HIGGS BOSONS WITH LARGE COUPLINGS TO LIGHT QUARKS

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arXiv: 1811.00017 (PRL 123.031802)
arXiv:1908.11375 (PRD 100.115041)
arXiv:1911.10203 (PRL 124.191801)
arXiv:very.soon

In collaboration with
Samuel Homiller
Patrick Meade

NEW PHYSICS THROUGH THE HIGGS

- The exploration of the Higgs sector properties is a powerful probe of new physics theories.

- This comes with theory selection: we explore preferentially theories that are *motivated* and *natural*.

- There has been a strong theoretical bias towards studying new physics with preferential couplings to heavy fermions.

TYPICAL EXTENDED HIGGS SECTORS

Example: type II 2HDM (quark sector)

$$\langle \phi_1 \rangle = \frac{v}{\sqrt{2}} \cos\beta \qquad \langle \phi_2 \rangle = \frac{v}{\sqrt{2}} \sin\beta$$

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

To avoid FCNCs!

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To avoid FCNCs!

$$\lambda^d = \frac{\sqrt{2} M^d}{v} \sec\beta \qquad \lambda^u = \frac{\sqrt{2} M^u}{v} \csc\beta$$

TYPICAL EXTENDED HIGGS SECTORS

- The new physics is more transparent if we perform a rotation in the $\Phi_1 - \Phi_2$ plane into an $H_1 - H_2$ plane where

$$\langle H_1 \rangle = \frac{v}{\sqrt{2}} \qquad \langle H_2 \rangle = 0$$

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$$\kappa_1^u Q H_1 \bar{u} + \kappa_1^d Q H_1^c \bar{d} + \kappa_2^u Q H_2 \bar{u} + \kappa_2^d Q H_2^c \bar{d}$$

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$$\kappa^d = -\sqrt{2} \tan\beta \, \mathrm{diag}(m_d, m_s, m_b)/v$$

EXTRA HIGGSES WITH LARGE COUPLINGS TO LIGHT QUARKS

- A new set of theories allow for Higgses with large couplings one sector of light quarks, in a *technically natural way.*

$$\kappa^d_{ij} = \mathrm{diag}(\kappa_d, \kappa_s, \kappa_b)$$

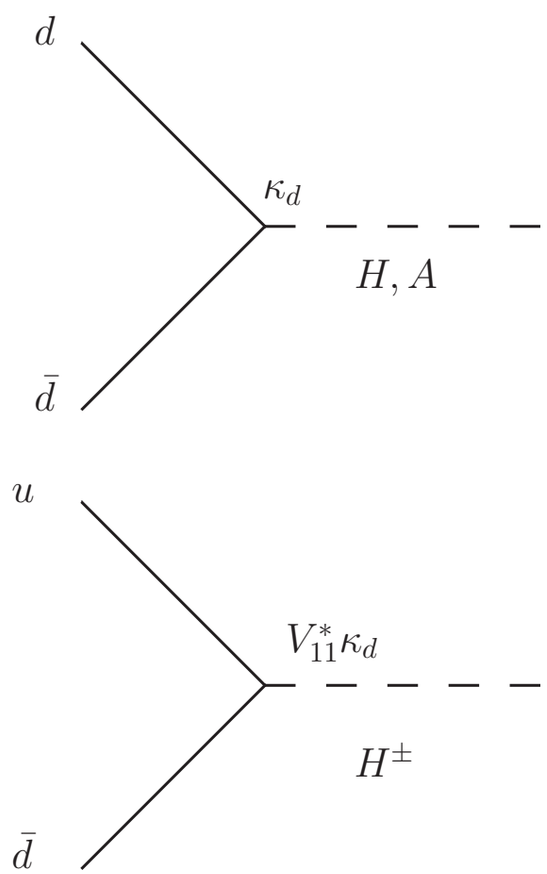
DEU, Homiller, Meade
arXiv: 1811.00017 (PRL 123.031802)
arXiv:1908.11375 (PRD 100.115041)

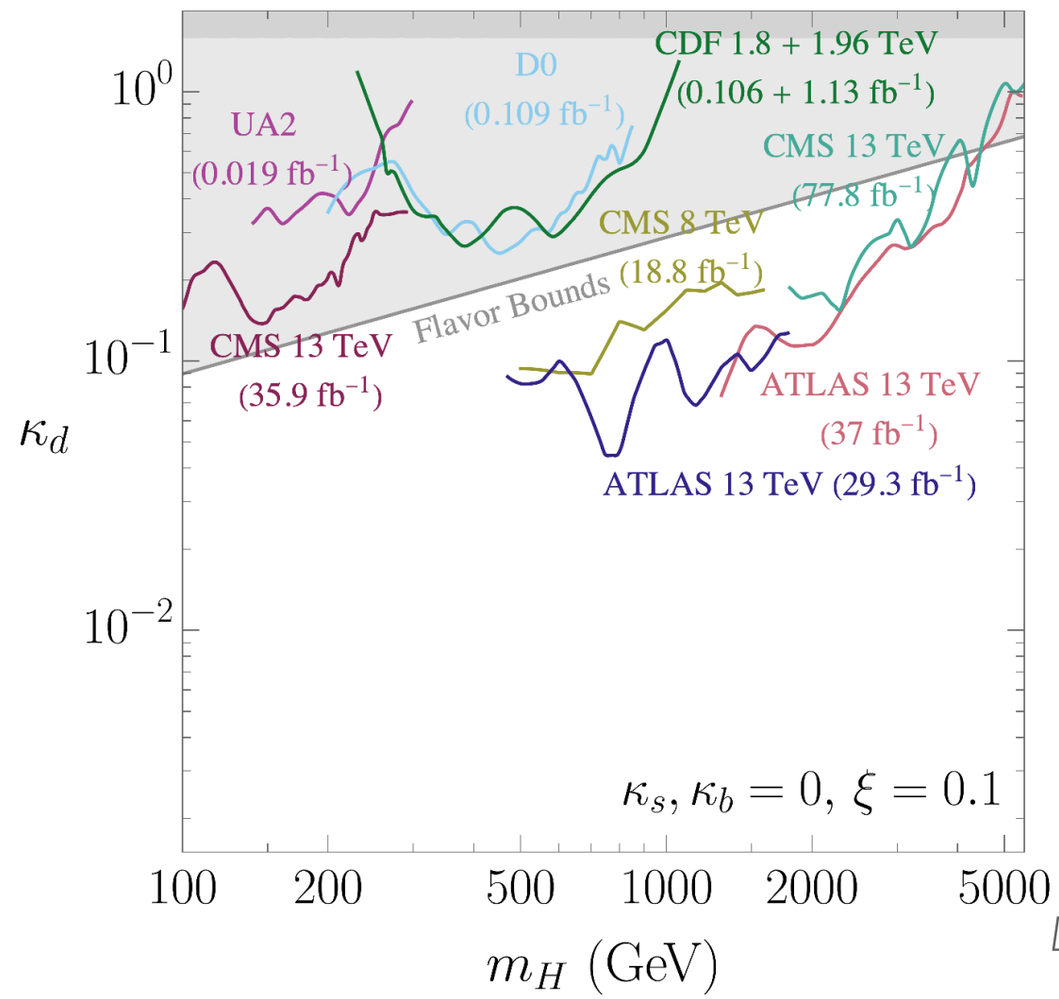
$$\kappa^u_{ij} = \xi \mathrm{diag}(m_u, m_c, m_t)/v$$

