THE INTERPLAY BETWEEN HIGGS & FLAVOR PHYSICS

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INTRODUCTION

- In the standard model (SM), flavor physics is linked to electroweak symmetry breaking (EWSB) & hence the Higgs via the Yukawa interactions.

- In TeV extensions of the SM with new & generic flavor-breaking terms, “Higgs-flavor connection” would be lost, but such theories are experimentally ruled out by now.

- In new-physics scenarios with close to minimal flavor structure, correlations between Higgs & flavor physics may remain. Of course, only experiment can tell.
HIGGS FCNCS: MOTIVATIONS

- Renewed interest in SM extensions with intricate Higgs sectors. Most of the proposed setups feature more than one Higgs doublet with potentially sizable flavor-changing neutral-current (FCNC) couplings.

- FCNC scalar amplitudes offer a unique tool to distinguish between different types of flavor-symmetry breaking:
  - easy to mimic the SM in the case of left-handed (LL) operators
  - more difficult to model the SM double suppression (down-type Yukawas & mixing angles) of left-right-chirality (LR) operators

- An interesting possibility to address “tensions” in $\Delta F = 2$ observables (i.e. mixing amplitudes) without spoiling the good overall agreement (at level of 20%) of the Cabibbo-Kobayashi-Maskawa (CKM) picture.
The main problem in extending the Higgs sector are excessive FCNCs. Generic Yukawa Lagrangian with 2 Higgs doublets (2HDM) reads:

\[ \mathcal{L}_{\text{Yukawa}} = \bar{Q}^i_L (X_{d1})_{ij} d^j_R \phi_d + \bar{Q}^i_L (X_{u2})_{ij} u^j_R \phi_u + \bar{Q}^i_L (X_{d2})_{ij} \tilde{d}^j_R \tilde{\phi}_d + \bar{Q}^i_L (X_{u1})_{ij} u^j_R \tilde{\phi}_u + \text{h.c.} \]

Couplings to the “wrong” Higgs doublet will generically induce tree-level FCNCs.
PROTECTION OF HIGGS FCNCs

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- There are two main strategies to get rid of this harmful effects

  i) By flavor-blind symmetries ("natural flavor conservation"): in case of 2HDM-II one uses \( Z_2 \) subgroup of \( U(1)_{\text{PQ}} \) such that \( X_{d2} = X_{u1} = 0 \),

\[ \phi_d \rightarrow -\phi_d \quad d_R \rightarrow -d_R \quad \text{remaining fields even under } Z_2 \]

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\[ \mathcal{L}_{\text{Yukawa}} = \bar{Q}_L^i \begin{pmatrix} X_{d1} \end{pmatrix}_{ij} d_R^j \phi_d + \bar{Q}_L^i \begin{pmatrix} X_{u2} \end{pmatrix}_{ij} u_R^j \phi_u \\
+ \bar{Q}_L^i \begin{pmatrix} X_{d2} \end{pmatrix}_{ij} d_R^j \tilde{\phi}_u + \bar{Q}_L^i \begin{pmatrix} X_{u1} \end{pmatrix}_{ij} u_R^j \tilde{\phi}_d + \text{h.c.} \]

There are two main strategies to get rid of this harmful effects

ii) By flavor symmetries (& symmetry breaking): for example one can use minimal-flavor violation (MFV), which at lowest order leads to

\[ X_{d1} \propto X_{d2} \propto Y_d \quad X_{u1} \propto X_{u2} \propto Y_u \]

PROTECTION OF HIGGS FCNCs

But both mechanism are not radiatively stable (problem is particularly severe if the theory contains additional states at the TeV scale):

i) To avoid massless pseudo scalar, U(1)$_{\text{PQ}}$ Peccei-Quinn symmetry must be necessarily broken explicitly (in Higgs potential, ...)

