Cherenkov light imaging detectors in current particle and nuclear physics experiments

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Sep. 15, 2025

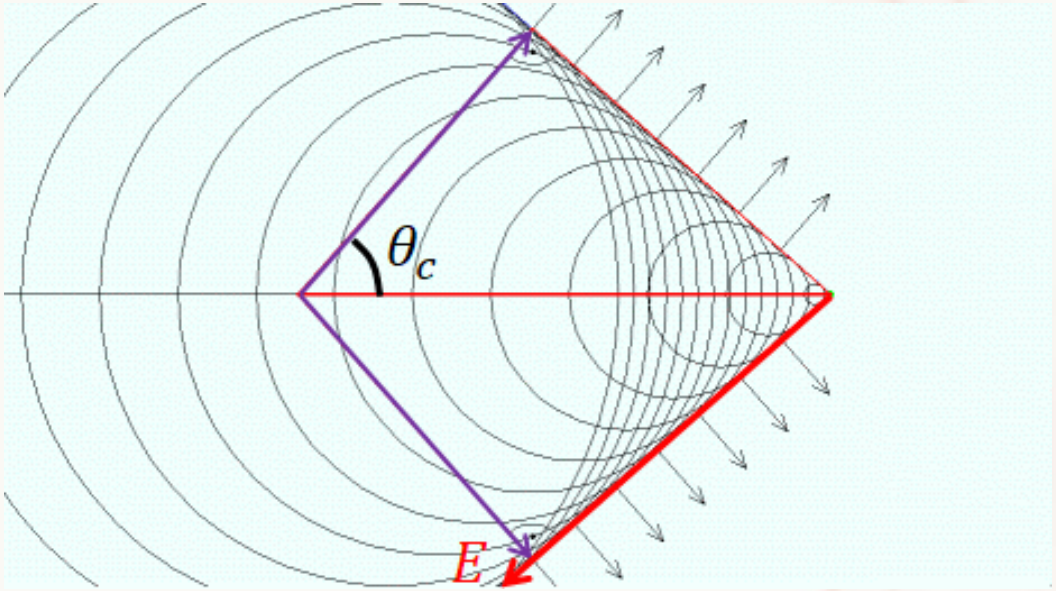
Contents

- Introduction
  - Review Cherenkov radiation and history of Cherenkov detectors
- RICH detectors in the current experiments
  - I will not go into the detail of each detector, since it will be covered by the subsequent talks.
  - I will try to digest the features of each detector.
- Challenges
  - I will not cover the R&D for upgrade or future experiments, since it will be covered by M. Fiorini (DRD4) and C. Chatterjee.
  - I will cover a few R&D topics conducted for the current detectors.
- Summary

Cherenkov radiation

Dissipation of energy of coherent electrons
"an electron moving in a medium does radiate light … provided that its velocity is greater than the velocity of light in the medium." (Tamm and Frank)

- **Timing**
  Immediate radiation
- **Threshold**
  $$\beta > \frac{1}{n(\lambda)}$$
- **Angle**
  $$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$
- **Number of photons**
  $$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c \approx 370\sin^2\theta_c(E)\ \text{eV}^{-1}\text{cm}^{-1}\ (z=1)$$
- **Polarization**
  Cherenkov light is linearly polarized.

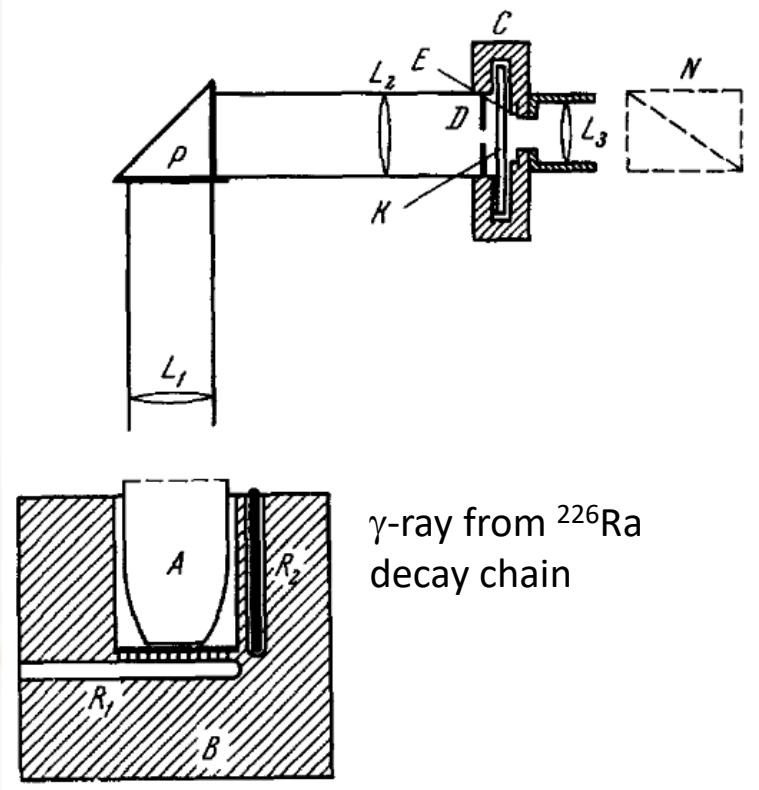


https://upload.wikimedia.org/wikipedia/commons/8/87/Cherenkov_radiation-animation.gif

These characteristics and the dependence on β enable particle identification.

History of Cherenkov detectors

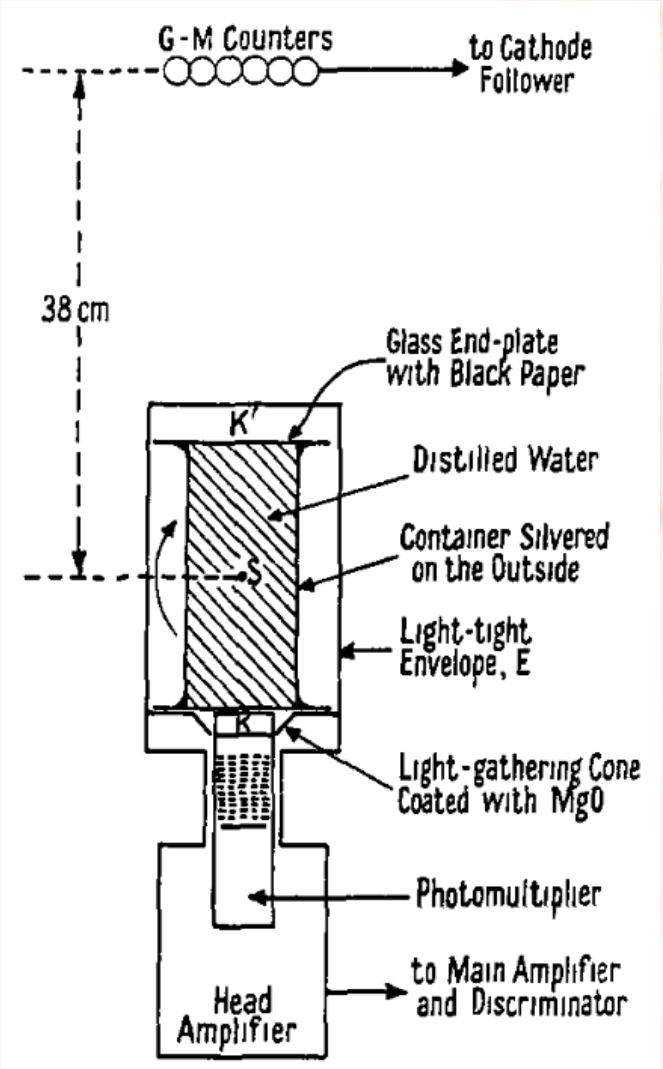
Cherenkov photons by electrons from Compton scattering.
Observation of light by eyes or films.
Polarization was also observed.



γ-ray from ^{226}Ra decay chain

P.A. Cherenkov, Dokl.Akad.Nauk SSSR 2 (1934) 8, 451-454
Usp.Fiz.Nauk 93 (1967) 2, 385-388

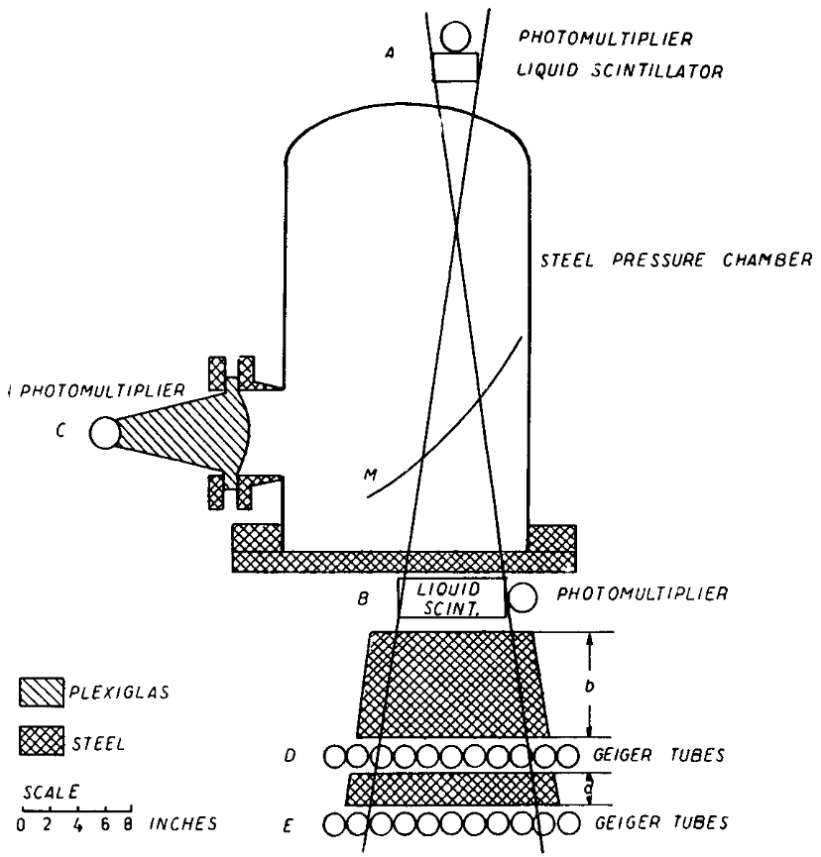
1st Cherenkov "counter" for cosmic muons



J V Jelley 1951 Proc. Phys. Soc. A 64 82

History of Cherenkov detectors

A cosmic-ray gas čerenkov counter with adjustable velocity threshold

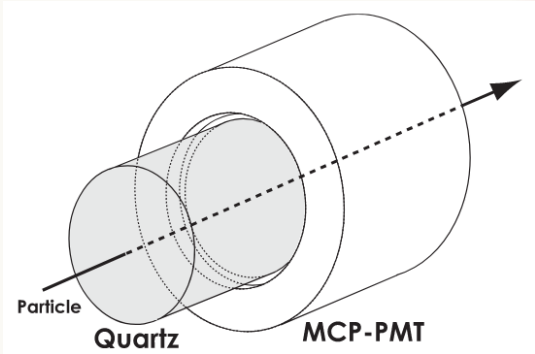


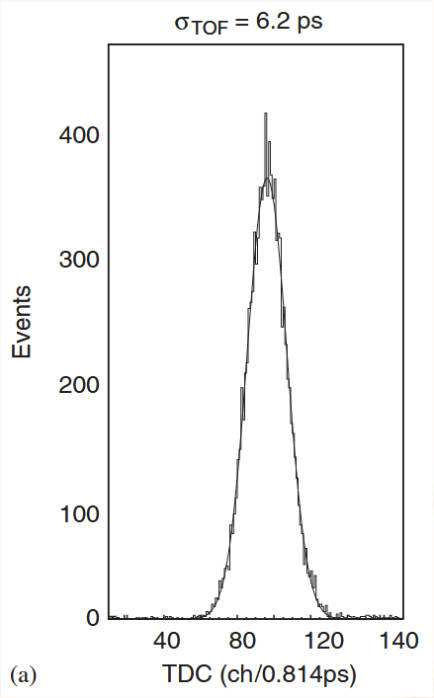
Hanson, E.J., Moore, D.C., *Nuovo Cim* **4**, 1558 (1956)

Threshold

World's best TOF resolution of 6.2 ps

K. Inami, et. al. NIMA 560 (2006) 303



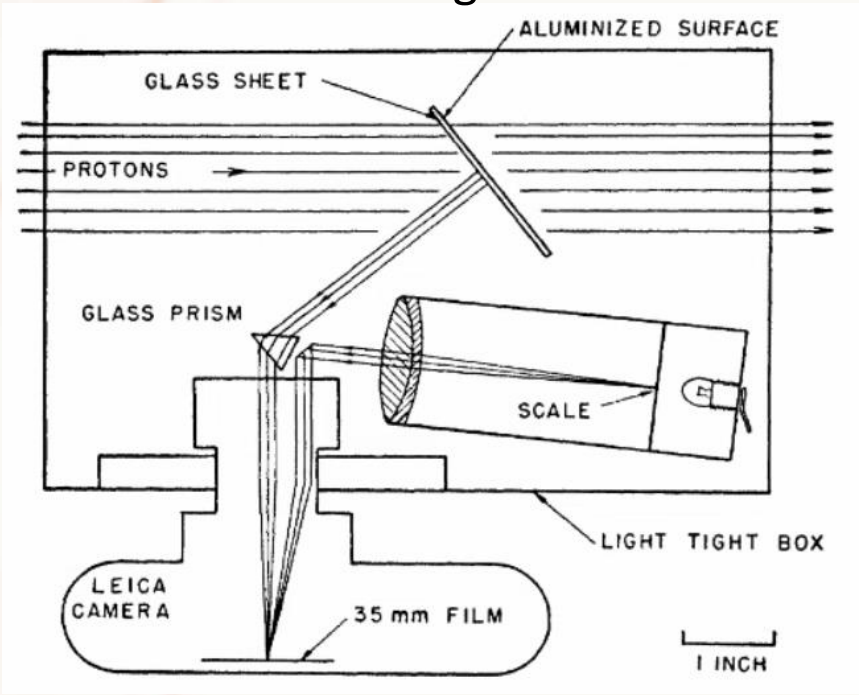


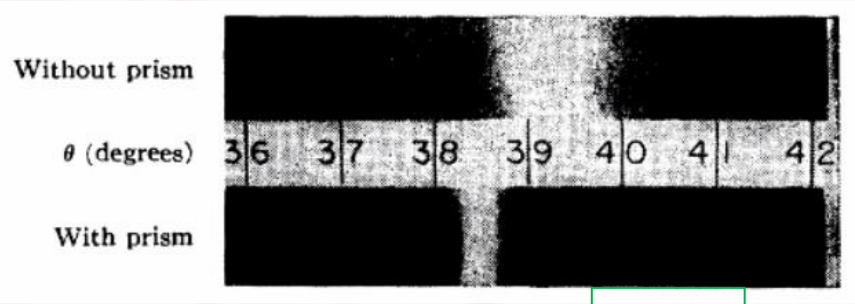
3 GeV/c π beam
13 mm thick quartz
4.1 ps by readout

