TAU 2023 Summary

a personal (and thus biased) selection of highlights

Soeren Prell (Iowa State University)
Tau 2023
December 4-6, 2023
Louisville, Kentucky
Searches for cLFV in \( \tau \) decays

**cLFV in SM:**

\( < O(1e^{-54}) \)

Petcov, 1977

- **New limits on** \( \tau \rightarrow V^0 \ell \) **from Belle**

- **New limits on** \( \tau \rightarrow 3\mu \) **from CMS and Belle II**
  - **Belle II limit better than Belle with \( \frac{1}{2} \) the data**

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Tau 2023 Summary

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**Table:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \varepsilon ) (%)</th>
<th>( N_{\text{BKG}} )</th>
<th>( \sigma_{\text{syst}} ) (%)</th>
<th>( N_{\text{obs}} )</th>
<th>( B_{\text{obs}} ) ( \times 10^{-8} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^\pm \rightarrow \mu^\pm \mu^0 )</td>
<td>7.78</td>
<td>0.95±0.20(stat.) ±0.15(syst.)</td>
<td>4.6</td>
<td>0</td>
<td>&lt; 1.7</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow e^\pm \mu^0 )</td>
<td>8.49</td>
<td>0.80±0.27(stat.) ±0.04(syst.)</td>
<td>4.4</td>
<td>1</td>
<td>&lt; 2.2</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow \mu^\pm \phi )</td>
<td>5.59</td>
<td>0.47±0.15(stat.) ±0.05(syst.)</td>
<td>4.8</td>
<td>0</td>
<td>&lt; 2.3</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow e^\pm \phi )</td>
<td>6.45</td>
<td>0.38±0.21(stat.) ±0.00(syst.)</td>
<td>4.5</td>
<td>0</td>
<td>&lt; 2.9</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow \mu^\pm \omega )</td>
<td>3.27</td>
<td>0.32±0.23(stat.) ±0.19(syst.)</td>
<td>4.8</td>
<td>0</td>
<td>&lt; 3.9</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow e^\pm \omega )</td>
<td>5.41</td>
<td>0.74±0.43(stat.) ±0.06(syst.)</td>
<td>4.5</td>
<td>0</td>
<td>&lt; 2.4</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow \mu^\pm K^\pm )</td>
<td>4.52</td>
<td>0.84±0.25(stat.) ±0.31(syst.)</td>
<td>4.3</td>
<td>0</td>
<td>&lt; 2.9</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow e^\pm K^\pm )</td>
<td>6.94</td>
<td>0.54±0.21(stat.) ±0.16(syst.)</td>
<td>4.1</td>
<td>0</td>
<td>&lt; 1.9</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow \mu^\pm K^*^0 )</td>
<td>4.58</td>
<td>0.58±0.17(stat.) ±0.12(syst.)</td>
<td>4.3</td>
<td>1</td>
<td>&lt; 4.3</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow e^\pm K^*^0 )</td>
<td>7.45</td>
<td>0.25±0.11(stat.) ±0.02(syst.)</td>
<td>4.1</td>
<td>0</td>
<td>&lt; 1.7</td>
</tr>
</tbody>
</table>

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**Graph:**

- **Belle II (Preliminary)**
  - Data: \( \int L dt = 424 fb^{-1} \)
  - Simulation: \( \int L dt = 4 ab^{-1} \)

- **1 event observed inside the SR**

- **Obtained most stringent limit**

\( @ 90\% \text{ C.L} \)

\( 1.9 \times 10^{-8} \)
cLFV (theory I)

• \( \tau \) decays may be good place to look for LFV
  – LFV may only occur in some \( \tau \) decays (and not in \( \mu \) decays at all) if lepton flavor triality is conserved

\[
L_{k_1} = \frac{1}{2} (2f_1 \bar{e}^c R \mu_R + f_2 \bar{e}^c e_R) k_1 + h.c.
\]

• Note to experimenters: Dalitz plot searches can be more sensitive to specific models

The idea: each charged lepton is charged under this \( Z_3 \) (flavour triality)

\[
\psi_{\tau} \rightarrow \left(e^{2ni/3}\right)^T \psi.
\]

T is a triality charge.

