Particle identification at Belle-II

Matthew Barrett
University of Hawaiʻi at Mānoa

University of Oxford seminar
29 April 2014
Outline

- The B factories
- Belle II and superKEKB
  - The Belle II sub-detectors
- The TOP sub-detector
  - Beam test at SPring-8
- Belle II schedule
  - Commissioning detector
The B factories

- Belle/KEKB at KEK (Japan) and BaBar/PEP-II at SLAC (USA).
The B factories

- The B factories: Belle and BaBar ran from 1999 to ~2010.
- They recorded over 1.5ab\(^{-1}\) of data.
- And provided the experimental confirmation that lead to the 2008 Nobel prize.
The B factories

- Physics highlights:
  - Measurement of the Unitarity triangle, and CKM parameters;
  - Observation of D meson mixing;
  - Observation of new (X, Y, Z) hadrons;
  - Observation of direct CP violation in B decays;
- In addition to being B factories – also $\tau$ and charm factories:
  - Search for rare $\tau$ decays.
  - Constraints on new physics from:
    - e.g. $B \rightarrow \tau\nu$ and $B \rightarrow s\gamma$. 
B physics prospects

- Is that the end of B-physics?
  Isn't all B-physics done by LHCb now?
B physics prospects

- Is that the end of B-physics? Isn't all B-physics done by LHCb now?
- Still many potential sources/signals of new physics:
  - Flavour changing neutral currents;
  - Lepton flavour violating decays;
  - $B \rightarrow \tau$ new physics in loops;
  - Precision CKM measurements/new sources of CPV

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM theory</th>
<th>Current measurement (early 2013)</th>
<th>Belle II (50 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S(B \rightarrow \phi K^0)$</td>
<td>0.68</td>
<td>0.56 ± 0.17</td>
<td>±0.03</td>
</tr>
<tr>
<td>$S(B \rightarrow \eta' K^0)$</td>
<td>0.68</td>
<td>0.59 ± 0.07</td>
<td>±0.02</td>
</tr>
<tr>
<td>$\alpha$ from $B \rightarrow \pi\pi$, $\rho\rho$</td>
<td>&lt; 0.05</td>
<td>±5.4$^\circ$</td>
<td>±1.5$^\circ$</td>
</tr>
<tr>
<td>$\gamma$ from $B \rightarrow DK$</td>
<td>&lt; 0.05</td>
<td>±11$^\circ$</td>
<td>±1.5$^\circ$</td>
</tr>
<tr>
<td>$S(B \rightarrow K_S\pi^0\gamma)$</td>
<td>&lt; 0.05</td>
<td>−0.15 ± 0.20</td>
<td>±0.03</td>
</tr>
<tr>
<td>$S(B \rightarrow \rho\gamma)$</td>
<td>&lt; 0.05</td>
<td>−0.83 ± 0.65</td>
<td>±0.15</td>
</tr>
<tr>
<td>$A_{CP}(B \rightarrow X_{s+d}\gamma)$</td>
<td>&lt; 0.005</td>
<td>0.06 ± 0.06</td>
<td>±0.02</td>
</tr>
<tr>
<td>$A_{SL}$</td>
<td>$-5 \times 10^{-4}$</td>
<td>$-0.0049 \pm 0.0038$</td>
<td>±0.001</td>
</tr>
<tr>
<td>$B(B \rightarrow \tau\nu)$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$(1.64 \pm 0.34) \times 10^{-4}$</td>
<td>±0.05 $\times 10^{-4}$</td>
</tr>
<tr>
<td>$B(B \rightarrow \mu\nu)$</td>
<td>$4.7 \times 10^{-7}$</td>
<td>$&lt; 1.0 \times 10^{-6}$</td>
<td>±0.2 $\times 10^{-7}$</td>
</tr>
<tr>
<td>$B(B \rightarrow X_{s}\gamma)$</td>
<td>$3.15 \times 10^{-4}$</td>
<td>$(3.55 \pm 0.26) \times 10^{-4}$</td>
<td>±0.13 $\times 10^{-4}$</td>
</tr>
<tr>
<td>$B(B \rightarrow K\nu\nu)$</td>
<td>$3.6 \times 10^{-6}$</td>
<td>$&lt; 1.3 \times 10^{-5}$</td>
<td>±1.0 $\times 10^{-6}$</td>
</tr>
<tr>
<td>$B(B \rightarrow X_{s}\ell^+\ell^-)$ (1 $&lt; q^2 &lt; 6$ GeV$^2$)</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$(4.5 \pm 1.0) \times 10^{-6}$</td>
<td>±0.10 $\times 10^{-6}$</td>
</tr>
<tr>
<td>$A_{FB}(B^0 \rightarrow K^{0}\ell^+\ell^-)$ zero crossing</td>
<td>7%</td>
<td>18%</td>
<td>5%</td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>$ from $B \rightarrow \pi\ell^+\nu$ ($q^2 &gt; 16$ GeV$^2$)</td>
<td>9% $\rightarrow$ 2%</td>
</tr>
</tbody>
</table>

