Software for TOP detector

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 Belle II collaboration

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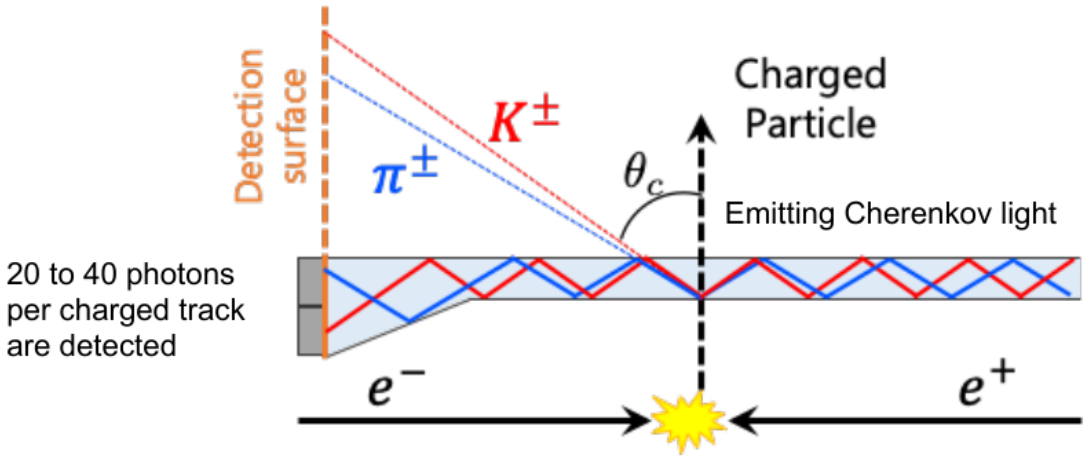
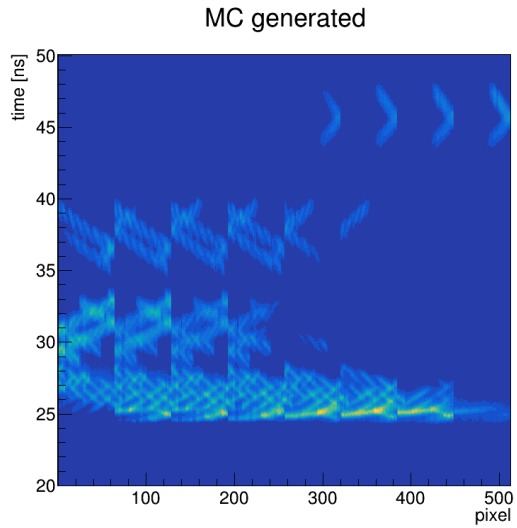
Time-Of-Propagation (TOP) detector

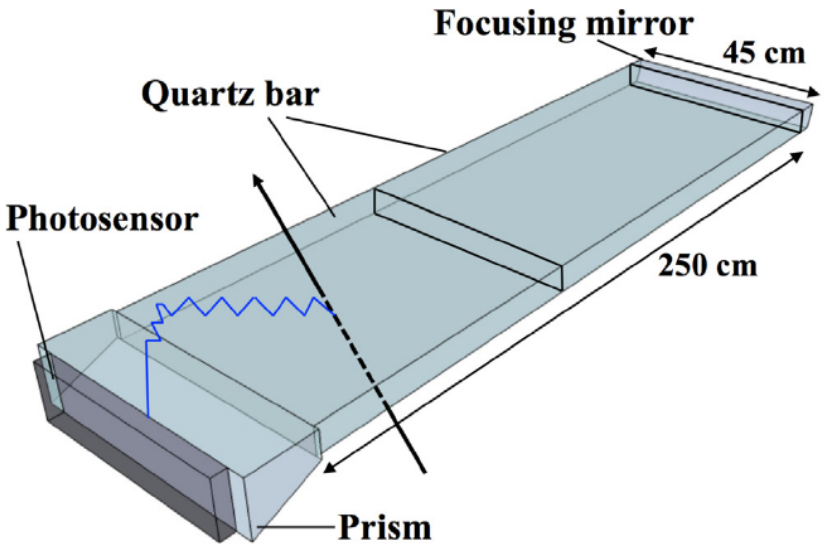
- Novel type of Cherenkov ring imaging detector
- Main hadron ID device in the barrel region of Belle II spectrometer
- Principle of operation
  - Cherenkov photons transported to photon sensors by means of total internal reflections in quartz bar (DIRC principle)
  - Two dimensional information about Cherenkov ring by measuring **time-of-arrival** and **position** of photons at photon sensors.

