Recent results on tau decays at Belle experiment

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Topics of tau physics at Belle

- New physics search
  - tau LFV
  - tau CPV
- SM precise measurement
  - BF measurement of hadronic decays
  - evaluation of the spectrum of the hadronic current
  - 2\textsuperscript{nd} class current search
  - measurement of |V_{us}|
- Tau property measurement
  - tau mass measurement
  - tau lifetime measurement
  - tau EDM measurement
  - tau Michel parameter measurement
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TAU EDM MEASUREMENT
Introduction for tau EDM (1)

- EDM violates CP since it signifies a charge asymmetry along spin direction.
- Standard model prediction: $\propto(10^{-37})$ ecm
  - Sizable EDM of tau is a signal of New Physics
  - Through a loop diagram with new particles, EDM can appear.
- Current upper limit:
  - Belle: 29.5 fb\(^{-1}\)
  - $2.2 < \text{Re}(d_\tau) \times 10^{17} < 4.5$ (emu)
  - $2.5 < \text{Im}(d_\tau) \times 10^{17} < 0.8$ (emu)
Introduction for tau EDM (2)

- Due to the short life time of tau (~90μm), a measurement via radiative process is difficult, differently from that for muon.
- In a B–factory, through the tau–pair production vertex, tau EDM can be evaluated.
Effective lagrangian and Spin density matrix element

- Effective Lagrangian with EDM for $e^+e^-\rightarrow \tau^+\tau^-$
\[
\mathcal{L} = \bar{\tau} (i\vec{\nabla} - eA)\tau - \frac{i}{2} d_\tau \bar{\tau} \sigma^{\mu\nu} \gamma_5 \tau F_{\mu\nu}
\]

- Squared spin density matrix
\[
M^2_{\text{prod}} = M^2_{\text{SM}} + \text{Re}(d_\tau)M^2_{\text{Re}} + \text{Im}(d_\tau)M^2_{\text{Im}} + |d_\tau|^2 M^2_{\text{SM}}
\]

- Through the interference term, EDM effect will be seen.

\[
M^2_{\text{Re}} \sim (\vec{S}_+ \times \vec{S}_-)\vec{k}, \quad (\vec{S}_+ \times \vec{S}_-)\vec{p} : \text{CP–odd, T–odd}
\]

\[
M^2_{\text{Im}} \sim (\vec{S}_+ - \vec{S}_-)\vec{k}, \quad (\vec{S}_+ - \vec{S}_-)\vec{p} : \text{CP–odd, T–even}
\]

$\vec{S}_\pm$: spin vector of $\tau^\pm$

$\vec{k}$: momentum for $\tau^+$

$\vec{p}$: momentum for beam $e^+$
Optimal observable method

- Optimal observable (OO) method is more sensitive than simple cross section measurement:

\[
\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{SM}}
\]

\[
\langle \mathcal{O}_{Re} \rangle \propto \int \mathcal{O}_{Re} d\sigma \propto \int \mathcal{O}_{Re} \mathcal{M}^2_{prod} d\phi
\]

\[
= \int \mathcal{M}^2_{Re} d\phi + \text{Re}(d_\tau) \int \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{SM}} d\phi
\]

- Calculate OO event by event and take the average of them, that is linear function of EDM. Here, parameters, a and b, should be evaluated using MC samples having various size of EDM.

- Similar formula of Im(\(d_\tau\)) can be obtained by replacing Re by Im.

MC simulation (ee \(\rightarrow\) \(\tau\tau\) \(\rightarrow\) \(\pi\pi\nu\nu\)) with/without EDM (5x10^{-16}ecm)
Evaluate OO

- Tau spin is also input to OO.
  - Need tau direction.
  - We can reconstruct tau direction with twofold ambiguity in case where both taus make hadronic decay.
  - In the case where one decay is leptonic, ambiguity gets continuous.
  - In any case, the average is taken over the possible tau directions.
  - The size of helicity is evaluated from daughters’ kinematical information.
Belle experiment

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

Belle has finished data taking in 2010.

