SPONTANEOUS FLAVOR VIOLATION

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The main questions
In the quest for new physics are:

1. Which new physics?

2. How does it couple to the Standard Model?

We will discuss *our theoretical expectations/assumptions* for the couplings of new physics to quarks. This is of great importance for LHC searches.

Are we missing BSM physics because of theory bias?

PLAN OF THIS TALK

1. Review typical expectations on the couplings of new physics to quarks, and the *Minimal Flavor Violation* Ansatz.

2. In MFV new physics couples preferentially to third-generation quarks. We will show how a new flavor Ansatz, "*Spontaneous Flavor Violation*", overcomes this limitation.

3. We will study the phenomenology of an example SFV theory, a theory of extra Higgs bosons that couple strongly to light quarks.

Expectations of the couplings of new physics to quarks and collider search strategies

Murillo, Mujeres en la Ventana

GAUGE SYMMETRIES AND FAMILY-UNIVERSAL COUPLINGS

I. Gauge symmetries

- Couplings to quarks are fixed by hypercharge, weak, color and other gauge charges of the NP field.

- Kinetic/gauge interactions respect an accidental SM flavor symmetry:

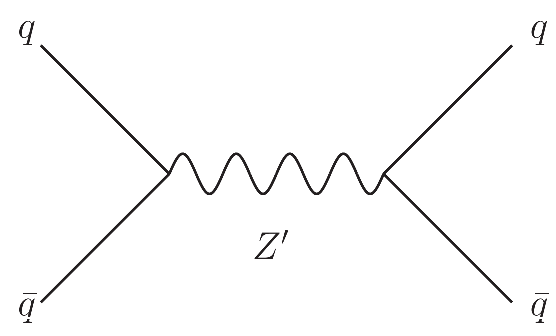
	$U(3)_Q$	$U(3)_{\bar{u}}$	$U(3)_{\bar{d}}$
Q	3		
$\bar{u}$		3	
$\bar{d}$			3

The SM quark flavor group

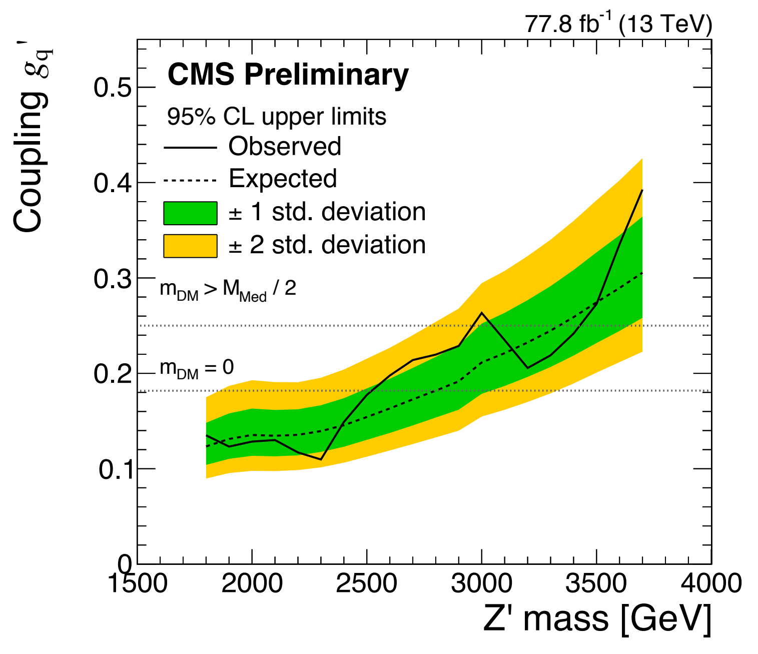
- As a consequence, in this case it is predicted that NP couples universally to the three quark generations.

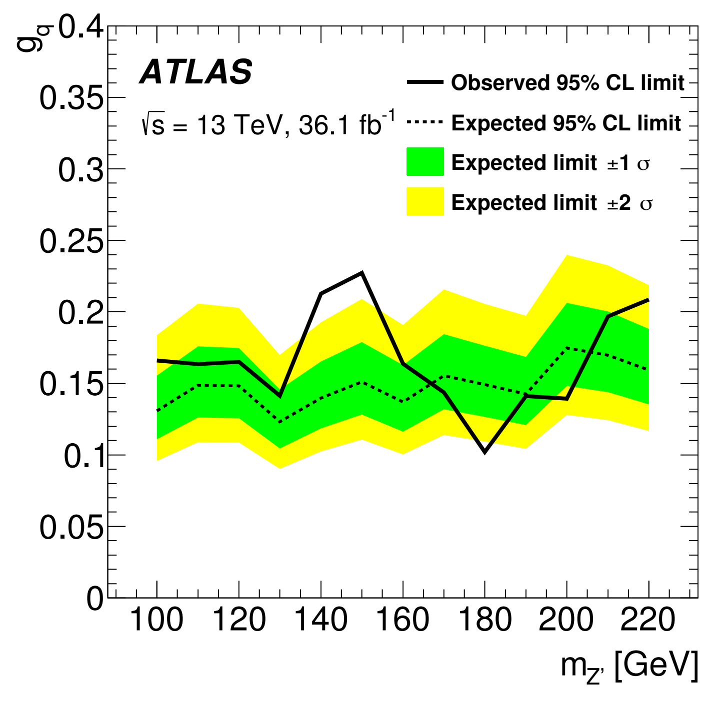
GAUGE SYMMETRIES AND FAMILY-UNIVERSAL COUPLINGS

Example: extra gauge bosons $g\left(d^{\dagger}\bar{\sigma}^{\mu}d\right)Z'^{\mu}$



Clear search strategy at LHC





FLAVOR BREAKING AND FAMILY NON-UNIVERSAL COUPLINGS

2. Flavor breaking

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

$$\lambda^u = V^T_{\rm CKM} Y^u \quad , \quad \lambda^d = Y^d \qquad Y^{u,d} = \frac{\sqrt{2}}{v} \mathrm{diag}(m_{u,d}, m_{c,s}, m_{t,b})$$

Yukawas are responsible for:

1. Breaking of mass degeneracy
2. Family number breaking

$$t \to s, b \to c...$$

FLAVOR BREAKING AND FAMILY NON-UNIVERSAL COUPLINGS

- For new physics, what should we write for the flavored couplings?