Electron: \( T = 1 \)
muon: \( T = 2 \)
tau: \( T = 3 \)

Triality-preserving charged-lepton decays:

<table>
<thead>
<tr>
<th>Observable</th>
<th>Present constraint</th>
<th>Projected sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BR}(\tau^- \rightarrow \mu^- \mu^- e^+) )</td>
<td>( &lt; 1.7 \times 10^{-8} ) [1]</td>
<td>( 2.6 \times 10^{-10} ) [2]</td>
</tr>
<tr>
<td>( \text{BR}(\tau^- \rightarrow \mu^+ e^- e^-) )</td>
<td>( &lt; 1.5 \times 10^{-8} ) [1]</td>
<td>( 2.3 \times 10^{-10} ) [2]</td>
</tr>
</tbody>
</table>
• Look everywhere. Sensitivities to NP are often complementary
  – Example: strong constraints from $\mu \to e\gamma$ on all LFV Higgs ($\to \ell\ell'$) decays
- Consider classes of models related by EFT operators
  - Don’t be discouraged to look for $\Delta B$ tau decays!
  - ... but sometimes proton decay may be more sensitive

Better:
\[ p \rightarrow \ell^+ \ell'^\pm \pi^\mp \nu_\tau \]
**cLFV in τ final states (I)**

- **New limits from Belle on** \( B_s \to ℓτ, B \to Kτℓ, \) and \( Υ(1S) \to ℓℓ'(γ) \)

<table>
<thead>
<tr>
<th>Decay</th>
<th>( ε (%) )</th>
<th>( N_{\text{fit}}^{\text{sig}} )</th>
<th>( N_{\text{UL}}^{\text{sig}} )</th>
<th>UL (90%CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Υ(1S) \to e^±μ^± )</td>
<td>32.5</td>
<td>−1.3 ± 3.7</td>
<td>3.6</td>
<td>( 3.9 \times 10^{-7} )</td>
</tr>
<tr>
<td>( Υ(1S) \to μ^±τ^± )</td>
<td>8.8</td>
<td>−1.5 ± 4.3</td>
<td>6.8</td>
<td>( 2.7 \times 10^{-6} )</td>
</tr>
<tr>
<td>( Υ(1S) \to e^±τ^± )</td>
<td>7.1</td>
<td>−3.5 ± 2.7</td>
<td>5.3</td>
<td>( 2.7 \times 10^{-6} )</td>
</tr>
</tbody>
</table>

- **Many new limits from ATLAS on** \( H \to ℓτ, Z' \to τℓ, LQ(bτ), \) etc.,

\[ \gamma(1S) \to μ^± τ^± \]

![Graph](image)

**ATLAS**

\( iS=13 \) TeV, 139 \( fb^{-1} \)

- 95% CL
- High b-jet \( p_T \) only
- Interference with SM neglected

**MCT**

\( \ell\tau_{\text{lep}}+\ell\tau_{\text{had}} \)

**BR** (SM):

- \( B(H \to eτ) < 0.20\% (0.11\%) @ 95\% CL \)
- \( B(H \to μτ) < 0.18\% (0.09\%) @ 95\% CL \)
LFV and other NP with $\tau$ final states

New limits from CMS on production of $W'$ (up to 4.8 TeV), LQ, QBH (6.6 TeV)

- Expect better $\tau$ reconstruction in Run 3 from reconstruction and tagging improvements
FCC-ee and CEPC can provide constraints on CLFV complimentary to LFV tau decays

EIC can provide tight constraints on cLFV (esp. on LQ models)
Rare $\tau$ final states at future $e^+e^-$ colliders

Clean environment and highly boosted $Z$'s at a Tera-$Z$ factory (Mega-LEP) provide a high sensitivity to $b$ decays to $\tau$ final states.
Mu2e

- **Mu2e** will look for $\mu$ to $e$ conversions in the electric field of a nucleus
  - Expect to reach $BF(\mu N \rightarrow eN) < 8 \times 10^{-17}$
- On track for commissioning to start 2024 with cosmics, with beam in 2025, and first physics data taking in 2026
- **Mu2e-II** will increase sensitivity by another order of magnitude with higher beam intensity

![Diagram](image)

Production Solenoid

Transport Solenoid

Detector Solenoid

8GeV, 8kW Protons

Selection Window

Delayed live-gate helps remove pion and beam backgrounds.
• **New Belle I/II searches for**
  – A long-lived HNL, a leptophilic scalar, a scalar in $\tau \rightarrow \ell \alpha$, a $\tau \tau$ resonance

• **New BaBar searches for**
  – A HNL, a dark baryon
Dark searches at future experiments

Consider 3 final states:
- Majorana: $e^+3j$
- Majorana: $e^+\mu^-j + \not{E}_T$
- Dirac: $\ell^+\ell^-j + \not{E}_T$

Also sensitive to invisible HNL decays via mono-jets.

