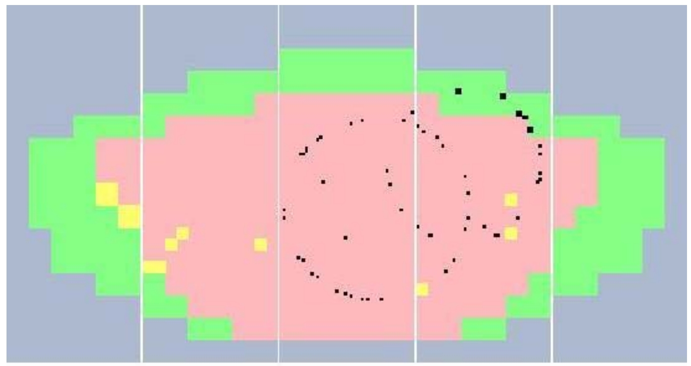
“Detectors – the Eyes of Physicists” Selected Topics on Detectors and Applications, 23 September – 2 October 2019 | DESY, Zeuthen



Recent advances in particle identification with Cherenkov and transition radiation detectors

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

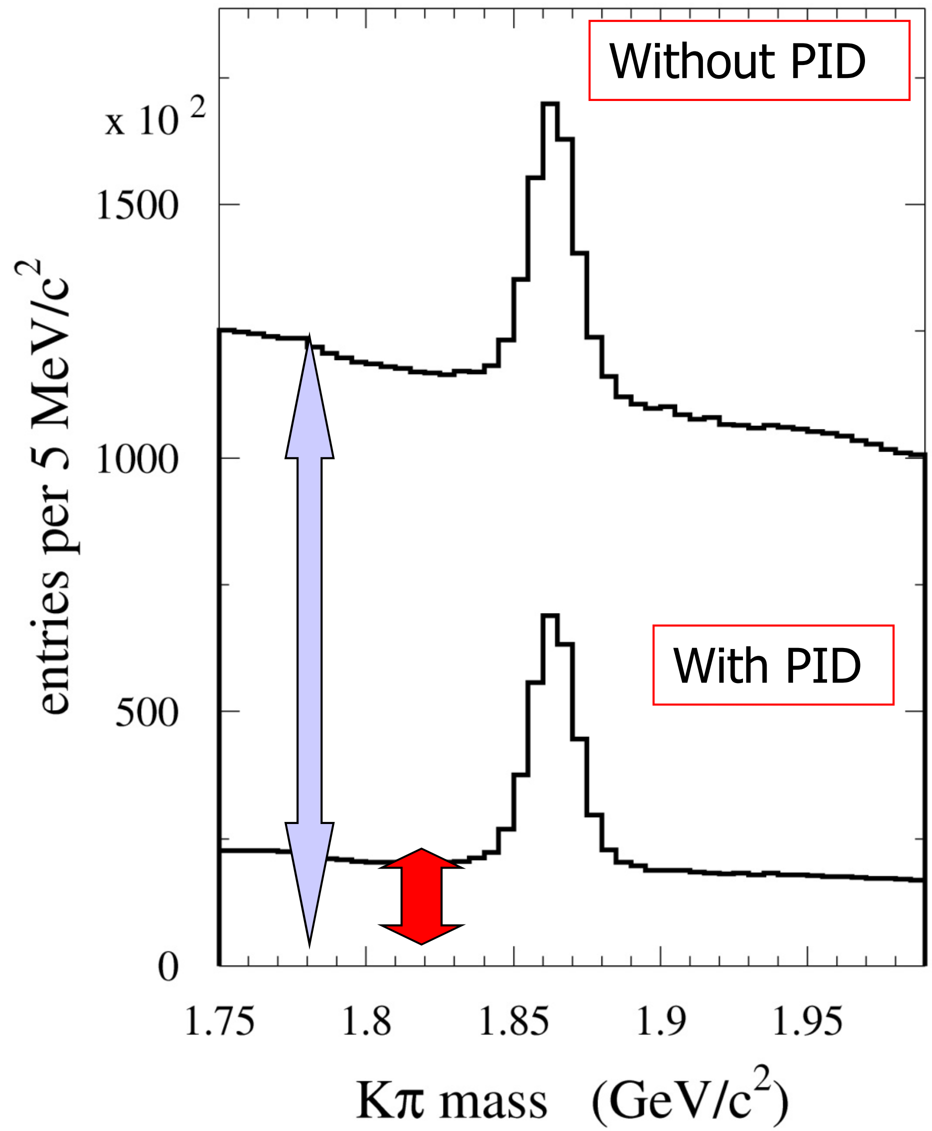
Why particle identification?

Ring Imaging CHerenkov counters

Transition radiation detectors

Summary

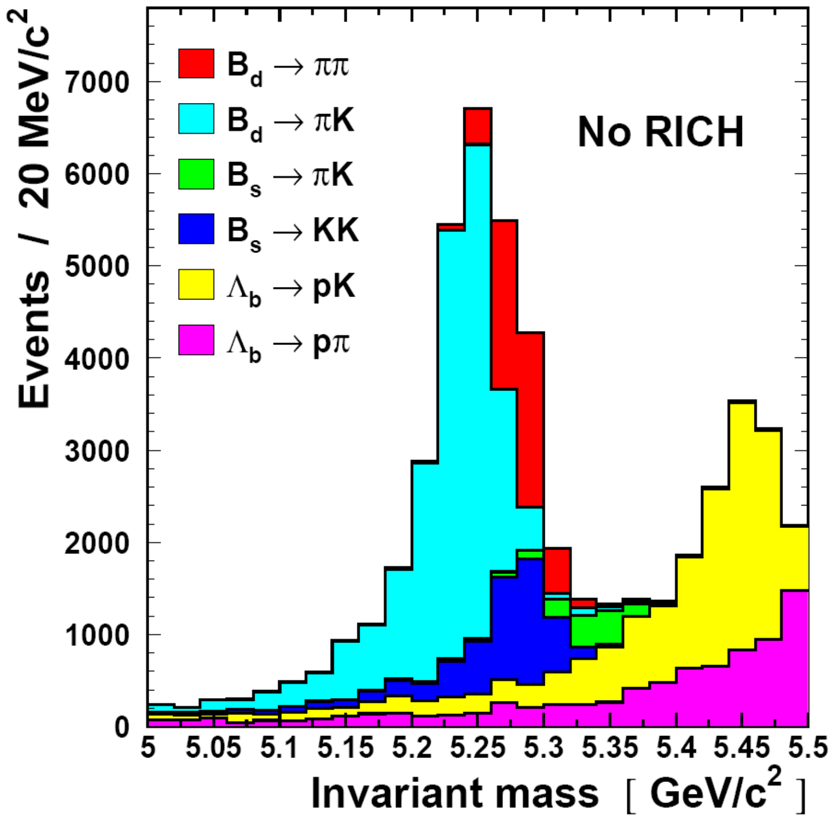
Why particle ID?



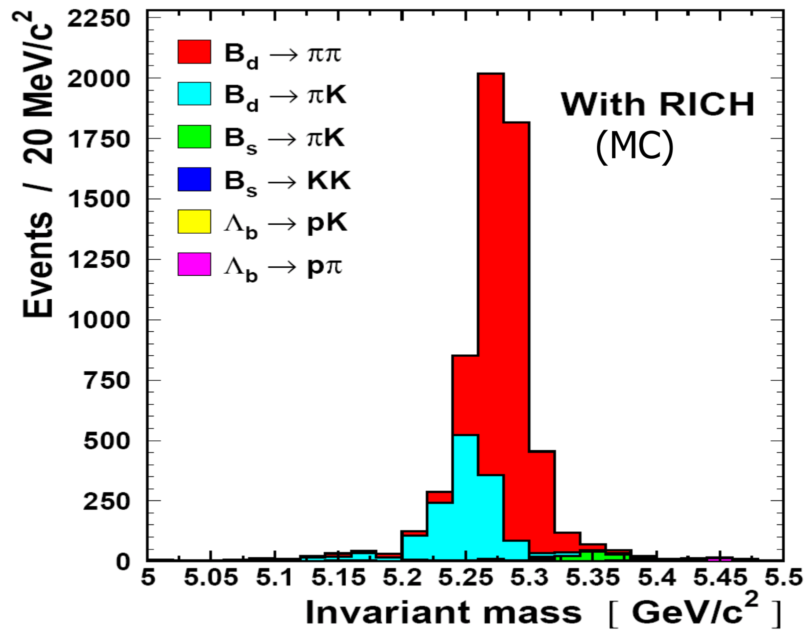
Example 1: B factory

Particle identification reduces the fraction of wrong Kπ combinations (combinatorial background) by ~5x

Why particle ID?

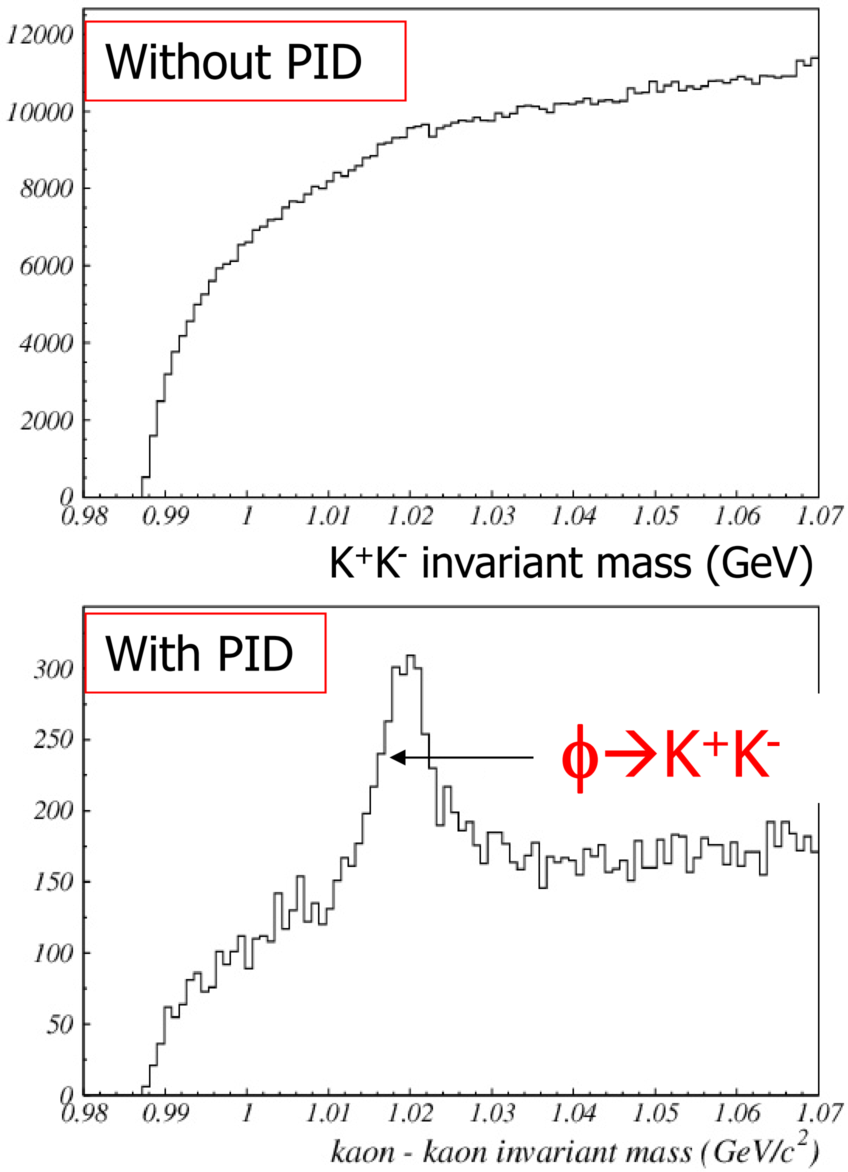


Example 2: LHCb



Need to distinguish $B_d \to \pi\pi$ from other similar topology 2-body decays and to distinguish B from anti-B using K tag.

Why particle ID?



Example 3: HERA-B

K^+K^- invariant mass.

The inclusive $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.

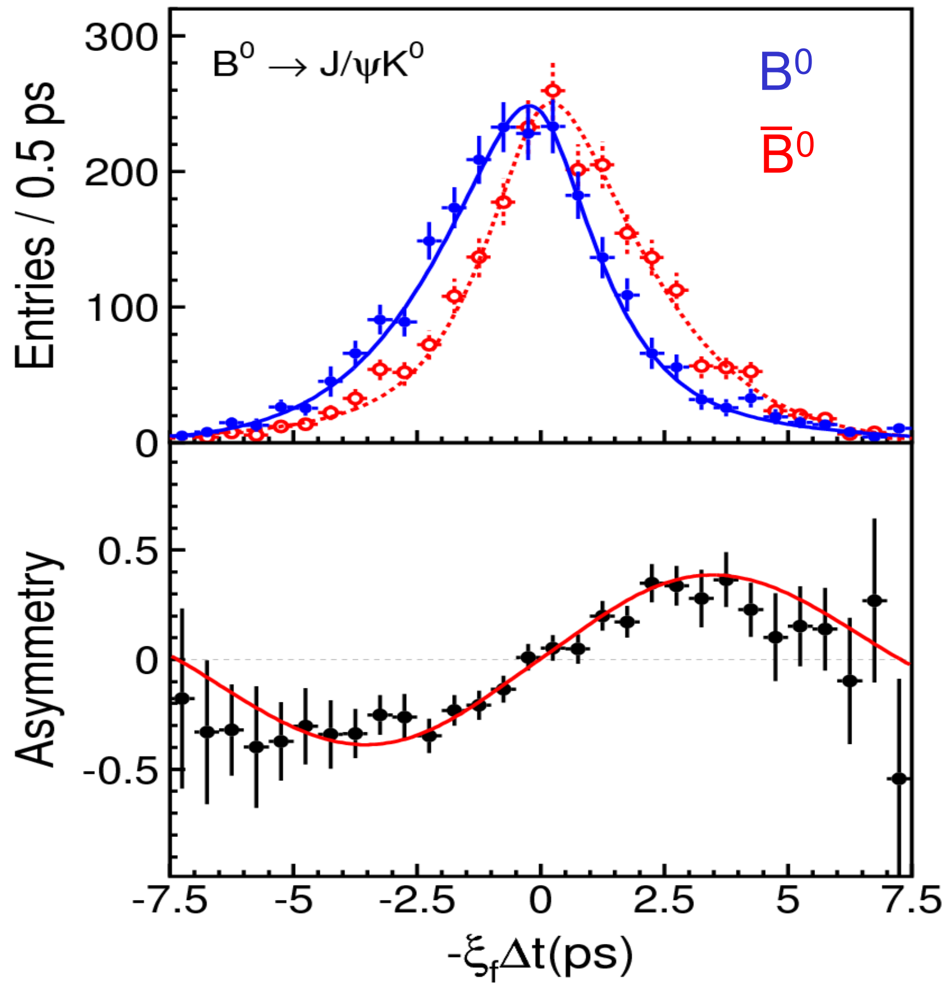
Why particle ID?

