The Belle II Experiment

James Kahn

Ludwig Maximilians Universität München
DFG cluster of excellence
“Origin and Structure of the Universe”

2016-08-21
Outline

- Motivation
- SuperKEKB
- Detector
- Software
- Milestones
Collaboration formed in 2009 following success of Belle experiment:
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- UT parameters, heavy flavour spectroscopy, CPV, rare B decays, etc.
Motivation

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- New physics searches (Sources of CPV, (semi–)leptonic decay, LFV, etc.)
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Unique advantages of B–factory:
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- Experimentally clean.
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- Missing particles, inclusive measurements, unique phase space.
- Sensitive to mass ranges above direct production.

Nobel prize to KM /
Decisive confirmation of CKM picture

Evidence for direct CP violation in \( B \rightarrow \pi^\pm \pi^- \)

Evidence for \( D^0 \) mixing

Observation of direct CP violation in \( B \rightarrow \pi^\pm \pi^- \)

Observation of \( B \rightarrow K^{(*)} \ell\ell \)

Observation of \( B \rightarrow K^{(*)} \ell\ell \)

Excess in \( B \rightarrow D^{(*)} \tau\nu \)

Observation of \( B \rightarrow \tau\nu \)

Observation of \( b \rightarrow d \gamma \)

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Current standing:

- 649 Members, 99 institutes, 22 countries (Aug 2016)
- First data: 2018
SuperKEKB

- **e+ 4 GeV 3.6 A**
- **e- 7 GeV 2.6 A**

- Belle II
- New IR

- New beam pipe & bellows
- Low emittance positrons to inject
- Damping ring
- Low emittance gun
- Low emittance electrons to inject
- Add / modify RF systems for higher beam current

- Positron source
- New positron target / capture section

---

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The Belle II Experiment
SuperKEKB

- **e+ 4 GeV 3.6 A**
- **e- 7 GeV 2.6 A**
- **Belle II**
- **New IR**
- **New beam pipe & bellows**
- **Add / modify RF systems for higher beam current**
- **Low emittance positrons to inject**
- **Damping ring**
- **Positron source**
- **New positron target / capture section**
- **Low emittance gun**
- **Low emittance electrons to inject**
Peak instantaneous luminosity:
\[ 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]
(Belle: \( 2.11 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \))

Total integrated luminosity:
\[ 50 \text{ab}^{-1} \]
(Belle: \( 1 \text{ab}^{-1} \))

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma [nb] )</th>
<th>No. events [( \times 10^9 )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{B}B )</td>
<td>1.1</td>
<td>55</td>
</tr>
<tr>
<td>( q\bar{q} )</td>
<td>2.52</td>
<td>185.45</td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>0.92</td>
<td>45.95</td>
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</table>
The Belle II Detector

- Electromagnetic Calorimeter: 8000 CsI crystals, 16X PMT/APD readout, Time of Propagation counter, DIRC with 20mm quartz bars, MCP-PMT readout, Aerogel RICH, Proximity focusing RICH with silica aerogel
- Central Drift Chamber: proportional wired drift chamber, 15000 sense wires in 58 layers
- Silicon Vertex Detector: 4 layer doublesided strips
- Pixel Vertex Detector: 2 layer pixel detector (8MP), DEPFET technology
Belle II Detector

The Belle II Experiment

- Electromagnetic Calorimeter with 8000 CsI crystals and PMT/APD readout
- Time of Propagation counter
- DIRC with 20 mm quartz bars
- MCP-PMT readout
- Aerogel RICH
- Proximity focusing RICH with silica aerogel
- Central Drift Chamber
  - Proportional wired drift chamber
  - 15000 sense wires in 58 layers
- Silicon Vertex Detector
  - 4 layer double sided strips
  - 20 – 50 ns shaping time
- Pixel Vertex Detector
  - 2 layer pixel detector (8MP)
  - DEPFET technology

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The Belle II Experiment
High luminosity  
→ high hit-rate.

- 14 mm and 22 mm from beampipe  
→ high occupancy.
High luminosity
→ high hit-rate.

14\text{mm} and 22\text{mm} from beampipe
→ high occupancy.

Ladder structure:
- Inner layer: 8 modules, 3.072M pixels.
- Outer layer: 12 modules, 4.608M pixels.
- High luminosity
  \rightarrow high hit-rate.

- 14\text{mm} and 22\text{mm} from beampipe
  \rightarrow high occupancy.

