Tau Lepton Studies at the Belle

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The primary goal of the Belle and BaBar experiments was to discover the CP violation in B mesons and to measure the parameters of CPV. This was achieved by both experiments in 2001.

However, wide research area became possible because of clean event environment and well defined initial state in the e+e– experiments as well as high luminosity and general-purpose detectors.

$E^- = 8 \text{ GeV}, \ E^+ = 3.5 \text{ GeV, } \sqrt{s} = 10.58 \text{ GeV, } \beta\gamma = 0.42$

Peak lumi record at KEKB: $L = 2.1 \times 10^{34}/\text{cm}^2/\text{sec}$ with crab cavities.

F/B asymmetric detector: High vertex resolution, magnetic spectrometry, excellent calorimetry and sophisticated particle ID ability.
Belle II Detector

EM Calorimeter:
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

Central Drift Chamber
Smaller cell size, long lever arm

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip
DSSD

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

Electrons (7 GeV)
Positrons (4 GeV)

+ New software, improved tracking, ...
+ Optimization for low multiplicity trigger
+ Improved simulation, generators and GRID

<table>
<thead>
<tr>
<th></th>
<th>E (GeV)</th>
<th>$\beta^*_y$ (mm)</th>
<th>$\beta^*_x$ (cm)</th>
<th>$\phi$ (mrad)</th>
<th>I (A)</th>
<th>L (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td>LER/HER</td>
<td></td>
</tr>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>11</td>
<td>1.6/1.2</td>
<td>2.1 x 10$^{34}$</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30</td>
<td>3.2/2.5</td>
<td>41.5</td>
<td>3.6/2.6</td>
<td>80 x 10$^{34}$</td>
</tr>
</tbody>
</table>
Tau studies at Belle

• 28 journal papers in total
• 18 papers on LVF
• 6 branching fractions and spectral functions

and

• Search for the Electric Dipole Moment of the tau lepton

• Measurement of the $\tau$ Lepton Mass and an Upper Limit on the Mass Difference between $\tau^+$ and $\tau^-$, M. Shapkin, K. Belous, A. Sokolov et al. (The Belle Collaboration), PRL 99, 011801 (2007)

• Measurement of the $\tau$-lepton Lifetime at Belle, K.Belous, M.Shapkin, A.Sokolov, et al. (Belle Collaboration), PRL 112, 031801 (2014)

• Search for CP Violation in $\tau^\pm \rightarrow K_S^0 \pi^\pm \nu_\tau$ Decays at Belle,
  M.Bischofberger, H.Hayashii, et al. (The Belle Collaboration), PRL 107, 131801 (2011)
Searches for lepton flavour violation in tau decays

In the SM the lepton flavour violation decays are extremely small:
\[ \text{Br}(\tau \rightarrow l\gamma) \sim 10^{-54} \]

Expected sensitivity
\[ \tau \rightarrow l\gamma \quad \text{Br} \sim O(10^{-8} \sim 9) \]
\[ \tau \rightarrow lll, l+\text{meson} \quad \text{Br} \sim O(10^{-9} \sim 10) \]
Lepton universality in the SM

\[ \Gamma(L^- \rightarrow l^- \nu_l \nu_L) = \frac{B(L^- \rightarrow l^- \nu_l \nu_L)}{\tau_\tau} = \frac{G_L G_i m_L^5}{192 \pi^3} f \left( \frac{m_i^2}{m_L^2} \right) R_w R_\gamma, \]

\[ G_i = \frac{g_i^2}{4 \sqrt{2} M_w^2}, \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x, \]

\[ R_w = 1 + \frac{3}{5} \frac{m_L^2}{M_w^2} + 9 \frac{m_i^2}{M_w^2}, \quad R_\gamma = 1 + \frac{\alpha(m_L)}{2 \pi} \left( \frac{25}{4} - \pi^2 \right), \]

\[ g_\tau/g_\mu = 1.0010 \pm 0.0015 \quad \text{HFLAV spring 2017} \]

\[ g_\tau/g_\mu = 1.0029 \pm 0.0015 \quad \text{A.Lusiani, PhiPsi 2017} \]

\[ g_\mu/g_e = 1.0019 \pm 0.0014 \]

precision: 0.20-0.23% pre-B-Factories \( \Rightarrow \) 0.14-0.15% today thanks essentially to the Belle tau lifetime measurement, PRL 112 (2014) 031801
Universality test uncertainty now limited by leptonic BRs and tau lifetime

<table>
<thead>
<tr>
<th>parameter</th>
<th>Δ(value)</th>
<th>Δ(ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_\tau$</td>
<td>0.090%</td>
<td>0.18%</td>
</tr>
<tr>
<td>$B_{\tau \to \mu e}$</td>
<td>0.115%</td>
<td>0.23%</td>
</tr>
<tr>
<td>$m_\tau$</td>
<td>0.022%</td>
<td>0.009%</td>
</tr>
</tbody>
</table>

A.Lusiani, PhiPsi 2017

$B(\tau \to \mu \nu \nu) = 17.392 \pm 0.040 \text{ (HFLAV2017 fit)} (17.319\pm0.070\pm0.032) \text{ (ALEPH)}$

$B(\tau \to e \nu \nu) = 17.816 \pm 0.041 \text{ (HFLAV 2017 fit)} (17.837\pm0.072\pm0.036) \text{ (ALEPH)}$