MSSM diagram

\[
\begin{align*}
X_{d2} &= 0 & X_{d1} &= Y_d \\
&
\text{One loop:} \\
X_{d2} &= \epsilon \Delta_d & X_{d1} &= Y_d + \ldots
\end{align*}
\]

[see for example Hall, Rattazzi & Sadridd, hep-ph/9306309]
PROTECTION OF HIGGS FCNCS

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strongest constraint arises from CP violation in neutral kaon system ($\epsilon_K$)

Tree level:

$$X_{d2} = 0 \quad X_{d1} = Y_d$$

One loop:

$$X_{d2} = \epsilon \Delta_d \quad X_{d1} = Y_d + \ldots$$

implies ($\Delta_d$)$_{ij} \ll O(10^{-4})$

chiral & RGE enhancements lead to factor of $O(100)$ between LR & LL contribution

$$|\epsilon| \ \text{Im} \left[ (\Delta^*_d)_{21} (\Delta_d)_{12} \right]^{1/2} \lesssim 3 \cdot 10^{-7} \ \frac{M_A}{100 \text{ GeV}} \cos \beta$$
PROTECTION OF HIGGS FCNCs

- But both mechanism are not radiatively stable (problem is particularly severe if the theory contains additional states at the TeV scale):
  
  ii) Even if exact (discrete case), symmetries do not protect FCNCs when higher-dimensional operators are taken into account

\[
\Delta \mathcal{L}_{\text{Yukawa}} = \frac{c_D}{\Lambda^2} \bar{Q}_L i \gamma_5 Q_L (\phi^\dagger \phi) + \frac{c_\phi}{\Lambda^2} \bar{Q}_L \phi d_R (\phi^\dagger \phi) + \ldots
\]

if Higgs is a pseudo-Goldstone-boson, operator aligned with SM Yukawa coupling (due to shift symmetry) & gives no FCNCs

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\]

chirally suppressed

unsuppressed

EWSB: \( \phi = v + h \)

\[
\Delta M_d = -v \left( c_D Y_d + c_\phi \right) \frac{v^2}{\Lambda^2} + \ldots
\]

mismatch leads to Higgs FCNCs (already for a single Higgs doublet)

\[
\Delta \mathcal{L}_h = -3 \left( c_D Y_d + c_\phi \right) \frac{v^2}{\Lambda^2} h \bar{d}_L d_R + \ldots
\]

PROTECTION OF HIGGS FCNCS

But both mechanism are not radiatively stable (problem is particularly severe if the theory contains additional states at the TeV scale):

i) To avoid massless pseudo scalar, $U(1)_{PQ}$ Peccei-Quinn symmetry must be necessarily broken explicitly (in Higgs potential, ...)

ii) Even if exact (discrete case), symmetries do not protect FCNCs when higher-dimensional operators are taken into account

To reach a sufficient protection of Higgs FCNCs one needs to protect the flavor-symmetry breaking. Possible ways to achieve such a protection is provided by MFV, warped extra dimensions (WEDs) or partial compositeness (hierarchical fermion profiles), ...
HIGGS FCNCS WITH MFV

- Structure of Higgs FCNC couplings (in limit $\tan\beta = \nu_u/\nu_d \gg 1$):

  $$\mathcal{L}^{\text{MFV}}_{\text{FCNC}} \propto \bar{d}_L^i V_{3i}^* \left[ a_0 + a_1 \delta_{3i} + a_2 \delta_{3k} \right] V_{3k} y_k^d d_R^k H$$

- double suppression by CKM ($V_{3i}$) & down-type Yukawas ($y_k^d$)
- $a_i$ are $O(1)$ parameters (encoding dependence from 3rd generation Yukawas), complex if one allows for flavor-blind CP-violating phases
- since in the MSSM the Yukawa insertions of power 5 are very small, one needs non-trivial models to get interesting CP-violating effects

