Lepton Flavour Violation in the Neutrinoless \( \tau \) Decay \( \tau \to 3\mu \) with the CMS Experiment

Manuel Giffels
on behalf of the CMS collaboration

III. Physikalisches Institut B
RWTH Aachen

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Introduction
- Standard Model & Massive Neutrinos
- LFV in New Physics

Theoretical Calculations
- Generic $\tau \rightarrow \mu\mu\mu$ Matrixelement
- Models
- Results (MC Level)

LFV in $\tau$ decays at CMS
- Introduction
- Results
Lepton Flavour Violation

LFV is possible in the SM, due to massive neutrinos

GIM Mechanism in the Lepton Sector

There is an almost complete cancelation of the amplitudes coming from the 3 contributing undistinguishable diagrams, due to the unitarity of the mixing matrix

Branching Ratios in the SM

The BR in the Standard Model are therefore rather small ($O(10^{-40})$) and not measurable in current experiments
Current Limits

Current limits of LFV $\tau$-decays (PDG 2008 @ 90%CL)

- $\text{BR}(\tau \rightarrow e\gamma) < 1.1 \cdot 10^{-7}$
- $\text{BR}(\tau \rightarrow \mu\gamma) < 6.8 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow e^- e^+ e^-) < 3.6 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow e^- \mu^+ \mu^-) < 3.7 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow e^+ \mu^- \mu^-) < 2.3 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow \mu^- e^+ e^-) < 2.7 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow \mu^+ e^- e^-) < 2.0 \cdot 10^{-8}$
- $\text{BR}(\tau \rightarrow \mu^- \mu^+ \mu^-) < 3.2 \cdot 10^{-8}$

Achievable Limits in the Future ($\tau \rightarrow \mu\mu\mu$)

- $b$ factories reached already $10^{-8}$ similar to a previous CMS study CMS NOTE 2002/37
- SuperB factories would probe $10^{-10}$-$10^{-9}$
LFV in new physics:

- Beyond the SM a large number of theories give rise to LFV in the range of current experimental limits
- Mass dependent couplings prefer $\tau$-LFV with respect to lighter leptons
- $\tau \to l\gamma$ and $\tau \to lll$ have different sensitivity to new physics

### Some Predictions in BSM Models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\text{BR}(\tau \to l\gamma)$</th>
<th>$\text{BR}(\tau \to lll)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA + seesaw</td>
<td>$10^{-7}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Non-Universal $Z'$</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SM + Heavy Majorana $\nu_R$</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

Swagato Banerjee (talk at the CERN flavour workshop (11/05))

⇒ LFV is an interesting option in search of new physics!
Most Generic Lagrangian

New physics models can affect physical values (angular distribution, $p_T$ distribution, etc.) → Do they change the reconstruction efficiency?

$$\mathcal{L} = \mathcal{G} \left( g_{LL}^S (\bar{\mu} P_R \mu) (\bar{\mu} P_L \tau) + g_{LR}^S (\bar{\mu} P_R \mu) (\bar{\mu} P_R \tau) + g_{RL}^S (\bar{\mu} P_L \mu) (\bar{\mu} P_L \tau) + g_{RR}^S (\bar{\mu} P_L \mu) (\bar{\mu} P_R \tau) ight)$$

$$+ g_{LL}^V (\bar{\mu} \gamma \nu P_R \mu) (\bar{\mu} \gamma \nu P_L \tau) + g_{LR}^V (\bar{\mu} \gamma \nu P_R \mu) (\bar{\mu} \gamma \nu P_R \tau)$$

$$+ g_{RL}^V (\bar{\mu} \gamma \nu P_L \mu) (\bar{\mu} \gamma \nu P_L \tau) + g_{RR}^V (\bar{\mu} \gamma \nu P_L \mu) (\bar{\mu} \gamma \nu P_R \tau)$$

$$+ g_{LR}^T \left( \bar{\mu} \frac{\sigma^{\rho \nu}}{\sqrt{2}} P_R \mu \right) \left( \bar{\mu} \frac{\sigma^{\rho \{\rho \nu}}}{\sqrt{2}} P_R \tau \right) + g_{RL}^T \left( \bar{\mu} \frac{\sigma^{\rho \nu}}{\sqrt{2}} P_L \mu \right) \left( \bar{\mu} \frac{\sigma^{\rho \nu}}{\sqrt{2}} P_L \tau \right)$$

Thanks to:

Current Implementation

- Matrix element is not yet implemented into a generator
- Choosing events during the generation process by hit or miss according to the matrix element
\( \tau \)-Polarization necessary to evaluate the matrix element

### W Boson

\( \tau \) leptons produced via W bosons are almost completely polarized (neglecting a correction in the order of \( \frac{m_\tau^2}{m_W^2} \))

### Z Boson

The polarization of \( \tau \) leptons produced via Z bosons is more complicated.

