The prospect of τ physics in the Belle II experiment

Chengping Shen

The 2nd International Workshop on High Intensity Electron-Positron Accelerator (HIEPA), UCAS, March 19-21, 2018
Outline

- Introduction
- Studies of $\tau$ at B factories
- Belle II experiment
- Belle II schedule
- LFV $\tau$ decays at Belle II
- CPV in hadronic $\tau$ decays at Belle II
- B decays involving $\tau$ at Belle II
- Summary
The B Factory Legacy

KEKB + PEP-II

- Nobel prize to KM
- Decisive confirmation of CKM picture
- Evidence of $D^0 - \bar{D}^0$ mixing
  (PRL 98 211803)
- Evidence of $B \rightarrow \tau \nu$
  (PRL 97 251802)
- Excess in $R(D^{(*)})$
  (PRL 109 101802)
- Observation of $b \rightarrow d\gamma$
  (PRL 96 221601)
- Difference in $A_{\text{CP}}(B \rightarrow K \pi)$
  (PRL 100 142001)
- Direct CP violation in $B^0 \rightarrow \pi^+ \pi^-$
  (PRL 93 021601)
- Observation of CP violation in $B^0$ mixing system
  (PRL 87 091801, PRL 87 091802)
- Direct CP violation in $B \rightarrow K \pi$
  (PRL 93 131801, PRL 93 191802)
- $X(3872)$
  (PRL 91 262001)
- Observation of $B \rightarrow K^* \pi \pi$
  (PRL 91 261601)

Integrated Luminosity in fb$^{-1}$

Year

1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
B factory is also a $\tau$ factory!

The world largest statistics of $\tau$ leptons collected by $e^+ e^- B$ factories (Belle and BABAR) opens new era in the precision tests of the Standard Model (SM).

Basic tau properties, like: lifetime, mass, couplings, electric dipole moment, anomalous magnetic dipole moment, etc. should be measured experimentally as precisely as possible in order to test SM and search for the effects of New Physics.

In the SM $\tau$ decays due to the charged weak interaction described by the exchange of $W^\pm$ with a pure vector coupling to only left-handed fermions. There are two main classes of tau decays:

- Decays with leptons, like: $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$, $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau \gamma$, $\tau^- \rightarrow \ell^- \ell' + \ell'^- \bar{\nu}_\ell \nu_\tau$; $\ell, \ell' = e, \mu$. They provide very clean laboratory to probe electroweak couplings, which is complementary/competitive to precision studies with muon (in experiments with muon beam). Plenty of New Physics models can be tested/constrained in the precision studies of the dynamics of decays with leptons.
- Hadronic decays of $\tau$ offer unique tools for the precision study of low energy QCD.
Results of LFV decays of $\tau$ at B factories

48 different LFV modes were studied at B factories

Next Generation SuperKEKB+ Belle II with $> 50 \text{ ab}^{-1}$

→ Discover (or constrain) new physics!
Need $O(100x)$ more data $\rightarrow$ Next generation B-factories
High-Luminosity Asymmetric B Factory

- Target luminosity is $\mathcal{L} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (x40 w.r.t. BELLE)
- Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

![Luminosity calculation formula]

<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB LER</th>
<th>KEKB HER</th>
<th>SuperKEKB LER</th>
<th>SuperKEKB HER</th>
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<td>beam energy</td>
<td>$E_b$</td>
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<td>8</td>
<td>4</td>
<td>7</td>
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<td>emittance ratio</td>
<td>$\kappa$</td>
<td>0.88</td>
<td>0.66</td>
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<td>0.40</td>
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<td>beta-function at IP</td>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>1200/5.9</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td></td>
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<td>beam currents</td>
<td>$I_b$</td>
<td>1.64</td>
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<td>3.6</td>
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<tr>
<td>beam-beam parameter</td>
<td>$\xi_y$</td>
<td>129</td>
<td>90</td>
<td>0.0881</td>
<td>0.0807</td>
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<tr>
<td>beam size at IP</td>
<td>$\sigma_x^<em>/\sigma_y^</em>$</td>
<td>100/2</td>
<td>10/0.059</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>2.1x10</td>
<td>8x10^{35}</td>
<td></td>
<td>cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>
High-Luminosity Asymmetric B Factory