Extensive program of dark searches at fixed target and beam dump expts, also Faser.
**LFU tests in τ decays**

- **Same coupling of the charged leptons to the gauge bosons**
  \[ g_e = g_\mu = g_\tau \text{ (SM)} \]
  \[
  \left( \frac{g_\mu}{g_e} \right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e(\gamma))}} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}
  \]
  \[ R_\mu = \frac{\mathcal{B}(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e(\gamma))} \text{ (SM)} = 0.9726 \]

- **Brand-new result from Belle II**
  - systematically limited by LID

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**Tau 2023 Summary**
**LFU tests with $b \rightarrow c\tau\nu$**

- **New measurements of $b \rightarrow c\tau\nu$ decays**
  - **LHCb**:
    * Measurement of the ratios of branching fractions $R(D^0)$ and $R(D^0)$  
    * Test of Lepton flavour universality using $B^0 \rightarrow D^+\tau^+\nu$ decay with hadronic $\tau$ channels  
      [Phys. Rev. D108 (2023) 012018]
    * Observation of the decay $\Lambda^0_b \rightarrow \Lambda_c^+\tau\bar{\nu}$  
  - **CMS: $R(J/\psi)$**
    - $R_{J/\psi} = 0.17^{+0.18}_{-0.17} \text{ (stat)}^{+0.21}_{-0.22} \text{ (syst)}^{+0.19}_{-0.18} \text{ (theo)}$
      
      compatible with the SM prediction within the experimental uncertainty (0.2582)

- LHCb, $B \rightarrow D^* \tau \nu$

- $D^*$ long. pol. consistent with SM ($1\sigma$)

- Arnau’s talk
SM H physics with \( \tau \) final states

- ATLAS sees evidence for associated \( VH(\rightarrow \tau\tau) \) production at 4.2\( \sigma \)
- ATLAS measures CP of \( H(\rightarrow \tau\tau) \) and rejects pure CP-odd at 3.4\( \sigma \)

| Soeren Prell | Tau 2023 Summary | 15 |
\[ \tau \text{ properties I (mass, EDM)} \]

- **Most precise tau mass measurement from Belle II**
  - Improved on results from threshold experiments by reducing systematics from beam energy and momentum measurement

- **New measurement of tau EDM from Belle using spin correlations**
  
  \[
  \Re(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17} \text{ ecm}, \\
  \Im(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17} \text{ ecm}.
  \]

  - Expect to reduce to \((1 - 2) \times 10^{-19} \text{ ecm}\) with improved technique and Belle II data, esp. with pol. beams
**τ properties II \( (g - 2) \)**

- Photoproduction cross-section of \( \tau \) pairs depends on \( \alpha_\tau \)
  - ATLAS result has similar precision to DELPHI result; ALICE analysis is in progress
- Also possible at Belle II (pol. beams help)

**Ultra peripheral Pb-Pb collisions**

1-loop QED, Schwinger term
\[
\alpha / 2\pi = 0.0012
\]
CMS measures tau pol. in Z decays and extracts $\sin^2 \theta_W$

$$\langle P_\tau \rangle_{75-120 \text{GeV}} = -0.140 \pm 0.006 \text{ (stat)} \pm 0.014 \text{ (syst)} = -0.140 \pm 0.015.$$  

$$P_\tau (Z) = -0.144 \pm 0.015$$

$$P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v^2 + a^2_\tau} \approx -2\frac{v_\tau}{a_\tau} = -2(1 - 4 \sin^2 \theta_W^{\text{eff}}).$$

$$\sin^2 \theta_W^{\text{eff}} = 0.2319 \pm 0.0008 \text{ (stat)} \pm 0.0018 \text{ (syst)} = 0.2319 \pm 0.0019.$$  

