HIGGS BOSONS WITH LARGE COUPLINGS TO LIGHT QUARKS

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and

arXiv:soon

In collaboration with

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Objective

Discuss models of new physics with large couplings to the first and second-generation quarks.

Focus on extended Higgs sectors: what I'll say applies also to other models

EXTENDED HIGGS SECTORS MAKE FLAVOR ASSUMPTIONS

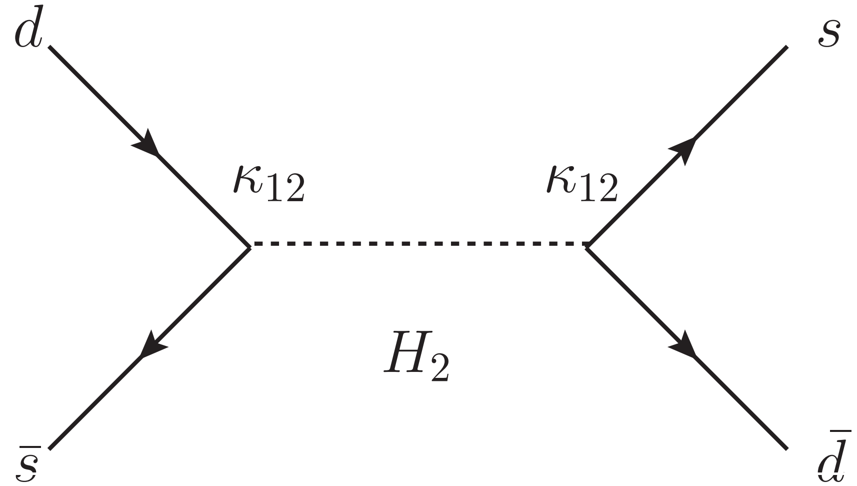
$$\boxed{\lambda^u_{ij} Q_i H \bar{u}_j - \lambda^{d\dagger}_{ij} Q_i H^c \bar{d}_j - \kappa^{d\dagger}_{ij} Q_i H^c_2 \bar{d}_j}$$

$$\lambda^u = V^T_{\mathrm{CKM}} Y^u = V^T_{\mathrm{CKM}} \mathrm{diag}(y_u, y_c, y_t)$$
$$\lambda^d = \mathrm{diag}(y_d, y_s, y_b)$$

Fixed by data

κ_d is a free matrix:
we <u>always</u> make an assumption
for its entries

CAN WE HAVE LARGE COUPLINGS IN THE FIRST GENERATIONS?



Strong limits from Kaon mixing:

$$m_H \gtrsim 10^4\,\mathrm{TeV}$$

$$\kappa^d_{ij} = \begin{pmatrix} \kappa_d & \times & \times \\ \times & \kappa_s & \times \\ \times & \times & \kappa_b \end{pmatrix}$$

Cannot set off-diagonal elements to zero: tuning

$$\lambda^u_{ij} = \begin{pmatrix} 10^{-5} & 10^{-3} & 10^{-2} \\ 10^{-6} & 10^{-3} & 10^{-2} \\ 10^{-8} & 10^{-4} & 1 \end{pmatrix}$$

THE SOLUTION IN THE MSSM, MFV AND OTHER POPULAR MODELS

- In the MSSM and 2HDM types I-IV, or in MFV theories, there is a symmetry-based solution (holomorphy, discrete symmetry or minimality)

$$\kappa_d \sim \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

Flavor-aligned, but proportional to SM Yukawas

Prediction: couplings <u>mostly along 3rd generation</u>

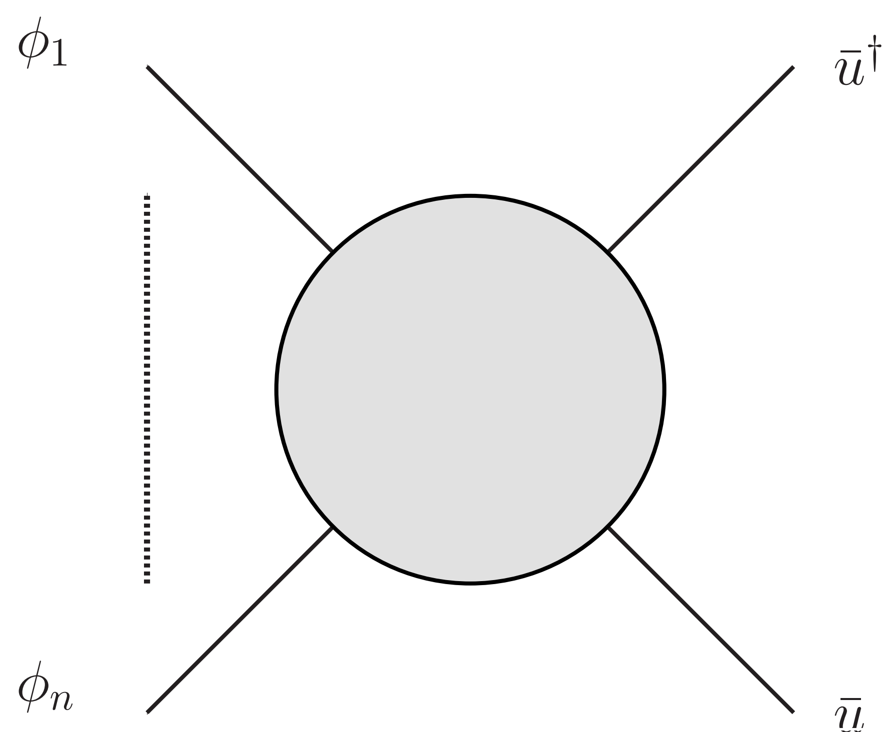
We propose a new solution to avoid large FCNCs:
Spontaneous Flavor Violation

It allows for large couplings
to light quarks

SPONTANEOUS FLAVOR VIOLATION (SFV)

