RICH Detector Principles and the Belle II TOP, ARICH

Shohei Nishida

KEK

Belle II Physics Week

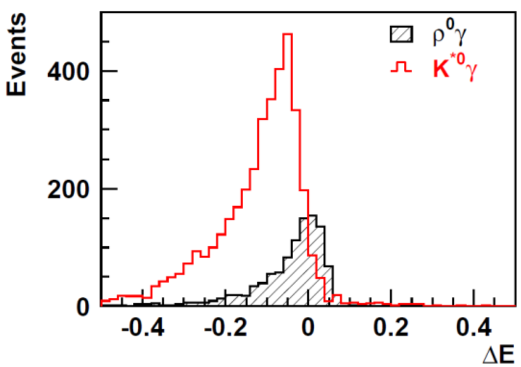
Dec. 2, 2021

Particle Identification

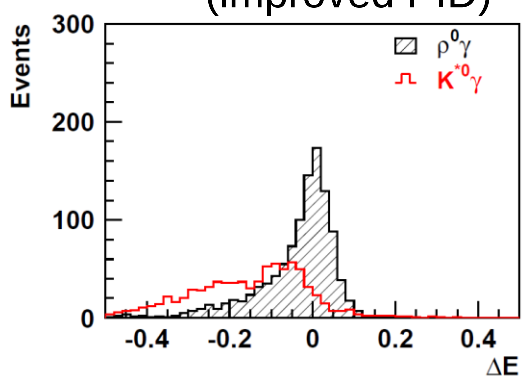
- Particle identification, especially K/π separation, is important in flavor physics experiment.
- Reduction of the background.
- e.g.) $B \to \rho\gamma$ v.s. $B \to K^*\gamma$

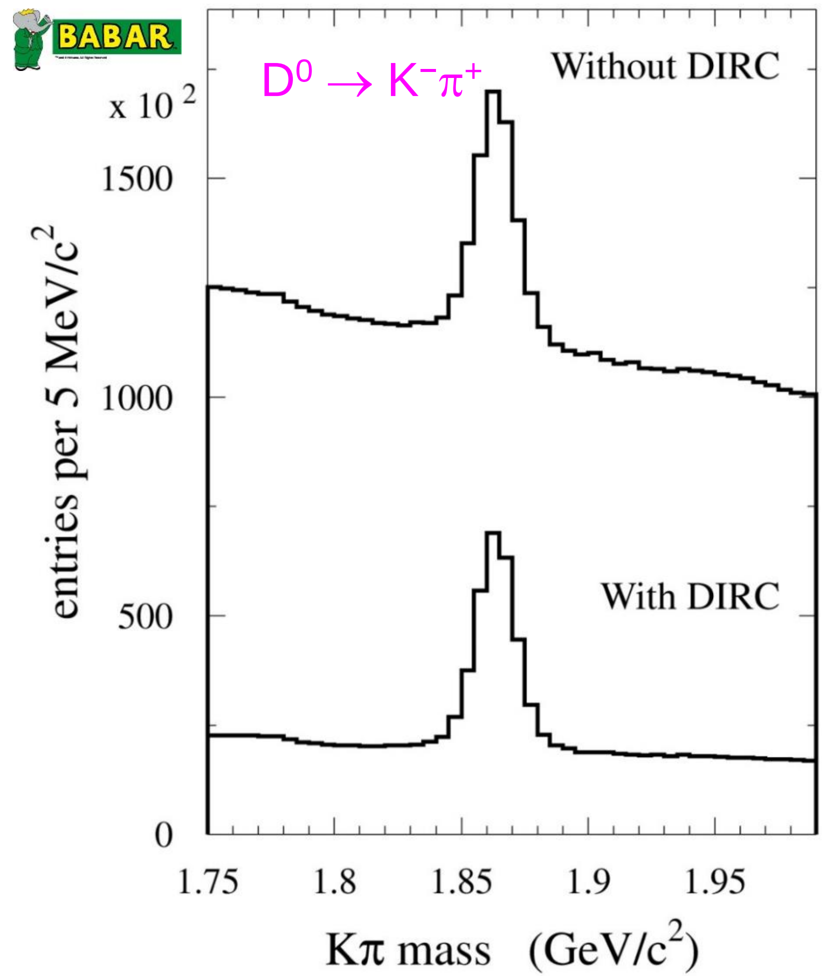
(old simulation study) 7.5 ab^{-1} [arXiv:0810.4084]

"Belle PID"

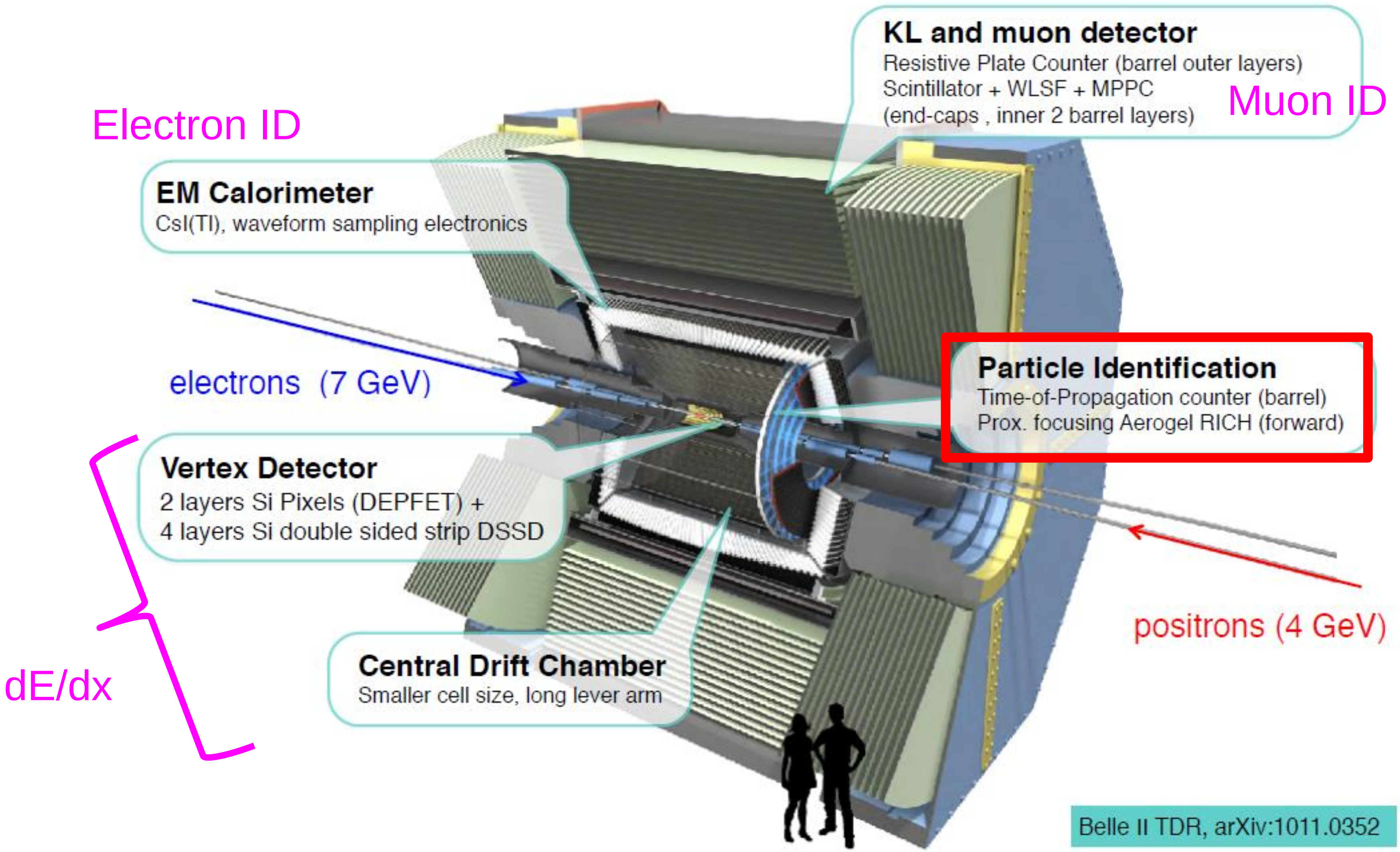


"Belle II PID" (improved PID)





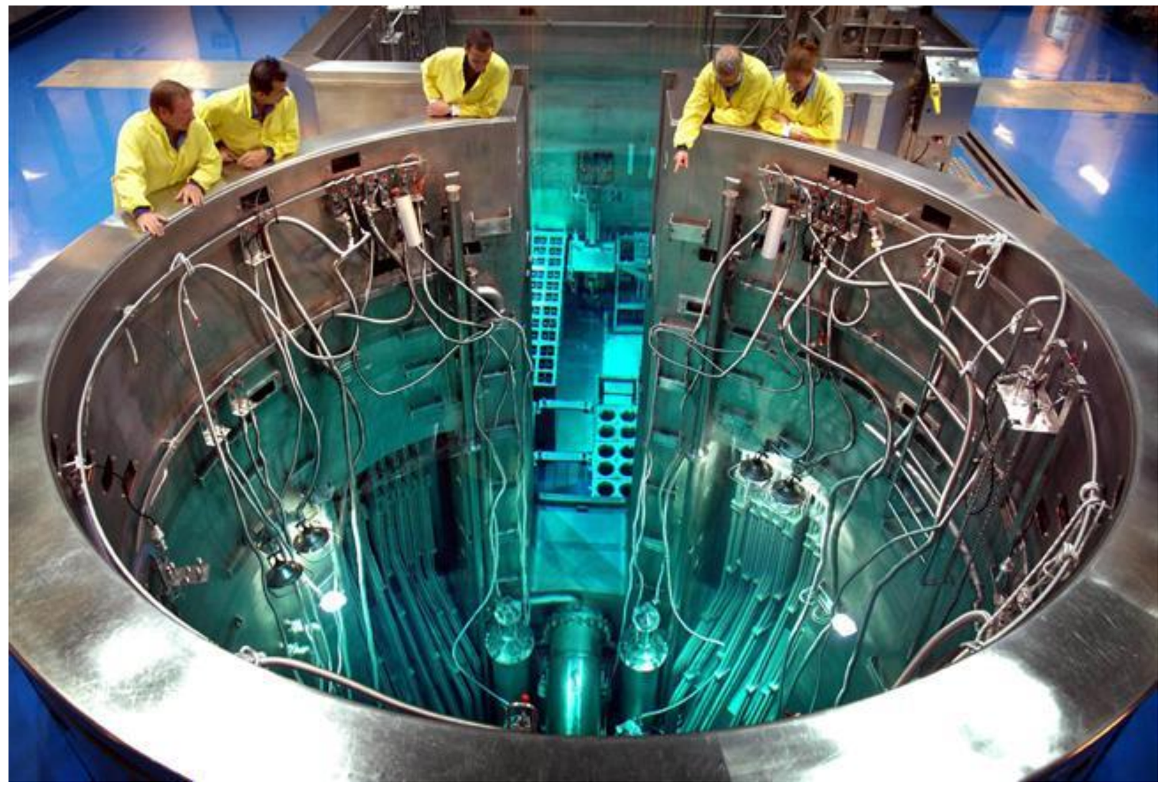
Belle II and Particle Identification



Cherenkov Light

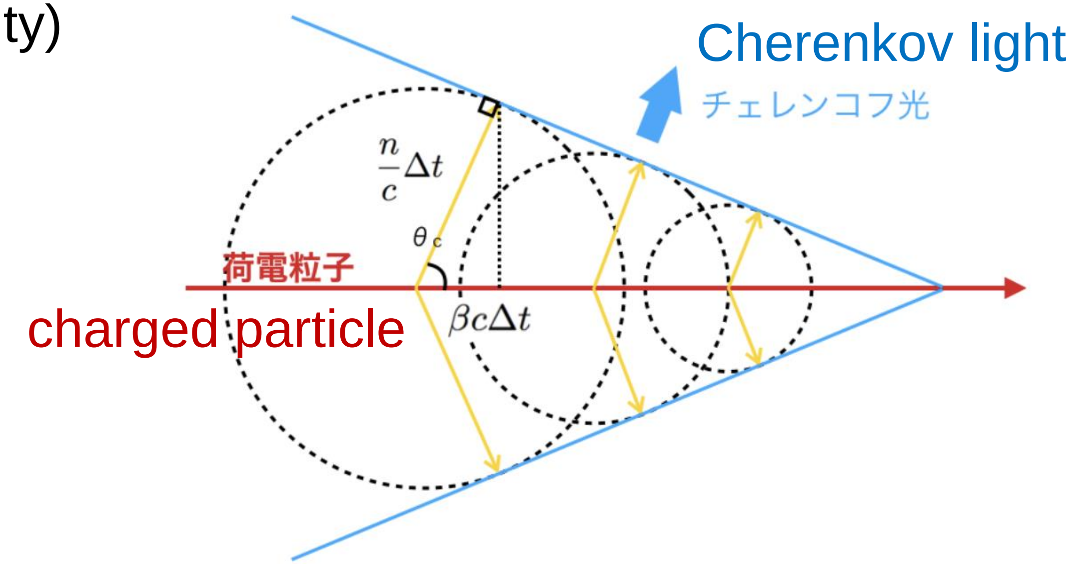
- Cherenkov Light is produced when a charged track that passes inside a material is faster than the speed of light inside the material.

Sonic boom



Cherenkov Light

(n: refractive index, β=v/c : velocity)



Condition

$$\beta > 1/n$$

Angle

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

Number of photons

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370\ \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z=1)\ ,$$

The number of photons is larger when the Cherenkov angle is larger (i.e. the charged particle is faster; the refractive index n is larger).

Cherenkov Light

How to utilize Cherenkov light for PID ?

$p = m \beta \gamma$

$\gamma = (1-\beta^2)^{-1/2}$

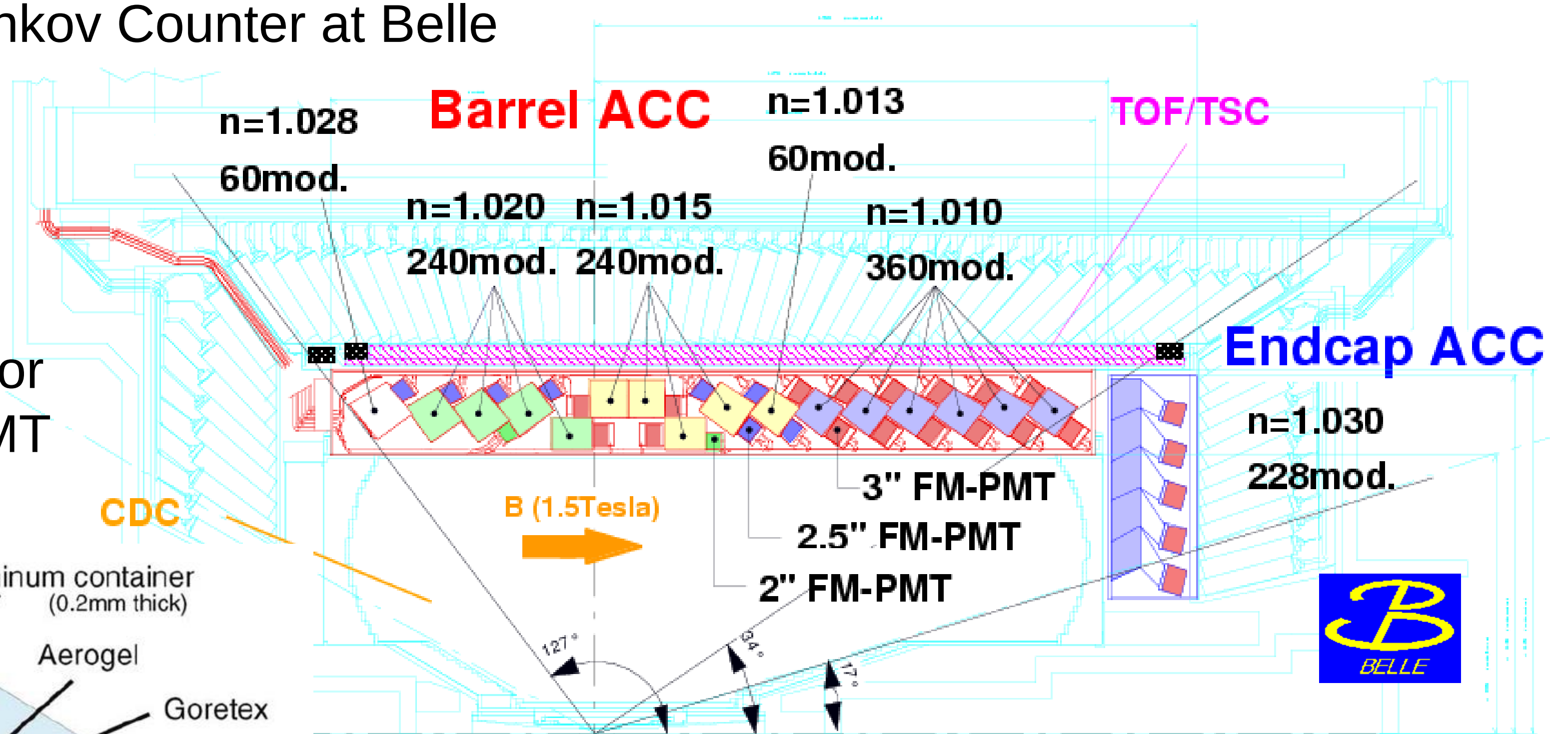
⇨ Obtain the information of β (velocity of the charged particle), independently from the momentum (measured by CDC etc.)

- Cherenkov light is emitted when $\beta > 1/n$.
  - ✓ By measuring Cherenkov light, one can tell whether the mass is smaller than a certain threshold (for a certain momentum).
  - ✓ Threshold-type Cherenkov Counter.
    - ➢ Aerogel Cherenkov Counter (ACC) @ Belle
- The Cherenkov angle depends on β (and n).
  - ✓ Measure the Cherenkov angle.
  - ✓ Ring Imaging CHerenkov counter (RICH).
    - ➢ DIRC @ BaBar
    - ➢ TOP, ARICH @ Belle II

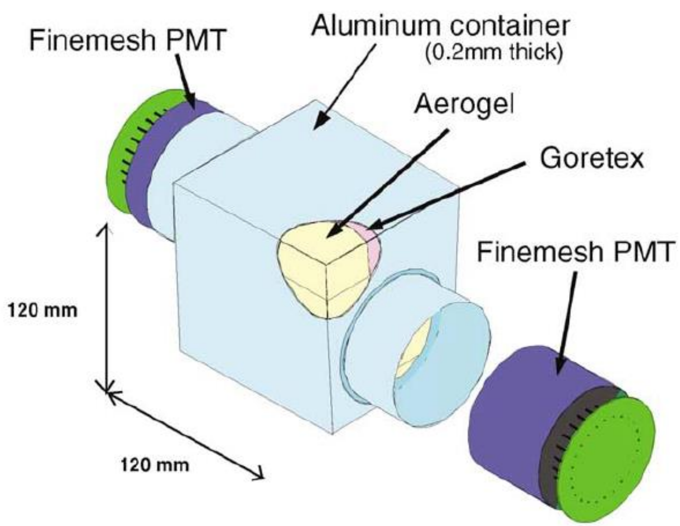
$$\cos\theta_c = \frac{1}{\beta n}$$

Aerogel Cherenkov Counter

Aerogel Cherenkov Counter at Belle



Aerogel Radiator
+ Finemesh PMT

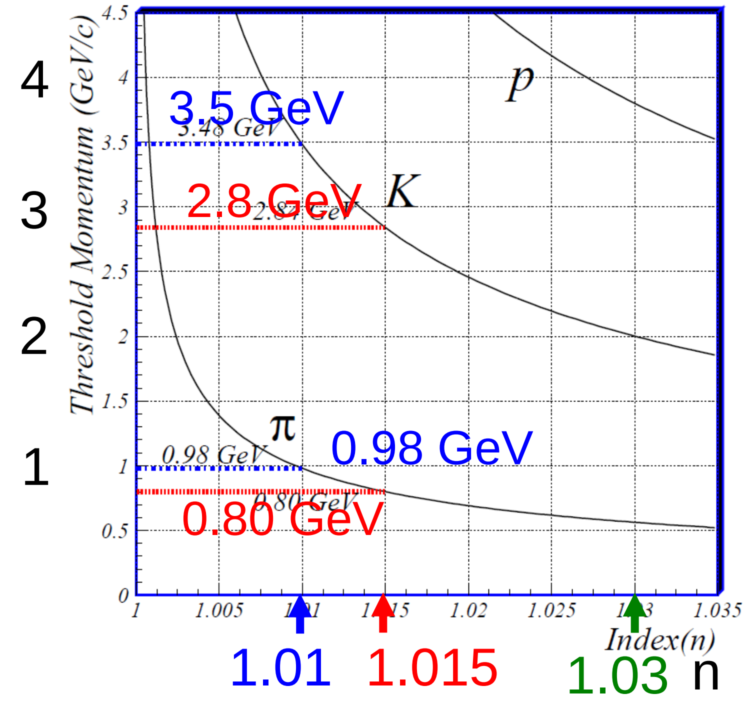


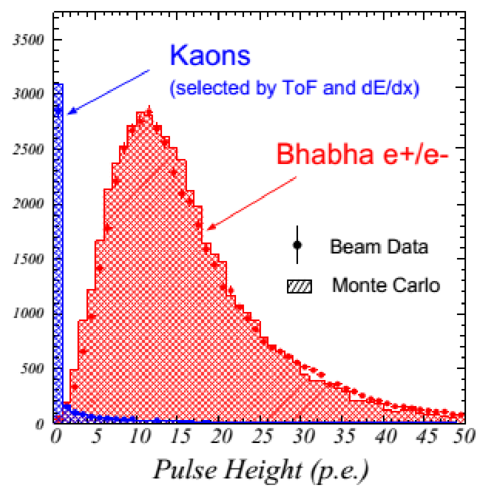
- The refractive index n of aerogels are varied to cover the momentum region in interest (see next page)
  - ✓ higher momentum in more forward
    $\rightarrow$ lower n (in barrel)

Aerogel Cherenkov Counter

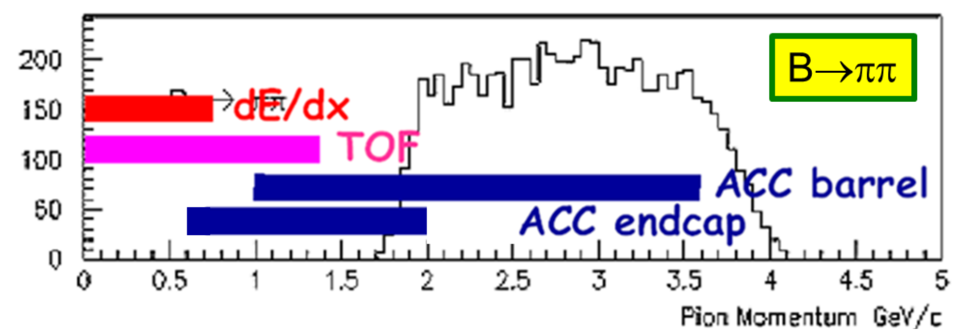
- K/π separation is possible only for
  - ✓ 0.98 < p < 3.5 GeV when n=1.01
  - ✓ 0.80 < p < 2.8 GeV when n=1.015
- Other momentum region needs to be covered by other detectors (dE/dx, TOF).
- Targeting lower momentum region (0.6 < p <2 GeV) in endcap ACC, because of no TOF.
- Simple and robust detector (it could work at Belle II environment)

Momentum threshold



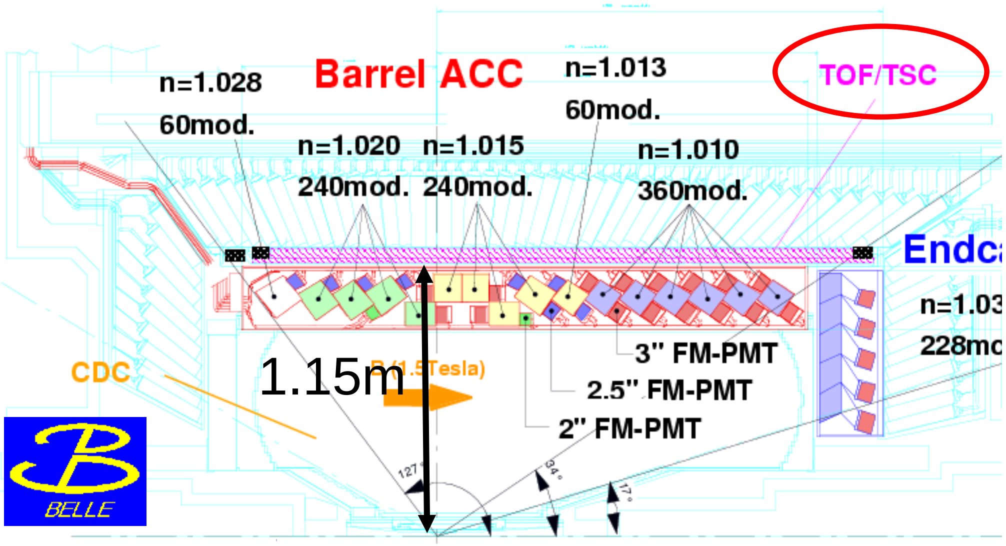


- Adequately good performance.
- Knock-on electrons cause mis-ID (source of limitation of the performance)



Time of Flight (TOF)

Another PID device at Belle: Time of Flight (TOF) counter



π^+ : 0.1396 GeV, K^+ : 0.4937 GeV

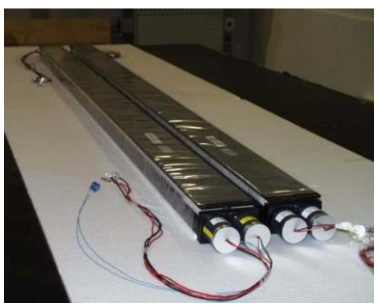
$\beta = p / E$

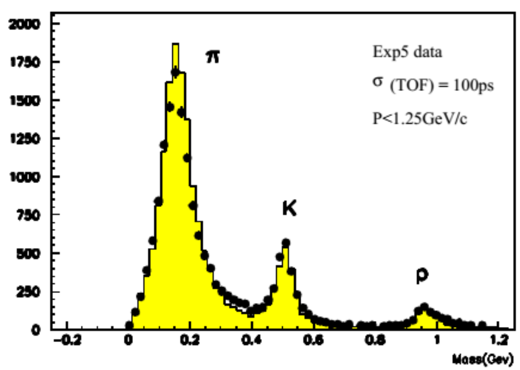
$E = \mathrm{sqrt}(p^2 + m^2)$

- For 1 GeV π, E = 1.010 GeV, β = 0.99
- For 1 GeV K, E = 1.115 GeV, β = 0.90

Time of flight from IP to the detector?

