Experimental searches for Flavour Violating Higgs decays

Shikma Bressler
Flavour violating couplings

\[ \mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) h + h.c. + \cdots \]

fermion mass term \quad Higgs-fermion coupling

If the mass basis and the interaction basis are different

\[ \iff \]

In this notation, if \( Y_{ij} \) is not diagonal

\[ \implies \]

Flavour violating couplings

Can easily occur in extensions of the SM
Pre-LHC results: indirect bounds

**Lepton sector**

\[ \text{BR}(H \rightarrow \tau e) \sim 15\% \]

is allowed

No sensitivity at the LHC*

\[ \text{BR}(H \rightarrow \tau \mu) \sim 15\% \]

is allowed

*Up to loop level cancelations

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Harnik, Kopp, Zupan 1209.1397
Pre-LHC results: indirect bounds

Quark sector

<table>
<thead>
<tr>
<th>Technique</th>
<th>Coupling</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$ oscillations</td>
<td>$</td>
<td>Y_{uc}</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>Y_{uc}Y_{cu}</td>
</tr>
<tr>
<td>$B^0_d$ oscillations</td>
<td>$</td>
<td>Y_{db}</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>$B^0_s$ oscillations</td>
<td>$</td>
<td>Y_{sb}</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>Y_{sb}Y_{bs}</td>
</tr>
<tr>
<td>$K^0$ oscillations</td>
<td>$\text{Re}(Y^2_{ds})$, $\text{Re}(Y^2_{sd})$</td>
<td>$[-5.9 \ldots 5.6] \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>$\text{Im}(Y^2_{ds})$, $\text{Im}(Y^2_{sd})$</td>
<td>$[-2.9 \ldots 1.6] \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>$\text{Re}(Y^*<em>{ds}Y</em>{sd})$</td>
<td>$[-5.6 \ldots 5.6] \times 10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>$\text{Im}(Y^*<em>{ds}Y</em>{sd})$</td>
<td>$[-1.4 \ldots 2.8] \times 10^{-13}$</td>
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</tbody>
</table>

Couplings not involving the top quark are highly suppressed

$\text{BR}(t \rightarrow qH) \sim 10\%$ are allowed
Two search channels
- $H \rightarrow \mu \tau_{\text{had}}$
- $H \rightarrow \mu \tau_e$

Three jet categories
- 0-jets $\Rightarrow$ targeting ggF production
- 1-jet $\Rightarrow$ targeting ggF production
- 2-jets $\Rightarrow$ targeting VBF production

More details later
CMS H$\rightarrow$$\tau\mu$

CMS collaboration 1502.07400
Observed limit: $\text{BR}(H \rightarrow \tau \mu) \leq 1.51\%$

Expected limit: $\text{BR}(H \rightarrow \tau \mu) \leq 0.75\%$

Best fit value:
$\text{BR}(H \rightarrow \tau \mu) = 0.84 \pm 0.39/0.37 \%$

$\Rightarrow \sim 2.4 \sigma$ excess
Observed limit: $\text{BR}(H \rightarrow \tau \mu) \leq 1.57\%$

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Theoretical motivation:
• Stringent test of the SM → $m_H = 125.5$ GeV
• Allowed in several BSM models
e.g 2HDM-III, quark-singlet...

Search-channel:
[t][tbar]→[Wb][Hc]→bcWγγ

Signal regions: 2γ
(selection similar to SM $H→γγ$)
• Fully hadronic W: no lep.
• Semi-leptonic W: one isolated lepton

Search strategy:
• Looking for ttbar topology:
  based on $M_{jjγγ}$ and $M_{jjj} + 1$ b-tag
• Look for peak in $m_{γγ}$

Data sets: 5 fb$^{-1}$ @ 7 TeV & 21 fb$^{-1}$ @ 8 TeV
Search-channel:
\[ [t][t\bar{t}] \rightarrow [Wb][Hc] \rightarrow bcW\gamma\gamma \]