* *In quark mass eigenbasis*

LHC phenomenology
of extra scalars with large couplings to light quarks

LIMITS FROM DIJET SEARCHES



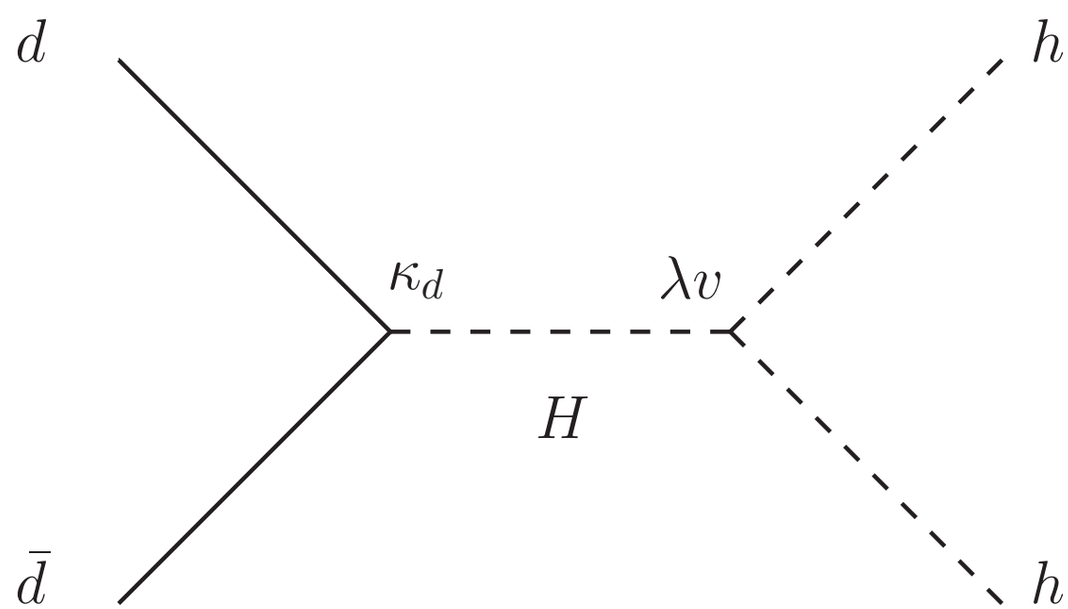


DEU, Homiller, Meade 1908.11376

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 at LHC/ ILC)

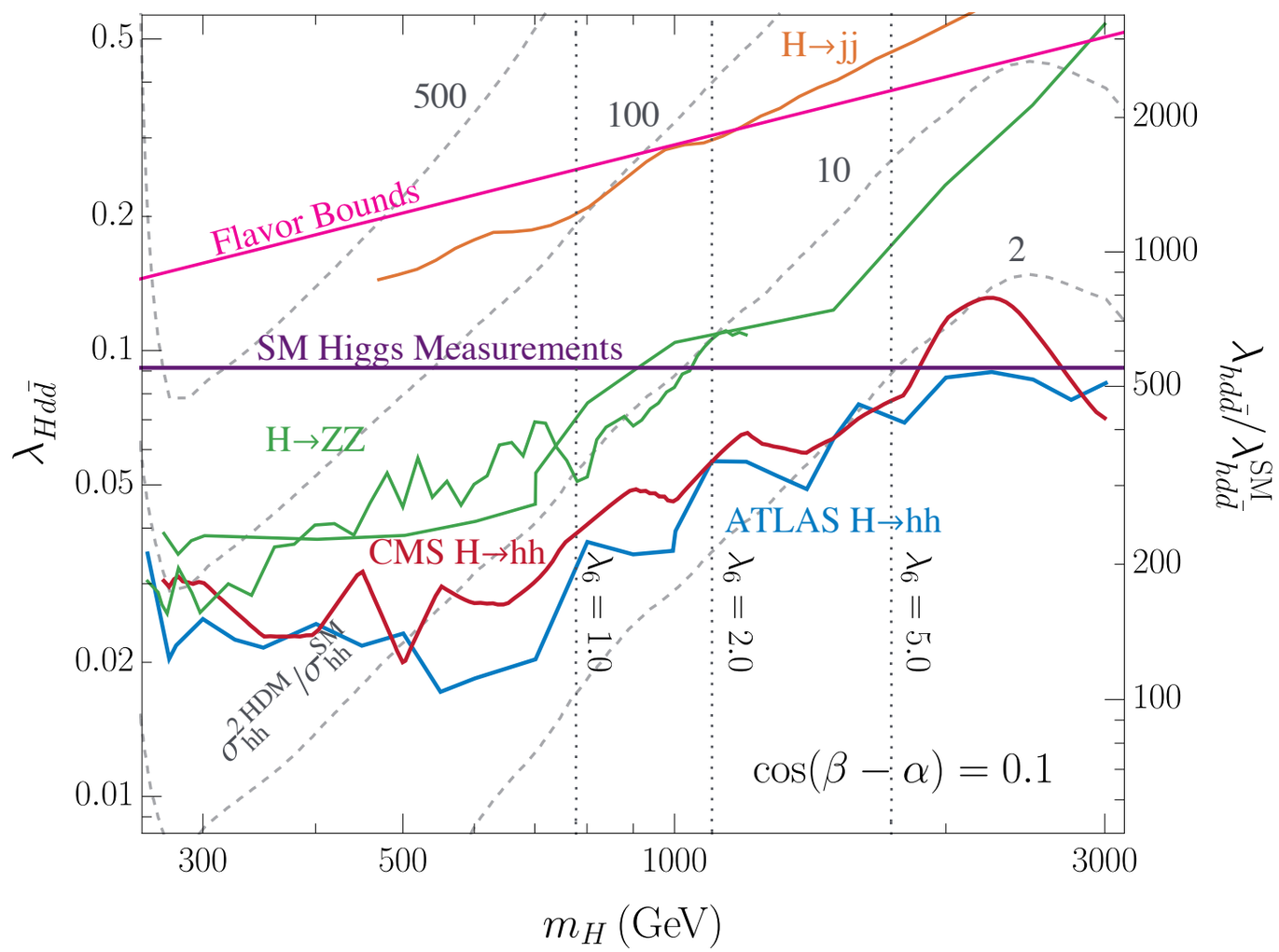
GIGANTIC DI-HIGGS RESONANT CROSS SECTIONS