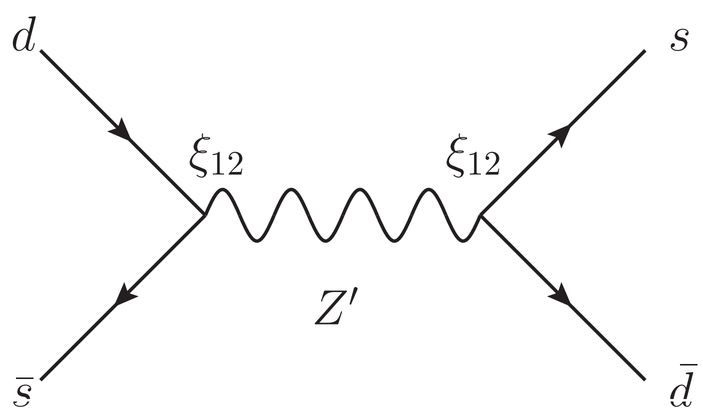
$$\kappa_{ij}^{d\dagger}\, Q_i \bar{d}_j H_2^c \quad , \quad \xi_{ij}\left(d_i^\dagger \bar{\sigma}^\mu d_j\right) Z'_\mu$$

Assumptions need to be made
to study the corresponding BSM phenomenology.
This affects our LHC search strategies!

THE MOST NAIVE ASSUMPTION: FLAVOR ANARCHY

- Example: Z' with flavor-changing couplings

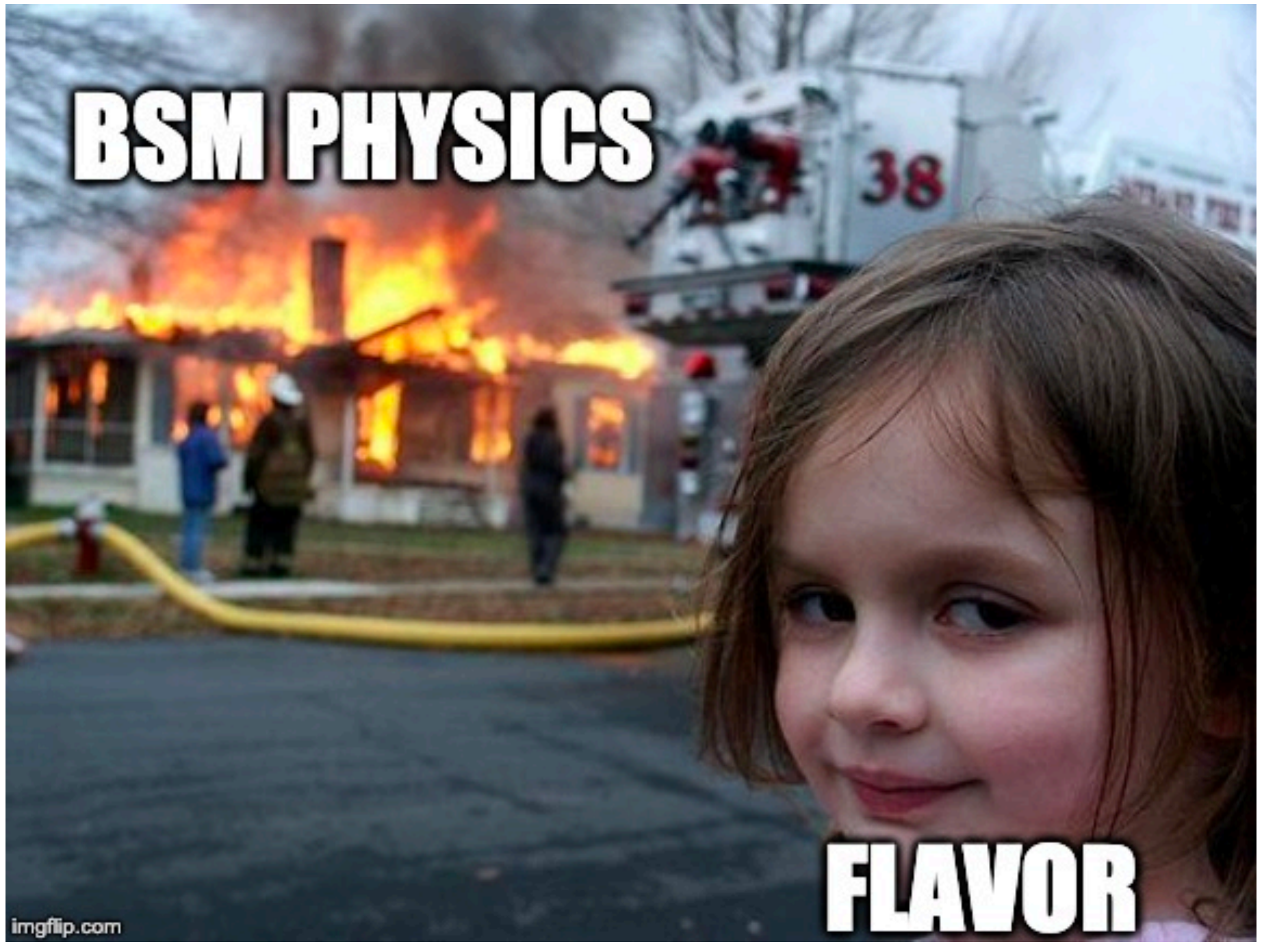
$$\xi_{12}\left(d_1^\dagger \bar{\sigma}^\mu d_2\right) Z'_\mu$$



Mixing of $K-\bar{K}$ *mesons*

- For O(1) couplings, limits on $K-\bar{K}$ mixing require $m_{Z'} \geq 10^4\ \mathrm{TeV}$

- Naive flavor assumption generically problematic for BSM physics!

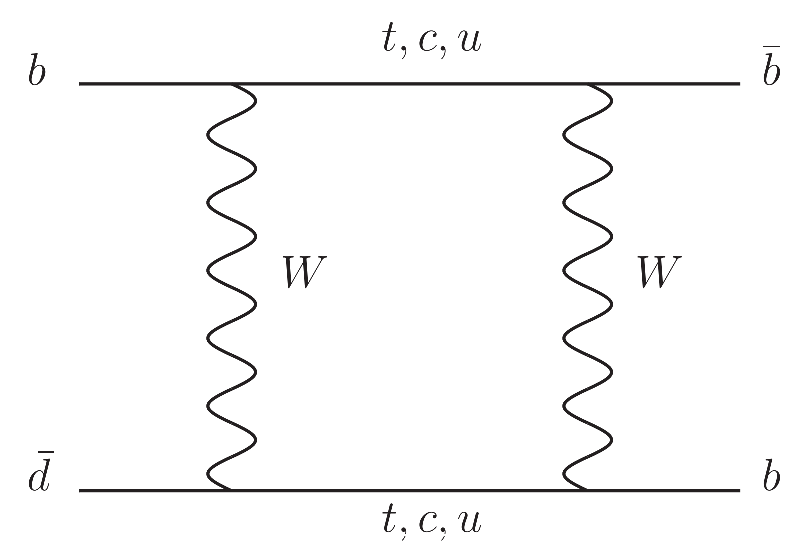


We must give up on new physics at the EW scale,
or we need to work on our flavor assumptions.

