Tau Lepton Physics at Belle II

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on behalf of the Belle II collaboration

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1) Overview of SuperKEKB and the Belle II experiment

2) First $\tau$ lepton physics results using early data

3) Prospects for $\tau$ lepton physics at Belle II

4) Summary and outlook
SuperKEKB Accelerator

- New facility to search for physics beyond the SM by studying $B$, $D$ meson and $\tau$ lepton decays
- Energy asymmetric electron-positron collider (7-4 GeV)
- Higher beam currents compared to KEKB, and can achieve 50 nm vertical beam spot size at IP:
  - Unprecedented design luminosity of $8.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
  - First beams and commissioning in 2016, Belle II detector rolled in 2017

@KEK
Tsukuba, Japan
Major upgrade of the Belle detector:

- **Pixel Detector**
- **Silicon Vertex Detector**
- **Central Drift Chamber**
- **TOP Counter**
- **Aerogel RICH Counter**
- **Electromagnetic Calorimeter**
- **K_L / Muon Detector**

**Tracking**

**Particle ID**
Belle II as $\tau$-factory, and schedule

- Belle II is not only a $B$-factory, but a next-generation $\tau$ lepton factory
  - $\sigma(e^+e^-\rightarrow Y(4s)) = 1.05$ nb, $\sigma(e^+e^-\rightarrow \tau^+\tau^-) = 0.92$ nb

- Over its lifetime Belle II aims to record 50 ab$^{-1}$ of $e^+e^-$ collision data (x50 that of Belle)
  - $4.6\times10^{10}$ $\tau$-pair events
  - unique environment to study $\tau$ lepton physics with high precision!

**Phase II** (2018, 3 months)
**Phase III** (starting later this month)

- Data taking in Phase II was performed with all subsystems, except full vertex detector
- VXD now installed and ready for Phase III
First collisions

- First collisions recorded by Belle II on 26th April 2018
- During Phase II (April-July) about 500 pb^{-1} of data was recorded
- Good performance of the subsystems. Clear mass peaks observed from both tracks and photons.
- τ leptons also observed…
• Targeting $e^+e^-\rightarrow \tau^+\tau^-$ with 3-by-1 prong decay: $\tau_{\text{tag}} \rightarrow \ell^\pm \nu_\ell \overline{\nu}_\tau$  $\tau_{\text{signal}} \rightarrow 3\pi^\pm \nu_\tau + n\pi^0$

• Events required to fire CDC track trigger: 291 pb$^{-1}$ of usable data

• Event topology and kinematic selections tailored to suppress $q\overline{q}$ and $ee\gamma$ backgrounds, driven by:
  - thrust value $= \sum_h \frac{\vec{p}_h \cdot \hat{T}}{|p_h|}$, large for the signal since both $\tau$ leptons are boosted (back-to-back)
  - total visible energy, below $\sqrt{s}$ for the signal due to the three undetected neutrinos

\[\sum h \cdot \hat{T} \]
Tau leptons in early Belle II data

- After trigger + offline selections, we have agreement between the data and MC

**inclusive decay:** \( \tau_{\text{signal}} \rightarrow 3\pi^{\pm} \nu_\tau + n\pi^0 \)

**exclusive decay:** \( \tau_{\text{signal}} \rightarrow 3\pi^{\pm} \nu_\tau \)

- Clear evidence for \( e^+e^- \rightarrow \tau^+\tau^- \) in the Phase II data, and a demonstration of the capacity for missing energy analyses with Belle II
$e^+e^- \rightarrow \tau^+\tau^-$ event candidate

hits in KLM
• First $m_\tau$ measurement at Belle II was performed with a pseudomass technique developed by the ARGUS collaboration:

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

• $M_{\text{min}}$ distribution in the $\tau_{\text{signal}} \rightarrow 3\pi^{\pm} \nu_\tau$ decay channel is fitted to an empirical edge pdf (where $m^*$ is an estimator for $m_\tau$):

$$F(M_{\text{min}}; a, b, c, d, m^*) = (aM_{\text{min}} + b) \times \tan^{-1}\left[(m^* - M_{\text{min}})/c\right] + dM_{\text{min}} + 1$$

• A fit to the pdf in the 1.7-185 GeV region yields an $m_\tau$ measurement of:

$$m_\tau = 1776.4 \pm 4.8 \text{ (stat) MeV}$$

which is in good agreement with previous measurements.
Prospects for tau lepton physics

• The Phase III of data taking is expected to start later this month

• The huge amount of data to be delivered (50 ab⁻¹, 2019 - 2027) will enable a broad program of τ lepton physics:
  
  ‣ Searches for Lepton Flavour Violation (LFV)
  
  ‣ CP violation
  
  ‣ Second class currents
  
    and much more…

    (Michel parameters, precision m_τ, electric dipole moment, …)

• A brief overview of the program is provided here. More info can be found in The Belle II Physics Book.
Searches for charged LFV

- LFV has been established for the neutrinos, but what about their charged partners (e, μ and τ)?