Table 3. The expected reach of Belle II with 50 ab$^{-1}$ of data for various topical B decay measurements. Also listed are the SM expectations and the current experimental results. For $B(B \rightarrow X_{s}\ell^+\ell^-)$, the quoted measurement [62] covers the full $q^2$ range. For $|V_{us}|$ and the $A_{FB}$ zero crossing, we list the fractional errors.

Report of the Quark Flavor Physics Working Group:
B physics prospects

- Is that the end of B-physics? Isn't all B-physics done by LHCb now?
- Still many potential sources/signals of new physics:
  - Flavour changing neutral currents;
  - Lepton flavour violating decays;
  - $B \rightarrow \tau$ new physics in loops;
  - Precision CKM measurements/new sources of CPV
- Different environment leads to complementary capabilities with LHCb.

Belle II and SuperKEKB
SuperKEKB

KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)

Redesign the lattices of HER & LER to squeeze the emittance

TIN-coated beam pipe with antechambers

New beam pipe & bellows

Colliding bunches

New superconducting /permanent final focusing quadrants near the IP

Belle II

New IR

e- 2.6 A

e+ 3.6 A

Add / modify RF systems for higher beam current

Positron source

New positron target / capture section

Low emittance positrons to inject

Damping ring

Low emittance gun

Low emittance electrons to inject

To obtain x40 higher luminosity
SuperKEKB is the intensity frontier

40x higher instantaneous luminosity than KEKB

Peak luminosity

trends at $e^+e^-$ colliders

SuperKEKB
Beam currents are increased by ~2, but the main increase in luminosity comes from the change in beamspot size from using nanobeams, and a crab waist scheme is also being examined.
From Belle to Belle-II

- Belle Detector is being upgraded to the Belle-II detector,
  - which will record data at a Luminosity ~40 times higher.
  - Belle sub-detectors are being upgraded or replaced.
- Belle detector used a time of flight (TOF) counter, and Aerogel Cherenkov counter for PID.
From Belle to Belle-II

- Belle Detector is being upgraded to the Belle-II detector,
  - which will record data at a Luminosity ∼40 times higher.
  - Belle sub-detectors are being upgraded or replaced.
- Belle detector used a time of flight (TOF) counter, and Aerogel Cherenkov counter for PID.
From Belle to Belle-II

- Belle Detector is being upgraded to the Belle-II detector,
  - which will record data at a Luminosity ~40 times higher.
  - Belle sub-detectors are being upgraded or replaced.
- Belle detector used a time of flight (TOF) counter, and Aerogel Cherenkov counter for PID.
- Belle II will replace these with an Aerogel RICH detector and a Time of Propagation detector.
- Other new sub-detectors include a new backward endcap calorimeter, and new vertex detectors.
Belle II Collaboration

- 599 collaborators, 97 institutions, 23 countries (as of February 2014).
Belle II subdetectors
Vertex detectors

- New vertex detectors: 2 layers of DEPFETs (Depleted P-Channel Field Effect Transistor) and 4 layers of DSSD (Double Sided Silicon Detectors).

- Beam pipe radius reduced from 2cm-1.5cm for Belle to 1cm for Belle II.
Central Drift Chamber (CDC)

- CDC for Belle II will be larger than Belle CDC.
- Stringing completed in January 2014.
  - 51456 wires.
Central Drift Chamber (CDC)

- Stringing in Fuji hall at KEK.

Expected performance from Geant4 simulation and Kalman filter
Aerogel RICH

- Aerogel Ring Imaging Cerenkov (ARICH) detector used for particle identification in the forward endcap.

2+2cm aerogel

→ NIM A548 (2005) 383

4cm aerogel single index

Uses 420 Hybrid Avalanche Photo Detectors (HAPD), each with 144 channels.
Two layers of aerogel lead to better photon yield, whilst maintaining resolution.

