Charged LFV searches at Belle II
with a brief review of Belle results

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For Belle II collaboration at WIN2017, Jun.19-24, 2017
Belle works on LFV, LNV, LUV

- charged LFV, LNV
  - $D^0 \to e^\pm \mu^\mp$
  - $B^0 \to e^\pm \mu^\mp$
  - $B \to K^{(*)} e^\pm \mu^\mp$
  - $B^+ \to D^- \ell^+ \ell'^+$
  - $\tau$ LFV, LNV decays

  This talk!

- charged LUV
  - $R(D), R(D^*)$
  - $B \to K^{(*)} e^+ e^- \text{ vs. } K^{(*)} \mu^+ \mu^-$

PRL 118, 111801 (2017)

3 Belle papers since 2015

PRD 81, 091102(R) (2010)
PRD 84, 071106(R) (2011)
on-going
Outline

Intro. & Motivation

• why LFV in \( \tau \) ?
• how to study \( \tau \) decays @ \( e^+e^- B \)-factory

\( \tau \) LFV (LNV) search results at Belle (reporting just a few)

• \( \tau^+ \rightarrow \ell^+\gamma \) and current status
  \[ \text{PLB 666, 16 (2008)} \]
• \( \tau^+ \rightarrow \ell_1^+\ell_2^-\ell_3^+ \)
  \[ \text{PLB 687, 139 (2010)} \]
• \( \tau^+ \rightarrow \ell^+h^-h'^+ \) and \( \ell^-h^+h'^+ \)
  \[ \text{PLB 719, 346 (2013)} \]

Belle II prospects

• MC study of \( \tau \rightarrow \mu\gamma \)
• other LFV, LFUV @ Belle II
New physics (NP) searches with $\tau$

- the $\tau$ lepton
  - the heaviest charged lepton
  - highly sensitive to NP

Unique lab to look for NP

- LFV
- EDM, $g$-2, CPV
- $B$ ($D$) decays to $\tau$
- BNV, too ($m_\tau > m_\Lambda, m_p, \ldots$)
Lepton-flavor-violating (LFV) $\tau$ decay

In the Standard Model with non-zero $\nu$ mass, $\tau$ LFV can happen, but the rate is really tiny.

$$B(\tau \to l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\tau i}^* U_{\mu i} \frac{\Delta_{3i}^2}{m_W^2} \right|^2 \leq 10^{-53} \sim 10^{-49}$$

However, in many new physics models it can become large enough to be within sensitivity of Belle (or Belle-II)

- For example, with SUSY-GUT,

Calibbi et al., PRD 74, 116002 (2006)

$$B(\tau \to \mu\gamma) \simeq (4.5 \times 10^{-6}) |(\delta_{LL})_{32}|^2 \left( \frac{500 \text{ GeV}}{m_{\text{SUSY}}} \right)^4 \left( \frac{\tan \beta}{10} \right)^2$$

- For $(\delta_{LL})_{32}$, not determined in generic SUSY, need to specify models.
**τ LFV in new physics beyond-SM**

Predicted in many theoretical models

Sensitivity of various channels to cLFV is model-dependent → discriminate theories by comparing branching ratios and spectra across multiple modes

<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+ $v$ oscillations</td>
<td>EPJ C8 (1999) 513</td>
<td>$10^{-40}$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>SM+ heavy Maj $v_R$</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>

Flavor-violation studies constrain SUSY breaking. Neutral K meson mixing and give stringent constraints on the SUSY breaking terms.

Proposals to SUSY flavor problem:

1) Universal scalar mass hypothesis: Supergravity, Gauge mediation, Anomaly mediation, etc.

2) Alignment hypothesis:

3) Decoupling hypothesis: Charged-LFV searches may probe pattern of SUSY breaking and constrain origin of SUSY breaking.
\section*{τ\textsuperscript{−} LFV in new physics beyond-SM}

Ratios of $\tau$ LFV decay’s BF’s allow one to discriminate between new physics models

