$\tau$ physics results and prospects at Belle II

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On behalf of the Belle II collaboration

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SuperKEKB and The Belle II experiment

- Challenges at L=8x10^{35} 1/cm^2/s:
  - Higher background (Radiative Bhabha, Touschek, beam-gas scattering, etc.).
  - Higher trigger rates (High performance DAQ, computing).

"Nano-beams": vertical beam size is 50nm at the IP.
The Belle II experiment

- Integrated luminosity expected: 50 ab\(^{-1}\) (x50 than the previous B factories)

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

**lectron (7 GeV)**

**Beryllium beam pipe:** 2 cm diameter

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

**Central Drift Chamber:** He(50%):C\(_2\)H\(_6\)(50%), Small cells, long lever arm, fast electronics

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

**Readout (TRG, DAQ):**
- Max. 30kHz L1 trigger
- ~100% efficient for hadronic events.
- 1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record
- Offline computing: Distributed over the world via the GRID

**Integrated luminosity expected:**

\[
\int \frac{1}{cm^2 s} = 8 \times 10^{35} \frac{1}{cm^2 s}
\]

\[
\int \frac{1}{ab} = 50 \frac{1}{ab}
\]
The Belle II experiment

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Electron (7 GeV)

Positron (4 GeV)

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To the date, we have reached an integrated luminosity of 50 fb^{-1}
τ lepton physics on the B-Factories

- B-Factories are also τ-factories!
  \[ \sigma(e^+e^- \rightarrow BB) = 1.05 \text{ fb}^{-1} \]
  \[ \sigma(e^+e^- \rightarrow \tau \tau) = 0.92 \text{ nb} \]

- τ lepton decays allow a clean analysis of hadronization, determination of SM parameters, properties of weak currents and BSM searches.

- Belle and BaBar provided many interesting results in τ lepton physics along the last two decades.

- Many of this results will be updated by Belle II
The physics program at Belle II

- The enormous number of $e^+e^-$ collisions features a unique environment for the study of $\tau$ physics with high precision.

- Further details can be found in “The Belle II Physics Book”, which is now available at: PTEP 2019 (2019) 12, 123C01

- The physics program of the Belle II experiment covers also high precision measurements in B decays, charm, dark sectors, exotic particles, etc.

- See the Belle II talks during FPCP 2020:
  - Charm and charmonium
  - First B physics results
  - Radiative and electroweak penguin decays
  - CKM matrix
  - Full Event Interpretation algorithm
  - Belle II status and prospects
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
Measurement of the $\tau$ lepton mass

- Measured in the decay mode $\tau \rightarrow 3\pi\nu$, using a pseudomass technique developed by the ARGUS collaboration:
  \[ M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \]

- The distribution of the pseudomass is fitted to a empirical edge function.

- Current best fit from Belle $^{1}$
  \[ 1776.61 \pm 0.13 \pm 0.35 \text{ MeV} \]

- Not so good compared to the BES III mass measurement in the production threshold $^{2}$
  \[ 1776.91 \pm 0.12 \pm 0.13 \text{ MeV} \]

Uncertainty in the $\tau$ mass has important consequences the accuracy of lepton universality measurements:

\[ \frac{\Gamma(\mu \rightarrow e\nu\bar{\nu})}{\Gamma(\tau \rightarrow e\nu\bar{\nu})} \sim \left( \frac{g_\mu}{g_\tau} \right)^2 m_\mu^5 m_\tau^5 \]

Our result, obtained from Belle II early data $^{3}$

\[ m_\tau = (1776.4 \pm 4.8 \text{ (stat)}) \text{ MeV/c}^2 \]

is consistent with previous experimental results.

We are updating the result using the most recent data.

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\[ \tau \rightarrow \ell + \alpha \] (invisible boson)

- It probes the existence of a long-lived BSM boson \( \alpha \).

- Peaking signal in a two-body decay spectrum in the \( \tau \) lepton rest frame (TRF).

- Since we cannot access to the TRF due to the missing neutrino, a pseudo-TRF is built with the following assumptions:
  - \( E_\tau \approx E_{\text{cms}}/2 \), \( \vec{p}_\tau \approx \vec{p}_{3\pi} \)

- Fit full spectrum with:
  - SM expectation
  - SM + NP expectation and compare likelihood of the two models

- Large smearing due to imprecise boost direction (lost \( \nu \)):
  \[ m(\alpha) = 0 \]
  \[ m(\alpha) = 1.4 \]

Latest results from
- ARGUS (472 pb\(^{-1}\)) *
- MARK III (9.4 pb\(^{-1}\))

* Belle II is competitive right now.

H. Albrecht et. al. (ARGUS)
CP violation in $\tau \rightarrow K_S \pi \nu$

- The decay of the $\tau$ lepton to final states containing a $K_s$ meson will have a nonzero decay-rate asymmetry due to CP violation in the kaon sector.

$$A_\tau = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau)}$$

- The SM prediction$^{1,2}$ is

$$A_{\tau}^{SM} = (3.6 \pm 0.1) \times 10^{-3}$$

- BaBar measured:

$$A_{\tau}^{BaBar} = (-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$$

2.8 $\sigma$ away from SM

A measurement of $A_\tau$ is a priority at Belle II.

- Improved vertexing and tracking algorithms play a key role.