A B–factory is also a tau factory since the production cross section for \( BB \) and \( \tau^- \text{pair} \) is very similar. (1.1nb vs 0.9nb)

Belle detector is a multi–purpose and asymmetric detector and has good:
- lepton identification
- hermeticity

Lepton ID \(~ 80\% \) for \( \mu \), 90\% for \( e \)
Fake ID \(~ 3\% \) for \( \mu \), 0.1\% for \( e \)
Selected tau decays and BG

• Select 8 final modes exclusively using 825 fb$^{-1}$ data sample
  • $\tau\tau \rightarrow e\mu(4\nu), e\pi(3\nu), \mu\pi(3\nu), \mu\rho(3\nu), \pi\rho(2\nu), \rho\rho(2\nu), \pi\pi(2\nu)$
  • PID for e, $\mu$, $\pi$
  • $\rho$ reconstructed from $\pi\pi^0(\rightarrow \gamma\gamma)$
  • Require high momentum and barrel region to reduce systematic errors

• Total yield: $3.5 \times 10^7$ events, Averaged purity: 87.7%

• Background
  • Main: from tau decay: Missing-$\pi^0$ and mis-PID

<table>
<thead>
<tr>
<th>mode</th>
<th>yield</th>
<th>purity (%)</th>
<th>Background (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>6434k</td>
<td>95.8</td>
<td>$2\gamma \rightarrow \mu\mu(2.5)$</td>
</tr>
<tr>
<td>$e\pi$</td>
<td>2645k</td>
<td>85.7</td>
<td>$\tau\tau \rightarrow e\rho(6.5) e\mu(5.1)$</td>
</tr>
<tr>
<td>$\mu\pi$</td>
<td>2504k</td>
<td>80.5</td>
<td>$\tau\tau \rightarrow \mu\rho(6.4) \mu\mu(4.9), 2\gamma \rightarrow \mu\mu(3.1)$</td>
</tr>
<tr>
<td>$e\rho$</td>
<td>7219k</td>
<td>91.7</td>
<td>$\tau\tau \rightarrow e\pi\pi^0\pi^0(4.6)$</td>
</tr>
<tr>
<td>$\mu\rho$</td>
<td>6203k</td>
<td>91.0</td>
<td>$\tau\tau \rightarrow \mu\pi\pi^0\pi^0(4.3)$</td>
</tr>
<tr>
<td>$\pi\rho$</td>
<td>2656k</td>
<td>77.0</td>
<td>$\tau\tau \rightarrow \rho\rho(6.7) \mu\rho(5.1) \pi\pi\pi^0\pi^0(3.9)$</td>
</tr>
<tr>
<td>$\rho\rho$</td>
<td>6554k</td>
<td>82.4</td>
<td>$\tau\tau \rightarrow \rho\pi\pi^0\pi^0(9.4) \rho K^*(3.1)$</td>
</tr>
<tr>
<td>$\pi\pi$</td>
<td>921k</td>
<td>71.9</td>
<td>$\tau\tau \rightarrow \pi\rho(11.3) \pi\mu(8.8) \pi K^*(2.5)$</td>
</tr>
</tbody>
</table>
Selected data and MC samples

- $\cos\theta$ (polar angle) and momentum distribution

- Good visual agreement between data and MC
  - However, there are small mismatches in the distribution, which are the dominant contribution to the systematic error. Discuss later
OO distributions

- Good agreement in the distributions
Since $\int M_{\text{Re}}^2 d\phi$ and $\int (M_{\text{Re}}^2)^2 M_{\text{SM}}^2 d\phi$ includes complicated detector and acceptance effects, they cannot be obtained by the analytic calculation. So, we use MC samples having different EDM values to evaluate them.

$$\langle O_{\text{Re}} \rangle = a_{\text{Re}} \text{Re}(d_\tau) + b_{\text{Re}}$$

$$\langle O_{\text{Im}} \rangle = a_{\text{Im}} \text{Im}(d_\tau) + b_{\text{Im}}$$
Parameters to extract EDM

- We evaluate $a$ and $b$ mode by mode as well as finally EDM value mode by mode. And then, average those EDM values.

