First Results and Prospects for τ Lepton Physics at Belle II

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on behalf of the Belle II collaboration

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Motivation

• The Standard Model (SM) is in trouble, as it can not answer questions to:
  • Dark Matter, CP problem, ...

• Precision measurements of Leptons to test the SM and new physics models
  • Well understood QED
  • Parameters measured are
    • Free parameters: mass, lifetime,…
    • Predicted observable: g-2, EDM,…

τ

• 3rd Generation Lepton
  • Mass: 1776 ± 0.12 MeV
  • Lifetime: 290.3 ± 0.5 fs

• Properties
  • Hadronic Decays
    ▶ Probe QCD
    ▶ CP violation
  • Bigger coupling to New Physics?
    • Lepton Flavour Violation
    • 4th Generation Neutrino
    • …

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Where can one study the \( \tau \)?

- At \( e^+e^- \) machines there is a low background and well understood production mechanism for \( \tau \).
- SuperKEKB collider
Where can one study the $\tau$?

- At $e^+e^-$ machines there is a low background and well understood production mechanism for $\tau$

- SuperKEKB collider
  - Increased Integrated Luminosity:
    
    $1 \text{ ab}^{-1}(\text{KEKB}) \rightarrow 50 \text{ ab}^{-1}(\text{SuperKEKB})$

  - SuperKEKB is a $\tau$-factory!
    
    - $\sigma(e^+e^- \rightarrow \Upsilon(4s)) \approx \sigma(e^+e^- \rightarrow \tau^+\tau^-)$
    
    - $\sim 45$ billion tau pairs for full Belle II program
How to Study $\tau$ at Belle II?

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

**Central drift chamber (CDC):**
He(50%):C$_2$H$_6$ (50%), small cells, fast electronics

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

**K$_L$ and muon detector (KLM):**
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

**Magnet:**
1.5 T superconducting

**Trigger:**
Hardware: < 30 kHz
Software: < 10 kHz

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

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

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One of The First $\tau^+\tau^-$ Event

Exp 3 Run 2730 Event 28993
• Tau mass measured using an analysis of a 3x1 prong decay.
• Mass extraction from pion decay only
• Using a dataset of approximately 291 pb⁻¹ of early data.
Tau mass measured using an analysis of a 3x1 prong decay.

- Mass extraction from pion decay only
- Using a dataset of approximately 291 pb\(^{-1}\) of early data.
- \(m_\tau = (1776.4 \pm 4.8)\) MeV
- First \(\tau\) physics results with early data: consistent with previous measurements!
**Exotic Hadronic Currents**

\[ J^{PG} = 0^{+-} (a_0) = 0^{-+} (\eta) = 1^{--} (\omega) = 1^{++} (b_1) \]

- Hadronic Decays are classified by spin, parity and G-parity

- Old measurements:
  - CLEO:
    \[ B(\tau \rightarrow \omega h^\pm \nu) = (1.91 \pm 0.07 \pm 0.06) \times 10^{-2} \]
  - ALEPH:
    \[ B(\tau \rightarrow \omega h^\pm \pi^0 \nu) = (4.3 \pm 0.6 \pm 0.5) \times 10^{-3} \]

- Yet to be observed:
  - Belle: \[ B(\tau \rightarrow \eta \pi \nu) < 7.3 \cdot 10^{-5} \]
  - BaBar: \[ B(\tau \rightarrow \eta \pi \nu) < 4.0 \cdot 10^{-6} \]
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Further Standard Model Measurements

- Michel Parameters

- Tau $g - 2$ and EDM
  - Belle (30 fb$^{-1}$): EDM < $\mathcal{O}(10^{-17})$
  - First ever test of SM $g - 2$!

\[
\frac{g - 2}{2} \equiv a^\text{SM}_\tau = (1.17721 \pm 0.00005) \cdot 10^{-3}
\]

\[
a^\text{Exp}_\tau = 0.018 \pm 0.017
\]
CP Violation

- SM prediction by Bigi and Sanda for CP-violating decay-rate asymmetry
  \[ A_Q^{SM} = (0.36 \pm 0.01)\% \]

- Measurement by BaBar:
  \[ A_Q^{Exp} = (-0.36 \pm 0.23 \pm 0.11)\% \]
  - 2.8 \( \sigma \) from SM prediction
  - Sensitivity increase by a factor of 8 for 50 ab\(^{-1} \)

\[
A_Q = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}
\]
LFV Search: $\tau \rightarrow l + \alpha$ (invisible)

- Motivation to look for a new Boson:
  - fermion/ν-hierarchy, ν-mixing, ν-masses
  - Light dark matter

- Idea: Search for a two body decay spectrum

- Signal will manifest as a peak in the tau rest frame (TRF)

