The Belle II Experiment

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Belle II

• Next generation B-factory, located at the SuperKEKB asymmetric $e^+e^-$ collider.

• 40x the peak luminosity of KEKB; 50 ab$^{-1}$ integrated luminosity = 30x the combined of BaBar and Belle.
Detector is an upgrade of Belle. New tracking and particle ID; upgrades to calorimeter and muon systems.

- **EM Calorimeter:** CsI(Tl), waveform sampling (baseline) (opt.) Pure CsI for end-caps
- **Vertex Detector:** 2 layers DEPFET + 4 layers DSSD
- **Central Drift Chamber:** He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics
- **Beryllium beam pipe:** 2cm diameter
- **Particle Identification:** Time-of-Propagation counter (barrel) Prox. focusing Aerogel RICH (fwd)
- **$K_L$ and muon detector:** Resistive Plate Counter (barrel outer layers) Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Electron (7GeV) and positron (4GeV) traces are shown on the diagram.
Physics

• Primary goal is to seek evidence for new physics through a wide range of measurements that are sensitive to the presence of heavy virtual particles.
  - asymmetries, rare decays, forbidden decays.
• Also direct searches for new physics;

• investigations of the nature of QCD through the studies of new bound states (XYZ);

• exploration of CP violation and the weak force.

• B physics; charm; tau (including lepton flavour violation); initial-state radiation production of $\pi^+\pi^-$ and other hadronic states; Upsilon decays
Search for light dark matter using $e^+e^- \rightarrow \gamma + \text{invisible}$

- Dark Sector models include light dark matter $\chi$ accessible through decay of a dark photon $A'$ that mixes with $\gamma$ with strength $\varepsilon$. Belle II will have unique capabilities, even with the initial small dataset.
Schedule / Status

- SuperKEKB commissioned with single beams in Spring 2016 (Phase 1 commissioning).

- Detector moved onto beam line April 2017.

- 1st collisions, no vertex detectors: Feb. 2018 (Phase 2).

- Collisions with full detector: Jan. 2019 (Phase 3).
SuperKEKB luminosity projection

Goal of Belle II/SuperKEKB

- Peak luminosity \( \text{cm}^{-2} \text{s}^{-1} \)
- Integrated luminosity \( \text{ab}^{-1} \)

Calendar Year:
- Peak luminosity by summer 2022, end of 4th “experiment”
- 50 ab\(^{-1}\) by summer 2024, end of 6th “experiment”
- Colliding beams with full detector, 1st “experiment”
Collaboration

• 23 countries, 100 institutions, 750 collaborators, including 380 PhD physicists & 260 graduate students.

• Canada joined in March 2013.
Canadian group: 10 faculty, 9 current and 4 completed grad students, 2 postdocs

- **UBC**: C. Hearty, J. McKenna, T. Mattison, T. Ferber, A. Hershenhorn

- **Victoria**: J. M. Roney, R. Kowalewski, R. Sobie, A. Sibidanov, A. Beaulieu, S. de Jong, S. Longo, C. Miller


- **Montreal**: J.-P. Martin, P. Taras, N. Starinski

faculty, postdoc, student, technical
Canadian activities

• Preparations for physics (including single photon);

• Background measurements and remediation;

• Calorimeter reconstruction and calibration.

• Detector material studies → not in my talk

• Computing (particularly cloud) → not in my talk

• Four students talks Monday 11:30 AM Botterell B139

Steve Robertson overview Thursday 8 AM Botterell B139
Single beam commissioning

- Initial commissioning;
- Vacuum scrubbing;
- Studies of non-luminosity backgrounds using specialized detectors ("BEAST")
  - \(^3\)He tubes for thermal neutrons; Sam DeJong (UVic)
  - CsI/CsI(Tl)/LYSO crystals; Alex Beaulieu (UVic)
BEAST commissioning detectors
Background measurements during Phase 1 commissioning

- Study beam gas scattering by varying pressure & current; Touschek (scattering within a bunch) by varying size & current.

- Critical point is to use residual gas analyzers to correct for the effective atomic number \( Z_e \) of the gas.
Background shields

• Considerable shielding built into final focus magnets.

