Prospects for $\tau$ lepton physics at Belle II

Michel Hernández Villanueva
Department of Physics
Cinvestav, Mexico

On behalf of the Belle II collaboration

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Outline:

• Achievements of B-factories in $\tau$ lepton physics.
• The Belle II experiment.
• First results with early data.
• Prospects of $\tau$ lepton physics
B Factories

- **B-Factory**: Production of $b$ pairs.

\[ \sigma(e^+e^- \rightarrow \mu^+\mu^-) = 1.05 \text{ nb} \]

\[ \sigma(e^+e^- \rightarrow e^+e^-) = 0.92 \text{ nb} \]

- **BaBar detector**
  - DIRC (PID) 144 quartz bars
  - EMC 6580 CsI(Tl) crystals
  - Drift Chamber 40 stereo layers
  - Silicon Vertex Tracker 5 layers, double sided strips

\[ \sqrt{s} = 10.58 \text{ GeV} \]
$\tau$ lepton physics results at B factories

$L_{\text{int}}$ (fb$^{-1}$)

- Electric dipole limit
- Limits in $\tau \rightarrow \mu \gamma$
- Limits in $\tau \rightarrow \ell \ell \ell$
- SCC searches
- Mass and CPT test
- LFV limits
- CP-Violation
- Lifetime and CPT test

Belle

BaBar

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Next gen: Belle II collaboration

- 800+ members, 108 institutions, 25 countries
- Located in KEK at Tsukuba, Japan
Next gen: SuperKEKB

- **Super B-Factory**
  (And $\tau$ factory too!)

  $\sigma(e^+e^- \rightarrow \Upsilon(4s)) = 1.05 \text{ nb}$
  $\sigma(e^+e^- \rightarrow \tau\tau) = 0.92 \text{ nb}$

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

  $4.6 \times 10^{10}$ $\tau$ pairs

@KEK
Tsukuba, Japan
Next gen: SuperKEKB

- Challenges at L=8x10^{35} 1/cm²/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.
Belle II Schedule

Goal of Belle II/SuperKEKB

Data taking in phase II was performed with all subsystems, except vertex detectors.

They are being installed and they will be ready for phase III.

Integrated luminosity (ab$^{-1}$)

Peak luminosity (cm$^{-2}$s$^{-1}$)

Calendar Year

Phase II (Partial Belle II)  Phase III (Full Belle II)
Most of the Belle II detector subsystems are working well. We have signals involving photons and charged tracks.
Candidates: 3 - 1 prong decay
\[ e^+e^- \rightarrow (\tau \rightarrow 3 \text{ tracks})(\tau_{\text{tag}} \rightarrow \text{track}) \]

We are assuming pion hypothesis in signal side.

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

\[ V_{\text{thrust}} = \frac{\sum_i |\vec{p}_{i \text{ cm}} \cdot \hat{n}_{\text{thrust}}|}{\sum_i |\vec{p}_{i \text{ cm}}|} \]
After selection cuts, we have an agreement between distributions in data and MC.

Performance of the subsystems is good.

M$_{3\pi}$ distribution @ 291 pb$^{-1}$
$\tau \rightarrow 3\pi \nu$ in Belle II early data
Measurement of $\tau$ mass

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

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

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

- A first measurement of $m_\tau$ at Belle II is performed using the data collected during the Phase II.

$M_{\text{min}}$ distribution @ 291 pb$^{-1}$:
Our result, obtained from Belle II early data

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

Is consistent with previous experimental results.
• The enormous amount of $e^+e^-$ collisions that are expected from the Belle II experiment features an unique environment for the study of $\tau$ physics with high precision.

• Further details can be looked at “The Belle II Physics Book”, which is now available at: arXiv:1808.10567
Upper limits for the BR of $\tau$ LFV decays.

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

Observation of LFV is a clear signature of New Physics.

Improvement of 2 orders of magnitude.

See Ami’s talk on Tuesday
CP violation in $\tau \rightarrow K_S \pi (\geq 0\pi^0)\nu$

- 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

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

- BaBar measured:

$$A_{\tau}^{BaBar} = (-3.6 \pm 2.3 \pm 1.1) \times 10^{-3} \quad 2.8 \sigma \text{ away from SM}$$

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

CP violation in $\tau \to K_s \pi \nu$

- CPV that could arise from a charged scalar boson exchange. It can be detected as a difference in the decay angular distributions

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

- $d\omega = dQ^2 d\cos \theta d\cos \beta$

- With 50 ab$^{-1}$ data at Belle II, we expect 70 times improvement, i.e., $|A_{i}^{CP}| < (0.5 - 3.8) \times 10^{-4}$, at 90% C.L. assuming the central value $A_{i}^{CP} = 0$. 

M. Bischofberger et. al (Belle)
PRL 107 (2011) 131801
Michel Parameters

When spin of $\tau$ lepton is not determined, $\rho$, $\eta$, $\xi$ and $\delta$ are the experimentally accessible parameters used in describing the phase space distribution of $\tau$ leptonic decays.

In SM:
$\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$ and $\delta = \frac{3}{4}$.

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

Comparing with current Belle performance$^1$, systematic uncertainties will be challenging at Belle II ($\sim 10^{-3}$).

