SPONTANEOUS FLAVOR VIOLATION

coming.soon

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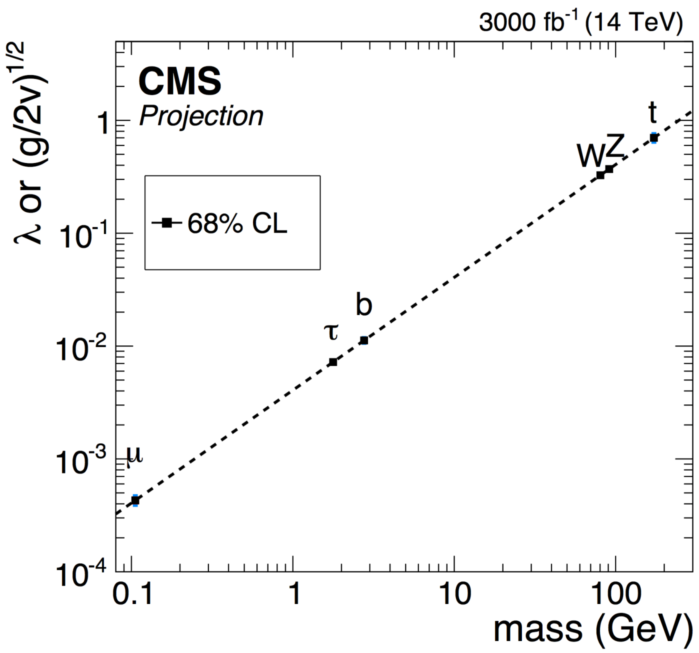
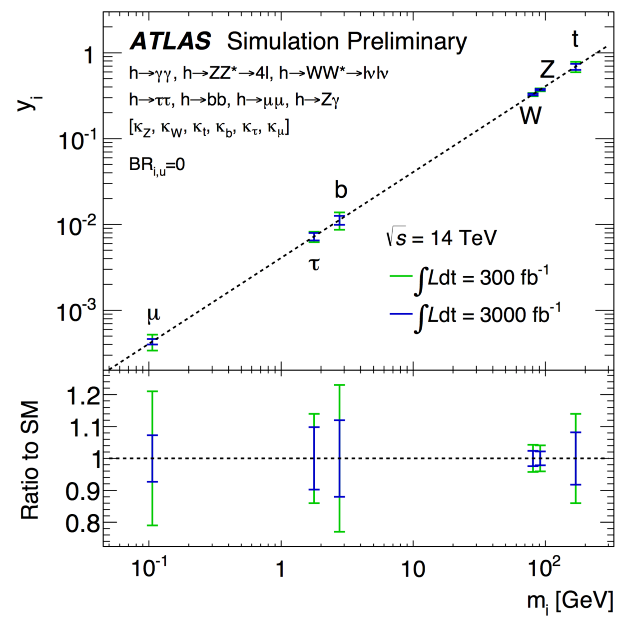
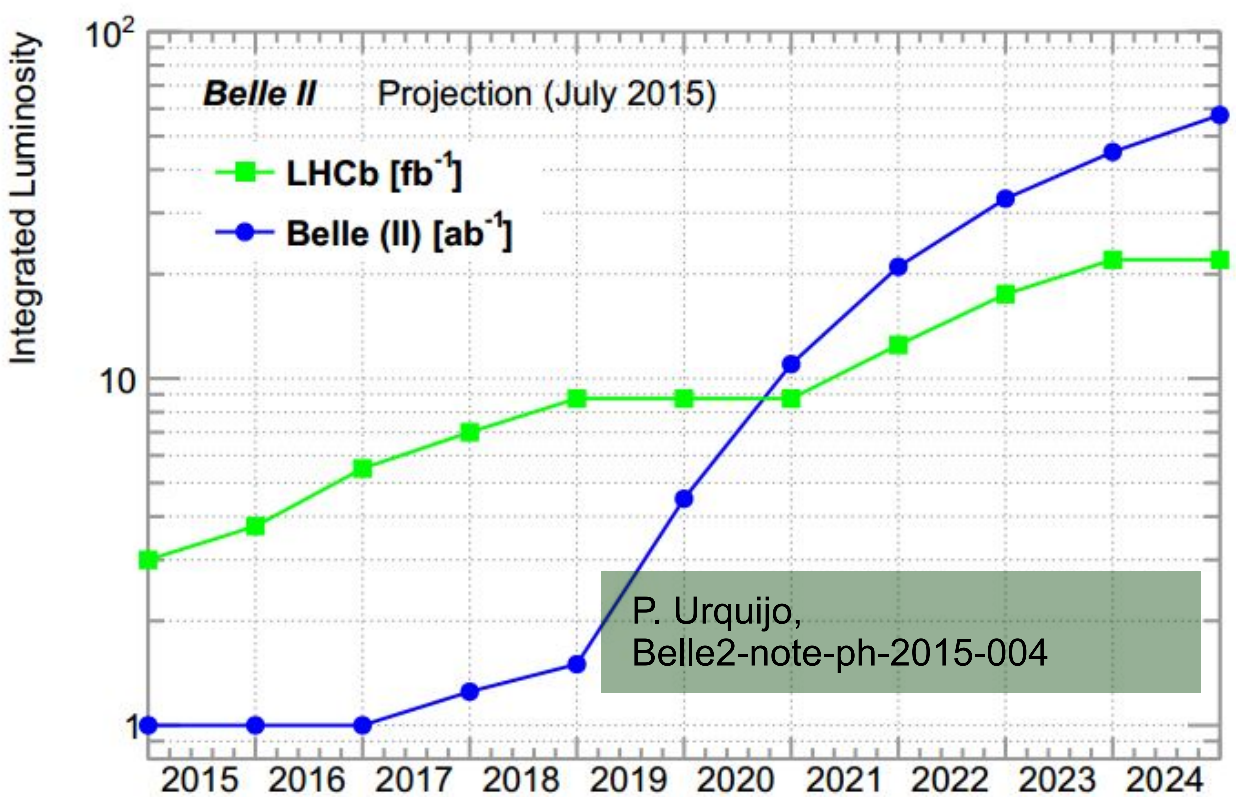
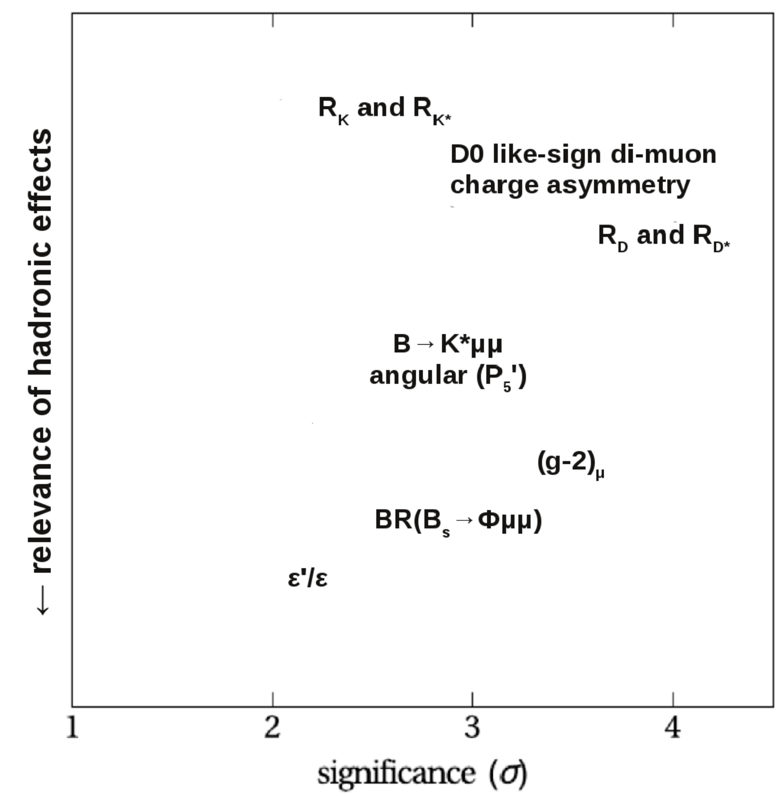
THESE ARE GOOD TIMES FOR THEORIES OF FLAVOR







