Физика τ лептона на B фабриках

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Outline

- KEKB and Belle
- SuperKEKB and Belle II

- \( \tau \) physics at Belle, Belle II
  - LFV in \( \tau \)-decays
  - Rare \( \tau \) decays \( (\tau \rightarrow \ell \ell \ell \nu \nu, \tau \rightarrow \ell \nu \nu \gamma) \)
  - CP violation in \( \tau \) decays \( (\tau \rightarrow K_S^0 \pi \nu) \)
  - \( \tau \) mass measurement
  - \( \tau \) lifetime measurement

- Summary
KEK Laboratory, Tsukuba Japan

Mt Tsukuba

Belle Detector

KEKB
The KEKB Collider

- Asymmetric energy collider (8 GeV e⁻ x 3.5 GeV e⁺)
  - $\sqrt{s} \approx m_{\Upsilon(4S)} (\Upsilon(nS), n=1,2,3,5)$
  - Lorentz boost: $\beta \gamma = 0.425$
- Finite angle beam crossing (22 mrad)

**Peak luminosity (WR!):**

$$2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} = 2 \times \text{design value}$$

First physics run on June 2, 1999
Last physics run on June 30, 2010
$L_{\text{peak}} = 2.1 \times 10^{34} / \text{cm}^2 / \text{s}$

$$\int \mathcal{L} \, dt = 1.04 \text{ ab}^{-1}$$
Data at KEKB/Belle

- KEKB
- PEP-II

- 772M $\bar{B}B$
- 487M $\bar{B}B$

- $> 1000 \text{ fb}^{-1}$ !
- $(1 \text{ ab}^{-1})$

- On resonance:
  - $\Upsilon(5S)$: 121 fb$^{-1}$
  - $\Upsilon(4S)$: 711 fb$^{-1}$
  - $\Upsilon(3S)$: 3 fb$^{-1}$
  - $\Upsilon(2S)$: 24 fb$^{-1}$
  - $\Upsilon(1S)$: 6 fb$^{-1}$

- Off resonance/scan:
  - $\sim 100 \text{ fb}^{-1}$

- $\sim 550 \text{ fb}^{-1}$

- On resonance:
  - $\Upsilon(4S)$: 433 fb$^{-1}$
  - $\Upsilon(3S)$: 30 fb$^{-1}$
  - $\Upsilon(2S)$: 14 fb$^{-1}$

- Off resonance:
  - $\sim 54 \text{ fb}^{-1}$
SuperKEKB Luminosity profile

Goal of Belle II/SuperKEKB

Assumes full operation funding profile

50 ab$^{-1}$

Assumes adequate staffing of SuperKEKB

Physics run will start in 2018
Belle II Detector

Belle II is built on basis of Belle

- Main structure and magnet are reused
- ECL and KLM are mostly reused
- Vertex detector, drift chamber, PID, partially KLM are upgraded
- All electronics is replaced
Detector improvements

- Smaller beam pipe radius allows to place the innermost PXD layer closer to the Interaction point \( (r = 1.4\text{cm}) \)
  - Significantly improves the vertex resolution along \( z \) direction.

- Pixel part of the vertex detector, larger SVD and CDC
  - Improve vertex and timing resolution, better flavor tagging, increases \( K_S \) efficiency.

- PID: TOP and ARICH
  - Better \( K/\pi \) separation covering the whole range momentum.

- ECL and KLM
  - Less material in front of ECL;
  - Improvements in ECL and KLM to compensate for a larger beam background.

- Improved hermeticity.

- Improved trigger and DAQ.
Physics at B factory

Accelerator
"B-Factory", KEKB @, KEK

\[ \Upsilon(4S) \]

"on resonance" production
\[ e^+e^- \to \Upsilon(4S) \to B_d^0\bar{B}_d^0, B^+B^- \]

\[ \sigma(e^+e^- \to B\bar{B}) \approx 1.1 \text{ nb} \ (\sim 10^9 \text{ B}\bar{B} \text{ pairs}) \]

"continuum" production
\[ \sigma(e^+e^- \to c\bar{c}) \approx 1.3 \text{ nb} \ (\sim 1.3 \times 10^9 X_c \bar{Y}_c \text{ pairs}) \]

\[ \tau^+\tau^- \text{ production} \]
\[ \sigma(e^+e^- \to \tau^+\tau^-) \approx 0.9 \text{ nb} \ (\sim 0.9 \times 10^9 \tau^+\tau^- \text{ pairs}) \]

Running at \( \Upsilon(nS) \), e.g. \( \Upsilon(5S) \to (B_s\bar{B}_s) \)

=> B-factory is also \( \tau \) factory!

Complement/Cooperative with \( \tau / \) Charm factory

Belle \( \int \mathcal{L}dt \approx 1020 \text{ fb}^{-1} \)

\( B\bar{B} \) threshold

Belle II \( \int \mathcal{L}dt \approx 50 \text{ ab}^{-1} \) => \( \sim 5 \times 10^{10} \tau \text{ pairs} \)

\( \approx 50 \times \text{the Belle data sample} \)
Introduction

- After discovery of CP-violation in B-decays by Belle and BaBar in 2001 (Nobel prize in physics for Kobayashi and Maskawa in 2008) and Higgs boson by CMS and ATLAS in 2012 (Nobel prize in physics for Higgs in 2013) experimental grounds of the Standard model are complete.