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**Observed:** \(\text{BR}(t \rightarrow cH) \leq 0.79\%\)

**Expected:** \(\text{BR}(t \rightarrow cH) \leq 0.51\%\)

**Data sets:**
- 5 \(\text{fb}^{-1}\) @ 7 TeV & 21 \(\text{fb}^{-1}\) @ 8 TeV
Search-channel:
\[ [t][\bar{t}] \rightarrow [Wb][Hc] \]
\[ \Rightarrow H \rightarrow WW/ZZ/\tau\tau \text{ or } \gamma\gamma \]

Signal region:
- lepton + 2\gamma
- multi-lepton

Background:
- multi-lepton
  - Irreducible - all leptons are prompt
    - Estimated from MC normalized to data in dedicated control regions
  - Reducible - 1 or 2 fake or non-prompt leptons
    - Estimated using data-driven techniques
- lepton + 2\gamma: side band fit

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20 fb\(^{-1}\) @ 8 TeV
CMS t→cH

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Data sets:

\[ 20 \text{ fb}^{-1} @ 8 \text{ TeV} \]

Observed: \( BR(t \rightarrow cH) \leq 0.56 \% \)

Expected: \( BR(t \rightarrow cH) \leq 0.65 \% \)
Searches that are also interpreted in the content of Higgs mediated FCNC

ATLAS 1504.04605: Analysis of events with $b$-jets and a pair of leptons of the same charge in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

CMS HIG-14-026: Search for Associated Production of a Single Top Quark and a Higgs Boson in Leptonic Channels

CMS HIG-14-001: Search for associated production of a single top quark and a Higgs boson in events where the Higgs boson decays to two photons at $\sqrt{s} = 8$ TeV

CMS HIG-14-015: Search for $H \rightarrow b\bar{b}$ in association with single top quarks as a test of Higgs boson couplings
Outline

The challenge at the LHC -

• Tiny S/B
• Background estimation
• Systematic uncertainties
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The challenge at the LHC -

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This is usually clear
At least until we subdivide into million different signal regions
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This is also when our talks become boring due to very heavy tables
The challenge at the LHC -

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This is usually clear at least until we subdivide into million different signal regions.

This becomes more complicated if we subdivide into more complicated signal regions, often employing sophisticated techniques which are hard to explain in a reasonable time.

I’ll use the search for Higgs LFV decays as an example.

This is the most challenging part in our analysis work.

This is also when our talks become boring due to very heavy tables.
4-5 orders of magnitude more background (🌟) than signal (🌟) for 100% BR for the signal

Not including background from events containing fake and not prompt leptons which is a priori unknown

In order to make a discovery

S/B has to be improved
Exploiting the unique event topology
The Higgs decay products are produced back to back
The $\tau$ and its decay products are collinear $\Rightarrow$
cut on various angular separation parameters

\[ \ell \quad h \quad \tau \quad \nu_{\tau} \quad \bar{\nu}_{\ell'} \quad q \quad q' \]

The lepton originating from the Higgs is more energetic $\Rightarrow$
cut on lepton $p_\ell$

Jets are from ISR or production mode $\Rightarrow$ exploit jet
multiplicity and jet topology
This approach was phenomenologically studied in 2011.

\[ H \rightarrow \mu \tau_e \]

Corresponds to the collinear approximation.

