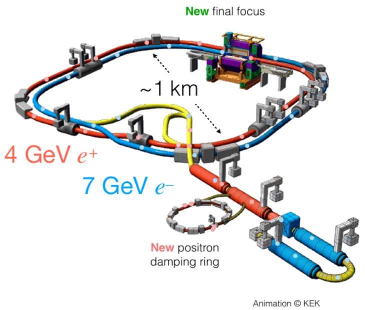
Operation and performance of the Belle II TOP counter

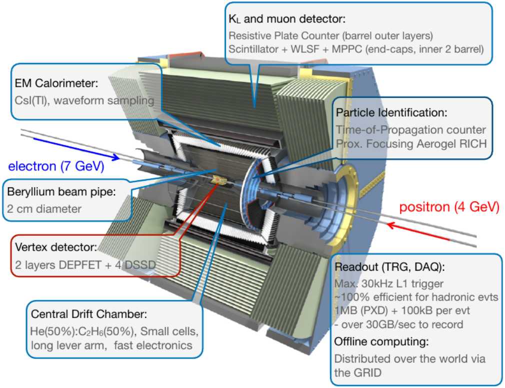
Marko Starič

Belle II collaboration   Jožef Stefan Institute, Ljubljana

RICH 2025

Belle II experiment: 2nd generation "Super B Factory"





SuperKEKB accelerator

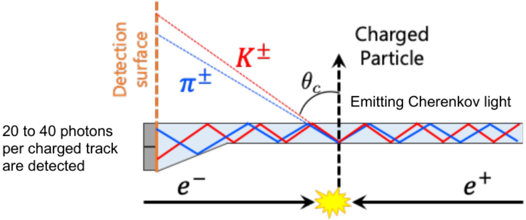
- upgraded KEKB
  $\rightarrow$ nano-beam optics
- target luminosity: 30 $\times$ KEKB

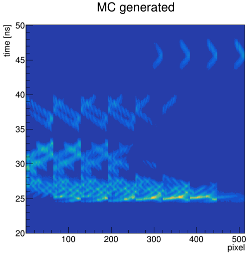
Belle II detector

- general purpose spectrometer
- vertexing, tracking, neutrals detection, PID

Time-of-propagation counter

- TOP counter is the main hadron ID device in the barrel region
- 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.

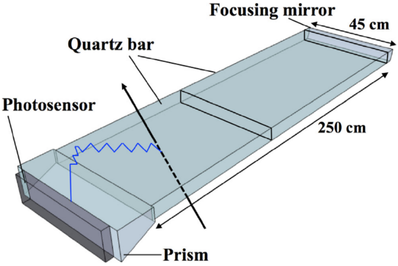


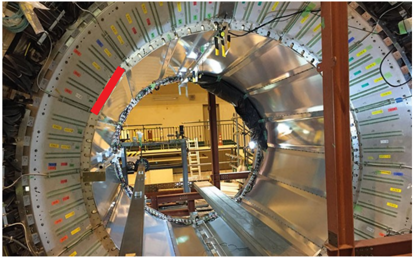


Belle II TOP: some design details

NIM A 1080 (2025) 170627

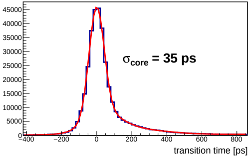
- 16 modules at $R = 120$ cm
- Quartz optics of a module
  - 2.6 m long quartz plate, $2\ \mathrm{cm} \times 45\ \mathrm{cm}$ in cross-section
  - spherical mirror at forward side
  - expansion prism at backward side

