The Belle II Experiment
and Synergies with FCC-ee

Leo Piilonen, Virginia Tech
on behalf of the Belle II Collaboration
4th FCC-ee Physics and Experiments Workshop  November 10, 2020

This work supported by U.S. Department of Energy Office of Science
Belle II is looking for evidence of New Physics

SuperKEKB + Belle II is the *Intensity Frontier facility* for beauty mesons, charm mesons and \( \tau \) leptons.

Unique new physics capabilities and unique detector capabilities (“single B meson beam,” neutrals, neutrinos), clean environment with good systematics, which are **critical** for New Physics searches: charged Higgs, new weak couplings and phases, lepton flavor violation, …

2014 US P5 report: This provides unique sensitivity to physics at energy scales far higher than can be accessed directly at colliders.

Photo credit: Ron Lipton (*Fermilab*)

from Tom Browder’s 2017 Belle II Summer School presentation
Belle II Physics “Mind Map” for Snowmass 2021


Snowmass LOIs: confluence.desy.de/display/BI/Snowmass+2021

Image courtesy of Tom Browder
A canonical $B\bar{B}$ Event: the “Golden Mode”

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0 \bar{B}^0$

$\rightarrow D^+ \mu^- \bar{\nu}_\mu$
$\rightarrow J/\psi \ K_S$
$\rightarrow \pi^+ \pi^-$
A canonical $B\bar{B}$ Event: the “Golden Mode”

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow D^+\mu^-\bar{\nu}_\mu$

$J/\psi \rightarrow K_S \rightarrow \pi^+\pi^-$

from “Belle II in Virtual Reality”
Example of a $B^+ \to \tau^+ \nu$ decay in Belle data

$B^+ \to D^0 \pi^+$
$\quad \to K^+ \pi^- \pi^+ \pi^-$

$B^- \to \tau^- \bar{\nu}$
$\quad \to e^- \nu \bar{\nu}$

Clean $e^+e^-$ environment and kinematic constraints (known initial 4-momentum, hadronic tag decay) make this possible
Dark-matter search: $Z' \rightarrow$ invisible

**Signature:** invisible recoil against a $\mu\mu$ or $\mu e$ pair

- Poorly constrained at low $Z'$ mass
- Might explain muon $g-2$ anomaly
- PRL 124, 141801 (2020)
Axion-like pseudoscalars coupling to bosons

Hook (2015), arXiv:1411.3325

3-photon final state in ALP-strahlung

1-photon if $a \rightarrow \chi \chi$

Only coupling to $\gamma$

With coupling to $Z$

SuperKEKB and Belle II: 2nd generation B Factory

electron–positron collider
detector

New final focus

New positron damping ring

4 GeV $e^+$

7 GeV $e^-$

$\bar{c}c$, $s\bar{s}$, $u\bar{u}$, $d\bar{d}$, $\ell^+\ell^-$ $\leftrightarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$

Animation © KEK
High luminosity achieved by squeezing beams @ IP

First-generation KEKB

- $e^+$
- $e^-$
- $\sigma = 4.5\,\text{mm}$
- $22\,\text{mrad}$

SuperKEKB

- $e^+$
- $e^-$
- $\sigma = 0.55\,\text{mm}$
- $83\,\text{mrad}$

- ✔ Beam currents $\approx$ doubled
- ✔ Much smaller $\beta_y^*$

Nano-beam scheme invented by Pantaleo Raimondi for Italian SuperB Factory
SuperKEKB peak & integrated luminosity vs time

Four steps:

✓ Intermediate luminosity: \((1 \rightarrow 3) \times 10^{35}\text{cm}^2\text{sec}, 5\text{ ab}^{-1}\)
✓ High Luminosity: \(6 \times 10^{35}\text{cm}^2\text{sec}, 50\text{ ab}^{-1}\) with a detector upgrade
✓ Beam-polarization upgrade, advanced R&D
✓ Ultra high luminosity: \(4 \times 10^{36}\text{cm}^2\text{sec}, 250\text{ ab}^{-1}\), R&D project
Belle II is a significant upgrade of Belle

✓ Improved vertexing and tracking
✓ Improved particle identification
✓ Better background insensitivity
✓ Higher event rate

