cLFV studies at Belle II

Outline
• Introduction
• Belle II status
• cLFV searches

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Introduction
Motivation to Belle II

- B factories (Belle / BaBar) collected 1.5 ab$^{-1}$
  - Asymmetric energy: 3.5 / 8.0 GeV
- Many discoveries in the Standard Model
  - CKM mechanism of CP violation
- Next generation: Search for New Physics via precision measurements
- Advantages of a new B-Factor
  - Clean event topology
    - Full reconstruction/flavor tagging
    - Neutral particles in final state
  - Rich and clear Tau decays
  - Sensitive to NP mass ranges complemental with LHCb
=> Sensitive to Lepton Flavor Violation

New Accelerator / Detector: SuperKEKB and Belle II
KEKB is upgraded to SuperKEKB!

• 40 times higher luminosity
  – Focus on small $\beta^*_y : \times 20$
  – Increase in current : $\times 2$

=> Integrated 50 ab$^{-1}$

=> $4.6 \times 10^{10}$ $\tau$ pairs will be collected
Belle II detector

**Electromagnetic Calorimeter (ECL)**
- Waveform sampling electronics
- CsI (TI) (barrel), Pure CsI (end-caps)

**KL and muon detector**
- Resistive Plate Chamber (barrel outer layers)
- Scintillator + WLS Fiber + SiPM (end-caps, inner 2 barrel layers)

**Vertex detectors**
- 2 pixel layers (DEPFET)
- 4 double-sided strip layers

**Tracking detector**
- Central Drift Chamber (CDC)
- He(50%):C2H6(50%), small cells, long lever arm, fast electronics

**Particle identification**
- Time Of Propagation counter (barrel)
- Aerogel Ring Imaging CHERENkov detector (forward end-cap)

Electron (7GeV) → Tracking detector → Electromagnetic Calorimeter (ECL)

Positron (4GeV) → Vertex detectors → KL and muon detector

CLFV at Belle II
History of Belle II

• KEKB stopped (2010)
• Phase 1 (2016)
  – SuperKEKB commissioning before collision
• Phase 2 (2018) : Beam collision
  – SuperKEKB +Belle II commissioning
  – Belle II (w/o VXD) + BEAST II (BG monitor)

• **Phase 3 (2019-) : Physics run**
  – Full Belle II (w/ VXD)
  – Search for new physics!
Belle II construction

May 2016: TOP
Oct. 2016: CDC
Apr 2017 Belle roll-in
Aug. 2017: ARICH
2015 KLM
Jan. 2017 BWD ECL
Jan. 2019 VXD
First Collision at Phase II run

First collision at 26/04/2018

• 3 months operation until 18th July
• Almost full detector worked well

Integrated Luminosity : \( \sim 500 \text{ pb}^{-1} \)
First plots

Rediscoveries in Phase II samples

- Integrated Luminosity: \( \sim 5 \text{pb}^{-1} \)
- Belle II is working nicely
  => Good Tracking, Clustering, PID

\[ K_S \rightarrow \pi^+\pi^- \]

\[ \pi^0 \rightarrow \gamma\gamma \]

\[ p_0 \rightarrow gg \]
First plots

Rediscoveries in Phase II samples

- Integrated Luminosity: $\sim 5\text{pb}^{-1}$
- Belle II is working nicely

$\Rightarrow$ Good Tracking, Clustering, PID

$$M_{bc} = \sqrt{(E_{CM})^2 - (\Sigma p_i)^2}$$

B mass

$J/\psi \rightarrow e^+e^-$

$\phi \rightarrow K^+K^-$

Belle II 2018 (preliminary)

$\int L \, dt = 250 \text{ pb}^{-1}$
Full event reconstruction for B tag

- ~571 (389+182) fully reconstructed B mesons
- Improvement of a factor of ~O(3.6) in overall efficiency
  => Advanced analysis method covering more decay channels
τ pair candidates with τ→3πν

- τ pair are also extracted in the beam commissioning data
Data has good agreement with MC after selection cuts
Performance of the subsystems is enough as expected
Tau mass from Belle early data is consistent to previous results.

\[ m_\tau = (1776.4 \pm 4.8 \text{ (stat)}) \text{ MeV/c}^2 \]

\[
M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})}
\]

Distribution of the pseudomass is fitted to an empirical edge curve.
Phase III started for physics!