- The Standard Model describes known processes quite well. 
  \textit{SM is a valid effective theory at the current E-scale.}

- However, there are indications that the Standard Model is not complete:
  - neutrino oscillations, baryon asymmetry, dark mater;
  - too many parameters, hierarchy problem.

- There should be something beyond the Standard Model – New Physics (NP).

\textbf{LHC} – New Physics beyond SM at \textbf{High Energy scale}

\textbf{B-, charm-, \(\tau\)- factories} – search for NP using \textbf{indirect probes}
Topics of $\tau$ physics at Belle

$\tau$ lepton

– the heaviest lepton = 1.78 GeV (expect strong coupling to NP)
– the only lepton able to decay to meson(s) = various decays allowed
– belonging to the third generation

- New physics search in $\tau$ decays
  - $\tau$ LFV  ($\tau \rightarrow \ell \gamma$, $\tau \rightarrow \ell \ell \ell$, $\tau \rightarrow \ell hh'$, ...)
  - rare decays  ($\tau \rightarrow \ell \ell \ell \nu \nu$, $\tau \rightarrow \ell \ell \pi \nu$, $\tau \rightarrow \ell \nu \nu \gamma$, $\tau \rightarrow \eta \pi \nu$, ...)
  - $\tau$ CPV  ($\tau \rightarrow K_S^0 \pi \nu ...$)

- SM precise measurement
  - $BF$ measurement of hadronic decays
  - evaluation of the spectrum of the hadronic current
  - 2nd class current search ($\tau \rightarrow \eta \pi \nu$, ...)
  - measurement of $|V_{us}|$

- $\tau$ property measurement
  - $\tau$ mass measurement
  - $\tau$ lifetime measurement
  - Lepton universality
  - $\tau$ EDM measurement
  - CPV
  - $\tau$ Michel parameter measurement
  - Lorentz structure of $\tau$ decays
LFV in $\tau$-decays
Lepton flavor is conserved in the SM

If we take into account neutrino mass and neutrino oscillations $Br(\tau \rightarrow \mu \gamma) \approx \mathcal{O}(10^{-40})$ and $Br(\tau \rightarrow \mu \mu \mu) \approx \mathcal{O}(10^{-14})$ (Pham, XY. Eur. Phys. J. C8 (1999) 513)

Unobservable with current experiments!

LFV is a clear signature of the New Physics

Many extensions of the SM predict LFV decays and their $BF$ may be enhanced to as high as $\mathcal{O}(10^{-8})$, which is within current experimental sensitivity

SUSY

Higgs-mediation LFV

R-parity violation
NP search with $\tau$ (LFV) (2)

- $\tau$ is the heaviest lepton: many possible LFV decay modes.

- Ratios of $B$Fs of $\tau$ LFV decays allow to discriminate NP models – need to measure LFV in as many modes as possible!

<table>
<thead>
<tr>
<th></th>
<th>SUSY+GUT (SUSY+Seesaw)</th>
<th>Higgs mediated</th>
<th>Little Higgs</th>
<th>non-universal $Z'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{B(\tau \rightarrow \mu \mu \mu)}{B(\tau \rightarrow \mu \gamma)}$</td>
<td>$\sim 2 \times 10^{-3}$</td>
<td>0.06 - 0.1</td>
<td>0.4 - 2.3</td>
<td>$\sim 16$</td>
</tr>
<tr>
<td>$\frac{B(\tau \rightarrow \mu e e)}{B(\tau \rightarrow \mu \gamma)}$</td>
<td>$\sim 1 \times 10^{-2}$</td>
<td>$\sim 1 \times 10^{-2}$</td>
<td>0.3 - 1.6</td>
<td>$\sim 16$</td>
</tr>
<tr>
<td>$B(\tau \rightarrow \mu \gamma)_{\text{max}}$</td>
<td>$&lt; 10^{-7}$</td>
<td>$&lt; 10^{-10}$</td>
<td>$&lt; 10^{-10}$</td>
<td>$&lt; 10^{-9}$</td>
</tr>
</tbody>
</table>

JHEP 0705, 013 (2007); PLB 547, 252 (2002)
Reconstruction of $\tau$-decays

- $\sigma(e^+e^-\rightarrow \tau^+\tau^-) = (0.919\pm0.003) \text{nb} \approx \sigma_{bb}$ at $\sqrt{s}=10.58 \text{ GeV} - \text{B-factory is } \tau\text{-factory!}$

- Due to Belle (II) hermeticity and clean environment we can reconstruct the whole event

- Divide event into two hemispheres by thrust

- Signal variables for neutrinoless LFV decays:
  
  $$m_\tau = \sqrt{E_{\text{sig}}^2 - p_{\text{sig}}^2}$$
  
  $$\Delta E = E_{\text{sig}}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$$

- Sidebands are used to evaluate expected background
Many backgrounds, but we have ways to reduce them

- Bkg for $\tau \rightarrow \mu\mu\mu, \tau \rightarrow e\mu\mu$
- Neutrinos on both sides
- Missing energy on signal side

- Bkg for $\tau \rightarrow e\mu\mu$
- Multiplicity
Predictions for Belle II are based on Belle analyses.