PID is also needed in:

- General purpose LHC experiments: final states with electrons and muons
- Searches for exotic states of matter (quark-gluon plasma)
- Spectroscopy and searches for exotic hadronic states
- Studies of fragmentation functions

Why particle ID?

Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.

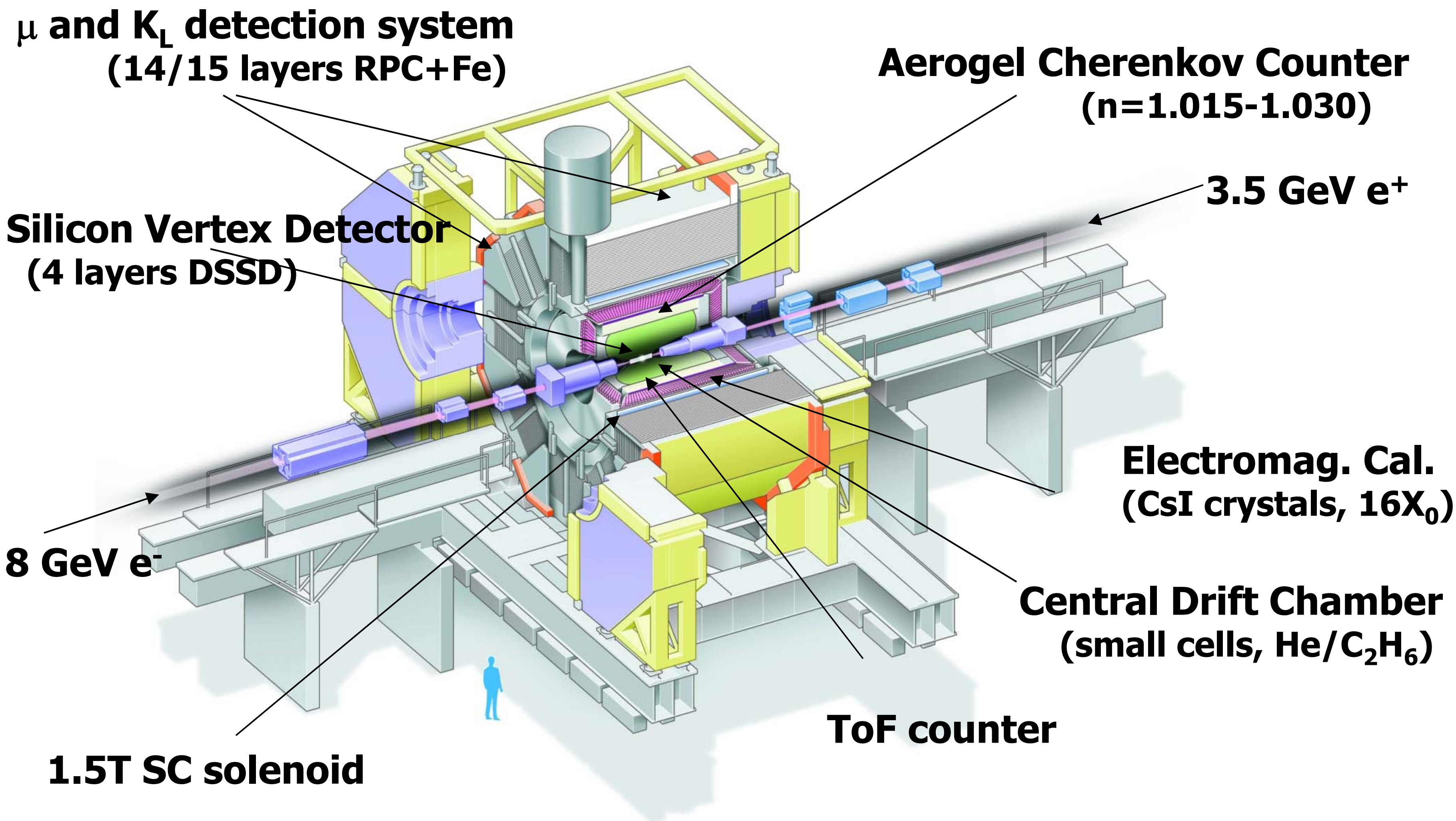


B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

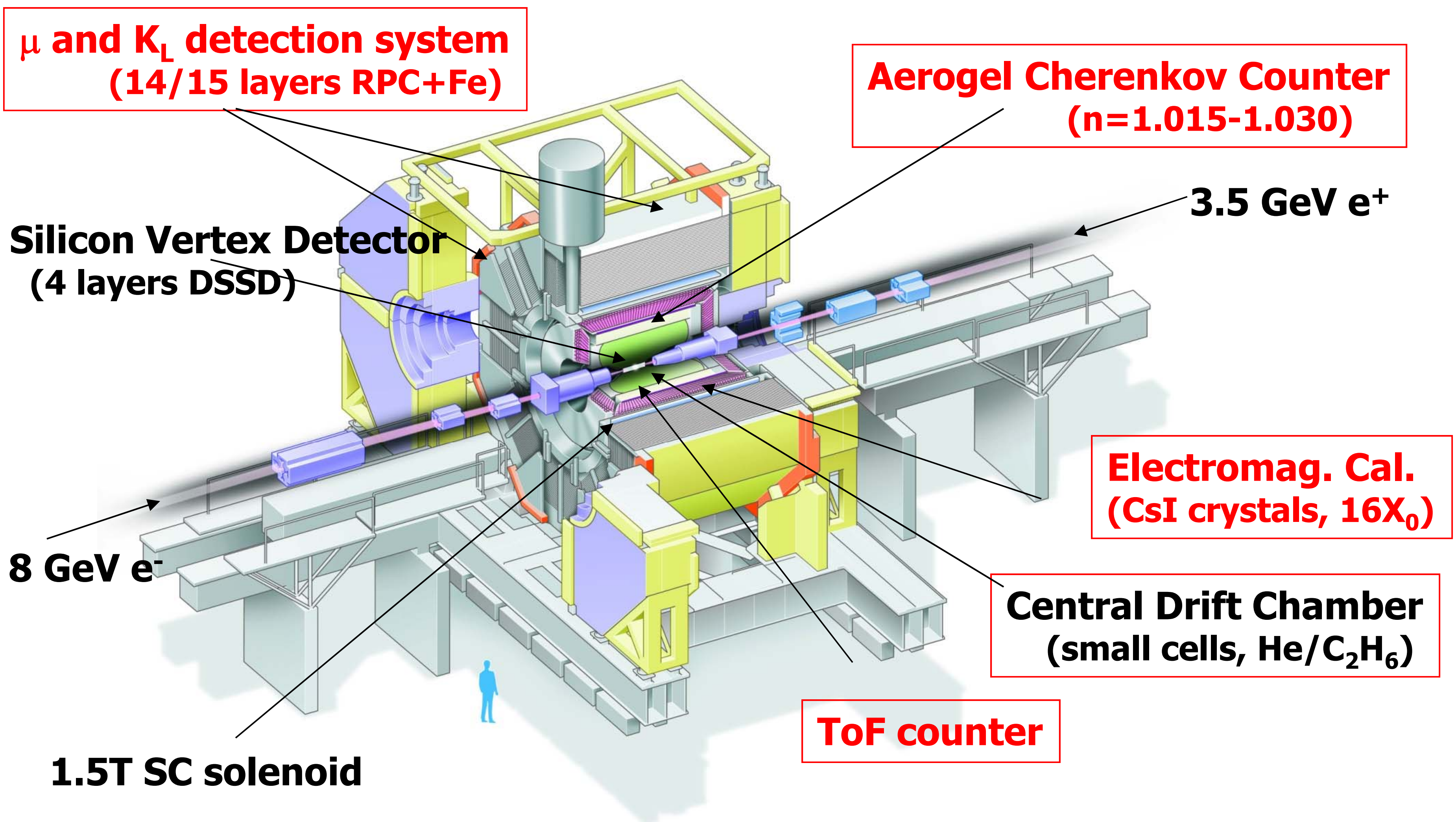
Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

→particle ID is compulsory

Example: Belle

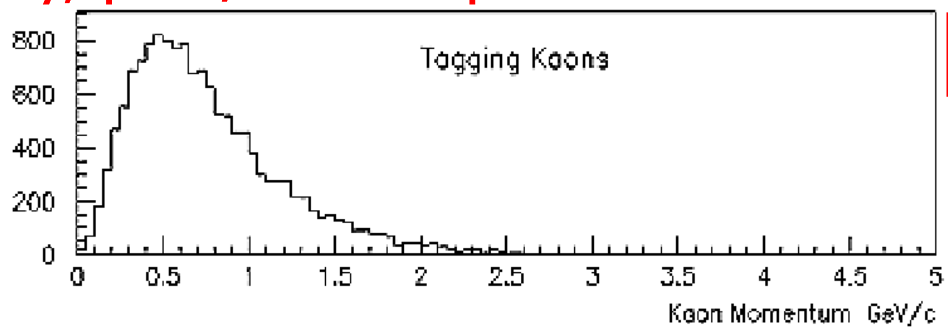


Particle identification systems in Belle



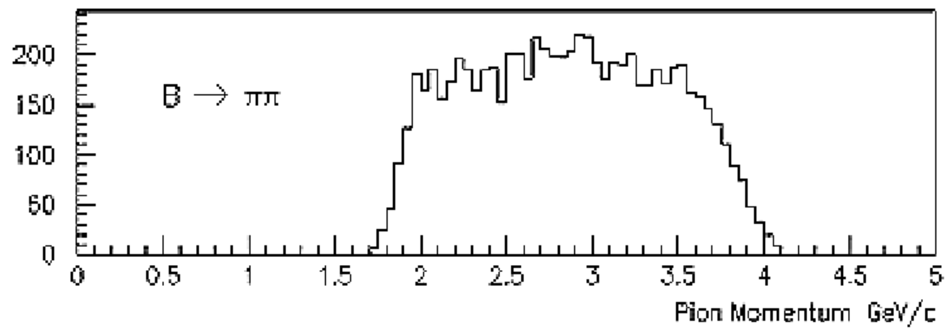
Particle identification methods depend on the requirements (physics channel, kinematics)