$R(\mu/e) = 0.9762 \pm 0.0028 \text{ (HFLAV 2017 fit)} (0.9796 \pm 0.0016 \pm 0.0036) \text{ BaBar}$

MASS = 1776.86±0.12 (PDG) 1776.91±0.12+0.10−0.13 BES-III

MEAN LIFE 290.3±0.5 $10^{-15}s$ (290.17±0.53±0.33 Belle)
High-statistics study of the $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decay

*Phys. Rev. D* 78, 072006

$5.6 \times 10^6 \tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decays (72.2/fb).

$$\text{Br}(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau) = (25.17 \pm 0.04 \pm 0.40)\%$$

Systematic uncertainties for branching fraction

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta B_{h\pi^0}$ (%)</th>
<th>$\Delta B/B$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>0.12</td>
<td>0.47</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>0.36</td>
<td>1.4</td>
</tr>
<tr>
<td>Background for $\tau^+\tau^-$</td>
<td>0.09</td>
<td>0.36</td>
</tr>
<tr>
<td>Feed-down background for $\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Non-$\tau$ background for $\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>$\gamma$ veto</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>0.40</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Measurements of branching fractions of $\tau$ lepton decays with one or more $K_S^0$ PRD 89, 072009 (2014)
Spectral functions

PLB 654, 65 (2007) 351 fb⁻¹

\[ \tau^{-}\rightarrow K_S \pi^- \nu_\tau \]

PRD 89, 072009 (2014) 669 fb⁻¹

\[ \tau^{-}\rightarrow \pi^- K_S K_S \pi^0 \nu_\tau \]

\[ m(\pi^- K_S) \]

\[ m(\pi^0 K_S K_S) \]

\[ B(f_1(1285)\pi^- \nu) \cdot B(f_1(1285) \rightarrow K^0_S K^0_S \pi^0) = (0.74 \pm 0.12 \pm 0.08) \cdot 10^{-5} \]

\[ B(f_1(1420) \pi^- \nu) \cdot B(f_1(1420) \rightarrow K^0_S K^0_S \pi^0) = (0.20 \pm 0.09 \pm 0.02) \cdot 10^{-5} \]

\[ B(K^{*-} \rightarrow K^0_S \pi^0) \cdot B(K^{*-} \rightarrow K^0_S \pi^-) = (1.06 \pm 0.15 \pm 0.11) \cdot 10^{-5} \]
Michel parameters

\[
\frac{d\Gamma(\tau^{\pm})}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\text{max}}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \left( x(1-x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0(1-x) \right) \\
+ \frac{1}{3} P_\tau \cos \theta_\ell \xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta (4x - 4 + \sqrt{1-x_0^2}) \right], \quad x = \frac{E_\ell}{E_{\text{max}}}, \quad x_0 = \frac{m_\ell}{E_{\text{max}}}
\]

In the SM: \( \rho = \frac{3}{4}, \eta = 0, \xi = 1, \delta = \frac{3}{4} \)

<table>
<thead>
<tr>
<th>Michel par.</th>
<th>Measured value</th>
<th>Experiment</th>
<th>SM value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho = )</td>
<td>0.747 ± 0.010 ± 0.006</td>
<td>CLEO-97</td>
<td>3/4</td>
</tr>
<tr>
<td>( \eta = )</td>
<td>0.012 ± 0.026 ± 0.004</td>
<td>ALEPH-01</td>
<td>0</td>
</tr>
<tr>
<td>( \xi = )</td>
<td>1.007 ± 0.040 ± 0.015</td>
<td>CLEO-97</td>
<td>1</td>
</tr>
<tr>
<td>( \xi \delta = )</td>
<td>0.745 ± 0.026 ± 0.009</td>
<td>CLEO-97</td>
<td>3/4</td>
</tr>
<tr>
<td>( \xi h = )</td>
<td>0.992 ± 0.007 ± 0.008</td>
<td>ALEPH-01</td>
<td>1</td>
</tr>
</tbody>
</table>

Effect of \( \tau \) spin-spin correlation is used to measure \( \xi \) and \( \delta \). Topology of Events (\( \tau^- \to l^-\nu\nu; \tau^+ \to \rho^+\nu \)) are used to measure: \( \rho, \eta, \xi \rho, \xi \rho \xi \delta \), while (\( \tau^- \to \rho^-\nu; \tau^+ \to \rho^+\nu \)) events are used to extract \( \xi \rho^2 \) (arXiv:1409.4969)

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LHCB SEMITAUONIC, Orsay, France
Conclusion

• At present, the SuperKEKB/Belle II project is in commissioning. Very high expected luminosity of this experiment provides a possibility of the precise study of the $\tau$ lepton physics.

• We hope that high statistics and improved detector will help to reduce considerably systematic uncertainties.
Effect of $\tau$ spin-spin correlation is used to measure $\xi$ and $\delta$ MP.
Events of the $(\tau^{+} \rightarrow \ell^{+}\nu\nu; \tau^{+} \rightarrow \rho^{\pm}\nu)$ topology are used to measure: $\rho$, $\eta$, $\xi_\rho$, $\xi_\delta$, and $\xi_\rho\xi_\delta$, while $(\tau^{+} \rightarrow \rho^{\mp}\nu; \tau^{\mp} \rightarrow \rho^{\pm}\nu)$ events are used to extract $\xi_\rho^2$.

From D.Epifanov