First Results and Prospects for $\tau$ Lepton Physics at Belle II

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on behalf of the Belle II Collaboration

05.09.2021
PANIC 2021
\( \tau \)-Pair Production at Belle II

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

- SuperKEKB is a \( \tau \)-factory!
  - \( \sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb} \)
  - \( \sigma(e^+e^- \rightarrow \Upsilon(4S)) \approx 1 \text{ nb} \)
SuperKEKB a (Super-)\(\tau\)-Factory

- At \(e^+e^-\) machines there is a low background and well understood production mechanism for \(\tau\)
- Exploit \(\tau\)-tag method
- SuperKEKB collider
  - Increased Integrated Luminosity: \(1\ \text{ab}^{-1}\) (KEKB) \(\rightarrow\) \(50\ \text{ab}^{-1}\) (SuperKEKB)
  - \(~45\) billion tau pairs for full Belle II program
  - World Record Peak Luminosity so far: \(3.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}\)
The 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%):C$_2$H$_6$ (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

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

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

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

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One of The First $\tau^+\tau^-$ Events
**τ Mass Measurement (Preliminary)**

- τ mass measured using an analysis of 3x1 prong decays.
- Mass extraction from 3-pion decay channel
- Using a dataset of approximately 8.8 fb$^{-1}$ of data.
- Systematic uncertainty dominated by track momentum scale → going to improve!

### Systematic uncertainty

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\( \tau \) Mass Measurement (Preliminary)

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

- First \( \tau \) physics results with early data: consistent with previous measurements!

- Future improvements of statistical precision and systematic uncertainties

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**PDG average**: 1776.86 ± 0.12 MeV/c²

**BES III (2014)**: 1776.91 ± 0.12 ± 0.13 MeV/c²

**ARGUS (1992)**: 1776.3 ± 2.4 ± 1.4 MeV/c²

**Belle (2007)**: 1776.61 ± 0.13 ± 0.35 MeV/c²

**BaBar (2009)**: 1776.68 ± 0.12 ± 0.41 MeV/c²

**Belle II (2020)**: 1777.28 ± 0.75 ± 0.33 MeV/c²

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**BELLE2-CONF-PH-2020-010**
\( \tau \) lifetime measurement

- Decay time given by \( t_{\tau} = \frac{l_{\tau}}{p_{\tau}} \)

- Belle: \( \tau_{\tau} = 290.17 \pm 0.53 \pm 0.33 \) fs
  with 711 fb\(^{-1}\) of data
  DOI: 10.1103/PhysRevLett.112.031801

- Exploits Belle II unique
  - Small beam spot size
  - High resolution of the vertex detector
    → Almost twice as good resolution as Belle.
    arXive:2108.03216

- Competitive results may be feasible with current dataset > 200 fb\(^{-1}\)
Further Standard Model Measurements

- $\tau g - 2$ and EDM
- Belle (30 fb$^{-1}$): $\text{EDM} < \mathcal{O}(10^{-17})$
  
  DOI: 10.1016/S0370-2693(02)02984-2

- To be updated: arxiv:2108.11543

- Prospect for first significant measurement of non-zero SM $g - 2$, with full Belle II luminosity!

$$\frac{g - 2}{2} \equiv a_{\tau}^{SM} = (1,17721 \pm 0.00005) \cdot 10^{-3}$$

$$a_{\tau}^{Exp} = 0.018 \pm 0.017$$

DOI: 10.1140/epjc/s2004-01852-y
Lepton Flavor Violation Motivation

- We expect LFV in many Beyond the Standard Models (BSM)
- For $\tau$ at Belle II the “golden modes” are:
  $\tau \rightarrow \mu\gamma$
  $\tau \rightarrow \nu\nu\nu$
- $\tau \rightarrow 3\mu$ one of the priorities

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

NP: $\mathcal{O}(10^{-10})-\mathcal{O}(10^{-7})$
Looking Forward To $\tau \rightarrow \mu \mu \mu$

- Highly suppressed backgrounds.

