(Tau) Flavor Physics at Belle II

Flavor 2019: new Physics in flavor from LHC to Belle II

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Outline

- SuperKEKB and the Belle II experiment
- Commissioning run and results with early data.
- Prospects, focusing on Tau physics.
  - See also:
    - Quarkonium Prospects → Vladimir Savinov
    - (Semi)leptonic results with early data → Lu Cao
- Summary and Outlook
SuperKEKB @KEK, Tsukuba

- **New facility** to search for BSM physics by studying B, D and τ decays.
- Asymmetric electron-positron collider.
- Major upgrade to the KEKB accelerator with *x40* the design luminosity (8x10^{35} cm^{-2}s^{-1}).
  - *x2* raw beam current.
  - *x20* smaller beam spot (*σ_y*\(^*=50\) nm) with new nano-beam collision scheme
- **First beams and commissioning in 2016**
SuperKEKB as a Flavor Factory

- Asymmetric beams colliding at (or near) the Y(nS) resonances
  - \( \sigma(e^+e^{-}\rightarrow Y(4S)) = 1.05 \text{ nb}, \quad \sigma(e^+e^{-}\rightarrow \tau^+\tau^-) = 0.92 \text{ nb} \)
  - Not just a B-factory, but also a charm and \( \tau \) factory

- Over its operation, Belle II plans to collect 50ab\(^{-1}\) of collision data (vs \( \sim 1\text{ab}\(^{-1}\) of Belle)
- Unique environment for precision flavor measurements
Belle II Detector

- Detector upgrade to mitigate the increased beam background
- Solid angle coverage >90% → High hermeticity for $E_{\text{miss}}$ measurements

**Vertex Detector**
- 2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

**Central Drift Chamber**
- Smaller cell size, long lever arm

**EM Calorimeter**
- CsI(Tl), waveform sampling electronics

**KL and muon detector**
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (forward)

- Electrons (7 GeV)
- Positrons (4 GeV)
"Phase 2"

- Follows from Phase 1 (accelerator commissioning)
- Pilot run to test nano-beam scheme
  - Partial vertex detector (2 PXD + 4 SVD modules)
  - BEAST II: commissioning detector to study beam and background conditions

<table>
<thead>
<tr>
<th>Calendar year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<tbody>
<tr>
<td>Japan FY</td>
<td>JFY2016</td>
<td>JFY2017</td>
<td>JFY2018</td>
<td>JFY2019</td>
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<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>Power saving after mid July 2018</td>
<td>Summer shutdown (power saving)</td>
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- Opportunity for analysis preparation and early physics results
First Collisions - April 2018
Thightening the Luminous Region

- Key to high luminosity is strong vertical focusing of beams to $\sigma_y = 50$ nm

- Reached $\beta^*_y = 3$ mm in Phase 2
- Final luminosity will require $\beta^*_y = 300 \mu$m

- Possible thanks to rapid feedback between accelerator team and tracking group

**FIG. 3:** Distribution of the longitudinal component of the interaction vertex estimated using $z_0$ parameter of single tracks originating from the interaction vertex. The plot is based on data collected in runs 1869-2047 in May 19th-21st 2018. The center of the distribution is estimated using its median. The spread of the distribution is estimated using half of the symmetric range around the median containing 68% of the distribution, $\sigma_{68} = 0.055$ cm. When the $z_0$ resolution is subtracted in quadrature, the unfolded $\sigma_z = 4.5$ mm.
Phase 2 Operation: April-July 2018

Max 800 mA (HER)
Max 860 mA (LER)

Beam Current

Luminosity

Beam Current [A]

Luminosity improvement

Vacuum scrubbing

03/19/2018 09:00 - 07/17/2018 09:00 JST

L\text{peak} = 5.55 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} 

(not optimized)

vs

1.2 \times 10^{34} (BaBar)
2.1 \times 10^{34} (Belle)


Physics Rediscovery

$\pi^0 \rightarrow \gamma \gamma$

$K_S \rightarrow \pi\pi$

$\phi \rightarrow KK$

$J/\Psi \rightarrow ee$

$J/\Psi \rightarrow \mu\mu$

$D \rightarrow K\pi$

$472 \text{ pb}^{-1}$ of physics data $\rightarrow$ first rediscoveries of known processes
First B Mesons

- B pairs produced on Y(4S) threshold (at rest in CMS frame)

BB-like event

Event shape

Hadronic modes
- Preliminary study and preparation for future analyses
- 3x1-prong topology:
  - $\tau_{\text{signal}} \rightarrow 3\pi \nu (+n\pi^0)$, $\tau_{\text{tag}} \rightarrow \ell\nu\bar{\nu}/\pi\nu$
  - Identified through event thrust = $\sum_h \frac{\vec{p} \cdot \hat{T}}{|p_h|}$
- Dominant backgrounds: $q\bar{q}$ and $eey$ (radiative Bhabha)
Tau Observation

- Correct for trigger efficiency (3+ tracks in CDC) → 291 fb\(^{-1}\) useable data
- After correction, good agreement between data and MC
Tau Mass Measurement

- Measurement in the exclusive $\tau \rightarrow 3\pi \nu$ channel using pseudomass technique developed at ARGUS:
  \[ M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \]

- Fit with empirical edge function

\[ \chi^2/\text{dof} = 0.7199 \]

\[ N_{\text{evts}} = 791 \]

\[ \int L \, dt = 291 \text{ pb}^{-1} \]

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

- First $\tau$ physics result from Phase 2
- Good agreement with existing measurements!
Phase 3 Preparations

RVC opening and QCS extraction

BEAST II extraction
Phase 3 Preparations

PXD mounted on beam pipe at KEK

→ Full PXD operation (with 2 layers) scheduled for 2020

PXD combined with one half of SVD
Start of Phase 3

- Regular operation started again in March
- Already collected 0.5 fb⁻¹, comparable with Phase 2
- Continuous injection for ~60% luminosity increase
- Current goal is keeping beam background in check
Phase 3 Studies

- Belle II is expected to deliver 50 ab\(^{-1}\) between 2019-2027, enabling a rich \(\tau\) physics program.