Example: B factory, pion/kaon separation



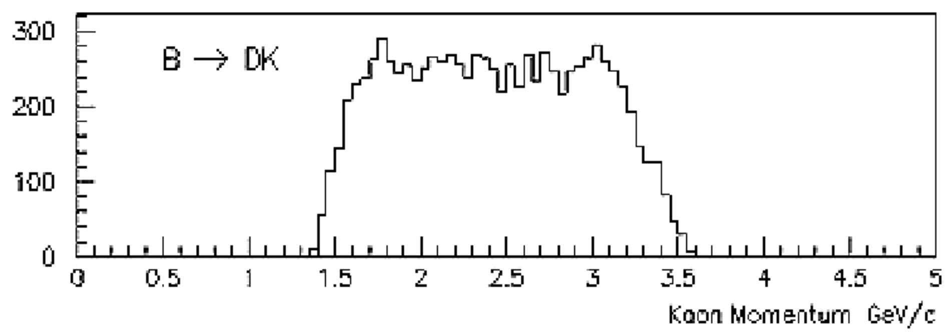
Tagging Kaons

Relatively soft, ms dominated for tracking



$B \to \pi\pi$

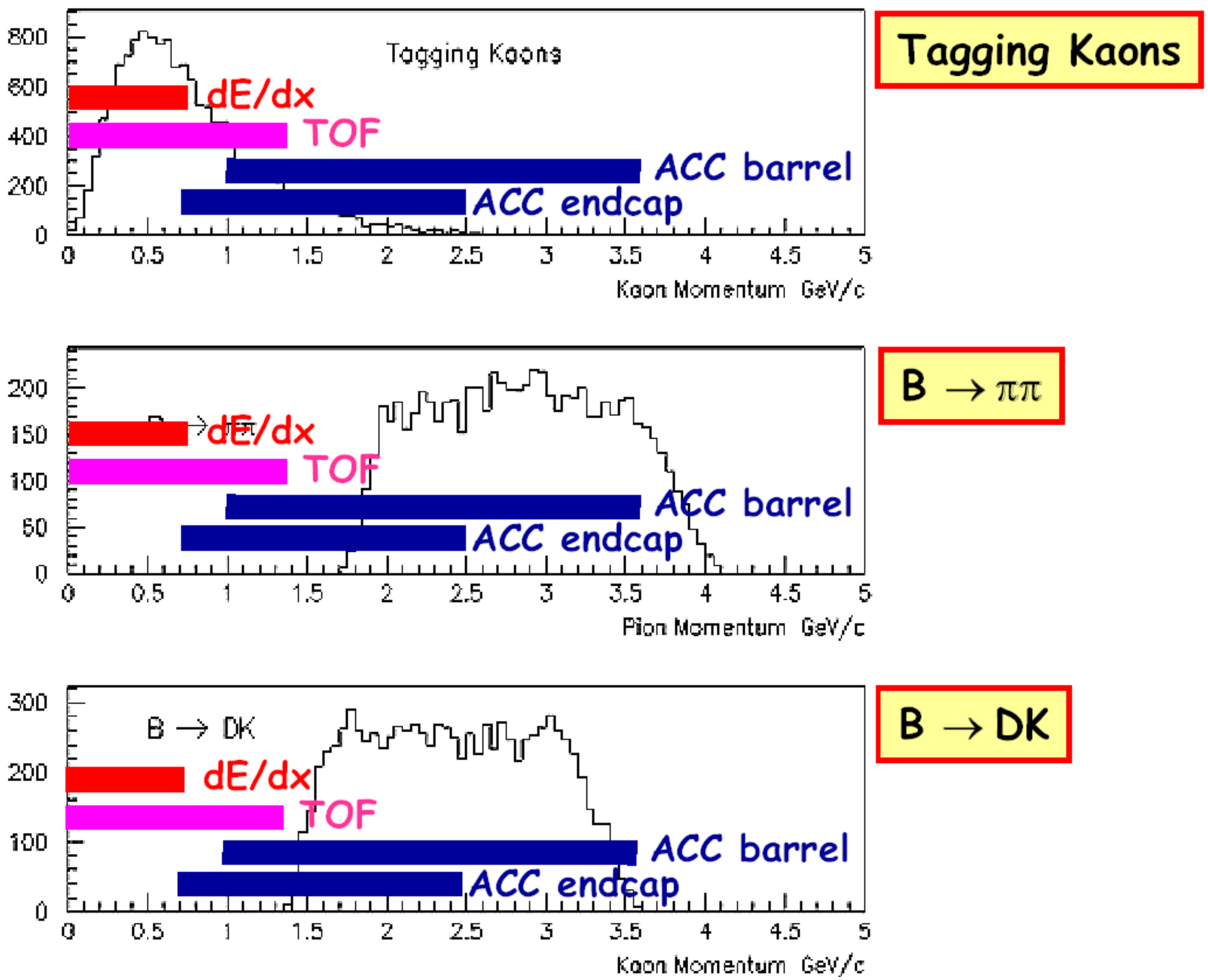
Requires dedicated PID



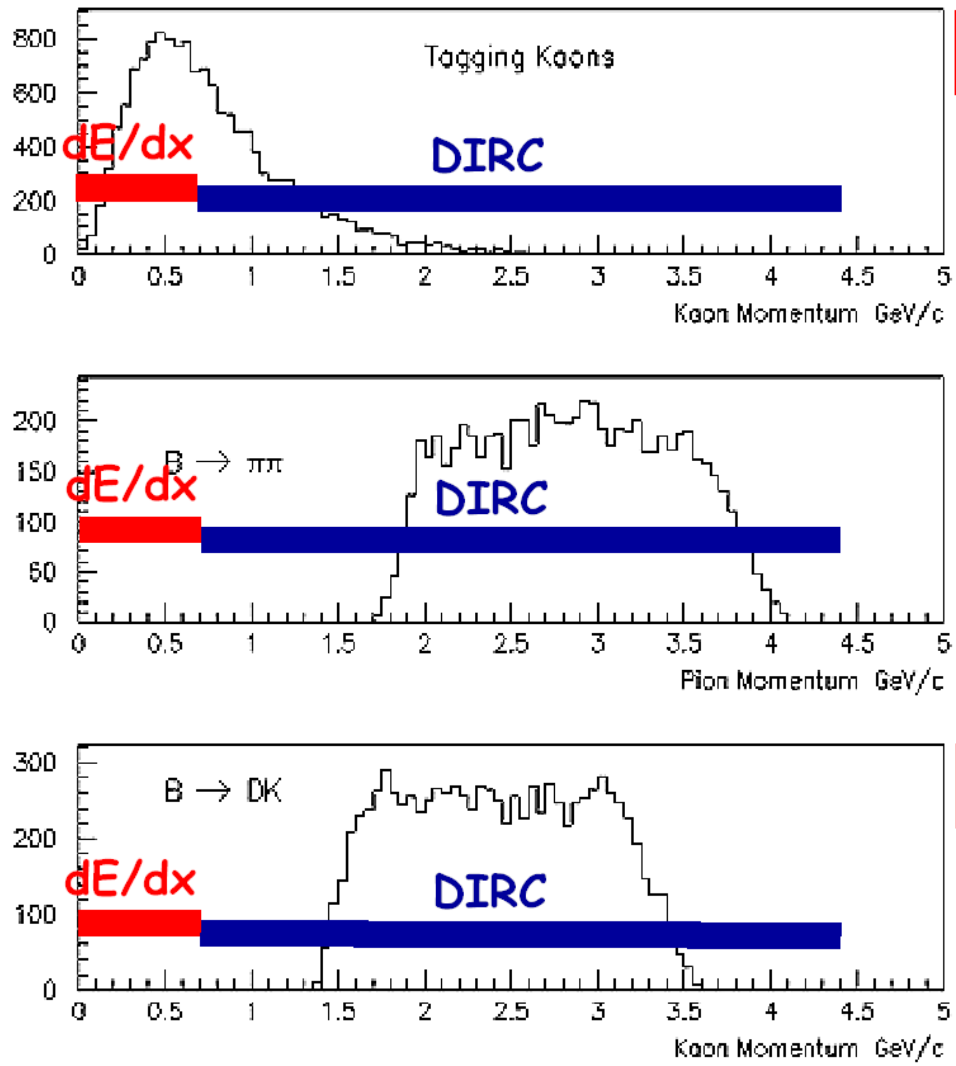
$B \to DK$

Requires dedicated PID

PID coverage of kaon/pion spectra in Belle



PID coverage of kaon/pion spectra in BaBar



Tagging Kaons

$B \to \pi\pi$

$B \to DK$

Identification of charged particles

Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters

Identification of charged particles

Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

Mainly used for the identification of hadrons.

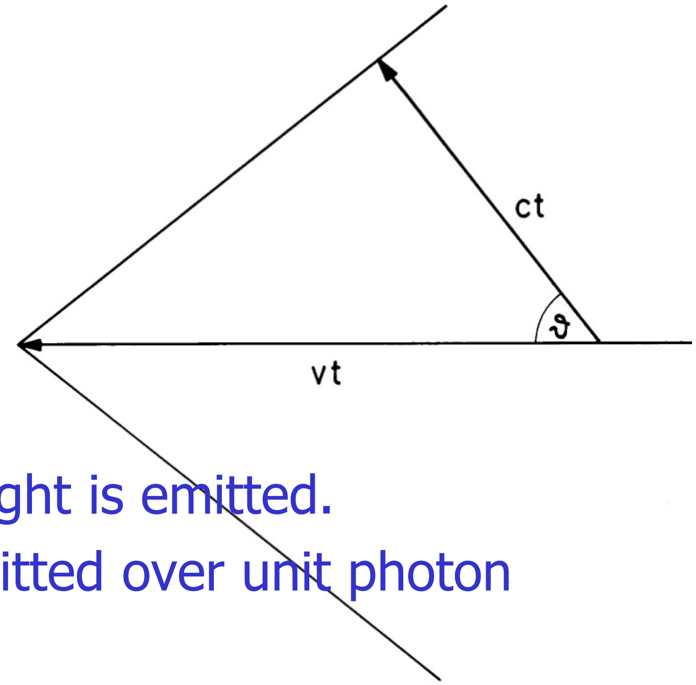
Identification through interaction: electrons and muons

- muon systems
- calorimeters

Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

$\cos\theta = c/nv = 1/\beta n$



Two cases:

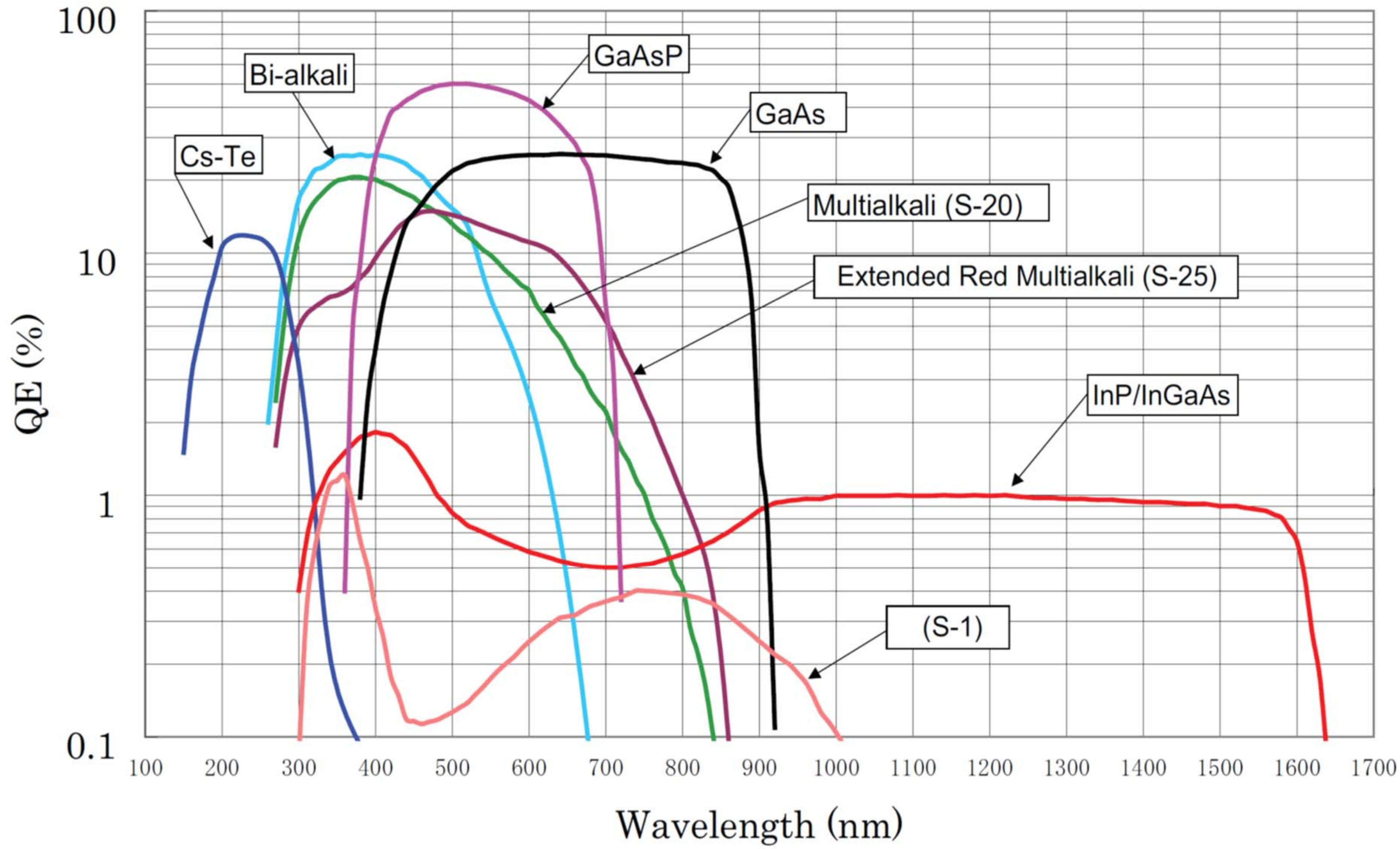
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370 (cm)^{-1} (eV)^{-1} L \sin^2\theta$$

→Few detected photons

Quantum efficiency



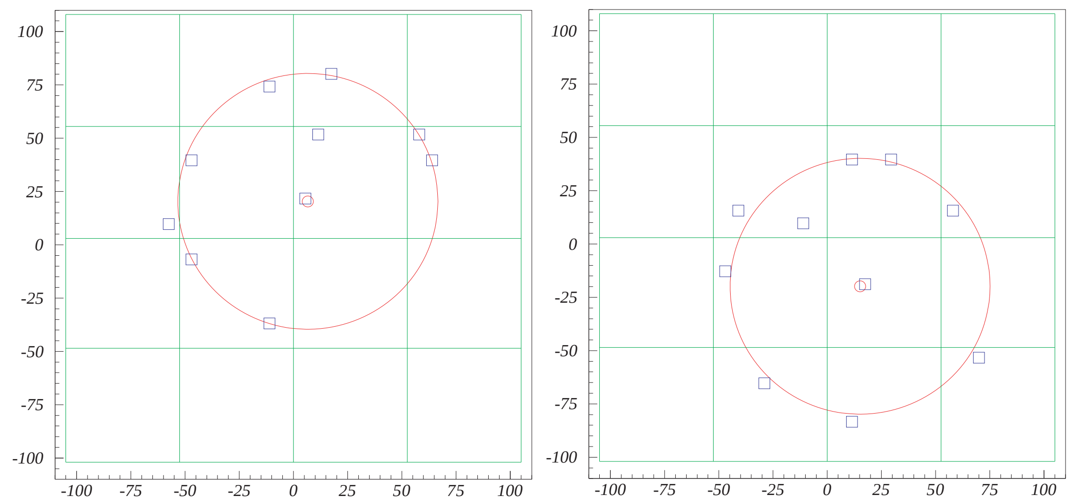
Number of detected photons

Example: in 1m of air (n=1.00027) a track with β=1 emits N=41 photons in the spectral range of visible light (ΔE ~ 2 eV).

If Čerenkov photons were detected with an average detection efficiency of ε=0.1 over this interval, N=4 photons would be measured.

Few photons detected

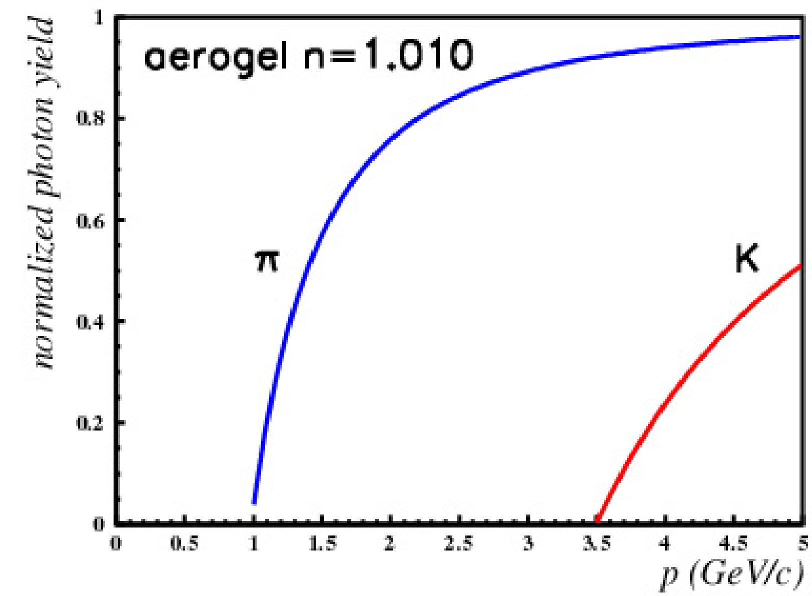
→Important to have a low noise detector



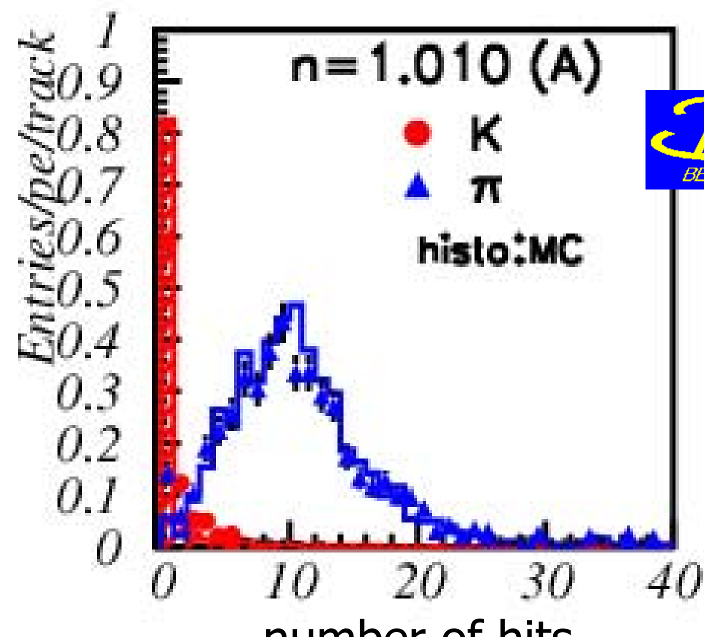
Threshold Cherenkov counter

$\cos\theta = c/nv = 1/\beta n$ → Separate K (below threshold) from π (above) by properly choosing n

Photon yield vs p



Choice of n: depends on the momentum range.

