Study of lepton flavor violation in the decay $\tau \rightarrow lll$

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Physics Motivation

• **In quark sector:** flavor mixing is well established.

• **Neutrino mixing:** \( \Rightarrow \) lepton flavor symmetry is violated

  \( \Rightarrow \) How about charged lepton sector??

• **SM + neutrino mixing (in the SM):**

\[
\text{Br} \sim (\Delta M_{ij}/M_W)^4 < 10^{-40}
\]

\[
\text{Br} \sim \log(M_i/M_j) \sim 10^{-14}
\]

\( \Rightarrow \) It is very small, if we find a signal \( \Rightarrow \) new physics
Physics motivation

- Many extensions of the SM naturally introduces LFV at order $\sim 10^{-7} - 10^{-10}$ => can be detected with current experiments.

<table>
<thead>
<tr>
<th>Model</th>
<th>Ref.</th>
<th>$\tau \rightarrow \mu \gamma$</th>
<th>$\tau \rightarrow \mu \mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM + heavy majorana</td>
<td>PRD 66.034008</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-universal $Z'$</td>
<td>PLB 547(3)252</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SUSY + seesaw</td>
<td>PRL 89:241802</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>SM + 4$^{th}$ generation</td>
<td>arXiv.1006.530 6</td>
<td>$10^{-8}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

- **Observe signal** => New physics.
- **Improve limits** => constrain parameters of theoretical modes.

Eg. SUSY + seesaw

$\text{Br}(\tau \rightarrow \mu \mu \mu) < 10^{-7}$
Search for LFV using $\tau$

- $\tau$ – the heaviest charged lepton:
  - Various decay modes for LFV search, even decay to hadron.
  - Strength of interaction relate to new physics is naively expected to be mass-dependent.

Belle II results are simply projected from Belle results.
Search for LFV using $\tau$

- $\tau \to l\gamma$ and $\tau \to lll$ are golden mode, which are expected to have the largest branching fraction.
- $\tau \to lll$ is more sensitive than $\tau \to l\gamma$ because of small background.
- Belle II will take 50ab$^{-1}$ data, $N_{\tau\tau} \sim 5 \times 10^{10}$
- The sensitivity:
  + $\tau \to l\gamma : \sim 1/\sqrt{L}$
  + $\tau \to lll : \sim 1/L$
  (good mass resolution and PID)
Search for LFV using $\tau$

Belle results:

• Data: $\sim 7 \times 10^8 \tau \tau$

$\Delta E = E_{\tau} - E_{\text{beam}}/2$

• Data; $\sim 4.8 \times 10^8 \tau \tau$

$\tau \rightarrow \mu \gamma$

- $M_{\mu\mu\mu}$ is reconstructed mass of LFV $\tau$ decay.
- $\Delta E = E_{\tau} - E_{\text{beam}}/2$
Previous searches for decay $\tau \rightarrow \mu \mu \mu$

- The most stringent upper limits are set currently by the Belle and Babar.
- Final signal are observed in $M-\Delta E$ windows.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Data</td>
<td>$468 \text{ fb}^{-1} (426M \tau^{-} \tau^{+})$</td>
<td>$782 \text{ fb}^{-1} (711M \tau^{-} \tau^{+})$</td>
</tr>
<tr>
<td>eff. (%)</td>
<td>6.6</td>
<td>7.6</td>
</tr>
<tr>
<td>$N_{\text{observed}}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$N_{\text{bkg}}$</td>
<td>$0.44 \pm 0.17$</td>
<td>$0.13 \pm 0.06$</td>
</tr>
<tr>
<td>UL @90 C.L.</td>
<td>$3.3 \times 10^{-8}$</td>
<td>$2.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

- LHCb @2014
  - $\tau$ from $b$ and $c$-hadron decays
  - 3 fb$^{-1}$ data ($\sim 90 \times 10^9 \tau^{-}$)
  - $Br < 4.6 \times 10^{-8}$ @90% C.L

- ATLAS @2016
  - $\tau$ from $W \rightarrow \tau \nu$
  - 20.3 fb$^{-1}$ at 8 TeV taken 2012. ($241 \times 10^6 \tau$)
  - $Br < 3.76 \times 10^{-7}$ @90% C.L
Super-KEKB

- At High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan.
- $E_{e^-} = 7 \text{ GeV}; \quad E_{e^+} = 4 \text{ GeV}$
- Upgrade of KEKB to increase luminosity by 40 times by:
  - Increase beam current
  - Reduce beam size

To get 40x luminosity of KEKB

Expected to take 50ab$^{-1}$ data sample

=> Detector will upgrade to cope with high beam background and improve measurement precision.
Belle II

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)

Electron
(7 GeV)

Beryllium beam pipe
2 cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

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

LFV study with decay $\tau \rightarrow \mu \mu \mu$
Analysis strategy

• Signal side contains 3 charged tracks.
• Tag side is 1 prog decay (Br~85%).
⇒ Select 4-track events, $\Sigma$ charge=0
• Apply general selection for all tag mode.
• Apply final selection tag-by-tag
Track filter

- Remove clone tracks, background tracks before reconstruction based on the impact parameters and number of hits.