- Target luminosity is $\mathcal{L} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (x40 w.r.t. BELLE)
- Achievable in the nano-beam scheme (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP

$squeezed \ beams \ @ \ IP$
- greatly improved constraint for decay chain vertex fitting

$x40 \ luminosity$
- higher background rates (-10-20x)
  - detectors occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- $x40$ produced signal events

<table>
<thead>
<tr>
<th>parameters</th>
<th>LER</th>
<th>HER</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>Eb</td>
<td>Eb</td>
<td>GeV</td>
</tr>
<tr>
<td>CM boost</td>
<td>$\beta_Y$</td>
<td>0.425</td>
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<tr>
<td>$x40$ luminosity</td>
<td>24</td>
<td>32/0.27</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>0.40</td>
<td>nm</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>25/0.30</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>2.6</td>
<td>$\mu$m</td>
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<tr>
<td></td>
<td>0</td>
<td>0.0881</td>
<td>0.0807</td>
</tr>
</tbody>
</table>
Belle II Detector

4. EM Calorimeter (barrel+endcap): CsI(Tl), waveform sampling

5. $K_L$ and $\mu$ detector: Resistive Plate Counter (barrel) Scintillator + WLSF + MPPC (end-caps)

1. Vertex Detector
   2 layers DEPFET + 4 layers DSSD

2. Central Drift Chamber
   smaller cell size, long lever arm

3. Particle Identification
   Barrel: Time-of-Propagation counters
   End-cap: prox. foc. ARICH

- All sub-detectors are upgraded from Belle II:
  - Except for ECL crystals and a part of Barrel KLM
- Improved IP and secondary vertex resolution
- Better $K/\pi$ separation and flavor tagging
- Higher $K_s, \pi^0$ and slow pion reconstruction efficiency
Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney

RELATED ARTICLES

Rare particle decays offer hope of new physics

Physicists excited by latest LHC anomaly

https://www.nature.com/articles/d41586-018-00162-x
Transitions to Operations

Photo credit: M. Friedl
SuperKEKB/Belle II schedule

- **Phase I**: commissioning of the main ring; installation of outer detectors; vacuum scrubbing and beam bkg. studies
- **Phase 2**: start of the collisions, detector commissioning without vertex detector; first physics runs on Y(4S) and Y(6S) (~20 ± 20 fb⁻¹) [now- July 2018]
- **Phase 3**: full detector operation in the end of 2018
Status of Belle II Physics Book

- Belle II physics book (>630 pages), to be printed by PTEP very soon
  
  https://confluence.desy.de/display/B2TiP+ReportStatus

- The contents include Belle II detector, simulation, reconstruction, analysis software, B decays, CKM angles, charm, quarkonium(-like), \( \tau \), new physics, ….  

- Some golden channels are given with Belle II MC simulations, theoretical discussions, sensitivity and systematic estimates