CP/family number breaking sector → *Flavor preserving SM and BSM sector*

Upon spontaneous breaking of flavor



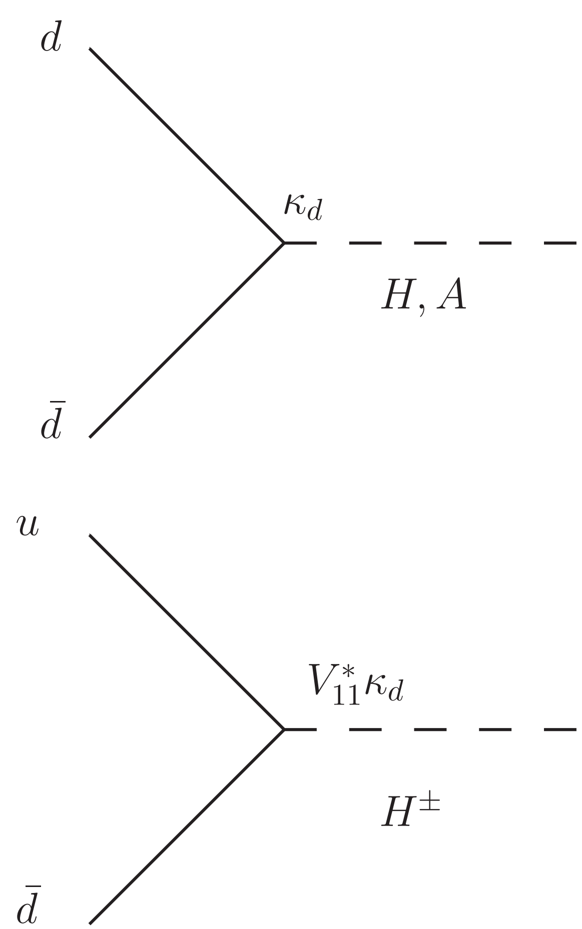
$$Z^u_{ij}\bar{u}_i^\dagger\bar{\sigma}^\mu D_\mu \bar{u}_j$$

DEU, Homiller, Meade
PRL 123, 3, 031802 (2019)

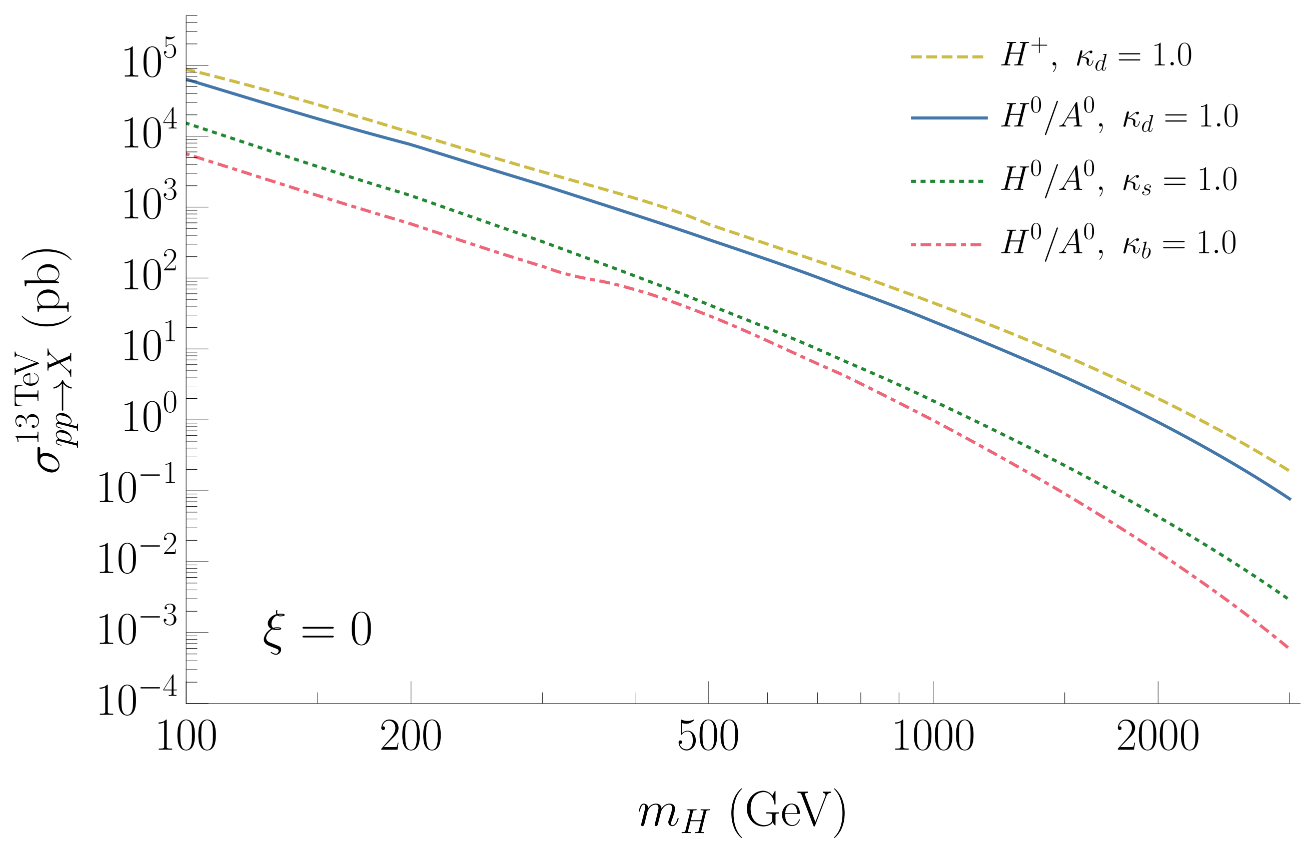
Phenomenology of Higgs bosons with large Couplings to light quarks

HIGGSES WITH LARGE COUPLINGS TO PROTONS!

