Tau LFV at Belle II

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on behalf of the Belle II Collaboration
07/12/2016
HINT2016
• Theoretical motivations for τ LFV searches
• SuperKEKB and Belle II
• τLF(U)V at Belle II
  • \( \tau \rightarrow \mu \gamma \)
  • \( B^+ \rightarrow K^+\tau l \)
• Conclusions and Outlook
Motivation for $\tau$ LFV searches

- Lepton flavour is conserved in the Standard Model (accidental symmetry)
- Neutrino oscillations $\rightarrow$ first sign of neutral LFV beyond the SM
- Also generates charged LFV, but at a non measurable level:

$$B_{\nu SM}(\tau \rightarrow \mu \gamma) = \frac{3\alpha}{32\pi} \left| U_{\tau i}^* U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2 < 10^{-40}$$

$\rightarrow$ Powerful probe for new physics
**LFV: Beyond the Standard Model**

- Predicted in many theoretical models $\mathcal{O}(10^{-7} \sim 10^{-10})$

<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+ $\nu$ oscillations</td>
<td>EPJ C8 (1999) 513</td>
<td>$10^{-40}$</td>
<td>$10^{-14}$</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>

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

- Model-independent approach with an effective Lagrangian:

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots
\]

<table>
<thead>
<tr>
<th>( \tau \rightarrow 3\mu )</th>
<th>( \tau \rightarrow \mu\gamma )</th>
<th>( \tau \rightarrow \mu\pi^+\pi^- )</th>
<th>( \tau \rightarrow \mu K\bar{K} )</th>
<th>( \tau \rightarrow \mu\pi )</th>
<th>( \tau \rightarrow \mu\eta^{(l)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O_{S,V}^{4\ell} )</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( O_D )</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>( O_V^q )</td>
<td>–</td>
<td>–</td>
<td>✓ (I=1)</td>
<td>✓ (I=0,1)</td>
<td>–</td>
</tr>
<tr>
<td>( O_S^q )</td>
<td>–</td>
<td>–</td>
<td>✓ (I=0)</td>
<td>✓ (I=0,1)</td>
<td>–</td>
</tr>
<tr>
<td>( O_{GG} )</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>( O_A^q )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓ (I=1)</td>
</tr>
<tr>
<td>( O_P^q )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓ (I=1)</td>
</tr>
<tr>
<td>( O_{GG} )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Celis, Cirigliano, Passemard (2014)
τ LFV at B Factories

- Large τ-pair production cross section at Y(4S) ($\sigma \sim 0.9$ nb)
- Can probe a large variety of modes
SuperKEKB and Belle II

KEKB → SuperKEKB (x40 luminosity)
• Smaller interaction point
• Increased current
Belle → Belle II (x50 int. luminosity)

First beams & commissioning in 2016
With the upgraded accelerator come increased event rates and beam background:

- Coulomb
- Bremsstrahlung
- Bhabha
- 2-photon Pair Production

... and *intra-beam* (Touschek) scattering

- Affects detector design and resolutions
  - Pileup from charged showers
  - Shift of calorimeter energies
The Belle II Detector

- **Electron (7 GeV)**
- **Positron (4 GeV)**

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

**EM Calorimeter (ECL)**
- CsI(Tl), waveform sampling (barrel)
- Pure CsI (end-caps) later

**Beryllium beam pipe**
- 2 cm diameter

**Vertex Detector (PXD + SVD)**
- 2 layers Si Pixels + 4 layers Si strips

**Target integrated luminosity:**
- 50 ab⁻¹

**KL and muon detector (KLM):**
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (forward)
Fig. 5: LFV UL (90% C.L.) results from CLEO, BaBar and Belle, and extrapolations for Belle II (50 ab$^{-1}$) and LHCb upgrade (50 fb$^{-1}$).

