Precision measurements from Belle and Lepton Flavor-violating decay prospects at SuperKEKB/Belle II

K.Inami (Nagoya univ.)
For Belle/Belle-II collaboration
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In the Standard Model, LFV is highly suppressed. Impossible to access; $\text{Br} < O(10^{-54})$

Many extensions of the SM predict LFV decays. Their branching fractions are enhanced as high as current experimental sensitivity

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

**Tau lepton**: the heaviest charged lepton
- Opens many possible LFV decay modes which depend on NP models

- SUSY
- Higgs-mediation LFV
- R-parity violation
Previous B-factory at KEK

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

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

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

Peak luminosity: $2.1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

World highest luminosity!

Belle Detector:

Good track reconstruction and particle identifications

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

Collected $\sim 10^9 \tau$ pairs
Analysis procedure

\[ e^+ e^- \rightarrow \tau^+ \tau^- \]

\( \text{Br} \sim 85\% \)

\( \rightarrow 1 \) prong + missing (tag side)

\( \rightarrow \mu \mu \mu \) (signal side)

Fully reconstructed

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

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

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

Estimate number of BG in the signal region using sideband data and MC
Search for $\tau \to 3$leptons at Belle

- Data: $\sim 7 \times 10^8 \tau \tau$
- No event is found in the signal region.
- $\mathrm{Br} < (1.5 - 2.7) \times 10^{-8}$ at 90% CL.

- Almost BG free
  - Because of good lepton ID

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}^{\text{EXP}}$</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>2.7</td>
</tr>
<tr>
<td>$\mu^-\mu^+\mu^-$</td>
<td>7.6</td>
<td>0.13+0.06</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^-\mu^+\mu^-$</td>
<td>6.1</td>
<td>0.10+0.04</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-e^+e^-$</td>
<td>9.3</td>
<td>0.04+0.04</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mu^-e^+\mu^-$</td>
<td>10.1</td>
<td>0.02+0.02</td>
<td>1.7</td>
</tr>
<tr>
<td>$e^-\mu^+e^-$</td>
<td>11.5</td>
<td>0.01+0.01</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Ex.) LHCb; Phys. Lett. B724 (2013) 36 $\mathrm{Br}(\tau \to \mu \mu \mu) < 8.0 \times 10^{-8}$ but seeing background in the fit.
• Data; $\sim 4.8 \times 10^8 \tau \tau$
  \[ \tau \rightarrow \mu \gamma \]
  \[ \tau \rightarrow e \gamma \]

  - $\text{Br} < 4.5 \times 10^{-8}$ at 90\% C.L.
  - $\text{Br} < 1.2 \times 10^{-7}$ at 90\% C.L.

■ Dominant background
  \[ e^+ e^- \rightarrow \tau^+ \tau^- \gamma , \tau \rightarrow \mu \nu \nu \]
  (Initial state radiation + normal tau decay)
Belle, Babar and LHCb reaching \( O(10^{-8}) \) branching ratio.

- \( \tau \rightarrow 3 \text{ leptons, l+mesons (to charged particles)} \) show better sensitivity because of less background, compared to \( \tau \rightarrow l \gamma \).
Belle II experiment

EM Calorimeter
CsI(Tl), waveform sampling

K_L and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner barrel layers)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Target integrated luminosity = 50ab^{-1} ➔ \sim 5 \times 10^{10} \tau \text{ pairs}

Further information
DEPFET: L. Andricek, Poster Aug 08 18:30
SVD: A. Paladino, Detector Aug 04 17:00
CsI: Y. Jin, Poster Aug 06 18:00
PID: A. Schwartz, Detector Aug 06 14:30
PID: K. Inami, Poster Aug 06 18:00
CPU: M. Schram, Computing Aug 04 12:50

• Belle II will collect $N_{\tau\tau} > 10^{10}$

• Branching ratio sensitivity vs. Integrated luminosity
  
  - $\tau \rightarrow \mu \gamma$, $e\gamma$; $\propto \frac{1}{\sqrt{L}}$ 
    - Irreducible background; $e^+e^- \rightarrow \tau^+\tau^-\gamma$
  
  - $\tau \rightarrow \ell\ell\ell$, $\ell\chi^0$; $\propto \frac{1}{L}$
    - Negligible background by particle ID and mass restriction

• **Important for background reduction (S/N improvement)**

Signal MC by Belle simulation

S/N can improve, if $E_\gamma$ resolution improves.

++ Less material before EM calorimeter.

?? Gamma energy resolution in high beam BG.
Future prospects at Belle II

• Sensitivity depends on BG level.
  – Recent improvement of the analysis
    (BG understanding, intelligent selection)
  → Improve achievable sensitivity

• $B(\tau \rightarrow \mu \mu \mu) \sim O(10^{-10})$
  at 50ab$^{-1}$
  – Improvement of BG reduction is important.
  • Beam BG
  • Signal resolution
### Experimental reach

- **Limiting parameter space of new physics models**
  - Reached the region of large $\tan\beta$ and small SUSY/Higgs mass

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>$\tau \rightarrow \mu \gamma$</th>
<th>$\tau \rightarrow \mu \mu \mu$</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>
Summary

- Previous Belle experiment reached $O(10^{-8})$ branching ratio sensitivity, using $\sim 10^9$ $\tau$ pair events.
- Belle II experiment will start soon and collect $\sim 5 \times 10^{10}$ $\tau$ pairs.
  - LFV sensitivity depends on the statistics.
  - The slope is different due to the background condition.
  - The background free modes, such as $\tau \rightarrow 3$ leptons, can be reached to $O(10^{-10})$ branching ratio sensitivity.
  - $\tau \rightarrow l+\gamma$ modes will be $O(10^{-9})$, highly depends on the background situation.
    - Detector resolution can improve the sensitivity, but the beam background may be an issue.