From W. Altmanshofer
adapted from Z. Ligeti



What would these anomalies mean if they persist?

FLAVOR IN THE STANDARD MODEL

- The quark sector flavor group is

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

- Flavor is broken by two "Yukawa spurions" or *"flavor vacuum fields"*

$$\lambda^u \sim (\bar{3}, \bar{3}, 1)_{\mathrm{SU}(3)^3_{\mathrm{q}}} \quad , \quad \lambda^d \sim (\bar{3}, 1, \bar{3})_{\mathrm{SU}(3)^3_{\mathrm{q}}} \quad .$$

- The flavor breaking is controlled by quark masses and CKM elements. In one flavor basis,

$$\lambda^u = V^T Y^u \quad , \quad \lambda^{d\dagger} = Y^d$$

FLAVOR IN MFV THEORIES

- FCNC's are strongly suppressed in the Standard Model.
- Very stringent bounds on FCNC's from meson mixing and rare meson decays.
- MFV theories are very popular, since *all down type FCNC's are suppressed by CKM elements and small Yukawas*

Example: $\left[Q\left(\lambda^{u}\lambda^{u\dagger}\right)Q^{\dagger}\right]^{2}$

$$(\lambda^u\lambda^{u\dagger})_{ij} = (\,V^T Y_u^2 V^*\,)_{ij} \approx \lambda_t^2 V_{3i} V_{3j}^* \qquad i \neq j \quad .$$

A USEFUL REMINDER: HIGGS COUPLING MEASUREMENTS

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

Within our academic lifetimes,
it is likely that we will not be able to
experimentally confirm
the MFV Standard Model flavor structure *

We will only be able to say that
whatever we're seeing now belongs to the *MFV class*

(*It is much easier to *rule it out*)

THE TWO OPTIONS FOR THE FUTURE

No new (flavored) physics 🤬	New (flavored) physics 😃
↓	↓
Beginning of a slow and painful process to experimentally confirm MFV ☠️	*We will need to interpret the underlying flavor structure.* *<u>Flavor vacuum?</u>*

MFV 🤔

? 😱

FEW CLASSES OF VACUA DIFFERENT FROM MFV

Maybe we will not discover the underlying flavor dynamics,
but we can experimentally test <u>classes</u> of flavor theories