Timing

History of Cherenkov detectors

Proton beam kinetic energy measurement from the Cherenkov angle

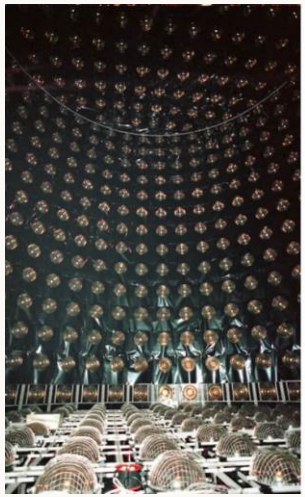


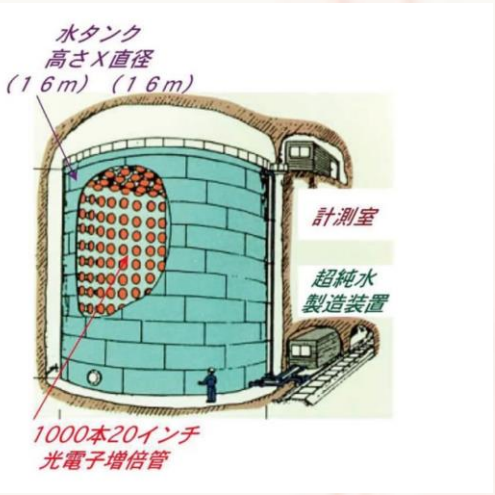


R. L. Mather, Phys. Rev. **84**, 181 (1951)

Angle

Kamiokande (1983–1996)
Water Cherenkov detector
for proton decay search





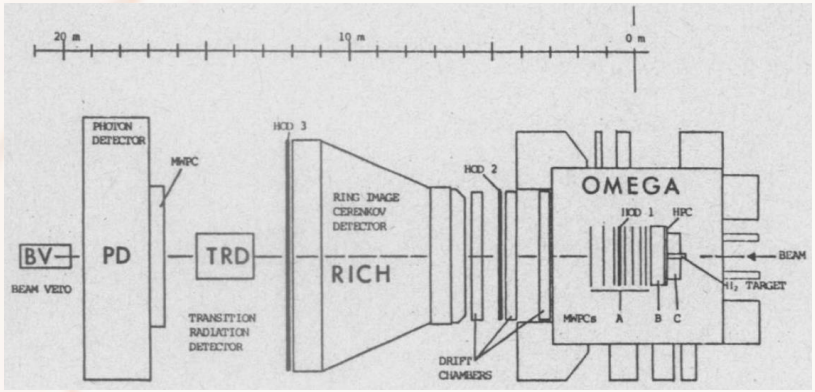
(c) Kamioka Observatory, ICRR

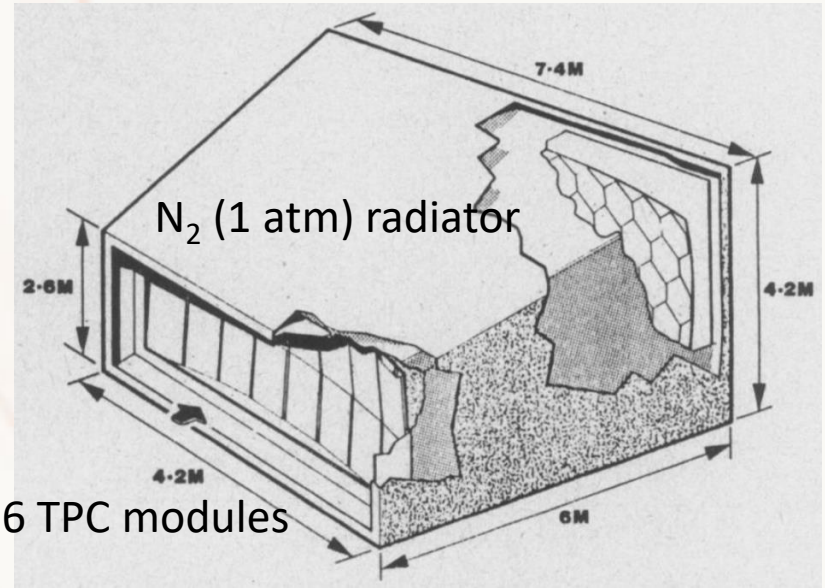
Angle **Number of photons**

History of Cherenkov detectors

RICH for the CERN OMEGA spectrometer

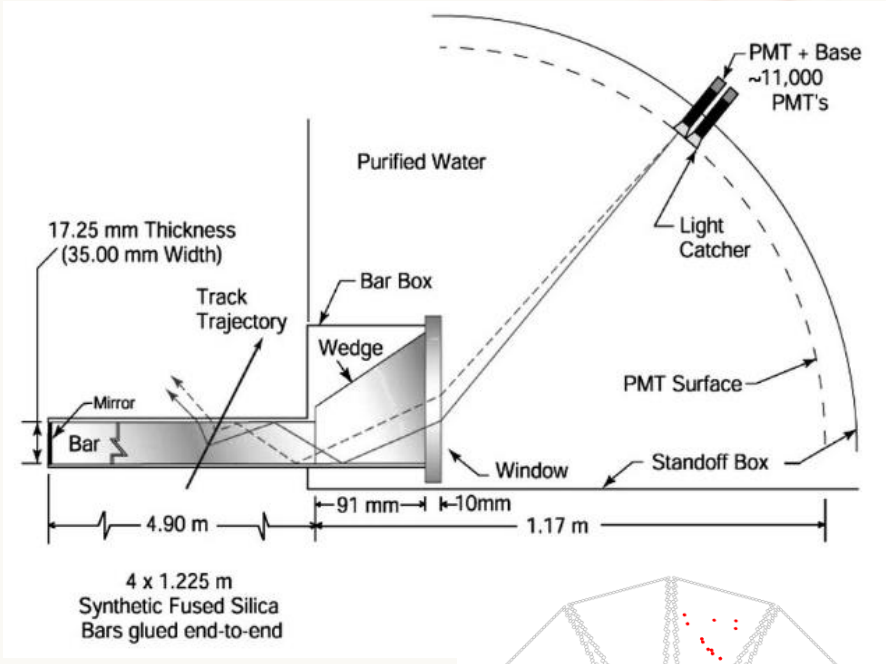
[IEEE Transactions on Nuclear Science, 32, 674 (1985)]

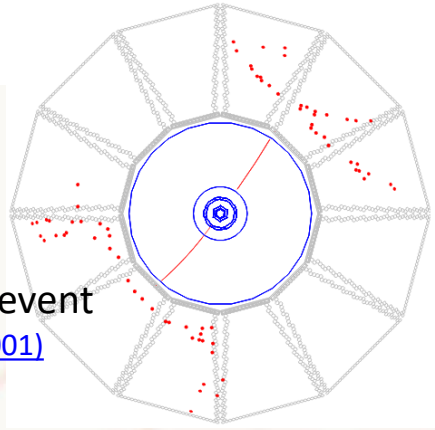




16 TPC modules

BaBar DIRC





$e^+e^- \to \mu^+\mu^-$ event

[SLAC–PUB–8783 (2001)]

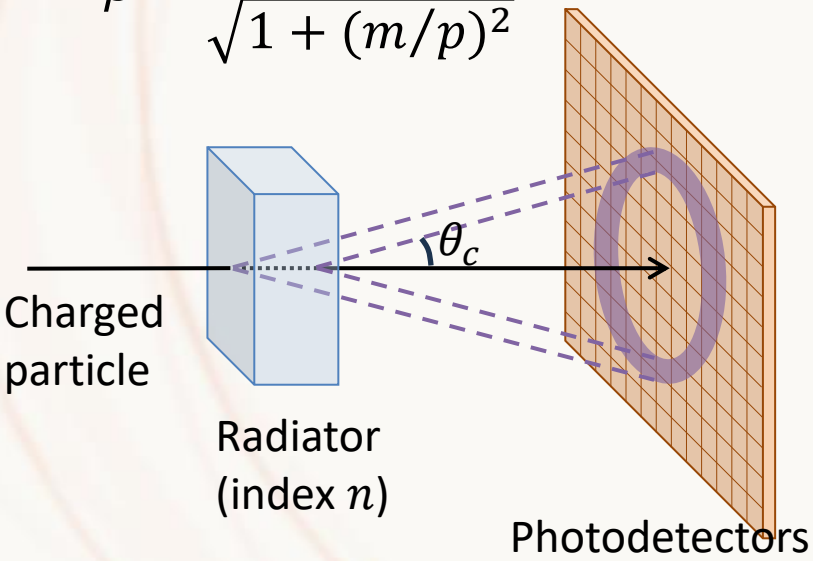
Angle **Number of photons**

Angle **Number of photons**

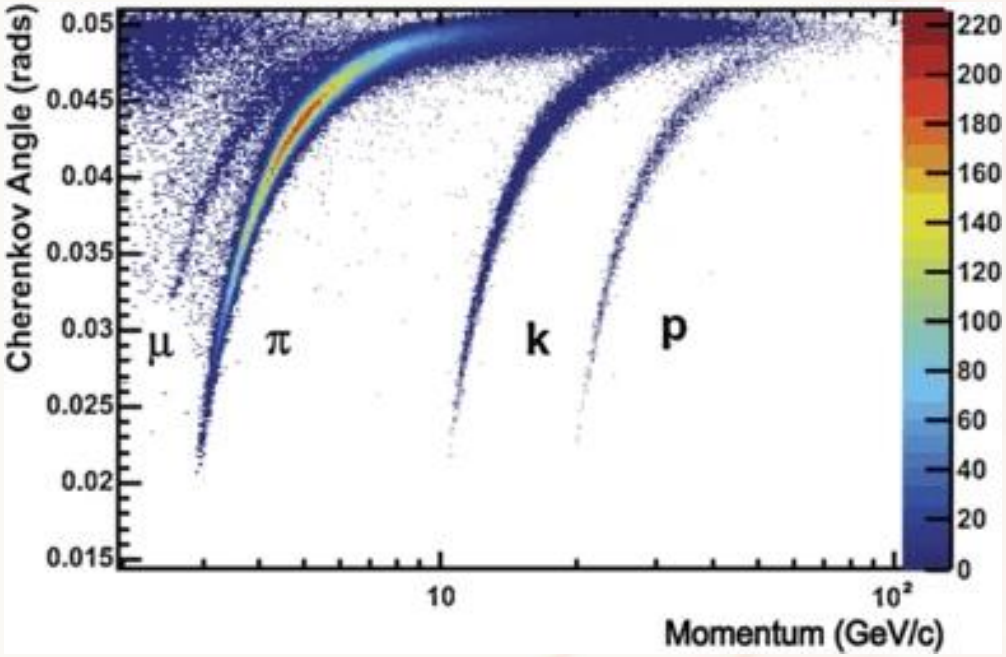
PID with a RICH detector

For a given particle mass m, predict the Cherenkov ring radius from its momentum p and trajectory measured by other tracking devices, and compare this predicted radius with the measured value.

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



LHCb RICH-1 (C_4F_{10}) Eur. Phys. J. C 73 (2013) 2431



PID performance

The number of σ separation between m_1 and m_2

for a particle of $\beta \approx 1$ well above the Cherenkov threshold

B. N. Ratcliff, NIMA 502 (2003) 211

$$N_\sigma \approx \frac{\left|m_1^2 - m_2^2\right|}{2p^2\sigma(\theta_c)\sqrt{n^2-1}},$$

Angular resolution

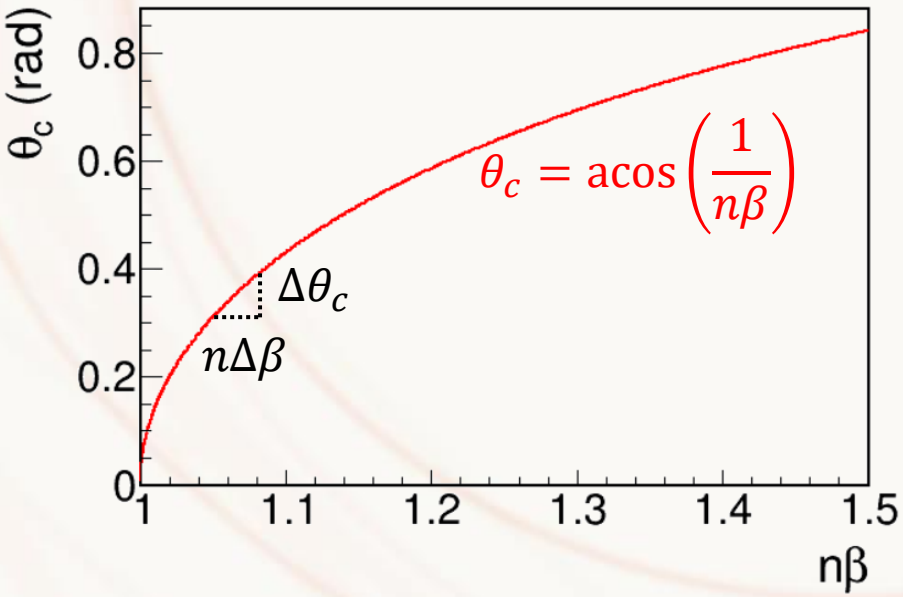
Average single p.e. resolution

$$\sigma(\theta_c) = \frac{\langle\sigma(\theta_i)\rangle}{\sqrt{N_{\text{p.e.}}}} \oplus C$$