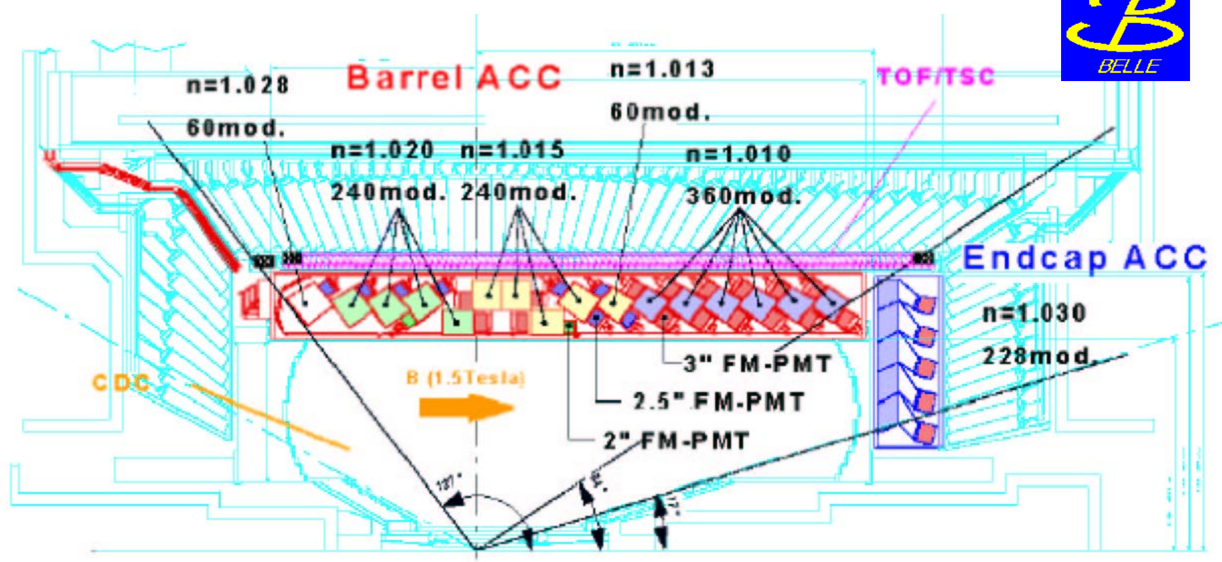


→ Good separation between pions (light) and kaons (no light) between ~1.5 GeV/c and 3.5 GeV/c

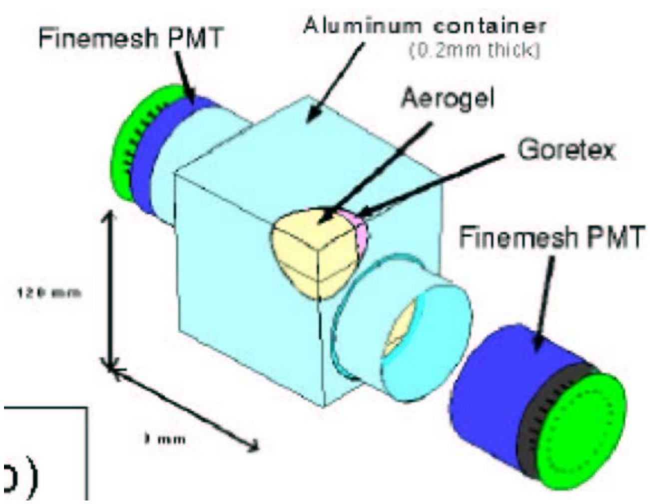
Belle: Threshold Cherenkov counter, ACC (aerogel Cherenkov counter)

K (below threshold) vs. π (above) by properly choosing n for a given kinematic region

→more energetic particles fly in the 'forward region' →lower n



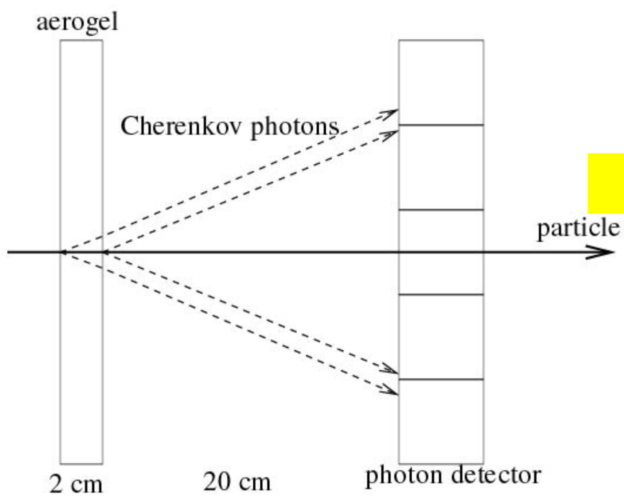
Detector unit: a block of aerogel and two fine-mesh PMTs

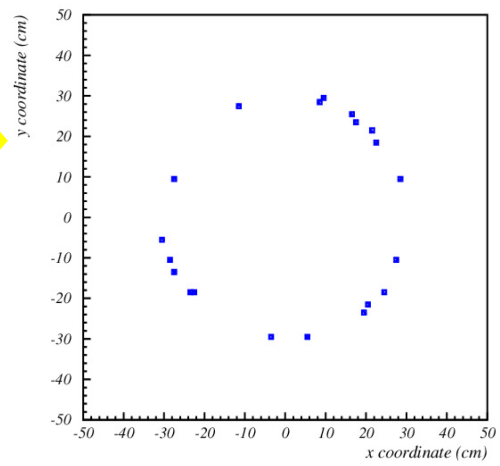


Fine-mesh PMT: works in high B fields (1.5 T)

Measuring the Cherenkov angle

Particles above threshold: measure θ



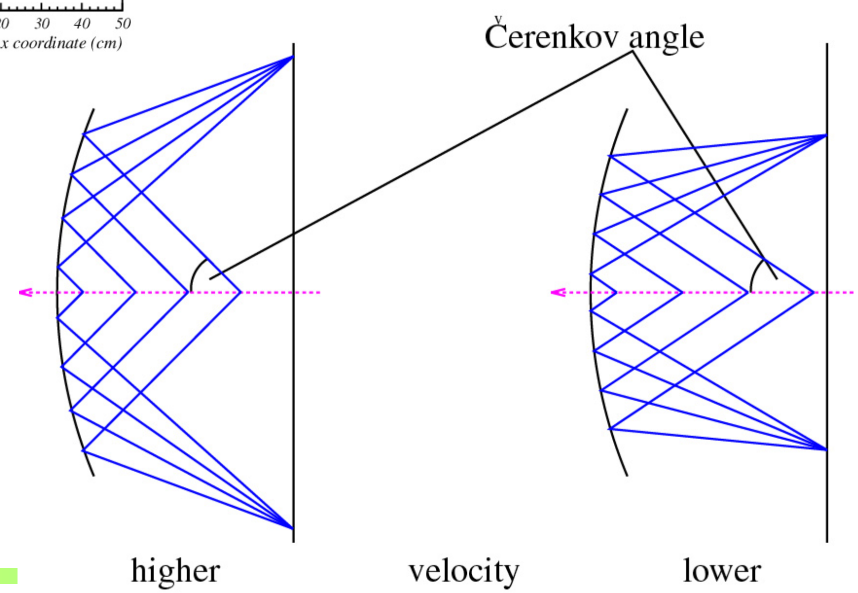


Idea: transform the direction into a coordinate → ring on the detection plane

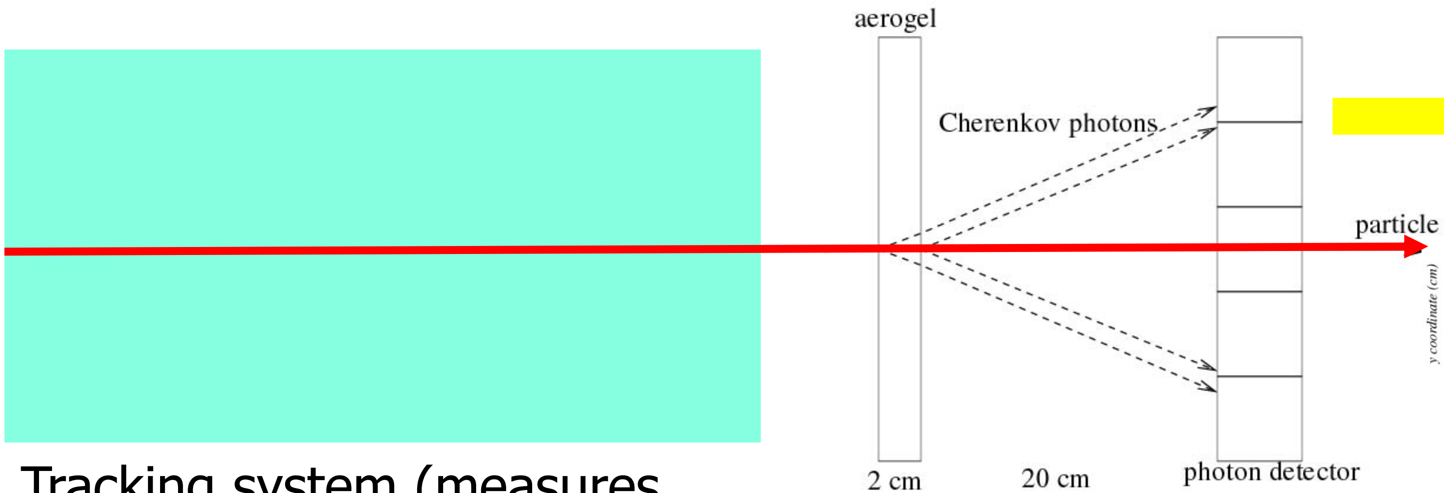
→ Ring Imaging Cherenkov (RICH) counter

Proximity focusing RICH

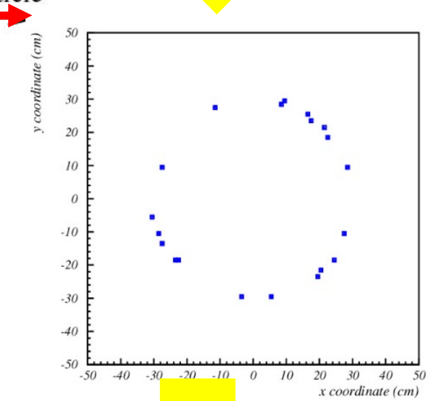
RICH with a focusing mirror

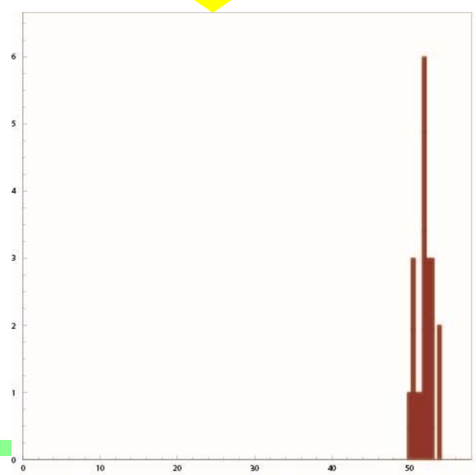


Measuring the Cherenkov angle



Tracking system (measures direction of the particle)



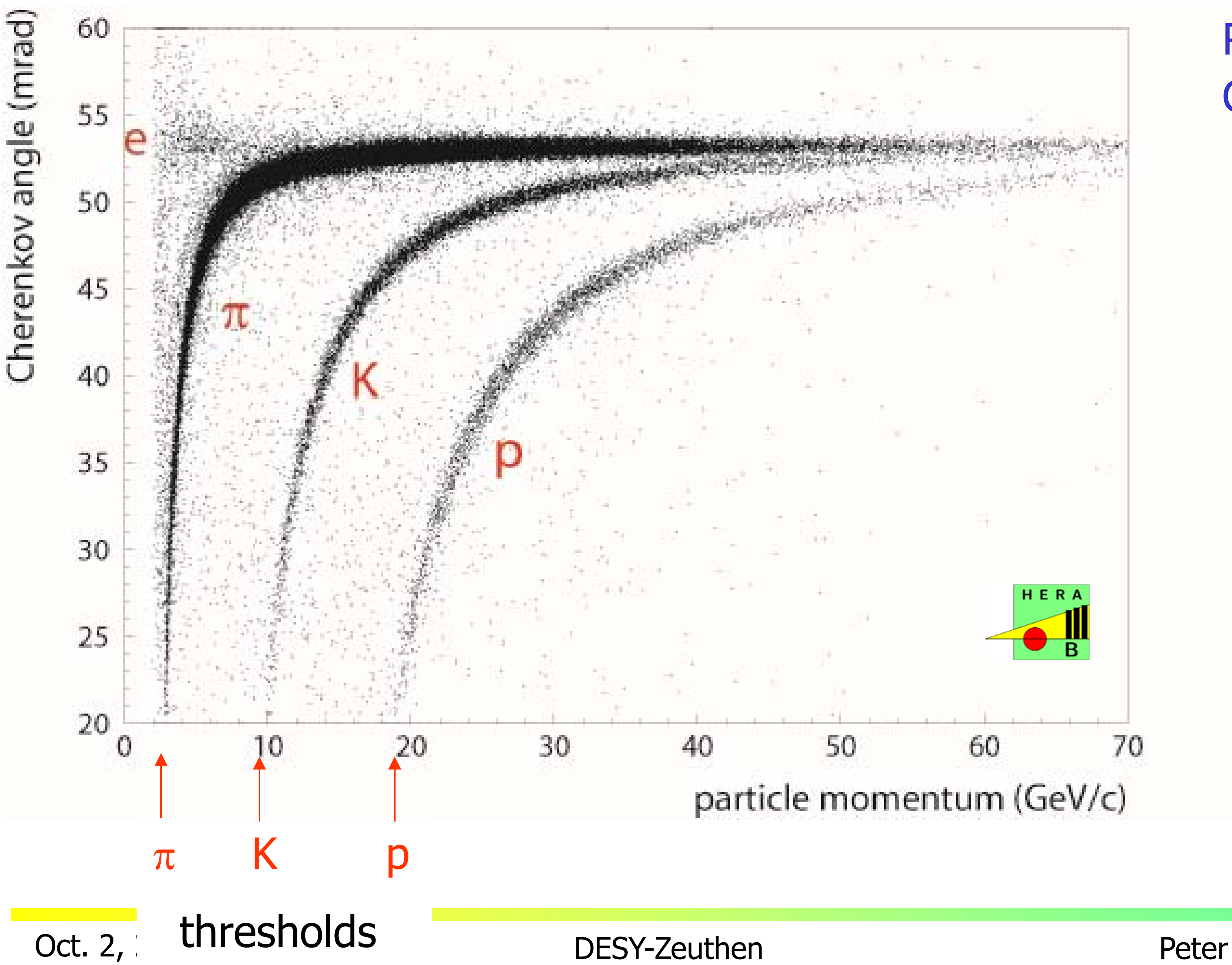


Cherekov angle distribution (mradian)

Tracking system tells us where the particle hit the radiator, and at which angle.