Lepton Flavor Violation (LFV) is highly suppressed in the SM, LFV $\tau$ decays are then clean and ambiguous probes for NP effects. Belle II can experimentally access LFV decay rates over 100 times smaller than Belle for the cleanest channels (as $\tau \rightarrow 3\ell$) and over 10 times smaller for other modes, such as $\tau \rightarrow \ell\pi$ that have irreducible background contributions.

Extrapolation of existing results to 50 ab$^{-1}$ (in the no-background hypothesis)
Constraints from High Energy

- $B(h \rightarrow \tau\mu) = (0.77 \pm 0.66)\%$
  
  by recasting existing
  
  ATLAS $h \rightarrow \tau\tau$ results

- Implied limit on $Y_{\tau\mu}$ coupling

- Contributes to LQ, LL and
  
  (at loop level) dipole modes:

Harnik, Kopp, Zupan (2012)
• CMS best fit $B(h \rightarrow \tau \mu) = (0.84^{+0.39}_{-0.37})\% \rightarrow 2.4\sigma$ excess

• Sensitivity UL: $B_{95}(h \rightarrow \tau \mu) < 1.51\%$
Constraints from High Energy

LFV Yukawa coupling tested by both LHC and Belle II
Past searches for $\tau \rightarrow \mu \gamma$

- Blinding box approach with BG evaluated outside the signal region
- Observables space:
  - $\Delta E = E_{CM}^{(\mu+\gamma)} + E_{\text{beam}}/2$ (expected $\Delta E = 0$)
  - Signal-side $m_{\text{inv}}$ (expected $m_{\text{inv}} = m_\tau = 1.777 \text{ GeV}/c^2$)
- Signal regions after BG rejection cuts — data (points) and signal MC (shaded):

\begin{align*}
\text{Belle} & : B_{90}(\tau \rightarrow \mu \gamma) < 4.5 \times 10^{-8} (535 \text{ fb}^{-1}) \\
\text{BaBar} & : B_{90}(\tau \rightarrow \mu \gamma) < 4.4 \times 10^{-8} (515 \text{ fb}^{-1})
\end{align*}
\( \tau \rightarrow \mu \gamma \) at Belle II

- Sensitivity study using Belle II MC

- Event signature:
  - signal \( \tau \): \( \mu \) track + \( \gamma \)
  - tag \( \tau \): generic (non-\( \mu \))

- Background:
  - \( \tau \rightarrow \mu \nu \nu \)
  - \( \tau \rightarrow e \nu \nu \) + \( \gamma \)
  - \( \tau \rightarrow \pi \nu \)
  - \( ee \rightarrow ee/\mu \mu \) (\( \gamma \))
  - \( ee \rightarrow \) hadronic
• Belle II MC normalised to 1ab\(^{-1}\) for comparison with Belle.
• Beam background is incorporated
• Observables for background rejection:
  — four-momentum,
  — angular distribution,
  — event topology and shape (thrust vector magnitude, momentum flow, Fox-Wolfram moments, …)

\[
T = \frac{\sum_{i=1}^{N} |\mathbf{T} \cdot \mathbf{p}_i|}{\sum_{i=1}^{N} |\mathbf{p}_i|}
\]
Results

Rotated signal region with $\tau \rightarrow \mu \gamma$ MC

Study elliptical signal region around mean:

- Signal efficiency $\varepsilon_{\text{signal}} = 4.59\%$
- No background $\rightarrow n_{\text{BG}} < 2.30$ at 90% CL (Poisson)
Sensitivity Comparison

<table>
<thead>
<tr>
<th></th>
<th>Belle (535 fb⁻¹)</th>
<th>Belle II (1 ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ (cm²/s)</td>
<td>$2.11 \times 10^{34}$</td>
<td>$80 \times 10^{34}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{signal}}$</td>
<td>5.09%</td>
<td>4.59%</td>
</tr>
<tr>
<td>$n_{\text{BG}}$</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>$B_{90}(\tau \rightarrow \mu \gamma)$</td>
<td>$4.5 \times 10^{-8}$</td>
<td>$2.726 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

