Search for tau LFV decays at Belle

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Lepton flavor violation (LFV) in charged leptons
⇒ negligibly small probability in the Standard Model (SM)
even including neutrino oscillations:
\[ B(\tau \to \mu \gamma) < O(10^{-54}) \]

Observation of LFV is a clear signature of New Physics (NP)

- Many extensions of the SM predict LFV decays.
  - These branching fractions could be enhanced as high as current experimental sensitivity. (~10^{-8})

- Tau lepton = The heaviest charged lepton
  - Expected strong coupling to NP
  - Many possible LFV decay modes
New Physics and $\tau$ LFV

We like to find LFV and New Physics (NP) as well as to know what NP induces LFV.

<table>
<thead>
<tr>
<th>ratio</th>
<th>LHT</th>
<th>MSSM (dipole)</th>
<th>MSSM (Higgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{B(\tau^+ \rightarrow e^+ e^-)}{B(\tau^+ \rightarrow e^-)}$</td>
<td>0.4...2.3</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
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<td>0.4...2.3</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.06...0.1</td>
</tr>
<tr>
<td>$\frac{B(\tau^+ \rightarrow \mu^+ \mu^-)}{B(\tau^+ \rightarrow e^-)}$</td>
<td>0.3...1.6</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.02...0.04</td>
</tr>
<tr>
<td>$\frac{B(\tau^- \rightarrow e^- e^-)}{B(\tau^- \rightarrow e^-)}$</td>
<td>0.3...1.6</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
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<td>$\frac{B(\tau^- \rightarrow \mu^- e^-)}{B(\tau^- \rightarrow e^-)}$</td>
<td>0.3...1.6</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>0.3...0.5</td>
</tr>
<tr>
<td>$\frac{B(\tau^- \rightarrow e^- e^-)}{B(\tau^- \rightarrow e^-)}$</td>
<td>1.2...1.6</td>
<td>$\sim 5$</td>
<td>0.3...0.5</td>
</tr>
<tr>
<td>$\frac{B(\tau^- \rightarrow \mu^- \mu^-)}{B(\tau^- \rightarrow \mu^-)}$</td>
<td>1.2...1.6</td>
<td>$\sim 0.2$</td>
<td>5...10</td>
</tr>
</tbody>
</table>

Various LFV searches are important because they can distinguish NP models even if one LFV decay has been observed.

$\rightarrow$ It is a strong advantage that $\tau$ has many kinds of LFV decays. Using Belle $\tau$ data, we search for $\tau$ LFV decays.
B-factory: \( E \) at \( CM = Y(4S) \)
\( e^+(3.5 \text{ GeV}) e^-(8 \text{ GeV}) \)
\( \sigma(\tau\tau) \sim 0.9 \text{nb}, \sigma(bb) \sim 1.1 \text{nb} \)

A B-factory is also a \( \tau \)-factory!

Peak luminosity: \( 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
World highest luminosity!

Total: > 1ab\(^{-1}\)

- \( Y(4S): 711 \text{fb}^{-1} \)
- \( Y(5S): 121 \text{fb}^{-1} \)
- \( Y(3S): 3.0 \text{fb}^{-1} \)
- \( Y(2S): 24 \text{fb}^{-1} \)
- \( Y(1S): 5.7 \text{fb}^{-1} \)
- Off-resonance: 87 \text{fb}^{-1} 

Belle Detector:
Good track reconstruction and particle identifications
Lepton efficiency: 90%
Fake rate: \( O(0.1) \% \) for \( e \)
\( O(1) \% \) for \( \mu \)

\( \sim 9 \times 10^8 \tau\tau \) at Belle
Analysis procedure

- $e^+e^- \rightarrow \tau^+\tau^-$  \hspace{0.5cm} Br~85%
- 1 prong + missing (tag side)
- $\mu\pi\pi$ (signal side)

Fully reconstructed

Signal extraction: $m_{\mu\pi\pi} - \Delta E$ plane

$$m_{\mu\pi\pi} = \sqrt{(E_{\mu\pi\pi}^2 - p_{\mu\pi\pi}^2)}$$

$$\Delta E = E_{\mu\pi\pi}^{CM} - E_{beam}^{CM}$$

Blind analysis $\Rightarrow$ Blind signal region

Estimate number of BG in the signal region using sideband data and MC
LFV $\tau$ decays; Signal and Background