Use this information to calculate the Cherenkov angle for each individual detected photon

Measuring Cherenkov angle



Radiator:

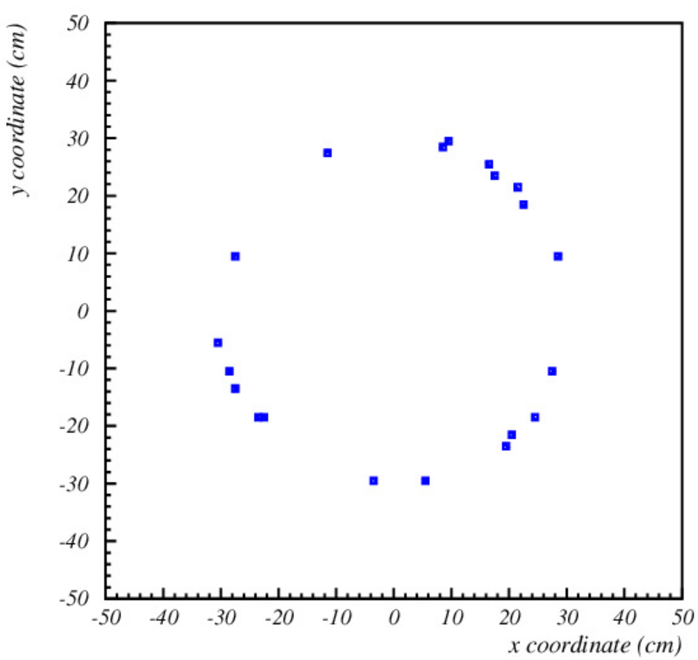
C_4F_{10} gas

Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

→ detection of single photons with

- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio (few photons!)
- over a large area (square meters)



Special requirements:

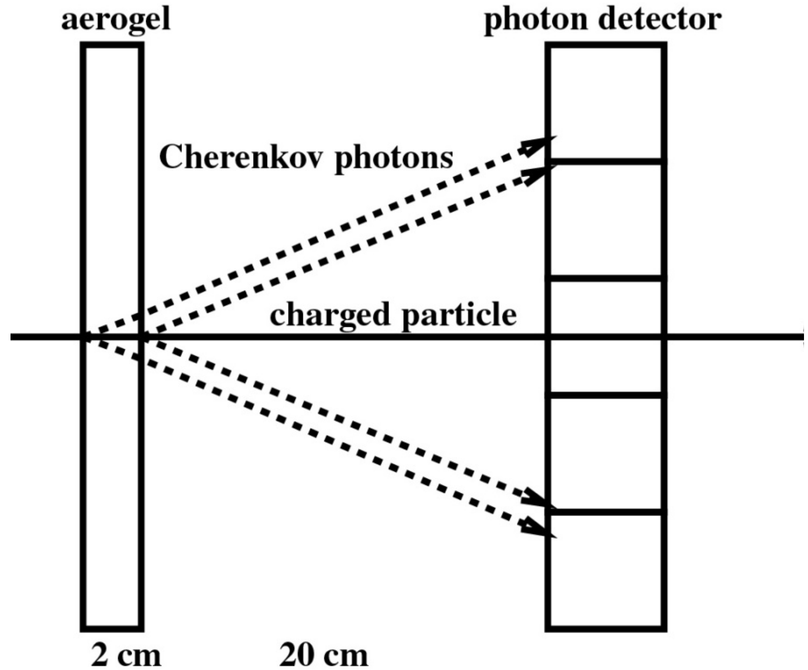
- Operation in magnetic field
- High rate capability
- Very high spatial resolution
- Excellent timing (time-of-arrival information)

Photon detector is the most crucial element of a RICH counter

Resolution of a RICH counter

Determined by:

- Photon impact point resolution (~photon detector granularity)
- Emission point uncertainty (not in a focusing RICH)
- Dispersion: $1/\beta = n(\lambda)\cos\theta$
- Errors of the optical system
- Uncertainty in track parameters



Resolution per track:

$$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

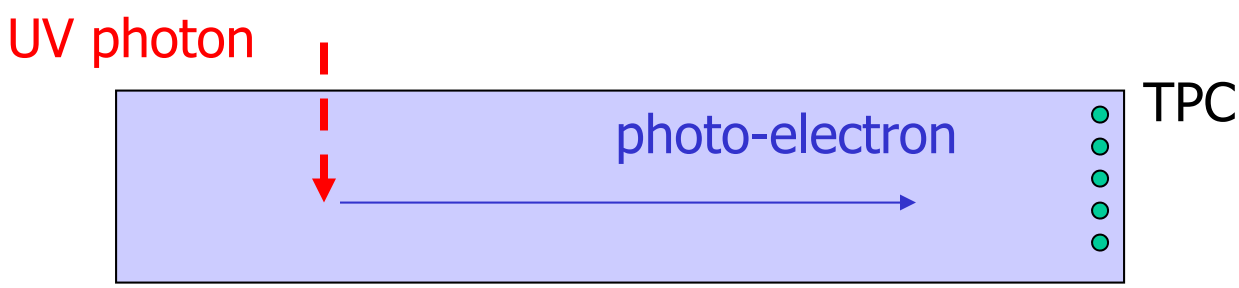
single photon resolution

# of detected photons

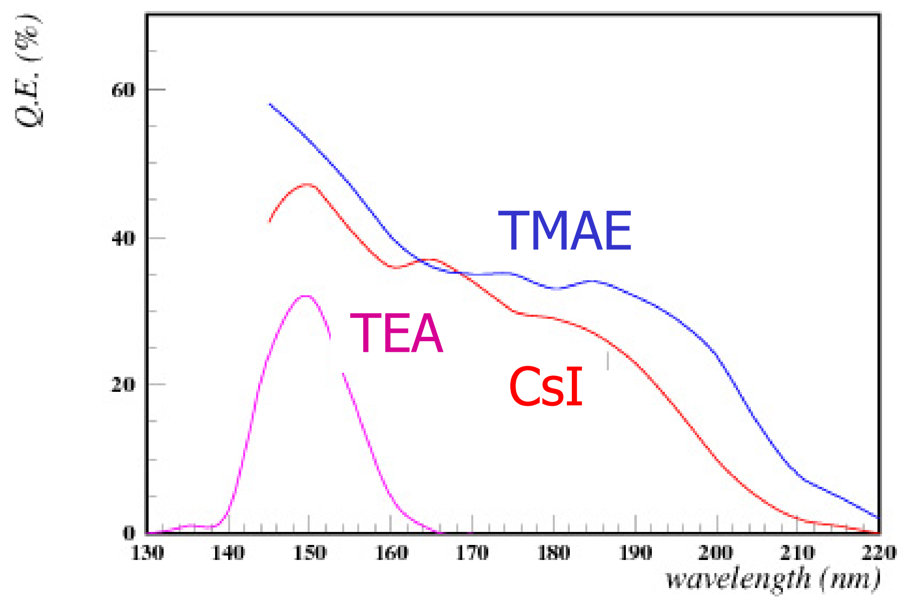
(in the case of low background)

First generation of RICH counters

DELPHI, SLD, OMEGA RICH counters: all employed wire chamber based photon detectors (UV photon → photo-electron → detection of a single electron in a TPC)

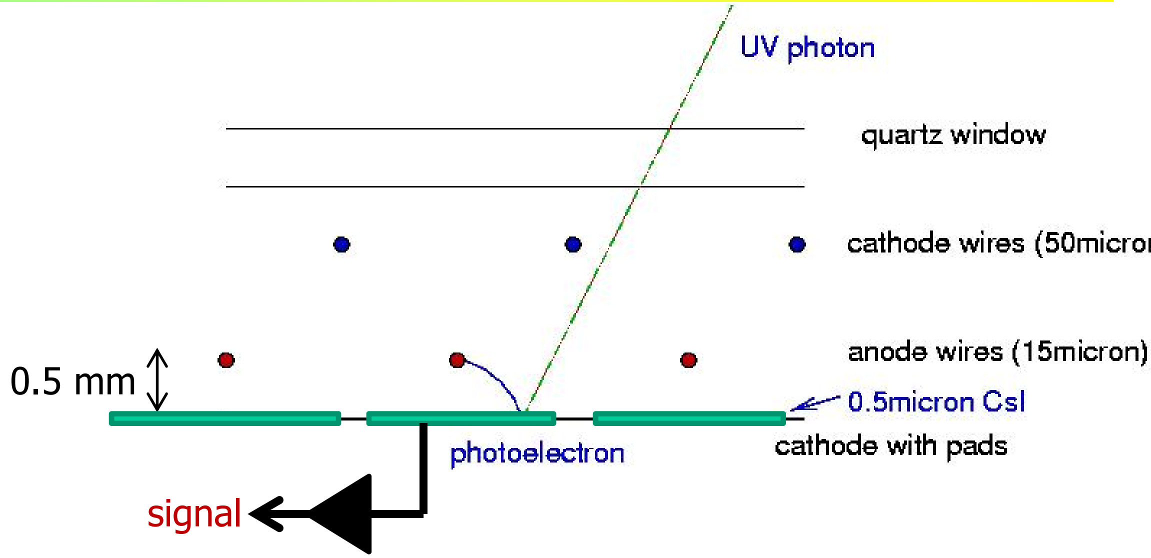


Photosensitive component:
TMAE added to the gas mixture



Fast RICH counters with wire chambers

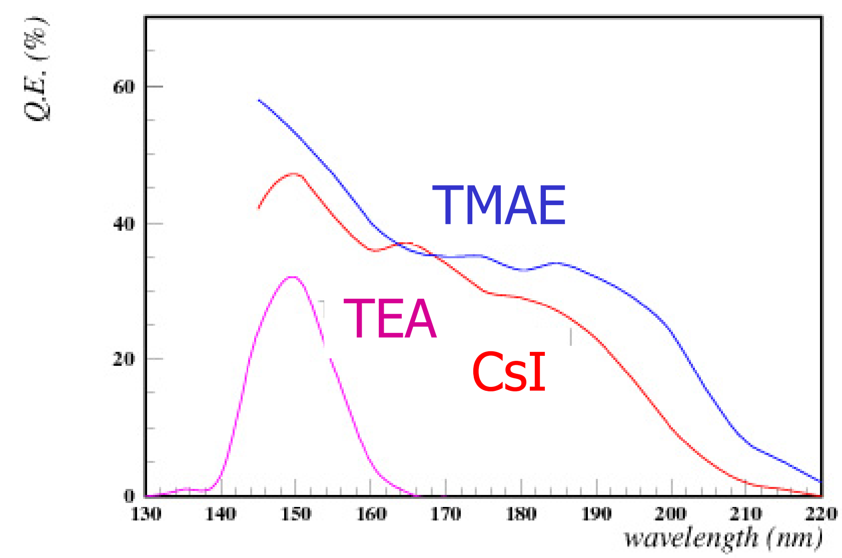
Multiwire chamber with
cathode pad read-out:
→ short drift distances,
fast detector



Photosensitive component:

•in the gas mixture (TEA):
CLEOIII RICH

•or a layer on one of the cathodes (CsI on the printed circuit cathode with pads) →