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. (%)</th>
<th>( N_{BG}^{\text{exp}} )</th>
<th>UL (10^{-8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \eta \to \gamma \gamma )</td>
<td>8.2</td>
<td>0.63 ± 0.37</td>
<td>3.6</td>
</tr>
<tr>
<td>( e \eta \to \gamma \gamma )</td>
<td>7.0</td>
<td>0.66 ± 0.38</td>
<td>8.2</td>
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<tr>
<td>( \mu \eta \to \pi \pi \pi^0 )</td>
<td>6.9</td>
<td>0.23 ± 0.23</td>
<td>8.6</td>
</tr>
<tr>
<td>( e \eta \to \pi \pi \pi^0 )</td>
<td>6.3</td>
<td>0.69 ± 0.40</td>
<td>8.1</td>
</tr>
<tr>
<td>( \mu \eta \text{(comb.)} )</td>
<td></td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>( e \eta \text{(comb.)} )</td>
<td></td>
<td></td>
<td>4.4</td>
</tr>
<tr>
<td>( \mu \eta' \to \pi \pi \eta )</td>
<td>8.1</td>
<td>0.00_{-0.00}^{+0.16}</td>
<td>10.0</td>
</tr>
<tr>
<td>( e \eta' \to \pi \pi \eta )</td>
<td>7.3</td>
<td>0.63 ± 0.45</td>
<td>9.4</td>
</tr>
<tr>
<td>( \mu \eta' \to \gamma \rho^0 )</td>
<td>6.2</td>
<td>0.59 ± 0.41</td>
<td>6.6</td>
</tr>
<tr>
<td>( e \eta' \to \gamma \rho^0 )</td>
<td>7.5</td>
<td>0.29 ± 0.29</td>
<td>6.8</td>
</tr>
<tr>
<td>( \mu \eta' \text{(comb.)} )</td>
<td></td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>( e \eta' \text{(comb.)} )</td>
<td></td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>( \mu \pi^0 )</td>
<td>4.2</td>
<td>0.64 ± 0.32</td>
<td>2.7</td>
</tr>
<tr>
<td>( e \pi^0 )</td>
<td>4.7</td>
<td>0.89 ± 0.40</td>
<td>2.2</td>
</tr>
</tbody>
</table>

MC signal and background estimates for \( \tau \to \gamma \mu \)
Belle II Collaboration

750 colleagues, 101 institutions, 23 countries/regions
国内单位：北航、北大、高能所、中科大、复旦
Lepton-flavor-violating (LFV) decays of $\tau$

- **Figure**: Diagram illustrating the decay of $\tau$ to $\gamma$.

- **Table**:

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>$\tau \rightarrow \mu \gamma$</th>
<th>$\tau \rightarrow \mu \mu \mu$</th>
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<tbody>
<tr>
<td>SM+ $\nu$ oscillations</td>
<td>EPJ C8 (1999) 513</td>
<td>$10^{-40}$</td>
<td>$10^{-14}$</td>
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<tr>
<td>SM+ heavy Major $\nu_R$</td>
<td>PRD 66 (2002) 034008</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-universal Z'</td>
<td>PLB 547 (2002) 252</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>PRD 68 (2003) 033012</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>mSUGRA+seesaw</td>
<td>PRD 66 (2002) 115013</td>
<td>$10^{-7}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>PLB 566 (2003) 217</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

- **Text**:

  - Probability of LFV decays of charged leptons is extremely small in the Standard Model, $\mathcal{B}(\tau \rightarrow l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\tau i}^* U_{\mu i} \frac{\Delta_{3i}^2}{m_W^2} \right|^2 \leq 10^{-53} \sim 10^{-49}$.

  - Many models beyond the SM predict LFV decays with the branching fractions up to $\lesssim 10^{-8}$. As a result, observation of LFV is a clear signature of New Physics (NP).

  - $\tau$ lepton is an excellent laboratory to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes.

  - Study of the different $\tau$ LFV decay modes allows us to test various NP models.
\[\tau\ \text{LFV in NP beyond SM}\]

Ratios of \(\tau\ \text{LFV decay's BF's}\) allow one to discriminate between new physics models

