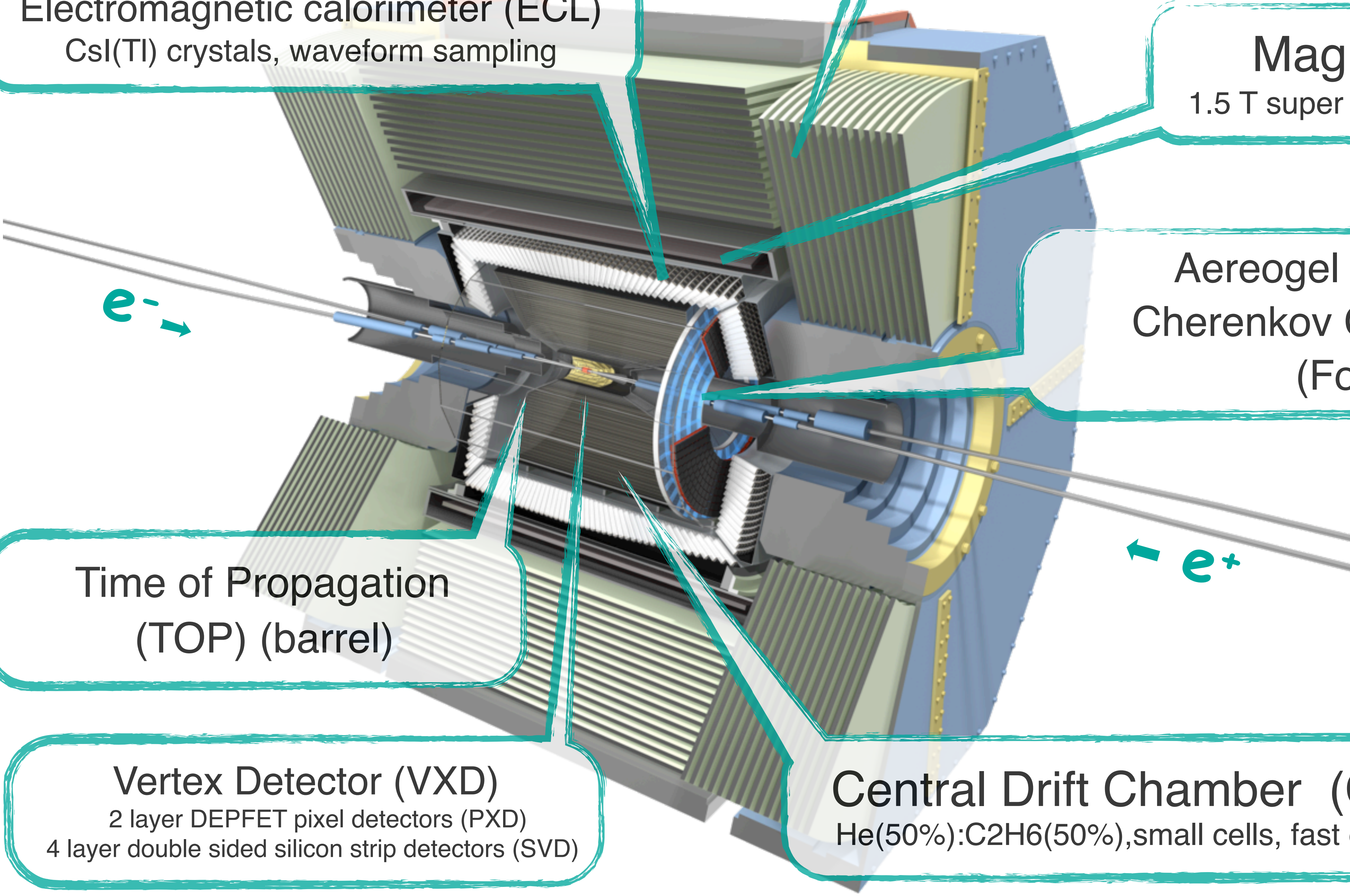
Performance of the TOP detector at Belle-II

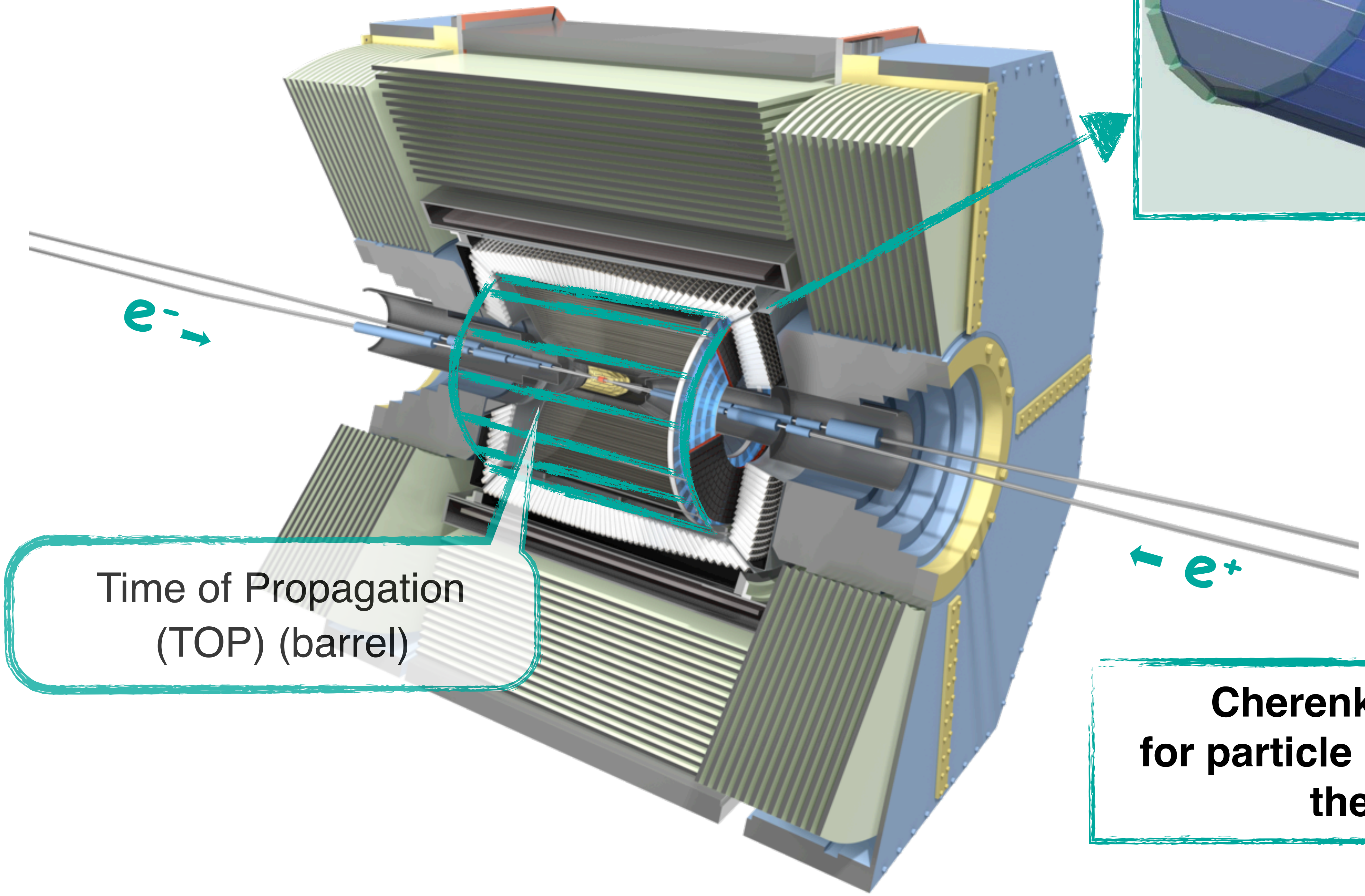
Gian Luca Pinna Angioni
(On behalf of the TOP group in the Belle II collaboration)
INFN and Università degli studi di Torino