- Ladder structure:
  - Inner layer: 8 modules, 3.072M pixels.
  - Outer layer: 12 modules, 4.608M pixels.

- DEPlleted Field Effect Transistor (DEPFET):
- High luminosity
  → high hit-rate.

- 14\,mm and 22\,mm from beampipe
  → high occupancy.

- Ladder structure:
  - Inner layer: 8 modules, 3.072M pixels.
  - Outer layer: 12 modules, 4.608M pixels.

- DEPlented Field Effect Transistor (DEPFET):
  - 50\,\mu m thin.
  - Air–cooled.
  - Radiation hard.

- Still in production (lithography in progress).
- Four ladder layers: 38, 80, 115, 140 mm.

Double Sided Strip Detectors (DSSD)

- Excellent timing resolution ($\sim 2-3 \, \text{ns}$) → complements PXD.
- Undergone beam tests at DESY.
Four ladder layers: 38, 80, 115, 140 mm.

Three sizes of DSSDs used for outer, inner, forward layers.
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- Three sizes of DSSDs used for outer, inner, forward layers.

- Excellent timing resolution ($\sim 2 – 3 \text{ns}$) → complements PXD.

- Undergone beam tests at DESY.
**Belle II Detector**

- **Electromagnetic Calorimeter**: 8000 CsI crystals, 16×0 PMT/APD readout
- **DIRC** with 20mm quartz bars, MCP-PMT readout
- **Aerogel RICH**
  - Proximity focusing RICH with silica aerogel
- **Central Drift Chamber**: Proportional wiredrift chamber, 15000 sense wires in 58 layers
- **Silicon Vertex Detector**: 4 layer double sided strips, 20 − 50 ns shaping time
- **Pixel Vertex Detector**: 2 layer pixel detector (8MP), DEPFET technology
Belle II Detector

Electromagnetic Calorimeter
- 8000 CsI crystals, 16×0
- PMT/APD readout
- Time of Propagation counter
- DIRC with 20mm quartz bars
- MCP-PMT readout

Aerogel RICH
- Proximity focusing RICH with silica aerogel

Central Drift Chamber
- Proportional wire drift chamber
- 15000 sense wires in 58 layers

Silicon Vertex Detector
- 4 layer double sided strips
- 20 – 50 ns shaping time

Pixel Vertex Detector
- 2 layer pixel detector (8MP)
- DEPFET technology
~ 51,500 sense wires inside 1.5$T$ magnetic field.
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- Key roles:
  1. Reconstruct charged tracks with precision momentum measurements.
  2. Particle identification using measurements of $\frac{dE}{dx}$.
  3. Trigger for charged particles.

Moving into final position + cosmic ray testing ongoing.
~ 51,500 sense wires inside 1.5$T$ magnetic field.

Key roles:
1. Reconstruct charged tracks with precision momentum measurements.
2. Particle identification using measurements of $\frac{dE}{dx}$.
3. Trigger for charged particles.

Moving into final position + cosmic ray testing ongoing.
**Belle II Detector**

**Electromagnetic Calorimeter**
- 8000 CsI crystals, 16X
- PMT/APD readout
- Time of Propagation counter
- DIRC with 20mm quartz bars
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**Aerogel RICH**
- Proximity focusing RICH with silica aerogel

**Central Drift Chamber**
- Proportional wire drift chamber
- 15000 sense wires in 58 layers

**Silicon Vertex Detector**
- 4 layer double sided strips
- 20 – 50 ns shaping time

**Pixel Vertex Detector**
- 2 layer pixel detector (8MP)
- DEPFET technology

Image of Belle II Detector with labels:
- **Pixel Vertex Detector**
- **Silicon Vertex Detector**
- **Central Drift Chamber**
The Belle II Experiment

**Time of Propagation counter**
- DIRC with 20 mm quartz bars
- MCP-PMT readout

**Pixel Vertex Detector**
- 2 layer pixel detector (8MP)
- DEPFET technology

**Silicon Vertex Detector**
- 4 layer double sided strips
- 20 – 50 ns shaping time

**Central Drift Chamber**
- Proportional wire drift chamber
- 15000 sense wires in 58 layers

**Aerogel RICH**
- Proximity focusing RICH with silica aerogel
Particle identification in barrel region.
▶ Particle identification in barrel region.

▶ Sixteen modules, each containing:
  ▶ Two 2.7m long quartz bars.
  ▶ A spherical mirror.
  ▶ An expansion prism.
  ▶ An array of photo–detectors.
- Particle identification in barrel region.