### Selection criteria

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>( N_{\text{backgd.}} )</th>
<th>( N_{h\rightarrow\tau\tau} )</th>
<th>( N_{h\rightarrow WW} )</th>
<th>( N_{h\rightarrow ZZ} )</th>
<th>Signal efficiency (%)</th>
<th>( N_{\text{sig.}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 1 ) muon with ( p_T &gt; 30 ) GeV and (</td>
<td>\eta</td>
<td>&lt; 2.1 ) and ( \geq 1 ) electron with ( p_T &gt; 15 ) GeV and (</td>
<td>\eta</td>
<td>&lt; 2.5 )</td>
<td>59271 ± 76</td>
<td>89. ± 3.</td>
</tr>
<tr>
<td>exactly 2 OS leptons</td>
<td>58447 ± 75</td>
<td>89. ± 3.</td>
<td>235. ± 5.</td>
<td>2.2 ± 0.5</td>
<td>21.2 ± 0.1</td>
<td>145.4 ± 0.9</td>
</tr>
<tr>
<td>jet veto: no jet with ( p_T &gt; 30 ) GeV and (</td>
<td>\eta</td>
<td>&lt; 2.5 )</td>
<td>19477 ± 44</td>
<td>51. ± 2.</td>
<td>123. ± 3.</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>( \Delta \phi(e, \mu) &gt; 2.7 )</td>
<td>13261 ± 36</td>
<td>40. ± 2.</td>
<td>8.7 ± 0.9</td>
<td>0.1 ± 0.1</td>
<td>10.7 ± 0.1</td>
<td>72.9 ± 0.7</td>
</tr>
<tr>
<td>( \Delta \phi(e, E_T) &lt; 0.3 )</td>
<td>3885 ± 20</td>
<td>15. ± 1.</td>
<td>2.4 ± 0.5</td>
<td>0.1 ± 0.1</td>
<td>7.85 ± 0.09</td>
<td>53.7 ± 0.6</td>
</tr>
<tr>
<td>2D cut in ( (\Delta E_T, p_T^\mu) ) plane</td>
<td>53 ± 2</td>
<td>0.6 ± 0.3</td>
<td>0.5 ± 0.2</td>
<td>0</td>
<td>5.34 ± 0.07</td>
<td>36.5 ± 0.5</td>
</tr>
</tbody>
</table>

Davidson, Verdier 1211.1248
In ‘real life’ - also reconstruct the mass of the Higgs

\[ M_{coll}^2 = 2p_T \mu(p_T^{e'} + MET)(\cosh \Delta \eta_{\mu e} - \cos \Delta \phi_{\mu e}) \]
**Search for LFV @ LHC**

**S/B - the strategy**

### Missing mass calculator

- Developed to improve the reconstructed mass resolution in $H \to \tau \tau$ decays
- Based on the requirement that the $\tau$ decay products are consistent with the mass of the $\tau$

**Diagram**

- **Transverse mass**
- **Collinear mass**

- Simplified version can be used in case of LFV decays with only 1 (2) neutrino(s) in the final state in the hadronic (leptonic) channel

Elagin, Murat, Pranko, Safonov 1012.4686

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Flavour15, 1-3 June, Munich

S. Bressler
Search for LFV @ LHC

CMS approach

Categorization similar to that developed for the H→ττ analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>H → μτ_e</th>
<th>H → μτ_h</th>
</tr>
</thead>
<tbody>
<tr>
<td>[GeV]</td>
<td>0-jet</td>
<td>1-jet</td>
</tr>
<tr>
<td>$p_T^\mu$ &gt;</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>$p_T^\tau$ &gt;</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$M_T^\mu$ &gt;</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$M_T^\tau$ &gt;</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>$M_T$ &lt;</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>[radians]</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_{p_T^\mu - p_T^\tau}$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta \phi_{p_T^\mu - E_{\text{miss}}}$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>$\Delta \phi_{p_T^\tau - E_{\text{miss}}}$</td>
<td>2.7</td>
<td>1.0</td>
<td>—</td>
</tr>
</tbody>
</table>

Instead of taking directly $E_{\text{miss}}$, use its projection on the electron direction:

$$M_{\text{coll}}^2 = 2p_T^\mu (p_T^e + \text{MET})(\cosh \Delta \eta_{ee} - \cos \Delta \phi_{ee})$$
Side bands extrapolation - a lesson from the $H \rightarrow \mu \mu$ search

