Start of the Belle II Experiment at SuperKEKB

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for the Belle II Collaboration

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The Belle II Collaboration

- Truly international: now ~980 researchers from 26 countries
B-Factory Experiments

- Asymmetric beam energies, high luminosity
  → High statistics of boosted B, D and $\tau$

- Flavour physics
  - CKM matrix, unitarity triangle
  - CPV in B system

- BSM limits
  - Rare B/D decays
    - $b \to s\gamma$, $b \to s l^+ l^-$
    - LFV in $\tau$ decays

- New particles
  - Tetraquarks
SuperKEKB

- 40x higher instantaneous luminosity
- Nano-Beam scheme
  - Almost completely new machine
  - New final focus system

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>units</th>
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<tbody>
<tr>
<td>LER</td>
<td>HER</td>
<td></td>
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<td>Beam energy $E_b$</td>
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<td>1.19</td>
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<td>$2.1 \times 10^{34}$</td>
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$\sigma_z$ 6-7 mm
overlap region = bunch length

$\sigma_z^{+}$ 100-150 $\mu$m

$\sigma_x^{+}$ 10-12 $\mu$m

$d = \frac{\sigma_z^{+}}{\phi}$

KEKB head-on (crab crossing)

Nano-Beam SuperKEKB

KEKB

- Electron-Positron linear accelerator
- Electron ring
- Positron ring
- Collision point
- Belle II detector

Electron-Positron linear accelerator

Positron damping ring
Challenges on the Detector Upgrade

- Significantly increased beam backgrounds ($\times 10^{-20}$)
  - Faster frontend electronics to reduce background pileup
- Increased trigger rates, data transfer bandwidth ($\times 10^{-100}$)
  - Overhauled DAQ system, pipelined readout
  - Full event reconstruction and data reduction in high level trigger farm (~3000 nodes)
- Reduced initial state boost (-30%)
  - Higher resolution vertexing detectors
  - Addition of pixel detector
Belle II Detector Upgrade

- K_L/Muon System
- Magnet Coil
- EM Calorimeter
- π/K Identification
- Drift Chamber
- Silicon Tracking
## Belle II Detector Upgrade

<table>
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<tr>
<th>Component</th>
<th>Description</th>
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</table>
| K⁻/Muon System          | New readout electronics
|                         | Many RPC layers replaced with scintillator strips + SiPMs                    |
| Magnet Coil             | No change                                                                   |
| EM Calorimeter          | New readout electronics
|                         | (Crystals, sensors not changed)                                             |
| π/K Identification      | Fully replaced                                                               |
| Drift Chamber           | Fully replaced                                                               |
| Silicon Tracking        | Fully replaced                                                               |
|                         | Larger outer radius for increased lever arm                                 |
|                         | 4 layers of double sided silicon strips + 2 layers of DEPFET pixels          |
Key Technologies in Detector Upgrade

- State-of-the-art silicon detectors
- Pixelated single photon sensors
  - MCP-PMTs in TOP (barrel PID) – time resolution
  - HAPDs in ARICH (end cap PID) – large area
  - SiPMs in KLM – low cost
- Waveform sampling readouts
  - TOP: 8192 channels, 2.7GSa/s: IRSX (Hawaii)
  - Sci-KLM: 16800 channels, 1GSa/s: TARGETX (Hawaii)
  - SVD: 224k channels, 32MSa/s: APV25 (adapted from CMS)
  - CDC: 14336 channels, 30Msa/s
  - ECL: 8736 channels, 2MSa/s
Belle II Vertex Detector

- Two layers of DEPFET pixel sensors
  - $r=14\text{mm}$, $r=22\text{mm}$
  - Only inner layer and small part of outer layer installed, replacement with full system in 2021
- Four layers of double sided strip detectors
  - $r=39\text{mm}$ to $r=140\text{mm}$
- Assembled and installed by November 2018 →
First Collision in Physics Run- 03/25/2019

Probably $e^+e^- \rightarrow Y(4s) \rightarrow B\bar{B}$
... and the Reaction
Luminosity in 2019

- 6.5fb\(^{-1}\) integrated from March 25\(^{th}\) to July 1\(^{st}\) 2019 (410pb\(^{-1}\) for EPS-HEP)
  - \(L_{\text{peak}}\): 6.1x10\(^{33}\) cm\(^{-2}\) s\(^{-1}\) (12x10\(^{33}\) with Belle II off)
  - Limited by backgrounds, beam-beam blowup
- New machine, entirely new concept, requires tuning
  - Already running at world record \(\beta^*_{y}=2\text{mm}\)
Impact Parameter Resolution

- Small luminous region used as a reference for vertexing resolution studies

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<td>$\hat{\sigma}(d_0)$ [$\mu$m]</td>
<td>$14.2 \pm 0.1$ (stat) $\pm 0.1$ (syst)</td>
</tr>
<tr>
<td>$\hat{\sigma}(z_0)$ [$\mu$m]</td>
<td>$16.1 \pm 0.1$ (stat) $\pm 0.1$ (syst)</td>
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**BB Pairs in First Data**

- Decompose measured $R^2$ distribution into $BB$ and continuum components
- Using off-resonance data to model continuum distribution
  - some discrepancies in continuum MC likely due to incomplete machine background modeling
- Many $BB$ pairs in first data set
  - We are stably operating on on the $Y(4S)$ resonance
Reconstructed B decays