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- Cherenkov ring reconstructed in 3D from time and the $x – y$ position.
- Particle identification in barrel region.

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  - Two 2.7m long quartz bars.
  - A spherical mirror.
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  - An array of photo–detectors.

- Cherenkov ring reconstructed in 3D from time and the $x-y$ position.

- TOP installed – undergoing background tests.
Time of Propagation Detector
Particle identification in forward end-cap.
Particle identification in forward end-cap.

Components:
Particle identification in forward end-cap.

Components:
- Aerogel radiator → produces Cherenkov photons.
- Expansion volume.
- 2D array of photon detectors (420 Hybrid Avalanche Photo Detectors).
- Read-out system for photon detectors.
- Particle identification in forward end-cap.

- Components:
  - Aerogel radiator → produces Cherenkov photons.
  - Expansion volume.
  - $2D$ array of photon detectors (420 Hybrid Avalanche Photo Detectors).
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- Focusing constructed to separate $K$ and $\pi$ photons across most of their momentum range.
Particle identification in forward end-cap.

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- Aerogel radiator → produces Cherenkov photons.
- Expansion volume.
- $2D$ array of photon detectors (420 Hybrid Avalanche Photo Detectors).
- Read–out system for photon detectors.

Focusing constructed to separate $K$ and $\pi$ photons across most of their momentum range.

Partially installed, cosmic ray tests ongoing.
**Belle II Detector**

- **Time of Propagation counter**
  - DIRC with 20 mm quartz bars
  - MCP-PMT readout

- **Pixel Vertex Detector**
  - 2 layer pixel detector (8MP)
  - DEPFET technology

- **Silicon Vertex Detector**
  - 4 layer double sided strips
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- **Central Drift Chamber**
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- **Aerogel RICH**
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Electromagnetic Calorimeter

- Reuse barrel crystals from Belle (new waveform sampling electronics).
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- Refurbished end–cap crystals (CsI(Tl) $\rightarrow$ CsI)

Roles:

- Detect photons with precision measurements.
- Identify electrons.
- Help detect $K_0$ together with the KLM.

Hardware tests carried out on crystals–Electronics still in construction/testing.
- Reuse barrel crystals from Belle (new waveform sampling electronics).

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Alternating layers of iron plates and detector components.
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- Iron plates:
  - $K_L$ shower hadronically.
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- Replaced end-cap and inner-most barrel RPCs with scintillators.
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- Barrel (End–cap) installed in 2013 (2014).
Alternating layers of iron plates and detector components.

Iron plates:
- $K_L$ shower hadronically.
- Flux return for magnet.

Replaced end-cap and inner-most barrel RPCs with scintillators.

Barrel (End-cap) installed in 2013 (2014).

Currently undergoing commissioning/cosmic ray testing.
- Rewritten (mostly) from scratch.
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- Standardise common processes.
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- Standardise common processes.

Example: \( B^0 \to D^0(\to \pi^0\pi^0)\pi^0 \)

```plaintext
# Load up a data set to analyse
inputMdstList('B2D0pi0_mdst.root')

# Create "pi0:all" and "pi0:good" ParticleLists
# from ECL clusters
goodPi0()

# Reconstruct D0 -> pi0 pi0 decay.
# Keep only candidates with: 1.7 < M(pi0pi0) < 2.0 GeV
reconstructDecay('D0:pi0pi0 -> pi0:good pi0:good',
'1.7 < M < 2.0')

# Reconstruct B0 -> D0 pi0 decay and keep only candidates with:
# Mbc > 5.24 GeV and -1 < Delta E < 1 GeV
reconstructDecay('B0:all -> D0:pi0pi0 pi0:good',
'5.24 < Mbc < 5.29 and abs(deltaE) < 1.0')

# Perform MC matching (MC truth association)
mMatchMCTruth('B0:all')

# Write out the flat ntuple
ntupleFile('B02D0Pi0-Reconstruction.root')
ntupleTree('b0', 'B0:all', toolsB0)

# Process the events
process(analysis_main)
```
- Rewritten (mostly) from scratch.
- Standardise common processes.
- Events independent → trivial parallelisation.

**Example: reconstruct $B^0 \to D^0(\pi^0 \pi^0)\pi^0$**

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# Perform MC matching (MC truth association)
mismatchMCTruth('B0:all')

# Write out the flat ntuple
ntupleFile('B02D0P10-Reconstruction.root')
ntupleTree('b0', 'B0:all', toolsB0)

# Process the events
process(analysis_main)
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- Rewritten (mostly) from scratch.
- Standardise common processes.
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- CVMFS mountable central builds OR ~ 1 min binaries setup.