- Since we reconstruct the mass - maybe can use side band extrapolation
- Similar to $H \rightarrow \mu \mu$ (or $H \rightarrow \gamma \gamma$)
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- Since we reconstruct the mass - maybe can use side band extrapolation
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Background estimation

Much wider mass range

Different background shape on the two sides

Side band fit is ‘impossible’
Search for LFV @ LHC

Background estimation

Z→ττ - using embedding techniques
Replacing the μ’s in Z→μμ data samples with simulated τ’s

Top - using MC samples

Other: H→ττ, WW, ZZ+jets, Wγ+jets - using MC samples

Miss-identified leptons - estimated in W+jets and QCD enriched control regions
Search for LFV @ LHC

Search a la H→ττ

**Background estimation**

- **Z→ττ** - using embedding techniques
  - Replacing the μ’s in Z→μμ data samples with simulated τ’s
- Other: H→ττ, WW, ZZ+jets, Wγ+jets
  - Using MC samples

Miss-identified leptons - estimated in W+jets and QCD enriched control regions
The symmetry approach

We realized that the $e/\mu$ symmetry is a unique property of the SM which is violated by the signal.

- **SM processes are symmetric** to the replacement of (prompt) $e$ and $\mu$
  - EM interaction - proportional to the charge
  - Weak interaction - universal
  - Yukawa - negligible (in particular in an $e\mu$ final state)
  - Phase space - small (negligible in an $e\mu$ final state)
- **$H \rightarrow \tau\mu$ decays break this symmetry** resulting also in $p_T^\mu > p_T^e$
  - $H \rightarrow \tau\mu$: the $\tau$ and $\mu$ take half the $H$ energy (on average)
  - $\tau \rightarrow e2\nu$: the $e$ takes $1/3$ of the $\tau$ energy (on average)
Divide the data

Sample I (µe): events with $p_T^{\mu} > p_T^e \Rightarrow \text{the signal is here}$

Sample II (eµ): events with $p_T^e > p_T^{\mu}$

Calculate the collinear mass for each sample separately

$$m_{\text{coll}} = \sqrt{2 p_T^{\ell_0} (p_T^{\ell_1} + \not\!E_T) (\cosh \Delta \eta - \cos \Delta \phi)}$$

• Use the leading and subleading leptons
Search for LFV @ LHC

Divide the data
Sample I (µe): events with $p_T^\mu > p_T^e \Rightarrow \text{the signal is here}$
Sample II (eµ): events with $p_T^e > p_T^\mu$

Calculate the collinear mass for each sample separately

$$m_{\text{coll}} = \sqrt{2p_T^\ell_0 \left(p_T^{\ell_1} + E_T\right) \left(\cosh \Delta \eta - \cos \Delta \phi\right)}$$

- Use the leading and subleading leptons correctly

Finally

- $e/\mu$ symmetry in the SM $\Rightarrow$
  the background processes in the two samples originate from the same distribution
- $H \rightarrow \tau \mu \Rightarrow \text{peaks at sample I (µe)}$
Search for LFV @ LHC

Background estimation

Note: H→τμ & H→τe are unlikely to co-exist in observable rate

- The bound on μ→eγ place strong bound on Y_{μτ}×Y_{τe}
- Expected limit on a 2D plane

DELPHES w/ ATLAS CARD

Uncertainties on background estimation

- Fake estimate - asymmetric contribution
- Correction for different e/μ turn on curves
Summary

- The LHC provides with a great opportunity to search for Flavour Violating Higgs decay
  Both in the lepton and the quark sectors

- Taking the optimistic perspective - exciting results from CMS
  - Possible excess in the LFV Higgs decay $H \rightarrow \tau \mu$
  - Expecting new results from both collaborations soon
    - ATLAS: $H \rightarrow \tau \mu$ & $H \rightarrow \tau e$
    - CMS: $H \rightarrow \tau e$ & $H \rightarrow \mu e$

- Plenty of room for improvement of existing analyses
  - More stats.
  - But also new techniques