“Tau Physics Prospects at Belle II”

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Electron-positron asymmetric beams collider:

- CMS energy $\sqrt{s} \approx m_{\gamma(4S)} \approx 10.58$ GeV
- Target instantaneous luminosity of $6.5 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ (x30 KEKB)
- Target integrated luminosity 50 ab$^{-1}$ (x50 Belle).

Higher luminosity requires:

- Narrow beams at IP (Nanobeams)
- Increased beam current (x2 Belle)
- Detector works with higher beam background and trigger rates.

\[
\sigma(e^+e^- \rightarrow BB) = 1.05 \\
\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.919 \rightarrow \tau \text{ factory!}
\]
The Belle II detector

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

EM Calorimeter
CsI(Tl), waveform sampling electronics

Central Drift Chamber
Smaller cell size, long lever arm

Particle identification
Time-Of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(end-caps, inner 2 barrel layers)

electrons (7 GeV)

positrons (4 GeV)

+ Trigger, DAQ and GRID system.
Luminosity status and projections

- First $e^+e^-$ collision: April 2018.
- Phase 3 data: $>210 \text{ fb}^{-1}$ collected so far.

- **Luminosity projection** for the coming years.

\[ L = 3.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]
Studies of the τ lepton are an extremely convenient tool to:

- Search for NP (LFV & LNV).
- Determine SM basic parameters (lifetime, $m_\tau$).
- Do precise tests of EW interactions.

Clean environment

- Low background, high resolution.

B-factories have provided many interesting results in τ lepton physics.

Wide physics program is documented in the Belle II Physics Book.

You can also take a look at the other Belle II talks at this conference! 😊
**Tau mass measurement**

The measurement is performed in the decay mode $\tau \to 3\pi\nu$ (3x1 prong topology), using a pseudomass technique developed by the ARGUS collaboration:

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

The distribution of the pseudomass is fitted to an empirical edge function to estimate $\tau$ lepton mass.

$$F(M_{\min}, \bar{P}) = (P_3 + P_4 \cdot M_{\min}) \cdot \tan^{-1}[(M_{\min} - P_1)/P_2] + P_3 \cdot M_{\min} + 1$$

$$m_\tau = 1777.28 \pm 0.75 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ MeV/c}^2$$

**Public Belle II note**

→ arxiv.2008.04665

**Accuracy of lepton universality measurements.**

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\[ B^{SM}_{\tau l} \propto B_{\mu e} \cdot \frac{\tau \tau}{\tau \mu} \cdot \frac{m_\tau^5}{m_\mu^5} \]
The goal is to achieve the best $m_\tau$ precision among pseudomass measurements.

Belle II have compatible results with previous experiments and comparable sys. errors with previous B factories BaBar and Belle.

~300 fb$^{-1}$ statistical precision as Belle/BaBar.
**Tau lifetime**

- Important parameter in the SM.
- Test of the lepton flavor universality (LFU).
- World best measurement by Belle (711 fb⁻¹): 
  \[ \tau = (290.17 \pm 0.53\text{(stat)} \pm 0.33\text{(sys)}) \text{ fs} \]

**Measurement strategy:**
- **Proper decay time** distribution.
  \[ p(t, \tau) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \]
  Proper time resolution

- Proper time related to the decay length and the momentum.
  \[ t = \frac{l_\tau}{\beta\gamma c} = \frac{m_\tau}{p_\tau c} \]
  \( l_\tau \) and \( p_\tau \) to be reconstructed from measurements.

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Production vertex → intersection of the \( \vec{p}_\tau \) direction with the plan \( y=IP_y \).

\[ \text{e}^+\text{e}^- \rightarrow \tau^-\tau^+ \]

3x1 topology

\[ \rho(\pi\pi^0)\nu \]

x5 higher efficiency than Belle using \( \tau \rightarrow 3\pi\nu \) x \( \tau \rightarrow 3\pi\nu \) topology.

**Competitive results at 150 fb⁻¹!**

Epiphany conference talk
Lepton Flavor Violation

LFV is strongly suppressed within the SM. Any observation of LFV is clear signal for New Physics!