LARGEST DI-HIGGS XSEC OF ANY KNOWN MODEL

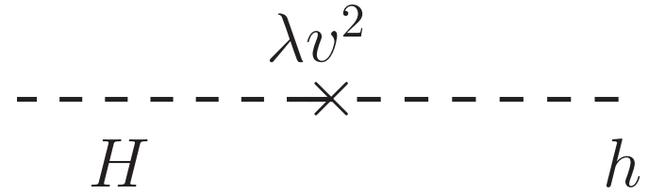
What are you actually testing with current LHC di-Higgs data?

The flavor of extended Higgs sectors

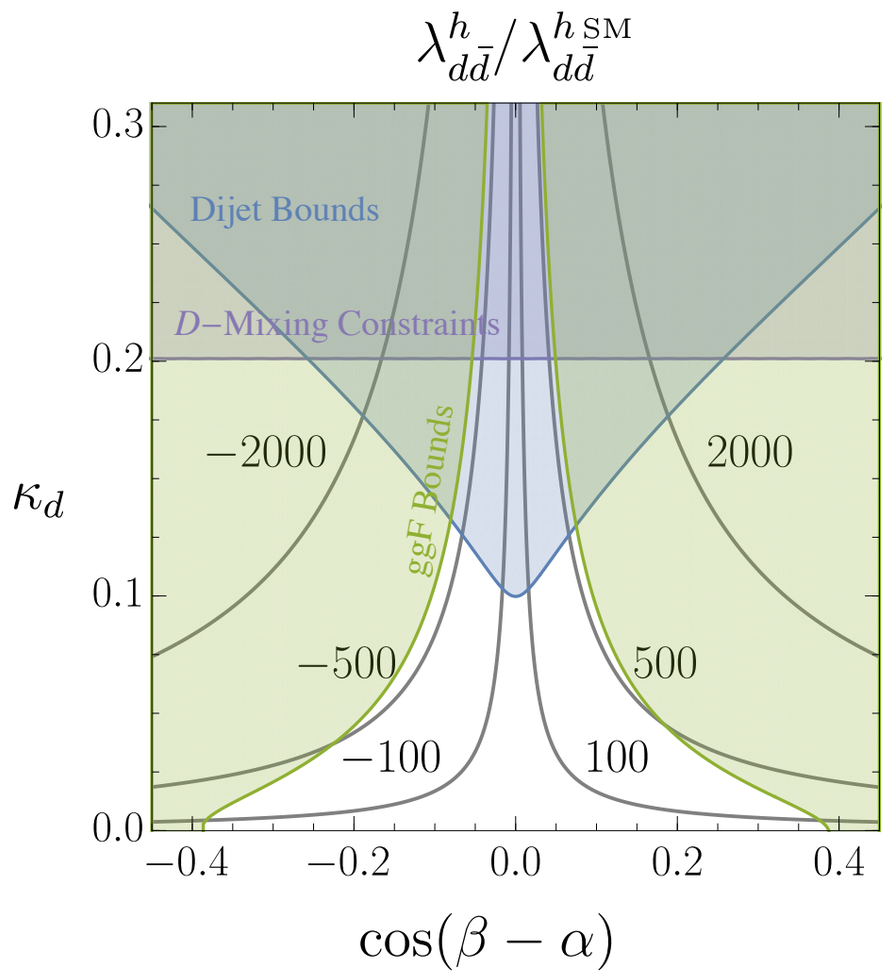


Preliminary:
DEU,
Homiller, Meade arXiv:xxxx

LARGE ENHANCEMENTS TO 125 GEV HIGGS YUKAWAS



DRAMATIC ENHANCEMENTS OF THE HIGGS YUKAWAS



DEU, Homiller, Meade 1908.11376

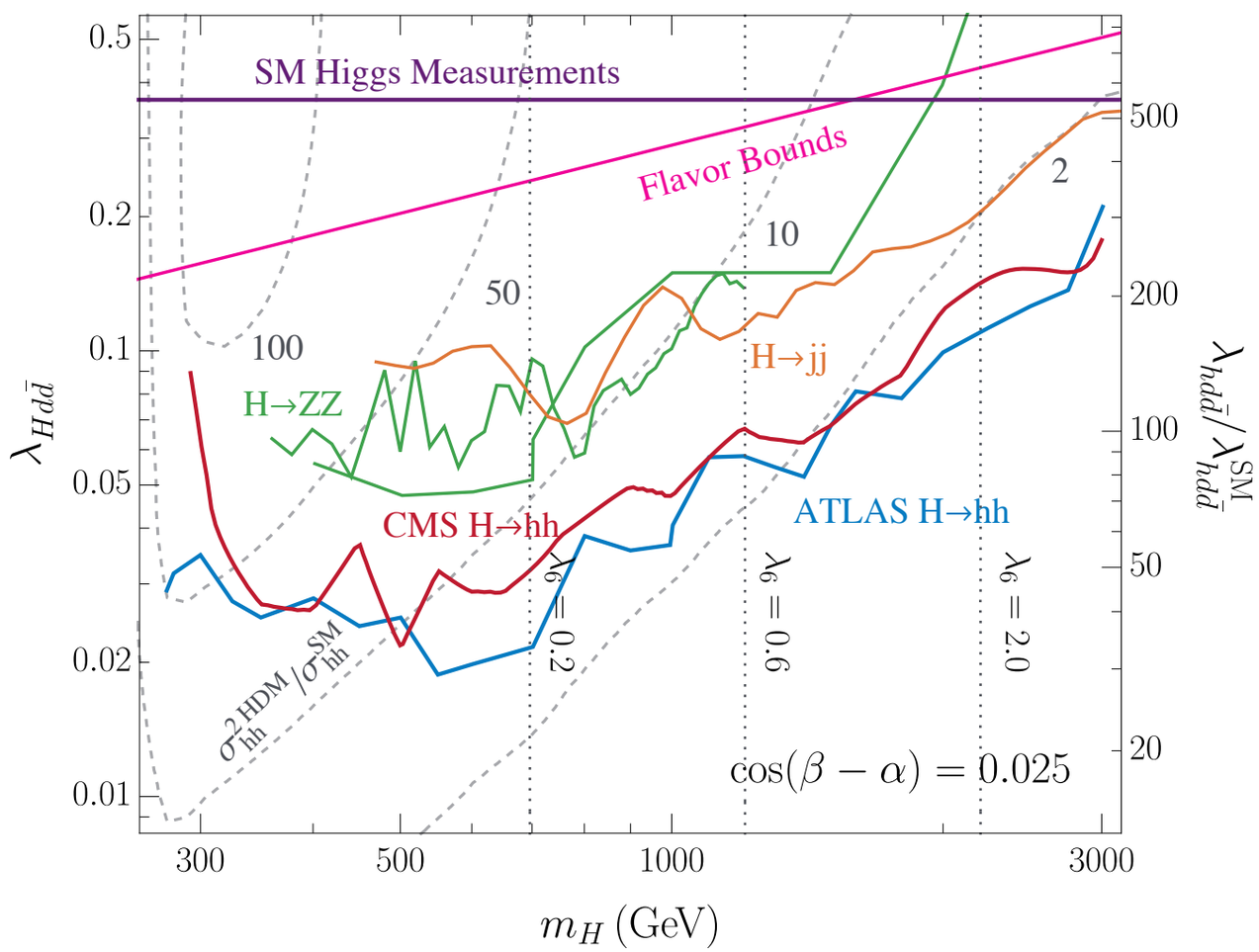
See also.
ILC TDR *1306.6352*
Kagan et.Al 1406.1722
Perez et.Al 1505.06689
Zhou 1505.06369
Brivio et.Al 1507.02916
Bishara et.Al 1606.09253
Soreq et.al 1606.09621
Duarte et.Al. 1811.09636
Coyle et.Al 1905.09360

