Spontaneous Flavor Violation and the 2HDM

Based on arXiv:1811.00017 and 190X.xxxx

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Phenomenology Symposium, May 7, 2019
University of Pittsburgh
The Search for New Physics

• The LHC has a broad, active program searching for new physics (NP) at the TeV scale.

• Great time to examine our assumptions about how NP couples to the Standard Model.

• Flavor violation bounds are already probing ~ 100s TeV scale. How do we reconcile this disparity?
Avoiding Flavor Bounds Requires Assumptions

For *flavored* new physics, simplest assumption is *Minimal Flavor Violation*

\[ \lambda_{2,ij}^d Q_i \bar{d}_j H^c_i, \quad \xi_{ij} (d_i^\dagger i\bar{\sigma}^\mu d_j) Z'_\mu \]

In a 2HDM MFV implies:

\[ \lambda_{2,ij}^u \propto y_{SM}^u, \quad \lambda_{2,ij}^d \propto y_{SM}^d \]

\[ y_{SM}^u = \begin{pmatrix} 10^{-5} & 10^{-3} & 10^{-2} \\ 10^{-6} & 10^{-3} & 10^{-2} \\ 10^{-8} & 10^{-4} & 1 \end{pmatrix} \]

This implicitly assumes NP couples mainly to *third generation* quarks!
Alignment Suppresses FCNCs

This is clear when we look in a particular basis:

\[ \mathcal{L} \supset - V^T_{ij} Y^u Q_i H \bar{u}_j + Y^d Q_i H^c d_j + K^d Q_i H^c_2 \bar{d}_j, \]

Couplings to new physics can be arbitrarily large, without introducing FCNCs

But demanding alignment without a UV completion is very ad hoc

\[ Y^u = \text{diag}(y^u_{SM}, y^c_{SM}, y^t_{SM}) \]
\[ Y^d = \text{diag}(y^u_{SM}, y^s_{SM}, y^b_{SM}) \]
\[ K^d = \text{diag}(\kappa_d, \kappa_s, \kappa_b) \]
Spontaneous Flavor Violation
A UV Completion for Flavor Alignment

\[ \mathcal{L} \supset -V_{i,j}^{T} Y^{u} Q_{i} H \bar{u}_{j} + Y^{d} Q_{i} H^{c} \bar{d}_{j} + K^{d} Q_{i} H_{2}^{c} \bar{d}_{j} \]

Flavor Violation “in the up sector”

Idea: *All* quark family number & CP breaking via renormalization of *either* right-handed up- or down-type quarks

\[ \mathcal{L} \supset i Z_{i,j}^{u} \bar{u}_{i} \gamma_{\mu} \sigma^{\mu} D_{\mu} \bar{u}_{j} + i d_{i} \gamma_{\mu} \sigma^{\mu} D_{\mu} \bar{d}_{i} + i Q_{i} \gamma_{\mu} \sigma^{\mu} D_{\mu} \bar{Q}_{i} + \]

\[ \implies \text{Couplings to the other sector remain } \text{aligned} \]
Mixing with Spontaneously Broken Flavor Vacuum

\[ L \supset iZ_{ij}^u \bar{u}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{d}_i + i\bar{Q}_i^\dagger \bar{\sigma}^\mu D_\mu \bar{Q}_i + \]

Note: Two distinct theories: up- or down-type SFV
Flavor Bounds in an SFV 2HDM
Charged Higgs Contributions to FCNCs arise at loop-level

Order ~ 0.1 couplings to first and second generation quarks are allowed for a large range of masses!
Limits from Dijet Searches
Heavy Higgs Produced in Tree-Level Quark Fusion, Decays to Dijets

Much of the parameter space is more efficiently probed with colliders — even for O(100 GeV) new Higgses!
Mixing Leads to Enhancement of SM Yukawas

Up-Type SFV

\[ \frac{\lambda^h_{s\bar{s}}}{\lambda^h_{s\bar{s}}^{SM}} \]

\[ \cos(\beta - \alpha) \]

Realistic targets for quark-flavor taggers!

Down-Type SFV

\[ \frac{\lambda^h_{c\bar{c}}}{\lambda^h_{c\bar{c}}^{SM}} \]

\[ \cos(\beta - \alpha) \]
Conclusions

• Flavor assumptions have *drastic* implications for new physics searches and collider phenomenology

• Spontaneous Flavor Violation ensures flavor alignment — allows for large couplings to light quarks

• In the 2HDM, this leads to strong production and enhanced Yukawas

• SFV can be applied to any BSM model!

SMEFT, MSSM, Z-primes, Leptoquarks, Vector-like quarks, Axions, Colored Scalars, …
Backup
Backup: Details of the UV Completion

\[ \mathcal{L} \supset M_{AB} U_A \bar{U}_B + \xi S_{iA} \bar{u}_i U_A \]

\[ - \left[ \eta_{ij}^u Q_i H \bar{u}_j - \eta_{ij}^d Q_i H^c \bar{d}_j + \text{h.c.} \right] + \mathcal{L}_{\text{BSM}} \]

Introduce mixing between up-quark and heavy VLQs in a flavor breaking vacuum

Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

\[ Z_{ij}^u = \delta_{ij} + \frac{\xi^* \xi}{M_A^* M_A} S_{iA}^* S_{jA} \]

No additional spurions/fields transforming under \( U(3)_\bar{u} \)

Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

The source of all flavor-breaking! CKM matrix arises from returning to canonical basis

\[
\begin{array}{c|cccc}
\hline
 & U(3)_U & U(3)_{\bar{U}} & U(3)_{\bar{u}} & U(1)_B & \mathbb{Z}_2 \\
\hline
U & 3 & & & 1/3 & -1 \\
\bar{U} & & 3 & & -1/3 & -1 \\
S & \bar{3} & & \bar{3} & & -1 \\
\hline
\end{array}
\]
Backup: Additional Flavor Bounds

- **$B_d, B_s, K$-Mixing Constraints**
- **$D$-Mixing Constraints**
- **$B 	o X_s \gamma$ Constraints**

Parameters:
- $\kappa_d, \kappa_b = 0, \xi = 1.0$
- $\xi y_t Q_3 H_2 \bar{t} + \kappa_d Q_1 H_2^c \bar{d}$
- $\kappa_s, \kappa_b = 0, \xi = 1.0$
- $\xi y_t Q_3 H_2 \bar{t} + \kappa_s Q_2 H_2^c \bar{s}$

Graphs showing the dependence of $m_H$ (GeV) on $\kappa_d$ and $\kappa_s$. The shaded regions represent different constraints and bounds on the parameter space.
Backup: Additional Flavor Bounds

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_b Q_3 H_2^c \bar{b} \]
\[ \kappa_d, \kappa_s = 0, \xi = 0.1 \]

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_b Q_3 H_2^c \bar{b} \]
\[ \kappa_d, \kappa_s = 0, \xi = 1.0 \]
Backup: Additional Collider Bounds

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_d Q_1 H_2^c d \]
\[ \kappa_s, \kappa_b = 0, \xi = 1.0 \]

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_s Q_2 H_2^c s \]
\[ \kappa_d, \kappa_b = 0, \xi = 1.0 \]
Backup: Additional Collider Bounds

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_b Q_3 H_2^c \bar{b} \]

\[ \kappa_d, \kappa_s = 0, \; \xi = 0.1 \]

\[ \xi y_t Q_3 H_2 \bar{t} + \kappa_b Q_3 H_2^c \bar{b} \]

\[ \kappa_d, \kappa_s = 0, \; \xi = 1.0 \]