Tau physics prospects at Belle II

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For Belle II collaboration
SuperKEKB and Belle II experiment

- Advanced B factory
- Asymmetric energy $e^+e^-$ collider
  - At $\sqrt{s}=10.58\text{GeV}$
  - $\sigma(\tau\tau)\sim0.9\text{nb}$, $\sigma(bb)\sim1.1\text{nb}$
  - A B-factory is also a tau-factory!
- Challenges to higher luminosity
  - Narrower beam at IP
  - Higher beam current
  - Detector works with higher beam background and trigger rates

Target integrated luminosity = 50ab$^{-1}$
$\Rightarrow \sim5 \times 10^{10}$ $\tau$ pairs
  - x50 higher than previous B factory

"Nano beam"
Vertical beam size is 50nm at IP
Belle II detector

General purpose, forward/backward asymmetric acceptance

**EM Calorimeter**
CsI(Tl), waveform sampling

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

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

**Beryllium beam pipe**
2cm diameter

**Vertex Detector**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

**Electron** (7GeV)

**Positron** (4GeV)
Physics data taking started in March 2019.
- Performed luminosity tuning during the data taking

Achieved world record
- \( L = 2.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

Data collected stably
- High beam background env.

Integrated luminosity; 73 fb\(^{-1}\)
- Physics analysis for ICHEP2020; ~8.8 fb\(^{-1}\)
Tau physics program

- The world largest number of tau-pair events in $e^+e^-$ collisions offer data for tau physics analyses with high precision.

- Lepton flavor violating decays
  - $\tau \rightarrow \mu \gamma, e\gamma, \mu \eta, e\eta, p\gamma, \Lambda \pi, lll, \ldots, 1+\alpha$ (→ talk by F. Tenchini)

- Electric Dipole Moment (CP/T violation)
- CP violation in tau decay; $\tau \rightarrow K_s \pi \nu$

- Tau mass, $\nu_\tau$ mass, Lifetime

- Test of Universality

- Hadronic decays
  - Search for second class current; $\tau \rightarrow \pi \eta \nu$
  - Mass spectrum in $\tau \rightarrow \pi \pi^0 \nu$
  - ...
• Performed tau mass analysis using early Belle II data (8.8fb⁻¹)
• Select $\tau \to 3\pi \nu + 1$-prong topology events and measure tau mass using the “pseudomass” technique developed by ARGUS

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$

- Current best value by Belle;
  
  $1776.61 \pm 0.13 \pm 0.35$ MeV
- Tau pair production at threshold energy shows better result.
  
  BESIII; $1776.91 \pm 0.12 \pm 0.13$ MeV
  - Phys. Rev. D 90, 012001 (2014)

• Clear shoulder in the data
  - Well rediscovered tau-pair events at Belle II.
• Extract mass by fitting to a empirical edge function
• Preliminary result; 
  \[1777.28 \pm 0.75 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ MeV/c}^2\]
  – Similar systematic error with previous B factory results
  – Can improve using more data and more precise corrections, then achieve best precision among pseudomass measurement.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>MeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum shift due to the B-field map</td>
<td>0.29</td>
</tr>
<tr>
<td>Estimator bias</td>
<td>0.12</td>
</tr>
<tr>
<td>Choice of p.d.f.</td>
<td>0.08</td>
</tr>
<tr>
<td>Fit window</td>
<td>0.04</td>
</tr>
<tr>
<td>Beam energy shifts</td>
<td>0.03</td>
</tr>
<tr>
<td>Mass dependence of bias</td>
<td>0.02</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Initial parameters</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Background processes</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Decay model</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>$\leq 0.01$</td>
</tr>
</tbody>
</table>
In the Standard Model, LFV is highly suppressed. Impossible to access; Br<\(10^{-54}\)

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
• $e^+e^- \rightarrow \tau^+\tau^-$  
  $\rightarrow$ 1 prong + missing (tag side)  
  $\rightarrow \mu\mu\mu$ (LFV mode, signal side)  
  **Br~85%**

**Fully reconstructed**

**Signal extraction**: $M_{3\mu}-\Delta E$ plane  
(or rotated signal plane to reduce correlation)  
**Evaluate background from side band**

**BG contribution is small for 3lepton modes** because of good PID performance, however **non-negligible for l+γ modes**
• Belle, Babar reached $O(10^{-8})$ branching ratio, LHCb improving the result
• $\tau \rightarrow 3$ leptons, l+mesons (to charged particles) show better sensitivity because of less background, compared to $\tau \rightarrow l \gamma$. 
Future prospects at Belle II

- Will collect 50ab\(^{-1}\) data by \sim2031, with upgrading detector and accelerator
- \(B(\tau \rightarrow \mu \mu \mu) \sim O(10^{-10})\) at \sim50ab\(^{-1}\)
- Background suppression is key issue.
  - Understanding of background (beam BG, fake PID etc.)
  - Improvement of reconstruction algorithms
  - Intelligent event selection by machine learning technique
Belle II experiment started
  – Achieved world record luminosity; $L = 2.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  – Accelerator tuning is on going and more data will be recorded.

Also started actual physics analyses
  – Tau mass measurement by early data shows clear tau rediscovery signal and promising sensitivity.
  – Preliminary result; $M_\tau = 1777.28 \pm 0.75 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ MeV/c}^2$

Belle II will collect $\sim 5 \times 10^{10}$ $\tau$ pairs
  – Tau LFV searches will reach the higher sensitivity compared to the previous experiments
  – The background free modes, such as $\tau \to 3$ leptons, can be reached to $O(10^{-10})$ branching ratio sensitivity.

More precise result with more data

Stay tuned!
Search for $\tau \rightarrow 3$leptons at Belle

- Data: $\sim 7 \times 10^8 \tau \tau$
- No event is found in the signal region.
- $\text{Br} < (1.5-2.7) \times 10^{-8}$ at 90% CL.

- Almost BG free
  - Because of good lepton ID

### Table

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}^{\text{EXP}}$</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>2.7</td>
</tr>
<tr>
<td>$\mu^- \mu^+ \mu^-$</td>
<td>7.6</td>
<td>0.13+0.06</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^- \mu^+ \mu^-$</td>
<td>6.1</td>
<td>0.10+0.04</td>
<td>2.7</td>
</tr>
<tr>
<td>$\mu^- e^+ e^-$</td>
<td>9.3</td>
<td>0.04+0.04</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mu^- e^+ e^-$</td>
<td>10.1</td>
<td>0.02+0.02</td>
<td>1.7</td>
</tr>
<tr>
<td>$e^- e^+ e^-$</td>
<td>11.5</td>
<td>0.01+0.01</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Data: 470 fb$^{-1}$ + 31 fb$^{-1}$ @ Y(3S) + 15 fb$^{-1}$ @ Y(2S)
  - (963 ± 7) x 10$^6$ $\tau$ decays

New kinematical cuts
+ Neural Net discri.
→ Improve S/N

Dominant BG:
$\tau \rightarrow l\nu\nu +$ radiation
  (irreducible BG)

$B(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$
$B(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$