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



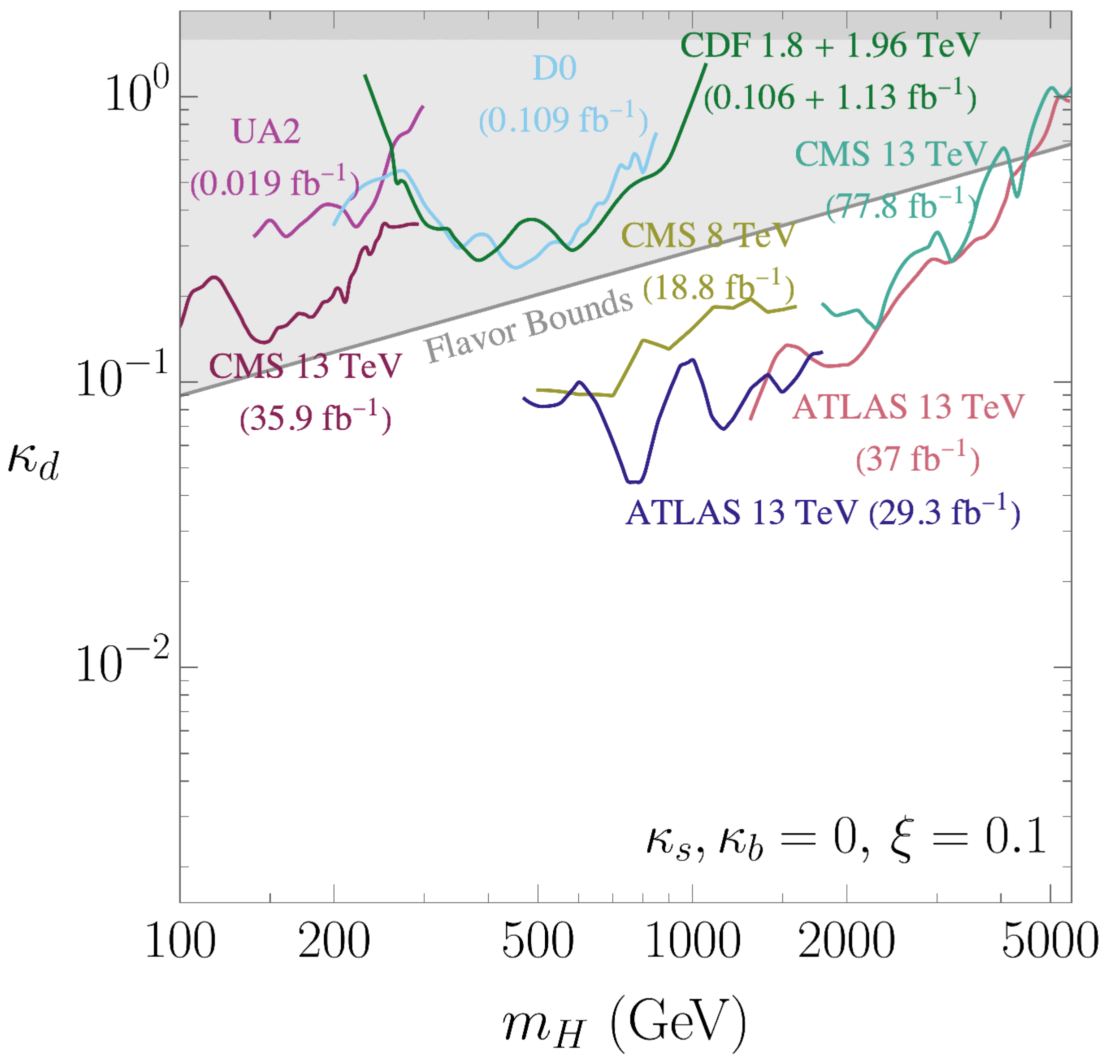
$$\sigma_{h\,SM}^{ggF} = 49\,\mathrm{pb}$$