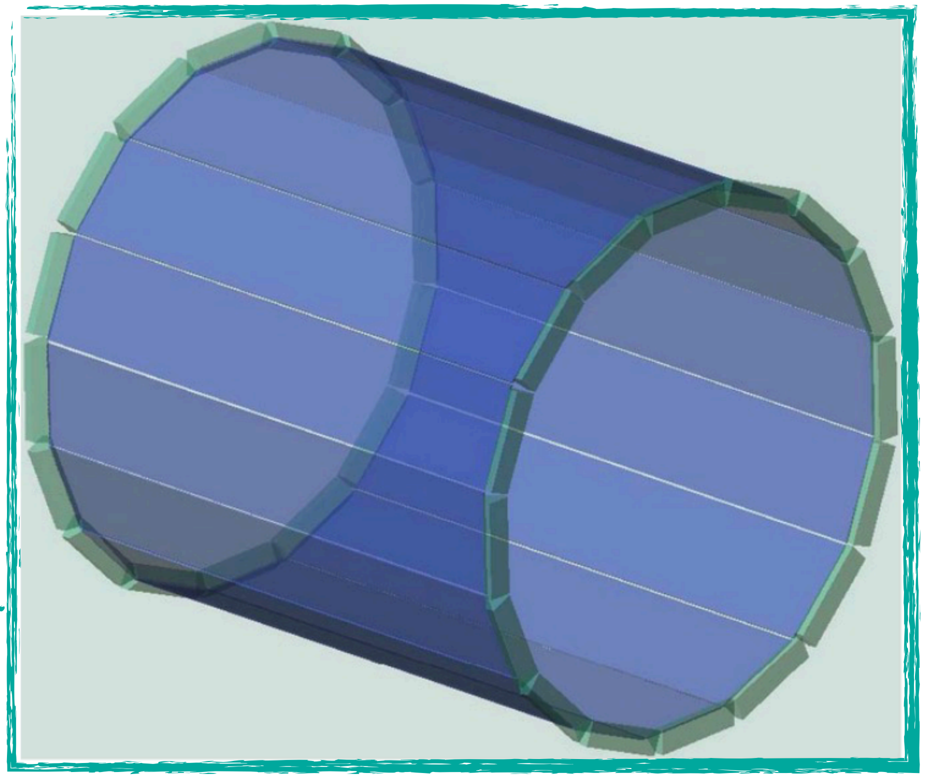
Belle II



K_L and muon detector KLM
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (Endcaps, Inner barrel)
Electromagnetic calorimeter (ECL)
CsI(Tl) crystals, waveform sampling
Magnet
1.5 T super conductive
Aereogel Ring imaging Cherenkov Counter (ARICH) (Forward)
e^-
e^+
Trigger
Hardware < 30 kHz
Software < 10 kHz
Time of Propagation (TOP) (barrel)
Vertex Detector (VXD)
2 layer DEPFET pixel detectors (PXD)
4 layer double sided silicon strip detectors (SVD)
Central Drift Chamber (CDC)
He(50%):C2H6(50%),small cells, fast electronic

