Recent Results on $\tau$ Lepton Physics from Belle

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Outline

1. Belle experiment
2. Search for LFV decays
3. Measurement of $\tau$ lifetime
4. Study of $\tau^- \rightarrow K^0_S X^- \nu_\tau$
5. Summary
Belle Experiment – I

Belle Detector

SC solenoid
1.5T

CsI(Tl)
16\times X_0

TOF counter

Aerogel Cherenkov cnt.
\text{n=1.015~1.030}

3.5 GeV $e^+$

8 GeV $e^-$

Central Drift Chamber
small cell +He/C_2H_6

Si vtx. det.
3 lyr. DSSD

$\mu / K_L$ detection
14/15 lyr. RPC+Fe

S. Eidelman, BINP
### Belle Experiment – II

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$, nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \to e^+e^-(\gamma)$</td>
<td>123.5</td>
</tr>
<tr>
<td>$15^\circ \leq \theta \leq 165^\circ$</td>
<td></td>
</tr>
<tr>
<td>$e^+e^- \to \mu^+\mu^-(\gamma)$</td>
<td>1.005</td>
</tr>
<tr>
<td>$e^+e^- \to q\bar{q}$ ($q = u, d, s, c$)</td>
<td>3.39</td>
</tr>
<tr>
<td>$e^+e^- \to b\bar{b}$</td>
<td>1.05</td>
</tr>
<tr>
<td>$e^+e^- \to e^+e^-f\bar{f}$</td>
<td>72.6</td>
</tr>
<tr>
<td>($f = u, d, s, c, e, \mu, \tau$)</td>
<td></td>
</tr>
<tr>
<td>$e^+e^- \to \tau^+\tau^-(\gamma)$</td>
<td>0.919</td>
</tr>
</tbody>
</table>

- ~ 450 members, 80 Inst., 18 countries
- $E_{e^-} = 8$ GeV, $E_{e^+} = 3.5$ GeV
- Continuous injection, record lumi
- $L_{\text{max}} = 2.11 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- $\int Ldt \simeq 1$ ab$^{-1}$, $N_{\tau\tau} \simeq 10^9$
- B-factory is also a $\tau$-factory
Lepton-flavor-violating (LFV) $\tau$ Decays

<table>
<thead>
<tr>
<th>Model</th>
<th>$B(\tau \to \mu \gamma)$</th>
<th>$B(\tau \to \ell\ell\ell)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA+seesaw</td>
<td>$10^{-8}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>SUSY+SO(10)</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>SM+seesaw</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-universal $Z'$</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SUSY+Higgs</td>
<td>$10^{-10}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

- Probability of LFV decays of charged leptons is extremely small in the Standard Model (SM), $B(\tau \to \ell\gamma) \sim \left(\frac{\Delta m^2_{\nu}}{m_W^2}\right)^2 < 10^{-54}$

- Many models beyond the SM predict LFV decays with the branching fractions up to $\sim 10^{-8}$. LFV observation – clear signature of New Physics (NP)

- $\tau$ lepton is an excellent laboratory to search for the LFV decays: enhanced couplings to new particles and large number of LFV decay modes

- Different $\tau$ LFV decay modes test various NP models
Search for $\tau \rightarrow \ell hh', \, \ell = e, \mu; \, h, h' = \pi^\pm, K^\pm$

14 modes were studied with 854 fb$^{-1}$: 8 LFV $\tau^- \rightarrow \ell^- h^+ h'^-$ and 6 lepton-number-violating $\tau^- \rightarrow \ell^+ h^- h'^-$ decays

One event in the signal region was found for \( \tau^{-} \to \mu^{+}\pi^{-}\pi^{-} \) and \( \tau^{-} \to \mu^{-}\pi^{+}K^{-} \), no events for the other 12 modes. For all modes the number of observed signal events agrees with the number of expected background events.

Obtained upper limits at 90% CL: \( \mathcal{B}(\tau \to \ell hh') < (2.0 \div 8.6) \times 10^{-8} \)
Results on LFV decays of $\tau$

48 different LFV modes were studied at Belle

46 modes were analysed with almost full Belle statistics ($\sim 1 \text{ ab}^{-1}$) and the world best upper limits were obtained. A full statistics study of $\tau \rightarrow \mu(e)\gamma$ is in progress and will be completed soon.
Ongoing studies of the general properties of $\tau$ at Belle: Lifetime of $\tau$-lepton, electric dipole moment, Michel parameters in leptonic and radiative leptonic $\tau$ decays, anomalous magnetic moment of $\tau$ in radiative leptonic decays

Precise measurement of $\tau_T$ – a test of lepton universality

$$\frac{2B(W \rightarrow \tau \nu_\tau)}{B(W \rightarrow \mu \nu_\mu) + B(W \rightarrow e \nu_e)} = 1.066 \pm 0.025: 2.6\sigma \text{ deviation from the SM}$$