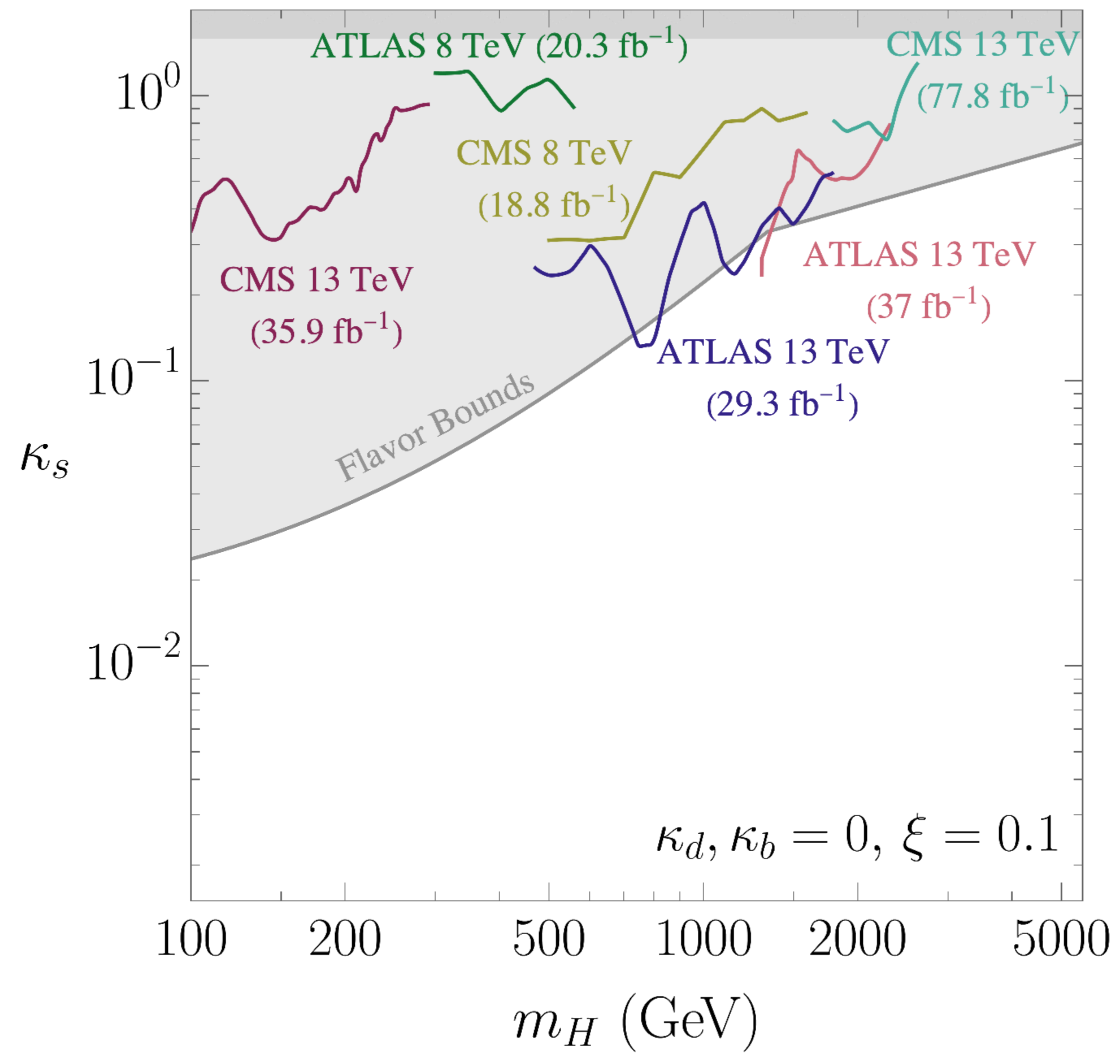


Typical production cross sections are much larger than for the SM Higgs

LIMITS FROM DIJET SEARCHES

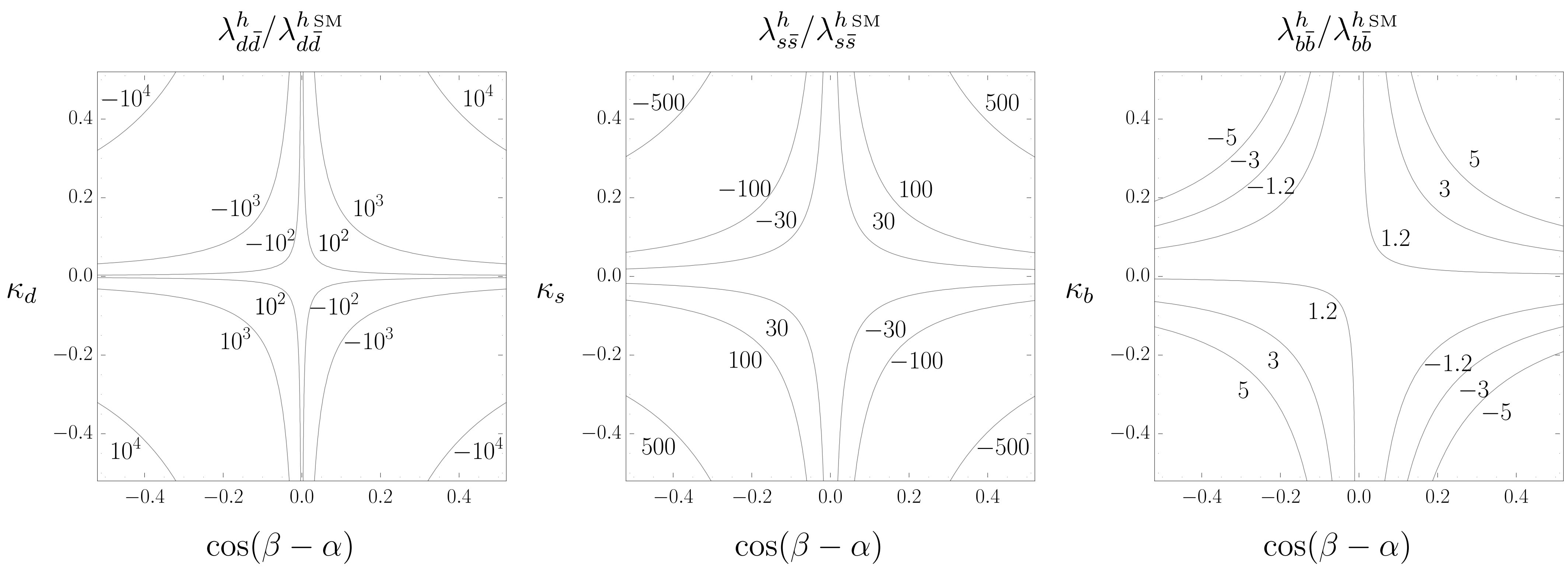
- Up-type SFV Higgses are copiously produced and decay to dijets





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

ENHANCEMENT OF THE SM HIGGS YUKAWAS



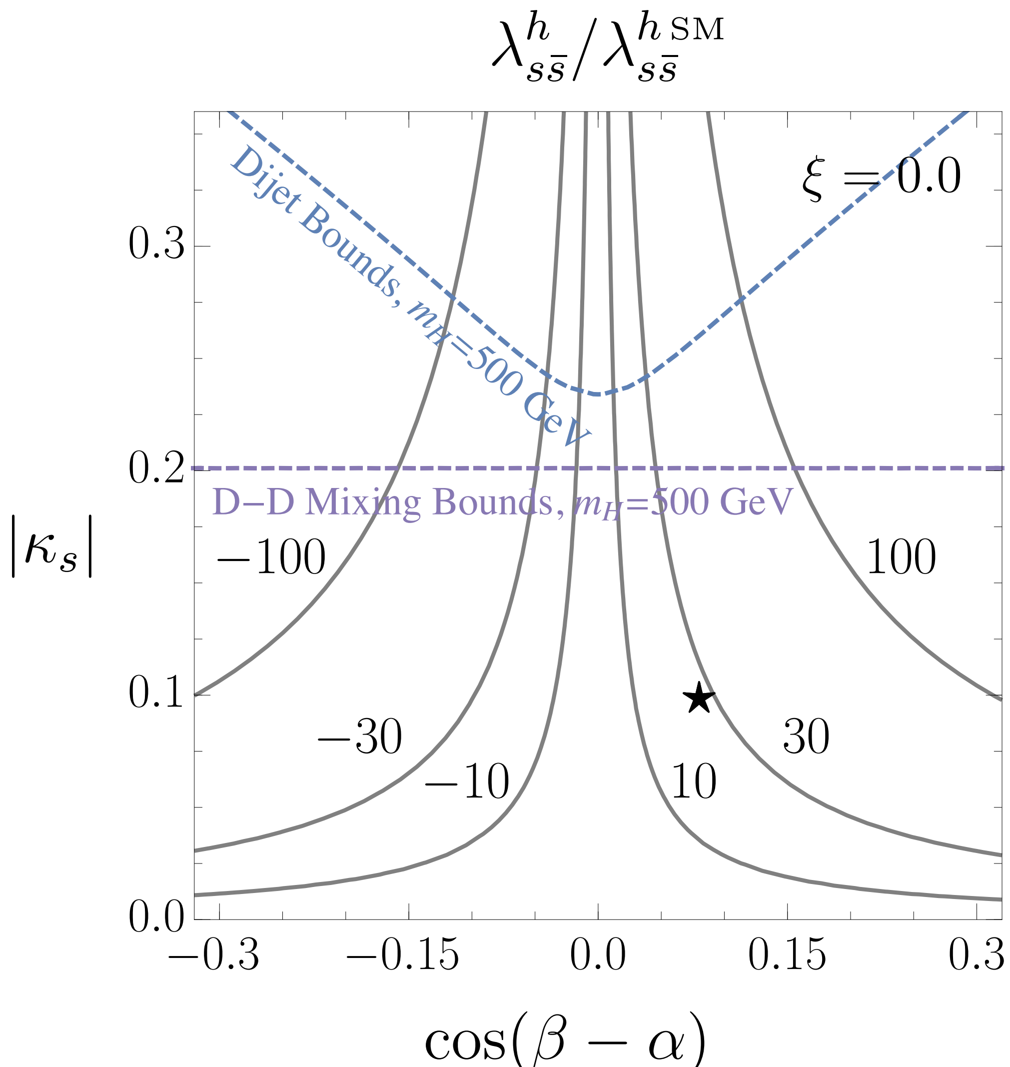
SFV leads to dramatic enhancements of the SM Higgs Yukawas