Belle II TOP

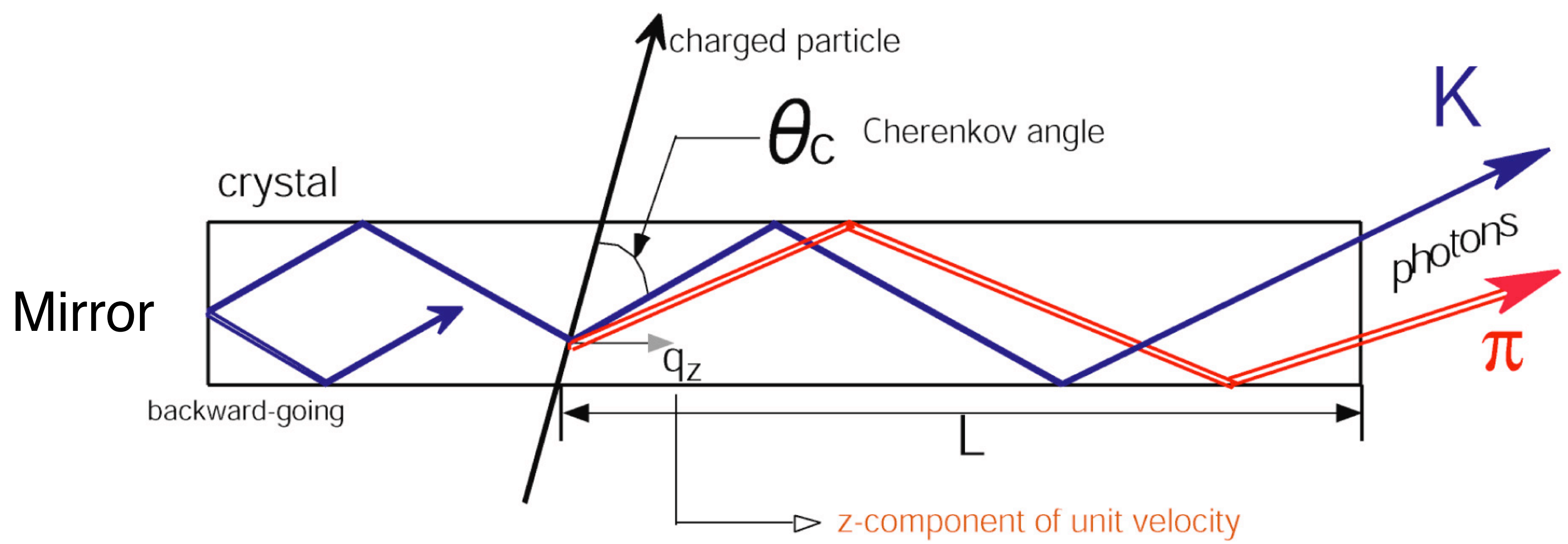




Cherenkov detector for particle identification in the barrel

Time-Of-Propagation (TOP) counter

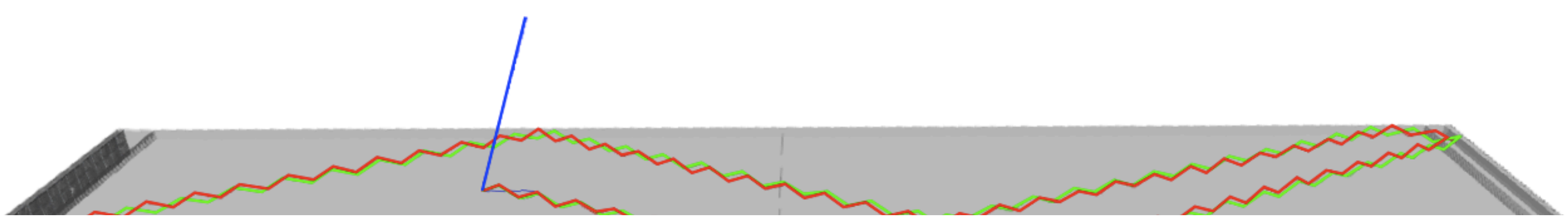
- Emission of Cherenkov light with angle depending on the particle mass and momentum.
  - $\cos(\theta) = \dfrac{1}{n\beta}$
- Photons propagate inside the quartz with total internal reflection
- The Cherenkov image is reconstructed from the 3-d information provided by two coordinates and precise timing



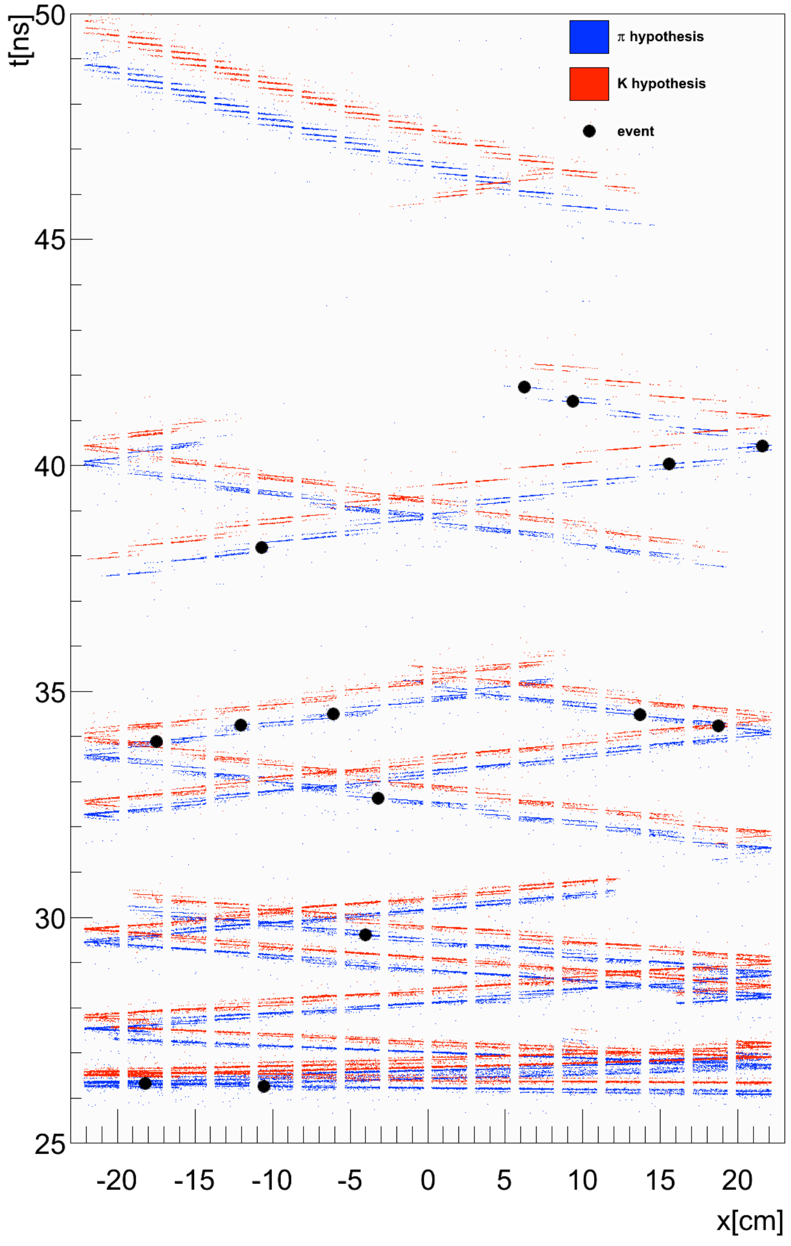
Time-Of-Propagation (TOP) counter

Particle identification PID

- 20-40 photons are typically detected.
- Compare their spatial and time distribution with probability density functions (PDFs) for different particle hypotheses.
  - Likelihood ratio method $\dfrac{L_K}{L_K + L_\pi}$
- Particle momentum and location of the impact point on the quartz bar needed
  - Measured by the Central Drift Chamber.
- Provides a combined measurement of both time of flight and Cherenkov angle
- Need ~100 ps resolution



