

- What about enhanced couplings to light leptons at future colliders, and di-Higgs production in that context?

- How do we improve bounds below the $2m_h$ threshold?

Conclusions

- 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!

Backups

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

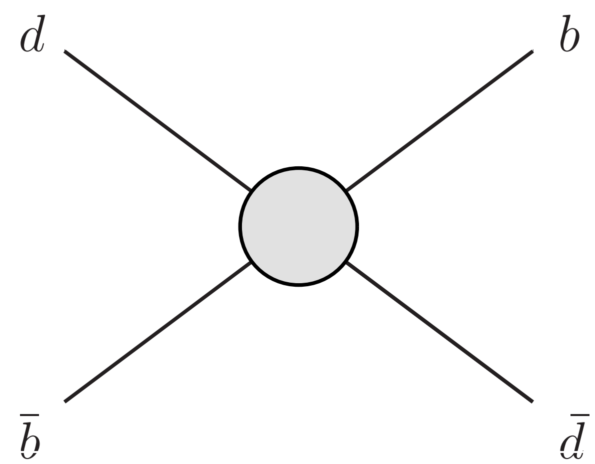
SFV Strongly Suppresses FCNCs

- 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



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

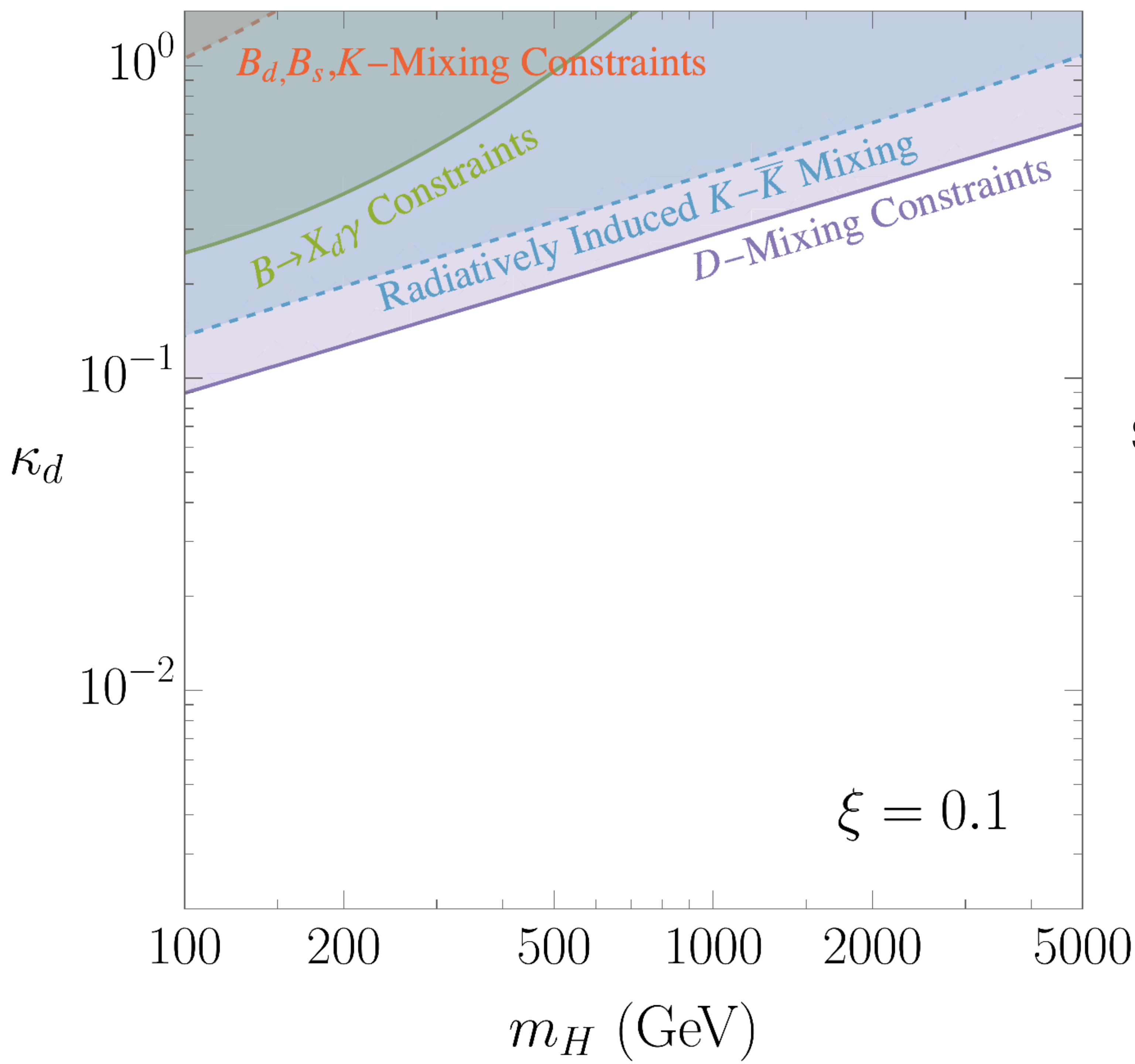
$$\downarrow$$

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

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

Yukawa, GIM and CKM suppression of FCNCs!

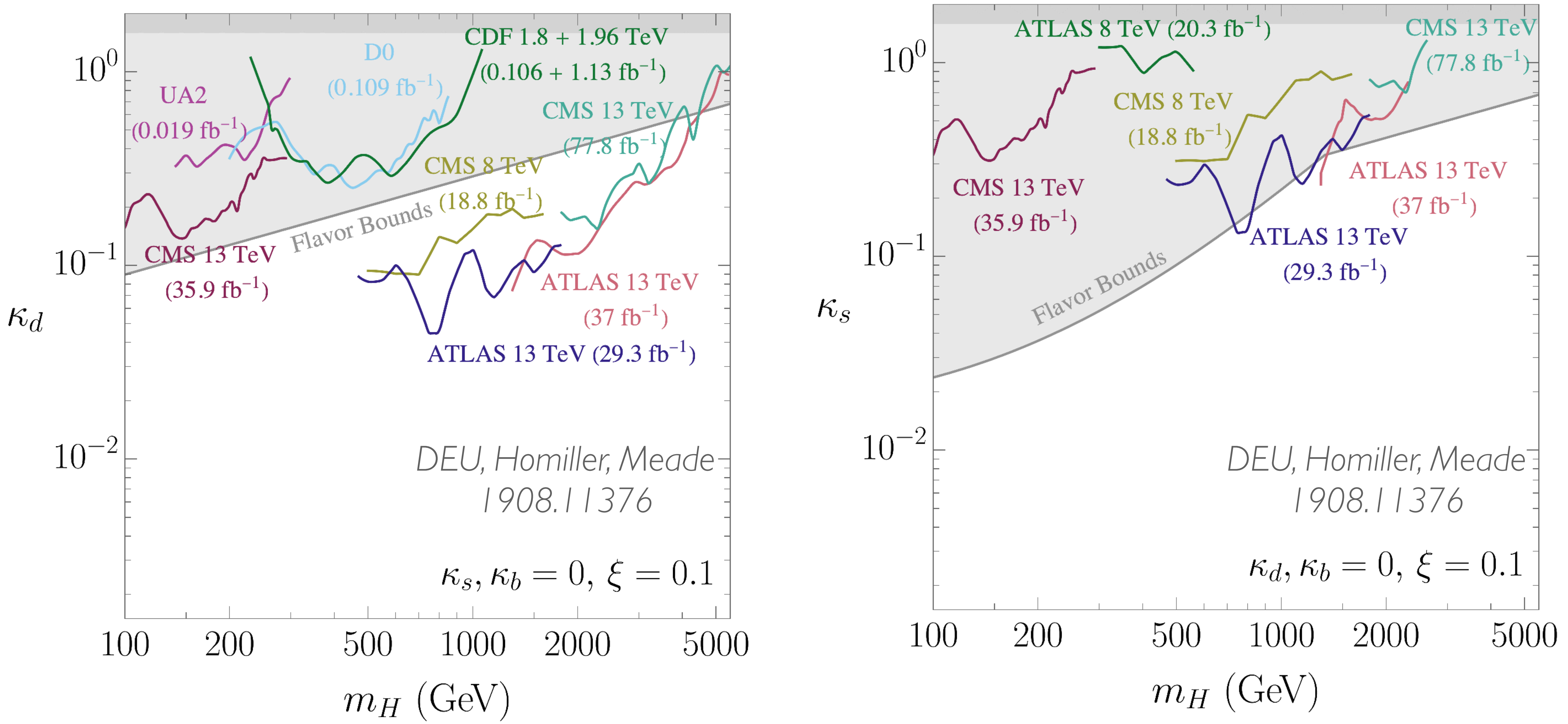
Radiatively Induced FCNCs



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)