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
 & SUSY+GUT \hspace{1cm} & Higgs mediated \hspace{1cm} & Little Higgs \hspace{1cm} & non-universal $Z'$ \\
 & (SUSY+Seesaw) \hspace{1cm} & \hspace{1cm} & \hspace{1cm} & \hspace{1cm} \\
\hline
$\frac{\mathcal{B}(\tau \to \mu \mu \mu)}{\mathcal{B}(\tau \to \mu \gamma)}$ & $\sim 2 \times 10^{-3}$ & 0.06 - 0.1 & 0.4 - 2.3 & $\sim 16$ \\
\hline
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu \gamma)}$ & $\sim 1 \times 10^{-2}$ & $\sim 1 \times 10^{-2}$ & 0.3 - 1.6 & $\sim 16$ \\
\hline
$\mathcal{B}(\tau \to \mu \gamma)_{\text{max}}$ & $< 10^{-7}$ & $< 10^{-10}$ & $< 10^{-10}$ & $< 10^{-9}$ \\
\hline
\end{tabular}
\end{table}

\textbf{:. Good to measure LFV in as many modes as possible!}

JHEP 0705, 013 (2007); PLB 547, 252 (2002)
KEKB & Belle

20 countries
90 institutions
~450 members

$\mathcal{L}_{\text{peak}} = 21.1 \text{ nb}^{-1} \text{s}^{-1}$

$e^- \rightarrow (\star) \rightarrow e^+$

$8 \text{ GeV} \rightarrow 3.5 \text{ GeV}$
The Belle experiment

- played critical role (along with BaBar) in verifying the KM hypothesis with CP violations in $B$ mesons; recognized and cited by the Nobel Foundation
- made a series of first observations of electroweak penguin $B$ decays
- discovered mixing in charm mesons
- discovered a series of exotic hadron states, e.g. $X(3872)$, $Z(4430)^+$, $Z_b(10610)^+$, etc.

...
**Studying $\tau$ LFV @ e+e- B-factory**

- **hermeticity** of Belle (and Belle II) helps greatly!
- efficient $\tau$-tagging, with minimal trigger bias
Studying $\tau$ LFV @ e+e- B-factory

- $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = (0.919 \pm 0.003) \text{ nb} \approx \sigma_{b\bar{b}}$, at $\sqrt{s} \approx 10.58$ GeV

$\therefore e^+e^-$ B-factory is, at the same time, a $\tau$-factory, too!

- tag-side and signal-side $\tau$ decays are cleanly separated

- signal extraction by $M_{\text{sig}}$ and $\Delta E$

\[ M_{\text{sig}} \sim m_\tau \]

\[ \Delta E = E_{\text{sig}}^* - E_{\text{beam}}^* \]

Signal Extraction

- Blind analysis $\Rightarrow$ Blind signal region
- Estimate BG level: sideband data and MC
- Signal extraction: UEML fit/counting on the $M_{\text{mg}} - E$ plane.
- If no excess: set upper limits @ 90%CL

$\text{UEML} = \text{Unbinned Extended Maximum Likelihood fit}$
\( \tau \) LFV signal & background signatures

**Signal**
- Signal side
  - Neutrinos in both side
  - Missing energy in signal side
  - Particle ID
  - Mass of mesons

**Tag side**
- Neutrino(s) in tag side

**qq**
- Many tracks and photons

**2 photon process**
- \( f = \text{leptons, quarks} \)

**Radiative Bhabha process**
- \( e^+ e^- \)

From K. Hayasaka @ Tau 2014
$\tau^+ \rightarrow \ell^+ \gamma$

**Motivations**

- There exists very stringent bound from $\mu \rightarrow e \gamma$,
- but, $\mu \rightarrow e \gamma$ alone will not provide enough info. to nail down the LFV mechanism
- many NP models predict sizable ($O(10^{-7} \sim 10^{-8})$) $BF(\tau \rightarrow \ell \gamma)$$$
- moreover, the $BF$'s of many LFV modes are correlated differently on different hypotheses

**Figure 5.51:** Scatter plot of $\mu \rightarrow e \gamma$ vs. $\tau \rightarrow \mu \gamma$ at $\tan \beta = 40$

$BR(\tau \rightarrow \ell \gamma) \cdot 10^{\gamma}$

$BR(\mu \rightarrow e \gamma) \cdot 10^{11}$

Calibbi et al.,
PRD 74, 116002 (2006)
Procedures

• 535 fb\(^{-1}\) sample with 4.77x10\(^8\) \(\tau^+\tau^-\) events
• generic \(\tau^+\tau^-\) events are suppressed by 2D \(p_{\text{miss}}\) vs. \(m^2_{\text{miss}}\) cut

Irreducible background
• \(\tau \rightarrow \ell \nu \nu\) with ISR

\[
\begin{align*}
\tau^+ &\rightarrow \ell^+ \gamma \\
\end{align*}
\]
$$\tau^+ \rightarrow \ell^+ \gamma$$