- 535 fb⁻¹ sample, $4.77 \times 10^8 \tau^+\tau^-$ events
- ±3σ blinded
- ±2σ for signal counting
- $\mathcal{B}(\tau^{-} \rightarrow \mu^- \gamma) < 4.5 \times 10^{-8}$ @90%CL
- $\mathcal{B}(\tau^{-} \rightarrow e^- \gamma) < 12.0 \times 10^{-8}$ @90%CL

\[
\begin{align*}
\mathcal{E} & \equiv \Delta E - \Delta E^{(0)} \\
M & \equiv 3.0 \times (M_{\tau} - M_{\tau}^{(0)}) \\
\alpha & = 46^\circ
\end{align*}
\]
$\tau \rightarrow \ell\ell\ell$

- 782 fb$^{-1}$ sample, $7.19 \times 10^8 \tau^+\tau^-$ events
- No events found in signal region
- $\mathcal{B} < (1.5-2.7) \times 10^{-8}$ @90%CL

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}^{EXP}$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>UL (x10$^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-e^+e^-$</td>
<td>6.0</td>
<td>0.21±0.15</td>
<td>9.8</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-\mu^+\mu^-$</td>
<td>7.6</td>
<td>0.13±0.06</td>
<td>7.4</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^-\mu^+\mu^-$</td>
<td>6.1</td>
<td>0.10±0.04</td>
<td>9.5</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^-e^+e^-$</td>
<td>9.3</td>
<td>0.04±0.04</td>
<td>7.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mu^-e^+\mu^-$</td>
<td>10.1</td>
<td>0.02±0.02</td>
<td>7.6</td>
<td>1.7</td>
</tr>
<tr>
<td>$e^-\mu^+e^-$</td>
<td>11.5</td>
<td>0.01±0.01</td>
<td>7.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>
854 fb⁻¹ sample


14 decay modes:
- \( h, h' = \pi^\pm, K^\pm \)
- \( \tau^- \rightarrow \ell^- h^+ h'^- \) (8 modes)
- \( \tau^- \rightarrow \ell^+ h^- h'^- \) (6 modes) (LNV)

\( \mathcal{B} < (2.0-8.6) \times 10^{-8} @90\% \text{CL} \)
Extension to Belle II

\( \tau \rightarrow l \gamma \)

- **BG situation**
  \( \tau \rightarrow l \nu \bar{\nu} + \text{gamma sources} \)

**ISR** : beam background \( \sim 9 : 1 \) for Belle case

ISR events, \( \tau \rightarrow l \gamma \propto \text{luminosity} \)
beam BG \( \propto \text{luminosity} \)

- **Efficiency**
  - In Belle analysis, \( \varepsilon_{\tau \rightarrow e \gamma} \sim 3\% \), \( \varepsilon_{\tau \rightarrow \mu \gamma} \sim 5\% \)
  - This difference comes from BhaBha veto by trigger
    - \( \tau \tau \) events have similar structure to BhaBha \( ee \rightarrow ee(\gamma) \) (back-to-back)
    \[ \sigma_{ee \rightarrow ee(\gamma)}/\sigma_{\tau \tau} \sim 5000 \]
  - In Belle II, more clever algorithm will be considered:
    - 2D(\( r-\phi \)) recognition of veto \( \rightarrow 3D(\tau-\theta-\phi) \)
    - position dependent energy threshold
Future prospects at Belle II

• Belle II will collect $N_{\tau\tau} > 10^{10}$

• Branching ratio sensitivity vs. Integrated luminosity

  $\tau \rightarrow \ell \gamma$; \( \propto \frac{1}{\sqrt{L}} \)
  - Irreducible background; $e^+e^- \rightarrow \tau^+\tau^-\gamma$

  $\tau \rightarrow \ell\ell\ell, \ell X^0$; \( \propto \frac{1}{L} \)
  - Negligible background by particle ID and mass restriction

• Important for background reduction (S/N improvement)

Signal MC by Belle simulation

S/N can improve, if $E_\gamma$ resolution improves.
++ Less material before EM calorimeter.
?? Gamma energy resolution in high beam BG.
The no-background regime improves as \( \propto \frac{1}{L} \). If there are background events, the improvement is \( \propto \frac{1}{\sqrt{L}} \).

\[ \tau \rightarrow \mu \gamma \quad \text{(bkg)} \]

expected limit \( \mathcal{O}(10^{-9}) \)

\[ \tau \rightarrow \mu \mu \mu \quad \text{(no bkg)} \]

expected limit \( \mathcal{O}(10^{-10}) \)

The full range of \( \tau \) LFV is only accessible at Belle II.
Belle (II) can study a whole spectrum of decays!

