Search for CLFV decays $\tau \rightarrow 3\mu$
with ATLAS and CMS Detectors

Andrey Korytov
University of Florida
(on behalf of the ATLAS and CMS Collaborations)
There are no fundamental symmetries explicitly forbidding CLFV processes

- In fact, in SM CLFV decays are possible via neutrino oscillations, e.g. $B(\tau \rightarrow 3\mu) \sim O(10^{-14})$
- In BSM, such decays can be “naturally” enhanced, e.g. $B(\tau \rightarrow 3\mu)$ can be as large as $O(10^{-8})$

Theoretical considerations in favor of $\tau \rightarrow 3\mu$:

- Tau lepton’s large mass means large phase space for decays
- couplings for new physics may be enhanced for heavy particles

Experimental considerations in favor of $\tau \rightarrow 3\mu$:

- there-muon signature is the cleanest at LHC (as opposed to $3e, \mu \mu e, \mu \gamma$, etc.)

Recent experimental limits (90% CL):

- Belle: $2.1 \times 10^{-8}$ (expected $\sim 2.3 \times 10^{-8}$) 
- BaBar: $3.3 \times 10^{-8}$ (expected $4.0 \times 10^{-8}$) 
- LHCb (Run 1): $4.6 \times 10^{-8}$ (expected $5.6 \times 10^{-8}$) 
  $\text{JHEP 02 (2015) 121}$
- ATLAS (Run 1, 8 TeV): $3.8 \times 10^{-7}$ (expected $3.9 \times 10^{-7}$) 
- CMS (Run 2, 2016 dataset): coming soon

Presented in this talk:

- CMS Projections for HL-LHC $\text{Phase 2 Muon Upgrade TDR, CMS-TDR-016 (2017)}$
## 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 \rightarrow cc, )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D \rightarrow \tau \nu )</td>
<td>( 3.6 \times 10^{14} )</td>
<td>95% ( D_s ), 5% ( D^\pm )</td>
</tr>
<tr>
<td>( pp \rightarrow bb, )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B \rightarrow \tau +... )</td>
<td>( 1.4 \times 10^{14} )</td>
<td>44% ( B^\pm ), 45% ( B^0 ), 11% ( B_s )</td>
</tr>
<tr>
<td>( B \rightarrow D(\tau \nu) +... )</td>
<td>( 0.6 \times 10^{14} )</td>
<td>98% ( D_s ), 2% ( D^\pm )</td>
</tr>
<tr>
<td><strong>NNLO</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( pp \rightarrow W \rightarrow \tau \nu )</td>
<td>( 6.0 \times 10^{10} )</td>
<td></td>
</tr>
<tr>
<td>( pp \rightarrow Z \rightarrow \tau \tau )</td>
<td>( 1.2 \times 10^{10} )</td>
<td>( 60 &lt; m_{\tau \tau} &lt; 120 , \text{GeV} )</td>
</tr>
</tbody>
</table>

**LHC is a prolific source of tau leptons:** \(~ 6 \times 10^{14} \) 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
Run 1, 8 TeV dataset:
- $L = 20.3 \text{ fb}^{-1}$
- Expected number of $W \to \tau \nu$ events: $2.4 \times 10^8$

Main signal characteristics exploited:
- Three muons:
  - $Q = \pm 1$
  - $p_T(3\mu) \sim 20-50$ GeV
  - common vertex, displaced wrt PV
  - boosted topology (muons close together)
  - trimuon system is isolated
  - trimuon invariant mass peaks at $m_\tau$ – the final observable
- Missing transverse momentum
  - 20-50 GeV
  - opposite to $p_T(3\mu)$
- Transverse mass of $p_T(3\mu)$ and MET
  - Consistent with $m_W$
- Little hadronic activity in an event
Event selection (1)

Trigger:
- Five different multi-muon triggers
- One dimuon trigger + MET
- Trigger efficiency in fiducial acceptance is \( \sim 30\% \)
  
  \( \text{(fiducial signal acceptance: } p_T > 2.5 \text{ GeV, } |\eta| < 2.4) \)

Reconstruction and event selection:
- three high-quality muons, \( Q=1 \)
- \( m_{3\mu} < 2.5 \text{ GeV} \)
- common vertex \( V_{3\mu} \)
- Loose trimuon event selection cuts on:
  - \( V_{3\mu} \) – PV displacement significance
  - impact parameter formed by \( p_T(3\mu) \) vector
  - \( p_T(3\mu) \)
  - Isolation
  - MET
  - \( m_T \)

Total signal efficiency: 6.6%

BDT-training sideband [750; 1450] and [2110; 2500]: 4672 events
After the final selection, the signal sideband (SB) is expected to have too few or even no events.