$t = L / \beta c \sim 3 / \beta$ [ns]





If we can measure the arrival time with a precision of well below 0.3 ns, we can separate π and K @ 1GeV.

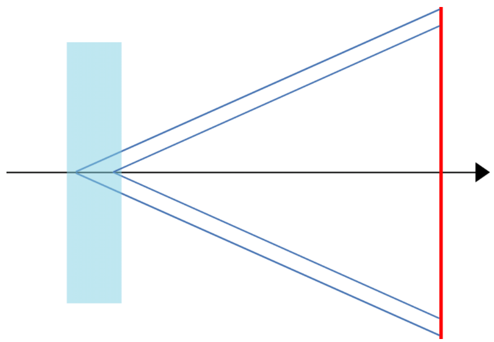
- Covers up to 1.5 GeV.
- TOF time resolution ~ 80 ps

Ring Imaging Cherenkov Counter (RICH)

Principle of RICH

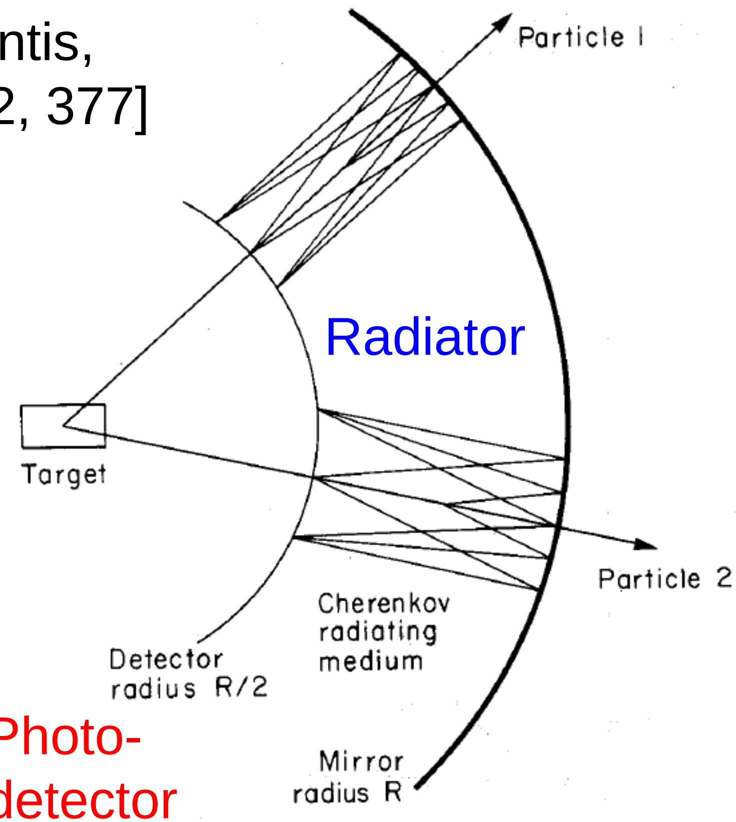
Ring Imaging CHerenkov counter (RICH) : measure the Cherenkov angle

Proximity(-focusing) type



Focusing type

[J.Seguinot and T.Ypsilantis, NIM 142, 377]



- Simple-minded RICH may be proximity type, but (historically) focusing type is the standard.
- Proposed by J.Seguinot and T.Ypsilantis in 1977.
- Enough path length over radiator
  $\rightarrow$ focus by mirror.
- Longer path $\leftrightarrow$ Less position resolution needed.

Principle of RICH

Materials	Refractive Index
Gas	1.0001~1.001 @ 1atm
Aerogel	1.01~1.1
Water	1.33
Quartz	1.46

$\beta > 1/n$

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

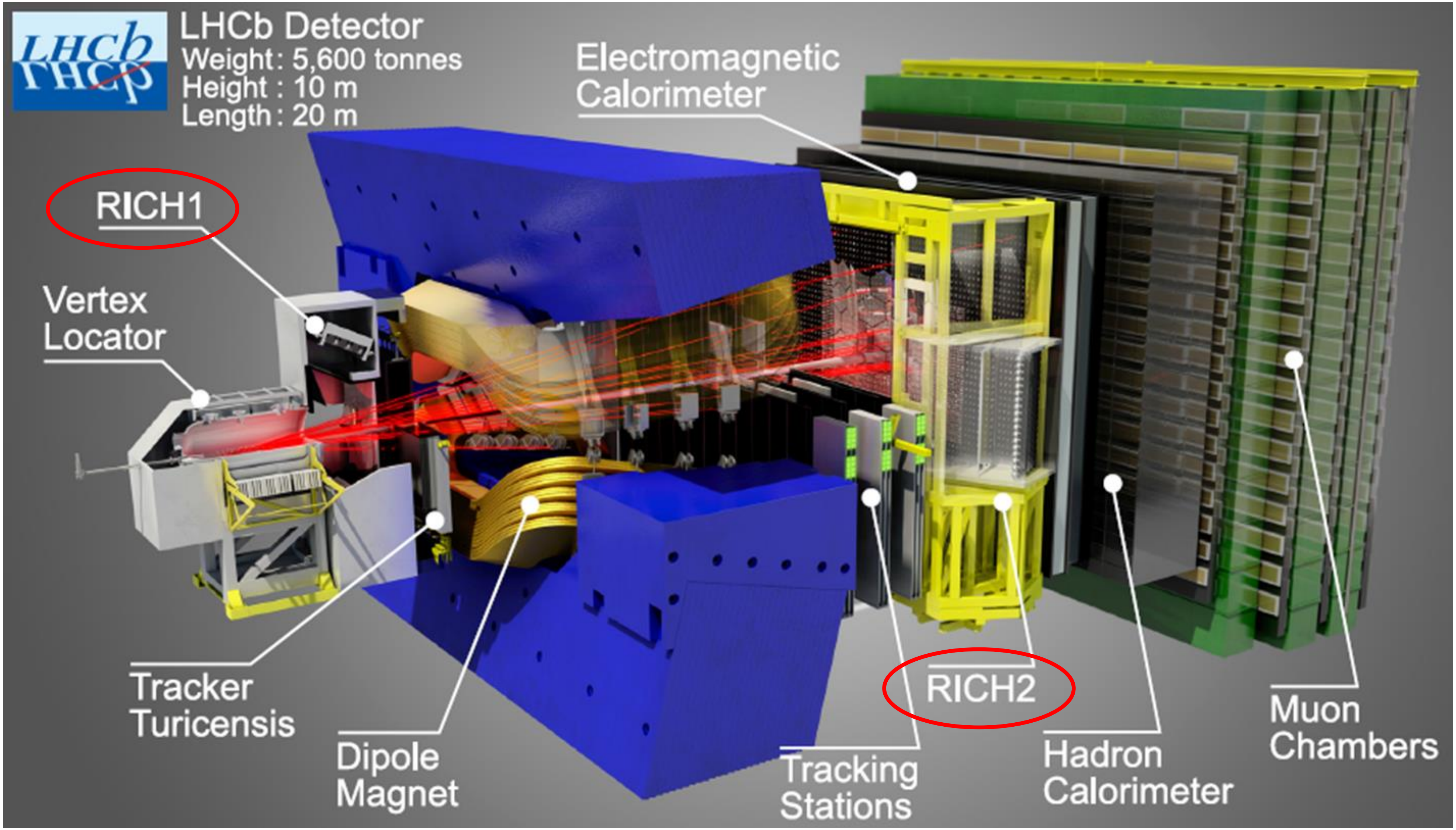
Radiator

- Refractive index and transparency.
- The choice is up to the momentum of the particles to be identified.
  - ✓ high momentum → gas
- But, the choice affects the configuration of the RICH detector.
  - ✓ Gas → Long path length in radiator.

Photodetector

- Detection of the single photon.
- Position measurements.
  - ✓ Necessary position resolution depends on the configuration. Multi-channel device may be required.
- Quantum efficiency (QE) / photon detection efficiency (PDE)
- Limitations from the experiment, environment.
  - Magnetic field.
  - Radiation.
  - Rate (necessary timing resolution).
  - Coverage; cost.

Example: LHCb RICH

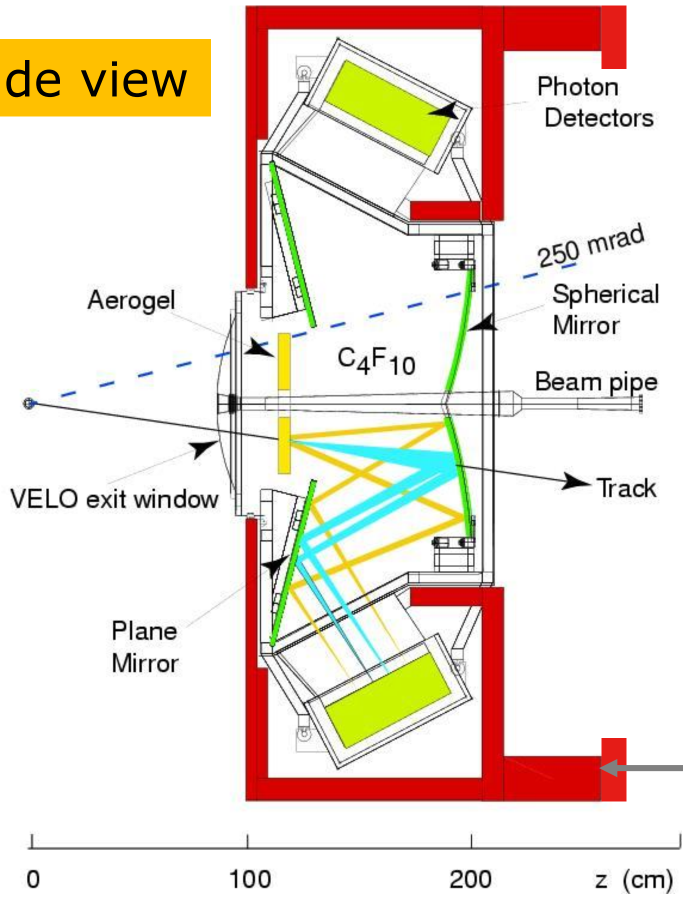


Example: LHCb RICH

RICH 1

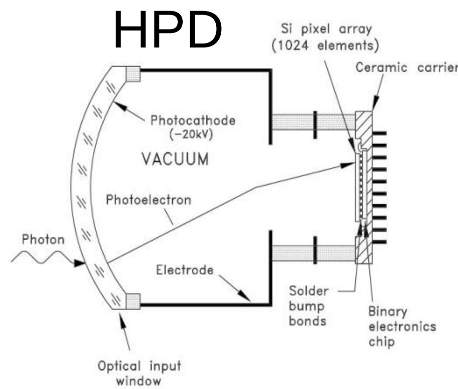
Acceptance 25-300 mrad

Side view



2 Detectors

3 Radiators

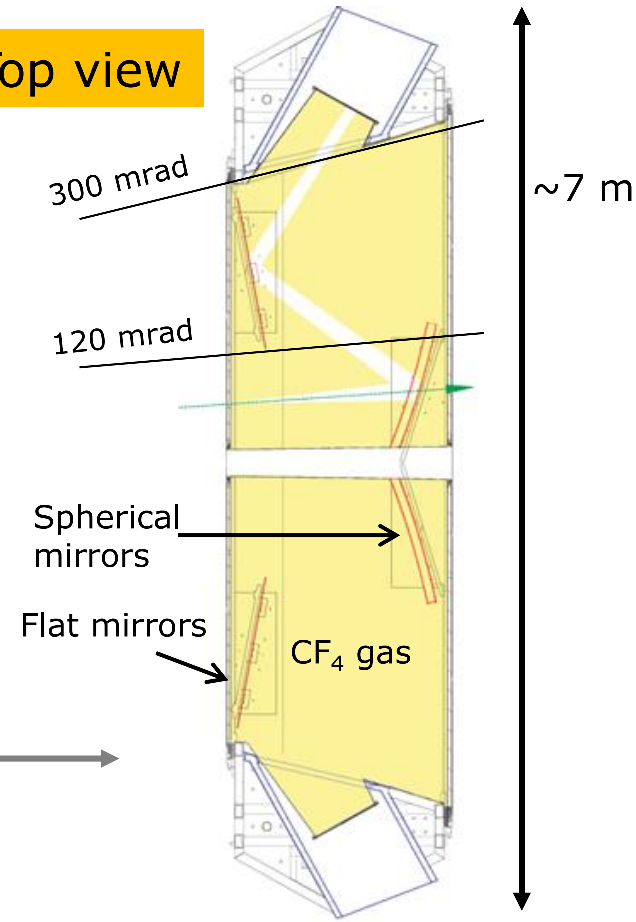


Note Scale Difference

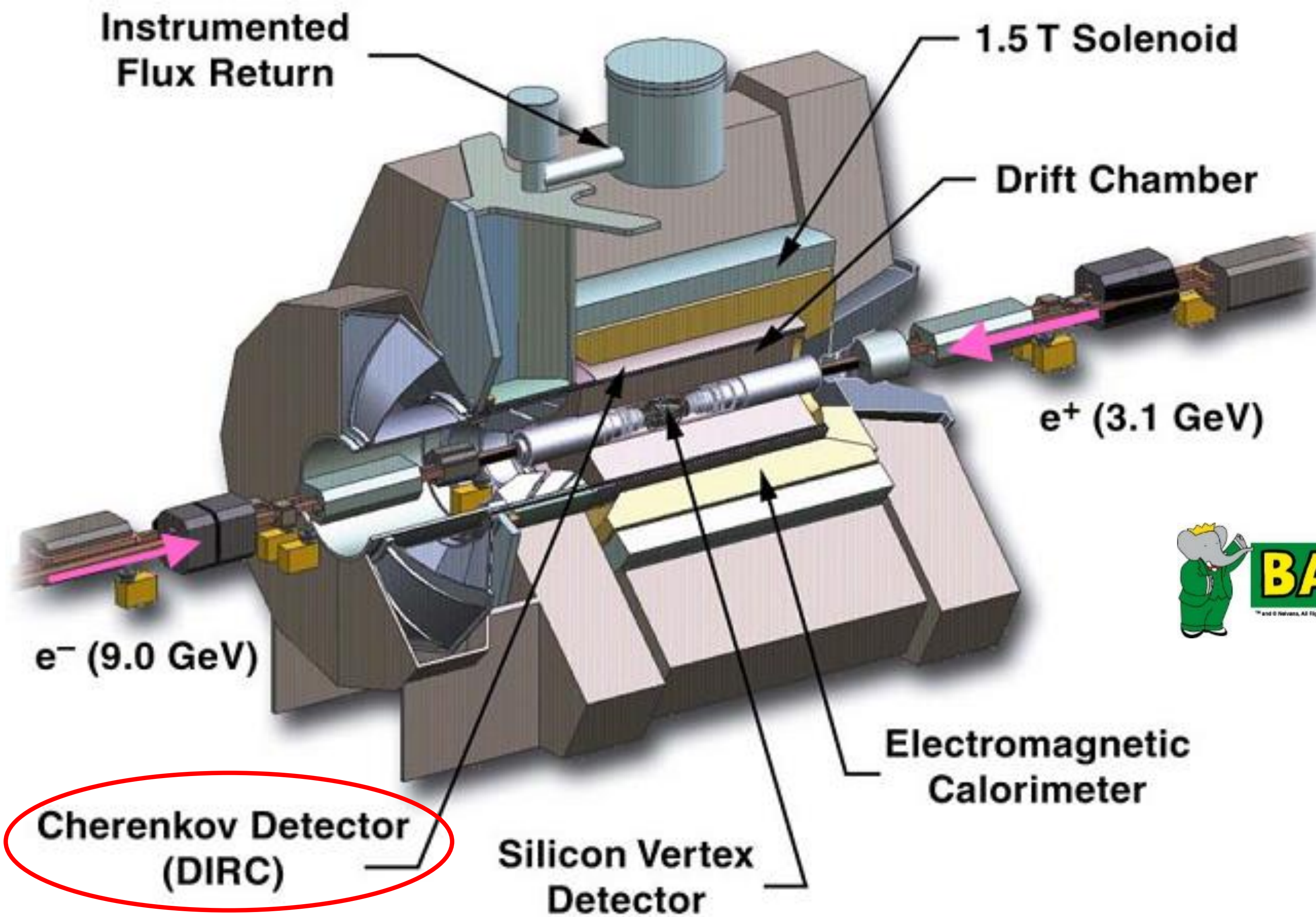
RICH 2

Acceptance 15-120 mrad

Top view

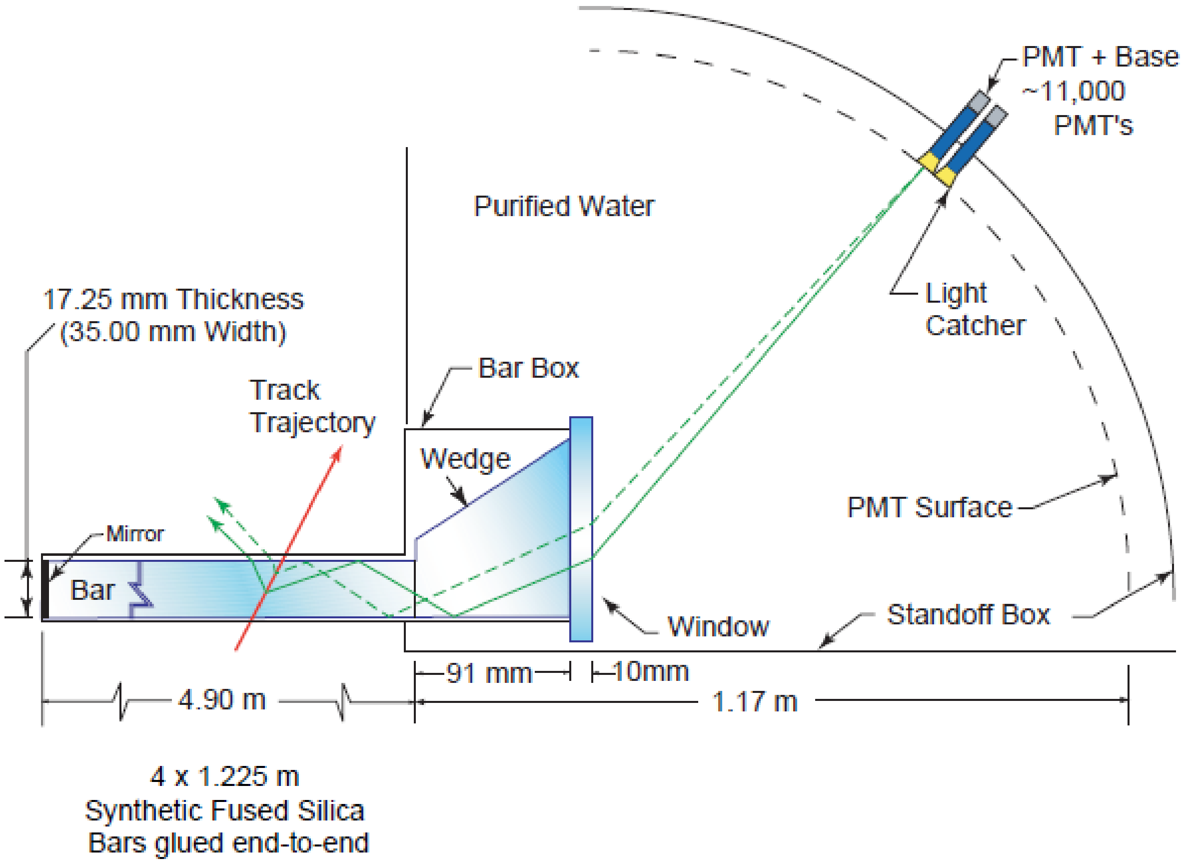


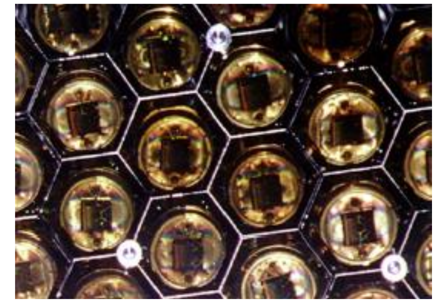
Example: BaBar DIRC



Example: BaBar DIRC

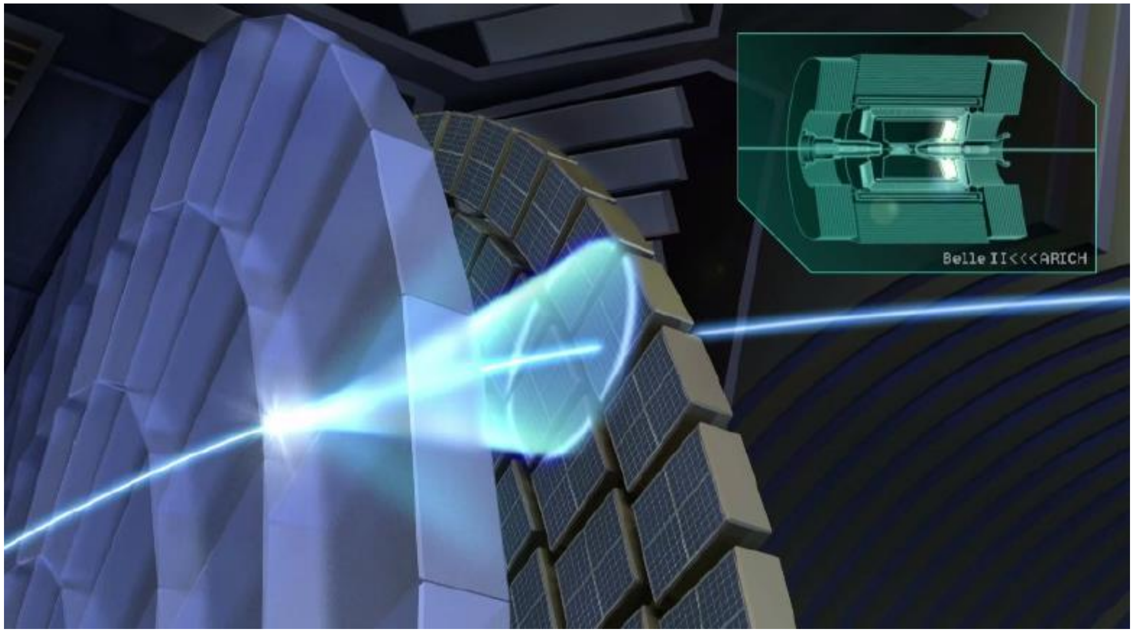
DIRC (Detection of Internal Reflected Cherenkov light)



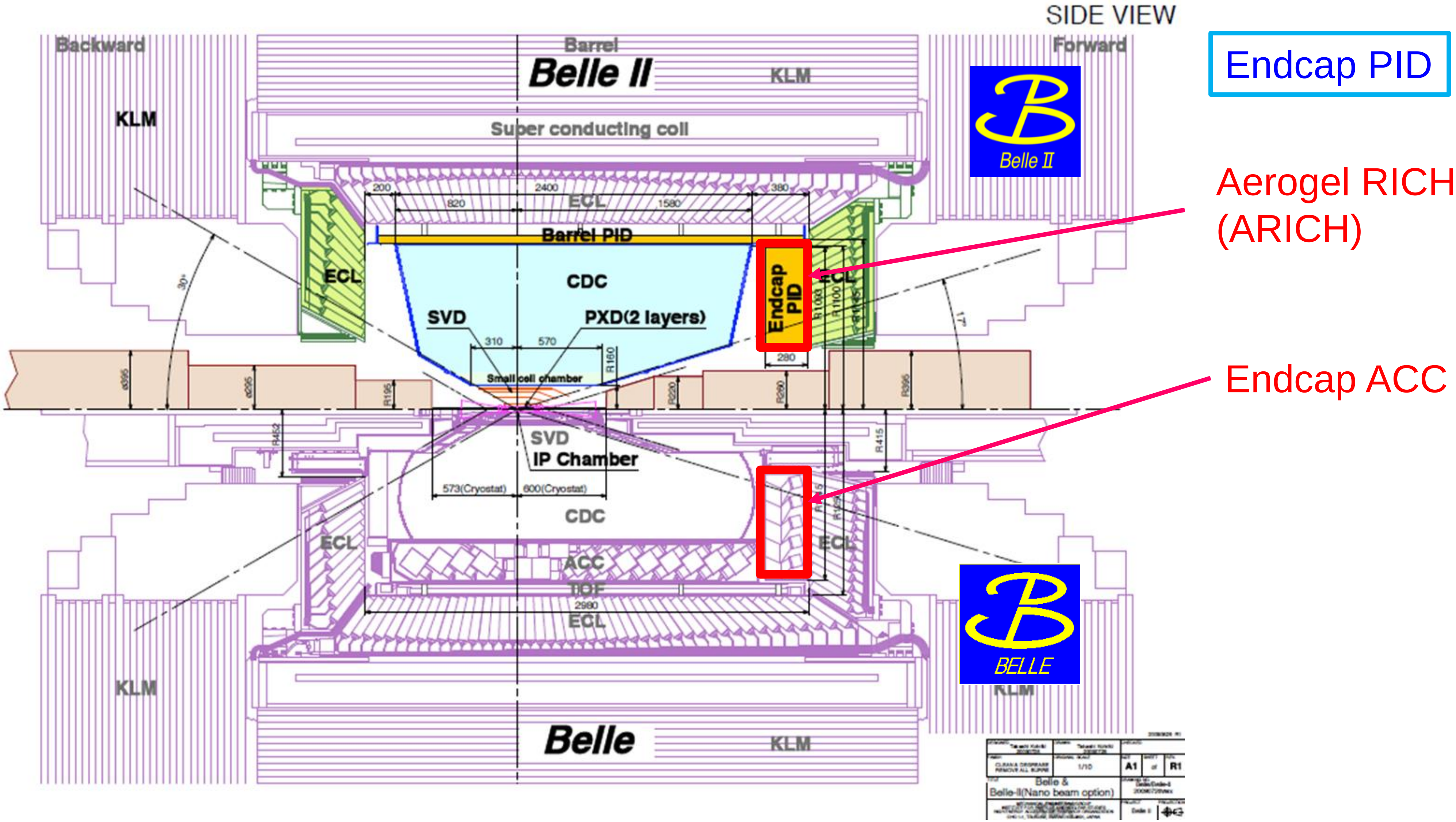


- Total reflection inside quartz bars
  - ✓ Angle information is kept.