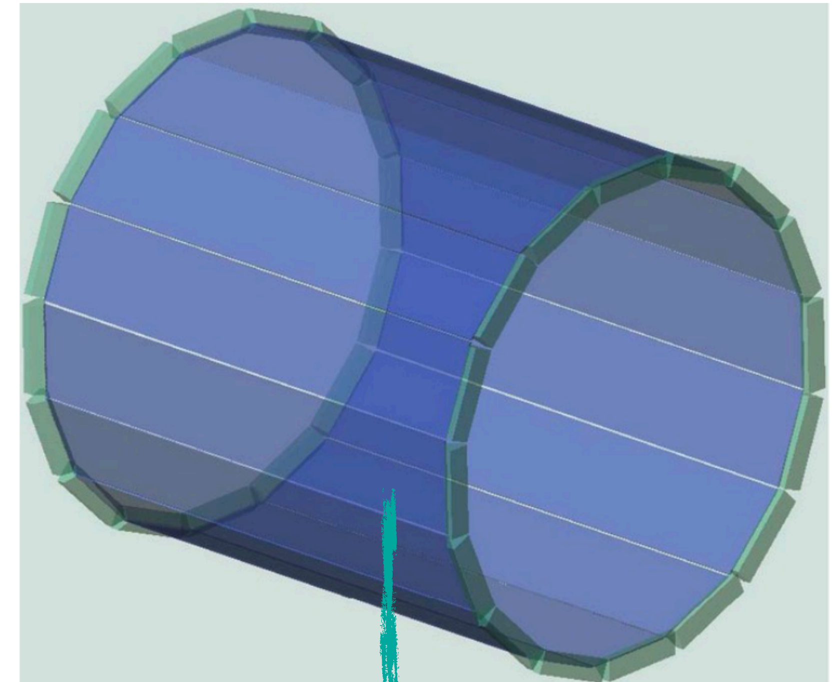
time

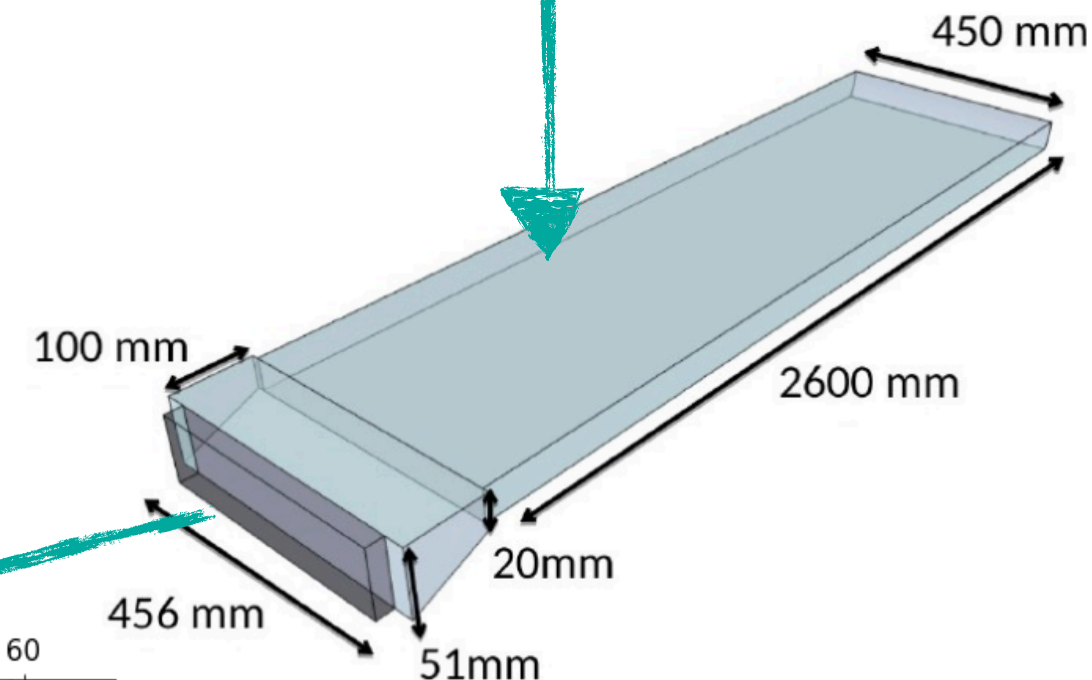


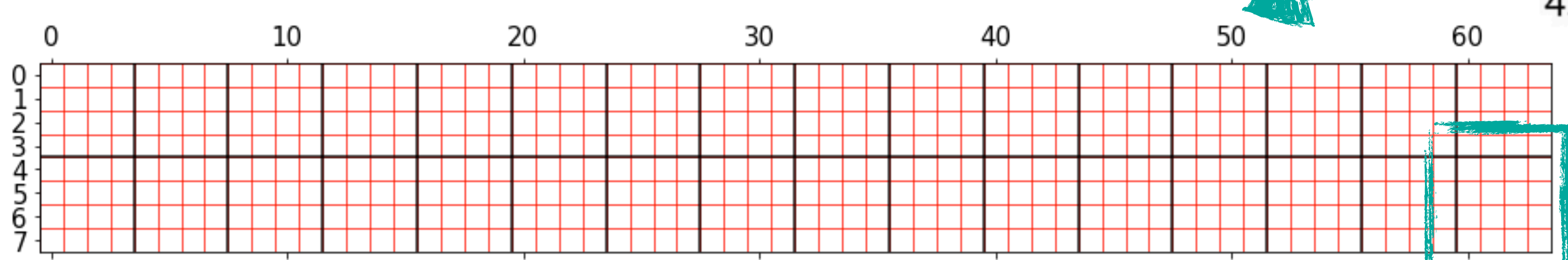
position

TOP detector

- 16 modules at R = 119 cm from interaction point
- Each Module:
  - Quartz bars:
    - 2 × 45 x 260 cm
  - Spherical mirrors in one side
  - Expansion prisms in the other side
  - 32 photon multipliers (512 channels)
    - Micro Channel Plate -PMT
    - 16 channels per MCP-PMT