Restarted at 25th March with Full Belle II / SuperKEKB

• Peak Lumi. : $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
• Int. Lumi : 3 fb$^{-1}$

=> Increasing Luminosity!
Channels to cLFV in Belle II

• A number of studies for charged Lepton Flavor Violation is carried out using (almost) full Belle data samples of 1ab$^{-1}$
  – $b \rightarrow ll\bar{s}$ : LFV in B decays
  – $\tau$ physics : tau decays from tau pair productions
• Both are very rare decay search and possible to investigate in B factory experiment thanks to clean signature
  – More statistics in Belle II will bring us to prediction in NP
• Review based on Belle results to prospect to Belle II
Flavor anomaly in $b \rightarrow sll$

- $b \rightarrow s\gamma$ followed by $\gamma \rightarrow ll$
  - Added a box diagram
  - Rare decay in the SM
  - Sensitive to Supersymmetry
    2HDM, Fourth generation, ...

$\Rightarrow$ Nice place to look for new physics
$B \rightarrow K^* l^+ l^-$

- Forward-backward Asymmetry to parent $B$

$$\frac{dA_{FB}(q^2)}{dq^2} = \frac{N(q^2; \theta_{B\ell^+} > \theta_{B\ell^-}) - N(q^2; \theta_{B\ell^+} < \theta_{B\ell^-})}{N(q^2; \theta_{B\ell^+} > \theta_{B\ell^-}) + N(q^2; \theta_{B\ell^+} < \theta_{B\ell^-})}$$

- Measured Wilson coefficients

$$\frac{dA_{FB}(q^2)}{dq^2} = -C_{10}\xi(q^2) \times \left[ \text{Re}(C_9)F_1 + \frac{1}{q^2}C_7F_2 \right]$$

- A deviation => Hints to New Physics?
$B \rightarrow K^* l^+ l^-$ sensitivity in Belle II

- Rich channels to probe not only LFV but LUV

$\Rightarrow$ Still difficult to measure the branching ratio precisely

- Belle II provides more precision measurements

\[ R(K^*) = 0.83 \pm 0.17 \pm 0.08 \]
\[ R(K) = 1.03 \pm 0.19 \pm 0.06 \]

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ ([1.0, 6.0] GeV$^2$)</td>
<td>28%</td>
<td>11%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_K$ (&gt; 14.4 GeV$^2$)</td>
<td>30%</td>
<td>12%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_{K^*}$ ([1.0, 6.0] GeV$^2$)</td>
<td>26%</td>
<td>10%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$R_{K^*}$ (&gt; 14.4 GeV$^2$)</td>
<td>24%</td>
<td>9.2%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$R_{X_s}$ ([1.0, 6.0] GeV$^2$)</td>
<td>32%</td>
<td>12%</td>
<td>4.0%</td>
</tr>
<tr>
<td>$R_{X_s}$ (&gt; 14.4 GeV$^2$)</td>
<td>28%</td>
<td>11%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

PRL 103:171801,2009

CLFV at Belle II
**LFV $K^* l^+ l^-$ decays**

[Belle, arXiv:1807.03267]

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{sig}$</th>
<th>$N_{UL}^{sig}$</th>
<th>$B^{UL}$ $(10^{-7})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^{*0} \mu^+ e^-$</td>
<td>8.8</td>
<td>$-1.5^{+4.7}_{-4.1}$</td>
<td>5.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} \mu^- e^+$</td>
<td>9.3</td>
<td>$0.40^{+4.8}_{-4.5}$</td>
<td>7.4</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} \mu^\pm e^\mp$ (combined)</td>
<td>9.0</td>
<td>$-1.18^{+6.8}_{-6.2}$</td>
<td>8.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Belle opened world best constraints of the LFV $K^* l^+ l^-$ modes

\[
\mathcal{B}(B^0 \to K^{*0} \mu^+ e^-) < 1.2 \times 10^{-7} \\
\mathcal{B}(B^0 \to K^{*0} \mu^- e^+) < 1.6 \times 10^{-7} \\
\mathcal{B}(B^0 \to K^{*0} \mu^\pm e^\mp) < 1.8 \times 10^{-7}
\]

