FLAVOR VIOLATING HIGGS DECAYS

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Higgs Couplings 2016, SLAC, Nov 11, 2016
OUTLINE

• introduction
• probing Higgs flavor violating couplings
• model building
• summary
HIGGS IN THE STANDARD MODEL

\[ h \]

\[ v \]
Higgs in the Standard Model

tested by:
direct - $h \rightarrow WW^*, ZZ^*$
indirect - Electroweak precision

unitarize: $V_L V_L \rightarrow V_L V_L$

$m_{W,Z} \neq 0$
Higgs in the standard model

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the Higgs is the main source of Electroweak symmetry breaking
**Higgs in the Standard Model**

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the Higgs is the main source of Electroweak symmetry breaking

$\bar{f} f \rightarrow V_L V_L$

$m_f \neq 0$

$y_f \propto m_f$

much less is known


**INTRODUCTION**

Standard Model

- non-universal and hierarchical
- diagonal
- flavor violating Higgs decays are suppressed by loop, mixing (CKM/PMNS) and GIM

\[
y^f_{SM} = \frac{m_f}{v}
\]
Standard Model

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$$y_f^{SM} = \frac{m_f}{v}$$

off diagonal Yukawa  new physics
\[ y_f^{SM} = \frac{m_f}{v} \]

Standard Model

- non-universal and hierarchical
- diagonal
- flavor violating Higgs decays are suppressed by loop, mixing (CKM/PMNS) and GIM

**off** diagonal Yukawa $\Rightarrow$ new physics

if at the TeV scale

NP flavor structure cannot be anarchic need to be aligned with the SM (or universal)
probing Higgs flavor violating couplings
Higgs data:

- **dedicated searches**: $h \rightarrow b\bar{b}$, $h \rightarrow \tau \mu$, $h \rightarrow M \gamma$, $t \rightarrow hj$, $t\bar{t}h$ (mostly 3rd generation)

- **indirect constraints**: total width, global fit, kinematical distributions

- **low energy process**: $\mu \rightarrow e\gamma$, meson mixing...
**LEPTON SECTOR**

**CMS:**
- $\text{BR}(h \rightarrow e\mu)_8 < 0.036\%$
- $\text{BR}(h \rightarrow e\tau)_8 < 0.70\%$
- $\text{BR}(h \rightarrow \mu\tau)_8 < 0.89 \pm 0.39\%$
- $\text{BR}(h \rightarrow \mu\tau)_{13} < 1.20\% (1.62\% \text{ expected})$

**ATLAS:**
- $\text{BR}(h \rightarrow e\tau)_8 < 1.04\%$
- $\text{BR}(h \rightarrow \mu\tau)_8 < 0.53 \pm 0.51\%$
**LEPTON SECTOR**

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$$Y^\ell = \begin{pmatrix} Y_e & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau} \end{pmatrix} < \begin{bmatrix} 0.54 & 2.4 \\ 0.54 & 3.2 \\ 2.4 & 3.2 \end{bmatrix} \times 10^{-3}$$

$3.6 \times 10^{-6}$ ($\mu \rightarrow e\gamma$)

$\left( |y_{\tau e} y_{\mu\tau}|^2 + |y_{e\tau} y_{\tau\mu}|^2 \right)^{1/4} < 3.4 \times 10^{-4}$ ($\mu \rightarrow e\gamma$)
UP QUARK SECTOR

**ATLAS:** $\text{BR}(t \rightarrow hj)_8 < 0.46\%$

**CMS:** $\text{BR}(t \rightarrow hj)_8 < 0.56\%$
**Up Quark Sector**

**ATLAS:** $\text{BR}(t \rightarrow hj) < 0.46\%$

**CMS:** $\text{BR}(t \rightarrow hj) < 0.56\%$

\[
Y^u = \begin{pmatrix}
Y_u & Y_{uc} & Y_{ut} \\
Y_{cu} & Y_c & Y_{ct} \\
Y_{tu} & Y_{tc} & Y_t
\end{pmatrix}
\]

