



Operation and Performance of Aerogel RICH detector at Belle II

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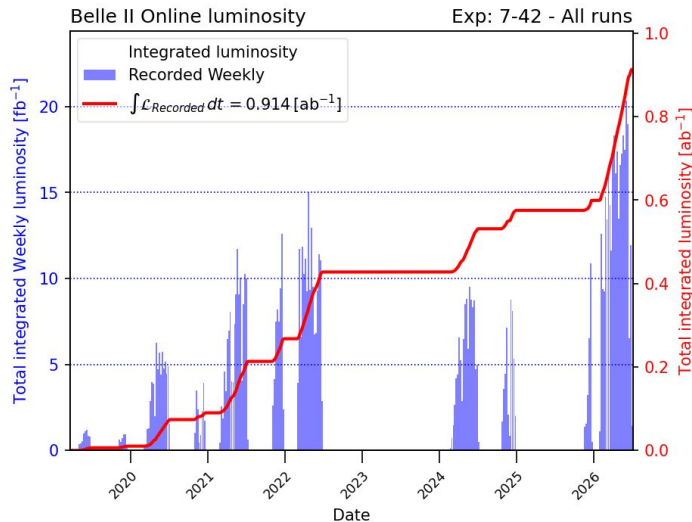
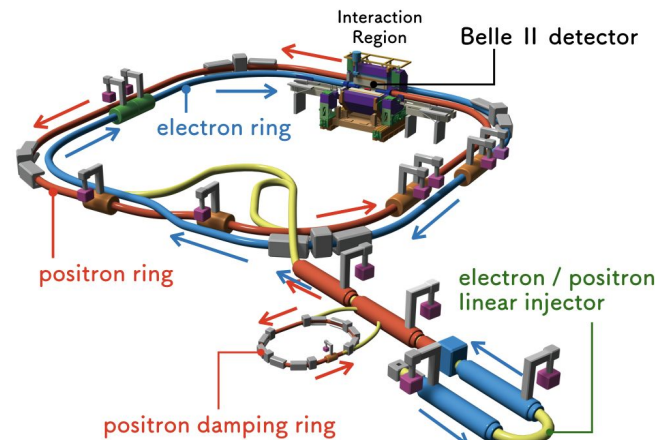
Indian Institute of Technology, Hyderabad

(On behalf of the Belle II ARICH Group)

SuperKEKB & Belle II

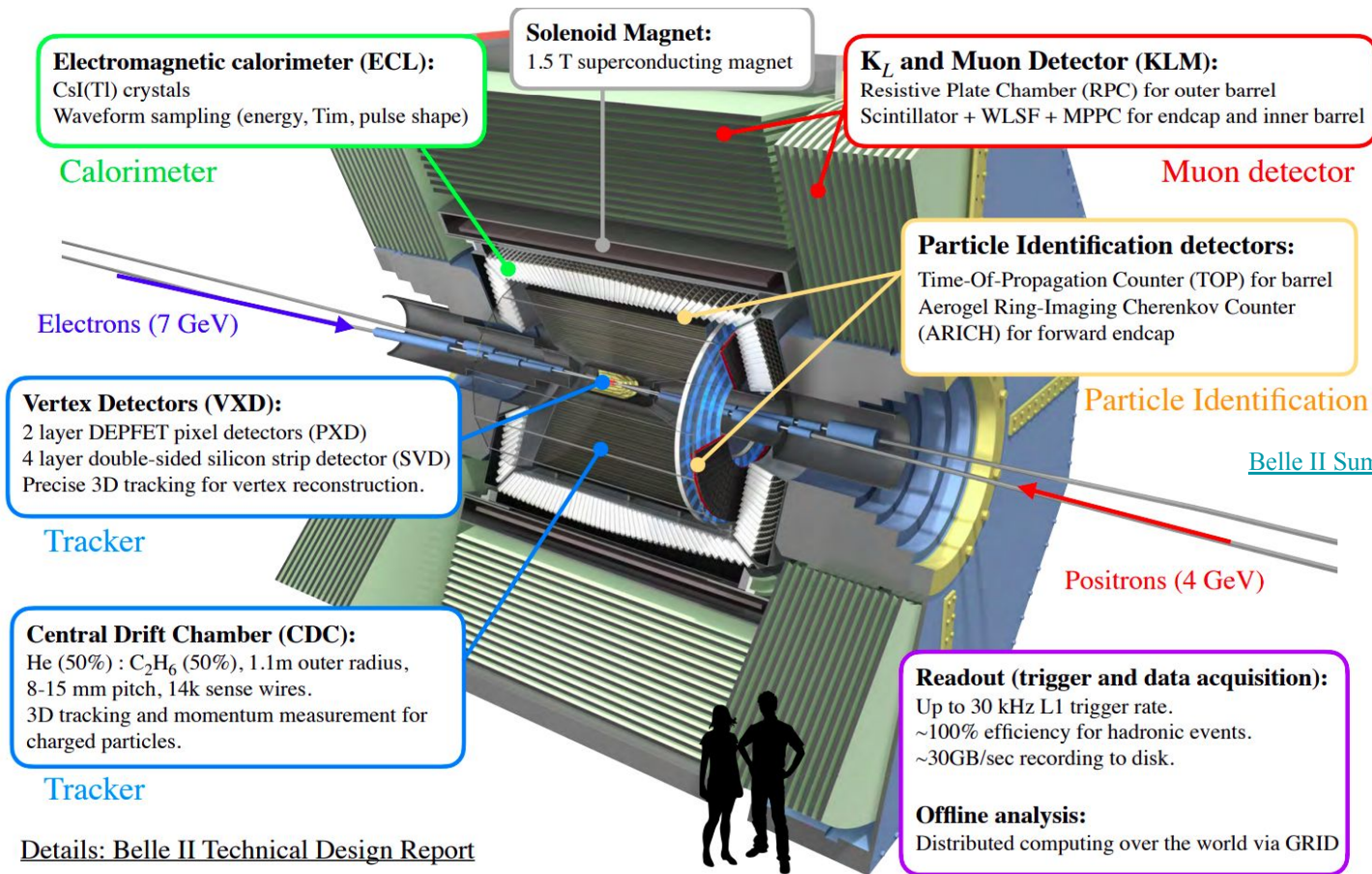
- **SuperKEKB accelerator:**

- Asymmetric e^+e^- **collider** located at KEK Japan.
- $\sqrt{s} \approx 10.58$ GeV , operates around **Y(4S)** resonance
- Provides a clean environment for **$B\bar{B}$** production
- Peak luminosity = $5.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



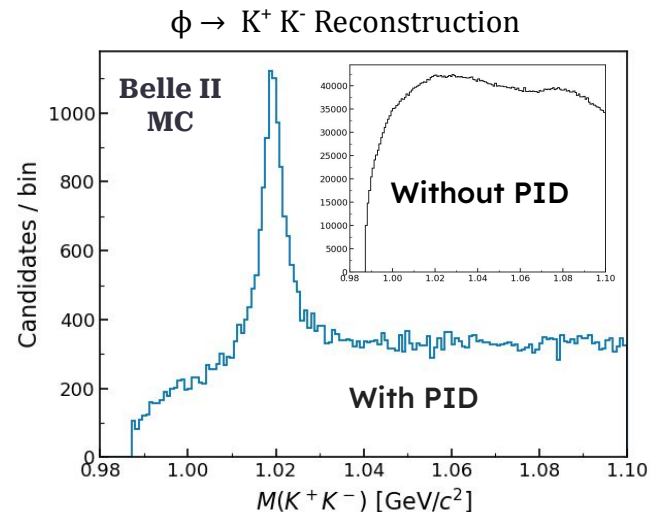
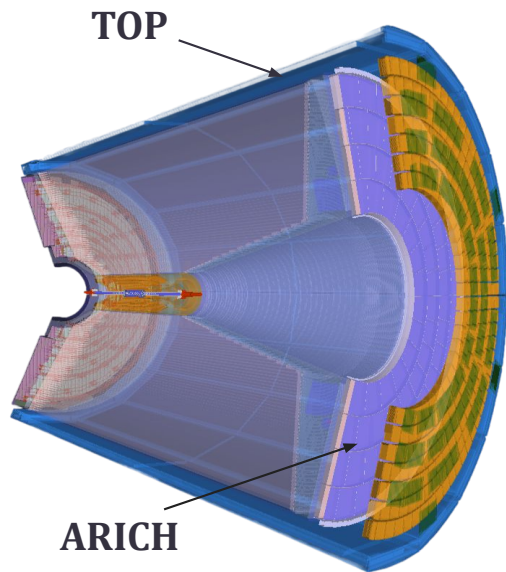
- Belle II Search for physics beyond the Standard Model through precision measurements of rare decays
- Physics data taking since 2019; Total 808 fb⁻¹ collected at the Y(4S)
- Long-term integrated luminosity goal : 50 ab⁻¹

Belle II Detector



Particle Identification at Belle II

- Charged particle identification is crucial for separating charged particles and suppressing background.
- Belle II requires π/K separation over a wide momentum range for flavor tagging and precision measurements.

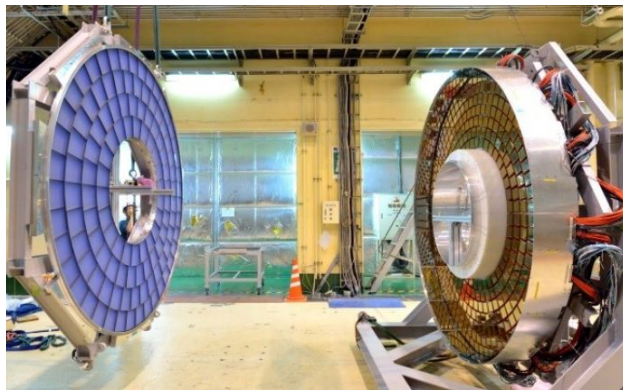
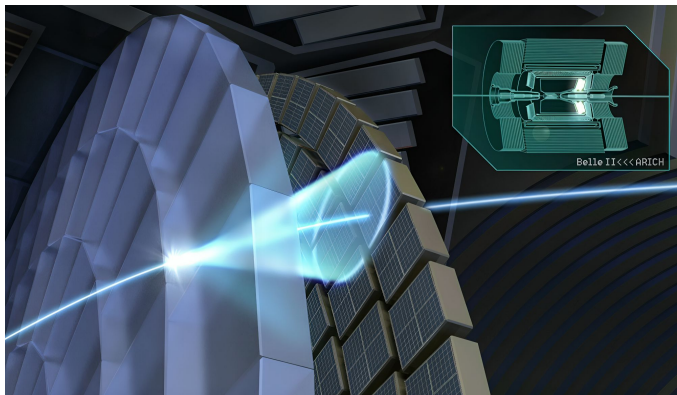
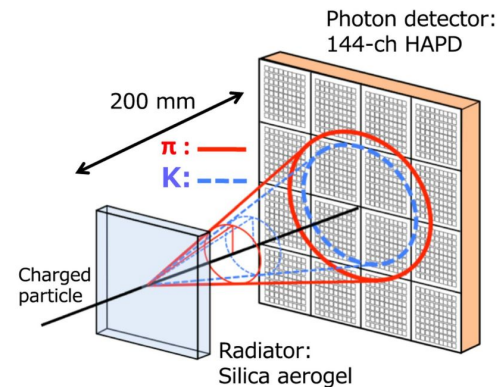


<https://arxiv.org/abs/1101.3276>

- Belle II has two dedicated detectors for PID:
 - TOP in Barrel Region
 - ARICH in the Forward End-cap region
- The global PID likelihood also uses information from SVD and CDC (dE/dx), ECL (shower information) and KLM (muon identification).

ARICH Detector

- ARICH (Aerogel Ring Imaging Cherenkov) is the dedicated Cherenkov PID detector in the forward end cap of Belle II.
- Designed to provide efficient π/K separation up to $p \sim 4$ GeV/c.
- Cherenkov photons produced in the aerogel propagate through the expansion region (~ 20 cm) and form a ring image on the photon-detector plane.
- Planar mirrors at the detector edges enhance the detected photon yield.



Aerogel and HAPD Planes during Installation

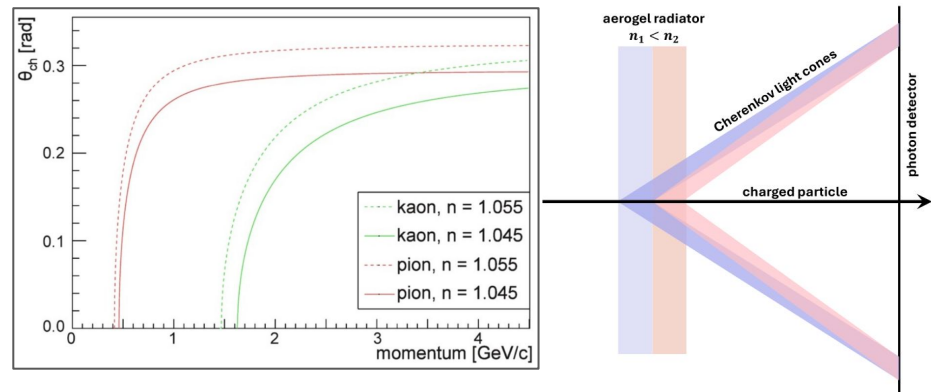
<https://arxiv.org/abs/2512.19146>

Principle of Aerogel radiator

- A charged particle emits Cherenkov radiation when;

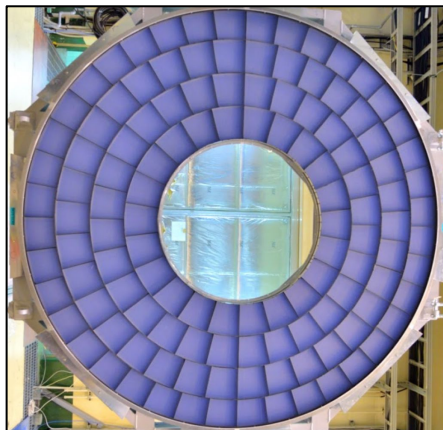
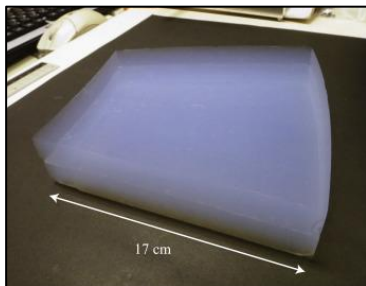
$$\beta n > 1 \quad \text{with,} \quad \cos \theta_C = \frac{1}{\beta n}$$

- The emitted photons form a cone around the particles path.
- At a given momentum, different masses give different velocities β , and therefore different Cherenkov angles.



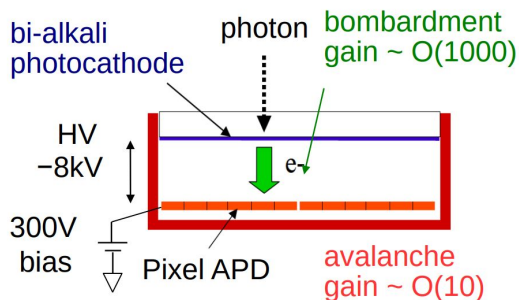
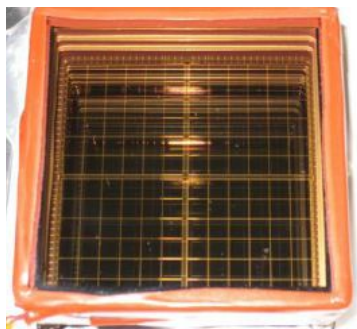
Dual-layer silica aerogel: $n_1 \approx 1.045$, $n_2 \approx 1.055$

- 124 $\times$ 2 tiles, $\sim 17 \times 17 \text{ cm}^2$, 2 cm + 2 cm thickness, arranged in four concentric rings
- The dual layer focusing improves the Cherenkov-angle resolution compared with a single 4 cm radiator.
 - single 4 cm radiator: $\sigma_\theta = 20.7 \text{ mrad}$
 - Dual-layer: $\sigma_\theta = 14.3 \text{ mrad}$

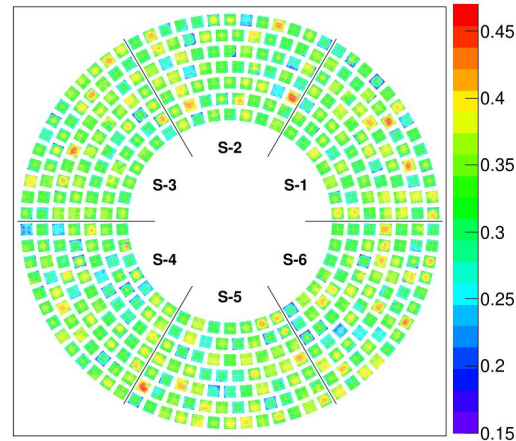


Photon Detectors (HAPDs)

- Photon detector requirements
 - Single photon sensitivity
 - Operation in 1.5 T magnetic field
 - Sufficient radiation tolerance for an accumulated neutron fluence of 10^{12} cm^{-2} (1 MeV equivalent).
- Hybrid Avalanche Photon detector:
 - Bi-alkali photocathode on quartz window $\rightarrow$ vacuum tube $\rightarrow$ 4 APD chips
 - 420 Hapd arranged in 7 rings; Each having 12×12 pixels = 144 channels
 - Pixel size: $4.9 \times 4.9 \text{ mm}^2$, Provide good spatial resolution



Mean quantum efficiency $\sim 32\%$

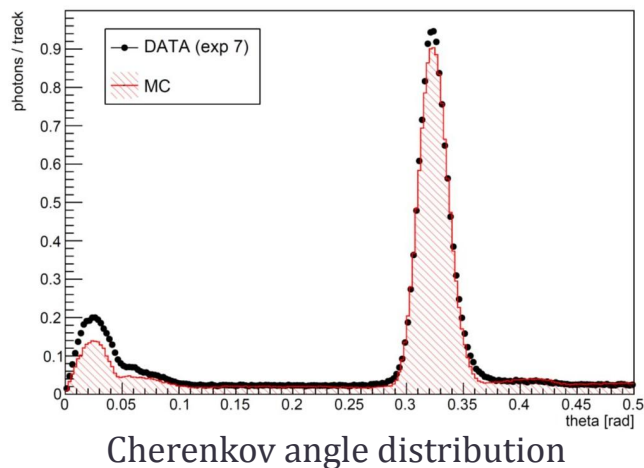
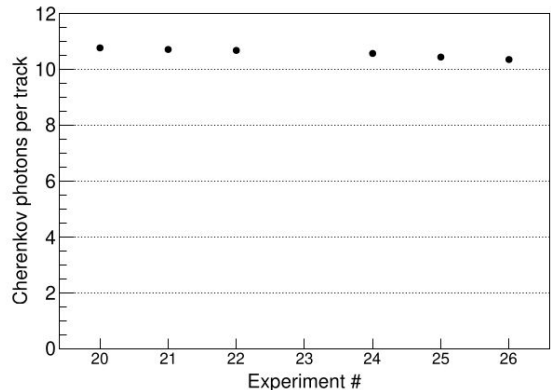
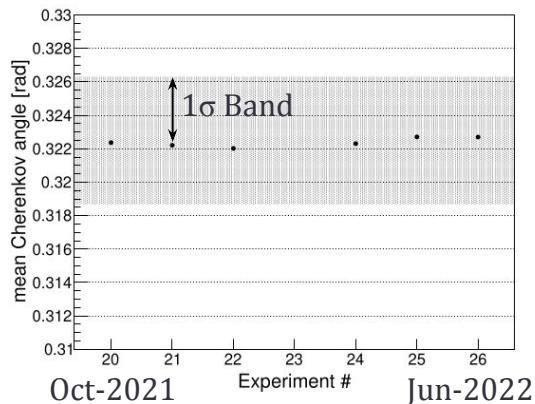


Quantum Efficiency at 400 nm

Working: Cherenkov photons produces photoelectrons at the photocathode, which are accelerated onto the APD and amplified by avalanche multiplication, Later processes by readout electronics.

Detector Operation: I

- High momentum ($p > 4 \text{ GeV}/c$) muons are used to track performance.
- Photon Cherenkov angle resolution $\sigma_{\text{photon}} \approx 12.7 \text{ mrad}$.
- Approximately 11 signal Cherenkov photons per muon track, giving an estimated $\sigma_{\text{track}} \approx 3.8 \text{ mrad}$.
- Mean Cherenkov angle and Photons per track remains stable over time



Detector performance as a function of time using muons $p > 4 \text{ GeV}/c$
(the gray region indicates the $\pm 1\sigma$ track band for 4 GeV/c pions)

Detector Operation: II

- ARICH remained operationally stable during recent run periods in 2025 and 2026.

Masked channels : Dead and problematic channels masked during runs.

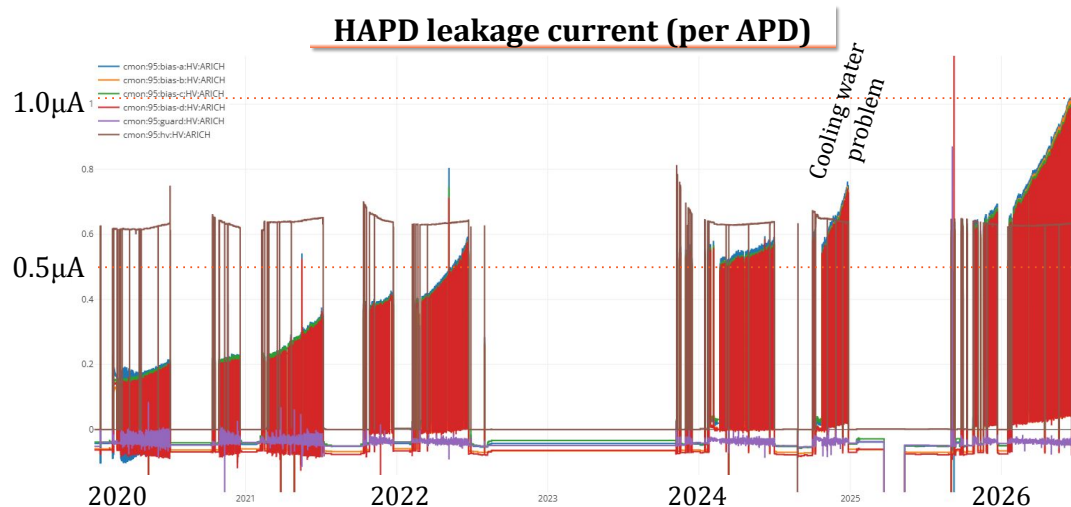
	2019	2020	2021	2022	2023	2024	2025	2026
Ratio	4.8%	5.6%	6.0%	6.5%	5.4%	6.6%	6.7%	7.0%

- Main causes of dead channels:
 - APD bias and guard problems
 - High voltage problems

The masked channels fraction has increased, and stabilized near 7% in 2026

Radiation damage

- Neutron damage increases APD leakage current and can affect photon detection.
- 2026 leakage current: $\sim 1 \mu\text{A}/\text{APD}$
- Increasing leakage current remains well within the tested tolerance below $30 \mu\text{A}/\text{APD}$ at fluences up to approximately $10^{12} \text{ neq}/\text{cm}^2$.



Likelihood Based PID

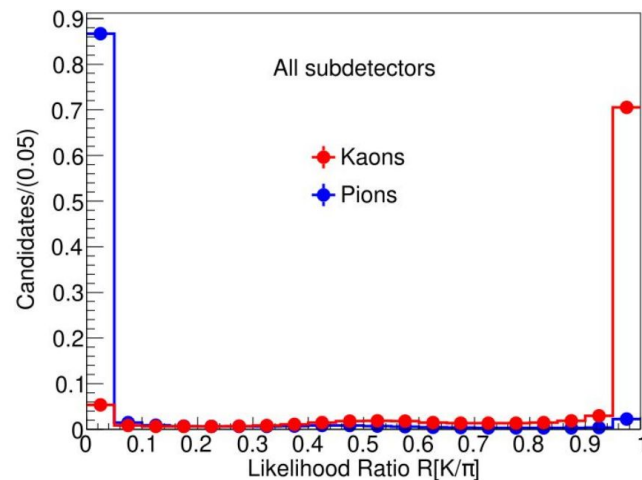
- Use the track's momentum, position and direction to predict the photon pattern for each particle hypothesis $h = e, \mu, \pi, K, p, d$.
- Calculate the expected photon count in each pixel, including signal and background.
- Compare the prediction with the recorded hit pattern. Both hit and empty pixels contribute to the likelihood.

$$\ln \mathcal{L}_h = -N_h + \sum_{\text{hit } i} [n_{h,i} + \ln(1 - e^{-n_{h,i}})]$$

Total Expected count

Sum over
hit pixels

Expected photon
count in pixel i

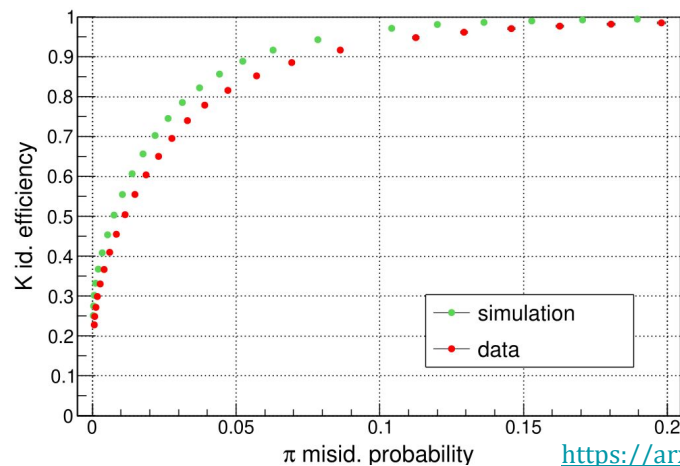
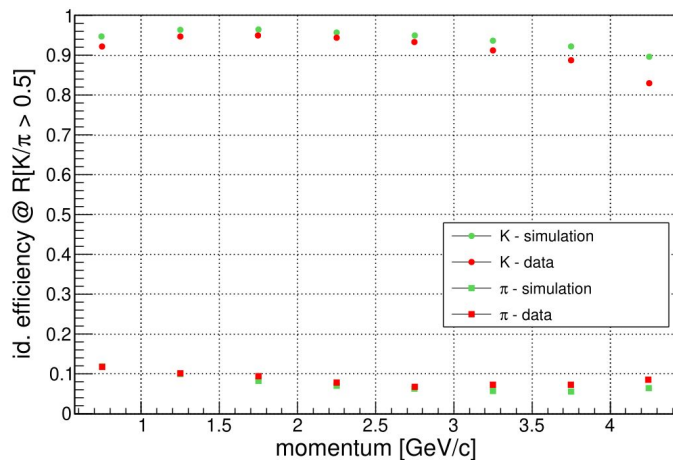


Binary PID at Belle II

- Compare the kaon and pion likelihoods using: $R(K/\pi) = \frac{L_K}{L_K + L_\pi}$

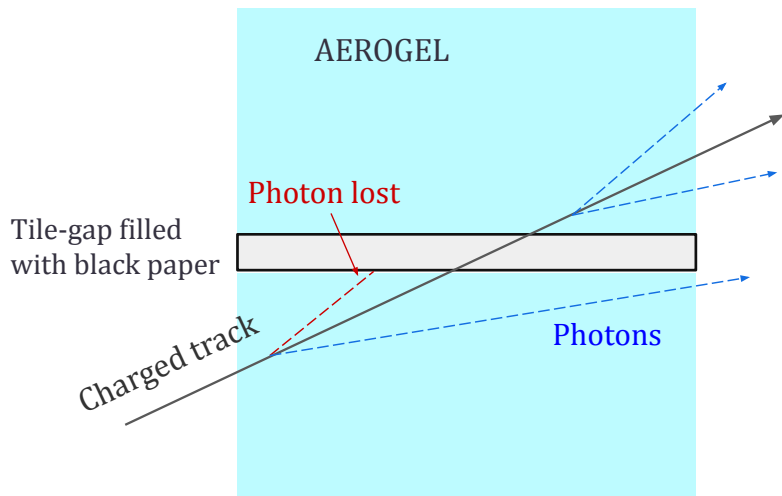
PID Performance

- PID performance studied by reconstructing decays $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K^- \pi^+$ decay
- At higher momentum Cherenkov angles difference decreases, making separation more difficult.
- We observe discrepancy between Data and MC
- The main reasons for discrepancy:
 - Imperfect modelling of aerogel tile boundaries and gaps
 - Incomplete treatment of charged particle decay in flight before reaching the aerogel.

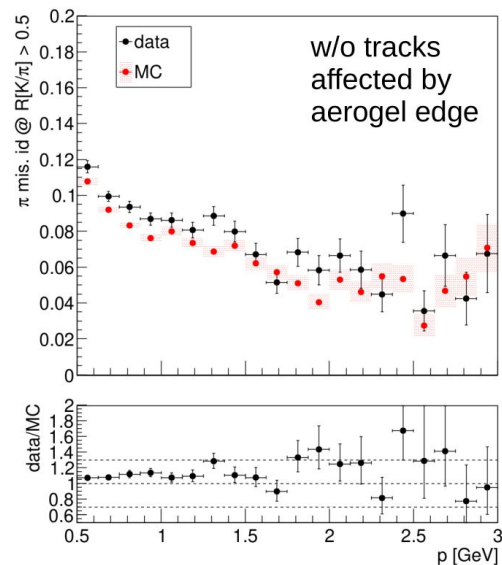
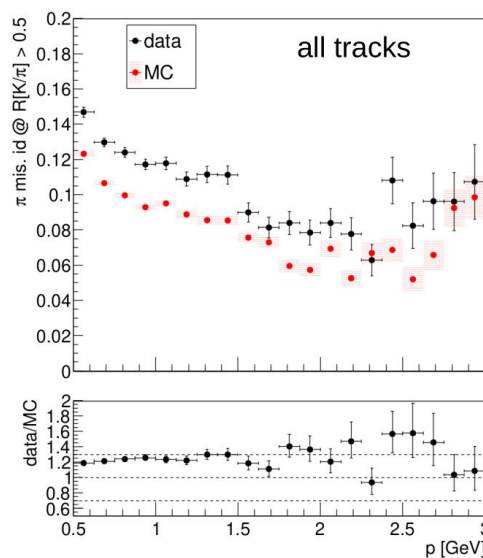


Aerogel Tile gaps studies: I (The problem)

- Actual aerogel tile positions and gaps differ from the nominal detector geometry.
- Photon losses near tile boundaries affect the detected photon yield and hit distribution, leading to inaccuracies in the PID likelihood calculation.
- Excluding tracks affected by tile edges improves data/MC agreement.

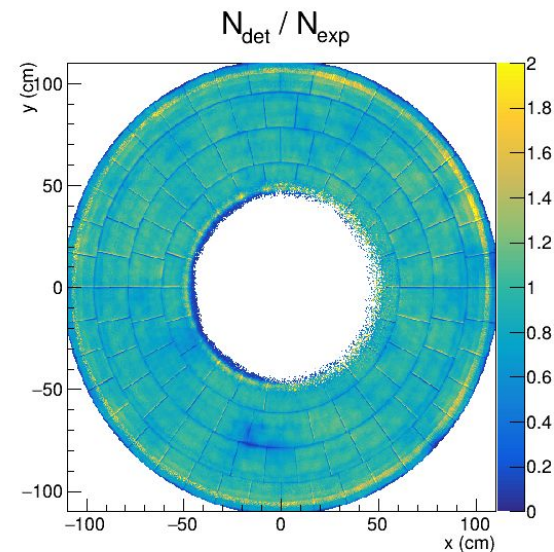
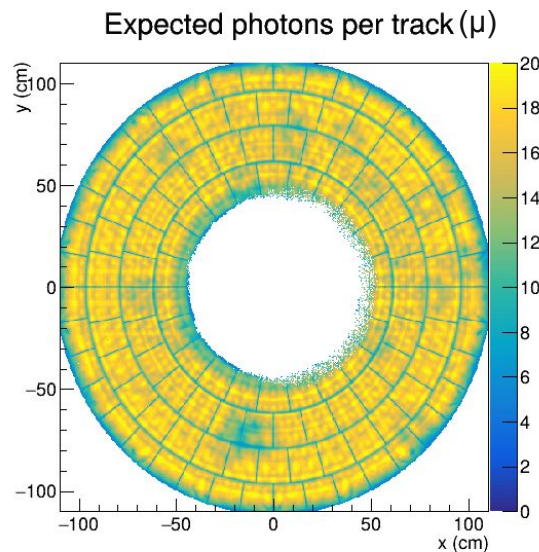
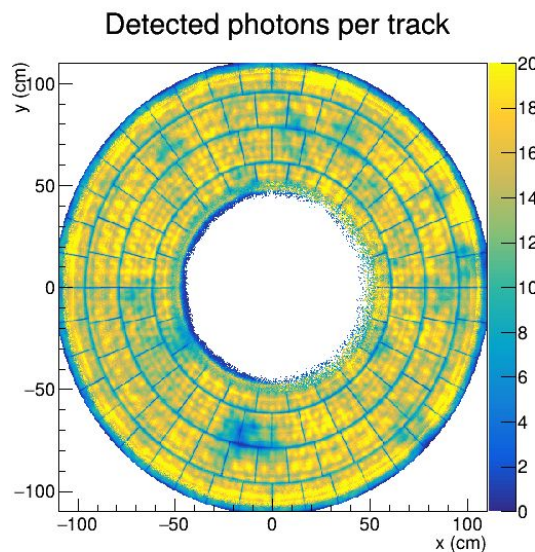


Goal: Study tile-gap positions and photon losses to improve the expected photon calculation.



Aerogel Tile gaps studies: II (Key observables)

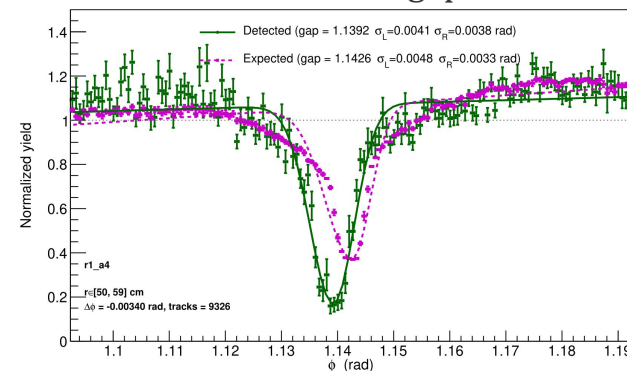
- **Dataset:** Saturated tracks reaching ARICH, from $e^+e^- \rightarrow \mu^+\mu^-$ process ($p_{\text{Lab}} \in 5.5\text{--}7.5\text{ GeV}/c$)
- Compare the detected and expected photon yields per track across the aerogel plane.
- Detected/expected Photon ratio highlights the differences near tile boundaries.



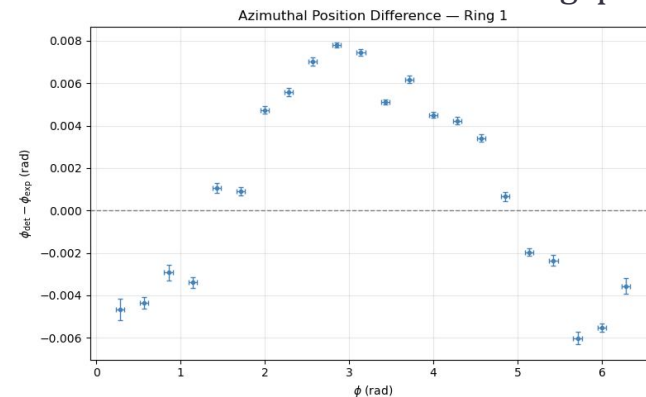
Aerogel Tile gaps studies: III (Results & Next steps)

- Expected and detected photon distribution near the gap positions are fitted separately using 1d binned fit.
- Fit model: Inverted Gaussian + 1st order polynomial
- Fitting results:**
 - Shift in position of the gaps is observed in both radial and azimuthal directions.
 - The detected photon yield dips are deeper than predicted, indicating higher photon loss.
- Next steps :** Implement the measured boundary corrections in the expected-photon calculation and evaluate their effect on data-MC agreement and PID performance

1d Azimuthal gap fit



Position difference in azimuthal gaps



Summary

- ARICH provides particle identification in the Belle II forward endcap over a wide momentum range
- Detector operation remains stable over time.
- It provides K efficiency $\sim 90\%$ while π mis-identification rate $\lesssim 10\%$
- Tile-gap positions measured with $e^+e^- \rightarrow \mu^+\mu^-$ events show radial and azimuthal shifts from the nominal geometry.
- Geometry corrections are yet to be implemented; their impact on data-MC agreement and PID performance is to be evaluated.

Thank You for your attention!

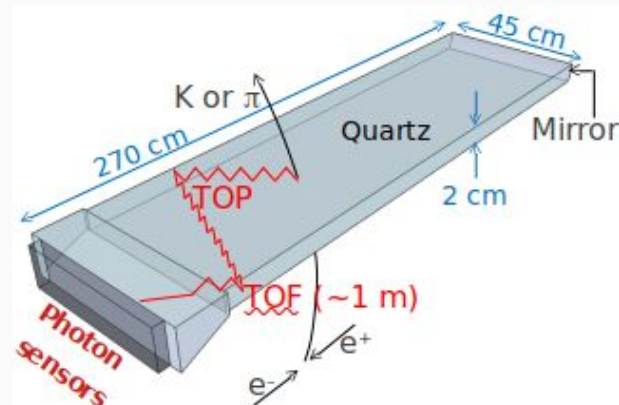
Backup

References

1. [T. Abe et al. Belle II Technical Design Report, KEK-REPORT-2010-1](#)
2. [Accelerator design at SuperKEKB Ohnishi et. al 2013. 10.1093/ptep/pts083.](#)
3. [Belle II Physics book](#)
4. [Aerogel RICH Counter at the Belle II Detector \(2025\)](#)
5. [Studies for the upgrade of Belle II Aerogel RICH - ScienceDirect](#)
6. <https://docs.belle2.org/files/4091/BELLE2-PTHESES-2021-008/1/BELLE2-PTHESES-2021-008.pdf>
7. [Recent developments in data reconstruction for aerogel RICH at Belle II - ScienceDirect](#)
8. [Particle identification performance of the prototype aerogel RICH counter for the Belle II experiment | Progress of Theoretical and Experimental Physics | Oxford Academic](#)
9. [Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider](#)

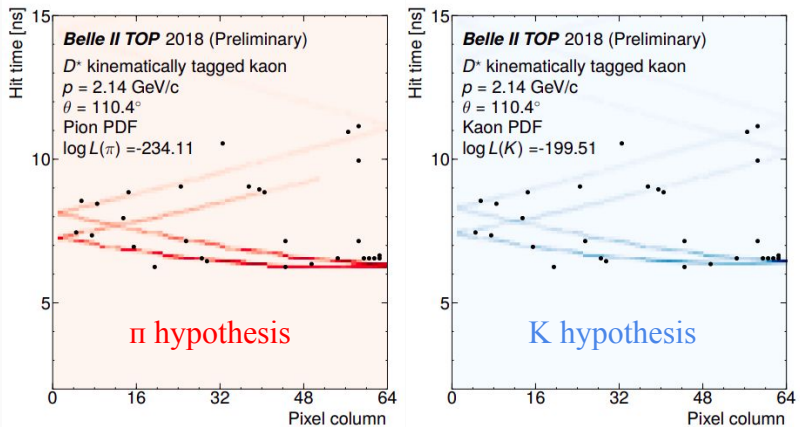
TOP Detector at Belle II

- 16 modules provide particle identification in the Belle II barrel region
- 32 MCP-PMTs per module, providing 512 readout channels.
- Each module contains two fused-silica bars, a spherical mirror, an expansion prism and MCP-PMTs.
- Single-photon timing resolution ≈ 50 ps.
- π/K discrimination up to approximately 4 GeV/c.



Working

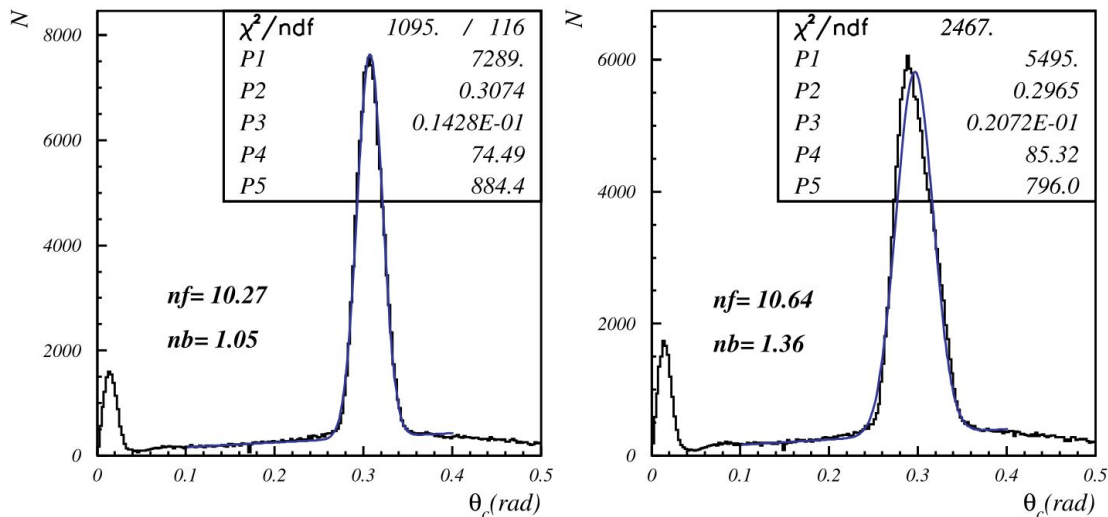
- Charged particles emit Cherenkov photons in the quartz.
- Photons travel through the bars by total internal reflection.
- MCP-PMTs measure the photon hit positions and arrival times.
- A likelihood compares the measured pattern with predictions for each particle hypothesis.



Cherenkov angle in 2 layer vs single layer configuration

Single layer configuration : $\sigma_\theta = 20.7$ mrad

Double layer configuration provide : $\sigma_\theta = 14.3$ mrad



Cherenkov angle for a focusing configuration with two 2 cm thick layers with $n_1 = 1.045$, $n_2 = 1.055$ (left) and for a 4 cm homogeneous radiator (right)

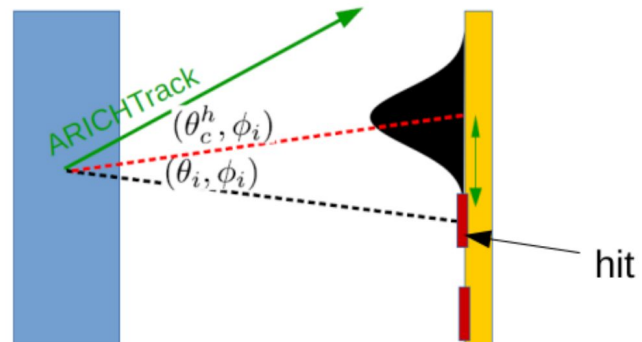
Expected Photons Calculation

- The reconstructed track gives the particle's momentum, position and direction at the aerogel plane.
- For each hypothesis ($h = e, \mu, \pi, K, p, d$) predict the Cherenkov angle and photon distribution on the HAPD plane.
- Integrate the predicted signal over each pixel and add background:

$$n_i(h) = n_{i,\text{signal}}(h) + n_{i,\text{background}}(h)$$

$$n_i(h): \text{expected mean count in pixel } i.$$
- The total expected count $N(h)$ accounts for tile-gap losses, detector acceptance and inactive channels.
- Detected photons: the recorded HAPD hits, including background. Each pixel records hit or no hit.

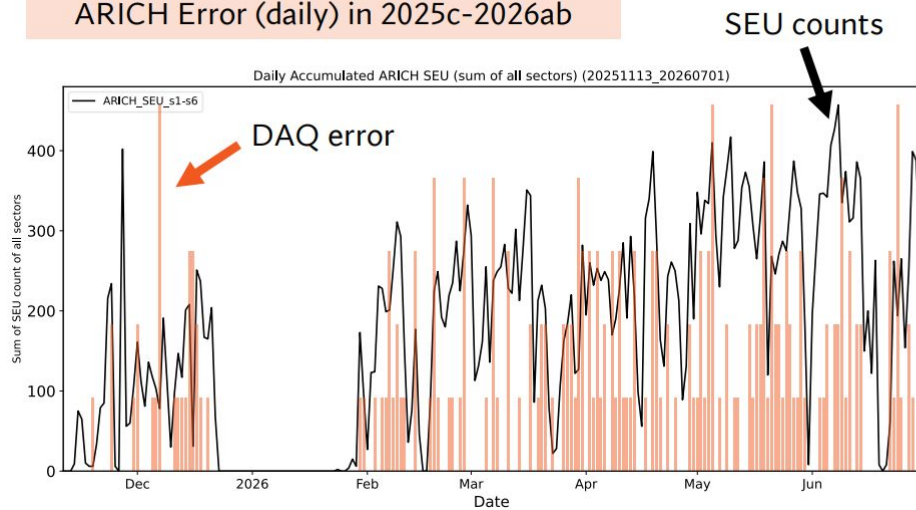
$N(h)$: total expected count



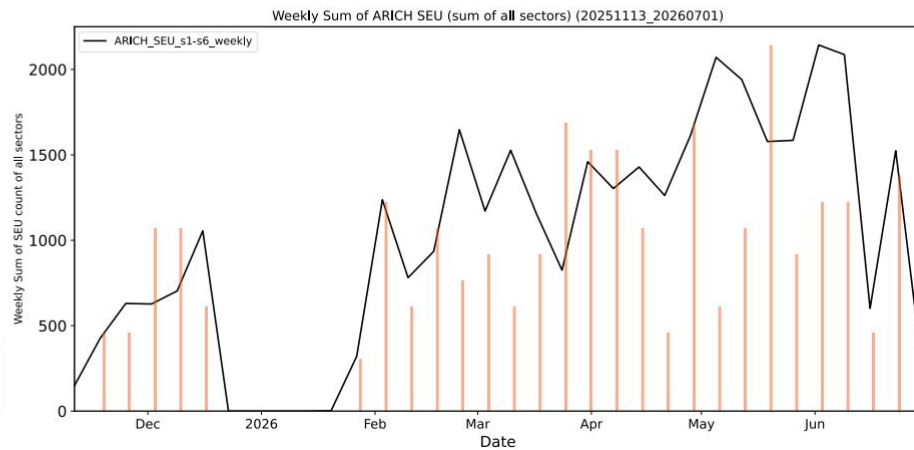
Data Acquisition Stability

- During data taking ARICH has been very stable during run period 2025c-2026ab.
- Single Event Upsets (SEUs) in the readout electronics can cause DAQ errors.
- Merger boards are reprogrammed during no beam periods to recover from SEU-related errors.

ARICH Error (daily) in 2025c-2026ab

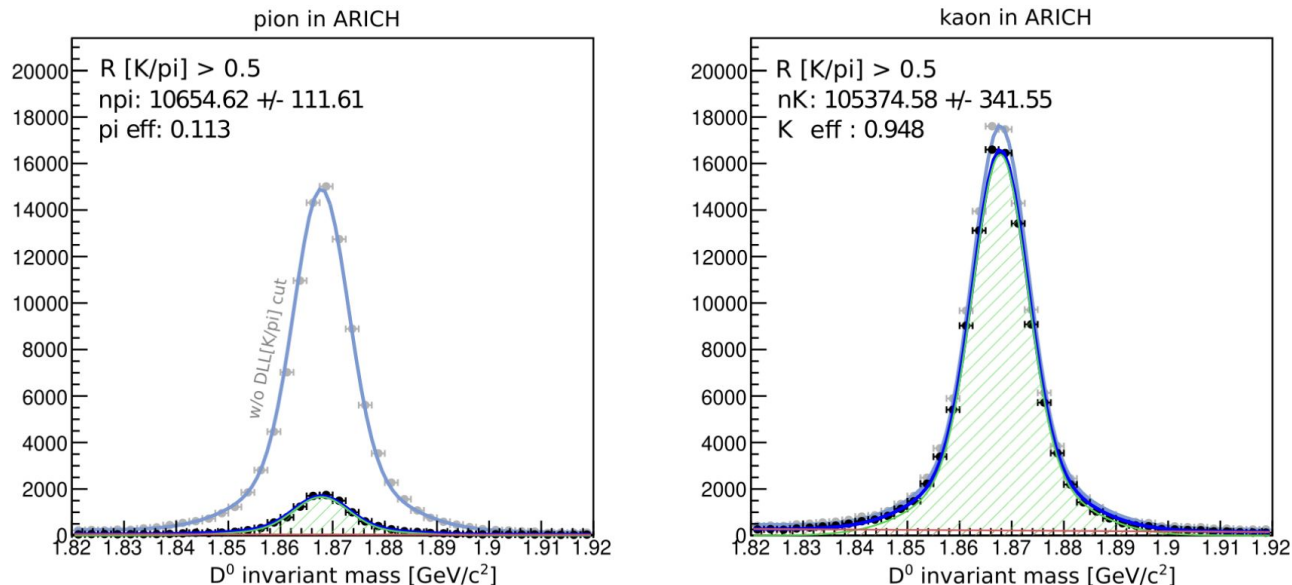


ARICH Error (weekly) in 2025c-2026ab



Pid performance of ARICH from $D^0 \rightarrow K \pi$ decay

Performance plot for Kaon efficiency and pion Mis-identification rate; obtained by reconstructing decays $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K \pi$ decay.



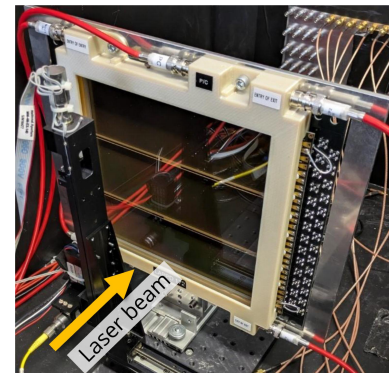
Plots are for pions (Left) and kaons (Right) reaching ARICH
 Green shaded area represent events after $R[K \pi] > 0.5$ cut

Replacements for HAPDs

- HAPDs: Dead channel fraction increasing gradually, manufacturing company (Hamamatsu) stopped production.
- New photon detectors: MPPC (SiPM) and LAPPD are being evaluated, together with new readout electronics.

	Current HAPD	MPPC (SiPM)	LAPPD
Size	$\sim 75 \times 75 \text{ mm}^2$	$25.8 \times 25.8 \text{ mm}^{2*}$	$\sim 30 \times 27 \text{ cm}^{2*}$
Gain	$\sim 5.6 \times 10^4$	$\sim 4 \times 10^6$	$\sim 10^6$
Main challenge	Production ended	Radiation-induced dark counts	Large size / magnetic-field tests

- MPPC: Neutron radiation increases dark counts (High noise); cooling and annealing reduce them. A 64-channel readout system has demonstrated single-photon detection.
- LAPPD: $\sim 92\%$ of the tested area is sensitive, with uniform gain. TOFPET2-based readout is being studied.



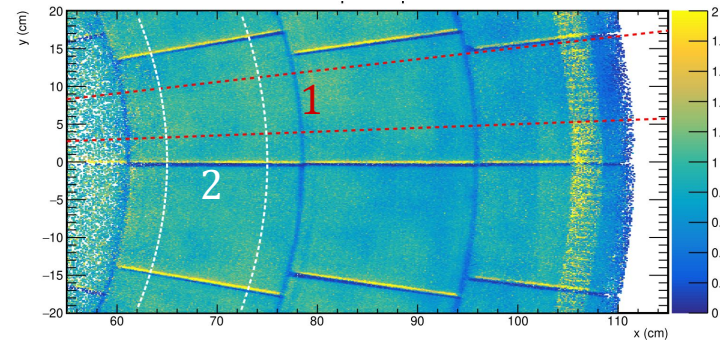
Setup for LAPPD performance evaluation using pulsed laser



prototype MPPC readout with custom TF01A64 ASIC

Aerogel Tile gaps studies: (Fitting Gaps)

- Gaps in radial (r) and azimuthal (ϕ) are fitted in suitable binning where one gap should not affect other.
- We fit the expected and detected photons 1-d histograms separately, to determine the shift in positions.
- The depth of the gaussian gives information about the amount of photon loss and size of gap region.

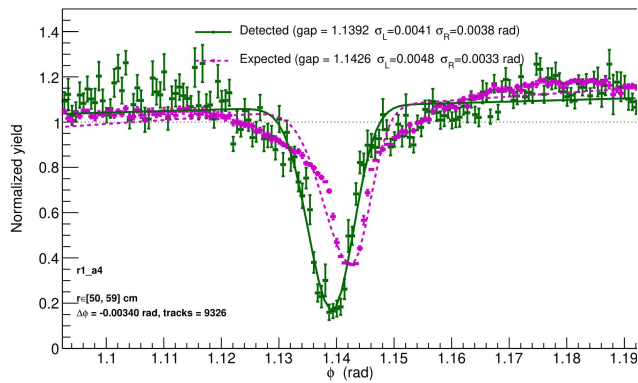


Selection of Bins for fitting the gaps

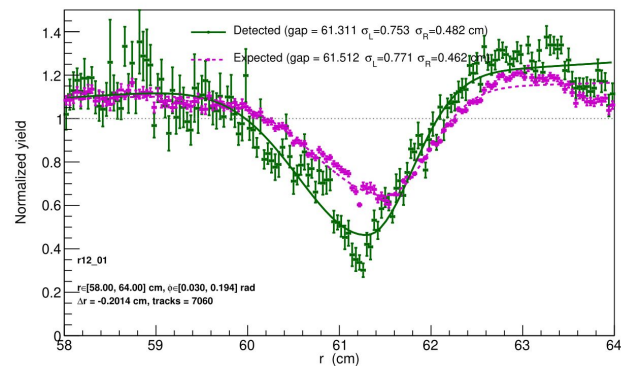
Fitting model:

$$f(x) = p_0 + p_1x - A \begin{cases} G(x; \mu, \sigma_L), & x < \mu \\ G(x; \mu, \sigma_R), & x \geq \mu \end{cases}$$

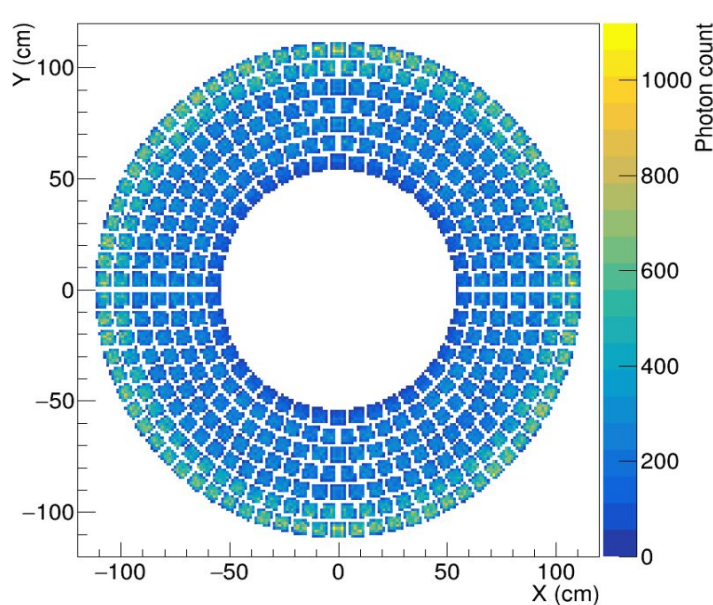
Azimuthal gap fit



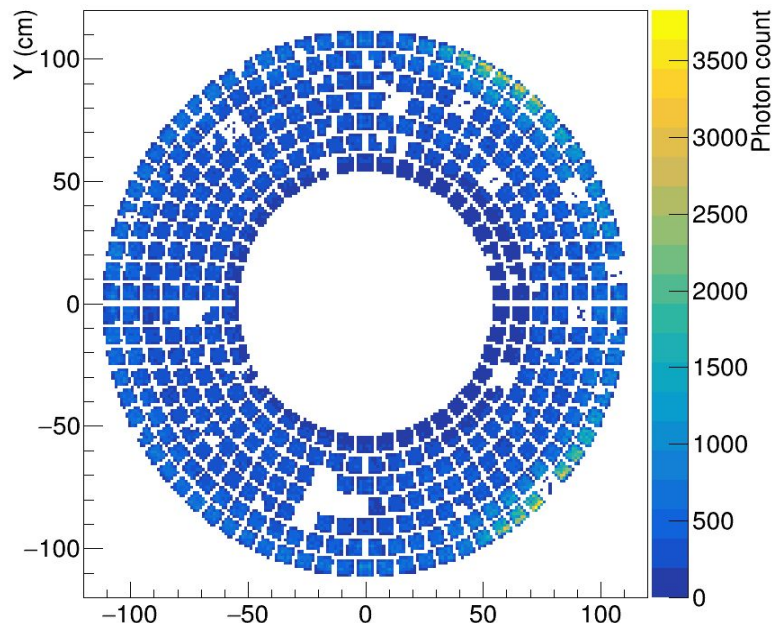
Radial gap fit



Aerogel Tile gaps studies: (Photon hit positions on HAPD)



IN MC



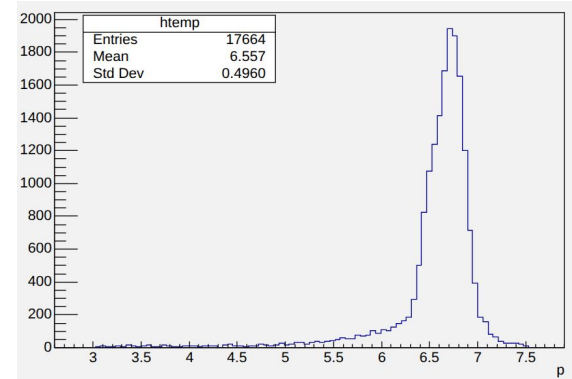
IN DATA

- Several HAPDs were inactive during data taking (bucket 26-36), visible as empty regions.
- They are fixed during long shutdown in 2022.

Aerogel Tile gaps studies: (Mumu tight Skim selections)

This used as preselection for events in Tile-gap alignment study.

- The event must contain exactly two charged tracks
 - **(nTracks == 2)**
- Each track must deposit less than 0.5 GeV in the ECL.
 - **(enECLTrack1 < 0.5 & enECLTrack2 < 0.5 GeV)**
- The total dimuon visible energy in ECL must be below 2 GeV.
 - **(EMumutot < 2 GeV)**
- The two tracks must be back-to-back in azimuth in the CMS within 10° .
 - **(fabs(180 - fabs($\phi_1 - \phi_2$))) < 10)**
- The two tracks must be back-to-back in polar angle in the CMS within 10° .
 - **(fabs(fabs($\theta_1 + \theta_2$) - 180) < 10)**
- Each track must have CMS momentum greater than 0.5 GeV.
 - **($P_{p1} > 0.5$ & $P_{p2} > 0.5$)**



Momentum distribution in Data