New flavored physics couples preferentially to 3rd generation fermions

☠️

U(2) symmetric theories
NMFV

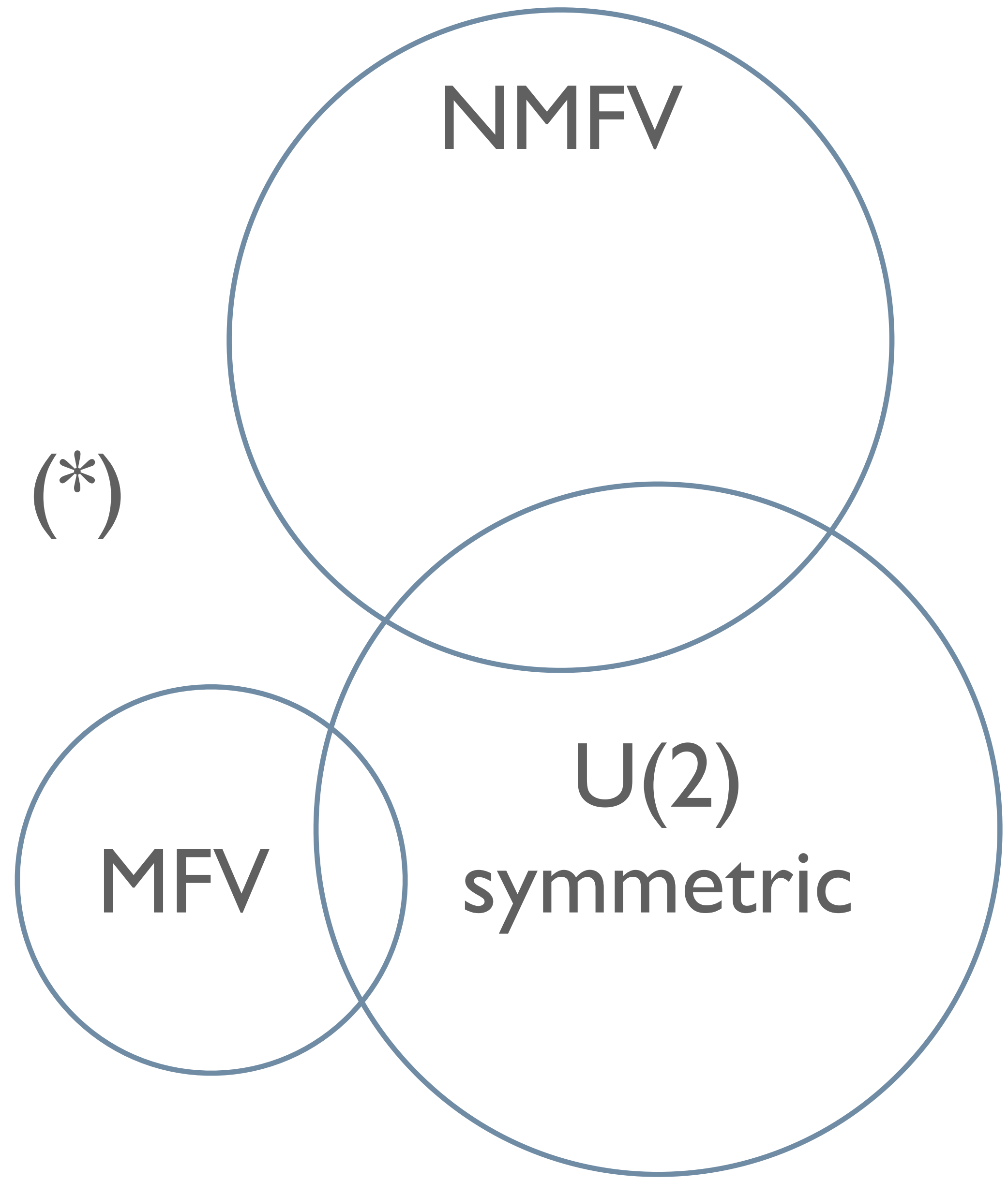
All other cases

????

* (*Maybe* chiral FV? 1606.00003.
* Other possibilities exist for particular UV completions)

CLASSES OF FLAVOR VACUA

All couple preferentially to 3rd generation (*)



Intersections mean *same physics* *in the infrared*

Determining in which *class* are we has both theoretical *and experimental* consequences

A NEW CLASS OF FLAVOR THEORY

Motivated by the following observation

Down sector
"contains the CKM"

Up sector
"contains the CKM"

$$\lambda^d = V^*_{\mathrm{CKM}} Y^d$$

$$\lambda^u = Y^u = \mathrm{diag}(y_u, y_c, y_t)$$

$$\lambda^u = V^*_{\mathrm{CKM}} Y^u$$

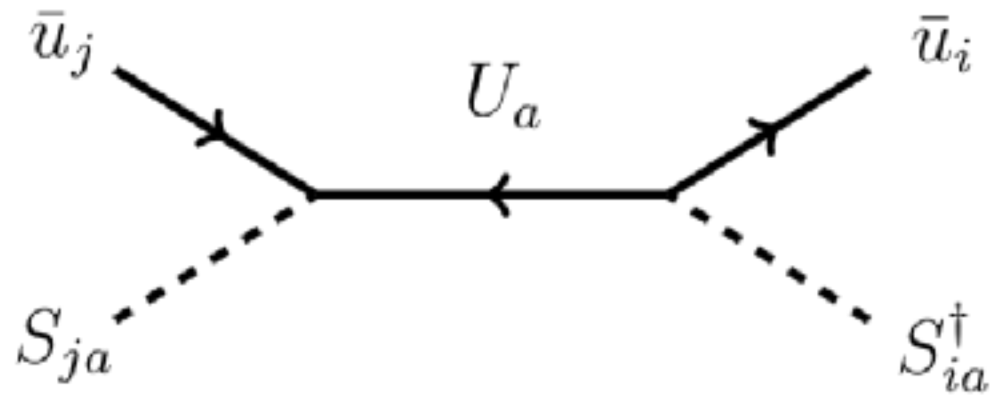
$$\lambda^d = Y^d = \mathrm{diag}(y_d, y_s, y_b)$$

Due to the SM field content and gauge invariance

The Spontaneous Flavor Violation Ansatz

SPONTANEOUS FLAVOR VIOLATION

<u>Postulate</u>:
The origin of all quark flavor mixing and CP violation is from mixing of <u>up or down singlet quarks</u> with heavy quarks in a flavor breaking vacuum.