HIGGS FCNCS WITH MFV

Structure of Higgs FCNC couplings (in limit \(\tan\beta = v_u/v_d \gg 1\)):

\[
\mathcal{L}_{\text{FCNC}}^{\text{MFV}} \propto \bar{d}_i^i L V_{3i}^* \left[ a_0 + a_1 \delta_{3i} + a_2 \delta_{3k} \right] V_{3k} y_d^d d_R^k H
\]

integrating out heavy Higgs fields H

\[
\mathcal{L}_{\Delta F=2}^{\text{MFV}} \propto y_i^d y_k^d (V_{3i}^* V_{3k})^2 (\bar{d}_R^i d_L^k)(\bar{d}_L^i d_R^k) \begin{cases} |a_0|^2, & i k = 21 \\ (a_0^* + a_1^*)(a_0 + a_2), & i k = 31, 32 \end{cases}
\]

effects scale (almost) as \(\{m_b m_s, m_b m_d, m_s m_d\}\) relative to SM

\{ large effects in Bs mixing, small effects in Bd mixing, tiny effects in kaon mixing \}

[Buras et al., arXiv:1005.5310]
HIGGS FCNCS IN WEDS

- SM quark fields couple to the new-physics sector via hierarchical wave functions $F_Q^i, F_u^i$ & $F_d^i$ such that

\[
(Y_d)_{ij} = F_Q^j Y_d^{5D} F_d^i \sim F_Q^j F_d^i
\]

\[
(Y_u)_{ij} = F_Q^i Y_u^{5D} F_u^j \sim F_Q^i F_u^j
\]

\[
F_Q^3 \gg F_Q^2 \gg F_Q^1
\]

\[
F_d^3 \gg F_d^2 \gg F_d^1
\]

\[
F_u^3 \gg F_u^2 \gg F_u^1
\]

\[
Y_{d,u}^{5D} = \text{anarchic, } \mathcal{O}(1) \text{ complex}
\]

[see for example Huber, hep-ph/0303183]
HIGGS FCNCS IN WEDS

SM quark fields couple to the new-physics sector via hierarchical wave functions $F_Q^i, F_u^i & F_d^i$ such that

$$(Y_d)_{ij} = F_Q^j Y_d^{5D} F_d^i \sim F_Q^i F_d^j \quad (Y_u)_{ij} = F_Q^i Y_u^{5D} F_u^j \sim F_Q^i F_u^j$$

- quark masses & CKM elements simply given in terms of profiles:

$$m_u^i \sim v F_Q^i F_u^i$$
$$m_d^i \sim v F_Q^i F_d^i$$

$$V_{ij} \sim \begin{cases} 
\frac{F_Q^i}{F_Q^j}, & i \leq j \\
\frac{F_Q^j}{F_Q^i}, & i > j 
\end{cases}$$

[see for example Huber, hep-ph/0303183]
HIGGS FCNCs IN WEDS

Lagrangian inducing Higgs FCNCs takes the form:

\[ \mathcal{L}_{\text{FCNC}}^{\text{WED}} \sim \left( \frac{v Y_d^{5D}}{M_{\text{KK}}} \right)^2 \bar{d}_L^i \left[ y_i^d F_{Q}^i F_{Q}^k + y_k^d F_{d}^i F_{d}^k + Y_d^{5D} F_{Q}^i F_{d}^k \right] d_R^k h \]

- Kaluza-Klein (KK) of O(few TeV)
- from "right" Yukawa couplings $\bar{Q}_L d_R$ (or derivative operators)
- from "wrong" Yukawa couplings $\bar{d}_L Q_R$ after regularizing Higgs profile & summing whole KK tower (or non-derivative operators)

- suppression by exponentially small wave functions $F_{Q}^i$ & $F_{d}^i$
- if present, term involving 3 powers of the 5D Yukawas gives dominant contribution to Higgs FCNCs involving light quarks

HIGGS FCNCS IN WEDS

- Lagrangian inducing Higgs FCNCs takes the form:

\[
\mathcal{L}_{\text{WED FCNC}} \sim \left( \frac{v Y^5_{d}}{M_{\text{KK}}} \right)^2 \bar{d}^i_L \left[ y^d_i F_Q F^k_Q + y^d_k F_d F^k_d + Y^5_{d} F^i_Q F^k_d \right] d^k_R h
\]