Momentum ↔ Refractive index → Number of photoelectrons

Choice of the radiator

Radiator thickness, photodetector



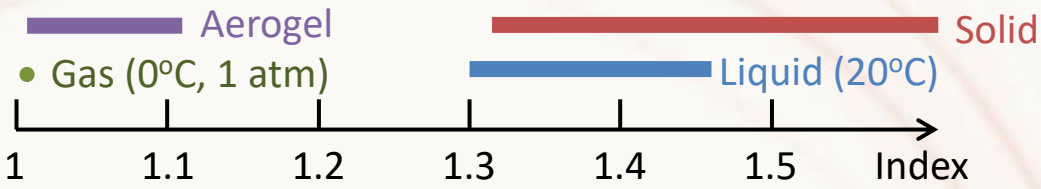
$\langle\sigma(\theta_i)\rangle$ dictated by

- Optics
- Detector resolution
- Chromaticity spread of refractive index

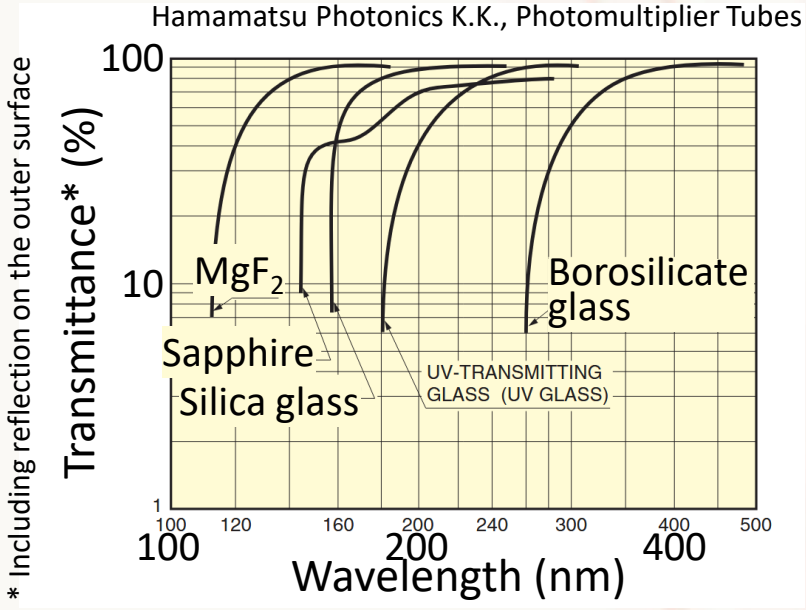
C dictated by

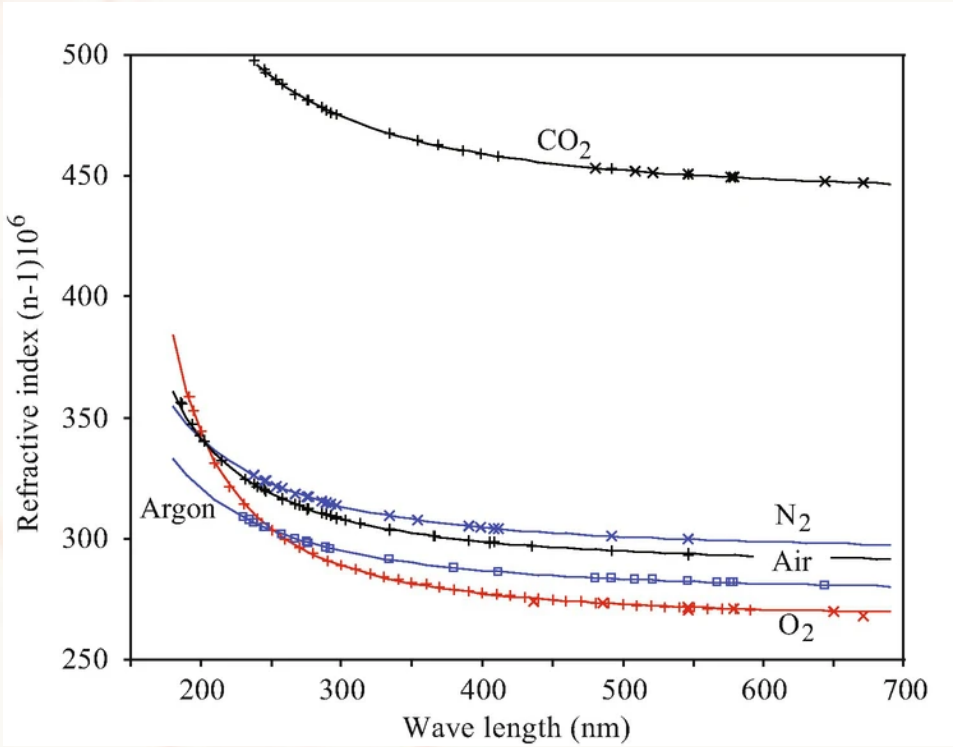
- Tracking, alignment, multiple scattering
- Hit ambiguities
- Background hits
- Hits coming from other tracks

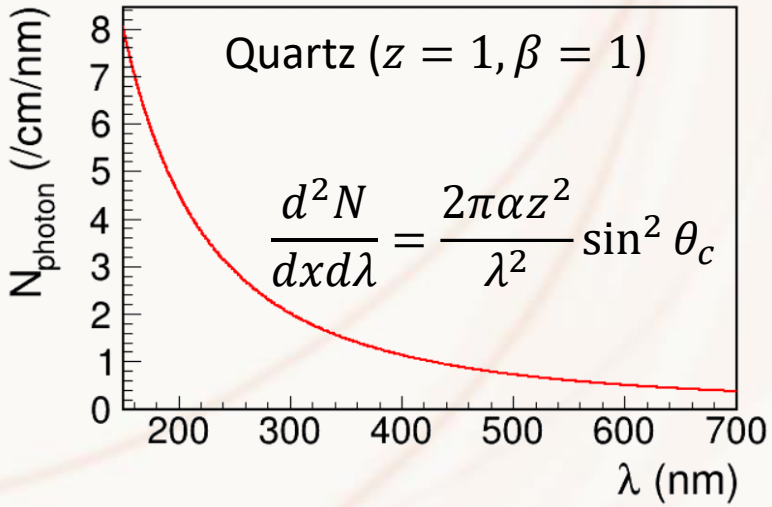
Radiators



- Appropriate refractive index
- Transparency in UV/visible range
- Low chromaticity spread

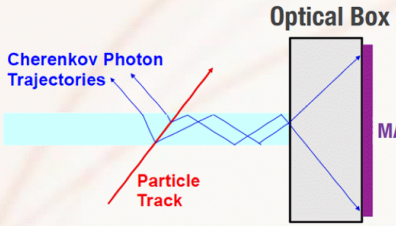




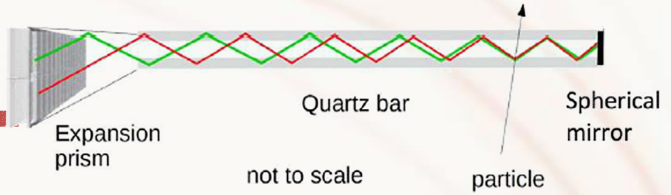


Forty, R., Ullaland, O. (2020). Particle Identification: Time-of-Flight, Cherenkov and Transition Radiation Detectors

Glass



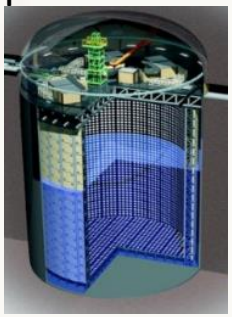
Belle II TOP



GlueX DIRC

Liquid

Super-Kamiokande



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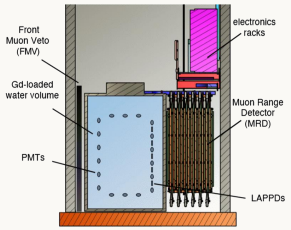
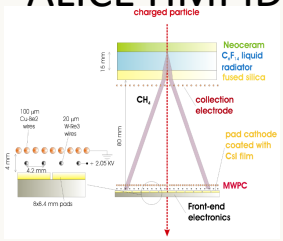
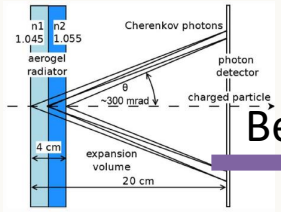


ALICE HMPID

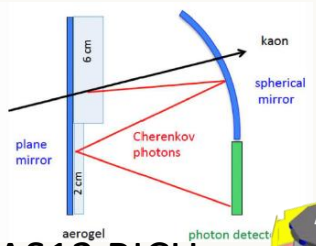


[Caveat]
Only detectors for currently running particle and nuclear physics experiments are displayed and are not exhaustive.

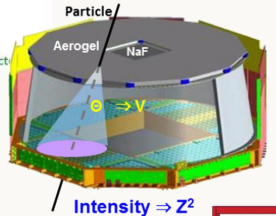
Aerogel



Belle II ARICH



CLAS12 RICH

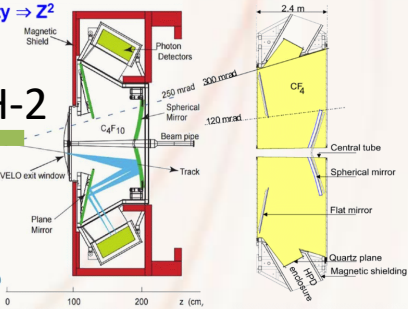


AMS-02 RICH

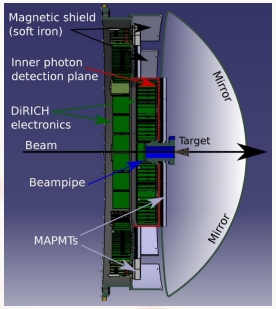
Gas

LHCb RICH-1

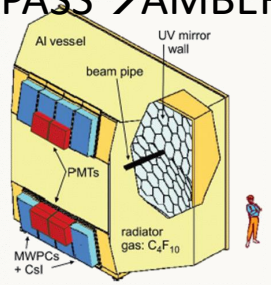
RICH-2



HADES RICH (hadron blind)