Even with much higher beam background, the sensitivity is comparable to that of Belle, scaled by luminosity (B. Moore BELLE2-THESIS-2017-002)
Conclusions

Tau lepton is a good probe for NP searches like LFV
B factories produced a huge data sample $\mathcal{O}(10^9)$ tau pairs

**BELLE:**
- 48 LFV decay modes have been investigated
- 90% C.L. Upper Limits have been set in $\mathcal{O}(10^{-8})$
- $\tau \rightarrow \mu \gamma/\epsilon\gamma$ will be updated with the full data set

**BELLE II:**
- machine upgrade is finished and detector upgrade is ongoing smoothly
- detector improvement will play a key role in background elimination and reduction of systematic effects (*beam BG, signal resolution*)
- start of full physics 2018, reach 50 ab$^{-1}$ by 2023-2024
- LFV will be probed up to $\mathcal{O}(10^{-9} – 10^{-10})$
Rare $\tau$ decays
Measurement of 5-body decay: $\tau \rightarrow ll\bar{\nu}\nu$

- In the Standard Model, $\mathcal{B}$ is $o(\alpha^2)$-suppressed.
  \[ B(\tau^- \rightarrow e^- e^+ e^- \nu\bar{\nu}) = (4.21 \pm 0.01) \times 10^{-5} \]
  \[ B(\tau^- \rightarrow e^- \mu^+ \mu^- \nu\bar{\nu}) = (1.247 \pm 0.001) \times 10^{-7} \]
  \[ B(\tau^- \rightarrow \mu^- e^+ e^- \nu\bar{\nu}) = (1.984 \pm 0.004) \times 10^{-5} \]
  \[ B(\tau^- \rightarrow \mu^- \mu^+ \mu^- \nu\bar{\nu}) = (1.183 \pm 0.001) \times 10^{-7} \]
- Theory predicts existence of sterile neutrinos enhances $\mathcal{B}$:
  \[ B(\tau^- \rightarrow e^- \mu^+ \mu^- \nu\bar{\nu}) \text{ up to } \sim 10^{-5} \]

- CLEO II experiment partially measured:
  \[ B(\tau^- \rightarrow e^- e^+ e^- \nu\bar{\nu}) = (2.7^{+1.5+0.4+0.1}_{-1.1-0.4-0.3}) \times 10^{-5} \]
  \[ B(\tau^- \rightarrow \mu^- e^+ e^- \nu\bar{\nu}) < 3.2 \times 10^{-5} \text{ (90\% C.L.)} \]

- We started to measure the BR of $\tau \rightarrow ll\bar{\nu}\nu$
  - Generator of $\tau$-decay (TAUOLA) is renewed based on up-to-date theoretical calculation:
  - largest background for $\tau \rightarrow eee\nu\bar{\nu}$ comes from radiative decay $\tau \rightarrow e\nu\bar{\nu}\gamma$ ($\gamma \rightarrow ee$)
  - sum of cosine is a good signature for the separation: $C = \sum \cos \theta_{i_1i_2} = \cos \theta_{i_1i_2} + \cos \theta_{i_2i_3} + \cos \theta_{i_3i_1}$

Decay mode | The number of events
--- | ---
$\tau^+ \rightarrow e^+ e^+ e^- \nu_e \nu_e$ | About 1400
$\tau^+ \rightarrow \mu^+ e^+ e^- \nu_e \nu_e$ | About 280
$\tau^+ \rightarrow e^+ \mu^+ e^- \nu_e \nu_e$ | About 2
$\tau^+ \rightarrow \mu^+ \mu^+ e^- \nu_e \nu_e$ | About 2

$\mathcal{L} = 3.60 \text{ fb}^{-1}$

$N_{\tau\tau} = (3.28 \pm 0.05) \times 10^6$

Generic MC simulation (~3ab$^{-1}$)
Summary

- Belle experiment collected $1 \text{ab}^{-1}$ ee collision data
- To proceed further tests of the SM, upgrade project of Belle II is on going where it is planned to collect 50 times larger statistics.
- $B$-factory is also $\tau$-factory. Belle experiment collected $N_{\tau\tau}\sim2 \times 10^9$ data.
- rare decay of $\tau$ opens many possibilities to search for the New Physics
  - Measurement of LFV decays: $\tau \to l\gamma$, $\tau \to lll$, $\tau \to lX$
  - measurement of other rare decays:
    - $\tau \to l\nu\bar{\nu}$: deviation of BR b.t.w exp/theory, new Michel Parameters $\tilde{\eta}$, $\xi\kappa$
    - $\tau \to lll\nu\nu$: $o(\alpha^2)$ suppressed, clean environment of the test of the lepton universality
    - $\tau \to ll\pi\nu$: useful test of chiral perturbation theory
    - $\tau \to \eta\pi\nu$: 2nd-current violating decay
CP violation in $\tau$ decays

- CP violation is so far observed only in the $B$ and $K$ systems

- NO CPV has been observed in the lepton sector

- The discovery of CPV in the tau sector would be a clean signature of NP

- One can search for CPV of several new physics model
  MSSM : T. Ibrahim and P. Nath 2008

- One of the most promising CP channels is $\tau^\pm \rightarrow K_S^0 \pi^\pm \nu_\tau$

- SM CP asymmetry from $K_S$-$K_L$ mixing is expect to be $\mathcal{O}(10^{-3})$
  (Biggi, Sanda PLB 625 47 (2005))
Multi Higgs Doublet Model (MHDM) (Grossman, NPB, 426, (1994))

New kind of CP violation could be observed in the difference of angular distribution in $\tau^{-} \rightarrow K_{S} \pi^{-} \nu$ decays (Kuhn, Mirekes, PLB 398 (1997))

$$L_{NP} = \sin \theta_{c} \frac{G_{F}}{\sqrt{2}} (\bar{\nu} \gamma^{\mu} (1 + \gamma_{5}) \tau) (\bar{s} \gamma_{\mu} (\eta_{s} + \eta_{p} \gamma_{5}) u)$$

