New Signatures of Flavor Violating Higgs Coupling

Xiao-Ping Wang

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Collaborated with Malte Buschmann, Joachim Kopp, and Jia Liu

[Logos and graphics for JGU, PRiSMA, and ICHEP2016]
Higgs Discovery

CMS Preliminary
\( \sqrt{s} = 7 \text{ TeV}, \, L = 5.1 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, \, L = 5.3 \text{ fb}^{-1} \)

Weighted Events / (1.67 GeV)

\( m_{\gamma\gamma} \) (GeV)
Higgs Discovery
Higgs Discovery
Higgs Properties

ATLAS

$H \rightarrow ZZ^* \rightarrow 4l$

- Data
- $J^P = 0^+$
- $J^P = 0^-$

$\sqrt{s} = 7$ TeV $\int L dt = 4.6$ fb$^{-1}$

$\sqrt{s} = 8$ TeV $\int L dt = 20.7$ fb$^{-1}$

ATLAS

$H \rightarrow \gamma\gamma$

- Data
- $J^P = 0^+$
- $J^P = 2^+$

$\sqrt{s} = 8$ TeV $\int L dt = 20.7$ fb$^{-1}$

($f_{\gamma\gamma} = 0\%$)
Higgs Properties
Higgs Properties

- **ATLAS**
  - $H \to ZZ^* \to 4l$
  - $\sqrt{s} = 7$ TeV $\int L dt = 4.6$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV $\int L dt = 20.7$ fb$^{-1}$

- **CMS**
  - $q\bar{q} \to X(1^+) \to ZZ$
  - $19.7$ fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
  - Normalized to unity

- **ATLAS**
  - $H \to \gamma\gamma$
  - 8 TeV $\int L dt = 20.7$ fb$^{-1}$
  - $J^P = 0^+$
  - $J^P = 2^+$

- **CMS**
  - $19.7$ fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
  - $\lambda_1$ or $(g_{\gamma Z})^2$
  - $-2 \times \ln(L_{95}/L_{68})$
  - Particle mass (GeV)
  - $\mu$, $\tau$, $t$
  - $68\%$ CL, $95\%$ CL, Standard Model Higgs

- **Graphs**
  - Data
  - Observed
  - $0^+$
  - $1^+$
Higgs Properties
Unknown Higgs properties

- Other source of EW symmetry breaking? more Higgs, **2HDM**
- Higgs self-interaction coupling? stability of EW vacuum
- light quark coupling? e.g. $h \rightarrow J/\Psi + \text{photon}$
- Exotic Higgs decay?
- Flavor alignment? **Flavor violation**? FV couplings?
Outline

- thh search in higher dimension operator
- thh search in type III 2HDM, via $H \rightarrow h\ h$
- $H^0 \rightarrow \tau\mu$ decay in type III 2HDM
Higher dimension operator

- The dimension 4 and 6 couplings in the up-type sector

\[ \mathcal{L} \supset -\lambda_{ij}^u Q_L^i \tilde{H} u_R^i - \frac{\lambda_{ij}^u}{\Lambda^2} Q_L^i \tilde{H} u_R^i (H^\dagger H) + h.c. \]

\[ \rightarrow -m_{ij}^u u_L^i u_R^j - y_{ij}^u u_L^i u_R^j h - \frac{f_{ij}^u}{v} u_L^i u_R^j h^2 + \mathcal{O}(h^3) + h.c. \]

- Constraints on couplings

\[ \text{BR} (t \to ch) < 0.0046 \]
\[ \text{BR} (t \to uh) < 0.0045 \]

- Our Benchmark point

\[ y_{ct}^u = y_{tc}^u = 0.08 \]
\[ y_{ut}^u = y_{tu}^u = 0.08 \]

\[ f_{ij}^u = \frac{3}{2} y_{ij}^u (i \neq j) \]
Fig. 1. Sample Feynman diagrams for \(thh\) production from the vertices in the effective Lagrangian in eq. (7). Red dots indicate the FCNC coupling of two Higgs boson to quarks (third term in eq. (7)), which is usually dominant, blue dots stand for the FCNC coupling of a single Higgs boson to quarks (second term in eq. (7)), the contributions of which are usually subdominant.