The simplest assumption:
Minimal Flavor Violation

FCNC'S ARE STRONGLY SUPPRESSED IN THE SM

- Example: mixing of B-mesons in the Standard Model

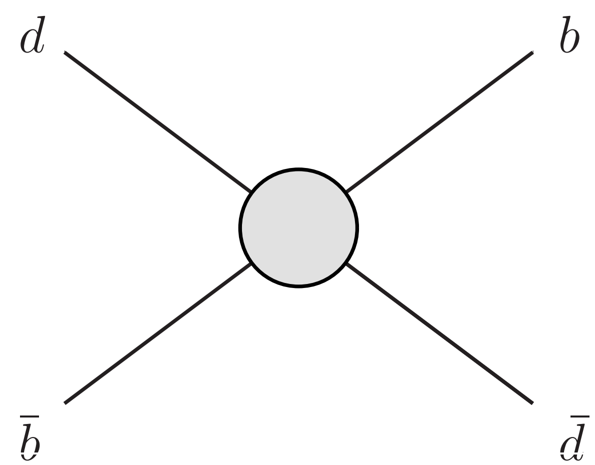


$$\langle B_d | H^{\Delta F=2} | \bar{B}_d \rangle \sim y_t^2 (V_{33}^* V_{31})^2 + y_c^2 V_{33}^* V_{31} V_{23}^* V_{21} + \ldots$$

Strongly suppressed by Yukawas and CKM elements

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!

MFV: assume that NP couples to quarks via the SM Yukawa matrices. Thus, Yukawa, GIM and CKM suppression of FCNCs are all retained.

This allows for new physics at the electroweak scale consistent with bounds from FCNCs

Operator	$\Lambda_{\rm NP}^{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	5.1
$(Q_1 \bar{d}_3)(Q_3^\dagger \bar{d}_1^\dagger)$	–
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	–
$2eH\sigma^{\mu\nu} Q_2\, \bar{d}_3\, F_{\mu\nu}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar{d}_2\, F_{\mu\nu}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar{d}_1\, F_{\mu\nu}$	7.0

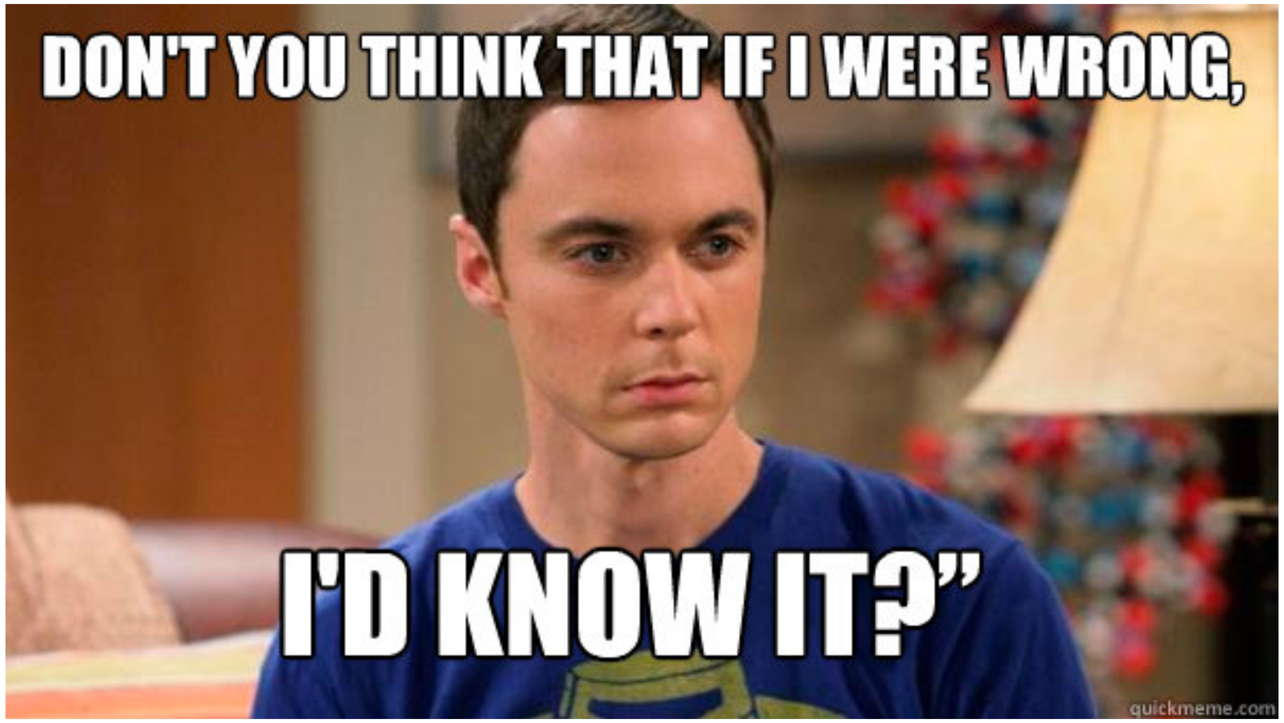
MFV INTRODUCES STRONG LIMITATIONS ON BSM PHYSICS

- MFV new physics couples preferentially to 3rd generation quarks.
- Example: a second Higgs doublet

$$\sim y_u \, H_2 u\bar{u} + y_c \, H_2 c\bar{c} + y_t \, H_2 t\bar{t}$$

- Is such expectation generic? Most (if not all) reasonable existing models of new flavored physics, couple only to third generation quarks.

Examples: the MSSM, 2HDM types I-IV,
U(2) theories and NMFV, flavored Z-prime models,
leptoquarks, composite models…



Could new physics couple instead
to the light quark generations preferentially?

