Belle results on Lepton Flavor Violation in tau decays

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B-factory at KEK

KEKB: $e^+(3.5 \text{ GeV}) e^-(8 \text{GeV})$

$\sigma(\tau\tau) \sim 0.9 \text{nb}$, $\sigma(bb) \sim 1.1 \text{nb}$

A B-factory is also a $\tau$-factory!

Peak luminosity: $2.1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$

World highest luminosity!

Belle Detector:

Good track reconstruction and particle identifications

Lepton efficiency: 90%
Fake rate: $O(0.1)\%$ for $e$
$O(1)\%$ for $\mu$
Belle Luminosity history

Integrated luminosity: $>1000 \text{ fb}^{-1}$
$\Rightarrow \sim 10^9 \text{ BB and } \tau\text{-pairs}$

$> 1 \text{ ab}^{-1}$
On resonance:
$\Upsilon(5S): 121 \text{ fb}^{-1}$
$\Upsilon(4S): 711 \text{ fb}^{-1}$
$\Upsilon(3S): 3 \text{ fb}^{-1}$
$\Upsilon(2S): 24 \text{ fb}^{-1}$
$\Upsilon(1S): 6 \text{ fb}^{-1}$
Off reson./scan:
$\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$
On resonance:
$\Upsilon(4S): 433 \text{ fb}^{-1}$
$\Upsilon(3S): 30 \text{ fb}^{-1}$
$\Upsilon(2S): 14 \text{ fb}^{-1}$
Off resonance:
$\sim 54 \text{ fb}^{-1}$

Belle is finished in 2010/6/30. Belle-II upgrade started.
$\Rightarrow$ Analysis with full data sample is on going.
Lepton Flavor Violation in tau decay

SUSY is the most popular candidate among new physics models

- naturally induce LFV at one-loop due to slepton mixing

\[ \tau \rightarrow \ell \gamma \] mode has the largest branching fraction in SUSY-Seesaw (or SUSY-GUT) models

When sleptons are much heavier than weak scale

- LFV associated with a neutral Higgs boson (h/H/A)

Higgs coupling is proportional to mass

\[ \Rightarrow \mu \mu \text{ or } ss (\eta, \eta' \text{ and so on}) \] are favored and B.R. is enhanced more than that of \( \tau \rightarrow \mu \gamma \).

To distinguish which model is favored, all of decay modes are important.
Analysis procedure

- $e^+e^- \rightarrow \tau^+\tau^-$  
  1 prong + missing (tag side)  
  $\mu\mu\mu$ (signal side)

Fully reconstructed

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

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

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

Blind analysis $\Rightarrow$ Blind signal region

Estimate number of BG in the signal region using sideband data and MC

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
  - $e^-$ $\tau^-$ $e^+$
  - $\mu^-$ $\mu^+$ $\mu^-$
  - Neutrinos in both sides
  - Missing energy in signal side

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

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

**Radiative Bhabha Process**
- $e^+ e^- \rightarrow e^+ e^- + \gamma$
  - Many tracks
Analysis strategy

- Rare decay searches
  - Need to understand background and reduce as much as possible

- $\tau \rightarrow \ell\ell\ell$
- $\tau \rightarrow \ell K_s$
- $\tau \rightarrow \ell V^0 (\rightarrow hh')$
- $\tau \rightarrow \ell P^0 (\rightarrow \gamma\gamma)$
- $\tau \rightarrow \ell hh'$
- $\tau \rightarrow \ell \gamma$

- Analyze the modes from simple selection to hard for background reduction
  - Provide feedback to next analysis of similar final state
Search for $\tau \rightarrow 3$leptons

- Data: 782 fb$^{-1}$
- No event is found in the signal region.
- Almost BG free
  - Because of good lepton ID
- $\text{Br} < (1.5-2.7) \times 10^{-8}$ at 90% CL.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}^{\text{EXP}}$</th>
<th>$\sigma_{\text{syst}}$ (%)</th>
<th>UL ($\times 10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-e^+e^-$</td>
<td>6.0</td>
<td>0.21+$-0.15$</td>
<td>9.8</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-\mu^+\mu^-$</td>
<td>7.6</td>
<td>0.13+$-0.06$</td>
<td>7.4</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^-\mu^+\mu^-$</td>
<td>6.1</td>
<td>0.10+$-0.04$</td>
<td>9.5</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-e^+e^-$</td>
<td>9.3</td>
<td>0.04+$-0.04$</td>
<td>7.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mu^-e^+\mu^-$</td>
<td>10.1</td>
<td>0.02+$-0.02$</td>
<td>7.6</td>
<td>1.7</td>
</tr>
<tr>
<td>$e^-\mu^+e^-$</td>
<td>11.5</td>
<td>0.01+$-0.01$</td>
<td>7.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Search for $\ell V^0(=\rho^0, K^{*0}, \omega, \phi)$

- Search with 854 fb$^{-1}$ data sample
  - Select one lepton and two hadrons
  - Require invariant mass to be a vector meson mass
    $\Rightarrow$ The requirement reduces background rather easily.

