Search for lepton flavour violation with the CMS detector

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On behalf of the CMS Collaboration

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Introduction

- In SM no known global symmetry requires lepton flavour conservation
  - Neutrino oscillation observed
- Charged LFV is a probe of BSM
  - Directly addresses physics of flavour and generation
- cLFV in SM due to non-zero neutrino mass is practically zero ==> Observation = unambiguous evidence of new physics
- CMS is a general purpose detector designed for high $p_T$ physics at LHC (proton-proton collisions)
- LFV searches at CMS experiment
  - Higgs decay: $H \rightarrow \mu \tau$ or $e \tau$
  - Heavy state: $X \rightarrow e \mu$
  - $\tau$-lepton LFV decay (HL-LHC projection)
  - Leptoquarks (not in this talk)

Outline of this talk
LFV in Higgs decays

- Higgs measurements so far show consistency with SM, while a significant contribution from exotic decays is still possible. Many new physics models allow Higgs LFV decays (1209.1397)

- Higgs to eµ decay is strongly constrained from the µ->eγ search limit => Br(H->eµ) < O(10^{-8})

- Weaker limits on Br(H->e/µτ) < O(0.1) from searches for τ->e/µγ and µ/e g-2 measurements
  - Direct searches for H->eτ and H->µτ promising

- CMS Run-1: a small excess (2.4σ) w.r.t. SM-only was observed for H->µτ; the best-fit branching fraction was 0.84 ± 0.38%

- H->µτ ( µτ_{e} or µτ_{h} ) and H->eτ ( eτ_{µ} or eτ_{h} ) analyses updated with 2016 data (13 TeV, 36 fb^{-1}) JHEP01(2018)001, arxiv:1712.07173
Event selection

In signal, neutrinos (Missing ET) is close to aligned with the visible $\tau$ decay product.

- The main background is $Z \rightarrow \tau\tau$.
- The decay products have on average higher $p_T$ than in $Z \rightarrow \tau\tau$ events (where part of the energy is lost by neutrinos in both $\tau$ decays), and in events with misidentified leptons (jet $\rightarrow e/\mu/\tau_h$ rate decreases with $p_T$).

**Signal event:**

- Prompt lepton
- Visible $\tau$
- MET

**$Z \rightarrow \tau\tau$ event:**

- Visible $\tau$
- Visible $\tau$
- 35.9 fb$^{-1}$ (13 TeV)

![Histograms showing signal and background distributions for $Z \rightarrow \tau\tau$ events](image)
Background estimation

The backgrounds are estimated from MC samples, except for:

- **Jet$\rightarrow$τ$_h$ background** in the eτ$_h$/µτ$_h$ final states (mostly W+jets): observed events with anti-isolated τ$_h$ re-weighted with a misidentification rate depending on $p_T$, $\eta$, and τ$_h$ decay mode

- **QCD multijet** in the eµ final state: obtained from events with same-sign leptons (other MC processes subtracted from data), and re-weighted by a scale factor that accounts for same-sign/ opposite-sign differences

*Validation in same-sign events*
Signal extraction

- Events divided into 4 categories to target different productions modes:
  - 0 jet: Targets $gg\rightarrow H$ events
  - 1 jet: Targets $gg\rightarrow H$ events produced in association with a jet
  - 2 jets, low $m_{jj}$: Targets $gg\rightarrow H$ events with additional jets
  - 2 jets, high $m_{jj}$: Targets $qq\rightarrow H$ events

- BDT trained on the signal against a selection of background samples (reducible background for $e\tau H$ and $\mu\tau H$, $ttbar$ and/or $Z\rightarrow\tau\tau$ for $e\tau\mu$ and $\mu\tau\mu$)

- Cross-check using a cut-based approach with the collinear mass as observable $\rightarrow$ compatible results but less sensitivity
Results of $H\to\mu\tau$ and $H\to\eta\tau$ searches

The most stringent to date

- No excess of data
- Best fit branching ratio: 0.00±0.12%
- $\text{Br}(H\to\mu\tau) < 0.25\%$ @ 95% CL

- Slight excess of data (1.6$\sigma$)
- Best fit branching ratio: 0.30±0.18%
- $\text{Br}(H\to\eta\tau) < 0.61\%$ @ 95% CL
LFV decay of heavy resonance X→eμ

