Belle II/SuperKEKB Status and Outlook
Tom Browder, University of Hawai‘i at Manoa

Some Highlights from First Collisions and the Phase 2 Belle II Pilot Run.

Physics and the Road Ahead to Phase 3

The complex superconducting final focus is partially visible here (before closing the endcap).
The Geography of the International Belle II collaboration

Belle II now has grown to ~800 researchers from 25 countries. This is rather unique in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an international collaboration.

Youth and potential: There are ~267 graduate students in the collaboration.
Indian contributions to rare B decays, $\gamma /\phi_3$ measurements and charm physics on Belle + major impact in Belle II first physics

India built layer 4 of the Belle II silicon vertex detector. Major GRID computing planned.
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron ($e^+e^-$) rather than proton-proton (pp))

Some items to note:
1) Brand-new positron damping ring (commissioned this spring).

2) New 3 km positron ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing this spring.

3) New complex superconducting final focus (commissioned this spring).
N.B. To realize this steep turn-on, requires close cooperation between Belle II and SuperKEKB [and some *international collaboration* on the accelerator].
Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney
Some Belle II jargon

**PHASE 1**: Simple background commissioning detector (diodes, diamonds TPCs, crystals...). No final focus. Only *single* beam background studies possible [started in Feb 2016 and completed in June 2016].

**PHASE 2**: More elaborate inner background commissioning detector (VXD samples). Full Belle II outer detector. Full superconducting final focus. *No vertex detectors.* **Collisions!**

*[Phase 2 collisions: April 26-July 17, 2018]*
Antimatter-matter annihilation in Tsukuba, Japan

IP size: 400 µm in X, 4 µm in Y
Peak luminosity: $7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$

Probably $e^+e^- \rightarrow q\bar{q}$
The scene at the experimental control room in Tsukuba Hall B3

This is scientific history in the making: SuperKEKB/Belle II joins DORIS/ARGUS, CESR/CLEO, and PEP-II/BaBar and KEKB/Belle
Welcome to the world of large crossing angle nano-beams!

As expected, the effective bunch length is reduced from \(~10\) mm (KEKB) to 0.5 mm (SuperKEKB).

We measure this in two track events in Belle II data.
How do we measure the vertical height of nanobeams?
Ans: Width of Luminosity scans with diamond detectors

At Phase 2 peak luminosity of $5 \times 10^{33}/\text{cm}^2/\text{sec}$, the vertical spot is $\sim 700\text{nm}$ high. There is still beam-beam blowup at high currents. At low currents, the vertical spot size is $330 \text{ nm}$ high (the final goal is $O(50\text{nm})$ with full capability of the QCS system).
Keep on squeezing the two beams with the superconducting final focus $\beta_y^*=3\text{mm}$, making sure that the two “thin pancakes” are well aligned. One then adds beam current.

$$L_{\text{peak}} = 5.5 \times 10^{33} / \text{cm}^2 / \text{sec}$$

Phase 2, July 2018

N.B. Still a long way to go with the superconducting final focus (one order of magnitude in $\beta_y^*$)

Luminosity tuning has priority. When accelerator physicists become tired, Belle II takes data (usually owl shift). Only able to record $0.5 \text{fb}^{-1}$. 
Belle II Detector

BEAST (Background commissioning detector)

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

Particle Identification
iTOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

Electrons (7 GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

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

Positrons (4 GeV)
Barrel Particle Identification (uses Cherenkov radiation)

The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar. (Japan, US, Slovenia, Italy)

Incoming track

Vertexing/Inner Tracking

Beampipe \( r = 10 \text{ mm} \)

DEPFET pixels (Germany, Czech Republic...)

Layer 1 \( r = 14 \text{ mm} \)
Layer 2 \( r = 22 \text{ mm} \)

DSSD (double sided silicon detectors)

Layer 3 \( r = 38 \text{ mm} \) (Australia)
Layer 4 \( r = 80 \text{ mm} \) (India)
Layer 5 \( r = 115 \text{ mm} \) (Austria)
Layer 6 \( r = 140 \text{ mm} \) (Japan)

+Poland, Korea

FWD/BWD Italy
Belle II has a modern DAQ and readout system

Item to note: Front-end readout electronics and Gb fiber optic link (Belle2link) to the back-end.