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Lepton Flavor Violation

• $\tau^- \rightarrow \ell \gamma$, $\tau^- \rightarrow hh\ell$, etc. (Almost) forbidden in the SM

Assuming Belle II full dataset (50 ab$^{-1}$):

- $B(\ell_1 \rightarrow \ell_2 \gamma) = \frac{3\alpha}{32\pi} \sum_{i=2,3} U_{\ell_1 i}^* U_{\ell_2 i} \frac{\Delta m_{\tau i}^2}{M_W^2}$

$\Delta m_{\tau i}^2$ is the mass squared difference between the $i$th and $1$st generations of neutrinos.

Prospective of Belle II:
- Improvement of 2 orders of magnitude
Lepton Flavor Violation

- $\tau^{-} \to \ell \gamma$, $\tau^{-} \to hhh$, etc. (Almost) forbidden in the SM

Assuming Belle II full dataset (50 ab$^{-1}$):

![Graph showing 90% C.L. upper limits for LFV $\tau$ decays](image)

Prospective of Belle II:
- Improvement of 2 orders of magnitude

SM case:
- BR $\sim 10^{-54}$

NP case:
- BR $\sim 10^{-7} \cdot 10^{-10}$

- Observation of LFV is a clear signature of New Physics!
Lepton Flavor Violation

- Signal identification in LFV analysis is done using a defining a region in the $M_\tau$ vs $\Delta E (= E_\tau - E_{beam})$ space.

- Rotated signal region:

$$
\begin{pmatrix}
M'_{3\mu} \\
\Delta E'
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
M_{3\mu} \\
\Delta E
\end{pmatrix}
$$

$\tau \rightarrow 3\mu$ Signal events

$\tau \rightarrow 3\mu$ (10$^7$ events)

$\tau \rightarrow \ell \gamma$ w/ background components

- Belle II PID algorithms will be crucial for LFV studies.

SM case:
$BR \sim 10^{-54}$

NP case:
$BR \sim 10^{-7}$ - $10^{-10}$
Searches of $\tau \rightarrow \eta \pi \nu$

- Mechanisms in the SM: isospin violation

\[
\epsilon_{\eta\pi} = \frac{\langle \pi^0 | H | \eta \rangle}{m_{\eta}^2 - m_{\pi^0}^2} = \sqrt{3} \frac{m_d - m_u}{4 m_s - m} \sim 1.5 \times 10^{-2}
\]

- The corresponding suppression of the SM contribution can make new physics visible.

- Constraints on scalar and tensor couplings can be obtained from upper limits on BRs.\(^2\)


Sensitivity of $\tau \rightarrow \eta \pi \nu$ @ Belle II

- We have the capability of testing QCD models
- Control of the background is fundamental

Previous results:
- $670 \text{ fb}^{-1}$
- $470 \text{ fb}^{-1}$

SM predictions: $\text{BR}(\tau \rightarrow \eta \pi \nu) \sim 10^{-5}$

<table>
<thead>
<tr>
<th>BR$_V$ (x10$^5$)</th>
<th>BR$_S$ (x10$^5$)</th>
<th>BR$_{V+S}$ (x10$^5$)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36</td>
<td>1.0</td>
<td>1.36</td>
<td>MDM, 1 resonance</td>
</tr>
<tr>
<td>[0.2, 0.6]</td>
<td>[0.2, 2.3]</td>
<td>[0.4, 2.9]</td>
<td>MDM, 1 and 2 resonances</td>
</tr>
<tr>
<td>0.44</td>
<td>0.04</td>
<td>0.48</td>
<td>Nambu-Jona-Lasinio</td>
</tr>
<tr>
<td>0.13</td>
<td>0.20</td>
<td>0.33</td>
<td>Analyticity, Unitarity</td>
</tr>
<tr>
<td>0.26</td>
<td>1.41</td>
<td>1.67</td>
<td>3 coupled channels</td>
</tr>
</tbody>
</table>

Other models:
- MDM, 1 resonance
- MDM, 1 and 2 resonances
- Nambu-Jona-Lasinio
- Analyticity, Unitarity
- 3 coupled channels

1R Escribano, S Gonzalez-Solis, P Roig - Physical Review D, 2016
Summary

• SuperKEKB and Belle II will produce a sample of $\tau$ pairs 50 times larger than previous B-factories. Precision studies with $\tau$ leptons involved will be performed.

• The performance of the detector in the first months of data taking is good. Belle II is reconstructing $e^+e^- \rightarrow \tau^+\tau^-$ events. Performance studies on going.

• The $\tau$ lepton decays presented aim to study:
  • Searches of a long-lived BSM boson $\alpha$ and heavy neutrinos
  • CP violation
  • Lepton Flavor Violation decays.
  • Properties of vector, scalar and tensorial interactions, isospin symmetries.

• Belle II will provide a sort of very interesting results in the next decade.
  See “The Belle II Physics Book” at PTEP 2019 (2019) 12, 123C01
Thank you
Event selection strategy

- Event is divided in two sides (signal and tag) using a plane defined by a **thrust axis**, build with all the final state particles:

  \[ V_{thrust} = \frac{\sum_i |\vec{p}_{i\,cm}^\ast \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_{i\,cm}|} \]

- Thrust axis: \( \hat{n}_{thrust} \) such that \( V_{thrust} \) is maximum.