Aerogel RICH

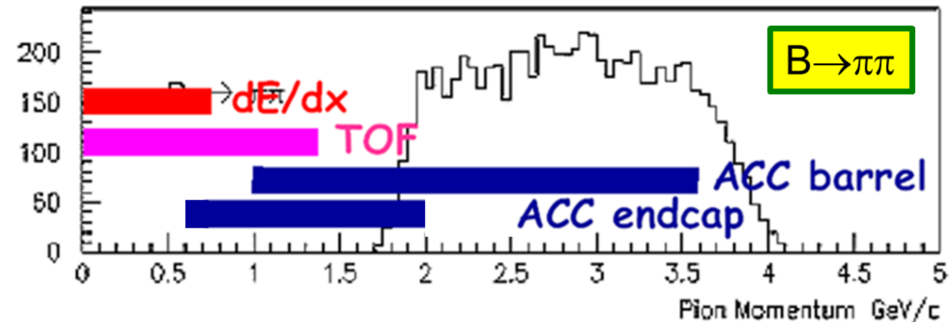


Aerogel RICH



Aerogel RICH

- Endcap ACC at Belle covered K/π separation at 0.6 < p < 2.0 GeV
  - ✓ Because TOF was not equipped at the endcap.

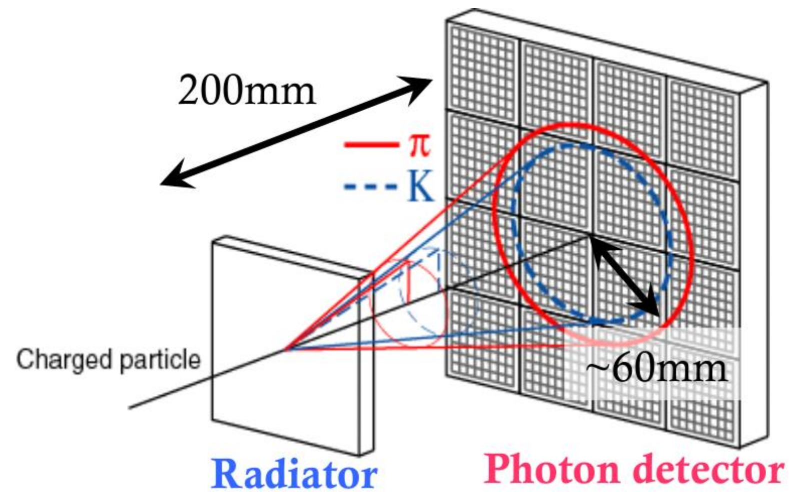


- Wider momentum range up to 4 GeV
  → RICH
- Available space was limited (same size as endcap ACC)
  → Proximity type

- Higher refractive index than Belle ACC
  → (still) Aerogel Radiator
  - ✓ possible to adjust the index.

⇨ Aerogel RICH (ARICH)

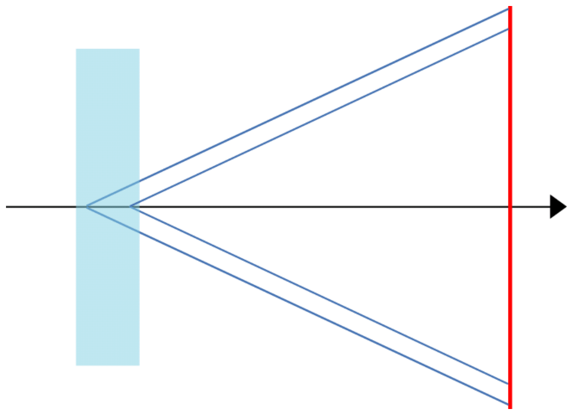
Concept of Aerogel RICH



$$\theta_C(\pi) - \theta_C(K) \simeq 23 \text{ mrad}$$

(@ 4 GeV; n = 1.05) (1.3°)

Proximity RICH



PID performance is determined by the Cherenkov angle resolution per track:

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

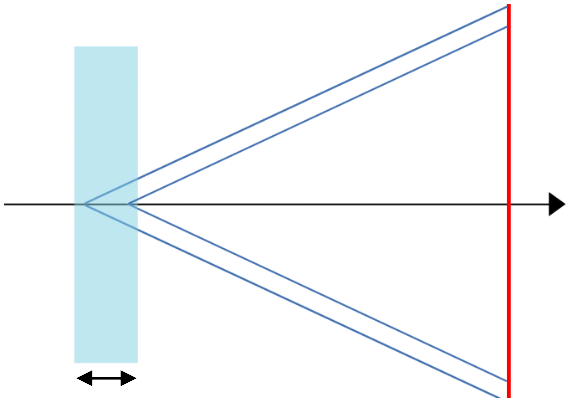
$N_{p.e.}$: Number of detected photons
σ_θ : Cherenkov angle resolution per photon (how precise we can measure the angle).

Main contribution to σ_θ

- Position resolution of the photon detector
- Thickness of the radiator
- Tracking resolution of the charged particle (position, angle)
- Multiple scattering of track (low momentum)
- Wave length dependence of the refractive index (Chromatic dispersion)

Proximity RICH

Normal Proximity RICH

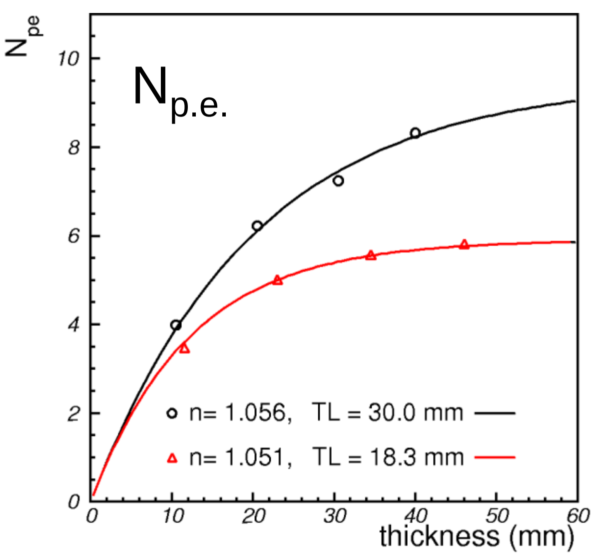


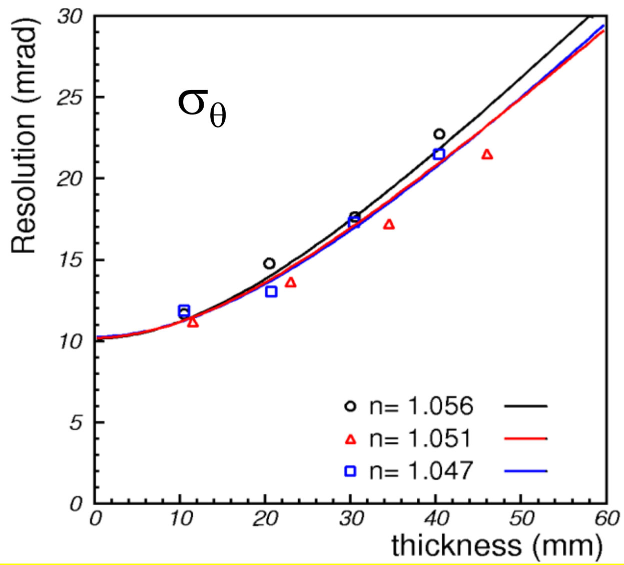
$$\sigma_{\rm track} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

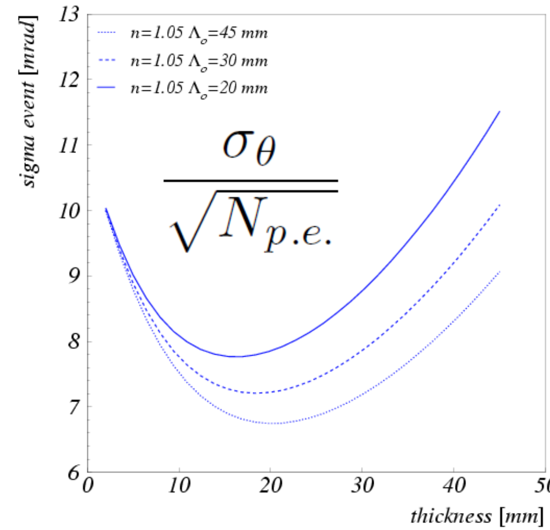
$N_{p.e.}$ and σ_θ is proportional to d (radiator thickness)

d → large ⇒ $N_{p.e.}$ → large, σ_θ → bad
d → small ⇒ $N_{p.e.}$ → small, σ_θ → good

Old beam test result

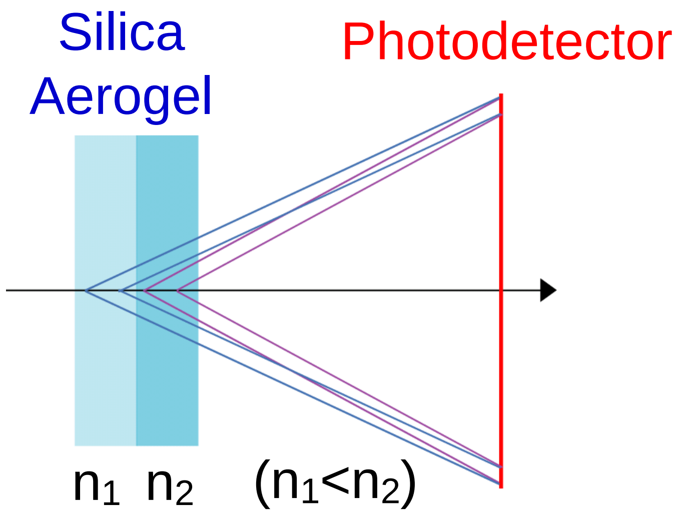






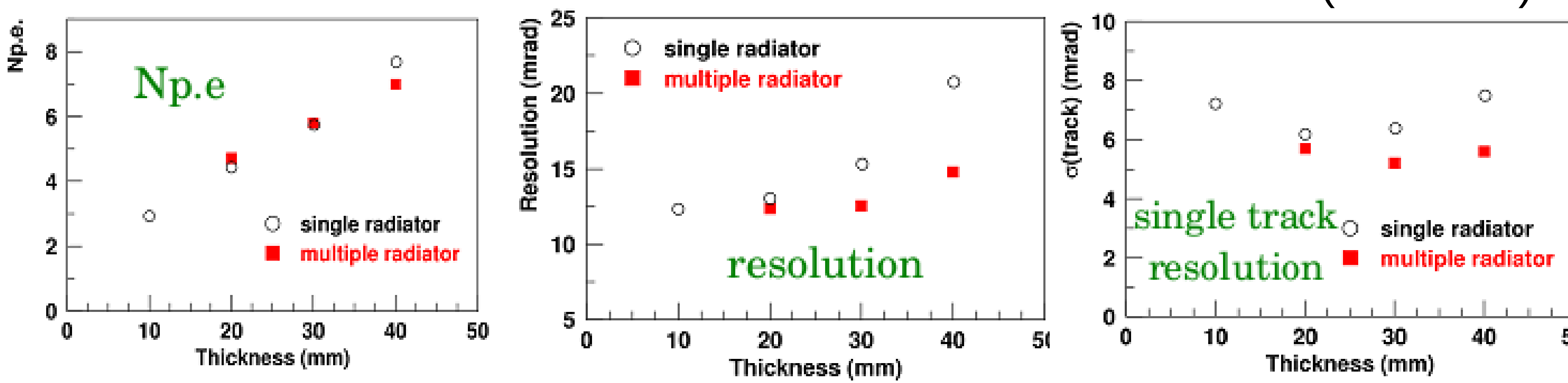
Dual Radiator RICH

Solution for the contradiction: dual radiator RICH



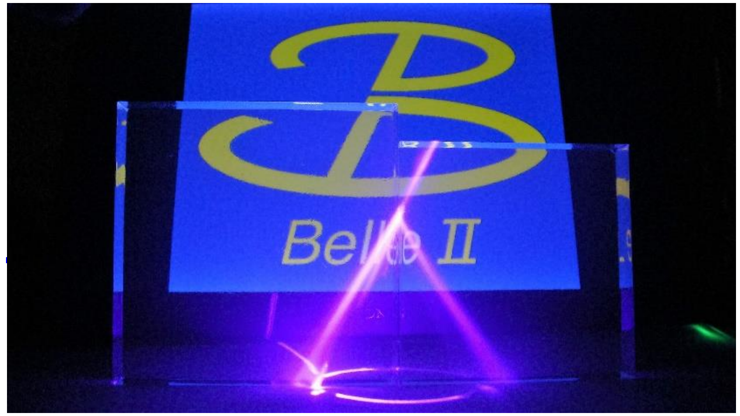
- Use two layer of aerogels with different refractive index.
  - ✓ Ring image overlap at the photo-detector.
  - ✓ Possible only with aerogels: we can adjust the index of aerogels.
  - ✓ More layers can make better performance (but not so much different).

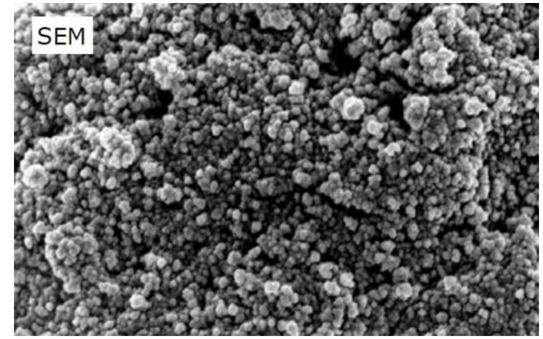
(old result)

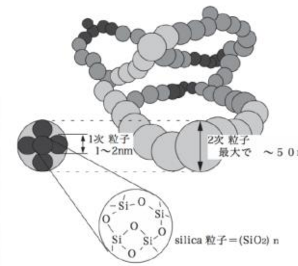


Aerogel

- Composition SiO_2. Very light. Sparse structure
- Refractive index is around 1.01-1.1, and can be adjusted.

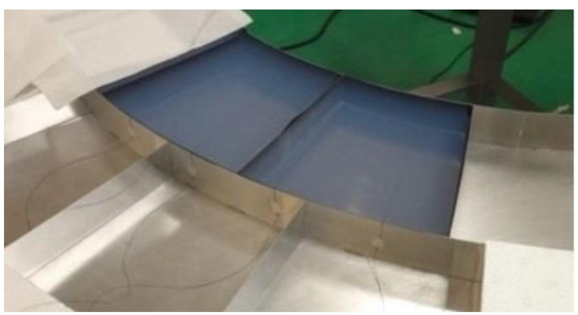


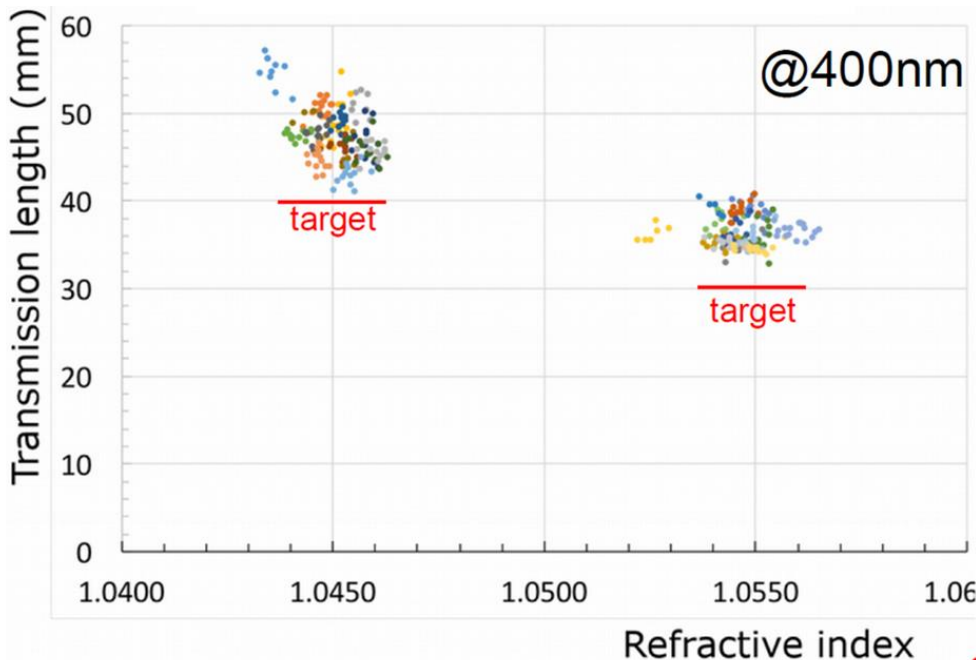




For Belle II ARICH

- 2cm × 2 layers.
- $n_1 = 1.045$ and $n_2 = 1.055$
- Good transparency (~40mm)
- 248 tiles in total
  - ✓ Cut with water jet from 18cm × 18cm tile.

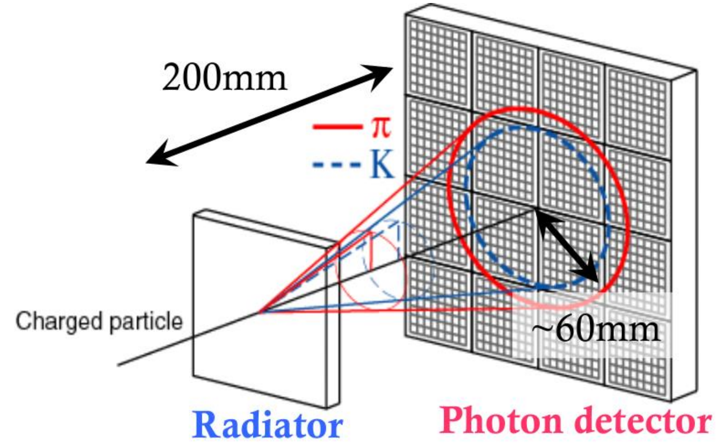




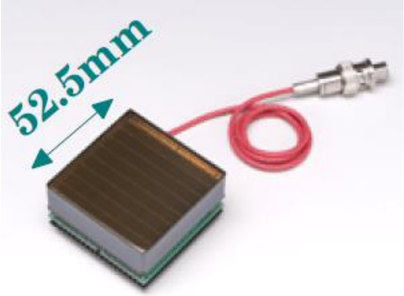
Photodetector

Requirement to the photon-detector:

- Single photon detection with good QE/PDE.
- ~5mm pixel size.
- Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).



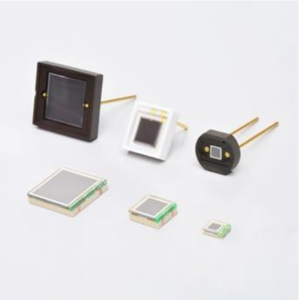
Multi-anode PMT



NG: magnetic field

used for
initial test

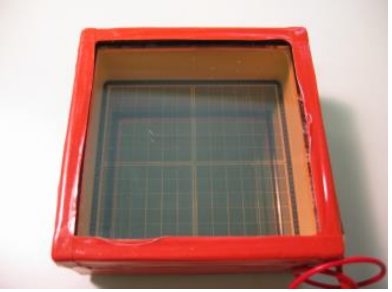
MPPC/SiPM



NG: radiation(neutron)

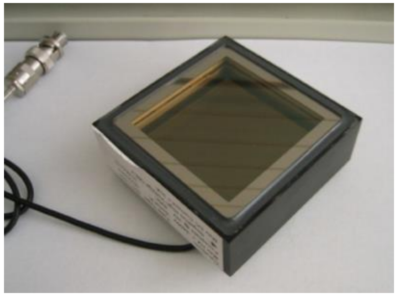
some test
was done

HAPD



OK

MCP-PMT



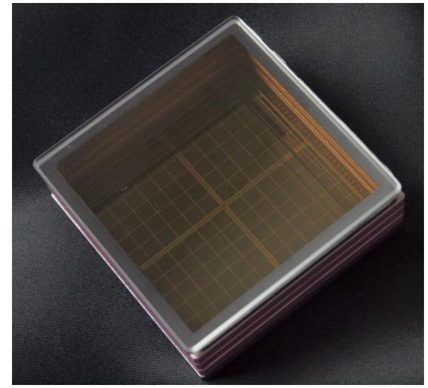
OK

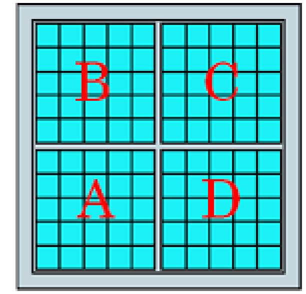
good timing resolution
(work as TOF too?)

HAPD

Photodetector

- Single photon detection.
- ~5mm pixel size. Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).