Item to note: Note ROI (Region of Interest) for PXD data volume.
Advanced & Innovative Technologies used in Belle II

Pixelated photo-sensors play a central role

- MCP-PMTs in the iTOP
- HAPDs in the ARICH
- SiPMs in the KLM

**Collaboration with Industry**

DEPFET pixel sensors

Waveform sampling with precise timing is “saving our butts”.

Front-end custom ASICs (Application Specific Integrated Circuits) for all subsystems

→ DAQ with high performance network switches, large HLT software trigger farm

→ a 21st century HEP experiment.

KLM (*TARGETX ASIC*)

ECL (New waveform sampling backend with good timing)

TOP (*IRSX ASIC*)

ARICH (KEK custom ASIC)

CDC (KEK custom ASIC)

SVD (APV2.5 readout chip adapted from CMS)

New *methods of neutron detection with TPC’s for the background. Directions*!
The B-anti B meson pairs at the Upsilon(4S) are produced in a coherent, entangled quantum mechanical state.

\[ | \Psi > = | B^0(t_1, f_1)\bar{B}^0(t_2, f_2) > | B^0(t_2, f_2)\bar{B}^0(t_1, f_1) > \]

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays \( \rightarrow \) collapses the flavor wavefunction of the other anti-B. (Exercise: Also one B must decay before the other can mix)

The beam energies are asymmetric (7 on 4 GeV)

The decay distance is increased by around a factor \(~7\)
Most of the Belle II detector subsystems are working well. Some nice examples of *signals* involving photons.

\[ e^+e^- \rightarrow + \]

\[ 1.00 \text{ GeV} < p(\text{recoil}) < 8.00 \text{ GeV} \]

**Belle II** 2018 (Preliminary)

\[ \int L \, dt = 250 \text{ pb}^{-1} \]

\[ \mu_m = 0.997 \pm 0.001 \]

Single Photon Lines

**Ready for the dark sector!**

\[ e^+e^- \rightarrow X \]

\[ e^+e^- \rightarrow ALPS \rightarrow ( ) \]
Most of the Belle II detector subsystems are working well. Here are some *signals* involving charged tracks.

\[ K_S \rightarrow ^+ \]

\[ J / \rightarrow ^+ , J / \rightarrow e^+ e^- \]
Performance of CDC $dE/dx$ particle identification with early calibrations in the hadronic event sample.

Extra cuts:
- $|d0| < 1$
- $|dz| < 3$
- # layers hit $> 20$
TOP Particle Identification.

\[ D^{*+} \rightarrow D^0_s^+; D^0 \rightarrow K^+ \]

N.B. The charge correlation with the slow pion determines which track is the kaon (or pion)

Kinematically identified kaon from a \( D^{*+} \) in the TOP; Cherenkov \( x \) vs \( t \) pattern (mapping of the Cherenkov ring)
→ $K^- K^+$ inclusive

Another example of TOP particle identification with early calibration and alignment.

No kaons identified

One kaon identified in the TOP.

Both kaons identified in the TOP.

FIG. 7: $m(K^+ K^-)$ distributions for runs with TOP calibration (run number up to 2531). Tracks are required to be in the TOP acceptance. Top: No PID requirement. Middle: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for one of the tracks. Bottom: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for both tracks.
Rediscovery of $D_s \rightarrow \phi \pi^+$, with $\phi \rightarrow K^+ K^-$.

No PID

Two identified charged kaons.

**FIG. 1:** This figure shows $M[(K^+ K^-) \pi^+]$ distribution, which was produced using phase-II 366 pb$^{-1}$ hadron skim data. No PID criteria are applied to any of the charged tracks ($K^\pm \pi^\mp$). Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.

