Belle II Commissioning, First Results, and Future Prospects

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On behalf of the BELLE II Collaboration
The Belle II Collaboration

- International collaboration hosted at KEK in Tsukuba, Japan
- ~980 collaborators from 112 institutions in 26 countries
**e^+e^- B Factories: B meson pairs in a clean environment**

- Aim to provide insights into new physics via precision measurements and rare decays
- **e^+e^-** collisions provided with asymmetric energy (7 GeV / 4 GeV)
  - Meson pairs boosted → measureable lifetimes
  - Individual quantum-correlated $B\bar{B}$ pairs
  - Clean event topology
    - Efficient detection of neutrals
    - Large sample of clear τ decays
- Complementary to LHCb hadron collisions
  - Different strengths and systematics
  - → Can work in tandem to achieve better results!
- Previous-gen B-Factories (Belle, BaBar) provided 1.5 ab$^{-1}$… Belle II will go much further!
From KEKB to SuperKEKB

- SuperKEKB: The B-factory at KEK
- Asymmetric energy $e^- - e^+$ collider
- 10.58 GeV $\sqrt{s}$ energy

**Doubled beam currents and change to 'nanobeam'**
- $1/20^{th}$ size at IP
- $40x$ KEKB instantaneous luminosity
- $50x$ KEKB integrated luminosity
Challenges in a High-Luminosity Environment

- Increased beam backgrounds
  - 10 - 20 fold increase expected
  - Problematic for data analysis
  - Radiation damage to detector components
    - Possibly reduced lifetime
- Increased occupancy
- Very high event rates (~30 kHz at L1 trigger)
In the Beginning: Commissioning Phases

Two dedicated runs to prepare for upcoming challenges and ensure running conditions would be safe for Belle as luminosity increases:

**Phase I**
- February – July 2016
- Accelerator commissioning focus
- No beam-beam collisions
- Dedicated background detection system (BEAST II) placed at IP
- Results of background studies published last year: [arXiv:1802.01366](https://arxiv.org/abs/1802.01366)

**Phase II**
- March – July 2018
- First collisions: April 26th
- More dedicated background studies carried out along with accelerator beam tuning
- Ultimately predicted Phase III could safely begin
- Results forthcoming! (Several papers in the works)
Belle II Data Taking Plan

Peak Luminosity $[\text{cm}^{-2}\text{s}^{-1}]$

Belle total integrated luminosity

Integrated Luminosity $[\text{ab}^{-1}]$

$\times 10^{35}$
Phase II Data: Early Particle Re-discoveries

\[ \mu = (497.614 \pm 0.004) \text{ MeV/c}^2 \]
\[ \sigma = (3.282 \pm 0.113) \text{ MeV/c}^2 \]
First Collisions - SuperKEKB Control Room
First Collisions - Belle II Control Room
Moving to Phase III - Vertex Detector Installation

One layer of two in Pixel Detector completed before Phase III. Remaining half to be installed later.
Phase III... so far

**Luminosity Performance**

- $L_p \times 10^{31}$ [cm$^{-2}$s$^{-1}$mA$^{-2}$]
- $2 \times 10^{33}$
- $5 \times 10^{34}$

- $\beta_y = 3$ mm $\eta_b = 789$
- $\beta_y = 3$ mm $\eta_b = 1576$
- $\beta_y = 3$ mm $\eta_b = 1576$ (V-angle)
- $\beta_y = 2$ mm $\eta_b = 789$
- $\beta_y = 2$ mm $\eta_b = 1576$

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**Belle II online luminosity**

Exp: 7-8 - All runs

- Integrated luminosity [fb$^{-1}$]
- Total $\int L \, dt = 6.49$ [fb$^{-1}$]

410 pb$^{-1}$ calibrated, aligned, and processed

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Plot on 2019/06/28
D⁰ Meson Lifetime

- Measured lifetime of D⁰
- Small subset of collected data used
- Tiny flight distances → great test of vertex detector performance
- Measurements in agreement with PDG (410.1 ± 1.5 fs)

Note: Figure not to scale
$R_2$ Fit and B Prediction

- $R_2$ provides discrimination between continuum and $B\bar{B}$

- Excess of data found at low values in on-resonance data → likely underestimated beam-gas BG

- Use off-resonance data for continuum modeling

\[ H_l = \sum_{i,j} \frac{|P_i||P_j|}{E_{vis}^j} P_l(cos\theta_{ij}) \]

\[ R_2 \equiv \frac{H_2}{H_0} \]