2016 data (13 TeV, 36 fb⁻¹)
JHEP04(2018)074, arxiv:1802.01122

Event selections are designed to be inclusive and model independent, requiring one prompt isolated electron and one prompt isolated muon

Background estimation

• Major background: events with 2 real leptons (ttbar, WW, etc), modelled by MC
• Other background: events with at least 1 fake lepton (mostly electron), estimated using jet-to-lepton fake rate from data control sample
In the region $m(\mu\mu) > 1.5$ TeV

Data: 4 events observed;

Expectation $4.64 \pm 1.28$

No significant excess is observed w.r.t SM expectation.

Limits are set on the product of the signal cross section and the branching fraction of signal to $\mu\mu$, based on the $\mu\mu$ invariant mass distribution.
X→eµ model interpretation

τ sneutrino production in R-parity violating SUSY (narrow resonance)

Heavy Z' gauge bosons (width 3% of the mass)

Quantum black-hole production in extra-dimension models (broader signal)

In all these interpretations, results improve previous limits by ~ 1 TeV;

The most sensitive values at colliders so far
The present $\tau\to3\mu$ search limits:

- Belle: $2.1 \times 10^{-8}$
- LHCb: $4.6 \times 10^{-8}$

$\tau\to3\mu$ is used as a benchmark of CMS muon detector upgrade performance

Forward muon detectors will be enhanced. The new ME0 detector extends pseudo-rapidity from $\eta = 2.4$ to 2.8

The most forward muon in $\tau\to3\mu$ (muon $p>2.5$ GeV; generator-level)

The major source of $\tau$ at LHC is D,B meson decays
τ→3µ @ HL-LHC

The signal acceptance is doubled at reconstruction level with ME0 detector.

But of course, these “extended” muons have worse momentum resolution.
\( \tau \rightarrow 3\mu @ \text{HL-LHC} \)

MC simulation study
Projected to 3000 fb\(^{-1}\)
Adding ME0 detector gains 15% sensitivity

**Category 1: Events without using ME0**

- **CMS Phase-2 Simulation**
- 3000 fb\(^{-1}\), 14 TeV, 200 PU
- Event category 1
  - Signal \((B_{\tau \rightarrow 3\mu} = 2 \times 10^{-3})\)
  - Background
- \(\sigma_{\text{peak}} = 18\) MeV

**Category 2: Events with at least one muon tagged by ME0**

- **CMS Phase-2 Simulation**
- 3000 fb\(^{-1}\), 14 TeV, 200 PU
- Event category 2
  - Signal \((B_{\tau \rightarrow 3\mu} = 2 \times 10^{-3})\)
  - Background
- \(\sigma_{\text{peak}} = 31\) MeV

Note: ME0 reconstruction software was not yet optimised at the time of this study

Signal and background yields in [1.55, 2.00] GeV, assuming \(Br(\tau \rightarrow 3\mu) = 2 \times 10^{-8}\)

<table>
<thead>
<tr>
<th>Category 1</th>
<th>Category 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of background events</td>
<td>(2.4 \times 10^6)</td>
</tr>
<tr>
<td>Number of signal events</td>
<td>4580</td>
</tr>
<tr>
<td>Trimuon mass resolution</td>
<td>18 MeV</td>
</tr>
<tr>
<td>(B(\tau \rightarrow 3\mu)) limit per event category</td>
<td>(4.3 \times 10^{-9})</td>
</tr>
<tr>
<td>(B(\tau \rightarrow 3\mu)) 90% C.L. limit</td>
<td>(3.7 \times 10^{-9})</td>
</tr>
</tbody>
</table>
Summary

• Search for LFV decays at the CMS experiment
  • $\text{Br}(H\rightarrow\mu\tau) < 0.25\%$; $\text{Br}(H\rightarrow e\tau) < 0.61\%$
    • Previous excess in $H\rightarrow\mu\tau$ not confirmed with new data
  • Heavy $X\rightarrow e\mu$, interpreted in various models
• More analyses using the full Run 2 (2015-2018) data to be released within one year
• CMS is also interested in LFV $\tau$ physics - stay tuned
BACK-UP
LFV Higgs

• Trigger
  • $\mu \tau$ channel: single isolated muon trigger
  • $e\tau_h$ channel: single isolated electron trigger
  • $e\tau_\mu$ channel: electron + muon trigger
Results of $H \rightarrow \mu\tau$ and $H \rightarrow e\tau$ searches
Table 1: Numbers of events for background processes, total background with its associated systematic uncertainties, and data, in four bins of \(e\mu\) invariant mass.