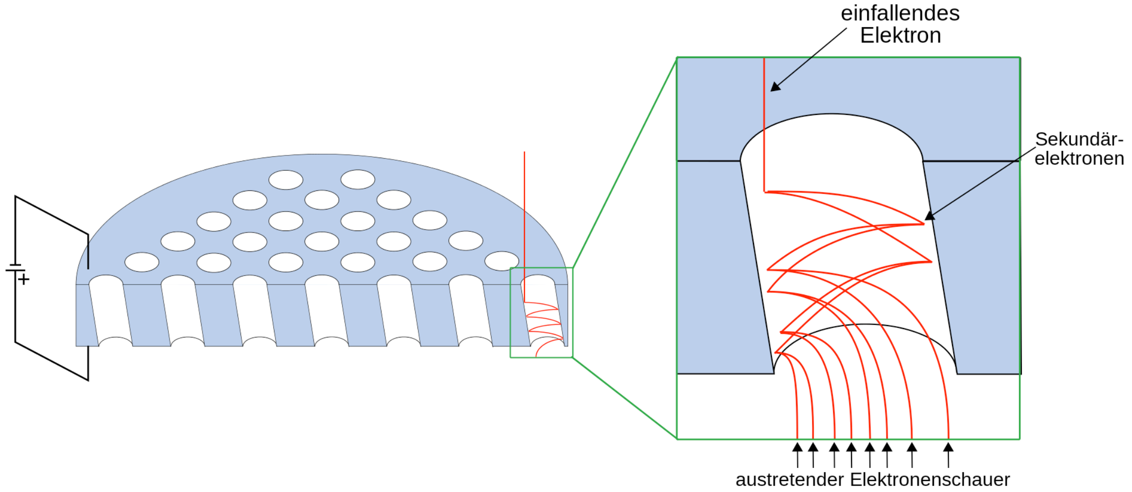


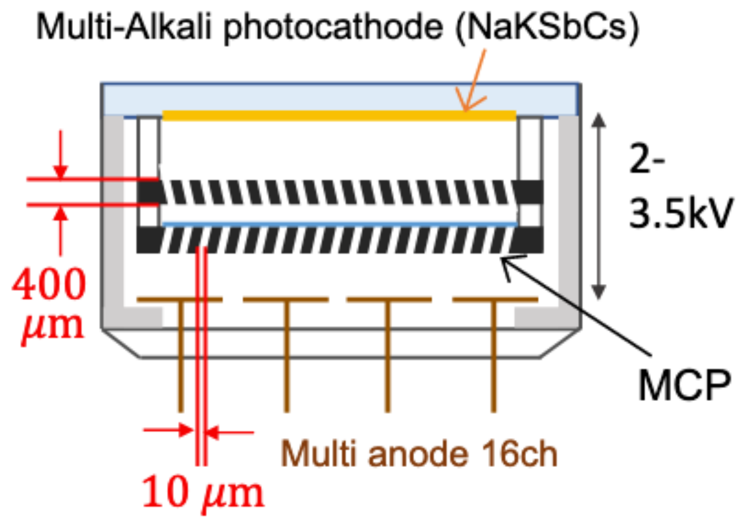


MCP-PMTs arrangement

MCP-PMTs

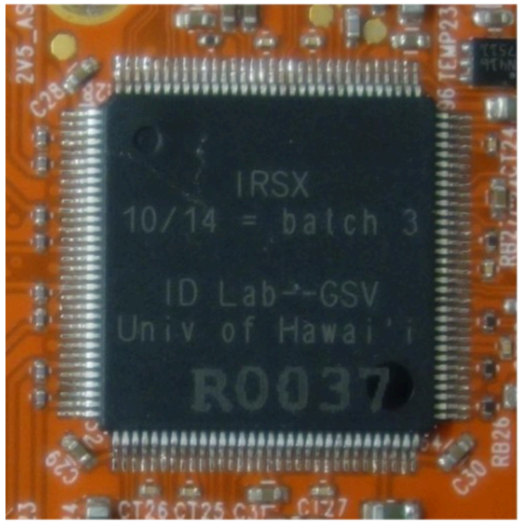
- Micro Channel plates PMTs by Hamamatsu
  - 25 mm x 25 mm
- 10 µm diameter channel
- 2 planes of channels
- Single photon sensitivity
- 34 ps time resolution for single photon detection
  - Thanks to the small transit time spread given by the multiplications short path
- Works in magnetic field (1.5T)
- Quantum efficiency (QE) = 29.3% at the peak wavelength
- Gain = 3.0 × 10^5





Analog signal sampling

- Need a single photon timing resolution of better than 100 ps. How to achieve that?
- Fast wave-form sampling electronics (2.7 Gsamples/s).
- 8 channel ASICs called Ice Ray Sampler version X (**IRSX**)
- Stores waveform in a 11 μs-long analog ring buffer with switching capacitor arrays.
- Information read out and digitised only after global trigger
  - 5 μs latency

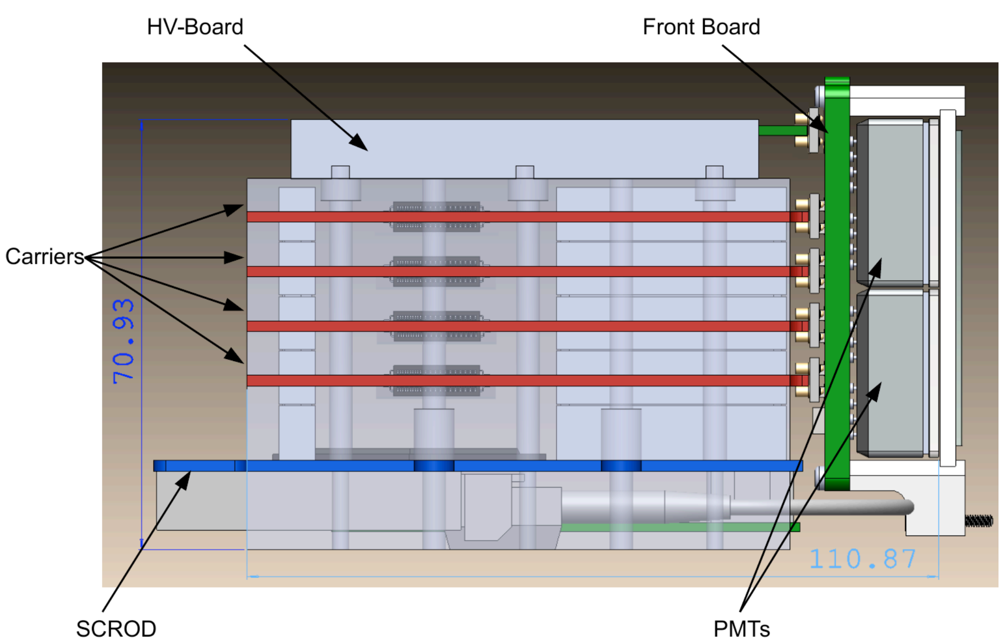


Readout system

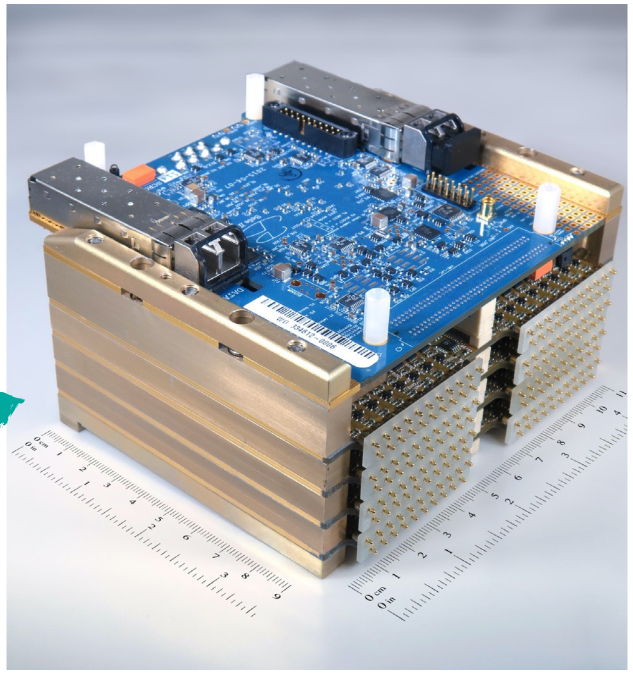
- Recorded waveforms are processed inside the Standard Control Read-Out Data (**SCROD**) board and only the timing and pulse parameters are transferred out of the detector.