**Signal**
- Signal side
  - $\mu^-$, $\pi^+$, $\pi^-$
  - $e^-$, $\tau^+$, $\tau^-$, $e^+$

**Tag Side**
- Many tracks and photons
- Neutrino(s) in tag side
- Particle ID
- Mass of mesons

**Two-Photon Process**
- $f$ = leptons, quarks
- $e^-$, $\gamma$, $\bar{f}$

**Radiative Bhabha Process**
- $e^+$, $e^-$, $\gamma$
Search for $\tau\rightarrow\ell hh'$

- NUHM favors $\tau^{-}\rightarrow\ell^{-}\pi^{+}\pi^{-}$ while doubly charged higgs induces $\tau^{-}\rightarrow\ell^{+}\pi^{-}\pi^{-}$.
- Update with 854 fb$^{-1}$ data
  - BaBar; $\text{Br}< (7-48) \times 10^{-8}$ at 221 fb$^{-1}$
- 14 modes are investigated ($h,h' = \pi^{\pm}$ and $K^{\pm}$)
  - $\tau^{-}\rightarrow \ell^{-}h^{+}h'$: 8 modes (lepton flavor violation)
  - $\tau^{-}\rightarrow \ell^{+}h^{-}h'$: 6 modes (lepton number violation)

Missing momentum can help to reject this kind of BGs since signal has $\nu$ only on tag side.
BG rejection for $\tau \rightarrow \ell hh'$

To reduce $\tau\tau$ and qq BG

- $\mu\pi K$ mode
  - $m_{\text{miss}}^2$ -- $p_{\text{miss}}$ correlation
  - 2d selection
    - 75% of eff. is kept while 75% of BG is rejected.
- $\text{ehh'}$, $\mu\pi\pi$ and $\mu KK$ modes
  - $m_{\text{miss}}^2$ selection
    - 90% of eff. is kept while 50% of BG is rejected.

To reduce $\tau\tau$ BG

- $\mu\pi K$ mode
  - Dominant BG is from $\tau \rightarrow \pi\pi\pi\nu$ with a $\pi\pi$ combination misidentified as $K\mu$.
  - $M_{\mu\pi K}$ is shifted into the $\tau$-mass signal region while the original $M_{\pi\pi\pi}$ will be below the $\tau$-mass due to the missing neutrino.
  - Assign $\pi\pi\pi$ mass for selected events
    - $M_{\pi\pi\pi} > 1.52$ GeV/c$^2$
      - 65% of eff. is kept while 65% of BG is rejected.
Result for $\tau\rightarrow\ell hh'$

In the signal region

1 event: in $\mu^+\pi^-\pi^-$ and $\mu^-\pi^+K^-$
no events: in other modes

⇒ no significant excess/Expected # of BG: 0.06-0.72

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$N_{obs}$</th>
<th>$s_{90}$</th>
<th>$B$ ($10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^-\rightarrow\mu^-\pi^+\pi^-$</td>
<td>5.83</td>
<td>0.63 ± 0.23</td>
<td>5.3</td>
<td>0</td>
<td>1.87</td>
<td>2.1</td>
</tr>
<tr>
<td>$\tau^-\rightarrow\mu^+\pi^-\pi^-$</td>
<td>6.55</td>
<td>0.33 ± 0.16</td>
<td>5.3</td>
<td>1</td>
<td>4.02</td>
<td>3.9</td>
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<tr>
<td>$\tau^-\rightarrow e^-\pi^+\pi^-$</td>
<td>5.45</td>
<td>0.55 ± 0.23</td>
<td>5.4</td>
<td>0</td>
<td>1.94</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^-\rightarrow e^+\pi^-\pi^-$</td>
<td>6.56</td>
<td>0.37 ± 0.18</td>
<td>5.4</td>
<td>0</td>
<td>2.10</td>
<td>2.0</td>
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<tr>
<td>$\tau^-\rightarrow \mu^-K^+K^-$</td>
<td>2.85</td>
<td>0.51 ± 0.18</td>
<td>5.9</td>
<td>0</td>
<td>1.97</td>
<td>4.4</td>
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<tr>
<td>$\tau^-\rightarrow \mu^+K^+K^-$</td>
<td>2.98</td>
<td>0.25 ± 0.13</td>
<td>5.9</td>
<td>0</td>
<td>2.21</td>
<td>4.7</td>
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<tr>
<td>$\tau^-\rightarrow e^-K^+K^-$</td>
<td>4.29</td>
<td>0.17 ± 0.10</td>
<td>6.0</td>
<td>0</td>
<td>2.28</td>
<td>3.4</td>
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<tr>
<td>$\tau^-\rightarrow e^+K^-K^-$</td>
<td>4.64</td>
<td>0.06 ± 0.06</td>
<td>6.0</td>
<td>0</td>
<td>2.38</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tau^-\rightarrow \mu^-\pi^+K^-$</td>
<td>2.72</td>
<td>0.72 ± 0.27</td>
<td>5.6</td>
<td>1</td>
<td>3.65</td>
<td>8.6</td>
</tr>
<tr>
<td>$\tau^-\rightarrow e^-\pi^+K^-$</td>
<td>3.97</td>
<td>0.18 ± 0.13</td>
<td>5.7</td>
<td>0</td>
<td>2.27</td>
<td>3.7</td>
</tr>
<tr>
<td>$\tau^-\rightarrow \mu^-K^+\pi^-$</td>
<td>2.62</td>
<td>0.64 ± 0.23</td>
<td>5.6</td>
<td>0</td>
<td>1.86</td>
<td>4.5</td>
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<tr>
<td>$\tau^-\rightarrow e^-K^+\pi^-$</td>
<td>4.07</td>
<td>0.55 ± 0.31</td>
<td>5.7</td>
<td>0</td>
<td>1.97</td>
<td>3.1</td>
</tr>
<tr>
<td>$\tau^-\rightarrow \mu^+K^-\pi^-$</td>
<td>2.55</td>
<td>0.56 ± 0.21</td>
<td>5.6</td>
<td>0</td>
<td>1.93</td>
<td>4.8</td>
</tr>
<tr>
<td>$\tau^-\rightarrow e^+K^-\pi^-$</td>
<td>4.00</td>
<td>0.46 ± 0.21</td>
<td>5.7</td>
<td>0</td>
<td>2.02</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Set upper limits at 90%CL:
$\text{Br}(\tau\rightarrow\ell hh')< (2.0-8.6)x10^{-8}$
→most sensitive results