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

Equivalently, all flavor mixing and CP violation is in *wave function renormalization*

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THERE ARE TWO TYPES OF SFV THEORIES

Up sector SFV

Down sector SFV

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

$$+\left[\tilde{Y}^u_{ij}\; Q_i H \bar{u}_j - \tilde{Y}^d_{ij} Q_i H^c \bar{d}_j + \text{h.c.}\right]$$

All Yukawas are real diagonal by definition of SFV

THE CKM MATRIX SHOWS UP AFTER A FIELD REDEFINITION

$\boxed{\text{Up sector SFV}}$

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

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

$\boxed{\text{Down sector SFV}}$

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

$$\tilde{Y}^d \to \sqrt{Z}^{-1} \tilde{Y}^d = \lambda^{d\dagger} = V_{\rm CKM}^* Y^d$$

SFV theories automatically solve the strong CP problem via the Nelson-Barr mechanism

HOW TO DISTINGUISH SFV FROM THE SM?

The difference is only seen
when we add *new physics (new flavor breaking spurions)*

For the rest of this talk consider an SFV theory
with <u>one additional flavor spurion</u>

THE DIFFERENCE COMES WHEN ADDING NEW PHYSICS

- Example: SFV through the up sector, and add *new down type Yukawa*

$$\boxed{Y^{\eta} \sim (\bar{3}, 1, \bar{3}) \qquad \text{New down type Yukawa}}$$

$$Z^u_{ij} \bar{u}^{\dagger}_i \bar{\sigma}^{\mu} D_{\mu} \bar{u}_j \, + \left[\tilde{Y}^u_{ij} \, Q_i H \bar{u}_j - Y^d_{ij} Q_i H^c \bar{d}_j + \text{h.c.} \right]$$

$$+ \, f(Y^{\eta}) O(Q, \bar{d}, \chi) + \ldots$$

Y^{η} <u>is real diagonal</u>

THE DIFFERENCE COMES WHEN ADDING NEW PHYSICS

- Go to the canonical kinetic basis

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

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

CKM enters through the up sector

$$\boxed{\begin{aligned} Y^d &= \text{diag}(y_d, y_s, y_b) \\ Y^\eta &= \text{diag}(\eta_d, \eta_s, \eta_b) \end{aligned}}$$

Down sector spurions remain diagonal, aligned, and are *flavor non-universal*

SFV IS VERY SAFE FROM FCNC'S

$$\lambda^u = V_{\mathrm{CKM}}^T Y^u$$

$$Y^d = \mathrm{diag}(y_d, y_s, y_b)$$

$$Y^\eta = \mathrm{diag}(\eta_d, \eta_s, \eta_b)$$

- Clearly, all mixing is suppressed by CKM elements.
- In fact, *all down type FCNC's* are suppressed by the combination

$$V_{\mathrm{CKM}}^T Y_u^2 V_{\mathrm{CKM}}^*$$ Just as in MFV theories!

SFV LEADS TO NATURALLY ALIGNED SPURIONS

Note that

I

Spontaneous flavor violation
is an efficient and simple mechanism
to *align* spurions in the down *or* up quark sectors

II

The distinctive signature of SFV through the up (down) sector
is new physics coupled non-universally to down (up) type quarks.

CONSTRAINTS ON DIMENSION SIX SFV OPERATORS

Operator	Observable	FCNC suppression factor
$(Q_1^\dagger \bar{\sigma}^\mu Q_2)(Q_1^\dagger \bar{\sigma}_\mu Q_2)$	$\Delta m_D, \lvert q/p \rvert, \phi_D$	$(V^* Y_{\eta,d}^2 V^T)_{21}^2$
	ϵ_K	$(V^* Y_u^2 V^T)_{21}^2$
$(Q_{1,2}^\dagger \bar{\sigma}^\mu Q_3)(Q_{1,2}^\dagger \bar{\sigma}_\mu Q_3)$	$\Delta m_{B_{d,s}}$	$(V^T Y_u^2 V^*)_{(1,2)3}^2$
$(\bar{d}_{1,2}^\dagger \bar{\sigma}^\mu \bar{d}_{2,3})(\bar{d}_{1,2}^\dagger \bar{\sigma}_\mu \bar{d}_{2,3})$	$\epsilon_K, \Delta m_{B_{d,s}}$	$\left[Y^{\eta,d} (V^T Y_u^2 V^*) Y^{\eta,d}\right]_{(1,2)(2,3)}^2$
$(Q_1 \bar{d}_2)(Q_2^\dagger \bar{d}_1^\dagger)$	ϵ_K	$(V^T Y_u^2 V^* Y^{\eta,d})_{12} (V^T Y_u^2 V^* Y^{\eta,d})_{21}^*$
$(Q_1 \bar{d}_3)(Q_3^\dagger \bar{d}_1^\dagger)$	Δm_{B_d}	$(V^T Y_u^2 V^* Y^{\eta,d})_{13} (V^T Y_u^2 V^* Y^{\eta,d})_{31}^*$
$eH \sigma^{\mu\nu} Q_2 \, \bar{d}_3 \, F_{\mu\nu}$	$B \to X_s(\gamma, \ell^+\ell^-), K^* \mu^+ \mu^-,$	$\left[(V^T Y_u^2 V^*) Y^{\eta,d}\right]_{23}$
$eH \sigma^{\mu\nu} Q_3 \, \bar{d}_2 \, F_{\mu\nu}$	$B \to X_s(\gamma, \ell^+\ell^-), K^*(\gamma, \mu^+ \mu^-)$	$\left[(V^T Y_u^2 V^*) Y^{\eta,d}\right]_{32}$
$eH \sigma^{\mu\nu} Q_3 \, \bar{d}_1 \, F_{\mu\nu}$	$B \to X_d \gamma$	$\left[(V^T Y_u^2 V^*) Y^{\eta,d}\right]_{31}$