COMPASS→AMBER RICH

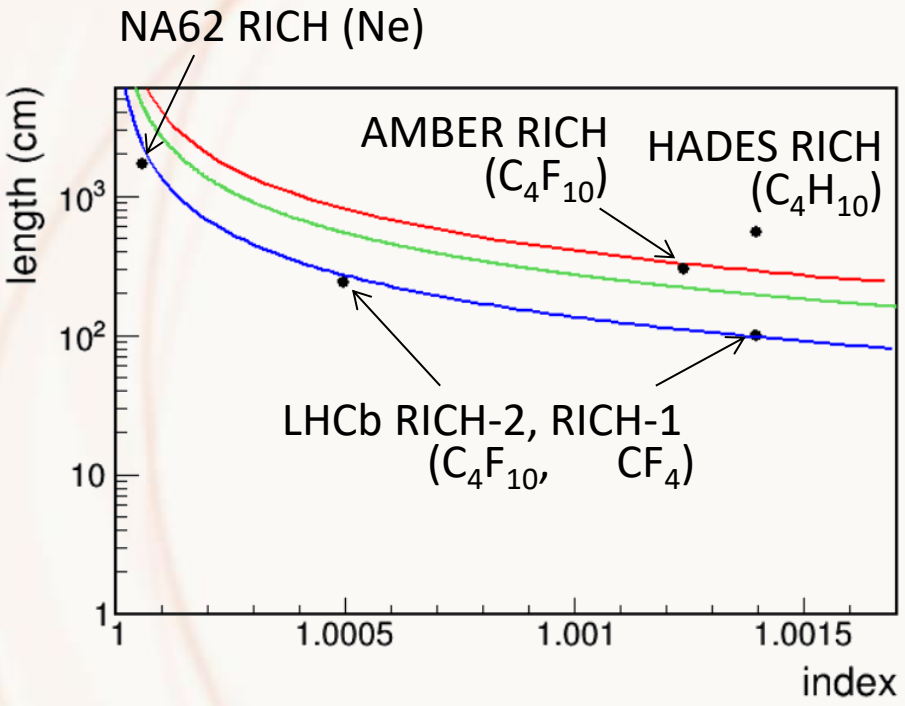


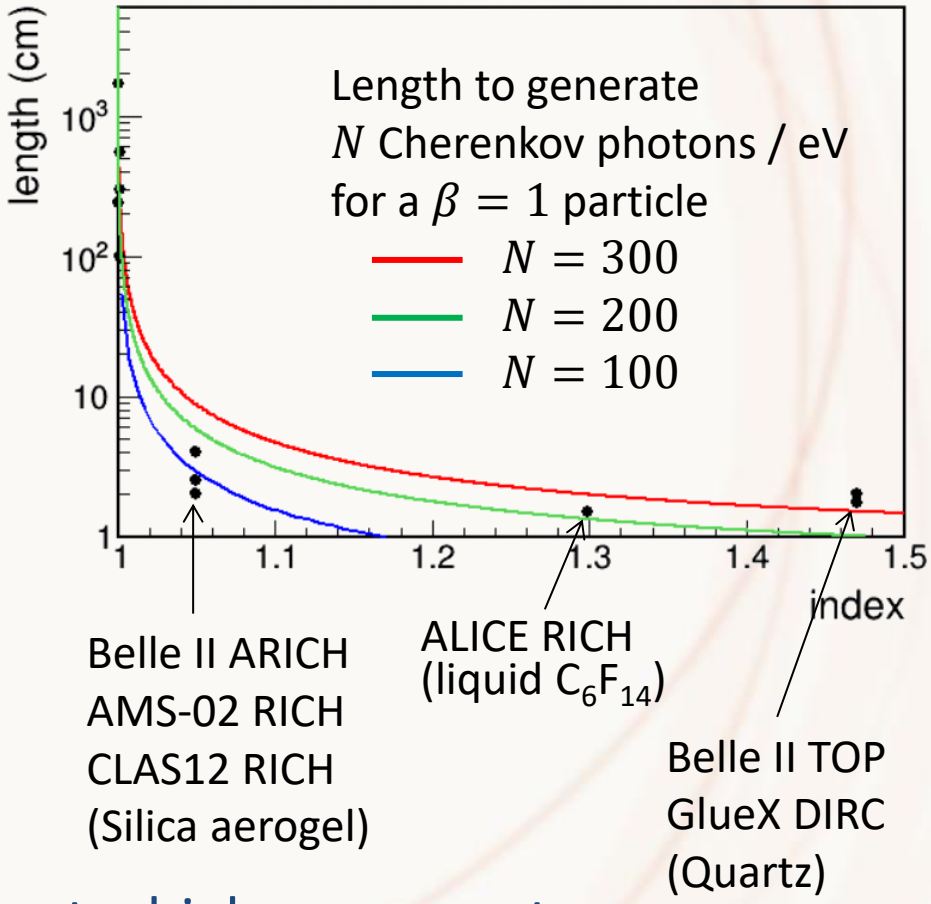
NA62 RICH

10 MeV | 100 MeV | 1 GeV | 10 GeV | Target momentum range

Number of generated Cherenkov photons

with respect to the radiator length and refractive index

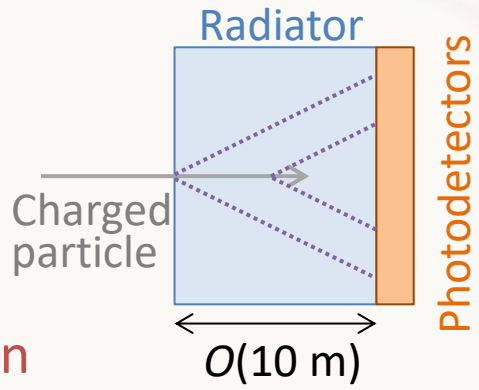


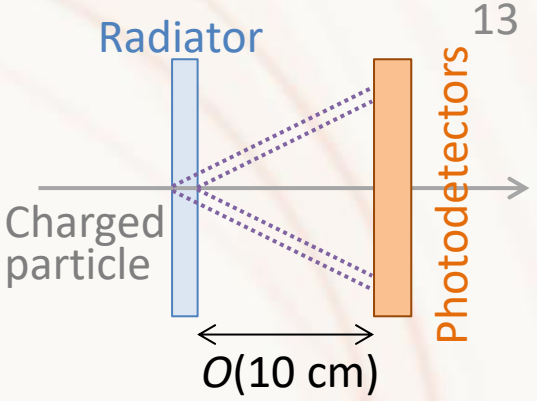


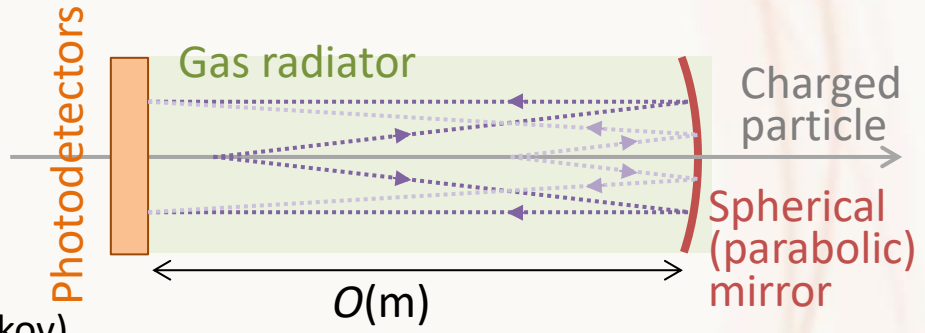
To achieve a good PID performance at a higher momentum, a longer radiator with a smaller index is required.

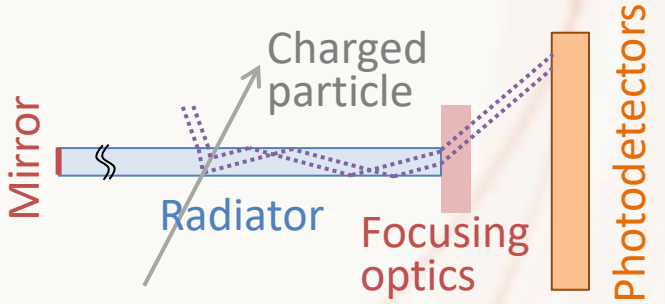
RICH types

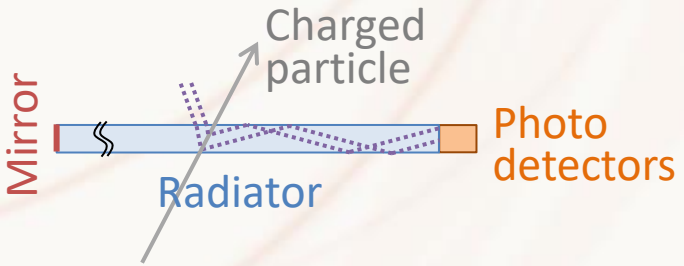
- (Water Cherenkov detector)
- Proximity focusing by limiting the emission region
  - Based on aerogel or liquid radiator, and compact
- Focusing by a lens or mirror
  - Wide and high momentum range by gas radiator, but large volume
- DIRC (Detection Internally Reflected Cherenkov)
  - Transport photons to a detector outside by total internal reflection, keeping the Cherenkov angle.
  - More compact in the detector active area.
- Imaging in space and time
  - Precisely measure Time-Of-Propagation (TOP) of photons, which correlates with the Cherenkov angle.
  - Even more compact.





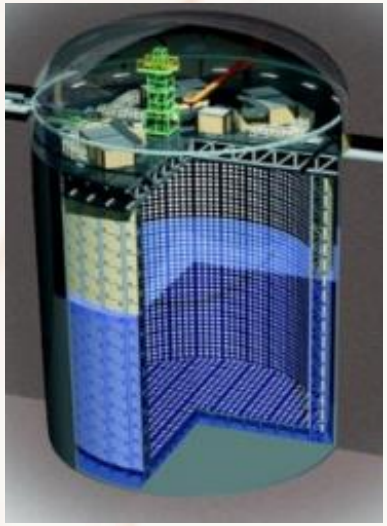






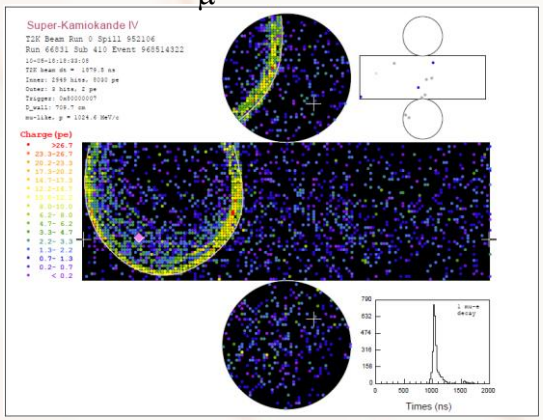
Water Cherenkov detector

Super-Kamiokande

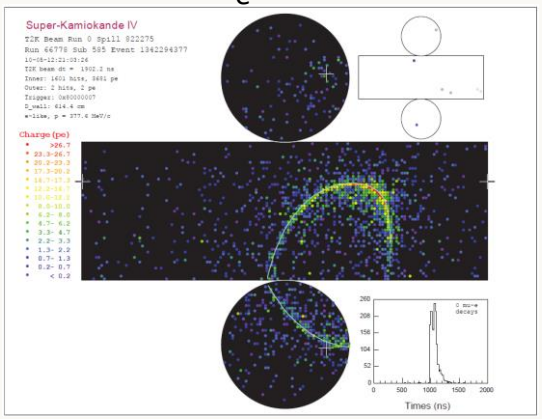


e/μ identification using fuzziness of rings due to multiple scattering

T2K ν_μ candidate



T2K first ν_e candidate



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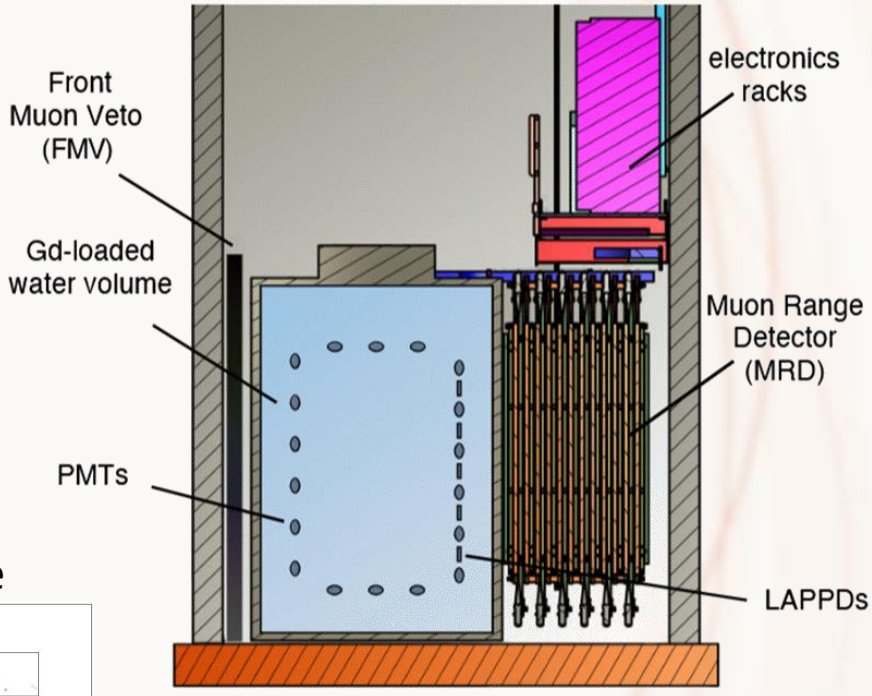


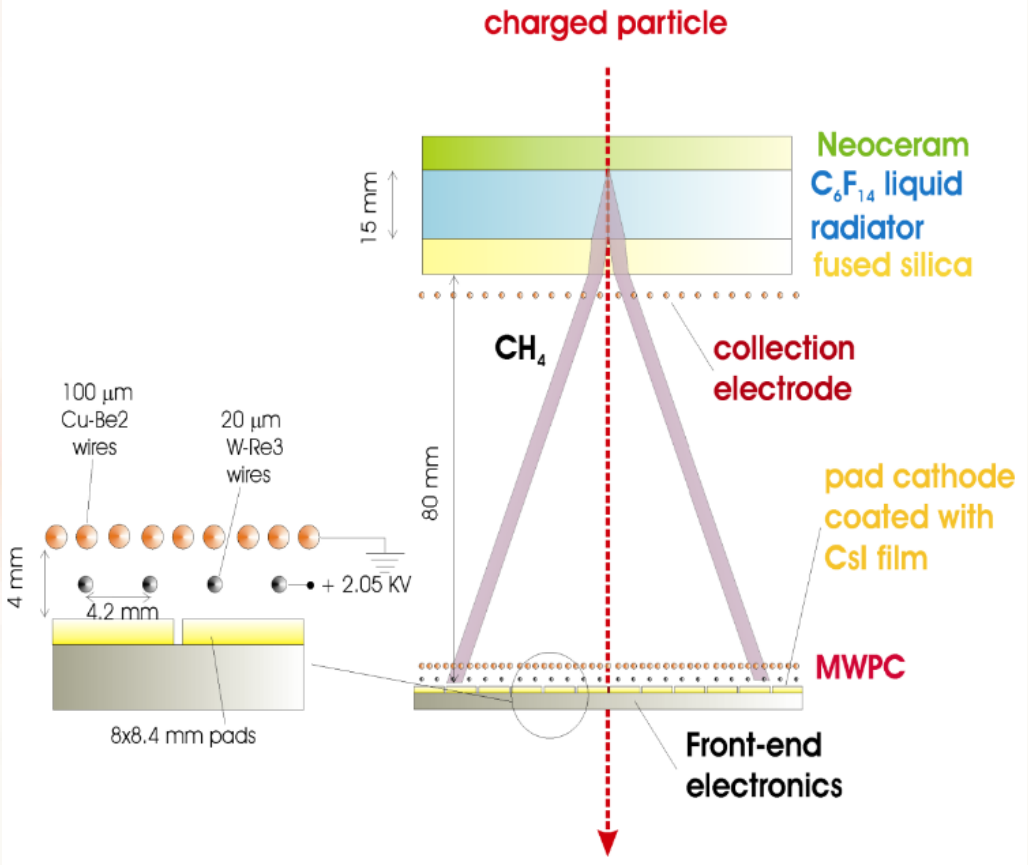
ν vertex reconstruction from the Cherenkov photon timing on LAPPD and muon momentum measured by MRD

→ Talk by A. Rychter (for Hyper-Kamiokande)

