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”

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

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

$$\lambda^u = V^T Y^u , \quad \lambda^{d\dagger} = Y^d$$
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: \[
\left[ Q \left( \lambda_u \lambda_u^\dagger \right) Q^\dagger \right]^2
\]

\[
\left( \lambda_u \lambda_u^\dagger \right)_{ij} = \left( V^T Y_u^2 V^* \right)_{ij} \approx \lambda_t^2 V_{3i} V_{3j}^* \quad i \neq j
\]
A USEFUL REMINDER: HIGGS COUPLING MEASUREMENTS

| | $|c_u|$ | $|c_d|$ | $|c_s|$ | $|c_c|$ |
|---|---|---|---|---|
| Perturbation | $< 1.1 \times 10^5$ | $< 5.1 \times 10^4$ | $< 2600$ | $< 190$ |
| $\Gamma_H < 1.7$ GeV Ref. [19] | $\lesssim 4.9 \times 10^4$ | $\lesssim 2.4 \times 10^4$ | $\lesssim 1200$ | $\lesssim 88$ |

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)

1406.1722 Kagan et.al.
1505.06369 Zhou

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THE TWO OPTIONS FOR THE FUTURE

No new (flavored) physics

Beginning of a slow and painful process to experimentally confirm MFV

New (flavored) physics

We will need to interpret the underlying flavor structure. Flavor vacuum?

MFV

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FEW CLASSES OF VACUA DIFFERENT FROM MFV

Maybe we will not discover the underlying flavor dynamics, but we can experimentally test classes 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”

\[
\lambda^d = V_{\text{CKM}}^* Y^d
\]

\[
\lambda^u = Y^u = \text{diag}(y_u, y_c, y_t)
\]

Up sector
“contains the CKM”

\[
\lambda^u = V_{\text{CKM}}^* Y^u
\]

\[
\lambda^d = Y^d = \text{diag}(y_d, y_s, y_b)
\]

Due to the SM field content and gauge invariance
The Spontaneous Flavor Violation Ansatz
SPONTANEOUS FLAVOR VIOLATION

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

Equivalently, all flavor mixing and CP violation is in wave function renormalization.
THERE ARE TWO TYPES OF SFV THEORIES

Up sector SFV

\[ Z^u_{ij} \bar{u}_i \, \bar{\sigma}^\mu \, D_\mu \, \bar{u}_j \]

Down sector SFV

\[ Z^d_{ij} \bar{d}_i \, \bar{\sigma}^\mu \, D_\mu \, \bar{d}_j \]

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

All Yukawas are real diagonal by definition of SFV
The CKM matrix shows up after a field redefinition.

**Up sector SFV**

\[ \tilde{u} \rightarrow \sqrt{Z^{d^{-1}}} \tilde{u} \]

\[ \tilde{Y}^u \rightarrow \sqrt{Z}^{-1} \tilde{Y}^u = \lambda^u = V^T_{\text{CKM}} Y^u \]

**Down sector SFV**

\[ \tilde{d} \rightarrow \sqrt{Z^{d^{-1}}} \tilde{d} \]

\[ \tilde{Y}^d \rightarrow \sqrt{Z}^{-1} \tilde{Y}^d = \lambda^{d\dagger} = V^*_{\text{CKM}} Y^d \]

*SFV theories automatically solve the strong CP problem via the Nelson-Barr mechanism*
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 one additional flavor spurion.
THE DIFFERENCE COMES WHEN ADDING NEW PHYSICS

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

\[ Y^\eta \sim (\bar{3}, 1, \bar{3}) \]

New down type Yukawa

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

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

\[ Y^\eta \text{ is real diagonal} \]
THE DIFFERENCE COMES WHEN ADDING NEW PHYSICS

Go to the canonical kinetic basis

\[ \tilde{u} \rightarrow \sqrt{Z}^{-1} \tilde{u} \]

\[ \tilde{Y}^u \rightarrow \sqrt{Z}^{-1} \tilde{Y}^u = \lambda^u = V_{\text{CKM}}^T Y^u \]

CKM enters through the up sector

\[ Y^d = \text{diag}(y_d, y_s, y_b) \]
\[ Y^\eta = \text{diag}(\eta_d, \eta_s, \eta_b) \]

Down sector spurions remain diagonal, aligned, and are \textit{flavor non-universal}
SFV IS VERY SAFE FROM FCNC’S

\[ \lambda^u = V^T_{\text{CKM}} Y^u \]

\[ Y^d = \text{diag}(y_d, y_s, y_b) \]

\[ Y^\eta = \text{diag}(\eta_d, \eta_s, \eta_b) \]

- Clearly, all mixing is suppressed by CKM elements.

- In fact, all down type FCNC’s are suppressed by the combination

\[ V^T_{\text{CKM}} Y_u^2 V^*_{\text{CKM}} \quad \text{Just as in MFV theories!} \]
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