1 SLOT → Board stack → Carrier → IRSX

Board stack → SCROD



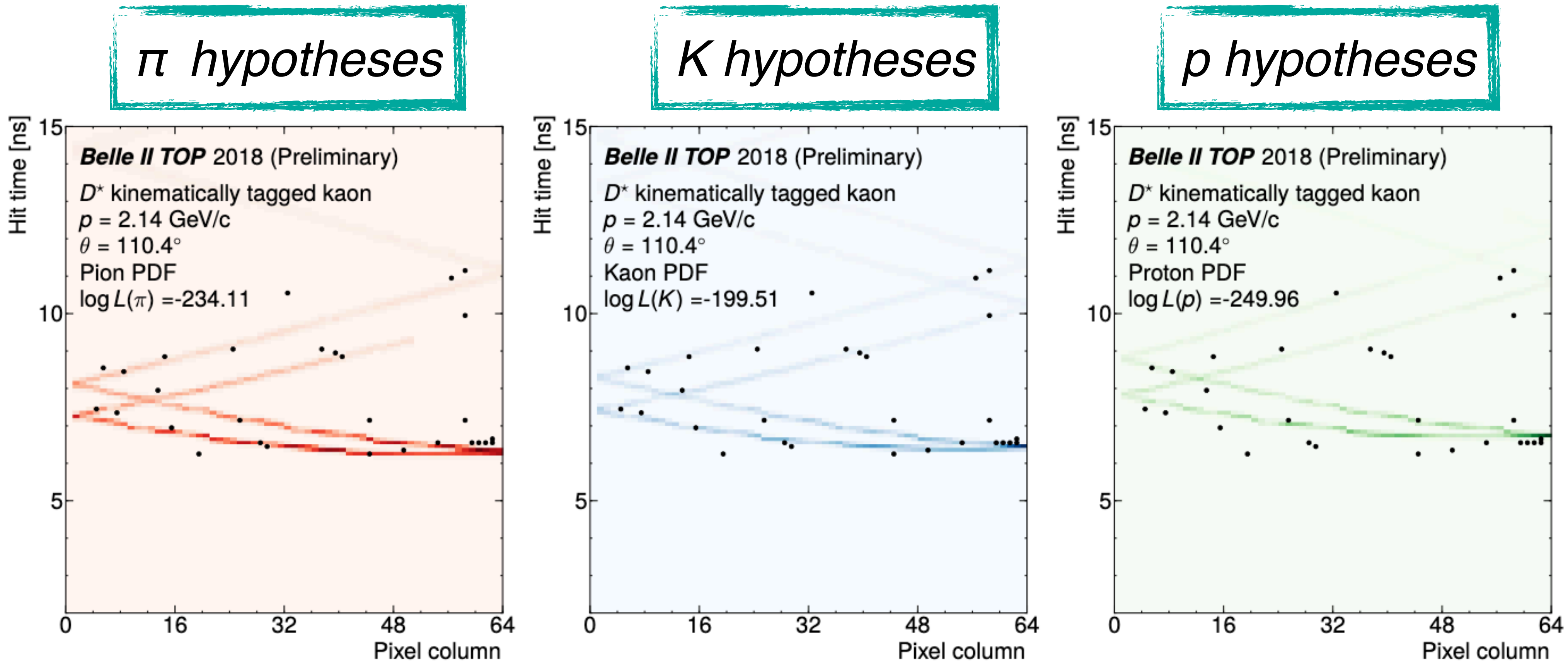
Board stack



Time resolution of 27.6 ps, measured with calibration pulses.

Reconstruction in real data

- 95% pure kaon sample from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+_{slow}$
  - No need of particle identification thanks to the selection
- Channel also used for performance study

