Belle II: Commissioning, First Results, Future Prospects

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Photo Credit: Shota Takahashi of KEK
The Intensity Frontier: “Quantum Mechanical Finesse versus Brute Force”

Sven Vahsen

Aspen, March 2019
Belle II @ SuperKEKB

- Super B Factory experiment at world’s highest luminosity electron-positron collider
- Precision measurements in a clean event environment
- Broad physics program
- Investigation of tantalizing, existing BSM hints

Belle II physics run has started!
Belle still producing new results – a hot one in this talk!
The B-factory idea in a nutshell

- Electron-positron collisions
- \( E_{\text{CM}} \approx m_{\Upsilon(4s)} \)
- \( \Upsilon(4s) \rightarrow \overline{B}B \) ---- quantum-entangled!
- Asymmetric beam energies
  - B-decay-time distributions via \( \Delta z \approx 200 \mu m \)
  - precision studies of B-meson mixing, mixing-induced CPV, quantum-decoherence, etc.

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55 billion B-meson pairs in target data sample
Analysis sensitivity in B, \( \tau \) and charm to \( O(10^{-9}) \) branching fractions

<table>
<thead>
<tr>
<th>Process ( q\bar{q} )</th>
<th>( \sigma ) (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( bb )</td>
<td>1.1</td>
</tr>
<tr>
<td>( cc )</td>
<td>1.3</td>
</tr>
<tr>
<td>Light quark ( qq )</td>
<td>( \sim2.1 )</td>
</tr>
<tr>
<td>( \tau\bar{\tau} )</td>
<td>0.9</td>
</tr>
<tr>
<td>( e^+e^- )</td>
<td>( \sim40 )</td>
</tr>
</tbody>
</table>
Belle II Physics Program

• The original B factory experiments BaBar and Belle confirmed the Kobayashi-Maskawa Mechanism
• A single, irreducible, complex CKM phase can explain all CPV observed in the quark sector to date
• This is now a validated part of the SM
• Belle II will look for deviations from this picture to provide evidence of BSM physics
• Question: How does the newly observed CPV in D’s (LHCb) fit into the figure to the right?

But the Belle II physics scope extends far beyond B physics and CPV Charm, tau, precision EW, quarkonium physics, dark sector searches, and more
SuperKEKB Accelerator

- Longer magnets (LER) than KEKB by 4m
- New beam pipe design to reduce the SR
- New final focusing magnets
- More RF cavities to increase the beam currents
- Damping ring for a low emittance e⁻ beam
- Change of the collision energy to increase beam lifetime
- Low emittance e⁻

\[ \sigma_y = 940 \text{nm} \]
\[ \sigma_y = 62 \text{nm (HER)} \]
\[ \sigma_y = 48 \text{nm (LER)} \]

**Nano-beam scheme**

**KEKB**

**SuperKEKB**

**e⁺-e⁻ IP**

**7.0GeV 2.6A e⁻**

**4.0GeV 3.6A e⁺**

- 40 x higher instantaneous luminosity than KEKB by:
  - doubling \( I_{\text{HER/LER}} \)
  - Extreme focusing of the beams – a.k.a. **nanobeam scheme**

- Note: this also strongly increases beam backgrounds [beam-gas and Touschek scattering]
- Background mitigation at the machine, detector, and reconstruction level are important ingredients for success

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The Belle II Detector

**KL and muon detector (KLM):**
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

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

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

**Central Drift Chamber (CDC):**
- He(50%):C$_2$H$_6$(50%), Small cells, long lever arm, fast electronics

**Vertex Detector (VXD):**
- 2 layers DEPFET (PXD)
- 4 layers DSSD (SVD)

**Beryllium beam pipe**
- 2cm diameter

**General purpose 4$\pi$ Detector**
- Significant upgrades to improve background tolerance
- New PID systems, Vertex detector

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The Geography of the International Belle II collaboration

- Belle II has grown substantially in recent years, to ~800 researchers from 26 countries
- Youth and potential: There are ~267 graduate students in the collaboration
2016: Phase 1 Commissioning Run
First SuperKEKB operation.
no final focus, no collisions, Belle II not rolled in
First look at Beam Backgrounds with BEAST II

https://doi.org/10.1016/j.nima.2018.05.071

Beam Exorcism for A Stable Experiment II
a.k.a. BEAST II
2017: Belle II Detector rolled into the beam line, final beam-focusing magnets installed
January 2018: The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector
2018 March-July “Phase 2” Commissioning Run

- First e⁺e⁻ collisions achieved
- Data taking with Belle II minus VXD (vertex detector) - a safety conscious approach
- Beam backgrounds are high but tolerable
  - Synchrotron radiation (VXD background) observed for first time

→ All goals achieved. Safe to proceed and install full VXD
Rediscovery of B mesons

- Clearly observed an excess of BB events
- Detector and full reconstruction analysis chain working well.