New physics with generation specific couplings:

Flavor alignment

FLAVOR ALIGNMENT

- A different, and much broader approach is to require *flavor alignment*

- Let's illustrate flavor alignment with a 2HDM

$$\lambda^u_{ij} Q_i H \bar{u}_j - \lambda^{d\dagger}_{ij} Q_i H^c \bar{d}_j - \kappa^{d\dagger}_{ij} Q_i H_2^c \bar{d}_j$$

$$\lambda^u = V^T_{\rm CKM} Y^u = V^T_{\rm CKM} {\rm diag}(y_u, y_c, y_t)$$

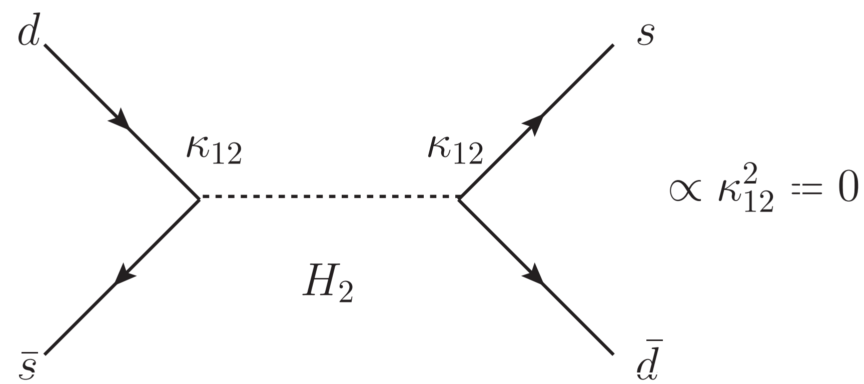
$$\lambda^d = {\rm diag}(y_d, y_s, y_b)$$

$$\kappa^d = {\rm diag}(\kappa_d, \kappa_s, \kappa_b)$$

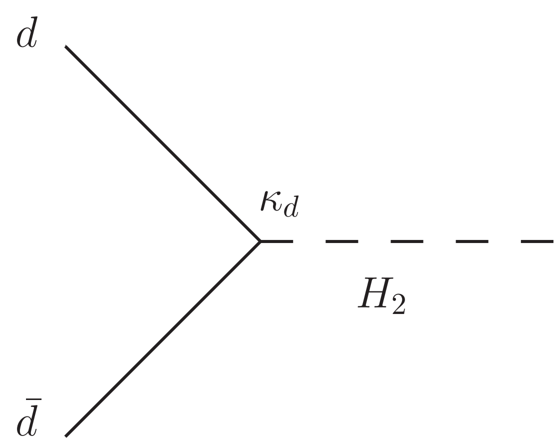
Flavor alignment: the only source of Flavor mixing is the CKM matrix

ALIGNMENT SUPPRESSES FCNC'S

- Moreover, in such a theory there would be no tree-level FCNCs



- However, in such a theory, *strong and preferential couplings to light quarks are allowed.*



Copious production of extra Higgses at LHC!

BSM PHYSICS COUPLING PREFERENTIALLY TO LIGHT QUARKS

- Why should the Yukawa of the second doublet be aligned with the SM Yukawa?

- No symmetry reason to suppress the off-diagonal elements of such Yukawa, since the quark family symmetry is already broken!

$$\lambda^u_{ij} = \begin{pmatrix} 10^{-5} & 10^{-3} & 10^{-2} \\ 10^{-6} & 10^{-3} & 10^{-2} \\ 10^{-8} & 10^{-4} & 1 \end{pmatrix} \qquad \kappa^d_{ij} = \begin{pmatrix} \kappa_d & \times & \times \\ \times & \kappa_s & \times \\ \times & \times & \kappa_b \end{pmatrix}$$

Flavor alignment

Philippe Petit crossing the Twin Towers, 1974

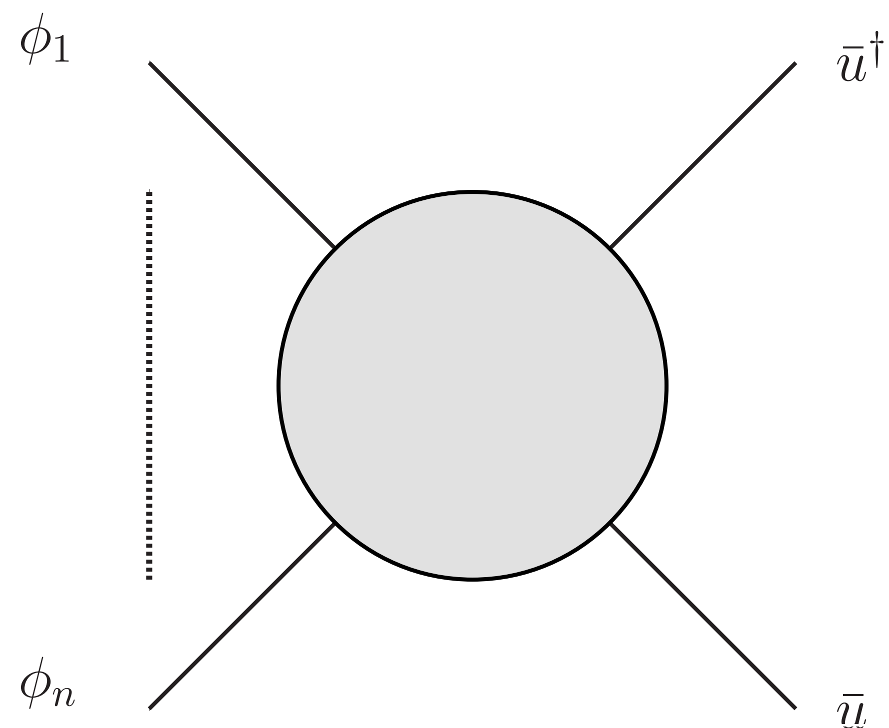
Flavor alignment leads to interesting pheno in the first and second generations, but requires either strong tuning… or a UV completion

Spontaneous flavor violation:
a UV realization of flavor alignment

SPONTANEOUS FLAVOR VIOLATION (SFV)

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

CP/family number breaking communicated through renormalization of RH up-quarks (or RH down-quarks)



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

or

$$Z^d_{ij}\bar{d}^\dagger_i\bar{\sigma}^\mu D_\mu \bar{d}_j$$

AN EXAMPLE UP-TYPE SFV LAGRANGIAN

- Let's go back to our two-Higgs doublet model example

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

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

All Yukawas are real diagonal by definition of SFV

- Go to the canonically normalized basis

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

CKM MATRIX FROM WAVE-FUNCTION RENORMALIZATION

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

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

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

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

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

THE LIMITATION OF SFV: ONE-SECTOR ALIGNMENT

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

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

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

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 $\kappa^u \propto \tilde{Y}^u$

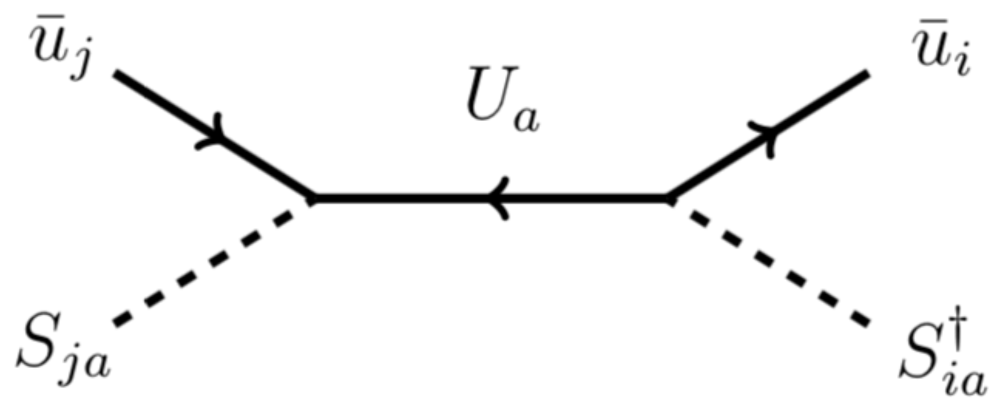
The smoking gun signature of SFV is aligned couplings in the up or down quark sector, and MFV-like couplings in the opposite sector

To the best of my knowledge, SFV is the only mechanism that ensures alignment in generic BSM theories.