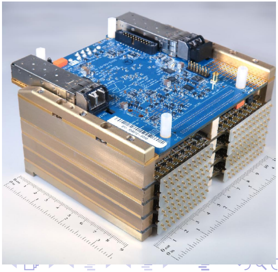




Belle II TOP: some design details

- Photon sensors
  - Hamamatsu MCP-PMT's
    - 4×4 channels, 5.5 mm pixel size
    - single photon sensitivity
    - excellent time resolution
    - works in magnetic field
  - 2 rows of 16 PMT's per module (512 pixels)
- Front-end electronics
  - waveform sampling with 2.7 Gs/sec
    - custom designed ASIC with 12 μs long analog ring buffer for storing waveforms $\rightarrow$ running continuously
  - 8 channels per ASIC
  - 16 ASIC's per boardstack (128 channels)
  - 4 boardstacks per module (512 channels)
  - digitization and feature extraction (50% CFD)
  - data sent-out by optical link





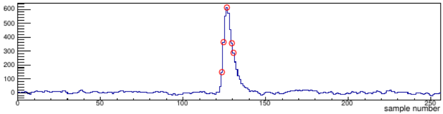
MC simulation

- MC simulation at Belle II based on Geant4
- Geometry of TOP
  - over 3000 physical volumes
  - 36 materials (10 are optically transparent)
- Quartz optics of each module composed of two box-shaped quartz segments, mirror segment and prism
  - all constructed with dimensions measured prior to installation
  - refractive index from specs of Corning HPFS 7980 (Sellmeier eq.)
  - glue joints, wavelength filter and silicone cookies also included
- Propagation of Cherenkov photons is done by Geant4
  - boundary process includes modeling of quartz surface roughness
- Each MCP-PMT is a separate volume consisting of body walls, an equivalent MCP material volume, an entrance window and a thin photo cathode as a sensitive volume
- Quantum and collection efficiencies modeled for each pixel separately
  - according to wavelength-dependent values measured during QA

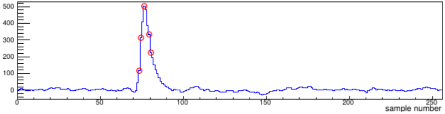
Digitization

- List of simulated hits (position, time) fed into digitizer
  - converts position into pixel number
  - generates transit-time spread and t0 jitter (6 mm bunch $\rightarrow$ 14 ps rms)
  - simulates waveform sampling
- For each hitted pixel waveform of 512 samples ($\sim$190 ns) constructed
  - for each simulated hit in the pixel
    - amplitude generated according to measured distribution for this pixel
    - signal pulse added to waveform (pulse shape from data)
  - electronic noise generated in each sample (r.m.s and BW from data)
- Feature extraction to determine digitized time (50% CF discr.)
  - multi-hit; pile-up and electronic time resolution inherently modeled

simulated waveform

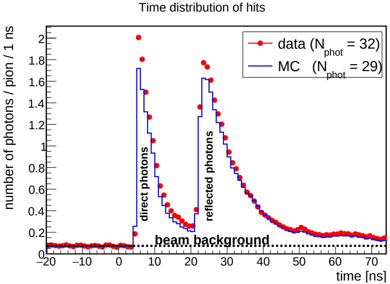


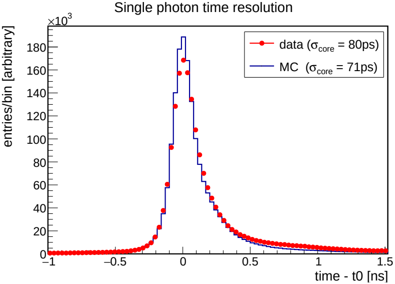
measured waveform



Beam background overlay

- Hits from measured beam background are finally appended to the list of digitized hits
  - beam background samples taken with delayed Bhabha trigger
- Reconstruction steps then follow (same as when processing data)
  - masking of dead/hot pixels
  - determination of bunch-crossing time to set time origin of hits
  - determination of particle likelihoods (NIM A 639 (2011) 252-255)