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SuperKEKB in Phase2

- Achieved
  - $L_{\text{peak}} = 5.55 \times 10^{33} \text{ cm}^2/\text{s}$
  - Belle II recorded ~ 500 pb$^{-1}$
  - Confirmed the nano-beam scheme
  - Reduced $\beta_y$ to 3 mm, $\sigma_y \sim 400$ nm (Final target $\beta_y^* = 0.3$ mm $\sigma_y^* \sim 50$ nm)

Squeezing the beams at the interaction point

Ramping up the beam currents
Phase 3: Physics Run

- Currently preparing for “factory mode” data taking
- Full vertex detector has been installed
- Phase 3 run began March 2019; planning ~8 months of operation this year
- All going smoothly so far!

- Exceed existing world $e^+e^- \rightarrow \Upsilon(4S)$ dataset by 2021
- Target of 50 ab$^{-1}$ recorded by 2027
Belle lacked dedicated single-photon trigger required for such searches.

BaBar sensitivity reduced due to lack of hermiticity of projective crystals in calorimeter.

Belle II has world-leading sensitivity with only 20 fb\(^{-1}\), expected in first year of running.
Light Higgs ($A^0$) and low-mass DM via Upsilon-tagging


**FIG. 2.** 90% C.L. upper limits on the BFs of the on-shell process $\Upsilon(1S) \to \gamma A^0$ with $A^0 \to \chi\chi$ (top) and the off-shell process $\Upsilon(1S) \to \gamma\chi\chi$ (bottom). The orange solid curves are the Belle limits and the blue dashed curves are the BaBar limits.

**FIG. 3.** WIMP-nucleon spin-independent scattering cross-section limits at 90% C.L. The black solid and dashed curves are the upper limits obtained by assuming the WIMP couples to all quarks and only b-quarks, respectively. The 90% C.L. exclusion limits of LUX [18], CRESST II [19], SuperCDMS [20], and ATLAS [21, 22] and CMS [23, 24] are shown for reference; and the 90% C.L. signal regions of CRESST II [25], CoGeNT [26], XENON 1T [27], CDMS II (silicon) [28] and DAMA (w/ ion Ch.) [29].

Highly competitive, though somewhat model-dependent limits on low-mass Dark Matter from Belle Straightforward to extend and improve with Belle II
Hot Topic: test of flavor universality in $B \to K^{(*)}\ell^+\ell^-$

- SM couplings flavor independent, predict $R_{K^{(*)}}$ close to 1
- LHCb measurements in tension with SM expectations at low $q^2$

\[
R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}
\]
New Belle result – four days old. Preprint coming soon. Belle result includes first measurement of charged mode \( R_{K^*} \). Belle strongly statistics limited. Belle II will clarify.
Hot Topic: $B \rightarrow D^{(*)}\tau\nu$

- $B \rightarrow D\tau\nu$ and $B \rightarrow D^*\tau\nu$ are tree-level SM decays containing 3\textsuperscript{rd} generation quarks and leptons

- Ratio of heavy-to-light lepton modes provides robust theoretical prediction

- Measurements from BaBar, Belle and LHCb all independently deviate from SM (combined $\sim 4\sigma$)

- Belle II can precisely measure $R(D)$ and $R(D^*)$ to constrain or identify BSM physics
- Both charged and neutral B and various final states
Rare and forbidden decays

Processes that are suppressed or forbidden within the SM can potentially be dramatically enhanced by new physics contributions

e.g. Lepton flavour violation in $\tau$ decays:

“forbidden” in SM, but many new physics models saturate existing limits

Expected Belle II sensitivity with full data sample

Very clean searches at B factories and unambiguous signal of new physics
Complementarity of $e^+e^-$ and LHC: Charged Higgs Search

The current combined $B \rightarrow \tau \nu$ limit places a stronger constraint than direct searches from LHC exps. for the next few years.

Currently inclusive $b \rightarrow s \gamma$ rules out $m_{H^+}$ below $\sim 480$ GeV/$c^2$ range at 95% CL (independent of $\tan\beta$), M. Misiak et al. (assuming no other NP)

• The upgrade from Belle/KEKB to Belle II/SuperKEKB started in 2010, proceeded in three phases, and is now essentially complete
• The Belle II flavor factory experiment will
  • perform precision measurements of CPV and
  • investigate existing flavor physics anomalies
  • carry out broad searches for physics BSM
• SuperKEKB has achieved first collisions and verified the nano-beam scheme
• The Belle II detector performance has been confirmed with the Phase 2 data
• VXD has been assembled and installed in Belle II
• The “Phase 3” main physics run has started
Backup
Complementarity of $e^+ e^-$ factories and LHC

Thanks to Luis Pesantez and Phil Urquijo

The current combined $B \to \tau \nu$ limit places a stronger constraint than direct searches from LHC exps. for the next few years.