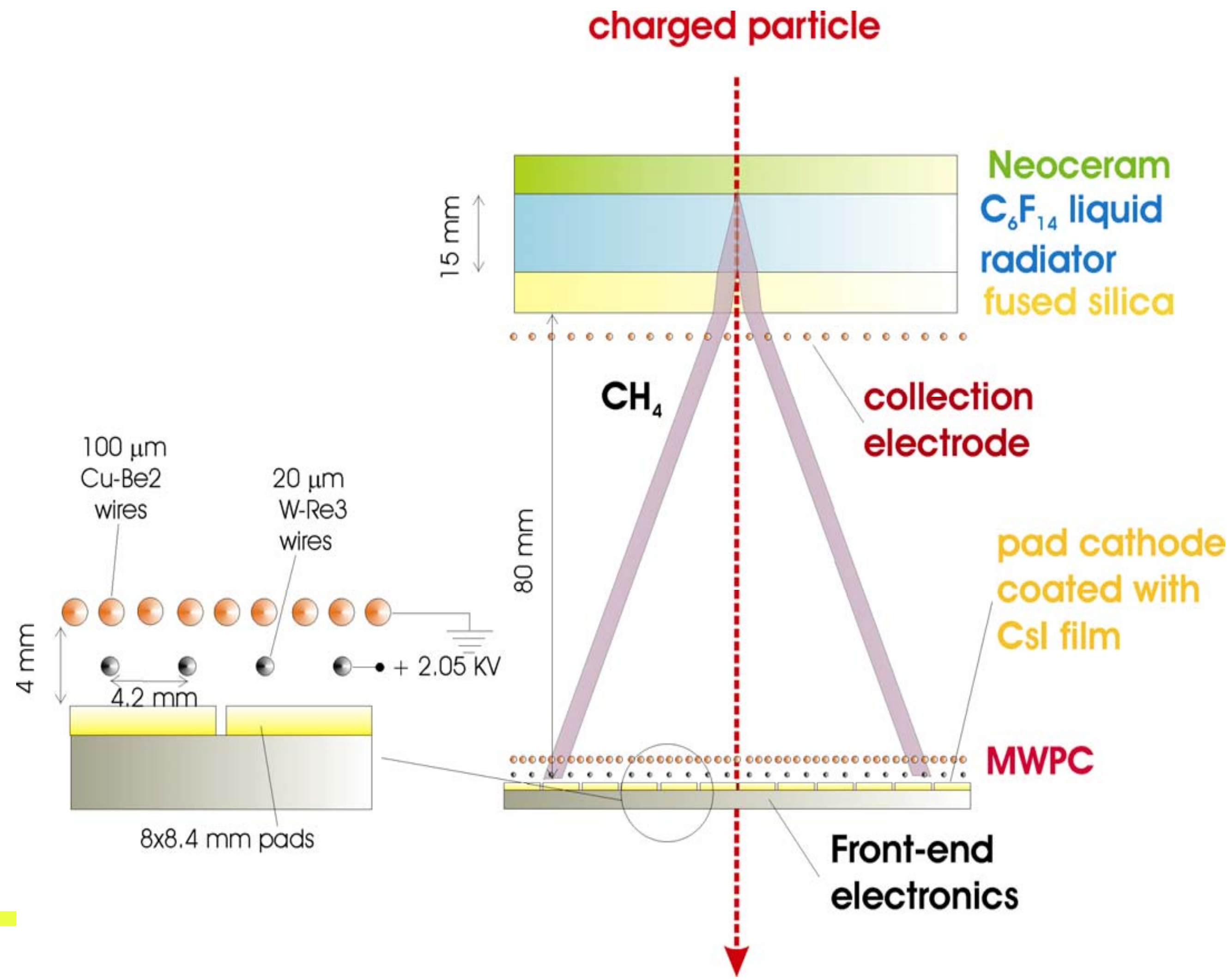
Works in high magnetic field!

CsI based RICH counters: HADES, COMPASS, ALICE

HADES and COMPASS RICH: gas radiator + CsI photocathode – long term experience in operation

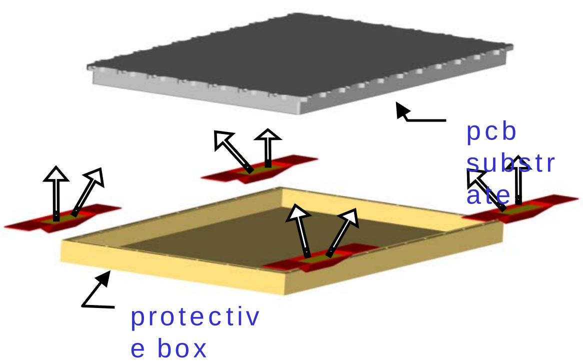
ALICE:

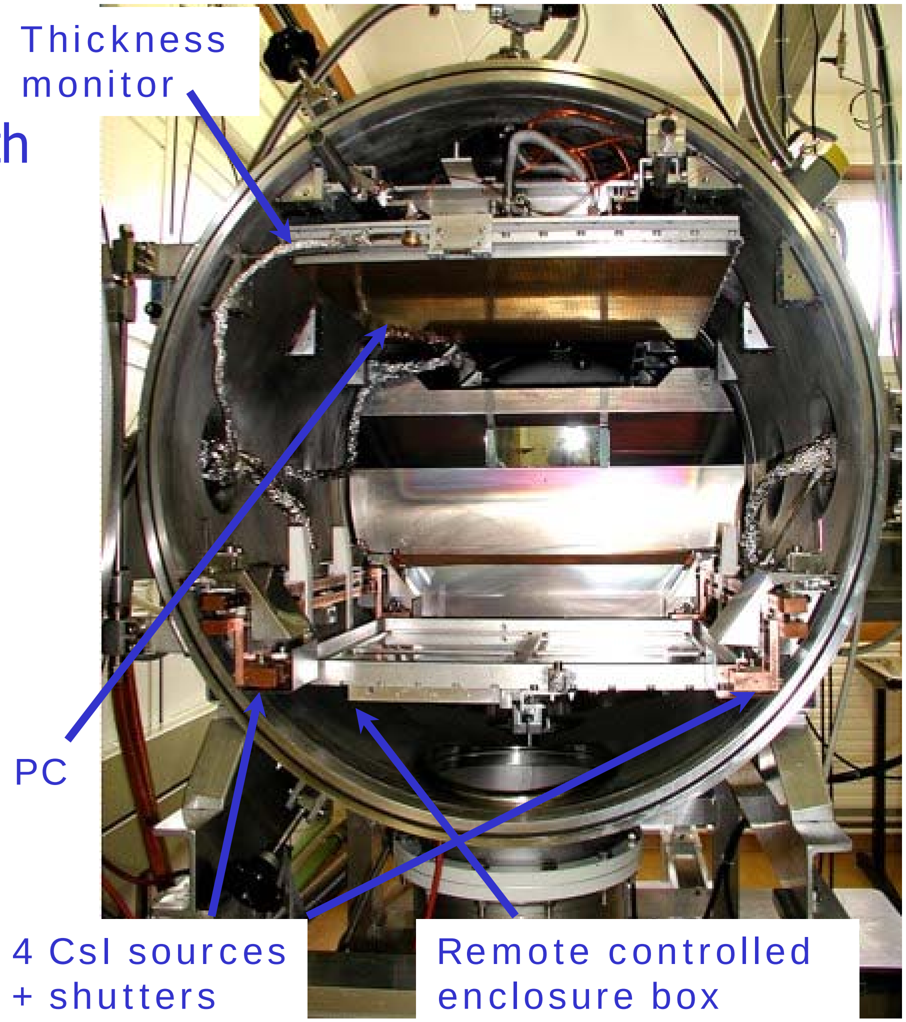
- liquid radiator
- proximity focusing



CERN CsI deposition plant

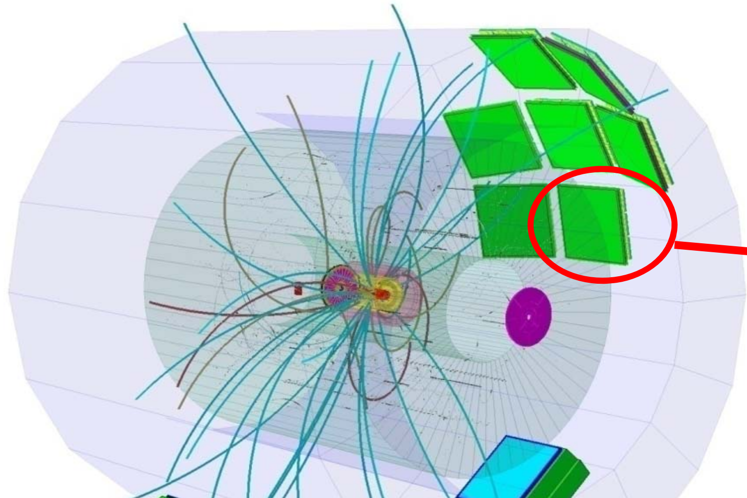
Photocathode produced with a well defined, several step procedure, with CsI vaccum deposition and subsequent heat conditioning



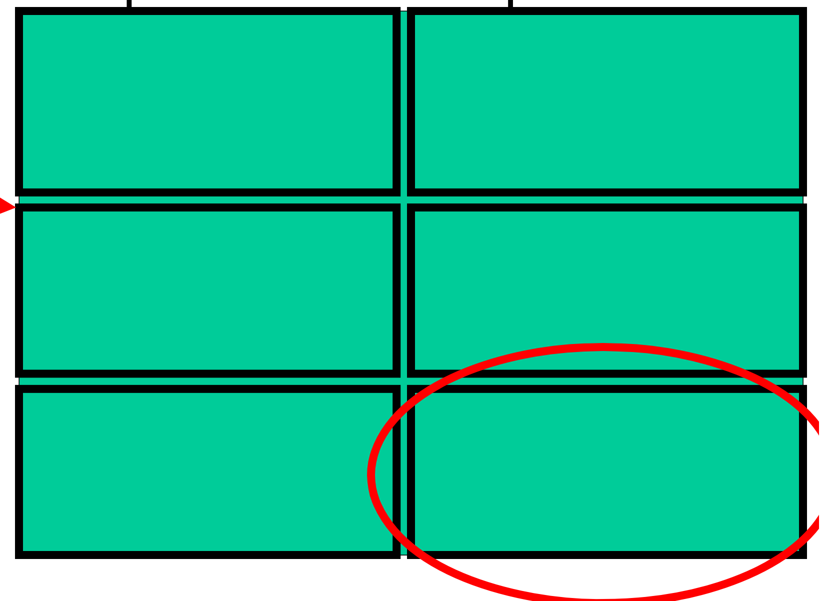


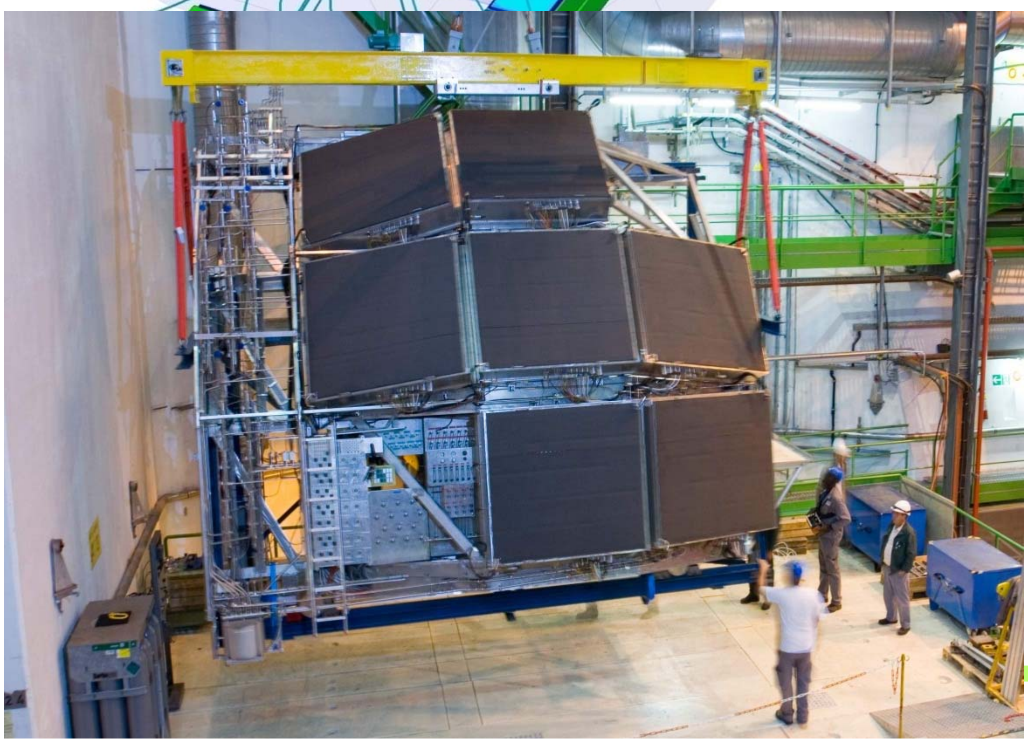
ALICE RICH = HMPID

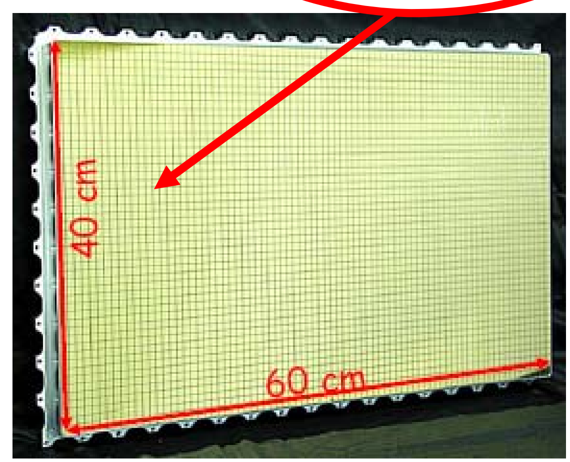
The largest scale (11 m^2) application of CsI photo-cathodes in HEP!



