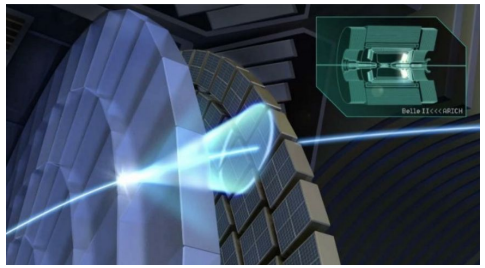


Operation and performance of the Belle II Aerogel RICH detector

Krištof Špenko,
Jozef Stefan Institute and University of Ljubljana
On behalf of the Belle II ARICH group

12th International Workshop on Ring Imaging Cherenkov Detectors
Mainz, 15 September 2025

Outline

Introduction:

- Belle II experiment
- Operation overview,
- ARICH detector,

Performance report:

- Detector alignment,
- Comparison between Run 1/2,
- Global neural network PID,

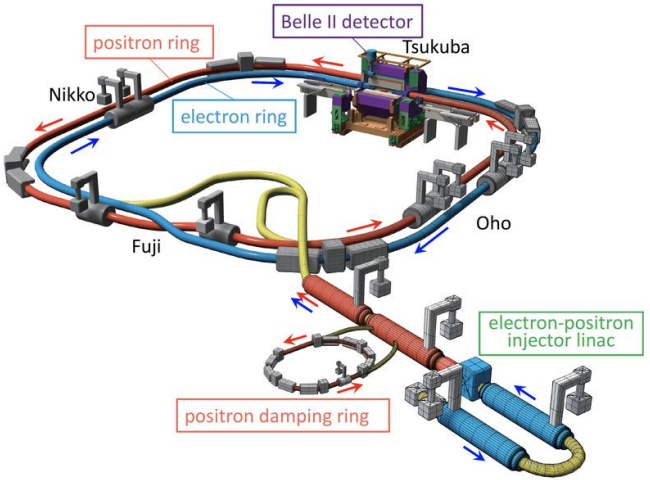
Operational challenges:

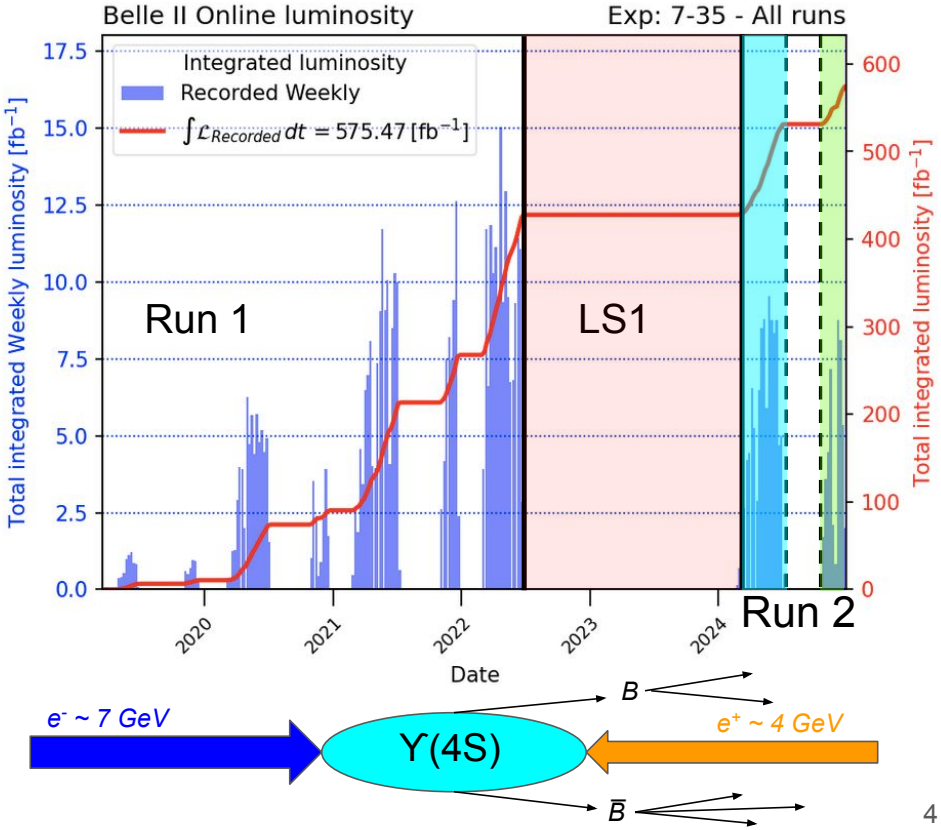
- Neutron radiation and leakage currents,
- Water cooling difficulties,

INTRODUCTION

Belle II experiment

- Asymmetric e^+e^- collider mainly at $s = 10.58$ GeV,
  - Produce B, charm, τ, etc..
- Goal: $50\ ab^{-1}$ data in ~ 20 years
  - 50 × Belle data: $N_{B\bar{B}} \sim 50 \times 10^9$

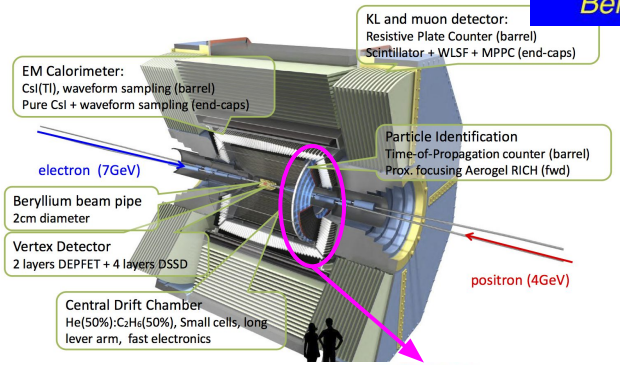


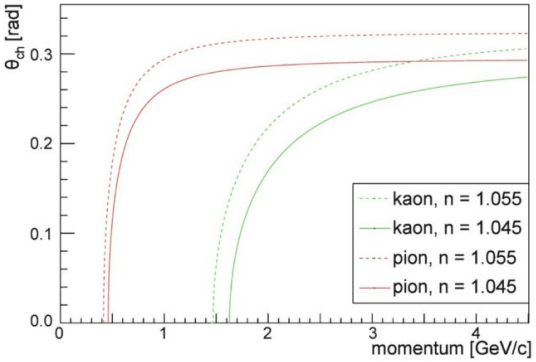


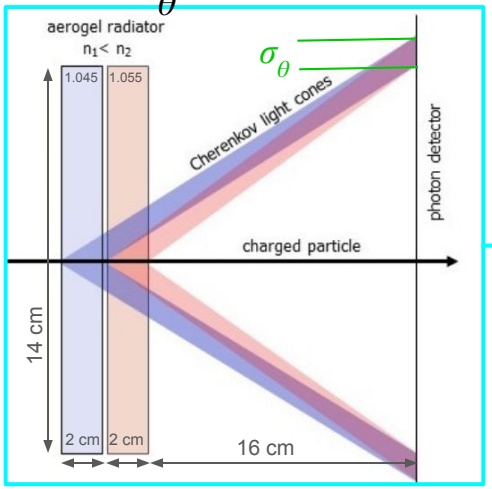
Aerogel RICH detector

Forward endcap detector for Particle ID:

- Goal: 4σ K/π separation
  - momentum regime $p \in 0.5$ - 4.0 GeV,
  - forward phase space region $\theta \in 0.29$ - 0.61 rad,
- Two layer aerogel radiator for improved Cherenkov angle resolution σ_θ.







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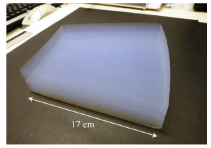
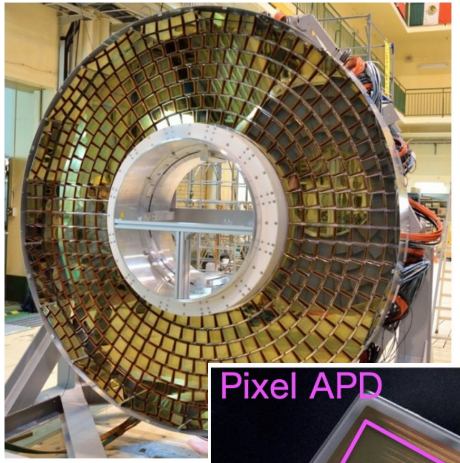
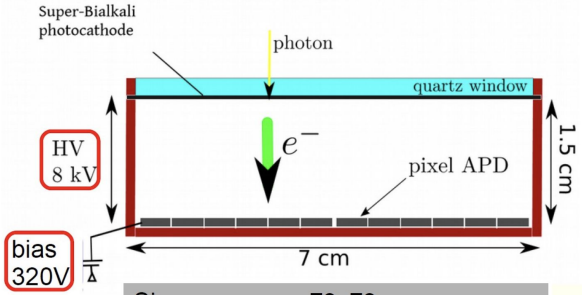


Aerogel RICH detector

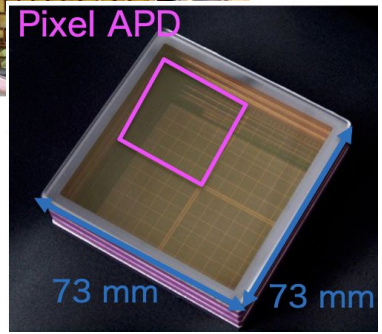
Hybrid Avalanche Photo-Detector (**HAPD**) used as photon detectors:

- Radiation tolerance (10^{12} *neutrons/cm*^{2})



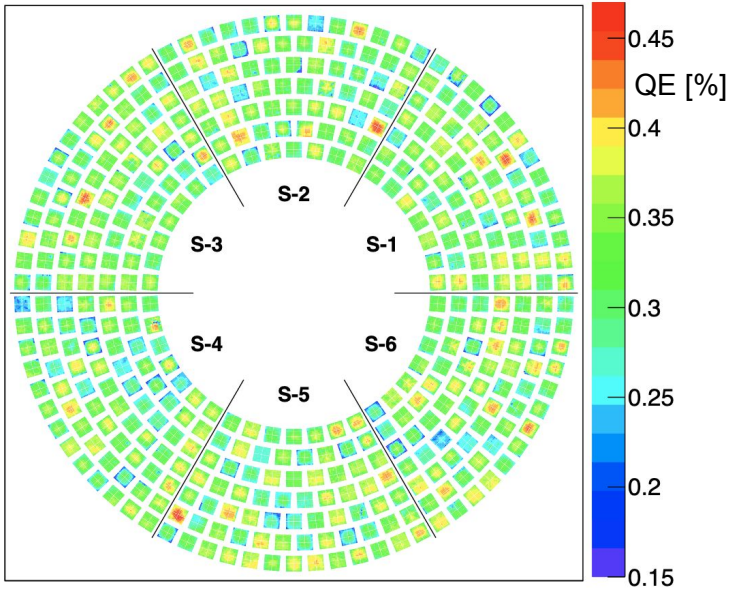


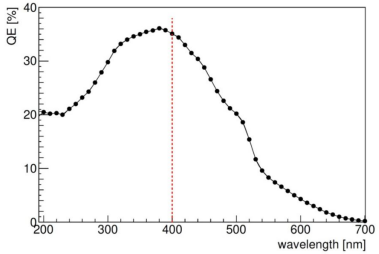
Size	73x73 mm
# of channels	144 (36-ch APDx4)
Total gain	>60000 (1500 x 40)
Peak QE	~30%
Active area	64%
Weight	220g

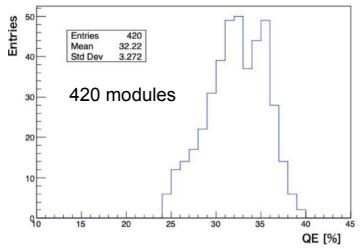


Developed in collaboration with Hamamatsu Photonics K.K.

→ *Studies for the Upgrade of Belle II Aerogel RICH*
Shunsuke KUROKAWA



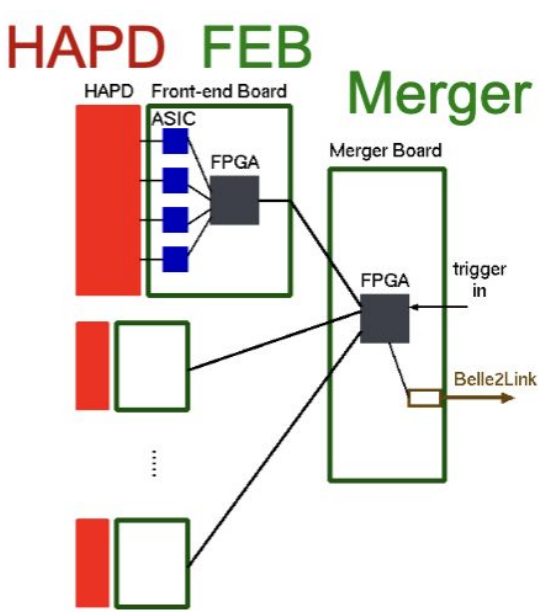


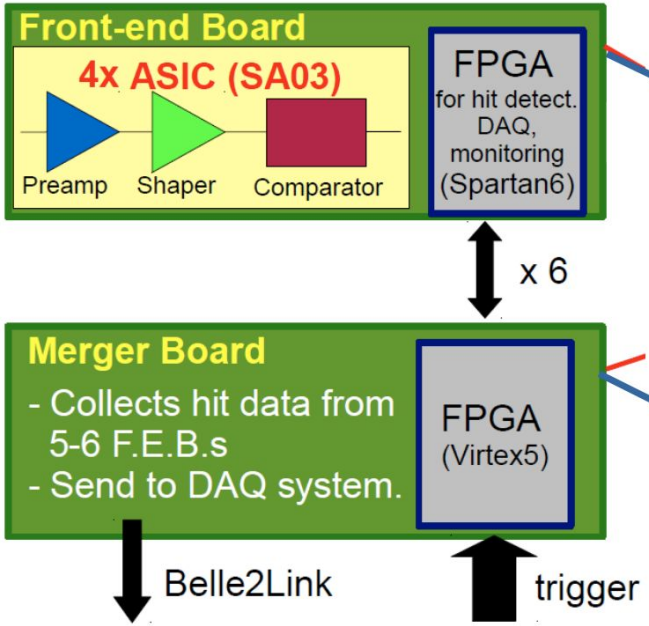


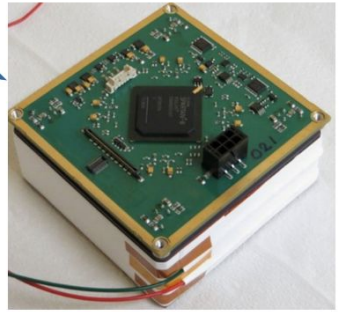
Aerogel RICH detector

Readout electronics (Total 60k channels):

- Signal from HAPD is digitized by FEB,
- 5-6 FEBs are connected to a merger board (72 in total).





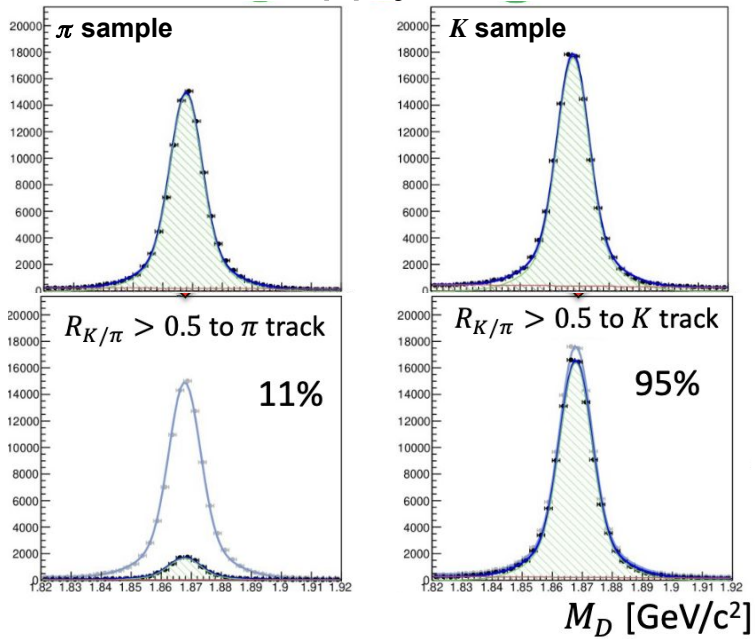


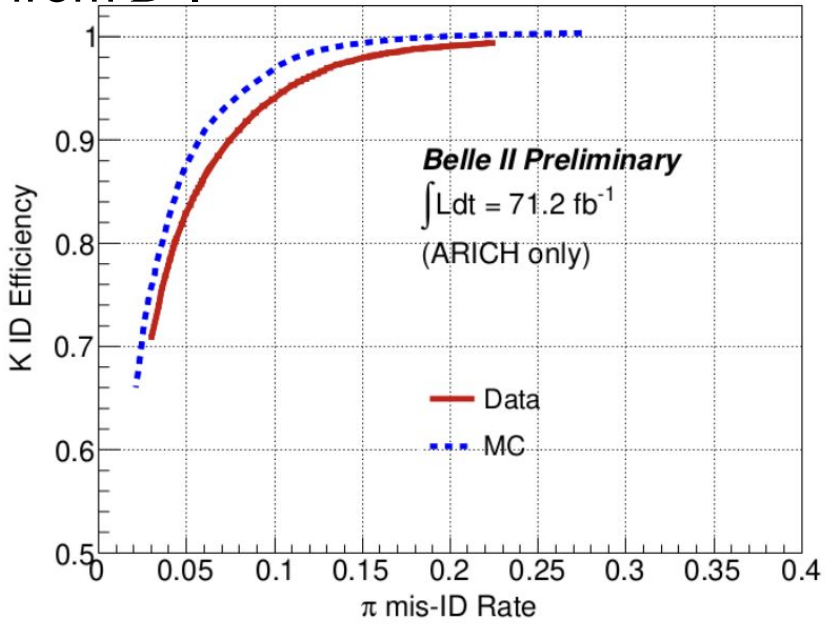
PERFORMANCE REPORT

Run 1 performance

To get an estimate on the performance of the ARICH detector, we use a clean sample of K/π tracks from: $D^{*+} \to D^0 \pi^+_{\text{slow}}$

- K eff: apply KID to the K track from D^0.
- π miss-id: apply KID to the π track from D^0.





Detector alignment

- New alignment was calculated post LS1 detector reassembly.
- Alignment is calculated on high momentum di-muon sample from data.
- Quasi-Newton iterative method is used to minimize the negative ARICH muon log likelihood by changing the detector parameters.
- Side mirror and aerogel tile alignment parameters remain as before LS1.

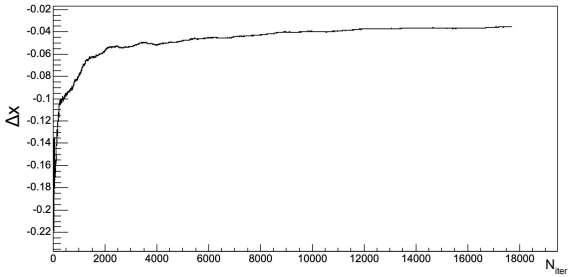
$$\chi^2 \equiv -2 \log \mathcal{L}_\mu^{(i+1)}(\hat{p}) + \Delta\hat{p}^T V_{(i)}^{-1} \Delta\hat{p} = \min$$

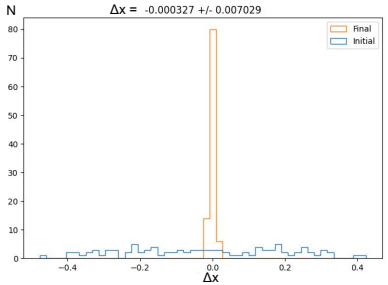
$$U^{(i+1)} = U^{(i)} - D^{(i)}$$

$$V^{(i+1)} = [U^{(i+1)}]^{-1}$$

$$\Delta\hat{p} = V^{(i+1)} \hat{s}^{(i)}$$

$$\hat{p}^{(i+1)} = \hat{p}^{(i)} + \Delta\hat{p}$$





Where:

- $U = V^{-1}$, $U^{(0)} = 0$
- D is matrix of second derivatives: $D_{jk} = \frac{\partial^2 \log \mathcal{L}_\mu}{\partial\hat{p}_j \partial\hat{p}_k}$
- $\hat{s}$ is vector of first derivatives: $\hat{s}_j = \frac{\partial \log \mathcal{L}_\mu}{\partial\hat{p}_j}$

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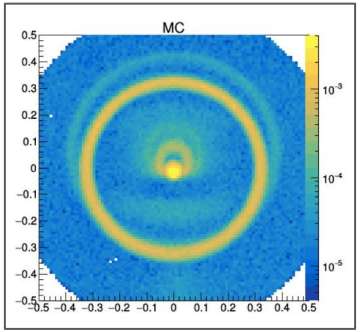
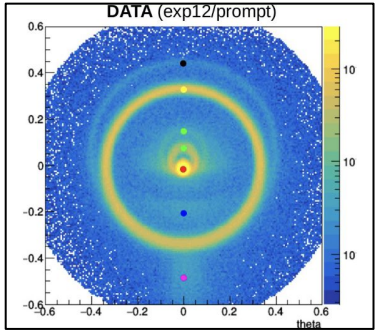
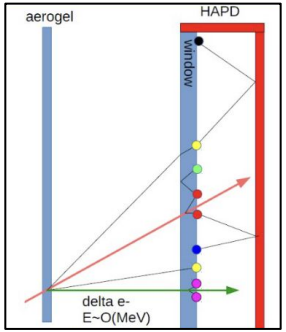
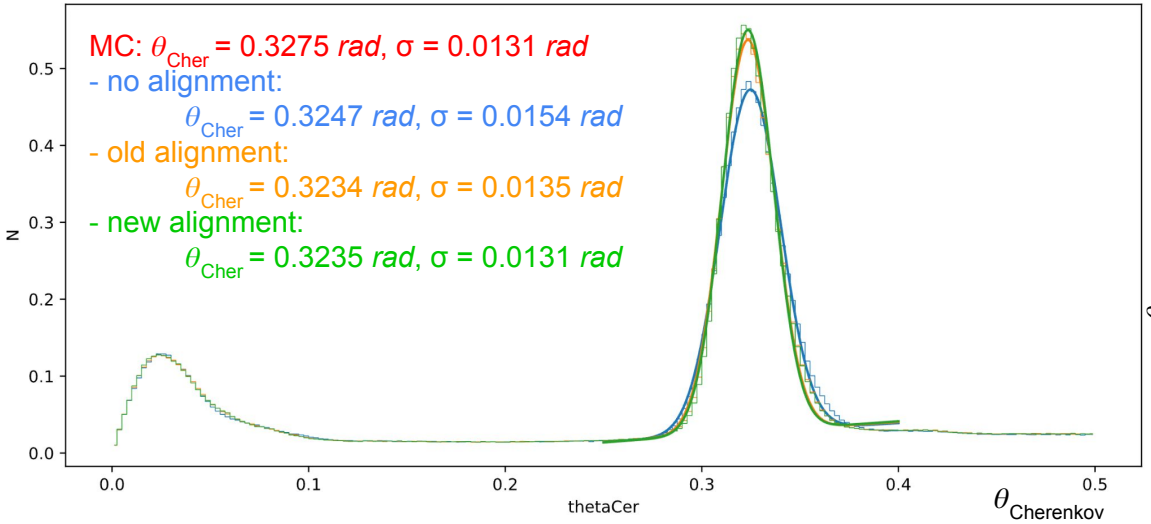
Detector alignment

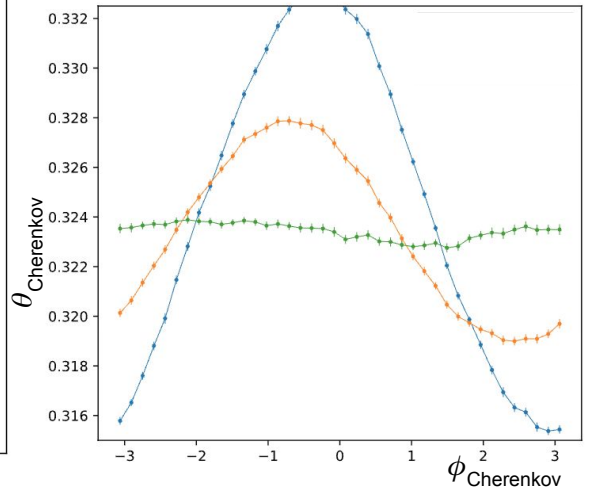
- In the MC we try to model the ARICH likelihood very accurately.
- Correct alignment very visibly improves the θ_{Cher} distribution.





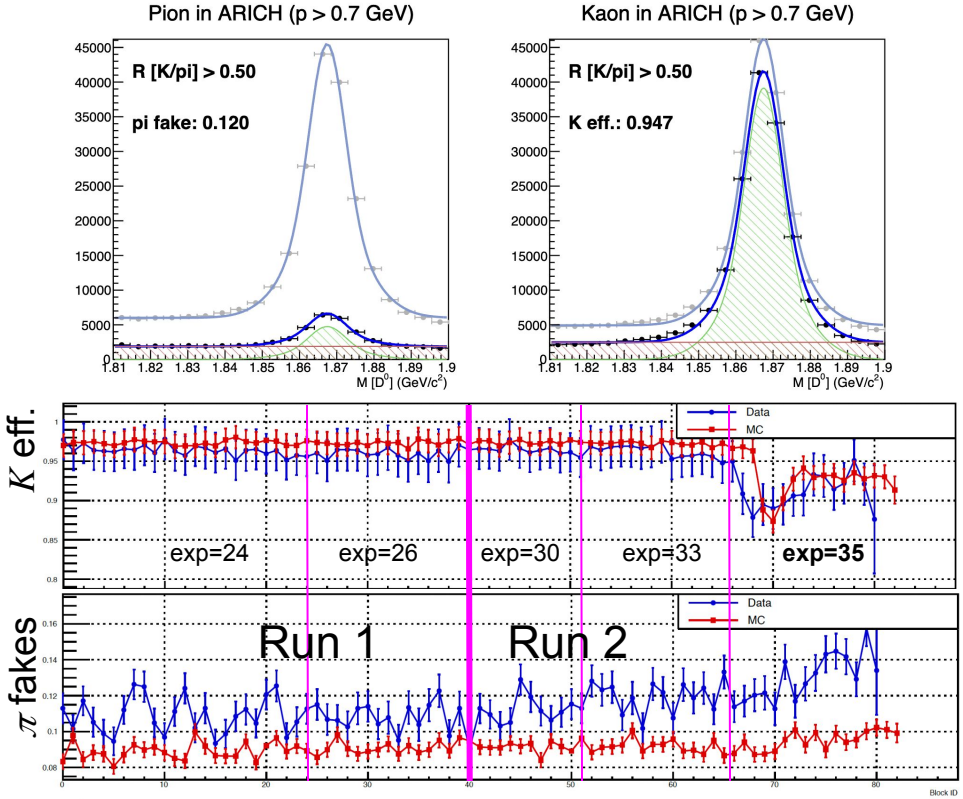


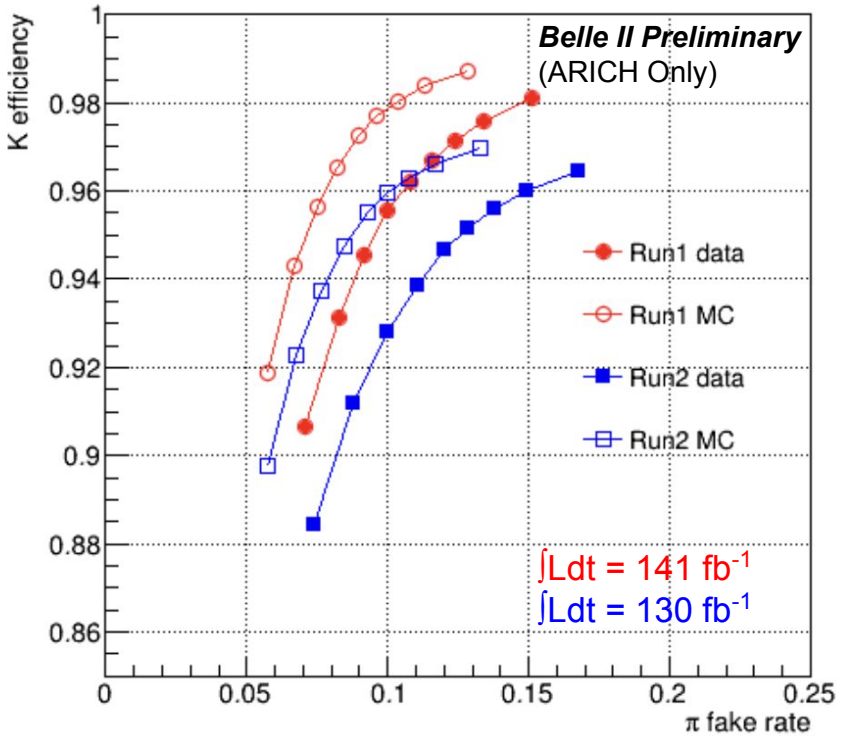




Run 2 performance

Performance during the beginning of Run 2:





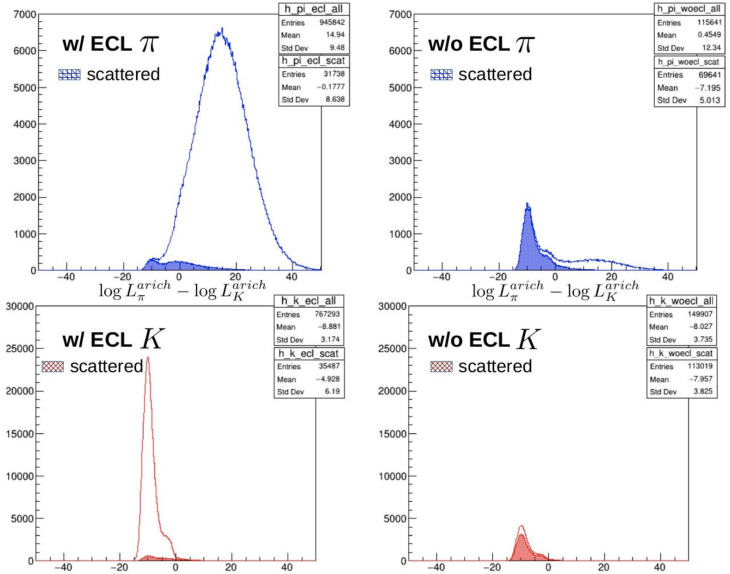
Neural Network Global PID

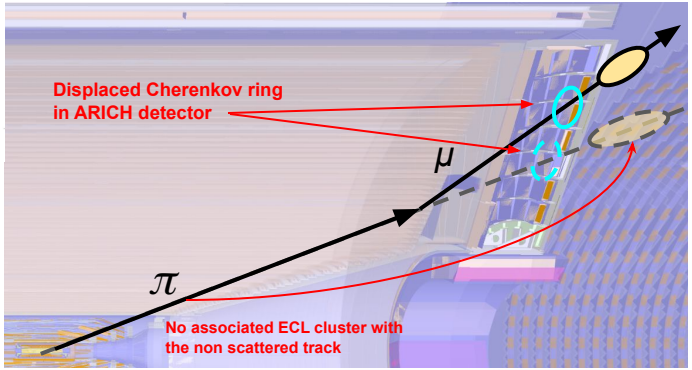
Default global PID:

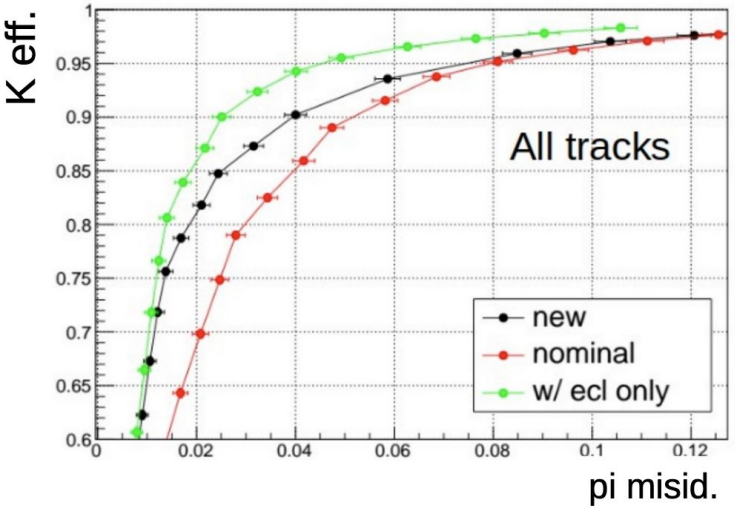
$$K \text{ id.} = \frac{\prod_{det} \mathcal{L}_{K,det}}{\sum_{part} \prod_{det} \mathcal{L}_{part,det}}$$

Previously tried to handle decayed/scattered particles:

~10% of particles with extrapolated track in the ARICH don't reach the detector.





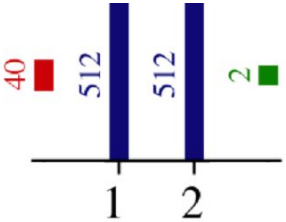


Neural Network Global PID

- NN input variables:

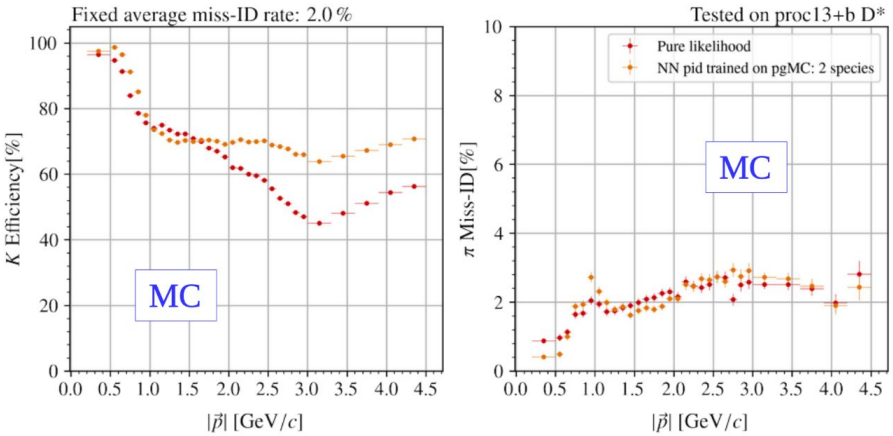
36 individual log-likelihoods: from 6 detectors d: TOP, ARICH, CDC, ECL, KLM, SVD for 6 particle-species hypotheses H: π, K, p, d, e, μ

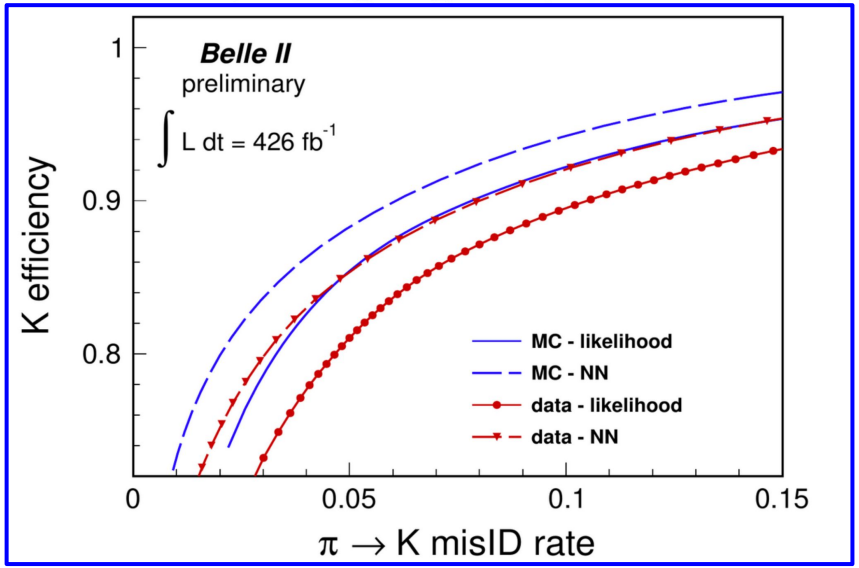
Information of the track: p, $\cos\theta$, ϕ, charge



Probabilities for particle-species hypotheses: π, K

- Next step: extend the NN approach to 6-species (e, μ, π, K, p, d) discrimination.



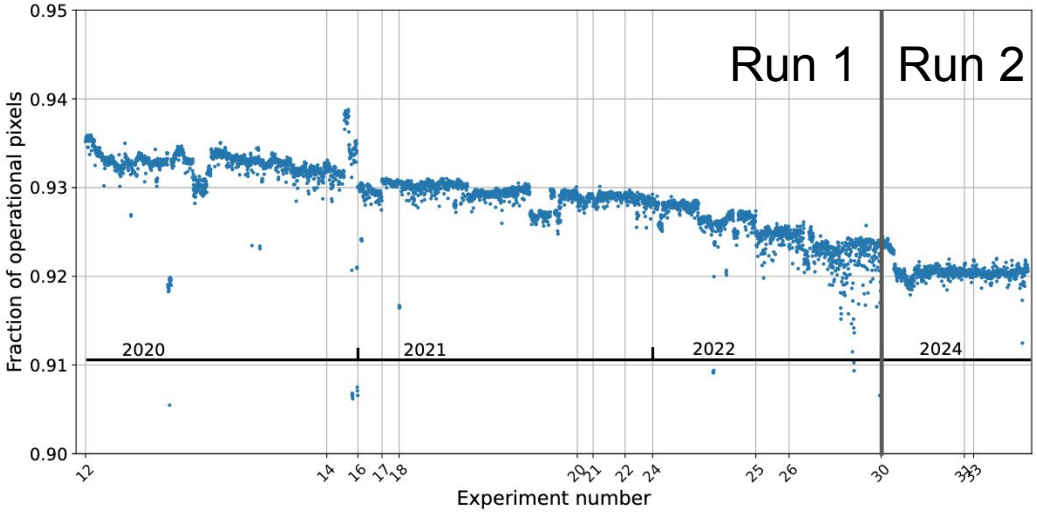


OPERATIONAL CHALLENGES

HAPD status

HAPD status:

- Broken APD; guard channels, bias, …
- HV problem (the problem is probably in HAPDs).
- There is no increase of dead channels during the operation in 2024.
- Now, the dead channel fraction is 6.7% (0.1% increase by disabling noisy channels).



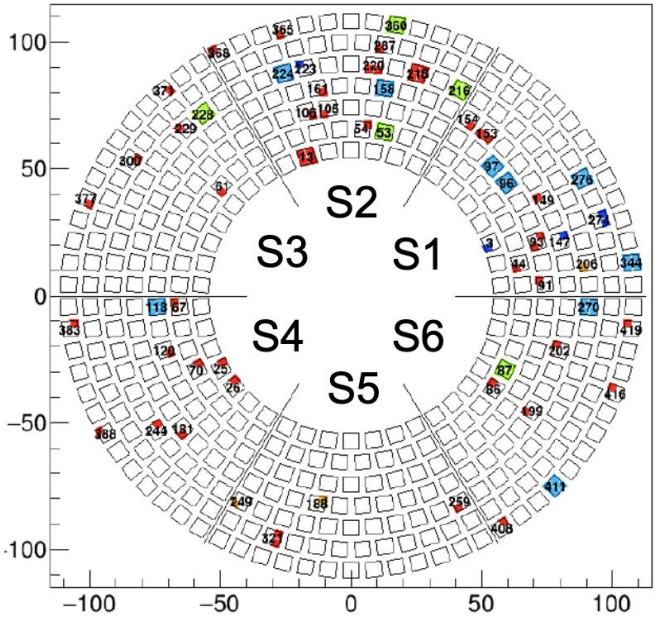
Fraction of dead channels

	2019	2020	2021	2022	2023	2024
Ratio	4.8%	5.6%	6.0%	6.5%	5.4%	6.6%

at the start of 2024a

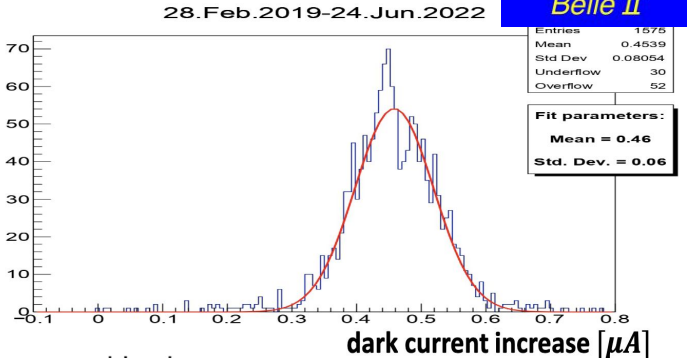
bias 56
guard 5
HV 9
(corresponding to 112 APDs)

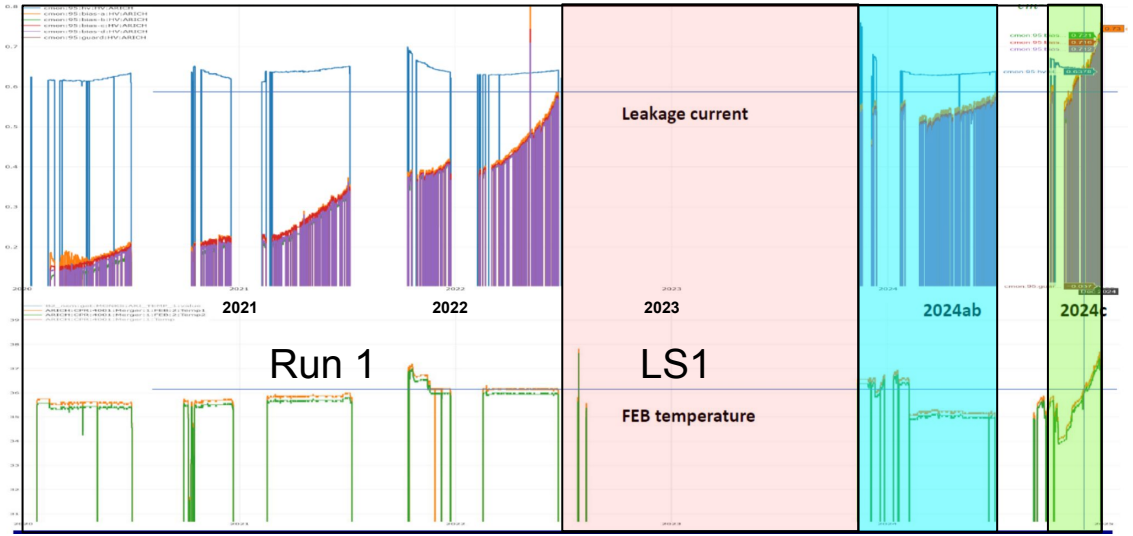
Red: disabled APDs due to bias problem
Blue: disabled APDs due to guard problem
Green: disabled APDs due to HV problem
Orange: set voltage of these APDs to 175V

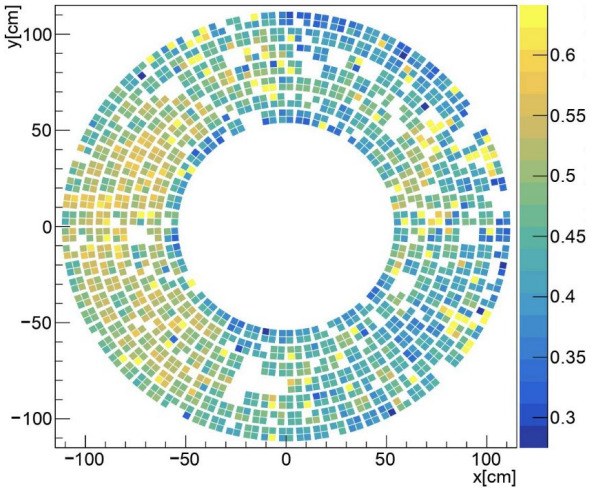


Neutron radiation & Leakage currents

- Currents show small drop (~30 nA) at the start of Run 2:
  - annealing/temperature change?
- fluence estimate:
  - $\Delta I_b \approx 500\ nA/\mathrm{APD} \rightarrow < 2 \cdot 10^{10}\ n/cm^2$,
  - $30\ \mathrm{nA} \rightarrow \approx 10^9\ n/cm^2$,
- after LS1 leakage current distribution shows similar pattern as before shutdown.

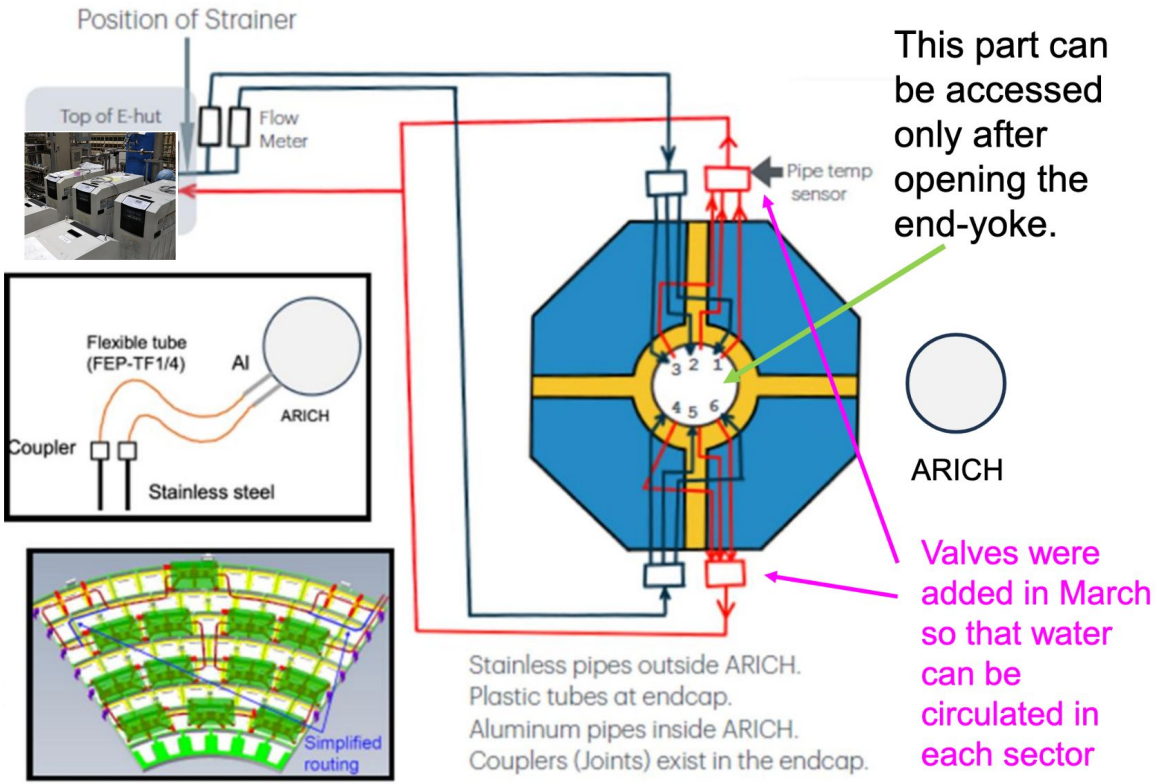






Water Cooling Problem

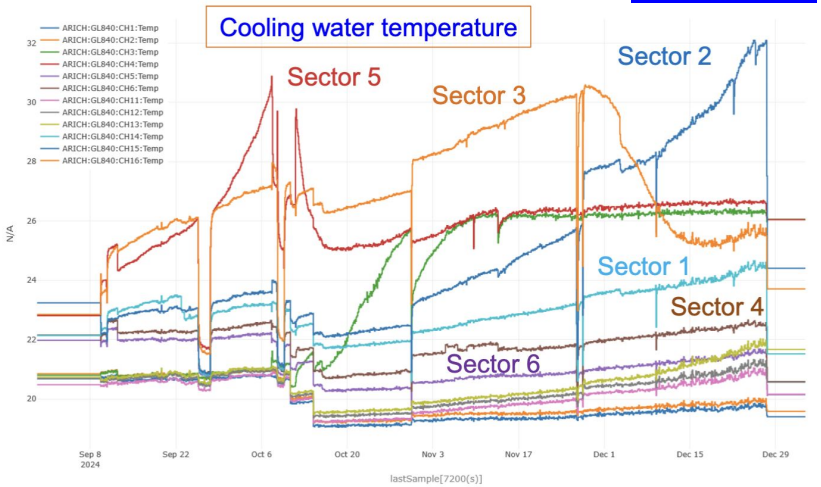
- The ARICH requires cooling of its electronics (HAPDs, FEBs, mergers ..)
- The water cooling system is composed of:
  - Chiller with water tank,
  - Stainless steel pipes outside ARICH,
  - Flexible tubes (with couplers) in the endcap together with **Al** pipes inside ARICH divided per each sector.
- During LS1 an **anti-corrosion agent** was added to the water.



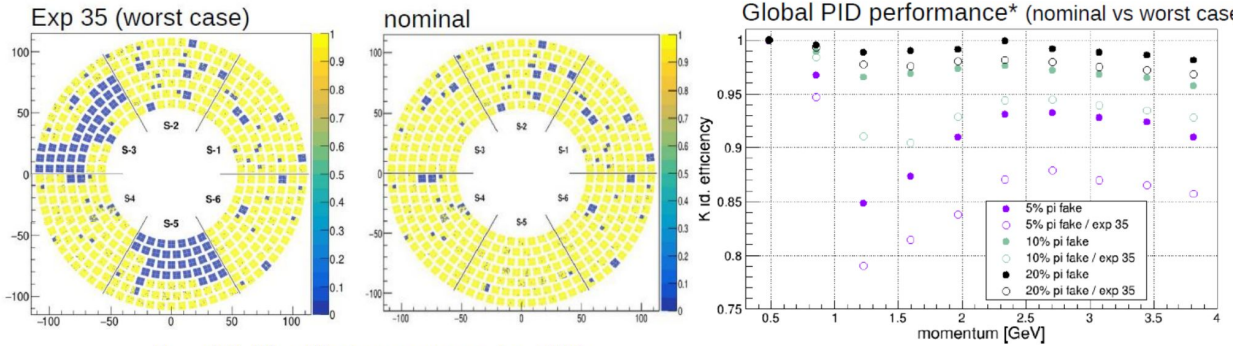
Water Cooling Problem

ARICH suffered a problem of the cooling water flow in autumn 2024.

The flow was significantly reduced in Sector 3 and 5, and we needed to turn off ~50% of the electronics in these sectors (10-20% of the entire ARICH).



The impact to PID was estimated by MC:



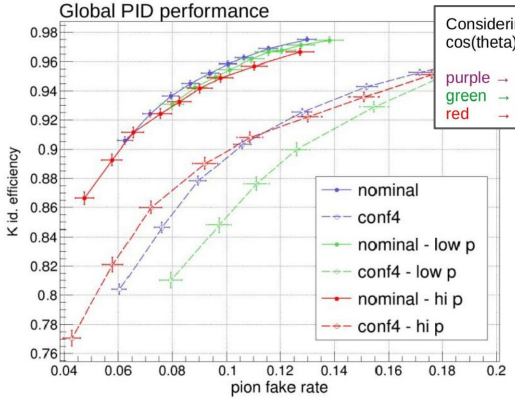
5 – 10 % efficiency loss in PID

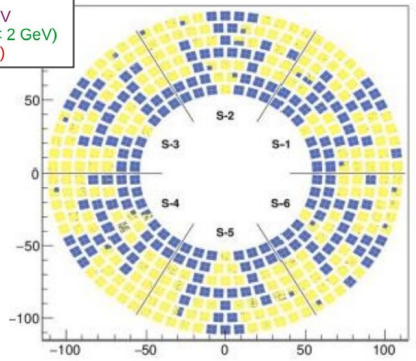
*includes only tracks in FWD endcap

Note:
- 7 % of charged particles reach ARICH for BB events.
- 13 % of charged particles above 0.5 GeV reach ARICH for BB events (larger fraction for higher momentum)

Water Cooling Problem

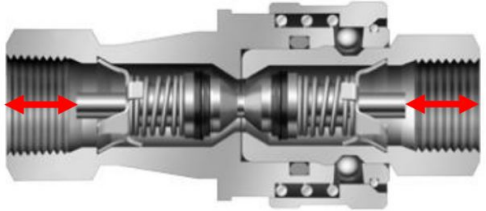
Potential mitigation strategies were considered, running with ~ 50% of HAPDs off, while minimising the impact on global PID.

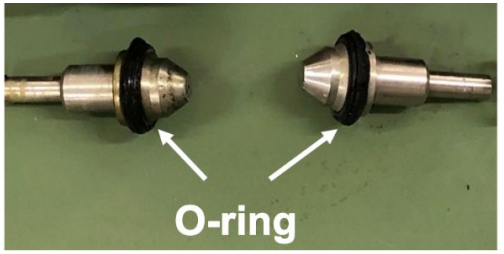




Opening the End Yoke:

- Belle II end yoke was opened on June 16, and we were able to access the pipes of ARICH.
- We started investigation and found that the flow was obstructed by the couplers.
  - If we remove (bypass) the couplers, the flow was fully recovered.
  - Swell of the O-ring (made of chloroprene rubber) was seen, probably due to a reaction with the **anti-corrosion agent** (still under investigation).





Summary

- During the beginning of the Belle II Run 2 operation the ARICH detector is performing as during Run 1.
- A new Neural Network PID has been designed to handle problematic phase space regions.
- Monitoring of the leakage currents in the photon detectors.
- Successfully resolved the water cooling difficulties.

Summary

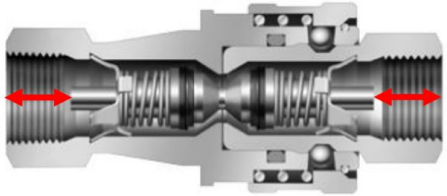
- During the beginning of the Belle II Run 2 operation the ARICH detector is performing as during Run 1.
- A new Neural Network PID has been designed to handle problematic phase space regions.
- Monitoring of the leakage currents in the photon detectors.
- Successfully resolved the water cooling difficulties.

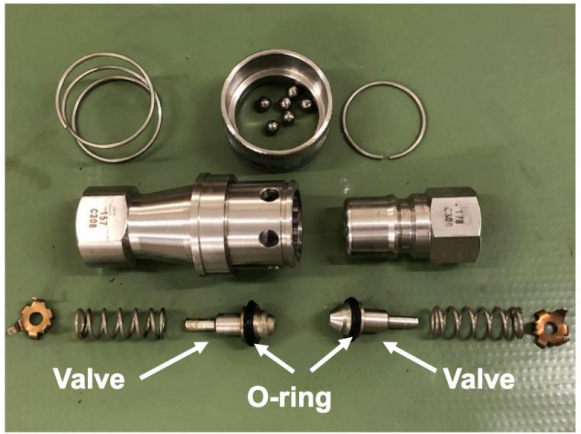
→ *Studies for the Upgrade of Belle II Aerogel RICH*
by Shunsuke KUROKAWA (Tokyo Metropolitan University)

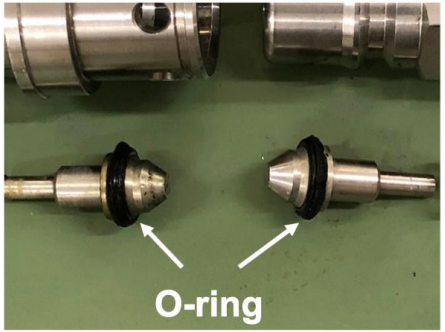
BACKUP

Water Cooling Problem

- The couplers were investigated recently.
- We did not find any solid matter inside.







- Swell of the O-ring (made of chloroprene rubber) was seen.
- Relation with anti-corrosion agent?

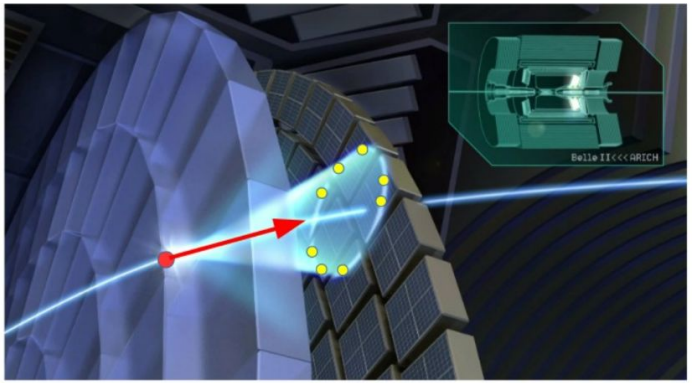
Likelihood calculation

Recap of the PID method

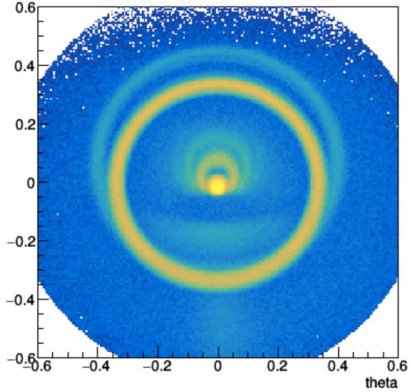
- reconstructed tracks are extrapolated from the CDC to the ARICH volume.

- we construct likelihood function for 6 particle (e, μ, π, K, p, d) type hypotheses for each track (independently)

- based on comparison of observed pattern of detected photons with the expected one assuming given track parameters and particle type.



Measured data



Likelihood function

$$\mathcal{L} = \prod_{i}^{pixels} p_i$$

$$p_i = e^{-n_i} n_i^{m_i} / m_i!$$

For each particle hypothesis h

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

Expected total number of hits

Expected number of hits on pixel i