<table>
<thead>
<tr>
<th>Mass range (GeV)</th>
<th>(m_{e\mu} &lt; 500)</th>
<th>(500 &lt; m_{e\mu} &lt; 1000)</th>
<th>(1000 &lt; m_{e\mu} &lt; 1500)</th>
<th>(m_{e\mu} &gt; 1500)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet(\rightarrow e) misidentification</td>
<td>3601</td>
<td>82.8</td>
<td>2.92</td>
<td>0.849</td>
</tr>
<tr>
<td>(W\gamma)</td>
<td>2462</td>
<td>56.2</td>
<td>2.76</td>
<td>0.562</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>2638</td>
<td>5.31</td>
<td>0.343</td>
<td>0.0145</td>
</tr>
<tr>
<td>Single (t)</td>
<td>9930</td>
<td>141</td>
<td>2.81</td>
<td>0.178</td>
</tr>
<tr>
<td>(WW, WZ, ZZ)</td>
<td>11126</td>
<td>239</td>
<td>13.0</td>
<td>2.03</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>96754</td>
<td>971</td>
<td>18.5</td>
<td>1.01</td>
</tr>
<tr>
<td>Total background</td>
<td>126513</td>
<td>1495</td>
<td>40.3</td>
<td>4.64</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>23495</td>
<td>420</td>
<td>13.5</td>
<td>1.28</td>
</tr>
<tr>
<td>Data</td>
<td>123150</td>
<td>1426</td>
<td>41</td>
<td>4</td>
</tr>
</tbody>
</table>
Tau production at HL-LHC (3000 fb⁻¹)

<table>
<thead>
<tr>
<th>Process</th>
<th># of taus</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PYTHIA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp → cc, D→τν</td>
<td>3.6 × 10¹⁴</td>
<td>95% D⁺, 5% D⁻⁺</td>
</tr>
<tr>
<td>pp → bb, B→τ+... B→D(τν)+...</td>
<td>1.4 × 10¹⁴</td>
<td>44% B⁺, 45% B⁰, 11% B⁻</td>
</tr>
<tr>
<td></td>
<td>0.6 × 10¹⁴</td>
<td>98% D⁺, 2% D⁻⁺</td>
</tr>
<tr>
<td><strong>NNLO</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp → W → τν</td>
<td>6.0 × 10¹⁰</td>
<td></td>
</tr>
<tr>
<td>pp → Z → ττ</td>
<td>1.2 × 10¹⁰</td>
<td>60 &lt; m_{ττ} &lt; 120 GeV</td>
</tr>
</tbody>
</table>

LHC is a prolific source of tau leptons: \( \sim 6 \times 10^{14} \) at HL-LHC (3000 fb⁻¹)

- **Hadronic taus:** lots, but challenging (soft, forward, poor S/B)
- **W/Z taus:** \(~10^4\) fewer, but relatively easier
Higgs LFV

- Lepton Flavor Violating decays of the Higgs boson would be a clear indication of physics BSM.
- Experimental LHC results:
  - **ATLAS**: 8 TeV results for $H \rightarrow \mu\tau/e\tau$ [1604.07730, 1508.03372]
  - **CMS**: $H \rightarrow \mu\tau/e\tau$: updated with 2016 data (HIG-17-001) and no excess left, $H \rightarrow e\mu$ results only with 2012 data (HIG-14-040)
  - **LHCb**: $H \rightarrow \mu\tau$ result expected soon

| BR($H \rightarrow \tau\mu$) | $< 1.43\%$ | $< 0.25\%$
|---------------------------|-------------|
| BR($H \rightarrow \tau e$) | $< 1.04\%$ | $< 0.61\%$
| BR($H \rightarrow e\mu$)  | $< 0.036\%$ |