Search for $\tau \rightarrow \mu \gamma$ with the full data sample collected by Belle

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for the Belle collaboration
Lepton flavor violation (LFV) in charged leptons
⇒ negligibly small probability in the Standard Model (SM)
even including neutrino oscillations:

\[ Br(\tau \to \ell \gamma)_{SM} \propto \left( \frac{\delta m^2_{\nu}}{m_{W}^2} \right)^2 < 10^{-54} \]

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

- Many extensions of the SM predict LFV decays.
  - These branching fractions could be enhanced as high as current experimental sensitivity. (~10^{-8})

- Tau lepton = The heaviest charged lepton
  - Expected strong coupling to NP
  - Many possible LFV decay modes

\[ \tau \text{ LFV search} = \text{ideal probe of NP} \]
Introduction(2)

- $\tau \rightarrow \mu \gamma$ is the simplest process among $\tau$ LFV decays.
  - Various models predict:
    - MSSM, LHT, ...
    - Some of them predict experimentally-reachable branching fraction.


- In addition, various LFV searches are important because they can distinguish NP models.

<table>
<thead>
<tr>
<th></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>$\tau \rightarrow \mu \mu \mu$</td>
<td>$\sim 2 \times 10^{-3}$</td>
<td>0.06~0.1</td>
<td>0.4~2.3</td>
<td>$\sim 16$</td>
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</table>
Upper Limits on $\tau$ LFV Decays

Reach upper limits around $10^{-8} \sim 100x$ more sensitive than CLEO
The remaining mode are $\tau \rightarrow \mu \gamma$ and $e \gamma$!
Previously, a 545 fb$^{-1}$ data subsample was analyzed.
Previous result for $\tau \rightarrow \mu \nu \nu$ search

- 545 fb$^{-1}$ Belle data sample
- 94 events are found while \((88.4 \pm 7.4)\) BG events are expected in 5$\sigma$ region and the detection eff. is 6.1%. Main BG comes from $\tau \rightarrow \mu \nu \nu +$ ISR $\gamma$.
- Upper Limits are evaluated by 2d UEML fit on $M-\Delta E$ plane.
- Expected UL: $7.8 \times 10^{-8}$ @90%CL
- Obtained UL: $4.5 \times 10^{-8}$ @90%CL

UEML=Unbinned Extended Maximum Likelihood fit
KEKB collider/Belle detector

B–factory: $E$ at CM = $Y\ (4S)$
$e^+(3.5\ \text{GeV})\ e^-(8\ \text{GeV})$

Good track reconstruction and particle identification
Lepton ID $\sim (80-90)\%$
Fake ID $\sim (0.1-3)\%$
$\sim 9 \times 10^8\ \tau\tau$ at Belle

$\sigma(\tau\tau) \sim 0.9\text{nb}$, $\sigma(b\bar{b}) \sim 1.1\text{nb}$

A B–factory is also a $\tau$–factory!

World-largest data sample!
Selection Criteria

- 1–1 prong & net charge=0
- Missing momentum should point into the detector volume.
- Visible energy should be smaller than beam energy.
- The charged track should be a muon while none of the tagging tracks can be an identified muon.

To select signal event

- $N_\gamma=1$ in signal side.
- $0.5< \cos \theta_{\mu-\gamma}^{\text{CM}}<0.8$ (requirement from 2–body decay ($\tau \rightarrow \mu\gamma$))
- $|M_\nu^2|<0.5\text{GeV}^2/c^4$ for hadronic tags and $0<M_\nu^2$ for leptonic tags.
- $0.99< \cos \Theta^{\text{CM}}$, where $\Theta$ means the angle between expected and reconstructed $\tau$ directions.
- Momentum asymmetry between $\mu$ and $\gamma$ should be less than 0.7
Blind analysis
⇒ Blind signal region

Estimate BG level using sideband data and MC
The signal extraction is performed by the UEML fit on the $M_{\mu\gamma}^{(c)}-\Delta E/\sqrt{s}$ plane
If no excess is found, set upper limits @ 90%CL using the UEML fit and toy MC

Signal Extraction

$$M_{\mu\gamma}^{(c)} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - (P_{\text{signal}}^{\text{CM}})^2}$$
$$\Delta E = E_{\text{signal}}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$$

$M_{\mu\gamma}^{(c)} \sim \tau$ mass

$\Delta E/\sqrt{s} \sim 0$
Tag side missing mass

- Tag side missing mass.

\[(\text{tag-side missing mass})^2\]

This can be reconstructed from another \(\tau\)

\[ (\text{tag side missing}) = (\text{reconstructed tag-side } \tau) - (\text{visible tracks and gammas belonging to tag side}) \]
In the CM frame, tau direction can be calculated from the charged tracks. This direction is compared with reconstructed one from $\mu$ and $\gamma$.