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

DIHIGGS LIMITS ON ENHANCED YUKAWAS

What are you actually testing with current LHC di-Higgs data?
Enhanced 125 GeV Higgs Yukawas



Preliminary:
DEU,
Homiller, Meade arXiv:xxxx

SOME IDEAS FOR NEW SEARCHES

- SM Higgs rates with new quark-fusion production channels?

- Di-Higgs production with higgs to jets in final state?

CONCLUSIONS

- Extended Higgs sectors with large couplings to light quarks arise naturally in some flavor constructions.

- Their LHC phenomenology is *fantastic, and very different from what you're used to.*

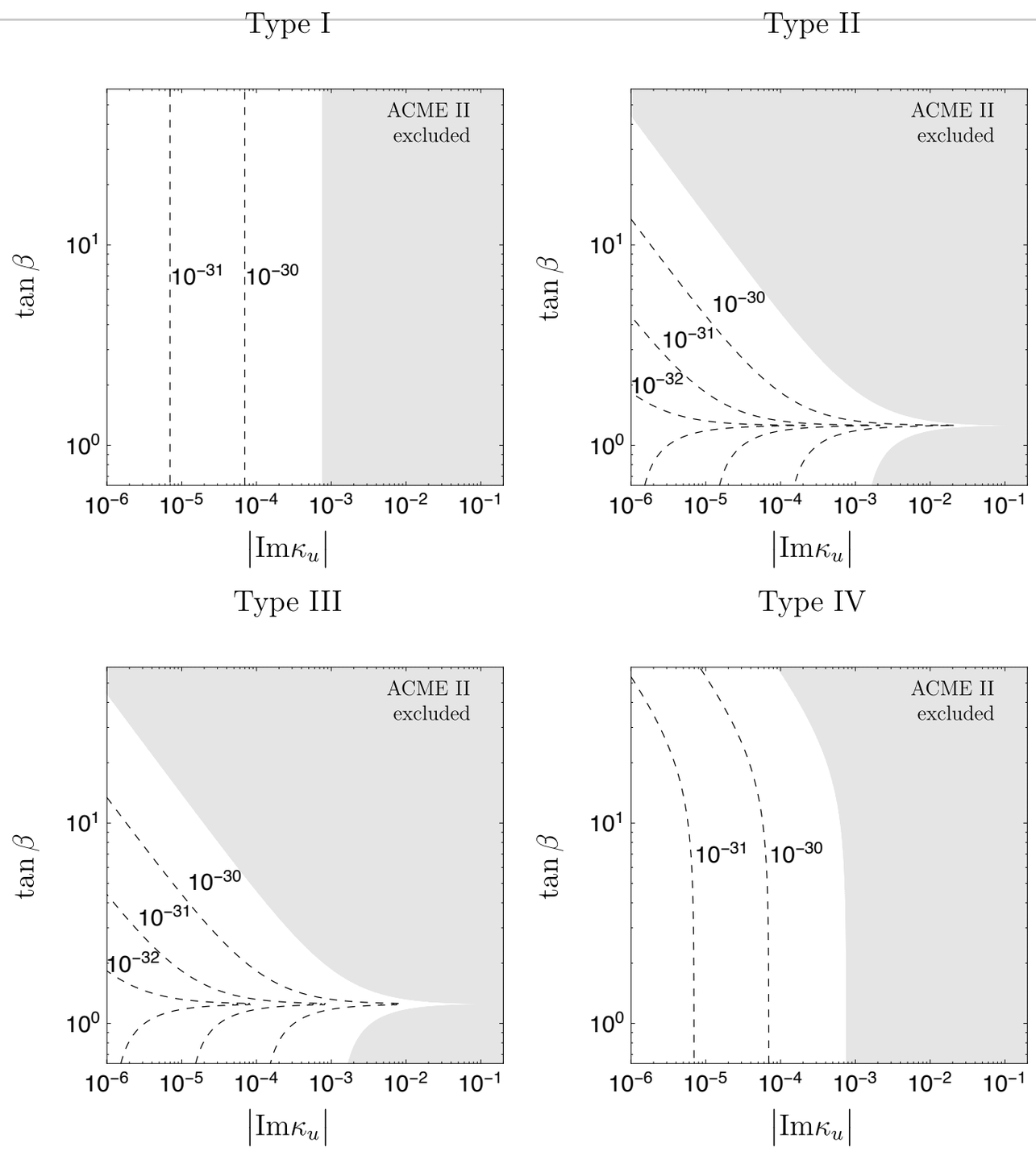
  - *Huge heavy Higgs LHC production rates*

