Status and Prospects for Tau Property Measurements at Belle II.

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DESY

On behalf of the Belle II collaboration

The 16th International Workshop on Tau Lepton Physics (TAU 2021)
Sep 27, 2021
SuperKEKB
A B factory of next generation

- Integrated luminosity expected: 50 ab$^{-1}$
  (x40 than previous B factories)

“Nano-beams”: vertical beam size is 50nm at the IP.
SuperKEKB
A B factory of next generation

Challenges at L=6.5x10^{35} cm^{-2} s^{-1}:

- Higher background (Radiative Bhabha, Touschek, beam-gas scattering, etc.).
- Higher trigger rates (High performance DAQ, computing).
The Belle II Collaboration
1100 members, 123 institutions, 26 countries

Mt. Tsukuba

Linac

Desy
The Belle II Collaboration
1100 members, 123 institutions, 26 countries
The Belle II Experiment

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

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

**Vertex detector:**
- 2 layers DEPFET + 4 layers DSSD

**Beryllium beam pipe:**
- 2 cm diameter

**Central Drift Chamber:**
- He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics

**Readout (TRG, DAQ):**
- Max: 30kHz L1 trigger
- ~100% efficient for hadronic events.
- 1MB (PXD) + 100kB (others) per event
- >30GB/sec to record

**Software:**
- Open-source sophisticated algorithms for simulation, reconstruction, visualization, and analysis.

**Offline computing:**
- Distributed over the world via grid.
• **Super B-factory performance levels**, despite a global pandemic.
  • World records:
    • 1.96 fb\(^{-1}\)/day,
    • 12 fb\(^{-1}\)/week,
    • 40 fb\(^{-1}\)/month
  • Luminosity above the B factories and LHC, with a product of beam currents 3.5 times lower than KEKB.

• “Social distancing” scheme for on-site shifts, and mobilized remote shifters around the world
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Integrated Luminosity

Today

L\(_{\text{peak}}\) = 3.1 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}

\[ \int L_{\text{recorded}} \, dt = 213.49 \, \text{[fb}^{-1}] \]

On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching \(3.1 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}\) in the Belle II detector. Until last year, the luminosity record stood at \(2.1 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}\), shared by the former KEKB accelerator and the LHC. In the summer of 2020, however, SuperKEKB/Belle II surpassed this value with a peak luminosity of \(2.4 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}\).

https://cerncourier.com/a/superkekb-raises-the-bar/
Integrated Luminosity

Projections

Target: x40 the integrated luminosity collected by the previous B-factories.

- Milestones:
  - ~500 fb\(^{-1}\) by the next summer (2022).
  - O(10 ab\(^{-1}\)) by the upgrade of the IR (2026).
  - 50 ab\(^{-1}\) after the upgrade, by 2030.

![Graph showing integrated luminosity projections](image-url)
Belle II Physics Program

• The physics program of Belle II covers measurements in B decays, charm, dark sectors, exotic particles, etc.

• Further details can be found in “The Belle II Physics Book”: PTEP 2019 (2019) 12, 123C01

• The enormous number of e+e- collisions features a unique environment for the study of \( \tau \) physics with high precision.
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The enormous number of e+e- collisions features a unique environment for the study of $\tau$ physics with high precision.
Let's talk about the tau leptons at the B factories

- At $Y(4S)$:
  \[ \sigma(e^+e^- \rightarrow B\bar{B}) = 1.05 \text{ nb} \]
  \[ \sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb} \]

- Approximately 1M tau pairs per fb$^{-1}$

- B-Factories are also $\tau$-factories

Figure: The particle zoo.
Let’s talk about the tau

- **Features of a B-Factory:**
  - Well-defined initial state.
  - High vertex resolution.
  - Excellent calorimetry.
  - Sophisticated particle ID.
  
- B-Factories are also \( \tau \)-factories

- B-Factories of first generation provided (and keep providing!) many interesting results as the luminosity increased:

Most of these results will be updated with the Belle II data set.
Contributions during TAU 2021 by Belle II

**Join us!**

**Tuesday 28/09**

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Note: Times in CET
Tau decay event in early Belle II data

Exp 7, Run 3521
Started at 2019/04/30 06:18 JST
Stopped at 2019/04/30 07:06 JST
Run type: physics
Performance
Towards precision measurements in tau lepton physics

• Tau pairs are not only tools for the comprehension of fundamental physics, but also for the understanding of our detector.

