The Belle II experiment: status and physics prospects

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Nagoya University
On behalf of the Belle II Collaboration

BSM 2017 @ Jasmine Palace Resort
Hurghada, Egypt
Physics motivations and goals

• CP violation (CPV) in the quark sector was elucidated by B-factories.
  – An essential part of the SM.
• The CPV is too small to account for the baryon-antibaryon asymmetry in the universe.
  – There must be undiscovered source(s) of CPV.
• The SM does not provide answers to various fundamental questions.
  – Fermion generations and mass hierarchy,
  – Diagonal hierarchy of the CKM matrix,
  – Constitution of Higgs sector, etc.

Belle II will search for new physics (NP) in the flavor sector at the intensity frontier.
Experimental strategy

• Upgrade the accelerator and detector.
  – Luminosity: \( L = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \) (40x Belle).
    Ø Intending to accumulate \( \int L \, dt \sim 50 \text{ ab}^{-1} \) (50x Belle).
    Ø Mitigating the beam BG level to be \( \sim 20 \times \text{Belle} \).
  – Better detector performance.
    Ø Tolerable to the high BG level.

• Running on \( \Upsilon (4S) \) mostly, utilizing the clean \( e^+ e^- \) collision environment and good detector hermiticity.
  – Full event reconstruction with kinematic constraint.

• Utilize the reach of indirect NP searches.
  – Reach of the NP energy scale can be pushed up to \( \sim O(100 \text{ TeV}) \).
  – Through \( W^\pm \) exchange processes with \( \tau \).
  – Through quantum loop processes of Flavor Changing Neutral Current (FCNC).
  – Over-constraining the Unitary Triangle.
  – etc.
SuperKEKB and Belle II at KEK

KEK (Tsukuba, Japan)

SuperKEKB accelerator

Electron source

Diameter: 53 km
(Circumference: 83 km)

Belle II spectrometer

SuperKEKB accelerator

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e^{-} 7 GeV
e^{+} 4 GeV
SuperKEKB accelerator

Factor of 2

\[ L = \frac{\gamma_{\pm}}{2e r_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) I_{\pm}^{5 \pm_y} \left( \frac{R_L}{R_y} \right) = 8 \times 10^{35} \text{cm}^2\text{s}^{-1} \]

Factor of 20

Nano-beam scheme

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Belle II detector

**K_{L} and muon detector:**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**EM Calorimeter:**
CsI(Tl), waveform sampling

**Beryllium beam pipe**
2cm diameter

**Vertex Detector:**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
He(50%):C_{2}H_{6}(50%), Small cells, long lever arm, fast electronics

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

**Readout (TRG, DAQ):**
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

**Offline computing:**
Distributed over the world via GRID

21/12/2017
Construction/commissioning status
Accelerator status (1)

Phase I (complete)
- Circulate both beams, **no collisions**, **no Belle II**
- Tune accelerator optics
- Vacuum scrub
- Beam studies with BEAST II
Accelerator status (2)

Install final focusing magnet systems (complete)
Accelerator status (4)

Belle II roll-in (complete) March 2017
Detector integration (1)

Belle II Detector Installation
- Barrel Cherenkov particle ID (TOP) installed **May 2016**
- Drift chamber (CDC) installed **October 2016**
- End-cap Cherenkov particle ID (ARICH) integration **August 2017**
- Global Cosmic Run DAQ **July 2017**—
- Vertex detector will be integrated after phase 2
Detector integration (2)

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Detector integration (3)

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- Vertex detector will be integrated after **phase 2**
## Detector commissioning

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Phase 1</td>
<td>Hits in four outer subdetectors</td>
</tr>
</tbody>
</table>
| 2017 | Phase 2 | Belle II Detector Installation:  
- Barrel Cherenkov particle ID (TOP) installed **May 2016**  
- Drift chamber (CDC) installed **October 2016**  
- End-cap Cherenkov particle ID (ARICH) integration **August 2017**  
- Global Cosmic Run DAQ **July 2017**—  
- Vertex detector will be integrated after phase 2 |
| 2018 | Phase 3 | |
| 2019 | | |

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Vertex detector status

**Belle II Detector Installation**

- Barrel Cherenkov particle ID (TOP) installed **May 2016**
- Drift chamber (CDC) installed **October 2016**
- End-cap Cherenkov particle ID (ARICH) integration **August 2017**
- Global Cosmic Run DAQ **July 2017**
- Vertex detector will be integrated after **phase 2**
Analysis tools (1)

• Getting ready for experiment.