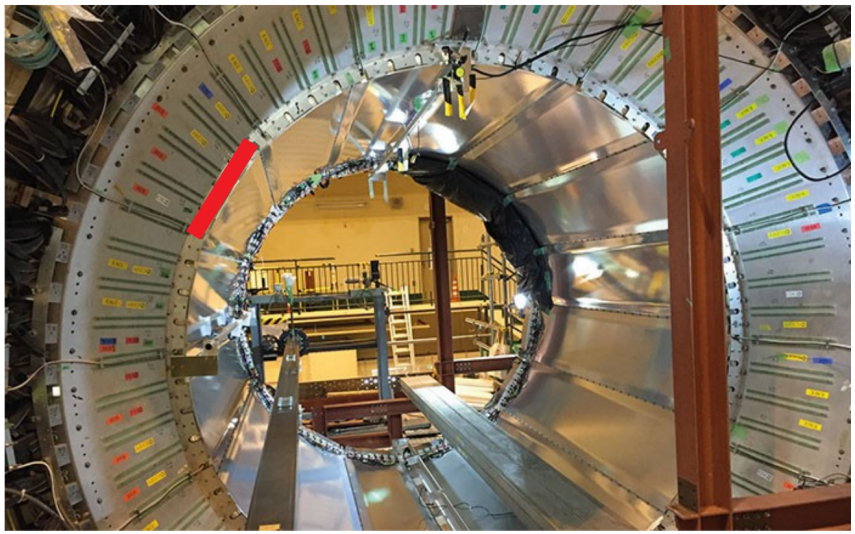




Some design details

- 16 modules at $R = 120$ cm
- Quartz optics of a module
  - 2.6 m long quartz plate, 2 cm $\times$ 45 cm in cross-section
  - spherical mirror at forward side
  - expansion prism at backward side





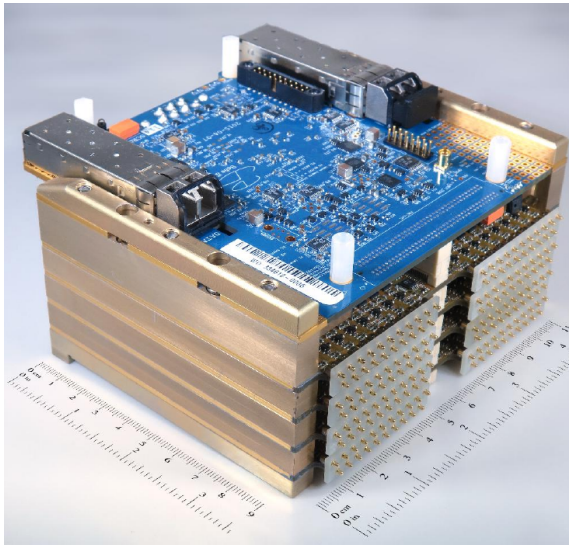
Some design details

- Photon sensors
  - Hamamatsu MCP-PMTs
    - 4×4 channels, 5.5 mm pixel size
    - single photon sensitivity
    - excellent time resolution of 35 ps
    - works in magnetic field
  - 2 rows of 16 PMTs per module (512 pixels)

