The Belle II Experiment: Status & Prospects

Jerome Baudot
for the Belle II collaboration

9th International Conference on New Frontiers in Physics (ICNFP 2020)
4-12 September 2020
A super B-factory?

- **B factories (e⁺e⁻ collisions at √s = 10.58 GeV)**
  - BaBar (PEPII) & Belle (KEKB) stopped in 2008/2010
  - accumulated ~ 1000 fb⁻¹
  - very successful analysis techniques

- **New inputs**
  - ATLAS / CMS → Higgs but no non-SM particles
  - LHCb/B-factories intriguing tensions in flavour physics

- **Motivations for a super B-factory**
  - Complementary search for New Physics / LHC
  - Precision test of Standard Model
  - Direct search for new light particles
  - Hadronic physics

With billions of $B\bar{B}$, $c\bar{c}$, $\tau\bar{\tau}$ pairs

⇒ The Belle II physics book

PTEP 12 (2019) 123C01

Clean environment (few particles / event)
Known initial state → kinematic constraints
Final state always starts with pairs ($q\bar{q}$, $l^-l^+$)

Luminosity frontier
Outline

→ The projects
  → SuperKEKB & Belle II

→ Status
  → Luminosity, data taking & performance results
  → First results

→ Prospects
  → Next expected results
  → SuperKEKB & Belle II in the next 10 years
SuperKEKB collider

**Recipe to high luminosity**

- **High currents:** > 1A
- **Nano-scale beam size:** $\sigma_x \times \sigma_y \sim 10\mu m \times 60\text{ nm}$
- $\beta_y^{*} \ll 1\text{ mm}$
- & specific beam crossing features:
  - Crossing angle (83 mrad) + crab waist (80%)

**Cost** = severe beam induced background
**SuperKEKB / Belle II Luminosity status**

### Machine progress

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>Nominal</td>
</tr>
<tr>
<td>Energy (GeV) LER/HER</td>
<td>3.5 / 8</td>
</tr>
<tr>
<td>Current (A) LER/HER</td>
<td>1.6/1.2</td>
</tr>
<tr>
<td>“Beam size” $\beta_y$ (mm)</td>
<td>5.9</td>
</tr>
<tr>
<td>Instant. Lumi. (cm$^{-2}$s$^{-1}$)</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
</tbody>
</table>

First collisions April 2018

### Data taken

- On-resonance 74 fb$^{-1}$
  - Analysis ready in Summer 2020 exploit $\sim 35$ fb$^{-1}$
  - **Analysis ready in** Winter 2019-20 exploit $< 10$ fb$^{-1}$
- Off-resonance 6 fb$^{-1}$ ($M_{\Upsilon(4S)} - 60$ MeV)

---

See ICHEP talk by Yukiyoshi Onishi

“Highlights from SuperKEKB...”
Belle II detector

- Planned for better performances / Belle under:
  - Higher beam-background rate
  - Higher trigger rate (30 kHz)

EM Calorimeter (CDC)
- CsI(Tl), waveform sampling (barrel+ endcap)
- upgraded

KLong and muon detector (KLM)
- Resistive Plate Chambers (barrel outer layers)
- Scintillator + WLSF + SiPM’s (end-caps, inner 2 barrel layers)
- upgraded

Particle Identification
- TOP detector system (barrel)
- Prox. focusing Aerogel RICH (fwd)
- new

Beryllium beam pipe
- 2cm diameter
- new

SuperCond. Solenoid
- 1.5 T magnetic field
- new

Vertex Detector (VXD = PXD+SVD)
- 2 layers DEPFET pixels + 4 layers DSSD
- new

Central Drift Chamber
- He(50%):C₂H₆(50%), small cells, long lever arm, fast electronics
- new

Belle II collab
~1000 researches / 26 countries
Special data taking conditions in 2020

- Non-stop operation with COVID-19 pandemic
  - Social distancing requirements
  - Strong developments for close to or fully remote sub-system operation
  - Huge commitment from Japanese colleagues & residents in Japan
    - Only 40 people on site from March to July

Belle II data taking efficiency ~ 85%
(target for coming run 90%)
Tracking performance

- **tag & probe technique with e+e- → τ+τ-**
  - Lepton-ID tags the event
  - 3 prongs provide probe
  - 4 charged tracks expected