Enhanced Yukawas, see e.g.
ILC TDR 1306.6352
See also M. Peskin's talk
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

	$\lvert c_u \rvert$	$\lvert c_d \rvert$	$\lvert c_s \rvert$	$\lvert c_c \rvert$
Perturbation	$< 1.1 \times 10^5$	$< 5.1 \times 10^4$	< 2600	< 190
$\Gamma_H < 1.7$ GeV	$\lesssim 4.9 \times 10^4$	$\lesssim 2.4 \times 10^4$	$\lesssim 1200$	$\lesssim 88$
Ref. [19]	$2100 - 2800$	$930 - 1400$	$35 - 70$	

1406.1722 Kagan et.al.
1505.06369 Zhou

IT IS IMPORTANT TO HAVE A WORKING UV COMPLETION



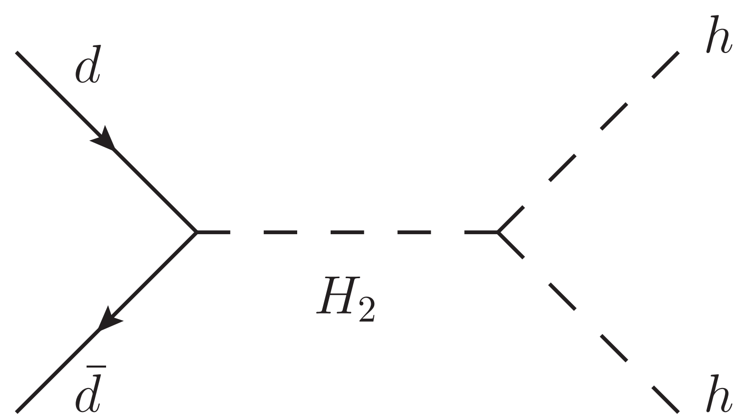
$$\mu_{ZH} = 0.93$$
$$\mu_{ggF} = 0.87$$
$$\mu_{VBF} = 0.88$$
$$\mu_{tth} = 0.85$$

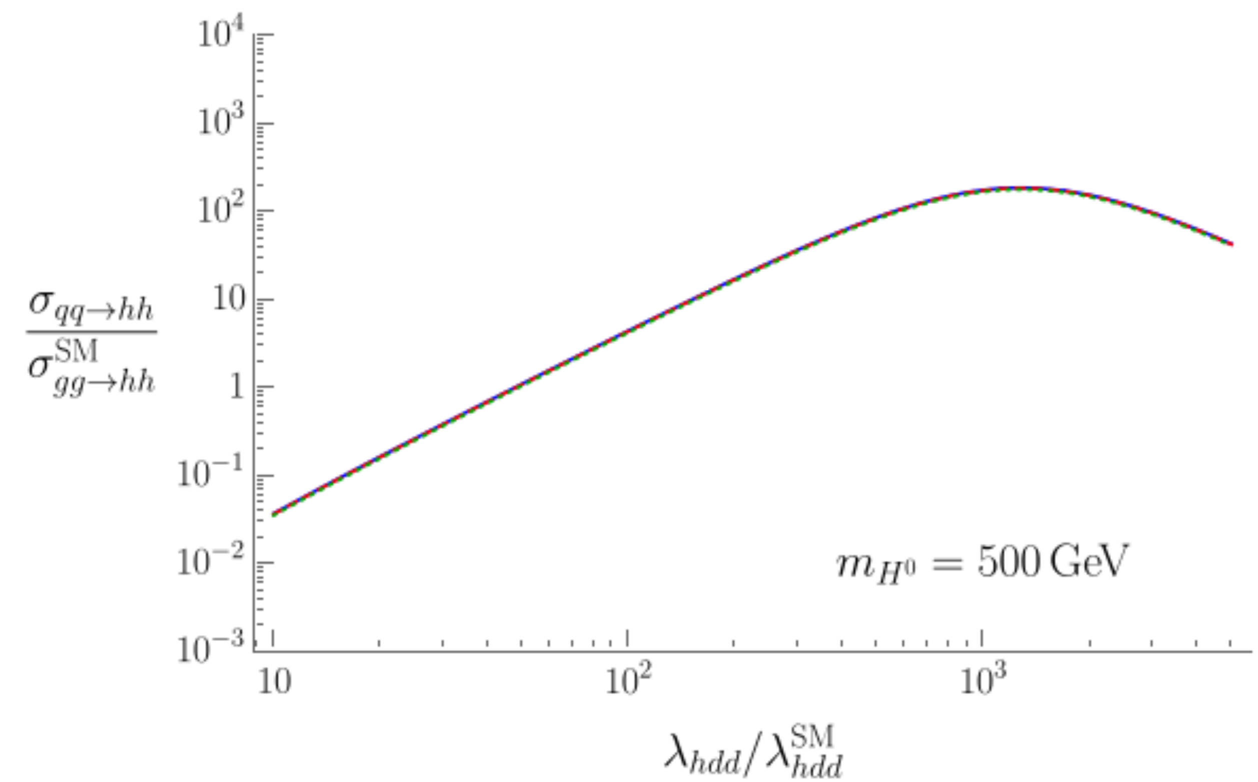
Consistent with ATLAS-CONF-2019-005, 80 fb^-1.
** also see 1905.09360.*

