Lepton Flavour Violation in the Neutrinoless τ Decay $\tau \to 3\mu$ with the CMS Experiment

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Neutrino Masses and Lepton Flavour Violation at the LHC
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Outline

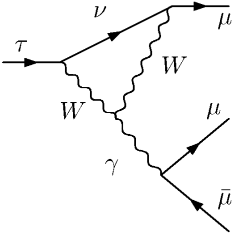
- Introduction
  - Standard Model & Massive Neutrinos
  - LFV in New Physics
- Theoretical Calculations
  - Generic $\tau \rightarrow \mu\mu\mu$ Matrixelement
  - Models
  - Results (MC Level)
- LFV in τ decays at CMS
  - Introduction
  - Results

Introduction

Standard Model + Massive Neutrinos

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 τ-decays (PDG 2008 @ 90%CL)

$$
\begin{array}{lcl}
\mathrm{BR}(\tau \to e\gamma) & < & 1.1 \cdot 10^{-7} \\
\mathrm{BR}(\tau \to \mu\gamma) & < & 6.8 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to e^- e^+ e^-) & < & 3.6 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to e^- \mu^+ \mu^-) & < & 3.7 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to e^+ \mu^- \mu^-) & < & 2.3 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to \mu^- e^+ e^-) & < & 2.7 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to \mu^+ e^- e^-) & < & 2.0 \cdot 10^{-8} \\
\mathrm{BR}(\tau \to \mu^- \mu^+ \mu^-) & < & 3.2 \cdot 10^{-8}
\end{array}
$$

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

- 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 τ-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

	$\mathrm{BR}(\tau \to l\gamma)$	$\mathrm{BR}(\tau \to lll)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

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

$\Rightarrow$ LFV is an interesting option in search of new physics!

Theoretical Calculations

Most Generic Lagrangian

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

$$\begin{aligned}\mathcal{L} = G\Big(& g^S_{LL}(\bar\mu P_R\mu)(\bar\mu P_L\tau) + g^S_{LR}(\bar\mu P_R\mu)(\bar\mu P_R\tau) + g^S_{RL}(\bar\mu P_L\mu)(\bar\mu P_L\tau) + g^S_{RR}(\bar\mu P_L\mu)(\bar\mu P_R\tau) \\ & + g^V_{LL}(\bar\mu\gamma_\nu P_R\mu)(\bar\mu\gamma^\nu P_L\tau) + g^V_{LR}(\bar\mu\gamma_\nu P_R\mu)(\bar\mu\gamma^\nu P_R\tau) \\ & + g^V_{RL}(\bar\mu\gamma_\nu P_L\mu)(\bar\mu\gamma^\nu P_L\tau) + g^V_{RR}(\bar\mu\gamma_\nu P_L\mu)(\bar\mu\gamma^\nu P_R\tau) \\ & + g^T_{LR}\left(\bar\mu\frac{\sigma_{\rho\nu}}{\sqrt{2}}P_R\mu\right)\left(\bar\mu\frac{\sigma^{\rho\nu}}{\sqrt{2}}P_R\tau\right) + g^T_{RL}\left(\bar\mu\frac{\sigma_{\rho\nu}}{\sqrt{2}}P_L\mu\right)\left(\bar\mu\frac{\sigma^{\rho\nu}}{\sqrt{2}}P_L\tau\right)\Big)\end{aligned}$$

<u>Thanks to:</u>
Jim Kallarackal *et al*, RWTH Aachen, JHEP 0710 (2007)
B. M. Dassinger *et al*, University of Siegen, Phys.Rev.D77:073010 (2008)

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

τ-Polarization necessary to evaluate the matrix element

W Boson

τ 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 τ leptons produced via Z bosons is more complicated.