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

- Prospects for 50 ab$^{-1}$: $\mathcal{O}(10^{-10})$

- Uncertainties scale with sample size!
  - Improvements through:
    - increase in luminosity
    - increase in signal detection efficiency
  → Motivation to improve efficiency

- Belle II could improve the efficiency by
  - Introducing momentum dependent muID optimisation
  - Increasing muon momentum range
  - Allowing a muon tag

Two Independent Variables
1. $M_\tau = \sqrt{E_{\mu\mu\mu}^2 - P_{\mu\mu\mu}^2}$
2. $\Delta E_\tau = E_{\mu\mu\mu}^{CMS} - E_{\text{beam}}^{CMS}$

⇒ For Signal:
  → $\Delta E_\tau$ close to 0
  → $M_\tau$ close to $m_\tau$
Looking Forward To $\tau \rightarrow l + \alpha$ (invisible)

- Search for a two body decay spectrum
- Signal will manifest as a peak in the $\tau$-rest-frame (TRF)

Various NP Scenarios:
- **LFV Z’**: strong bound from ARGUS
- **Light ALP $\alpha$**: unique parameter space accessible

Wolfgang Altmannshofer, Chien-Yi Chen, P.S. Bhupal Dev, Amarjit Soni
Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan,
Current status: $\tau \to l + \alpha$ (invisible)

- Idea: search for a two body decay spectrum
- Challenge: Estimate TRF with missing $\nu_\tau$ momentum
- Using
  $$E_\tau \approx E_{CMS}/2$$
  $$\vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} p^i_\pi$$
- No signal region $\to$ fit full spectrum with
  - SM expectation
  - SM + BSM expectation
  $\to$ compare likelihood of the two models

- Sensitivity depends on $m_\alpha$
- Last results from
  - ARGUS (472 pb$^{-1}$)
  - MARK III (9.4 pb$^{-1}$)
$\to$ we aim to update with $\sim 60$ fb$^{-1}$ of Belle II data
Analysis Strategy

- Using a cut-based Selection
- Statistical treatment with a template Fit
- The data can be modelled as: \( f(x) = N_{\text{sig}} \cdot f_{\text{ea}}(x) + N_{\text{ev\ nu}} \cdot f_{\text{ev\ nu}}(x) + N_{\text{BG}} \cdot f_{\text{BG}}(x) \)

- With \( x \) being the momentum in the tau rest-frame

Upper Limit estimated with a Frequentist profile-like-hood method:

\[
CL_{\text{sig}} = \frac{CL_{\text{sig+bg}}}{CL_{\text{bg}}}
\]
ICHEP MC-study: Upper Limit Estimate

- UL estimate for ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$

- No systematics were taken into account
  → work in progress

### Performance of ARGUS and Thrust method

**ICHEP selection:** Efficiency 13.95% Purity 90.74%

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<tbody>
<tr>
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<td>0.015</td>
<td>0.0025</td>
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<td>1.0</td>
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<td>1.4</td>
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<td>1.6</td>
<td>0.006</td>
<td>0.001</td>
<td>0.0009</td>
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**Performance of ARGUS and Thrust method is similar**
Conclusion And Outlook

• The $\tau$ has various interesting physics prospects at Belle II:
  
  • Improvements of SM Parameters
    
    • $\tau$-mass
    • $\tau$-lifetime
  
  • Potential measurements/verifications of SM parameters: $g-2$ or EDM
  
  • Potential observation of LFV
    
    • $\tau \to l + \alpha$
    • $\tau \to \mu\mu\mu$
    • $\tau \to l\gamma$, ...
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
    ▶ …
• τ mass measured using an analysis of 3x1 prong decays.
  • Mass extraction from 3-pion decay channel
• Using a dataset of approximately 8.8 fb⁻¹ of data.
• Systematic uncertainty dominated by track momentum scale
  → going to improve!

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

**Statistical**

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- Interaction vertex for off-shell $\gamma$ and on-shell $\tau\tau$:
\[ \Gamma^\mu(q^2 \to 0) \propto i a_{\tau} - \frac{2m_{\tau}d_{\tau}}{e} \]
- $e$: positron charge
- $m_{\tau}$: $\tau$-mass
- $d_{\tau}$: electric dipole moment

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**DELPHI**

\[ \sigma(ee \to e\tau\tau) \text{ (pb)} \]

- Measurements
- Mean
- Standard Model

G-2 influences correction


https://doi.org/10.1140/epjc/s2004-01852-y