**FIG. 2:** This figure shows $M[(K^+ K^-) \pi^+]$ distribution, which was produced using phase-II 366 pb$^{-1}$ hadron skim data. Combined PID criteria, $\text{Prob}(K: \pi) > 0.5$ for $K^\pm$ tracks and $\text{Prob}(\pi: K) > 0.5$ for $\pi^\pm$ tracks are applied. Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.
Endcap particle identification via Aerogel RICH (ARICH)
Clearly illustrates the capabilities of Belle II and the potential for charm physics and the building blocks of B mesons.

$e^+ e^- \rightarrow cc$

$D^{*+} \rightarrow D^0 +$,

$D^0 \rightarrow K^+ , K^- + 0 , K^- +$
$CP$ Eigenstate: $D^0 \rightarrow K_S^0$

FIG. 36: $\Delta M$ (left) and $M_D$ (right) signal-enhanced projections in 250 pb$^{-1}$ prod4 data sample for $D \rightarrow K_S^0\pi^0$ final state.

Also illustrates some of the important capabilities of Belle II.
More matter-antimatter annihilation in Tsukuba: Another event from Belle II’s first evening

\[ e^+e^- \rightarrow \star \rightarrow B\bar{B} \]

A potential \( e^+ e^- \rightarrow B \) anti-B candidate
We are on the $\Upsilon(4S)$ resonance and recording $B$ anti-$B$ pairs with $\sim 99\%$ efficiency.

Event Topology tells us we are seeing $B$’s

B pairs produced at rest in the CM with no extra particles

We are on the $\Upsilon(4S)$ resonance and recording $B$ anti-$B$ pairs with $\sim 99\%$ efficiency.
Event Topology (fits to $R_2$) tells us we are seeing $B$’s.

Not so obvious: When we change accelerator optics, we remain on the Upsilon(4S).
We have "rediscovered" the B meson!

1983:

**Observation of Exclusive Decay Modes of b-Flavored Mesons**

*B*-meson decays to final states consisting of a $D^0$ or $D^{**}$ and one or two charged pions have been observed. The charged-$B$ mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-$B$ mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.
Onwards to Phase 3 and the Physics Run

The VXD will be installed in Phase 3.
Restart Belle II data taking in February 2019.

PXD layer 1 ladders
First PXD half-shell
being tested at DESY
Completed L4 (India)
Physics Competition and Complementarity

<table>
<thead>
<tr>
<th>Year</th>
<th>Run III</th>
<th>Run IV</th>
<th>Run V</th>
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<tbody>
<tr>
<td>2019</td>
<td>LHCb 40 MHz UPGRADE I</td>
<td>L = 2 \times 10^{33}</td>
<td>LHCb UPGRADE II</td>
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<td>2021</td>
<td>ATLAS Phase I Upgr</td>
<td>L = 2 \times 10^{34}</td>
<td>HL-LHC</td>
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<tr>
<td>2023</td>
<td>CMS Phase I Upgr</td>
<td>300 fb^{-1}</td>
<td>ATLAS</td>
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<tr>
<td>2026</td>
<td>Belle II</td>
<td>5 ab^{-1}</td>
<td>HL-LHC</td>
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</table>

- **Belle II**
  - L = 5 \times 10^{33} cm^{-2}s^{-1} achieved!
  - Physics with VXD in 2019

Outside perspective:
Plenary talk by Niels Tuning, ICHEP 2018 in Seoul, Korea
Examples of Physics Competition and Complementarity

Use publicly available LHCb projections.
How can we establish NP in $B \rightarrow K^* l^- l^+$?

Ans: Observe and measure the rate for $B \rightarrow s$ and thus isolate the Z penguin ($C_9$) at Belle II