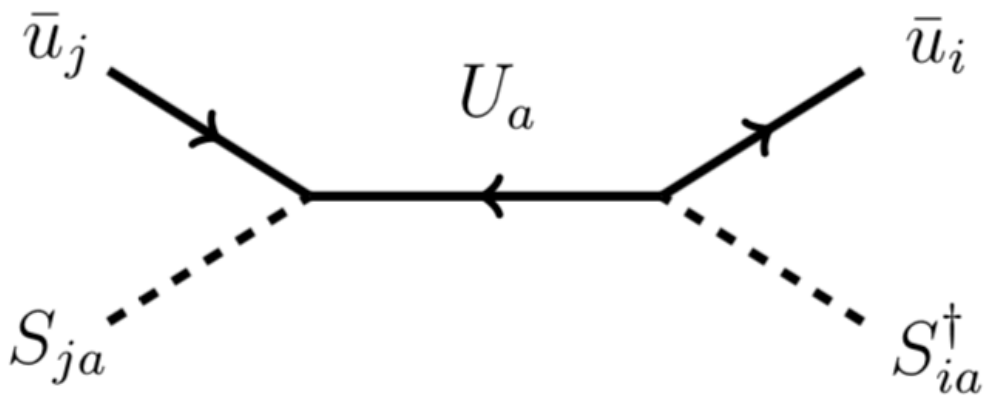
UV Completion for Flavor Alignment

Assume we start with a completely flavor symmetric SM:

Flavor-preserving SM + BSM+

$$M_{AB} U_A \bar{U}_B + \zeta S_{iA} U_A \bar{u}_i$$

$$M_{AB} > 100\,\mathrm{TeV}$$



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

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***

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

CKM via Wave-Function Renormalization

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

$$+\left[Y^u_{ij} Q_i H \bar{u}_j - Y^d_{ij} Q_i H \bar{d}_j - \alpha Y^u_{ij} Q_i H_2 \bar{u}_j - \kappa^d_{ij} Q_i H_2 \bar{d}_j\right]$$

. . . .