AN EXAMPLE UV COMPLETION OF SFV

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

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



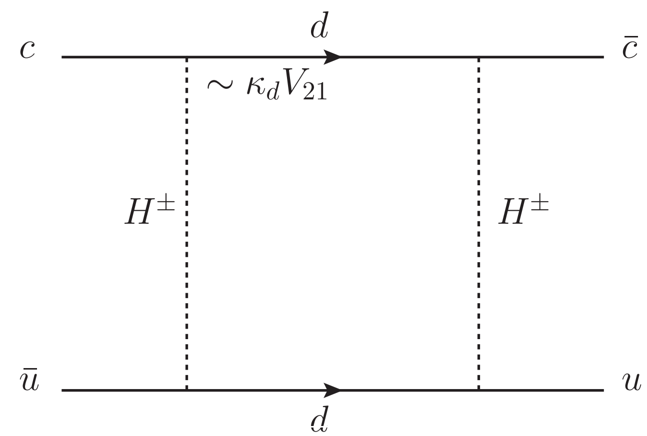
$$\sim Z^u_{ij} \bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j$$

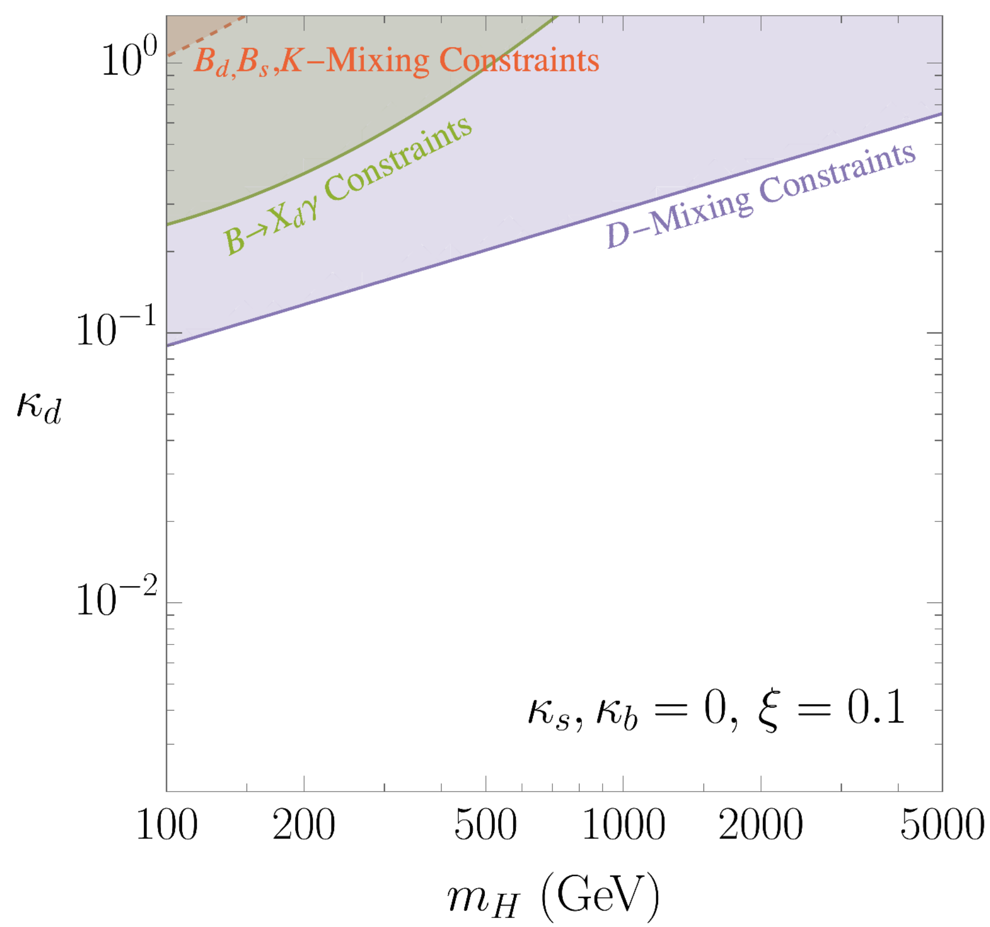
- This is nothing else than a Nelson-Barr model. <u>In fact the strong CP problem is automatically solved in all SFV realizations.</u>

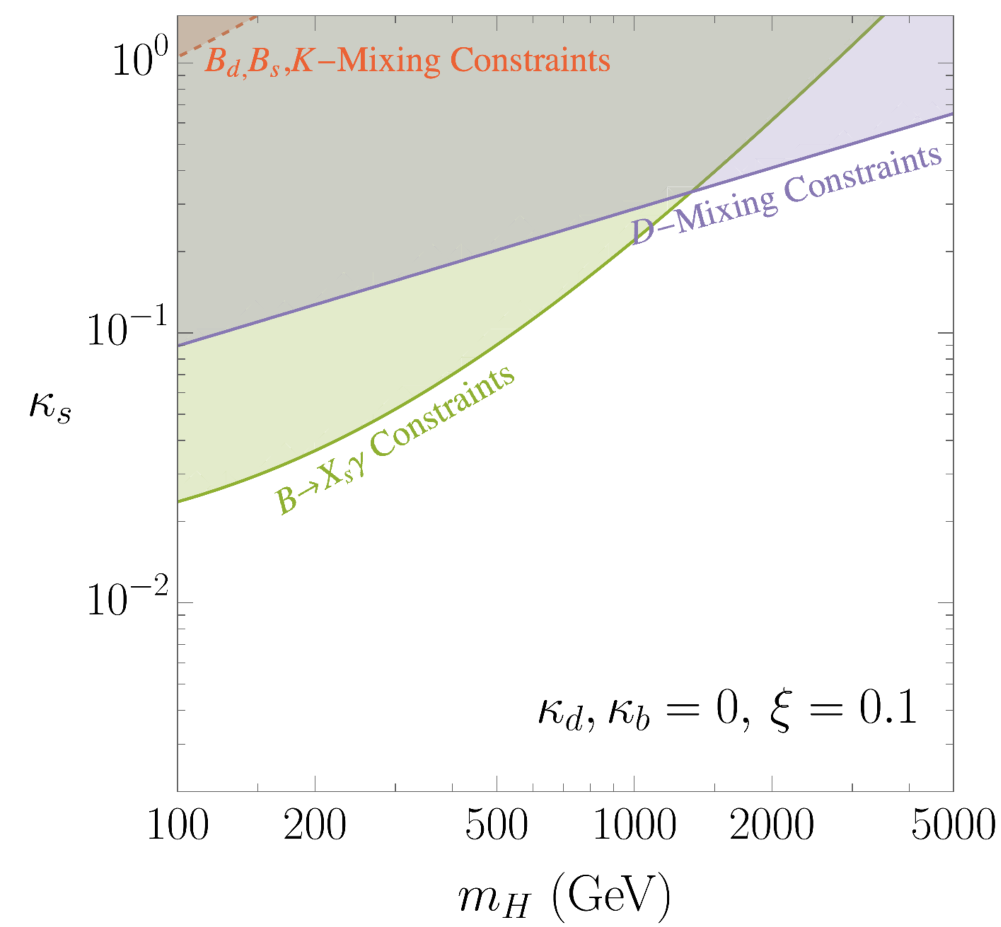
Phenomenology of Higgs bosons with large Couplings to light quarks

