Tau Physics at the Super B-Factory

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- Introduction
- Lepton Flavor Violation
- CP Violation
- Summary
Introduction

• A fun of physics in $\tau$ lepton
  • The heaviest lepton known to date
    ⇒ Naively expected to be sensitive to the New Physics
  • The only lepton heavy enough to decay hadronically
    ⇒ Include a rich physical contents

Why $\tau$ in B-Factory?
Production cross section @ $\sqrt{s} = 10.58$ GeV:

$\sigma(e^+e^- \rightarrow B\bar{B}) = 1.05$nb, $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.89$nb

⇒ B-Factory = $\tau$-Factory

Plan of this talk
Two major topics to search for the physics beyond the SM at the current and Super B-Factory:

• Search for the Lepton Flavor Violation in $\tau$ decays
• Search for the $CP$ Violation in $\tau$ lepton
Lepton Flavor Violation in $\tau$ Lepton

- Lepton Flavor Violation (LFV)
  Forbidden in the SM (w/ massless $\nu$)
  - Charged lepton sector: Has not been observed
  - Neutrino sector: Observation of the neutrino oscillation

- LFV in the SM with $\nu$-oscillation
  $\nu$-oscillation induces the LFV in the charged lepton sector. However, it is suppressed drastically:
  \[ Br(\text{LFV } \tau \text{ decays}) \lesssim 10^{-40} (m_\nu/1\text{eV})^4 \]

- LFV in Physics beyond the Standard Model: SUSY, GUT, ···
  $\Rightarrow$ Predictions can be observed in the (Super) B-Factory.
  Two promising modes expected in some SUSY models:
  - $\tau \rightarrow \mu \gamma$ : cf) MSSM with Seesaw
    (J. Hisano et al., PRD60(1999)055008), ···
  - $\tau \rightarrow \mu \eta$ : cf) Higgs mediated in MSSM
    (K. Babu and C. Kolda, PRL89(2002)241802), ···
LFV: Current Experimental Status

Upper Limit

<table>
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<tr>
<th>Year</th>
<th>10^{-8}</th>
<th>10^{-6}</th>
<th>10^{-4}</th>
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<td>1990</td>
<td>9.6x10^{-6}@CLEO</td>
<td>4.2x10^{-6}@CLEO</td>
<td>2.0x10^{-4}@CRYSTAL BALL</td>
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<tr>
<td>2000</td>
<td>3.4x10^{-5}/1.2x10^{-4}@ARGUS</td>
<td>6.2x10^{-5}/1.1x10^{-4}@DELPHI</td>
<td>3.0x10^{-6}/2.7x10^{-6}@CLEO</td>
</tr>
<tr>
<td>2010</td>
<td>3.1x10^{-7}@Belle</td>
<td>1.1x10^{-6}@CLEO</td>
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</table>

SUSY SM/GUT with $V_R$

SUSY SU(5) GUT w/o $V_R$

- $\tau \rightarrow \mu \gamma$
- $\tau \rightarrow e \gamma$
- $\tau \rightarrow \mu \eta$

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**LFV: $\tau \rightarrow \mu \gamma$ of Belle/BaBar**

**Table:**

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<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Babar</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>$86.7 \text{ fb}^{-1}$</td>
<td>$232 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>Signal Region</td>
<td>$\pm 3\sigma$ box</td>
<td>$\pm 2\sigma$ ellipse</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$10.9%$</td>
<td>$7.42%$</td>
</tr>
<tr>
<td>Expected BG</td>
<td>$20.2 \pm 2.1$</td>
<td>$6.2 \pm 0.5$</td>
</tr>
<tr>
<td>Observed ev</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>UL of Br ($\times 10^{-7}$)</td>
<td>3.1</td>
<td>0.68</td>
</tr>
</tbody>
</table>
**LFV: $\tau \rightarrow \mu \gamma$**

- **MSSM with Seesaw**
  
  (J. Hisano et al., PRD60(1999)055008):

  \[
  Br(\tau \rightarrow \mu \gamma) \simeq 7 \times 10^{-7} \left( \frac{\tan \beta}{60} \right)^2 \left( \frac{1 \text{TeV}/c^2}{m_{\text{SUSY}}} \right)^4
  \]

- **Upper Limit by BaBar's Preliminary result:**

  \[
  Br(\tau \rightarrow \mu \gamma) < 6.8 \times 10^{-8}
  \]

  @BaBar (hep-ex/0502032)

  ⇒ Constraint on $\tan \beta - m_{\text{SUSY}}$

  \[
  \tan \beta \propto m_{\text{SUSY}}^2
  \]
**LFV: $\tau \rightarrow \mu \eta$**

Higgs mediated in MSSM
(Babu & Kolda PRL\textbf{89}(2002)241802):

$$Br(\tau \rightarrow \mu \eta) = 8.4 \times 10^{-7} \left(\frac{\tan \beta}{60}\right)^6 \left(\frac{100\text{GeV}/c^2}{m_A}\right)^4$$

Upper Limit by Belle’s Preliminary result:

$$Br(\tau \rightarrow \mu \eta) < 1.5 \times 10^{-7}$$

@Belle (hep-ex/0503041) 
⇒ Constraint on $\tan \beta - m_A$

$$(\tan \beta \propto m_A^{2/3})$$

We’ve obtained more stringent limit than CDF.
Thanks to Prof. I. Bigi, here is a summary of the CPV in τ Physics.