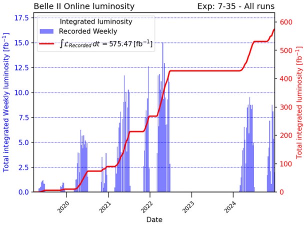




diff. in N_{phot} attributed to ∼30% more δ-rays in data

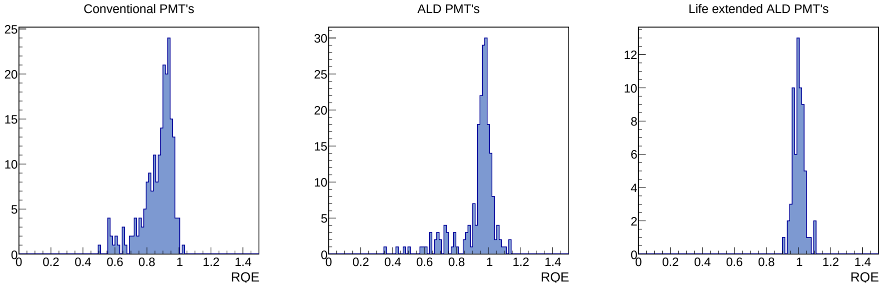
Detector operation

- TOP modules installed in 2016
  - detector inaccessible until 2022
- Data taking started in 2019 (Run 1)
- Long shutdown in 2022-2023 (LS1)
- Data taking resumed in 2024 (Run 2)



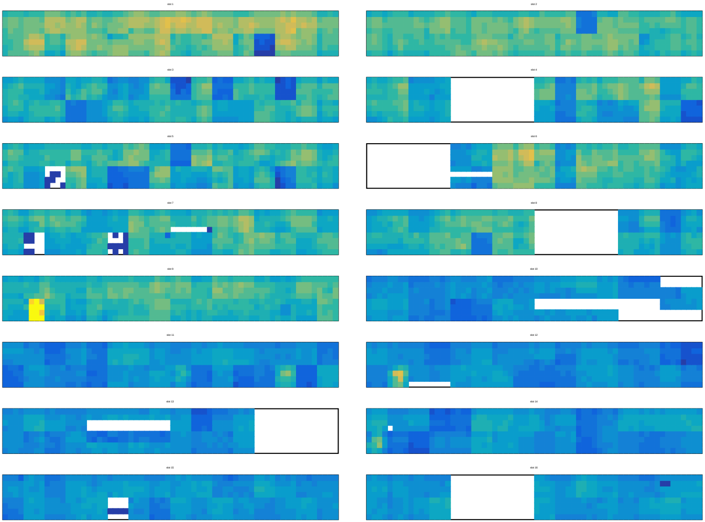
- Overall, the TOP detector has operated robustly, with few issues affecting its performance in Run 1
  - drop in quantum efficiency of conventional-type PMTs
    $\rightarrow$ replaced during LS1 with life-extended ALD-type
  - electronic component failures (various reasons)
    $\rightarrow$ faulty ones replaced during LS1
  - delamination of optical coupling of some PMT's due to magnetic force
    $\rightarrow$ special shim added to prevent PMT rotation

Drop in quantum efficiency



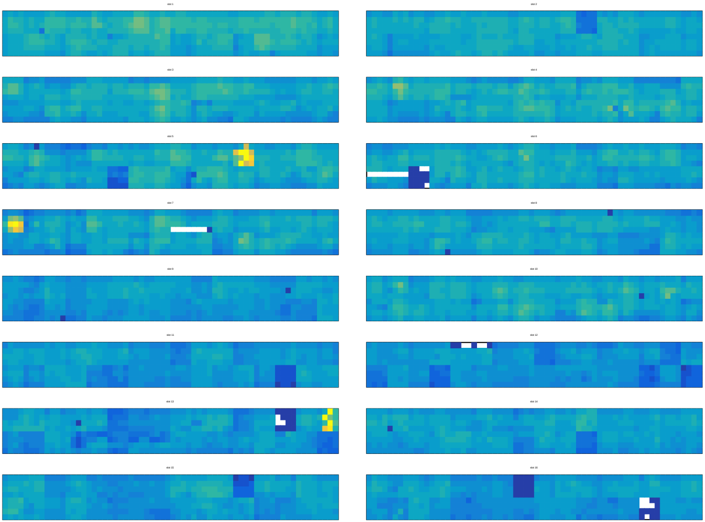
RQE = ratio of N_{phot} for di-muon events measured in April 2022 and Nov. 2020