<table>
<thead>
<tr>
<th>(\frac{\mathcal{B}(\tau \rightarrow \mu \mu \mu)}{\mathcal{B}(\tau \rightarrow \mu \gamma)})</th>
<th>SUSY+GUT (\text{(SUSY+Seesaw)})</th>
<th>Higgs mediated</th>
<th>Little Higgs</th>
<th>non-universal (Z')</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 2 \times 10^{-3})</td>
<td>0.06 - 0.1</td>
<td>0.4 - 2.3</td>
<td>(\sim 16)</td>
<td></td>
</tr>
<tr>
<td>(\frac{\mathcal{B}(\tau \rightarrow \mu e e)}{\mathcal{B}(\tau \rightarrow \mu \gamma)})</td>
<td>(\sim 1 \times 10^{-2})</td>
<td>(\sim 1 \times 10^{-2})</td>
<td>0.3 - 1.6</td>
<td>(\sim 16)</td>
</tr>
<tr>
<td>(\mathcal{B}(\tau \rightarrow \mu \gamma)_{\text{max}})</td>
<td>(&lt; 10^{-7})</td>
<td>(&lt; 10^{-10})</td>
<td>(&lt; 10^{-10})</td>
<td>(&lt; 10^{-9})</td>
</tr>
</tbody>
</table>

\(\text{JHEP 0705, 013 (2007); PLB 547, 252 (2002)}\)

\(\therefore\) Good to measure LFV in as many modes as possible!
Past searches for $\tau \rightarrow \gamma \mu$ at Belle

- Blinding box approach with BG evaluated outside the signal region
- Observables space: $\Delta E = E_{\text{CM}}^{(\mu+\gamma)} - E_{\text{beam}}/2$ (expected $\Delta E = 0$)  
  - Signal-side $m_{\text{inv}}$ (expected $m_{\text{inv}} = m_\tau = 1.777$ GeV/$c^2$)
- Signal regions after BG rejection cuts — data (points) and signal MC (shaded):

\[ B(\tau^- \rightarrow \mu^-\gamma) < 4.5 \times 10^{-8} \]
\[ B(\tau^- \rightarrow e^-\gamma) < 12.0 \times 10^{-8} \text{ @ 90\%CL} \]

Belle: PLB 666,16(2008)

τ→ γμ at Belle II

sensitivity study using Belle II MC incl. beam background simulation

- for sensitivity comparison with Belle (with ∫Ldt = 1 ab⁻¹)

Background:

- τ → μνν
- τ → eνν
- τ → πν
- ee → ee/μμ (γ)
- ee → hadronic

Background rejection by

- event shape variables — thrust, Fox-Wolfram moments, momentum flow distributions (“CLEO cones”), etc.

Signal extraction by (ΔE, M_{inv})

- rotating (M_{inv}, ΔE) to minimize correlation
\[ \tau \rightarrow \gamma \mu \] sensitivity at Belle II

<table>
<thead>
<tr>
<th></th>
<th>Belle (535 fb(^{-1}))</th>
<th>Belle II (1 ab(^{-1}))</th>
<th>Belle II (50 ab(^{-1}))</th>
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<tbody>
<tr>
<td>( \mathcal{L} ) (cm(^2)/s)</td>
<td>2.11 \times 10^{34}</td>
<td>80 \times 10^{34}</td>
<td>a naive extrapolation by luminosity</td>
</tr>
<tr>
<td>( \varepsilon_{\text{signal}} )</td>
<td>5.09%</td>
<td>4.59%</td>
<td>5.5 \times 10^{-10}</td>
</tr>
<tr>
<td>( n_{\text{BG}} )</td>
<td>10</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( B_{90}(\tau \rightarrow \mu \gamma) )</td>
<td>4.5 \times 10^{-8}</td>
<td>2.7 \times 10^{-8}</td>
<td></td>
</tr>
</tbody>
</table>

First \( \tau \) LFV sensitivity study at Belle II

- even with much higher beam background, the sensitivity is comparable to that of Belle (scaled by luminosity)
- signal region is background-free
Sensitivity study of searching for $\tau^- \rightarrow \gamma \mu^-$ at HIEPA

Yu-Bo Li · Cheng-Ping Shen · Chang-Zheng Yuan

1. The remaining backgrounds are due to $\mu/\pi$ misidentification based on BESIII simulation.
2. The expected $\mu/\pi$ separation power will increase (>10 times) at HIEPA compared to BESIII.
3. If the backgrounds can be neglected, the upper limit can reach $10^{-9}$ with $\text{Lum}=18.3\text{ab}^{-1}$ at 4.26 GeV.