(preliminary)
Search for $\tau \rightarrow \Lambda h/\bar{\Lambda} h$

- GUT allows $\tau^- \rightarrow \bar{\Lambda} h^-$ while more complicated model is required for $\tau^- \rightarrow \Lambda h^-$. 
- Search with 904 fb$^{-1}$ data sample
  - Select three hadrons
  - Require Lambda vertex
- 4 modes are searched for. ($h=\pi$ and $K$)
  - $\tau^- \rightarrow \bar{\Lambda} h^-$: (B-L) conserving decay
  - $\tau^- \rightarrow \Lambda h^-$: (B-L) violating decay
BG rejection for $\tau \rightarrow \Lambda h/\bar{\Lambda} h$

To reduce $\tau\tau$ BG including $K_S^0$
$\Rightarrow$ reconstruct $K_S^0$ and reject events that are likely to be $K_S^0$

- 85% of eff. is kept while
- 75% of $K_S^0$ BG events is rejected.

To reduce $q\bar{q}$ BG including $\Lambda$
$\Rightarrow$ reject events with a proton in tag side
(due to BN conservation, the events including a $\Lambda$ tend to have baryon on tag side.)

- A third of $q\bar{q}$ BG events are rejected while a loss of eff. is negligibly small.
Results for $\tau \rightarrow \Lambda h/\bar{\Lambda}h$

In the signal region:
no candidate event are found
⇒ no significant excess

• Expected # of BG: (0.21-0.42)

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<th>$s_{90}$</th>
</tr>
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<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.80</td>
<td>0.21 ± 0.15</td>
<td>8.2</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.39</td>
<td>0.31 ± 0.18</td>
<td>8.2</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \bar{\Lambda}K^-$</td>
<td>4.11</td>
<td>0.31 ± 0.14</td>
<td>8.6</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \bar{\Lambda}K^-$</td>
<td>3.16</td>
<td>0.42 ± 0.19</td>
<td>8.6</td>
<td>0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Set upper limits@90%CL:
$\text{Br}(\tau^- \rightarrow \bar{\Lambda}\pi^-) < 2.8 \times 10^{-8}$ (B-L) cons.
$\text{Br}(\tau^- \rightarrow \bar{\Lambda}K^-) < 3.1 \times 10^{-8}$ (B-L) viol.
$\text{Br}(\tau^- \rightarrow \Lambda\pi^-) < 3.0 \times 10^{-8}$ (preliminary)
$\text{Br}(\tau^- \rightarrow \bar{\Lambda}K^-) < 4.2 \times 10^{-8}$ (preliminary)

→ most sensitive results
Previous result for $\tau \to \mu \gamma$ search

- 545 fb$^{-1}$ Belle data sample
- 94 events are found while (88.4±7.4) BG events are expected in 5σ region and the detection eff. is 6.1%. **Main BG comes from $\tau \to \mu \nu \nu + \text{ISR } \gamma$.**
- Upper Limits are evaluated by 2d UEML fit on $M-\Delta E$ plane.
- Expected UL: $7.8 \times 10^{-8}$ @90%CL
- Obtained UL: $4.5 \times 10^{-8}$ @90%CL

Now, we are updating the result with Belle full data sample (980 fb$^{-1}$)!