BABAR measures $\ell^{-}$ beam pol. with $\tau$ polarization

$$P_\tau^- = P_e \frac{\cos \theta}{1 + \cos^2 \theta} \cdot \frac{8G_Fg_\tau^\ell}{4\sqrt{2}\pi \alpha} \left(g_\lambda^\ell \frac{|\vec{p}|}{p^0} + 2g_\rho^\ell \frac{\cos \theta}{1 + \cos^2 \theta}\right)$$

- EM term
- Electroweak correction $\sim 0.003$

$$\langle P \rangle = 0.0035 \pm 0.0024 \text{ stat} + 0.0029 \text{ sys}$$
Chiral Belle

Upgrade SuperKEKB beams at $\sqrt{s} = 10.58$ GeV to 70% beam polarization

Plan for end of decade

$a_\tau^{BSM} \sim a_\mu^{BSM} \left( \frac{m_\tau}{m_\mu} \right)^2 \sim 10^{-6}$

Current bound in tau $\sim \mathcal{O}(10^{-2})$
Chiral Belle reach $\sim \mathcal{O}(10^{-5})$ with 50 ab$^{-1}$
Hadronic $\tau$ decays (theory)

- **Updated $\tau$ generators**
  - KKMC for $e^+ e^- \rightarrow \tau^+ \tau^- (n\gamma)$ incl. $\tau$ decays
  - Emission of additional pairs of SM and NP
  - Anomalous MDM and EDM

- **Precise BFs of hadronic $\tau$ decays can limit NP contributions**
  - E.g., new work on structure-dep. contributions to rad. corrections in hadronic $\tau$ decays reduces uncertainty $\times 2$

- **New theory work on $V_{us}$ and $\alpha_s$**
  - Unfortunately, no new experimental $\tau$ results in these areas

Flash back to grad student times →
\[ \mu \left( g - 2 \right) \]

- **New FNAL \( \mu \left( g - 2 \right) \) result from Run 2+3 at 200 ppb precision**
  - Error is statistically limited, expect to < 100 ppb with Run 1-6 (data taken this year)
- **J-PARC Muon EDM / g-2 (2028+)**
  - Not quite at the same precision
  - Different approach with low emittance \( \mu \) beam and no strong focusing is more sensitive to EDM \( \left( 10^{-21} \right) \)
  - First demonstration of cooled muons

\[ \mathbf{\tilde{\omega}} = -\frac{e}{m} \left[ a_{\mu} \mathbf{\tilde{B}} + \frac{\eta}{2} \left( \mathbf{\beta} \times \mathbf{\tilde{B}} \right) \right] \]

J-PARC E34

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**2006: 540 ppb**

- April 7\(^{th}\), 2021
  - FNAL Run-1
- August 10\(^{th}\), 2023
  - FNAL Run-2/3
  - FNAL Run-1 + Run-2/3 (203 ppb)

**2023: 190 ppb**

- World Average

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**\( a_{\mu} \times 10^{-9} - 1165900 \)**

- Signal of Cold muon

- Laser injection

- Background due to laser lights

**Raw data (Very preliminary)**

- Entries
- Underflow
- Overflow

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**Soeren Prell**

**Tau 2023 Summary**
Experimental \( a_\mu \) value has been stable ... what is the SM prediction?

Expected theory progress

- Radiative corrections and MC generators are being scrutinized
- New LQCD results for total HVP contribution and "window observables" and data-driven approach ... goal is < 0.5% precision
- \( \muonE \) will provide new method to compute the HVP contribution (2026+)

\( e^+e^- \) data needs to be understood!

New measurements of HVP contribution expected from KLOE, BESIII, SND, Belle II (eventually also from \( \tau \) decays)
Some stats

• 89 plenary talks
• 90 participants
• 6 Kentucky bourbons ... maybe more
Many thanks to Sourav Patra and Naveen Kumar Baghel for taking care of the registration and Indico and Zoom connections.

Many thanks to Swagato for hosting this great event !!!
Conclusions

We have seen a lot of exciting results since the last TAU conference

Tau physics is going strong!

I am looking forward to TAU 2025
The 18th International Workshop on Tau Lepton Physics will be held in autumn of 2025 hosted by Aix-Marseille Université in Marseille, France.

Justine Serrano serrano@cppm.in2p3.fr serving as Chair of the Local Organizing Committee

Exact dates are to be decided later.