Without a full UV completion it is not possible to assess the viability of enhanced Higgs Yukawas

GIGANTIC ENHANCEMENT OF DI-HIGGS XSEC

- A new di-Higgs production mode: Higgs mediated quark fusion





Strong limits may be set with current data! (work in progress)

And ILC 500 (M. Peskin's talk), HE-LHC 1811.02572 & others

CONCLUSIONS

- Models with large couplings to light quarks are may be motivated by UV constructions *while keeping consistency with flavor bounds*

- Extra Higgses with such couplings lead to fantastic signatures, including significant enhancements to Higgs Yukawas testable at LHC and ILC!

SFV strongly motivates developing searches for each specific quark generation, which require jet taggers for each single quark of the Standard Model.

E.g. Fraser, Schwartz, 1803.08066
Duarte el.Al. 1811.09636
(strange tagging at ILC)

AN EXAMPLE UP-TYPE SFV LAGRANGIAN

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

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

All Yukawas are <u>real diagonal</u> by definition of SFV

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

CKM MATRIX FROM WAVE-FUNCTION RENORMALIZATION

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

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

• •

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

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

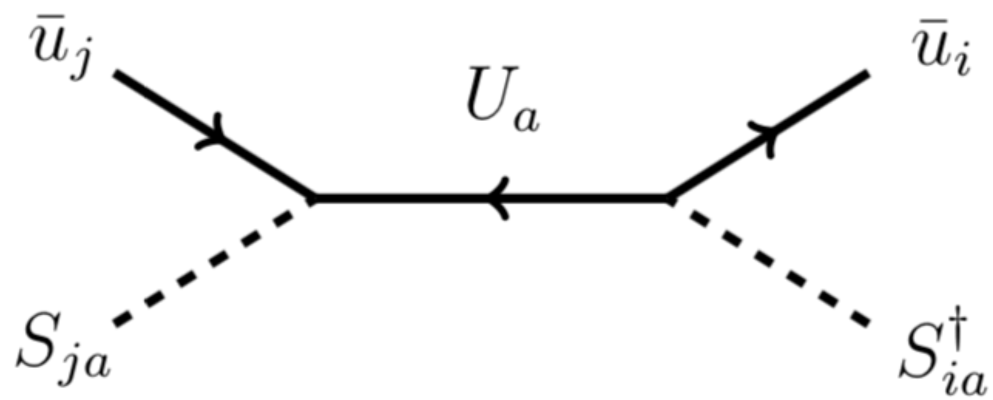
A new type of 2HDM: the up-type SFV 2HDM

AN EXAMPLE UV COMPLETION OF SFV

- Such a setup is easily realized by mixing right-handed up quark with heavy vector-like quarks

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

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



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

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

SFV in the Standard Model EFT

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

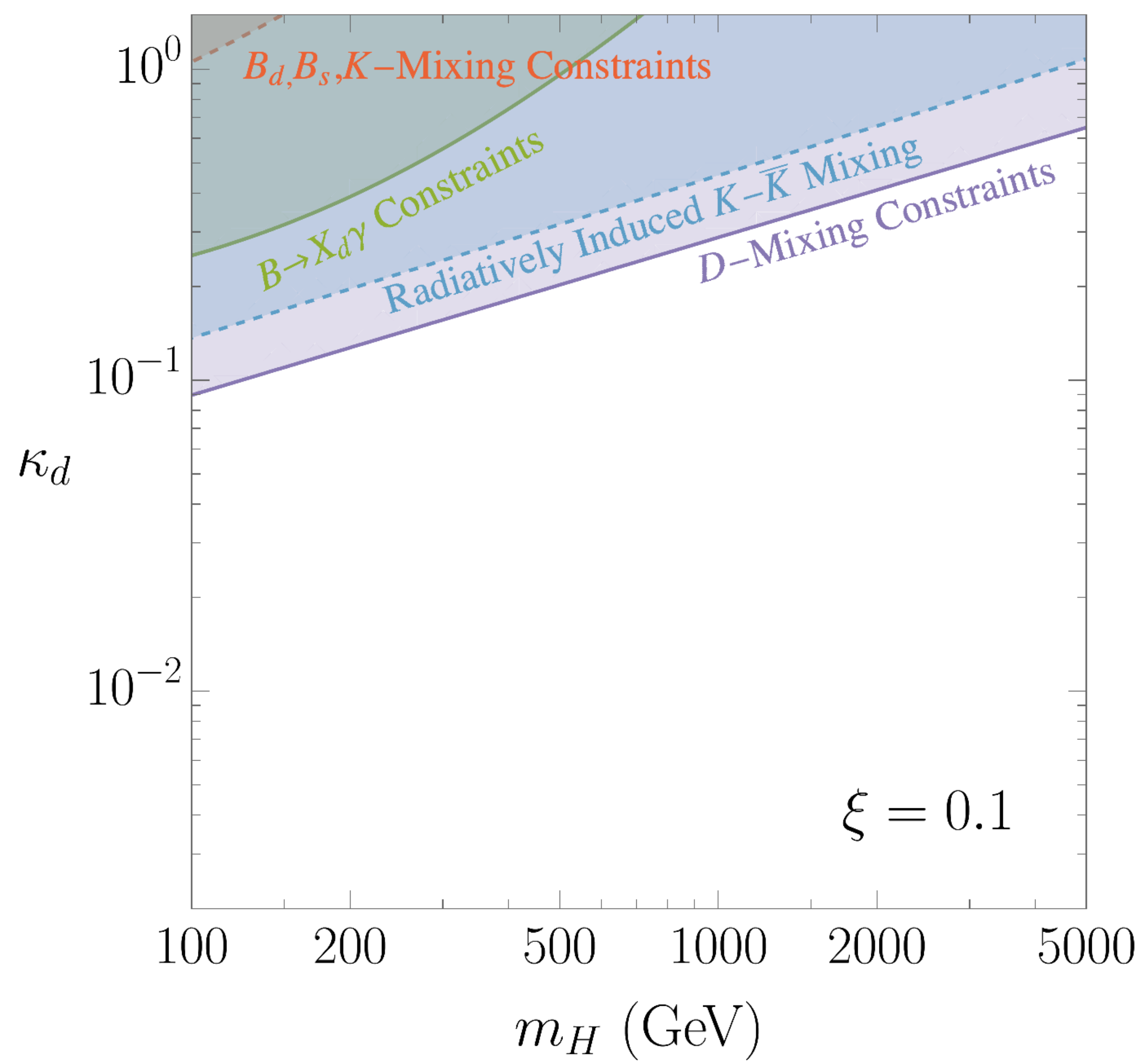
Operator	SFV factor
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	$C_D^1 = (\,V^* K_d^2 V^T\,)_{12}^2$ $C_K^1 = (\,V^T Y_u^2 V^*\,)_{12}^2$
$(Q_1 \bar{d}_2)(Q_2^\dagger\, \bar{d}_1^\dagger)$	$\Big[(V^T Y_u^2 V^* K^d)_{12}\,(V^T Y_u^2 V^* K^d)_{21}^*\Big]$
$Q_2 H^c\, \sigma^{\mu\nu} \bar{d}_3\, F_{\mu\nu}$	$\big[\,(V^T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