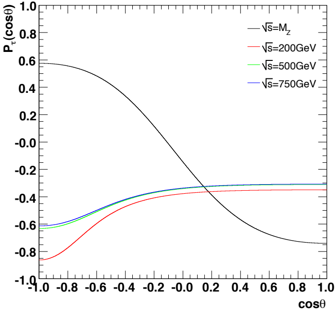
Origin	P_{τ^+}	P_{τ^-}	Probability
Charged vector boson: $W^\pm$	$P_{\tau^+} = +1$	$P_{\tau^-} = -1$	1.0
Neutral vector boson: Z/γ^*	$P_{\tau^+} = +1$	$P_{\tau^-} = -1$	P_Z
	$P_{\tau^+} = -1$	$P_{\tau^-} = +1$	$1 - P_Z$

$$P_Z = \frac{|\mathcal{M}|^2_{f\bar{f}\to\tau^+\tau^-}(+,-)}{|\mathcal{M}|^2_{f\bar{f}\to\tau^+\tau^-}(+,-) + |\mathcal{M}|^2_{f\bar{f}\to\tau^+\tau^-}(-,+)} \quad (1)$$

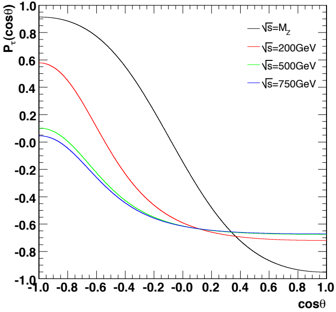
Using TAUOLA (KORALZ) routines to calculate the probability P_z.

$$P_Z(s,\theta) = \frac{\frac{d\sigma_{Born}}{d\cos\theta}(s,\cos\theta;+1)}{\frac{d\sigma_{Born}}{d\cos\theta}(s,\cos\theta;+1)+\frac{d\sigma_{Born}}{d\cos\theta}(s,\cos\theta;-1)} \qquad (2)$$

Depends on the center-of-mass energy s, the decay angle θ and the couplings of the fermions to the Z.



Up-Type quarks



Down-Type quarks

Some Models with $\tau \to \mu\mu\mu$

Topcolor–assisted Technicolor

[Yue, Zong, Zhou and Yang, Phys. Rev. D 71 (2005); Yue, Zhang and Liu, Phys. Lett. B 547 (2002)]

See–Saw MSSM

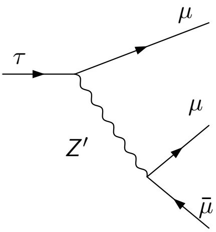
[Babu and Kolda, Phys. Rev. Lett. 89 (2002)]

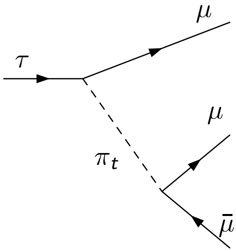
Littlest Higgs with T–Parity

[Buras *et al*, JHEP 0705 (2007)]

Kallarackal, Kraemer, O'Leary (2008)

Topcolor–Assisted Technicolor





Technicolor

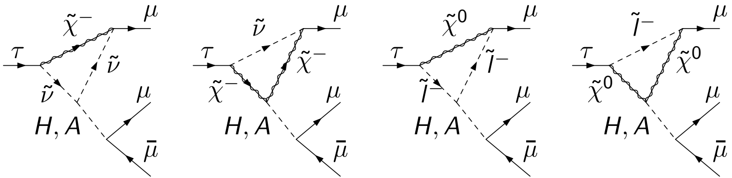
New QCD–like force and particles $\Rightarrow$ Higgs replaced by bound states analogous to mesons.

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

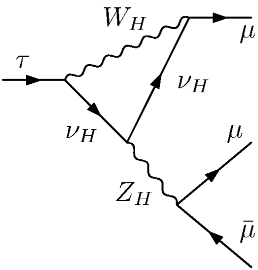


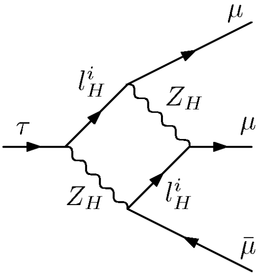
See-Saw MSSM

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

Kallarackal, Kraemer, O'Leary (2008)