  - *Gigantic dihiggs rates*

  - *Large enhancements of the light-quark SM Yukawas in a robust model.*

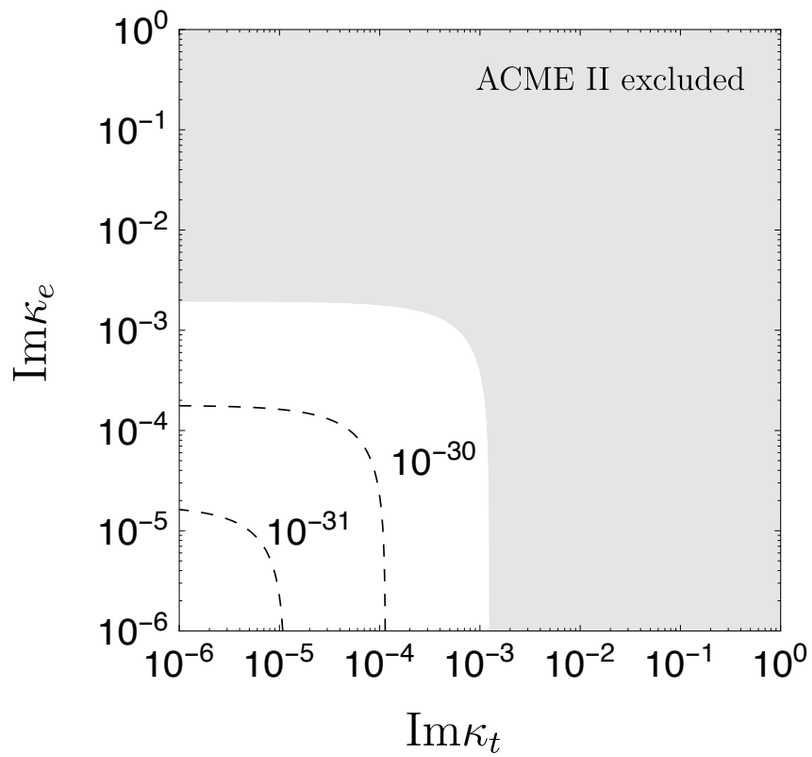
Backup

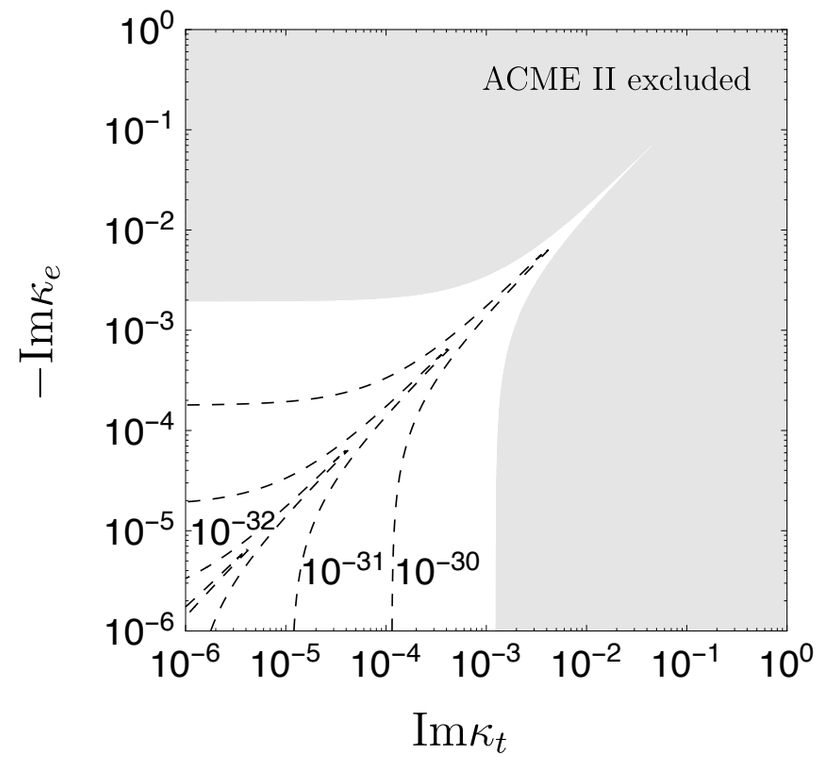
CP VIOLATION



DEU, S.Thomas
1810.08631

CP VIOLATION





DEU, S.Thomas
1810.08631

2HDMS ARE DEFINED BY THEIR YUKAWAS

SM Higgs doublet

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

$$\langle H^\dagger H \rangle = v^2$$

$$\lambda^u = V^T_{\rm CKM} {\rm diag}(m_u, m_c, m_t)/v \quad , \quad \lambda^d = {\rm diag}(m_d, m_s, m_b)/v$$

2HDMS ARE DEFINED BY THEIR YUKAWAS

SM Higgs doublet

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

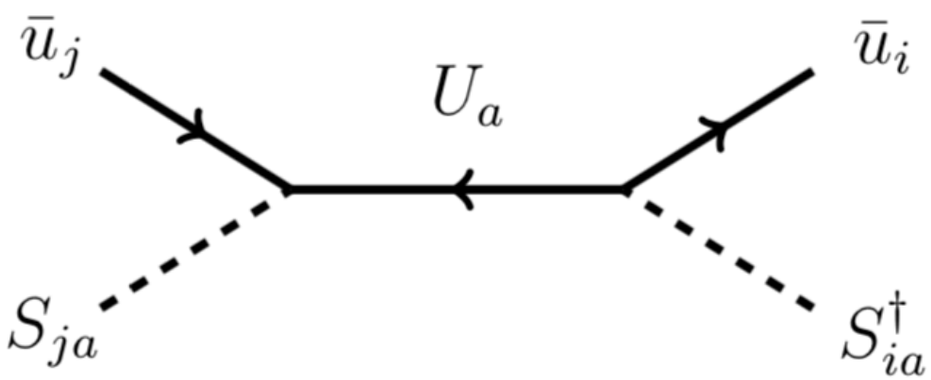
Second Higgs doublet

$$\kappa^u_{ij} Q_i H_2 \bar{u}_j + \kappa^d_{ij} Q_i H_2^c \bar{d}_j + V(H, H_2)$$