$\tau^{-} \rightarrow K_{S} \pi^{-} \nu$ channel consist of two form factors: vector ($F_{V}(Q^{2})$) and scalar ($F_{S}(Q^{2})$)

$$J_{\mu} = \langle K_{S}(p_{1}) \pi(p_{2})|\bar{s} \gamma_{\mu} u|0\rangle$$

$$= (p_{1} - p_{2})^{\nu} T_{\nu \mu} F(Q^{2}) + Q_{\mu} F_{S}(Q^{2})$$

New scalar boson changes the SM scalar form factor ($F_{S}(Q^{2})$) to the new one ($F'_{S}(Q^{2})$)

$$F_{S}(Q^{2}) \rightarrow F'_{S}(Q^{2}) = F_{S}(Q^{2}) + \frac{\eta_{S}}{m_{\tau}} F_{H}(Q^{2})$$
Analysis Methods

- Differential Decay width of $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$

\[ \frac{d\Gamma(-)}{dQ^2 d\cos \theta d\cos \beta} = \left[ A(Q^2) - B(Q^2)(3\cos^2 \psi - 1)(3\cos^2 \beta - 1) \right] |F|^2 + m_\tau |F_S|^2 - C(Q^2) \cos \beta \cos \psi (\text{Re}(FF^*_S(\eta_S))) \]

$A(Q^2), B(Q^2), C(Q^2)$: known function

$\beta$: direction of $K_s$ in $K_s \pi$ rest frame

$\psi$: direction of $\tau$ in $K_s \pi$ rest frame

$\theta$: direction of $K_s \pi$ system in $\tau$ rest frame $\rightarrow$ correlated with $\psi$

- CP observable that proportional to $\cos \beta \cos \psi$,

\[ A^{W}_{CP}(Q^2) = \int \left( \frac{d\Gamma(-)}{d\omega} \cos \beta \cos \psi - \frac{d\Gamma(+)}{d\omega} \cos \beta \cos \psi \right) / \int \left( \frac{d\Gamma(-)}{d\omega} + \frac{d\Gamma(+)}{d\omega} \right) \]

$\propto \langle \cos \beta \cos \psi \rangle_{\tau^-} - \langle \cos \beta \cos \psi \rangle_{\tau^+}$

$\omega = dQ^2 d\cos \beta d\cos \psi$

- This is not the total rate asymmetry. (different from BABAR)
\section*{Results}

\textbf{Belle} \hspace{0.5cm} \textit{PRL} 107, 131801 (2011)

699 fb\(^{-1}\) data sample used

162K \(\tau^{\pm} \rightarrow K_{S}^{0}\pi^{\pm}\nu_{\tau}\)

- \(A_{CP} = (1.8 \pm 2.1 \pm 1.4) \times 10^{-3}\)
  for \(0.89 \leq M_{K\pi} \leq 1.11\) GeV

- CP phase extraction \(\eta_{s}\)

- \(|\text{Im}(\eta_{s})| < (0.012 - 0.026)\) @ 90 \% C.L
  Limit depends on the parametrization of form factor

- Application to 3HDM

\[
\eta_{s} \approx \frac{m_{\tau}m_{S}}{M_{H^{\pm}}^{2}}X^{*}Z
\]

\[
|\text{Im}(X^{*}Z)| \leq 0.15 \frac{M_{H}^{2}}{(1\text{GeV})^{2}}
\]
Summary

• CP violation in $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$ decay has been studied using 699 fb$^{-1}$ and resulted in no evidence at $\mathcal{O}(10^{-3})$

$$A_{cp} = (1.8\pm2.1\pm1.4) \times 10^{-3}$$

• This give a stringent limit on the CPV parameter $\eta_s$ and MHDM

$$\eta_s \approx \frac{m_\tau m_S}{M_{H^\pm}^2} X^* Z \quad |\text{Im}(X^* Z)| \leq 0.15 \frac{M_H^2}{(1 GeV)^2}$$
$M_\tau$, $\tau$- lifetime

$M_\tau$, $\tau$- lifetime are fundamental parameters of Standard Model.

Precise measurement of $M_\tau$, $\tau$- lifetime and $Br(\tau \rightarrow e \nu \bar{\nu})$ can serve for test of lepton universality.
Measurement of the $\tau$ mass
Pseudomass method

All in CMS

\[ M_{\text{min}} \leq M_{\tau} \]

\[ M_{\text{min}}^2 = M_x^2 + 2(E_\tau - E_x)(E_x - P_x) \]

\( E_\tau = E_{\text{beam}} \): beam energy, run dependence is corrected

\( E_x \): hadron system energy

\( P_x \): hadron system momentum

\( M_x \): mass of the hadron system

We take edge position \( P_1 \) as an estimator of the \( \tau \) mass.

The shift \( \delta P_1 = P_1 - M_\tau \) was taken from the Monte Carlo.

\( \delta P_1 \approx 1.0 \) MeV.