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**TABLE I: Projections for the statistical uncertainties on the $B \rightarrow K^{(*)} \nu \bar{\nu}$ branching fractions.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B \ [10^{-6}]$</th>
<th>Efficiency</th>
<th>$N_{\text{Backg.}} \ [10^{-4}]$</th>
<th>$N_{\text{Sig-exp.}} \ [10^{-4}]$</th>
<th>Statistical Error</th>
<th>Total Error</th>
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<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \nu \bar{\nu}$</td>
<td>3.98</td>
<td>5.68</td>
<td>21</td>
<td>3.5</td>
<td>23%</td>
<td>24%</td>
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<tr>
<td>$B^0 \rightarrow K^{0}_{S} \nu \bar{\nu}$</td>
<td>1.85</td>
<td>0.84</td>
<td>4</td>
<td>0.24</td>
<td>110%</td>
<td>110%</td>
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<tr>
<td>$B^+ \rightarrow K^{*+} \nu \bar{\nu}$</td>
<td>9.91</td>
<td>1.47</td>
<td>7</td>
<td>2.2</td>
<td>21%</td>
<td>22%</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} \nu \bar{\nu}$</td>
<td>9.19</td>
<td>1.44</td>
<td>5</td>
<td>2.0</td>
<td>20%</td>
<td>22%</td>
</tr>
<tr>
<td>$B \rightarrow K^* \nu \bar{\nu}$ combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15%</td>
<td>17%</td>
</tr>
</tbody>
</table>
What’s Ahead?

“Missing Energy Decay” in a Belle II GEANT4 MC simulation

Signal: $B \rightarrow K \nu \nu$

Tag mode: $B \rightarrow D\pi; \ D \rightarrow K\pi$

Zoomed view of the vertex region in r--phi

View in r-z
Belle II can do both inclusive and exclusive. Equally strong capabilities for electrons and muons.

NP in $b \rightarrow s \ell^+\ell^-$

Prepared by D. Straub et al. for the Belle II Physics Book (edited by P. Urquijo and E. Kou)
Conclusions

• Belle II will explore New Physics on the Luminosity or Intensity Frontier. This is different and complementary to the LHC high $p_T$ experiments, which operate on the Energy Frontier.

• There is competition and complementarity with LHCb

• We are ready to start a long physics run in the Super Factory mode. This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world’s highest luminosity accelerator.

• The world is waiting for our results.
Backup Slides
Results from Global Fits to Data (CKMFit Group)

Great progress on $\phi_3$ or $\gamma$ (first from B factories and now in the last four years from LHCb). These measure the phase of $V_{ub}$.

Similar results from UTFIT


Looking good (except for an issue with $|V_{ub}|$)

But a 10-20% NP amplitude in $B_d$ mixing is perfectly compatible with all current data.
More examples of Physics Competition and Complementarity

FIG. 6: Projected precision for various measurements of semileptonic $B$ decays.

Use publicly available LHCb projections.
τ Lepton Flavor Violation

Belle II will push many limits below $10^{-9}$; LHCb, CMS and ATLAS have very limited capabilities.

LHC high pt: The modes $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow \mu \ h^+ \ h^-$ provide important constraints on $H \rightarrow \mu \tau$
Acknowledgements

We thank the dedicated and talented Belle II students, postdocs, engineers and professors as well as the funding agencies of:

Australia  Mexico
Austria  Poland
Canada  Russia
China  Saudi Arabia
Czechia  Slovenia
France  South Korea
Germany  Spain
India  Taiwan
Israel  Thailand
Italy  Turkey
Japan  Ukraine
Malaysia  USA
Vietnam

Early physics within two months of first collisions was made possible by the extensive preparations of the software, computing and data production teams.
FIG. 2: SuperKEKB and LHCb integrated luminosity projections in fb\(^{-1}\) and ab\(^{-1}\) respectively.
FIG. 5: Projected precision for various measurements of direct CP violation.
The CP Violation predicted by Kobayashi and Maskawa is too small by \( \sim 10 \) orders of magnitude in the Standard Model.

What does this mean?

New Physics
We are on the \( \Upsilon (4S) \) resonance and recording B-anti B pairs with \( \sim 99\% \) efficiency.

**Event Topology tells us we are seeing B’s**

B pairs produced at rest in the CM with no extra particles.

We are on the \( \Upsilon (4S) \) resonance and recording B-anti B pairs with \( \sim 99\% \) efficiency.
Phase III:
Milestone: Completion of +X clam-shell of the SVD on Jan 18, 2018
# Machine Parameters

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<th>LER</th>
<th>HER</th>
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