• Canadian group is providing lead/polyethylene shields, particularly for calorimeter endcaps; factor of 2 reduction in peak rates.
  - Alex Beaulieu

• First job of this type for contractor, Turbulent Diffusion Technology.
Radiative Bhabha beam backgrounds

- Biggest source of beam backgrounds are radiative Bhabhas, $e^+e^- \rightarrow e^+e^-\gamma$. ~3500 per beam crossing.
  - low energy $\gamma$ and $n$; shower debris

- Despite shielding, many 1—2 MeV photons reach the detector.
Background monitors

- McGill and Montreal groups are developing background monitors embedded in the shields to provide real-time feedback to operators:
  - collimator adjustments
  - characterizing injection background

Hardware developed by Montreal electronics group headed by J. P. Martin:
- LYSO crystal
- fine-mesh PMT
- pseudo differential readout
- 258 MHz ADC = bunch spacing
- can synchronize with trickle injection
Calorimeter reconstruction

- Precision calorimetry is critical to the physics program, particularly with respect to LHCb.

- CLEO, BaBar, and Belle have all used CsI(Tl) before, but we will have much higher backgrounds.

- New readout electronics with waveform fitting gives much better timing resolution to reduce out-of-time backgrounds.

Simulation of a 100 MeV $\gamma$ in CsI(Tl) calorimeter includes 600 MeV of 1–2 MeV background photons.
• Torben Ferber (UBC postdoc) has developed innovative reconstruction code for the calorimeter.

• number of crystals included in the cluster varies with background level;

• also depends on the hypothesis made on the particle type: hadron vs photon.

• machine learning to reduce position bias compared to Belle and BaBar
• Result is a dramatic improvement in energy resolution over existing algorithm.
Shower shapes

• Photon showers are regular shaped, symmetric; hadronic showers are much more variable.

• Alon Hershenhorn (UBC) has exploited the hypothesis-based clusters to quantify these differences using Zernike moments.
  - BDT with 11 moments vs 1 for BaBar

• Compare how much a shower looks a photon if we assume it is a photon to how much it looks like a photon if we assume it is a hadron.
Pulse shape discrimination (PSD)

- Heavily-ionizing particles produce CsI(Tl) signals with noticeably different time structures than photons.  
  - well known in nuclear physics, but not used in previous collider experiments.

- Savino Longo (UVic) has proposed implementing PSD particle ID in Belle II: $R_{\text{PID}} \equiv \frac{Q(1.2\mu s)}{Q(7.4\mu s)}$

\[ \text{Integrated charge vs time from CsI(Tl), } \alpha \text{ and } \gamma \]

\[ \frac{Q(t)}{Q(7.4\mu s)} \]

\[ \text{Time (} \mu \text{s)} \]

\[ \text{DATA} \]

\[ \text{Alpha} \]

\[ \text{Gamma} \]
• Data from two beam tests at TRIUMF: M11 (summer 2015), and Proton/Neutron Irradiation Facility (fall 2016).

![Graph showing data from beam tests.](image)

M11 300 MeV/c BaBar crystal, PMT readout

PIN Diode Data

PIF Background

Neutron and cosmic background events in PIF; Belle II crystal, photodiode

Savino Longo
Challenges in implementing PSD in Belle II

- Currently obtain amplitude and time of energy deposition in each crystal using a real-time waveform fit in an FPGA.
- Need a new FPGA algorithm that also extracts a PSD discriminator. Must be robust, fast, and not damage existing E and t measurements. Alexei Sibidanov UVic RA
- Template needs to be individually trained for each crystal using full waveforms, including hadrons.
• GEANT (at least, our model) does not produce a difference in pulse shape. Savino is working on this.

• Proposal is to record full waveforms for a fraction of the Phase 2 colliding beam data. May even test new FPGA code.
Summary

• Belle II will have first colliding beam data within a year. Physics opportunities with the first data include a search for light dark matter.

• Canadian group’s contributions include:
  - physics
  - backgrounds: characterization, shields, monitor
  - calorimeter reconstruction, shower shapes, pulse shape discrimination

• Addition details in students’ talks tomorrow and Steve Robertson’s talk on Thursday.