<table>
<thead>
<tr>
<th>Origin</th>
<th>( P_{\tau^+} )</th>
<th>( P_{\tau^-} )</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged vector boson: ( W^\pm )</td>
<td>( P_{\tau^+} = +1 )</td>
<td>( P_{\tau^-} = -1 )</td>
<td>1.0</td>
</tr>
<tr>
<td>Neutral vector boson: ( Z/\gamma^* )</td>
<td>( P_{\tau^+} = +1 )</td>
<td>( P_{\tau^-} = -1 )</td>
<td>( P_Z )</td>
</tr>
<tr>
<td></td>
<td>( P_{\tau^-} = +1 )</td>
<td></td>
<td>( 1 - P_Z )</td>
</tr>
</tbody>
</table>

\[
P_Z = \frac{|M|_{f\bar{f} \to \tau^+\tau^-}^2 (+, -) + |M|_{f\bar{f} \to \tau^+\tau^-}^2 (-, +)}{|M|_{f\bar{f} \to \tau^+\tau^-}^2 (+, -) + |M|_{f\bar{f} \to \tau^+\tau^-}^2 (-, +)}
\]

(1)

Using TAUOLA (KORALZ) routines to calculate the probability \( P_Z \).
\[ P_Z(s, \theta) = \frac{d\sigma_{\text{Born}}}{d\cos \theta} (s, \cos \theta; +1) \]

\[ + \frac{d\sigma_{\text{Born}}}{d\cos \theta} (s, \cos \theta; -1) \]

Depends on the center-of-mass energy \( s \), the decay angle \( \theta \) and the couplings of the fermions to the \( Z \).
Some Models with $\tau \rightarrow \mu \mu \mu$

Topcolor–assisted Technicolor

See–Saw MSSM

Littlest Higgs with $T$–Parity
[Buras et al, JHEP 0705 (2007)]

Kallarackal, Kraemer, O’Leary (2008)
**Topcolor–Assisted Technicolor**

**Technicolor**
New QCD–like force and particles \(\Rightarrow\) Higgs replaced by bound states analogous to mesons.

**Topcolor**
New \(U(1)\) gauge group coupling preferentially to third generation \(\Rightarrow\) new \(Z'\) with tree–level LFV.

Kallarackal, Kraemer, O'Leary (2008)
See-Saw MSSM

- Right-handed neutrinos in MSSM
- Higgs couplings to charged leptons, charginos and neutralinos $\propto \tan(\beta)$
  $\leftrightarrow$ Large $\tan(\beta) \Rightarrow$ Higgs contributions dominant

Kallarackal, Kraemer, O'Leary (2008)
Littlest Higgs with $T$–Parity

Hierarchy problem postponed by extra symmetries for Higgs particles. $T$–parity $\Rightarrow T$–odd partners with in general different mixings and larger mass splittings.

Kallarackal, Kraemer, O’Leary (2008)
\( \theta \) is defined as angle between the \( \tau \) polarization vector and the momentum vector of \( \bar{\mu} \).
Introduction

Theoretical Calculations

LFV in \( \tau \) decays at CMS

Model-Independant Way

The \( \tau \)-Polarization

Models

Results (MC level)

\begin{align*}
\text{No Model} & \quad \begin{array}{c}
\text{Technicolor} \\
\text{Little Higgs} \\
\text{SUSY Seesaw}
\end{array} \\
& \quad \begin{array}{c}
\text{Technicolor} \\
\text{Little Higgs} \\
\text{SUSY Seesaw}
\end{array}
\end{align*}
\( p_T \) Distribution

- **Trigger:** 1\( \mu \): \( p_T > 19 \text{ GeV} \)
- **Trigger:** 2\( \mu \): \( p_T > 7 \text{ GeV} \)
- **All muons** \( p_T > 3 \text{ GeV} \)

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**Leading muon**

- **No Model**
- **RPV Susy LL**
- **RPV Susy RR**
- **TC2**
- **Susy Seesaw**
- **Little Higgs**
- **Higgs Triplet**
- **Top Pion**
- **Zee Babu**

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**Next-to leading muon**

- **No Model**
- **RPV Susy LL**
- **RPV Susy RR**
- **TC2**
- **Susy Seesaw**
- **Little Higgs**
- **Higgs Triplet**
- **Top Pion**
- **Zee Babu**

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**Next-to-next-to leading muon**

- **No Model**
- **RPV Susy LL**
- **RPV Susy RR**
- **TC2**
- **Susy Seesaw**
- **Little Higgs**
- **Higgs Triplet**
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Results (MC level)

Detector acceptance: $-2.5 < \eta < 2.5$

Sum over $\Delta R_{ij}$ ($i, j = 1, 2, 3$ and $j > i$)

No significant differences between the considered models.
Suitable Acceptance Cuts on Generator Level