- **Signal extraction**
  - by unbinned extended max. lik. fit to $\Delta E$ vs. $M_{\text{inv}}$

- **$\Delta E$ & $M_{\text{inv}}$ as main variables**
  - $\pm 5\sigma$ for background estimation
  - $\pm 3\sigma$ ellipse: blinded
  - $\pm 2\sigma$ ellipse: for signal counting

- **Results**
  - $\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) < 4.5 \times 10^{-8}$ at 90% CL
  - $\mathcal{B}(\tau^- \rightarrow e^- \gamma) < 12.0 \times 10^{-8}$

\[
\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) < 4.5 \times 10^{-8} \quad \text{at } 90\% \text{ CL}
\]

\[
\mathcal{B}(\tau^- \rightarrow e^- \gamma) < 12.0 \times 10^{-8}
\]
$\tau^+ \rightarrow \ell^+ \gamma$

a signal candidate
\( \tau^+ \rightarrow \ell^+ \ell^- \ell^+ \)

**Event selection** \( \int \mathcal{L} dt = 782 \text{ fb}^{-1} \)

- 1-vs-3 event topology
- two hemispheres: “signal” side and “tag” side
- \( \vec{p}_{\text{miss}} \) within the tag side & \( p_{\text{miss}} > 0.4 \text{ GeV/c} \)
- use **thrust** for \( q\bar{q} \) suppression
- \( \gamma \rightarrow e^+e^- \) veto: \( M_{ee} > 0.2 \text{ GeV/c}^2 \)
- generic \( \tau^+\tau^- \) event suppression by 2D cut on \( p_{\text{miss}} \)-vs.-\( m_{\text{miss}}^2 \)

**\( \Delta E \) & \( M_{3\ell} \) as main variables**

- \( \pm 20\sigma \) for analysis
- blinded analysis
- background estimation in the \( M_{3\ell} \) side-band
Elliptical signal region was blinded
\ \tau^+ \rightarrow \ell^+ \ell^- \ell^+

Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>\varepsilon (%)</th>
<th>N_{BG}</th>
<th>\sigma_{syst} (%)</th>
<th>N_{obs}</th>
<th>\mathcal{B} (\times 10^{-8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>\tau^- \rightarrow e^-e^+e^-</td>
<td>6.0</td>
<td>0.21 ± 0.15</td>
<td>9.8</td>
<td>0</td>
<td>&lt; 2.7</td>
</tr>
<tr>
<td>\tau^- \rightarrow \mu^-\mu^+\mu^-</td>
<td>7.6</td>
<td>0.13 ± 0.06</td>
<td>7.4</td>
<td>0</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td>\tau^- \rightarrow e^-\mu^+\mu^-</td>
<td>6.1</td>
<td>0.10 ± 0.04</td>
<td>9.5</td>
<td>0</td>
<td>&lt; 2.7</td>
</tr>
<tr>
<td>\tau^- \rightarrow \mu^-e^+e^-</td>
<td>9.3</td>
<td>0.04 ± 0.04</td>
<td>7.8</td>
<td>0</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>\tau^- \rightarrow e^+\mu^-\mu^-</td>
<td>10.1</td>
<td>0.02 ± 0.02</td>
<td>7.6</td>
<td>0</td>
<td>&lt; 1.7</td>
</tr>
<tr>
<td>\tau^- \rightarrow \mu^+e^-e^-</td>
<td>11.5</td>
<td>0.01 ± 0.01</td>
<td>7.7</td>
<td>0</td>
<td>&lt; 1.5</td>
</tr>
</tbody>
</table>

\mathcal{B}(\tau^- \rightarrow \ell^-\ell^+\ell^-) < \frac{S_{90}}{2N_{\tau\tau \varepsilon}}

N_{\tau\tau} = 719 \times 10^6
\( \tau^+ \rightarrow \ell^+ h^- h'^+ \) and \( \ell^- h^+ h'^+ \) (\( h = \pi, K \))

\[ \Delta E (\text{GeV}) \]

\[ M_{\mu\pi} (\text{GeV}/c^2) \]

\[ M_{\mu\pi} (\text{GeV}/c^2) \]

\[ M_{\mu K K} (\text{GeV}/c^2) \]

\[ M_{\mu K K} (\text{GeV}/c^2) \]

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\[ M_{\mu K K} (\text{GeV}/c^2) \]
$\tau^+ \rightarrow \ell^+ h^- h'^+ \text{ and } \ell^- h^+ h'^+$