<table>
<thead>
<tr>
<th>Operator</th>
<th>Observable</th>
<th>FCNC suppression factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(Q_1^+ \bar{\sigma}^\mu Q_2)(Q_1^+ \bar{\sigma}_\mu Q_2)$</td>
<td>$\Delta m_D, \left</td>
<td>q/p \right</td>
</tr>
<tr>
<td>$(Q_{1,2}^+ \bar{\sigma}^\mu Q_3)(Q_{1,2}^+ \bar{\sigma}_\mu Q_3)$</td>
<td>$\epsilon_K$</td>
<td>$(V^* Y_{\eta,u}^2 V^T)_{21}^2$</td>
</tr>
<tr>
<td>$(d_{1,2}^+ \bar{\sigma}^\mu d_{2,3})(d_{1,2}^+ \bar{\sigma}<em>\mu d</em>{2,3})$</td>
<td>$\Delta m_{B_d,s}, \epsilon_K, \Delta m_{B_d,s}$</td>
<td>$(V^T Y_{\eta,u}^2 V^*)<em>{21}^2 (1,2)</em>{3}$</td>
</tr>
<tr>
<td>$(Q_{1}^+ \bar{d}<em>2)(Q</em>{2}^+ \bar{d}_1)$</td>
<td>$\epsilon_K$</td>
<td>$(V^T Y_{\eta,u}^2 V^<em>)<em>{12} (V^T Y</em>{\eta,u}^2 V^</em>)<em>{21}^*</em>{13}$</td>
</tr>
<tr>
<td>$(Q_{1}^+ \bar{d}<em>3)(Q</em>{3}^+ \bar{d}_1)$</td>
<td>$\Delta m_{B_d}$</td>
<td>$(V^T Y_{\eta,u}^2 V^<em>)<em>{13} (V^T Y</em>{\eta,u}^2 V^</em>)<em>{31}^*</em>{23}$</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_2 \bar{d}<em>3 F</em>{\mu\nu}$</td>
<td>$B \rightarrow X_s(\gamma, \ell^+ \ell^-), K^* \mu^+ \mu^-$</td>
<td>$[ (V^T Y_{\eta,u}^2 V^<em>) Y_{\eta,d} ]_{23}^</em>$</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_3 \bar{d}<em>2 F</em>{\mu\nu}$</td>
<td>$B \rightarrow X_s(\gamma, \ell^+ \ell^-), K^*(\gamma, \mu^+ \mu^-)$</td>
<td>$[ (V^T Y_{\eta,u}^2 V^<em>) Y_{\eta,d} ]_{32}^</em>$</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_3 \bar{d}<em>1 F</em>{\mu\nu}$</td>
<td>$B \rightarrow X_d \gamma$</td>
<td>$[ (V^T Y_{\eta,u}^2 V^<em>) Y_{\eta,d} ]_{31}^</em>$</td>
</tr>
</tbody>
</table>
# Constraints on Dimension Six SFV Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>$\Lambda$ [TeV]</th>
<th>$\Lambda_{SFV}$ [TeV]</th>
<th>$\Lambda_{MFV}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(Q_1^\dagger \bar{\sigma}^\mu Q_2)(Q_1^\dagger \bar{\sigma}_\mu Q_2)$</td>
<td>$1.5 \times 10^4$</td>
<td>262.7 $</td>
<td>\eta_d^2 - \eta_s^2</td>
</tr>
<tr>
<td>$(Q_{1,2}^\dagger \bar{\sigma}^\mu Q_3)(Q_{1,2}^\dagger \bar{\sigma}_\mu Q_3)$</td>
<td>$2.1 \times 10^3$</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>$(d_1^\dagger \bar{\sigma}^\mu d_2)(d_1^\dagger \bar{\sigma}_\mu d_2)$</td>
<td>$1.5 \times 10^4$</td>
<td>4.54 $</td>
<td>\eta_d \eta_s</td>
</tr>
<tr>
<td>$(d_2^\dagger \bar{\sigma}^\mu d_3)(d_2^\dagger \bar{\sigma}_\mu d_3)$</td>
<td>$0.21 \times 10^3$</td>
<td>1.77 $</td>
<td>\eta_d \eta_b</td>
</tr>
<tr>
<td>$(Q_1 \tilde{d}_3)(Q_3^\dagger \tilde{d}_1^\dagger)$</td>
<td>$2.2 \times 10^3$</td>
<td>18.8 $</td>
<td>\eta_d \eta_b</td>
</tr>
<tr>
<td>$(Q_1 \tilde{d}_2)(Q_2^\dagger \tilde{d}_1^\dagger)$</td>
<td>$2.4 \times 10^5$</td>
<td>74.9 $</td>
<td>\eta_d \eta_s</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_2 \tilde{d}<em>3 F</em>{\mu\nu}$</td>
<td>330.2</td>
<td>65.4 $</td>
<td>\eta_b</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_3 \tilde{d}<em>2 F</em>{\mu\nu}$</td>
<td>308.9</td>
<td>61.2 $</td>
<td>\eta_s</td>
</tr>
<tr>
<td>$eH \sigma^{\mu\nu} Q_3 \tilde{d}<em>1 F</em>{\mu\nu}$</td>
<td>203.1</td>
<td>18.7 $</td>
<td>\eta_d</td>
</tr>
</tbody>
</table>
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

\[ \kappa \lambda^u Q H^2 \bar{u} - Y^\eta Q H^c_2 \bar{d} \]

Up-type SFV 2HDM

- An SFV theory with a new up-Yukawa gives

\[ Y^\eta Q H^2 \bar{u} - \kappa \lambda^d Q H^c_2 \bar{d} \]

Down-type SFV 2HDM
ABSENCE OF TREE-LEVEL FCNC'S

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

\[ Y_{ij}^\eta \ d_i H_2^0 \bar{d}_j + \kappa \begin{bmatrix} V^T \ Y_u \end{bmatrix}_{i,j} u_i H_2^0 \bar{u}_j \]

- Go to the quark mass eigenbasis \( u \rightarrow u V^* \)

\[ Y_{ij}^\eta \ d_i H_2^0 \bar{d}_j + \kappa Y_{ij}^u u_i H_2^0 \bar{u}_j \]

1. No tree-level FCNC's
2. Non universal couplings to down quarks
**APPLICATION 1: HIGGSES THAT -DO- COUPLE TO PROTONS**

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

![Diagram showing Higgs production through flavor non-universal couplings]
WE CAN LOOK FOR THESE HIGGSSES 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, testable, falsifiable, and may be found at LHC.
CLASSES OF FLAVOR VACUA

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

Intersections mean same physics in the infrared.