LFV in Tau Decays: Results and Prospects at the LHC

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On behalf of the ATLAS, CMS & LHCb Collaborations

Tau 2016
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Charged Lepton Flavour Violation

Neutrino Oscillation

Neutrino Masses

Lepton Flavour Violation

- Loop suppressed
- $\mathcal{B} \propto (m_\nu/m_W)^4 \to \mathcal{O}(10^{-40})$

- Ideal playground to search for Beyond the SM physics
- Many BSM models with TeV scale new physics predict rates within reach of current experiments.

→ Is there a counterpart in the charged lepton sector?
LHC Experiments

\[ B(\tau^− \to \mu^− \mu^+ \mu^-) \quad Z^0 \to \tau^\pm \mu^\mp \quad D^0 \to e^\pm \mu^\mp \]

Prospects

LHC Experiments

Kristof De Bruyn (CPPM)  
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Tau 2016
Overview

This Talk

1. $\tau^- \rightarrow \mu^- \mu^+ \mu^-$
2. $Z^0 \rightarrow \tau^\pm \mu^\mp$
3. $D^0 \rightarrow e^\pm \mu^\mp$

Other LHC Results

- $H \rightarrow \tau^\pm \mu^\mp$
- $H \rightarrow \tau^\pm e^\mp$
- $Z \rightarrow e^\pm \mu^\mp$
- $\tau^- \rightarrow p\mu^- \mu^-$
- $B^0_{(s)} \rightarrow e^\pm \mu^\mp$

See preceding ATLAS & CMS Talks

See preceding ATLAS & CMS Talks

ATLAS, PRD 90 (2014) 072010, arxiv:1408.5774

LHCb, PLB 724 (2013), arxiv:1304.4518

LHCb, PRL 111 (2013) 141801, arxiv:1307.4889
$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$ @ ATLAS & LHCb
Neutrino-less $\tau$ Decay

- Strongly suppressed in the Standard Model

- Can be enhanced by new physics at tree level ($Z'$, ...) or loops (SUSY, ...)

- Current best limit:

\[ \mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 2.1 \times 10^{-8} \text{ @ 90\% C.L.} \]


Experimental Signature

- No missing energy in $\tau$ decay
- Three muons with invariant mass $m_{3\mu} \approx m_{\tau}$
- Displaced vertex
**ATLAS: Strategy**

- Analysis based on 20.3 fb$^{-1}$ of data, collected at 8 TeV in 2012

**Experimental Setup**

- Uses $W^- \rightarrow \tau^- \bar{\nu}_\tau$ decays (highest efficiency for trigger & reconstruction)

\[
B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = \frac{N_{\text{sig}}}{\epsilon_{\text{sig}} \times \sigma_{W^- \rightarrow \tau^- \bar{\nu}_\tau} \times L}
\]

- $N_{\text{sig}} = \text{signal yield}$, $\epsilon_{\text{sig}} = \text{selection efficiency}$, $\sigma = \text{cross section}$, $L = \text{luminosity}$
- Relies on the $W^- \rightarrow \ell^- \bar{\nu}$ cross-section measurement

- Estimate about $(2.41 \pm 0.08) \times 10^8 \tau$’s produced
- Contamination from other sources ($Z^0 \rightarrow \tau^+ \tau^-$, heavy flavour) is less than 3%
\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) \]
\[ Z^0 \rightarrow \tau^\pm \mu^\mp \]
\[ D^0 \rightarrow e^\pm \mu^\mp \]

**ATLAS: Strategy**

**Selection**

1. Cut-based *loose* selection
2. Train Boosted Decision Tree and apply loose cut \( x_0 \) on BDT output \( x \)
3. Cut-based *tight* selection
4. Apply tight cut \( x_1 \) on BDT output, optimising for the expected \( B \) limit

**Fit Strategy**

- Blinded analysis: ignore signal region: \( m_{3\mu} \in [1713, 1841] \ \text{MeV}/c^2 \)
- Estimate background yield from mass sidebands using “tight + \( x > x_0 \)”
- Fit BDT output in region \( x > x_0 \)
- Extrapolate background yield for “tight + \( x > x_1 \)”