MCP-PMT

- Front-end electronics
  - waveform sampling with 2.7 Gs/sec
  - analog ring buffer for storing waveforms
  - digitization and feature extraction
  - 8 channels per ASIC
  - 16 ASICs per boardstack (128 channels)
  - 4 boardstacks per module (512 channels)

boardstack



Software

Main ingredients

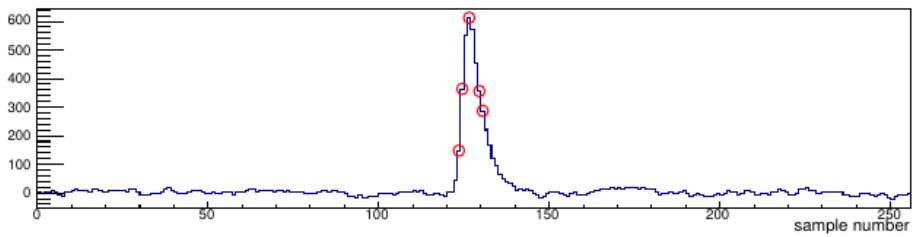
- detector simulation
- reconstruction
- calibration
- online data quality monitoring

Detector simulation

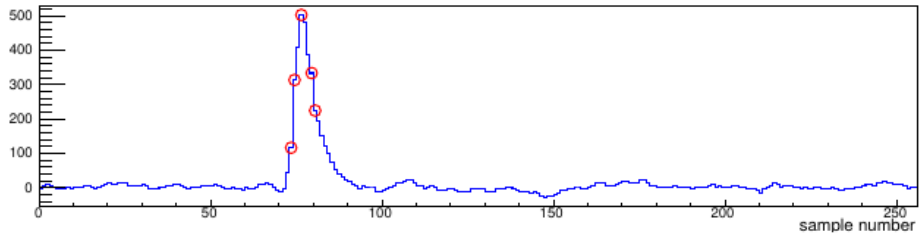
- Geant4 based MC simulation
  - over 3000 physical volumes, 36 materials (10 are optically transparent)
  - propagation of Cherenkov photons done by Geant4
  - quantum and collection efficiencies modeled for each pixel separately according to wavelength-dependent values measured during QA
- Digitization of simulated hits
  - convert position to pixel number
  - generate transit-time spread, t0 jitter and signal amplitude
  - simulate waveform sampling (including electronic noise)
  - perform feature extraction to determine digitized time

  $\rightarrow$ multi-hit; pile-up and electronic time resolution inherently modeled
- Add beam background (samples from delayed Bhabha trigger)