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

Y^d , κ^d Remain real-diagonal and <u>aligned</u>

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

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

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

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

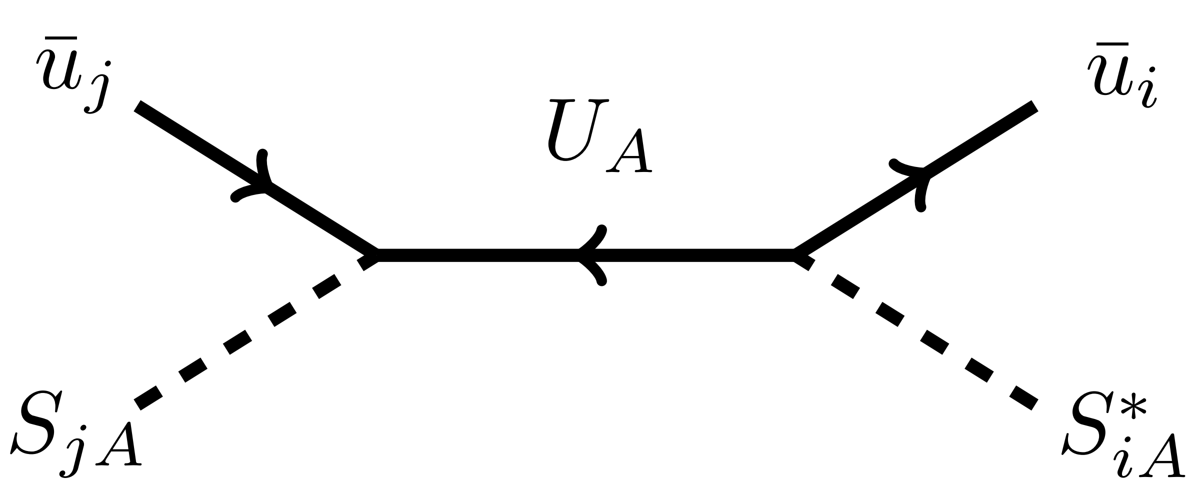
More Details on the UV Completion

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

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



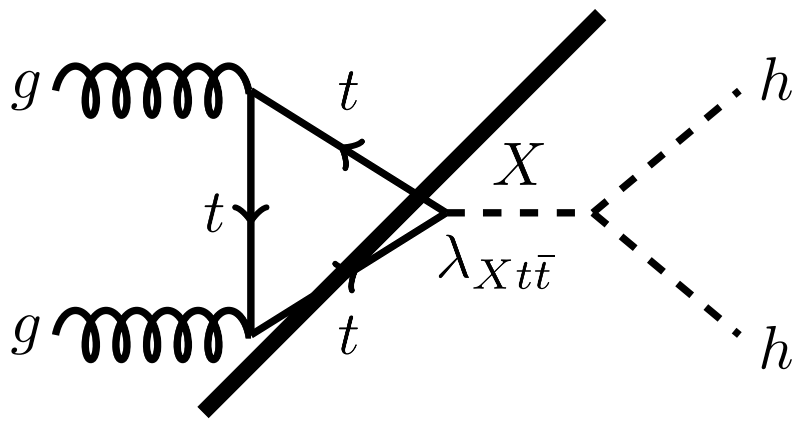
Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

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

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

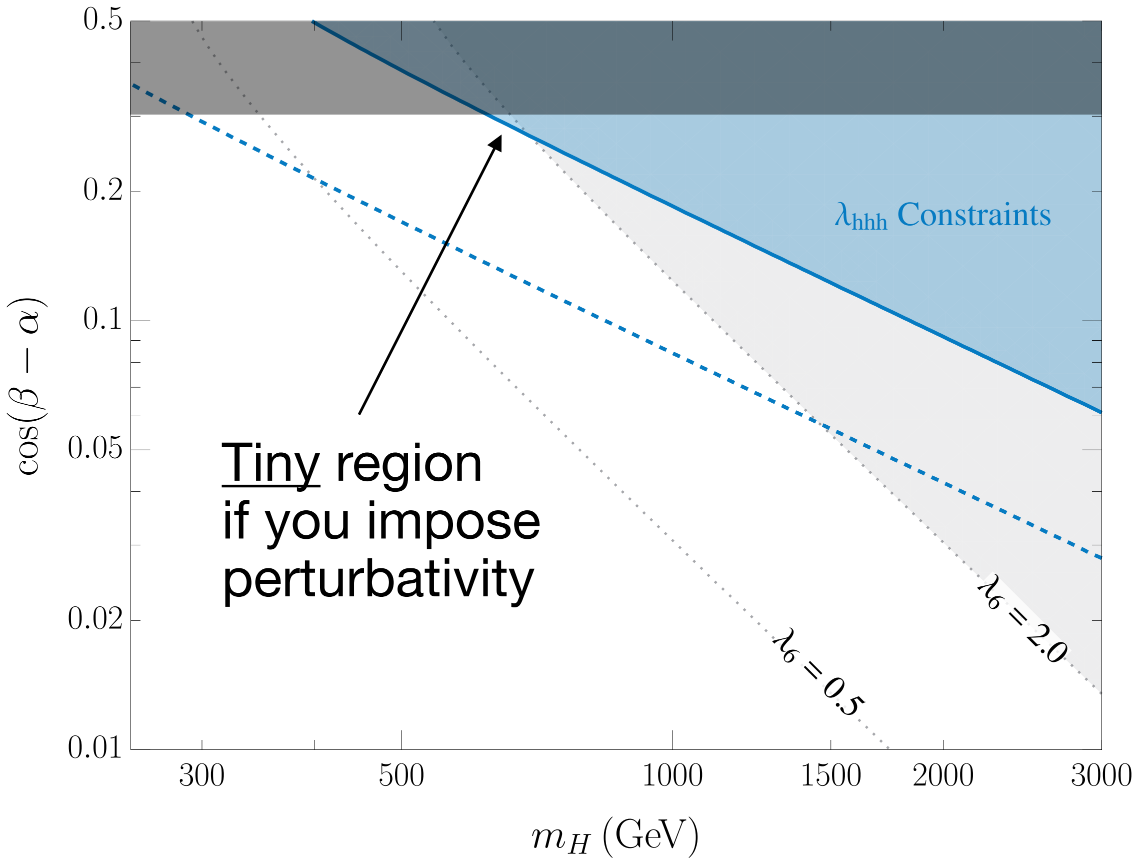
Is Non-Resonant Di-Higgs Ever Important?