**UEML=Unbinned Extended Maximum Likelihood fit**
Tag side missing mass

- Tag side missing mass.

\[(\text{tag side missing mass})^2 = (\text{reconstructed tag-side } \tau) - (\text{visible tracks and gammas belonging to tag side})\]
**ee → μμγ rejection**

- Mainly, ee → μμγ events are rejected by muon-veto for tag-side charged track. But, due to the inefficiency of the muon ID, some ee → μμγ events survive.

![Diagram showing ee → μμγ events in the e-e-γ rest frame](image)

In the e-e-γ rest frame, μ-μ direction should be opposite.

![Graph showing cosα distribution](image)

$$\cos \alpha = \text{opening angle between signal- and tag-side tracks in e-e-γ rest frame.}$$
Remaining events and eff.

✓ After the selections, 105 events are found and the detection efficiency is 6.5%.
→ For the blinded region, 10.2 ± 2.2 BG events are expected.

✓ In total, 115.2 ± 11.4 events are expected. BG level reduced by 33% while efficiency is similar to the previous analysis.

As a result, the evaluated 90% CL expected UL for BF is $5.3 \times 10^{-8}$.

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<tr>
<th></th>
<th>Previous</th>
<th>New analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lum.</td>
<td>545fb$^{-1}$</td>
<td>980fb$^{-1}$</td>
</tr>
<tr>
<td>Eff.</td>
<td>6.1%</td>
<td>6.5%</td>
</tr>
<tr>
<td>#BG</td>
<td>94</td>
<td>115</td>
</tr>
<tr>
<td>Expected UL</td>
<td>$7.8 \times 10^{-8}$</td>
<td>$5.3 \times 10^{-8}$</td>
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About x1.5 gain is obtained for expected UL while the sqrt. of increase for lum. is 1.3. Final result will be shown soon!
Upper Limits on $\tau$ LFV Decays

Reach upper limits around $10^{-8} \sim 100x$ more sensitive than CLEO
The remaining mode are $\tau \rightarrow \mu \gamma$ and $e \gamma$!

Previously, a 545 fb$^{-1}$ data subsample was analyzed.
Belle completed operation with a 1000fb$^{-1}$ data sample, which contains $\sim 10^9$ tau-pairs. This is the world’s largest $\tau$ data sample.

There are many kinds of $\tau$ LFV including lepton number (L) violation or violation of (B−L), i.e., baryon number − lepton number.

- $\tau \rightarrow \ell hh' : \tau \rightarrow \ell^- h^+ h^- \ (L \ cons.)$
- $\tau \rightarrow \Lambda h : \tau \rightarrow \Lambda h^- (B-L \ cons.)$
- $\tau \rightarrow \ell^+ h^- h^- \ (L \ viol.)$
- $\tau \rightarrow \Lambda h^- (B-L \ viol.)$

By adding more data and studying the dominant BGs and optimizing the analyses to suppress these BGs, we have significantly improved $\tau$ LFV upper limits.

$$\text{Br}(\tau \rightarrow \ell hh') < (2.0-8.4) \times 10^{-8} \quad \text{Br}(\tau \rightarrow \Lambda h) < (2.8-4.2) \times 10^{-8}$$

@90%CL

The most sensitive results for these modes. (preliminary)

Almost all $\tau$ LFV modes have been investigated with the 1000fb$^{-1}$ data sample. The last remaining ones are $\tau \rightarrow e\gamma/\mu\gamma$.

Search for $\tau \rightarrow e\gamma/\mu\gamma$ with the full data sample is on-going and the final result will be shown soon!
$\tau \rightarrow \mu \gamma$ vs $\mu \rightarrow e\gamma$

Lepton sector constraints in an SU(3)-flavored MSSM

SUSY GUT SU(5)+νR,non-- - degenerate νR(l),normal Hierarchy

Even if $\mu \rightarrow e\gamma$ has very small BF, some model predicts that $\tau \rightarrow \mu \gamma$ can have sufficiently large BF to observe it experimentally. ex.) SU(3)$^3$ symmetry in SUSY model: arXiv:1204.0688v1 [hep-ph]
In the CM frame, tau direction can be calculated from the charged tracks. This direction is compared with the reconstructed one from μ and γ.

Here, \( p_A (p_B) \) means 3-vector for μ (hadron) in CM frame and \( q_A (q_B) \) is a unit vector parallel to \( p_A (p_B) \).