→ Talk by Matthew Wetstein

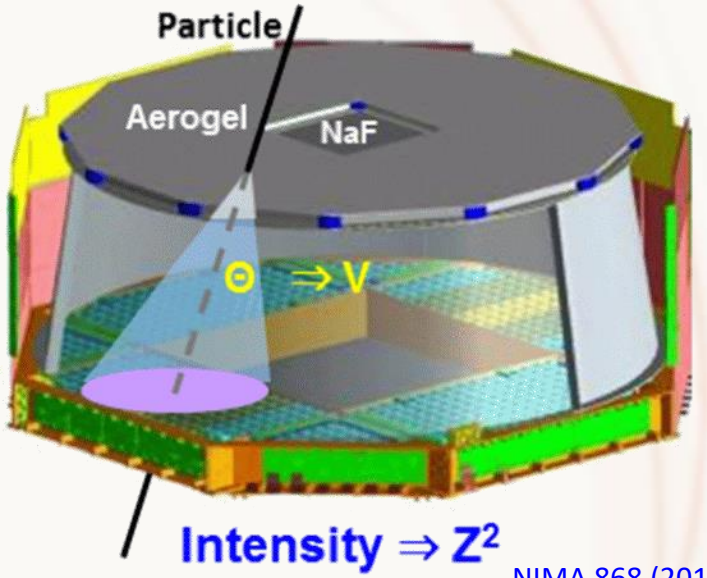
Proximity focusing RICH

ALICE HMPID

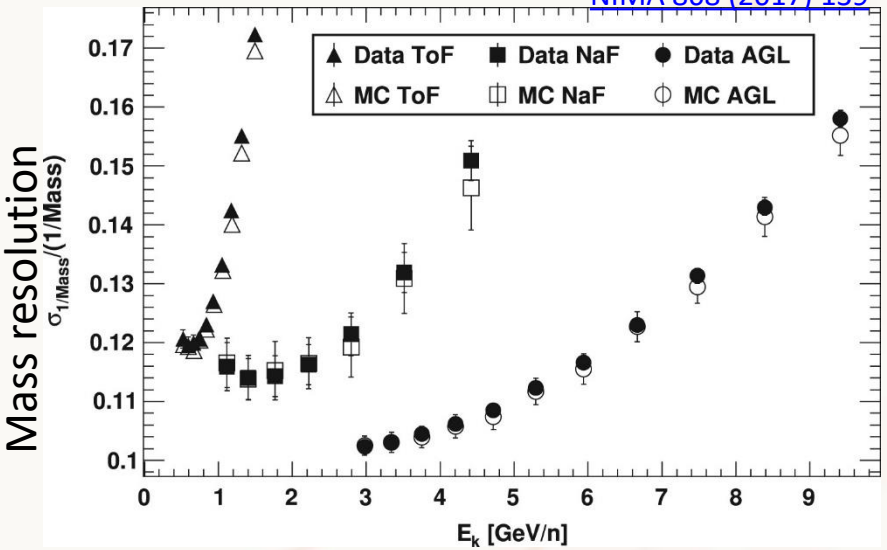


→ Talk by Giacomo Volpe

AMS-02 RICH



NIMA 868 (2017) 139

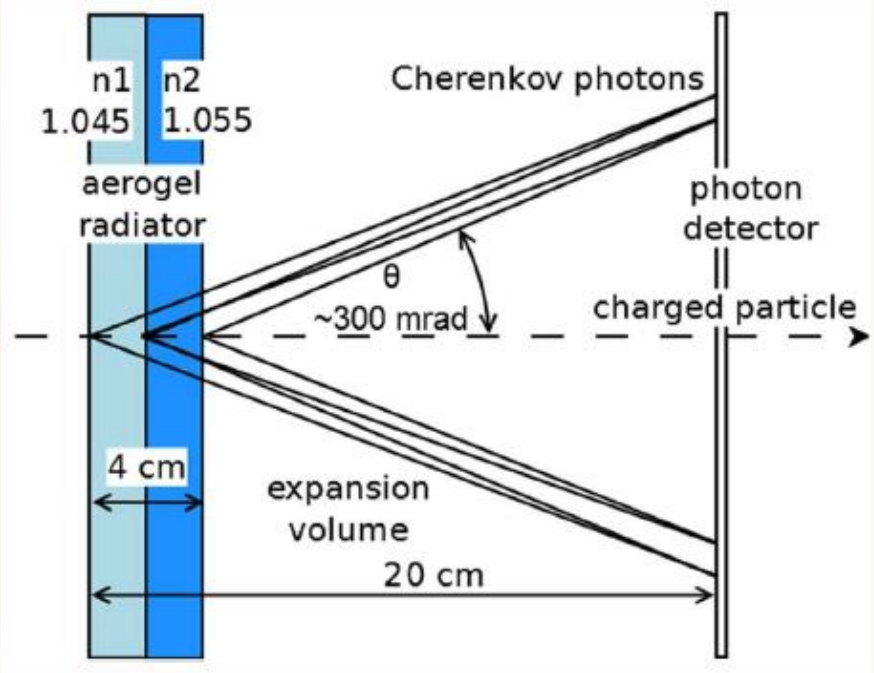


Kinetic energy (GeV/n)

→ Talk by Jianan Xiao

Proximity focusing RICH

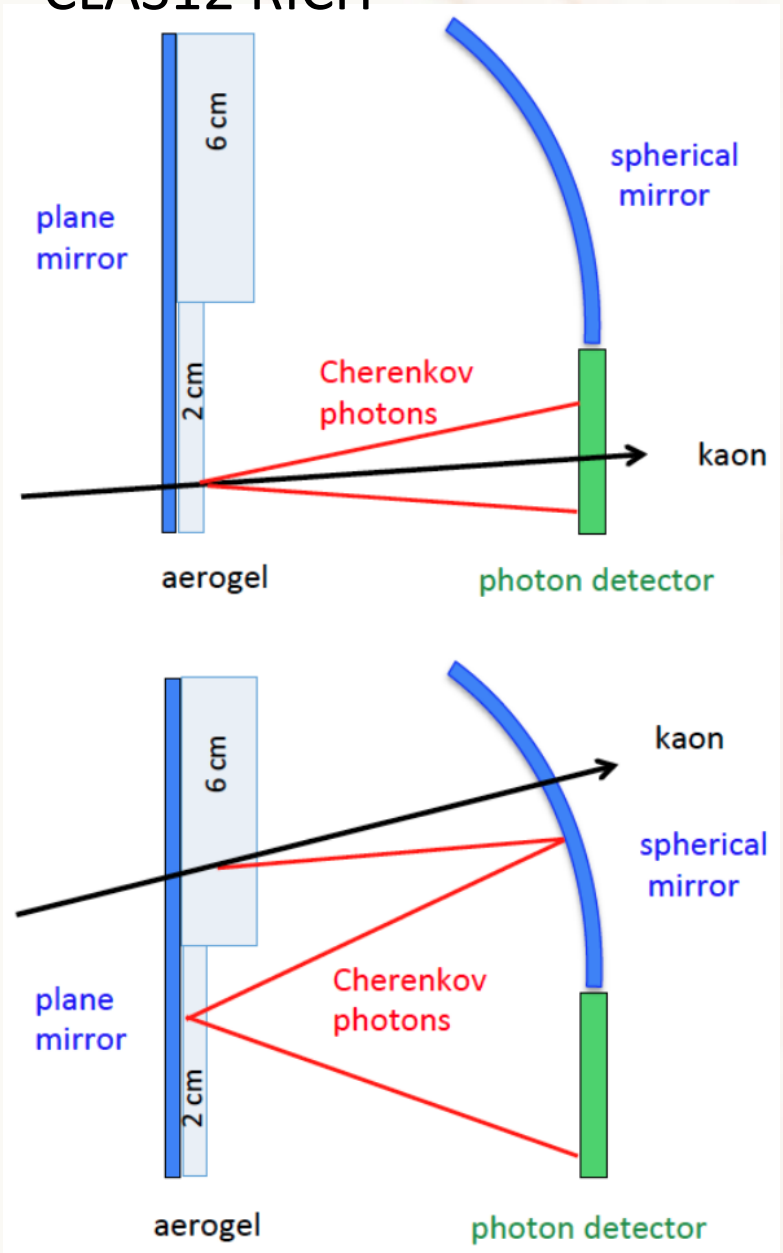
Belle II ARICH



Two layers of aerogel of different index to increase N_{photon} while keeping the ring image resolution.

→ Talk by Kristof Spenko

CLAS12 RICH



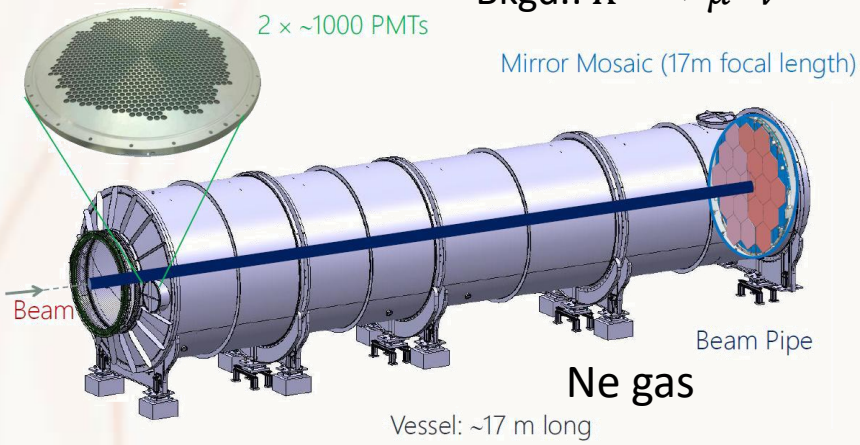
→ Talk by Marco Mirazita

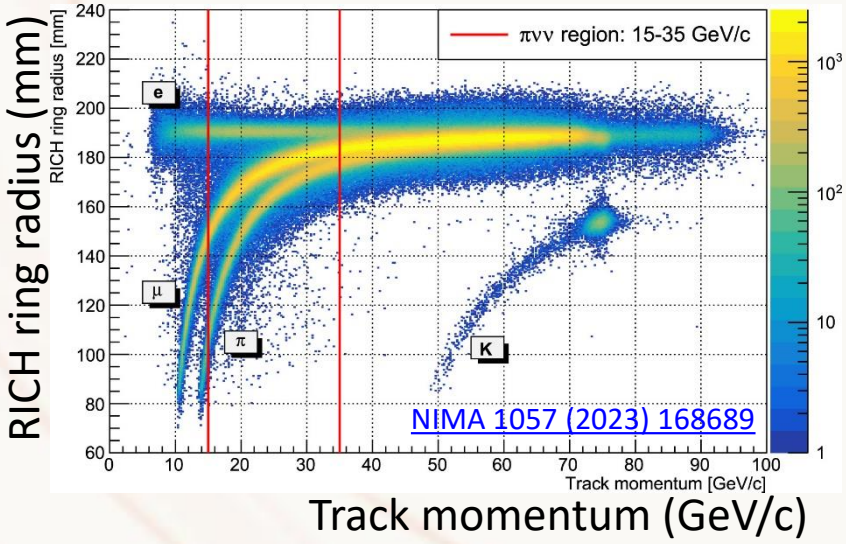
Focusing RICH

NA62 RICH

Signal: $K^+ \to \pi^+ \nu\bar{\nu}$

Bkgd.: $K^+ \to \mu^+ \nu$



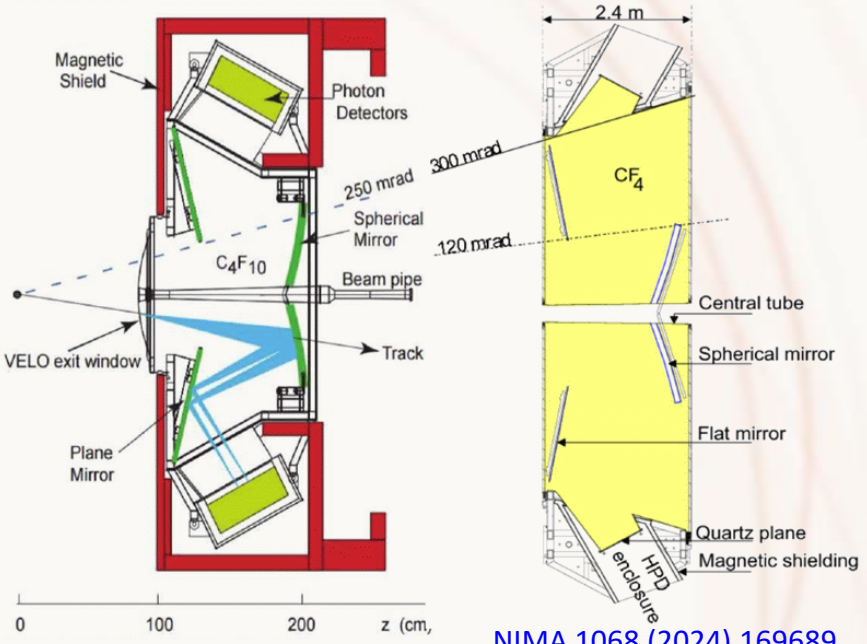


Track momentum (GeV/c)

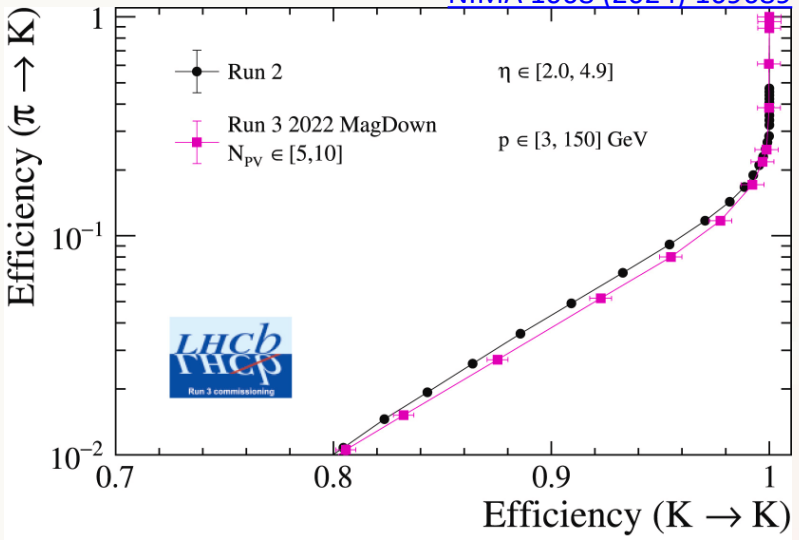
→ Talk by Francesca Bucci, Viacheslav Duk

LHCb RICH-1,2

Upgraded during LS2 (2019-2022)



NIMA 1068 (2024) 169689

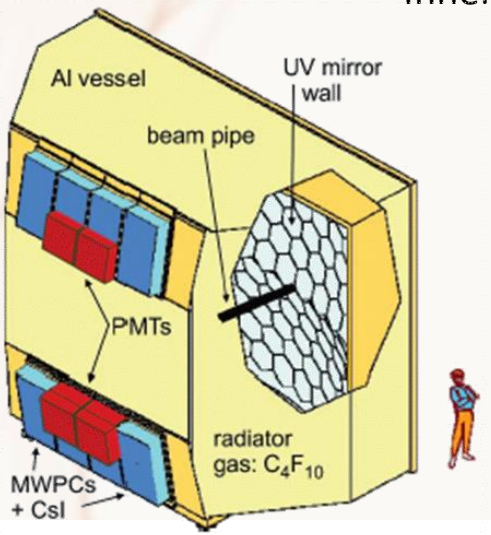


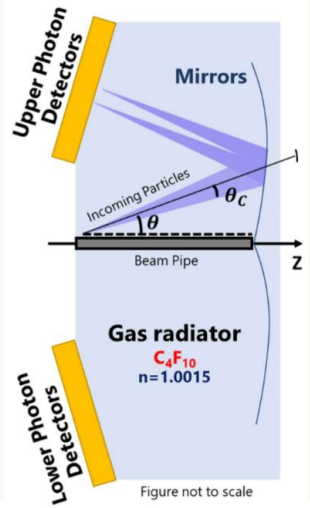
→ Talk by Giovanni Cavallero
Abhinaba Upadhyay