<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>$B \times 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^- \pi^+ \pi^-$</td>
<td>5.83</td>
<td>0.63 ± 0.23</td>
<td>5.7</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>5.6</td>
<td>1</td>
<td>4.01</td>
<td>3.9</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- \pi^+ \pi^-$</td>
<td>5.45</td>
<td>0.55 ± 0.23</td>
<td>5.7</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 ± 0.19</td>
<td>5.5</td>
<td>0</td>
<td>2.10</td>
<td>2.0</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- K^+ K^-$</td>
<td>2.85</td>
<td>0.51 ± 0.19</td>
<td>6.1</td>
<td>0</td>
<td>1.97</td>
<td>4.4</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+ K^- K^-$</td>
<td>2.98</td>
<td>0.25 ± 0.13</td>
<td>6.2</td>
<td>0</td>
<td>2.21</td>
<td>4.7</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- K^+ K^-$</td>
<td>4.29</td>
<td>0.17 ± 0.10</td>
<td>6.7</td>
<td>0</td>
<td>2.29</td>
<td>3.4</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^+ K^- K^-$</td>
<td>4.64</td>
<td>0.06 ± 0.06</td>
<td>6.5</td>
<td>0</td>
<td>2.39</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \pi^+ K^-$</td>
<td>2.72</td>
<td>0.72 ± 0.28</td>
<td>6.2</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>6.4</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>5.7</td>
<td>0</td>
<td>1.86</td>
<td>4.5</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- K^+ \pi^-$</td>
<td>4.07</td>
<td>0.55 ± 0.31</td>
<td>6.2</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>6.1</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>6.2</td>
<td>0</td>
<td>2.03</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Next step: Luminosity upgrade
SuperKEKB & Belle II

\[ e^- \rightarrow (\ast) \rightarrow e^+ \]

\[ L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]

\[ \int \mathcal{L} \, dt = 50 \text{ ab}^{-1} \]
Challenges & responses for Belle II

Severe beam background
• due to $\times 40$ increase in $L_{\text{peak}}$
• fine segmentation and fast readout $\Rightarrow$ reduce occupancy
• replace detector components

Some big changes
• vertex: SVD (4 layers) $\Rightarrow$ PXD (2) + SVD (4)
• hadron identification: binary Cherenkov $\Rightarrow$ iTOP ("imaging Time-of-Propagation")
**Vertexing for Belle II**

**SVD**
- 4 layers of DSSD
- \( r = 3.8, 8.0, 11.5, 14.0 \) (cm)
- \( L = 60 \) cm

**PXD (pixel detector)**
- 2 layers of DEPFET
- \( r = 1.4, 2.2 \) (cm)
- \( L = 12 \) cm

**Graph**
- \( \sigma_z(\mu m) \)
- \( p\beta\sin(\theta) \) [GeV/c]
- PXD+SVD
- Belle
- Belle II
hadron ID for Belle II

512 Hamamatsu 4 x 4 MCP-PMT

TOP test beam data
Challenges & responses: ECL
Challenges & responses: ECL

- ECL is essential for $\gamma$ and $e^\pm$ detection
  - hence indispensable for $\tau$ LFV ($\tau^\pm \rightarrow e^\pm \gamma$, $\ell^\pm \ell^\pm \ell^-$ etc.)

- Belle ECL
  - CsI(Tl) crystals with PIN photodiode

- Belle II ECL
  - upgrade is needed due to higher rates & radiation load
  - waveform sampling in new readout electronics
    - timing resolution $< 4.5$ ns in cosmic-ray test of barrel ECL
  - use of pure-CsI for endcap crystals being considered
Belle II ECL performances (TB)

- Energy resolution
- Timing resolution
- Pile-up noise suppression w/ new electronics
Challenges & responses: KLM
Challenges & responses: KLM

KLM is essential for $\mu^\pm$ detection
  • hence indispensable for $\tau$ LFV ($\tau^\pm \rightarrow \mu^\pm \gamma$, $\ell^\pm \ell^+ \ell^-$ etc.)