Second class currents: $\tau \rightarrow \eta \pi \nu$ decay

- Mechanisms in the SM: isospin violation

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

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

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Estimated Upper Limits for $\tau \to \eta \pi \nu$

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

<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>Analiticity, Unitarity</td>
</tr>
<tr>
<td>0.26</td>
<td>1.41</td>
<td>1.67</td>
<td>3 coupled channels</td>
</tr>
</tbody>
</table>

We have the capability of testing models in the first years of data taking.

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

Semileptonic $\tau$ decays provides a clean environment to study SM processes with QCD involved.

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

Systematic uncertainties will become dominant. Improvements with respect to the last generation of B-factories are required.

$\tau$ decays @ Belle II will provide very interesting results in the next decade. See “The Belle II Physics Book” at arXiv:1808.10567.
Thank you
Backup
# B-Factories

<table>
<thead>
<tr>
<th>Detector</th>
<th>PEP-II</th>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td></td>
<td>Belle</td>
<td>Belle II</td>
</tr>
<tr>
<td>Start date</td>
<td>1999</td>
<td>1999</td>
<td>2016</td>
</tr>
<tr>
<td>End of operations</td>
<td>2008</td>
<td>2010</td>
<td>-</td>
</tr>
<tr>
<td>Beam Energy (GeV)</td>
<td>e-: 9.0</td>
<td>e-: 8.0</td>
<td>e-: 7.0</td>
</tr>
<tr>
<td></td>
<td>e+: 3.1</td>
<td>e+: 3.5</td>
<td>e+: 4.0</td>
</tr>
<tr>
<td>Int luminosity</td>
<td>550 fb⁻¹</td>
<td>1 ab⁻¹</td>
<td>50 ab⁻¹</td>
</tr>
</tbody>
</table>
### Event Selection

**Tracks**
- $p_T > 0.1$ GeV
- $|dz| < 5$ cm
- $|drl| < 1$ cm
- $-0.8660 < \cos(\theta) < 0.9565$
- $E/p < 0.8$

**γ’s**
- $E > 200$ MeV
- nHits $> 1.5$
- $E_9E_{25} > 0.9$
- $-0.8660 < \cos(\theta) < 0.9565$

**Event**
- 3 - 1 prong
- thrustValue $> 0.87$
- visibleEnergyCMS $< 9.7$
- $-0.8660 < \cos(\theta) < 0.9565$
- $E_\tau$ signal at CMS $< 5.29$
- $E_\tau$ tag at CMS $< 5.22$
- $\pi^0$ - veto in signal side.
- $\pi^0 < 3$ in tag side.
- $N_\gamma \leq 1$ in signal side.
- $N_\gamma \leq 5$ in tag side.
- We require data to fire the L1 CDC trigger.
\[ |V_{us}|_{\tau} = \sqrt{R_s / \left[ \frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}} \right]} \]

- At present, the total $V_{us}$ error is strongly dominated by the uncertainties in the weighted flavor spectral integrals.

- Significantly reduced $V_{us}$ errors should be possible through improvements of the strange mode branching fractions.

\begin{itemize}
  \item $K_{i3}$, PDG 2016
    \begin{align*}
      0.2237 & \pm 0.0010 \\
    \end{align*}
  \item $K_{i2}$, PDG 2016
    \begin{align*}
      0.2254 & \pm 0.0007 \\
    \end{align*}
  \item CKM unitarity, PDG 2016
    \begin{align*}
      0.2258 & \pm 0.0009 \\
    \end{align*}
  \item $\tau \to s$ incl., HFLAV Spring 2017
    \begin{align*}
      0.2186 & \pm 0.0021 \\
    \end{align*}
  \item $\tau \to K \nu / \tau \to \pi \nu$, HFLAV Spring 2017
    \begin{align*}
      0.2236 & \pm 0.0018 \\
    \end{align*}
  \item $\tau$ average, HFLAV Spring 2017
    \begin{align*}
      0.2216 & \pm 0.0015 \\
    \end{align*}
\end{itemize}
Measurement of $\alpha_s(m_\tau)$

- Analyses of the $\tau$ hadronic decay width and spectral functions have been performed, leading to precise determinations of $\alpha_s$.

- They are based on different approaches to treat perturbative and non-perturbative contributions.
Sensitivity of $R(D^{(*)})$

- Current measurements are dominated by statistical uncertainty.

- Dominant systematic: limited signal MC samples (Larger at Belle II).

### Uncertainties at Belle II

<table>
<thead>
<tr>
<th></th>
<th>5 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>$(±6.0 ± 3.9)%$</td>
<td>$(±2.0 ± 2.5)%$</td>
</tr>
<tr>
<td>$R_{D^*}$</td>
<td>$(±3.0 ± 2.5)%$</td>
<td>$(±1.0 ± 2.0)%$</td>
</tr>
<tr>
<td>$P_\tau(D^*)$</td>
<td>$±0.18 ± 0.08$</td>
<td>$±0.06 ± 0.04$</td>
</tr>
</tbody>
</table>

### Plot

- Belle II Projection
- Belle Combination
- Babar
- LHCb
- World Combination

1 $\sigma$ contours

Michel H. Villanueva