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process(analysis_main)
```
Rewritten (mostly) from scratch.
Standardise common processes.
Events independent → trivial parallelisation.
CVMFS mountable central builds OR ~ 1 min binaries setup.
First full release: 08.2017

Example: reconstruct $B^0 \rightarrow D^0 (\rightarrow \pi^0 \pi^0) \pi^0$

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Phase 1 (Feb 2016):
Beam commissioning + beam background measurements
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  Details in next talk.
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Phase 2 (Dec 2017):
Detector in place without VXD
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  ▶ Details in next talk.

Phase 2 (Dec 2017): Detector in place without VXD

Phase 3 (Nov 2018): Physics run
New physics motivation for new B–factory.
New physics motivation for new B–factory.

SuperKEKB to set new world record instantaneous luminosity.
\[ 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]
\[ 50 \text{ab}^{-1} \]
- New physics motivation for new B–factory.

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- Detector component construction/installation ongoing.
New physics motivation for new B–factory.

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Detector component construction/installation ongoing.

Software still in development → mid–2017 full release.
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Detector component construction/installation ongoing.

Software still in development \(\rightarrow\) mid–2017 full release.

End–2018: Data taking to begin.
BACKUP
<table>
<thead>
<tr>
<th>Belle II</th>
<th>Overlap</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Missing particles</td>
<td>▶ CPV</td>
<td></td>
</tr>
<tr>
<td>▶ Inclusive measurements</td>
<td>▶ Semi-leptonic</td>
<td>▶ Large baryonic samples</td>
</tr>
<tr>
<td>▶ LFV</td>
<td>▶ EWP</td>
<td>▶ Deccays to visible particles.</td>
</tr>
<tr>
<td></td>
<td>▶ Charm physics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>▶ Low-multiplicity signatures.</td>
<td></td>
</tr>
</tbody>
</table>
Belle II is the upgraded Belle detector. Most components have been upgraded. The key changes are:

- The old silicon strip detector immediately outside the beam pipe will be replaced with a two–layer pixel detector.
- The remaining silicon strip detector is to be extended to have a larger radius than in Belle.
- The readout of the silicon strip detector will be changed from one based on the VA1TA chip to one based on the APV25 chip featuring a decreased shaping time.
- The central drift chamber, the primary tracking device, will have a larger volume and smaller cell sizes than in Belle.
- Particle identification is to be performed by entirely new devices using Čerenkov imaging with faster read–outs than in Belle.
- The end–cap scintillator crystals (CsI(T1)) in the electromagnetic calorimeter will be replaced with faster, more radiation tolerant pure CsI crystals, and new electronics will be used.
- The end–cap and inner layers of the $K_L$ and $\mu$ detector are to be replaced with scintillators.
1. Particle hits → electron–hole pairs produced.
2. Holes drift to the p+ back contact. Electrons accumulate in 'internal gate'.
3. Current from p+ source → p+ drain through FET modulated by FET gate and field from electrons in 'internal gate'.
4. Current is measured and amplified as it’s carried away.
5. n+ clear pulse to 'internal gate' removes collected electrons and signal charge.
6. Device is now reset and ready again.
1. Particle hits → electron–hole pairs produced.
1. Particle hits $\rightarrow$ electron–hole pairs produced.

2. Holes drift to the p+ back contact.
   Electrons accumulate in ‘internal gate’.
1. Particle hits $\rightarrow$ electron–hole pairs produced.

2. Holes drift to the p+ back contact. Electrons accumulate in ‘internal gate’.

3. Current p+ source $\rightarrow$ p+ drain through FET modulated by FET gate and field from electrons in ‘internal gate’.

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### Milestones

**Belle II construction schedule reconsideration: 2016 May 31**

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>8</td>
<td>Phase 1 (5mo)</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>3</td>
<td>Summer Shutdown</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>5</td>
<td>Phase 2 (5mo)</td>
<td></td>
</tr>
</tbody>
</table>

**Global Operation**
- Global Operation: machine time per JFY
- Belle rollout/in

**Global Position**
- TOP
  - Solenoid field measurement
  - CDC

**Cryogenics (for Solenoid)**
- IBBelle, CO2 ready on site

**COMP**

**On Beam Line**
- GCR -VF (details to be worked out)
- GCR -V (details to be worked out)

**ECL**
- ARICH
- Ecaps
- VXD