FLAVOR CONSTRAINTS ON THE UP TYPE SFV 2HDM

- FCNCs do not arise at tree level, but at one-loop level we must be careful.

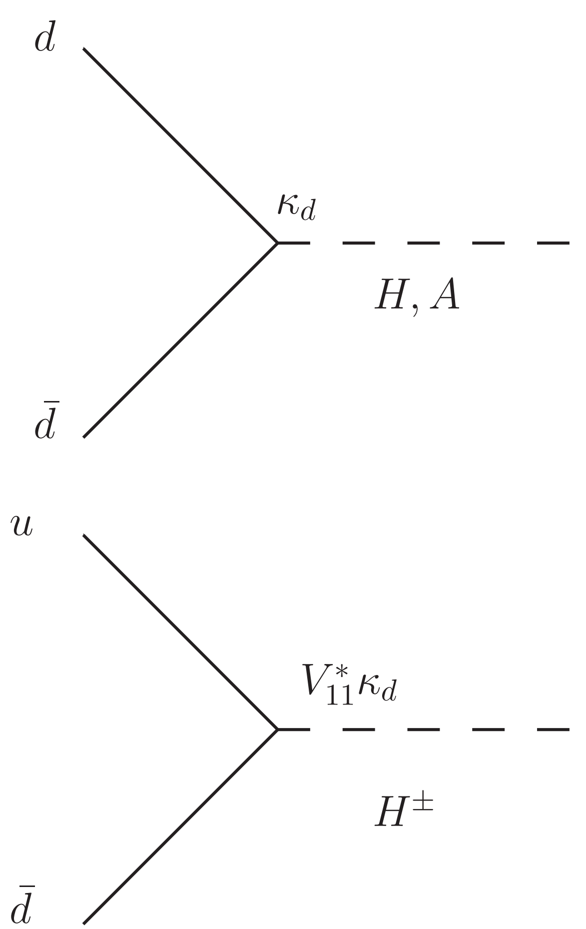




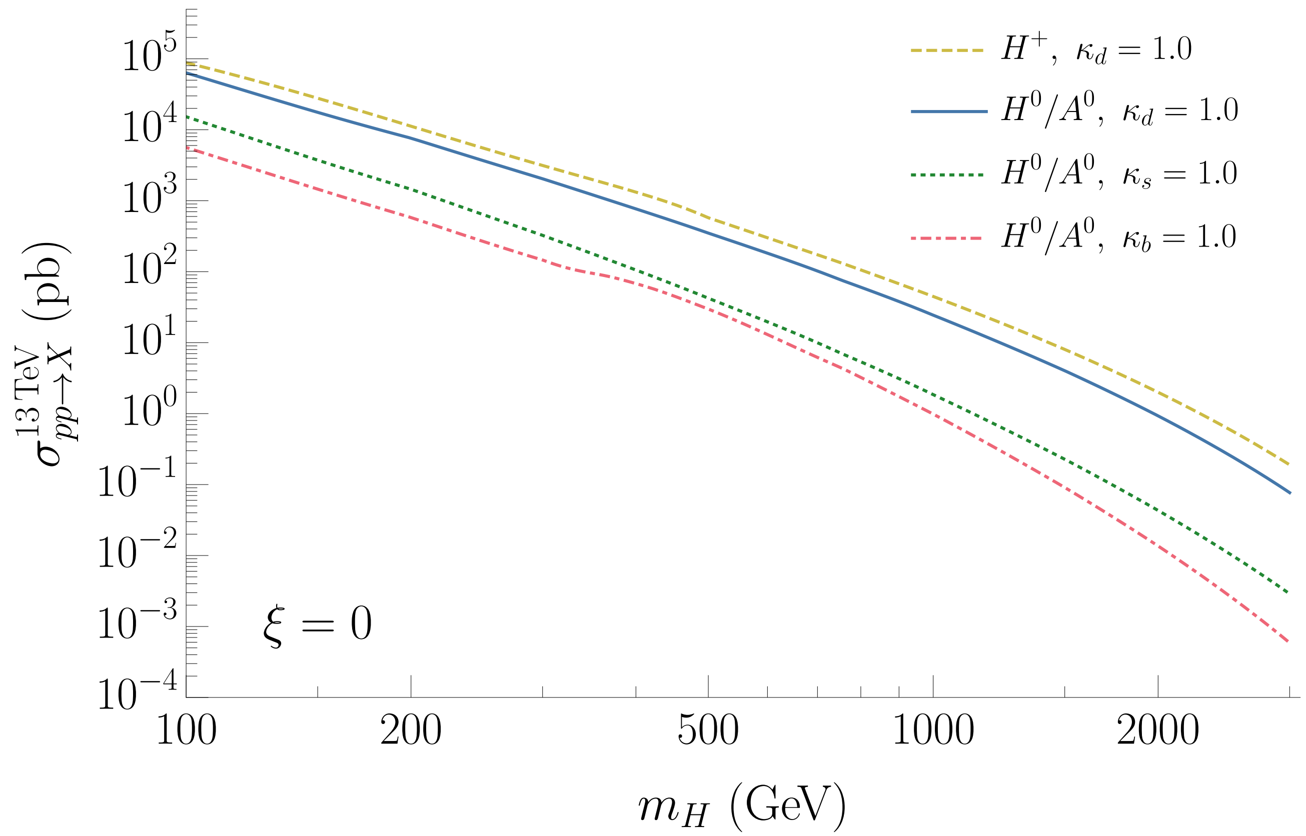


HIGGSES WITH LARGE COUPLINGS TO PROTONS!