The advantage compared to B-factory is ISR $\tau^+ \tau^-$ background can be neglected in lower CMS.
τ LFV summary & prospects

HFAG summary plot for τ LFV decays, overlaid with Belle II extrapolation to 50 ab$^{-1}$ assuming zero background
CPV in hadronic $\tau$ decays

- CPV has never been observed in lepton decays
- It is strongly suppressed in the SM ($A_{CP} \leq 10^{-12}$) and observation of large CPV in lepton sector would be clear signal of NP, for example, minimum supersymmetric standard model [IHEP12,021;RMP80,577], multi-Higgs-doublet-models [PRL37,657;NPB426,355]
- $\tau$ lepton provides unique possibility to search for CPV effects, as it is the only lepton decaying to hadrons, so that the associated strong phases allow us to visualize CPV in hadronic $\tau$ decays
- The decays $\tau \to 2\pi\nu$ [PRD50,4544], $K\pi\nu$[PLB398,407], $3\pi\nu$[PRD52,1614], $K\pi\pi\nu$, $KK\pi\nu$ [Z. Phys.G62,413; PRD78, 113008; PRD91, 073006] have been suggested to do CPV measurements.

Two ways to measure CPV in hadronic $\tau$ decays:

I: CPV in $\tau^- \to \pi^- K_S (\geq 0\pi^0)\nu_\tau$ at BaBar (PRD85, 031102(2012); 476 fb$^{-1}$)

$$A_{CP} = \frac{\Gamma(\tau^+ \to \pi^+ K_S (\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S (\geq 0\pi^0)\bar{\nu}_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S (\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S (\geq 0\pi^0)\bar{\nu}_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

2.8$\sigma$ deviation from the SM expectation: $A_{CP(SM)} = (+0.36 \pm 0.01)\%$
CPV in hadronic $\tau$ decays

II: CPV in $\tau^- \to \pi^- K_S \nu_\tau$ at Belle (PRL107, 131801(2011); 699 fb$^{-1}$)

Angular distributions were analyzed, $A_{CP}(W = M_{K_S\pi})$ was measured

$\eta_S$ is the dimensionless complex coupling constant

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

$$\approx \langle \cos \beta \cos \psi \rangle_{\tau^-}^{i} - \langle \cos \beta \cos \psi \rangle_{\tau^+}^{i}, \quad d\omega = dQ^2 d\cos \theta d\cos \beta$$

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

- Branching ratio depends strongly on the mass of the lepton due to helicity suppression. Thus $B^+ \rightarrow \tau^+ \nu_\tau$ is expected to have the largest leptonic branching fraction.
- NP could significantly suppress or enhance the branching ratio i.e. via exchange a charged Higgs boson from supersymmetry or from two-Higgs doublet models (2HDM).
- In the absence of NP, this channel provides a direct determination of the $B$ decay constant $f_B$ and the CKM matrix $|V_{ub}|$.

**Hadronic tagging**
- dominate backgrounds: $B^- \rightarrow D^{(*)0} \ell^- \bar{\nu}_\ell$
  
  
  $[0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$.

**Semi-leptonic tagging** (agree with Had. tag and SM)

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = [1.25 \pm 0.28(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-4}$$

- **tau decays:**
  - $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$
  - $\tau^- \rightarrow \pi^- \nu_\tau$
  - $\tau^- \rightarrow \rho^- \nu_\tau$

Belle PRL 110 131801 (2013)
Belle PRD 92 051102 (2015)

The orange (red) filled distribution represents the BB$^-$ (continuum) background.
$B^+ \rightarrow \tau^+ \nu\tau$ prospect at Belle II

- Analysis on Belle II full simulation using hadronic $B$ reconstruction.
- Signal yields extracted from fit to extra neutral energy.
- The extra energy resolution at Belle II is better than Belle despite the increased beam background.