NIM A548 (2005) 383
Electromagnetic Calorimeter (ECL)

- Need upgrade for high backgrounds
- Barrel: CsI(Tl), waveform sampling.
- Endcaps: Pure CsI, waveform sampling.

Expected performance from Geant4 simulation.
Endcaps and parts of the barrel KLM RPCs of Belle needed to be replaced with scintillators due to increased backgrounds expected in Belle II.

Barrel KLM was the first sub-detector to be installed in Belle II.

Endcap KLM expected to be installed later this year.
K_L and Muon systems (KLM)

- Endcaps and parts of the barrel KLM RPCs of Belle needed to be replaced with scintillators due to increased backgrounds expected in Belle II.
- Barrel KLM was the first sub-detector to be installed in Belle II.
- Endcap KLM expected to be installed later this year.
Endcaps and parts of the barrel KLM RPCs of Belle needed to be replaced with scintillators due to increased backgrounds expected in Belle II.

Barrel KLM was the first sub-detector to be installed in Belle II.

Endcap KLM expected to be installed later this year.
The TOP detector

- The (imaging) Time of Propagation subdetector (TOP or iTOP) will be used for particle identification in the barrel region of Belle II.
- Each TOP module contains two quartz bars (~2.5m in length), and expansion volume, mirror, and array of photodetectors.

When a charged particle passes through the quartz, it emits Cherenkov photons:
- The Cherenkov angle, and hence detection time/position depends on the mass of particle (for given track parameters).
TOP modules

- There are 16 TOP modules to be installed in Belle II,
  - Forming a “Roman Arch” structure.
- 32 quartz bars are needed for the full Belle-II detector, each 20×450 ×1250mm³, with two per module.
- The quartz needs to be of high quality to ensure that photon losses are minimised, and that the Cherenkov photon reflection angles are maintained.

### Quartz Property

<table>
<thead>
<tr>
<th>Quartz Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flatness</td>
<td>&lt;6.3μm</td>
</tr>
<tr>
<td>Perpendicularity</td>
<td>&lt;20 arcsec</td>
</tr>
<tr>
<td>Parallelism</td>
<td>&lt;4 arcsec</td>
</tr>
<tr>
<td>Roughness</td>
<td>&lt; 0.5nm (RMS)</td>
</tr>
<tr>
<td>Bulk transmittance</td>
<td>&gt; 98%/m</td>
</tr>
<tr>
<td>Surface reflectance</td>
<td>&gt;99.9%/reflection</td>
</tr>
</tbody>
</table>
Photons are detected by an array of 32 Micro Channel Plate Photomultiplier Tubes (MCP-PMT) in each module.

- Each MCP-PMT has an active area of \( \approx 23 \times 23 \text{mm}^2 \).
  - NaKsBcCs photocathode.
  - Readout via 4×4 channels – 512 total channels per TOP module.
- PMTs required to have a peak quantum efficiency of >24%, and a collection efficiency of \( \approx 55\% \).
  - PMTs have a gain of \( \approx 2 \times 10^6 \) at operating HV, and an intrinsic transit time spread of \( \approx 40\text{ps} \).
Photon Detection

- Photons are detected by an array of 32 Micro Channel Plate Photomultiplier Tubes (MCP-PMT) in each module.

- Each MCP-PMT has an active area of \( \sim 23 \times 23 \text{mm}^2 \).
  - NaKSBcCs photocathode.
  - Readout via 4\times4 channels – 512 total channels per TOP module.

- PMTs required to have a peak quantum efficiency of \( >24\% \), and a collection efficiency of \( \sim 55\% \).
  - PMTs have a gain of \( \sim 2 \times 10^6 \) at operating HV, and an intrinsic transit time spread of \( \sim 40\text{ps} \).
Electronics

- The PMTs are readout by electronics including waveform sampling ASICs (IRS3B).
  - Two ASICs are used to readout each PMT.
  - These are assembled into readout modules, each with 8 PMTs/16ASICS.
  - 4 readout modules per iTOP module.
- Deposited charge on the PMT anode is converted into a waveform.
  - Used to determine photon detection time.
  - Time resolution goal of 50ps.
- System needs to be calibrated for optimum performance.
Ring images

- Each detected photon is identified by a time and a position within a module (plus charge and waveform quality values).

- Plotting time against position gives a representation of the Cherenkov ring.