Tracking efficiency

• Tracking efficiency and fake rates have been measured using $\tau \tau$ events, with one of the leptons decaying to $\tau^- \rightarrow 3\pi^\pm \nu_\tau + n\pi^0$.

Calibrated discrepancy between data/MC:

$$\delta^* = 1 - \frac{c_{\text{data}}}{c_{\text{MC}}}$$

Overall: $0.28 \pm 0.15\text{(stat)} \pm 0.73\text{(sys)}$
Performance
Towards precision measurements in tau lepton physics

Lepton ID performance

- Particle identification is based on the global likelihood ratio from all sub detectors.

- With the same tag-and-probe approach, lepton misidentification rates are calculated with pions from the 3-prong decay $\tau^- \rightarrow 3\pi^\pm + \nu_\tau$

\[
\ell \text{ ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}
\]
Performance
Towards precision measurements in tau lepton physics

Trigger efficiencies

- The Level 1 trigger efficiency has been studied using $e^+e^- \rightarrow \tau^+\tau^-$ events with 1x1 and 3x1 topologies.
- Full track triggers present low efficiency in endcaps.
- To compensate, the CDC trigger also searches for short tracks, providing a significant gain in efficiency for endcaps/low $p_T$.
- Identification of tau events with 1x1 topologies still represents a challenge.

(More details on Tuesday by A. Martini).

BELLE2-NOTE-PL-2020-015
Single Track Trigger

Neural-net based hardware track trigger

• A neural-net based hardware trigger ("y trigger") is now operational, showing great performance.

• It fires if it finds a track within 15 cm from the collision vertex and a momentum larger than 700 MeV.

  • Single hidden layer with 81 neurons and 27 inputs.
  • Inputs: Hits on wires of the CDC.
  • Execution time: 300 ns

First results coming, with promising results.
Measurement of tau properties at Belle II

Mass, lifetime, leptonic decays

- Lepton Flavor Universality test:
  \[ B_{\tau\ell} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \]

- Inputs from tau decays:
  - Tau mass \( m_\tau \)
  - Tau lifetime \( \tau_\tau \)
  - Leptonic BR \( B_{\tau\ell} \)

- Belle II has the potential of provide precise measurements of these parameters.

- “Wait, did you just say LFU?”
  Join us on Tuesday!

Figure: [EPJ Web Conf., 218 (2019) 05002](http://example.com)
Tau Lepton Mass Measurement

**Historical overview**

- The lepton masses are fundamental parameters of the SM:

  \[
  m_e = (0.5109989461 \pm 0.0000000031) \text{ MeV},
  \]

  \[
  m_\mu = (105.6583745 \pm 0.000024) \text{ MeV},
  \]

  \[
  m_\tau = (1776.86 \pm 0.12) \text{ MeV}.
  \]

- Precision of \( m_\tau \) have consequences in LFU tests.

- Two methods for measuring \( m_\tau \):
  - Measurement in the production threshold (DELCO, BES, KEDR, BES III).
  - Pseudomass distribution (ARGUS, OPAL, BaBar, Belle).

- The latter will be exploited in Belle II.
Tau Lepton Mass Measurement

Pseudomass distribution

- Measured in the decay mode $\tau \rightarrow 3\pi \nu$, using a pseudomass technique developed by the ARGUS collaboration.

- The tau mass can be calculated as

$$m_{\tau}^2 = (p_h + p_\nu)^2$$

$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|p_h|(E_\tau - E_h) \cos(p_h, p_\nu)$$

- As the direction of the neutrino is not known, the approximation $\cos(p_\nu, p_h) = 1$ is taken, resulting in

$$M_{\text{min}}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|p_h|(E_\tau - E_h) < m_{\tau}^2$$

- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass.

Figure: The ARGUS detector at DESY

**Tau Lepton Mass Measurement**

**Performance test @ 8.76 fb⁻¹**

- Our latest result¹ (8.76 fb⁻¹, ICHEP 2020): **1777.28 ± 0.75 ± 0.33 MeV/c²**.
- Main systematic sources:
  - Momentum shift due to imperfections on the B-Field map: 0.29 MeV/c².
  - Bias of the $m_\tau$ estimator: 0.12 MeV/c².

**Pseudomass distribution, data vs MC**

FIT to edge p.d.f. in the cutoff region

$$F(M_{\text{min}}, \bar{P}) = (P_3 + P_4 M_{\text{min}}) \cdot \tan^{-1}[(M_{\text{min}} - P_1)/P_2] + P_5 M_{\text{min}} + 1$$

Tau Mass Measurement at Belle II

Projection towards high luminosity

- Our result is still dominated by statistical uncertainty, and consistent with previous measurements:

![Graph showing mass measurements with error bars and labels, indicating statistical and systematic uncertainties.]