S. Schael et al. arXiv:1302.3415

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Measurement of $\tau\tau$ – Method

$e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\pi^+\pi^+\pi^-\bar{\nu}_\tau, \pi^+\pi^-\pi^-\nu_\tau)$ with $\int Ldt = 711 \text{ fb}^{-1}$, $N_{\tau\tau} = 650 \times 10^6$

- $p_\tau$ direction – two-fold ambiguity in CMS, we use the average axis

- Asymmetric-energy layout $\Rightarrow \tau^+\tau^-$ production point in LAB determined independently of IP

- CPT test from separate $\tau^-$ and $\tau^+$ lifetimes
Measurement of $\tau_\tau$ – Selection 1

Selection criteria:

- Event is separated into two hemispheres in CMS, thrust $> 0.9$
- Each hemisphere contains 3 charged pions with the $\pm 1$ net charge
- There are no additional $K^0_S$, $\Lambda$, $\pi^0$ candidates, the number of additional photons $N_\gamma < 6$ with $E_\gamma^{TOT} < 0.7$ GeV
- $P_\perp(6\pi) > 0.5$ GeV/$c$, $4$ GeV/$c^2 < M_{inv}(6\pi) < 10.25$ GeV/$c^2$
- Pseudomass $\sqrt{M_h^2 + 2(E_{beam} - E_h)(E_h - P_h)} < 1.8$ GeV/$c^2$, $h = (3\pi^-)$, $(3\pi)^+$
- Cuts on the quality parameters of the vertex fits and $\tau$ axis reconstruction
- Minimal distance between $\tau^-$ and $\tau^+$ axes in LAB $dl < 0.02$ cm

$1.15 \times 10^6$ events selected with $\sim 2\%$ background, mainly from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$)
Measurement of $\tau\tau$ – Selection 2

Pseudomass spectrum,
black - data, blue - MC

Stability of the $dl$-cut
Measurement of $\tau_\tau$ – A Fit of the Decay Length Distribution

Decay length PDF

$$P(x) = \mathcal{N} \int e^{-x'/\lambda_\tau} R(x - x'; \vec{P}) dx' + N_{uds} R(x; \vec{P}) + P_{cb}(x),$$

$$R(x; \vec{P}) = (1 - 2.5x) \cdot \exp \left( -\frac{(x - P_1)^2}{2\sigma^2} \right),$$

$$\sigma = P_2 + P_3|x - P_1|^{1/2} + P_4|x - P_1| + P_5|x - P_1|^{3/2}$$

- Free parameters of the fit: $\lambda_\tau$, $\mathcal{N}$, $\vec{P} = (P_1, ..., P_5)$
- $\lambda_\tau$ - estimator of $c\tau_\tau$, $c\tau_\tau = \lambda_\tau + \Delta_{\text{corr}}$, $\Delta_{\text{corr}}$ is determined from MC;
- $R(x; \vec{P})$ - detector resolution function;
- $N_{uds}$ - contribution of background from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$) (predicted by MC)
- $P_{cb}(x)$ - PDF for background from $e^+e^- \rightarrow q\bar{q}$ ($q = c, b$) (fixed from MC)

From the fit $\lambda_\tau = 86.53 \pm 0.16 \mu m$ and with $\Delta_{\text{corr}} = 0.46 \mu m$: $c\tau_\tau = 86.99 \pm 0.16 \mu m$
Measurement of $\tau_{\tau}$ - Resolution

From $\phi$ to $\psi$, Rome

September 9-12, 2013

Entries / 2.5 $\mu$m

$\sqrt{\text{Frac}}$ = 770.8 / 794

$P_1$: $0.2692\times 10^{05}$
$P_2$: $0.4629\times 10^{-05}$
$P_3$: $0.3845\times 10^{-02}$
$P_4$: $0.1015\times 10^{-02}$
$P_5$: $0.7377\times 10^{-02}$
$P_6$: $0.1705\times 10^{-01}$

$\text{l}_{\text{uds}} + \text{yy}$

$\text{charm}$

$\text{BB}$

Pull
Measurement of $\tau_\tau$ – Preliminary Result

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta c\tau$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVD alignment</td>
<td>0.090</td>
</tr>
<tr>
<td>Fit range</td>
<td>0.020</td>
</tr>
<tr>
<td>ISR and FSR description</td>
<td>0.018</td>
</tr>
<tr>
<td>Beam energy</td>
<td>0.016</td>
</tr>
<tr>
<td>Background contribution</td>
<td>0.010</td>
</tr>
<tr>
<td>$\tau$-lepton mass accuracy</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.096</strong></td>
</tr>
</tbody>
</table>