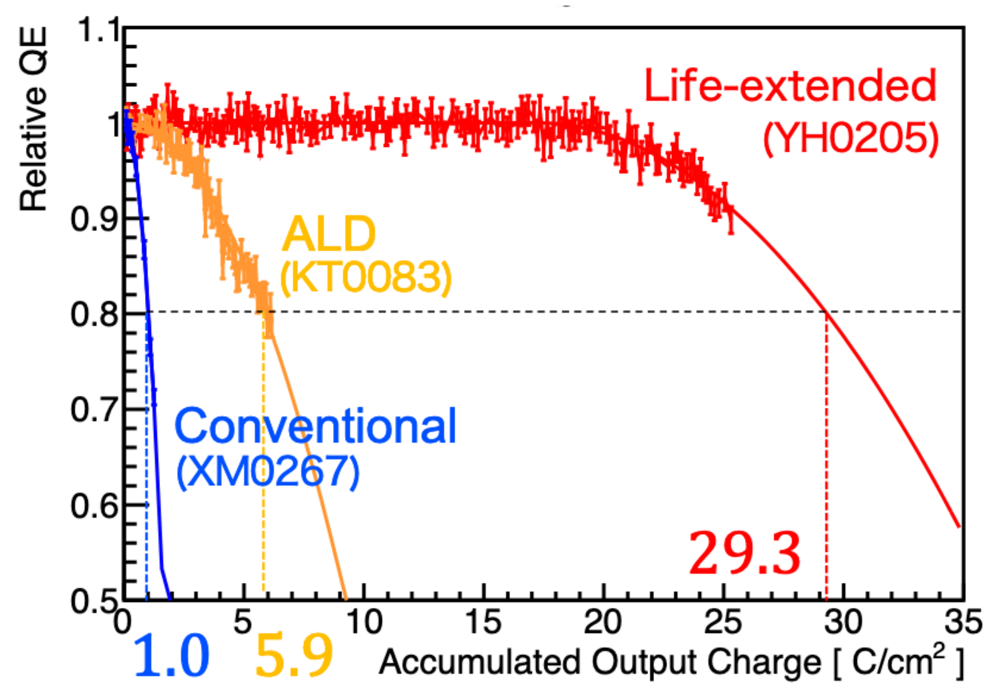


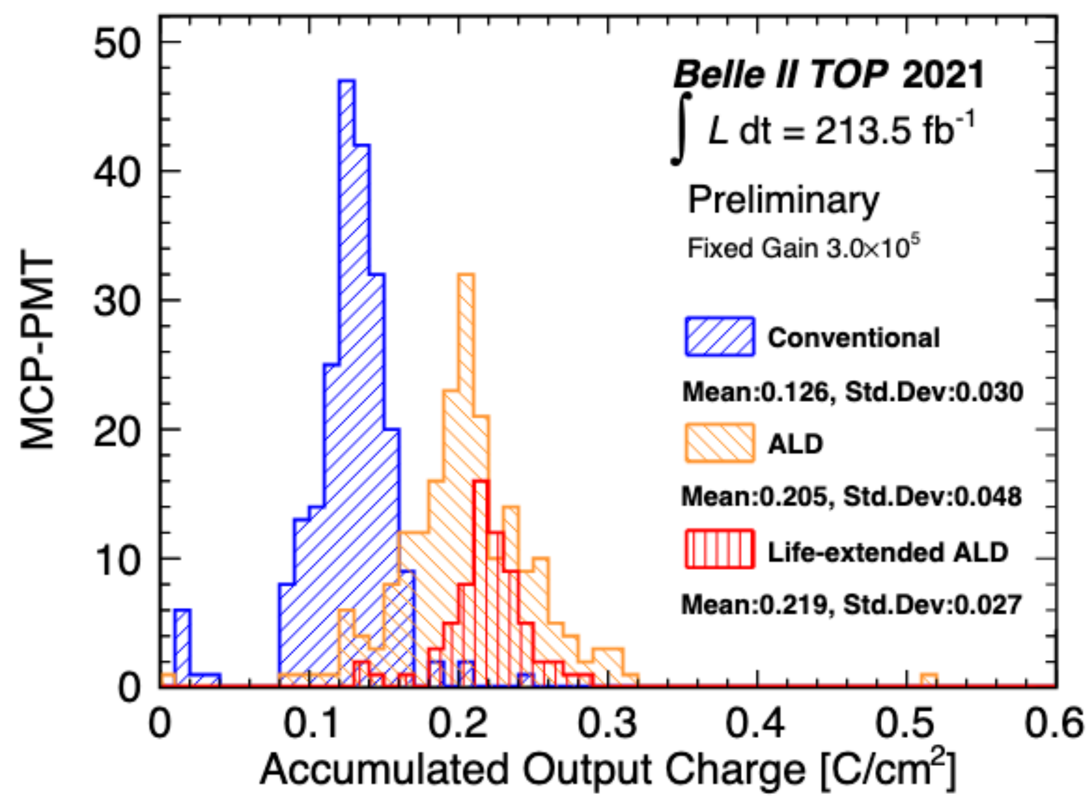
MCP-PMT lifetime 1/2

- Lifetime of the photocathode is a major problem in the high background of Belle II.
- Deterioration by gas and positive ions desorbed from the Micro Channel plates and scattered back to the photocathode.
- MCP-PMT Lifetime (τ_{QE}) defined as the accumulated charge (Σ_Q) needed to decrease 20% original quantum efficiency (QE).
- $$R_{QE} = \frac{QE(\Sigma_Q)}{QE(0)} = 1 - 0.2(\frac{\Sigma_Q}{\tau_{QE}})^2$$
- Expected an accumulated charge >10 C/cm^2 during Belle II lifetime

MCP-PMT lifetime 2/2

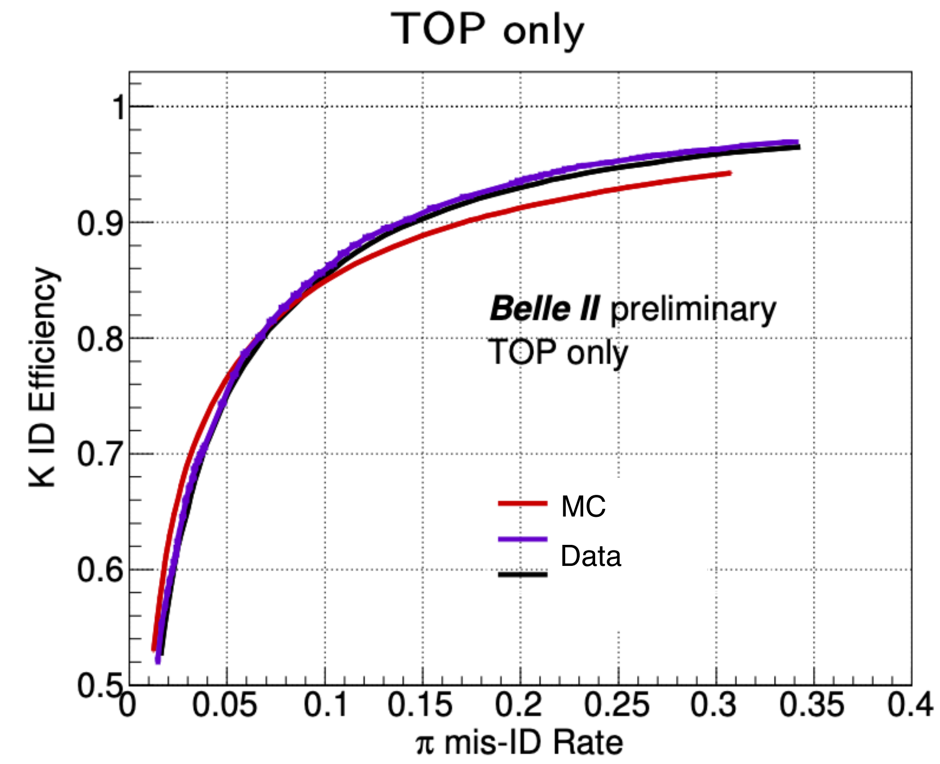
- 3 type of MCP-PMT installed
  - Improvements during mass production
- **Conventional**
  - τ_{QE} = 1.1 C/cm²
  - To be replaced in 2022
- **ALD "Atomic layer deposition"**
  - τ_{QE} = 10.5 C/cm²
  - To be replaced in 2026
- **Life extended ALD**
  - τ_{QE} > 13.6 C/cm²
- big spread on τ_{QE} between same types