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Unblinding

- **No events** found in signal region
- Expected background $N_{\text{bkg}} = 0.193 \pm 0.037 \text{ (stat)} \pm 0.131 \text{ (syst)}$
  (dominant uncertainty = extrapolation procedure)
- Efficiency $\epsilon_{\text{sig}} = 0.0231 \pm 0.0005 \text{ (Jet)} \pm 0.0009 \text{ (MC)} \pm 0.0025 \text{ (trig)} \pm 0.0030 \text{ (reco)}$
- Limit:
  $$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 3.76 \times 10^{-7} \text{ @ 90\% C.L.}$$

Outlook

- Not competitive with results from $B$-factories or LHCb
- Demonstrates ATLAS' potential for LFV searches
- Helped improve muon trigger and reconstruction of “low-$p_T$” muons (4 – 18 GeV/c)
LHCb: Strategy

▶ Analysis based on 3 fb\(^{-1}\) of data (full Run 1)

Experimental Setup

▶ \(\tau\) originate from \(b\) and \(c\)-hadron decays

▶ Normalisation mode: \(D_s^- \rightarrow \phi(\rightarrow \mu^+ \mu^-)\pi^-\)

\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = \frac{B(D_s^- \rightarrow \phi(\rightarrow \mu^+ \mu^-)\pi^-)}{B(D_s^- \rightarrow \tau^- \bar{\nu}_\tau)} \times f_{D_s}^\tau \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}} = \alpha \times N_{\text{sig}} \]

▶ \(N_{\text{sig}}\) = signal yield, \(N_{\text{cal}}\) = yield of calibration mode, \(\epsilon\) = selection efficiency

▶ \(f_{\tau}^{D_s} = 0.80 \pm 0.03\) is the fraction of \(\tau\) that originates from \(D_s\) mesons

→ Input: \(b \bar{b}, c \bar{c}\) cross-sections

→ Input: inclusive \(b \rightarrow D_s, c \rightarrow D_s, b \rightarrow \tau\) and \(c \rightarrow \tau\) branching fractions

▶ Normalisation factor:
\[ \alpha(7 \text{ TeV}) = (7.20 \pm 0.98) \times 10^{-9} \quad \alpha(8 \text{ TeV}) = (3.37 \pm 0.50) \times 10^{-9} \]

Different trigger: \(p_T(\mu) > 1.48 \text{ GeV/c (2011) vs } p_T(\mu) > 1.76 \text{ GeV/c (2012)}\)

▶ Corresponds to about 8.5 to 9 \(\times 10^{10}\) \(\tau\)'s produced
LHCb: Strategy

Selection

- Cut-based loose selection
- Three likelihoods to distinguish signal from background
  1. MVA exploiting the geometrical properties $M_{3\text{body}}$
  2. Neural Network for muon particle identification $M_{\text{PID}}$
  3. Invariant mass $m_{3\mu}$ of three muons

**Fit Strategy**

- Fit invariant mass in each bin of $M_{3\text{body}} \times M_{\text{PID}}$
- Blinded analysis: ignore signal region: $(m_{\tau} \pm 30)$ MeV/c$^2$
LHCb: Results

\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) \]

\[ Z^0 \rightarrow \tau^\pm \mu^\mp \]

\[ D^0 \rightarrow e^\pm \mu^\pm \]

Propects

LHCb, JHEP 02 (2015) 121, arxiv:1409.8548

- All bins consistent with background-only hypothesis
- Limit:

\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 4.6 \times 10^{-8} \quad \text{@ 90\% C.L.} \]

Outlook
- Still factor 2.5 worse than Belle
- Run 2: Might overtake Belle . . .
- . . .and be overtaken again by Belle II
\[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) \]

\[ Z^0 \rightarrow \tau^\pm \mu^\mp \]

\[ D^0 \rightarrow e^\pm \mu^\mp \]