- $B \to D(\ast)h$ exclusive ($h=\pi,\rho$)
  - Various D decays
- $\sim 300$ selected event candidates in first 410pb$^{-1}$

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<tr>
<td>$B \to D\pi$</td>
<td>140 ± 13</td>
</tr>
<tr>
<td>$B \to D\rho$</td>
<td>58 ± 11</td>
</tr>
<tr>
<td>$B \to D^{*0}\pi$</td>
<td>24 ± 5</td>
</tr>
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<td>$B^0 \to D^{*\pm}\pi$</td>
<td>32 ± 6</td>
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<tr>
<td>$B^0 \to D^-\pi^+$</td>
<td>31 ± 7</td>
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<tr>
<td>$B^0 \to D^-\rho^+$</td>
<td>14 ± 7</td>
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Summary

• The Belle II detector is assembled and ready for operation
  – Extensive detector upgrade with cutting edge silicon detectors and readout electronics upgrades

• We started our first physics running period in March 2019
  – The SuperKEKB nano beam scheme works and is already running at world record $\beta^*_y=2\text{mm}$
  – Delivered and recorded luminosities are ramping up, but still below Belle levels

• Clear signs of first physics out of the detector
Other Belle II Talks at EPS-HEP

- **First Physics:**
  - I. Ripp-Baudot: “First look at CKM parameters from early Belle II data”
    Flavour Physics and CP Violation: Thursday 09:00
  - K. Lautenbach: “Exotic and Conventional Quarkonium Physics Prospects at Belle II”
    QCD and Hadronic Physics: Thursday 14:45
  - S. Cunliffe: “Dark Sector Physics with Belle II“
    Dark Matter: Thursday 15:10
  - W. Sutcliffe: “Missing energy and electroweak penguin modes in early Belle II data”
    Flavour Physics and CP Violation: Friday 09:45
  - F. Forti: “BELLE II and flavor physics in e+e-“
    Plenary: Tuesday 10:00

- **Detectors:**
  - H. Ye: “Commissioning of the Belle II Pixel Vertex Detector”
    Detector R&D and Data Handling: Thursday 10:15
  - OH: “First Experiences with the Novel Time of Propagation (TOP) Barrel PID Detector in the Belle II Experiment”
    Detector R&D and Data Handling: Thursday 11:30
  - S. Longo: “A Novel Approach to Calorimeter-based Particle Identification at the Belle II Experiment using Scintillator Pulse Shape Discrimination”
    Detector R&D and Data Handling: Friday 09:30
  - A. Paladino: “Performance of the Belle II Silicon Vertex Detector”
    Poster: Monday 18:30
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SuperKEKB Beam Spot

- Measurement for all three dimensions
- Nanobeam scheme works as intended

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<td>14.6 $\pm$ 0.4 (stat) $\pm$ 0.2 (syst)</td>
<td>346.9 $\pm$ 1.8 (stat) $\pm$ 0.1 (syst)</td>
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PXD: Inner Vertexing with DEPFET Pixels

- **DEPFET**: internal charge to current amplification
  - Very good S/N for thin sensors
  - Relatively low power (no cooling in active area)
  - Rolling shutter readout (20us frame time)

- Sensors thinned to 75um
  - <0.25% $X_0$ per layer

- Two layers ($r=14mm$, 22mm)
  - Down to 50*55um pixels
  - 40 sensors total, 7.7Mpixel
PXD: Current Installation

- After technical troubles in module production and assembly: only inner layer installed
  - +2 ladders on outer layer
  - 10/20 sensors (3.8Mpixel)
- Restarted production of all sensor types to provide modules for a complete replacement of the currently installed PXD by 2021
PXD: Readout

- PXD is virtually noise free, but rather long integration time (20us, two full accelerator revolutions)
- ONSEN system reads out full PXD on each trigger and keeps data in local buffer
  - HLT reconstruction identifies regions of interest on PXD surface, ONSEN only transfers relevant parts of PXD hitmaps to EB2/storage
  - DATCON: FPGA based tracking to generate RoIs directly from SVD raw data
- Still PXD accounts for ~75% of total Belle II raw data size
SVD: Silicon Vertex Detector

- Four layers of double-sided strip detectors
  - \( r = 39 \text{mm} \) to \( r = 140 \text{mm} \)
  - Lampshade geometry
- 224k strips
  - 50-75um pitch tangential
  - 160-240um pitch axial
- Read out by APV25 ASICs
  - Adapted from CMS
  - 50ns shaping, 40MHz sampling
  - Partially thinned to 100um
SVD: Production

- Readout chips of central sensors bonded to “Origami” Kapton flex
  - Folded around sensors
- Ladders assembled all around the world:
  - Layer 3: Uni Melbourne, Australia
  - Layer 4: TIFR, India
  - Layer 5: HEPHY, Austria
  - Layer 6: Kavli-IPMU, Japan
- Final assembly into half shells and full vertexing system at KEK
Hawaii Waveform Sampling ASICs

• Hawaii Instrumentation Development Lab spinoff: Nalu Scientific
  – Founded by Isar Mostafanezhad (ex-postdoc of IDLab)

• Commercialisation of switched capacitor waveform sampling ASICs based on IDLab designs

• Three ASICs available:
  – SiRead: 32 channels, ~1 GSa/s
  – ASoC: 8 Channels, ~3 GSa/s
  – Aardvarc: 4 Channels, ~14 Gsa/s
Understanding Belle II

X-Y view

opposite-sign vertices

same-sign vertices + protonID
Understanding Belle II

X-Z view