Currently inclusive $b \to s \nu$ rules out $m_{H^+}$ below $\sim 480$ GeV/$c^2$ range at 95% CL (independent of $\tan \beta$), M. Misiak et al. (assuming no other NP)

Figure 2: Existing constraints on ALPs with photon coupling (left) and hypercharge coupling (right). Proton beam dump constraints are taken from ref. [22], LEP constraints on $e^+e^- \rightarrow \gamma \gamma$ from ref. [21], CDF constraints on $Z \rightarrow \gamma \gamma$ from ref. [28], bounds from horizontal branch stars from ref. [11], bounds from visible decays of ALPs produced in SN 1987A from ref [50] and bounds from heavy-ion collisions from ref. [51]. All other constraints have been revisited and updated in the present work.
Electroweak FCNCs

\[ B \rightarrow X_{s/d} \gamma \]

\[ B_{s/d}^0 \rightarrow l^+l^- \]

\[ C_7 \text{ (Photon penguin)} \]

\[ C_{10} \text{ (Axial vector EW)} \]

Products of field operators
(non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of \( m_b \))

Wilson coefficients
(calculated perturbatively; encode short-distance physics)

New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

Potentially many observables:
- Branching fractions, CP asymmetries, kinematic distributions, angular distributions and asymmetries

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$B \rightarrow K^{(*)} l^+ l^-$ and $R_{K^{(*)}}$

$B \rightarrow K^{(*)} \mu^+ \mu^-$

$B \rightarrow K^{(*)} e^+ e^-$

LHCb measurements in tension with SM expectations for ratio of muon and electronic final states:

$$R_{K^{(*)}}(q^2) = \frac{BF(B \rightarrow K^{(*)} \mu^+ \mu^-)}{BF(B \rightarrow K^{(*)} e^+ e^-)}$$
\[ \text{B} \rightarrow \text{K}(\star)l^+l^- \text{ and } R_{\text{K}(\star)} \]

- \[ \text{B} \rightarrow \text{K}(\star)\mu^+\mu^- \]
- \[ \text{B} \rightarrow \text{K}(\star)e^+e^- \]
- \[ \text{B}^0 \rightarrow \text{K}(\star)^0l^+l^- \]
- \[ \text{B}^+ \rightarrow \text{K}(\star)^+l^+l^- \]
- \[ \text{B} \rightarrow \pi l^+l^- \]
- \[ \text{B} \rightarrow X_{s/d} l^+l^- \]

Belle II can measure absolute branching fractions, and has symmetric e/\mu PID performance.

... but there are also two distinct B charge/flavour states

... and two different final-state quark flavours (s,d)

... and also “inclusive” \( X_{s/d} \) hadronic systems vs exclusive \( \pi, \text{K}, \text{K}^* \) reconstruction
B → $K^{(*)}l^+l^-$ and $R_{K^{(*)}}$

- $B \rightarrow K^{(*)}\mu^+\mu^-$
- $B \rightarrow K^{(*)}e^+e^-$
- $B^0 \rightarrow K^{(*)0}l^+l^-$
- $B^+ \rightarrow K^{(*)+}l^+l^-$
- $B \rightarrow \pi l^+l^-$
- $B \rightarrow X_{s/d} l^+l^-$
- $B \rightarrow K^{(*)}\tau^+\tau^-$
- $B \rightarrow K^{(*)}\nu\bar{\nu}$
- $B \rightarrow K^{(*)}\tau^+l^-$

...also two additional lepton species ($\tau, \nu$) which can be studied

...and of course lepton flavour violating modes.

All with distinct experimental sensitivities and systematics, and theoretical sensitivities to various new physics scenarios.
Missing energy decays

Unique capability to study B decay modes with missing energy:

- FCNC modes such as $B \rightarrow K^{(*)}\nu\nu$, $B^0 \rightarrow \nu\nu$, $B \rightarrow K^{(*)}\tau^+\tau^-$ etc.