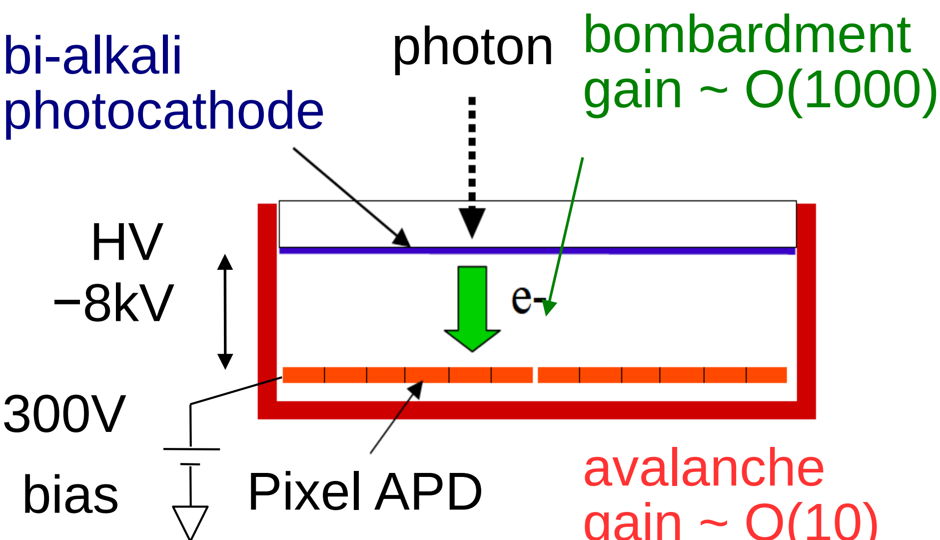




□4. 9 [mm]

⇨ HAPD (Hybrid Avalanche Photo-Detector)

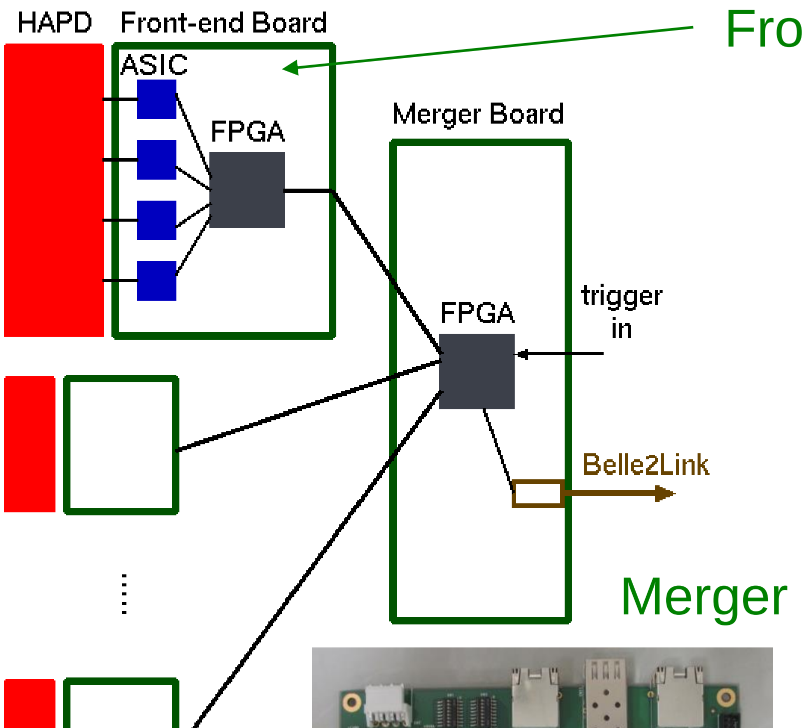
Hybrid: Vacuum tube + semi-conductor



- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip × 4).
- Gain ≥45000.
- Peak QE ~28%
- Size 73mm × 73mm.
- Effective area 63mm×63mm (65%).

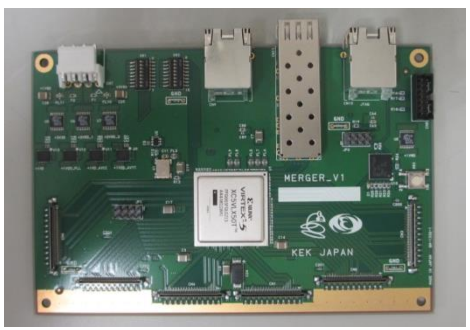
Total 420 HAPDs

ARICH Electronics

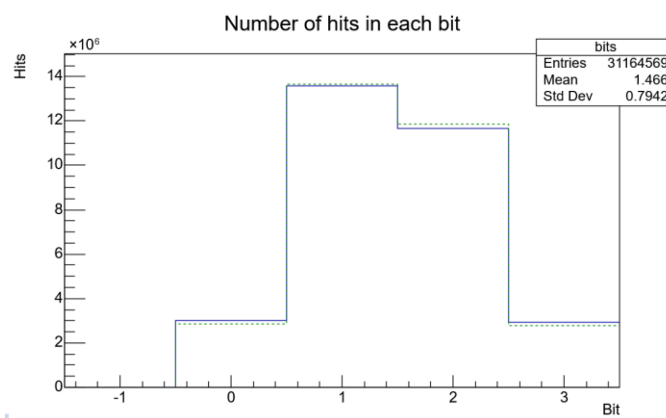


Front-end Board

- 4 ASIC + Xilinx FPGA (Spartan6).



- Total 60480 channel
- Only ON/OFF information
  - ✓ Pulse height not readout.
  - ✓ Readout the hits for 4 different timings (i.e. 4 bit per channel)

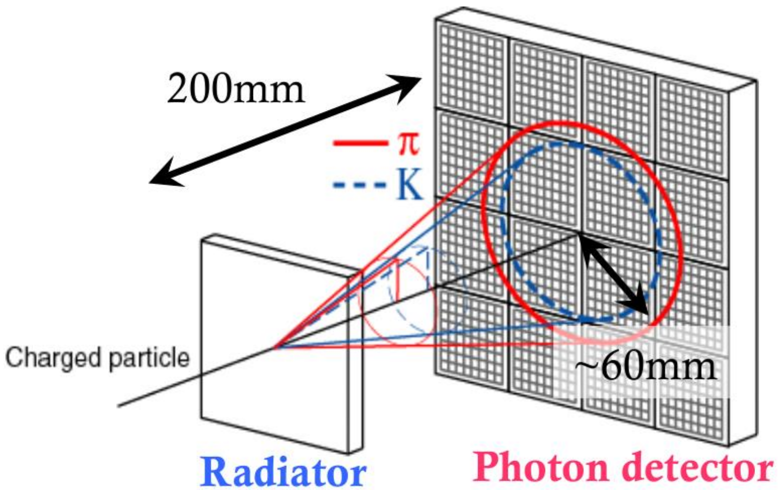


1 bin = 126 ns

DQM

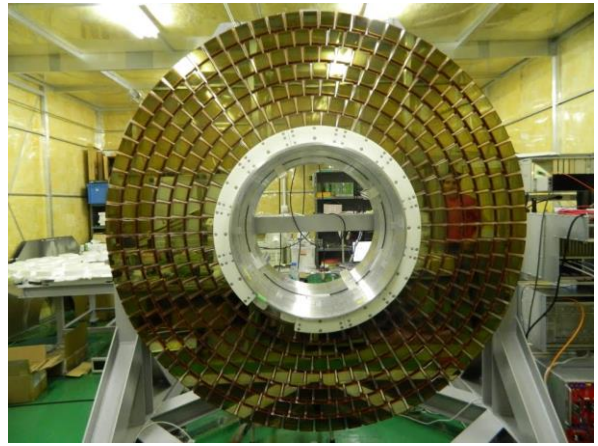
- Receive hitdata from 5-6 front-end boards, and send to DAQ.

ARICH

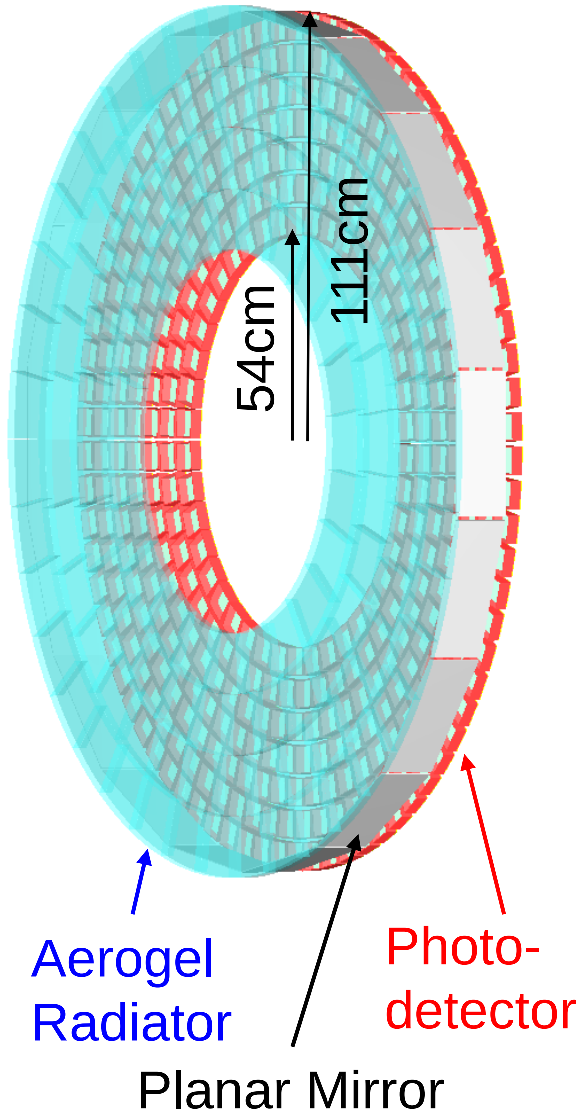


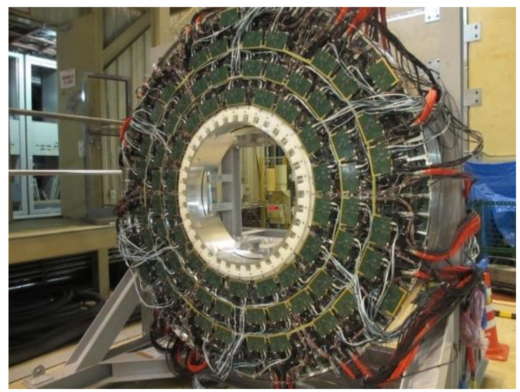
Aerogel (2cm×2)

HAPD



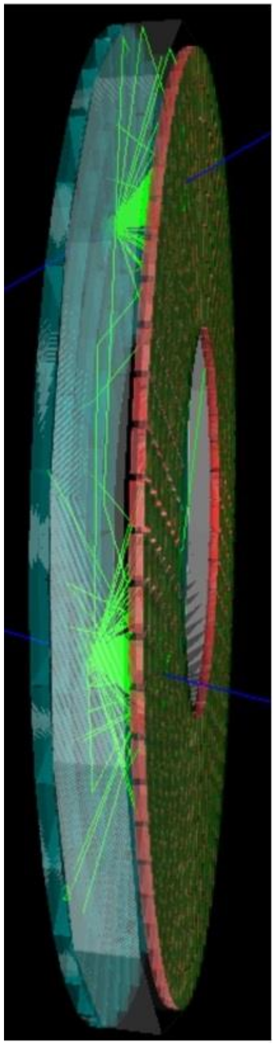
420 HAPDs



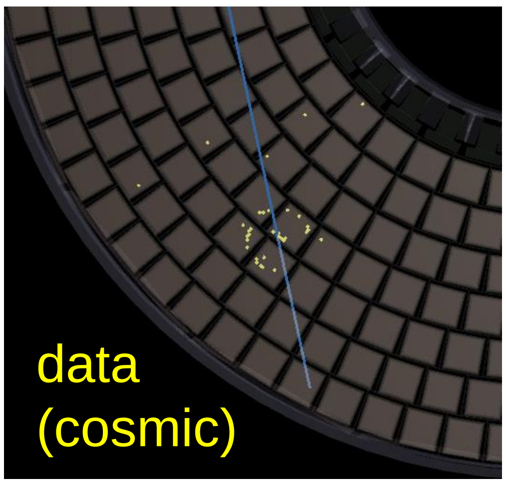


Cherenkov Angle

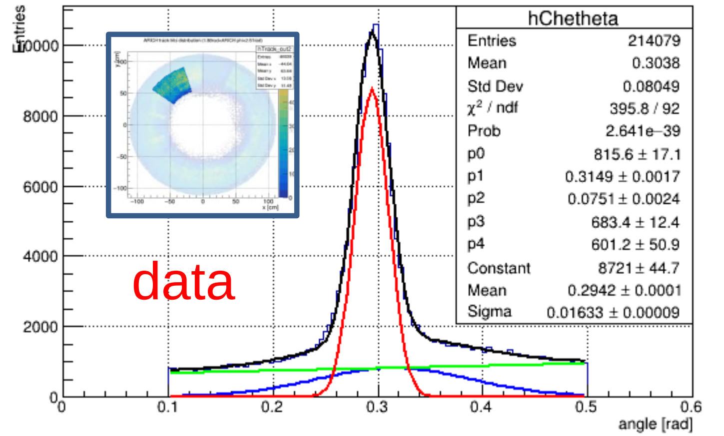
MC

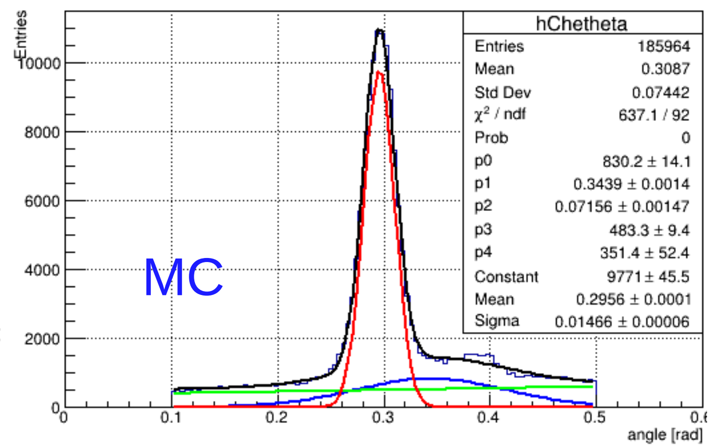


- Rough performance can be obtained Cherenkov angle (σ_θ) and Number of photons per track ($N_{p.e.}$)
- Distribution with Bhabha sample from the commissioning run (2018).
  - ✓ $N_{p.e.}$ = 9.5 (10.4), σ_θ = 16.3 (14.7) mrad in data (MC)
  - ✓ corresponding to 4.3 σ K/π separation at 4 GeV.



Cherenkov Angle distribution (Bhabha, 2018)





ARICH is working well

performance:

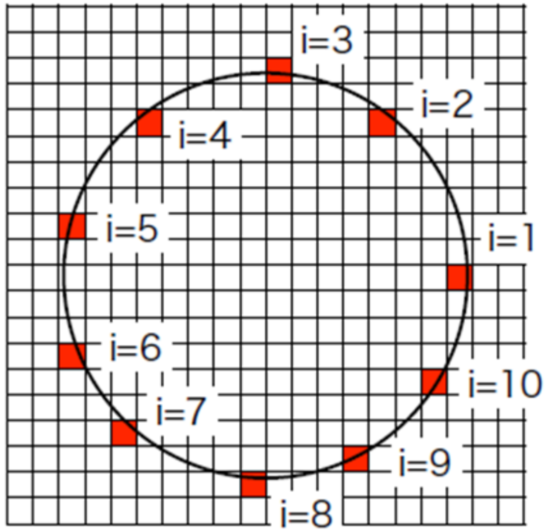
$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

Particle Identification

Particle Identification (PID) by ARICH is obtained from the comparison of the hit pattern and the expected PDF for different particle hypothesis.

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

h: particle hypothesis (e, μ, π, K, p,..)
N_h : expected total number of hits
$n_{h,i}$: expected number of hits (probability) at pixel i



Note: ARICH has only ON/OFF information in each channel (pixel).

Likelihood ratio

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

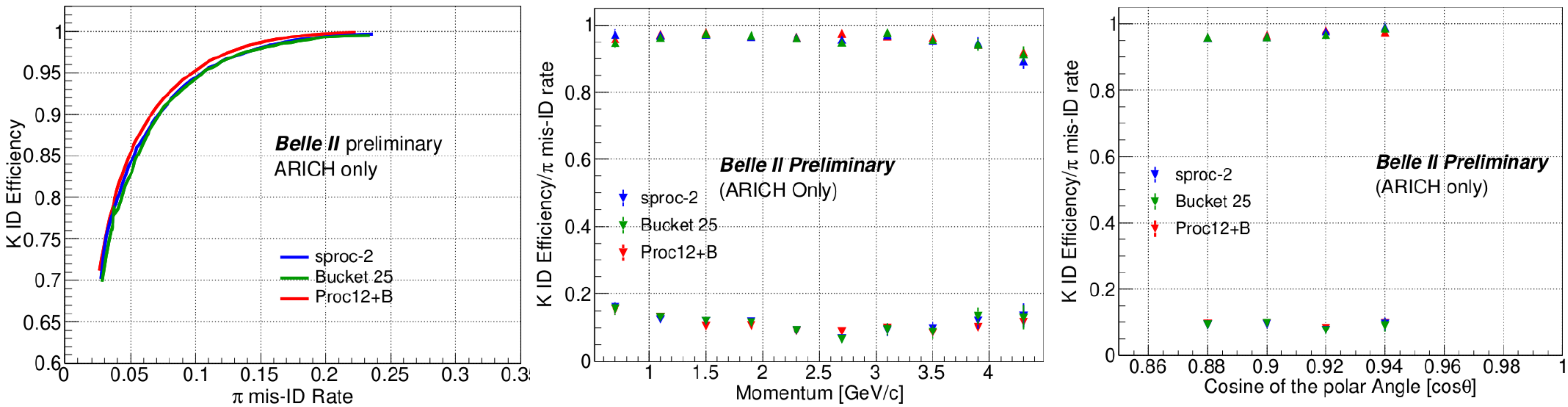
$$R_{\pi/K} = \frac{\mathcal{L}_\pi}{\mathcal{L}_K + \mathcal{L}_\pi} = 1 - R_{K/\pi}$$

Recent Performance [D* study by Vismaya V S (hadron ID group)]

K/π separation

ARICH works as a threshold-type counter

ARICH is a combination of RICH and threshold type counter



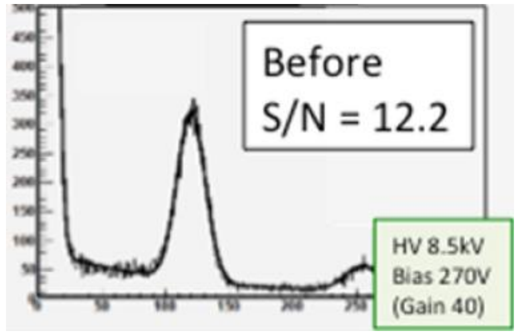
Bucket 25: exp 18, run 2646-2986, release-05
Sproc-2: release-06

- Working well generally.
- Trying to improve the performance (alignment, improving PDFs)

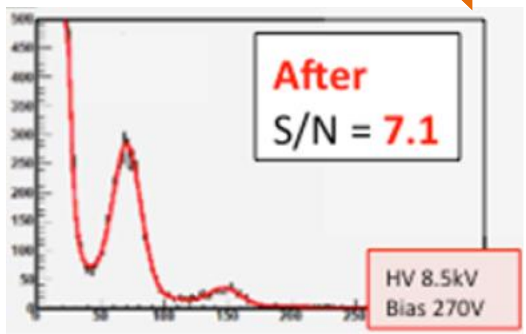
Radiation Tolerance

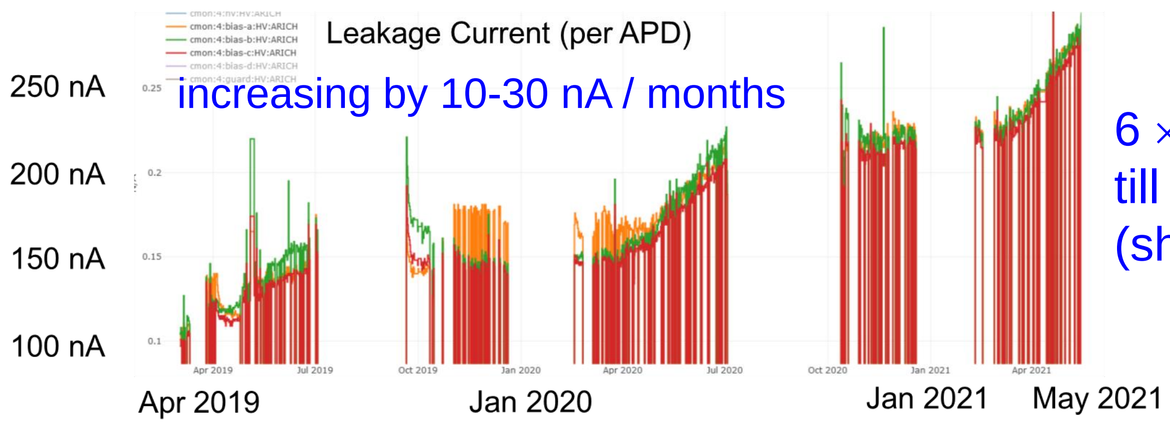
- ARICH is relatively tolerant to the beam background.
  - ✓ Only small number of background hits are seen; negligible to the performance at this moment.
- Deterioration of HAPDs (increase of the leakage current, larger noise) due to silicon bulk damage by neutrons.
  - ✓ Tolerant to 10^{12} neutrons / cm^2 @ 1MeV equiv., assumed for to 10 years' operation.
  - ✓ Sensor performance will be gradually degraded, with a very modest effect on the PID performance.
- SEU (single event upset) in the FPGAs of the front-end.

neutron irradiation test of HAPD



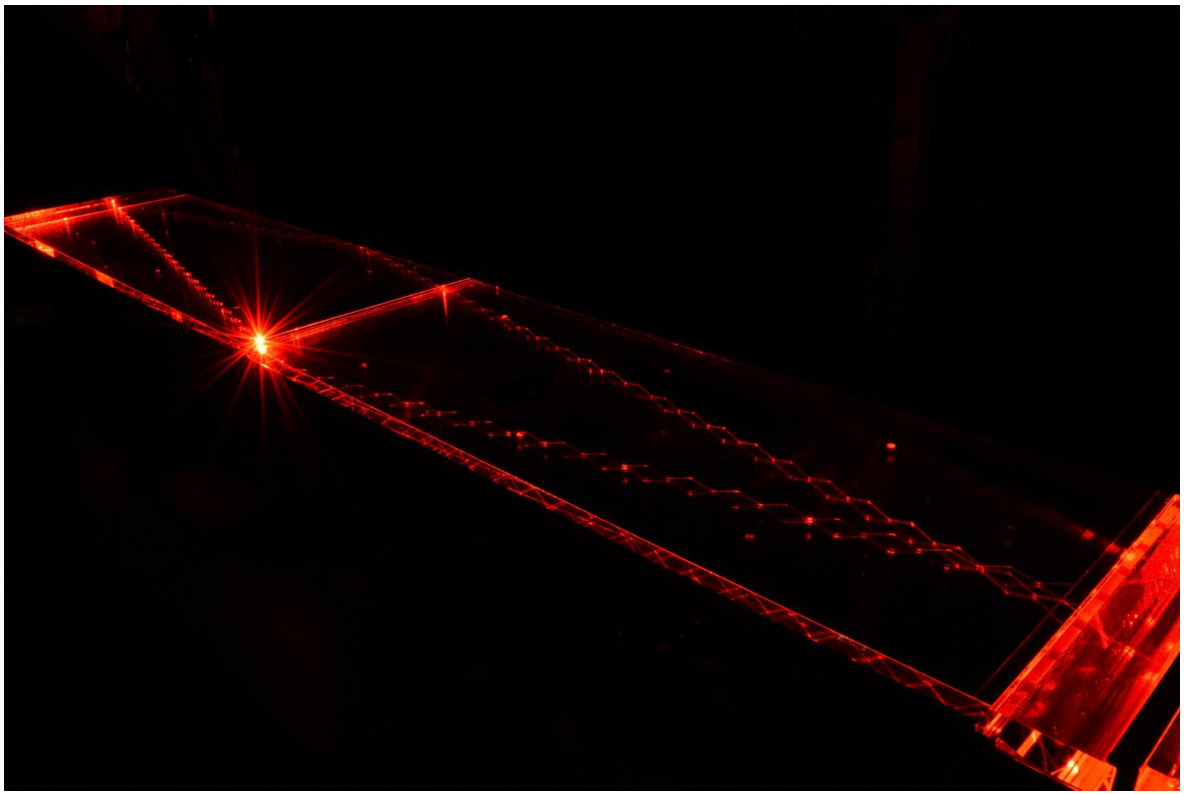
0.5×10^{12} n / cm^2





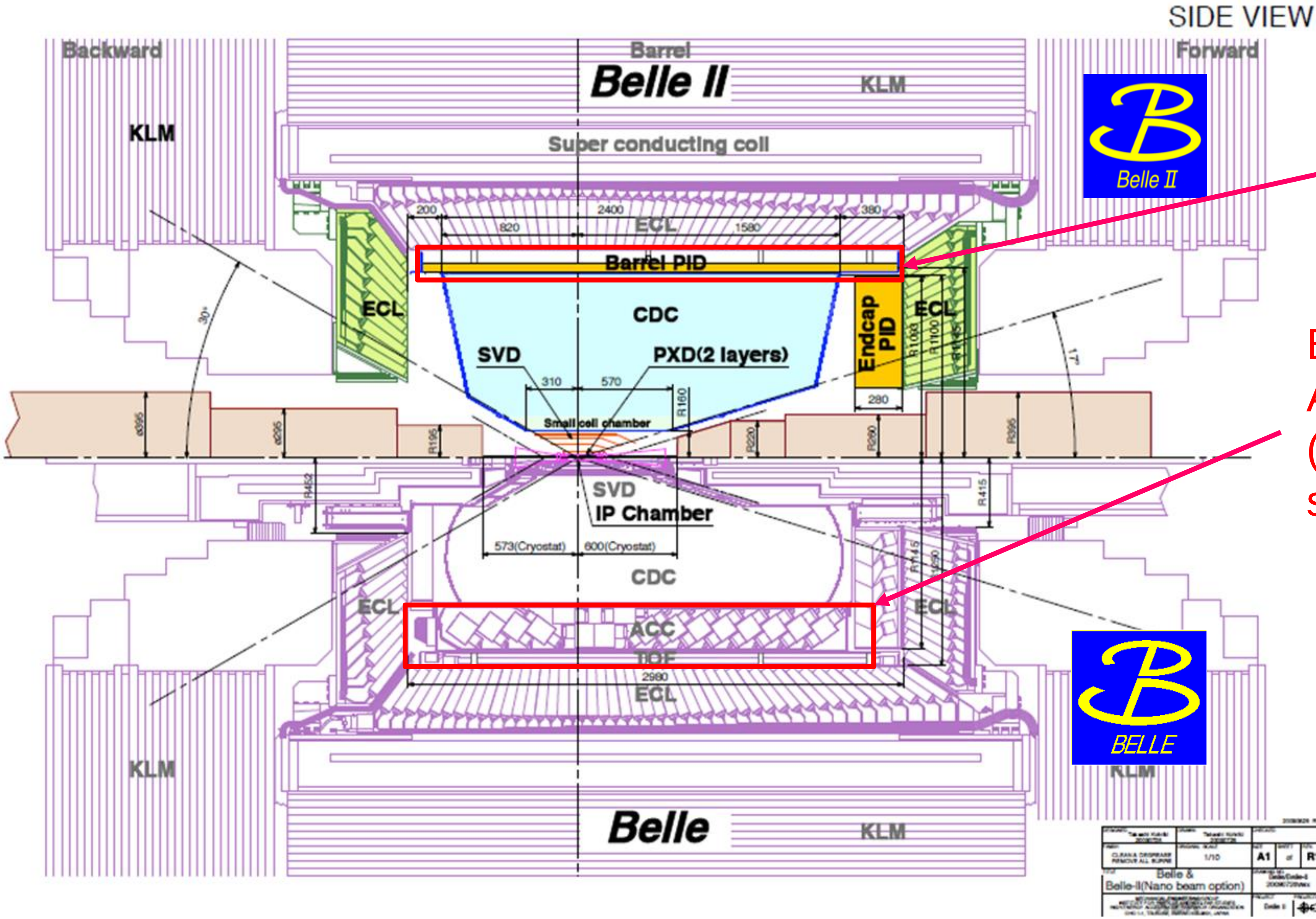
6×10^9 n / cm^2 till now (should be ok)

TOP (Time Of Propagation)



Some figures are taken from presentations by
K. Matsuoka @ RICH2016,
U.Tamponi @ RICH2018,
S. Sandiya @ TIPP2021.