Already underway (feasible with \(~1\text{fb}^{-1}\)):
- Branching ratio of main \(\tau\) decay modes
- \(\tau\) mass measurement
- \(\tau \rightarrow \ell \alpha\) (invisible)

Under preparation:
- \(\tau \rightarrow \eta\pi\nu\) (Second Class Currents)
- CP Violation in \(\tau \rightarrow K_S\pi(+\pi\pi^0)\nu\)
- \(\tau\) Lepton Flavor Violation
Search for $\tau \rightarrow \ell^+ \alpha$ (invisible)

- Last studied at ARGUS using 0.5 fb$^{-1}$ → Belle II is already competitive
- Study the lepton momentum spectrum in the $\tau$ frame:
  - Exploit same 3x1 topology as the mass measurement: $\tau_{\text{tag}} \rightarrow 3\pi \nu$, $\tau_{\text{signal}} \rightarrow \ell \alpha$
  - $E^*(\tau) = \sqrt{s}/2$ and $\vec{p}(3\pi)\sim\vec{p}(\tau) \rightarrow$ signal $\tau$ frame can be approximated.
- Sensitivity is mostly independent from the $\alpha$ mass:

![Graphs showing the distribution of $\tau \rightarrow \ell \nu\bar{\nu}$ and $\tau \rightarrow \ell \nu\bar{\nu}$ as functions of $p(\text{lab})$, $p^*(\tau)$, and $M(\alpha)$]
Second class currents in $\tau \rightarrow \eta \pi \nu$

- In the SM, the $\tau \rightarrow \eta \pi \nu$ decay proceeds through SCCs (isospin-violating, e.g. $\pi$-$\eta$ mixing):
  - **SM prediction:** $\text{BR} \sim \mathcal{O}(10^{-5})$

- Searched for at last-gen B factories but not observed:
  - Belle: $\text{BR} < 7.3 \times 10^{-5}$
  - BaBar: $\text{BR} < 9.9 \times 10^{-5}$

- Observation becomes possible at Belle II within the first years of data taking (1 ab^{-1})

- **Large deviation could indicate New Physics!**

- An accurate measurement could also apply strong bounds to NP models.
CP Violation in the Tau sector

- CP violation in the Kaon sector induces a decay rate asymmetry in the SM:
  \[
  A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_s^0 \nu_\tau) - \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_s^0 \nu_\tau) + \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}
  \]

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

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

- High priority improved measurement at Belle II
CP Violation in the Tau sector

- Charged scalar boson exchange could also induce CPV, which would then be detected as a difference in the decay angular distributions for $\tau \rightarrow P_1P_2\nu_\tau$:

$$A_{i}^{CP} \approx \langle \cos \beta \cos \psi \rangle_{\tau^-} - \langle \cos \beta \cos \psi \rangle_{\tau^+}$$

$\cos \beta \rightarrow$ measured
$\cos \psi \rightarrow$ decay kinematics

- Studied at Belle

- With 50 ab$^{-1}$ of data, Belle II is expected to provide a $\sqrt{70}$ more precise measurement:

$$|A_{CP}| < (0.4-2.6) \times 10^{-4}$$

(assuming central value $A_{CP} = 0$)
Charged Lepton Flavor Violation

- Lepton flavor is conserved in the SM (accidental symmetry)
- Observed in the neutral sector ($\nu$ oscillation) → first sign of BSM physics!
- Also implies (immeasurably small) cLFV: powerful probe for new physics!
  - Several NP models enhance this process
  - $\mu \rightarrow e\gamma$: strong bounds from MEG
  - $\tau \rightarrow \ell^+\gamma$: weaker constraints from CLEO, BaBar, Belle, CMS...

$$B_{\nu SM}(\tau \rightarrow \mu\gamma) = \frac{3\alpha}{32\pi} \frac{1}{m_W} \left| U_{\tau i}^* U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2 < 10^{-40}$$
Prospects for cLFV at Belle II

- Due to its mass, $\tau$ decays allow to probe for additional LFV/LNV couplings:
  - $\tau \rightarrow \ell \gamma$, $\tau \rightarrow \ell \ell \ell$ but also $\tau \rightarrow \ell h(h)$
- Past experiments approached the regime sensitive to New Physics
- Belle II will push the boundaries by $O(10)$ to rule out or confirm NP models
Conclusions and Outlook

- The Belle II commissioning phase has concluded, providing a pilot test of the new collision scheme as well as some preliminary physics measurements.
- Full detector operation has begun earlier this year in March.
- Belle II has a broad physics program to probe the $\tau$ sector for New Physics.
- Potential already exists for exciting results in the first years of data taking.

Thank you for your attention!