$D^0 - \bar{D}^0$ mixing

$t \rightarrow hj$: decay and $th$ production

<table>
<thead>
<tr>
<th>$\text{BR}(t \rightarrow hj)$</th>
<th>$7 \times 10^{-5}$</th>
<th>0.13</th>
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<tbody>
<tr>
<td>$7 \times 10^{-5}$</td>
<td>7.00</td>
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<td>0.13</td>
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Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

Greljo, Kamenik, Koop 1404.1278
**UP QUARK SECTOR**

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7 \times 10^{-5} & 0.13 \\
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\]

*ATLAS: BR(t→hj) < 0.46%*

*CMS: BR(t→hj) < 0.56%*

**D^0-\bar{D}^0 mixing**

\[t→hj: \text{decay and } th \text{ production}\]

- bounds from meson mixing may be relaxed in models where the Higgs is part of flavor multiplet
- direct probing of \(y_{cu,uc}: h→D^*γ\) - weak sensitivity

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

Greljo, Kamenik, Koop 1404.1278

Kagan et al- 1406.1722
**Down Quark Sector**

\[ Y^d = \begin{pmatrix} y_d & y_{ds} & y_{db} \\ y_{sd} & y_s & y_{sb} \\ y_{bd} & y_{bs} & y_b \end{pmatrix} \]

- **K^0-\bar{K}^0 mixing**
- **B_d-\bar{B}_d mixing**
- **B_s-\bar{B}_s mixing**

<table>
<thead>
<tr>
<th>Re (Im)</th>
<th>(2.4(0.17) \times 10^{-5})</th>
<th>(1.5 \times 10^{-4})</th>
</tr>
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<td>(y_d)</td>
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<tr>
<td>(y_{ds})</td>
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- bounds from meson mixing may be relaxed in models where the Higgs is part of flavor multiplet
- direct probing of \(y_{bd,db}, y_{bs,sb}, y_{ds,sd}\): \(h \rightarrow K^*\gamma,B_s\gamma,B_d\gamma\) - weak sensitivity

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

Kagan et al- 1406.1722
model building for flavor changing Higgs couplings
\[ \lambda_{i,j}^f \bar{\psi}_R^i \psi_L^j H + \frac{\lambda_{i,j}^f}{\Lambda^2} \bar{\psi}_R^i \psi_L^j H(H^\dagger H) \]
\[\lambda_{ij}^f \bar{\psi}_R^i \psi_L^j H + \frac{\lambda_{ij}^f}{\Lambda^2} \bar{\psi}_R^i \psi_L^j H(H^\dagger H)\]

\[Y_{ij}^f = \frac{\sqrt{2}m_i^f}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} \hat{\lambda}_{ij}^f = \frac{\sqrt{2}m_i^f}{v} \delta_{ij} + 0.01 \left( \frac{\hat{\lambda}_{ij}^f}{0.17} \right) \left( \frac{\text{TeV}}{\Lambda} \right)\]
MODEL BUILDING - EFT

\[ \lambda_{i,j}^f \bar{\psi}_R^i \psi_L^j H + \frac{\lambda_{i,j}^f}{\Lambda^2} \bar{\psi}_R^i \psi_L^j H (H^\dagger H) \]

\[ \hat{\lambda}^f = V_L^f \lambda^f V_R^{f\dagger} \]

\[ Y_{i,j}^f = \frac{\sqrt{2} m_i^f}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} \hat{\lambda}_{ij}^f = \frac{\sqrt{2} m_i^f}{v} \delta_{ij} + 0.01 \left( \frac{\hat{\lambda}_{ij}^f}{0.17} \right) \left( \frac{\text{TeV}}{\Lambda} \right) \]

\[ \text{BR}(h \rightarrow \tau \mu) \simeq 0.8\% \left( \frac{\text{TeV}}{\Lambda} \right)^4 \left( \left| \hat{\lambda}_{\mu \tau}^e \right|^2 + \left| \hat{\lambda}_{\tau \mu}^e \right|^2 \right) \]

\[ \text{BR}(t \rightarrow ch) \simeq 0.4\% \left( \frac{\text{TeV}}{\Lambda} \right)^4 \left( \left| \hat{\lambda}_{tc}^u \right|^2 + \left| \hat{\lambda}_{ct}^u \right|^2 \right) \]
Model Building - EFT

\[
\frac{\lambda'_{ij}}{\Lambda^2} \bar{\psi}^i_R \psi^j_L \bar{H} (H^\dagger H)
\]

\[
\frac{c_{ij}}{\Lambda^2} \bar{\psi}^i_R \sigma_{\mu\nu} \psi^j_L H F^{\mu\nu}
\]

loop generated dipole operators

similar flavor structure
\[
\frac{\lambda_{ij}'}{\Lambda^2} \psi^i_R \psi^j_L H(H^\dagger H)
\]

loop generated dipole operators

\[
\frac{c_{ij}'}{\Lambda^2} \psi^i_R \sigma_{\mu\nu} \psi^j_L H F_{\mu\nu}
\]
similar flavor structure

\[
\psi^i \rightarrow \psi^j \gamma
\]
correlate

\[
h \rightarrow \bar{\psi}^i \psi^j
\]

naive: \( c \sim \lambda e / 16\pi^2 \)

\[
\text{BR}(h \rightarrow \tau \mu) \sim 26 \times \text{BR}(\tau \rightarrow \mu \gamma) \approx 10^{-6}
\]
FIG. 3. Correlation between \( B(\tau \to \mu \gamma) \) and \( B(h \to \tau \mu) \) in various NP scenarios. The present experimental result for \( B(h \to \tau \mu) \) is shown in horizontal blue band \([3]\). Current and future projections for \( B(\tau \to \mu \gamma) \) experimental sensitivity are represented with vertical light \([24]\) and dark \([25]\) gray bands, respectively. Superimposed are the predictions within the EFT approach (diagonal dashed orange line), in the type-III THDM (green and black bands), in models with vector-like leptons (diagonal dotted purple line) and in models with scalar leptoquarks (diagonal red and orange shaded band). See text for details.

In the SM (without neutrino masses), the charged lepton Yukawa matrix \( \langle 3, \bar{3} \rangle \) is the only source of \( G_F \) breaking. Consequently all lepton interactions are flavor conserving in the charged lepton mass basis. Conversely, as also demonstrated explicitly in Eq. (8), the generation of lepton flavor violating Higgs interactions requires at least two non-aligned sources of lepton flavor symmetry breaking. At the tree level, there are only two possibilities: (1) one can enlarge the SM scalar sector, such that more than one Higgs doublet couples to the leptons (corresponding to the first term in Eq. (8)); (2) one can extend the leptonic sector by vector-like fermions, whose Dirac masses and mixing terms with SM chiral fields can provide additional sources of \( G_F \) breaking. This leads to the appearance of the \( 0 \) contributions after integrating out the new heavy fermionic states. Both possibilities are explored in the following sections. Example of an enlarged Higgs sector is given in Sec. III whereas the vector-like fermion case is discussed in Sec. IV.

\[ \text{BR}(h \to \tau \mu) \]

\[ \text{BR}(\tau \to \mu \gamma) \]

Dorsner et al- 1502.07784
FIG. 3. Correlation between $B(h \rightarrow \tau \mu)$ and $B(\tau \rightarrow \mu \gamma)$ in various NP scenarios. The present experimental result for $B(h \rightarrow \tau \mu)$ is shown in horizontal blue band [3]. Current and future projections for $B(\tau \rightarrow \mu \gamma)$ experimental sensitivity are represented with vertical light [24] and dark [25] gray bands, respectively. Superimposed are the predictions within the EFT approach (diagonal dashed orange line), in the type-III THDM (green and black bands), in models with vector-like leptons (diagonal dotted purple line) and in models with scalar leptoquarks (diagonal red and orange shaded band). See text for details.