  Coefficient $a$ (~sensitivity)

  Offset $b$

- Reduced sensitivity for leptonic decays due to additional missing neutrinos
- Offset $b_{\text{Im}}$ due to the F/B asymmetric acceptance
Mismatch of distribution gives large contribution. 
The systematic uncertainties are comparable to the statistical one.
Sensitivity of this measurement

- By adding statistical and systematic uncertainties for each mode quadratically, the error can be evaluated for the final result.

- The error of this measurement:

  \[
  \text{Re}(d_{\tau}) \times 10^{17} : \pm 0.33 \text{ (ecm)}
  \]

  \[
  \text{Im}(d_{\tau}) \times 10^{17} : \pm 0.30 \text{ (ecm)}
  \]

- The error of \(\text{Re}(d_{\tau})\) is around 5 times smaller than previously.
  - Almost proportional to \(1/\sqrt{N_{\tau\tau}}\)
  - The error of \(\text{Im}(d_{\tau})\) is dominated by the systematics.

The result will be shown soon.
TAU MICHEL PARAMETERS MEASUREMENT
Introduction for tau Michel parameters

- Michel parameters (MP) well express the property of Weak interaction in tau decay and definition is:

\[
d\Gamma(\tau \to \ell \nu \nu) = \frac{4G_F^2 M_\tau E^4_{\text{max}}}{(2\pi)^4} \sqrt{x^2 - x_0^2} \left( x(1 - x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0 (1 - x) \right)
\]

\[
\mp \frac{1}{3} P_{\tau} \cos \theta_{\ell} \xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta (4x - 4 + \sqrt{1 - x_0^2}) \right], \quad x = \frac{E_\ell}{E_{\text{max}}}, \quad x_0 = \frac{m_\ell}{E_{\text{max}}}
\]

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

- Type II 2HFM predicts: \( \eta = \frac{m_\mu M_\tau}{2} \left( \tan^2 \beta \right) \left( \frac{M_{H^+}^2}{M_{H^+}^2} \right)^2 \)

Similarly, new physics effects can appear in Michel parameters, that more strongly couple to tau than muon.
Current status of the measurement of MPs

Using 300x more data sample at Belle than the previous experiment, one-order-magnitude improvement of the measurement is expected since Belle and BaBar have never evaluated them yet so far.
Using 300x more data sample at Belle than the previous experiment, one-order-magnitude improvement of the measurement is expected since Belle and BaBar have never evaluated them yet so far. **O(0.1)%!**
Analysis method

- Since tau spin information is necessary to measure some MPs, we utilize both tau decays:
  - Background:
    - $\tau^+\rightarrow\pi^+\pi^0\pi^0\nu / \tau^-\rightarrow\ell^-\nu\nu (~10\%)$,
    - $\tau^+\rightarrow\rho^+\nu / \tau^-\rightarrow\pi^-\nu (~1.5\%)$,
    - others($~2.0\%),\text{non}-\tau\tau<0.1\%$
  - By an unbinned maximum likelihood fit, we evaluate MPs and amount of signal and BG.
Likelihood function

\[ P(x) = \frac{\bar{\varepsilon}(x)}{\varepsilon} \left( 1 - \sum_{i} \lambda_i \right) \int \frac{S(x)}{\bar{\varepsilon}(x)} S(x) dx + \lambda_{3\pi} \int \frac{\tilde{B}_{3\pi}(x)}{\bar{\varepsilon}(x)} \tilde{B}_{3\pi}(x) dx + \lambda_{\pi} \int \frac{\tilde{B}_{\pi}(x)}{\bar{\varepsilon}(x)} \tilde{B}_{\pi}(x) dx + \lambda_{\text{other}} \int \frac{B_{\text{MC}}(x)}{\bar{\varepsilon}(x)} B_{\text{MC}}(x) dx \]

\[ \tilde{B}_{3\pi}(x) = \int (1 - \varepsilon_0^0(y)) \varepsilon_{\text{add}}(y) B_{3\pi}(x, y) dy, \quad \tilde{B}_{\pi}(x) = \frac{\varepsilon_{\mu\mu}(x)}{\varepsilon_{\mu\mu}(x)} B_{\pi}(x) \]

\[ x = (p_\ell, \Omega_\ell, p_\rho, \Omega_\rho, m_\pi^0, \Omega_\pi), \quad y = (p_\pi^0, \Omega_\pi^0) \]