Stay tuned!
Luminosity history at Belle

Belle is finished in 2010/6/30. Belle-II upgrade started. → Analysis with full data sample is on going.

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 resonance/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:
$\sim 54 \text{ fb}^{-1}$

• SYSY seesaw [arXiv:hep-ex/0406071]
SuperKEKB

Colliding bunches

New superconducting/permanent final focusing quads near the IP

Replace short dipoles with longer ones (LER)

Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

Low emittance positrons to inject

Damping ring

Low emittance electrons to inject

Low emittance gun

Add / modify RF systems for higher beam current

New positron target / capture section

Target: $L = 8 \times 10^{35} / \text{cm}^2 / \text{s}$
LFV $\tau$ decays; Signal and Background

- $e^+e^- \rightarrow \tau^+ \tau^-$
  - 1 prong tau decay (BR~85%)

**Signal**
- Neutrinos in both side
- Missing energy in signal side

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

**2-photon process**
- $f=\text{leptons, quarks}$
- $e^- \rightarrow \gamma \rightarrow f, \bar{f}$

**Radiative Bhabha process**
- $e^+ e^- \rightarrow e^+ e^-$
  - many tracks
Optimization of event selection

Sensitivity depends on BG level and signal efficiency.

To state 99% C.L. evidence
- Need 2 events for $N_{BG} \sim 0.1$
- Need 4 events for $N_{BG} \sim 0.5$
→ Diff. of effective efficiency is 2.

Unless the efficiency drops significantly, we set the criteria to reduce $N_{BG}$ as much as possible.

Number of observed events, $N_{99}^{\text{obs.}}$, which we need for 99% CL evidence, as a function of expected BG, $N_{BG}$
• Data: 470fb\(^{-1}\)+31fb\(^{-1}\) @ Y(3S)+15fb\(^{-1}\) @ Y(2S)
  – (963 ± 7)x10\(^{6}\) \(\tau\) decays

• New kinematical cuts
  + Neural Net discri.
  \(\rightarrow\) Improve S/N

• Dominant BG:
  \(\tau \rightarrow l\nu\nu +\) radiation
  (irreducible BG)

• \(B(\tau \rightarrow \mu\gamma)<4.4\times10^{-8}\)
• \(B(\tau \rightarrow e\gamma)<3.3\times10^{-8}\)
SUSY is the most popular candidate among new physics models naturally induce LFV at one-loop due to slepton mixing.

\[ \tau \rightarrow l \gamma \] 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:

\[ \mu \mu \text{ or } ss \] (\( \eta, \eta' \) 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.
- LFV through slepton mixing

\[
\begin{align*}
\tau & \xrightarrow{\tilde{\chi}^0} \mu \\
\tau & \xrightarrow{\tilde{\chi}^-} \mu
\end{align*}
\]

- Independent parameter from $\mu \to e\gamma$

- SUSY seesaw (J. Hisano et al., PRD 60 (1999) 055008)

\[
\mathcal{B}(\tau \to \mu \gamma) \simeq 3.0 \times 10^{-7} \left( \frac{\tan \beta}{60} \right)^2 \left( \frac{1 \text{ TeV}/c^2}{m_{\text{SUSY}}} \right)^4
\]

- Achievable BR, if $\tan \beta \sim 60$, $m_{\text{SUSY}} \sim 1 \text{TeV}/c^2$
- Suppressed, if slepton is heavier than weak scale
• Higgs-mediated MSSM
  - $\tau \rightarrow 3\mu$ (A.Brignole, A.Rossi, PLB 566 (2003) 217)
    $$B(\tau \rightarrow 3\mu) \sim 10^{-7} \left( \frac{\tan \beta}{50} \right)^6 \left( \frac{100 \text{ GeV}/c^2}{m_A} \right)^4 \left( \frac{|50 \Delta_L|^2 + |50 \Delta_R|^2}{10^{-3}} \right)$$
  - $\tau \rightarrow \mu \eta$ (M.Sher, PRD 66 (2002) 057301)
    $$B(\tau \rightarrow \mu \eta) \simeq 8.4 \times 10^{-7} \left( \frac{\tan \beta}{60} \right)^6 \left( \frac{100 \text{ GeV}/c^2}{m_A} \right)^4$$
    - Accessible if, large $\tan \beta$ and small Higgs mass

• MSSM seesaw (E.Arganda, arXiv:0803.2039v1)
  - Br of $\tau \rightarrow \mu \eta, \mu \eta', \mu K^+K^-$; O(10$^{-7}$)