$\tau_\tau = (290.17 \pm 0.50 \text{(stat.)} \pm 0.33 \text{(syst.)}) \times 10^{-15} \text{ s} \quad (290.6 \pm 1.0) \times 10^{-15} \text{ s}$

$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}$ at 90% CL
Hadronic $\tau$ Decays

Cabibbo-allowed decays ($\mathcal{B} \sim \cos^2 \theta_C$)

$\mathcal{B}(S = 0) = (61.85 \pm 0.11)\%$ (PDG)

Cabibbo-suppressed decays ($\mathcal{B} \sim \sin^2 \theta_C$)

$\mathcal{B}(S = -1) = (2.87 \pm 0.07)\%$ (PDG)

- Search for CP violation
- High-precision measurement of branching fractions, studies of rare decays
- Measurement of low-energy hadronic spectral functions
  - Determination of intermediate mechanisms
  - Precise measurement of masses and widths of the intermediate mesons
- Comparison with hadronic form factors from $e^+e^-$ experiments to check CVC
- Measurement of $\Gamma_{\text{inclusive}}(S = -1)$ to determine s-quark mass and $V_{us}$:

$$|V_{us}| = \sqrt{\frac{R_{\text{strange}}}{R_{\text{non-strange}}} - \delta R_{\text{theory}}}$$

- $R_{\text{strange}} = \mathcal{B}_{\text{strange}}/\mathcal{B}_e$
- $R_{\text{non-strange}} = \mathcal{B}_{\text{non-strange}}/\mathcal{B}_e$
- $\delta R_{\text{theory}}$ - SU(3)-breaking contribution
Study of $\tau^- \to K^0_S X^- \nu_\tau$ decays

A data sample of $\int L dt = 669 \text{ fb}^{-1}$ with $N_{\tau\tau} = 616 \times 10^6$ was used to study inclusive decay $\tau^- \to K^0_S X^- \nu_\tau$ as well as 6 exclusive modes:

$\pi^- K^0_S \nu_\tau, \ K^- K^0_S \nu_\tau, \ \pi^- K^0_S K^0_S \nu_\tau$

$\pi^- K^0_S \pi^0 \nu_\tau, \ K^- K^0_S \pi^0 \nu_\tau, \ \pi^- K^0_S K^0_S \pi^0 \nu_\tau$

After the standard $\tau\tau$ preselection we select events with particular configuration.

- Event is separated into two hemispheres in CMS, thrust > 0.9
- Tag side: 1-prong ($e$, $\mu$ or $\pi/K(n \geq 0)\pi^0$)
- Signal side:
  - $K^0_S \to \pi^+ \pi^-$: $0.485 < M_{\pi\pi} < 0.511 \text{ GeV/c}^2 (\pm 5\sigma)$, $2 \text{ cm} < L_{K^0_S} < 20 \text{ cm}$, $\Delta Z_{1,2} < 2.5 \text{ cm}$
  - $\pi^0 \to \gamma\gamma$: $-6 < S_{\gamma\gamma}(= \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}}) < 5$
  - Charged kaon (pion): $P_{K/\pi} = \frac{L_K}{L_{\pi^+} + L_K} > 0.7 (< 0.7)$
- $E_{\gamma extra}^{LAB} < 0.2 \text{ GeV}$
## Calculation of Branching Fractions

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\pi^- K^0_S$</th>
<th>$K^- K^0_S$</th>
<th>$\pi^- K^0_S \pi^0$</th>
<th>$K^- K^0_S \pi^0$</th>
<th>$\pi^0 K^0_S K^0_S$</th>
<th>$\pi^- K^0_S K^0_S \pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{data}}$</td>
<td>397806 ± 631</td>
<td>157836 ± 541</td>
<td>32701 ± 295</td>
<td>26605 ± 208</td>
<td>8267 ± 109</td>
<td>6684 ± 96</td>
</tr>
<tr>
<td>$\varepsilon_{\text{det}}$ (%)</td>
<td>9.66</td>
<td>7.09</td>
<td>6.69</td>
<td>2.65</td>
<td>2.19</td>
<td>2.47</td>
</tr>
<tr>
<td>$N_{\text{bg}}$ (%)</td>
<td>4.20 ± 0.46</td>
<td>8.86 ± 0.05</td>
<td>3.55 ± 0.07</td>
<td>5.60 ± 0.10</td>
<td>2.43 ± 0.10</td>
<td>7.89 ± 0.24</td>
</tr>
<tr>
<td>$N_{\text{data}}$ (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\Delta B_B)^{\text{syst}}$ (%)</td>
<td>2.4</td>
<td>2.5</td>
<td>4.0</td>
<td>3.9</td>
<td>5.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