The following analysis strategy is employed:

- Train BDT using:
  - signal MC
  - data from BDT-training sideband
- Apply BDT cut $x > x_0$
- Apply tight event selection
  - Use the signal sidebands to predict background in signal region $B_{SR}(\text{tight, } x > x_0)$
  - Use the BDT distribution to compute a reduction factor $f$ for going from $x > x_0$ to $x > x_1$
- Apply BDT cut $x > x_1$

- Predicted background in the signal region SR
  
  $B_{SR}(\text{tight, } x > x_1) = B_{SR}(\text{tight, } x > x_0) \times f = 0.19 \text{ events}$

- Overall signal selection efficiency: 2.3%
Expected $W \rightarrow \tau \nu$ events: $2.4 \times 10^8$

Signal region:
- Signal A x eff = 0.023
- Background (how?) = 0.19 events
- Observed: 0 events

Exclusion limits on B at 90% CL
- Expected: $3.9 \times 10^{-7}$
- Observed: $3.8 \times 10^{-7}$

Side note: for $B = 2 \times 10^{-8}$, S/B ~ 1:2
My naïve extrapolation toward HL-LHC

If I naively assume (all faults are mine!)
- no deterioration due to high PU
- no improvements in the detector
- no changes in the analysis
- no systematic uncertainties whatsoever
- background event rate scales from 8 TeV to 14 TeV in sync with the W rate

Number of $W \rightarrow \tau \nu$ events:

$$\sigma_{14\text{TeV}}(W) \times B(W \rightarrow \tau \nu) \times L = (2 \times 10^8 \text{fb}) \times 0.11 \times (3000 \text{ fb}^{-1}) = 6 \times 10^{10}$$

Signal $A \times \text{eff} = 0.023$ (no changes)

Background in signal region: $(6 \times 10^{10} / 2.4 \times 10^8) \times 0.19 \sim 50 \text{ events}$

Such naïve extrapolation gives expected limit $9 \times 10^{-9}$ at 90% CL
CMS: Search projection using hadronic taus

**HL-LHC:**
- 14 TeV
- PU = 200 \( (L \sim 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}) \)
- \( L_{\text{int}} = 3000 \text{ fb}^{-1} \)
- Expected number of hadronic taus: \( 5.6 \times 10^{14} \)
  (72% of which originate from \( D_s \to \tau \nu \))

**CMS Upgrades most relevant for this analysis:**
- Enhanced forward muon system:
  - improved momentum measurement at L1 Trigger
  - extended eta-coverage from 2.4 to 2.8
- Track-trigger capabilities for tracks with \( p_T > 2 \text{ GeV} \)
- Higher trigger bandwidth (100 kHz \( \to 750 \text{ kHz} \))

**Main signal trimuon characteristics exploited:**
- \( Q=1 \)
- common vertex, \( V_{3\mu} \)
- \( V \) – PV displacement
- collinearity of \( p(3\mu) \) and PV-\( V_{3\mu} \) vectors
- trimuon invariant mass peaks at \( m_\tau \) – the final observable
Event Selection (1)

Basic signal acceptance ($|\eta| < 2.8$, $p > 2.5$ GeV): 2.6%
factor of two gain due to extension of muon $\eta$-acceptance from 2.4 to 2.8

Muon reconstruction:
- Tracker-muons: Tracker track + at least one matching segment in Muon System
- Signal efficiency in acceptance is about 30%
- the gained events due to the Muon System extension have a **worse trimuon mass resolution**

Two event categories are introduced:
- Category 1: events reconstructed using the present muon chambers
- Category 2: events with at least one ME0-only muon