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

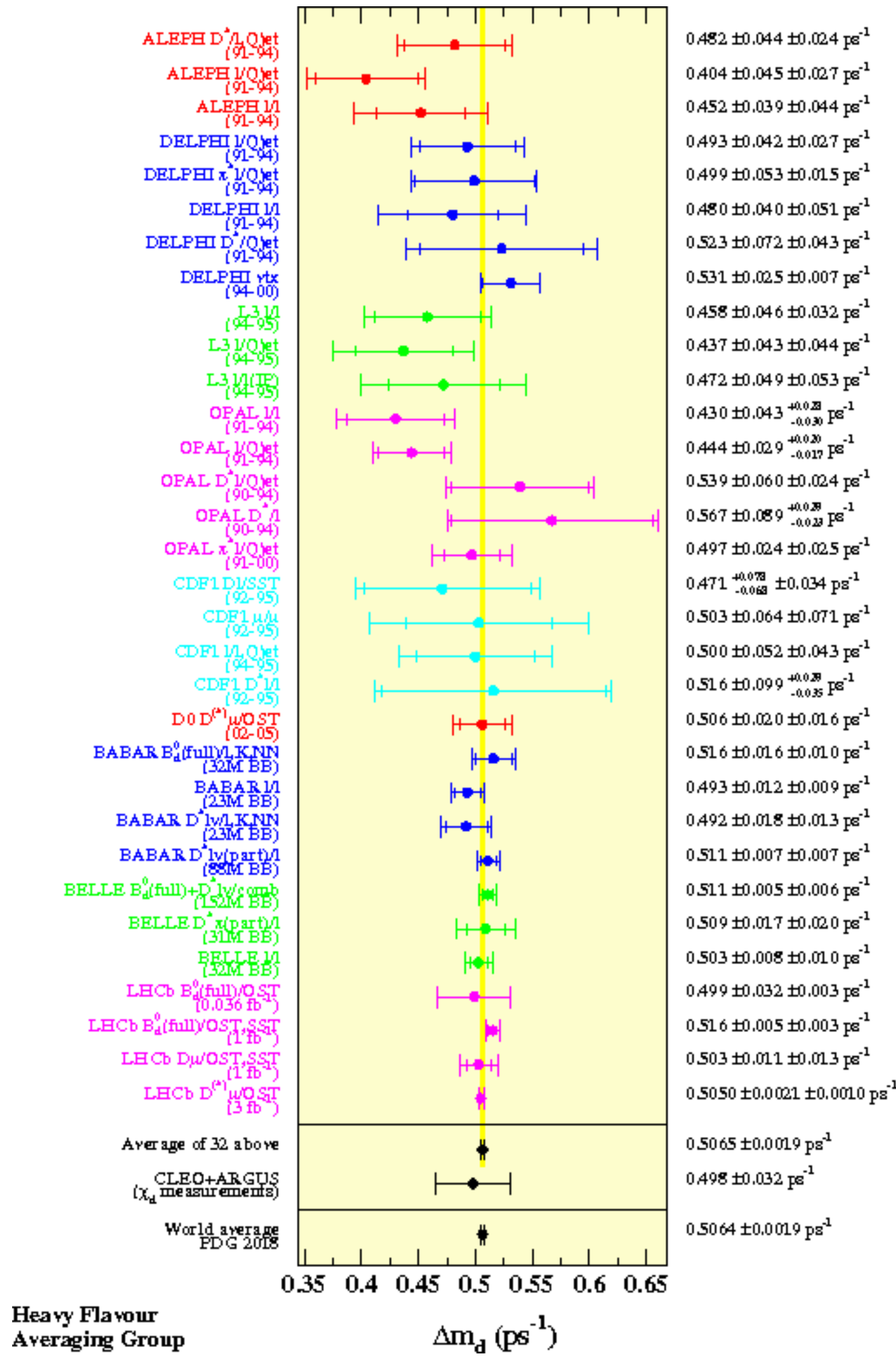
Operator	$\Lambda_{\rm NP}^{\rm anarchic}$ [TeV]	$\Lambda_{\rm NP}^{\rm SFV}$ [TeV]	$\Lambda_{\rm NP}^{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	1.5×10^4 (Im)	$262.7\,\lvert\kappa_d^2 - \kappa_s^2\rvert$	5.1
$(Q_1 \bar{d}_3)(Q_3^\dagger \bar{d}_1^\dagger)$	2.1×10^3 (Abs)	$19.3\,\sqrt{\lvert\kappa_d \kappa_b\rvert}$	–
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	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