TOP



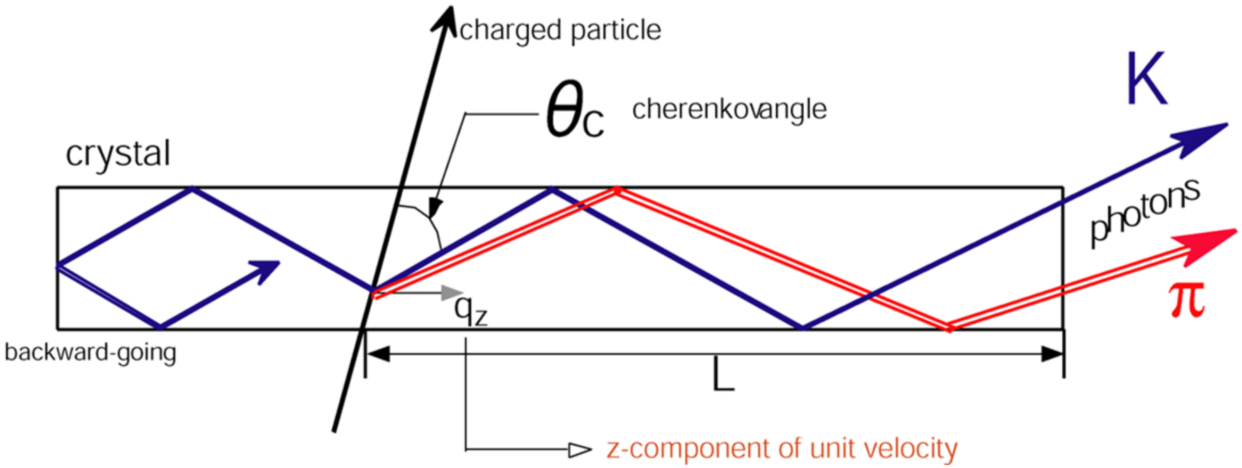
Barrel PID

TOP

Belle equipped ACC and TOF (i.e. larger space for PID)

More space to VXD and CDC at Belle II

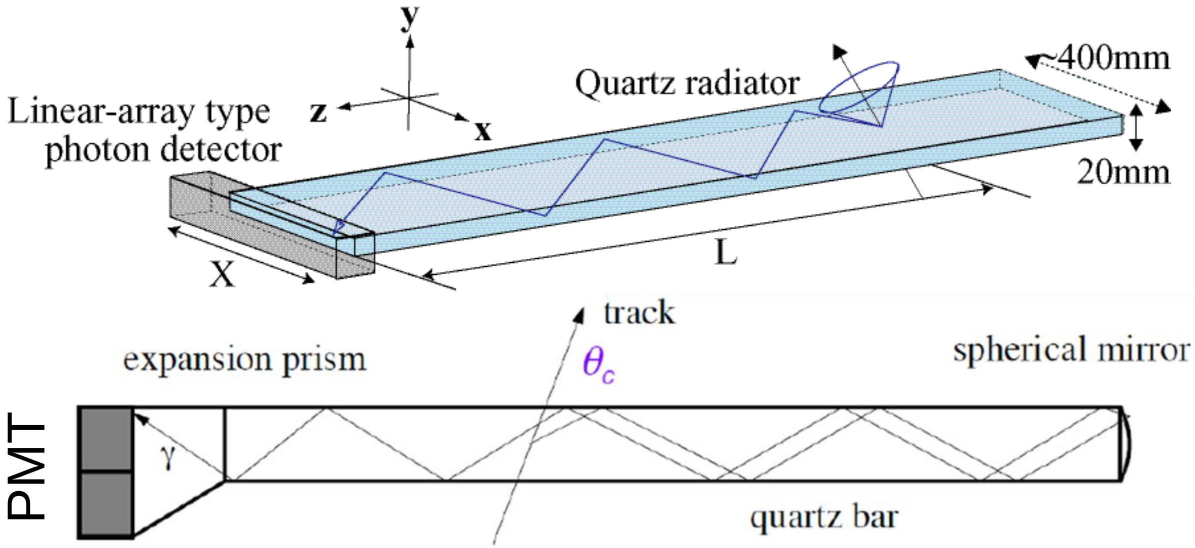
Measurement principle of TOP (Time of Propagation) Detector

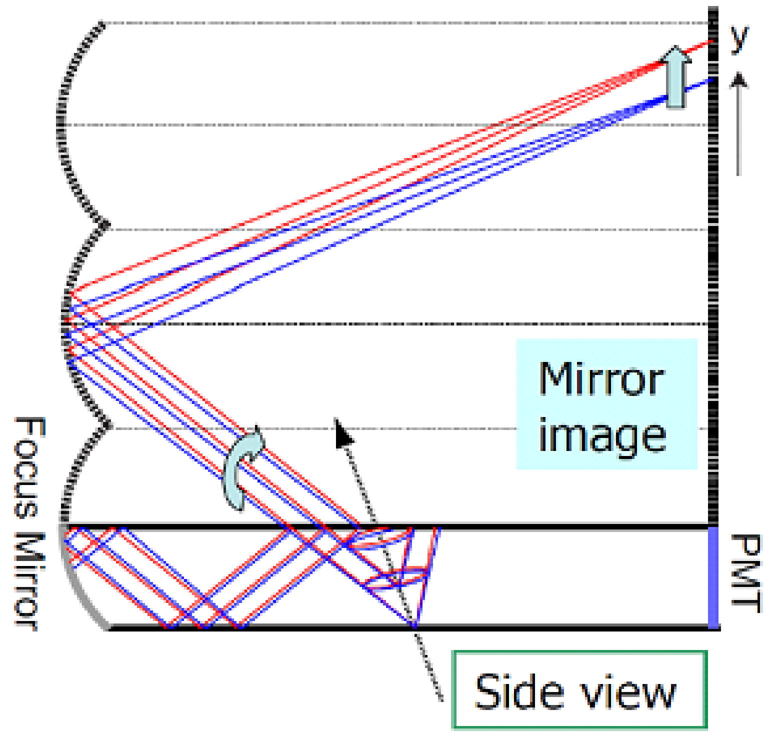


Different Cherenkov angle
→ Different photon path
→ Different time of propagation.

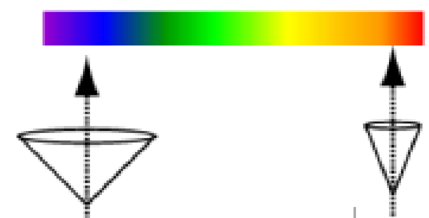
- Measure the time of propagation of K and π: need ~ 50 ps timing resolution
- Measure the position of photons, too.
- Also works as a TOF (Time of Flight) detector for low momentum particles.
  - ✓ Combination of TOF and RICH with a single device

TOP





- Very flat quartz bar
- Photo-detector with good timing resolution.
- Focus Mirror
  - ✓ Parallel photons are focused: remove the uncertainty from the bar thickness.
  - ✓ y actually differs with different θ_c (when wave length is different).
    $\rightarrow$ Correction of chromatic dispersion
    (look at the relation of y and t)



$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$

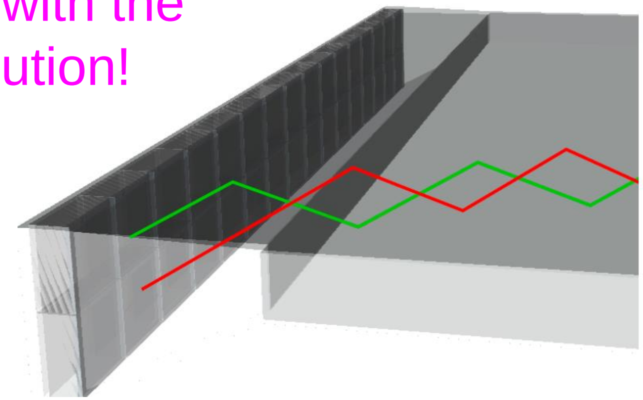
MCP-PMT

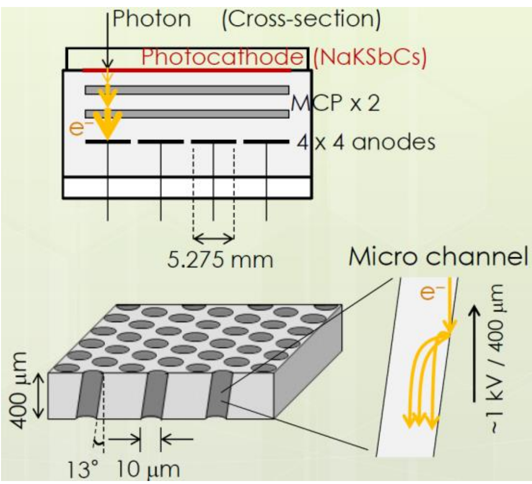
MCP (Micro Channel Plate) -PMT

Photodetector with the best time resolution!

- 4×4 channels
- NaKSbCs photo cathode; QE>24%
- TTS (Transit Time Spread)* < 40ps

  * = Fluctuation of the signal timing for single photon input.





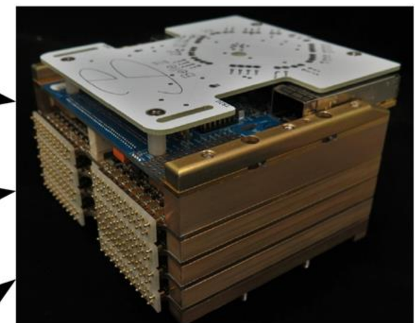
Each module is read by 64 ASICs packed into 4 ***boardstacks***

16 IRSX asics

4 Xilinx Zynq Z-7030 (1 per 4 Asics)

1 Xilinx Zynq Z-7045 (global data flow)

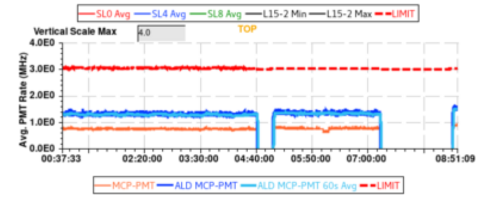
1 HV board



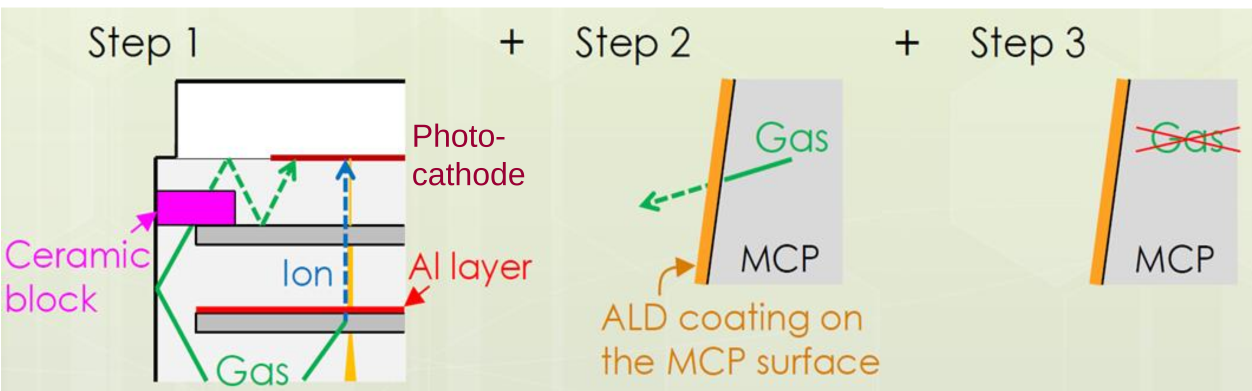
- IRSX developed by Hawaii Univ.
- Full waveform output.

MCP-PMT

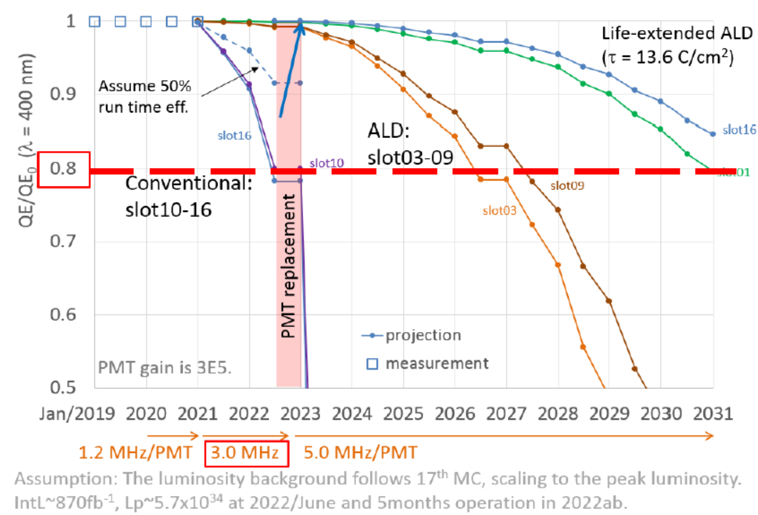
Aging problem of MCP



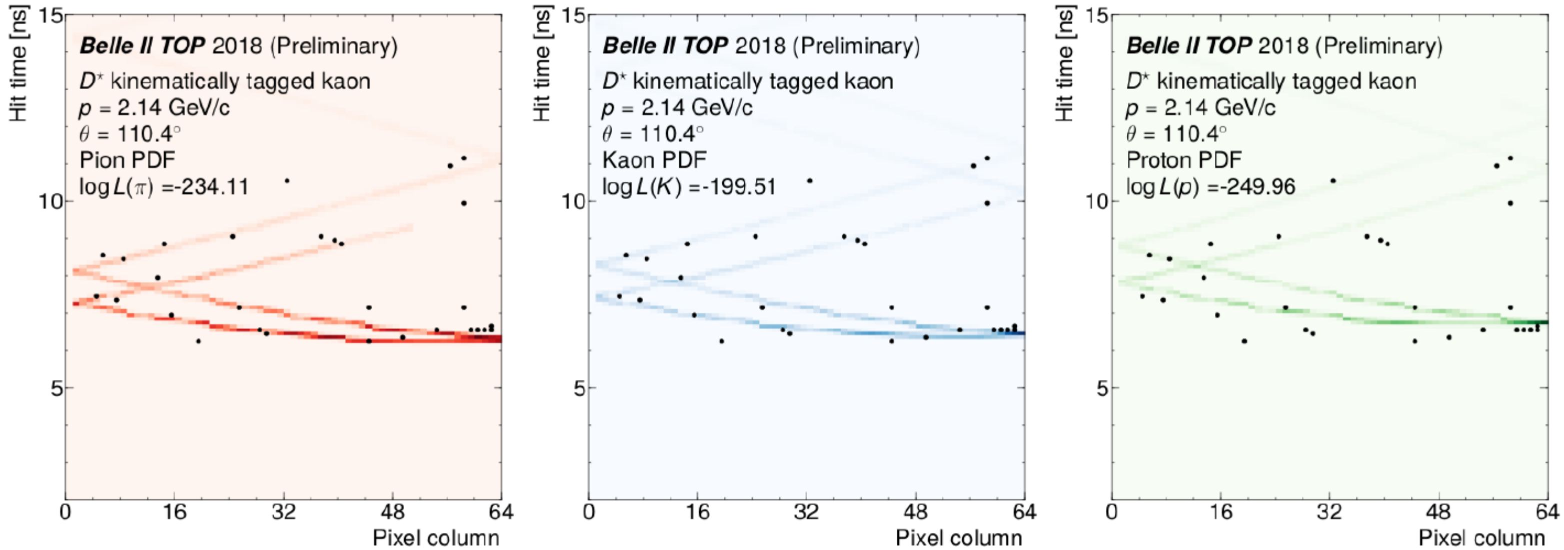
- QE drops as a function of accumulated charge.
  - ✓ The gas and ion from MCP damage the photo-cathode.
- ALD (Atomic Layer Deposition) and life-extended ALD type were developed during mass production.
- Conventional type (40% of installed MCP) will be replaced in 2023 (LS1).
- The MCP-PMT rate (~accumulate charge) is now limited to 3 MHz so that MCP-PMTs survive till the replacement



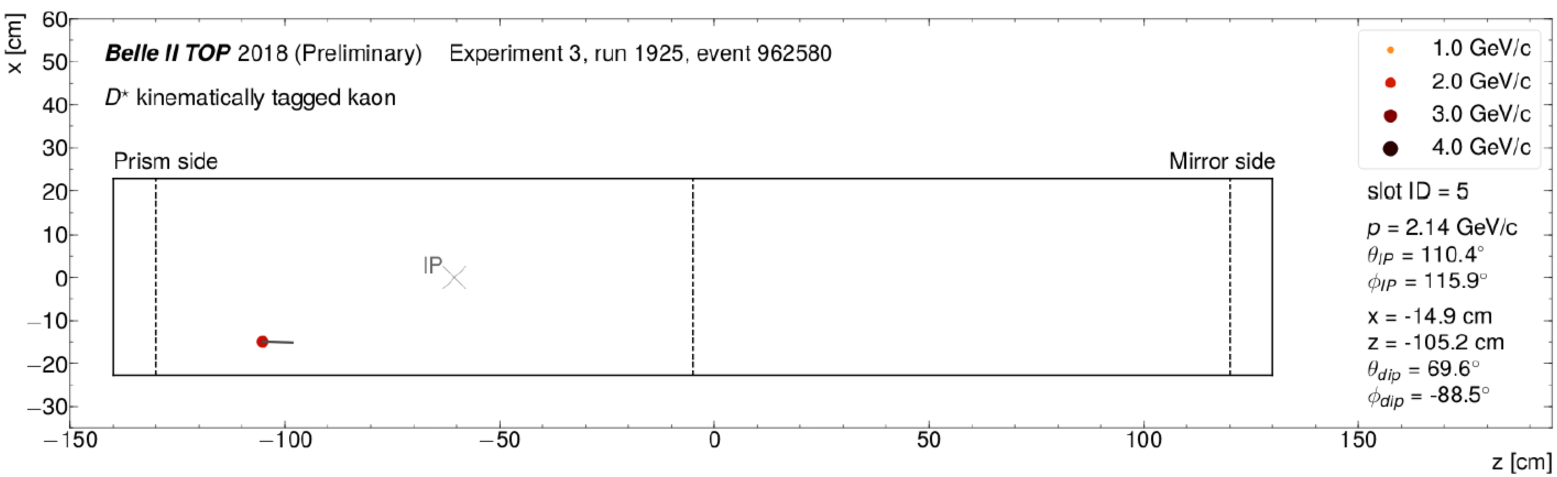
Conventional ALD Life-extended ALD



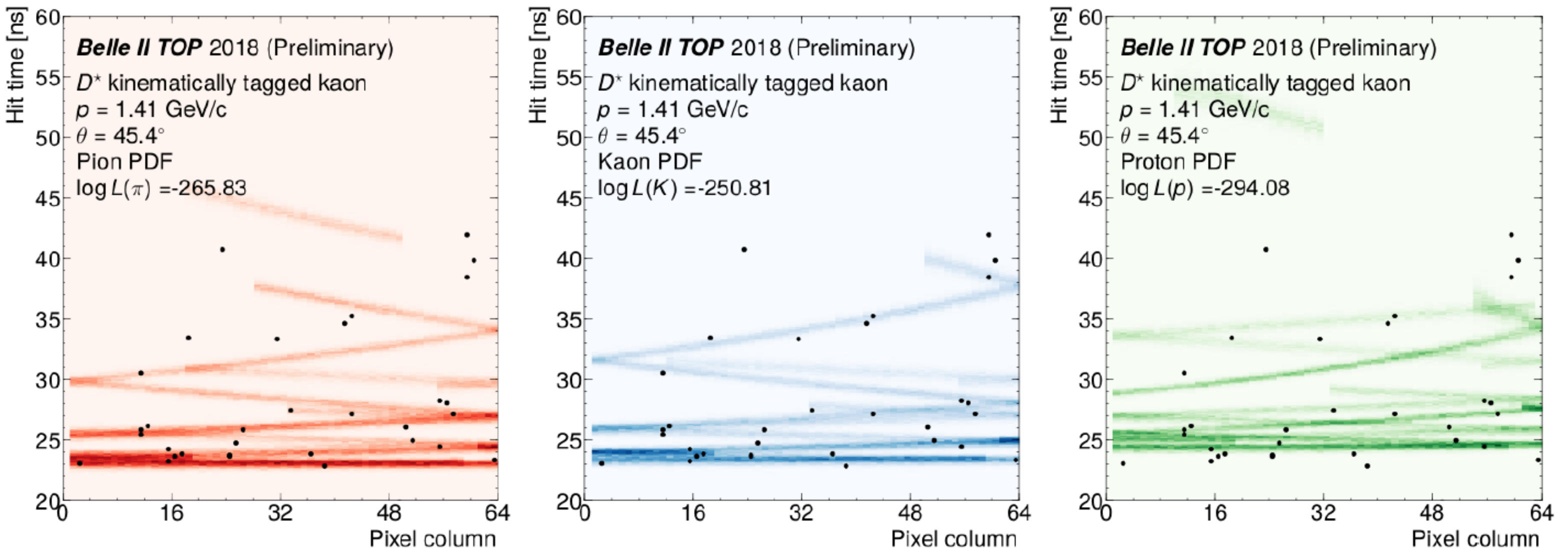
PID at TOP



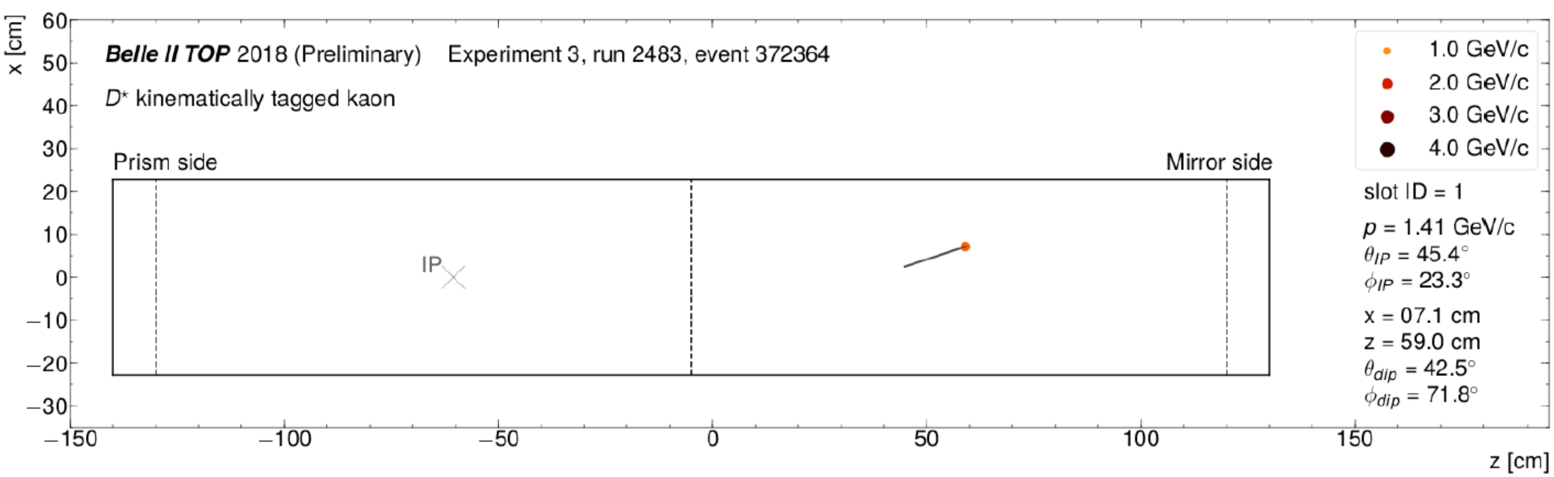
2.14 GeV kaon
(prism-facing)



PID at TOP



1.41 GeV kaon
(mirror-facing)



PID at TOP

TOP needs very accurate timing and calibration, e.g.)