Trigger:
- Category 1:
  - At least two tracker-muons ($p_T > 2$ GeV, $\delta p_T/p_T \sim 2$–3%)
  - One station-1 ME0-CSC segment ($\delta p_T/p_T \sim 20\%$)
  - Trimuon mass < 3 GeV
  - Efficiency wrt reconstructed/selected trimuon events: ~80%
- Category 2:
  - At least one tracker-muon
  - Two station-1 segments, allowing for **ME0-only** segments ($\delta p_T/p_T \sim 40\%$)
  - Trimuon mass < 3 GeV
  - Trigger efficiency for reconstructed/selected trimuon events: ~50%
Loose cuts on variables to mitigate pile-up background

- $Q = \pm 1$
- minimum trimuon vertex $\chi^2$
- minimum transverse displacement of the trimuon vertex
- maximum $\Delta R$ distance between the three muons

This basic event selection

- has signal efficiency $\sim 30\%$ for events with all three muons reconstructed
- and practically eliminates pile-up background

Remaining background is mostly due to $B$ production with

- two muons from $B$ cascade decays
- and one “fake” muon from $\pi/K$-decays in flight accidental “alignment” of a track in the Tracker stub found in a muon chamber
Event Selection (3)

Observables used to build the final S/B log-likelihood ratio, $\ln Q$, where $Q = \prod \frac{pdf_s(x_i)}{pdf_b(x_i)}$
- trimuon vertex $\chi^2$
- transverse displacement of the trimuon vertex
- decay collinearity angle $\alpha$
- minimum $\Delta R$ distance between between dimuon pairs
- highest and lowest muon momentum
- number of b-jets in the event
- …

A cut on $\ln Q$ is then imposed
The final overall signal efficiency $\sim 0.06\%$

Andrey Korytov (UF)
Final mass distributions and sensitivity

Number of background events | Category 1 | Category 2 |
-------------------------------|------------|------------|
Number of signal events \((B = 2 \times 10^{-8})\) | \(4580\) | \(3640\) |
Trimuon mass resolution | \(18\) MeV | \(31\) MeV |
\(B(\tau \rightarrow 3\mu)\) limit per event category | \(4.3 \times 10^{-9}\) | \(7.0 \times 10^{-9}\) |
\(B(\tau \rightarrow 3\mu)\) 90\% C.L. limit | \(3.7 \times 10^{-9}\) |
\(B(\tau \rightarrow 3\mu)\) for 3\(\sigma\)-evidence | \(6.7 \times 10^{-9}\) |
\(B(\tau \rightarrow 3\mu)\) for 5\(\sigma\)-observation | \(1.1 \times 10^{-8}\) |
Conclusions

The present best limit on $\tau \to 3\mu$ decays:

$\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% CL

Belle-II projection for 50 ab$^{-1}$ [PoS FPCP2015 (2015) 049]:

$4 \times 10^{-10}$ at 90% CL

HL-LHC is a prolific source of tau leptons: $\sigma(pp \to \tau + X) \sim 2 \times 10^{11}$ fb

- Both **hadronic** and **electroweak** ($\sigma \sim 2 \times 10^7$ fb) taus can be exploited for the $\tau \to 3\mu$ search; each branch is being explored by both ATLAS and CMS

- **HL-LHC Projections** (limit at 90% CL) **based on the three public results available so far:**

<table>
<thead>
<tr>
<th></th>
<th>Luminosity</th>
<th>Tau source</th>
<th>Source of projection</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>3000 fb$^{-1}$</td>
<td>$W \to \tau \nu$</td>
<td>My naïve extrapolation from the Run 1 (8 TeV, 20.3 fb$^{-1}$) results (slide 8)</td>
<td>$9 \times 10^{-9}$</td>
</tr>
<tr>
<td>CMS</td>
<td>3000 fb$^{-1}$</td>
<td>Hadronic</td>
<td>Simulated analysis for the Upgraded CMS at HL-LHC</td>
<td>$4 \times 10^{-9}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>300 fb$^{-1}$</td>
<td>Hadronic</td>
<td>My naïve $1/\sqrt{N}$ extrapolation from the Run 1 (8 TeV, 3 fb$^{-1}$) results</td>
<td>$6 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

- LHC analyses are not limited by the number of taus, but rather by how well one can separate signal from large background – **plenty of opportunities for further optimization.** The actual results will be for sure better than the presented simplified/naïve projections (e.g., compare the earlier projections and the actual results for $ttH$, $H \to bb$, $VBF H \to$ invisible)