simulated waveform

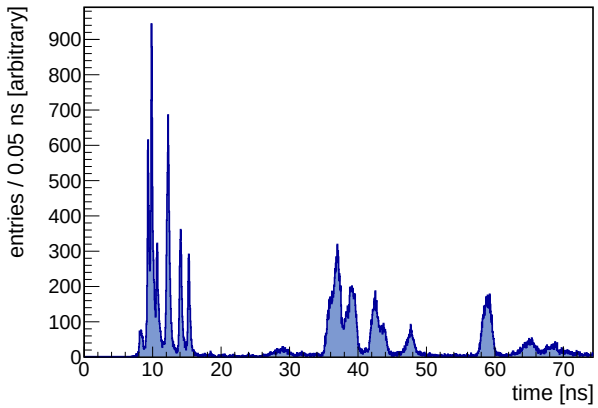


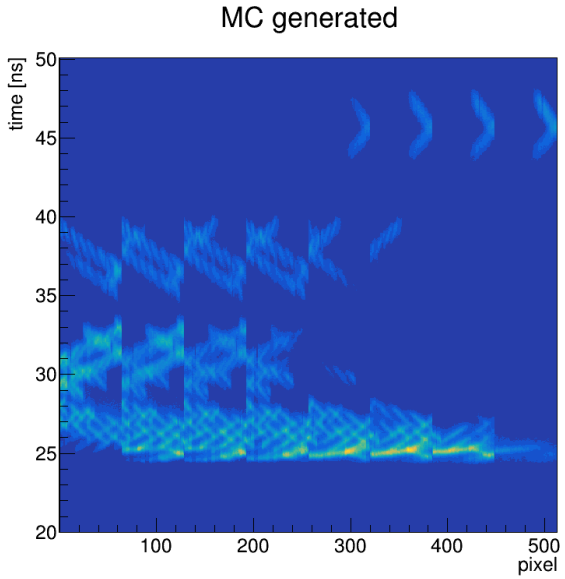
measured waveform

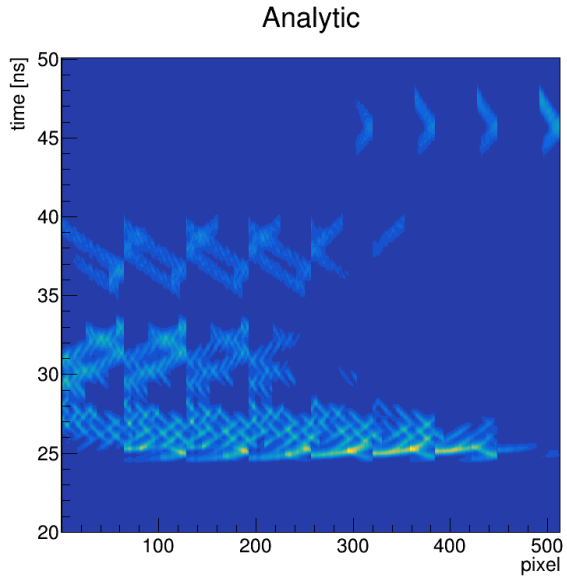


Reconstruction: particle likelihoods

- Computation of likelihoods for six particle hypotheses: e, μ, π, K, p, d
- Based on an analytic construction of PDFs
- Signal PDF in a single pixel described with a sum of Gaussian peaks
  - separate peaks correspond to different numbers of internal reflections
  - positions, widths and normalizations depend on particle impact position and angles, particle momentum and mass







Bunch-crossing reconstruction

- Collision time given by L1 trigger is not precise enough to identify bunch-crossing of the event, which only can provide a sufficiently precise time origin
- Determined off-line using fully reconstructed tracks
- Method relies on maximizing the sum of log likelihoods for a common time offset subtracted from photon arrival times
- The result is rounded to the nearest bunch-crossing time and then used to correct the measured photon times

Detector calibration

Time calibration:

- time-base of wave-sampling electronics
  - double-pulses injected into ASIC channels, precision < 50 ps
- time alignment of channels within module
  - laser pulses injected into a module, precision < 50 ps
- time alignment of modules
  - collision data (dimuon events), precision < 10 ps
- offset to RF clock (common T0)
  - collision data (dimuon events), precision < 10 ps
  - must be done per each run

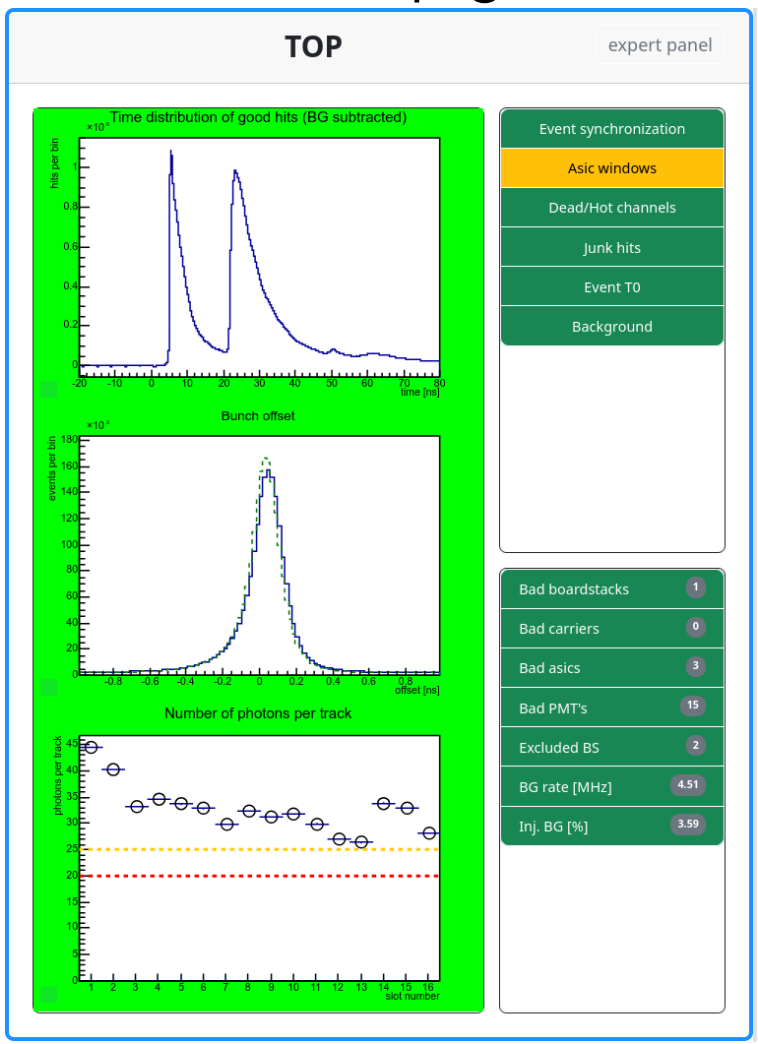
$\rightarrow$ last two based on intermediate results of bunch-crossing reconstruction