CONSTRAINTS ON DIMENSION SIX SFV OPERATORS

Operator	Λ [TeV]	$\Lambda_{\rm SFV}$ [TeV]	$\Lambda_{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar\sigma^\mu Q_2)(Q_1^\dagger \bar\sigma_\mu Q_2)$	1.5×10^4	$262.7\,\lvert\eta_d^2 - \eta_s^2\rvert$	5.1
$(Q_{1,2}^\dagger \bar\sigma^\mu Q_3)(Q_{1,2}^\dagger \bar\sigma_\mu Q_3)$	2.1×10^3	5.1	5.1
$(\bar d_1^\dagger \bar\sigma^\mu \bar d_2)(\bar d_1^\dagger \bar\sigma_\mu \bar d_2)$	1.5×10^4	$4.54\sqrt{\lvert\eta_d\eta_s\rvert}$	–
$(\bar d_2^\dagger \bar\sigma^\mu \bar d_3)(\bar d_2^\dagger \bar\sigma_\mu \bar d_3)$	0.21×10^3	$1.77\sqrt{\lvert\eta_d\eta_b\rvert}$	–
$(Q_1 \bar d_3)(Q_3^\dagger \bar d_1^\dagger)$	2.2×10^3	$18.8\,\sqrt{\lvert\eta_d\eta_b\rvert}$	–
$(Q_1 \bar d_2)(Q_2^\dagger \bar d_1^\dagger)$	2.4×10^5	$74.9\,\sqrt{\lvert\eta_d\eta_s\rvert}$	–
$eH\sigma^{\mu\nu} Q_2\, \bar d_3\, F_{\mu\nu}$	330.2	$65.4\,\sqrt{\lvert\eta_b\rvert}$	9.3
$eH\sigma^{\mu\nu} Q_3\, \bar d_2\, F_{\mu\nu}$	308.9	$61.2\,\sqrt{\lvert\eta_s\rvert}$	9.3
$eH\sigma^{\mu\nu} Q_3\, \bar d_1\, F_{\mu\nu}$	203.1	$18.7\,\sqrt{\lvert\eta_d\rvert}$	9.3

Spontaneous flavor violation within concrete new physics models

TWO DOUBLET THEORIES WITH NO FCNC'S

- *Out of the box* SFV gives two *new types* of 2HDM
- Our SFV theory with the new down-Yukawa gives

$$\kappa\lambda^u \, QH_2\bar{u} - Y^\eta QH_2^c\bar{d} \qquad \text{Up-type SFV 2HDM}$$

- An SFV theory with a new up-Yukawa gives

$$Y^\eta QH_2\bar{u} - \kappa\lambda^d QH_2^c\bar{d} \qquad \text{Down-type SFV 2HDM}$$

ABSENCE OF TREE-LEVEL FCNC'S

- Consider up-type SFV: flavor non-universal couplings to down-quarks

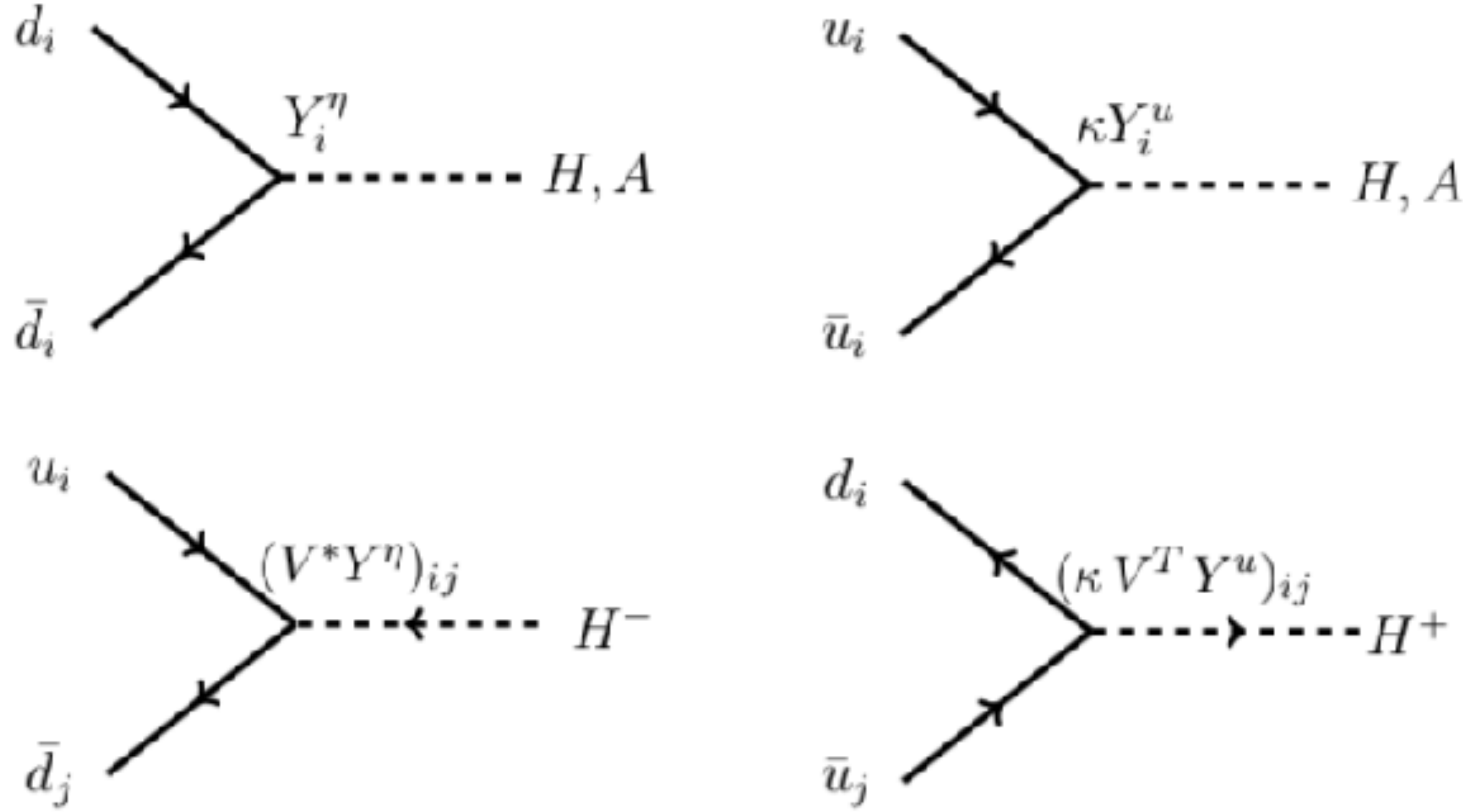
$$Y^{\eta}_{ij}\; d_i H_2^{0*} \bar{d}_j + \kappa \big[\underbrace{V^T\, Y^u}_{\lambda^u} \big]_{ij}\, u_i H_2^0 \bar{u}_j$$