RADIATIVELY INDUCED FCNCS

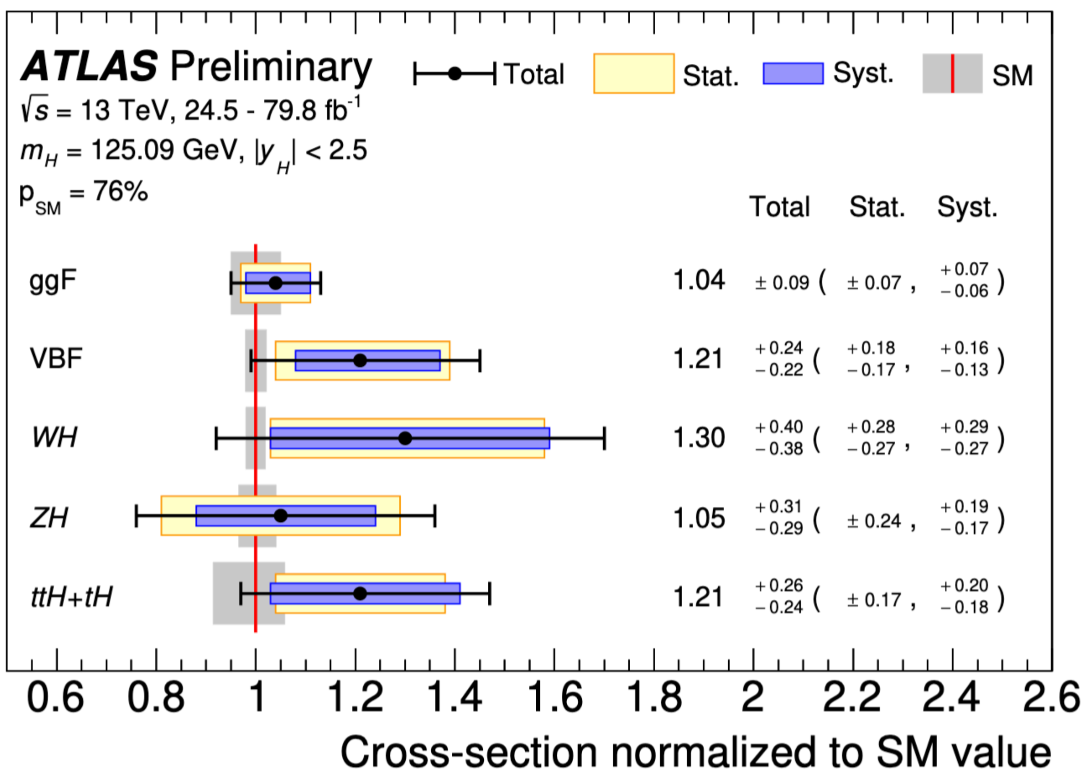


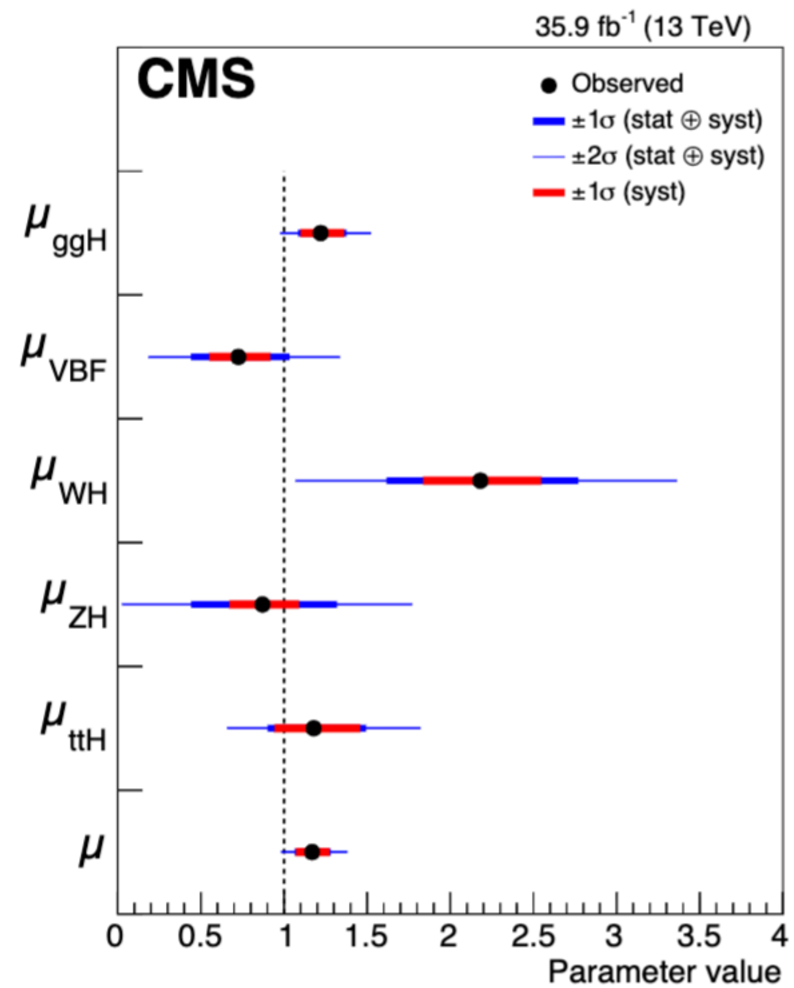
UV SFV scale set at 100 TeV

B MIXING SUMMARY



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


ATLAS Preliminary
Total
Stat.
Syst.
SM
√s = 13 TeV, 24.5 - 79.8 fb-1
mH = 125.09 GeV, |yH| < 2.5
pSM = 76%
Total Stat. Syst.
ggF 1.04 ± 0.09 (± 0.07 , +0.07 −0.06)
VBF 1.21 +0.24 −0.22 (+0.18 −0.17 , +0.16 −0.13)
WH 1.30 +0.40 −0.38 (+0.28 −0.27 , +0.29 −0.27)
ZH 1.05 +0.31 −0.29 (± 0.24 , +0.19 −0.17)
ttH+tH 1.21 +0.26 −0.24 (± 0.17 , +0.20 −0.18)
0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6
Cross-section normalized to SM value


35.9 fb-1 (13 TeV)
CMS
Observed
±1σ (stat ⊕ syst)
±2σ (stat ⊕ syst)
±1σ (syst)
μggH
μVBF
μWH
μZH
μttH
μ
0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value