The TOP sampling clock is locked to the accelerator radio-frequency clock (RF clock)

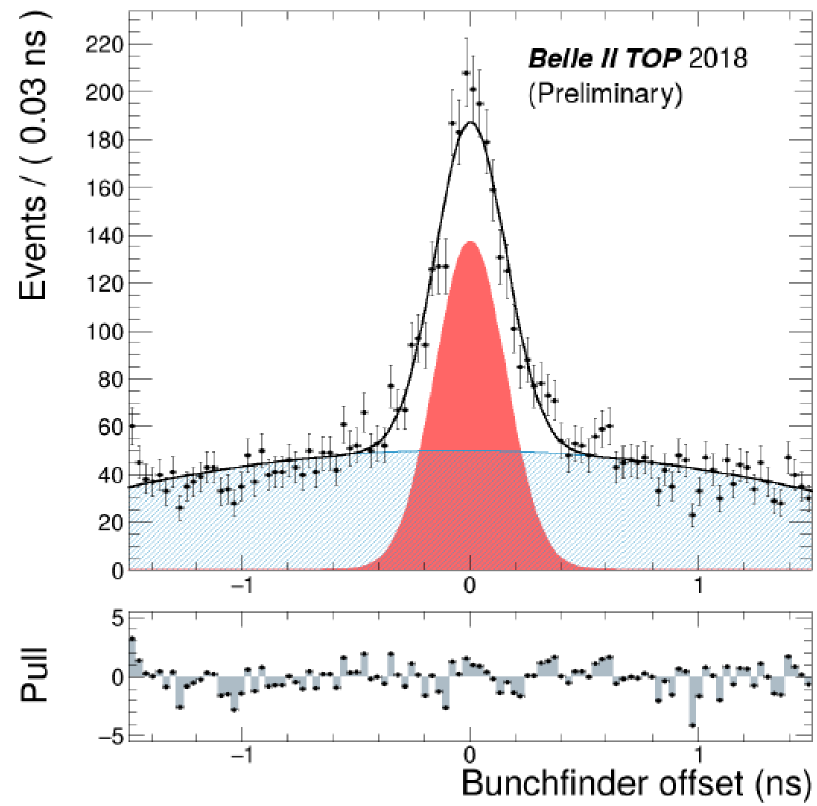
$\rightarrow$ Any offset between the two will result in a mis-reconstruction of the PDFs

<u>Most probable collision time</u>

$\rightarrow$ reconstructed back-fitting the higher momentum tracks in the event

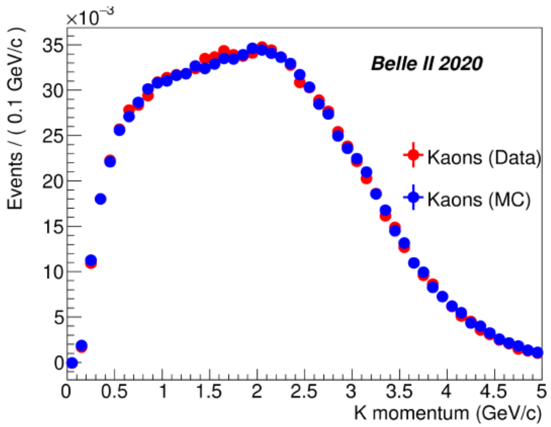
$\rightarrow$ If calibrations are correct, it will match with a tick of the RF clock

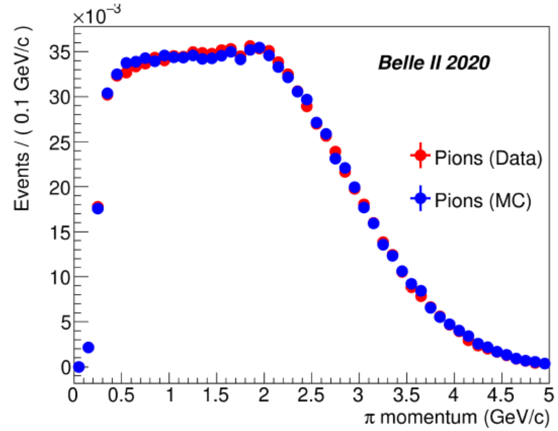
$\rightarrow$ Resolution on data: 150 ps (bunch crossing: 2 ns)



Performance

- Momentum distribution of the K and π sample:

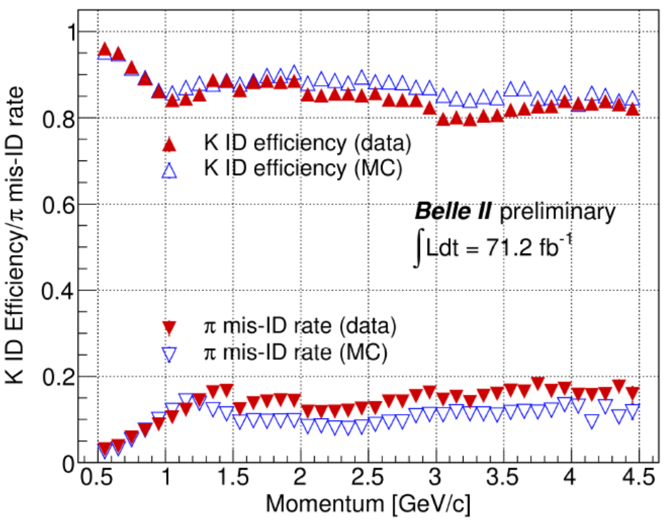




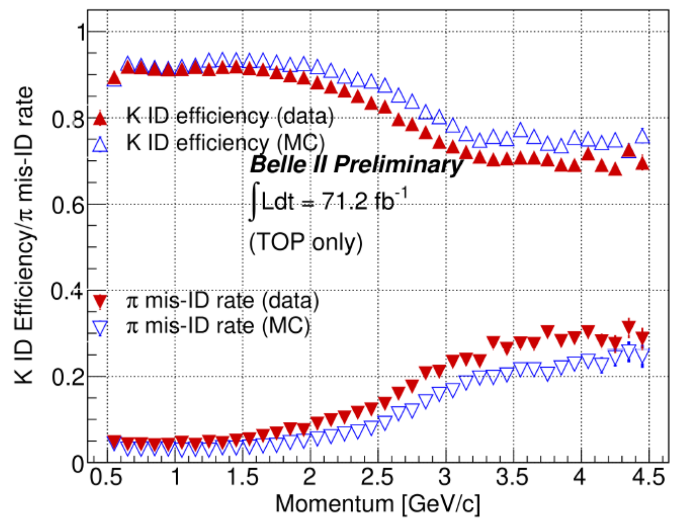
TOP works well, but the performance is not very good yet.

- Data-MC comparison for K-eff. and π mis-ID rate for R[K/π] > 0.5 w.r.t. momenta

All sub-detectors



TOP only



The overall PID performance is still worse than Belle.

R&D for Future

ARICH

Repair of bad HAPDs (+ replace aerogels?)

Replace HAPDs (+ aerogels)

2021	2022	2023	2024	2025	~2026	2027	2028	2029	2030	~2031

Replacement of conventional MCP-PMT

Replacement of no life-extended ALD MCP-PMT

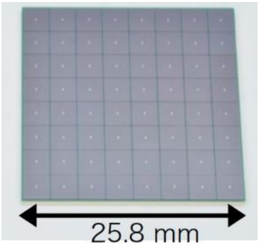
TOP readout upgrade

Replacement all ADL MCP-PMT

TOP

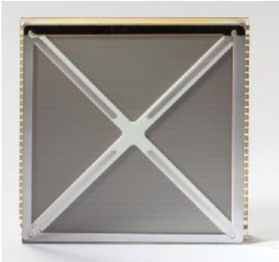
(based on E.Torassa's slides at UWG)

R&D for the photon sensors (SiPM), electronics are going on.



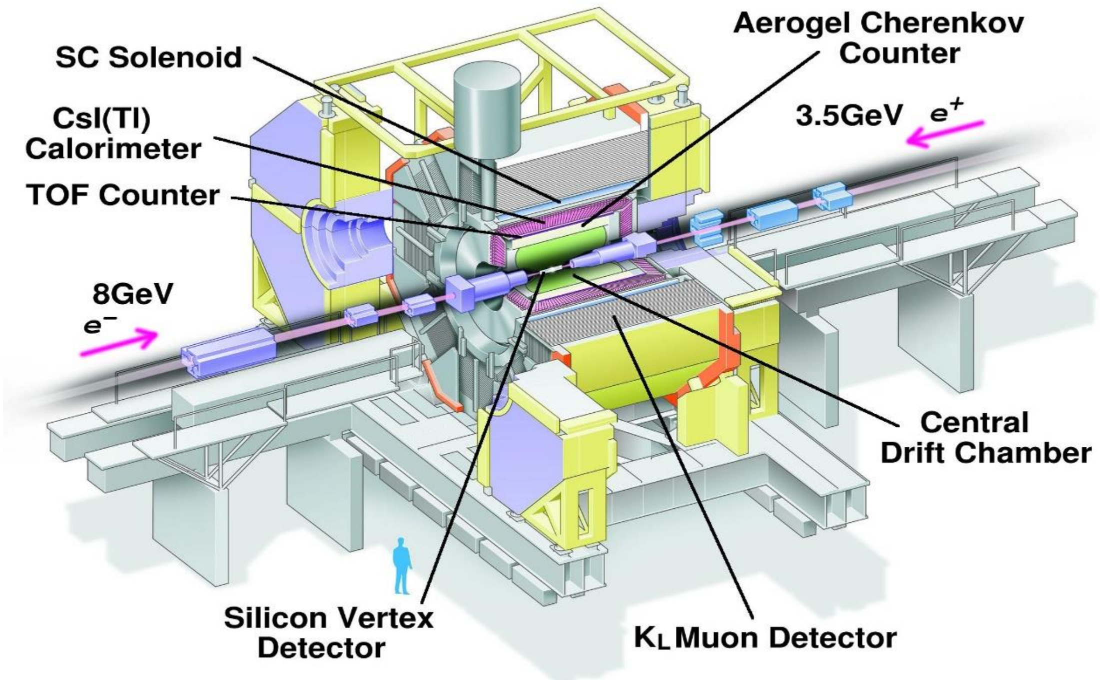
MPPC(SiPM)

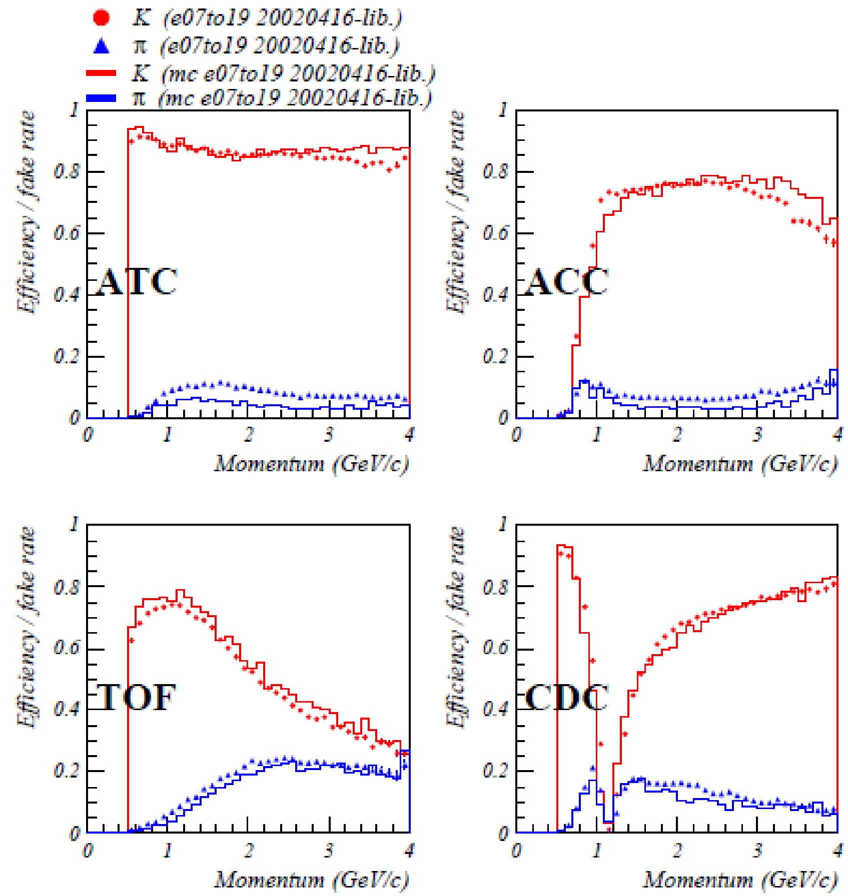
LaPPD (Large-area Picosecond PhotoDetector) for ARICH



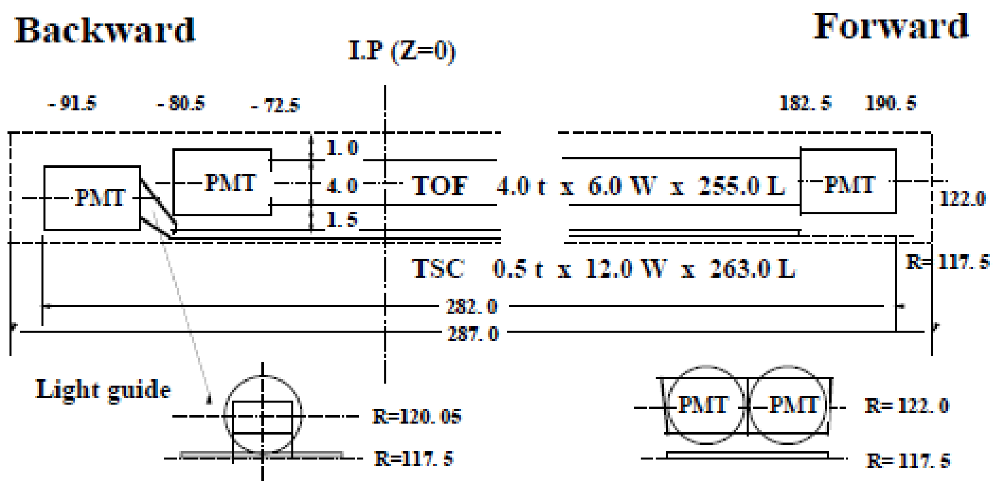
Backup

Belle and PID

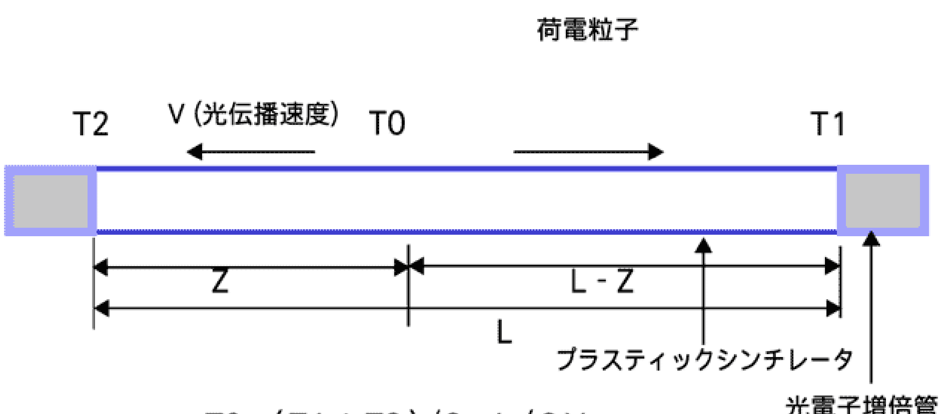




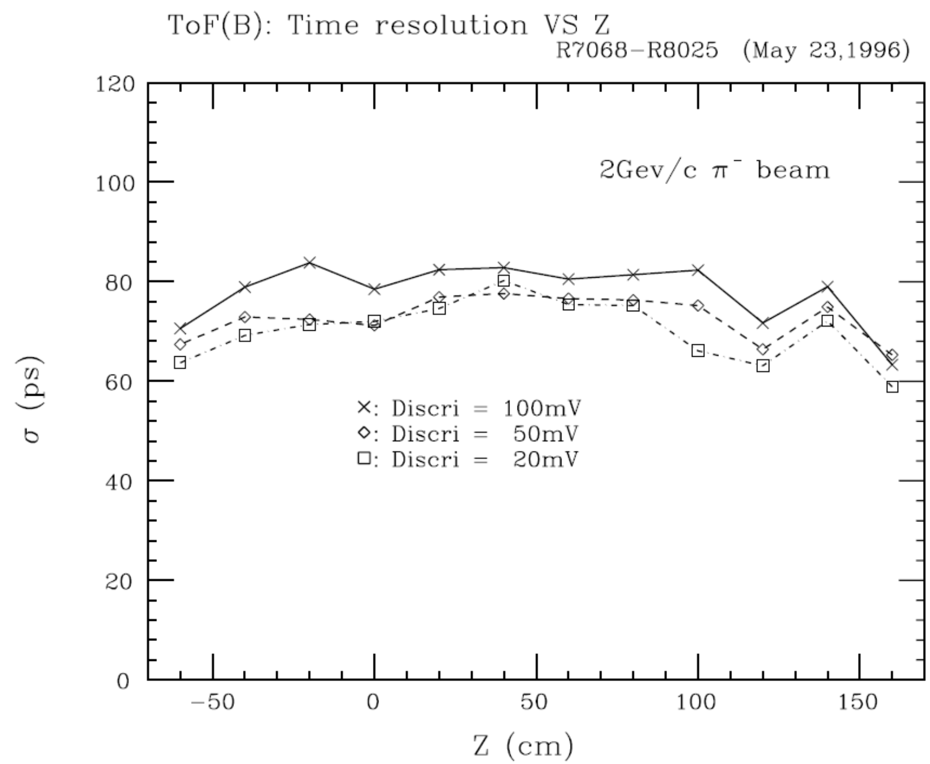
TOF @ Belle



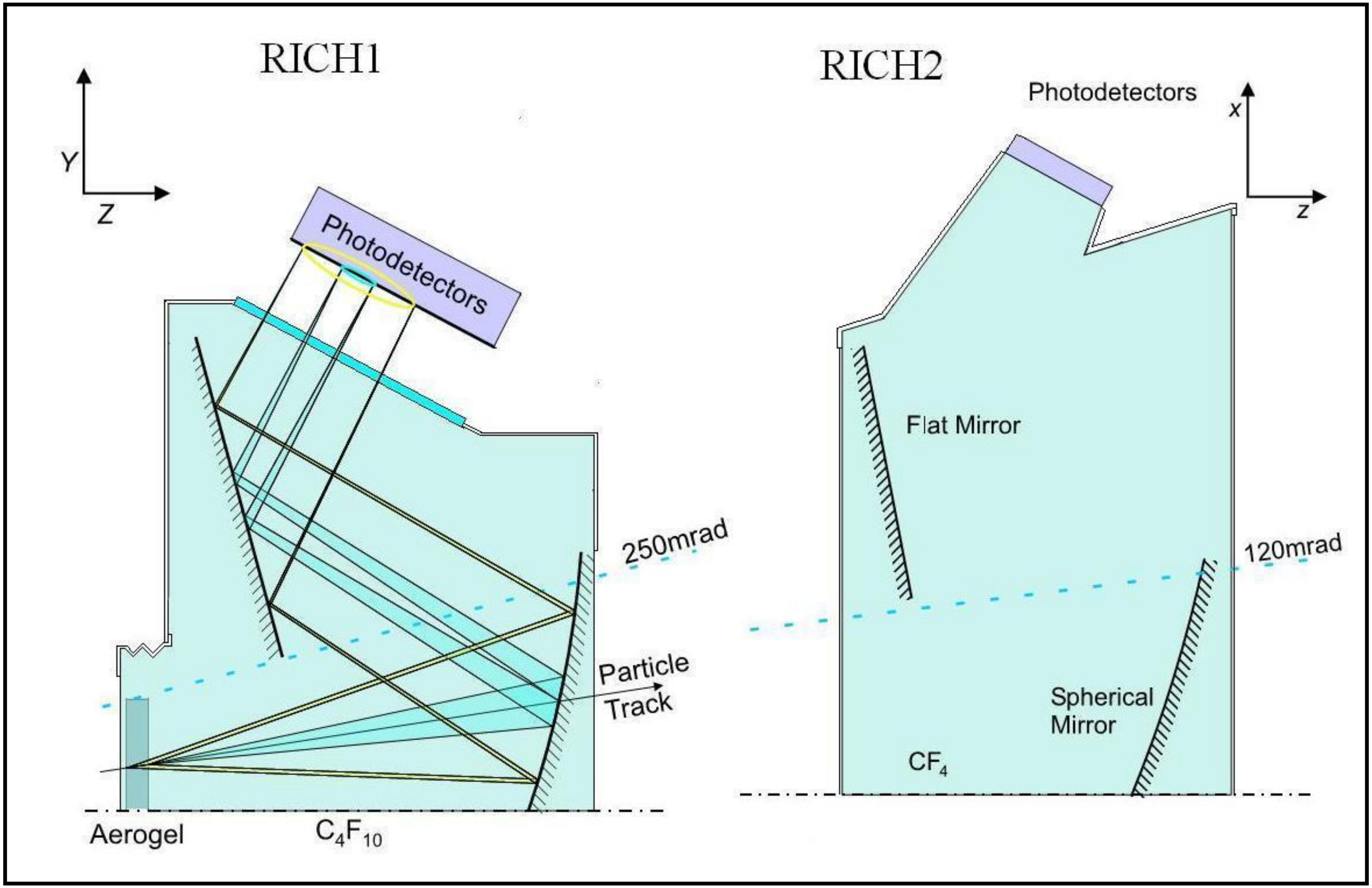
- Fast scintillator with small attenuation.
- Photo-detector with good timing resolution (~100ns) and high light collection efficiency.
  - ✓ Usable in the magnetic field.