- The two dimensional array of PMT channels is mapped to a single channel/pixel number parameter (1 to 512).
  - Seven discontinuities between rows.
Ring images

- Each detected photon is identified by a time and a position within a module (plus charge and waveform quality values).
- Plotting time against position gives a representation of the Cherenkov ring.
- The two dimensional array of PMT channels is mapped to a single channel/pixel number parameter (1 to 512).
  - Seven discontinuities between rows.
Ring images

- Example ring image is shown for tracks hitting the quartz bars at normal incidence.
- It includes both photons that have reflected back from the mirror.
- And photons that have travelled to the PMTs directly.
- For other incident angles only direct photons or “mirror” photons may be present.
- There is also a contribution from delta rays.
Channel time distributions

- For each channel there is a time distribution.
- The peaks correspond to different numbers of reflections on the long thin sides of the quartz bar.
Channel time distributions – direct photons

- Individual channels have a time distribution with peaks, corresponding to different numbers of reflections.

**Normal Incidence**

1st peak width:

- No dispersion: 6-8ps
- With dispersion: 90-100ps
- +TTS/T0 jitter: 110-120ps
- + electronics: 120-150ps
Individual channels have a time distribution with peaks, corresponding to different numbers of reflections.

**Mirror peaks:**

- No dispersion: 6-8ps
- With dispersion: 300-350ps
- + TTS/T0 jitter: 300-350ps as above plus 0-10ps
- + electronics: 300-350ps as above plus 10-20ps
Kaon/Pion separation

- The primary use for the TOP will be to discriminate between kaons and pions.

- A 2-dimensional PDF can be constructed based on detection time and detection position of Cherenkov photons.

- The different Cherenkov angle for photons from kaons leads to a later arrival time than for photons from pions.

- The TOP readout needs to have excellent time resolution to distinguish between particle types, with a requirement of better than 100ps, and a goal of 50ps.

- Final PID performance will also include information from other subdetectors, e.g. dE/dx to form a likelihood for each particle hypothesis.
TOP performance

- Preliminary estimates of the TOP performance from Belle II Geant 4 simulation.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\pi$ efficiency with 2% K fakes $\pi$ rate 100ps electronics jitter</th>
<th>$\pi$ efficiency with 4% K fakes $\pi$ rate 100ps electronics jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to \pi \eta \gamma$ vs $K \eta \gamma$</td>
<td>84.28 +/- 0.91</td>
<td>94.13 +/- 0.57</td>
</tr>
<tr>
<td>$B^+ \to \rho \gamma$ vs $K^* \gamma$</td>
<td>80.71 +/- 1.07</td>
<td>93.19 +/- 0.67</td>
</tr>
<tr>
<td>$B^0 \to \rho \gamma$ vs $K^* \gamma$</td>
<td>81.50 +/- 0.78</td>
<td>92.63 +/- 0.49</td>
</tr>
<tr>
<td>$B^+ \to \pi \pi \pi^0 \gamma$ vs $K \pi \pi^0 \gamma$</td>
<td>83.55 +/- 0.76</td>
<td>94.03 +/- 0.46</td>
</tr>
<tr>
<td>$B^0 \to \pi \pi \pi \gamma$ vs $K \pi \pi \gamma$</td>
<td>79.50 +/- 0.67</td>
<td>91.48 +/- 0.45</td>
</tr>
<tr>
<td>$B^+ \to \pi \pi \pi \pi^0 \gamma$ vs $K \pi \pi \pi^0 \gamma$</td>
<td>75.00 +/- 0.72</td>
<td>90.50 +/- 0.44</td>
</tr>
<tr>
<td>$B^0 \to \pi \pi \pi \pi \gamma$ vs $K \pi \pi \pi \gamma$</td>
<td>76.33 +/- 0.37</td>
<td>90.00 +/- 0.33</td>
</tr>
</tbody>
</table>
Beam test at SPring-8

- Beam test in June 2013 at the LEPS beamline at SPring-8 in Japan.
- Used a positron beam with energy ~2.1 GeV.
- Prototype iTOP module was placed in LEPS experiment – LEPS subdetectors used to provide tracking and momentum information.
- Data taken with beam hitting module at normal incidence and at forward angles.
Beam Test Single Event

- Single events have a mean of ~30 Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.

![Graph showing time vs. channel number for Beamtest Experiment 2 Run 568 Event 1]
Beam Test Single Event

- Single events have a mean of \(~30\) Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.
- Greyscale image shows expected distribution from simulation.
Beam test data/MC comparison

- Comparison between data and MC for beamtest with normally incident beam.