<table>
<thead>
<tr>
<th>$E_{ECL}$</th>
<th>(&lt; 0.25 \text{ GeV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle II</td>
<td># background events 1348</td>
</tr>
<tr>
<td></td>
<td># signal events 136</td>
</tr>
<tr>
<td></td>
<td>signal efficiency (%) 1.6</td>
</tr>
<tr>
<td>Belle</td>
<td># background events 365</td>
</tr>
<tr>
<td></td>
<td># signal events 60</td>
</tr>
<tr>
<td></td>
<td>signal efficiency (%) 0.7</td>
</tr>
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</table>

- Extrapolation at full Belle II statistics

<table>
<thead>
<tr>
<th></th>
<th>Integrated Luminosity ((ab^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic tag</td>
<td>50</td>
</tr>
<tr>
<td>systematic uncertainty (%)</td>
<td>4.1</td>
</tr>
<tr>
<td>total uncertainty (%)</td>
<td>6.2</td>
</tr>
<tr>
<td>semileptonic tag</td>
<td>2.7</td>
</tr>
<tr>
<td>systematic uncertainty (%)</td>
<td>4.5</td>
</tr>
<tr>
<td>total uncertainty (%)</td>
<td>5.3</td>
</tr>
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</table>
Search NP in $B \rightarrow D^{(*)}\tau^+\nu_\tau$

- In the Standard Model (SM), the only difference between $B \rightarrow D^{(*)}\tau^+\nu_\tau$ and $B \rightarrow D^{(*)}\mu^+\nu_\mu$ is the mass of the lepton.
- The ratio of them is sensitive to additional amplitudes, i.e. involving an intermediate charged Higgs boson.
- NP: type-II-2HDM (charged Higgs boson appears), Leptoquarks(LQ) model...
- NP could affect this decay topology in two ways:
  - Branching fraction
  - $\tau$ polarization
\[ R(D^{(*)}) \text{ in } B \rightarrow D^{(*)} \tau^+ \nu_\tau \]

Test for lepton universality using the ratio typically:

\[ R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)} \quad (\ell = e, \mu). \]

SM: 
- \( R(D) = 0.300 \pm 0.008 \) Phys. Rev. D 92, 034506 (2015)
- \( R(D^*) = 0.252 \pm 0.003 \) Phys. Rev. D 85, 094025 (2012)

- Current world average for \( R(D^{(*)}) \) is in \( \sim 4.1\sigma \) tension with SM!


\[ \tau \text{ Polarization in } B \rightarrow D^{(*)}\tau^+\nu_\tau \]

First measurement of the tau polarization in this decay.
First use tau had. decays in \( B \rightarrow D^{(*)}\tau^+\nu_\tau \)

\[ \tau^- \rightarrow \pi^-\nu_\tau \quad \tau^- \rightarrow \rho^-\nu_\tau \]

Belle PRL 118, 211801 (2017) had. tag

\[ P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \]

\( \Gamma^{+(-)} \) for right-(left-)handed \( \tau \)

\[ R(D^*) = 0.270 \pm 0.035 \text{ (stat.)} \quad ^{+0.028}_{-0.025} \text{ (syst.)} \]

\[ \mathcal{P}_{\tau}(D^*) = -0.38 \pm 0.51 \text{ (stat.)} \quad ^{+0.21}_{-0.16} \text{ (syst.)} \]

Compatibility with the SM.

\[ P_\tau(D^*)_{\text{SM}} = -0.497 \pm 0.013 \text{ Phys. Rev. D 87, 034028 (2013)} \]
$B \rightarrow D^{(*)} \tau^+ \nu_\tau$ prospect at Belle II

- Current measurements are statistically limited, dominant systematics from
  - limited MC -> larger at Belle II
  - limited knowledge of dominant bkg.
    (involving soft pions) —> dedicated studies with large data sample at Belle II
- With higher statistics, study polarization and $q^2$ distributions, essential to distinguish NP.

