Electromagnetic calorimeter reconstruction in Belle II.

2019-03-12, ACAT, Saas-Fee

Torben Ferber (torben.ferber@desy.de) for the Belle II ECL group
SuperKEKB

KEKB $e^+ / e^-$
- $E$ (GeV): 3.5/8.0
- $I$ (A): $\sim$ 1.6/1.2
- $\beta^*_y$ (mm): $\sim$5.9/5.9
- Crossing angle (mrad): 22

SuperKEKB $e^+ / e^-$
- $E$ (GeV): 4.0/7.0
- $I$ (A): $\sim$ 3.6/2.6
- $\beta^*_y$ (mm): $\sim$0.27/0.3
- Crossing angle (mrad): 83

$\rightarrow$ Luminosity increase x40
Belle II at SuperKEKB

Belle II up to today: 0.0005 ab$^{-1}$

Belle II goal (50 ab$^{-1}$)
**Electromagnetic calorimeter (ECL):**
CsI(Tl) crystals, waveform sampling

**K_{L} and muon detector (KLM):**
- Resistive Plate Counters (RPC) (outer barrel)
- Scintillator + WLSF + MPPC (endcaps, inner barrel)

**Magnet:**
1.5 T superconducting

**Vertex detectors (VXD):**
- 2 layer DEPFET pixel detectors (PXD)
- 4 layer double-sided silicon strip detectors (SVD)

**Central drift chamber (CDC):**
- He(50%):C_{2}H_{6} (50%), small cells, fast electronics

**Particle Identification (PID):**
- Time-Of-Propagation counter (TOP) (barrel)
- Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

**Trigger:**
- Hardware: < 30 kHz
- Software: < 10 kHz

**DEPFET:** depleting p-channel field-effect transistor
**WLSF:** wavelength-shifting fiber
**MPPC:** multi-pixel photon counter
Belle II Calorimeter (ECL)

- 8736 crystals
- \( \sim 5 \times 5 \times 30 \text{ cm}^3 \text{ CsI(Tl)} \rightarrow 16.1 \ X_0 \)
- Crystals, photodiodes and preamplifiers reused from Belle experiment
- New shapers and digitizers/FPGAs
Signal processing: Belle and Belle II

Shaper output ($\tau=0.5\,\mu s$)

Gate width ($\Delta t=100\,\text{ns}$)

Signal charge

Charge-to-time converter (QTC)

Digitizer (TDC)

Amplitude

Shaper output ($\tau=1.0\,\mu s$)

Gate width ($\Delta t=100\,\text{ns}$)

Signal charge

Charge-to-time converter (QTC)

Digitizer (TDC)

Amplitude

Waveform Digitizer, 1.76 MHz, 18 bit

FPGA fits to extract Amplitude and Time
Calorimeter tasks at Belle II

**Multiple detectors:**
- Track-cluster matching
- Electron ID

**Calorimeter basics:**
- Photon energy and position (30 MeV - 7 GeV)
- Neutral trigger (L1 and HLT)
- Online luminosity

**Advanced:**
- "Extra energy" (hermeticity at an e+e- collider)
- Hadron ID
- Pulse-shape discrimination
- Low $p_t$ muon identification
Calorimeter challenges at Belle II

- Higher beam backgrounds
- More demanding analyses
- Higher collision rates
  (= tighter trigger conditions)
Calorimeter challenges at Belle II: L1 and HLT Trigger

2018

0.5kHz, \(\sigma \approx (5+450) \text{ nb} \)
(no HLT)

2025

10kHz, \(\sigma \approx (5+8) \text{ nb} \)
(after HLT, compare to BaBar: (5+70) nb)

Higher collision rates
(= tighter trigger conditions)

Calibration, low multiplicity events:
Dominated by \(ee \rightarrow ee(\gamma) \) debris
Calorimeter challenges at Belle II: Beam background

Belle II Simulation (2018)

~20 cluster candidates per event

Belle II Simulation (2025)

~100 cluster candidates per event

Higher beam backgrounds
Offline reconstruction flow

Crystal calibration
(time, energy)

Clustering

Seed Finder
Connected Region
Shower splitting

Cluster shapes

Calibration

Leakage Correction
Energy calibration
Tail calibration

Tracking

Track-Cluster Matching

Charged PID

User analysis

Energy
Position
Relation to track(s) and PID information
Cluster shapes (similar to image moments)
Crystal information is not available!
Offline reconstruction in pictures
Offline reconstruction

For the case of the large pile-up noise the Belle algorithm for cluster reconstruction is not optimal. Belle 1: sum of the energy $E_i$ in a 5x5 matrix $E_i > 0.5$ MeV. Other approach: Sum of $N$ most energetic hits, $N$ depends on energy and background.