- In the SM, charged LFV decays via neutrino oscillation are highly suppressed and immeasurably small:

  \[ Br(\ell_1 \rightarrow \ell_2 \gamma)_{SM} \propto \left( \frac{\delta m^2_{\nu}}{m_W^2} \right)^2 \sim 10^{-54} - 10^{-49} \]

- Observation of charged LFV would be a clear signature for New Physics!
  - \( Br \) enhanced in many NP models (\( 10^{-10} - 10^{-7} \))
  - SUSY, extended Higgs sector, seesaw, leptoquarks, non-universal \( Z' \), and many more
  - \( \mu \rightarrow e \): stringent bounds exist from MEG
  - \( \tau \rightarrow \mu/e \): weaker bounds (Belle, BaBar and CLEO)

- As heaviest lepton, NP can have preferential \( \tau \) LFV couplings
Prospects for $\tau$ LFV decays

• Due to their large mass, $\tau$ leptons provide a wide variety of LFV (and LNV) decay modes to study:
  
  - radiative: $\tau \rightarrow \ell \gamma$
  
  - leptonic: $\tau \rightarrow \ell \ell \ell$
  
  - semileptonic: $\tau \rightarrow \ell h(h)$

} “golden channels” for discovery: $\tau \rightarrow \mu \gamma$, $\tau \rightarrow \mu \mu \mu$

• complementary: semileptonic modes allow us to test LFV couplings b/w quarks and leptons, and better discriminate b/w NP models

• So far, searches for $\tau$ LFV decays mostly occurred at last-gen $B$ factories

• Upper limits had approached the regime sensitive to NP ($10^{-10}$-$10^{-7}$)

Extrapolating from Belle results (50 ab$^{-1}$):

Belle II will push the current bounds forward by at least one order of magnitude!

arXiv:1808.10567
CP violation in $\tau \to K_S \pi^\pm \nu_\tau + \pi^0$

- Due to CP violation in the kaon sector, $\tau \to K_S \pi^\pm \nu_\tau$ decays in the SM have a nonzero decay-rate asymmetry:

  \[ A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)} \]

- SM prediction: \((3.6 \pm 0.1) \times 10^{-3}\)

- BaBar measurement: \((-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}\) \((2.8\sigma)\)

- An improved $A_\tau$ measurement is a priority at Belle II
CP violation could also arise from a charged scalar boson exchange. It would be detected as a difference in the decay angular distributions:

\[
A_{CP}^i = \frac{\int_{Q_{2,i}}^{Q_{1,i}} \cos \beta \cos \psi \left( \frac{d\Gamma_{i-}}{d\omega} - \frac{d\Gamma_{i+}}{d\omega} \right) d\omega}{\frac{1}{2} \int_{Q_{2,i}}^{Q_{1,i}} \left( \frac{d\Gamma_{i-}}{d\omega} + \frac{d\Gamma_{i+}}{d\omega} \right) d\omega} \\
\approx \langle \cos \beta \cos \psi \rangle_{\tau-} - \langle \cos \beta \cos \psi \rangle_{\tau+},
\]

\[d\omega = dQ^2 d\cos \theta d\cos \beta\]

With 50 ab\(^{-1}\) of data, Belle II is expected to provide a x70 more precise measurement:

\[|A_{CP}| < (0.5-3.8) \times 10^{-4}\] (assuming central value \(A_{CP} = 0\))
Second class currents in $\tau \to \eta \pi \nu$

- Hadronic currents classified as first or second class according to their spin, parity and G-parity quantum numbers
  - Second Class Current (SCC): $J^{PG} = 0^{+-} (a_0), 0^{-+} (\eta), 1^{++} (b_1), 1^{--} (\omega)$ \implies yet to be observed!