- Similar technique to evaluate fake rate/track: \( r_{\text{fake}} = (0.97 \pm 0.34_{\text{stat}} \pm 0.06_{\text{syst}}) \% \)

\[
e = \frac{N_{\text{evts}}(4\text{tracks})}{N_{\text{evts}}(4\text{tracks}) + N_{\text{evts}}(3\text{tracks})}
\]

\[
\delta^* = 1 - \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}}
\]

\( \Rightarrow \) Track finding algo: BELLE2-PUB-TE-2020-001
\( \Rightarrow \) BELLE2-NOTE-PL-2020-014
Vertexing performances

- **$D^0$ lifetime**
  - Measurement with 3 channels: $D^0 \rightarrow K\pi^+, K\pi^+\pi^0, K\pi^+\pi^+\pi^-$
  - Estimated **vertex resolution ~40 μm**
  \[ \tau(D^0) = (412.3 \pm 2.0_{\text{stat}}) \text{ fs} \]
  World Average (410.1±1.5) fs

- **$B^0$ lifetime**
  - Smaller $\Upsilon(4S)$ boost: 0.42 (Belle) → 0.28 (Belle II)
  - Average distance between $B$-mesons 200μm → 130 μm
  - Hadronic channels $B \rightarrow D^{(*)}\pi^+/\rho^+
  - Estimated resolutions
    - Time: $\Delta t \sim 1$ ps  \(\leftrightarrow\) $\Delta t \sim 80$ μm
    - Dominated by "tag"-side
  \[ \tau(B^0) = (1.48 \pm 0.28_{\text{stat}} \pm 0.06_{\text{syst}}) \text{ ps} \]
  World Average (1.519±0.004) ps
Particle identification: leptons

- **Using fully reconstructed channels**
  - Extract both efficiencies & mis-ID probability from data
  - For various leptonID & angular acceptance

\[
\text{leptonID} = \frac{\mathcal{L}_{\text{lepton}}}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}
\]

KLM
- Total accept. \(0.82 \leq \theta < 2.13 \text{ rad}, \mu\text{onID} > 0.9\)

ECL
- 1 accept. bin \(1.13 \leq \theta < 1.57 \text{ rad}, \text{electronID} > 0.9\)

Belle II (Preliminary), \(\int L dt = 34.6 \text{ fb}^{-1}\)

- \(J/\psi \rightarrow \mu\mu - \varepsilon(\mu)\)
- \(K_S \rightarrow \pi\pi - \text{mis-ID}(\pi \rightarrow \mu) \times 3\)

- \(J/\psi \rightarrow ee - \varepsilon(e)\)
- \(ee \rightarrow eee - \varepsilon(e)\)
- \(K_S \rightarrow \pi\pi - \text{mis-ID}(\pi \rightarrow e) \times 3\)
- \(D^* \rightarrow D^0(K\pi) - \text{mis-ID}(K \rightarrow e) \times 3\)
- \(\tau(1p)\tau(3p) - \text{mis-ID}(\pi \rightarrow e) \times 3\)
- \(D^* \rightarrow D^0(K^0) - \text{mis-ID}(K \rightarrow e) \times 3\)
Particle identification: hadrons

- **Using fully reconstructed channels**
  - $D^* \rightarrow D^0(K\pi^+)\pi^+$
  - Slow $\pi$ from $D^*$ tags $D^0$ flavour $\Rightarrow K$ & $\pi$ identified in data

\[
\frac{K/\pi - \text{ID}}{L_{K/\pi}} = \frac{L_K}{L_K + L_{\pi}}
\]
Full Event Interpretation

- **B exclusive reconstruction in tag-side**
  - Critical tool for signal channels with missing particles
  - 10^4 channels identified via successive (200) Boosted Decision Trees
    - Provides classifier \( \rho_{\text{tag}} \) with \( \text{eff.-purity} \) calibrated on data
  - Tag side with fully hadronic or semileptonic decays

- **Rediscovery of charmless B decay**
  - Missing 4-momenta \( \Rightarrow M_{\text{miss}}^2 \)

\[ B(B^0 \rightarrow \pi^- l^+ \nu_l) = (1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-4} \]