Here, we have used the leading order expression for the branching ratio [50], supplemented by a correction factor \(\phi_{QCD}'^{1+0.97 s=1.10} [50, 56]\) accounting for NLO QCD contributions:

\[
\text{BR}(t\rightarrow hq) = |y_{tq}|^2 + |y_{qt}|^2 < 0.
\]

Note that a refined analysis taking into account also the process \(pp\rightarrow th\), which is relevant in the case of \(tuh\) couplings (but not for \(tch\) couplings) could improve the bounds on \(\text{BR}(t\rightarrow uh)\) and \(p\bigg|y_{ut}\bigg|^2 + \bigg|y_{tu}\bigg|^2 < 0.14 [57–59].\)

The same bound holds also for \(tuh\) couplings. A secondary process sensitive to anomalous \(tuh\) and \(tch\) couplings is same-sign top production through \(t\)-channel Higgs exchange. The author of ref. [60] has derived limits on \(p\bigg|y_{tq}\bigg|^2 + \bigg|y_{qt}\bigg|^2\) from this channel by recasting the CMS same-sign di-lepton plus b-jet measurements [61]. However, the resulting bounds are weaker than those from \(t\rightarrow qh\) decays. Finally, an effective \(tuh\) or \(tch\) coupling may lead to anomalous di-Higgs production, mediated by a top quark in the \(t\)-channel. Unfortunately, since the rate of this process is suppressed by four powers of the small coupling constants \(y_{tq}\) and \(y_{qt}\) (\(q\) = u, c), it is irrelevant in practice.

For instance, for \(y_{ut} = y_{tu} = 0.08\) at the upper limit from eq. (13), the cross section for \(pp\rightarrow hh\) is only \(\sim 4\) fb at \(p_s = 8\) TeV and \(\sim 7.4\) fb at \(p_s = 13\) TeV.

In view of the above constraints, we will in the following use benchmark values of \(y_{tq} = y_{qt} = 0.08\), leading to the expectation of potentially measurable rates for the process \(pp\rightarrow thh\), on which we will focus in the first part of this paper. The corresponding Feynman diagrams are given in Fig. 1.

- \(thh\) production processes @ LHC
\( \chi^2 \equiv \frac{(m_{jj}^{(1)} - m_h)^2}{(\Delta m_h)^2} + \frac{(m_{jj}^{(2)} - m_h)^2}{(\Delta m_h)^2} + \frac{(m_{j\ell\nu} - m_t)^2}{(\Delta m_t)^2} \)

- **Topology:**
  \( (h \rightarrow b\bar{b})(h \rightarrow b\bar{b})(t \rightarrow b\ell^+\nu_\ell) \)

- **reconstruction of two h and top mass**
• Cut Flow Table

<table>
<thead>
<tr>
<th>cut</th>
<th>signal (thh)</th>
<th>background (tt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{prod}}$ [fb]</td>
<td>6.1</td>
<td>$5.9 \times 10^5$</td>
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<tr>
<td>preselection</td>
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<td>b-tagging</td>
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<td>0.55%</td>
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<td>$p_T^{j_1} &gt; 140$ GeV</td>
<td>76.5%</td>
<td>31.1%</td>
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<tr>
<td>$p_T^{j_2} &gt; 100$ GeV</td>
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<td>66.3%</td>
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<tr>
<td>$p_T^{j_3} &gt; 60$ GeV</td>
<td>95.7%</td>
<td>84.6%</td>
</tr>
<tr>
<td>Higgs, top mass window</td>
<td>24.4%</td>
<td>8.55%</td>
</tr>
<tr>
<td>$p_T^{h_2} &gt; 150$ GeV</td>
<td>73.3%</td>
<td>35.3%</td>
</tr>
<tr>
<td>$p_T^{h_1} &gt; 300$ GeV</td>
<td>65.5%</td>
<td>32.3%</td>
</tr>
<tr>
<td>$\Delta R_{bb}^{\text{max}} &lt; 1.5$</td>
<td>96.1%</td>
<td>77.2%</td>
</tr>
<tr>
<td>$\sigma_{\text{final}}$ [fb]</td>
<td>0.022</td>
<td>0.093</td>
</tr>
</tbody>
</table>

• Need Integrate Luminosity to Exclude EFT

$870 fb^{-1} (95\% C.L.)$
• General Scalar Potential for 2HDM

\[ V = \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + (\mu_3^2 \Phi_1^\dagger \Phi_2 + h.c.) + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[ (\lambda_5 \Phi_1^\dagger \Phi_2 + \lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2)(\phi_1^\dagger \phi_2) + h.c. \right] \]

• Reducing the parameters into four

\[
\begin{bmatrix}
\sin \alpha & \lambda_3 & \lambda_7 & m_{H^0} = m_{H^\pm} = m_{A^0}
\end{bmatrix}
\]