Pixel hit distributions before LS1



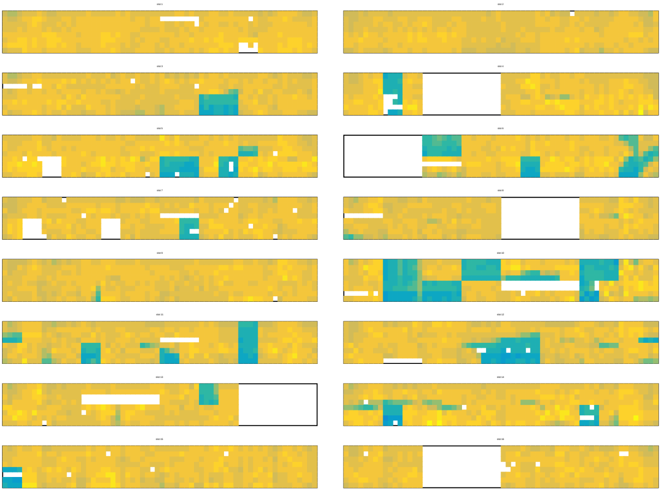
9.7% of faulty electronic channels at the end of Run 1

Pixel hit distributions after LS1



0.3% of faulty electronic channels at begin of Run 2

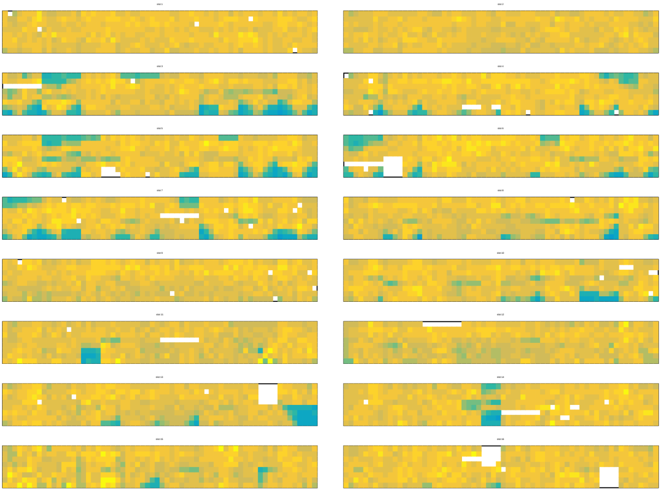
Delamination of optical couplings before LS1



affected surface area: 8.9%

Determined from experimental data → see backup slide for the method

Delamination of optical couplings after LS1

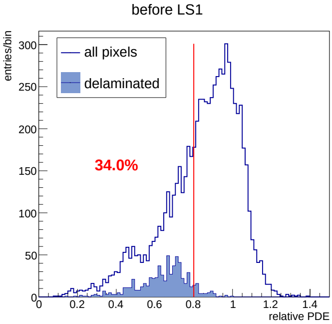


affected surface area: 7.4%

Special shim to prevent PMT rotation not working as expected

Relative PDE

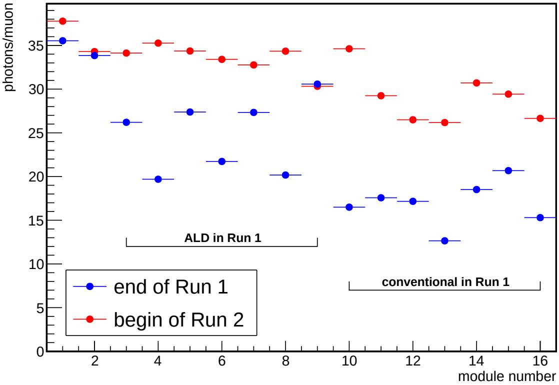
Photon detection efficiency relative to MC simulation



