Tau physics prospects at Belle II

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on behalf of the Belle II collaboration

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Tau physics prospects at Belle II

SuperKEKB and status of Belle II

**Electron (7 GeV) - Positron (4 GeV) collider.**

\[ e^+ e^- \rightarrow \Upsilon(4S)[10.58 \text{ GeV}] \rightarrow B\bar{B} \quad (\sigma = 1.1 \text{ nb}) \]

\[ e^+ e^- \rightarrow \tau^+ \tau^- \quad (\sigma = 0.9 \text{ nb}) \]

**Targeted peak luminosity:** $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

Today: $\sim 160 \text{ fb}^{-1}$ of data collected  |  Goal: $50 \text{ ab}^{-1}$

**Higher beam currents**  
**Lower beam size**  
30x KEKB peak luminosity
Belle II detector

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

VerteX detectors (VXD):
2 layer DEPFET pixel detectors (PXD, partially installed)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C₂H₆ (50%), small cells, fast electronics

K_{L} and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICHI) (FWD)

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz
The large tau production cross section allows us to study tau physics with high precision, as a probe of new physics or a test of the standard model.

**Tau studies at Belle II:**
- Lepton flavour violating (LFV) decays: $\tau \rightarrow l\gamma$, $lll$, $lhh$, $lV^0$...
- LFV decay with new particles: $\tau \rightarrow l+\alpha$,
- Tau electric dipole moment,
- CP violation: $\tau \rightarrow K_S\pi\nu$,
- Tau mass measurement,
- Tau lifetime measurement,
- Michel parameters determination,
- $V_{us}$ and $\alpha_s$ determinations,
- ...

**Motivations:**
- LFV decays: testing predictions from SUSY, little Higgs models, leptoquark models, etc.,
- $\tau \rightarrow l+\alpha$: related to axion-like particles and dark matter studies (cf. backup slides),
- Tau mass and lifetime: tests of leptonic universality depend on these parameters and their accuracies...
Tau mass measurement (Preliminary)

- **Tau mass measurement** analysis performed using Belle II early Phase 3 data (integrated luminosity of $8.8 \text{ fb}^{-1}$).

- $[\tau \rightarrow 3\pi \nu] + [\tau \rightarrow 1\text{-prong}]$ events are selected and the tau mass is measured following the pseudomass technique developed by the ARGUS collaboration:

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

- The tau mass is extracted by fitting the pseudomass to an empirical edge function.

![Graph showing tau mass measurement results](image-url)
Tau mass measurement (Preliminary)

- Current best fit by Belle (414 fb\(^{-1}\)):
  \[1776.61 \pm 0.13_{\text{stat}} \pm 0.35_{\text{syst}} \text{ MeV}\]

- More precise measurement done by BES III near \(\tau\) pair production threshold:
  \[1776.91 \pm 0.12_{\text{stat}} \pm 0.13_{\text{syst}} \text{ MeV}\]

- Preliminary result from Belle II early Phase 3 data:
  \[m_\tau = 1777.28 \pm 0.75_{\text{stat}} \pm 0.33_{\text{syst}} \text{ MeV}\]

  → Consistent with previous measurements, improvable statistical uncertainty, systematic error similar to Belle but could be reduced in the future.

<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>
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</tr>
<tr>
<td>Choice of p.d.f.</td>
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<tr>
<td>Fit window</td>
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<tr>
<td>Beam energy shifts</td>
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<tr>
<td>Mass dependence of bias</td>
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<tr>
<td>Trigger efficiency</td>
<td>(\leq 0.01)</td>
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<tr>
<td>Initial parameters</td>
<td>(\leq 0.01)</td>
</tr>
<tr>
<td>Background processes</td>
<td>(\leq 0.01)</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>(\leq 0.01)</td>
</tr>
</tbody>
</table>


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now
Tau lifetime measurement

- **Tau lifetime** is measured thanks to the relation:

\[ \ell_\tau = \beta \gamma c t = \frac{p_\tau c t}{m_\tau} \]

\( \ell_\tau \) = decay length in lab. frame  
\( p_\tau \) = momentum in lab. frame  
\( t \) = proper decay time

- The challenge consists in measuring precisely \( \ell_\tau \) and \( p_\tau \).