Belle II can reach 90% of UL at $O(10^{-8})$ with 50 ab$^{-1}$
Search for tau LFV

- **Lepton Flavor Violation (LFV)** is highly suppressed in the Standard Model (SM) even if neutrino oscillation is taken
  - $\text{Br} < O(10^{-54}) \Rightarrow$ Experimentally unreachable
- **Many extensions to SM** predict to enhance LFV to be observable in current experiment facilities: $\text{Br} \sim O(10^{-8})$
  => Observation of LFV is an clear signature of the New Physics (NP)!
- Tau lepton - the heaviest charged lepton coupling to the NP
  => Many possible LFV decay modes related to the NP models

**Standard Model**

**SUSY**

**Higgs mediated**
# Predicted BF in various models

Various models predict BF for $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow \mu \mu \mu$

<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>EPJ C8 (1999) 513</td>
<td>$&lt; 10^{-54}$</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>

Numbers correspond to the most optimistic case.

**Super B factory will reach a possible region to $\tau$ LFV!**
Predicted BF in various models

- Ratio of Tau LFV decay BF provides discrimination of NP models

(M.Blanke, et al., JHEP 0705, 013(2007), C.Yue, et al., PLB547, 252 (2002))

<table>
<thead>
<tr>
<th>Model</th>
<th>SUSY+GUT (SUSY+Seesaw)</th>
<th>Higgs mediated</th>
<th>Little Higgs</th>
<th>non-universal Z' boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$ ($\tau \rightarrow \mu\gamma$)</td>
<td>$\sim 2 \times 10^{-3}$</td>
<td>0.06$\sim$0.1</td>
<td>0.4$\sim$2.3</td>
<td>$\sim 16$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$ ($\tau \rightarrow \mu\gamma$)</td>
<td>$\sim 1 \times 10^{-2}$</td>
<td>$\sim 1 \times 10^{-2}$</td>
<td>0.3$\sim$1.6</td>
<td>$\sim 16$</td>
</tr>
<tr>
<td>$\text{Br} (\tau \rightarrow \mu\gamma)$</td>
<td>$&lt; 10^{-7}$</td>
<td>$&lt; 10^{-10}$</td>
<td>$&lt; 10^{-10}$</td>
<td>$&lt; 10^{-9}$</td>
</tr>
</tbody>
</table>

Favorite modes $\tau \rightarrow \mu\gamma$ $\tau \rightarrow \mu\mu\mu$

- It is important to search for various kinds of $\tau$ LFV

$\Rightarrow$ Almost all decay modes were studied using the Belle data
Search for tau LFV in B factory

- Various interesting channels studied in B factories
  => Pick up **two modes** in this talk
  - $\tau \rightarrow \ell\ell\ell$  
    Possible to access in early Belle II
  - $\tau \rightarrow \ell K_S, \Lambda h$
  - $\tau \rightarrow \ell V_0(\rightarrow hh')$
  - $\tau \rightarrow \ell P^0 (\rightarrow \gamma\gamma)$
  - $\tau \rightarrow \ell hh'$
  - $\tau \rightarrow \ell\gamma$  
    Sensitive to many NP models  
    More serious in BG in Belle II

- Rare decay search :
  => Understand backgrounds and reduce as much as possible

- **Review Belle results proceeding to Belle II**
Analysis procedure

- $e^+e^- \rightarrow \tau^+\tau^-$: No missing in signal side
  - **Signal side**: $\mu\mu\mu$
    - Fully reconstructed
  - **Tag side**: 1 prong + missing
    - $\text{Br} \sim 85\%$

- Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane
  - $m_{\mu\mu\mu} = \sqrt{E_{\mu\mu\mu}^2 - p_{\mu\mu\mu}^2} \sim m_\tau$
  - $\Delta E = E_{\mu\mu\mu}^{CM} - E_{\text{beam}}^{CM} \sim 0$

- Number of Background is estimated using sideband data and MC
Signal and backgrounds

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

**SM ττ**
- Neutrinos in both sides
- Missing energy in signal side

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

**q\overline{q}**
- Many tracks

Major BG differs between LFV decay channels

CLFV at Belle II
Belle result:
\( \tau \rightarrow \ell \ell \ell \)


- Data: 782fb\(^{-1}\)
- No events are found in the signal region.
- Almost BG free!
  - Expected # of BG: 0.01-0.21

=> Emphasize the low background compared to LHCb

Br < ~ 10\(^{-8}\) at 90\%CL
Belle result: $\tau \rightarrow \mu \gamma, e \gamma$

Blinding box approach evaluating BG outside the signal region

- Search with 545 fb$^{-1}$
  - Main BG: $\tau \rightarrow \mu \nu \nu + \text{ISR } \gamma$
  - miss/missing tracks
- $\tau \rightarrow \mu \gamma$: $\text{Br} < 4.5 \times 10^{-8}$ (90%CL)
- $\tau \rightarrow e \gamma$: $\text{Br} < 1.2 \times 10^{-8}$ (90%CL)
Background reduction at Belle II

- Timing information helps to reduce $\gamma$ from beam BG
  - 16% inefficiency in $\tau \to \mu \gamma$
- Event shape information provides good separation of ISR- from signal

$\Delta E$ vs. $M_{inv}$

Simulation in Belle II
Expectation of LFV search at Belle II

Belle II will reach the New Physics Models in first several years

• Sensitivity depends on BG level
  => Improve achievable sensitivity

With final statistics at 50ab⁻¹

• \( B(\tau \rightarrow \mu \gamma) \sim O(10^{-9}) \) and \( B(\tau \rightarrow \mu \mu \mu) \sim O(10^{-9}) \)
• Slopes depend on background
Upper limits at (Super) B factories

- Current estimation with Belle II final statistics: $\sim 10^{-2}$ lower

$\Rightarrow$ Many decay modes are reachable in Belle II!
Summary

• B factory is open for both B and τ physics in new physics search
  – Studies with B/τ pairs are carried out in Belle and BaBar
  – No significant result has been found yet

• **Belle II started full operation at March 2019!**
  – Belle II detector is confirmed in Phase II run of 2018

• LFV in B decays into dileptons is nice to look for new physics
  – Search for $B \rightarrow K^* l^+ l^-$ in Belle opened best constraints

• Many of τ LFV channels are reachable in early years of Belle II
  – Improved Upper limit of Branching fraction by $O(10^{-2})$

Backup
τ-factory at Belle

τLFV search using full Belle data

- KEKB: asymmetric e+(3.5 GeV) e-(8 GeV)
  - Peak luminosity: \(2.1 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  => World highest peak luminosity
- \(\sigma(\tau\tau) \sim 0.9\) nb
- \(\sigma(bb) \sim 1.1\) nb
  => pure \(\tau\tau\) can be collected
- Belle Detector:
  - Good tracking and PID
  => Lepton efficiency: 90 %
  Fake rate: O(0.1) % for e
  O(1) % for \(\mu\)

~10\(^9\) \(\tau\) pairs
Theoretical predictions

• MSSM cannot make $\tau \rightarrow \mu \gamma$ according to recent results

Non-minimal SUSY SM

CMSSM

=> These models are possible to search by $\tau \rightarrow \mu \gamma$ in Belle II
τ pairs selection in Belle II data

τ pairs are collected by tagging method

- \( e^+ e^- \rightarrow \tau^+ \tau^- \)

Signal side: 3 tracks
Tag side: 1 prong + missing

Event shapes help to reduce backgrounds significantly

\[
T = \frac{\sum_{i=1}^{N} |T \cdot p_i|}{\sum_{i=1}^{N} |p_i|}
\]

Thrust vector, minimizing \( T \), shows sphericity of an event
Upper Limits of Tau LFV

- Belle best upper limits in most of the channels