The main non-$\tau\tau$ background comes from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$). To take into account cross-feed background, 6 decay modes are analysed simultaneously:

$$N_{\text{sig}}^i = \sum_j (E^{-1})_{ij} (N_{\text{data}}^j - N_{\text{bg}}^j)$$

For the $\pi^- K^0_S \nu$, $K^- K^0_S \nu$, $\pi^- K^0_S \pi^0 \nu$, and $K^- K^0_S \pi^0 \nu$ modes lepton tag is applied and normalisation to the two-lepton events ($\tau^{\mp} \rightarrow e^{\mp} \nu \nu$, $\tau^{\pm} \rightarrow \mu^{\pm} \nu \nu$) method is used to calculate branching fractions:

$$B_i = \frac{N_{\text{sig}}^i}{\varepsilon_{e-\mu} B_{e} B_{\mu}}$$

To increase statistics for the remaining $\pi^- K^0_S K^0_S \nu$ and $\pi^- K^0_S K^0_S \pi^0 \nu$ modes, the one-prong tag and luminosity normalisation method are used:

$$B_i = \frac{N_{\text{sig}}^i}{2 L \sigma_{\tau\tau} B_{1-\text{prong}}}$$
Preliminary Results on Branching Fractions

\[ B(\tau \to K_S^0 \pi^- \nu_\tau) = (9.15 \pm 0.01 \pm 0.15) \times 10^{-3} \]
Unfolded invariant mass distributions (all combinations) were obtained for the $\tau^− \rightarrow K_S^0\pi^-\pi^0\nu_\tau$ and $\tau^− \rightarrow K_S^0K^-\pi^0\nu_\tau$ modes.
In the study of visible invariant mass spectra for $\tau^- \rightarrow \pi^- K^0_S K^0_S \pi^0 \nu_\tau$ events, intermediate structures are observed, as well as indication of the $f_1(1420)\pi^- \nu_\tau$ (2.7$\sigma$) mechanism is seen.

$f_1(1285)\pi^- \nu_\tau$ (5.9$\sigma$) and $K^*(892)K^0_S \nu_\tau$ intermediate structures are observed, as well as indication of the $f_1(1420)\pi^- \nu_\tau$ (2.7$\sigma$) mechanism is seen.

$$B(\tau^- \rightarrow f_1(1285) \rightarrow K^0_S K^0_S \pi^0) \pi^- \nu_\tau = (0.74 \pm 0.12 \pm 0.07) \times 10^{-5}$$

$$B(\tau^- \rightarrow K^*(892) \rightarrow K^0_S \pi^-) K^0_S \pi^0 \nu_\tau = (1.06 \pm 0.15 \pm 0.09) \times 10^{-5}$$
Ongoing Studies of Hadronic $\tau$ Decays at Belle

- Spectral function of $\tau^- \rightarrow \pi^- \pi^- \pi^+ \pi^0 \nu_\tau$ decay
- Spectral function of $\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$ decay
- Search for CP violation in $\tau^- \rightarrow K^- \pi^- \pi^+ \nu_\tau$ decay
- Branching fractions of $\tau^- \rightarrow \pi^- \geq 2\pi^0 \nu_\tau$
- Branching fractions of $\tau^- \rightarrow h_1^- h_2^- h_3^+ \nu_\tau$, $h_{1,2,3} = \pi$, $K$
- Search for 2nd class currents in $\tau^- \rightarrow \eta \pi^- \nu_\tau$ and $\tau^- \rightarrow \eta' \pi^- \nu_\tau$
Summary

- Belle collected the world largest data sample of $\sim 1 \text{ ab}^{-1}$ ($N_{\tau\tau} \approx 10^9$) near the $\Upsilon(4S)$ opening a new era in precise $\tau$ physics.

- 48 different LFV modes studied, upper limits on $B$ of the order of $10^{-8}$ obtained.

- With 711 fb$^{-1}$ the $\tau$ lifetime measured using a new method:
  
  $\tau_{\tau} = (290.17 \pm 0.50 \text{(stat.)} \pm 0.33 \text{(syst.)}) \times 10^{-15}$ s

  $|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}$ at 90% CL

- Branching fractions for six $\tau$ decay modes with $K_S^0$ and for the inclusive decay $\tau^- \rightarrow K_S^0X^0\nu_{\tau}$ have been measured. Unfolded invariant mass spectra have been obtained for the $\tau^- \rightarrow K_S^0\pi^-\pi^0\nu_{\tau}$ and $\tau^- \rightarrow K_S^0K^-\pi^0\nu_{\tau}$ modes, for the latter $f_1(1285)\pi^-\nu_{\tau}$ and $K^{*-}(892)K_S^0\nu_{\tau}$ mechanisms observed.

- Various ongoing analyses of $\tau$ decays, new results expected soon.