- Go to the *quark mass eigenbasis* $u \to u V^*$

$$Y^{\eta}_{ij}\; d_i H_2^{0*} \bar{d}_j + \kappa\, Y^u_{ij}\, u_i H_2^0 \bar{u}_j$$

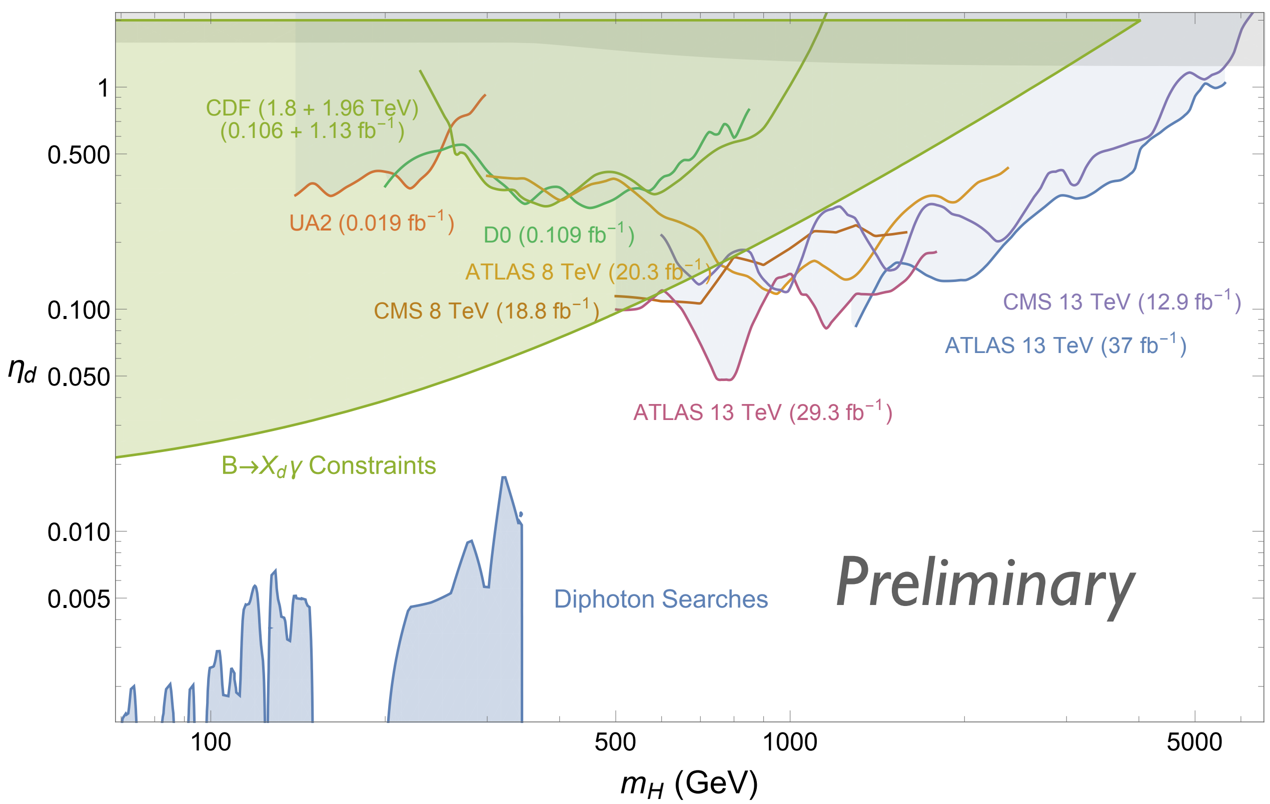
1. No tree-level FCNC's
2. Non universal couplings to down quarks