World Average \((1.50 \pm 0.06) \times 10^{-4}\)
Dark Matter searches

The Belle II way: **light dark sector access via light mediators**

⇒ implies New Physics & DM
⇒ already competitive measurements

### New light $Z'$
- Couples ($g'$) both to SM particles & DM constituents
  - only 2nd & 3rd SM generations
- Search for
  - $e^+e^-\rightarrow\mu^+\mu^-Z'(\rightarrow\text{invisible DM})$
  - $e^+e^-\rightarrow e^\pm\mu^\mp Z'(\rightarrow\text{invisible DM})$
- Exploit recoil mass against $ll$-system

### Other searches on-going
- Axion Like Particles
- Dark photons

---

See Wednesday talk by Marcello Campajola

"**Dark Sector first results at Belle II**"
Time-dependent analysis for B-physics

- **Major tool for**
  - SM precision test, CP violation ($\phi_1$)
  - NP sensitivity $b \to q\bar{q}s$ ($q = u, d, s$)

- **Main analysis steps**
  - Time-resolution: see lifetime measurement
  - Flavour tagger: effective efficiency~34 %

- **Mixing $B^0 \to D^-\pi^+$**

- **Initial sin2$\phi_1$ measurement $B^0 \to J/\psi K_S$**

\[ \Delta m_d(B^0) = (0.531 \pm 0.046_{\text{stat}} \pm 0.013_{\text{syst}}) \text{ps} \]

World Average (0.5065± 0.019) ps

\[ \sin 2\phi_1 = 0.55 \pm 0.21_{\text{stat}} \pm 0.04_{\text{syst}} \]

World Average 0.685 ± 0.019
Semileptonic $B$-decays

- **Major tool for**
  - SM precision test, CKM elements $|V_{ub}|$, $|V_{cb}|$
  - Lepton Flavor Universality test

- Build $Y=D^*l$ system to separate signal/background

$\Rightarrow B(\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}_l) = (4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} + 0.45\pi_s)\%$

World Average $5.05 \pm 0.14\%$

- **Untagged exclusive analysis**
  - 2 channels $\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}_l$ and $B^- \rightarrow D^0l^-\bar{\nu}_l$

- Partial decay rates $\Delta \Gamma$ unfolded over 

$$\text{hadronic recoil parameter } w = \frac{m_B^2 + m_{D^*}^2 - (p_B - p_{D^*})^2}{2m_B m_{D^*}}$$

Prediction with hadronic form factor $\Rightarrow |V_{cb}|$ extraction
Charmless B-decays

**Major tool for**

- SM precision test: Unitarity Triangle $\phi_2$, isospin sum rules
- Sensitive to NP through loop contributions

**Current focus**

- Two- to Three- body decays with branching fractions $\sim 10^{-6}$
  - Reconstruction efficiency range =15-40%
- Challenging $e^+e^- \rightarrow q\bar{q}$ background (continuum)
  - Boosted Decision Tree feed by 39 discriminating variable
- For flavour-specific channels extract charge asymmetry
  $\rightarrow$ Probe direct CP-violation
  $\rightarrow$ Correction of instrumental-induced asymmetries with data

\[ \Delta E = E_{\text{Breco}} - \sqrt{S}/2 \]

World average compatible
### Tau physics

#### Major tool for
- Lepton Flavor Violation with various decays $\tau \to e\gamma, \mu\gamma, \mu\eta, l\alpha, lll \ldots$
- SM precision test with $\tau$ characteristics

#### Tau mass measurement
- **Pseudomass** technique ($\leftarrow$ ARGUS)
- Event selection: 3 charged-$\pi$ / 1 prong ($+\pi^0$)

$\Rightarrow m(\tau) = 1777.28 \pm 0.75 \pm 0.33$ MeV/c$^2$

World Average $1776.86 \pm 0.12$ MeV/c$^2$

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

$\Rightarrow$ BELLE2-CONF-PH-2020-010
Prospects for SuperKEKB schedule overview

- **Till 2026**
  - Continuous machine tuning
    - Beam optics ($\beta_y \rightarrow 0.5$ mm)
  - Beam background mitigation
    (current limiting factor in 2020)
    - New collimators

- **Upgrade foreseen in 2026**
  - "Long" shutdown
  - New final focussing magnets (QCS)
  - New beam pipe for interact. region
  - Partial RF power upgrade