I’ll focus on these

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLS fiber + MPPC (end-caps & inner 2 barrel layers)

EM Calorimeter: CsI(Tl), waveform sampling

electrons (7GeV)

Beryllium beam pipe 2cm diameter

Vertex Detector 2 layers DEPFET + 4 layers DSSD

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


positrons (4GeV)

Belle II is a significant upgrade of Belle

✓ Improved vertexing and tracking
✓ Improved particle identification
✓ Better background insensitivity
✓ Higher event rate

I’ll focus on these

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLS fiber + MPPC (end-caps & inner 2 barrel layers)

EM Calorimeter: CsI(Tl), waveform sampling

electrons (7GeV)

Beryllium beam pipe 2cm diameter

Vertex Detector 2 layers DEPFET + 4 layers DSSD

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


positrons (4GeV)
Advanced & innovative technologies in Belle II

*developed in collaboration with industry*

✓ Pixelated photosensors
  - MCP-PMTs in imaging time-of-propagation detector (iTOP)
  - HAPDs in aerogel ring-imaging Cherenkov detector (ARICH)
  - MPPCs (aka SiPMs) in $K_L$-muon detector (KLM)

✓ DEPFET pixel sensors in vertex detector

✓ Front-end custom ASICS for waveform sampling with precise timing
  - APV2.5 (*adapted from CMS*) in silicon-strip vertex detector (SVD)
  - 3 custom ASICs in pixel vertex detector (PXD)
  - TARGETX ASIC in KLM
  - IRSX ASIC in iTOP
  - KEK-custom ASICs in ARICH & drift chamber (CDC)

✓ High-performance data-acquisition system for 30 kHz trigger rate
  - high-throughput network switches to aggregate event data
  - large computer farm for high-level software trigger

✓ TPCs and diamond sensors for background monitoring/characterization
## Vertex Detector

<table>
<thead>
<tr>
<th>Component</th>
<th>r (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>10</td>
</tr>
<tr>
<td>Pixels – layer 1</td>
<td>14</td>
</tr>
<tr>
<td>Pixels – layer 2</td>
<td>22</td>
</tr>
<tr>
<td>Strips – layer 3</td>
<td>39</td>
</tr>
<tr>
<td>Strips – layer 4</td>
<td>80</td>
</tr>
<tr>
<td>Strips – layer 5</td>
<td>104</td>
</tr>
<tr>
<td>Strips – layer 6</td>
<td>135</td>
</tr>
</tbody>
</table>

Beryllium beam pipe at interaction point

Assembled silicon-strip vertex detector (SVD)

Partially assembled pixel detector (PXD)
Vertex Detector installation: Nov 21, 2018

Pixel Detector (PXD): Layer 1 and partial Layer 2
Silicon-strip Vertex Detector (SVD): all 4 layers
Vertexing performance improves significantly vs Belle

Improved vertexing is vital for a key time-dependent CP-violation measurement

\[ B^0 \rightarrow K_S \pi^0 \gamma \]

\[ B \text{ decay-point reconstruction using intersection of back-projected } K_S \text{ with the interaction-point profile} \]

\[ \text{Uncertainty in } S(B^0 \rightarrow K_S \pi^0 \gamma) \]

\[ \text{Integrated luminosity (ab}^{-1}) \]

\[ \text{Pixel detector closer to interaction point} \]

Less Coulomb scattering
Particle ID detectors: iTOP and ARICH

✓ Distinguish $\pi$ from $K$ with high efficiency and low fake rate
✓ Fit within existing electromagnetic calorimeter
✓ Accommodate larger-radius drift chamber
✓ Operate in 1.5T solenoidal magnetic field
Particle ID: measure the Čerenkov cone

Barrel PID uses imaging time-of-propagation counter (16 quartz staves)

Čerenkov photons from kaon vs pion arrive at photosensors at different location and time.
Čerenkov light in the iTOP (barrel particle ID)

from “Belle II in Virtual Reality”
Measure the Čerenkov cone in barrel PID (iTOP)

- ✘ pion-like hypothesis
- ✓ kaon-like hypothesis 😬
- ✗ proton-like hypothesis

---

**Belle II TOP 2018 (Preliminary)**

- $D^*$ kinematically tagged kaon
  - $p = 1.73 \text{ GeV/c}$
  - $\theta = 94.1^\circ$
  - Pion PDF $\log L(\pi) = -257.51$