Blue: statistical; Green: systematic
Tau Mass Measurement at Belle II

Projection towards high luminosity

- Our result is still dominated by statistical uncertainty, and consistent with previous measurements:

- We expect significant reduction in the main systematic uncertainties.

Blue: statistical; Green: systematic

“Can wait to see more details!”
Join us on Friday!

Current luminosity

Current syst: 0.33 MeV

0.75 MeV/c² @ 8.76 [fb⁻¹]

0.31 MeV² @ 50 [fb⁻¹]

0.22 MeV² @ 100 [fb⁻¹]

0.13 MeV² @ 300 [fb⁻¹]
Tau Lifetime Measurement

Exploiting the nano-beam scheme

- Important SM parameter. Its precision has implications in LFU, $\alpha_s(m_t)$, etc.
- Previous measurements:
  - Z-peak: LEP (DELPHI, L3, ALEPH, OPAL).
  - Y-peak: CLEO, BaBar, **Belle**

- The world-leading measurement by Belle\(^1\) uses a **3x3 topology**, with both tau leptons decaying to $3\pi\nu_\tau$.
  \[ \tau_\tau = 290.17 \pm 0.53 \text{(stat)} \pm 0.33 \text{(syst)} \text{ fs} \]

\(^1\) PRL 112, 031801 (2014), arXiv:1310.8503 [hep-ex]
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- **Strategy at Belle II:**
  1. Reconstruct vertex for 3-prong $\tau$. Only one 3-prong = higher statistics.
  2. Estimate the $\tau$ momentum $\vec{p}_\tau$. Hadronic decays in both sides.
  3. Find the production vertex. Intersection of $\vec{p}_\tau$ with the plane IP$_y$.

---

Tau Lifetime Measurement

Sensitivity at 200 fb\(^{-1}\)

- \(\ell_\tau\) reconstruction and IP constrain:
  \[ \vec{n}_\tau = \vec{p}_\tau / |\vec{p}_\tau| \]
  3-prong vertex
  \[ IP + \ell_\tau \vec{n}_\tau = \vec{v}_{3\pi} \]

- Lifetime extraction:
  - \(\tau_\tau = 287.2 \pm 0.5\) (stat) fs
  - Same statistical uncertainty of Belle.
    (200 fb\(^{-1}\) vs 711 fb\(^{-1}\))
  - \(\tau_\tau\) presents \(\approx 3\) fs bias.
    (Generated lifetime: 290.57 fs)
  - ISR/FSR losses = underestimation of the proper time.
  - And intrinsic bias in the measurement.

- Further studies to estimate systematics:
  - Test dependence from resolution function in the fit
  - Beam-spot position
  - ISR/FSR simulation
  - Vertex detector alignment
    (dominant at Belle and Babar)
Tau Lifetime Measurement

Detector performance

- In MC simulations, the Belle II proper time resolution is \(\sim 2x\) better than Belle.
  - Due to PXD and smaller beam pipe diameter.

Proper decay time resolution:

- For comparison, the D meson lifetime measurement by Belle II was recently published\(^1\).
  - Improvement in resolution is confirmed

\[
\tau(D^0) = 410.5 \pm 1.1 \text{(stat)} \pm 0.8 \text{(syst)} \text{ fs}
\]

\[
\tau(D^+) = 1030.4 \pm 4.7 \text{(stat)} \pm 3.1 \text{(syst)} \text{ fs}
\]

\(^1\) arXiv:2108.03216 [hep-ex] (submitted to PRL)
Summary

• In 2021, SuperKEKB has set a new record in peak luminosity at $L_{\text{peak}} = 3.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

• To the date, 213 fb$^{-1}$ of collision data have been recorded by Belle II. By summer, we expect to collect of the order of ~ BaBar data set.

• Since its discovery, the tau lepton has been studied at new every $e^+e^-$ collider into operation, improving the measurements with every upgrade.

  ‣ In Belle II we are very motivated, and ready to reach new limits in the precision.

• **Tau mass studies** with the early data show potential for an update in the measurement of $m_\tau$ using the pseudomass technique.

• The **lifetime measurements** at Belle II show the potential of the nano-beam scheme with an upgraded vertex detection system. First studies of $\tau_\ell$ very promising, with an update in the measurement feasible in the coming months.
Thank you
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