Other calibrations with collision data:

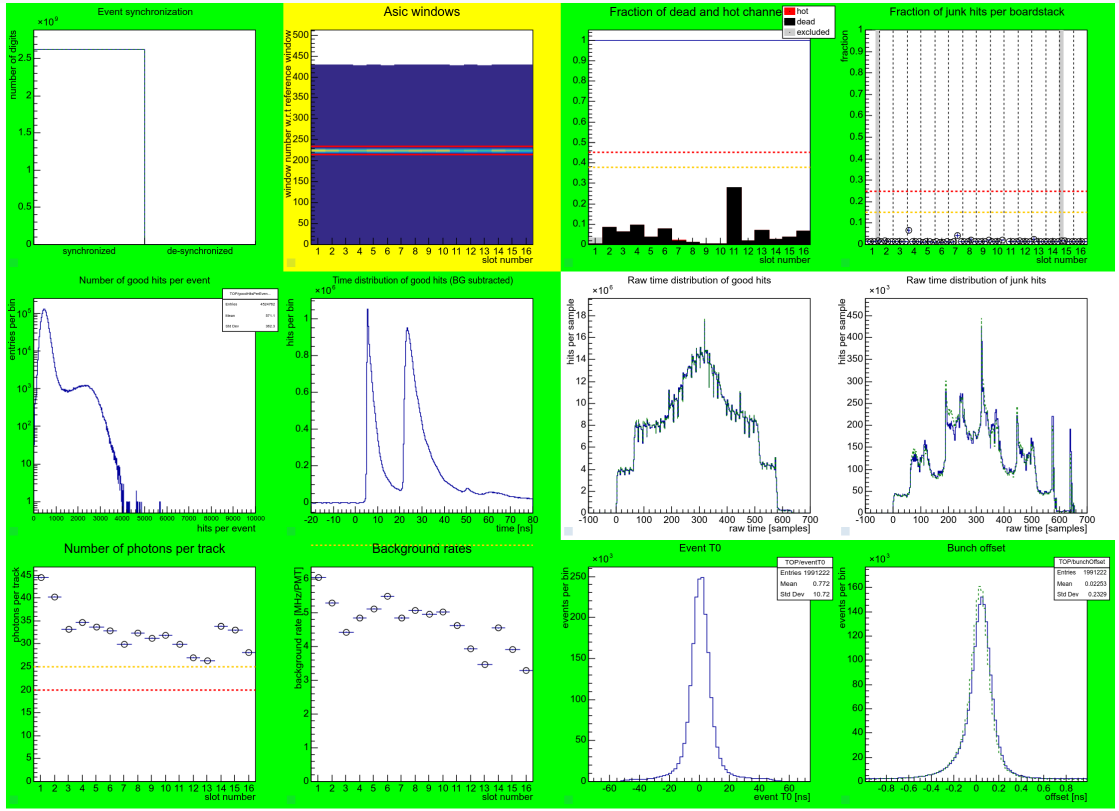
- masks of dead and hot pixels (per run)
- photon detection efficiencies of pixels

Online data quality monitoring

shifter page



expert pages



+ 15 more

credits to Luka who developed a common framework for JSROOT based web display

PID performance

With kinematically tagged pions and kaons from $D^0 \to K^- \pi^+$ decays