- First $\tau$ LFV sensitivity study at Belle II
- Background-free search (even with high beam BG)
- Sensitivity comparable with Belle
- Naive extrapolation to 50 ab⁻¹
• The SM is built with the assumption of universality
• Measurements of \( R(D^{(*)}) \) show a 4σ deviation from SM predictions
• Sensitive to NP couplings with Higgs-like particles
• Interesting to study \( \tau \) LF(U)V

\[
R(D^{(*)}) = \frac{BR(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{BR(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)}
\]
\( \tau \) LFUV in \( b \to s \)

- \( b \to s \) transitions are penguin/box suppressed
- Signs of deviations have been found there in the past; e.g. at LHCb:

\[
R(K) = \frac{Br(B^+ \to K^+\mu^+\mu^-)}{Br(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \text{(stat.)} \pm 0.036 \text{(sys.)}
\]

- Processes such as \( B^+ \to K^+\tau \bar{\nu} \) sensitive to NP contributions, e.g. Leptoquarks

- If such a state mediating the transition existed, we could observe it at Belle II

<table>
<thead>
<tr>
<th>( \tau \to \mu \pi^+ \pi^- )</th>
<th>( \tau \to \mu K \bar{K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O^{4\ell}_{S,V} )</td>
<td>( - )</td>
</tr>
<tr>
<td>( O_D )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( O^{qV}_{V} )</td>
<td>( \checkmark ) (I=1)</td>
</tr>
<tr>
<td>( O^{qS}_{S} )</td>
<td>( \checkmark ) (I=0)</td>
</tr>
<tr>
<td>( O_{GG} )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( O^{qA}_{A} )</td>
<td>( - )</td>
</tr>
<tr>
<td>( O^{qP}_{P} )</td>
<td>( - )</td>
</tr>
<tr>
<td>( O_{GG} )</td>
<td>( - )</td>
</tr>
</tbody>
</table>
B\(^+\) → K\(^+\)τ\(\bar{\nu}\) in Belle II

- Feasibility study based on cut and count approach
- Past search on 429 fb\(^{-1}\) BaBar data (PRD 86, 012004 (2012))

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\mathcal{B}(B \rightarrow h\tau\ell) \times 10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \rightarrow K^+\tau\mu)</td>
<td>0.0 (\pm 2.7) (\pm 1.4) (&lt; 4.8)</td>
</tr>
<tr>
<td>(B^+ \rightarrow K^+\tau e)</td>
<td>-0.6 (\pm 1.7) (&lt; 3.0)</td>
</tr>
<tr>
<td>(B^+ \rightarrow \pi^+\tau\mu)</td>
<td>0.5 (\pm 3.8) (\pm 3.2) (&lt; 7.2)</td>
</tr>
<tr>
<td>(B^+ \rightarrow \pi^+\tau e)</td>
<td>2.3 (\pm 2.8) (\pm 1.7) (&lt; 7.5)</td>
</tr>
</tbody>
</table>

- Simulated signal events:
  - B\(\text{sig}\): \(B^+ \rightarrow K^+\tau^\pm\bar{\nu}\)
  - B\(\text{tag}\): generic

- Background events: B\(\bar{B}\)/q\(\bar{q}\) generic MC

<table>
<thead>
<tr>
<th>MC</th>
<th>(\sigma \ [nb])</th>
<th>(N_{\text{events}})</th>
<th>(\mathcal{L}_{\text{int}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+B^-)</td>
<td>0.55</td>
<td>100 (\times 10^6)</td>
<td>180 fb(^{-1})</td>
</tr>
<tr>
<td>(B^0\bar{B}^0)</td>
<td>0.55</td>
<td>100 (\times 10^6)</td>
<td>180 fb(^{-1})</td>
</tr>
<tr>
<td>uu</td>
<td>1.61</td>
<td>50 (\times 10^6)</td>
<td>31 fb(^{-1})</td>
</tr>
<tr>
<td>dd</td>
<td>0.40</td>
<td>50 (\times 10^6)</td>
<td>130 fb(^{-1})</td>
</tr>
<tr>
<td>ss</td>
<td>0.38</td>
<td>50 (\times 10^6)</td>
<td>130 fb(^{-1})</td>
</tr>
<tr>
<td>cc</td>
<td>1.30</td>
<td>50 (\times 10^6)</td>
<td>38 fb(^{-1})</td>
</tr>
</tbody>
</table>
Selection and Outlook