**Belle II 2019 Preliminary**

- $\int Ldt = 410 \text{ pb}^{-1}$

- Y(4S) data
- BB
- Off-resonance

Spherical BB-like events

Continuum-like events
B → Dh Reconstruction

- B meson signals reconstructed from early data set
- ~300 candidate events reconstructed from a 410 pb⁻¹ sample
• Fast BDT-based algorithm fully reconstructs B decays with > 1000 B decay modes
• Useful for channels with weak signature, e.g., missing momentum (vs in final state)
• Performance on early data shows improvement compared to predecessor algorithm

Belle II Physics Plan

- Wide-ranging plan for physics studies, including:
  - Precision CKM
  - EW Penguin decays
  - Tauonic decays
  - Charm decays
  - Dark Sector searches
  - Hadron spectroscopy

<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Theory</th>
<th>System limit (Discovery)</th>
<th>ab (fb)</th>
<th>Belle II</th>
<th>LHCb</th>
<th>BELLE II/LHCb</th>
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<tbody>
<tr>
<td>(B \rightarrow K^{(*)} l \nu)</td>
<td>(B_{cL} F_{L})</td>
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Also see talk by S. Sandilya for more on rare decays and lepton universality
CKM Improvement Projections

Current fitted parameters

Belle II + LHCb Projection

50 ab⁻¹
Projected to be able to resolve NP in CKM triangle

Current fitted parameters

Belle II + LHCb Projection

CKM Improvement Projections
Dark Sector Searches: Dark Photons and ALPs

Improved luminosity and calorimeter hermiticity can allow great improvement!

Projected Sensitivity
The Belle II experiment at SuperKEKB is running with a full detector.

- Physics run began Spring 2019 following 2 dedicated commissioning phases:
  - Vertex detector installed around IP before physics runs for precision measurements.
- 6.49 fb\(^{-1}\) collected so far, of a planned 50 ab\(^{-1}\).
- Wide ranging physics plan, including precision measurements, dark sector searches, and much more.
- Still ramping up to full luminosity:
  - Many exciting results to come!
Stay tuned for more!

Follow us on social media for updates and information!

Facebook: @belle2collab
Twitter: @belle2collab
Instagram: @belle2collab

JP: @belle2japan
Supplementary Material
CKM Improvement Projections

Current fitted parameters

Belle II + LHCb Projection

50 ab⁻¹
Moving to Phase 3 - Vertex Detector Installation
Dark $\gamma \rightarrow$ Invisible

- Light (GeV scale) hidden dark sector weakly coupled to SM by dark photon $A'$
- Experimental signature: only 1 high-energy photon in detector
- Needs single photon trigger
  - Not present in Belle
  - Only present of $\sim$10% of BaBar
  - Implemented for Phase 2
- $\sim$No true physics backgrounds
  - Only missing particle backgrounds:
    - Radiative bhabha, $\gamma\gamma$ events with one $\gamma$ not reconstructed
Axion-Like Particles (ALPs)

- Pseudoscalars that couple to bosons
  - Can target photon coupling $g_{a\gamma\gamma}$

- Coupling not related to mass
  - Different from QCD axions

- Three-Photon signature
  - One $\gamma$ from recoil
  - Pair from $a\rightarrow\gamma\gamma$

- Four calorimeter signatures
  - (Determined by displacement, $\theta$ of photon pair)
ALPs: Dark Sector Pseudoscalar Portal

- Only coupling to $\gamma$
- Coupling to $\gamma + Z$

Graphs showing the coupling of ALPs to $\gamma$ and $\gamma + Z$ with varying masses and coupling constants.
Dark Sector Searches: Invisible Dark γ and ALPs

**Vector:** Dark γ → Invisible

**Pseudoscalar:** Axion-Like Particles
Dark Sector Searches: Invisible Dark γ and ALPs

Other searches possible!
- Magnetic Monopoles
- Invisible Z’, Z’ → LFV (e-μ coupling)
- Dark scalars
- Dark Higgs
- Off-shell A’ decays
- Even more…

**Vector:** Dark γ → Invisible

**Pseudoscalar:** Axion-Like Particles
Dark $\gamma \rightarrow$ Invisible: Prospects

Improved luminosity and calorimeter hermiticity can allow great improvement!
Dark $\gamma \rightarrow$ Visible dileptons: Heavier DM

Project sensitivity

Belle II TiP Report