Belle KLM
  • alternating layers of iron plates (partly for flux return) and RPC

Belle II KLM
  • Belle’s RPC system cannot handle high background rates
  • all RPC’s in endcaps and 2 innermost barrel layers are replaced with scintillators
  • readout electronic under production (will be ready by summer 2017)
Scintillator-KLM (Belle II)

Mirror

track

Reflective coating

Reflective tape

Optical glue

SiPM-fiber connector

scintillator light

green light

WLS fiber

600–3000

40

7–10

Iron plate

y-strip plane

x-strip plane
$\tau \rightarrow \mu \gamma$ in Belle II (MC study)

- Sensitivity study using Belle II MC incl. beam background simulation
  - MS thesis work by B. Moore (U. Melbourne)
  - For sensitivity comparison with Belle (with $\int \mathcal{L} \, dt = 1 \, \text{ab}^{-1}$)

Background rejection by

- Event shape variables — thrust, Fox-Wolfram moments, momentum flow distributions (“CLEO cones”), etc.

Signal extraction by $(\Delta E, M_{\text{inv}})$

$$T = \max \frac{\sum_{i=1}^{N} |T \cdot p_i|}{\sum_{i=1}^{N} |p_i|}$$
After selection, we are left with a far reduced number of background events and a non-zero amount of expected signal events. We can now analyse events within the signal region. This is an example of $E$ vs $M_{\text{inv}}$ space, with $0.4 < E < 0.2$ and $1.65 < M_{\text{inv}} < 1.85$.

$E$ and $M_{\text{inv}}$ are fit with asymmetric Gaussians to determine mean and $\sigma E \approx 47 \text{ MeV}$ and $M_{\text{inv}} \approx 1.79 \text{ GeV}/c^2$; this is consistent with our expectation of $E \approx 0$ and $M_{\text{inv}} \approx m_\tau$. The signal region is shown in Figure 8.1, with signal and background MC distributions overlayed.

In the entire signal region we find 6 $\tau \rightarrow \mu \gamma$ events, and 163 $\tau \rightarrow \mu \nu \nu$ events, 40 $\tau \rightarrow \mu \nu\nu$ events, 15 $e^+e^- \rightarrow \mu^+\mu^-$ events, 3 $e^+e^- \rightarrow u\bar{u}$ events, and 3 $e^+e^- \rightarrow d\bar{d}$ events. This totals to 6 signal events and 232 background events. We then produce a rotated plot to decorrelate the x- and y-axes. In this plot we set an elliptical region of phase space centred near the means for $M_{\text{inv}}$ and $E$.

The selected signal region contains 0 background events and has a signal efficiency of 41.59%.
\( \tau \to \mu \gamma \) in Belle II (MC study)

- rotating \((M_{\text{inv}}, \Delta E)\) to minimize correlation
- \(\varepsilon_{\text{sig}} = 4.59\%\) with zero background
First $\tau$ LFV sensitivity study at Belle II

- even with much higher beam background, the sensitivity is comparable to that of Belle (scaled by luminosity)
- signal region is background-free
HFAG summary plot for $\tau$ LFV decays, overlaid with Belle II extrapolation to 50 ab$^{-1}$ assuming zero background
Other related subjects in Belle II

- LFUV involving B decays to $\tau$
  - $R(D), R(D^*)$

- LFUV, LFV involving EW penguin B decays
  - $R(K), R(K^*)$ for LFUV
  - $B \to K^{(*)}\ell^\pm \tau^\mp, K^{(*)}e^\pm \mu^\mp$, etc. for LFV

- With 50 times increase of data and detector improvement, these too will provide exciting opportunities for Belle II
Belle II milestones

• Phase 1 (Feb. 2016): beam commissioning + beam background measurements
  ✓ circulate beams; no collision
  ✓ BEAST II (in place of Belle II) as a commissioning detector

• Recent highlights
  ✓ Final Quads installed in Feb. 2017
  ✓ Belle II roll-in on Apr. 11, 2017

• Phase 2 (Dec. 2017): Detector in place without SVD + PXD
  ✓ *Dark-sector search can start!*

• Phase 3 (Nov. 2018): Start physics run with full Belle II detector
Belle, being an $e^+e^- B$-factory experiment, is a $\tau$-factory experiment at the same time.

With nearly 1 billion $\tau^+\tau^-$ sample, Belle has obtained most stringent upper limits in most of the $\tau$ LFV, LNV and BNV decays, with 90% UL of $O(10^{-8})$.

With $\sim$50 billion $\tau^+\tau^-$ events expected in the upgraded Belle II experiment, these searches will be greatly improved.

For very clean modes (e.g. $\tau^+ \rightarrow \ell^+\ell^-\ell^+$), the upper limit is expected to improve linearly with luminosity. And it will be a very powerful probe for new physics beyond the SM.