- **Hit time (ns)**

**Pixel column**

- 0
- 16
- 32
- 48
- 64

---

**Belle II TOP 2018 (Preliminary)**

- $D^*$ kinematically tagged kaon
  - $p = 1.73 \text{ GeV/c}$
  - $\theta = 94.1^\circ$
  - Kaon PDF $\log L(K) = -236.38$

- **Hit time (ns)**

**Pixel column**

- 0
- 16
- 32
- 48
- 64

---

**Belle II TOP 2018 (Preliminary)**

- $D^*$ kinematically tagged kaon
  - $p = 1.73 \text{ GeV/c}$
  - $\theta = 94.1^\circ$
  - Proton PDF $\log L(p) = -263.53$

- **Hit time (ns)**

**Pixel column**

- 0
- 16
- 32
- 48
- 64

---

**Belle II TOP 2018 (Preliminary)**

- Experiment 3, run 1889, event 72284

- $D^*$ kinematically tagged kaon

- **Hit time (ns)**

**Pixel column**

- 0
- 16
- 32
- 48
- 64

---

**Mirror side**

- Prism side

- IP projection

- Slot ID = 15
  - $p = 1.73 \text{ GeV/c}$
  - $\theta_{IP} = 94.1^\circ$
  - $\phi_{IP} = -50.0^\circ$
  - $x = 15.5 \text{ cm}$
  - $z = -69.1 \text{ cm}$
  - $\theta_{dip} = 85.6^\circ$
  - $\phi_{dip} = -21.5^\circ$
Measure the Čerenkov cone in endcap PID (ARICH)

Forward-endcap PID uses aerogel RICH with two-layer radiator ("focusing")

Graded-refractive-index aerogel radiator focuses light onto photosensors

Pixelated photosensors (Hamamatsu)
Čerenkov light in the ARICH (forward particle ID)

from “Belle II in Virtual Reality”
Management of accelerator-induced backgrounds is critical for detector operation and physics extraction.

**Background types:**

- Beam-beam
- Beam-gas
- Touschek
- Synchrotron
- Injection transients

**Potential negative impacts:**

- Reduced beam lifetime
- Shortened lifetime of Belle II detector components
- Instantaneous damage to these components
- Increased hit occupancy in detectors
- Reconstruction and analysis challenges
Summary

- Belle II will explore New Physics and make precision measurements of SM physics with 50x more data than Belle.


- Belle II design was optimized for the physics reach, subject to the constraints of the accelerator final-focus design and the re-use of electromagnetic calorimeter and solenoid+yoke.

- Backgrounds must be characterized, modeled accurately and mitigated for successful operation.
Backup
Belle II collaboration

- 1050 active collaborators … 15% are women and **32% are graduate students**
- 120 institutions
- 26 countries/regions
Belle II Integrated Luminosity

Integrated luminosity
- Recorded Daily

\[ \int L_{\text{Recorded}} \, dt = 74.10 \, [\text{fb}^{-1}] \]

- \( L_{\text{peak}} = 2.4 \times 10^{34}/\text{cm}^2/\text{sec} \)

- World record, above the B factories and LHC
- Product of beam currents a factor of ~5 lower
- Smallest \( \beta_y^* = 1\text{mm} \) – pushing downward

- Covid-19 era
KEKB - SuperKEKB parameters

Hourglass effect condition:
\[ \beta_y^* \geq d = \frac{\sigma_x^*}{\sin(2\theta_x)} \]

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [GeV]</td>
<td>3.5</td>
</tr>
<tr>
<td>\theta_x [mrad]</td>
<td>0 (11)</td>
</tr>
<tr>
<td>\epsilon_x [nm]</td>
<td>18</td>
</tr>
<tr>
<td>\epsilon_y [pm]</td>
<td>150</td>
</tr>
<tr>
<td>\beta_x^* [mm]</td>
<td>1200</td>
</tr>
<tr>
<td>\beta_y^* [mm]</td>
<td>5.9</td>
</tr>
<tr>
<td>\sigma_x^* [\mu m]</td>
<td>147</td>
</tr>
<tr>
<td>\sigma_y^* [nm]</td>
<td>940</td>
</tr>
<tr>
<td>\nb</td>
<td>1584</td>
</tr>
<tr>
<td>I [A]</td>
<td>1.64</td>
</tr>
<tr>
<td>L [cm$^2$ s$^{-1}$]</td>
<td>2.1 x 10$^{34}$</td>
</tr>
</tbody>
</table>
Belle II physics program is broad and deep