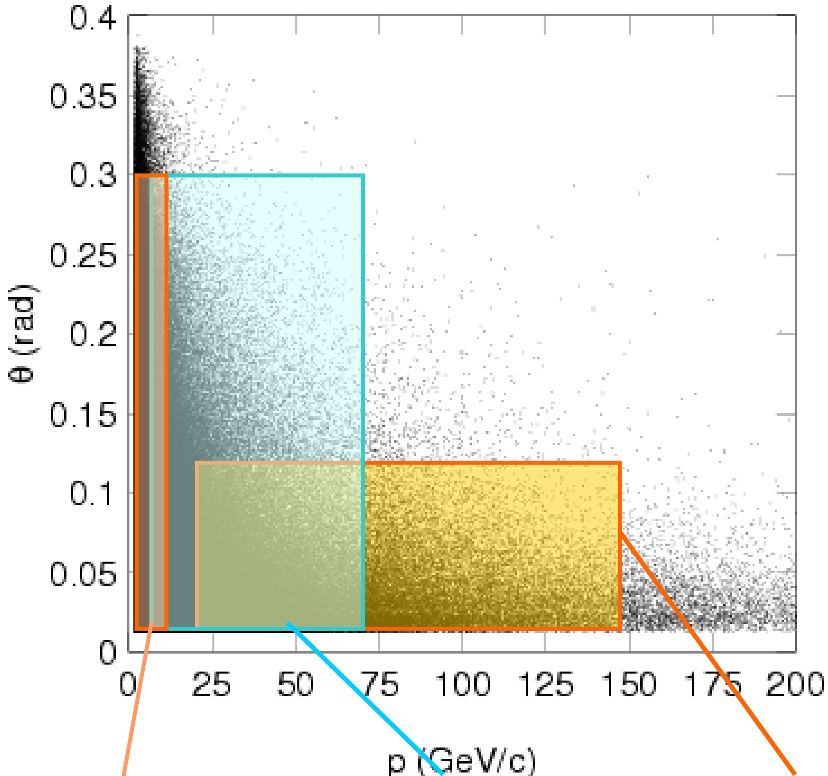
T0=(T1+T2)/2−L/2V
Z=V(T2−T1)/2+L/2

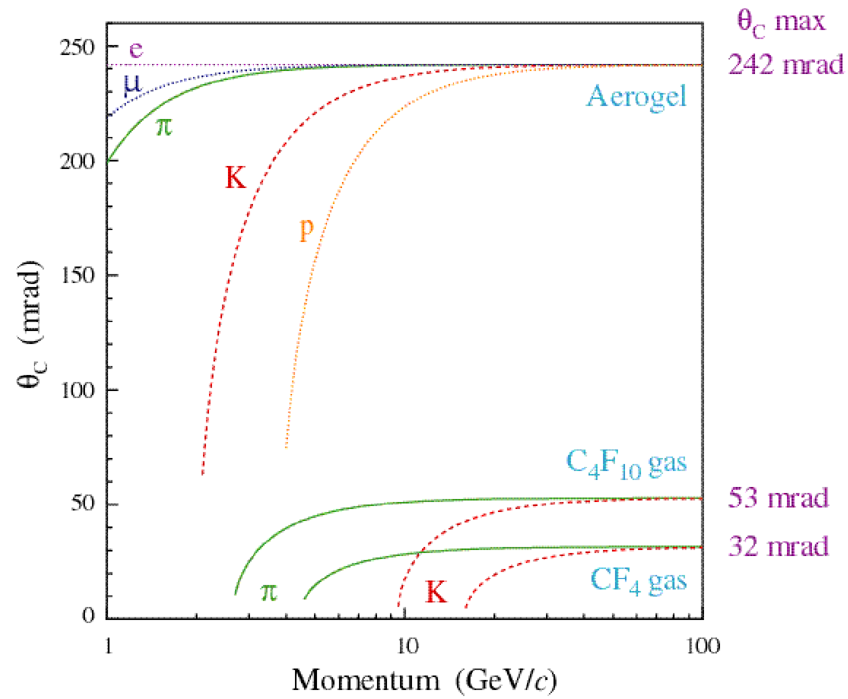


LHCb RICH


RICH1
RICH2
Y
Z
Photodetectors
250mrad
Particle
Track
Aerogel
C_4F_{10}
Photodetectors
x
z
Flat Mirror
120mrad
Spherical
Mirror
CF_4

Example: LHCb RICH





Silica Aerogel
n=1.03
1-10 GeV/c

C_4F_{10} gas
n=1.0014
Up to ~70 GeV/c

CF_4 gas
n=1.0005
Beyond ~100 GeV/c

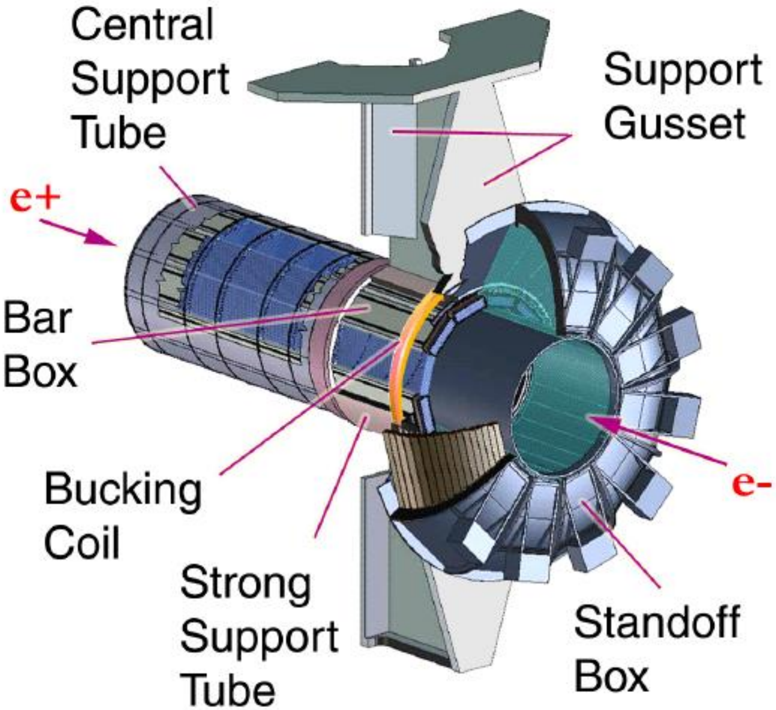
RICH1:
25→250 mrad vertical
25→300 mrad horizontal

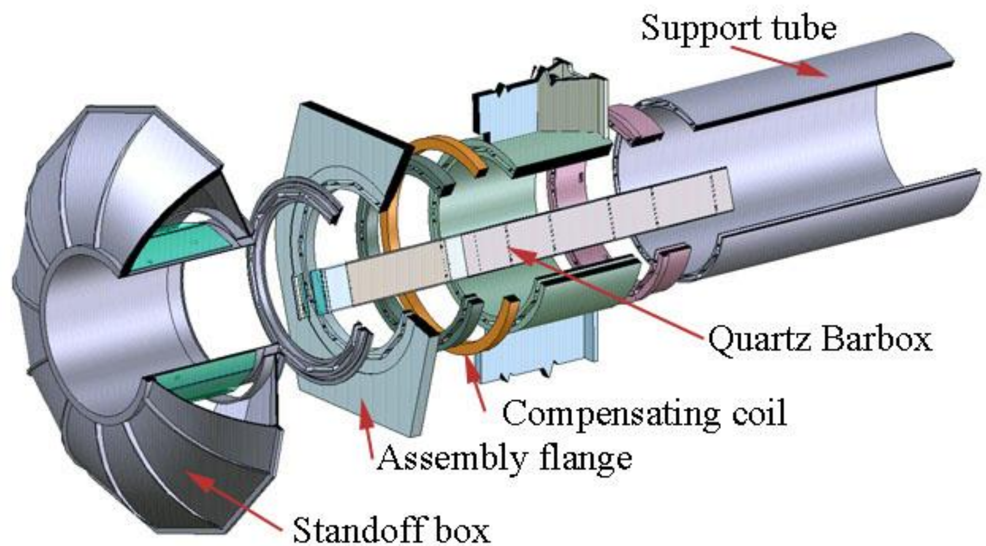
RICH2:
15→100 mrad vertical,
15→120 mrad horizontal

Expected photon yields – for isolated saturated particles

Aerogel	C_4F_{10}	CF_4
5.3	24.0	18.4

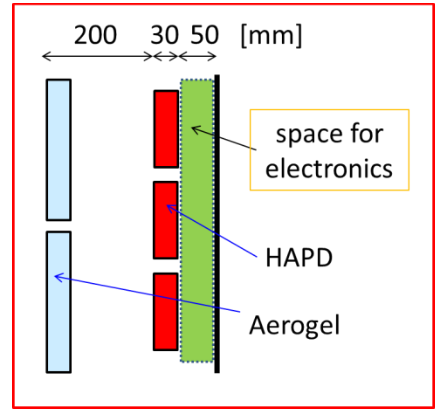
DIRC (Detection of Internal Reflected Cherenkov light)



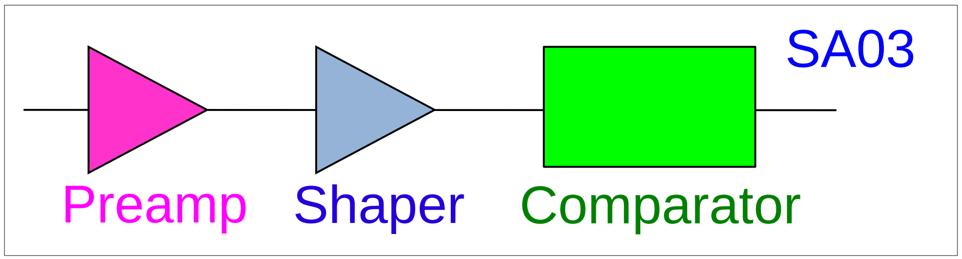


ARICH Electronics

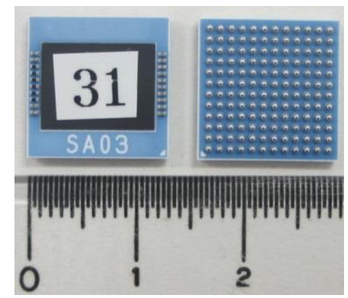
- Total 60000 channels.
  - ✓ 1-bit ON/OFF information is enough.
- High-gain, low-noise.
- Only 5 cm available behind HAPD



➡ ASIC (SA03)



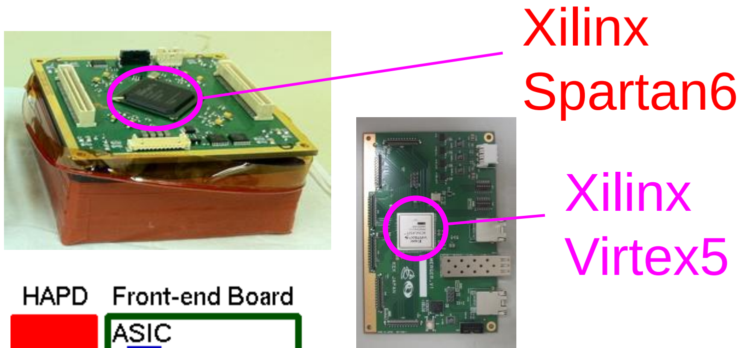
FPGA for readout



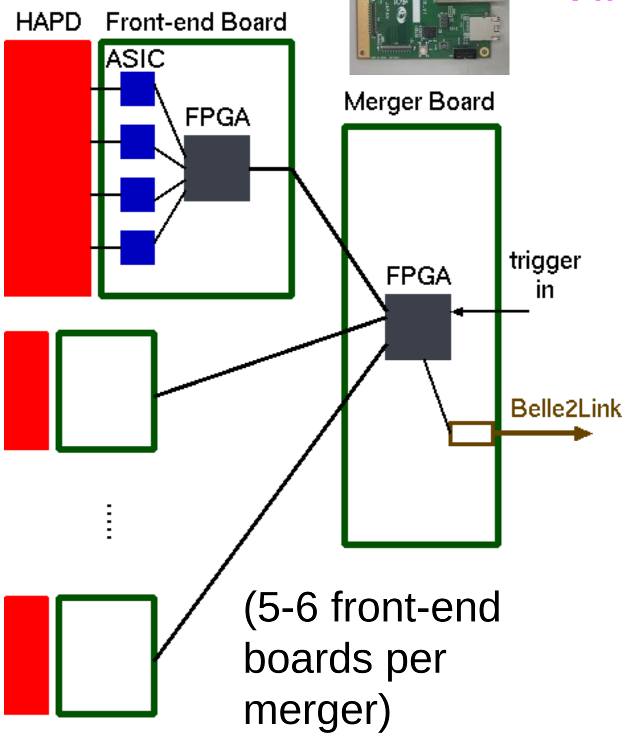
- CMOS 0.35 μm process @ TSMC and X-FAB.
- 36 ch / chip (i.e. 4 ASIC for one HAPD).
- Variable gain (3.1-12.5 V/pC) and shaping time (100-200ns).
- Common threshold but adjustable offset (16-bit; for each channel).
- DICE (Dual Interlocked CEll) register to be tolerant to SEU.
- Mass production done at X-FAB.

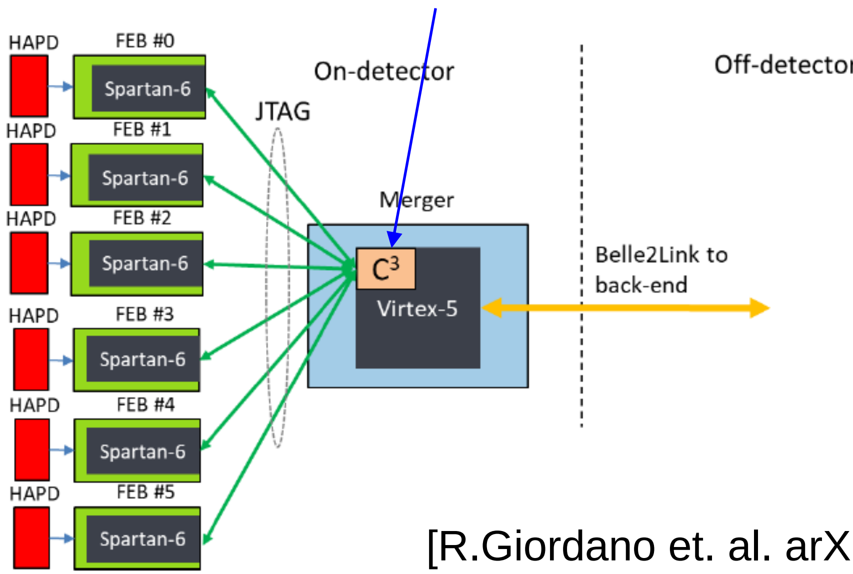
SEU in the front-end

Another effect from neutrons is SEU in the FPGAs in the front-end.



- Frequent SEUs expected at Spartan 6.
  - ✓ Boron is used as p-type dopant.
  - ✓ old estimation: 8 SEUs / h / HAPD in the firmware.
- Configuration consistency corrector (C^3) is implemented in the merger firmware.

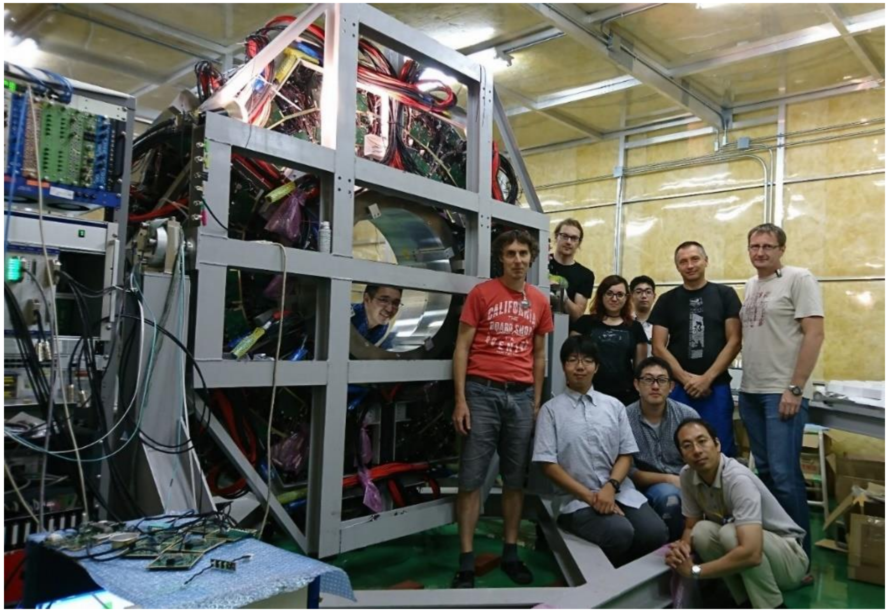


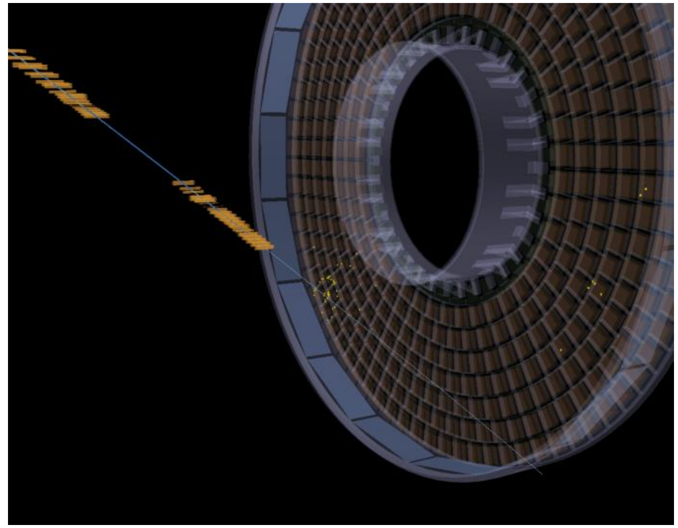


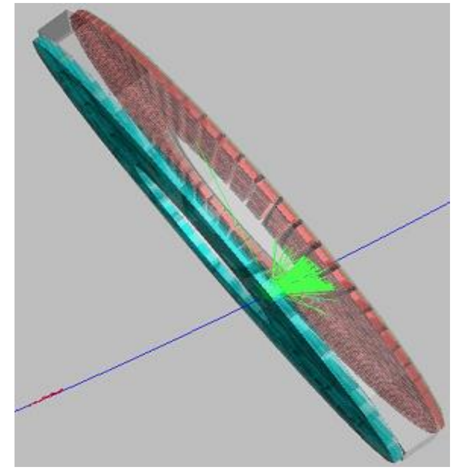
Real-time majority voting + partial reconfiguration of the firmware.

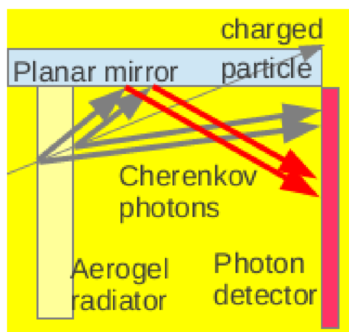
[R.Giordano et. al. arXiv:2010.16194]

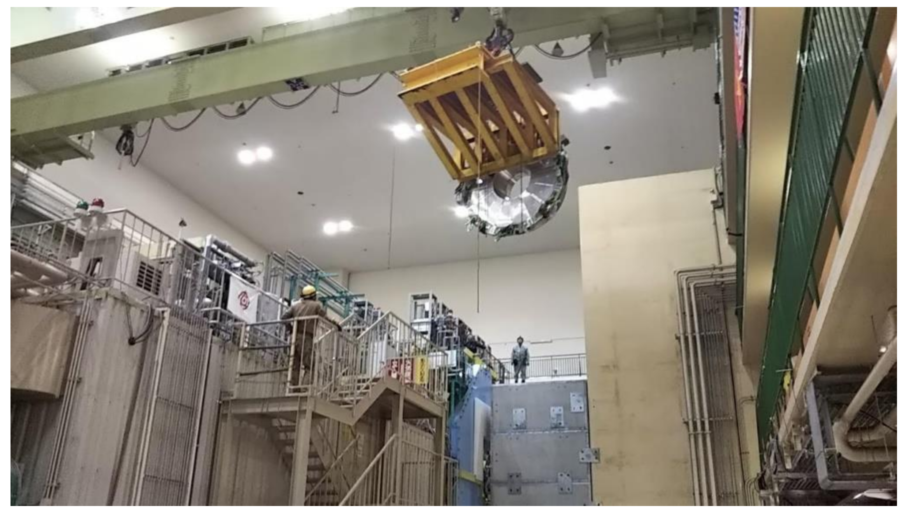
ARICH Gallery



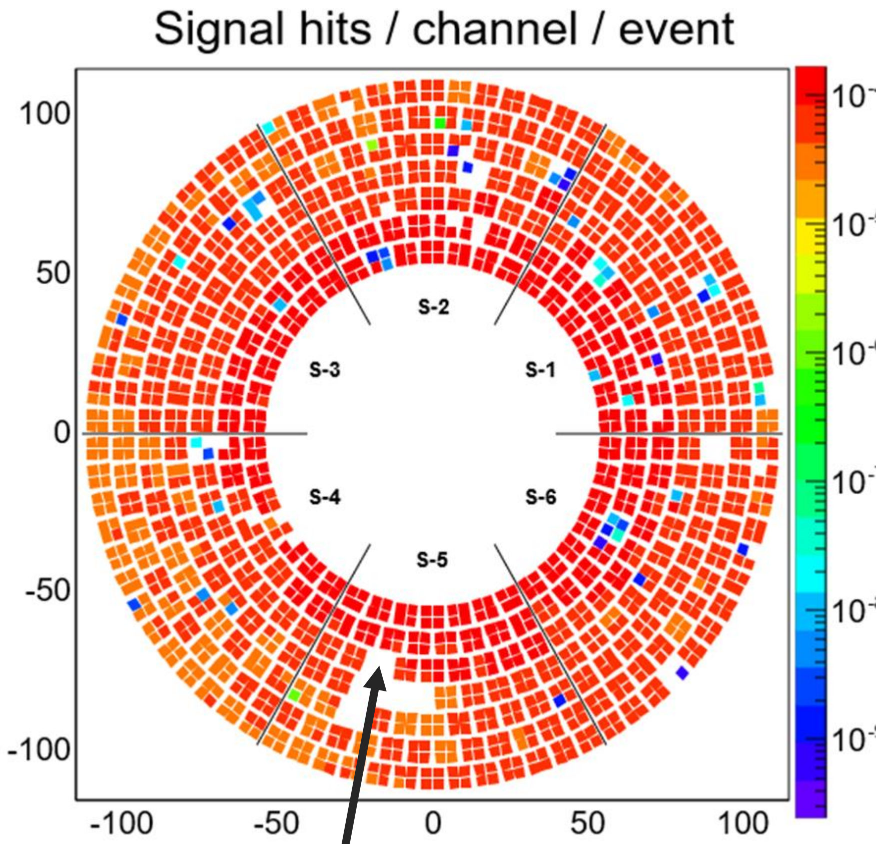




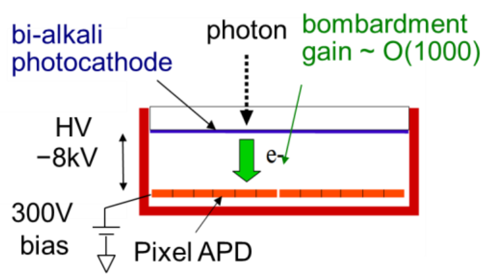




HAPDs



LV cable failure



Current status of HAPD operations

- 5 HAPDs (1.2%) are off due to a problem of LV cable to the front-end electronics.
  - ✓ To be repaired (in long-shutdown)
- 3.0% of channels suffer bias (or guard) problem inside APD.
  - ✓ Typically sudden increase of leakage current.
- 1.7% of channels suffer HV problem.
  - ✓ Various reasons.

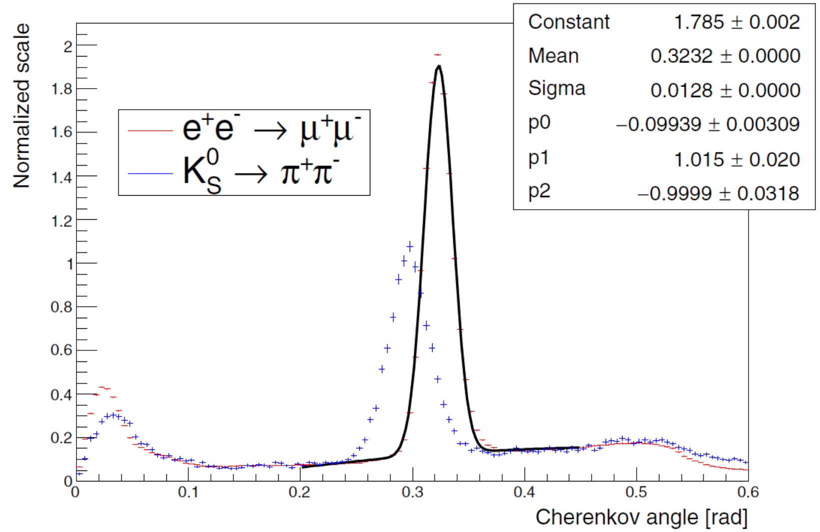
Total 5.9% dead

The problem of APD is still increasing, but is getting stabilized.

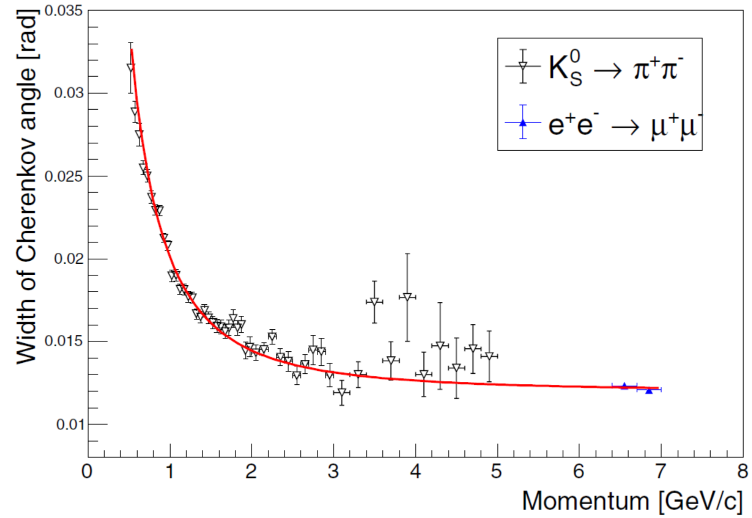
ARICH PDF

PDF components:

- Cherenkov photons from the aerogel.
- Background correlated to particles.
    - ✓ Depends on whether particles pass the quartz window of HAPDs. Separate PDF for the two cases.
- Random background.