- CPV is necessary for baryogenesis. However, CKM dynamics is irrelevant for it.

- One attractive alternative: Leptogenesis driving baryogenesis
  cf) Previous talk by H. Paes
  ⇒ Search for CPV in lepton sector

- CPV in the lepton sector
  Has not been observed yet, in contrast with the quark sector.
  - Search for CPV in the neutrino sector
    A very tough challenge.
  - Search for EDM of charged leptons
    In some model, τ is most sensitive due to its heaviest mass.
  - Search for CPV in tau decays
    One of the most promising mode: \( \tau \rightarrow K\pi\nu \)
    (J. Kühn and E. Mirkes, PL B398(1997)407)
    Bigi pointed out: \( \mathcal{O}(10^{-3}) \) is expected in \( \tau \rightarrow K_S\pi\nu \)
Non-vanishing $\tau$’s EDM, $d_\tau$ $\Rightarrow$ T Violation ($\Leftrightarrow$ CPV under CPT)

- $d_\tau$ should be proportional to the spin $S$: $d_\tau \propto S$
- Under T transformation: $d_\tau \rightarrow d_\tau$, $S \rightarrow -S$

$\Rightarrow$ If T is retained, $d_\tau = 0$.

Theoretical predictions

- SM (w/ massless $\nu$): $|d_\tau| \lesssim 10^{-34} e \text{ cm}$
- Mult-Higgs: $|d_\tau| \lesssim 10^{-23} e \text{ cm} \propto (m_\ell^3/m_\phi^2)$
- Leptoquarks: $|d_\tau| \lesssim 10^{-19} e \text{ cm} \propto m_t^2 m_\tau$
$\tau$’s EDM: Experimental Status

![Graph showing upper limits on EDM measurements from various experiments: Grifols et al., Delaguila et al., OPAL, L3, ARGUS, and Belle.](image)

- **Re(EDM):**
  - Grifols et al.: $-2.5 \times 10^{-17}$
  - Delaguila et al.: $-2.5 \times 10^{-17}$
  - OPAL: $-2.5 \times 10^{-17}$
  - L3: $-2.5 \times 10^{-17}$
  - ARGUS: $-2.5 \times 10^{-17}$

- **Im(EDM):**
  - Belle: $-2.2 \times 10^{-17}$ to $4.5 \times 10^{-17}$

Expected upper limit at 1000 fb$^{-1}$:

- **Leptoquark**
  - Expected upper limit: $10^{-18}$

Years:
- 1990
- 2000
- 2010

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DCPV in $\tau \rightarrow K_S\pi\nu$

According to the similar argument as the DCPV of $D^+ \rightarrow K_S\pi^+\nu$ in the Bigi and Sanda’s famous text book, DCPV in $\tau^- \rightarrow K_S\pi^-\nu$

$$\mathcal{A}_{CP} = \frac{\Gamma(\tau^+ \rightarrow K_S\pi^+\nu) - \Gamma(\tau^- \rightarrow K_S\pi^-\nu)}{\Gamma(\tau^+ \rightarrow K_S\pi^+\nu) + \Gamma(\tau^- \rightarrow K_S\pi^-\nu)} \simeq 3 \times 10^{-3}$$

is expected due to the well-known $CP$ impurity in $K_S$:

$$K_S = \frac{(1 - \epsilon)K^0 - (1 + \epsilon)\bar{K}^0}{\sqrt{2}}$$

⇒ This should be observed!


$$-0.172 < Im(\Lambda) < 0.067$$

for the coupling constant $\Lambda$ defined as

$$A(\tau^- \rightarrow K\pi^-\nu) \sim \bar{\nu}\gamma_\mu(1 - \gamma_5)\tau f_V Q^\mu + \Lambda\bar{\nu}(1 + \gamma_5)\tau f_SM$$

We can reach the sensitivity of $10^{-3}$ order at a few ab$^{-1}$

⇒ $CPV$ in lepton sector can be found at the Super B-Factory!
Summary

Current status of two major topics to search for the physics beyond the Standard Model in $\tau$ Lepton are reviewed:

- **Lepton Flavor Violation:** $\tau \rightarrow \mu \gamma, \quad \tau \rightarrow \mu \eta$
- **CP Violation:** $\tau$’s EDM, $\tau \rightarrow K_S \pi \nu$

We discussed the expected sensitivities in these physics at the Super B-Factory.

- **LFV**
  We have already obtained the constraints on parameter spaces of the models of New Physics. More stringent limits can be obtained, or we can observe the New Physics at the Super B-Factory.