$$\left\langle H_2^\dagger H_2 \right\rangle = 0$$

AN EXAMPLE UV COMPLETION OF SFV

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



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

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

AN EXAMPLE SFV LAGRANGIAN

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

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

All Yukawas are <u>real diagonal</u>

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

CKM MATRIX FROM WAVE-FUNCTION RENORMALIZATION

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

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

• • • •

THE LIMITATION OF SFV: ONE-SECTOR ALIGNMENT

- 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

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

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

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

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

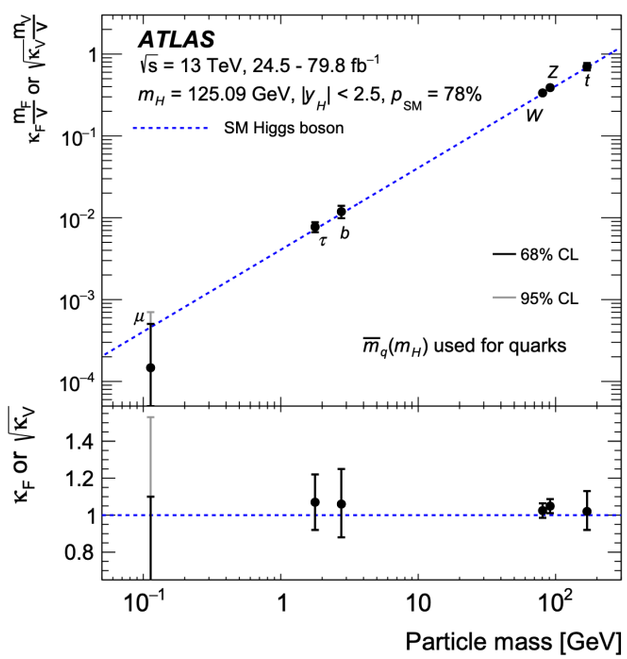
Operator	SFV factor
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	$C_D^1 = (V^* K_d^2 V^T)_{12}^2$ $C_K^1 = (V^T Y_u^2 V^*)_{12}^2$
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	$\Big[(V^T Y_u^2 V^* K^d)_{12}$ $(V^T Y_u^2 V^* K^d)_{21}^*\Big]$
$Q_2 H^c \sigma^{\mu\nu} \bar{d}_3 F_{\mu\nu}$	$\big[(V^T Y_u^2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

SFV STRONGLY SUPPRESSES FCNCS

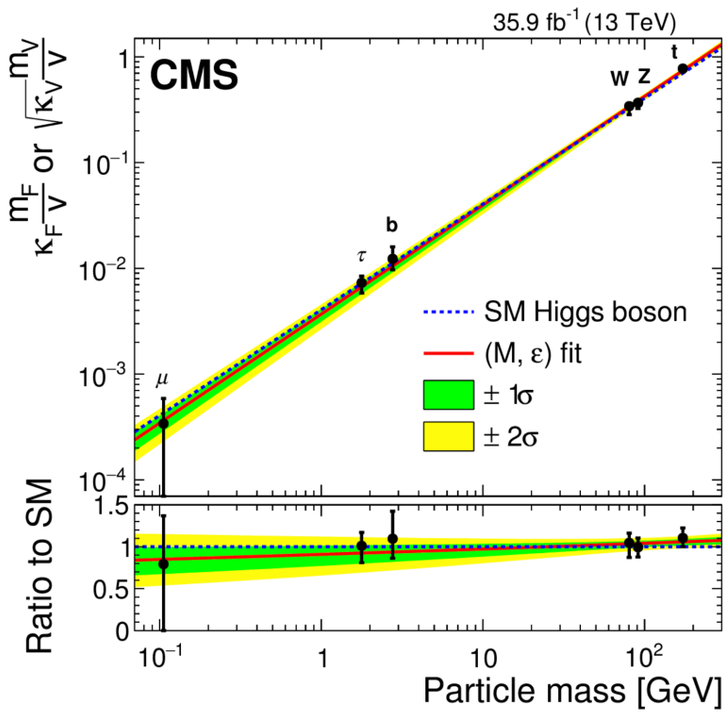
- Even if you allow for *any imaginable FCNC operator*, new physics close to the EW scale may preferentially couple to light quarks without being excluded by flavor bounds

Operator	$\Lambda_{\rm NP}^{\rm anarchic}$ [TeV]	$\Lambda_{\rm NP}^{\rm SFV}$ [TeV]	$\Lambda_{\rm NP}^{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	$1.5 \times 10^4{}_{\rm (Im)}$	$262.7\,\lvert\kappa_d^2 - \kappa_s^2\rvert$	5.1
$(Q_1 \bar{d}_3)(Q_3^\dagger \bar{d}_1^\dagger)$	$2.1 \times 10^3{}_{\rm (Abs)}$	$19.3\,\sqrt{\lvert\kappa_d \kappa_b\rvert}$	–
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	$2.4 \times 10^5{}_{\rm (Im)}$	$72.7\,\sqrt{\lvert\kappa_d \kappa_s\rvert}$	–
$2eH\sigma^{\mu\nu} Q_2\, \bar{d}_3\, F_{\mu\nu}$	$276.3_{\rm (Re)}$	$54.3\,\sqrt{\lvert\kappa_b\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar{d}_2\, F_{\mu\nu}$	$276.3_{\rm (Re)}$	$54.3\,\sqrt{\lvert\kappa_s\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar{d}_1\, F_{\mu\nu}$	$140.5_{\rm (Abs)}$	$13.2\,\sqrt{\lvert\kappa_d\rvert}$	7.0

We already know from the LHC that third-generation Higgs-fermion couplings look SM-like



1909.02845

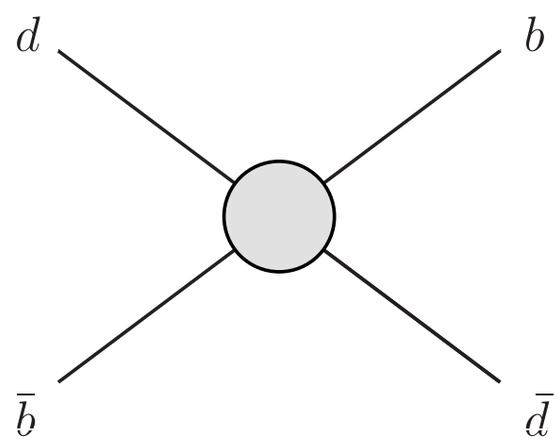


1811.09689

Does this mean that we cannot expect significant deviations in the first two generations?