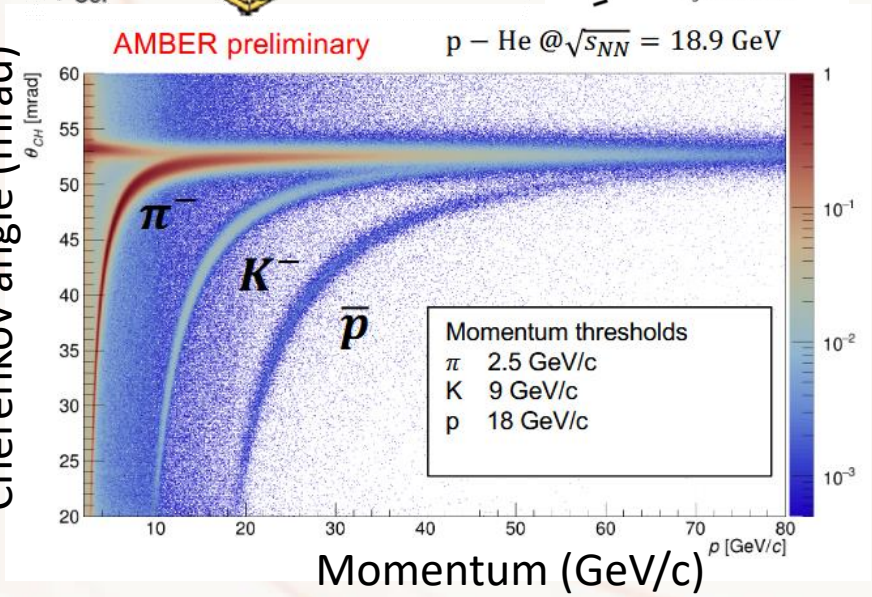
Focusing RICH

AMBER RICH

Inherited from COMPASS

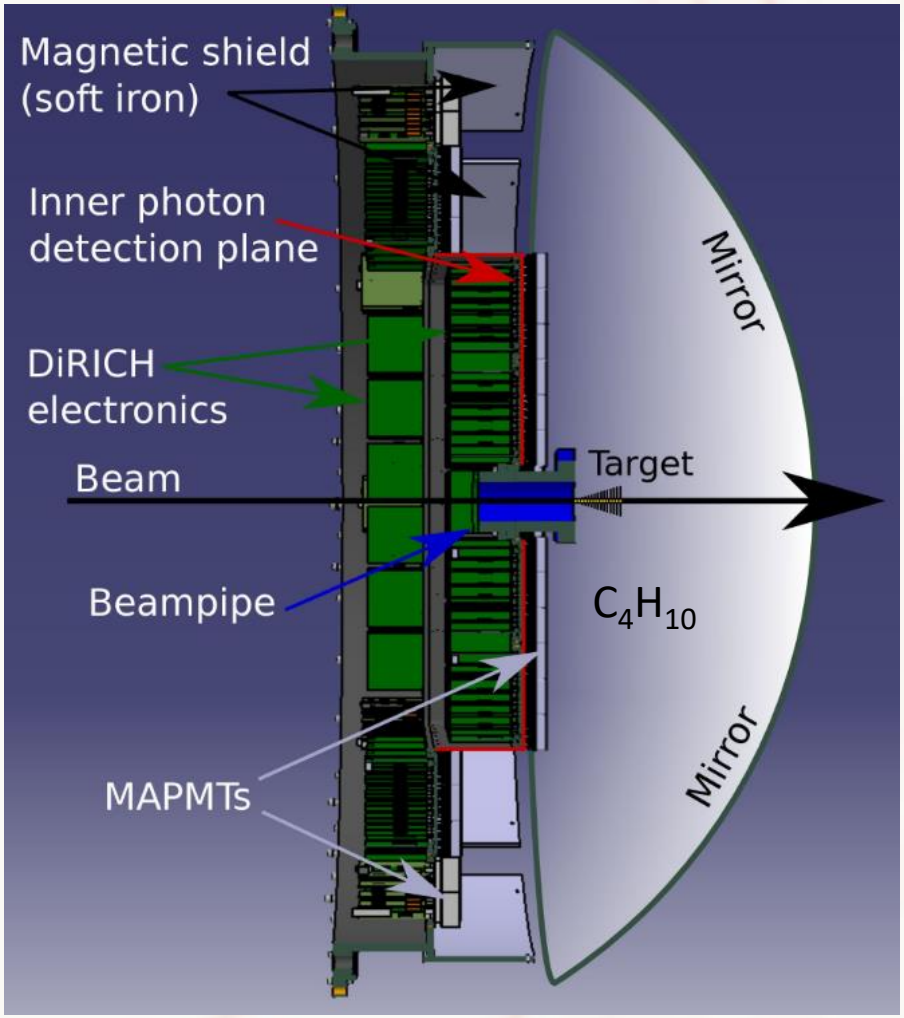






HADES RICH

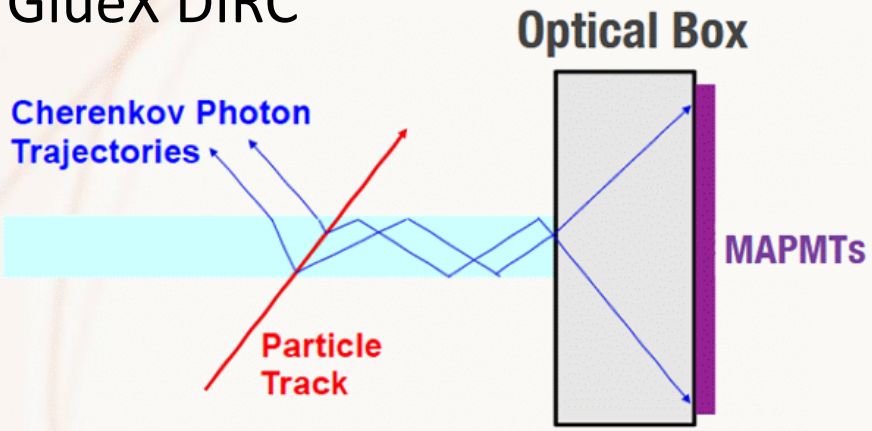
$e^{\pm}$ ID, hadron blind

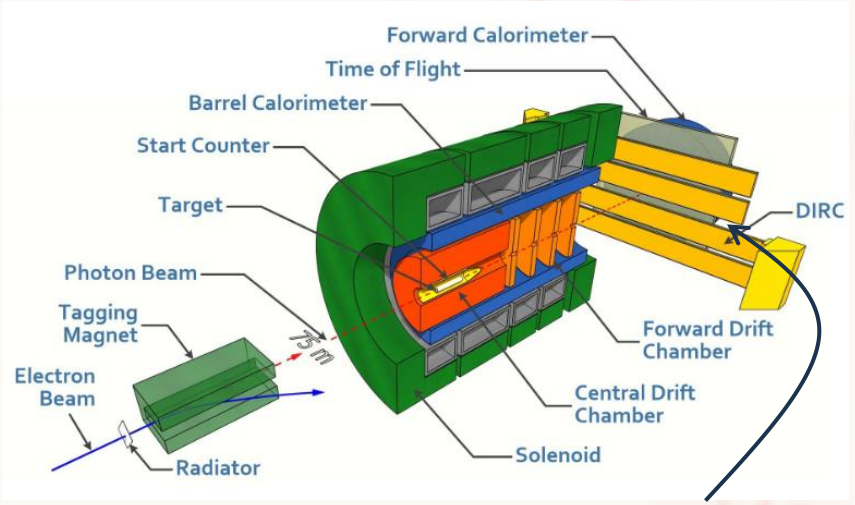


T. Pöschl, "Overview of the AMBER Experiment", KHuK Annual Meeting 2024

DIRC, TOP

GlueX DIRC

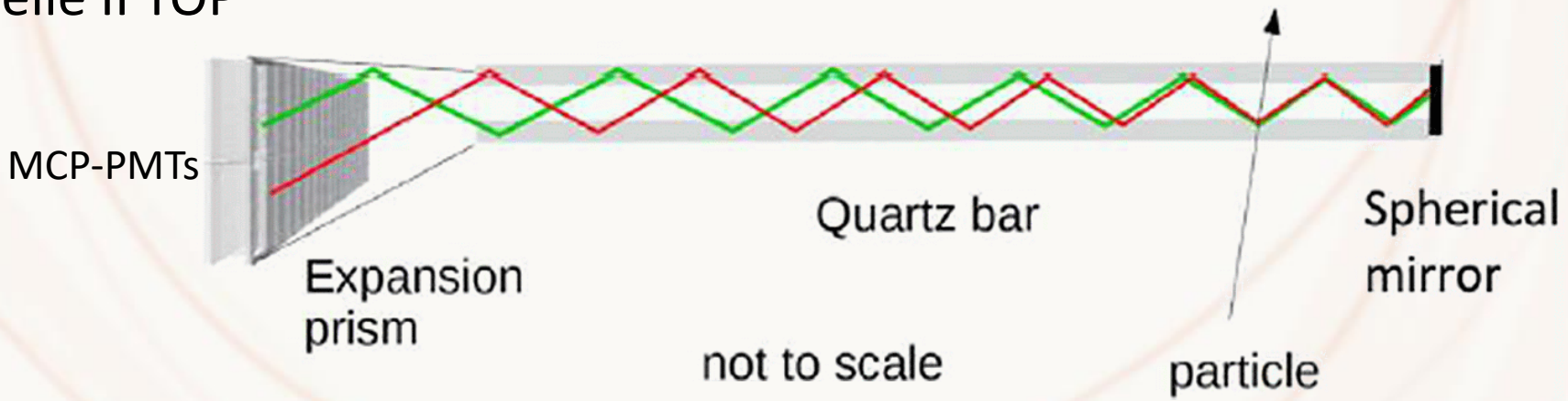




Four decommissioned BaBar DIRC modules, coupled to upgraded optics and readout,

→ Talk by Justin Stevens

Belle II TOP



→ Talk by Marko Staric

Poster by Ryotaro Komori, Shanette De La Motte

Challenges

The RICH detectors in the current experiments are working fine, but some concerns remain for the operation at higher luminosity, background and radiation and for the environment.

- Photocathode lifetime
  - e.g. ALICE HMPID CsI photocathode ageing NIM A553 (2005) 187, NIM A574 (2007) 28
  - e.g. TOP MCP-PMT photocathode degradation NIM A876 (2017) 93

➢ The lifetime is dictated by the accumulated output charge.
It can also be extended by lowering the detector gain (while increasing the readout gain instead).

- Occupancy
  - e.g. LHCb RICH → Upgraded for Run 3
- Alternative to C_4F_{10} and CF_4 gas radiator
  - They have a large Global Warming Potential.

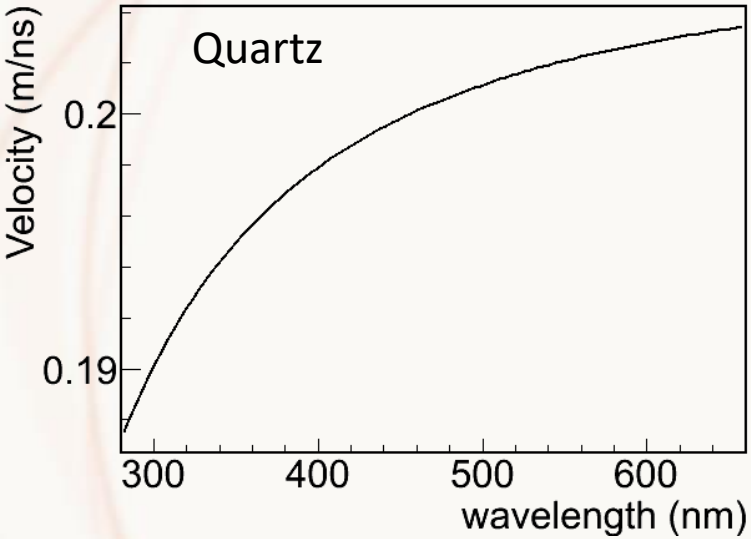
Challenges

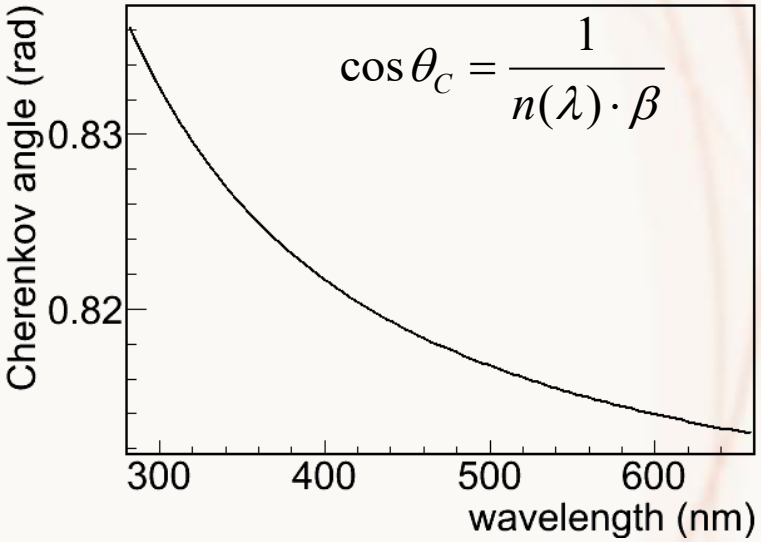
There is also some room for performance improvement.

- Chromatic dispersion
  - The photon velocity in a material varies with the wavelength.
- Polarization of Cherenkov photons
  - May be necessary to fully understand the detector response, or fully exploit the characteristics of Cherenkov radiation (timing, N_{photon}, angle, polarization) to achieve a better PID performance.

Focusing mirror to correct chromatic dispersion

Belle II TOP counter

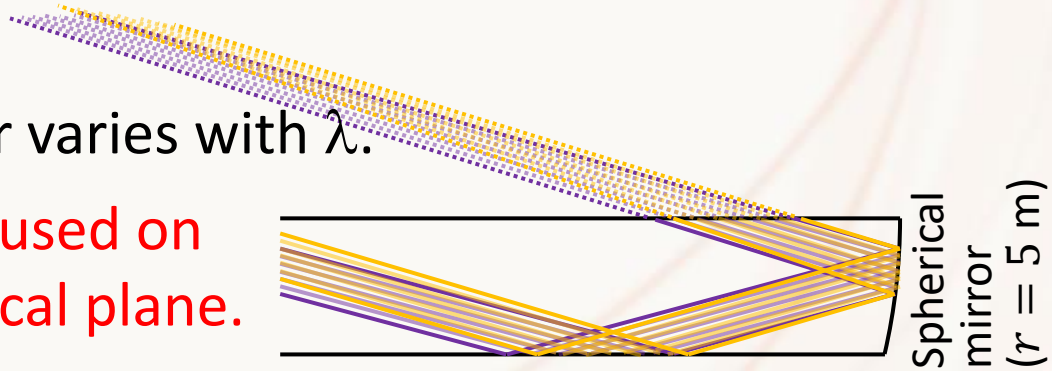




Incident angle to the mirror varies with λ.