- Events corresponding to \([\tau \rightarrow 3\pi \nu] + [\tau \rightarrow \rho \nu]\) are selected, the measurement is done on the 3-prong \( \tau \).

- The proper time is fitted with the convolution of an exponential distribution and a resolution function: and the lifetime \( \tau_\tau \) is extracted from there.

- World-best measurement comes from Belle (711 fb\(^{-1}\)):

\[ \tau_\tau = 290.17 \pm 0.53_{\text{stat}} \pm 0.33_{\text{syst}} \text{ fs} \]


- Belle II's study on simulation done with 200 fb\(^{-1}\):

\[ \tau_\tau = 287.2 \pm 0.5_{\text{stat}} \text{ fs} \]

generated \( \tau_\tau = 290.2 \pm 0.4_{\text{stat}} \text{ fs} \)

**Belle II already competitive at \( \sim 150 \text{ fb}^{-1} \) (5\times more events than in Belle study)**
Tau lepton flavour violation

- **Lepton flavour violation** is heavily suppressed in the SM (extended with neutrino masses).
- Many NP models allow LFV at scales that can be probed by particle physics experiments.
- In tau physics, the "golden modes" are $\tau \to \mu \gamma$ and $\tau \to 3\mu$, but a lot more are also studied ($l\gamma$, $lll$, $lhh$, $lV\nu_0$...).

NP models: $\text{Br} \sim \mathcal{O}(10^{-10}) - \mathcal{O}(10^{-7})$

Improvement of 2 orders of magnitude expected for Belle II!
• The signal is looked for within the $M_\tau$-$\Delta E$ space ($\Delta E = E_\tau - E_{\text{beam}}$), in an optimised region defined around the signal peak in simulation.

• Usually the signal region is rotated to get rid of the correlations: 

\[
\begin{pmatrix}
M'_\tau \\
\Delta E'
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix} \begin{pmatrix}
M_\tau \\
\Delta E
\end{pmatrix}
\]

• Background is evaluated from side bands. Some channels require a more thorough background suppression strategy (e.g. $\tau\rightarrow\mu\gamma$ is much more contaminated than $\tau\rightarrow3\mu$).
Tau physics prospects at Belle II

LFV decay $\tau \to l + \alpha$ (invisible)

- Search for LFV two-body decay $\tau \to l + \alpha$, $l = e/\mu$ and $\alpha$ being an invisible particle.

- The opposite $\tau$ decays as $\tau \to 3\pi\nu$. Due to the missing energy from neutrino, we approximate: $E_\tau \approx E_{CMS}/2$, $\vec{p}_\tau \approx \vec{p}_{3\pi}$

- Signal manifests as a **peak in the $\tau$ momentum in pseudo-rest frame**, stacking on the $\tau \to l\nu\nu$ background.

- Full spectrum is fitted with (SM) and (SM+NP) expectations and respective likelihoods are compared.

- Latest results are from:
  - ARGUS (472 pb$^{-1}$)
  - MARK III (9.4 pb$^{-1}$)

Belle II is already competitive with respect to ARGUS.

![Graph showing LFV decay results](image-url)
Summary

• The Belle II experiment is currently collecting data with a final goal of 50 ab⁻¹ by ~ 2031. → ~ 5×10¹⁰ τ pairs, much larger sample than in previous B-factories.

• This amount of data will enable researchers to perform analyses probing new physics or testing with high precision the parameters of the standard model with respect to τ particles.

• Some analyses are already progressing well:
  • *Tau mass measurement*: $m_\tau = 1777.28 \pm 0.75 \pm 0.33$ MeV (with a small set of data),
  • *Tau lifetime measurement*: already competitive w.r.t. Belle,
  • *Lepton flavour violating decays*: $\tau \rightarrow \mu \gamma$ & $\tau \rightarrow 3\mu$, $\tau \rightarrow l+\alpha$...
  • Many other analyses are ongoing or in preparation (electric dipole moment, CP violation, hadronic currents...).
Future results from $\tau \rightarrow l + \alpha$ searches at Belle II might put boundaries on several NP models, for example:

- Models with axion-like particles, where Belle II should be able to put a stronger constraint on $f_a$ (decay constant in effective Lagrangian) than the bound from ARGUS, in particular for high ALP masses.