- corrections scale as \( \{m_b m_s, m_b m_d, m_s m_d\} \) in absolute terms

- small effects in \( B_s \) mixing
- small effects in \( B_d \) mixing
- large effects in kaon mixing

FCNCs associated to virtual tree-level exchange of Higgs bosons can show notably different patterns of enhancements. For example:

**MFV:** double suppression by CKM & down-type Yukawas

\[
\begin{align*}
\text{large effects in } B_s \text{ mixing} \\
\text{small effects in } B_d \text{ mixing} \\
\text{tiny effects in kaon mixing}
\end{align*}
\]

\[
\begin{align*}
\text{unobservable effects in rare top decay } t \rightarrow c(u)h
\end{align*}
\]

**WEDs:** suppression by down-type Yukawas only

\[
\begin{align*}
\text{small effects in } B_s \text{ mixing} \\
\text{small effects in } B_d \text{ mixing} \\
\text{large effects in kaon mixing}
\end{align*}
\]

\[
\begin{align*}
\text{promising corrections to rare top decay } t \rightarrow c(u)h
\end{align*}
\]
RARE TOP DECAYS IN WEDS

Due to compositeness of top, huge enhancements relative to SM possible in $t \rightarrow ch$ for low KK scales. Still challenging at LHC

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Minimum of $6.5 \cdot 10^{-5}$ for $3\sigma$ discovery by LHC, 100 fb$^{-1}$

95% CL limit of $4.5 \cdot 10^{-5}$ from LHC, 100 fb$^{-1}$

Consistent with all flavor constraints

FCNC CONSTRAINTS ON 2HDM-II

2HDM-II diagrams

- Including the available flavor data ($B \rightarrow X_s\gamma$, $B \rightarrow \tau\nu$, $B \rightarrow D\tau\nu$ & $K \rightarrow \mu\nu$) disfavors a large portion of the parameter space in $\tan\beta - M_{H^\pm}$ plane of the 2HDM model of type II (2HDM-II)

HEAVY HIGGSES: FLAVOR & LHC INTERPLAY

- The current constraints on the 2HDM-II parameters that follow from flavor physics are comparable & thus complementary to the expected 95% CL exclusion limits of the LHC from gg/gb → t(b)H⁺, H⁺ → τν/τb

[Robertson, talk SuperB Physics Workshop, Warwick; ATLAS Collaboration, arXiv:0901.0512]
HEAVY HIGGSES: 2011 LHC DATA

\[ m_{h}^{\text{max}} \text{ scenario:} \]

\[ M_{\text{SUSY}} = \frac{X_t}{\sqrt{6}} = 1 \text{ TeV} \]
\[ 2M_1 = M_2 = -\mu = 200 \text{ GeV} \]
\[ m_{\tilde{g}} = 800 \text{ GeV} \]

\[ m_{h} \in [120, 130] \text{ GeV} \quad \text{CMS, } 1 \text{ fb}^{-1} \]

- Assuming a Higgs signal (& invoking flavor constraints) allows to derive lower bounds \( \tan \beta \gtrsim 3 \) & \( M_{H^\pm} \gtrsim 150 \text{ GeV} \). These limits are only weakly dependent on \( M_{\text{SUSY}} \) & stronger than direct exclusions from LHC

[CMS-HIG-11-008; Heinemeyer, Stal & Weiglein, arXiv:1112.3026]
\(m_h^{\text{max}}\)-like scenario:

\[
M_{\text{SUSY}} = X_t / 1.8 = 1 \text{ TeV} \\
2M_1 = M_2 = -\mu = 200 \text{ GeV} \\
m_\tilde{g} = 800 \text{ GeV}
\]

\[
R_{\gamma\gamma} = \frac{[\sigma(pp \rightarrow h) Br(h \rightarrow \gamma\gamma)]_{\text{MSSM}}}{[\sigma(pp \rightarrow h) Br(h \rightarrow \gamma\gamma)]_{\text{SM}}}
\]