- Semileptonic B decays such as $B \rightarrow D^{(*)}\tau^+\nu$, $B^+ \rightarrow \mu^+\nu$, and $B^+ \rightarrow \tau^+\nu$

Precisely known CM energy, combined with exclusive hadronic reconstruction of the accompanying B, permit the decay daughters of missing energy decays to be uniquely identified:

```
Hadronic system
D^{(*)0}, D^{(*)+}

"Signal" B

E, µ

Event missing energy

m_{BC} \equiv \sqrt{E_{beam}^* - p_B^2}

\Delta E^* \equiv E_B^* - E_{beam}^*
```

Similar methodology exists for reconstructing semileptonic B tags
Expected Beam Backgrounds in Phase 3

- dangerously high
- *predictions*, based purely on simulation
- assume perfect collimators, with ideal settings

Goal of beam background group: achieve comprehensive understanding: *measure* all beam background components, and their scaling with beam conditions, in Phases 1,2
Phase 1

- Phase 1 results: [https://arxiv.org/abs/1802.01366](https://arxiv.org/abs/1802.01366)
- 1.5 years of work. 101 pages, 127 figures.
- Accepted by NIMA May 30\textsuperscript{th} 2018
BEAST II Phase 1

- Collection of detectors aimed at studying beam backgrounds
- Independent detectors, no global event building

<table>
<thead>
<tr>
<th>System</th>
<th>Detectors Installed</th>
<th>Unique Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN Diodes</td>
<td>64/64</td>
<td>neutral vs charged radiation dose</td>
</tr>
<tr>
<td>Diamonds</td>
<td>4/4</td>
<td>ionizing radiation dose</td>
</tr>
<tr>
<td>Micro-TPCs</td>
<td>4/4</td>
<td>directional fast neutron flux</td>
</tr>
<tr>
<td>He-3 tubes</td>
<td>4/4</td>
<td>thermal neutron rate</td>
</tr>
<tr>
<td>Crystals</td>
<td>6/6 Csi(Tl) 6/6 Csi 6/6/ LYSO</td>
<td>EM energy spectrum</td>
</tr>
<tr>
<td>BGO</td>
<td>8/8</td>
<td>EM dose rate</td>
</tr>
<tr>
<td>&quot;CLAWS&quot;</td>
<td>8/8</td>
<td>Inj. BG</td>
</tr>
<tr>
<td>Scintillator</td>
<td>4/4</td>
<td>EM particle rate</td>
</tr>
</tbody>
</table>
Beam size scans

- Allowed us to separate beam-gas & Touschek contributions
- Allows validation of simulation
- Then use simulation to extrapolate to Phase 3
- We think separating backgrounds into components and then extrapolating is the only reliable way to extrapolate backgrounds to Phase 3
Touschek Experiment/Simulation ratios

Lewis, Jaegle, and all detector groups

CLAWS
BGO
Diamond
PIN
LYSO rate
He$^3$

$LER: 1.4^{+1.8}_{-1.1}$
$HER: 4.8^{+8.2}_{-2.8}$
Beam-gas Experiment/Simulation ratios

**CLAWS**

**BGO**

**Diamond**

**PIN**

**LYSO rate**

**He**\(^3\)

**LER:** \(2.8^{+3.4}_{-2.3}\)

**HER:** \(108^{+180}_{-64}\)

\(O_{\text{bg}}^{\text{data}} / O_{\text{bg}}^{\text{MC}}\)
Fast Neutrons: Recoils

- Recoil energy spectrum (=negative derivative of neutron spectrum) agrees quite well with simulation.
- Validates simulation of neutron production, propagation, and material description.
- LER rate agrees fairly well with simulation. 5 x higher fast neutron rate from HER than predicted.
• Total phase 1 dose on surface of beam pipe ~ 100-200 kRad.
• PINs, diamond sensors, and dosimeters roughly consistent within uncertainties.
• No significant dose from Synchrotron Radiation (preliminary limit: < 1.7 krad)
## Status at end of Phase 1

<table>
<thead>
<tr>
<th>Background Type</th>
<th>Simulation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touschek</td>
<td>SAD generates scattered particles and tracks them. Particles lost in IR are passed to GEANT4 fullsim.</td>
</tr>
<tr>
<td>Beam-gas Coulomb</td>
<td></td>
</tr>
<tr>
<td>Beam-gas Brems</td>
<td></td>
</tr>
<tr>
<td>Radiative Bhabha</td>
<td>BBBrem/BHWide $\rightarrow$ GEANT4</td>
</tr>
<tr>
<td>QED 2-photon</td>
<td>Aafh $\rightarrow$ GEANT4</td>
</tr>
<tr>
<td>Synchrotron Radiation</td>
<td>SR generation in GEANT4</td>
</tr>
<tr>
<td>Injection BG</td>
<td>Injection particles provided by accelerator group $\rightarrow$ SAD $\rightarrow$ GEANT4</td>
</tr>
<tr>
<td>Beam dust</td>
<td>-</td>
</tr>
<tr>
<td>neutrons</td>
<td></td>
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</table>

**Beam gas:** appears elevated w.r.t. simulation, but subdominant BG $\rightarrow$ level still safe

**Touschek:** agrees fairly well with simulation, appears safe.

**Neutrons:** elevated and should be checked further in Phase 2

**Radiative Bhaba, two-photon, and SR most dangerous and not yet measured $\rightarrow$ major goal for Phase 2 to measure these**