- Possible background
  - For $\ell=\mu$, hadronic tau decay and qq with miss $\mu$-ID
  - For $\ell=e$, 2photon process could be large BG.
  - It turns out that not only 2photon process but also ee+X process become large background. $\Rightarrow$ Reduced using missing-momentum direction
Result for $\ell V^0(=\rho^0, K^0, \omega, \phi)$

After event selection
- 1 event $\mu\phi$, $\mu K^0$, $\mu K^0$
- 0 events others

No signal compared to expected BG

Expected number of background (0.1-1.5) events

$$\text{Br}(\tau \rightarrow \ell V^0) < (1.2-8.4) \times 10^{-8}$$

<table>
<thead>
<tr>
<th>$\tau^{-} \rightarrow \ell$</th>
<th>Eff. (%)</th>
<th>$N_{BG}^{\text{exp}}$</th>
<th>$N_{\text{obs.}}$</th>
<th>$N_{\text{UL}}^{\times 10^{-8}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{-}$ $\rho^0$</td>
<td>7.6%</td>
<td>$0.29 \pm 0.15$</td>
<td>0</td>
<td>$1.8$</td>
</tr>
<tr>
<td>$\mu^{-}$ $\rho^0$</td>
<td>7.1%</td>
<td>$1.48 \pm 0.35$</td>
<td>0</td>
<td>$1.2$</td>
</tr>
<tr>
<td>$e^{-}$ $\phi$</td>
<td>4.2%</td>
<td>$0.47 \pm 0.19$</td>
<td>0</td>
<td>$3.1$</td>
</tr>
<tr>
<td>$\mu^{-}$ $\phi$</td>
<td>3.2%</td>
<td>$0.06 \pm 0.06$</td>
<td>1</td>
<td>$8.4$</td>
</tr>
<tr>
<td>$e^{-}$ $\omega$</td>
<td>2.9%</td>
<td>$0.30 \pm 0.14$</td>
<td>0</td>
<td>$4.8$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\tau^{-} \rightarrow \ell$</th>
<th>Eff. (%)</th>
<th>$N_{BG}^{\text{exp}}$</th>
<th>$N_{\text{obs.}}$</th>
<th>$N_{\text{UL}}^{\times 10^{-8}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{-}$ $K^*$</td>
<td>4.4%</td>
<td>$0.39 \pm 0.14$</td>
<td>0</td>
<td>$3.2$</td>
</tr>
<tr>
<td>$\mu^{-}$ $K^*$</td>
<td>3.4%</td>
<td>$0.53 \pm 0.20$</td>
<td>1</td>
<td>$7.2$</td>
</tr>
<tr>
<td>$e^{-}$ $K^*$</td>
<td>4.4%</td>
<td>$0.08 \pm 0.08$</td>
<td>0</td>
<td>$3.4$</td>
</tr>
<tr>
<td>$\mu^{-}$ $K^*$</td>
<td>3.6%</td>
<td>$0.45 \pm 0.17$</td>
<td>1</td>
<td>$7.0$</td>
</tr>
<tr>
<td>$\mu^{-}$ $\omega$</td>
<td>2.4%</td>
<td>$0.72 \pm 0.18$</td>
<td>0</td>
<td>$4.7$</td>
</tr>
</tbody>
</table>

Search for $\ell hh'$

- 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.
In the signal region

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

Set upper limits at 90%CL:
$\text{Br}(\tau \to \ell hh') < (2.0-8.6) \times 10^{-8}$
(preliminary)
Upper limits on LFV $\tau$ decays

90\% C.L. Upper limits for LFV $\tau$ decays

Updated this summer

Under studying with full data sample
Effect to physics models

- Experimental results have already ruled out some parts of the parameter space.
  - Exclude large $\tan\beta$, small SUSY/Higgs mass

<table>
<thead>
<tr>
<th>Model</th>
<th>reference</th>
<th>$\tau \to \mu\gamma$</th>
<th>$\tau \to \mu\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM+ $\nu$ mixing</td>
<td>PRD45(1980)1908, EPJ C8(1999)513</td>
<td>Undetectable</td>
<td></td>
</tr>
<tr>
<td>SM + heavy Maj $\nu_R$</td>
<td>PRD 66(2002)034008</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-universal Z’</td>
<td>PLB 547(2002)252</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>PRD 68(2003)033012</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>mSUGRA+seesaw</td>
<td>PRD 66(2002)115013</td>
<td>$10^{-7}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>PLB 566(2003)217</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

- Accessing other models and other parameter space
• Belle-II will produce >$10^{10}$ tau leptons.
• Sensitivity depends on BG level.
  – Recent improvement of the analysis
    (BG understanding, intelligent selection)
  → Improve achievable sensitivity
• $B(\tau \to \mu\mu\mu) \sim O(10^{-10})$ at 50ab$^{-1}$
  – Improvement of BG reduction is important.
    • Beam BG
    • Signal resolution
• Search for LFV $\tau$ decays using $\sim 10^9 \tau$ decays
  – 48 modes have been investigated.
• **No evidence** is observed yet.
• Upper limits on branching ratio around $O(10^{-8})$
  – $B(\tau \rightarrow \mu \mu \mu) < 2.1 \times 10^{-8}$, $Br(\tau \rightarrow \mu \nu^0) < (1.2-8.4) \times 10^{-8}$
  – $B(\tau \rightarrow \mu h h') < (2.1-8.6) \times 10^{-8}$, $Br(\tau \rightarrow \Lambda h) < (2.8-4.2) \times 10^{-8}$ etc.
  – Exploring some new-physics parameters space.