• Yukawa coupling for up-type quarks

\[ L = -\eta_{u,1}^{ij} \overline{Q}^i_L \Phi_1 u_R^i - \eta_{u,2}^{ij} \overline{Q}^i_L \Phi_2 u_R^i + h.c. = -m_i \overline{u}_L^i u_R^i - y_{u,h}^{ij} \overline{u}_L^i u_R^i h - y_{u,H}^{ij} \overline{u}_L^i u_R^i H^0 + h.c. \]

Where

\[ y_{u,h}^{ij} = \frac{m_i}{v} \delta^{ij} \cos \alpha + \frac{1}{\sqrt{2}} \eta_{u,2}^{ij} \sin \alpha \]

\[ y_{u,H}^{ij} = -\frac{m_i}{v} \delta^{ij} \sin \alpha + \frac{1}{\sqrt{2}} \eta_{u,2}^{ij} \cos \alpha \]
Constraints on QFV 2HDM

- Direct Search for $t \rightarrow qh$ decay
- Same-sign di-leptons and b-jet (CMS/ATLAS)
- Heavy Higgs decay to WW
- Heavy Higgs decay to ZZ
- Global fits on Higgs couplings
• thh production processes in 2HDM

![Feynman diagrams for thh production](image)

• Benchmark Points for QFV 2HDM

<table>
<thead>
<tr>
<th>Benchmark 1</th>
<th>Benchmark 2</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>$\sin \alpha$</td>
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<td>0.2</td>
</tr>
<tr>
<td>$\eta_{2}^{ut}$</td>
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<td>0</td>
</tr>
<tr>
<td>$\eta_{2}^{tu}$</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$\lambda_{7}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\lambda_{3}$</td>
<td>0</td>
<td>$-3$</td>
</tr>
<tr>
<td>$m_{A^{0}}$</td>
<td>$m_{H^{\pm}}$</td>
<td>$m_{H^{\pm}}$</td>
</tr>
<tr>
<td>$m_{H^{\pm}}$</td>
<td>$m_{H^{0}}$</td>
<td>$m_{H^{0}}$</td>
</tr>
</tbody>
</table>

- $b \rightarrow d\gamma$
- see fig. 5
- enters $g_{H^{0}hh}$ only at $O(\sin^{2} \alpha)$
- influences $g_{H^{0}hh}$
- preferred by custodial symmetry
- preferred by perturbativity (see fig. 4 (b))
\( \lambda_3 = -3 \quad \sigma_{\text{final}} = 0.72 \, fb \)

\( \lambda_3 = 0 \quad \sigma_{\text{final}} = 0.508 \, fb \)
Barr–Zee diagrams with a top quark loop. Regarding the neglected diagrams involving the mixing with the other neutral Higgs bosons, the only relevant diagrams containing top quarks assume that the only nonzero Yukawa couplings of the Higgs fields are given by expressions from ref. [14] by replacing the up quark Yukawa coupling with the corresponding one for the bottom quark: 

\[
\lambda_3 = 0, \quad \lambda_7 = 0, \quad \sin \alpha = 0.2
\]

These diagrams are flavor conserving one. According to eq. (42), this implies that most of the diagrams involving heavy Higgs masses tend to cancel each other. The reason is that each diagram contains one flavor violating Yukawa coupling and one flavor conserving one. The dimension-5 operators can be obtained in a similar way [22], by replacing the up quark Yukawa couplings in the Wilson coefficients, and the dimension-5 operators in eqs. (31) and (32) for top quarks. Note that diagrams containing heavy Higgs bosons and the lepton Yukawa couplings by expressions from their counterparts involving light Higgs bosons are two benchmark points in table II.

The strongest indirect constraint on the top quark coupling is obtained from searches for the rare decay \( t \to h + \mu^+\mu^- \) [65], i.e.,

\[
\text{BR}(t \to h) < 10^{-3}\]

For comparison, we also show the current limit on \( \text{BR}(t \to h) < 0.001 \) for a direct search for the same-sign di-leptons (SSL) [50].

In the context of the 2HDM, we show the 95% CL sensitivity of the proposed search for the decay

\[
\text{BR}(t \to h) \to hh
\]

Figure 9. In the context of the 2HDM, we show the 95% CL sensitivity of the proposed search for the decay \( t \to h + \mu^+\mu^- \) + di-Higgs (SSL) scenario [10]. The black dots are the Brazilian bands. Comparing to the projected sensitivity of a direct search for \( t \to h + \mu^+\mu^- \) (red shaded regions), the black dots are the current limit on \( \text{BR}(t \to h) < 0.001 \). For comparison, we also show the current limit on \( \text{BR}(t \to h) < 0.001 \) for a direct search for the same-sign di-leptons (SSL) + di-Higgs (SSL). The 2-loop contributions are comparable to the 1-loop terms because the latter are suppressed by the factor \( \frac{1}{v^2} \), where \( v \) is the vacuum expectation value. The loop diagrams involving only 

\[
\lambda_3 = 0, \quad \lambda_7 = 0, \quad \sin \alpha = 0.2
\]

are given by

\[
\lambda_3 = -3, \quad \lambda_7 = 0, \quad \sin \alpha = 0.2
\]