#ntracks/events

4-track events are selected for the $\tau$ reconstruction.

(a) Without beam background

(b) With beam background
General selections

- Require $\mu$-ID for one charged tracks
- Average energy deposited in ECL of charged tracks at signal side

$\mathcal{L}(\mu/\pi) > 0.9$
Background suppression

- 4-vector missing momentum: \( P_{\text{miss}} = -P_{\tau} - P_{\text{tag}} \)
  \[ P_{\text{tag}} = P_{\text{charged Track or } \rho} \quad \text{if tag is } \pi\nu, \mu\nu, \mu\nu, \rho\nu \]
  \[ P_{\text{tag}} = P_{\text{charged Track}} + P_{\text{gamma}} \quad \text{if tag is } \pi\pi^0\pi^0\nu \]
- \( P_{\text{miss}} \) is required to point into fiducial volume of detector.
- Magnitude selection will be different for each mode.

- Count \( N_{\text{gamma}} \) which has \( E > 0.1 \) GeV.
- Maximum 1 gamma is allow at signal side.
## Separate tag modes

<table>
<thead>
<tr>
<th>Tag modes</th>
<th>Branching fraction (%)</th>
<th>Conditions</th>
</tr>
</thead>
</table>
| $\tau \to e^- \bar{\nu}_e \nu_\tau$ | 17.36                  | • $\mathcal{L}(e/\pi) > 0.1$  
• $N_{\gamma}^{tag} \leq 1$                                      |
| $\tau \to \mu^- \bar{\nu}_e \nu_\tau$ | 17.85                  | • $\mathcal{L}(\mu/\pi) > 0.8$  
• $N_{\gamma}^{tag} \leq 1$                                      |
| $\tau \to \pi^- \nu_\tau$             | 10.91                  | • $\mathcal{L}(\mu/\pi) < 0.8$ && $\mathcal{L}(e/\pi) < 0.1$  
• there is no reconstructed $\pi^0$  
• $N_{\gamma}^{tag} \leq 1$                                      |
| $\tau \to \rho^- \nu_\tau$             | 25.51                  | • $\mathcal{L}(\mu/\pi) < 0.8$ && $\mathcal{L}(e/\pi) < 0.1$  
• $\rho^- \to \pi^+ \pi^0$ is reconstructed                                      |
| $\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$ | 10.85                  | • Remaining                                                                  |
Tag-by-tag bkg suppression

• Using variables:
  • Reconstructed pi0, rho, for background suppression.
  • Missing information: $M_{mis}^2$, $P_{miss}$
  • PID of the second charged track.
  • Eecl of charged tracks
  • Mass of two charged tracks ($M_{ee}$)
  • $P_{total}^{cms}$
Selections for tag $\tau^- \rightarrow \mu^- \bar{\nu}_e \nu_\tau$

- Required 2$^{nd}$ $\mu$-ID if a photon appears at tag side.
- Missing mass and momentum.

To suppress:
- Two-photon process: $e^+ e^- \rightarrow \mu^+ \mu^- e^+ e^-$
- $\mu$-pair process: $e^+ e^- \rightarrow \mu^+ \mu^-(\gamma \rightarrow e^+ e^-)$

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Thanch Dong
Mass and $\Delta E$ distribution

Distributions of the Belle II are significantly narrower.
Signal analysis

- Select signal event in the $2\sigma$ region (11038 events).
  
  \[
  \text{eff.} = 11.04\% 
  \]
  
  \text{~1.5 times higher than that obtained at Belle.}

- Estimated background by loosening the selections then propagate from $5\sigma$ to $2\sigma$ region.
  
  \[N_{\text{bkg}} = 0.13 \pm 0.06\]
  
  The same as belle result.

- Estimate the UL: $\mathcal{B}(\tau \to \mu\mu\mu) < \frac{N_{90}^{UL}}{2N_{\tau\tau\epsilon}}$
  
  For 1 ab$^{-1}$ with no observed event.
  
  \[\mathcal{B}(\tau \to \mu\mu\mu) < 1.1 \times 10^{-8}\] at 90% C.L
  
  \text{~2 times lower than the current limits.}
Thank you very much
Back up

- LFV search with muon
  - Experimental set-up is simple and cheap (compared with tau exp).
  - Possible to produce intensity muon beams.
  - But number of decay channel for LFV is limited.

![Graph showing history of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$.]