We apply this correction to obtain the \( \tau \) mass from the fit of the data
Real Data

$\tau \to 3\pi \nu_{\tau}$

Fit by function:

$$(P_3 + P_4 \cdot x) \cdot \text{atan}((x - P_1) / P_2) + P_5 + P_6 \cdot x$$

$P_1 = 1777.77 \pm 0.13 \text{ MeV/c}^2$
Mass difference between $\tau^+$ and $\tau^-$

Fitting separately pseudomass distributions for $\tau^+$ and $\tau^-$ can give the value of mass difference

\[ M_{\tau^+} - M_{\tau^-} = 0.05 \pm 0.23 \text{(stat.)} \pm 0.14 \text{(sys.)} \text{ MeV} \]

Combining statistical and systematic errors:

\[ M_{\tau^+} - M_{\tau^-} = 0.05 \pm 0.27 \text{ MeV} \]

Upper limit:

\[ \frac{|M_{\tau^+} - M_{\tau^-}|}{M_{\tau}} < 2.8 \cdot 10^{-4} \text{ @ 90\% CL} \]

PDG (2006):

\[ \frac{(M_{\tau^+} - M_{\tau^-})}{M_{\tau}} < 3.0 \cdot 10^{-3}, \text{ CL}=90\% \]

\[ \Delta M = 0.0 \pm 3.0 \text{ (stat.) MeV} \]
Summary

Analyzing the pseudomass spectrum for decay $\tau \to 3\pi \nu_\tau$ with the Belle detector at KEK we obtained the following results:

$$M_\tau = 1776.77 \pm 0.25\text{(stat.)} \pm 0.62\text{(sys.)} \text{ MeV}$$
$$M_{\tau^+} - M_{\tau^-} = -0.12 \pm 0.45\text{(stat.)} \pm 0.15\text{(sys.)} \text{ MeV}$$
$$|M_{\tau^+} - M_{\tau^-}| / M_\tau < 5.01 \cdot 10^{-4} \@ 90\% \text{ CL}$$

**Belle**
$$|\Delta M_\tau| / M_\tau = 3.76 \cdot 10^{-4}$$

**Belle II** (10 ab$^{-1}$)
$$|\Delta M_\tau| / M_\tau = 2.07 \cdot 10^{-4}$$
Measurement of the $\tau$ lifetime from Belle
Analysis method

- We consider $e^+e^- \rightarrow \tau^+\tau^- \rightarrow 3\pi^+3\pi^-$ events.
- In **CM frame**:
  - Flight directions of $\tau^+$ and $\tau^-$ are back-to-back;
  - Energy of each tau-lepton is $\sqrt{s}/2$;
  - Assuming neutrino mass to be zero, the angle between $\tau$ flight direction and momentum of the corresponding $3\pi$-hadronic system ($P_x$) is determined as:

\[
\cos \theta^* = \frac{2E^*_\tau E^*_x - m^2_\tau - m^2_\tau}{2P^*_\tau P^*_x} = \frac{2E^*_\tau E^*_x - m^2_\tau - m^2_\tau}{2\sqrt{(E^*_\tau)^2 - m^2_\tau}P^*_x}
\]

- **The unit vector in the direction of the positive tau-lepton can be obtained** as a solution of the following system of equations:

\[
\left\{
\begin{array}{l}
\left(\vec{P}_1^* \cdot \vec{n}_+^*\right) = x^*P_{x1}^* + y^*P_{y1}^* + z^*P_{z1}^* = |P_1^*| \cos \theta_1^*
\\
\left(\vec{P}_2^* \cdot \vec{n}_+^*\right) = x^*P_{x2}^* + y^*P_{y2}^* + z^*P_{z2}^* = -|P_2^*| \cos \theta_2^*
\\
\left(\vec{n}_+^* \right)^2 = \left(x^*\right)^2 + \left(y^*\right)^2 + \left(z^*\right)^2 = 1
\end{array}
\right.
\]
Analysis method (cont.)

- We perform Lorentz boost of $\tau$-lepton 4-momenta from CM to Laboratory frame.
- $\tau$ decay vertices ($V_1$ and $V_2$) are determined as the 3D-points of intersections of the pions triplets momenta.
- For the $\tau$ production point of each $\tau$-lepton we take the points ($V_{01}$ and $V_{02}$) which are the points of the closest approach of the two crossing lines defined by $\tau$ decay vertices and flight directions.

\[
ct_1 = \frac{l_1}{(\beta \gamma)_1}, \quad ct_2 = \frac{l_2}{(\beta \gamma)_2}
\]

$dl \neq 0$ for ideal case

No information about the beam spot position is needed in this approach
Resolution function is obtained by the fit of the $(ct_{\text{rec}} - ct_{\text{true}})$ MC distribution

Fitting function $\text{res}(x) = p_1 \cdot R(x, p_2, ..., p_6) = p_1 \cdot (1 - 2.5 \cdot x) \cdot \exp\left(-\frac{(x - p_2)^2}{2 \cdot \sigma^2}\right)$

\[\sigma = p_3 + p_4 \cdot |x - p_2|^{1/2} + p_5 \cdot |x - p_2| + p_6 \cdot |x - p_2|^{3/2}, \quad p_i \text{ are free parameters.}\]
Experimental $ct$ distribution