- In the SM, $\tau \to \eta \pi \nu$ decays proceed via SCCs (isospin-violating) with tiny BRs $\lesssim \mathcal{O}(10^{-5})$

- Searched for at last-gen $B$ factories:
  - Belle: $Br < 7.3 \times 10^{-5}$
  - BaBar: $Br < 9.9 \times 10^{-5}$

- The observation of SCC via $\tau \to \eta \pi \nu$ decay is a priority at Belle II
- SM predictions can be tested for the first time with the first years data taking (1 ab$^{-1}$)
- Clear signal could suggest New Physics!
• SuperKEKB has completed the commissioning phase. Phase II data is available and delivering results.

• The Phase III of data taking with the full Belle II detector installed will start later this month.

• Belle II has a broad program of $\tau$ lepton physics planned, and will be a major player in the near future.

• Exciting times ahead!
BACKUP
**Tracks**
- $p_T > 100 \text{ MeV}$
- $|dz| < 5 \text{ cm, } |dr| < 1 \text{ cm}$
- $-0.8660 < \cos(\theta) < 0.9565$
- $E/p < 0.8$

**Photons**
- $E > 200 \text{ MeV}$
- $n\text{Hits} > 1.5$
- $E_9E_{25} > 0.9$
- $-0.8660 < \cos(\theta) < 0.9565$

**Trigger**
- CDC track trigger bit 3
  - $\geq 3 \text{ tracks @ L1}$

**Event Selections**
- 4 tracks per event
- sum charge zero
- two hemispheres wrt thrust axis, 3 tracks on one side and 1 track in opposite
- thrustValue > 0.87
- visibleEnergyCMS < 9.7
- $E_T$ signal at CMS < 5.29
- $E_T$ tag at CMS < 5.29
- $\pi^0 \leq 2, N_{\gamma} \leq 5$ on tag side
- inclusive decay channel: $\pi^0 \leq 1, N_{\gamma} \leq 3$ on signal side
- exclusive decay channel $\pi^0$-veto, $N_{\gamma} \leq 1$ on signal side
• Reduced mass window:

$$m_\tau = (1777.3 \pm 4.6) \text{ MeV}$$
• 40 times higher luminosity comes at the cost of higher beam related backgrounds
  - expect 20 higher than at Belle

• Understanding the beam background is essential for $\tau$ physics in Belle II!

• Beam bkg is controllable in an event by imposing track selections and using timing information from calorimeter
Beam background reduction

- For photon clusters:
  - $E_\gamma > 0.100$(forward endcap), 0.090(barrel), 0.160(backwards endcap) GeV;
  - $|\Delta t_{\text{cluster}}| < 50$ ns.
- For charged particles:
  - Track fit p-value > 0.01;

  - Beam background rejection mainly coming from two-energy based selections

arXiv:1808.10567v2
Analysis strategy for LFV $\tau$ decays

- Rare decay search:
  $\Rightarrow$ understand and reduce as much as possible the backgrounds

- Search in various decay modes:
  - $\tau \rightarrow \ell \ell \ell$
  - $\tau \rightarrow \ell K_s, \Lambda h$
  - $\tau \rightarrow \ell V_0 (\rightarrow hh')$
  - $\tau \rightarrow \ell P^0 (\rightarrow \gamma \gamma)$
  - $\tau \rightarrow \ell hh'$
  - $\tau \rightarrow \ell \gamma$

Difficulty of background reduction
• Two independent variables are used to evaluate signal yield:

\[ M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - p_{\mu\gamma}^2} \]

• For signal: \( \Delta E \) close to 0 and \( M_{\mu\gamma} \) close to \( \tau \)-mass

\[ \Delta E = E_{\mu\gamma}^{CM} - E_{\text{beam}}^{CM} \]

• Feasibility studies were performed, using MC that included the larger beam bkg. They show that the larger bkg should have minimal impact on sensitivity @ Belle II.
In SM, \( \tau \) lepton decay is due to the interaction with a charged weak current.

Leptonic decays are of particular interest since absence of strong interaction allows precise study of EW Lorentz structure.

When spin of \( \tau \) lepton is not determined, only four bilinear combinations of the coupling constants are experimentally accessible:

- \( \rho, \eta, \xi \) and \( \delta \)
- In SM: 3/4, 0, 1 and 3/4

With full dataset (50 ab\(^{-1}\)), the stat uncertainty is expected to be \( \sim 10^{-4} \)

Systematic uncertainties will be challenging at Belle II (\( \sim 10^{-3} \))