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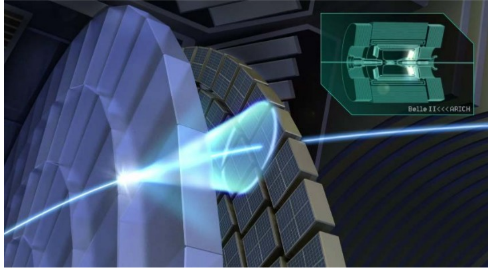


Belle II

Aerogel RICH Counter at the Belle II experiment

Luka Šantelj

F9 department seminar,

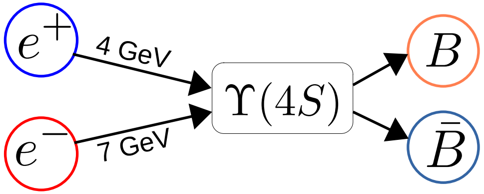
23.5.2024

Belle II @ SuperKEKB – B factory of 2nd generation

- Experiment on the **intensity frontier**

  → search for New Physics via precise measurements of rare decays of B, D mesons and τ leptons

- Successor of the very successful Belle@KEKB, in Tsukuba, Japan.
- **SuperKEKB**: asymmetric $e^{+}e^{-}$ collider operating nominally at $\Upsilon(4S)$

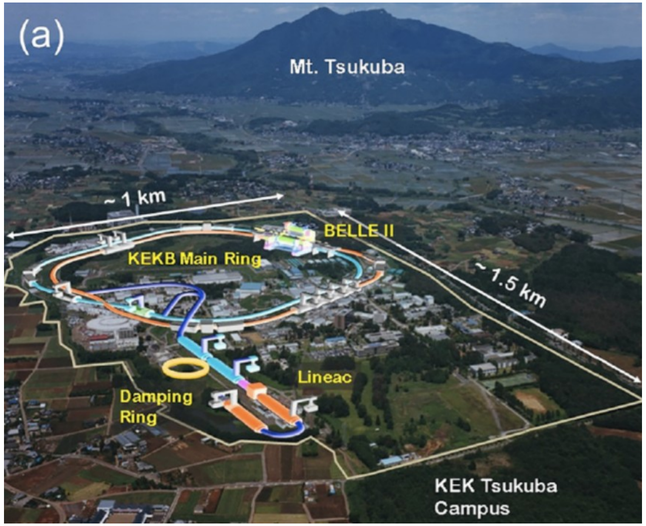


(+ large number of D, τ !)

- design luminosity of $\sim 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

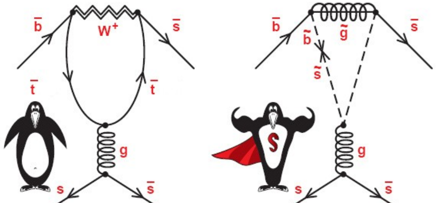
  30 x higher than KEKB!

- Plan to collect **50 x Belle** data sample



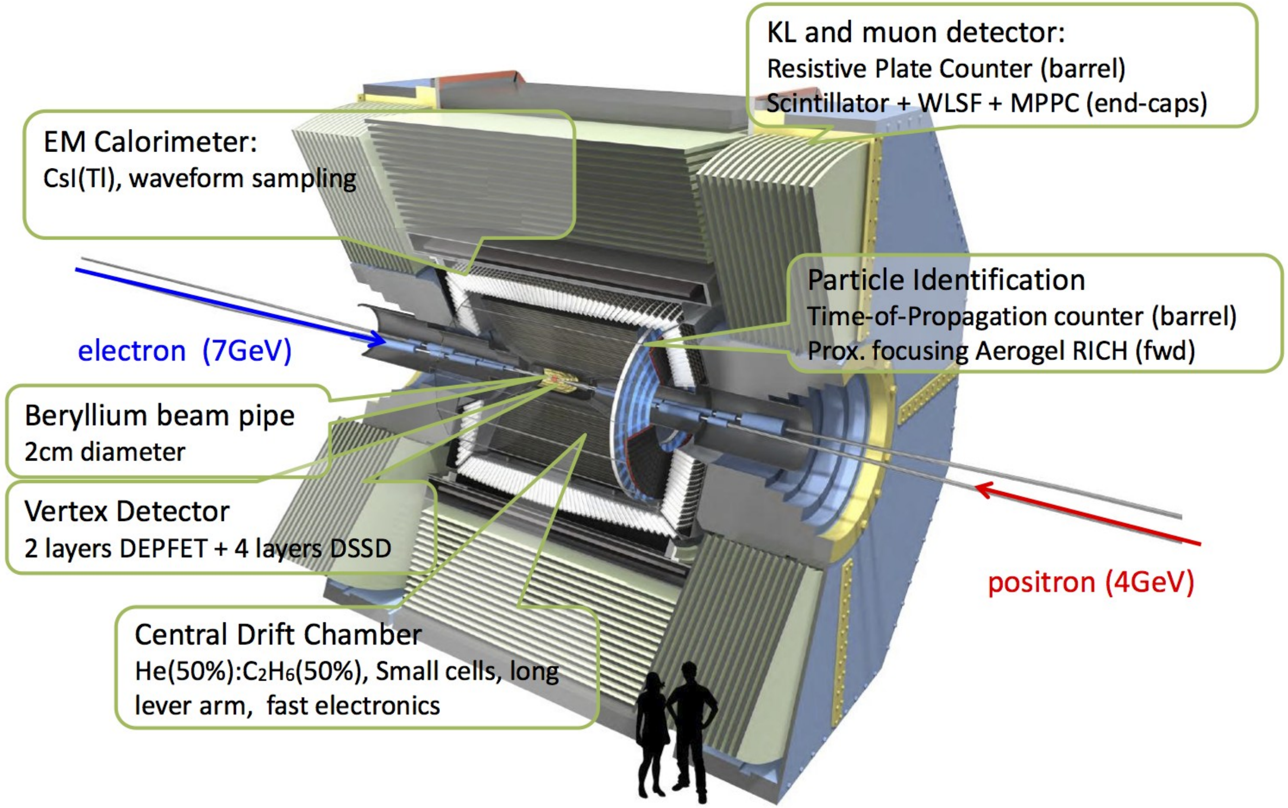
Flavour physics

- New CP violation phases?
- Is Lepton Flavour Universality broken?
- Right-handed currents from NP?
- Multiple Higgs bosons?



Belle II @ SuperKEKB – B factory of 2nd generation

The Belle II detector



- General purpose spectrometer (B=1.5 T)
- Clean e^+e^- environment
- Known initial state ($B\bar{B}$)
- $\sim 4\pi$ coverage
- high efficiency for neutrals (γ, π^0, η)
  → complementarity with LHCb
  (modes with missing energy || neutrals in fs)
- Excellent decay vertex resolution
  ($\sigma \sim 60\ \mu$m for B,D vertices)
- **two novel PID detectors**
  → Time-of-propagation counter (barrel)
  → Aerogel RICH (FWD endcap)

So far collected data

- **SuperKEKB** achieved world record instantaneous luminosity of

$$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ KEKB
$1.2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ PEP-II

- **Belle II** data taking efficiency ~ 90%

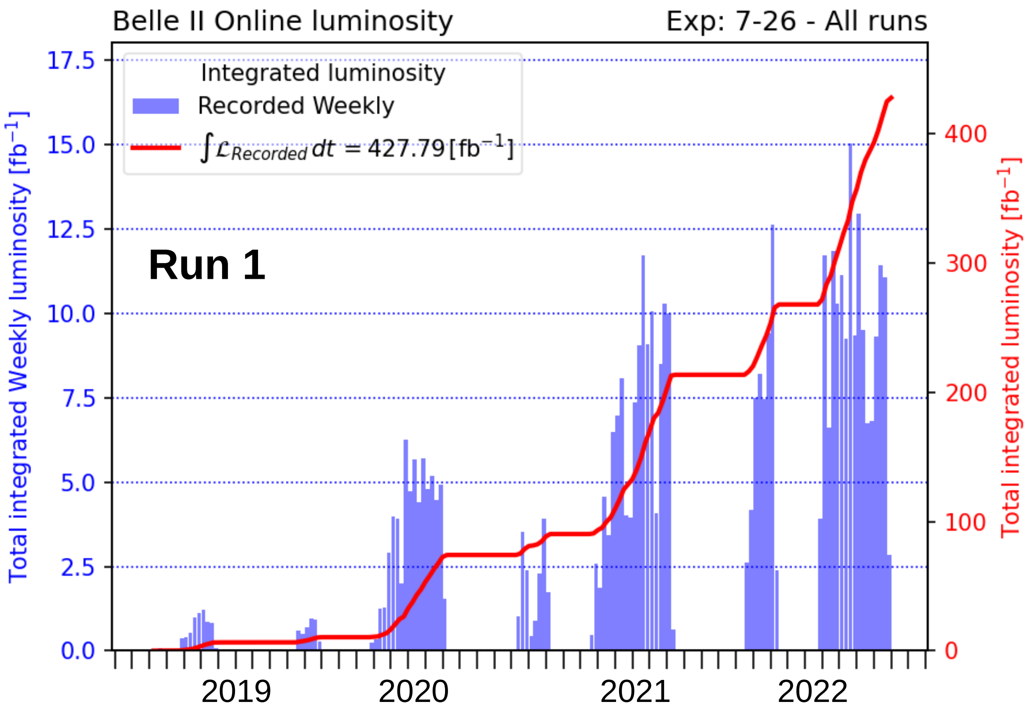
- Recorded luminosity @ Belle II

$$\sim 500\ \mathrm{fb}^{-1}$$

$988\ \mathrm{fb}^{-1}$ @ Belle
$513\ \mathrm{fb}^{-1}$ @ BaBar

- After LS1 expect boost in instantaneous luminosity

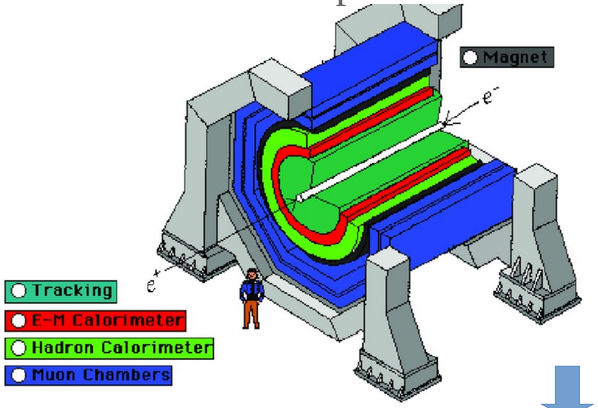
→ expect $50\ \mathrm{ab}^{-1}$ in the next 10 years

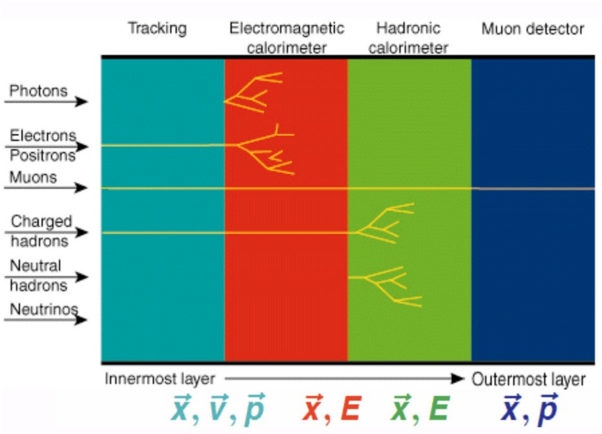


Run 2 started beginning of March
(collected ~60 fb-1 so far)

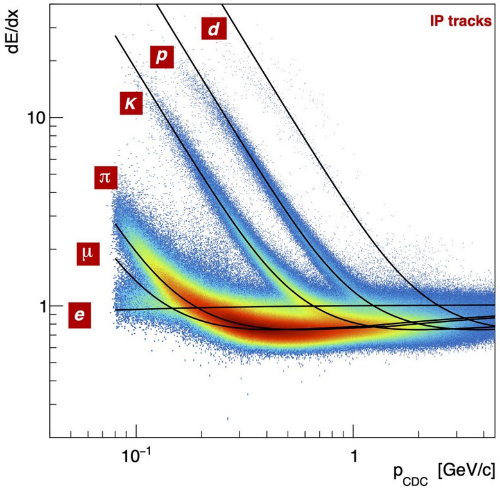
Particle ID @ Belle II

Generic collider experiment





Up to $p \sim 0.5$ GeV

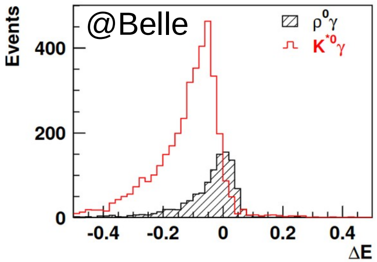


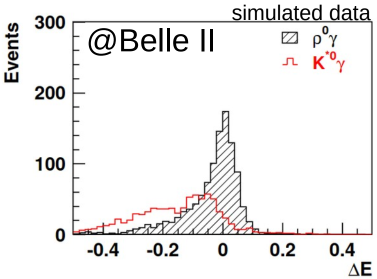
What about charged hadrons? π/K is key issue for B physics

→ background reduction

e.g. $B \to \rho\gamma, B \to K^{\star}\gamma$

$(\rho^0 \to \pi^+\pi^-;\ K^{*0} \to K^+\pi^-)$





→ efficient flavor tagging

(B^0 or $\bar{B}^0$)

$b \to c \to s\ (K^-)$

$\bar{b} \to \bar{c} \to \bar{s}\ (K^+)$

At higher momenta

$0.5 \lesssim p \lesssim 4$ GeV

→ measure particle velocity

(at given p different for different particle masses → ID)

→ go beyond TOF measurements by using **Cherenkov light**

Aerogel RICH detector

Target

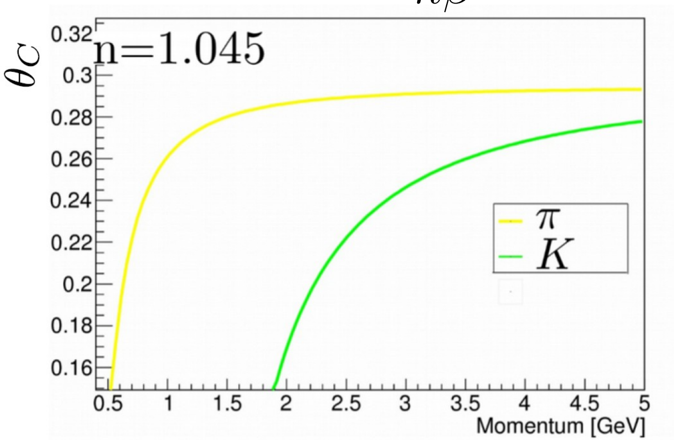
$4\sigma\ \pi/K$ separation @ 0.5 - 4.0 GeV
+ contribute to low momentum lepton ID