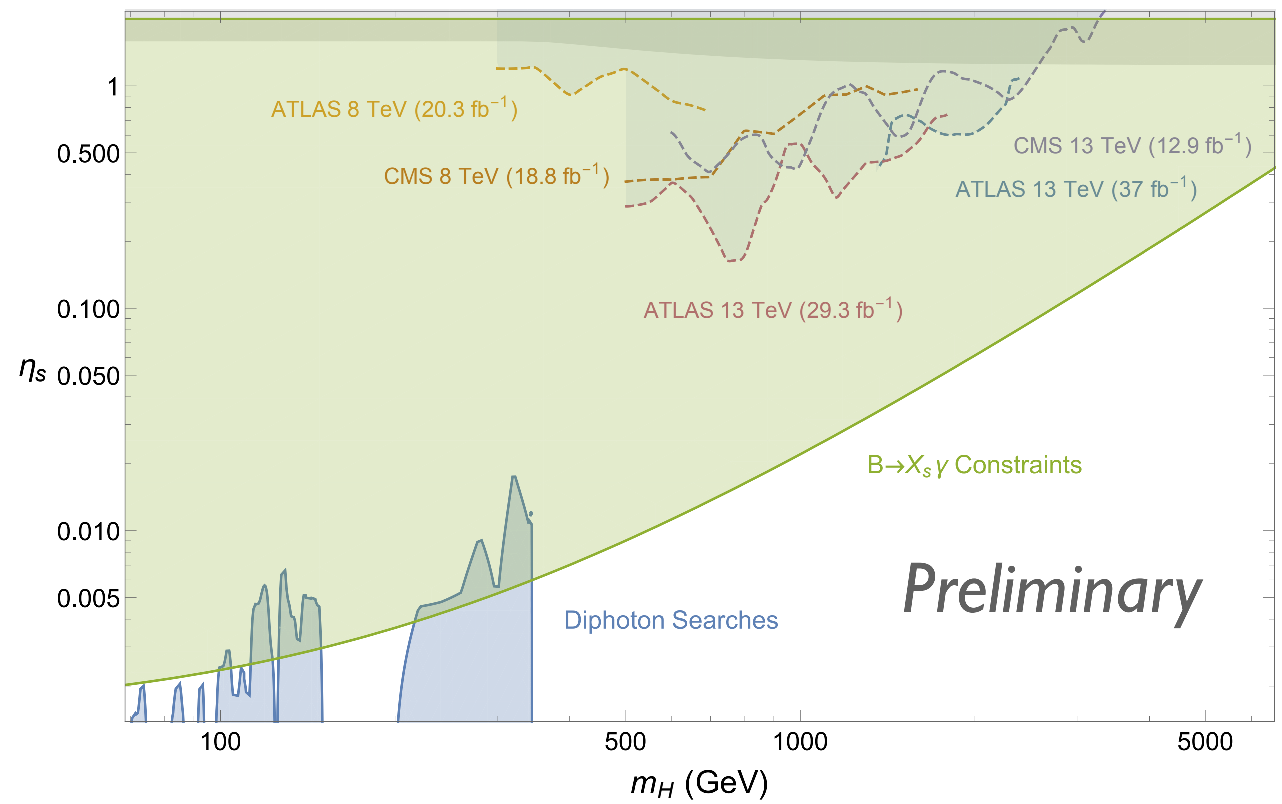
- Flavor non-universal couplings to down-quarks allow for tree-level s-channel production at LHC



WE CAN LOOK FOR THESE HIGGSES AT LHC

These are Higgses that -do- couple at tree level to protons
easiest scalars to test at LHC