τ is the heaviest charged lepton

Large variety of leptonic and semi-leptonic decays to search for LFV(LNV).

Two orders of magnitude of improvement @ 50ab⁻¹.
\( \tau \rightarrow l + \gamma, \ \tau \rightarrow 3l \)

Golden channels

In SM LFV is highly suppressed \( \text{Br} \sim O(10^{-54}) \)

\[
B(\tau \rightarrow \mu \gamma) = \frac{3\alpha}{32\pi} \left| \sum U_{\tau i}^* U_{\mu i} \frac{\Delta m^2_{31}}{m_W^2} \right|^2.
\]

Full reconstructed

\[
e^+e^- \rightarrow \tau^-\tau^+
\]

\[\mu\gamma, \ \mu\mu\mu \text{(LFV mode)}\]

1 prong + missing(\(\nu, \gamma\))

NP model predictions:

\(O(10^{-10} - 10^{-8})\).

Strategy:

- \(M_{inv}^{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2}\)
- \(\Delta E = E_{CM}^{\mu\gamma} - E_{beam}^{CM}\)

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

Belle II Physics Book.

BKG free selection w/ 1 ab^{-1}.

\(\text{BR}(\tau \rightarrow \mu + \gamma) < 2.72 \times 10^{-8}\)

Improvement ~Belle limit/2.

(no sys. unc. included)

Belle: \(2.1 \times 10^{-8}\) (782 fb^{-1}).

Belle II: \(~10^{-10}\).
**LFV** $\tau \rightarrow l + \alpha$  

- $\alpha$ is assumed to be an invisible (undetected) long-lived massive BSM boson.
- Previous studies by Mark III ($9.4\text{ pb}^{-1}$) and ARGUS ($476\text{ pb}^{-1}$).

ARGUS:

- Search for 2 body decay in $\tau$ rest frame will manifest as a peak.
- cannot access $\tau$ rest frame directly due to neutrino.

"$\tau$ pseudo rest frame":

$$E_\tau \approx E_{CMS}/2 + \begin{cases} \vec{e}_\tau \simeq -\vec{e}_3 \text{ prong (ARGUS)} \\ \vec{e}_\tau \simeq \vec{e}_{\hat{n}_{thrust}} \end{cases}$$

$$V_{\text{thrust}} = \sum |\vec{p}_{i\text{ cm}} \cdot \hat{n}_{\text{thrust}}| / \sum |\vec{p}_{i\text{ cm}}|$$
**LFV** \( \tau \rightarrow l + \alpha \)

- Upper limit estimation for \( \frac{BR(\tau \rightarrow l\alpha)}{BR(\tau \rightarrow l\nu\bar{\nu})} \)
- Using a Frequentist method: CLs method.

Considerable improvement for 25 fb\(^{-1}\).

Right now finishing the study with all the systematics included!! 😊

**BELLE2-NOTE-PL-2020-018**
Summary

- Belle II is not only a B factory, it is also a $\tau$ factory.
- Large data collected so far (>210 fb$^{-1}$) with the final goal of 50 ab$^{-1}$.
- Very rich physics program of SM precisions measurements and New Physics with $\tau$’s.

- Many ongoing $\tau$ studies, where competitive results are expected.
  - $\tau$ mass measurement (systematics already comparable to Belle/BaBar).
  - $\tau$ lifetime (x5 higher efficiency than Belle).
  - $\tau \rightarrow l + \alpha$ (Final results coming soon).
  - Near future: Test of LFU, LFV($\tau \rightarrow l + \gamma$, $\tau \rightarrow 3 l$), CP violation, electric dipole moment, ...

More exciting results coming in the future!
Models axion-like particles (ALP). Exploring regions of parameter space not reachable by other experiments.

Models giving rise a Z' boson. Searches for $\tau \rightarrow \mu + (\text{missing energy})$ can constrain the Z' parameter space ($g'_R$).

ARGUS

$g_L = g_R$

$\tau \rightarrow e + \chi$

$\chi \rightarrow \tau + \chi$

$@50fb^{-1}$

P3H-20-024, TTP20-025