Tag B

• Fully reconstruct tag side in the \( B \rightarrow D^0 X_{\text{had}} \) modes with a multivariate classifier (\( \epsilon_{\text{tag}} = 0.83\% \))

• Keep the one with the highest MVA likelihood.

Signal B

• \( B_{\text{sig}} \) from rest of the event after tag-side reconstruction.

• Signal region around reconstructed \( m_\tau \) peak.

• Reject background with cuts on: \( m(K\pi) \), event shape variables, vertex fit quality…

Available data set is \( x100 \) of BaBar (2012) → potential \( x10 \) improvement (assumes dominant BG)
Summary

• τLFV is a powerful tool to search for new physics.
• Belle II will effectively probe a wide set of decay channels.

• Preliminary study for $\tau \rightarrow \mu \gamma$:
  — $B_{90}(\tau \rightarrow \mu \gamma) < 2.726 \times 10^{-8}$ estimated sensitivity at 1 ab$^{-1}$
  — effectively rejects beam BG (comparable to Belle).
  — Naive extrapolation: $B_{90}(\tau \rightarrow \mu \gamma) < 5.452 \times 10^{-10}$ at 50 ab$^{-1}$

• LFUV feasibility study for $B^+ \rightarrow K^+\tau\ell$ with a fully reconstructed tag using a multivariate classifier.
  — Potential $\times 10$ sensitivity improvement of previous result.
BACKUP
• Phase 1 (2016, complete):
  — Accelerator commissioning
  — No detector
• Phase 2 (start of 2018):
  — Partial detector
  — Background studies
  — First physics
• Phase 3 (end of 2018):
  — Full detector
  — Belle II run
Background Rejection

\[ \tau \rightarrow l\nu\nu \quad \tau \rightarrow \text{hadronic} \]

- Energy of signal-side photon
- Number of tracks
- \( \cos^o_{CM} \) for signal track and signal photon
- Magnitude of rest-of-event thrust vector

**Belle II MC**
Background Rejection

\[ ee \rightarrow ee \]

\[ ee \rightarrow \mu\mu \]

**Centre-of-mass momentum of signal-side track**

- Signal: $\mu$ $\gamma$
- Background: $e$ $e$ ($\gamma$)

**Cosine of polar angle of signal-side track**

**Centre-of-mass energy of signal-side track + photon and tag-side track**
### τ → μγ: After Selection

<table>
<thead>
<tr>
<th>Event type</th>
<th>Events projected (scaled to 1ab⁻¹)</th>
<th>After selection (scaled to 1ab⁻¹)</th>
<th>Signal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ⁻→μ⁺γ</td>
<td>83</td>
<td>6</td>
<td>7.23%</td>
</tr>
<tr>
<td>τ⁻→μ⁺ντνμ</td>
<td>159,997,900</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>τ⁻→π⁺ντ</td>
<td>334,056,500</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>τ⁻→e⁺ντνe</td>
<td>163,857,700</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻→μ⁺μ⁻(γ)</td>
<td>1,148,000,000</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻→e⁺e⁻(γ)</td>
<td>300,000,000,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻→B⁺B⁻</td>
<td>550,000,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻→B⁰B⁰</td>
<td>550,000,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻→q̅q</td>
<td>3,690,000,000</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Tot. background events (for 1ab⁻¹)
Impact of each selection after applying the rest of the cuts