- Models giving rise to a $Z'$ boson, that could address issues like the $(g - 2)_\mu$ anomaly or in dark matter phenomenology. Searches for $\tau \rightarrow \mu +$ (missing energy) can constrain the $Z'$ parameter space ($g'_R$: right-handed coupling).
A decay rate asymmetry is expected in $\tau \to K_s\pi\nu$ according to the SM because the $K_s$ is subject to CP violation:

$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_s^0\nu_\tau) - \Gamma(\tau^- \to \pi^- K_s^0\nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_s^0\nu_\tau) + \Gamma(\tau^- \to \pi^- K_s^0\nu_\tau)}$$

The SM predicts: $\mathcal{A}_\tau^{SM} \approx (0.36 \pm 0.01)\%$

... while BaBar has measured: $\mathcal{A}_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%$

→ $2.8\sigma$ discrepancy w.r.t. the SM.

A measurement of the decay rate asymmetry is a priority for Belle II, which should improve the precision by a factor $\sim 8$ at 50 ab$^{-1}$.
**Second-class hadronic currents**: \( \tau \rightarrow \pi \eta \nu \\

- **Second-class hadronic currents** violate G-parity, still present in the SM because of the charge and mass differences between *up* and *down* quarks, but heavily suppressed.

- \( \tau \rightarrow \pi \eta \nu \) is a SCC, therefore it is a potential probe for new physics.

- The SM predicts: \( \text{Br}(\tau \rightarrow \pi \eta \nu) \sim 10^{-5} \)

- Upper limits from two previous experiments:
  - BaBar (470 fb\(^{-1}\)): \( \text{Br}(\tau \rightarrow \pi \eta \nu) < 9.9 \times 10^{-5} \)
    

  - Belle (670 fb\(^{-1}\)): \( \text{Br}(\tau \rightarrow \pi \eta \nu) < 7.3 \times 10^{-5} \)
    

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**Charged Higgs exchange**

- \( \tau \rightarrow \pi \eta \nu \) with \( \nu_\tau \) and \( a_0, a'_0 \) exchange

**Leptoquark exchange**

- \( \tau \rightarrow \pi \eta \nu \) with \( a_0, a'_0 \) exchange

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**Belle II Simulation**

Upper Limit of \( \text{BR}(\tau \rightarrow \pi \eta \nu) \times 10^5 \) vs Luminosity (ab\(^{-1}\))
Other topics

**Michel parameters:**
- 4 parameters $\rho$, $\eta$, $\xi$ and $\delta$ (combinations of coupling constants in four-lepton point interaction Lagrangian), experimentally accessible in decay $\tau \rightarrow \nu_\tau \nu_\tau$.
- Belle II expected to improve statistical uncertainties at 50 ab$^{-1}$ by one order of magnitude w.r.t. Belle ($10^{-3}$ → $10^{-4}$).

**Electric and magnetic dipole moments of the $\tau$:**
- Evaluating some observables that are proportional to the EDM and getting maximal sensitivity by combining results from multiple $\tau$ decay modes. Belle II expected to gain in precision by a factor 40: $|\text{Re, Im}(d_\tau)| < 10^{-18} – 10^{-19}$.
- $g-2$ can be evaluated similarly but sensitivity is expected to be worse than that of the $\tau$ EDM.

**Measurements of $V_{us}$ and $\alpha_s$:**
- Determinations of the CKM matrix element and the strong coupling constant at the tau mass (+ running to the Z mass) with the help of inclusive hadronic $\tau$ decays and observable: 
  \[ R_\tau = \frac{\Gamma(\tau^- \rightarrow \nu_\tau \text{ hadrons}^- (\gamma))}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \nu_\nu (\gamma))} \]

More details in: