Operation and performance of the Belle II Aerogel RICH detector

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RICH2022

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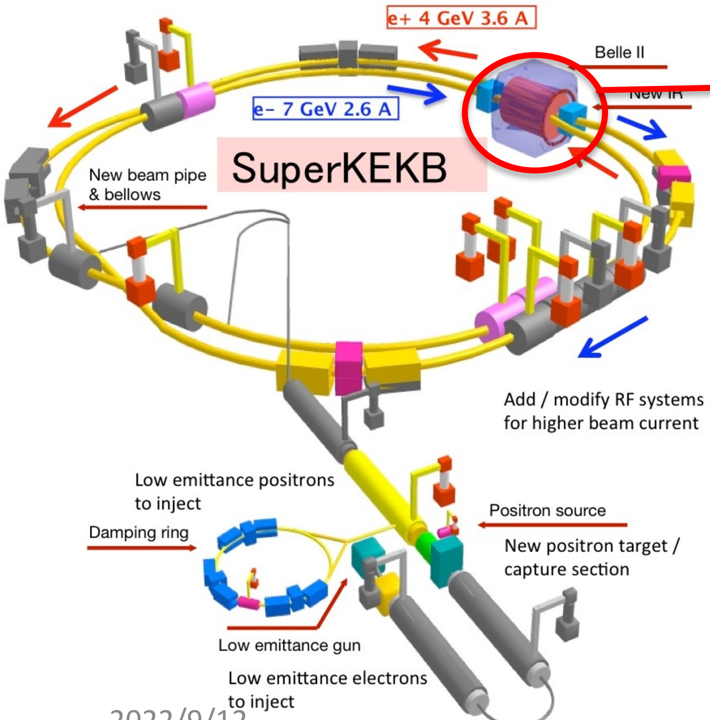
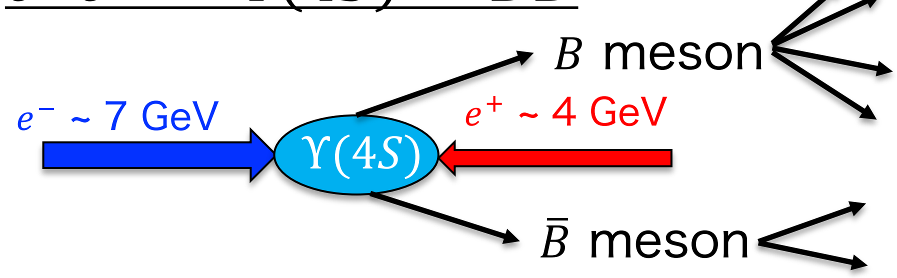
Belle II experiment

Flavor physics experiment to search for new physics

- Asymmetric e^+e^- collider mainly at $\sqrt{s} = 10.58$ GeV
  - Produce B, D, τ, etc..
- Goal: 50 ab^{-1} data in ~10 years
  - 50 × Belle data: $N_{B\bar{B}} \sim 50\times10^9$



$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$



Reconstruct particles by Belle II detector

Belle II operation started in 2019

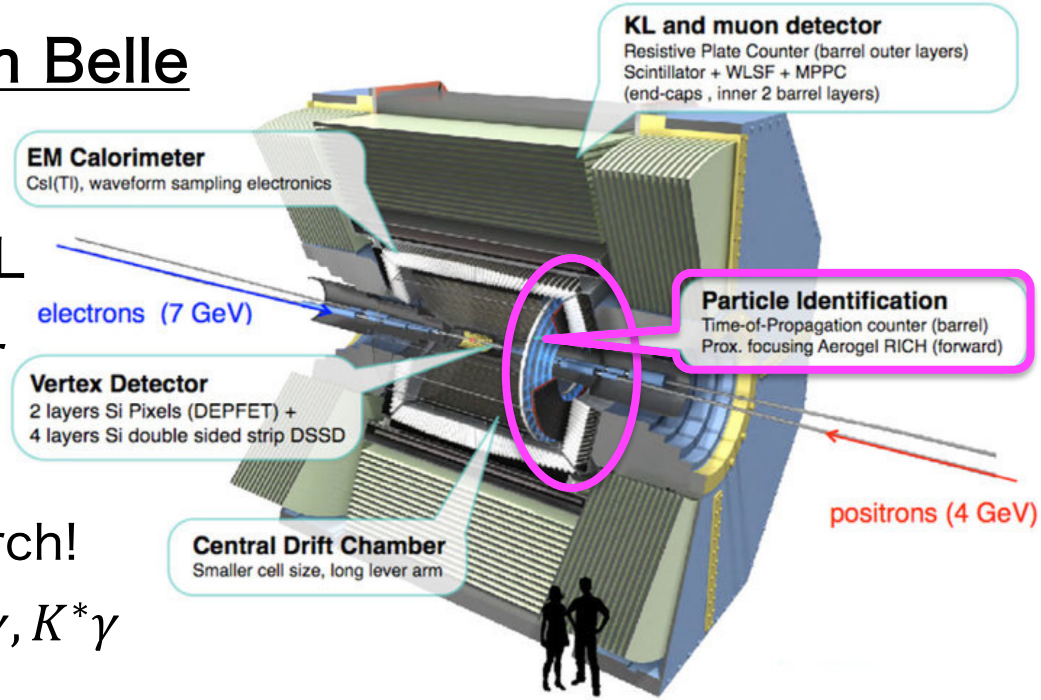
Belle II detector

General-purpose spectrometer

Improve performance from Belle

- Vertex resolution
- Energy measurement in ECL
- New trigger for dark sector
- Particle Identification (PID)
  - Crucial for rare decay search!

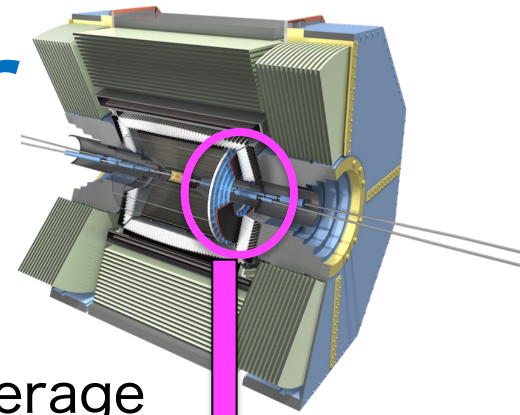
eg. $B \to \rho\gamma, K^{*}\gamma$



Installed two new detectors

- Barrel: Time-of-propagation counter (TOP)
- Forward: Aerogel Ring Imaging Cherenkov Counter (ARICH)

Aerogel RICH detector



PID detector at the forward endcap

- Target: 4σ K/π separation at $0.5 - 4.0$ GeV
- Constrain: limited space (30 cm), large area coverage

→ Adopt proximity-focusing RICH

Emission angle of the Cherenkov photons

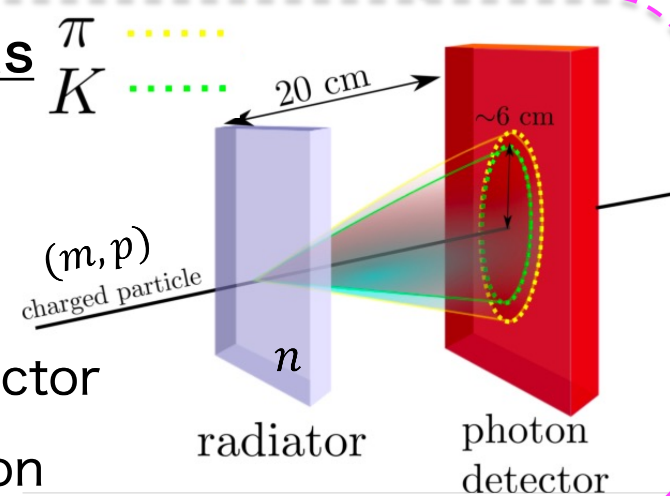
$$cos\theta_c = \frac{1}{\beta n} = \frac{\sqrt{(m/p)^2 + 1}}{n}$$

Cherenkov angle resolution of a track

$$\sigma_{trk} = \frac{\sigma_\theta}{\sqrt{N_{p.e}}}$$

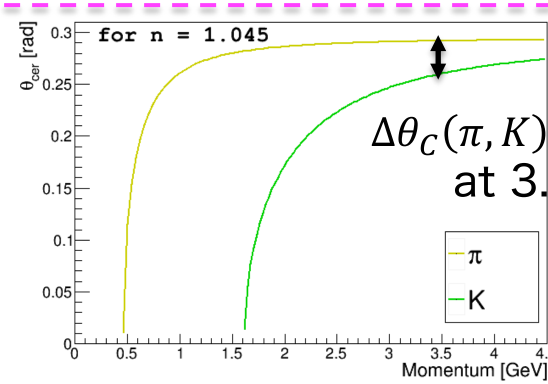
σ_θ: Angle resolution in the detector

$N_{p.e}$: Number of detected photon



Key point

- Design proper refractive index (n)
- Smaller σ_θ and larger $N_{p.e}$



$\Delta\theta_C(\pi, K) \sim 30$ mrad at 3.5 GeV

Aerogel radiator

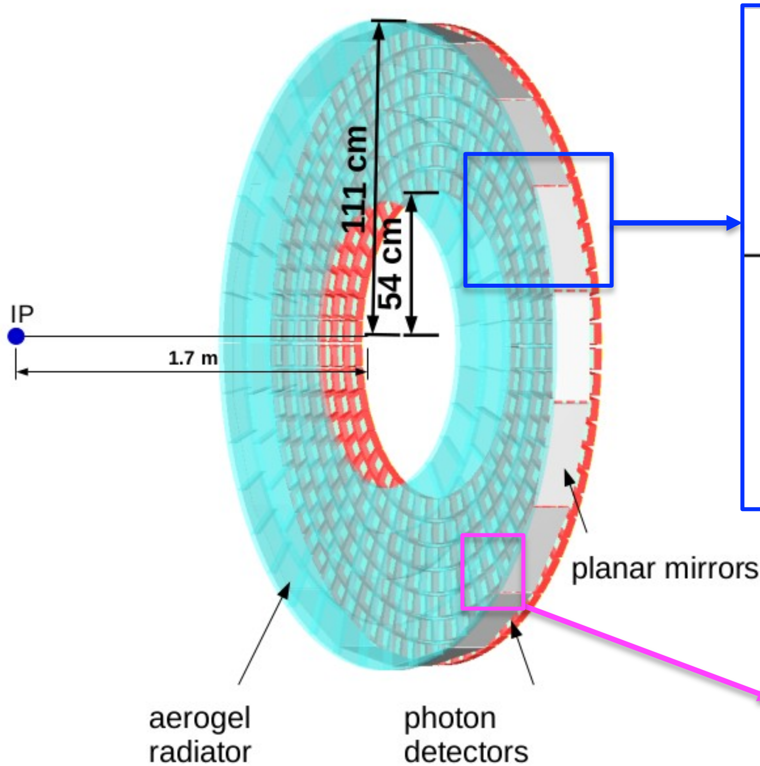
σ_θ: Angle resolution in the detector

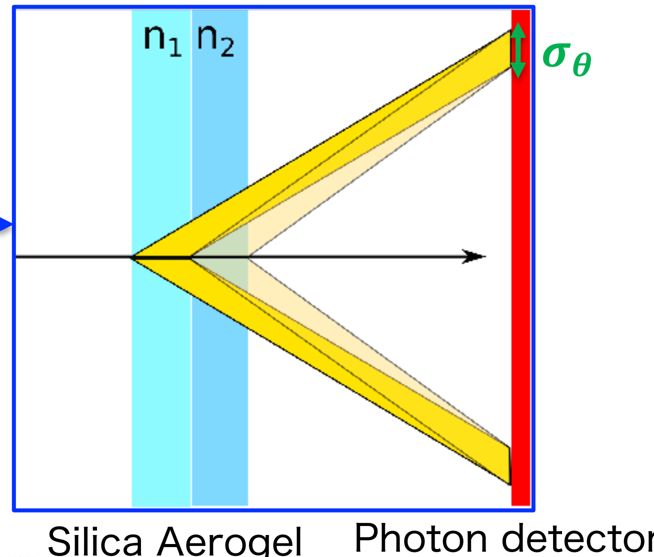
$N_{p.e}$: Number of detected photon

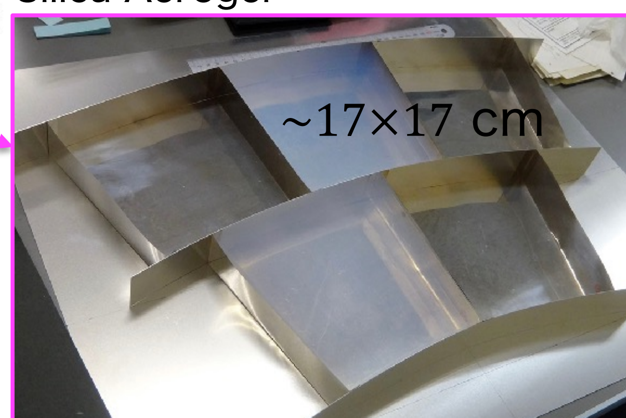
Important to increase $N_{p.e}$ w/o degrading σ_θ

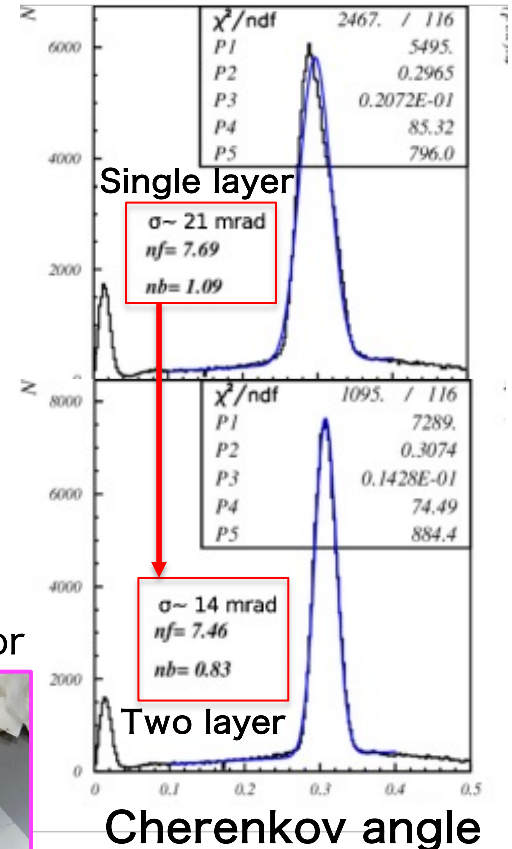
- Two aerogel layers with different indices: $n_1 = 1.045, n_2 = 1.055$

→ Improve σ_θ without reducing $N_{p.e}$







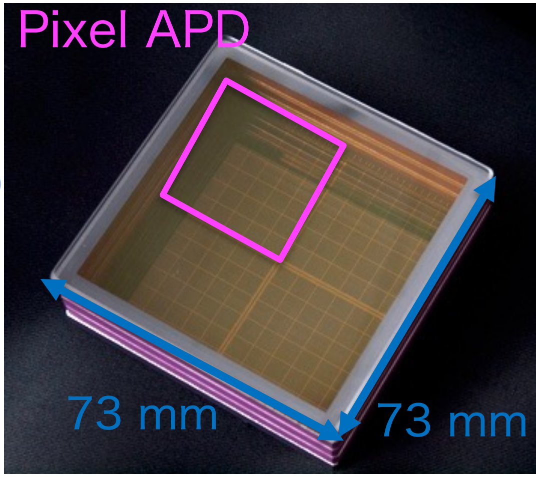


248 aerogel tiles in total

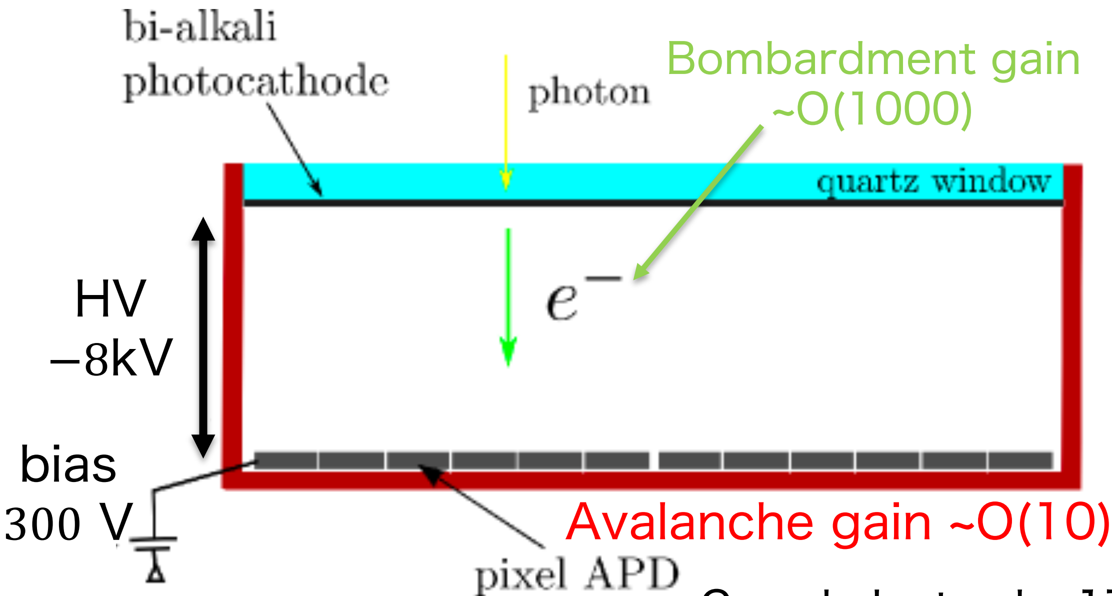
Photon detector

Hybrid Avalanche Photo-Detector(HAPD)

- Radiation tolerance (10^{11} neutrons/cm^2/year)
- Work in 1.5 T magnetic field
- Good single photon detection efficiency



Developed by Hamamatsu Photonics



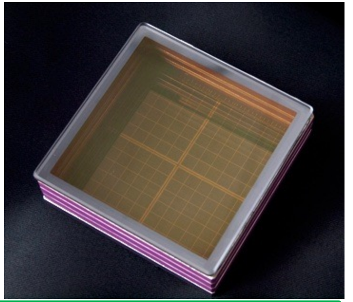
	HAPD
Size	73×73×28 mm^3
# of channels	12×12 = 144 ch
Channel size	4.9×4.9 mm^2
Effective area	65%
Peak QE	~30%
Total Gain	~70000

Guard electrode: 175V

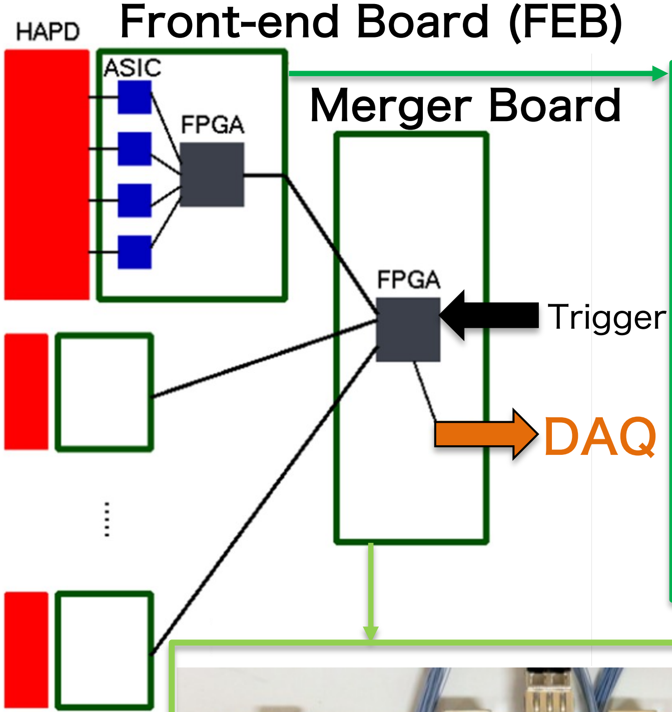
In total, 420 HAPDs are used (1 HAPD: 4 APDs)

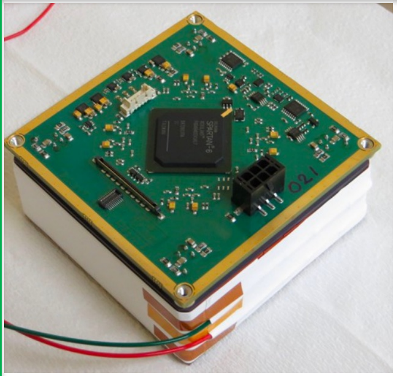
Readout electronics

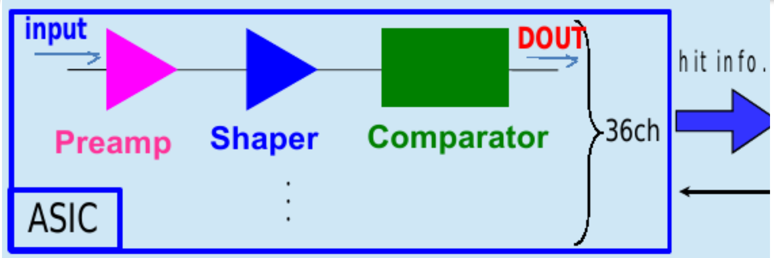
Send 1-bit information from each channel



Total: 60000 channels



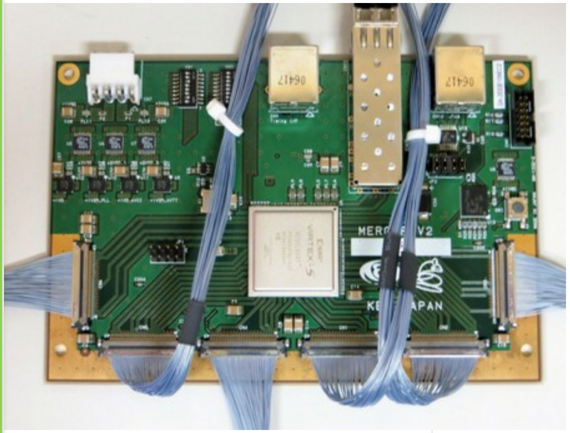




<u>Xilinx Spartan-6 FPGA</u>

- Digitize signals from HAPD

→ 420 FEBs in total



<u>Xilinx Vertex-5 FPGA: Control 5-6 FEBs</u>

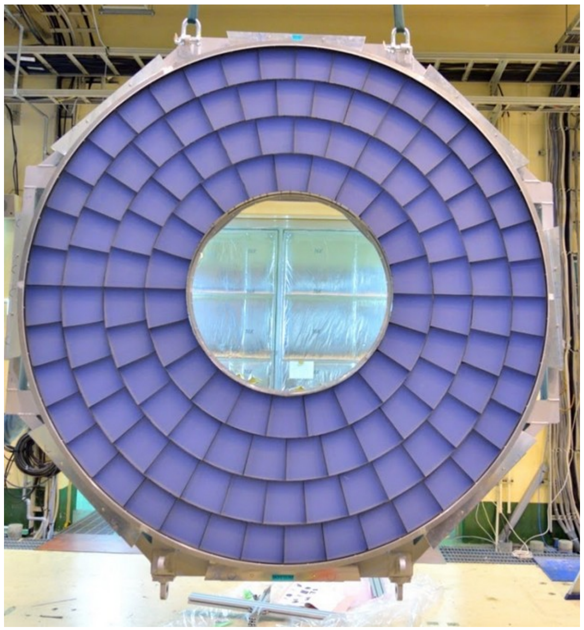
- Firmware download, parameter setting
- Monitor temperature, voltage, SEU etc
- Combine FEB data and send to DAQ

→ 72 merger boards in total

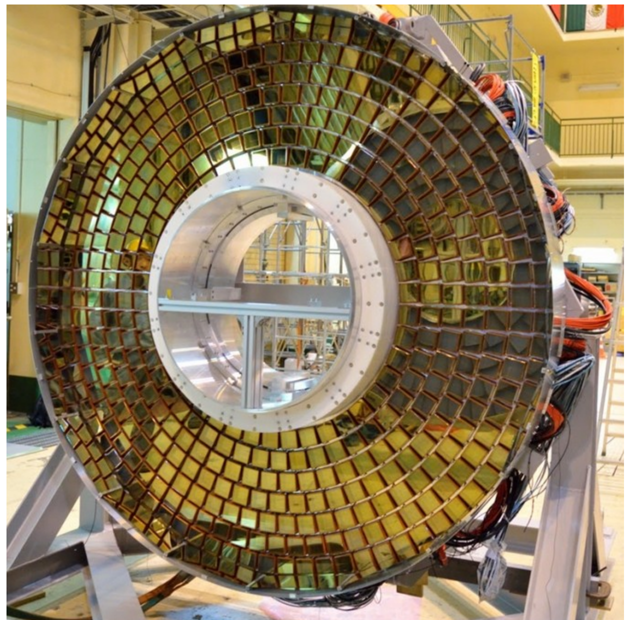
Detector construction

- 2016 – 2018 ARICH construction and installation
- 2018: Belle II commissioning run

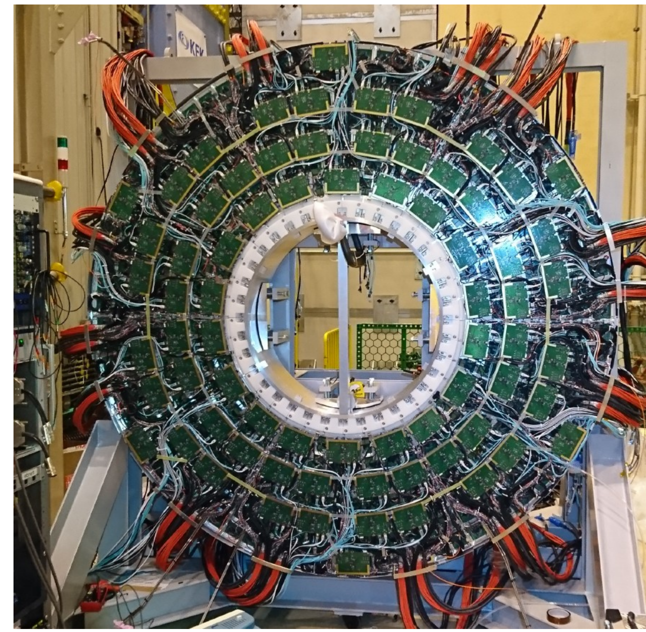
Radiator plane



Photon detector plane



Backside plane



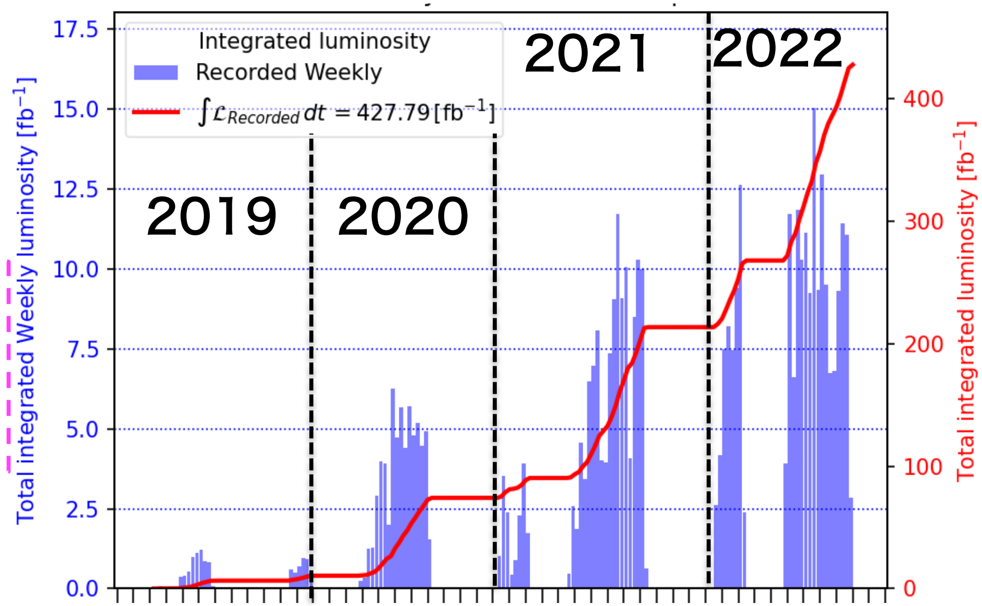
ARICH operation
2019 – 2022 run period

ARICH operation

Belle II operation: 2019 – June.2022

- Recorded 424 fb^{-1}
- $L_{peak} = 4.7\times10^{34}$ cm^{-2} s^{-1}

High luminosity environment
↓
Detector operation challenging!



ARICH operation

- HAPD: important for **PID performance**
  - (Almost) no degradation due to neutron radiation
- Readout electronics: important for **data-taking efficiency**
  - New firmware to detect/repair the error due to FEB SEU
  - Introduced quick recovery system for the errors

single event upset

HAPD operation status

ARICH: 420 HAPDs (420 × 4 APDs) in total

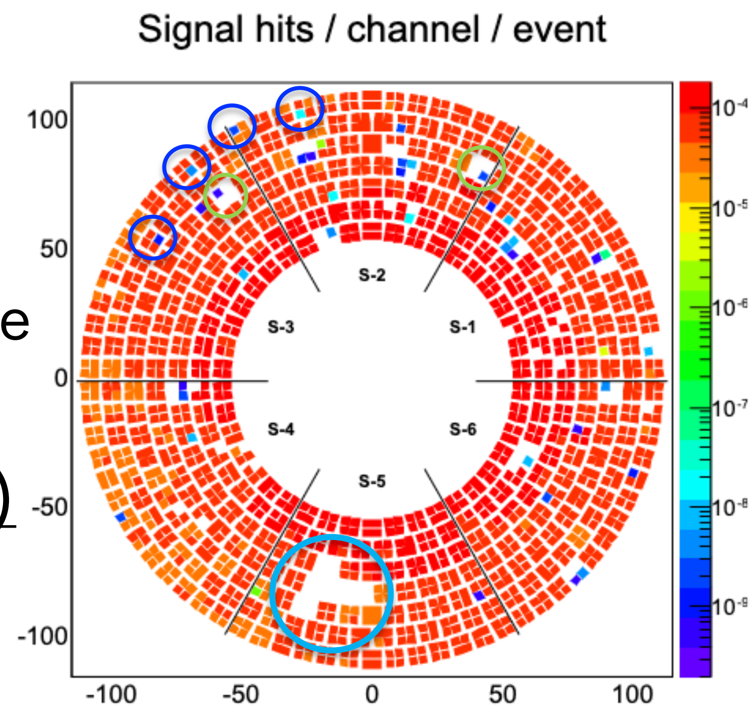
- 3.0% of APDs: bias or guard problem
  - Sudden increase of leakage current
- 1.7% of HAPDs: HV problem
- 5 HAPDs (1.2%) are off: LV cable failure
  - Fixed it → will enable from 2023 run!

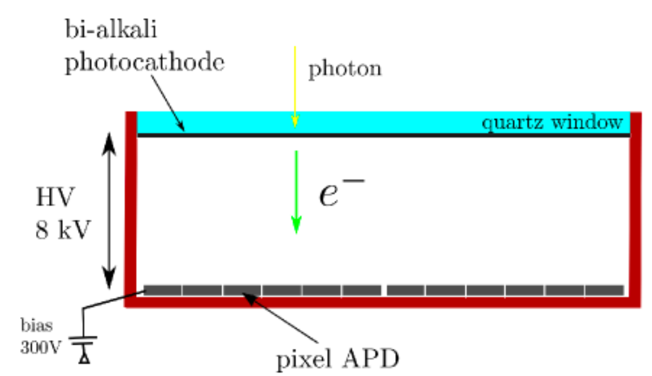
6.2% of APDs were off now (2022)

	2019	2020	2021	2022	2023
Ratio	4.8%	5.6%	6.0%	6.2%	5.0%

The problem of APD is getting stabilized

Negligible effect of PID performance due to masked APDs (6.2%)

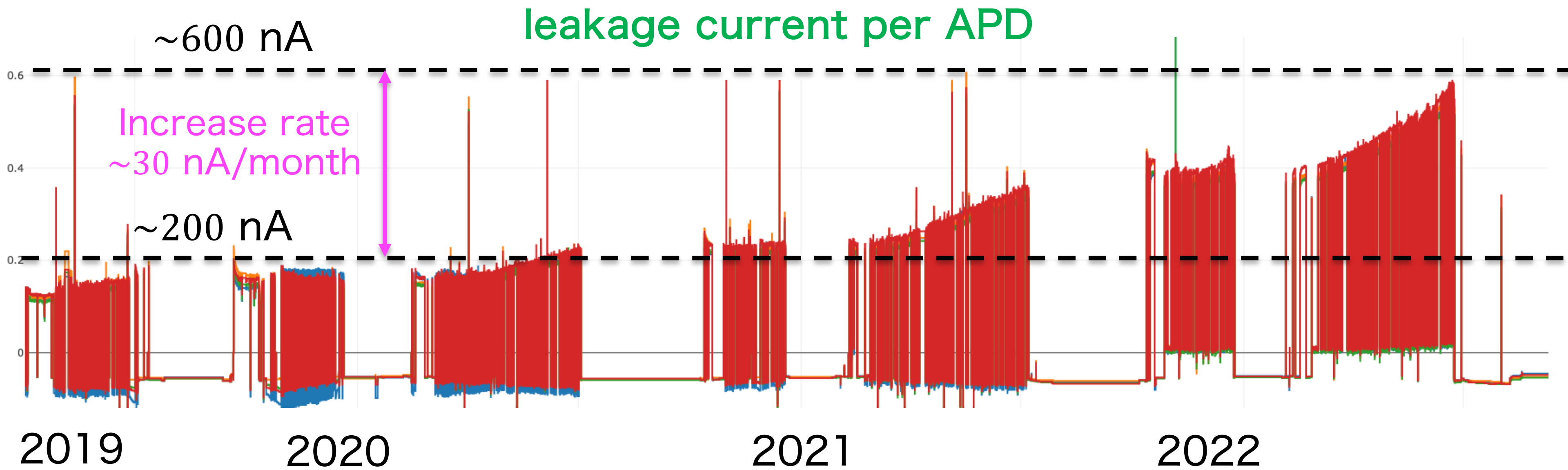




Neutron radiation

Neutron radiation → <u>increase of the leakage current</u>

- Deterioration of HAPDs due to silicon bulk damage by neutrons



Estimated neutron ~10^9 n/cm²/month < expectation 10^{11} n/cm²/year

Expect larger neutron radiation as higher luminosity

- Acceptable from simulation.. Keep watching

> 10^{35} cm^{-2} s^{-1}

Readout: Self-repair on FEB SEU

Effect from neutrons is SEU in the FEB FPGAs

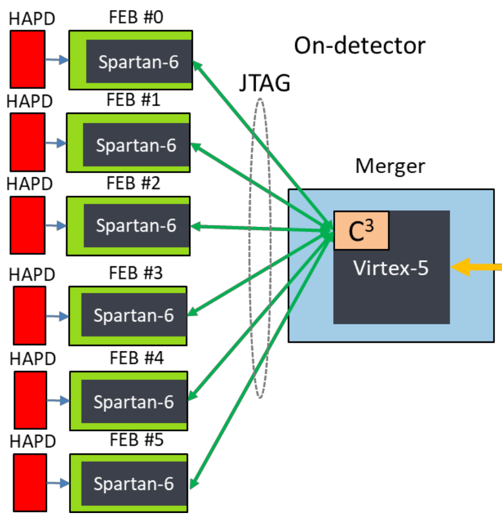
- Frequent SEUs expected in Spartan-6 FPGA: 8 SEUs/(hour, FEB)

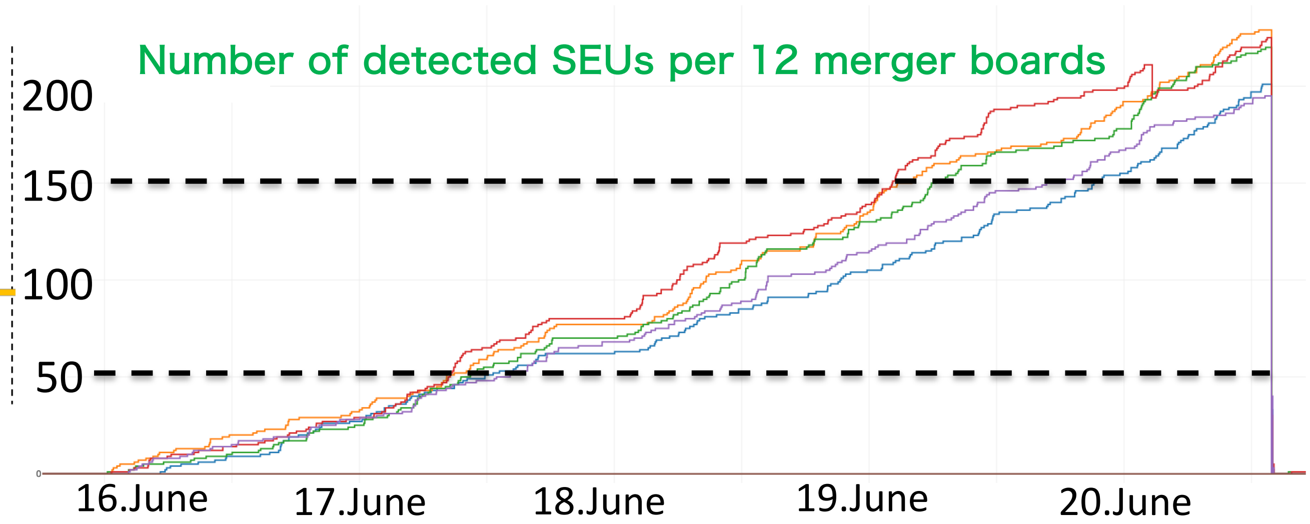
→ <u>Less data-taking efficiency</u>

[R.Giordano et. al: arXiv:2010.16194](https://arxiv.org/abs/2010.16194)

<u>Designed firmware: Configuration consistency corrector (C^3)</u>

- Detect damaged frame by majority voting redundant frame bits
  - Partial reconfiguration of the firmware → No DAQ failure





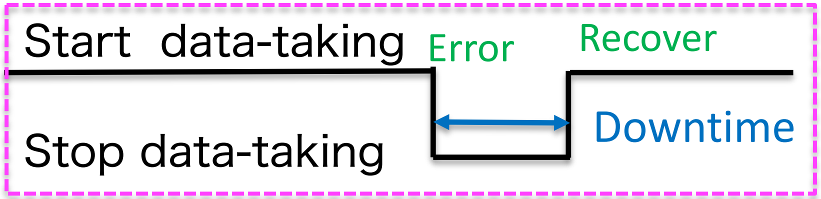
<u>We used this firmware from June.2020</u> → efficiency improved!

Quick recovery system

Essential to improve data-taking efficiency

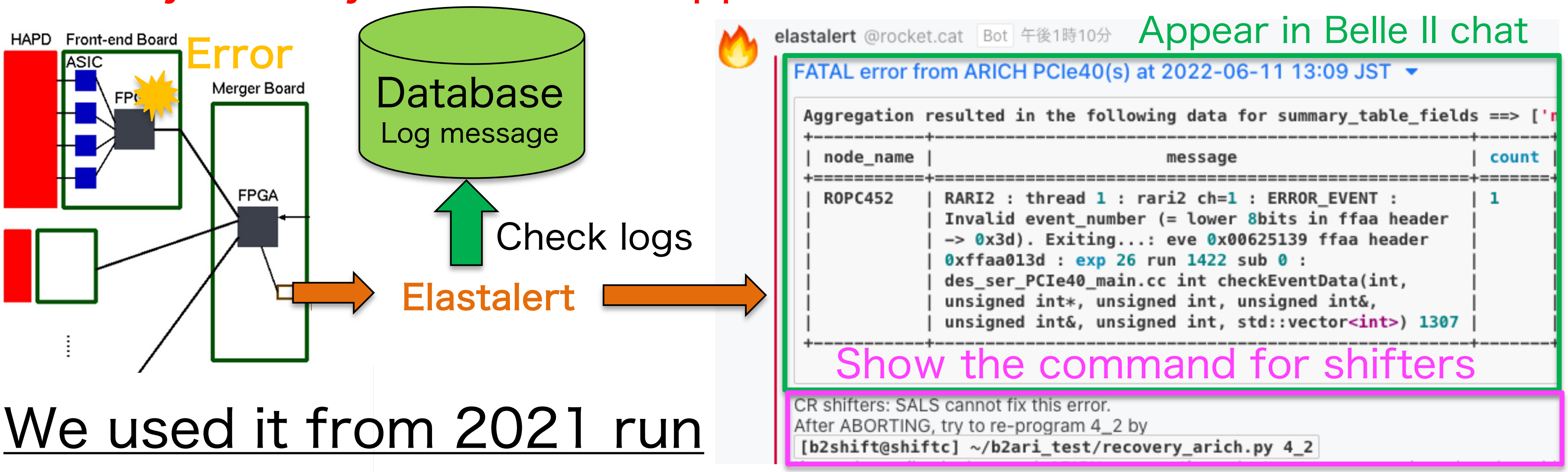
- 6 hours downtime at $L \sim 4.7\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ → Lose 1 fb^{-1}!

Utilize Elastalert (third-party tool)



- Always monitor log messages
- Alert shifters if error occurred

→ Easily identify what error happened and how to fix it



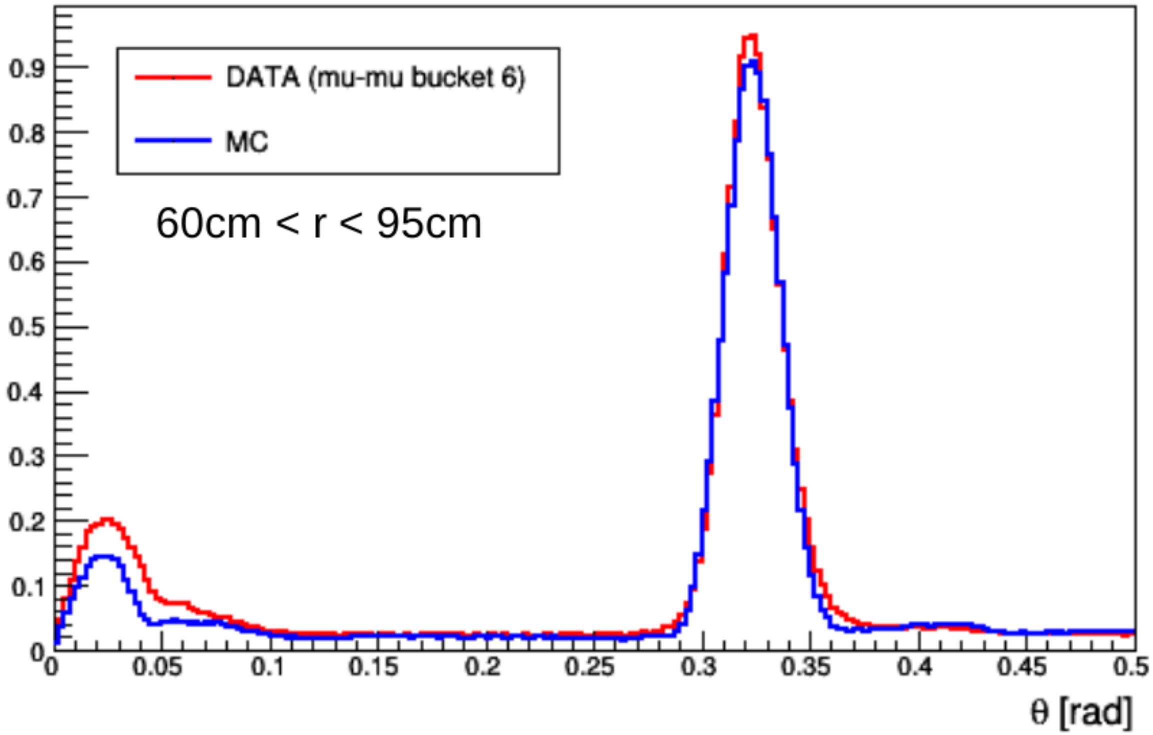
We used it from 2021 run

- Reduced ARICH downtime, < 1hour in 2022 (~6hours in 2020)

PID performance of ARICH

Cherenkov angle distribution

$e^+e^- \to \mu^+\mu^-$ events, 2019 data



DATA

$N_{sig} = 11.38/\mathrm{track}$

$\sigma_c = 12.7\ \mathrm{mrad}$

MC

$N_{sig} = 11.27/\mathrm{track}$

$\sigma_c = 12.75\ \mathrm{mrad}$

- Good agreement between data and MC simulation

Particle Identification in ARICH

Comparison b.t.w observed hit and the expected PDF

- PDF: Cherenkov angle distribution
- Construct likelihood function for 6 type hypotheses (e, μ, π, K, p, d)

$$\ln \mathcal{L}_h = -N_h + \sum_{hit\ i} \left[n_i^h + \ln\left(1 - e^{-n_i^h}\right) \right]$$

h: particle hypothesis

N_h: expected total number of hits

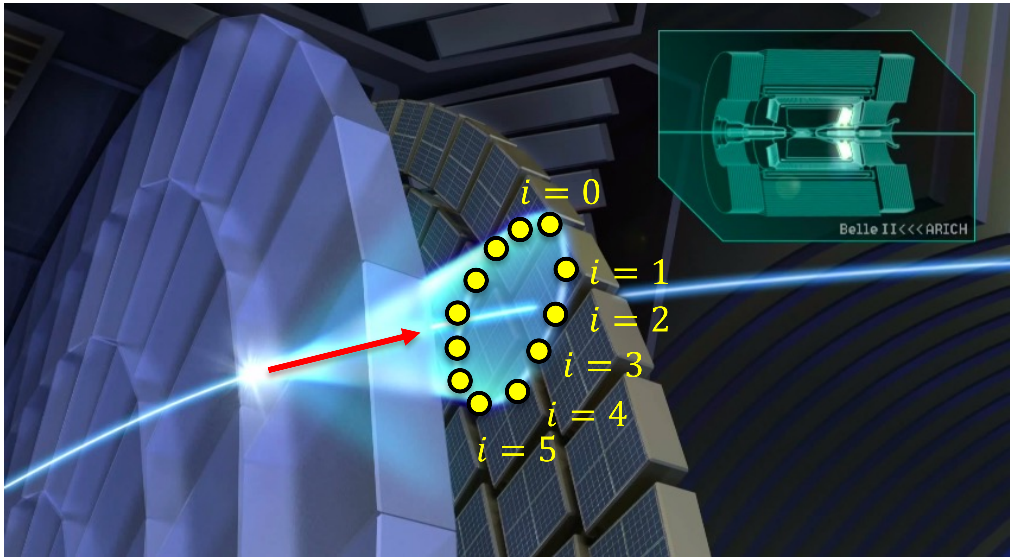
n_i^h: expected number of hits on pixel i

※ 1 bit (ON/OFF) information in each pixel

Likelihood ratio

$$R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

$$R_{\pi/K} = \frac{\mathcal{L}_\pi}{\mathcal{L}_K + \mathcal{L}_\pi} = 1 - R_{K/\pi}$$

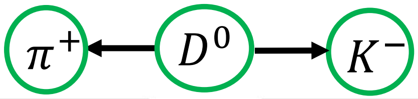


Performance of K/π separation

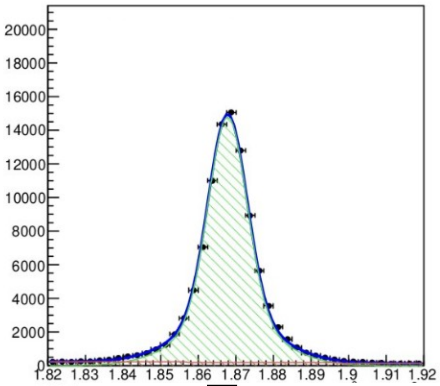
Clean sample of K,π tracks from D^* decays: **eg.** $\boldsymbol{D^{*+} \rightarrow D^0\pi^+_{slow}}$

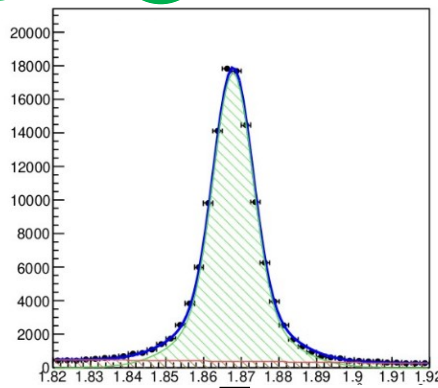
- K eff: Apply πID to another track from D^0 to increase the purity
- π miss-eff: KID to another track

For π miss-eff

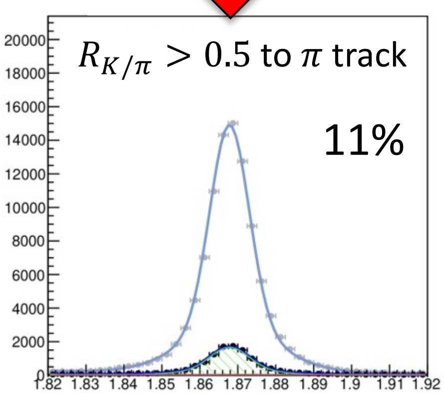


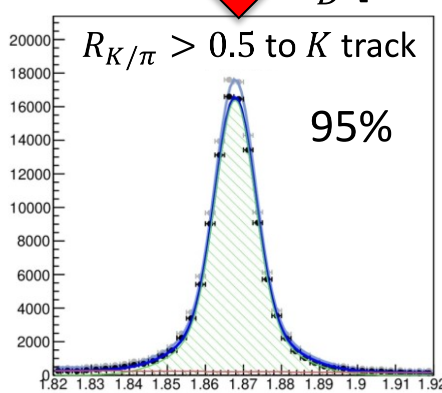
For K eff





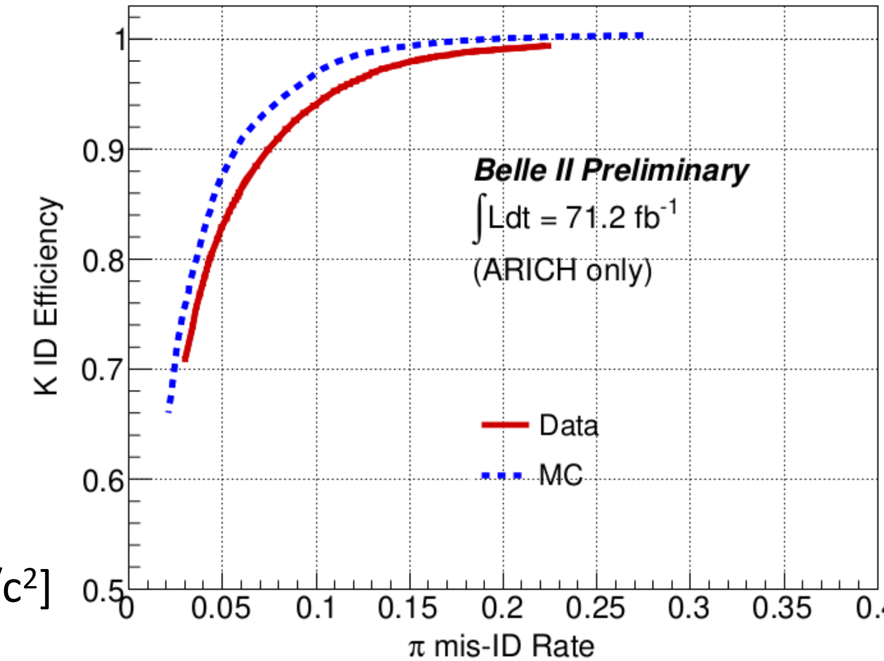
M_D [GeV/c^2]





M_D [GeV/c^2]

$$R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$



Close to MC expectation

※ Detector alignment, calibration

- Key to identify data/MC difference

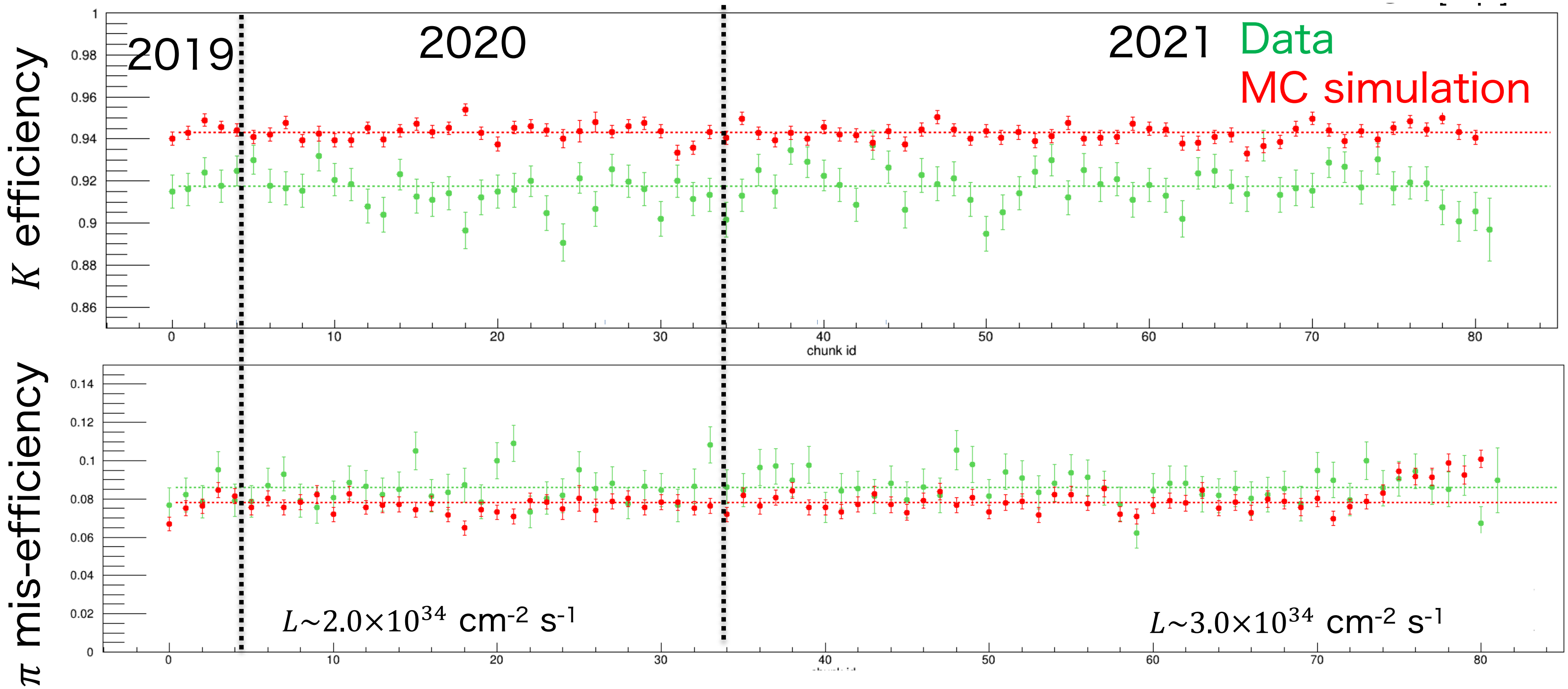
→ L.Santelj's talk on 13.Sep

Stability of PID performance

Calculate K efficiency and π miss-efficiency run-by-run

- $R_{K/\pi} > 0.5$ using D^* sample

Point: beam-induced background increases as higher luminosity



Observed stable PID performance against beam-induced background

Summary

ARICH is PID detector in the forward endcap at Belle II

- Use a proximity focusing RICH and utilize Cherenkov ring image

Stable ARICH operation since 2019

- Observed increase of leakage current, but negligible PID effect
- The fluence of the neutrons are below the tolerable level.
- Several improvement of firmware and operation system

Good PID performance in Belle II data

- PID performance in data is close to MC expectation!

We have one more talk and two posters in this conference.

L.Santelj: Recent developments in data reconstruction for aerogel RICH at Belle II
G. Ghevondyan: ARICH performance study in the Belle II experiment (poster)
R. Pestotnik: Slow control of the Belle II Aerogel Ring Imaging detector (poster)

Backup

Refractive index

The radiator is required to have

- Large transmission length and suitable refractive index

The refractive index is required to make

- The ring radius to be a few decimeters, emitting enough the number of photons, and avoiding total reflection at the boundary between radiator and air

→ The range of refractive index: 1.01 - 1.1

The silica aerogel can satisfy the index, 1.003 – 1.026

- It can control the value of the refractive index at its production

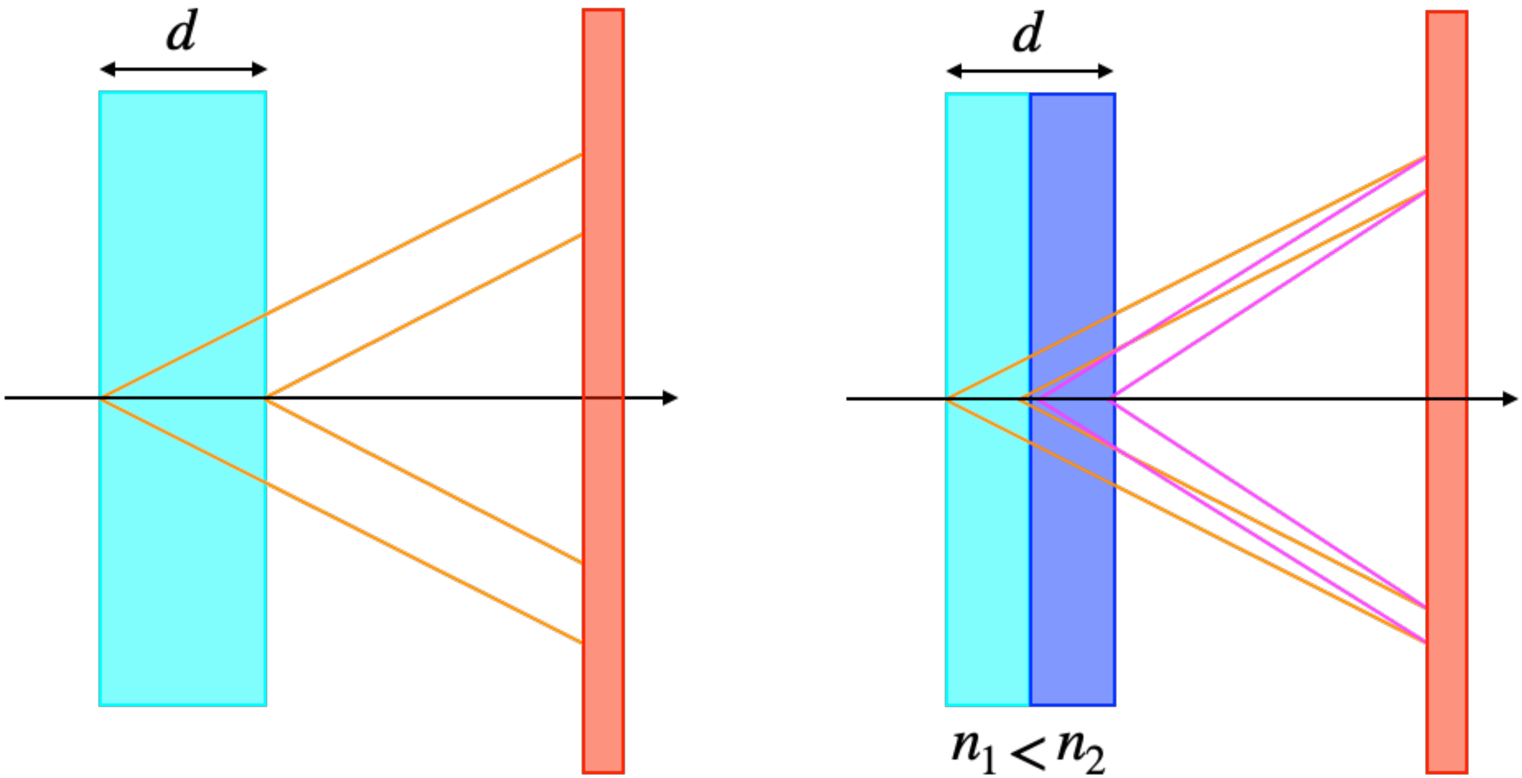
→ Most suitable material of the radiator of ARICH

Taking number of emitted photons and transmission length into account:

- Larger refractive index: produce more photons
- Transmission length decreases in proportion to the refractive index

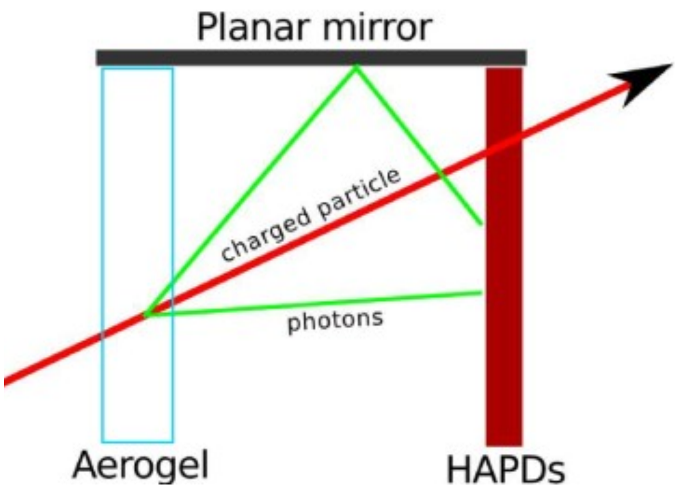
→ Choose 1.05

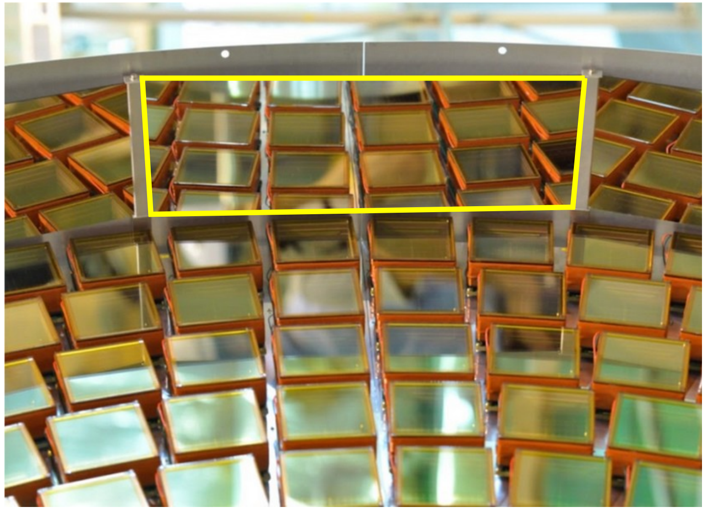
Impact of dual layer



Planar mirror

- To prevent photon loss for track on the outer edge of the detector
- Possible to photon reflections properly considered in the reconstruction algorithm



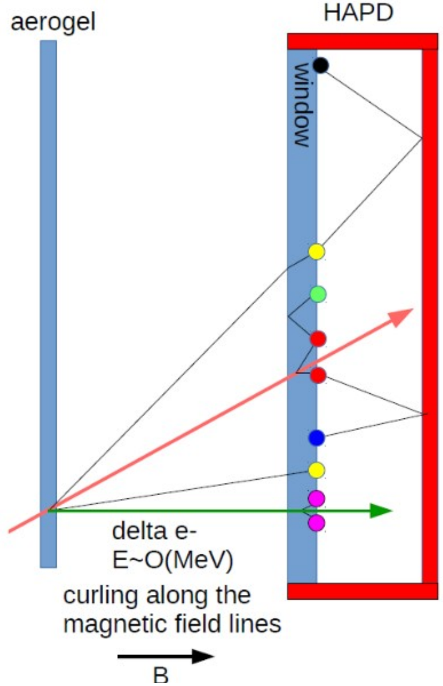


Quartz window

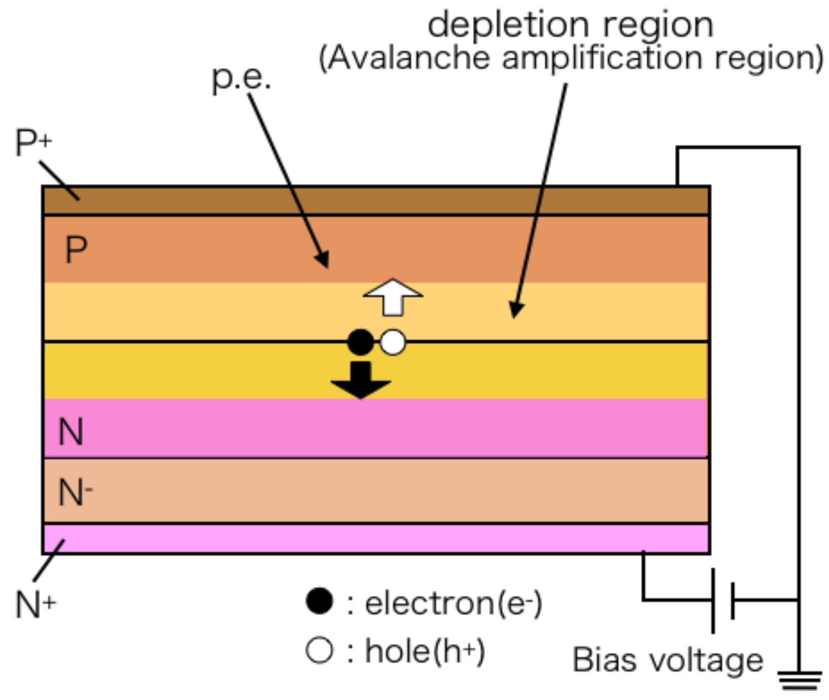
Cherenkov photons are also emitted when a particle passes through the quartz window of an HAPD.

- They can be converted to photoelectrons on their first impact on the photocathode or after repeated total internal reflections in the quartz window (refractive index: ~1.5 for quartz)

→ Small Cherenkov angle



APD structure



Sudden increase of leakage current