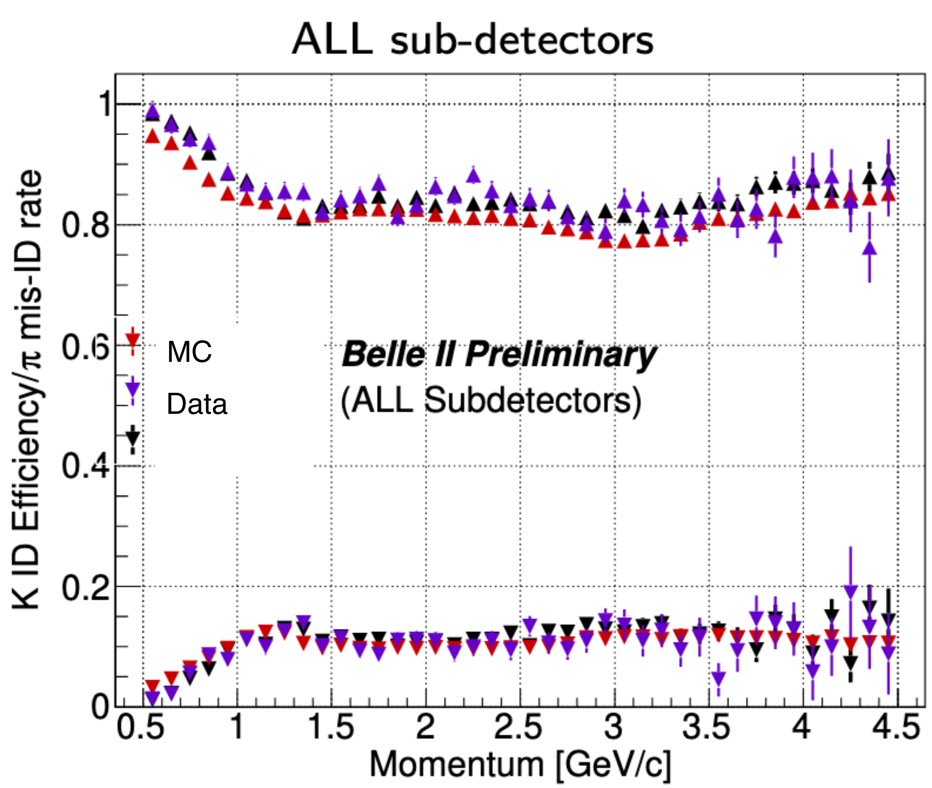


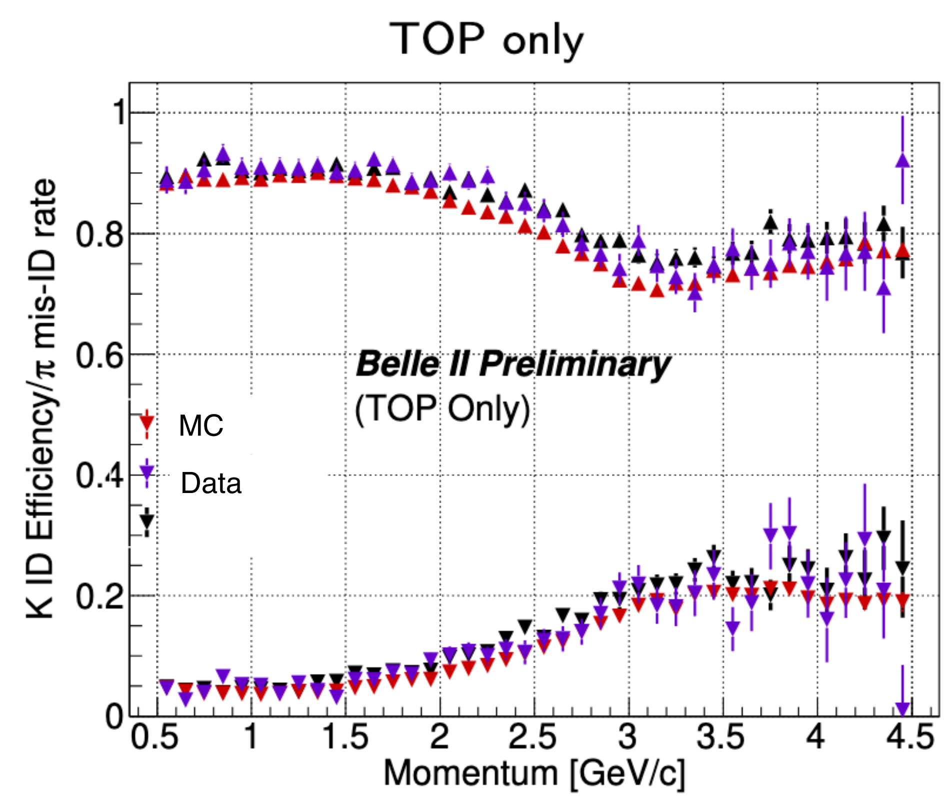
Particle identification performance

- 85% K ID efficiency with 10% π mis ID rate
- Comparison with 2 data-set periods
- Small discrepancy between the data and the Monte Carlo simulation under investigation
- Several studies in progress to improve performance in near future.



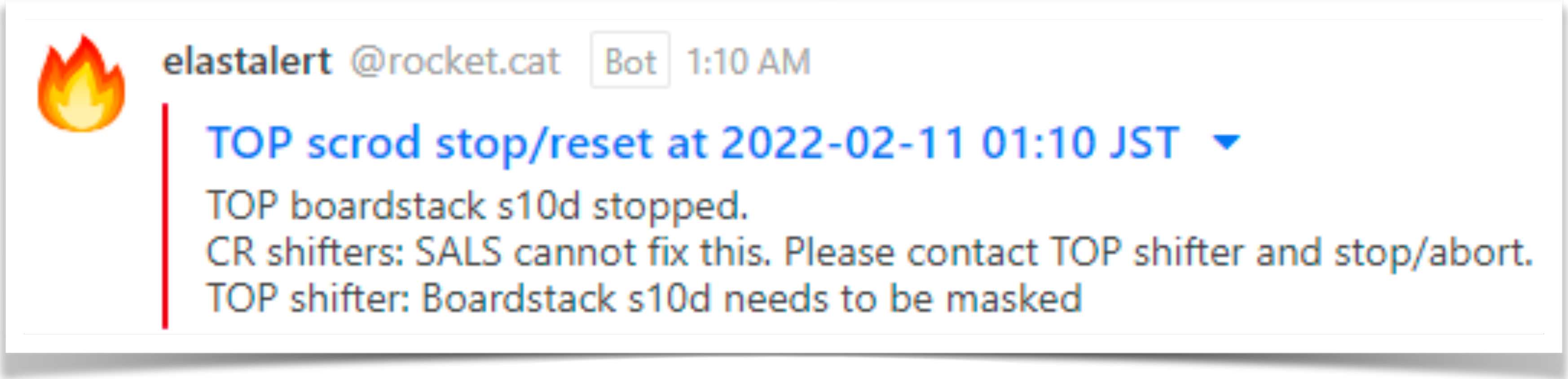
$$\frac{L_K}{L_K + L_\pi} > 0.5$$





Operation Efficiency 2021

- The active channels were 94.4% on average.
  - 7737 channels out of 8192
- Two board stacks were disabled all the time due to a persistent issue.
  - Three board stacks from May 2021
  - To be replaced in 2022 long shutdown.
- Radiation-induced Single Event Upset of the FPGAs on the board stacks cause stops of board stacks that require to be masked
  - Few board stacks per day.
  - Automated detection, masked and recovered by experts



Bot alert message example from working chat

- Running smoothly even with Covid-19 pandemic crisis

Possible upgrade

- Planned to replace the readout electronic.
  - Reduce power consumption
  - Improve readout robustness under high backgrounds
    - Needed for the expected high rates of Single Event Upsets (SEUs)
- MCP-PMTs may not survive until the target integrated luminosity.
  - Two options:
    - Replace all MCP-PMT with life extended ALD
    - Replace all MCP-PMT with SiPMT
      - Pro:
        - Cost, Life-time
      - Con:
        - Cooling needed.
          - Mechanical constraints need to be investigated
        - Increased dark-count
      - R&D needed

Summary

- TOP is a new concept Cherenkov detector type for particle identification that relies on precise timing of individual photons.
- It has been successfully operating since the first collision physics in April 2018
- Concern of the MCP-PMTs use under a high background in terms of the lifetime of the photocathode and the performance degradation.
  - Conventional and ALD types are expected to exceed their lifetime before Belle II lifetime and will be replaced
- Active channels > 94% in 2021.
- PID: 85% K ID efficiency with 10% π mis ID rate
- Knowledge of the detector and PID performance increasing with time
- Upgrade under investigation

Stay tuned