$G_\text{SU}(3)_L \times G_\text{SU}(3)_E$. In the SM (without neutrino masses), the charged lepton Yukawa matrix $\lambda (3, \bar{3})$ is the only source of $G_\text{SU}(3)$ breaking. Consequently all lepton interactions are flavor conserving in the charged lepton mass basis. Conversely, as also demonstrated explicitly in Eq. (8), the generation of lepton flavor violating Higgs interactions requires at least two non-aligned sources of lepton flavor symmetry breaking. At the tree level, there are only two possibilities: (1) one can enlarge the SM scalar sector, such that more than one Higgs doublet couples to the leptons (corresponding to the first term in Eq. (8)); (2) one can extend the leptonic sector by vector-like fermions, whose Dirac masses and mixing terms with SM chiral fields can provide additional sources of $G_\text{SU}(3)$ breaking. This leads to the appearance of the $0^+$ contributions after integrating out the new heavy fermionic states. Both possibilities are explored in the following sections. Example of an enlarged Higgs sector is given in Sec. III whereas the vector-like fermion case is discussed in Sec. IV.
$\chi'_{ij}^f \frac{\bar{\psi}_R^i \psi_L^j}{\Lambda^2} H(H^+ H)$

$\text{BR}(h \to \tau \mu)$

$\text{BR}(\tau \to \mu \gamma)$

Projection

Current bound ($\text{BABAR}$)

CMS run 1

$\frac{C_{ij}^f}{\Lambda^2} \bar{\psi}_R^i \sigma_{\mu \nu} \psi_L^j H F^{\mu \nu}$

Dorsner et al- 1502.07784
\[ \frac{\lambda'_{i j}}{\Lambda^2} \bar{\psi}_R^i \psi_L^j H (H^\dagger H) \]

\( \text{BR}(h \rightarrow \tau \mu) \)

\( \tau \rightarrow \mu \gamma \) constrain can be avoid by:

- **tuning** (MSSM example: Aloni, Nir, Stamou - 1511.00979)
- first two generations (\( e \) and \( \mu \)) receive their masses from additional source of EWSB \( (h \rightarrow \tau \mu): \text{Altmannshofer et al 1507.07927, Yukawa less: Ghosh et al 1508.01501) \)

\[ \text{BR}(\tau \rightarrow \mu \gamma) \]

Current bound \( \text{(BABAR)} \)

Dorsner et al - 1502.07784
how can we have both

\[ \text{BR}(t \rightarrow ch) \sim 4 \times 10^{-3} \]

\[ \text{BR}(h \rightarrow \tau\mu) \sim 10^{-2} \]
how can we have both non trivial flavor structure?

BR\((t \rightarrow ch) \sim 4 \times 10^{-3}\)
BR\((h \rightarrow \tau\mu) \sim 10^{-2}\)

new physics at the TeV scale
how can we have both non trivial flavor structure?

new physics at the TeV scale

SM-EFT with flavor models

Minimal Flavor Violation (MFV) solves the NP flavor puzzle

Froggatt-Nielsen (FN) solves both SM and NP flavor puzzles

\[ \text{BR}(t \to ch) \sim 4 \times 10^{-3} \]
\[ \text{BR}(h \to \tau \mu) \sim 10^{-2} \]
up sector:

\[
\lambda'_{\nu u} = Y_{u}^{u} \left( A_{u} + B_{u} Y_{u}^{u} Y_{u}^{u*} + C_{u} Y_{d}^{d} Y_{d}^{d*} \right)
\]

\[
\frac{Y_{ct}}{Y_{tt}} = \frac{C_{u} y_{b}^{2} V_{cb} V_{tb}^{*}}{A_{u} + B_{u} y_{t}^{2} + C_{u} y_{b}^{2} |V_{tb}|^{2}} \lesssim V_{cb}
\]

maximal \( t \to ch \) rate small by order of magnitude than current bounds

lepton sector:

\[
\frac{Y_{\mu \tau}}{Y_{\tau \tau}} = \frac{C_{\nu} y_{3}^{2} U_{\mu 3} U_{\tau 3}^{*}}{A_{\nu} + B_{\nu} y_{\tau}^{2} + C_{\nu} y_{3}^{2} |U_{\tau 3}|^{2}} \lesssim U_{\mu 3} / U_{\tau 3},
\]

small rates

from \( \mu \to e \gamma \):

\[ |Y_{\mu \tau}| \lesssim 10^{-4} \]
Approximate U(1)’s symmetries are suppressed by different powers of the breaking parameters $\epsilon_i \simeq \lambda = 0.2$.