- Trigger: 1µ: $p_T > 19$ GeV
- Trigger: 2µ: $p_T > 7$ GeV
- Detector acceptance: $-2.5 < \eta < 2.5$
- All muons $p_T > 3$ GeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Model</td>
<td>27.1%</td>
</tr>
<tr>
<td>Higgs Triplet</td>
<td>28.0%</td>
</tr>
<tr>
<td>Little Higgs</td>
<td>27.9%</td>
</tr>
<tr>
<td>RPVSUSYLL</td>
<td>27.7%</td>
</tr>
<tr>
<td>RPVSUSYRR</td>
<td>27.0%</td>
</tr>
<tr>
<td>Technicolor</td>
<td>27.3%</td>
</tr>
<tr>
<td>Top Pion</td>
<td>27.6%</td>
</tr>
<tr>
<td>Zee-Babu</td>
<td>27.0%</td>
</tr>
</tbody>
</table>

No major differences concerning efficiency between the models recognizable

$\rightarrow$ No special matrix element necessary for the further analysis
The CMS Detector

Well suited for studying $\tau \rightarrow 3\mu$:
- vertexing
- large muon system

Luminosity goals:
- $10 - 30 \text{ fb}^{-1}/y$ (low lumi)
- $100 - 300 \text{ fb}^{-1}/y$ (high lumi)
Introduction

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LFV in $\tau$ decays at CMS

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LFV in $\tau$-decays at CMS

Possible decay channels@low lumi

- $\tau \rightarrow \mu \gamma$ (huge background)
- $\tau \rightarrow \mu \mu \mu$

$\tau$-sources at the LHC (Pythia 6.325)

<table>
<thead>
<tr>
<th>decay channel</th>
<th>$N_{\tau}/\gamma$ (low lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \tau \nu_\tau$</td>
<td>$1.5 \cdot 10^8$</td>
</tr>
<tr>
<td>$\gamma/Z \rightarrow \tau \tau$</td>
<td>$2.9 \cdot 10^7$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau X$</td>
<td>$3.1 \cdot 10^{11}$</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \tau X$</td>
<td>$3.4 \cdot 10^{11}$</td>
</tr>
<tr>
<td>$B_s \rightarrow \tau X$</td>
<td>$9.4 \cdot 10^{10}$</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau X$</td>
<td>$6.0 \cdot 10^{11}$</td>
</tr>
</tbody>
</table>

Trigger at CMS (L1)

- single muon $p_t > 14$ GeV
- di-muon $p_t > 3$ GeV

High Level Trigger (HLT)

- single muon $p_t > 19$ GeV
- di-muon $p_t > 7$ GeV

Backgrounds

- Main backgrounds from charm/bottom production
  - $c\bar{c} \rightarrow D_s \rightarrow \mu \phi + X$, $\phi \rightarrow \mu \mu(\gamma)$
  - $c\bar{c} \rightarrow D_s \rightarrow \mu \eta + X$, $\eta \rightarrow \mu \mu(\gamma)$
- Other rare decays
With current standard triggers $\tau \rightarrow 3\mu$ from $D_s$ and $B$'s will hardly be recorded.

$\leftrightarrow$ Have to rely on $\tau$ leptons coming from $W/Z$ decays
\( \tau \rightarrow \mu \mu \mu \) (\( W/Z\)-Source)

Mass Resolution 24 MeV

\[
\begin{array}{c|c|c|c}
\text{entry} & \text{mean} & \text{RMS} & \text{chi}\text{^2}\text{/ndf} \\
2396 & 1.787 & 0.04399 & 6.851 / 4 \\
\end{array}
\]

\[
\text{Mean} = 1.785 \pm 0.001, \quad \text{Sigma} = 0.02382 \pm 0.00059
\]

Assuming that \( B_r = 3.2 \cdot 10^{-8} \)

<table>
<thead>
<tr>
<th>( \tau ) source</th>
<th>#events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W ) boson</td>
<td>( \approx 5 )</td>
</tr>
<tr>
<td>( Z ) boson</td>
<td>( \approx 1 )</td>
</tr>
</tbody>
</table>

Challenging Analysis

- Trigger
- Muon Reconstruction

\( \rightarrow \) Not an analysis for first day physics.

Older results (CMS Note 2002/037)

**Expected limit: (W-Source)**
- \( \text{BR}(\tau \rightarrow \mu \mu \mu) = 7.0 \cdot 10^{-8} \) (10 \( \text{fb}^{-1} \))
- \( \text{BR}(\tau \rightarrow \mu \mu \mu) = 3.8 \cdot 10^{-8} \) (30 \( \text{fb}^{-1} \))

**Expected limit: (Z-Source)**
- \( \text{BR}(\tau \rightarrow \mu \mu \mu) = 3.4 \cdot 10^{-7} \) (30 \( \text{fb}^{-1} \))
Conclusion

- Generic matrix element implementation for $\tau \rightarrow \mu\mu\mu$ available
  → Re-weight MC according to model specific ME
- 8 different models have been tested on MC level
- No major differences concerning signal efficiency between models
  recognizable (MC level)

- Copious $\tau$ lepton production at CMS
  $\rightarrow$ roughly $10^{12}$ $\tau$'s per year
- Unfortunately only $W$ and $Z$ sources are usable at the moment
  $\rightarrow$ roughly $10^8$ $\tau$'s per year
- Challenging analysis for the muon reconstruction and triggers
- Achievable limits are comparable to limits recently published by
  $b$-factories