Littlest Higgs with T–Parity

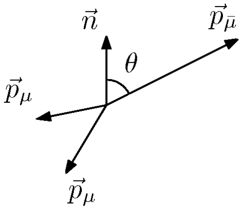




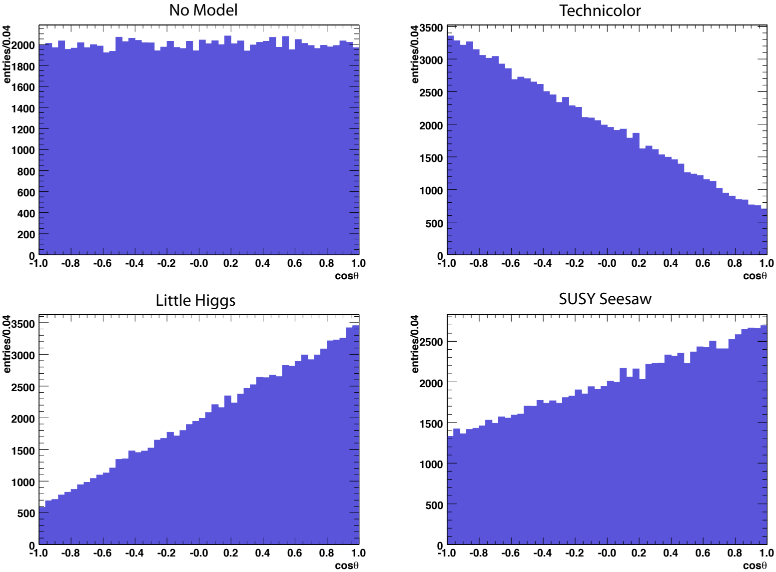
Littlest Higgs Model

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)



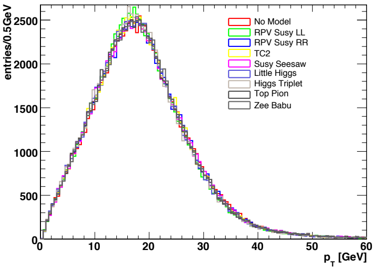
θ is defined as angle between the τ polarization vector and the momentum vector of $\bar{\mu}$


No Model
Technicolor
Little Higgs
SUSY Seesaw
entries/0.04
cosθ

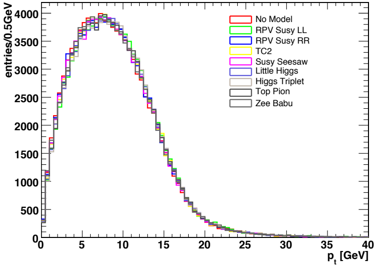
p_T Distribution

- Trigger: 1μ: $p_T > 19\,\mathrm{GeV}$
- Trigger: 2μ: $p_T > 7\,\mathrm{GeV}$
- All muons $p_T > 3\,\mathrm{GeV}$

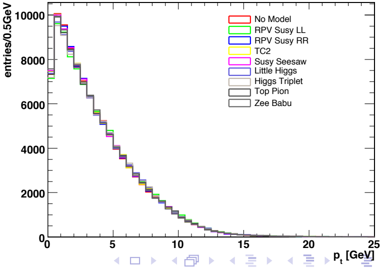
Leading muon

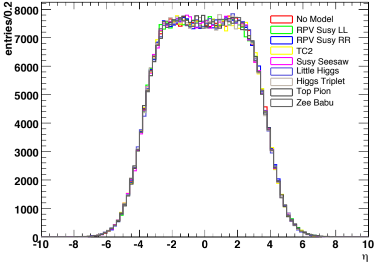


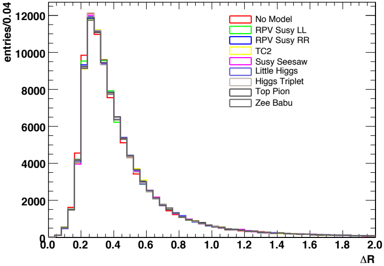
Next-to leading muon



Next-to-next-to leading muon







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

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

No significant differences between the considered models.

Suitable Acceptance Cuts on Generator Level

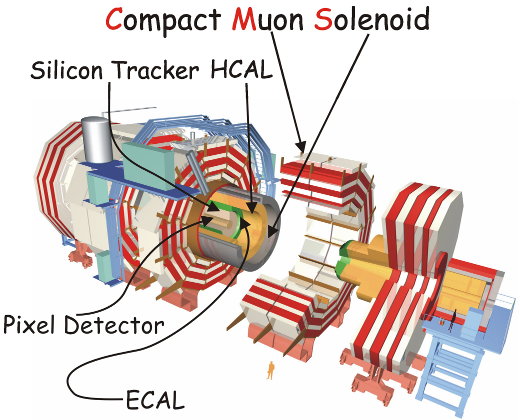
- Trigger: 1μ: $p_T > 19\,\mathrm{GeV}$
- Trigger: 2μ: $p_T > 7\,\mathrm{GeV}$
- Detector acceptance: $-2.5 < \eta < 2.5$
- All muons $p_T > 3\,\mathrm{GeV}$