Impact parameter resolution

Track efficiency
Analysis tools (2)

• Getting ready for experiment. (cont’d)
Luminosity projection

**Goal of Belle II/SuperKEKB**

- **Phase 2:**
  - Peak luminosity reaches $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (Belle)
  - $20 \text{ fb}^{-1}$ for physics near $Y(4S)$

- **Timeline:**
  - Feb 1, 2018: Global cosmic ray runs.
  - March 2, 2018: First LER beam.
  - April 2018: First collisions “Phase 2”
  - July 2018: End of commissioning run.

- **Phase 3:**
  - 50 $\text{ ab}^{-1}$ by 2025
  - 50x Belle, 100x Babar

**Early 2019:** “Phase 3”
Physics prospect
Leptonic and semileptonic B decays (1)

- $B \to \tau \nu$, $\mu \nu$
  - BF is sensitive to NP.
    - 4 $\sigma$ level $B \to \tau \nu$ evidences in Belle and BaBar.
    - Currently consistent with SM.
    - The uncertainty will be reduced to 5-6% at 50 ab$^{-1}$ in Belle II.
  - Excellent mode to test the Lepton Flavor Universality.

Evidence is expected at $\sim$2 ab$^{-1}$.

<table>
<thead>
<tr>
<th>I</th>
<th>$BF_{SM}$</th>
<th>$BF_{Exp \ (WA)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$(7.71 \pm 0.62) \times 10^{-5}$</td>
<td>$(1.06 \pm 0.19) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$(3.46 \pm 0.28) \times 10^{-7}$</td>
<td>$&lt; 1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>e</td>
<td>$(0.811 \pm 0.065) \times 10^{-11}$</td>
<td>$&lt; 0.98 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Leptonic and semileptonic B decays (1)

- \( B \rightarrow \tau \nu , \mu \nu \)
  - BF is sensitive to NP.
    - 4\( \sigma \) level \( B \rightarrow \tau \nu \) evidences in Belle and BaBar.
    - Currently consistent with SM.
    - The uncertainty will be reduced to 5-6% at 50 ab\(^{-1}\) in Belle II.
  - Excellent mode to test the Lepton Flavor Universality.
  - If no NP, can extract \(|V_{ub}|\).
    - Independent from \( b \rightarrow ul \nu \).

<table>
<thead>
<tr>
<th>( l )</th>
<th>( BF_{SM} ) ( \times 10^{-\text{X}} )</th>
<th>( BF_{Exp} ) ( \times 10^{-\text{Y}} )</th>
</tr>
</thead>
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Leptonic and semileptonic B decays (2)

- $b \rightarrow u l \, \nu \, , \, c l \, \nu \, (l = \mu \, , \, e)$
  - $|V_{ub}|$ and $|V_{cb}|$ determinations.
    - Using incl. and excl. final states.
    - $\delta |V_{ub}| \sim 5\%$, $\delta |V_{cb}| \sim 2\%$.
    - Large $X_c l \, \nu$ BG in $X_u l \, \nu$ mode.
    - QCD predictions for form factors, inclusive processes, quark masses.
  - Tension: incl. vs excl. meas.
    - $|V_{ub}|$: $X_u l \, \nu$ vs $\pi l \, \nu$
    - $|V_{cb}|$: $X_c l \, \nu$ vs $D(\ast) l \, \nu$
Leptonic and semileptonic B decays (2)