→ Light of different λ is focused on different points on the focal plane.

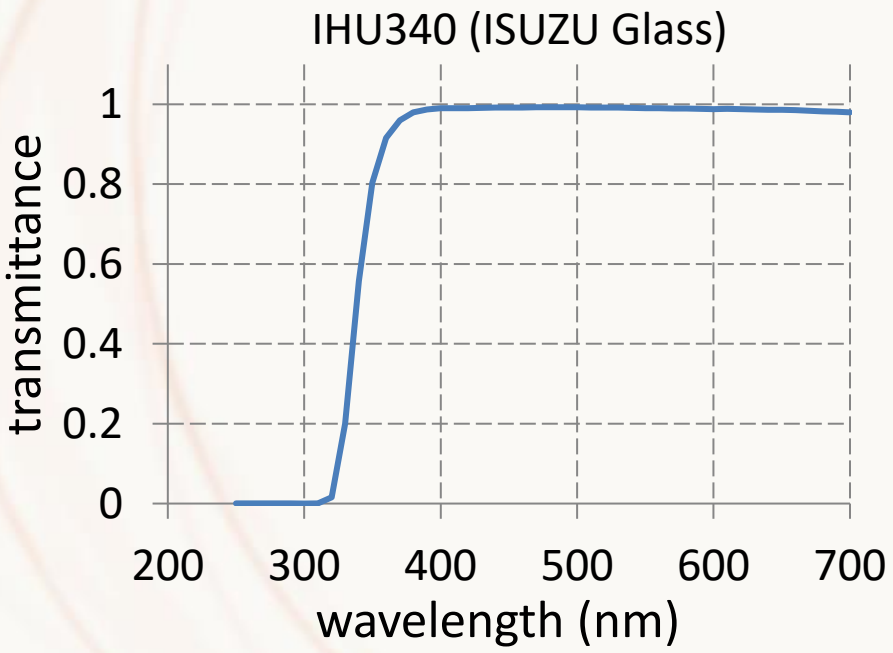
→ Correction of the chromatic error.

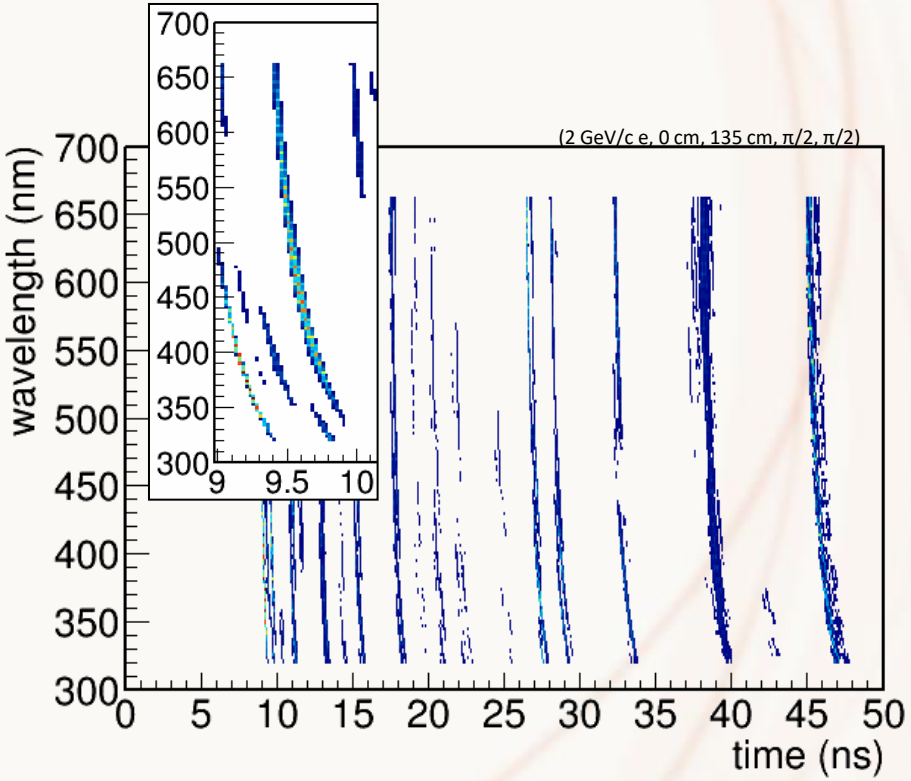


Wavelength cut filter to reduce chromatic dispersion

Belle II TOP counter

- Cut light below 340 nm with a filter in front of the PMT.



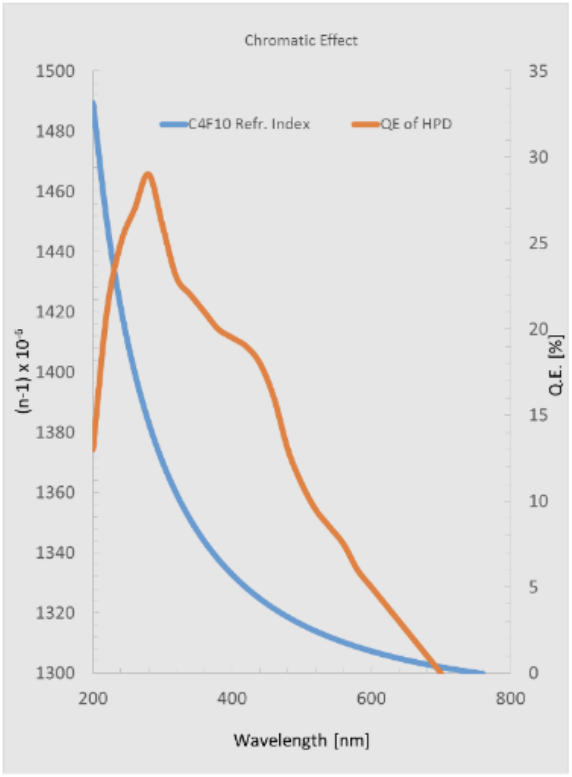


Higher QE at longer λ to reduce chromatic dispersion

LHCb RICH

HPD

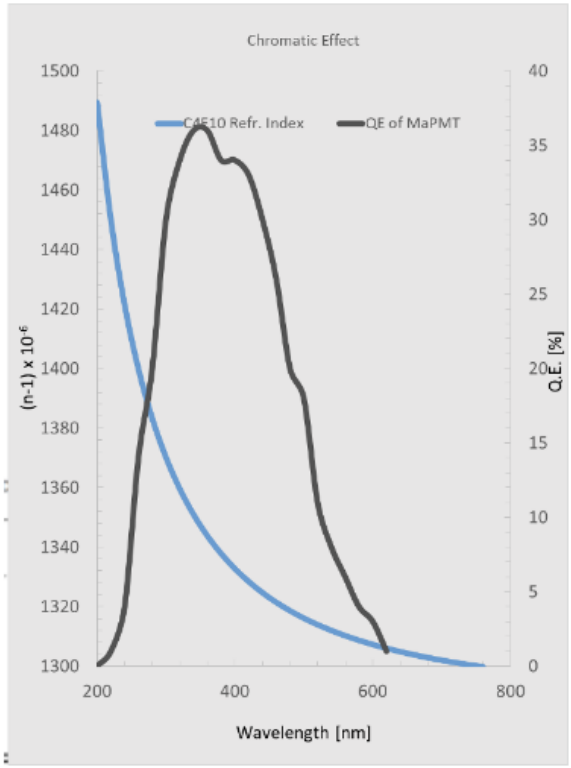
Run 1 and 2



$$\sigma^{\mathrm{RICH1}}_{\mathrm{chromatic}} = 0.84 \text{ mrad}$$
$$\sigma^{\mathrm{RICH2}}_{\mathrm{chromatic}} = 0.48 \text{ mrad}$$

MaPMT

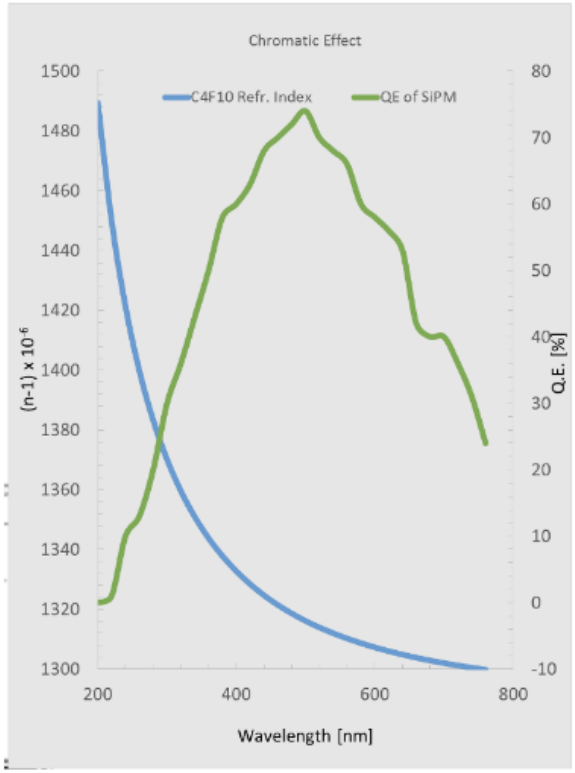
Run 3 and 4



$$\sigma^{\mathrm{RICH1}}_{\mathrm{chromatic}} = 0.52 \text{ mrad}$$
$$\sigma^{\mathrm{RICH2}}_{\mathrm{chromatic}} = 0.34 \text{ mrad}$$

SiPM

Run 5 candidate

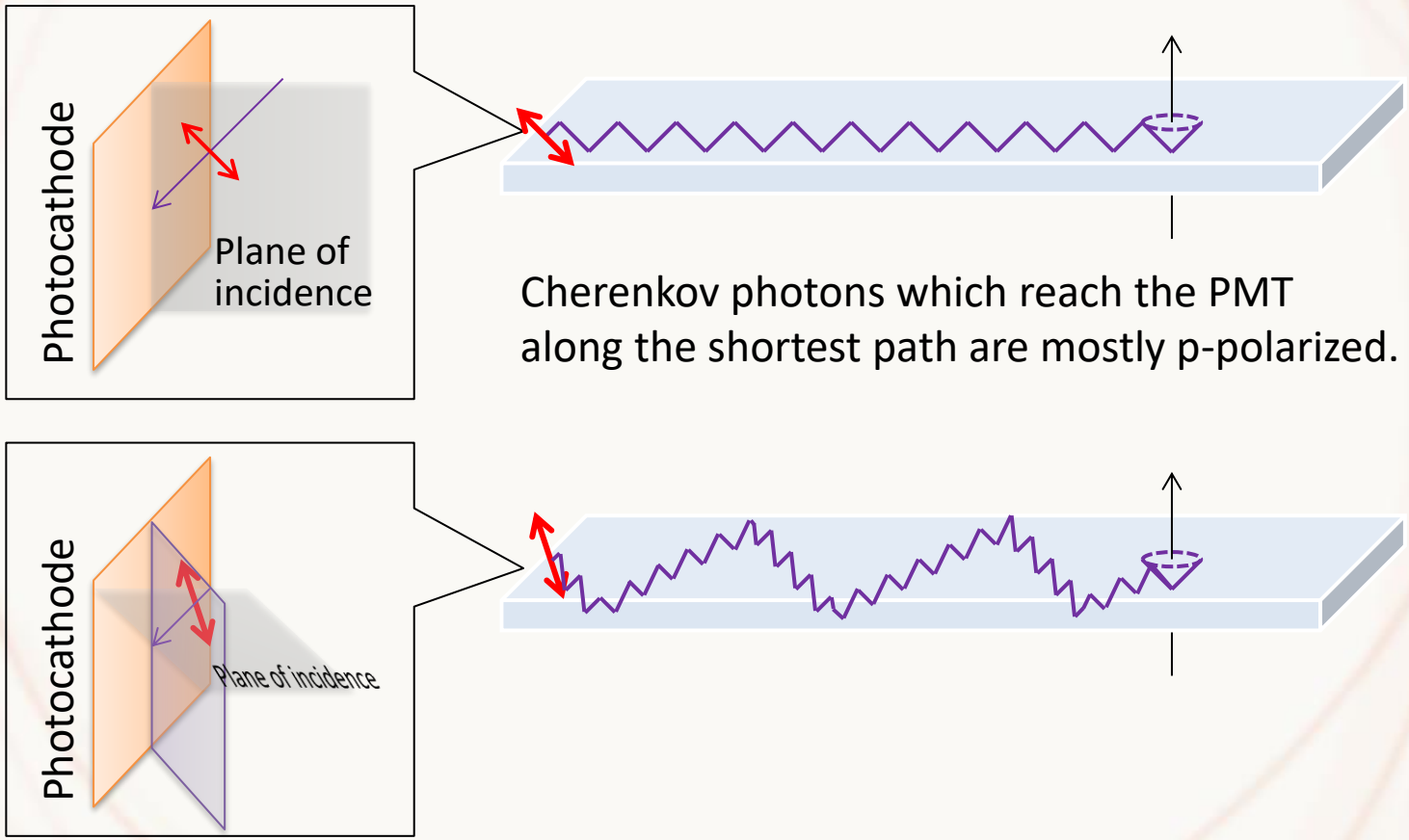


$$\sigma^{\mathrm{RICH1}}_{\mathrm{chromatic}} = 0.11 \text{ mrad}$$
$$\sigma^{\mathrm{RICH2}}_{\mathrm{chromatic}} = 0.10 \text{ mrad}$$