Nominal luminosity $6 \times 10^{35}$ cm$^{-2}$s$^{-1}$

$L_{\text{int}} = 50$ ab$^{-1}$ after a few years
Prospects for Belle II

Continuous improvement with 2 major steps

- **2022 shutdown**
  - On-going DAQ board replacement
  - Renew PXD: complete two inner layers with same DEPFET technology
  - TOP-Photomultiplier replacement for longevity against beam-background

- **2026 shutdown**
  - SuperKEKB requires long shutdown (see previous slides)
  - Opportunity for detector upgrades
    - Highest resilience against beam-background
    - Improve some performances
  - Letter of intents prepared this Fall
    - Vertexing / Tracking / PID / Calorimetry / Triggering

In the next 2 years

- **Shortly expected analysis results**
  - Combined Belle + Belle II measurement for $\varphi_3$
  - Radiative $b \rightarrow s \gamma$ transitions
  - Inclusive $B^+ \rightarrow K^+ \nu \nu$
  - Inclusive (FEI tagged) $b \rightarrow s \gamma$
  - Dark sector:
    - $Z'$ to visible, dark Higgsstrahlung, more ALPs search
  - Tau physics:
    - $\tau \rightarrow l\alpha$, $lll$

- **Expected cumulated luminosity**
  - March 2021: 140-240 fb$^{-1}$
  - July 2022: 1 ab$^{-1}$ (BaBar / Belle $L_{int}$ level)
Conclusion

• SuperKEKB & Belle II have a clear plan to deliver & accumulate $L_{\text{int}} \sim 50 \text{ ab}^{-1}$
• Current analysis performances similar or better than Belle
  → Many measurements delivered & on-going
• Already some competitive results

Real hadronic event

Monte-Carlo simulation with $Z' \rightarrow$ invisible

Opportunities for new ideas
More results not covered

- **Charmless B decays**
  - Channels for φ2 measurement: \( B^+ \rightarrow \phi K^+, B^+ \rightarrow \phi K^{*+}, B^+ \rightarrow \phi K_S^0 \)
  - \( B \rightarrow \) charmless BF's and A_CP's

- **Semileptonic decays**
  - Tagged (Full Event Interpretation) \( \bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu}_l \)
  - Hadronic mass moments of \( B \rightarrow X_c l \nu_l \)

- **Radiative and electroweak Penguin B decays**

- **Charm physics**

- **Charmonia studies**
The collider

**SuperKEKB**

- **Target:** $L = 8 \times 10^{35} / \text{cm}^2 / \text{s}$

**Beams:**
- $e^+ 4 \text{GeV} \ 3.6 \text{A}$
- $e^- 7 \text{GeV} \ 2.6 \text{A}$

**Key Components:**
- **Damping ring** @1.1 GeV
- **Positron source**
- **New superconducting / permanent final focusing quads near the IP**
- **Colliding bunches**
- **Low emittance gun**
- **New IR TiN-coated beam pipe with antechambers Cu for wigglers and Al alloy for the rest**
- **Replace short dipoles with longer ones (LER)**
- **Redesign the lattices of HER & LER to squeeze the emittance**
- **Add / modify RF systems for higher beam current**
- **New positron target / capture section**
- **New superconducting / permanent final focusing quads near the IP**
- **Colliding bunches**

**Equation for $L$:**

$$L = \frac{\gamma_{\pm} B_y^*}{2e \varepsilon_e} \left(1 + \frac{\sigma_y^* (L \pm \frac{\varepsilon_{xx}^*}{\beta_y^*} R_L)}{\sigma_x^*} \right)$$
Beam induced background

- **Various sources**
  - Single beam backgrounds
    - scale with $I, I^2, 1/\text{beam-size}$
  - Beam-Beam (QED) effects
    - scale with luminosity

- **Current main issues**
  - TOP MCP-PMT QE decrease with total charge
  - Synchrotron radiations in PXD

- **Mitigation measures**
  - Tuning
    - Injection
    - Beam geometry
  - Collimators
  - Shielding

- **At luminosities > $10^{35}$ cm$^{-2}.s^{-1}$**
  - Concern is occupancy
    - especially / inner layers → few % range
  - Predictions robust to a factor <5
    - From current data / MC rate ratio
  - Opportunity for detector upgrades
    - Get safer by lowering occupancy
    - Get better performances for physics