PDFs are calibrated with $e^+e^- \to \mu^+\mu^-$ (higher momentum), $K_S \to \pi^+\pi^-$ (lower momentum)



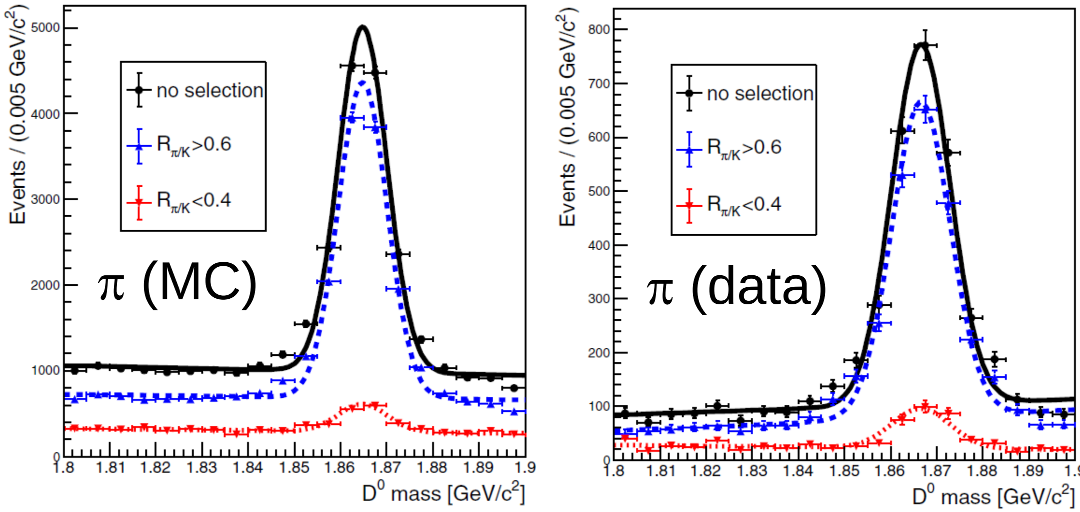
ARICH Performance

PID performance estimated with D* using 5.2 fb^{-1} data (taken in 2019).

- Use tracks that enter ARICH.
- Apply D* mass selection and look at D^0 mass.

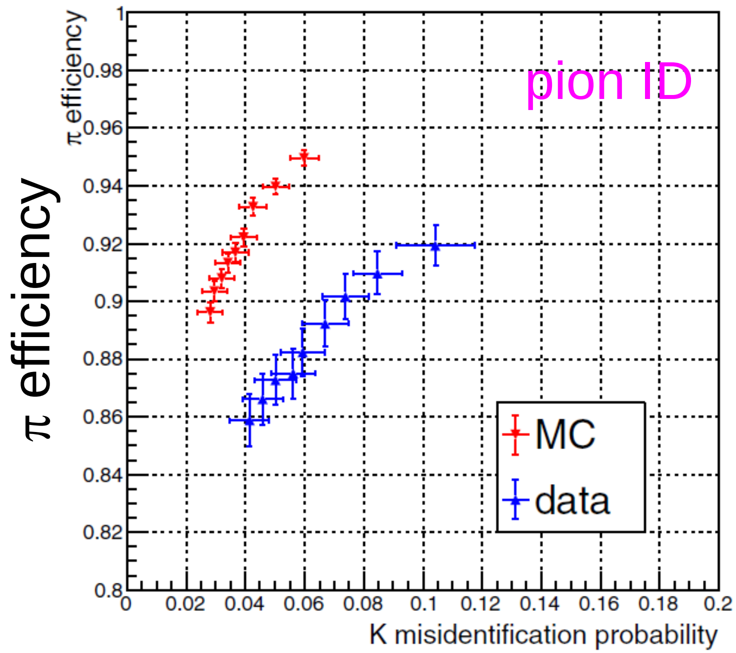
$$D^{*+} \to D^0 \, \pi^+_{slow}, \quad D^0 \to K^- \pi^+$$

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



kaon ID | pion ID

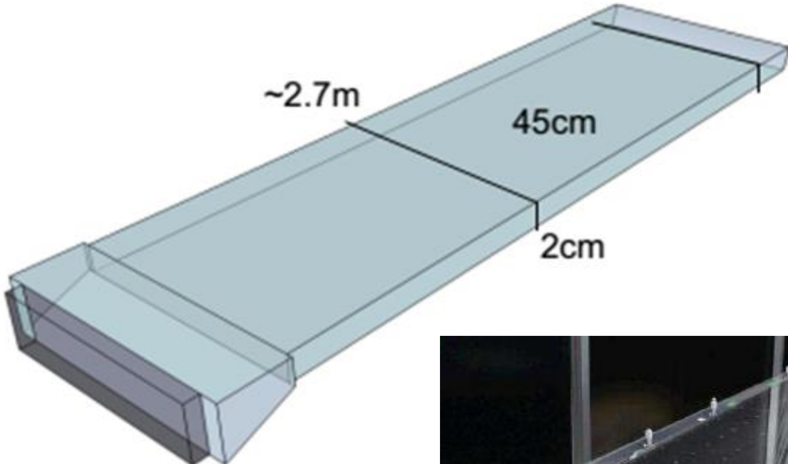
	K eff.	π mis.	π eff.	K mis.
Data	$93.5 \pm 0.6\,\%$	$10.9 \pm 0.9\,\%$	$87.5 \pm 0.9\,\%$	$5.6 \pm 0.3\,\%$
MC	$96.7 \pm 0.2\,\%$	$7.9 \pm 0.4\,\%$	$91.3 \pm 0.3\,\%$	$3.4 \pm 0.4\,\%$



K misidentification

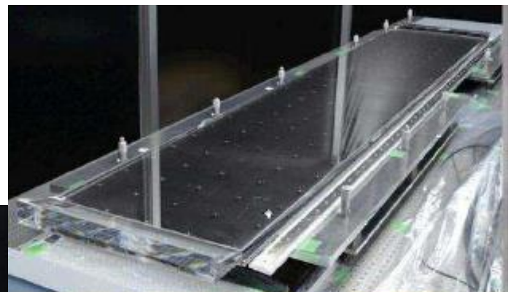
[PTEP, 2020, 093H01 (arXiv:2008.06251)]

TOP Quartz Bar

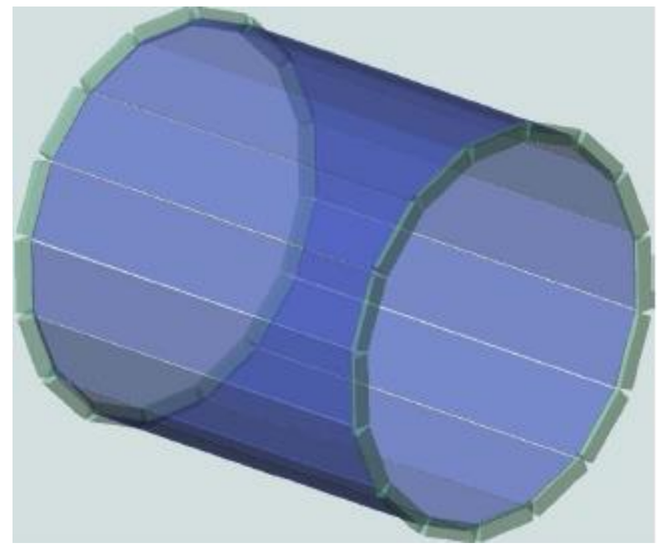


Quartz

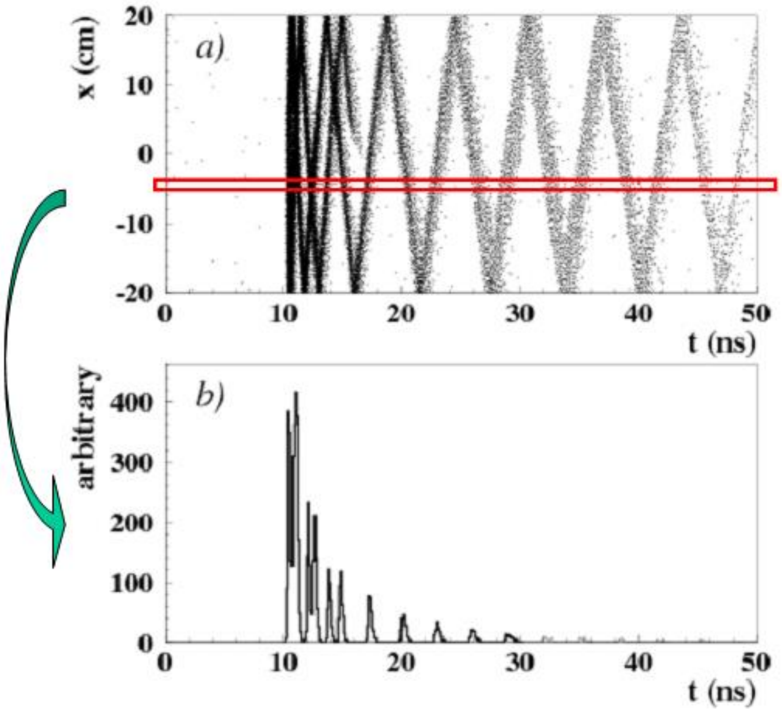
- Connect 2 bars with 1.25m × 45cm × 2cm
- Roughness < 0.5nm, flatness < 6μm
- + Focusing Mirror + Expansion Block
- Readout with 32 of 16ch PMT
- Polishing: Okamoto & Zygo



16 TOP modules

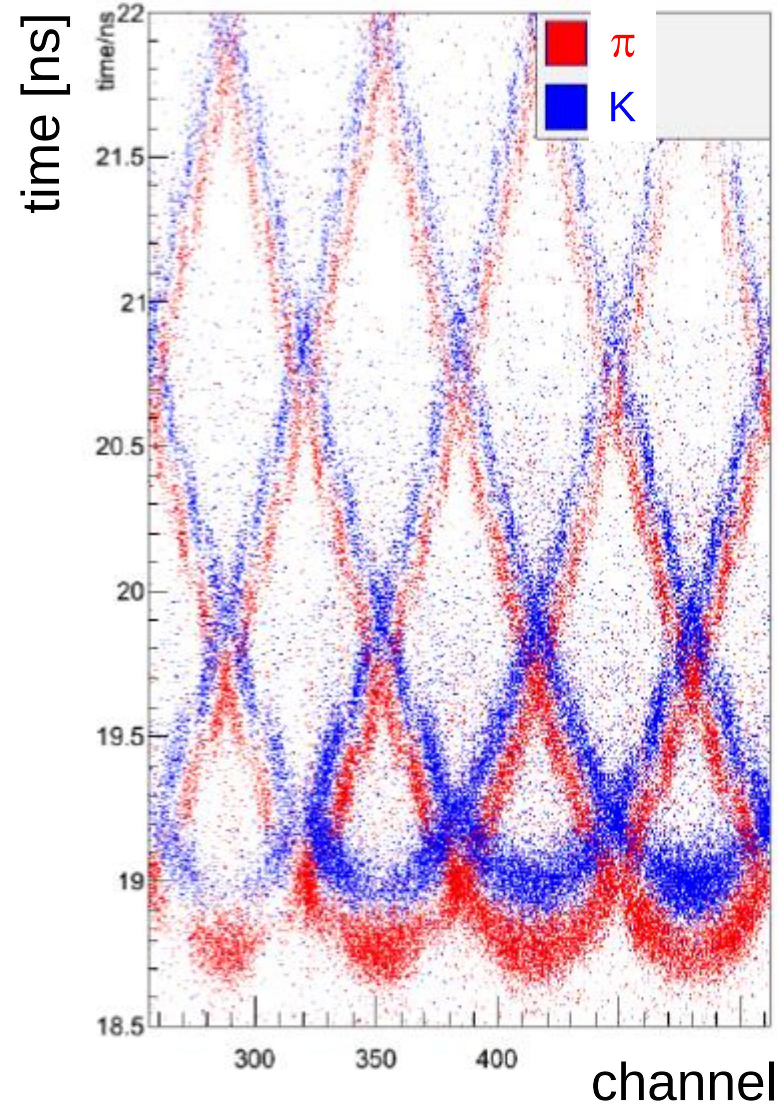


TOP



Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)



The TOP sampling clock is locked to the accelerator radio-frequency clock (RF clock)

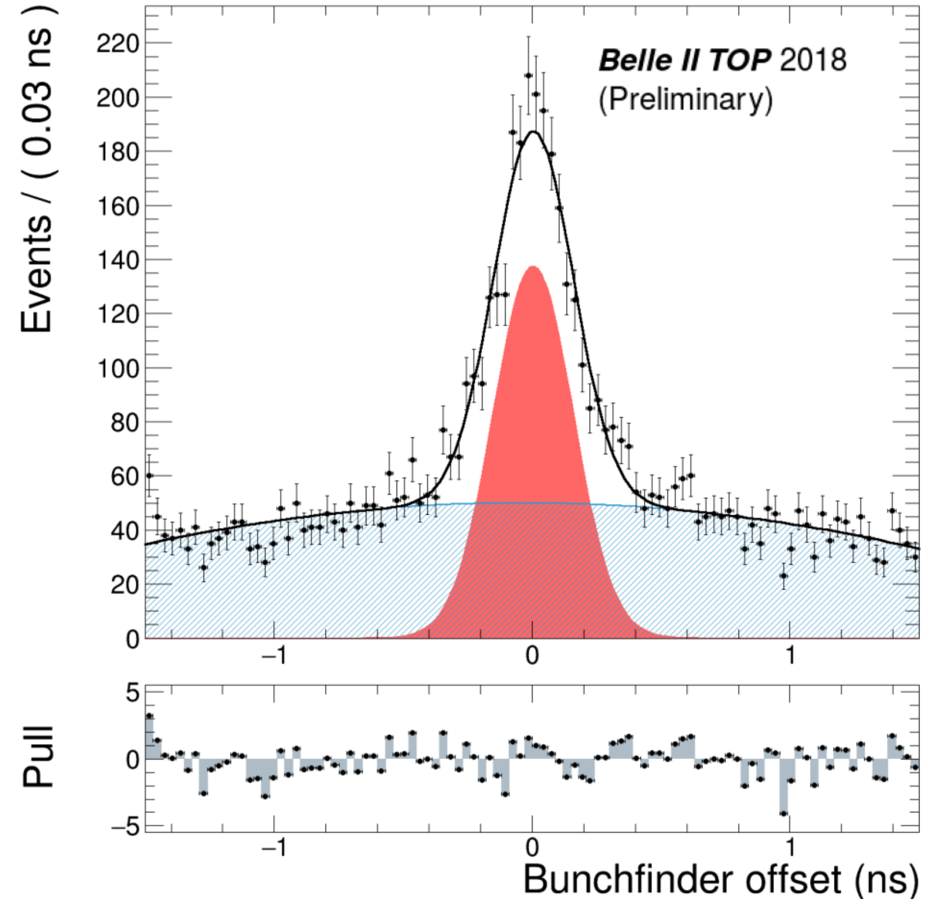
→ Any offset between the two will result in a mis-reconstruction of the PDFs

<u>Most probable collision time</u>

→ reconstructed back-fitting the higher momentum tracks in the event

→ If calibrations are correct, it will match with a tick of the RF clock

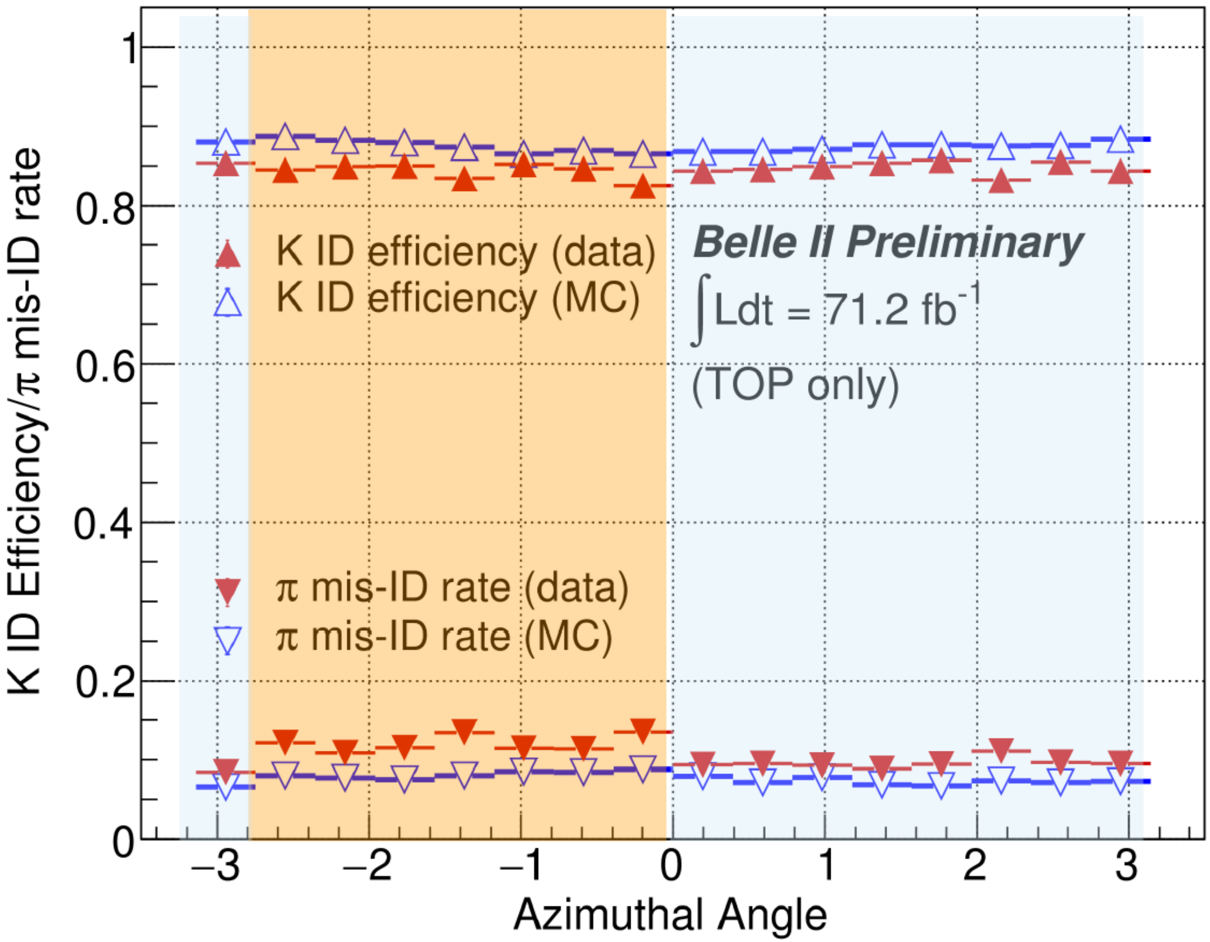
→ Resolution on data: 150 ps (bunch crossing: 2 ns)

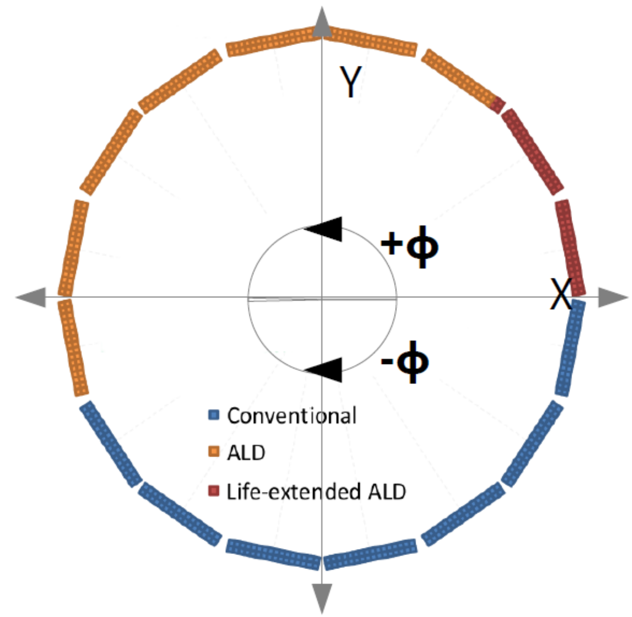


[U.Tamponi@RICH2018]

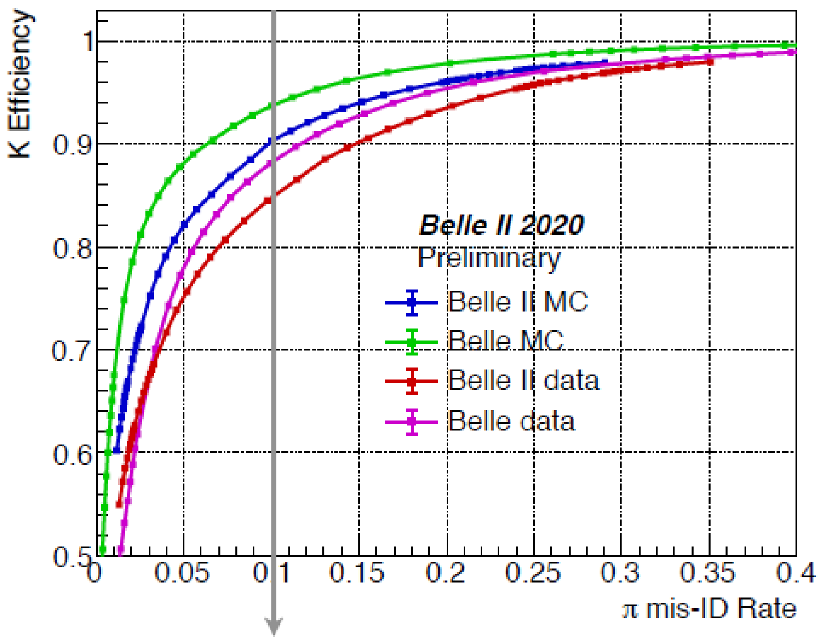
TOP Performance

- Data-MC comparison for K-eff. and π mis-ID rate (TOP only) for R[K/π] > 0.5 w.r.t. azimuthal angle.





Comparison of Performance



K efficiency at 10% π mis-ID

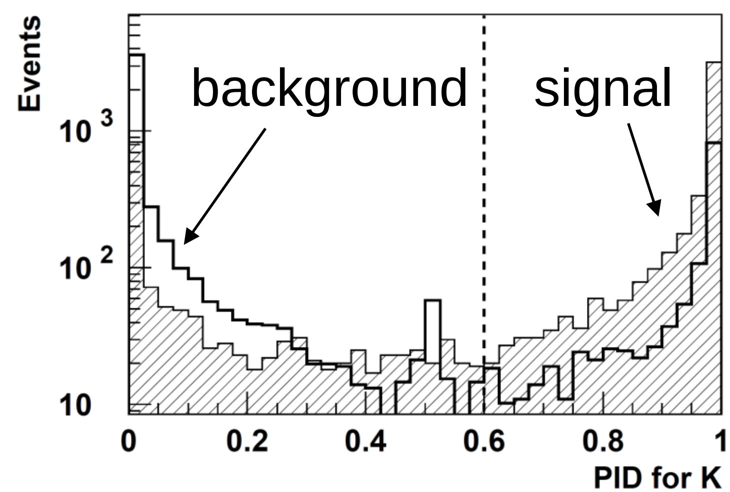
	Data	MC
Belle	88%	94%
Belle II	84%	90%

- Current Belle II hadron ID performance is slightly worse than what achieved by Belle at the end of the run
- Data-simulation agreement already at a comparable level

Likelihood

- In Belle and Belle II, total PID is obtained with likelihood.
- For that purpose, likelihood values for 5 (e,μ,π,K,p) or 6 (+deuteron) mass hypotheses are calculated by each detector.
- Selection is applied by comparing two particle hypotheses:
  PID(i:j) = L(i) / (L(i)+L(j))
- Likelihood from different detectors is combined by making a product:
  $L(i) = L_{ACC}(i) \times L_{TOF}(i) \times L_{CDC}(i)$ (@ Belle, i.e. atc_pid)
- PID(K:π) tends to be 1 if the particle is K-like, and 0 if it is π-like.
- PID(i:j) = 1 − PID(j:i)
- Do not use a selection PID(i:j)>0.5 .
  - ✓ There can be many tracks that PID(i:j) become exactly 0.5, so PID(i:j)>0.5 and PID(i:j)>=0.5 gives different results.
- It is better to use “recommended values” in Belle analysis, since official systematic error table is already calculated.

(c) PID for K^+



Likelihood

- Q) We can compare only two particle hypotheses. Why do we use only PID(K:π) to select kaon?
  - ✓ If you want, you can apply cuts on PID(K:e), PID(K:μ), PID(K:p) too, but this is not necessary (maybe even harmful for systematic study).
  - ✓ A) PID is mainly done by mass difference. So, if you apply a cut on PID(K:π), this automatically cut electrons and muons, too.
  - ✓ A) The number of produced particles at Belle: π > K > e, p > μ.
  - ✓ A) From physics. You may have similar (background) processes where K is replaced by π. (e.g. with different CKM factor).

- But, if μ becomes background, you can explicitly veto μ. In this case, you reject it using Muid, because Muid uses KLM information.