Prospects

\[ Z^0 \rightarrow \tau^\pm \mu^\mp \quad \odot \text{ATLAS} \]
ATLAS: Strategy

- Analysis based on 20.3 fb$^{-1}$ of data, collected at 8 TeV in 2012

Experimental Setup

- Reconstructed in $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ mode

- Background decomposition
  - $W$ + jets (using dedicated control region)
  - $Z^0 \rightarrow \tau^+ \tau^-$ (modelled using $Z^0 \rightarrow \mu^+ \mu^-$)
  - Combinatorial bkg (taken from same-sign data)

→ Adopt data-driven techniques to control them

- Analysis strategy similar to $H \rightarrow \mu^\pm \tau^{\mp}_{\text{had}}$ ATLAS, JHEP 1511 (2015) 211, arxiv:1508.03372
- But larger contribution from $W$ + jets
→ More detailed study of this component
Fit Strategy:

- Combined analysis of signal region + control regions
  - Two signal search windows: SR1 & SR2
  - Control region for the modelling of $W+$ jets (WCR) background
  - Control region for $t\bar{t}$ events (normalisation)
- Regions defined in terms of the *transverse mass*

\[ m_{\ell,E_{\text{miss}}} \equiv \sqrt{2p_T^{\ell}E_{\text{miss}}^T(1 - \cos \Delta \phi)} \]

with $\Delta \phi$ angle between $\ell$ and the direction of $E_{\text{miss}}^T$
\[ \mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) \quad Z^0 \rightarrow \tau^\pm \mu^\mp \quad D^0 \rightarrow e^\pm \mu^\mp \]

**Prospects**

**ATLAS: Results**

**ATLAS, arxiv:1604.07730**

**Signal Region 1**

![Graph showing signal region 1 results](image1)

- Small deficit compared to background expectation
- Limit:

\[ \mathcal{B}(Z \rightarrow \tau^\pm \mu^\mp) < 1.69 \times 10^{-5} \quad @ \text{95}\% \text{ C.L.} \]

**Signal Region 2**

![Graph showing signal region 2 results](image2)
$B(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$

$Z^0 \rightarrow \tau^\pm \mu^\mp$

$D^0 \rightarrow e^\pm \mu^\mp$

Prospects

$D^0 \rightarrow e^\pm \mu^\mp \ @ \ LHCb$
Forbidden Decay

- Strongly suppressed in the Standard Model

- Enhanced in many beyond the SM theories:
  - SUSY with R-parity violation: $\mathcal{O}(10^{-6})$
  - Leptoquarks: $\approx 4 \times 10^{-8}$
  - Multiple Higgs doublets: $\approx 7 \times 10^{-10}$

- Previous best limit:

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 2.6 \times 10^{-7} \quad @ 90\% \, C.L.$$

LHCb: Strategy

▶ Analysis based on 3 fb\(^{-1}\) of data (full Run 1)

Experimental Setup

▶ Candidates selected from \(D^{*+} \to D^0\pi^+\) decays
▶ Normalisation mode: \(D^0 \to K^-\pi^+\)

\[
\mathcal{B}(D^0 \to e^\pm \mu^\mp) = \mathcal{B}(D^0 \to K^-\pi^+) \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}}
\]

▶ \(N_{\text{sig}} = \) signal yield, \(N_{\text{cal}} = \) yield of calibration mode, \(\epsilon = \) selection efficiency
▶ Efficiencies: \(\epsilon_{\text{sig}} = (4.4 \pm 0.3) \times 10^{-4}\), \(\epsilon_{\text{cal}} = (2.5 \pm 0.1) \times 10^{-6}\)
▶ Difference: keep only 1% of triggered \(D^0 \to K^-\pi^+\) events

Backgrounds

▶ Main background: misID-ed \(D^0 \to \pi^+\pi^-\)