Emphasis on new-physics reach in each section

**Belle II Theory Interface Platform (B2TIP)**
Workshop series, 2015-2018:

<table>
<thead>
<tr>
<th>WG1</th>
<th>WG6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semileptonic &amp; Leptonic B decays</td>
<td>Charm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WG2</th>
<th>WG7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative &amp; Electroweak Penguins</td>
<td>Quarkonium(-like)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WG3</th>
<th>WG8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha/\phi_2 \beta/\phi_1$</td>
<td>Tau, low multiplicity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WG4</th>
<th>WG9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma/\phi_3$</td>
<td>New Physics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WG5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charmless Hadronic B Decay</td>
</tr>
</tbody>
</table>

... a fruitful collaboration among theorists and experimentalists

---

**The Belle II Physics Book**
Emi Kou and Phill Urquijo, editors

PTEP 2019, 123C01 (2019)
arXiv: 1808.10567
Dark-photon search requires single-photon trigger

since the event contains exactly one photon ... and nothing else

$e^+e^- \rightarrow \gamma A', \ A' \rightarrow \chi\chi$

$A' = \text{dark photon}$

$\chi = \text{dark matter}$

Belle II 50 ab$^{-1}$
New-physics prospects for Belle II
based on the Belle II Physics Book

Visualization by Giacomo De Pietro

All the details are in "The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://inspirehep.net/record/1692393/
Belle II conference papers at ICHEP 2020:

✓ Measurement of the branching ratios of $B^0 \to D^{(*)-} \ell^+ \nu$ (untagged) 34.6 fb$^{-1}$

✓ Calibration of the Belle II hadronic Full Event Interpretation (FEI) 34.6 fb$^{-1}$

✓ Measurement of the hadronic mass moments of $B \to X_c \ell^+ \nu$ decays 34.6 fb$^{-1}$

✓ Measurement of the branching ratios of $B^0 \to D^{*-} \ell^+ \nu$ (using hadronic FEI) 34.6 fb$^{-1}$

✓ Rediscovery of $B^0 \to \pi^- \ell^+ \nu$ (using the hadronic FEI) 34.6 fb$^{-1}$

✓ Calibration of the Belle II B Flavor Tagger 8.7 fb$^{-1}$

✓ Rediscovery of $B \to \phi K^{(*)}$ decays, and measurement of the longitudinal polarization fraction of $B \to \phi K^{*}$ 34.6 fb$^{-1}$

✓ Branching ratios and direct CP asymmetries of $B \to$ charmless decays 34.6 fb$^{-1}$

✓ Measurement of the $\tau$ lepton mass 8.8 fb$^{-1}$

docs.belle2.org → Conference Submissions
More Belle II results at ICHEP 2020:

- Inclusive $B^0 \to X_u \ell^+ \ell^-$ from the lepton momentum endpoint 34.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-026

- Preparatory studies for $B^+ \to \tau^+ \nu$ 34.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-023

- $e^+e^- \to J/\psi \gamma$ ISR 37.8 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-017

- $D^0 \to K_S \pi^+ \pi^-$ 9.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-010

- “Wrong sign” $D^0$ decays 37.8 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-021

- $D^0 \to K_S K_S$ 37.8 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-020

- $D^0 \to K_S \pi^0$ 34.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-022

- Measurement of the $D^0$ lifetime 9.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-008

- $D_s^+ \to \phi \pi^+, K^{*+} K^-, K_S K^+$ 8.8 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-016

- Rediscovery of the $\Lambda_c$ 8.8 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-008

- Time-dependent analysis of $B^0 \to J/\psi K_S$ 34.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-011

- Trigger performance for the single-photon analysis ($e^+e^- \to A'\gamma$) 34.6 fb$^{-1}$
  
  BELLE2-NOTE-PL-2020-009