• $b \rightarrow ul \nu, cl \nu$ ($l = \mu, e$)
  - $|V_{ub}|$ and $|V_{cb}|$ determinations.
    - Using incl. and excl. final states.
    - $\delta |V_{ub}| \sim 5\%$, $\delta |V_{cb}| \sim 2\%$.
    - Large $X_c l \nu$ BG in $X_u l \nu$ mode.
    - QCD predictions for form factors, inclusive processes, quark masses.
  - Tension: incl. vs excl. meas.
    - $|V_{ub}|$: $X_u l \nu$ vs $\pi l \nu$
    - $|V_{cb}|$: $X_c l \nu$ vs $D(\ast) l \nu$ Seems to be solved by a different form factor parameterization.
  - Major effort with much higher statistics at Belle II is required to improve the precisions.
    - More detailed BG decomposition.
    - Further progress in QCD calc.

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Leptonic and semileptonic B decays (3)

- $B \to D^{(*)} \tau \nu$
  - $R(D^{(*)})$ measurements show deviations from the SM.
    - Combined result is $4.1 \sigma$ away from the SM.
  - Hint of NP which violates the Lepton Flavor Universality?
    - Charged Higgs, leptoquark, …

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)} \tau^+ \nu_\tau)}{\Gamma(B \to D^{(*)} \ell^+ \nu_\ell)}$$

$I = e, \mu$
Leptonic and semileptonic B decays (3)

- \( B \to D^{(*)} \tau \nu \)
  - \( R(D^{(*)}) \) measurements show deviations from the SM.
    - Combined result is 4.1 \( \sigma \) away from the SM.
    - Hint of NP which violates the Lepton Flavor Universality?
      - Charged Higgs, leptoquark, …
  - The uncertainties will be reduced to 2-3% at 50 ab\(^{-1}\) in Belle II.
EW penguin $b \to s$ transitions (1)

- Test on the Lepton Flavor Universality: $R(K^*)$.

<table>
<thead>
<tr>
<th>$q^2$ range [GeV$^2$/c$^4$]</th>
<th>Belle 0.71/ab</th>
<th>Belle II 5/ab</th>
<th>Belle II 50/ab</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(K^*)$</td>
<td>1 – 6</td>
<td>26%</td>
<td>10%</td>
</tr>
<tr>
<td>$R(K^*)$</td>
<td>&gt; 14.4</td>
<td>24%</td>
<td>9.2%</td>
</tr>
<tr>
<td>$R(K)$</td>
<td>1 – 6</td>
<td>28%</td>
<td>11%</td>
</tr>
<tr>
<td>$R(K)$</td>
<td>&gt; 14.4</td>
<td>30%</td>
<td>12%</td>
</tr>
</tbody>
</table>

$R(K^*) = \frac{\text{Br}(B^0 \to \bar{K}^*0 \mu^+ \mu^-)}{\text{Br}(B^0 \to \bar{K}^*0 e^+ e^-)}$

$R(K) = \frac{\text{Br}(B^+ \to \bar{K}^+ \mu^+ \mu^-)}{\text{Br}(B^+ \to \bar{K}^+ e^+ e^-)}$

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**EW penguin b→s transitions (2)**

- **B→K( hypotheses (l = μ, e)**
  - The Angular distribution can be expressed in terms of helicity amplitudes that depend on
    - di-lepton invariant mass squared (q^2),
    - Wilson coefficients C_7, C_9, C_{10}, → Probe to NP contribution
    - B→K* form factors.

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i\mathcal{O}_i + C'_i\mathcal{O}'_i)
\]

- C_i: Wilson coefficients (short distance effect)
- O_i: Operators (depend on hadronic form factors)
EW penguin $b \rightarrow s$ transitions (2)

• $B \rightarrow K^{(*)}ll$ ($l = \mu, e$)
  - Test on the anomaly in the $B \rightarrow K^{*}ll$ angular analysis: $P'_5$.
    -Insensitive to form factors.
    - LHCb meas. shows 3.3 $\sigma$ to SM.
    - Consistent with the Belle meas.