• Update $\tau \rightarrow \mu \gamma/e\gamma$ with full data sample ($\sim 1000 fb^{-1}$)
• Optimization for BG reduction is important for future experiment
  – Belle-II try to obtain the sensitivity of $O(10^{-9\sim10})$. 
Result for $\tau \rightarrow J P^0 (=\pi^0, \eta, \eta')$

$(2.1-4.4)$ times more stringent results than previous Belle result $(401 fb^{-1})$

<table>
<thead>
<tr>
<th>$\tau \rightarrow$</th>
<th>Eff. %</th>
<th>$N_{BG}^{exp}$</th>
<th>$N_{obs}$</th>
<th>UL x10$^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\eta'(\rightarrow \pi\pi\eta)$</td>
<td>8.1%</td>
<td>0.00$^{+0.16}_{-0.00}$</td>
<td>0</td>
<td>10.0</td>
</tr>
<tr>
<td>$\mu\eta'(\rightarrow \rho^0\gamma)$</td>
<td>6.2%</td>
<td>0.59$^{+0.41}_{-0.00}$</td>
<td>0</td>
<td>6.6</td>
</tr>
<tr>
<td>$\mu\eta'(\text{comb.})$</td>
<td></td>
<td></td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>$\eta'(\rightarrow \pi\pi\eta)$</td>
<td>7.3%</td>
<td>0.63$^{+0.45}_{-0.00}$</td>
<td>0</td>
<td>9.4</td>
</tr>
<tr>
<td>$\eta'(\rightarrow \rho^0\gamma)$</td>
<td>7.5%</td>
<td>0.29$^{+0.29}_{-0.00}$</td>
<td>0</td>
<td>6.8</td>
</tr>
<tr>
<td>$\eta'(\text{comb.})$</td>
<td></td>
<td></td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>$\mu\pi^0(\rightarrow \gamma\gamma)$</td>
<td>4.2%</td>
<td>0.64$^{+0.32}_{-0.00}$</td>
<td>0</td>
<td>2.7</td>
</tr>
<tr>
<td>$e\pi^0(\rightarrow \gamma\gamma)$</td>
<td>4.7%</td>
<td>0.89$^{+0.40}_{-0.00}$</td>
<td>0</td>
<td>2.2</td>
</tr>
</tbody>
</table>
eK*, eK*, ep modes

Other BG for eK*, eK* and ep
⇒ Event with γ conversion

For example, eK* mode

\[ \tau^- \rightarrow \pi^- \pi^0 \nu \]

with γ conversion from π^0

Require large invariant mass of e^+e^- candidate, to reduce the BG

data γ-conversion
generic ττ MC

eK* MC

overlap dE/dx region between e and K

Fake K* as miss KID

\[ e^- \rightarrow \pi^- \pi^0 \]

\[ \gamma \rightarrow \nu \pi \]

\[ \text{Mee with } e^- K^+ \text{ MC} \]
4 modes are searched for. (h=\(\pi\) and K)
- \(\tau^- \rightarrow \Lambda h^-\): (L-B) conserving decay
- \(\tau^- \rightarrow \Lambda h^-\): (L-B) violating decay

Current upper limits (no search for \(\Lambda K\) on Belle)
- Belle \(Br < (7.2-14) \times 10^{-8} @ 154 fb^{-1}\)
- BaBar \(Br < (5.8-15) \times 10^{-8} @ 237 fb^{-1}\)

update with 906 fb\(^{-1}\) @ Belle
BG rejection for $\Lambda h$

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

A half of $K_s^0$ BG events are rejected.

To reduce $q\bar{q}$ BG including $\Lambda$
⇒ 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.
Results of $\Lambda h$

(preliminary)

In the signal region

no candidate event are found

$\Rightarrow$ no significant excess

<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>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.80 ± 0.15</td>
<td>8.2</td>
<td></td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.39 ± 0.18</td>
<td>8.2</td>
<td></td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda K^-$</td>
<td>4.11 ± 0.14</td>
<td>8.6</td>
<td></td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda K^-$</td>
<td>3.16 ± 0.19</td>
<td>8.6</td>
<td></td>
<td>0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Set upper limits@90%CL:

$\text{Br}(\tau^- \rightarrow \Lambda \pi^-) < 2.8 \times 10^{-8}$ (L-V) cons.
$\text{Br}(\tau^- \rightarrow \Lambda K^-) < 3.1 \times 10^{-8}$ (L-V) viol.
$\text{Br}(\tau^- \rightarrow \Lambda \pi^-) < 3.0 \times 10^{-8}$
$\text{Br}(\tau^- \rightarrow \Lambda K^-) < 4.2 \times 10^{-8}$

Around x(2–3) improvement from the previous BaBar results