Consider two possibilities:
- SM + nonrenormalizable terms
- Supersymmetric model + nonrenormalizable terms
SM + nonrenormalizable terms:

\[
\mathcal{L}_Y = -\lambda_{ij}^u Q_i \bar{U}_j \phi - \frac{\lambda'_{ij}}{\Lambda^2} Q_i \bar{U}_j \phi (\phi^\dagger \phi) + \text{h.c.}
\]

\[
Y_{ij}^u = \frac{\sqrt{2}m_i^u}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} (V_L^{u} \lambda' u V_R^{u\dagger})_{ij}
\]

\( (\phi^\dagger \phi) \) does not carry a FN charge

\( \lambda \) and \( \lambda' \) have the same parametric structure

\[
\epsilon_i \approx \lambda = 0.2
\]

\[
Y_{tc} \sim \frac{v^2}{\Lambda^2} \lambda \lesssim 10^{-3} \ll 0.14
\]

Current bound

FCNC bounds (charm mixing)

\[
\frac{v^2}{\Lambda^2} \lesssim 10^{-2}
\]
Supersymmetric model + nonrenormalizable terms:

\[ \mathcal{L}_Y = \lambda_{ij}^u Q_i \bar{U}_j \phi_u + \frac{\lambda_{ij}^u}{\Lambda^2} Q_i \bar{U}_j \phi_u (\phi_u \phi_d) \]

\[ (Y_h^u)_{ij} = \frac{c_\alpha}{s_\beta} \frac{m_i^u}{v} \delta_{ij} + \frac{v^2 c_\alpha + \beta s_\beta}{2 \sqrt{2} \Lambda^2} (V_L^u \lambda^' u V_R^u)_{ij} \]

If \((\phi_u \phi_d)\) carry a FN charge

\(\lambda\) and \(\lambda'\) have different parametric structure

Use “holomorphic zeros” to align the new sources of flavor violation and avoid FCNC bounds

Leurer, Nir, Seiberg
hep-ph/9310320
Supersymmetric model + nonrenormalizable terms:

\[ \mathcal{L}_Y = \lambda_{ij}^u Q_i \bar{U}_j \phi_u + \frac{\lambda_{ij}^u}{\Lambda^2} Q_i \bar{U}_j \phi_u (\phi_u \phi_d) \]

\[ (Y_h^u)_{ij} = \frac{c_\alpha}{s_\beta} \frac{m_{u_i}}{v} \delta_{ij} + \frac{v^2 c_\alpha + \beta s_\beta}{2\sqrt{2}\Lambda^2} (V_L^u \lambda' u V_R^{u^\dagger})_{ij} \]

Approximate U(1)×U(1) FN symmetry:

\[ \hat{\lambda}^u \sim \frac{1}{\lambda} \begin{pmatrix} \lambda^{15} & \lambda^{12} & \lambda^{13} \\ \lambda^8 & \lambda^5 & \lambda^6 \\ \lambda^4 & \lambda^1 & \lambda^2 \end{pmatrix}, \quad \hat{\lambda}^d = 0, \quad \hat{\lambda}^e \sim \frac{1}{\lambda} \begin{pmatrix} \lambda^8 & 0 & 0 \\ 0 & \lambda^5 & \lambda^3 \\ 0 & \lambda^5 & \lambda^3 \end{pmatrix} \]

safe from meson mixing and \( \mu \to e\gamma \)

\[ Y_{tc} \sim \frac{v^2}{\Lambda^2} \sim 0.1 \quad Y_{\mu\tau} \sim \frac{v^2}{\Lambda^2} \lambda^2 \sim 0.004 \]
the Higgs flavor violating couplings to leptons and to top can be directly probed at the sub percent level

low energy processes constrain the other flavor violating Higgs couplings to the per-mil level

visible signals $t \rightarrow hj$ and $h \rightarrow \tau \mu$ require non trivial flavor structure. Additional sub-dominant source of EWSB can be used to relax low energy constraints.
Backup Slides