To get the photon energy: cluster energy is corrected by a function depending on energy, angles, and the background level.

Background level is estimated from multiplicity off time events.

Measured per event

- BGx1.0
- BGx0.5
- BGx0.1
- BGx0

#crystals in energy sums

![Graph showing photon energy resolution as a function of true photon energy for different backgrounds.](arXiv:1808.10567 [hep-ex])

The likelihood selectors rely on likelihood ratios constructed in the following way. First, the PID log likelihoods from each detector are summed to create a combined PID likelihood for each of six long-lived charged particle hypotheses: electron, muon, pion, kaon, proton, and deuteron. Next, the difference in log likelihood between two particle hypotheses is used to construct a PID value $L_{\text{diff}}(\rho)$ according to:

$$L_{\text{diff}}(\rho) = \frac{1}{1 + e^{\ln L_{\text{diff}} \ln L_{\text{true}}}} = Q_{\text{det}} L_{\text{diff}}(\rho) + Q_{\text{det}} L_{\text{true}},$$

where $\rho$ and $\rho'$ represent two different particle types and the product is over the active detectors for the PID type of interest. The value $L_{\text{diff}}(\rho)$ is greater than 0.5 for a charged track that more closely resembles a particle of type $\rho'$ than one of type $\rho$ and is less than 0.5 otherwise. More details on the PID types are given in the following sections.
Performance: $\pi^0$

**FIG. 1:** This figure shows the invariant mass distribution of $\pi^0$! in 5 pb$^{-1}$ of collision data. Events are required to contain at least three good tracks to purity the sample with processes of the type $e^+e^-$! to hadrons, while rejecting beam induced background, Bhabha scattering, and other low multiplicity background sources. The photon daughters of the $\pi^0$ candidates are required to have an energy of greater than 150 MeV, and to be within the acceptance of the Central Drift Chamber (CDC). The internal document reference is BELLE2-NOTE-PH-2018-002.

**FIG. 2:** A peak at about 542 MeV/c$^2$ is visible.

$\int L \, dt = \sim 5$ pb$^{-1}$

$E_\gamma > 0.15$ GeV

Few days after the start of data taking.

BELLE2-NOTE-PL-2018-009
Offline reconstruction flow

Crystal calibration
(time, energy)

Clustering

Seed Finder

Connected Region

Shower splitting

Leakage Correction

Energy calibration

Tail calibration

Calibration

Cluster shapes

Track-Cluster Matching

Charged Particle Identification

User analysis

Energy
Position
Relation to track(s)
Cluster shapes (similar to image moments)
Crystal information is not available!
Pulse-Shape Discrimination (PSD)

- Online FPGA waveform fits use photon templates only and provide time and amplitude fit results (2 variables)

- New: Exploit the fact that hadronic and electromagnetic scintillation components are different
  - If crystal energy $E > 30$ MeV: Store waveform data (31 variables) and repeat fit offline with different templates.

- Third information from a crystal: PSD

S. Longo, ICHEP2018
Pulse-Shape Discrimination (PSD)

- First time pulse shape discrimination (PSD) is used in an $e^+e^-$ collider experiment
- New variable based on a BDT trained (on MC) to separate photons and K$_0^L$ using all pulse shapes in a cluster
- Will be included in charged particle identification to improve muon vs. pion separation
Low $p_t$ Particle Identification plans: Muon vs Pion

- Particles with low transverse momentum ($p_t < 0.5$ GeV/c) do not reach our muon system:
  - Baseline particle identification depends on $E/p$ and is very poor
  - Clustering itself difficult, since these particles leave long, charge dependent, trails in the calorimeter
Low $p_t$ Particle Identification plans

- Approach under study:
  - No clustering
  - Extrapolate tracks to calorimeter
  - Analyse 5×5 pixel calorimeter images around impact crystal using convolutional networks

**Pions**

**Electrons**

**Muons**

Belle II Simulation (work in progress)
Summary

- Belle II is starting physics runs in ~7 days
- Calorimeter reconstruction priorities so far: Robust reconstruction, calibration
- Calorimeter reconstruction priorities now: Getting ready for high and varying beam backgrounds, and complex physics analyses
- Bonus: The knowledge of the initial state at an $e^+e^-$ collider and the huge event rate makes this a perfect playground to develop data-driven ML applications
Contact

DESY.
Deutsches Elektronen Synchrotron
www.desy.de

Torben Ferber
torben.ferber@desy.de
ORCID: 0000-0002-6849-0427