$P'_5 = \sqrt{2} \frac{\text{Re}(A^L_0A^{L*}_1 - A^R_0A^{R*}_1)}{\sqrt{(|A^L_0|^2 + |A^R_0|^2)(|A^L_1|^2 + |A^R_1|^2 + |A^L_\parallel|^2 + |A^R_\parallel|^2)}}$

$A_0, \parallel, \perp^{LR}$: decay amplitudes for different $K^0$ transversity states (subscript),
• di-lepton chiralities (superscript).

<table>
<thead>
<tr>
<th>q$^2$ range [GeV$^2$/c$^4$]</th>
<th>Belle 0.71/ab</th>
<th>Belle II 5/ab</th>
<th>Belle II 50/ab</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 2.5</td>
<td>0.47</td>
<td>0.17</td>
<td>0.054</td>
</tr>
<tr>
<td>2.5 – 4</td>
<td>0.42</td>
<td>0.15</td>
<td>0.049</td>
</tr>
<tr>
<td>4 – 6</td>
<td>0.34</td>
<td>0.12</td>
<td>0.040</td>
</tr>
<tr>
<td>&gt; 14.2</td>
<td>0.23</td>
<td>0.088</td>
<td>0.027</td>
</tr>
</tbody>
</table>

36-38% 11-12%

• Belle II also has access to
  - $B \rightarrow K^{(*)} \tau^+ \tau^-$, $B \rightarrow K^{(*)} \nu \bar{\nu}$.
QCD penguin $b \rightarrow s$ transitions (1)

- Indirect CPV (ICPV) in $b \rightarrow s\bar{q}q$
  - ICPV: interference between the non-mixed and mixed decays to a CP eigenstate.
    - Giving a time-dependent CP asymmetry ($A(\Delta t)$).
  - For the tree-dominant $b \rightarrow c\bar{c}s$ transitions,
    - $S = -\eta_f \sin 2 \phi_1$, $C = 0$,
    - $\eta_f$: CP eigenvalue of the final state.
  - For the penguin-dominant $b \rightarrow s\bar{q}q$ transitions,
    - Same as $b \rightarrow c\bar{c}s$ in SM.
    - If NP exists through the loop of FCNC, the $S$ and $C$ terms may change.

\[ A(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t) \]

$\Delta t$: decay time difference between $B^0$ and $\bar{B}^0$
QCD penguin $b \to s$ transitions (2)

- Indirect CPV (ICPV) in $b \to s \bar{q}q$
  (cont’d)
  - Currently $b \to s \bar{q}q$ show consistent results with $b \to c \bar{c}s$.
  - The uncertainties (δ) will be reduced significantly at 50 ab$^{-1}$
    - $b \to c \bar{c}s$: to 20-25% of present δ, systematics limited.
    - $b \to s \bar{q}q$: to ~15% of present δ, mostly scaled to the luminosity.
    - Both are theoretically clean.
  - Will probe NP through the precision meas. on $\sin 2 \phi_1$.

$$\sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}})$$

<table>
<thead>
<tr>
<th>$b \to c \bar{c}s$</th>
<th>World Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K^0$</td>
<td>0.74±0.11</td>
</tr>
<tr>
<td>$\eta' K^\pm$</td>
<td>0.63±0.06</td>
</tr>
<tr>
<td>$K_S K_\bar{S}$</td>
<td>0.72±0.19</td>
</tr>
<tr>
<td>$\pi^0 K^\pm$</td>
<td>0.57±0.17</td>
</tr>
<tr>
<td>$\phi K_S$</td>
<td>0.54±0.19</td>
</tr>
<tr>
<td>$\omega K_S$</td>
<td>0.71±0.21</td>
</tr>
<tr>
<td>$l_0 K_S$</td>
<td>0.69±0.10</td>
</tr>
<tr>
<td>$l_2 K_S$</td>
<td>0.48±0.53</td>
</tr>
<tr>
<td>$l_4 K_S$</td>
<td>0.20±0.53</td>
</tr>
<tr>
<td>$\pi^0 \pi^\pm K_S$</td>
<td>-0.72±0.71</td>
</tr>
<tr>
<td>$\omega \pi^0 K_S$</td>
<td>0.97±0.03</td>
</tr>
<tr>
<td>$\pi^+ \pi^- K_S$</td>
<td>0.01±0.33</td>
</tr>
<tr>
<td>$K^{-} K^+ K^0$</td>
<td>0.68±0.09</td>
</tr>
</tbody>
</table>