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



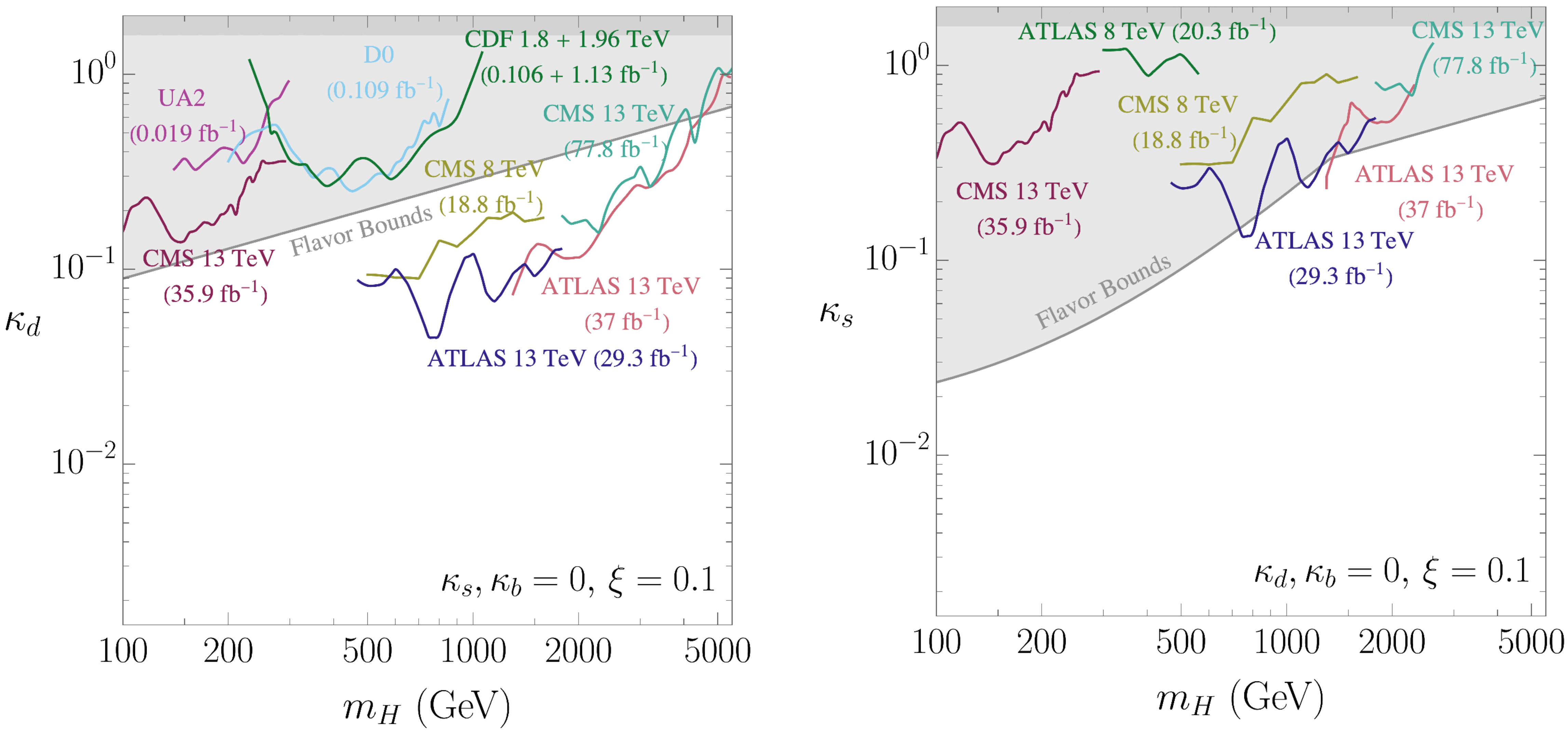
$$\sigma_{h\,SM}^{ggF} = 49\,\mathrm{pb}$$