- It was fitted by:
  $$F(x) = P_1 \int e^{-t/P_2} R((x-t), P_3, \ldots, P_7) dt +$$
  $$+ A_{qq} R(x, P_3, \ldots, P_7) + Bkg_{cc+b\bar{b}}(x)$$

  $P_1, \ldots, P_7$ – are free parameters,

- $A_{qq}$ is fixed at MC prediction,
  $Bkg_{cc+b\bar{b}}(x)$ is fixed from MC.

$$\chi^2/Ndf = 143 / 153$$

- From the fit we obtain the value of the $\tau$-lepton lifetime estimator
  $$P_2 = 86.53 \pm 0.16\mathrm{(stat.)} \mu$m
The result of the analysis

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$289.0 \pm 2.8 \pm 4.0$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$289.2 \pm 1.7 \pm 1.2$</td>
</tr>
<tr>
<td>ALEPH</td>
<td>$290.1 \pm 1.5 \pm 1.1$</td>
</tr>
<tr>
<td>L3</td>
<td>$293.2 \pm 2.0 \pm 1.5$</td>
</tr>
<tr>
<td>DELPHI</td>
<td>$290.9 \pm 1.4 \pm 1.0$</td>
</tr>
</tbody>
</table>

Mean PDG: $290.6 \pm 1.0$

Belle: $290.27 \pm 0.5 \pm 0.27$

\[ \tau_\tau = \tau_\mu \left( \frac{g_\mu}{g_\tau} \right)^2 \left( \frac{m_\mu}{m_\tau} \right)^5 \]

Belle result: \[ \left( \frac{g_\tau}{g_\mu} \right)^2 = 1.0041 \pm 0.0035 \]
The method of $\tau$-lepton lifetime measurement at Belle is presented.

Using 711 fb$^{-1}$ of the Belle data we measured $\tau$-lepton lifetime. The result is

$$\tau = 290.17 \pm 0.53 \text{ (stat.)} \pm 0.33 \text{ (syst.) fs}$$

$$c\tau = 86.99 \pm 0.16 \text{ (stat.)} \pm 0.10 \text{ (syst.) } \mu\text{m}$$

The first measurement of the lifetime difference between $\tau^+$ and $\tau^-$ is performed. The upper limit on the relative lifetime difference between positive and negative $\tau$-leptons is

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

**Belle**

$$|\Delta \tau|/\tau = 0.215 \%$$

**Belle II (10 ab$^{-1}$)**

$$|\Delta \tau|/\tau = 0.128 \%$$
Summary

- Belle, being an $e^+e^-$ B-factory experiment, is a $\tau$-factory experiment at the same time.
- With nearly $10^9 \tau^+\tau^-$ sample, Belle has obtained most stringent upper limits in most of the $\tau$ LFV decays, with 90% UL of $\mathcal{O}(10^{-8})$.
- With $\sim 50 \cdot 10^9 \tau^+\tau^-$ events expected in the upgraded Belle II experiment, these searches will be greatly improved (90% C.L. UL of $\mathcal{O}(10^{-9})$).
- For very clean modes (e.g. $\tau \to \ell\ell\ell$), the upper limit is expected to improve linearly with luminosity. And it will be a very powerful probe for new physics beyond the SM (90% C.L. UL of $\mathcal{O}(10^{-10})$).
- Rare $\tau$ decays.
- CPV search in $\tau$ decay having $K_s^0$ has been performed: Belle’s result give a stringent limit on the CPV parameter $\eta_s$ and MHDM (BaBar’s result is $2.8\sigma$ away from SM prediction).
- Precise measurement of $M_\tau$, $\tau$-lifetime and $Br(\tau \to e\nu\nu)$ can serve for test of lepton universality. The accuracy of $M_\tau$, $\tau$-lifetime measurement is expected to improve by a factor $\sim 2$ at Belle II.
Backup
Lepton Flavor Violation in tau decay

In the Standard Model, LFV is highly suppressed. Impossible to access; $Br < O(10^{-54})$
Many extensions of the SM predict LFV decays. Their branching fractions are enhanced as high as current experimental sensitivity
⇒ Observation of LFV is a clear signature of New Physics (NP)
Tau lepton: the heaviest charged lepton
- Opens many possible LFV decay modes which depend on NP models
Lepton Flavor Violation in tau decay

SUSY is the most popular candidate among new physics models naturally induce LFV at one-loop due to slepton mixing.

$\tau \rightarrow l \gamma$ mode has the largest branching fraction in SUSY-Seesaw (or SUSY-GUT) models.

When sleptons are much heavier than weak scale LFV associated with a neutral Higgs boson ($h/H/A$).

Higgs coupling is proportional to mass $\Rightarrow \mu \mu$ or $ss$ ($\eta, \eta'$ and so on) are favored and B.R. is enhanced more than that of $\tau \rightarrow \mu \gamma$.