**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>$(6.0 \pm 3.9)$%</td>
<td>$(2.0 \pm 2.5)$%</td>
</tr>
<tr>
<td>$R_{D^*}$</td>
<td>$(3.0 \pm 2.5)$%</td>
<td>$(1.0 \pm 2.0)$%</td>
</tr>
<tr>
<td>$P_\tau(D^*)$</td>
<td>$0.18 \pm 0.08$</td>
<td>$0.06 \pm 0.04$</td>
</tr>
</tbody>
</table>

The first and the second values are the expected statistical and systematic errors.
Precise studies of $\tau$ at (Super)-B factories

**Michel parameters in $\tau \rightarrow \ell \nu \nu (\rho, \eta, \xi, \delta)$ at Belle:** arXiv:1409.4969

**Study of the radiative leptonic decays $\tau \rightarrow \ell \nu \nu \gamma$:**

**BABAR:** Measurement of $B(\tau \rightarrow \ell \nu \nu \gamma)$; PRD 91, 051103(R) (2015)

**Belle (prelim.):** $\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$, $\xi \kappa = 0.5 \pm 0.4 \pm 0.2$; arXiv:1609.08280

**Lepton universality with $\tau \rightarrow \ell \nu \nu$ and $\tau \rightarrow h \nu$ ($h=\pi, K$) at BABAR:**

$\left( \frac{g_{\mu}}{g_e} \right)_\tau = 1.0036 \pm 0.0020$, $\left( \frac{g_{\tau}}{g_{\mu}} \right)_h = 0.9850 \pm 0.0054$; PRL 105, 051602 (2010)

**Tau lifetime:**

**Belle:** $\tau_\tau = (290.17 \pm 0.53 \text{(stat)} \pm 0.33 \text{(syst)})$ fs; PRL 112, 031801 (2014)

**BABAR (prelim.):** $\tau_\tau = (289.40 \pm 0.91 \text{(stat)} \pm 0.90 \text{(syst)})$ fs; Nucl. Phys. B 144, 105 (2005)

**Tau mass:**

**Belle:** $m_\tau = (1776.61 \pm 0.13 \text{(stat)} \pm 0.35 \text{(syst)})$ MeV/c$^2$; PRL 99, 011801 (2007)

**BABAR:** $m_\tau = (1776.68 \pm 0.12 \text{(stat)} \pm 0.41 \text{(syst)})$ MeV/c$^2$; PRD 80, 092005 (2009)

Accuracy comparable with the most precision measurements done by BES and KEDR at the $\tau^+ \tau^-$ production threshold.

**Tau electric dipole moment (EDM):**

**Belle:** $\text{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ e·cm, $\text{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ e·cm; PLB 551, 16 (2003) ($\int L dt = 29.5$ fb$^{-1}$) We are working on EDM with full Belle statistics

**Hadronic contribution to $a_\mu (\tau^- \rightarrow \pi^- \pi^0 \nu_\tau)$:**

**Belle:** $a_{\mu}^{\pi \pi} = (523.5 \pm 1.1 \text{(stat)} \pm 3.7 \text{(syst)}) \times 10^{-10}$; PRD 78, 072006 (2008)
Belle, being an $e^+e^-$ B-factory experiment, is also a $\tau$-factory experiment at the same time.

With nearly 1 billion $\tau^+\tau^-$ sample, Belle has performed many precise measurements and obtained most stringent upper limits in most of the $\tau$ LFV, LNV and BNV decays, with 90% UL of $O(10^{-8})$.

With $\sim$50 billion $\tau^+\tau^-$ events expected at Belle II, these searches will be greatly improved.

For very clean modes (for example $\tau \rightarrow lll$), the upper limits are expected to improve linearly with luminosity. New physics beyond SM can be searched for in these decays, and also in B decays with $\tau$ final states.
Michel parameters

In the SM charged weak interaction is described by the exchange of $W^\pm$ with a pure vector coupling to only left-handed fermions ("V-A" Lorentz structure). Deviations from "V-A" indicate New Physics. $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$ ($\ell = e, \mu$) decays provide clean laboratory to probe electroweak couplings.