G. Cavallero, “RICH detectors at LHCb”

Polarization of Cherenkov photons

Belle II TOP counter

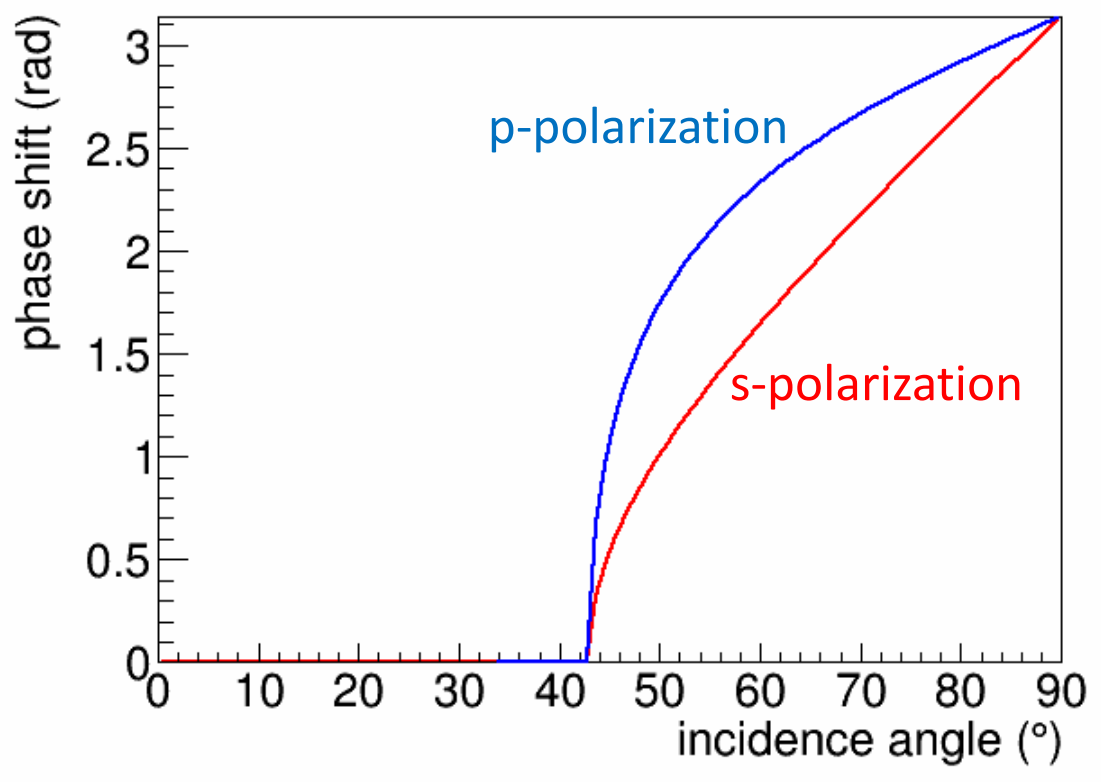


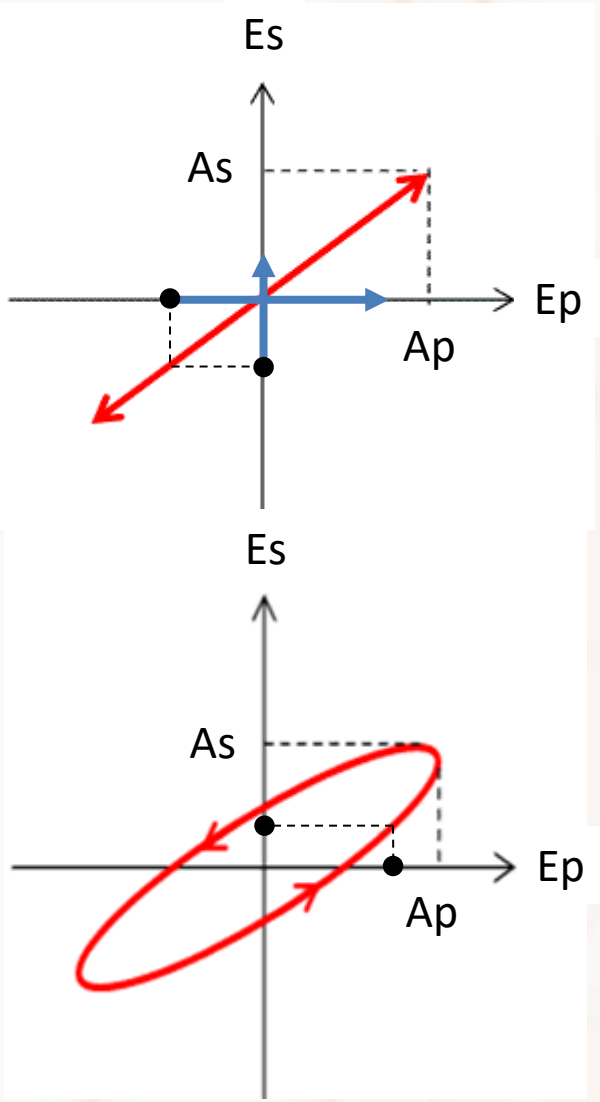
The polarization of the Cherenkov photon varies depending on the photon incident angle to the PMT, or the photon path, or TOP.

Phase shift at reflection

Fresnel coefficient:

$$\frac{E_R}{E_I} = r = |r| \exp(i\delta_r)$$

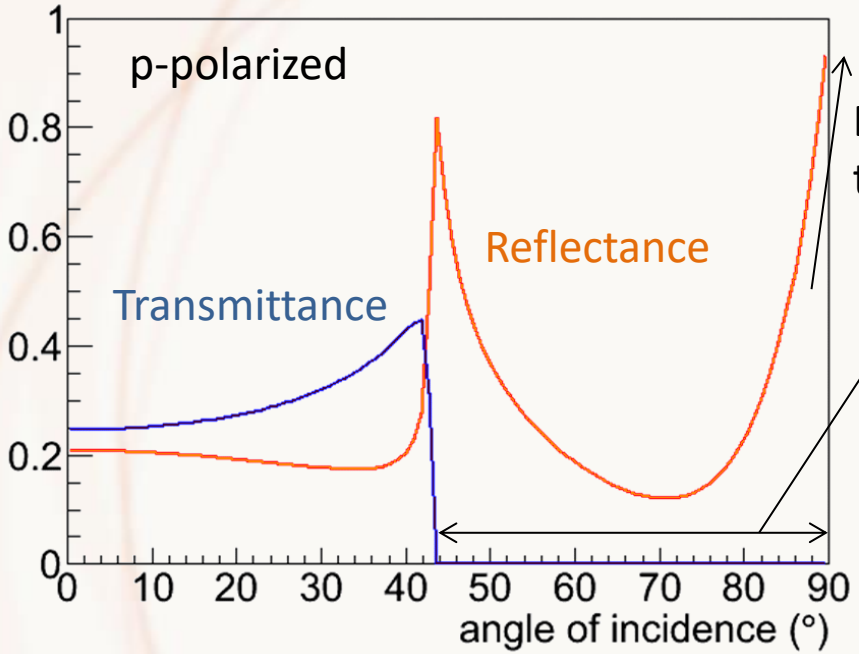




Linear polarization → Elliptical polarization

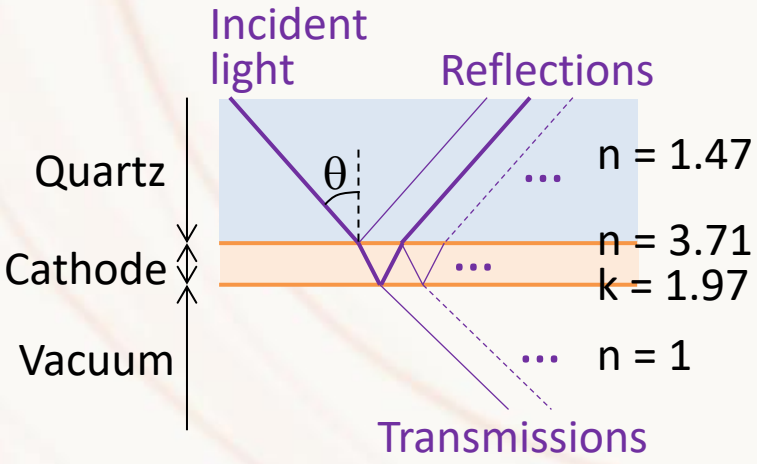
Angle/polarization dependence of QE

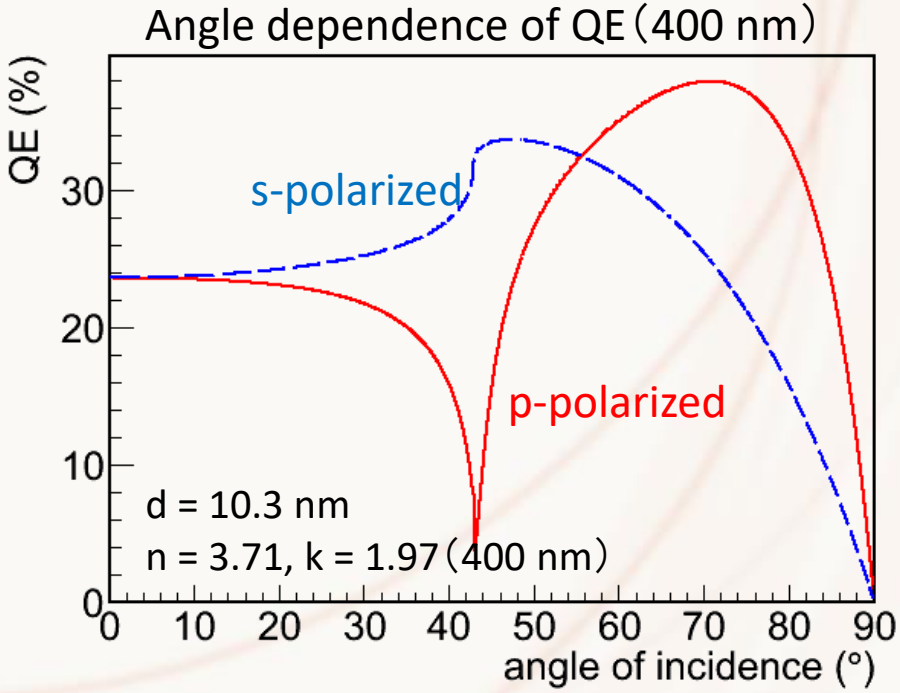
K. Matsuoka, Prog. Theor. Exp. Phys. 2018, 123H01



Dominated by the reflection at the quartz-cathode surface

Total reflection at the cathode-vacuum surface



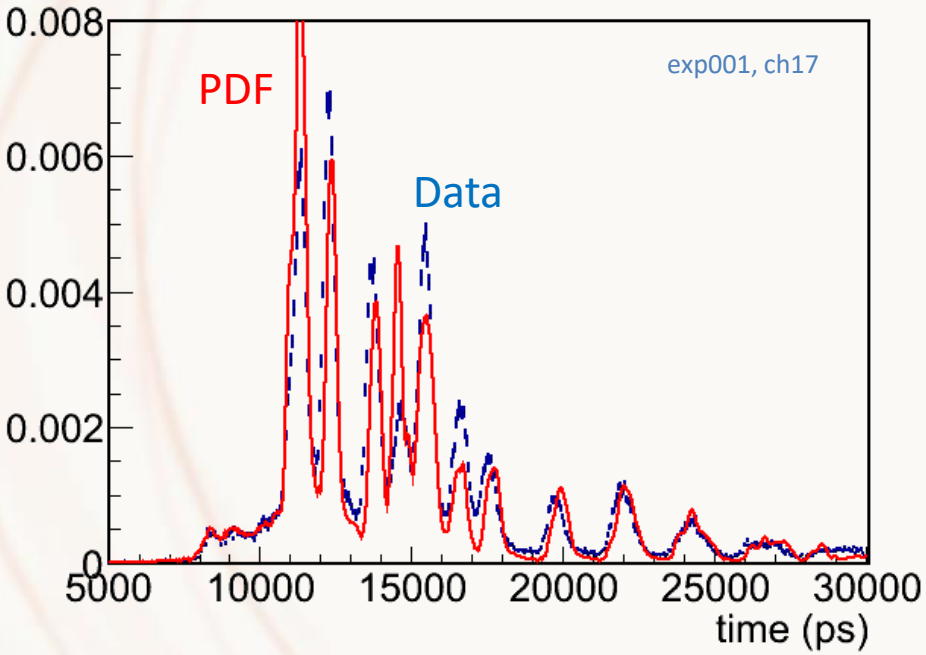


Angle/polarization dependence for TOP

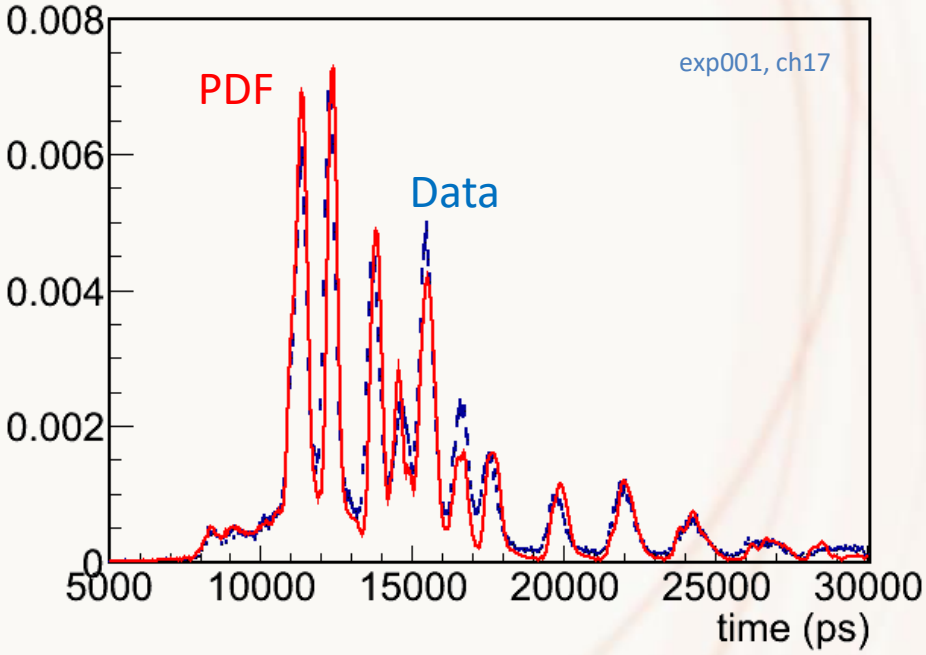
Beam test result of Belle II TOP counter at LEPS (no B-field)

PoS(TIPP2014)093

PDF without angle/polarization dependence



PDF with angle/polarization dependence



In a B-field, the Faraday effect should be considered.

Summary

- Cherenkov detectors have evolved since 1980's to meet the requirements of various experiments.
  - Counter, Water Cherenkov, RICH, DIRC, TOP, …
- "Cherenkov ring imaging" detectors provide excellent PID.
- Those currently used in experiments have been well designed and optimized for each experiment in terms of the radiator, optics, photodetector.
  - Important to transfer the expertise and knowledge to the next generation.
- Let's hear about their excellent work in the subsequent talks.