Here, $p_A(p_B)$ means 3-vector for $\mu$ (hadron) in CM frame and $q_A(q_B)$ is a unit vector parallel to $p_A(p_B)$. 

Cosine of the angle between expected and reconstructed tau directions

$$\cos \Theta_{\text{CM}}>-0.99$$
After applying all selections, 105 events are found and the detection efficiency is 6.5%. For the blinded region, $10.2 \pm 2.2$ BG events are expected. In total, $115.2 \pm 11.4$ events are expected. $\rightarrow$ BG level reduced by 33% while efficiency is similar to the previous analysis.
The function

\[ D(x, y) = h(1 + \alpha(x - 1.78)) \]

\[ \times \left( a + e^{-\frac{(y-c)^2}{2\sigma^2}} \right) \]

reproduced the BG distribution in the narrow region \((M_{\mu\gamma}, \Delta E/\sqrt{s} : \pm 5s)\), where \((x,y)\) means \((M_{\mu\gamma}, \Delta E/\sqrt{s})\).

Fit to total MC dist., and then compare it with the data dist.
UEML fit with PDFs

Unbinned Extended Maximal Log Likelihood fit

\[ L = \frac{e^{-s-b}}{N!} \prod_{i=1}^{N} \left( s \times PDF_{sig}(M_{\mu\gamma}^{(c)}_i, (\Delta E)_i/\sqrt{s}) + b \times PDF_{bg}(M_{\mu\gamma}^{(c)}_i, (\Delta E)_i/\sqrt{s}) \right), \]

where \( N \) is a number of observed events in \( \pm 5\sigma \) region, \( (M_{\mu\gamma}^{(c)}_i) \) and \( (\Delta E)_i/\sqrt{s} \) are the coordinate of \( i \)-th observed event on \( M_{\mu\gamma}^{(c)} - \Delta E/\sqrt{s} \) plane and \( s \) and \( b \) are free parameters, those corresponds to the number of signal and BG events, respectively.
Since we still have a blind for the ±2σ region, we assume that we obtain $s_{\text{fit}}=0$, $b_{\text{fit}}=115.2$ as an UEML fit result to the data events.

Upper limit for $s$ is obtained by using toy MC samples, where $b$ is fixed and $s$ is varied until finding $s$ that gives a 90% chance of $s^{\text{MC}}$ being larger than $s$. Here $s^{\text{MC}}$ means the result of an UEML fit to events generated by toy MC and we generate 50,000 toy MC events for each $s$.

As a result, $s_{90}=5.7$ is obtained. $\Rightarrow B<4.8\times10^{-8}$ @ 90%CL

- Including systematics $\Rightarrow B<5.3\times10^{-8}$ @ 90%CL
  
  (largest contribution: uncertainty in BG PDF shape)
Summary

- Belle completed operation with a 980\,fb\(^{-1}\) data sample, which contains \(\sim10^9\) tau-pairs. This is the world’s largest $\tau$ data sample.

- Search for $\tau \rightarrow \mu \gamma$ is being performed with the full data sample.
  - By adding more data and optimizing the analyses to suppress BGs, the sensitivity to $\tau$ LFV is improved significantly.
  - If the observed signal is consistent with the background, the expected upper limit is $\mathcal{B}(\tau \rightarrow \mu \gamma) < 5.3 \times 10^{-8} \text{ @90\%CL.}$

  *The highest sensitivity for this mode.* (preliminary)

- The blinded region is not opened yet.
  
  Final results for $\tau \rightarrow \mu \gamma$ as well as $\tau \rightarrow e \gamma$ will be shown soon.

- All major $\tau$ LFV modes have been investigated with the final $\sim1000\,fb\^{-1}$ data sample.