The most general, Lorentz invariant four-lepton interaction matrix element:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} \sum_{N=S,V,T} \sum_{i,j=L,R} g^N_{ij} \left[ \bar{u}_i(l^-) \Gamma^N v_n(\bar{\nu}_l) \right] \left[ \bar{u}_m(\nu_\tau) \Gamma_N u_j(\tau^-) \right],$$

$$\Gamma^S = 1, \quad \Gamma^V = \gamma^\mu, \quad \Gamma^T = \frac{i}{2\sqrt{2}} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)$$

Ten couplings $g^N_{ij}$, in the SM the only non-zero constant is $g^V_{LL} = 1$

Four bilinear combinations of $g^N_{ij}$, which are called as Michel parameters (MP): $\rho, \eta, \xi$ and $\delta$ appear in the energy spectrum of the outgoing lepton:

$$\frac{d\Gamma(\tau^\pm)}{d\Omega dx} = \frac{4G^2_F M_\tau E_{\text{max}}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \left( x(1-x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0 (1-x) \right)$$

$$\mp \frac{1}{3} P_\tau \cos \theta_\ell \xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta (4x - 4 + \sqrt{1 - x_0^2}) \right], \quad x = \frac{E_\ell}{E_{\text{max}}}, \quad x_0 = \frac{m_\ell}{E_{\text{max}}}$$

In the SM: $\rho = \frac{3}{4}, \eta = 0, \xi = 1, \delta = \frac{3}{4}$
SVD ladder mount

- Jan 2018: Mount of the +X half shell was successfully completed
First Measurements of Beam Backgrounds at SuperKEKB, submitted to NIMA, 101 pages

Final experiment/simulation

*LER beam* gas : $2.8^{+3.4}_{-2.3}$

*LER Touschek*: $1.4^{+1.8}_{-1.1}$

*HER beam* gas : $108^{+180}_{-64}$

*HER Touschek*: $4.8^{+8.2}_{-2.8}$

Phase 2 dedicated beam background detectors installed
- VXD Volume: FANGS, CLAWS, PLUME
- VXD dock space: TPCs, He-3 tubes
- On QCS: PIN diodes, scintillators

Next challenge: Phase 2 integration of DAQ and simulation

S. Vahsen, H. Nakayama et al
Phase III:

Milestone: Completion of +X clam-shell of the SVD on Jan 18, 2018
Higher energy run

- Design: original design maximum energy is 11.05 GeV at Y(6S)
- Possible higher energy run (11.5 GeV – 12 GeV)?
  - If any, higher energy run will be after several years running at Y(4S)~Y(6S)
  - **Present max** $E_{\text{cm}}$ is **11.24 GeV**, limited by $e^-$ Linac and $e^+$ BT magnets
  - In order to inject the electron beam to HER at the required energy for 12 GeV operation, there must be huge reinforcement of Linac (replacement of S-band with C-band, 7.571 → 8.6 GeV)

11.24 GeV region: $\Lambda_b\bar{\Lambda}_b$ threshold

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**Graphical Representation**

- **e^- Linac (present limit)**
- **e^- BT magnets**
- **QC1E(HER) 90% quench limit**

**Axes:**
- LER Energy (GeV)
- HER Energy (GeV)

**Points and Lines:**
- **E=\{7.32, 4.18\}**
- **11.05 GeV; original $E_{\text{cm, max}}$**
- **11.24 GeV; present attainable $E_{\text{cm, max}}$**
- **4.364 GeV @ 860A**
- **Power supply of LER main dipoles**
- **QC1P(LER) 90%**
- **e^+ BT magnets (with replacing power supplies)**

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**Additional Information:**

- *e.g. [arXiv:1211.0103]*
- On-going discussion with SuperKEKB people about beam energy measurement using backscattered photons produced by laser radiation scattered head-on on the beams