- Challenge: Estimate TRF with missing $\nu_\tau$ momentum

- Using
  $E_{\tau} \approx E_{CMS}/2$
  $\overrightarrow{p}_{\tau} \approx \overrightarrow{p}_{3\pi} = \sum_{i=1}^{3} \overrightarrow{p}_{\pi}^{i}$

\[ \Rightarrow \text{Pseudo-TRF } \tau^* \]
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- Signal will manifest as a peak in the tau momentum rest frame (TRF)
  - Challenge: Estimate TRF with missing $\nu_\tau$ momentum
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    $\rightarrow$ Pseudo-TRF $\tau^*$
- No signal region $\rightarrow$ fit full spectrum with
  - SM expectation
  - SM + NP expectation
  $\rightarrow$ compare likelihood of the two models
LFV Search: $\tau \rightarrow l + \alpha$ (invisible)

- Idea: search for a two body decay spectrum
- No signal region $\rightarrow$ fit full spectrum with
  - SM expectation
  - SM + NP expectation
  - $\rightarrow$ compare likelihood of the two models
- Sensitivity dependent on $m_\alpha$
- Last results from
  - ARGUS (472 pb$^{-1}$) $\rightarrow$ Belle II is competitive with early data
  - MARK III (9.4 pb$^{-1}$)
  - $\sim 10$ fb$^{-1}$
Lepton Flavour Violation Motivation

- We expect LFV in many Beyond the Standard Model (BSM) models
- For Tau at Belle II the “golden modes” are: $\tau \rightarrow \mu \gamma$  
  $\tau \rightarrow lll$
- See talk from Alberto Martini

**Lepton Flavour Violation (LFV)** is highly suppressed in the Standard Model (SM), even if neutrino oscillation is taken. Many possible LFV decay modes related to the New Physics (NP) models have irreducible background contributions.

**Introduction to tau LFV**

Many extensions to Standard Model (BSM) models predict to enhance LFV to be experimentally unreachable. For Tau at Belle II the “golden modes” are:

1. $\tau \rightarrow \mu \gamma$
2. $\tau \rightarrow lll$

**See talk from Alberto Martini**

**SM:** $\mathcal{O}(10^{-49}) - \mathcal{O}(10^{-54})$

**NP:** $\mathcal{O}(10^{-7}) - \mathcal{O}(10^{-10})$
Conclusion

• The Tau has various interesting physics opportunities at Belle II:

  • Interesting results with early data possible
    • Potential observation of LFV in $\tau \rightarrow e + \alpha$
    • Exotic hadronic currents

  • With larger data set rich physics program with various interesting results
    • Improvements of SM Parameters
    • Potential measurements/verifications of SM parameters: $g - 2$
    • Potential verification of non SM CP violation
    • Potential observation of LFV in $\tau \rightarrow l\gamma$, $\tau \rightarrow lll$, ...
• Tau mass measured using an analysis of a 3x1 prong pion decay.

• Using a dataset of approximately 291 pb$^{-1}$ of early data.

• $m_\tau = (1776.4 \pm 4.8)$ MeV
Why Study the $\tau$ at Belle II?

- At $e^+e^-$ machines there is a well understood production mechanism for $\tau$
- SuperKEKB collider
  - Electron - Positron Asymmetric Accelerator
  - Runs at $\Upsilon(4S)$ resonance
  - Increased Integrated Luminosity: $1 \text{ ab}^{-1}$(KEKB) -> $50 \text{ ab}^{-1}$
What is the Tau particle?

- 3rd generation Lepton
  - Point like, fundamental
- \( M_\tau = 1776 \pm 0.12 \text{ MeV} \)
  - Can decay hadronically
- \( \tau_\tau = 290.3 \pm 0.5 \text{ fs} \)
Physics Prospects at Belle II

• The most anticipated results can be grouped in three sectors:
  
  • Lepton Flavour Violation (LFV)
  
  • Charged Parity (CP) violation
  
  • Standard Model (SM) measurements
LFV in $\tau$ Decays

- Decay with highest predicted branching ratio:
  $\tau \to \mu \gamma$

- Neutrino induced LFV in $\tau$ is expected at a level of:
  $B(\tau \to \mu \gamma) \sim 10^{-45}$

- Current Limit: $B(\tau \to \mu \gamma) < 4.4 \times 10^{-8}$

- For 50 ab$^{-1}$ the sensitivity is expected to improve by a factor of 2

- Serious background (BG) from SM process: $\tau \to \mu \nu \nu$
LFV in $\tau$ Decays

- Interesting alternative:

$\tau \to lll$

  - Highly suppressed backgrounds.
  
  - Uncertainties scale with sample size.

- Current limits are $B(\tau \to \mu\mu\mu) = 2.1 \times 10^{-8}$

- Prospects for 50 ab$^{-1}$: $\mathcal{O}(10^{-10})$
Physics in the Early Phases of Belle II

• Performance studies

• 1 prong decays
  - $\tau \rightarrow \pi \nu$ for probing Lepton Universality

• 3 prong decays
  - $\tau \rightarrow \pi \pi \pi \nu$ for measurements of the mass, lifetime, …