- The MC consists of events generated with Belle II Geant4, with additional backgrounds simulated using data driven background estimates.
Beam test data/MC comparison

- Comparison between data and MC for beamtest with a beam hitting the quartz at a forward angle.
Channel Time distributions

- Time distributions for individual channels recorded during the beam test.
- Comparison is between data and Belle II Geant4 simulation with additional backgrounds simulated using data driven methods.
Beam test summary

- The beam test at SPring-8 was the first test of the full TOP system.
  - Both electronics and optics were tested.
  - Electronics had a timing resolution of 100ps, meeting requirements.
  - Subsequent testing of the electronics with a laser has achieved close to goal of 50ps resolution.
- The prototype module has been moved to KEK where it is being tested with cosmic rays.
- A cosmic ray test stand is being commissioned which will be used to test every TOP module before installation.
Schedule

Goal of Belle II/SuperKEKB

Plan to reach 50 ab\(^{-1}\) by end of 2022

Commissioning starts in early 2015.


Schedule

- SuperKEKB will start circulating beams in 2015.
- Phase 1: Without Belle II.
- Phase 2: Belle II is rolled in, but without vertex detector.
- Phase 3: With full Belle II.
- Physics data taking will start in late 2016.
Commissioning Detector

- During phases 1 and 2 a commissioning detector will be used – BEAST II (Beam Exorcisms for A Stable ExperimenT).
- Will be used to measure beam backgrounds, before Belle II is rolled in and fully installed.
- Phase 1: 2 MicroTPCs in 8 positions used to measure neutron backgrounds, and PIN diodes used to measure ionising particle backgrounds.
- Every other PIN diode coated in gold paint, to allow for separation of charged particle and x-ray contributions.
Commissioning Detector

- During phases 1 and 2 a commissioning detector will be used – BEAST II (Beam Exorcisms for A Stable Experiment).
- Will be used to measure beam backgrounds, before Belle II is rolled in and fully installed.
- Phase 1: PIN diodes.
- Phase 2: 8 MicroTPCs and pin diodes used alongside Belle II – vertex detector will not be installed until Phase 3.
Belle II will operate at an instantaneous luminosity 40 times higher than its predecessor.

It is projected to record $50\text{ab}^{-1}$ of data during its lifetime.

- Allowing for precision measurements with sensitivity to many new physics models.

The construction of Belle II and superKEKB is well under way,

- The first sub detectors have been installed.
- TOP sub detector has been tested at beam test.

The first beams in superKEKB will be in 2015,

- And the first physics run is due to start in late 2016.
Summary

- Belle II will operate at an instantaneous luminosity 40 times higher than its predecessor.
- It is projected to record $50 \text{ab}^{-1}$ of data during its lifetime.
  - Allowing for precision measurements with sensitivity to many new physics models.
- The construction of Belle II and superKEKB is well under way,
  - The first sub detectors have been installed.
  - TOP sub detector has been tested at beam test.
- The first beams in superKEKB will be in 2015,
  - And the first physics run is due to start in late 2016.

ありがとうございました
Thank you for listening,

And thank you to the many Belle II collaborators whose plots I have shown, including:
T Browder, S Vahsen, L Piilonen, K Matsuoka, M Petric, T Hara, M Rosen, B Kirby, G Varner, and many others...
Backup
The comparison between data and MC for beamtest with a beam hitting the quartz at a forward angle is shown.
Final Micro-TPC Prototype Design

- Sensitive volume
- Field cage
- Charge amplification (GEMs)
- Charge Detection (Pixel Chip)

Aluminum vacuum vessel
## SuperKEKB

### Machine design parameters

<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td>Beam energy</td>
<td>$E_b$</td>
<td>3.5</td>
</tr>
<tr>
<td>Half crossing angle</td>
<td>$\varphi$</td>
<td>11</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>$\varepsilon_x$</td>
<td>18</td>
</tr>
<tr>
<td>Emittance ratio</td>
<td>$\kappa$</td>
<td>0.88</td>
</tr>
<tr>
<td>Beta functions at IP</td>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>1200/5.9</td>
</tr>
<tr>
<td>Beam currents</td>
<td>$I_b$</td>
<td>1.64</td>
</tr>
<tr>
<td>beam-beam parameter</td>
<td>$\xi_y$</td>
<td>0.129</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
</tbody>
</table>

**units**

- GeV
- mrad
- nm
- %
- mm
- A
- cm$^{-2}$s$^{-1}$
Hardware Resources for Belle II

T. Hara et al. (Belle II Computing Steering Group)
Photon reflections in module
Photon reflections in module
Photon reflections in module
Belle and KEKB