▶ Probability

\[
[\pi\pi \to e\mu] = (1.8 \pm 0.4) \times 10^{-8}
\]
▶ \(\mathcal{B}(D^0 \to \pi^+\pi^-) = (1.421 \pm 0.025) \times 10^{-3}\)
▶ Electron momentum corrected for bremsstrahlung losses (\(\to\) Tails)
LHCb: Strategy

Fit Strategy

- Cut-based + BDT selection → divide data in 3 bins
- Simultaneous fit to \( m_{D^0} \) and \( \Delta m = m_{D^{*+}} - m_{D^0} \)
- Legend: \( D^0 \rightarrow e^\pm \mu^\mp \) \( D^0 \rightarrow \pi^+\pi^- \)

Most Bkg-like

Intermediate

Most Sig-like

\[ \Delta m = m_{D^{*+}} - m_{D^0} \]
Simultaneous fit to the 3 BDT bins gives: $N_{\text{sig}} = -7 \pm 15$

Limit:

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8} \text{ @ 90\% C.L.}$$

Factor 20 improvement over Belle
Prospects for LHC Run 2 and Beyond
Prospects

LHC Run 2 and Beyond

GPD
LHCb: 3fb⁻¹

150 fb⁻¹
Upgrade

75% nominal luminosity

13 TeV


7 TeV
8 TeV

nominal luminosity

experiment beam pipes

splice consolidation button collimators R2E project

LS1

EYETS

13.5-14 TeV

LS2

injection upgrade cryo Point 4
DS collimation P2-P7(11 T dip.)
Civil Eng. P1-P5

2019 2020 2021 2022 2023

experiment upgrade phase 1

14 TeV

LS3

HL-LHC installation

cryolith interaction regions

2x nominal luminosity

radiation damage

2024 2025 2026 2027

experiment upgrade phase 2

5 to 7 x nominal luminosity

2037

center of physics des particules de Marseille

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LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3
---|---|---
LS1 splice consolidation button collimators R2E project | EYETS | LS2 injection upgrade cryo Point 4 DS collimation P2-P7(11 T dip.) Civil Eng. P1-P5

Run 4 - 5...

0.30 fb⁻¹
LHCb: 3fb⁻¹

5fb⁻¹ Upgrade

300 fb⁻¹

3000 fb⁻¹ integrated luminosity

(300fb⁻¹)
Prospects for LHC Run 2 and Beyond

Ambitious Plans:

- Sensitivities strongly depend on trigger settings
- These depend on pile-up, available bandwidth, . . .
- Difficult to predict ⇒ no official numbers!

ATLAS:

- Added insertable B layer in 2014, for improved tracking
- Improved trigger and reconstruction for “low-p_T” muons
- Aim for result on $\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$ with Run 2 data that is competitive with LHCb and/or Belle II

CMS:

- Will replace the inner tracker during EYETS 2016/17 (extra layer)
- Beneficial for $B$-physics programme
- Plans to study $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ with the future upgrade

LHCb:

- Aim for a limit on $\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$ of $\mathcal{O}(10^{-9}) - \mathcal{O}(10^{-10})$ with Run 2 data, may be competitive with Belle II
Conclusion

- ATLAS limit on the $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ branching ratio
  \[ \mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 3.76 \times 10^{-7} \quad @ 90\% \text{ C.L.} \]

- LHCb limit on the $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ branching ratio
  \[ \mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 4.6 \times 10^{-8} \quad @ 90\% \text{ C.L.} \]

- ATLAS limit on the $Z^0 \rightarrow \tau^\pm \mu^\mp$ branching ratio
  \[ \mathcal{B}(Z \rightarrow \tau^\pm \mu^\mp) < 1.69 \times 10^{-5} \quad @ 95\% \text{ C.L.} \]

- LHCb limit on the $D^0 \rightarrow e^\pm \mu^\mp$ branching ratio
  \[ \mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) < 1.3 \times 10^{-8} \quad @ 90\% \text{ C.L.} \]

- Decays involving $\tau$’s play an important role in searches for charged lepton flavour violation