- \( S(x) \): density of signal (\( \ell^\mp, \pi^\pm 0 \)) events
- \( B_{3\pi}(x) \): density of background (\( \ell^\mp, \pi^\pm 2\pi^0 \)) events
- \( B_{\pi}(x) \): density of background (\( \pi^\mp, \pi^\pm 2\pi^0 \)) events
- \( B_{\text{MC}}(x) \): MC density of the remaining background
- \( \varepsilon(x) \): detection efficiency for signal events
- \( \varepsilon_0^0(x) \): \( \pi^0 \) efficiency
- \( \varepsilon_{\text{add}}(x) \): additional efficiency background (\( \ell^\mp, \pi^\pm 2\pi^0 \)) events
- \( \varepsilon_\pi(x) \): detection efficiency for (\( \pi^\mp, \pi^\pm 2\pi^0 \)) events
Test of the fitter with MC

For each configuration 5M MC sample is fitted. The other, statistically independent, 5M MC sample was used to calculate normalization.

\[(e^+; \pi^-\pi^0)\]
\[
\begin{array}{lll}
\rho & = & 0.7517 \pm 0.0010 \\
\eta & = & 0 \quad \text{fixed} \\
\xi & = & 1.0092 \pm 0.0043 \\
\xi\delta & = & 0.7538 \pm 0.0027 \\
\end{array}
\]

\[(\mu^+; \pi^-\pi^0)\]
\[
\begin{array}{lll}
\rho & = & 0.7494 \pm 0.0027 \\
\eta & = & 0.0052 \pm 0.0101 \\
\xi & = & 0.9995 \pm 0.0050 \\
\xi\delta & = & 0.7519 \pm 0.0033 \\
\end{array}
\]
Corrections

- Effects which should be included into the fit are listed up.
  - Physics corrections
    - Higher order corrections of EW for $e^+e^-\rightarrow\tau^+\tau^-$ reaction upto $O(\alpha^3)$
    - Radiative decays $\tau^-\rightarrow\ell^-\nu\nu\gamma$, $\tau^-\rightarrow\pi^0\nu\gamma$
  - Detector effects
    - Track momentum resolution
    - $\gamma$ energy and angular resolution
    - Beam energy spread
    - Effect of bremsstrahlung for e
    - DATA/MC efficiency correction for trigger, track rec., PID and so on.
Fit for the experimental data

Here, $4.5 \times 10^6$ tau-pair events are used.

\[ (e^+; \rho^-) \]

\[ (e^+; 3\pi) \]
O(0.1)% measurements will be achieved.

Now, studying details for the fit bias, which increases the systematics.

After understanding the fit result, we can show the final result.
Summary

- We are measuring tau EDM and tau Michel parameters using the world largest tau data sample. $\sim O(10^9)$

- **Tau EDM**
  
  $$\text{Re}(d_\tau) \times 10^{17} : \pm 0.33 \ (ecm)$$
  $$\text{Im}(d_\tau) \times 10^{17} : \pm 0.30 \ (ecm)$$

  - For $\text{Re}(d_\tau)$, improvement by $\sqrt{N_{\tau\tau}}$, For $\text{Im}(d_\tau)$, systematic dominant.

- **Tau Michel parameters**
  
  - Errors of four parameters will be $O(0.1)\%$

- Previous result
  
  $$\text{Re}(d_\tau) \times 10^{17} : 1.15 \pm 1.70 \ (ecm)$$
  $$\text{Im}(d_\tau) \times 10^{17} : -0.83 \pm 0.86 \ (ecm)$$
Summary

- We are measuring tau EDM and tau Michel parameters using the world largest tau data sample. ~O(10^9)

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- Tau Michel parameters
  - Errors of four parameters will be \( O(0.1)\% \)

  Around summer, we will show the final results for both!
Contents of this talk

a. Topics of tau physics at Belle
b. Tau EDM measurement
c. Tau Michel parameter measurement