Model	Acceptance
No Model	27.1%
Higgs Triplet	28.0%
Little Higgs	27.9%
RPVSUSYLL	27.7%
RPVSUSYRR	27.0%
Technicolor	27.3%
Top Pion	27.6%
Zee-Babu	27.0%

No major differences concerning efficiency between the models recognizable
$\hookrightarrow$ No special matrix element necessary for the further analysis

LFV in τ decays at CMS

The CMS Detector



Well suited for studying $\tau \to 3\mu$:

- vertexing
- large muon system

Luminosity goals:

$10 - 30\,\mathrm{fb}^{-1}/\mathrm{y}$ (low lumi)
$100 - 300\,\mathrm{fb}^{-1}/\mathrm{y}$ (high lumi)

LFV in τ-decays at CMS

Possible decay channels@low lumi

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

Trigger at CMS (L1)

- single muon $p_t > 14\,\mathrm{GeV}$
- di-muon $p_t > 3\,\mathrm{GeV}$

High Level Trigger (HLT)

- single muon $p_t > 19 GeV$
- di-muon $p_t > 7\,\mathrm{GeV}$

τ-sources at the LHC (Pythia 6.325)

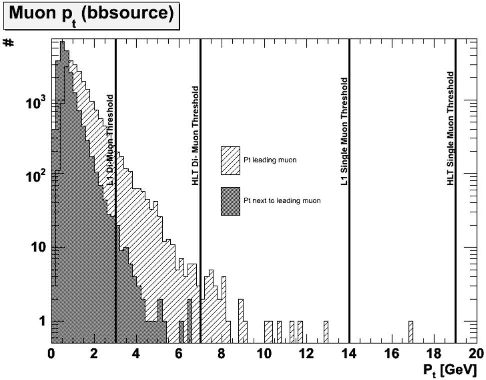
decay channel	N_τ/y (low lumi)
$W \to \tau\nu_\tau$	$1.5 \cdot 10^8$
$\gamma/Z \to \tau\tau$	$2.9 \cdot 10^7$
$B^0 \to \tau X$	$3.1 \cdot 10^{11}$
$B^\pm \to \tau X$	$3.4 \cdot 10^{11}$
$B_s \to \tau X$	$9.4 \cdot 10^{10}$
$D_s \to \tau X$	$6.0 \cdot 10^{11}$

Backgrounds

- Main backgrounds from charm/bottom production
- $c\bar{c} \to D_s \to \mu\phi + X,\ \phi \to \mu\mu(\gamma)$
- $c\bar{c} \to D_s \to \mu\eta + X,\ \eta \to \mu\mu(\gamma)$
- Other rare decays

D_s/B Sources

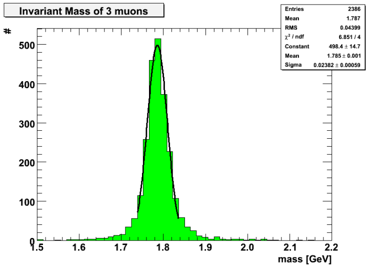
With current standard triggers $\tau \to 3\mu$ from D_s and B's will hardly be recorded



$\hookrightarrow$ Have to rely on τ leptons coming from W/Z decays

$\tau \to \mu\mu\mu$ (W/Z-Source)

Mass Resolution 24 MeV



Assuming that $\mathcal{B}_r = 3.2 \cdot 10^{-8}$

τ source	#events/year
W boson	≈ 5
Z boson	≈ 1

Challenging Analysis

- Trigger
- Muon Reconstruction

$\hookrightarrow$ Not an analysis for first day physics.

Older results (CMS Note 2002/037)

Expected limit:(W-Source)

- $\mathrm{BR}(\tau \to \mu\mu\mu) = 7.0 \cdot 10^{-8}$ $(10\,\mathrm{fb}^{-1})$
- $\mathrm{BR}(\tau \to \mu\mu\mu) = 3.8 \cdot 10^{-8}$ $(30\,\mathrm{fb}^{-1})$

Expected limit:(Z-Source)

- $\mathrm{BR}(\tau \to \mu\mu\mu) = 3.4 \cdot 10^{-7}$ $(30\,\mathrm{fb}^{-1})$

Conclusion

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