Yes, but barely, 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

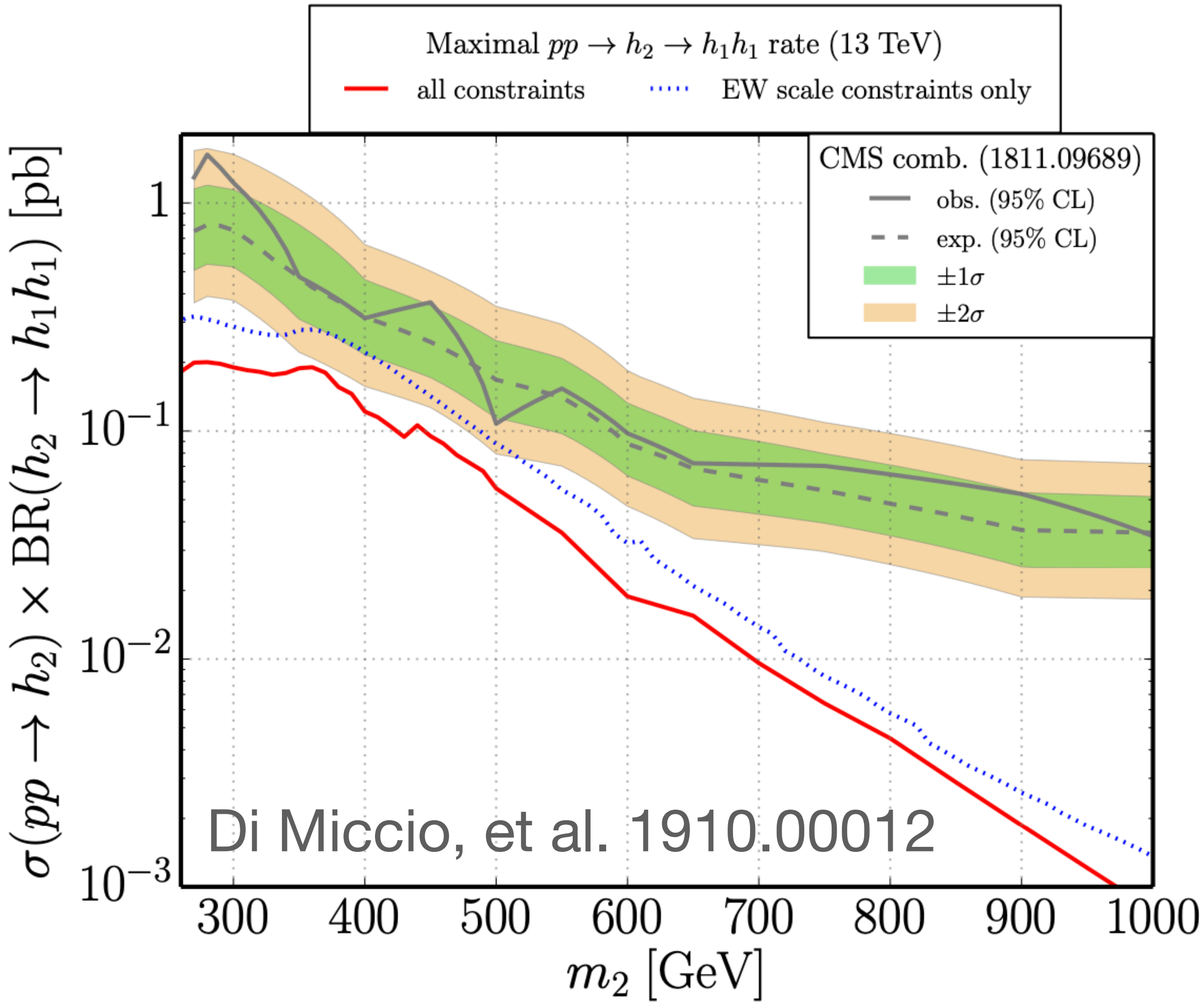


Figure 3.1: Maximal allowed $pp \to h_2 \to h_1 h_1$ signal rate at the 13 TeV LHC in the softly-broken Z_2-symmetric case. Shown are values after applying (red solid) all constraints and (blue dotted) only constraints at the EW scale. The corresponding $\mathrm{BR}_{\mathrm{max}}^{h_2 \to h_1 h_1}$ 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].

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