- In wide ranges of MSSM parameter space Higgs to di-photon signal depleted. Combination of Higgs measurements & indirect constraints provide powerful tool to tighten the MSSM parameter space

[see recently for example Hall, Pinner & Ruderman, arXiv:1112.2703; Carena et al., arXiv:1112.3336]
In typical mSUGRA spectrum only masses of heavy Higgses & lightest stau show dependence on $\tan\beta$. SM decay modes of Higgses hard to detect at LHC & stau mass can be measured with precision of 20% at best. As a result, LHC sensitivity to $\tan\beta$ rather restricted.
B physics is quite sensitive to $\tan\beta$ (both branching fractions & isospin asymmetries). By measuring correlated shifts in observables one can determine $\tan\beta$ with 10% accuracy. This exceeds LHC sensitivity based on discovery of stop, $A^0$ & lightest Higgs.
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In universal extra dimension (UED) models, the KK contributions always reduce $B \to X_s \gamma$ rate relative to SM. This feature implies stringent limits on KK scale of $1/R > 550, 650$ GeV in 5D, 6D UED.

UED: FLAVOR & HIGGS INTERPLAY

- Virtual effects in UED associated to top partners also alter notably the Higgs properties & enhance channels with respect to SM. Higgs physics has better potential to find evidence/constrain UED than flavor physics.

[see for example Petriello, hep-ph/0204067]
CONCLUSIONS

- Like flavor physics, precision studies of Higgs properties allow to probe indirectly for beyond TeV mass scales, complementing the direct LHC searches for new physics.

- It is possible to build viable SM extensions with minimal or next-to-minimal flavor structure that feature testable correlations between Higgs & flavor physics observables.

- Higgs-mediated FCNCs would provide (if observed) a very interesting window on both the Higgs sector & on the structure of flavor-symmetry breaking.
In WEDs addressing hierarchy problem (which must be considered as effective theories with ultra-violet cutoff) ggh coupling suppressed. Dominant effect due to KK-quark loops which contribute universal

\[ \kappa_g \approx \Re \kappa_t - \frac{v^2}{2M_{KK}^2} \sum_q \text{Tr} \left( Y_q^5 Y_q^5 \dagger \right) \]

\[ \kappa_q \approx 1 - \frac{v^2}{M_{KK}^2} \left\{ \frac{(Y_q^5 Y_q^5 \dagger Y_q^5)}{3(Y_q^5 Y_q^5)}_{33} + \delta_{tq} |Y_q^5|^2 \left[ (F_Q^3)^2 + (F_q^3)^2 \right] \right\} \]

HIGGS PRODUCTION & DECAY IN WEDS

The contribution of W boson & its KK modes to effective $\gamma\gamma h$ vertex interfere destructively with SM. Gauge-boson-Higgs couplings reduced. Both types of corrections enhanced by extra-dimensional volume $L$

$$\kappa_V \approx 1 - \frac{v^2}{M_{KK}^2} (L - 1), \quad V = W, Z$$

$$\approx -\frac{21}{8} (\kappa_W - 1)$$

“volume” of extra dimension $\ln(M_P/M_W) \approx 37$

$\kappa_V \approx 1 - \frac{v^2}{M_{KK}^2} (L - 1), \quad V = W, Z$

Notable relative suppressions in minimal WED (mWED) model of products ($R_{ff}$) of total cross section & braching ratios $h \rightarrow ff$. Effects particularly large for $|Y_q^{5D}| = y_{max}$ close to perturbative bound $y_{max} = 3$

Due to higher multiplicity of fermionic states in custodial WED model (cWED) shifts in $R_{ff}$ even more pronounced. Measurements of Higgs properties can probe KK masses far beyond direct LHC reach of 3 TeV.