FCNC SUPPRESSION DUE TO PATTERN OF FLAVOR BREAKING

- Such suppression can be easily seen from symmetries



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

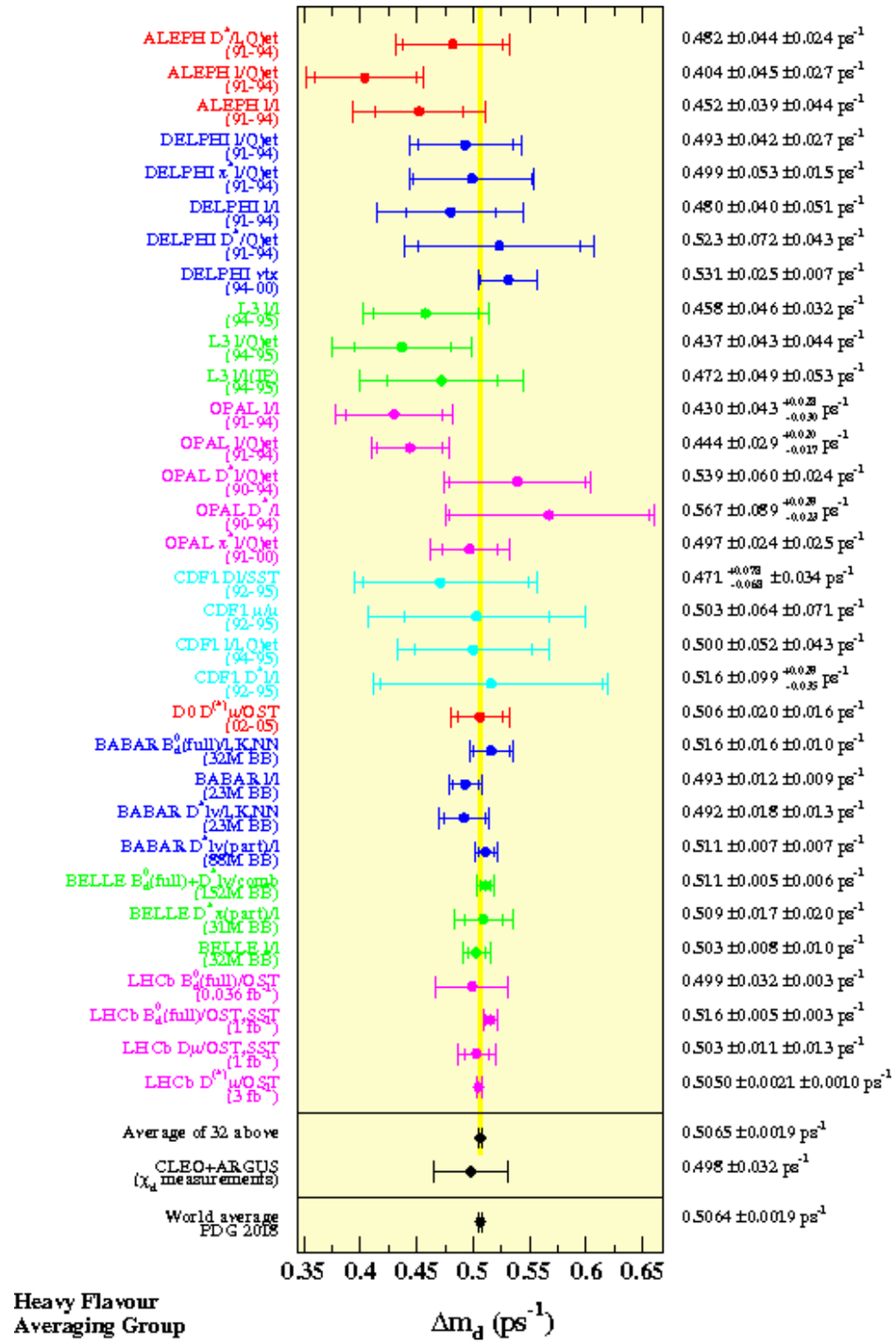
$$\downarrow$$

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

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

Yukawa, GIM and CKM suppression of FCNCs!

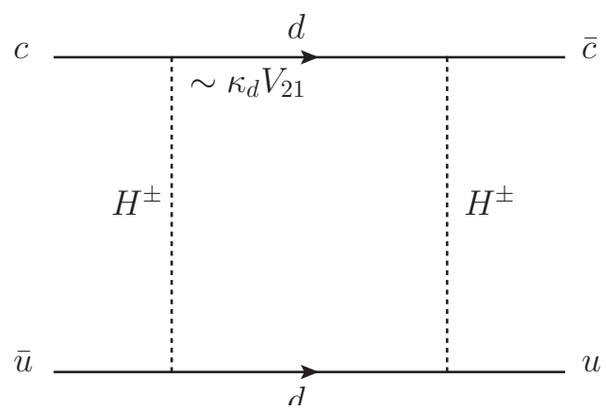
B MIXING SUMMARY



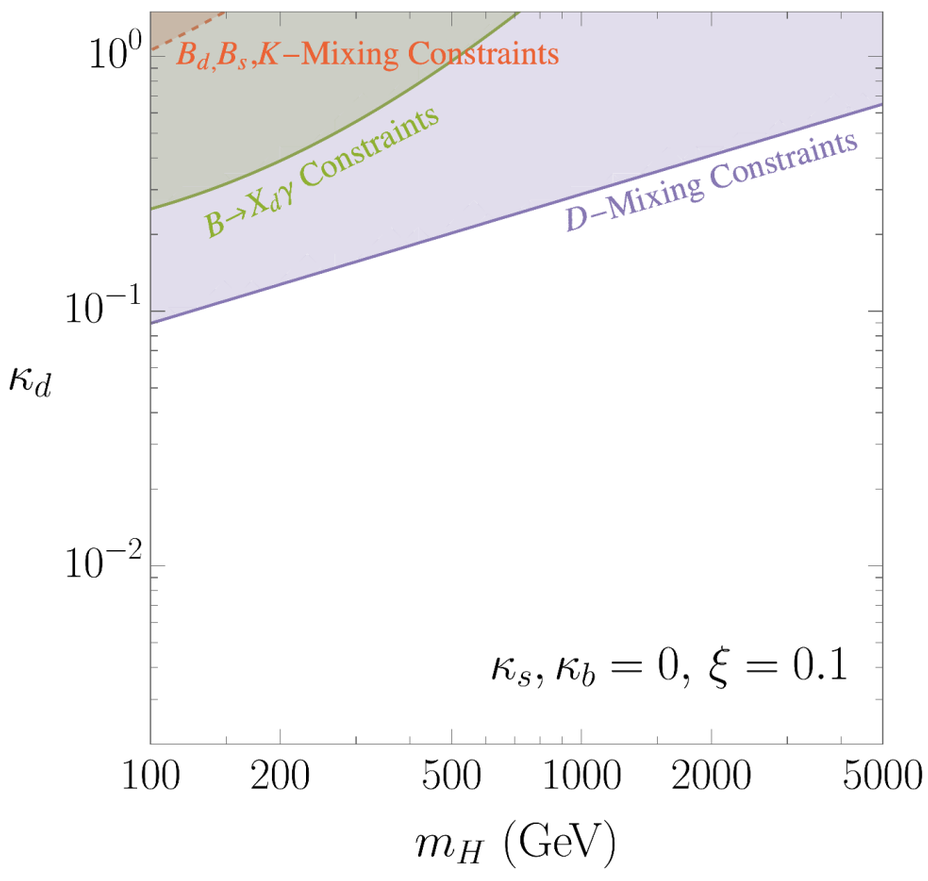
http://www.slac.stanford.edu/xorg/hflav/osc/PDG_2018/