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

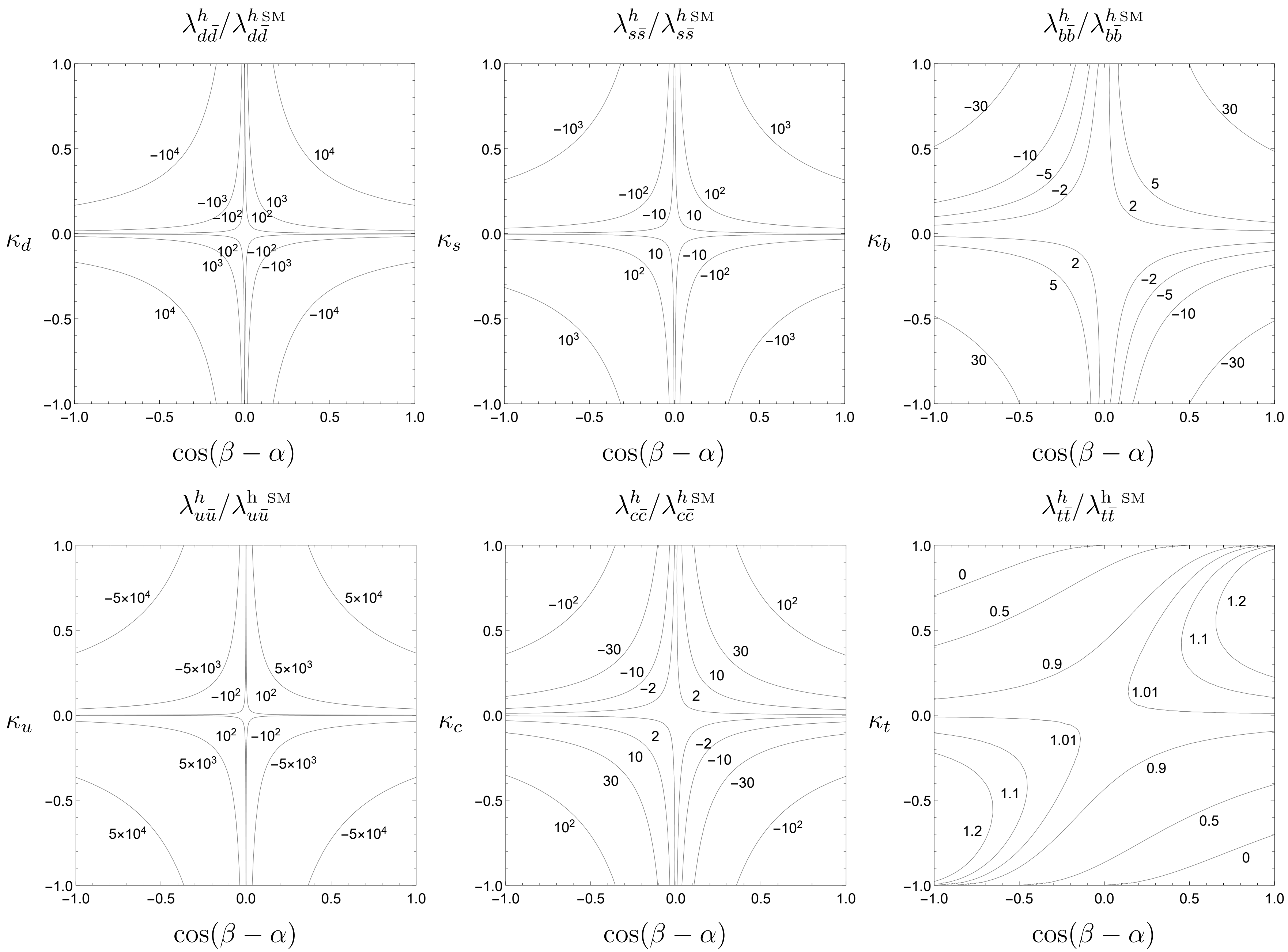
LIMITS FROM DIJET SEARCHES

- 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 may lead to dramatic enhancements of the SM Higgs Yukawas

	$\lvert c_u \rvert$	$\lvert c_d \rvert$	$\lvert c_s \rvert$	$\lvert c_c \rvert$
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

CONCLUSIONS

- Usual assumptions on the couplings severely limit the phenomenology of BSM models to third-generation physics.

- A new flavor Ansatz, Spontaneous Flavor Violation, overcomes this limitation.

- SFV can be applied to pretty much any BSM physics, allowing for large couplings to light quarks while reducing flavor constraints,

The MSSM, the Standard Model EFT, two Higgs doublet models, Z’ models, leptoquarks, vector-like quarks, pseudo-Goldstones (axions), colored scalars…

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

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

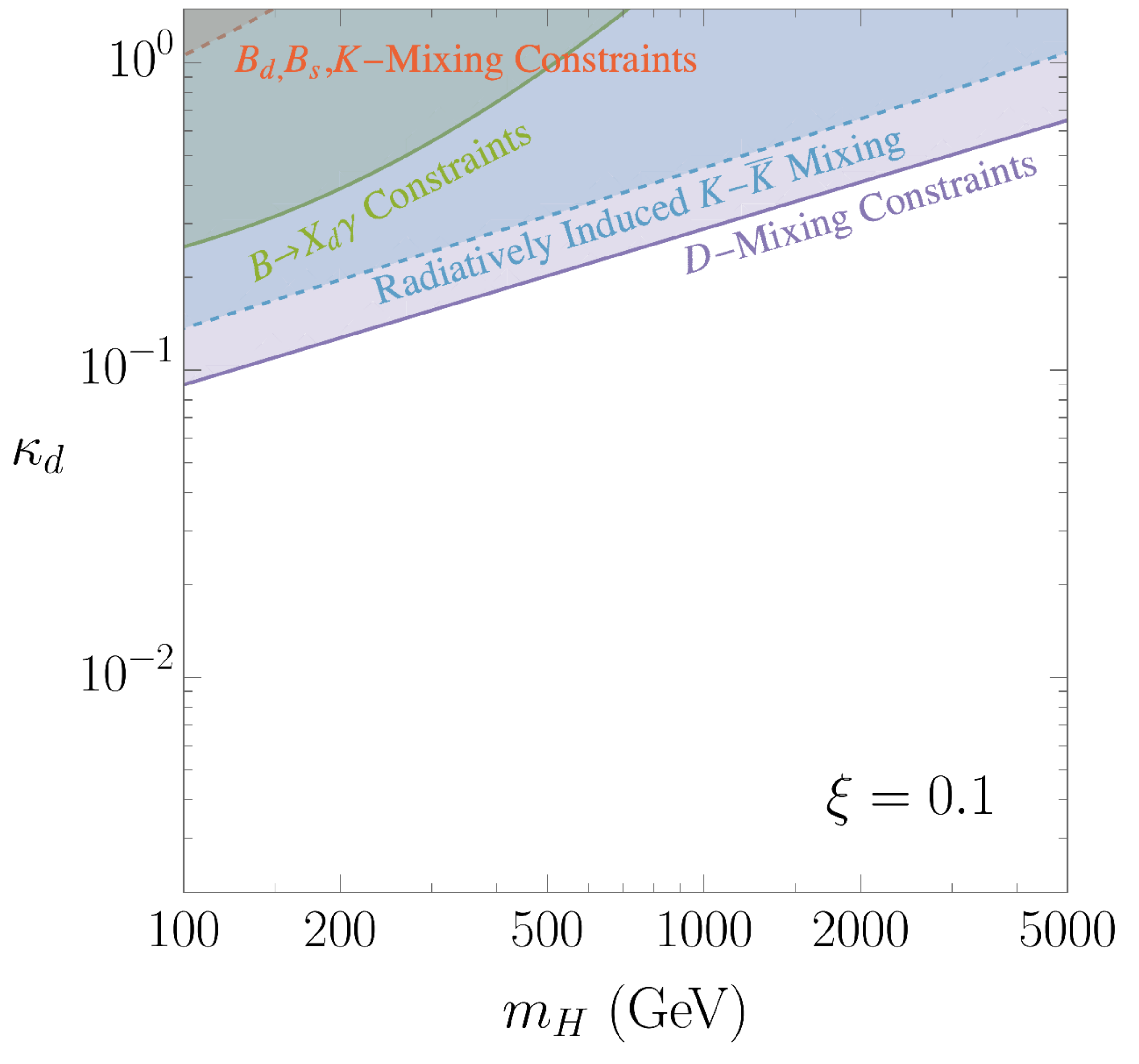
Operator	SFV factor
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)^2$	$C_D^1 = (V^* K_d^2 V^T)_{12}^2$ $C_K^1 = (V^T Y_u^2 V^*)_{12}^2$
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	$\Big[(V^T Y_u^2 V^* K^d)_{12}$ $(V^T Y_u^2 V^* K^d)_{21}^*\Big]$
$Q_2 H^c \sigma^{\mu\nu} \bar{d}_3 F_{\mu\nu}$	$\left[(V^T Y_u^2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

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

RADIATIVELY INDUCED FCNCS



UV SFV scale set at 100 TeV