Constraints

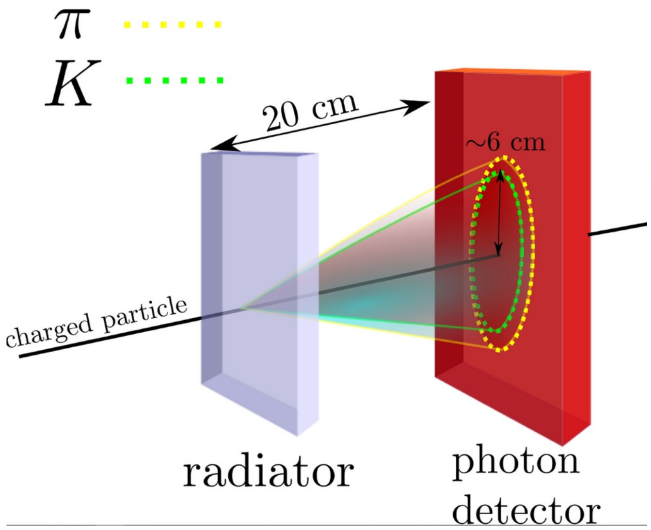
- 1.5 T magnetic field
- limited space (doughnut with L~28 cm)
- radiation hardness ($> 10^{12}$ 1 MeV n eq/cm^2)
- covers a large area (~3 m^2)

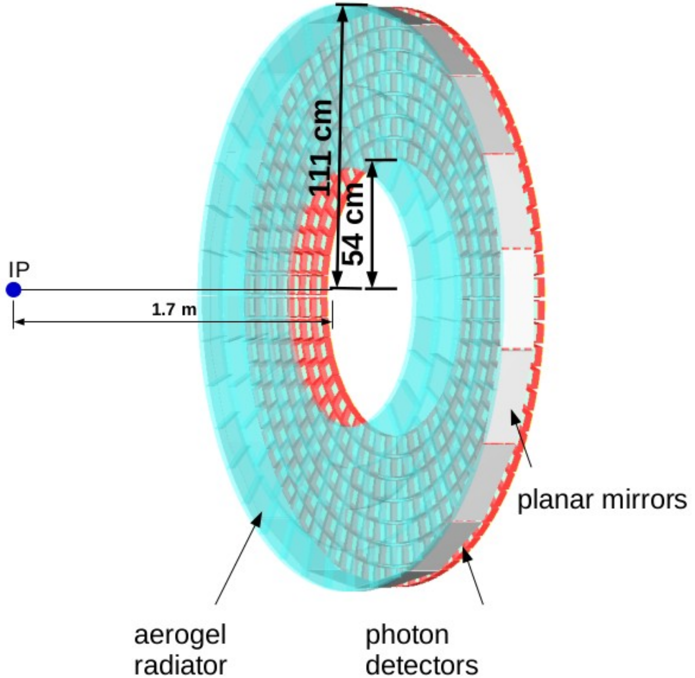
proximity focusing RICH with aerogel radiator

$$\cos\theta_c = \frac{1}{n\beta}$$



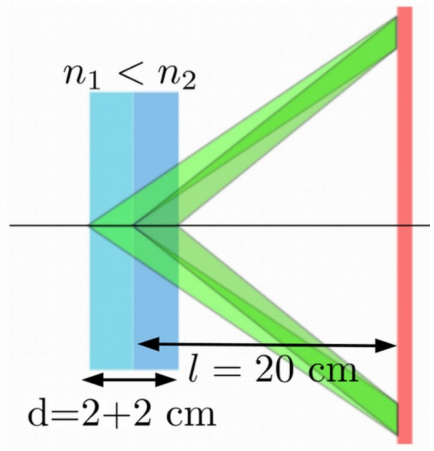
$\theta_C(\pi) - \theta_C(K) \sim 30$ mrad @ 3.5 GeV





ARICH design and components

Radiator – Silica Aerogel



- two aerogel layers in focusing configuration

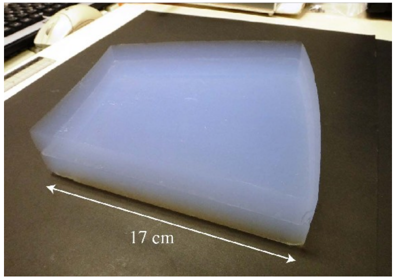
$$n_1 = 1.045, \; n_2 = 1.055$$

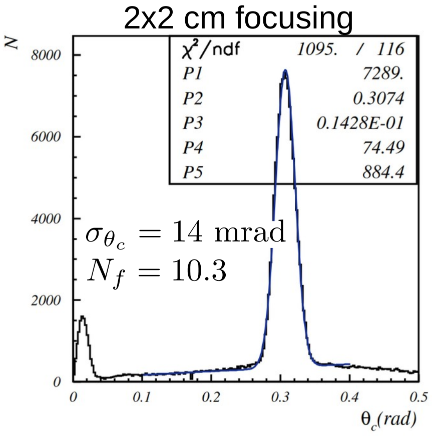
→ increase number of photons w/o degrading Cherenkov angle resolution!
(due to uncertainty in the photon emission position)

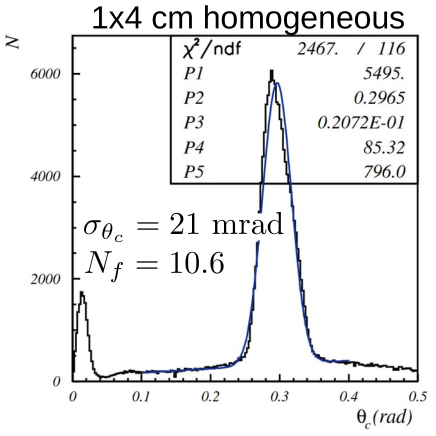
$$\sigma_{gel} = \frac{d \sin\theta_C \cos\theta_C}{l\sqrt{12}} \frac{1}{\sqrt{N_{p.e.}}} \qquad N_{p.e.} \propto d$$

- Requires aerogel with high transparency! ($\lambda_T \sim 45$ mm)

- Detector plane covered with 2 x 124 water-jet cut tiles (~ 17x17cm)



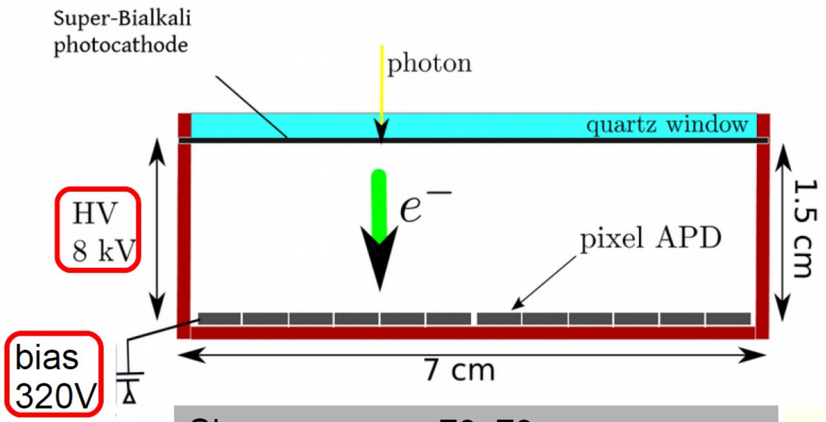




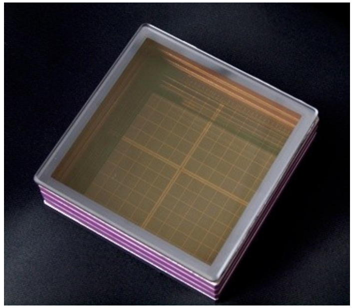
ARICH design and components

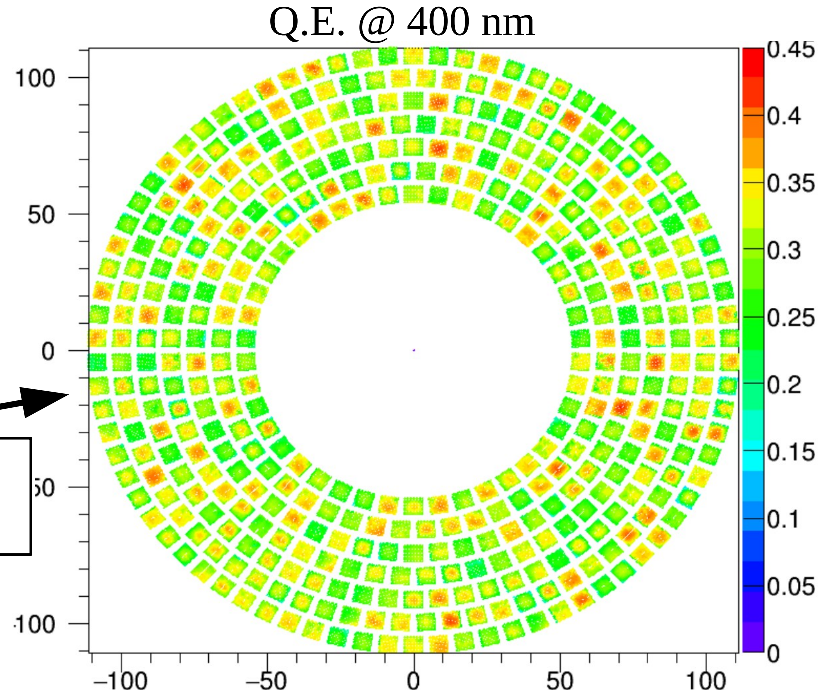
Photon detector – HAPD

- 1.5 T + $> 10^{12}\ n/\mathrm{cm}^2$, good single photon detection efficiency, sufficient position resolution.
- HAPD – Hybrid Avalanche Photo-Detector (developed in collaboration with Hamamatsu Photonics K.K.)



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



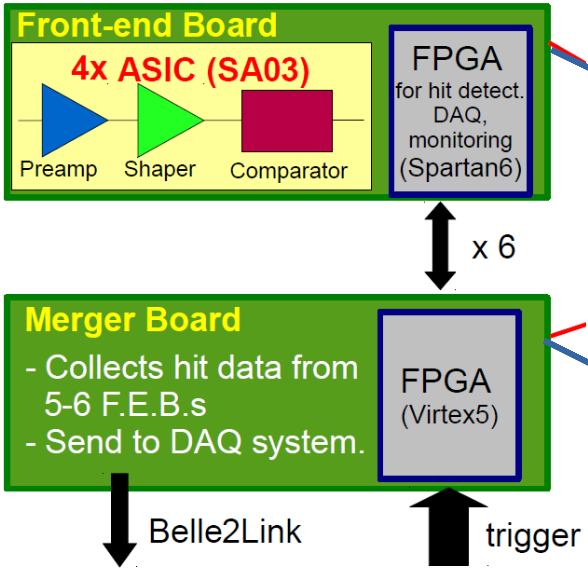


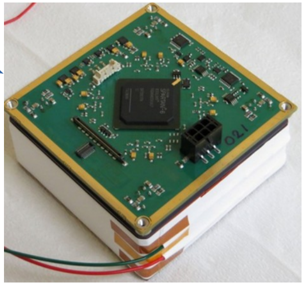
ARICH design and components

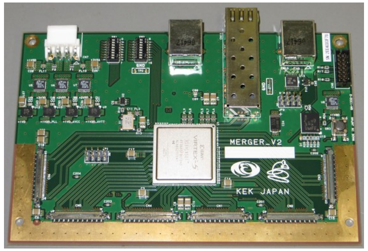
Readout electronics

- In total ~ 60k channels
- Very limited space of 5 cm behind HAPDs (including cabling+cooling)
- Variable gain and shaping time
  (3.1-12.5 V/pC) (100-200 ns)

  → optimization for increased noise levels

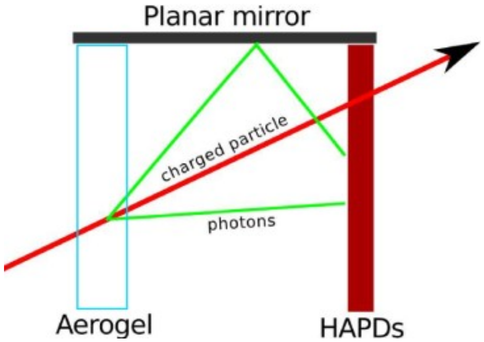


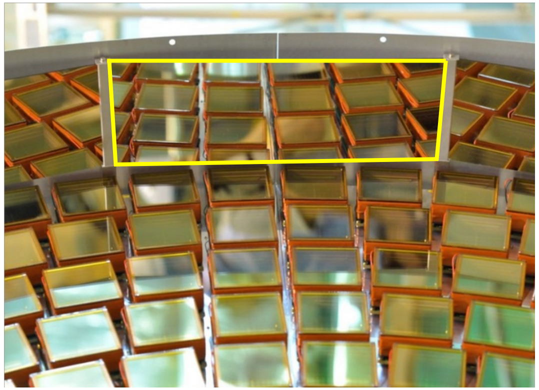




Planar mirrors

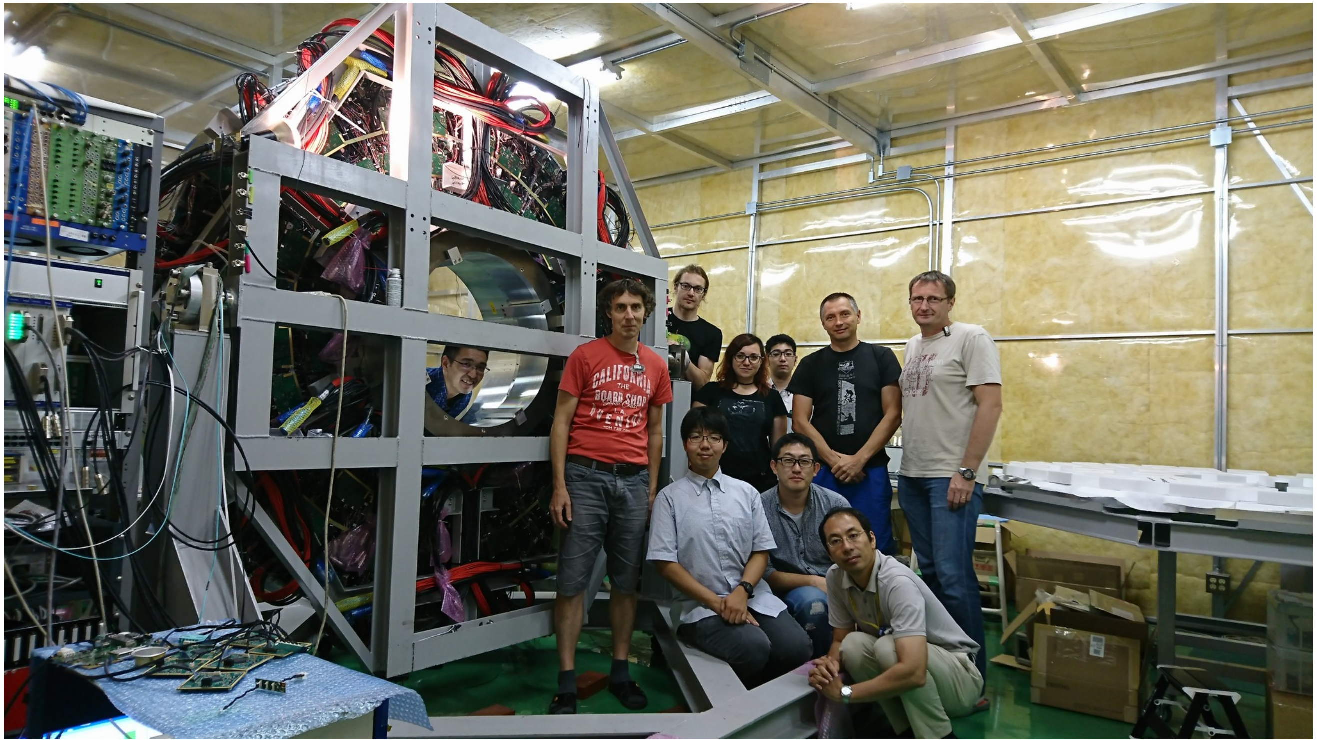
- To prevent photon loss for track on the outter edge of the detector
- possible photon reflections properly considered in the reconstruction algorithms

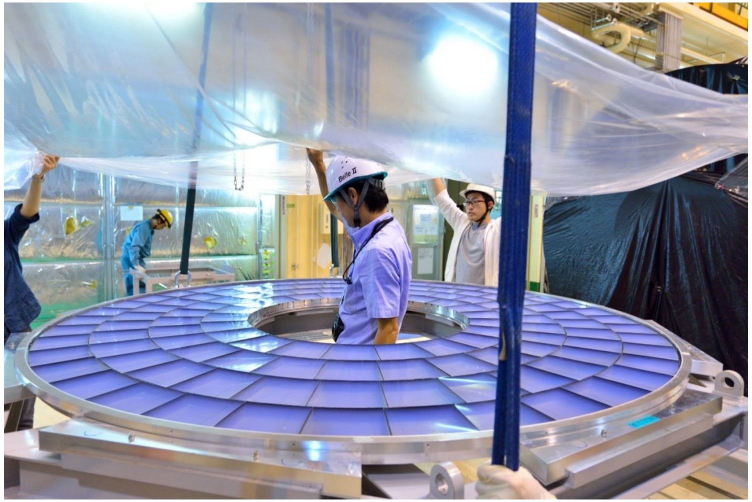


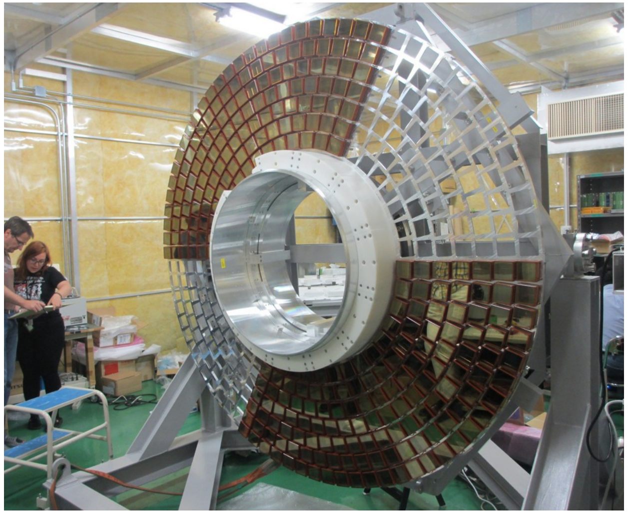


Detector construction and installation

- ARICH was constructed between 2016-2018.



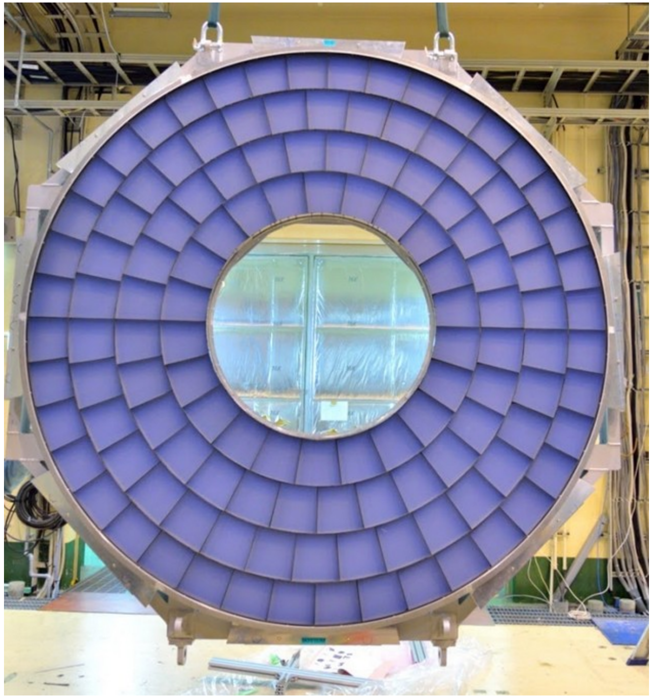




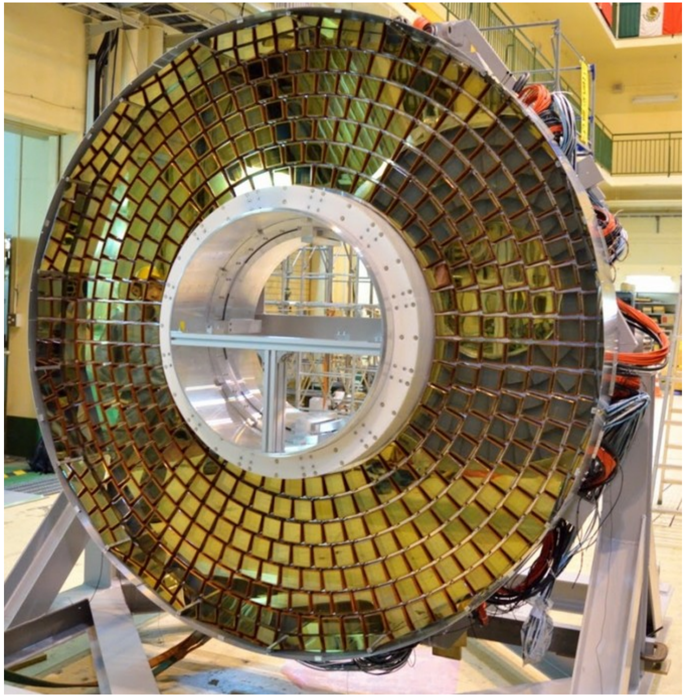
Detector construction and installation

- After the early Belle II operation (so-called phase II) upgrade of cooling system was carried out.

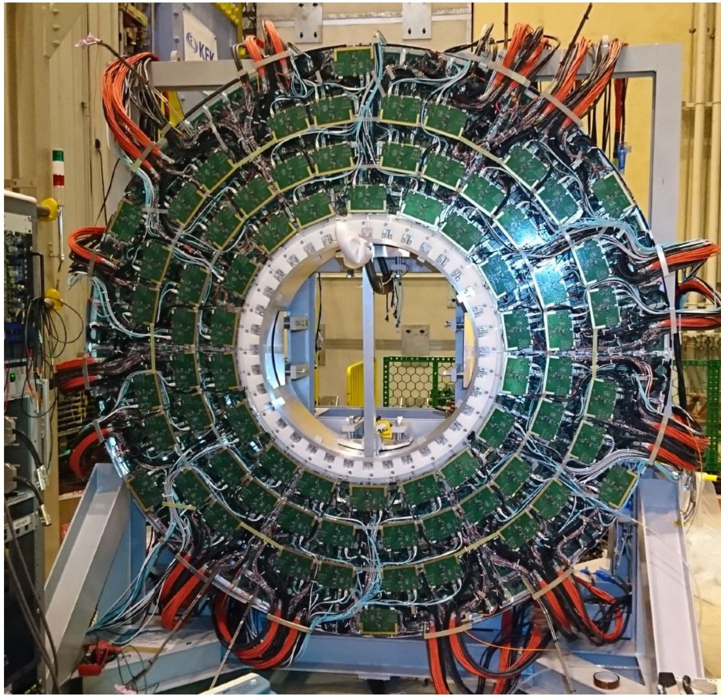
radiator plane



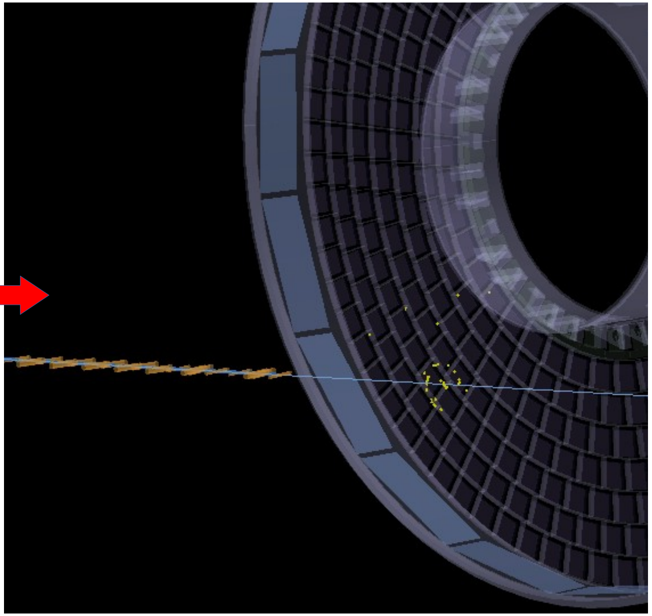
photon-detector plane



backside plane



Detector construction and installation



One of the first seen rings from cosmics!

→ Belle II full operation since 2019 (phase 3)

Operation experience – HAPD status

HAPD status after 3 years of operation

- In Run 1, 5 HAPDs non-operational due to LV cable connection problem (1.2% of channels)

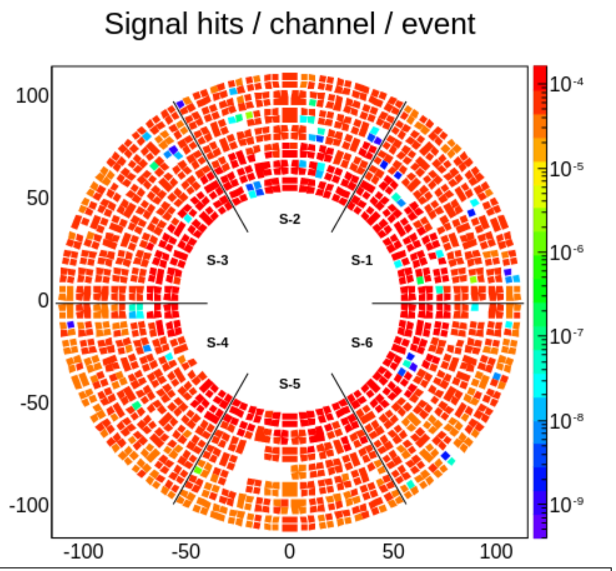
  → repaired during the started long shutdown (Jul. 22 → Dec. 2023)

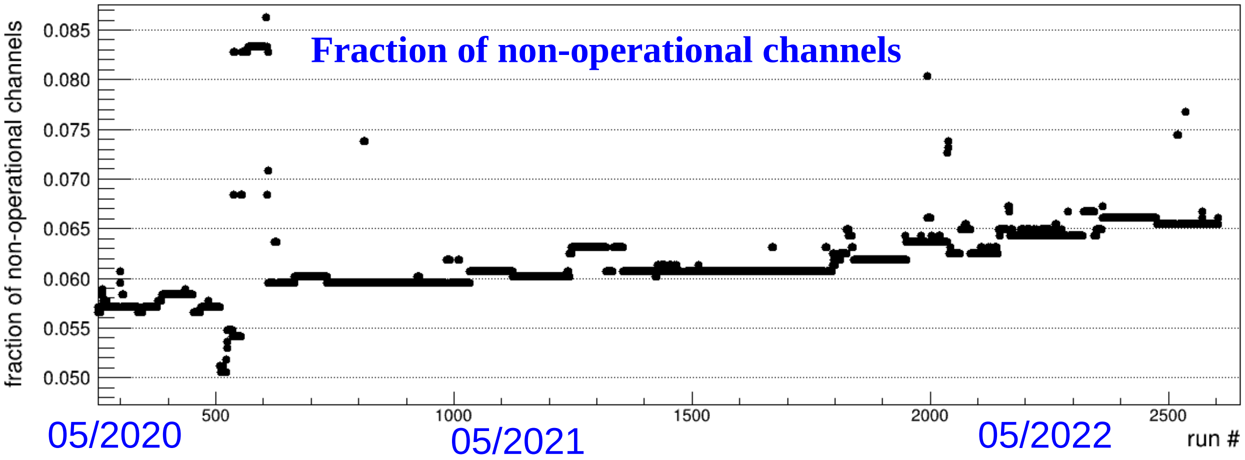
- ~ 4% of APDs suffer bias or guard problem

  → most commonly sudden leakage current increase

- ~ 1.7% of HAPDs with HV problem

→ **~ 93% of channels operational**





Impact of beam induced backgrounds

APD leakage current increase

→ steady increase due to the neutron silicon bulk damage
→ deteriorates the S/N ratio
→ expect minimal impact on PID performance up to $10^{12}\ \mathrm{n/cm}^2$ (1 MeV equiv.)

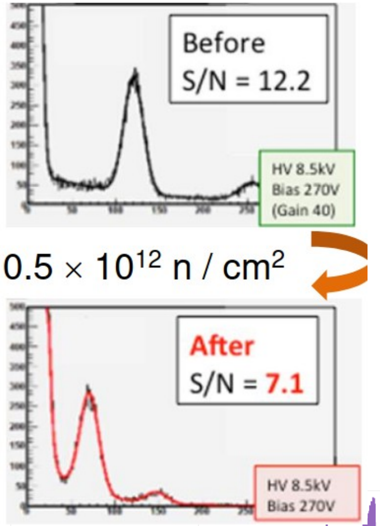
- in the periods of the SuperKEKB highest luminosity achieved so far we observe an increase rate of ~30 nA / month

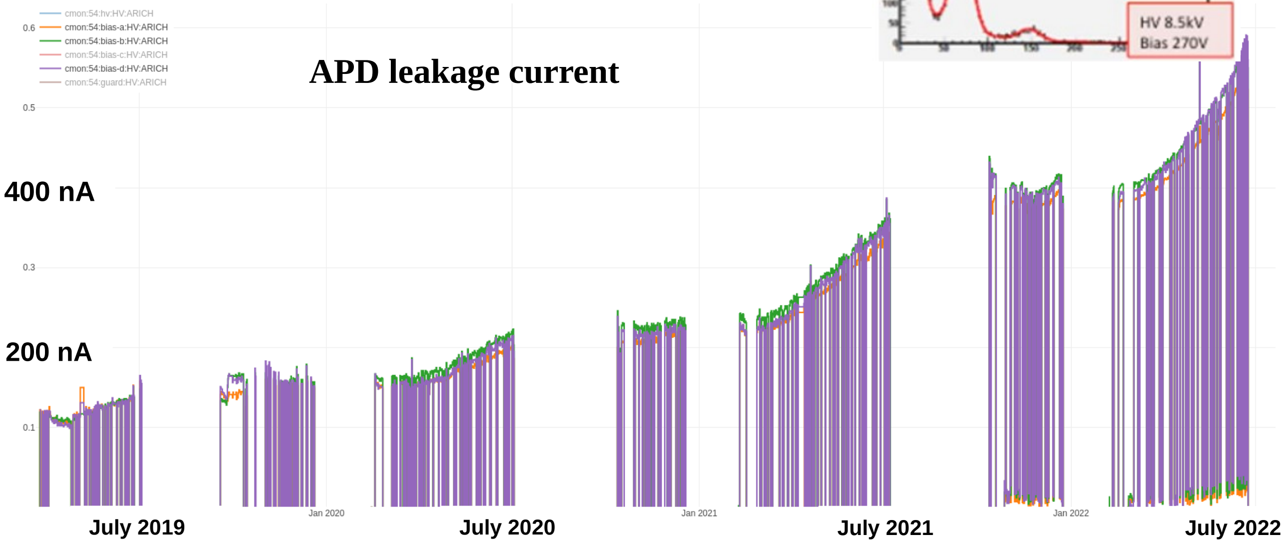
$$\sim 10^9\ \mathrm{n/cm}^2/\mathrm{month}$$

- note that the SuperKEKB luminosity is still ~ 20 x below its design value

- from the background simulations at design luminosity we expect

$$\sim 10^{11}\ \mathrm{n/cm}^2/\mathrm{year}$$





Impact of Beam induced backgrounds

- **Single-event-upsets (SEU) in the front-end FPGAs**

  → FEB spartan-6 + Merger board Virtex-5

- Frequent SEU expected in Spartan-6: Boron dopant used

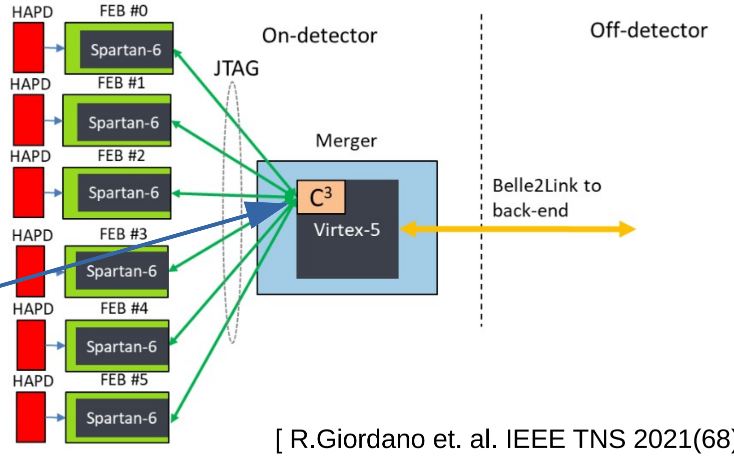
- Configuration consistency corrector (C^3) is implemented in the merger firmware.

  → real-time majority voting
  + partial reconfiguration of the firmware

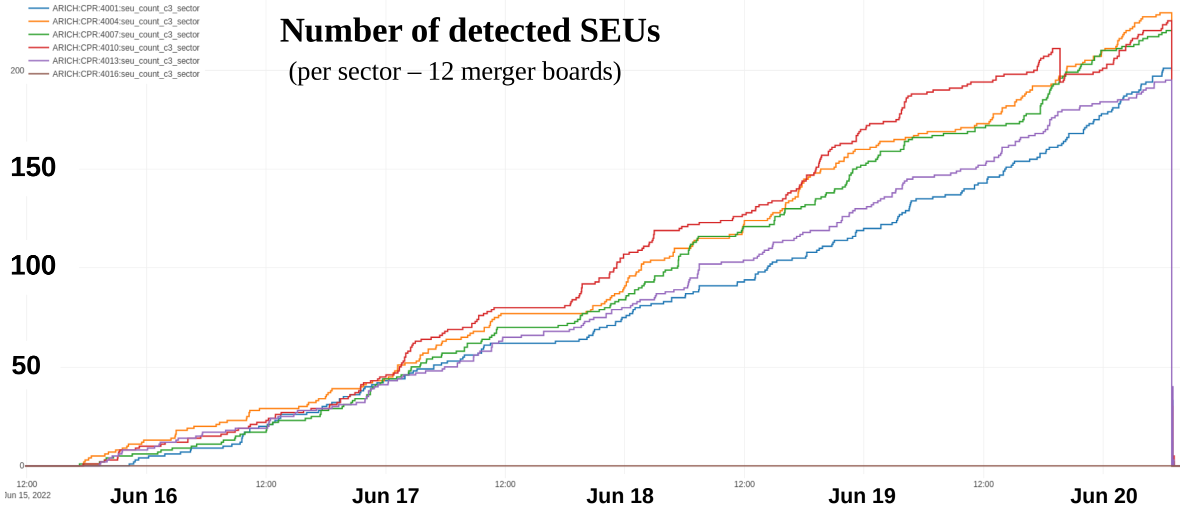
- Improved performance w.r.t. Xilinx Soft Error Mitigation (SEM).

- We observe O(1) SEU / HAPD / day

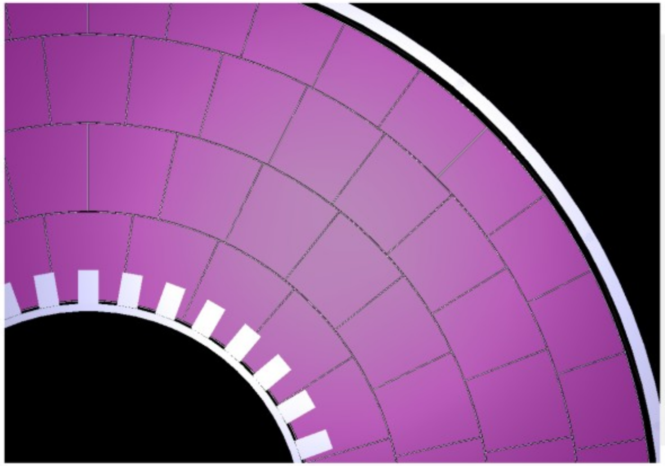
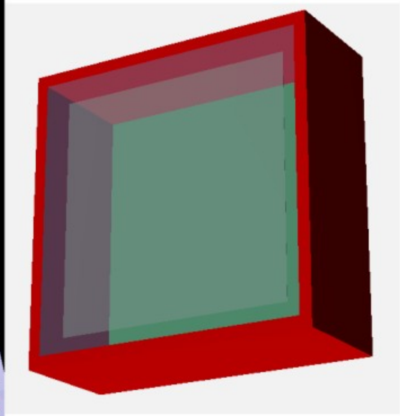
- SEU in merger FPGA much rarer (but potential problem @ high luminosity)



[R.Giordano et. al. IEEE TNS 2021(68)2810]



Geant4 simulation of the ARICH detector

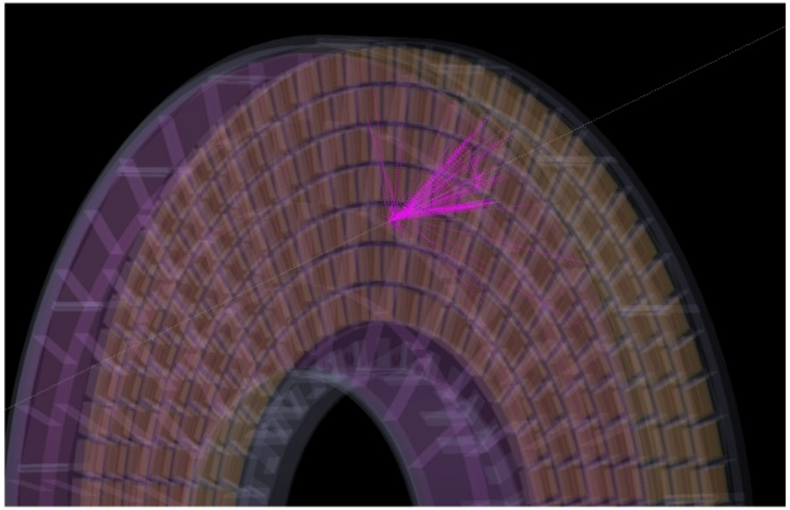
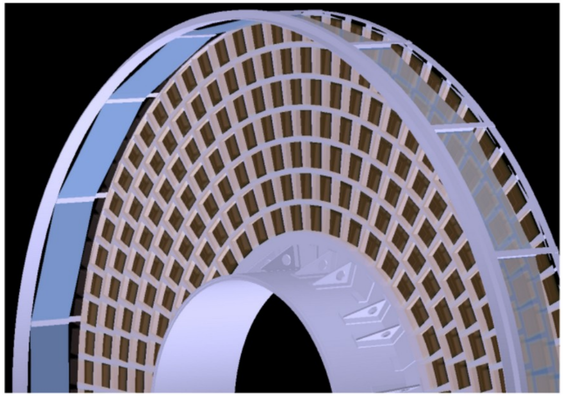



- part of the full Belle II simulation

- detailed geometry description
  → including support and cooling structures

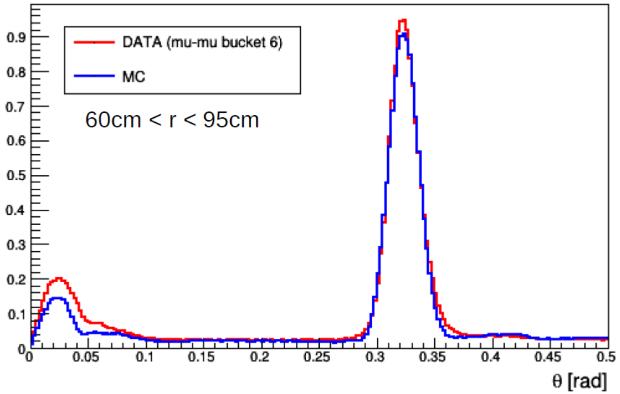
- digitization includes channel-by-channel QE map of each HAPD

- run-dependent MC also includes run-by-run determined masks of inactive/dead channels

Cherenkov angle distribution

- Accumulated Cherenkov angle distribution as observed in $\mathbf{e^+e^-} \rightarrow \mu^+\mu^-$ events



DATA

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

$\sigma_c = 12.7$ mrad

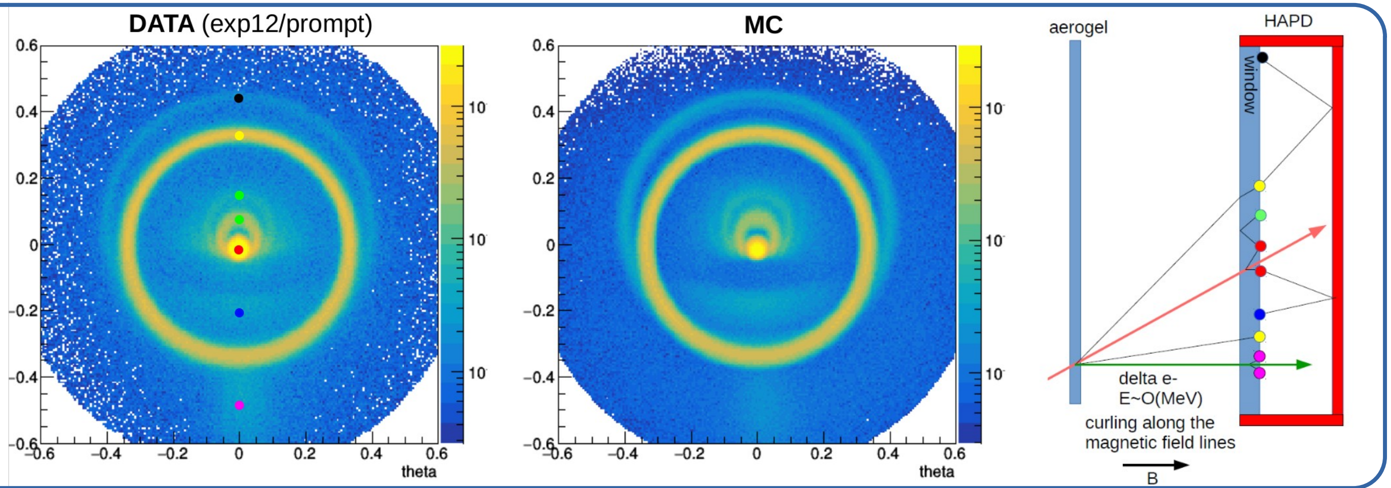
> 6 GeV/c muons → fully saturated Cherenkov rings

MC

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

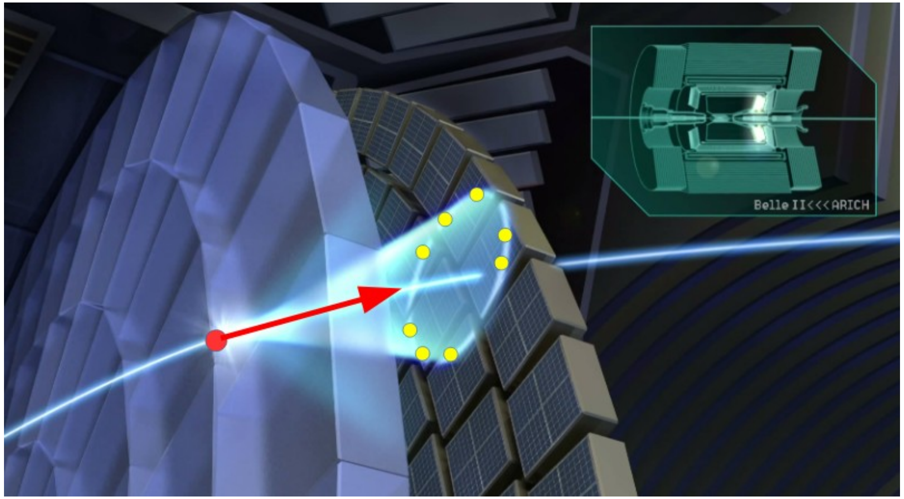
$\sigma_c = 12.75$ mrad

→ **good DATA/MC agreement !**



Particle Identification

- reconstructed tracks are extrapolated from the drift chamber to the ARICH volume.
- we construct likelihood function for 6 particle type hypotheses for each track (e, μ, π, K, p, d)
- based on comparison of observed pattern of detected photons with the expected one assuming given track parameters and particle type.



Likelihood function

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

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

n_i - expected number of hits of pixel i

m_i - observed number of hits

For each particle hypothesis h

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

N^h: Expected total number of hits

n_i^h: Expected number of hits on pixel i

We only distinguish

$m_i = 0$ (not fired pixels)

$\rightarrow p_i = e^{-n_i}$

$m_i > 0$ (fired pixels)

$\rightarrow p_i = 1 - e^{-n_i}$

Particle Identification

Expected number of hits on pixel i

$$n_i = n_i^1 + n_i^2 + n_i^b$$

(1st aeogel layer, 2nd, background)

$$n_i^r = \epsilon_{det} N^r \int_{\Omega_i} \frac{1}{2\pi} G(\theta, \theta_h^r, \sigma_h^r) d\theta d\phi$$

N^r: expected number of photons emitted from aerogel layer r (1,2)

$G(\theta, \theta_h^r, \sigma_h^r)$: Expected cherenkov peak for given hypothesis h

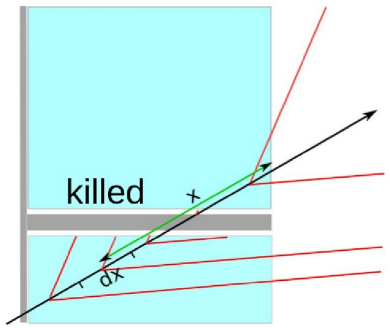
Ω_i: Solid angle covered by I-th pixel

$$N^r = \frac{dN_{ch}}{dx} \lambda_{abs} (1 - e^{-d/\lambda_{abs}})$$

Expected total number of hits

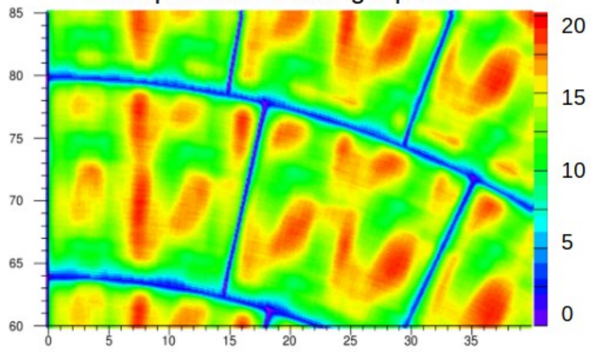
$$N = \epsilon_{acc} \epsilon_{det} (N^1 + N^2) + N_b$$

ϵ_{acc}: Fraction of ring that falls on photo-sensitive area → Toy simulation of 200 "photons" uniformly distributed in ϕ at θ_c^h from 5 points along the particle path in aerogel



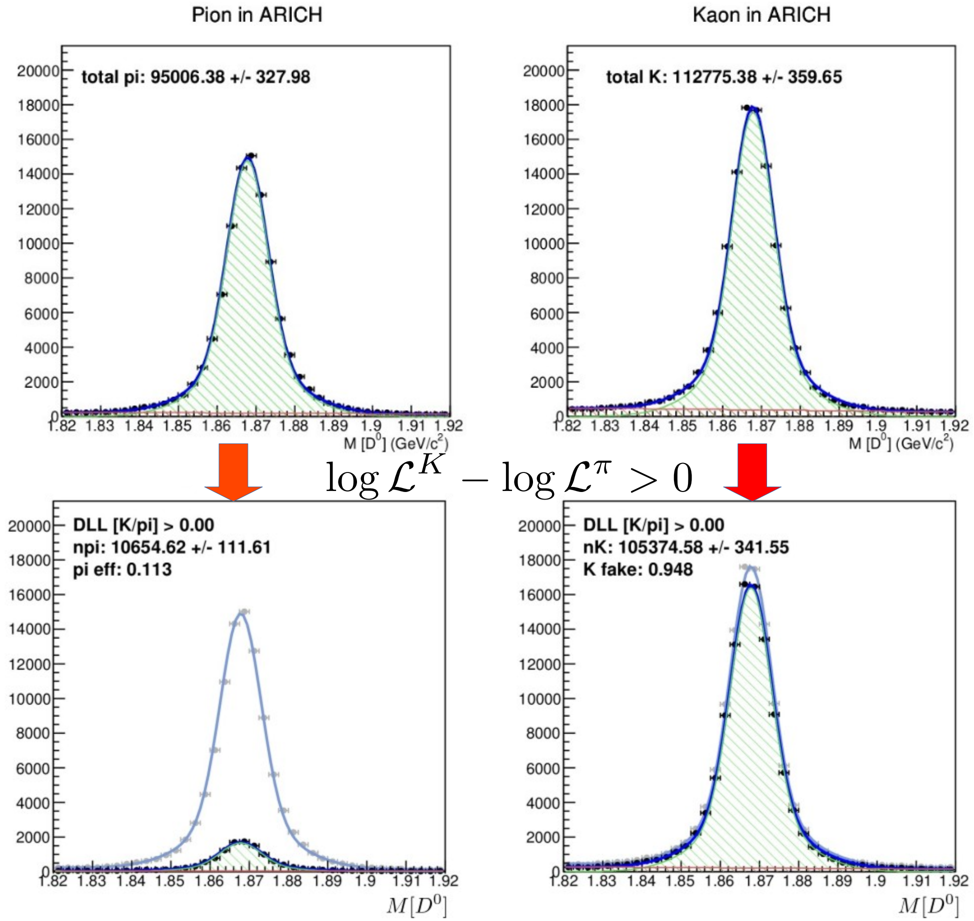
$$\Delta N_{ch} = \frac{dN_{ch}}{dx} \Delta x \; e^{-x/\lambda_{abs}}$$

Number of expected photons vs track position on aerogel plane



Performance

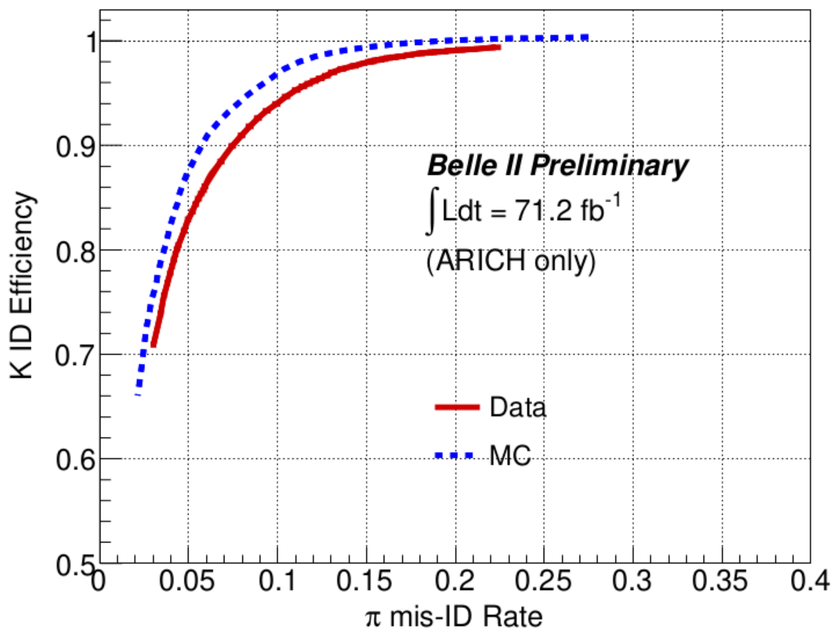
- K/pi discrimination performance is studied using a clean sample of K/pi tracks from D* decays



$\log \mathcal{L}^K - \log \mathcal{L}^\pi > 0$

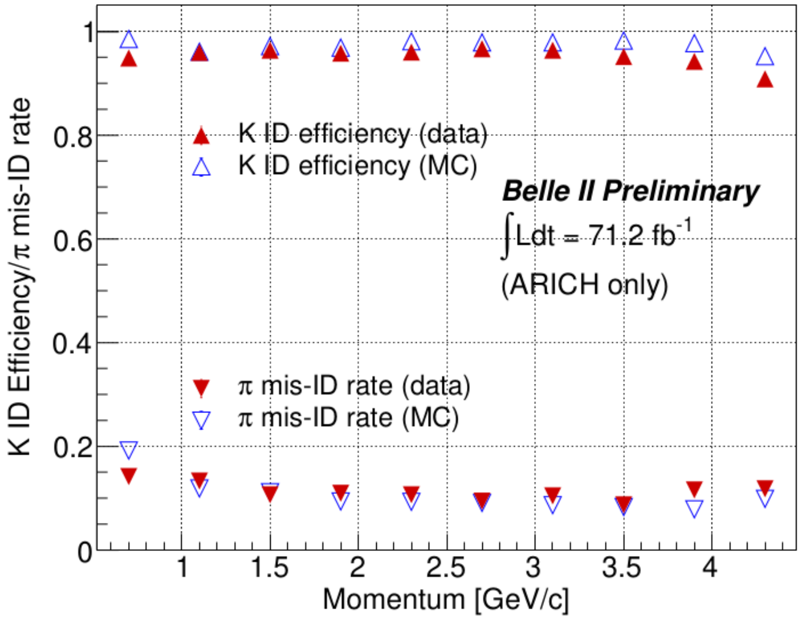
$D^{*+} \to D^0 \pi^+_{\mathrm{slow}}$, $D^0 \to K^- \pi^+$

$D^{*-} \to \bar{D}^0 \pi^-_{\mathrm{slow}}$, $\bar{D}^0 \to K^+ \pi^-$

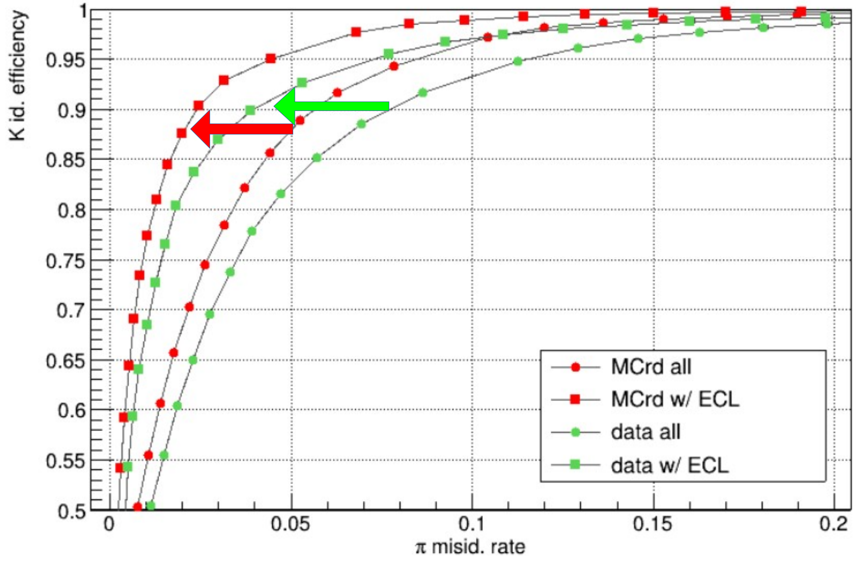


Performance

- track momentum dependency



Large fraction of misid. rate induced by particles that have extrapolated track to ARICH but don't enter it either due to decay in flight or scattering in the material



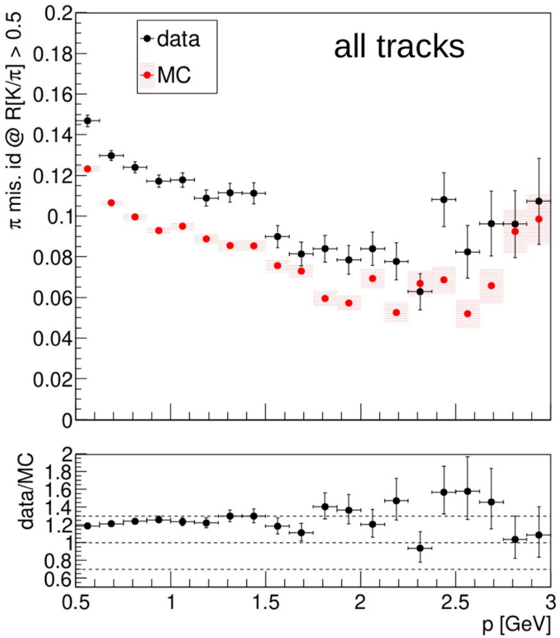
* based on the track associated cluster in the ECL we can remove decayed/scattered particles

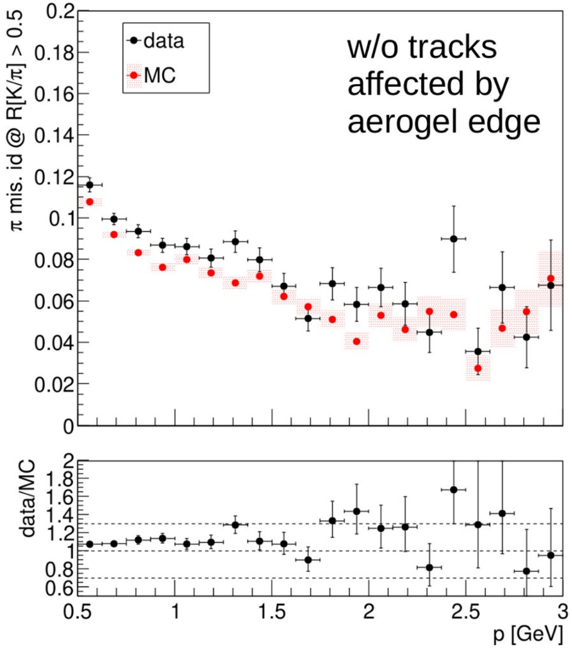
- Many further improvements of reconstruction and calibration methods are ongoing

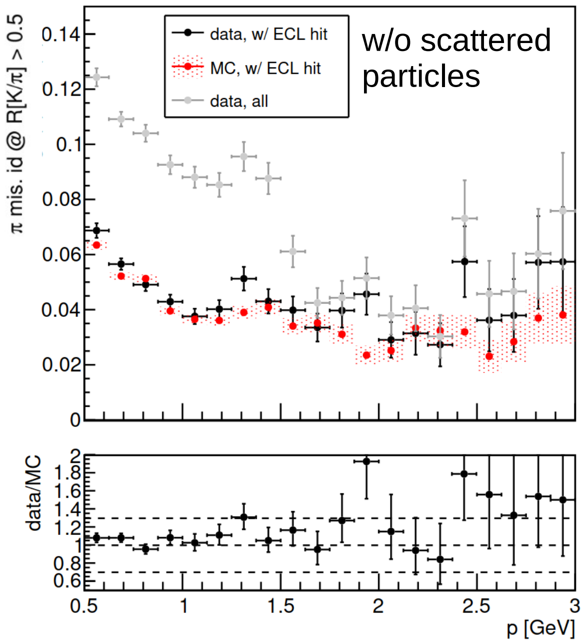
Performance – DATA/MC discrepancies

- identified sources of this discrepancy:

→ imperfect description of gaps between the aerogel tiles in the MC (photon loss)
→ misalignment of aerogel tile positions (reality w.r.t. assumed in reconstruction)
→ possible underestimate of amount of material in front of ARICH in MC
→ imperfect other alignments (global, mirrors)



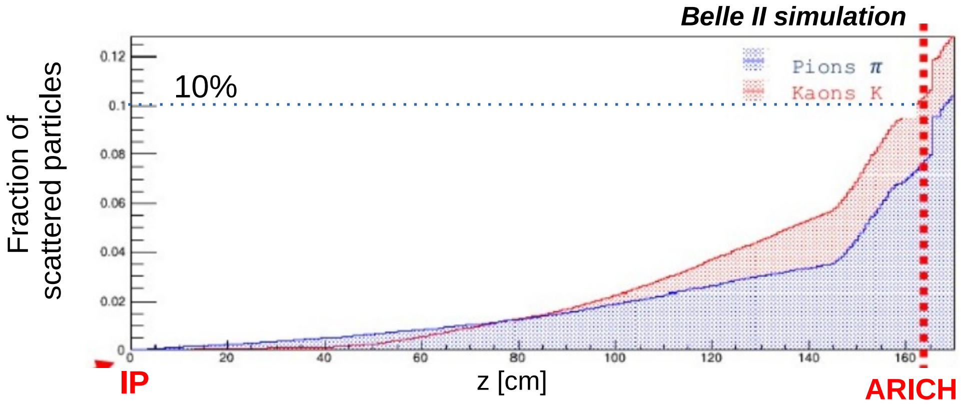


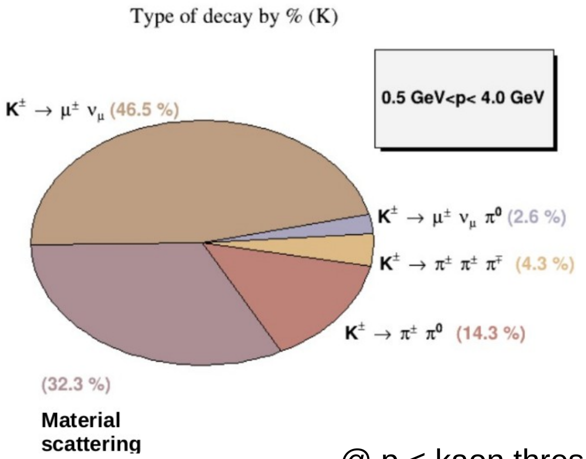


bonus topics

Treatment of decayed/scattered particles

- According to MC ~10% of particles with extrapolated track in the ARICH don't reach the detector
  → decay in flight + inelastic hadronic scattering in the material

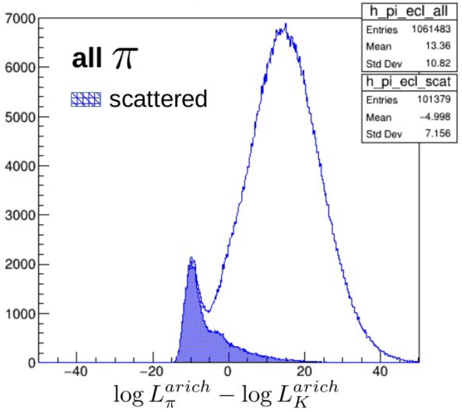


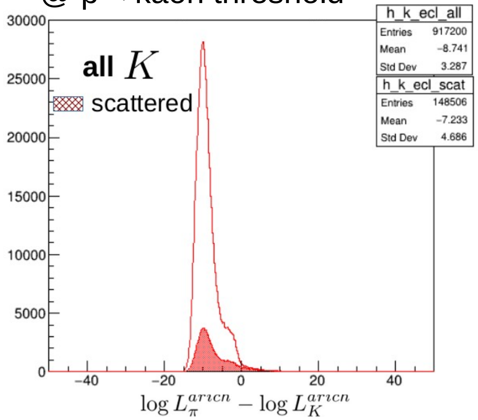


- significant contribution to the misidentification rates
  (e.g. scattered pion → strongly id. as kaon)

- recognizing decayed/scattered particles could improve Belle II global PID
  (at least where dE/dx contributes)

@ p < kaon threshold

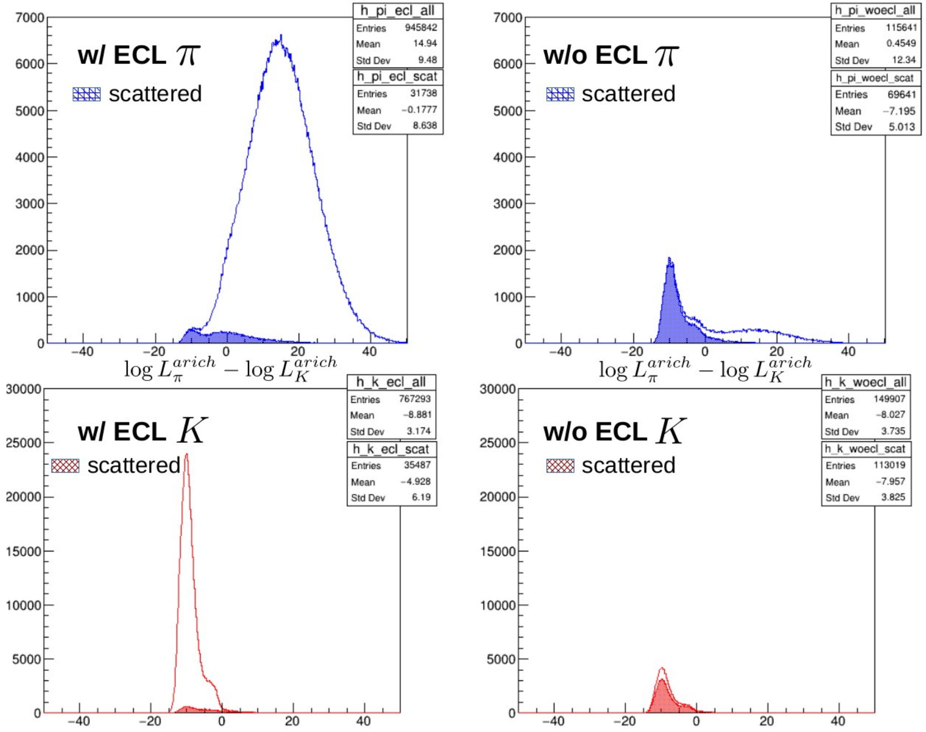


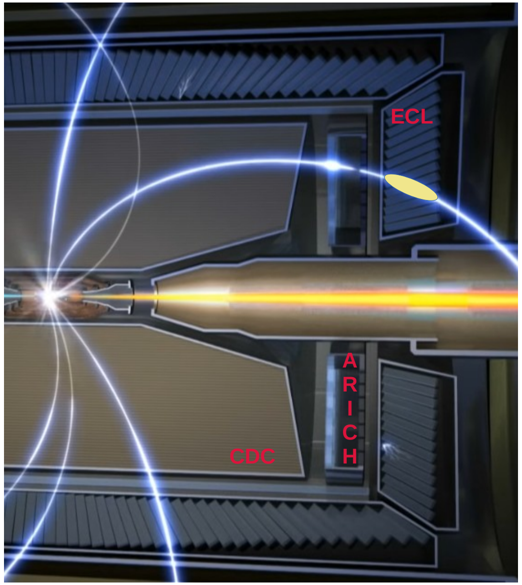


Treatment of decayed/scattered particles

- search for track associated cluster in the electromagnetic calorimeter (ECL)

→ ~10% of tracks have no ECL cluster
→ ~75% of decayed/scattered particles are contained in this sub-sample





Treatment of decayed/scattered particles

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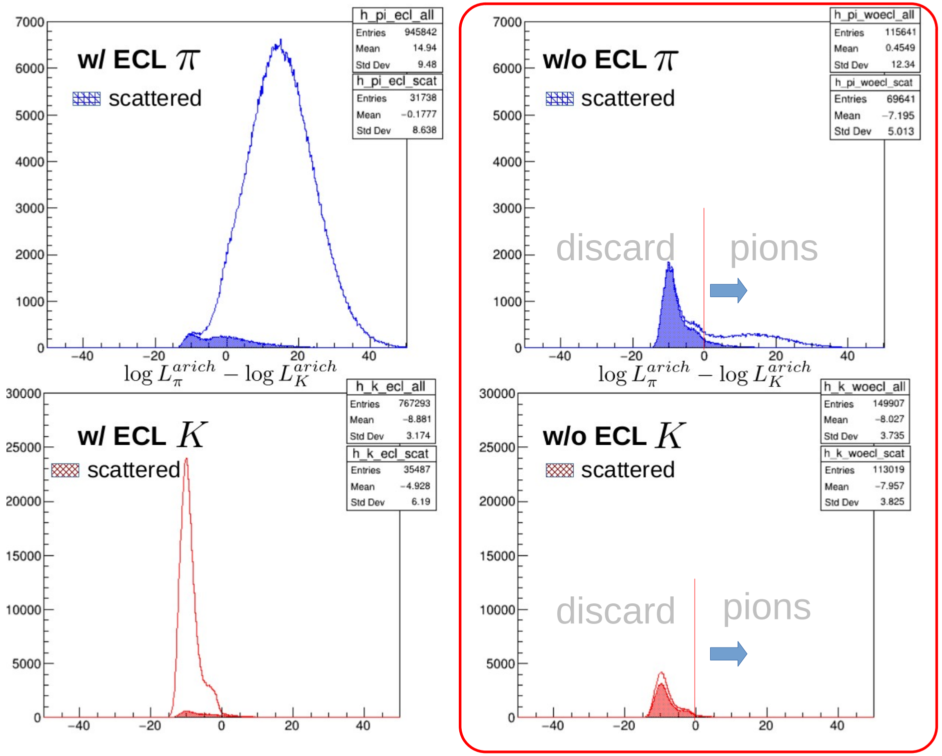
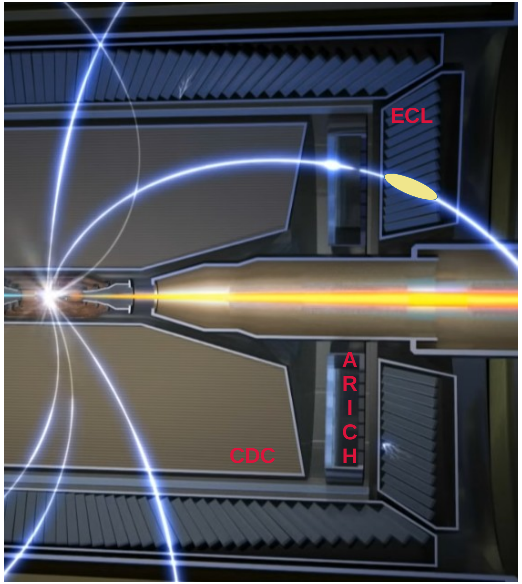




→ for tracks w/o the ECL cluster adopt the following treatment:

- if $\log L_\pi^{arich} - \log L_K^{arich} > 0$ include ARICH to global PID

- otherwise discard arich info.

Treatment of decayed/scattered particles

Impact on the Belle II global PID

- we study the PID performance using $D^{*+} \rightarrow D^0[K^-\pi^+]\pi^+$

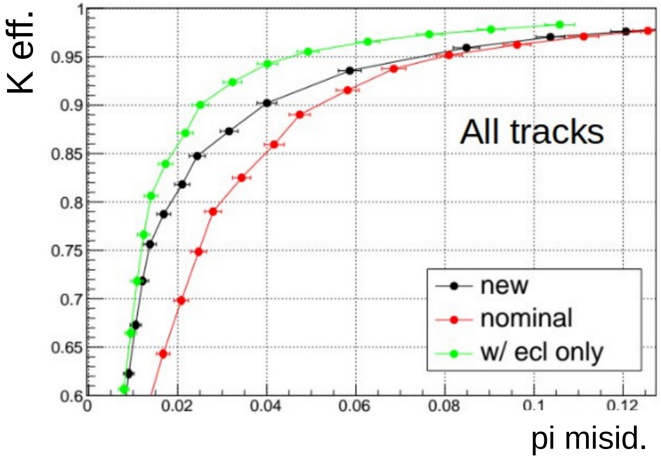
→ clean sample of pi/K tracks that covers well the kinematic region of interest (0.5 - 4.0 GeV/c)

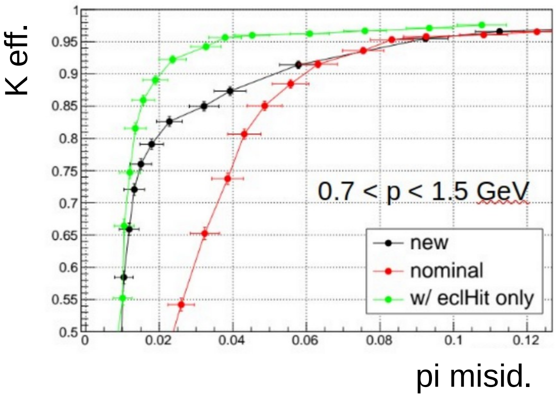
- clear performance improvement is observed:

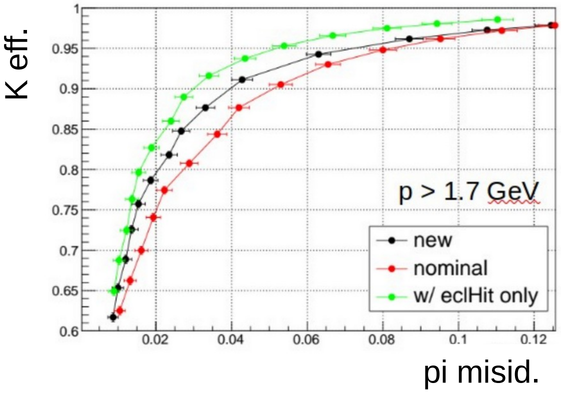
→ most notably below the kaon Cherenkov threshold

→ at 85% kaon id. efficiency pion misid. rate is halved (from 4% → 2%)

- further efforts are ongoing in order to improve the recognition of decayed/scattered particles based on responses from other sub-systems





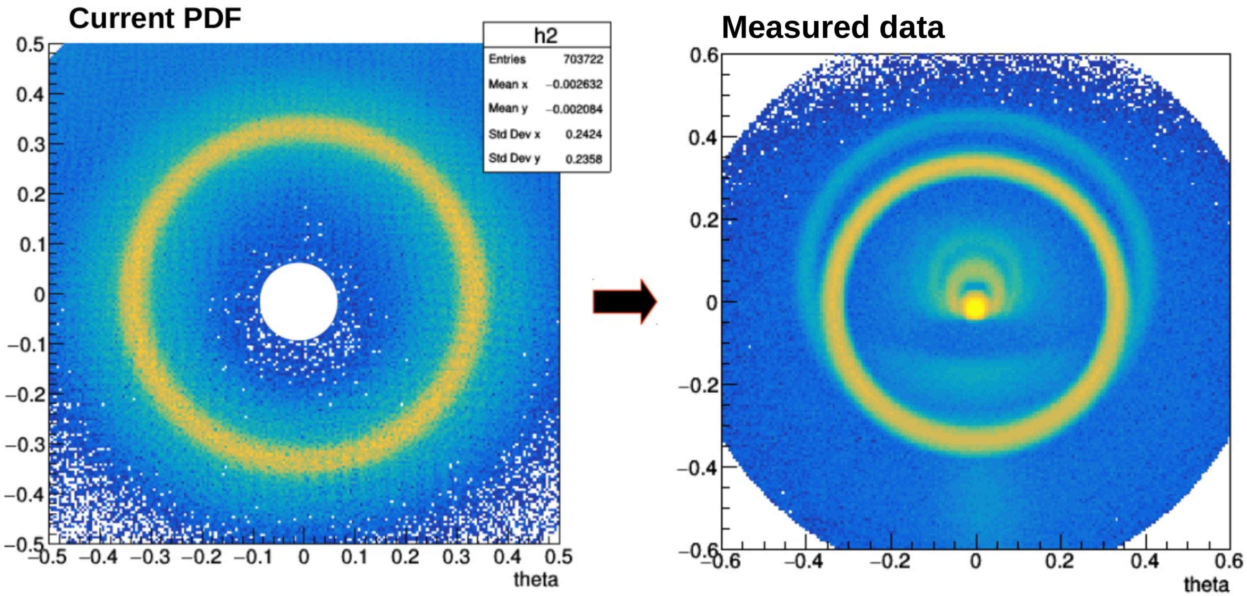


Improving the PID likelihood PDFs

- expected number of hits on a given pixel (n_i^h) is calculated by a propagation of “toy” photon from the mean emission point in the aerogel (at the expected Cherenkov angle) to the photon detector plane.

- nominally our PDF for each particle hypothesis likelihood includes only the main Cherenkov ring and a flat background

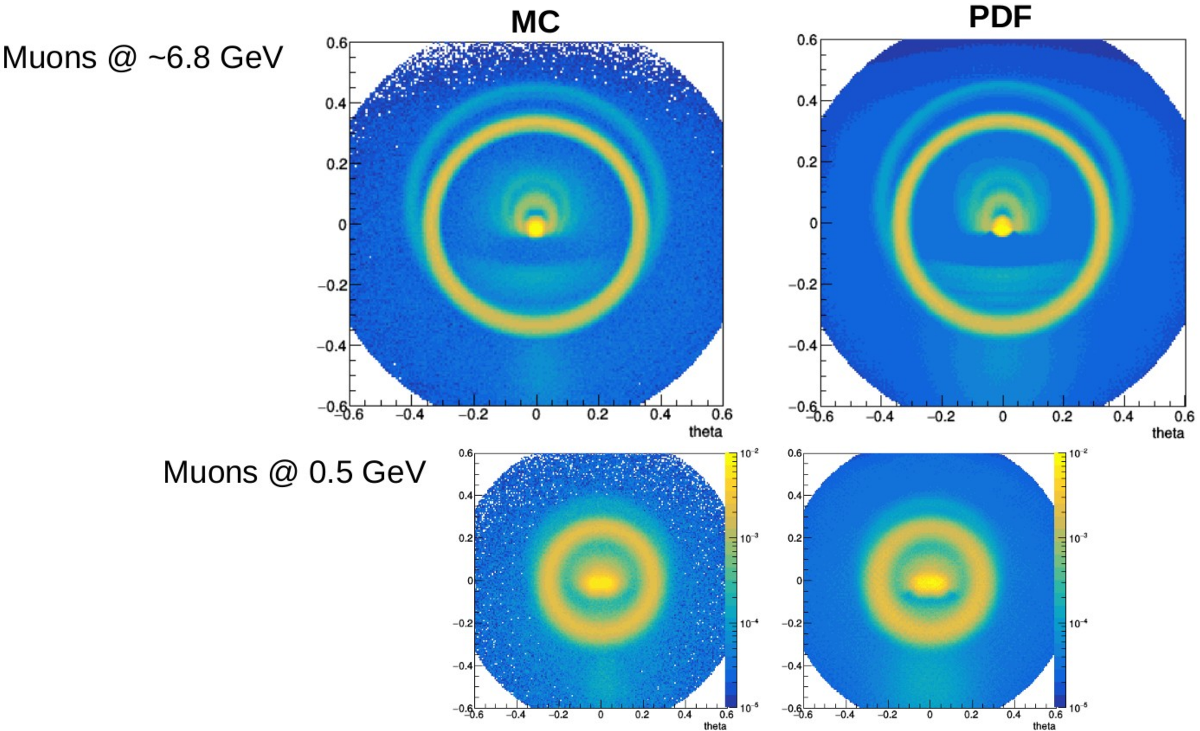
→ but the observed ring image has several other features which might contribute to PID!



Improving likelihood PDF

- recently the “toy” simulation was extended to include the missing effects
  (photons from HAPD quartz window, possible photon reflections withing HAPD, delta electrons)

- shape and intensity dependencies of each component on the particle velocity are fully determined
  from the expected Cherenkov angle in aerogel and quartz, and the track impact position on aerogel plane

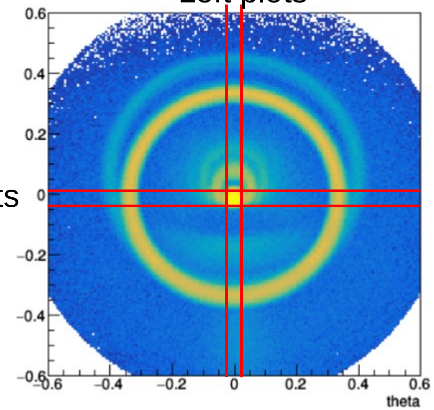


Improving likelihood PDF

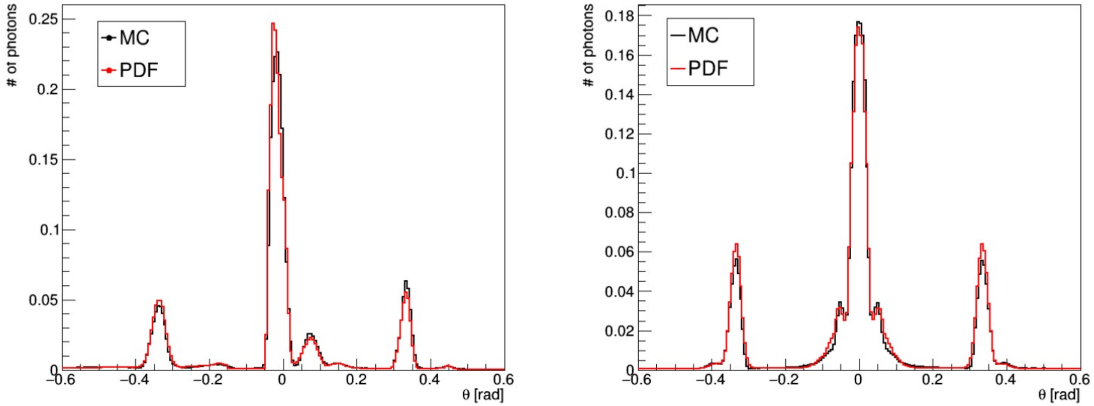
Projections

Left plots

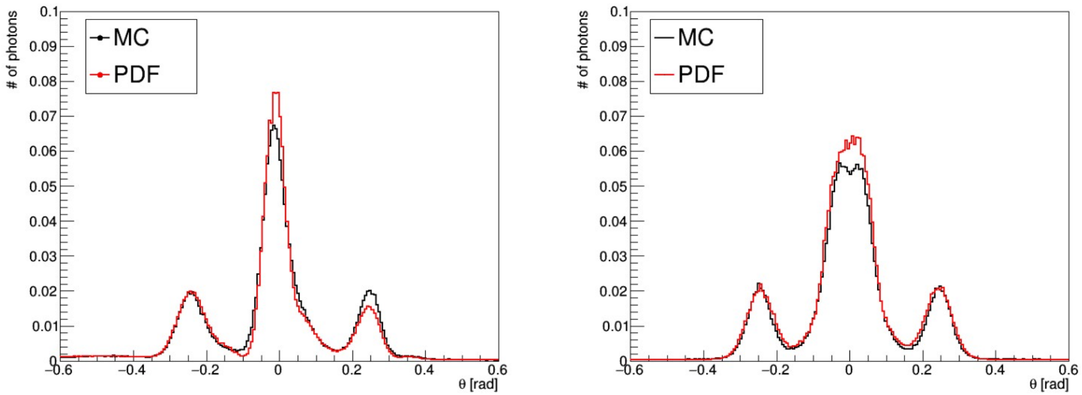
Right plots



Muons @ ~6.8 GeV

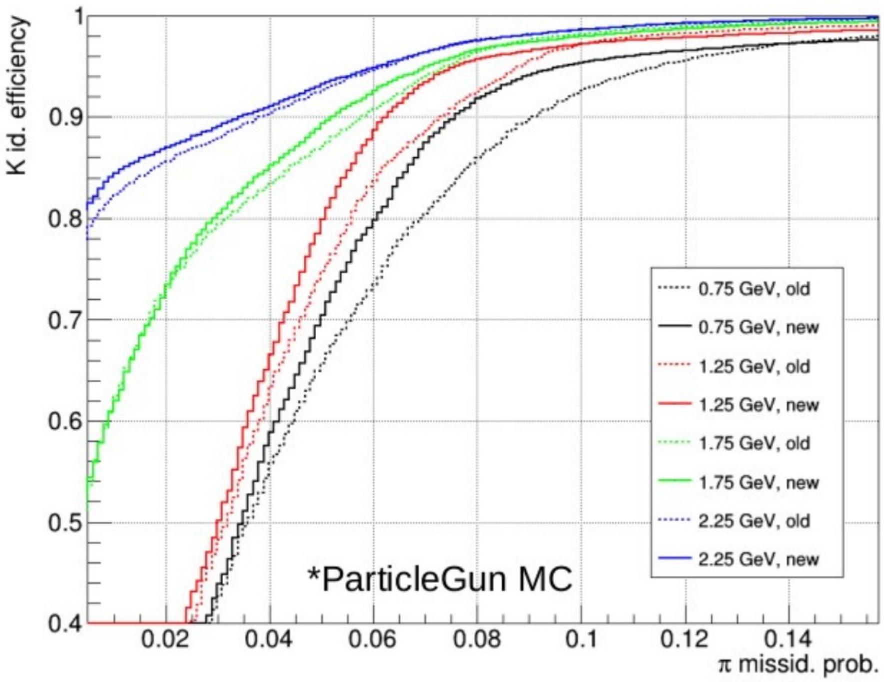


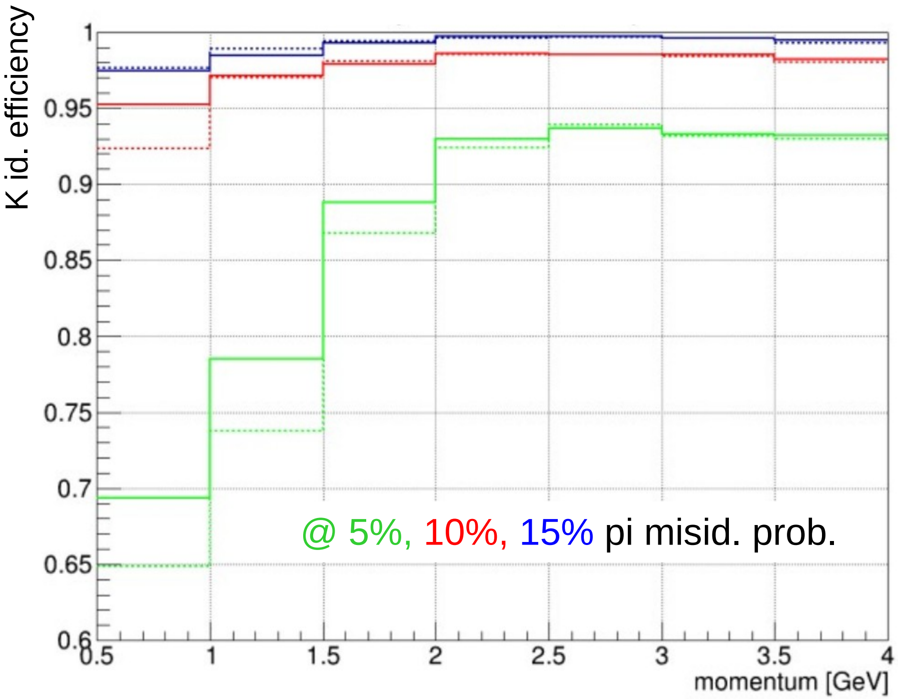
Muons @ 0.5 GeV



Improving likelihood PDF

- Impact on the PID performance





- at low momenta noticeable improvement can be seen

- studies of improvement in the measured data are ongoing.

Summary

- ARICH is a proximity focusing RICH detector providing PID in the forward-endcap of the Belle II. It utilizes a novel two layer aerogel configuration to boost its performance.

- Running stably since the start of Belle II data taking in 2019.

- PID performance close to expected from MC: 95% kaon id. efficiency @ 10% pion misid. rate.

- Further improvements of reconstruction and calibration methods are onging.
  → treatment of decayed/scattered particles
  → spatial alignment of aerogel tiles
  → improved likelihood PDF

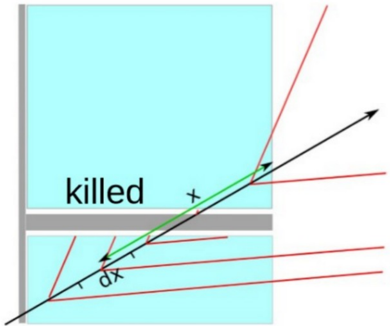
- Neutron radiation is a concern: (leakage increase + SEU)
  - at present well below the tolerable levels
  - hard to predict the fluence at increased SuperKEKB luminosities (acceptable according to present projections)

- Long term upgrade considerations: SiPM, LAPPD

Backup

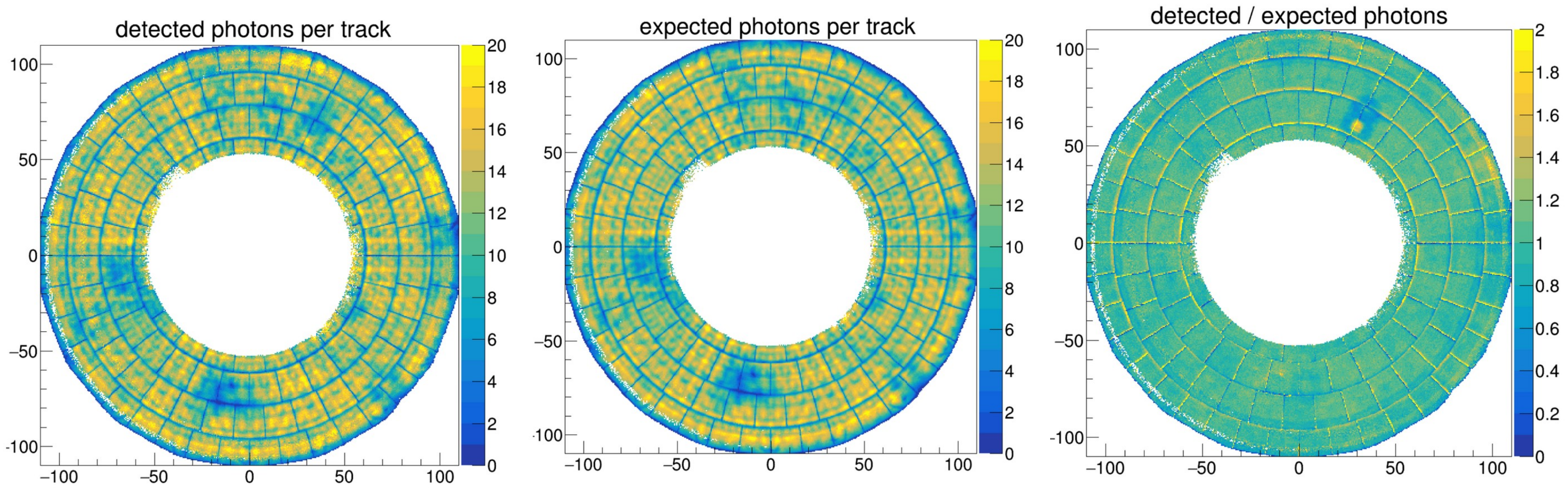
→ Aerogel tile alignment

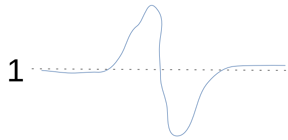
Aerogel tile alignment



- photon loss in the gaps between aerogel tiles taken into account in calculation of expected number of photons for given hypothesis

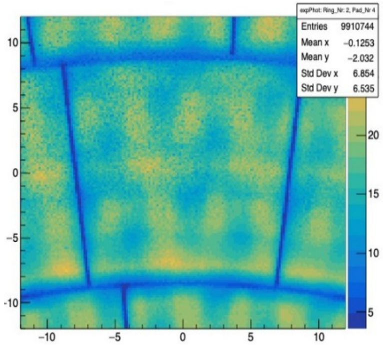
- misalignment of gap positions (actual vs. assumed) is observed in measured data → increased particle misid. rate

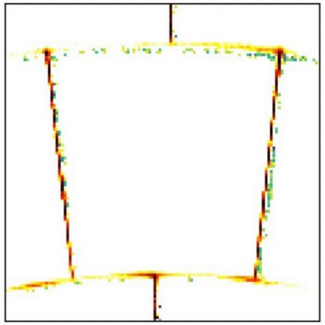




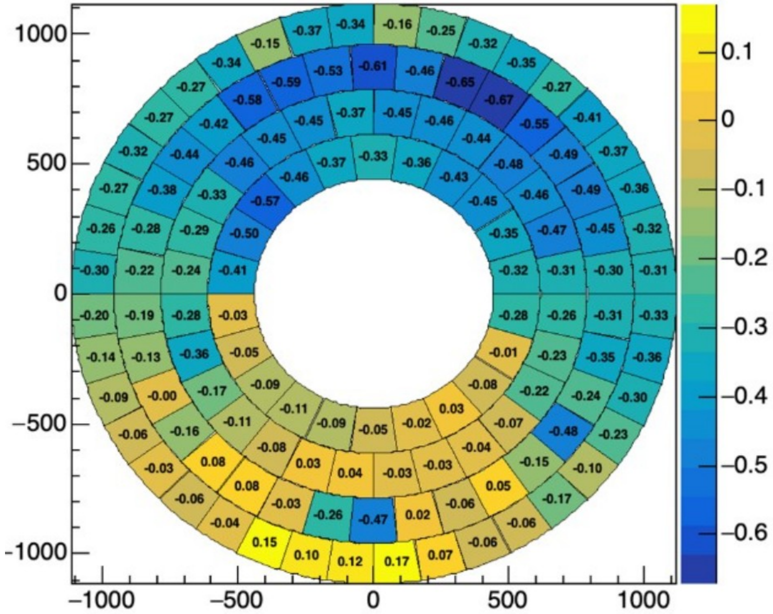
Aerogel tile alignment

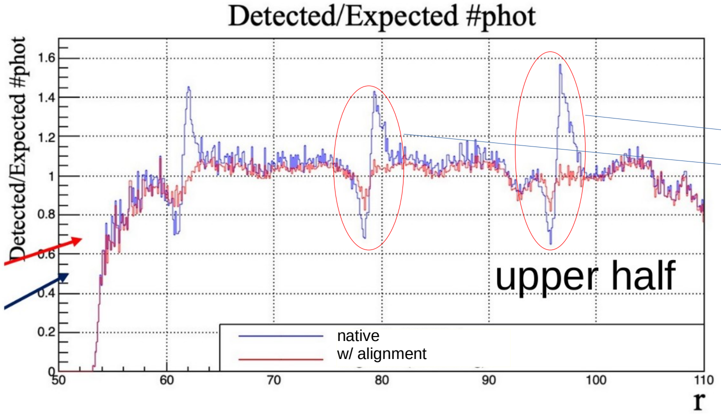
- we use the OpenCV library algorithm for edge detection on the expected & detected images to obtain the misalignment parameters for each aerogel tile





tile shifts in y-direction



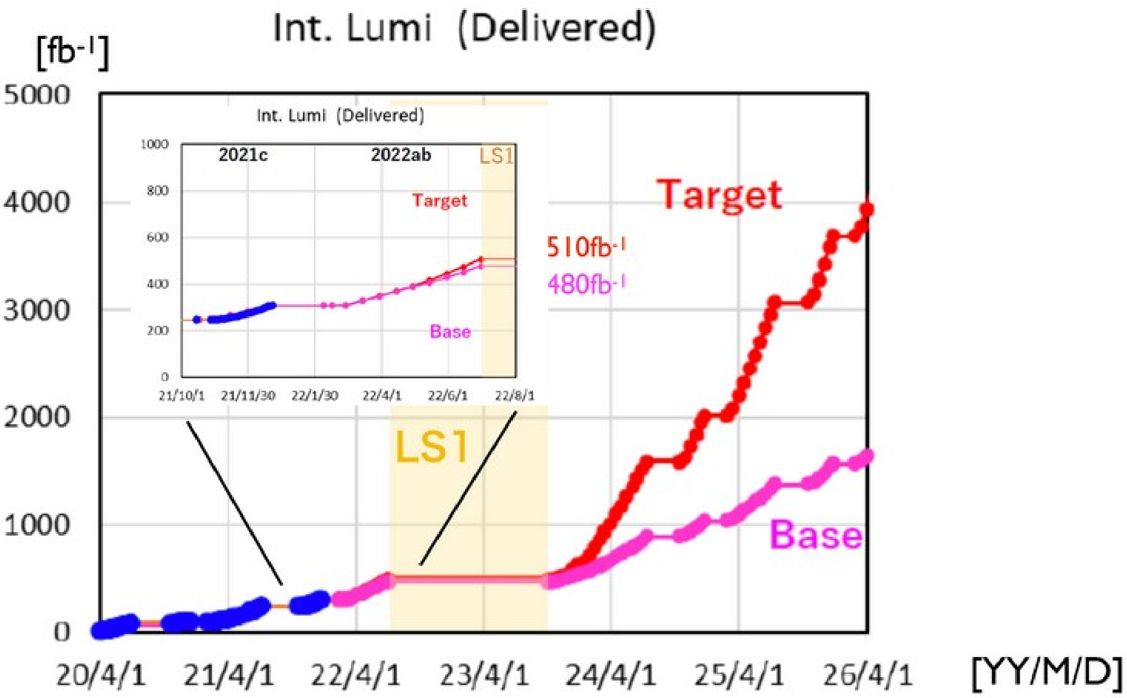


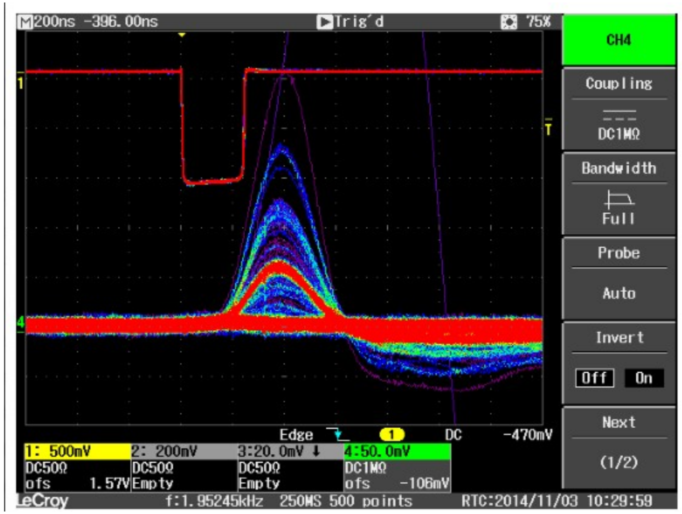
Clear improvement is observed after the alignment

→ preliminary performance study shows ~0.5% reduction in pion fake rate

→ further improvements are ongoing

Belle II luminosity projection




200ns -396.00ns
Trig'd
75%
CH4
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DC1MΩ
Bandwidth
Full
Probe
Auto
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Next
(1/2)
Edge
DC
-470mV
1: 500mV
2: 200mV
3:20.0mV
4:50.0mV
DC50Ω
DC50Ω
DC50Ω
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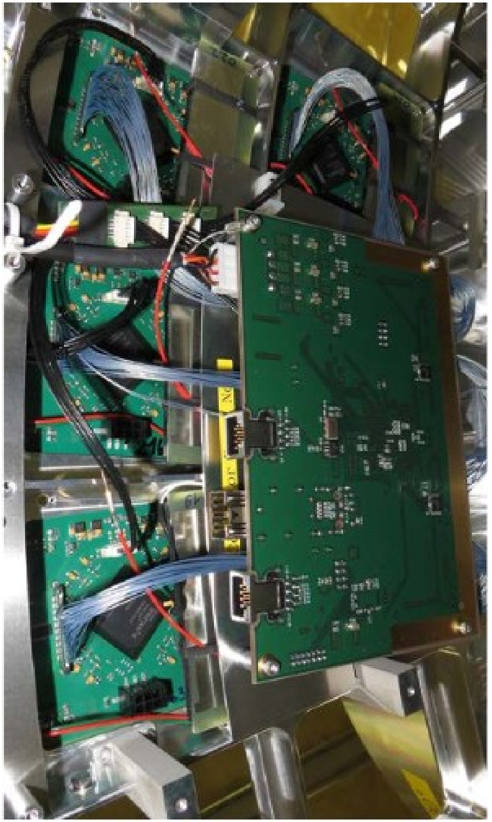

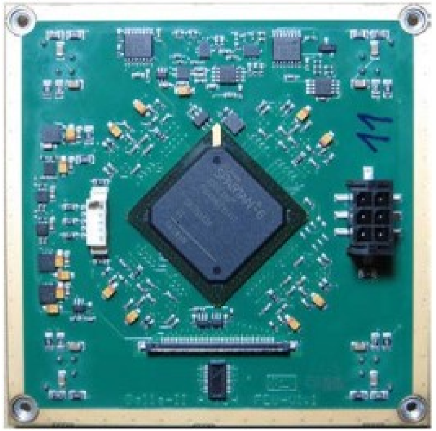

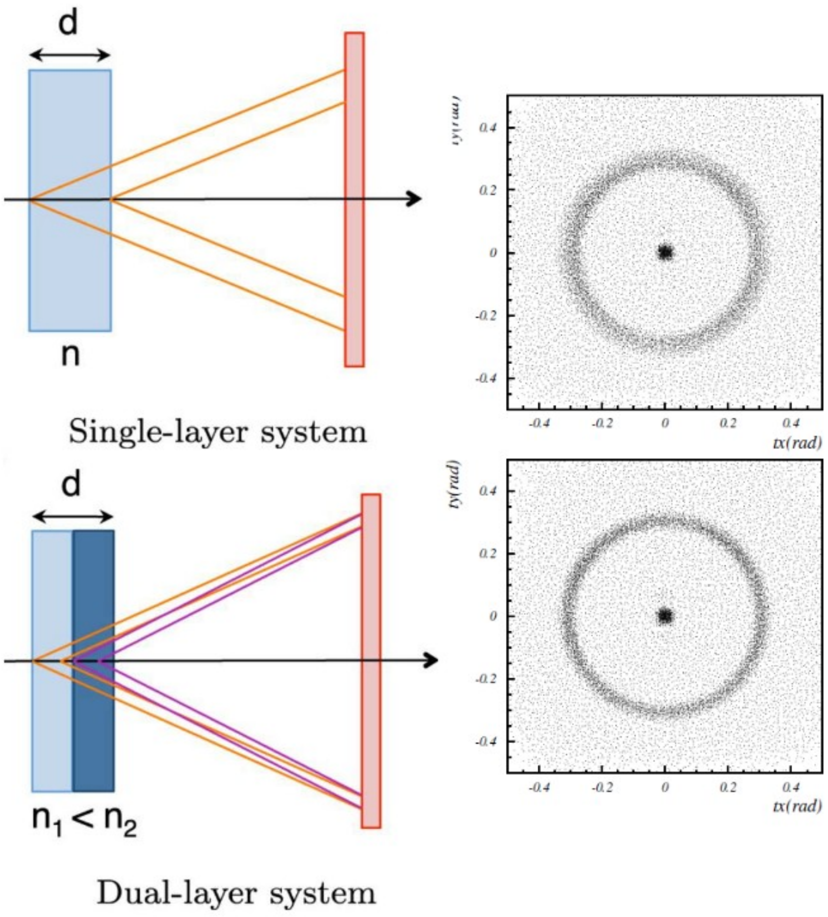
d
n
Single-layer system
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ty(rad)
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