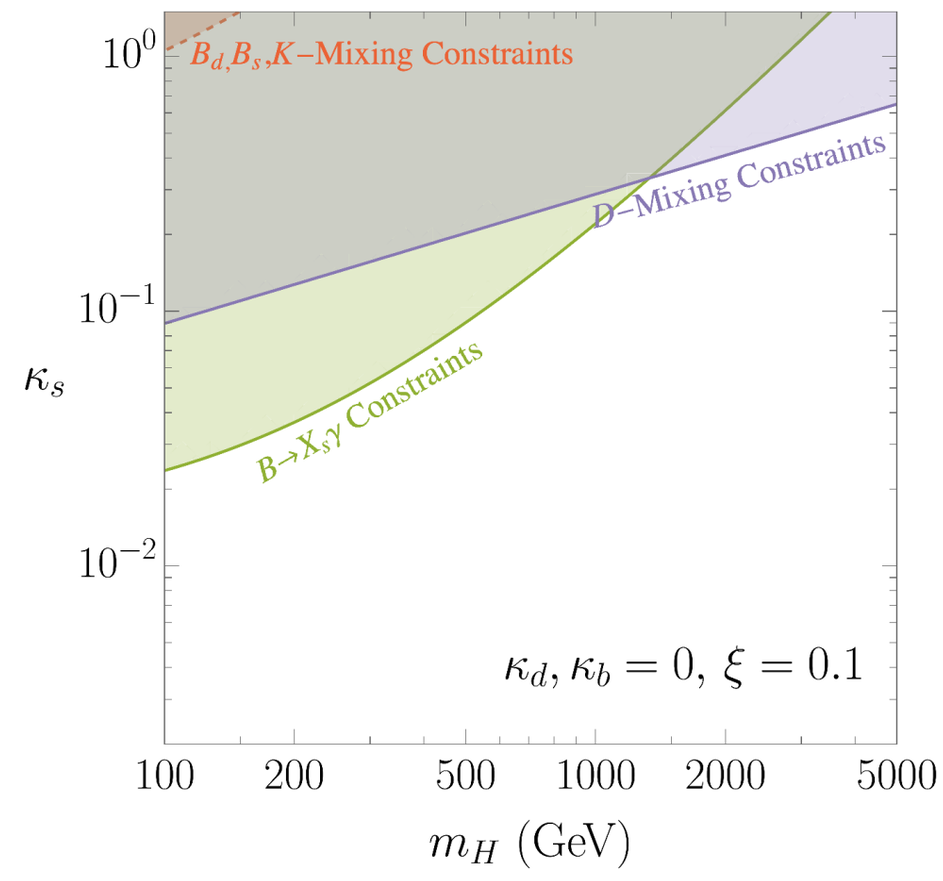
FLAVOR CONSTRAINTS ON THE UP TYPE SFV 2HDM

- A second Higgs doublet contains three Higgs bosons: $H, A, H^{\pm}$

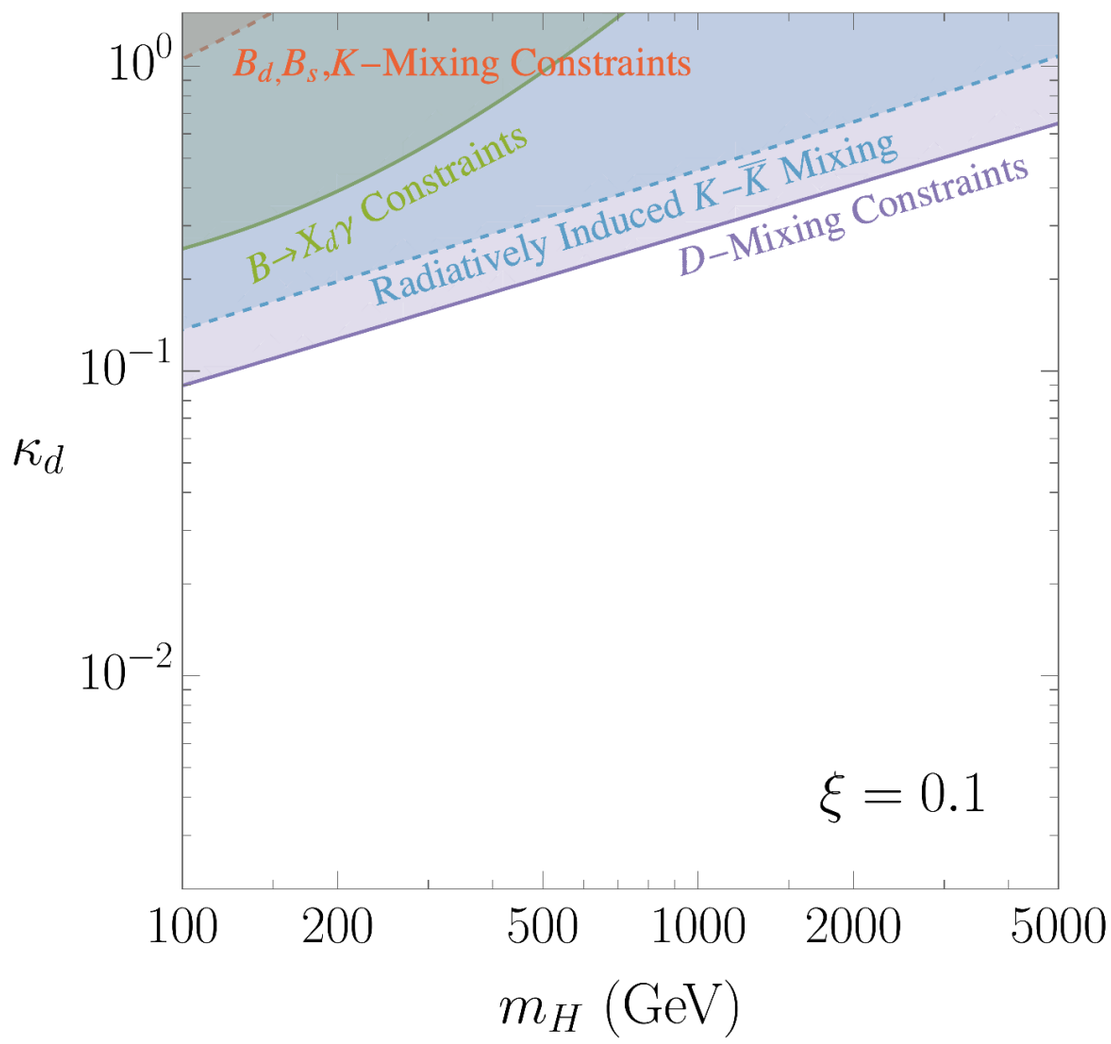


1-loop FCNCs





RADIATIVELY INDUCED FCNCS



UV SFV scale set at 100 TeV