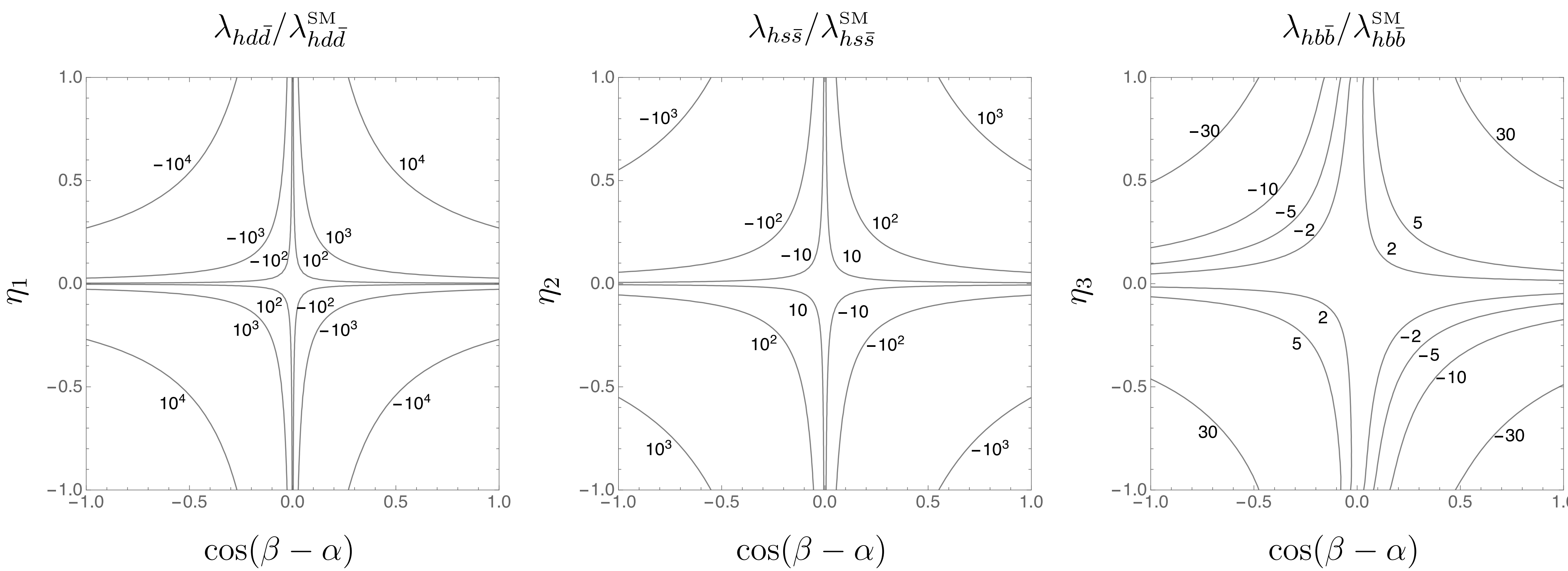




New physics with large non-universal couplings to light quarks, invisible to B-factories…

APPLICATION II: 125 GEV HIGGS YUKAWAS THAT CAN BE MEASURED

- **If the extra Higgses mix with the 125 GeV Higgs, we get gigantic enhancements on the 125 GeV Higgs Yukawas to light quarks**

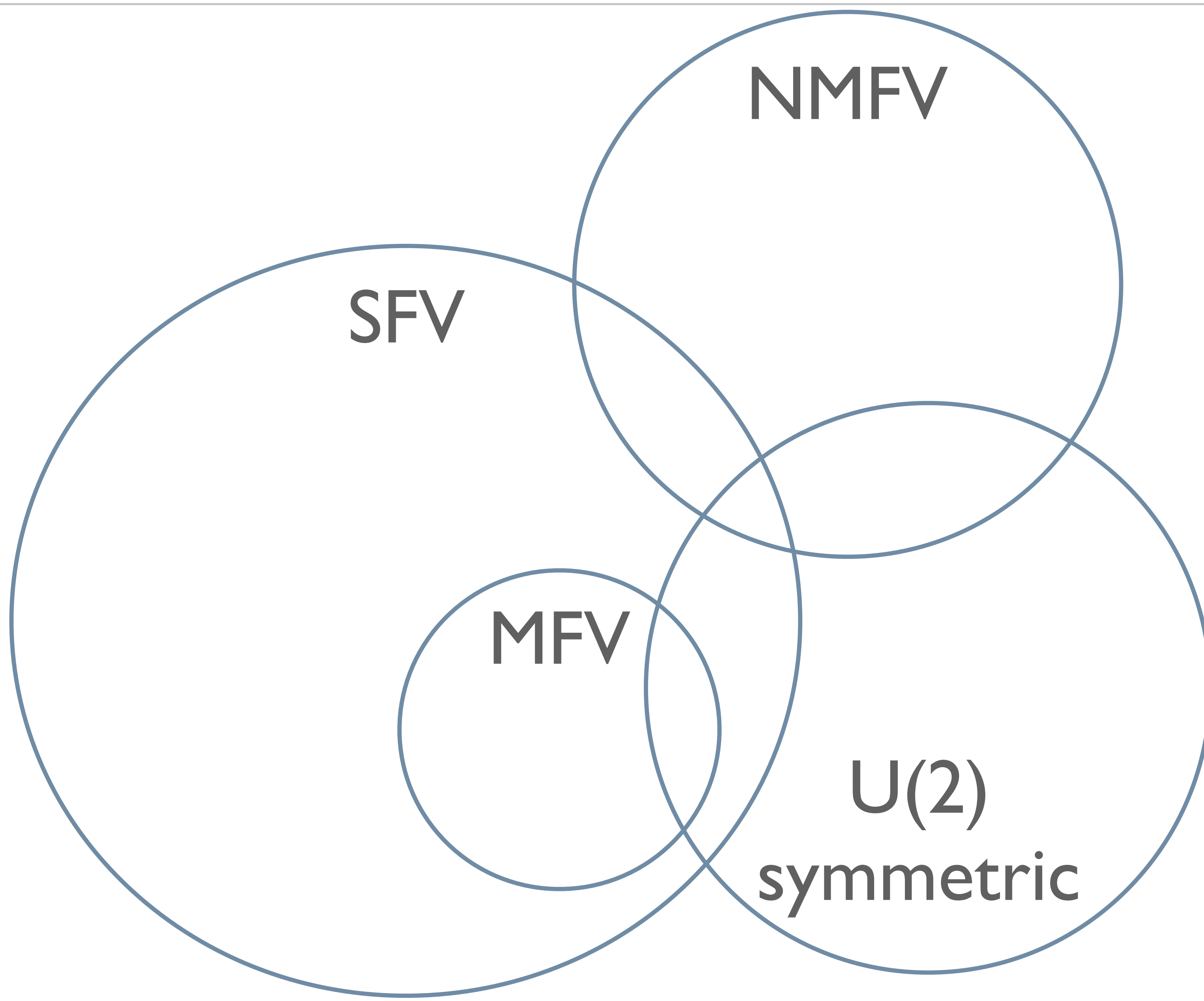


Within collider reach!

CONCLUSIONS

- We are far from confirming the MFV hypothesis.
- Unless someone finds a smart way to measure light quark Higgs Yukawas, we will stay far. *Even if we find new physics*.
- In the meantime we can test other *classes of flavor vacua.*
- The Spontaneous Flavor Violation class is well motivated, <u>testable, falsifiable</u>, and may be found at LHC.

CLASSES OF FLAVOR VACUA



Intersections
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Determining in which *class* are we has both theoretical *<u>and experimental</u>* consequences