- **CPV**
  We’ve not observed any CPV in the lepton sector including $\tau$. We can reach the sensitivity to the prediction of the New Physics at the Super B-Factory. Especially, DCPV in $\tau \rightarrow K_S \pi \nu$ should be observed.

One of the important advantage of the B-Factory ($e^+e^-$ collider) to the hadron collider: We can look for $\tau$ polarization dependence CP asymmetry w/o needing polarized beam!
τ’s EDM: How to measure?

Effective Lagrangian with non-zero EDM term:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EDM}} = \bar{\psi}(i\partial - eQA)\psi - \frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi d_\tau F_{\mu\nu} \]

\[ \Rightarrow \text{Deviation of the cross section, i.e. amplitude } \mathcal{M}, \text{ from the SM:} \]

\[ \mathcal{M}^2_{e^+e^-\rightarrow \tau^+\tau^-} = \mathcal{M}^2_{\text{SM}} + \text{Re}(d_\tau)\mathcal{M}^2_{\text{Re}} + \text{Im}(d_\tau)\mathcal{M}^2_{\text{Im}} + O(d^2_\tau) \]

where

\[ \mathcal{M}^2_{\text{Re}} \sim (S_+ \times S_-) \cdot \hat{k}, \quad (S_+ \times S_-) \cdot \hat{p}, \]

\[ \mathcal{M}^2_{\text{Im}} \sim (S_+ - S_-) \cdot \hat{k}, \quad (S_+ - S_-) \cdot \hat{p} \]

\[ S_\pm : \tau^\pm \text{ spin vector, } \quad \hat{p} : e^+ \text{ direction, } \quad \hat{k} : \tau^+ \text{ direction.} \]

Optimal Observable for the τ’s EDM:

\[ \mathcal{O}_{\text{Re}} = \frac{\mathcal{M}^2_{\text{Re}}}{\mathcal{M}^2_{\text{SM}}}, \quad \mathcal{O}_{\text{Im}} = \frac{\mathcal{M}^2_{\text{Im}}}{\mathcal{M}^2_{\text{SM}}} \Rightarrow \text{Maximize S/N} \]

We can extract the τ’s EDM from \( \mathcal{O} \) by using the following Eq.:

\[ \langle \mathcal{O}_{\text{Re}} \rangle = a_{\text{Re}} \cdot \text{Re}(d_\tau) + b_{\text{Re}} \]

\[ \langle \mathcal{O}_{\text{Im}} \rangle = a_{\text{Im}} \cdot \text{Im}(d_\tau) + b_{\text{Im}} \]
Evaluation of $A_{CP}(\tau^+ \rightarrow K_S \pi^+ \nu)$

In the SM one has
\[ \Gamma(\tau^+ \rightarrow K^0 \pi^+) = \Gamma(\tau^- \rightarrow \bar{K}^0 \pi^-). \]

And we know that $K_S$ is CP impurity as the experimental result:
\[ K_S = \frac{1}{\sqrt{2}} \left( \frac{1 - \epsilon}{\sqrt{1 + \epsilon^2}} K^0 - \frac{1 + \epsilon}{\sqrt{1 + \epsilon^2}} \bar{K}^0 \right) \equiv q_K K^0 + p_K \bar{K}^0. \]

We here consider the amplitude of this decay mode:
\[ A(\tau^+ \rightarrow K_S^\pi^+) = A(\tau^+ \rightarrow \bar{K}^0 \pi^+)\langle K_S | \bar{K}^0 \rangle + A(\tau^+ \rightarrow K^0 \pi^+)\langle K_S | K^0 \rangle. \]

We can neglect $A(\tau^+ \rightarrow K^0 \pi^+)/A(\tau^+ \rightarrow \bar{K}^0 \pi^+)$ and obtain
\[ \Gamma(\tau^+ \rightarrow K_S^\pi^+) \simeq \Gamma(\tau^+ \rightarrow \bar{K}^0 \pi^+) |q_K|^2 \]
and similarly,
\[ \Gamma(\tau^- \rightarrow K_S^\pi^-) \simeq \Gamma(\tau^+ \rightarrow K^0 \pi^+) |p_K|^2. \]

Finally,
\[ A_{CP} \simeq \frac{|q_K|^2 - |p_K|^2}{|q_K|^2 + |p_K|^2} \simeq 2 Re(\epsilon) \simeq 10^{-3}, \]

we here used measured value of $\epsilon$ in $K_L \rightarrow \pi \pi$. 
Babu and Kolda pointed out (PRL89(2002)241802)):

$$Br(\tau \rightarrow \mu \eta) : Br(\tau \rightarrow 3\mu) : Br(\tau \rightarrow 3\mu) = 8 : 1.5 : 1$$

for Higgs mediated process.

Comparing $\tau \rightarrow \mu \eta$ with $\tau \rightarrow 3\mu\eta$:

- Color factor: 3
- Phase space: 2-body and 3-body decay
- Mass: $m_s > m_{\mu}$
\( \tau \) LFV: Other Modes

Red: Preliminary  Blue: Published

\( \Box \): CLEO Result  \( \triangle \): BaBar Result  \( \bullet \): Belle Result