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• Lepton Yukawa Couplings

\[ \mathcal{L}_l \supset -\eta_{l,1}^{ij} L_L^i \Phi_1 e_R^j - \eta_{l,2}^{ij} L_L^i \Phi_2 e_R^j + h.c. \]

\[ = -\bar{e}_L^i e_R^j [y_{l,h}^{ij} h + y_{l,H}^{ij} H^0] + h.c. \]

Where

\[ y_{l,h}^{ij} = \frac{m_i}{v} \delta^{ij} \cos \alpha + \frac{1}{\sqrt{2}} \eta_{l,2}^{ij} \sin \alpha \]

\[ y_{l,H}^{ij} = -\frac{m_i}{v} \delta^{ij} \sin \alpha + \frac{1}{\sqrt{2}} \eta_{l,2}^{ij} \cos \alpha \]

• \( H^0 \) production cross section

\[ \sigma(pp \to H^0) \simeq (\sin \alpha - \eta_{2t}^{tt} \cos \alpha \frac{v}{\sqrt{2}m_t})^2 \times \sigma(gg \to h)_{m_h = m_{H^0}}^{SM} \]

• The decay rates for \( h, H^0 \to \tau \mu \)

\[ \Gamma(H^0 \to \tau \mu) = \frac{1}{16\pi} m_{H^0} \cos^2 \alpha (|\eta_2^{\mu\tau}|^2 + |\eta_2^{\tau\mu}|^2) \]

\[ \Gamma(h \to \tau \mu) = \frac{1}{16\pi} m_h \sin^2 \alpha (|\eta_2^{\mu\tau}|^2 + |\eta_2^{\tau\mu}|^2) \]
In summary, we have discussed several so far unexplored signatures related to flavor violating Higgs couplings. For the case of flavor violation in the quark sector, we have studied the $t^+hh$ (single top plus di-Higgs) final state, working first in an effective field theory (EFT) framework with operators of the form $Q_i^L \tilde{u} H_j^R (H^* H)$ and then in a Two Higgs Doublet Model (2HDM). In the EFT case, we find that only the high-luminosity LHC may be sensitive to $t^+hh$ production, while in the 2HDM, discovery prospects are excellent already in Run II, with $O(300 \text{ fb}^{-1})$ of 13 TeV data, see fig. 9. In particular, the expected limits from our proposed search can surpass those from the traditional search for $t^+h\rightarrow q\bar{q}$ decays by almost an order of magnitude. The reason for the enhanced discovery reach for $t^+hh$ events in the 2HDM is the contribution from the process $pp \rightarrow t^+(H^0 \rightarrow hh)$, where $H^0$ is the heavy CP even neutral Higgs boson.

We have considered also flavor violation in the lepton sector, as motivated in particular by the recent CMS excess in the $h \rightarrow \tau\mu$ channel. Perhaps the simplest explanations of this excess is provided by the 2HDM, where it is related to the possibility of large flavor violating couplings of the second (heavy) Higgs doublet, which mixes with $h$. Consequently, we have studied direct production of heavy Higgs bosons and their flavor violating decay in the process $pp \rightarrow H^0 \rightarrow \tau\mu$.

We have used existing CMS data to search for this process and to set new limits on the lepton flavor violating 2HDM. Our limits are summarized in fig. 13.
Constraints on LFV 2HDM

• CMS Search recasting for $H^0 \rightarrow \tau \mu$
• CMS Best fit for $h \rightarrow \tau \mu$, BR~0.84%
• BR Constraint from $h \rightarrow \tau \mu$
• Loop constraint for $\tau \rightarrow \mu \gamma$

This coupling is visible within the chosen plot ranges. The panels on the left show constraints on the heavy Higgs as large (dot-dashed curves) or cancels (solid curves, shaded regions). The uncertainty of this coupling within the chosen plot ranges is shown in the panels on the right.
Summary

- In the EFT, thh search is only sensitive by high-luminosity LHC.
- In 2HDM, discovery prospects for thh are excellent already in LHC Run II, which could be more sensitive than t decay to hq.
- CMS excess of $h \rightarrow \tau \mu$ can be explained by LFV 2HDM.
- CMS search also can set limit on LVF 2HDM from $pp \rightarrow H^0 \rightarrow \tau \mu$

Thanks for your attention