→ ~20% photon loss on delaminated optical coupling

Number of photons

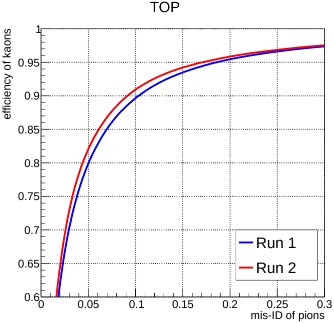
Average number of photons per muon ($e^+e^- \rightarrow \mu^+\mu^-$)

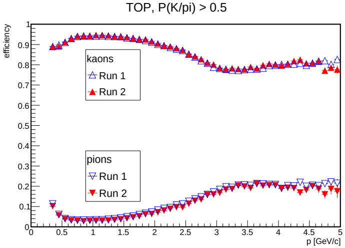


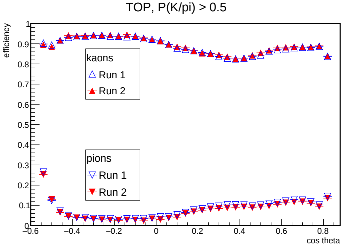
large improvement after PMT and faulty electronics replacements

PID performance: Run 1 vs. Run 2

Measured with K and π from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$





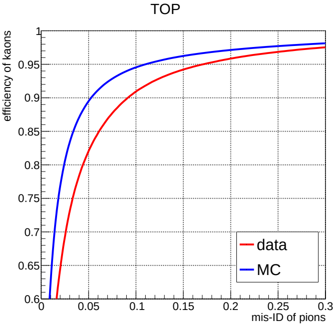


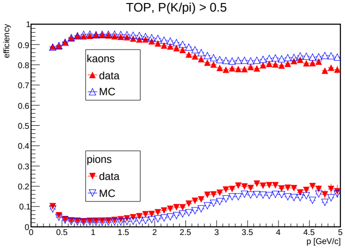
K effi @ 10% π mis-ID	
Run 1	89.6%
Run 2	90.9%

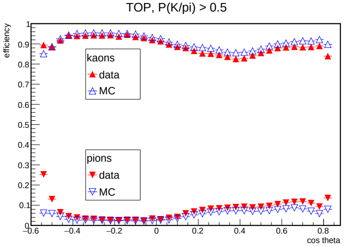
performance improvement in Run 2

PID performance: data vs. MC (Run 2)

Measured with K and π from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$







K effi @ 10% π mis-ID	
data	90.9%
MC	94.5%

discrepancy not fully understood yet

Conclusions

- The Belle II TOP has been operated robustly over past years.
- We observe faster-than-expected aging of conventional type PMT's.
- They have been replaced during LS1 with life-extended ALD ones, as well as some faulty electronic components.
- The detector performance has improved after the replacement.
- We still see a not-well-understood discrepancy in PID performance between data and MC. Investigation continues.

Other presentations (posters)

Performance evaluation in different environments of the MCP-PMT for the TOP counter in the Belle II experiment (R. Komori)

MANTRA: Measuring anti-neutron energy with the TOP counter of Belle II (S. De La Motte)

Backup slide: Measurement of pixel optical couplings

- With di-muon events (clean sample of muons)
- Using s-Plot technique to assign photon to PDF peak (or to background) giving access to photon impact angle α on PMT
- Make ratio of photon counts in $\alpha > 30^0$ and $\alpha < 30^0$ and then make double ratio (data/MC) to equalize the image
  - independent of photon detection efficiency
  - to enhance the effect, muons within $|z_{local}| < 50$ cm are excluded