To distinguish which model is favored, all of decay modes are important.
SUSY

- LFV through slepton mixing

- Independent parameter from $\mu \rightarrow e\gamma$

- SUSY seesaw (J. Hisano et. al., PRD 60 (1999) 055008)

  $$\mathcal{B}(\tau \rightarrow \mu \gamma) \approx 3.0 \times 10^{-7} \left( \frac{\tan \beta}{60} \right)^2 \left( \frac{1 \text{ TeV/c}^2}{m_{\text{SUSY}}} \right)^4$$

  - Achievable BR, if $\tan \beta \approx 60$, $m_{\text{SUSY}} \approx 1 \text{ TeV/c}^2$
  - Suppressed, if slepton is heavier than weak scale
SUSY Higgs

- Higgs-mediated MSSM
  - \( \tau \rightarrow 3\mu \) (A. Brignole, A. Rossi, PLB 566 (2003) 217)
    \[
    B(\tau \rightarrow 3\mu) \sim 10^{-7} \left( \frac{\tan \beta}{50} \right)^6 \left( \frac{100 \text{ GeV}/c^2}{m_A} \right)^4 \left( \frac{|50 \Delta_L|^2 + |50 \Delta_R|^2}{10^{-3}} \right)
    \]
  - \( \tau \rightarrow \mu \eta \) (M. Sher, PRD 66 (2002) 057301)
    \[
    B(\tau \rightarrow \mu \eta) \simeq 8.4 \times 10^{-7} \left( \frac{\tan \beta}{60} \right)^6 \left( \frac{100 \text{ GeV}/c^2}{m_A} \right)^4
    \]
    - Accessible if, large \( \tan \beta \) and small Higgs mass

- MSSM seesaw (E. Arganda, arXiv:0803.2039v1)
  - Br of \( \tau \rightarrow \mu \eta, \mu \eta', \mu K^+K^- \); \( O(10^{-7}) \)
Measurement of BR of $\tau \rightarrow l\bar{l}\pi\nu$

- clean environment for the study of low hadronic interactions
  - notable BG for $\tau \rightarrow ll\bar{l}$ (due to mis-ID of $\pi \rightarrow \mu$)
  - Chiral perturbation theory ($\chi$PT) predicts $\mathcal{B}(\tau \rightarrow \pi ll\nu) \sim 10^{-5} \div 10^{-6}$

<table>
<thead>
<tr>
<th>$\ell = e$</th>
<th>$\ell = \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$IB$</td>
<td>$1.461 \times 10^{-5}$</td>
</tr>
<tr>
<td>$IB - V$</td>
<td>$-2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$IB - A$</td>
<td>$-9 \times 10^{-7}$</td>
</tr>
<tr>
<td>$VV$</td>
<td>$1.16 \times 10^{-6}$</td>
</tr>
<tr>
<td>$AA$</td>
<td>$2.20 \times 10^{-6}$</td>
</tr>
<tr>
<td>$V - A$</td>
<td>$2 \times 10^{-10}$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.710 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

- search for long-lived sterile neutrino
  - sterile neutrinos could have long lifetime $\tau_N \sim 10^{-9}$ s
  - vertex allows us to see decay point
  - resonance of $m_N$ could be observed from $\pi^-\mu^+$
  - BaBar experiment searched for $l\bar{l}$ but did not for $\pi\mu$

- We just started to measure BR
  - we newly implemented dedicated generator for $\tau \rightarrow l\bar{l}\pi\nu$ decay
  - major BG for $\tau \rightarrow ee\pi\nu$ comes from $\tau \rightarrow \pi\pi^0(\rightarrow \gamma\gamma)\nu$ where $\gamma$ generates $ee$-pairs
Measurement of BR of decays via 2nd class current

- **G-parity:** $\hat{G} = \hat{C} e^{i\pi I_2}$
  - Isospin symmetry of the strong force: $\hat{G}|I, I_3\rangle = \hat{C}(-)^I|I, -I_3\rangle = (-)^I|I, I_3\rangle$
    
    Ex. $\hat{G}|\pi^+\rangle = -|\pi^+\rangle$, $\hat{G}|\pi^-\rangle = -|\pi^-\rangle$, $\hat{G}|\eta\rangle = |\eta\rangle$
  - G-conservation exactly holds in $m_{d,u} \rightarrow 0$ & $Q_d = Q_u = 0$
  - The current which violates G-parity is called “2nd-class” current
    
    $\tau \rightarrow \eta \pi \nu$ proceed through $j^{PG} = 0^- \ (\text{scalar}) \ or \ 1^- \ (\text{vector})$
  - Estimated BR: various models predicts $B \sim 10^{-5}$

- **Measurement of BR of $\tau \rightarrow \eta (\rightarrow \pi \pi \pi^0) \pi \nu$ decay by **Belle** (660 fb⁻¹)**
  - Continuous background mainly comes from $\tau \rightarrow \pi \pi \pi \pi^0 \nu$ decay and extrapolated from side band region
  - Around $m_\eta = 548 \ (\text{MeV})$, peaking BG is separately evaluated
    - Four $\tau$ decays including $\eta$ were considered: $\tau \rightarrow \pi \pi ^0 \eta \nu$, $\tau \rightarrow K^* \eta \nu$, $\tau \rightarrow K \eta \nu$, $\tau \rightarrow \pi f_1 (\rightarrow \eta \pi \pi) \nu$
    - Number of events for corresponding peak is evaluated by Gaussians
      
      $N_{\text{obs.}} = 190.0 \pm 68.6 \ \text{events}$
      
      $B < 7.3 \times 10^{-5}$
    - Dominant error comes from stat. error and $B(\tau \rightarrow \pi \pi \eta \nu)$
  - 50 times statistics of Belle II will reach the theoretical expectation!