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QCD penguin $b \rightarrow s$ transitions (3)

• Direct CPV (DCPV) in $B \rightarrow K \pi$
  – DCPV: interference between amplitudes to a final state.
    - Giving a time-integrated CP asymmetry ($A_{CP}$).

\[
A_{CP}(B \rightarrow f) \equiv \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)} = -C \text{ for } f = f_{CP}
\]
QCD penguin $b \to s$ transitions (3)

- **Direct CPV (DCPV) in $B \to K \pi$**
  \[ A_{\text{CP}}(B \to f) = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = -C \text{ for } f = f_{CP} \]

  - **DCPV**: interference between amplitudes to a final state.
    - Giving a time-integrated CP asymmetry ($A_{\text{CP}}$).
  - **Non-negligible contributions from several diagrams.**
    - Because of suppressed charmless $b \to u, s$ transitions.
  - **A sum rule of $A_{\text{CP}}$ was proposed.**
    - Applying the isospin symmetry to the leading contributions.
    - Violation could be NP in $b \to s\bar{q}q$.

QCD penguin $b \to s$ transitions (3)

- Direct CPV (DCPV) in $B \to K\pi$
  - DCPV: interference between amplitudes to a final state.
    - Giving a time-integrated CP asymmetry ($A_{CP}$).
  - Non-negligible contributions from several diagrams.
    - Because of suppressed charmless $b \to u$, s transitions.
  - A sum rule of $A_{CP}$ was proposed.
    - Applying the isospin symmetry to the leading contributions.
    - Violation could be NP in $b \to s\bar{q}q$.
  - Important to systematically study all $K\pi$ modes with high precision in Belle II.
Prospect on Unitarity Triangle

Present

For a SM-like scenario

Belle II @ 50 ab⁻¹

<table>
<thead>
<tr>
<th>Observable</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ₁ [deg.]</td>
<td>0.4</td>
</tr>
<tr>
<td>φ₂ [deg.]</td>
<td>1.0</td>
</tr>
<tr>
<td>φ₃ [deg.]</td>
<td>1.0 (w/ LHCb)</td>
</tr>
<tr>
<td></td>
<td>V_{cb}</td>
</tr>
<tr>
<td></td>
<td>V_{cb}</td>
</tr>
<tr>
<td></td>
<td>V_{ub}</td>
</tr>
<tr>
<td></td>
<td>V_{ub}</td>
</tr>
</tbody>
</table>
Prospect on Unitarity Triangle

For a SM-like scenario

Belle II @ 50 ab⁻¹

If the current WAs hold

Present

B \rightarrow \pi \pi

B \rightarrow (cc)K⁰

b \rightarrow ulv

b \rightarrow clv

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Non-B physics

• Various decays will be used
  – to probe new physics beyond SM,
  – to have significant progress in flavor physics.
  – $\tau$ decays, charm decays, dark sectors, quarkonium(-like)/exotic states, …

Lepton flavor violation in $\tau$ decays

Future prospect
SuperKEKB and Belle II are in the final integration and commissioning phase.
- The detector systems, except the vertex detectors, have been in commissioning with cosmic rays.
- The “Phase 2” commissioning will start in early 2018.

Belle II will search for new physics beyond the SM in the flavor sector at the intensity frontier.
- $W$-exchanging process with $\tau$,
- One loop FCNC processes,
- Over-constraining the Unitarity Triangle.

The physics prospects at Belle II indicate exciting future.
- New physics hunting,
- Significant progress in flavor physics.