Six photo-cathodes per module

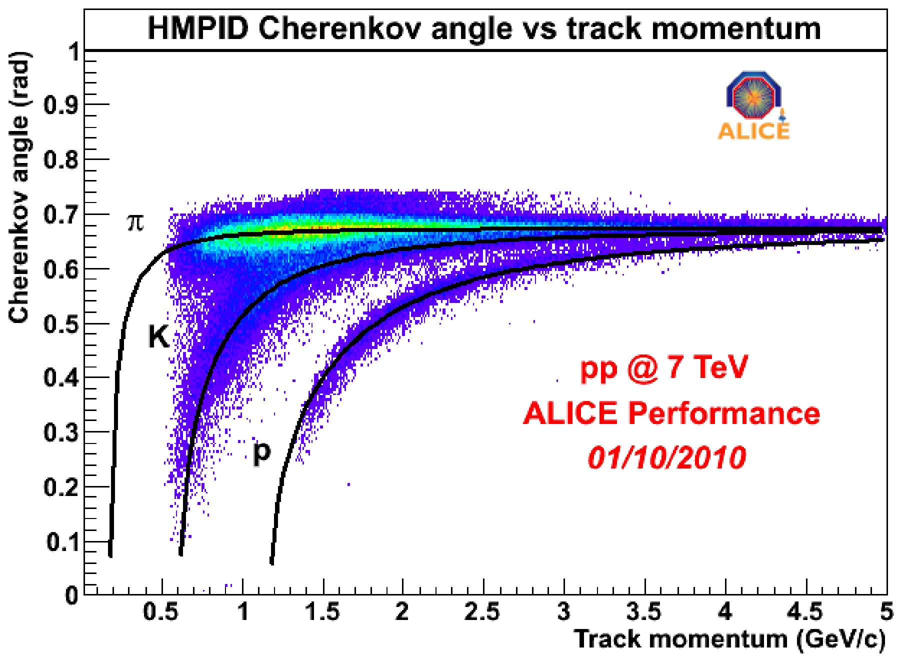


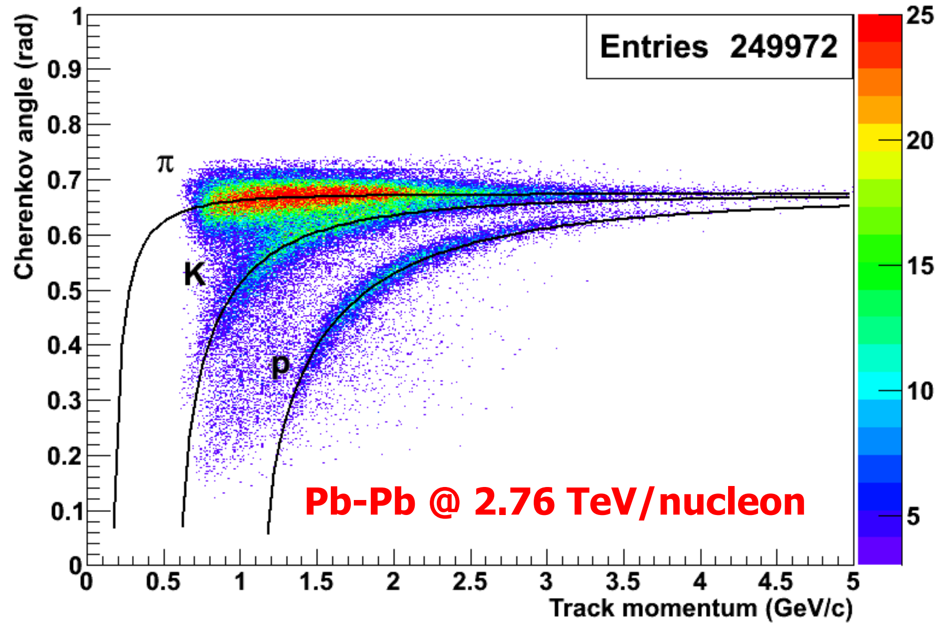


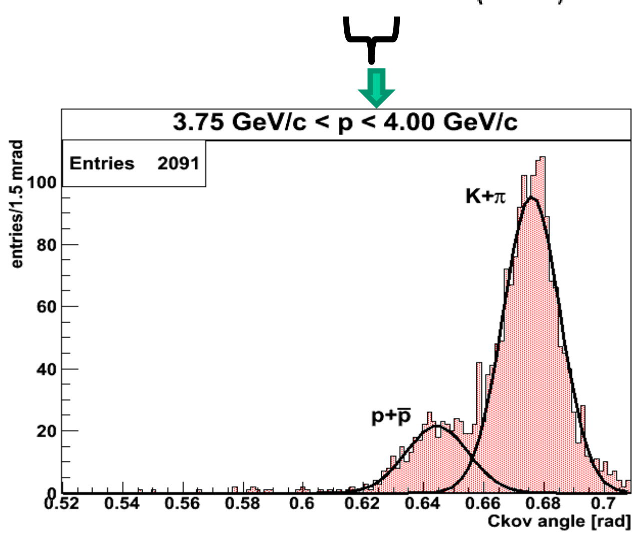


CsI photo-cathode is segmented in 0.8x0.84 cm pads

ALICE HMPID performance







Cherenkov counters with vacuum based photodetectors

Many applications: operation at high rates over extended running periods (years) → wire chamber based photon detectors were found to be unsuitable (problems in high rate operation, ageing, only UV photons, difficult handling in 4π spectrometers)

→ Need vacuum based photon detectors (e.g. PMTs)

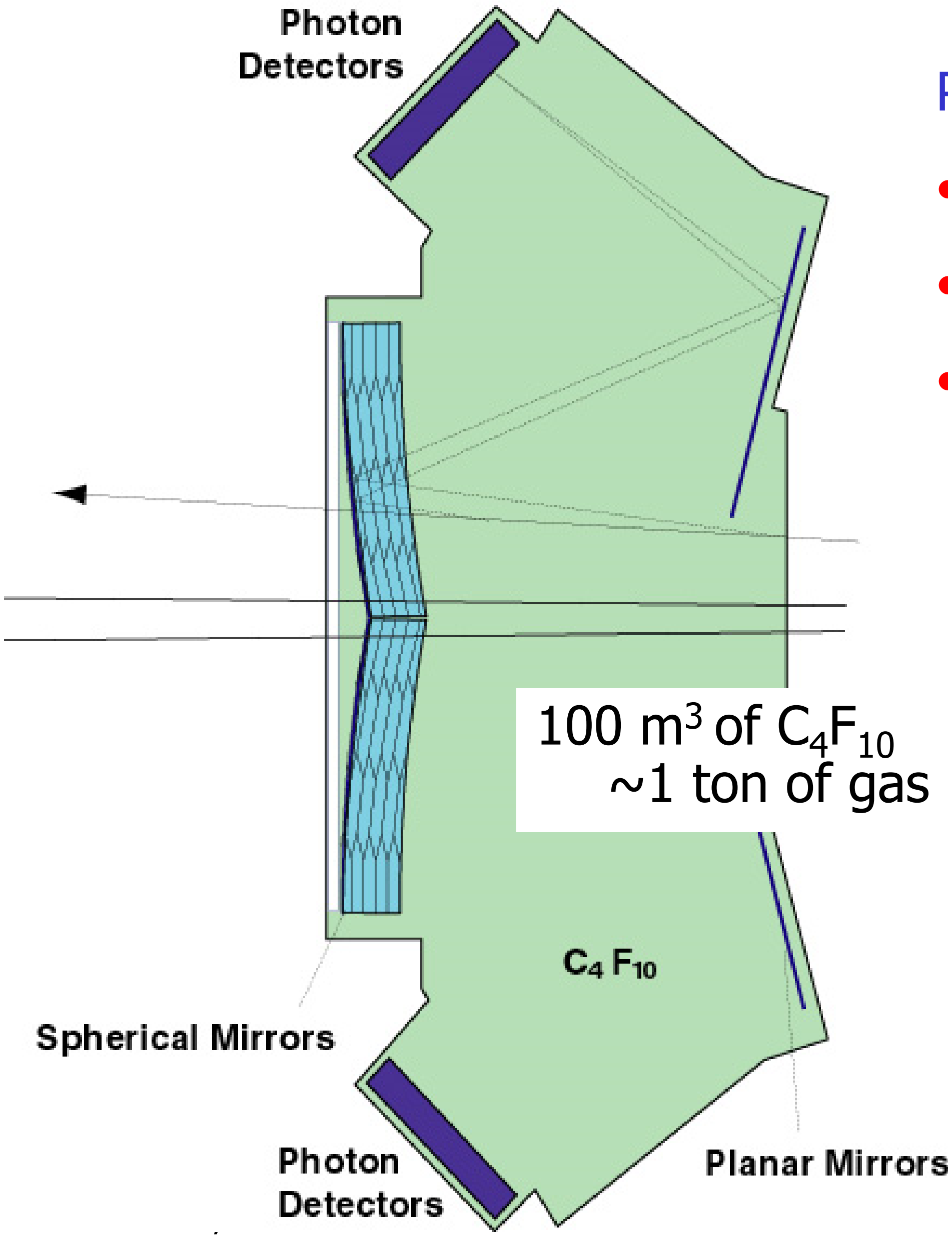
Good spacial resolution (pads with ~5 mm size)

→ Need multianode PMTs

HERA-B RICH

Photon detector requirements:

- High QE over ~3m^2
- Rates ~1MHz
- Long term stability



100 m^3 of C_4F_{10}
~1 ton of gas

Multianode PMTs

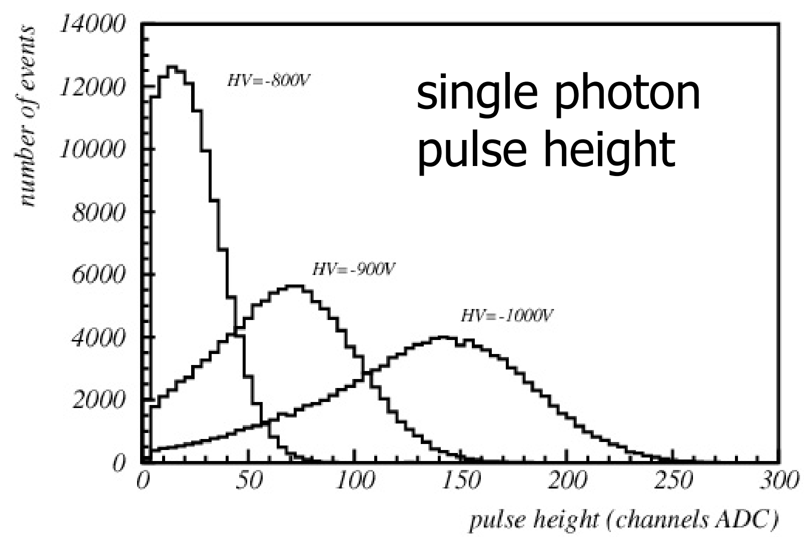
Multianode PMTs with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

→Excellent single photon pulse height spectrum

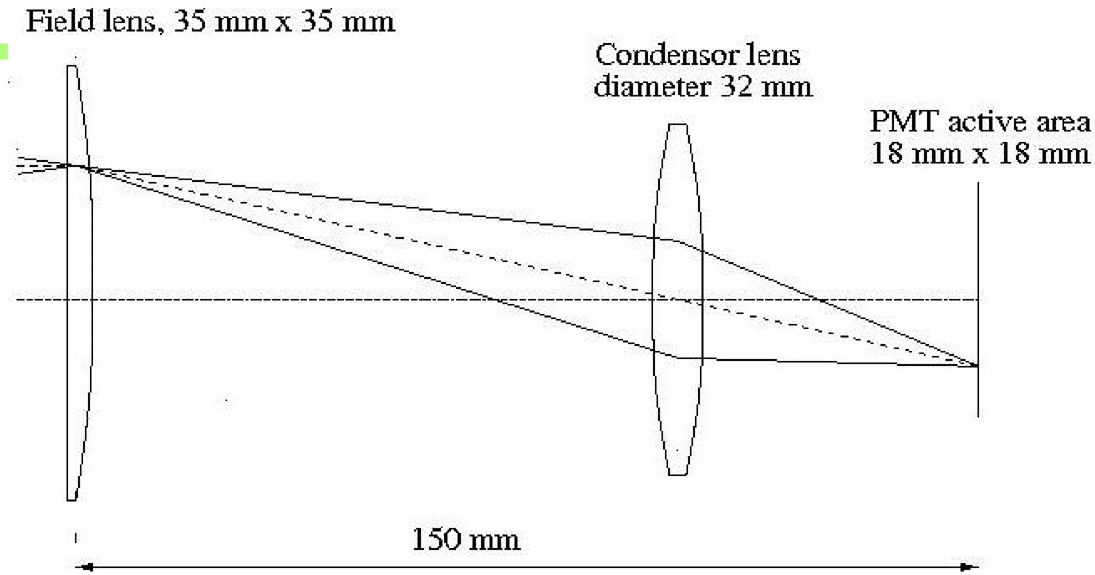
→Low noise (few Hz/ch)

→Low cross-talk (<1%)

→ NIM A394 (1997) 27



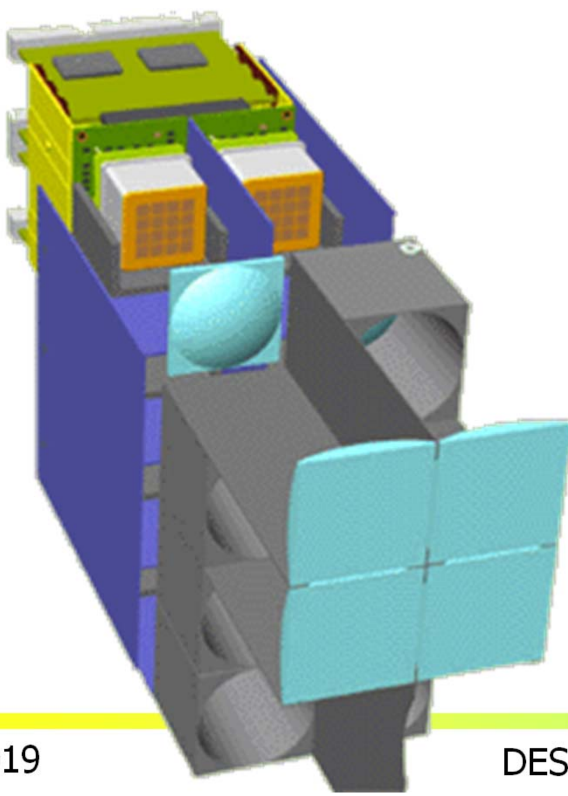
HERA-B RICH photon detector

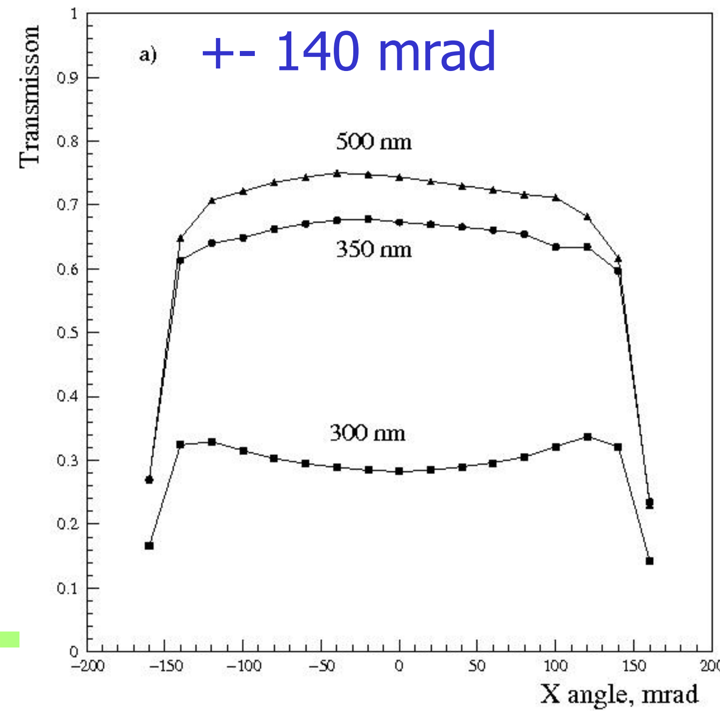


Light collection system (imaging!) to:

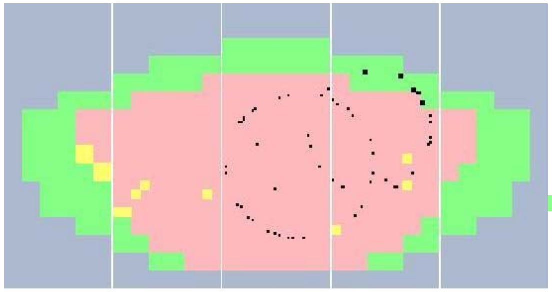
-Eliminate dead areas

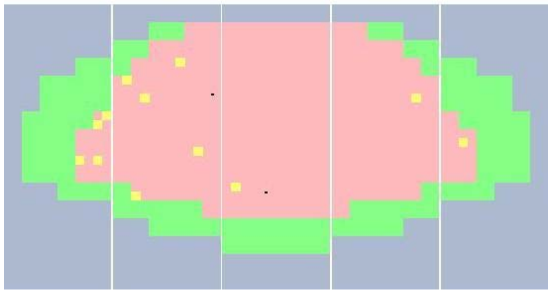
-Adapt the pad size





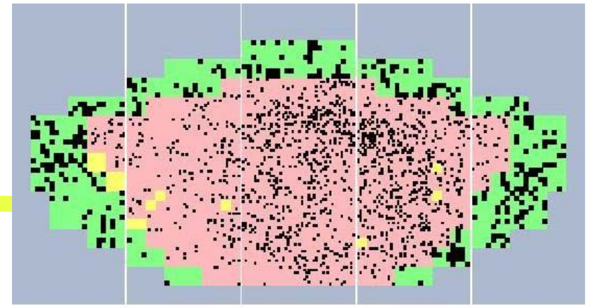
HERA-B RICH

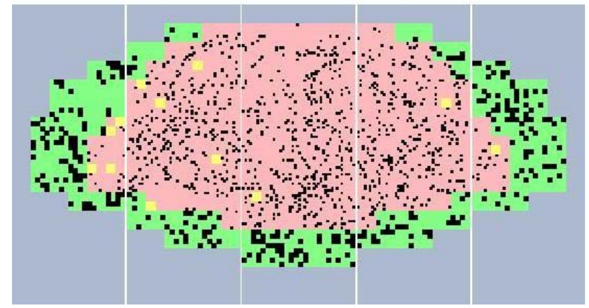




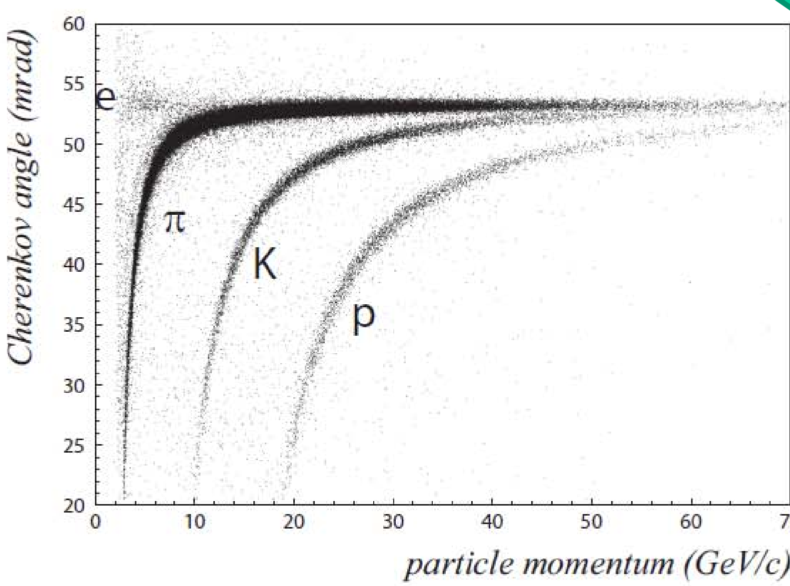
← Little noise, ~30 photons per ring

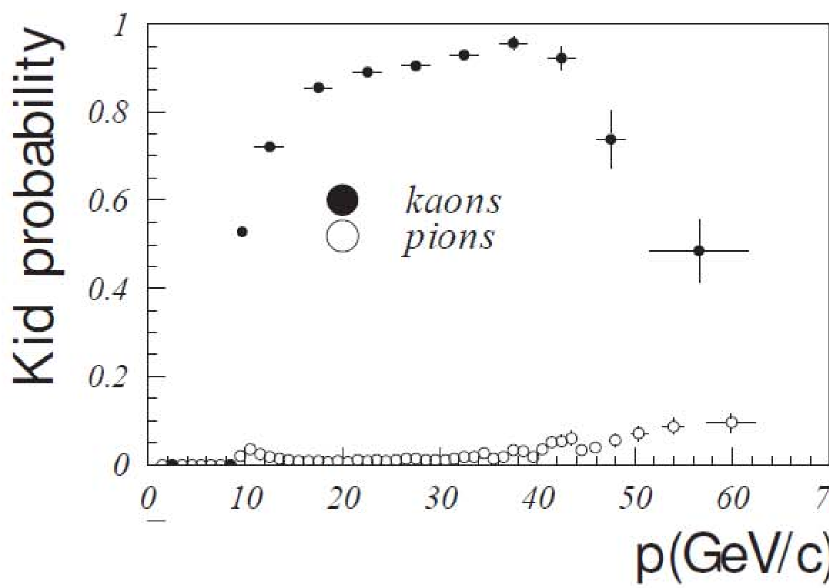
Typical event →





Worked very well!

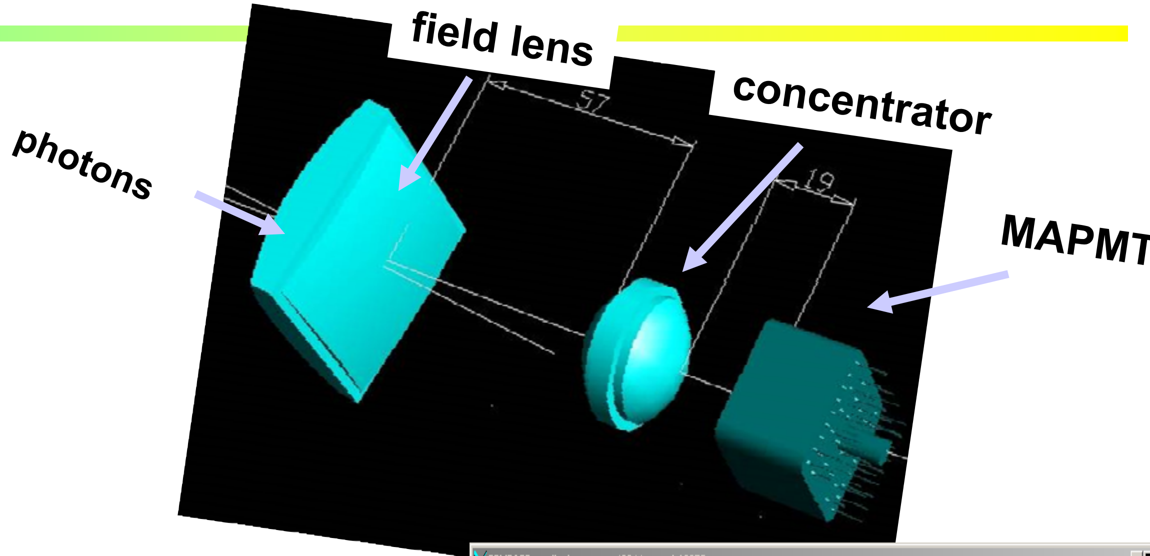




Kaon efficiency and pion fake probability

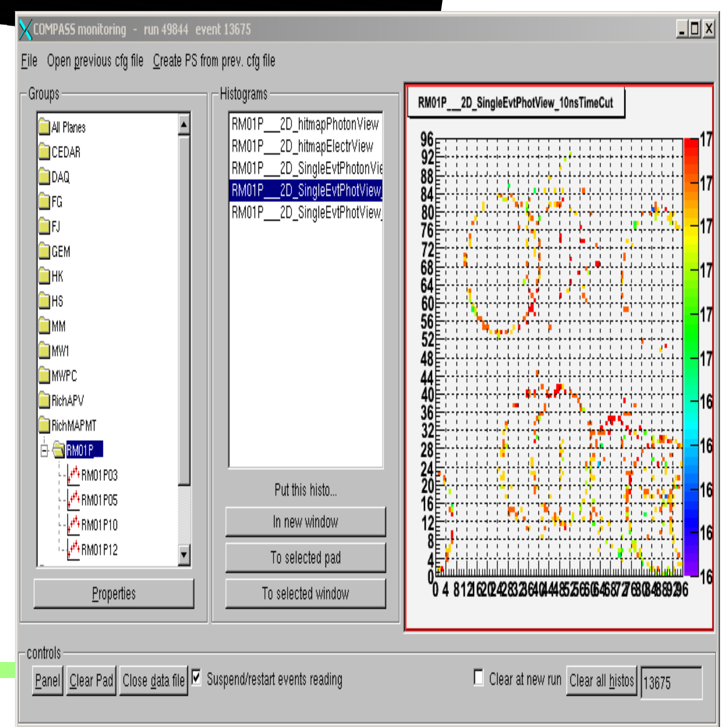
Photon detector for the COMPASS RICH-1

Upgraded COMPASS RICH-1:
similar concept as in the HERA-B RICH

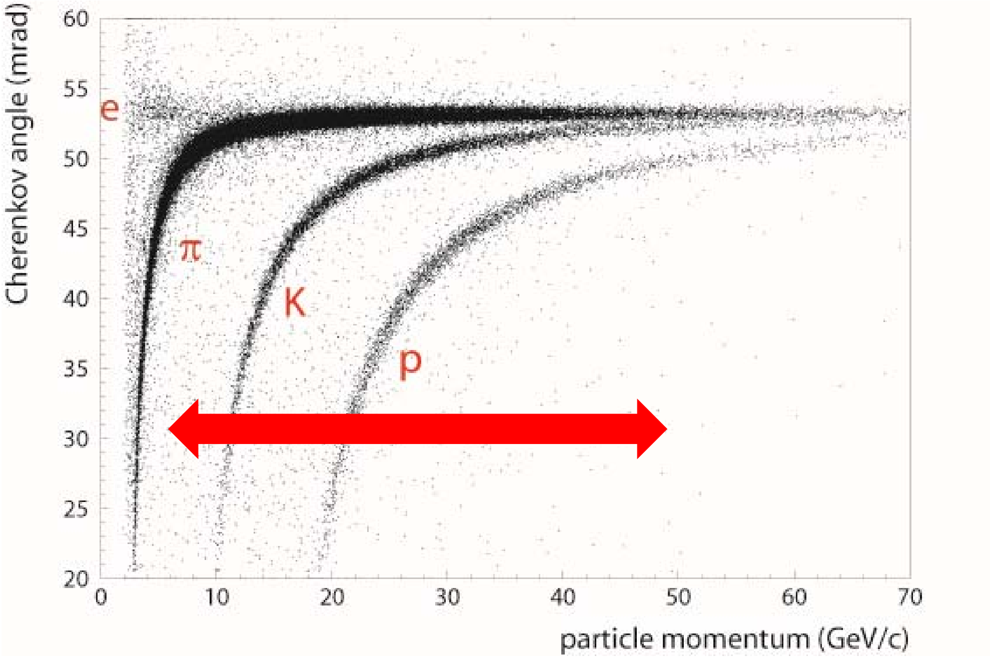


New features:

- UV extended PMTs & lenses (down to 200 nm) → more photons
- surface ratio = (telescope entrance surface) / (photocathode surface) = 7
- fast electronics with <120 ps time resolution



Kinematic range of a RICH counter



Example: kinematic range for kaon/pion separation

Kinematic range for separation of two particle types:

•Lower limit p_{min}: sufficiently above lighter particle threshold

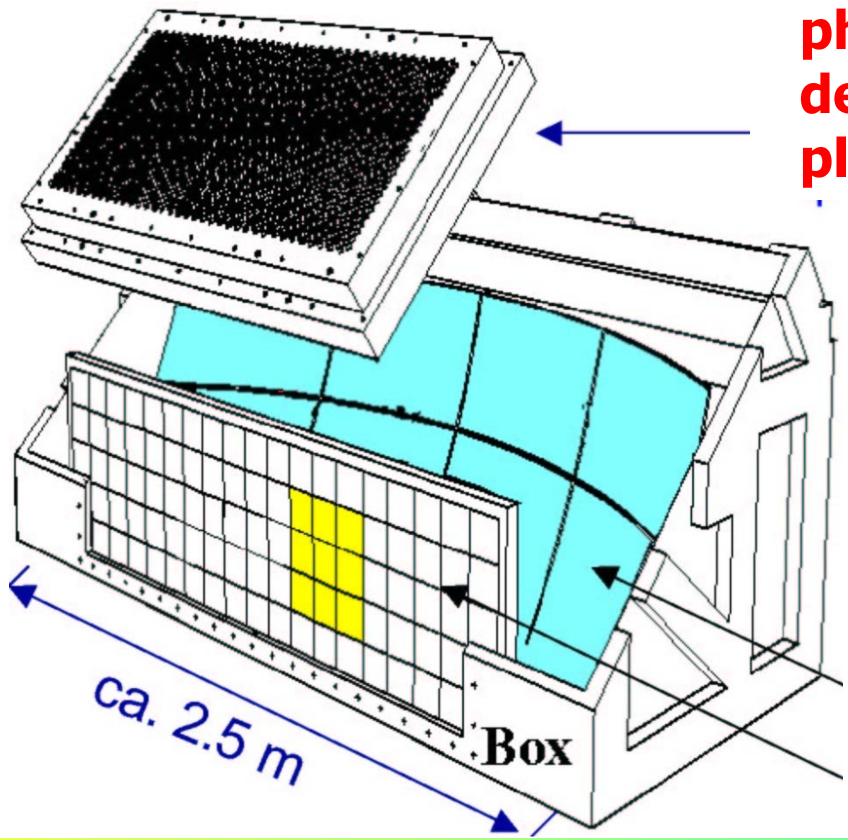
•Upper limit p_{max}: given by Cherenkov angle resolution – overlap of the two bands

Rule of thumb: $p_{max} / p_{min} < 10$

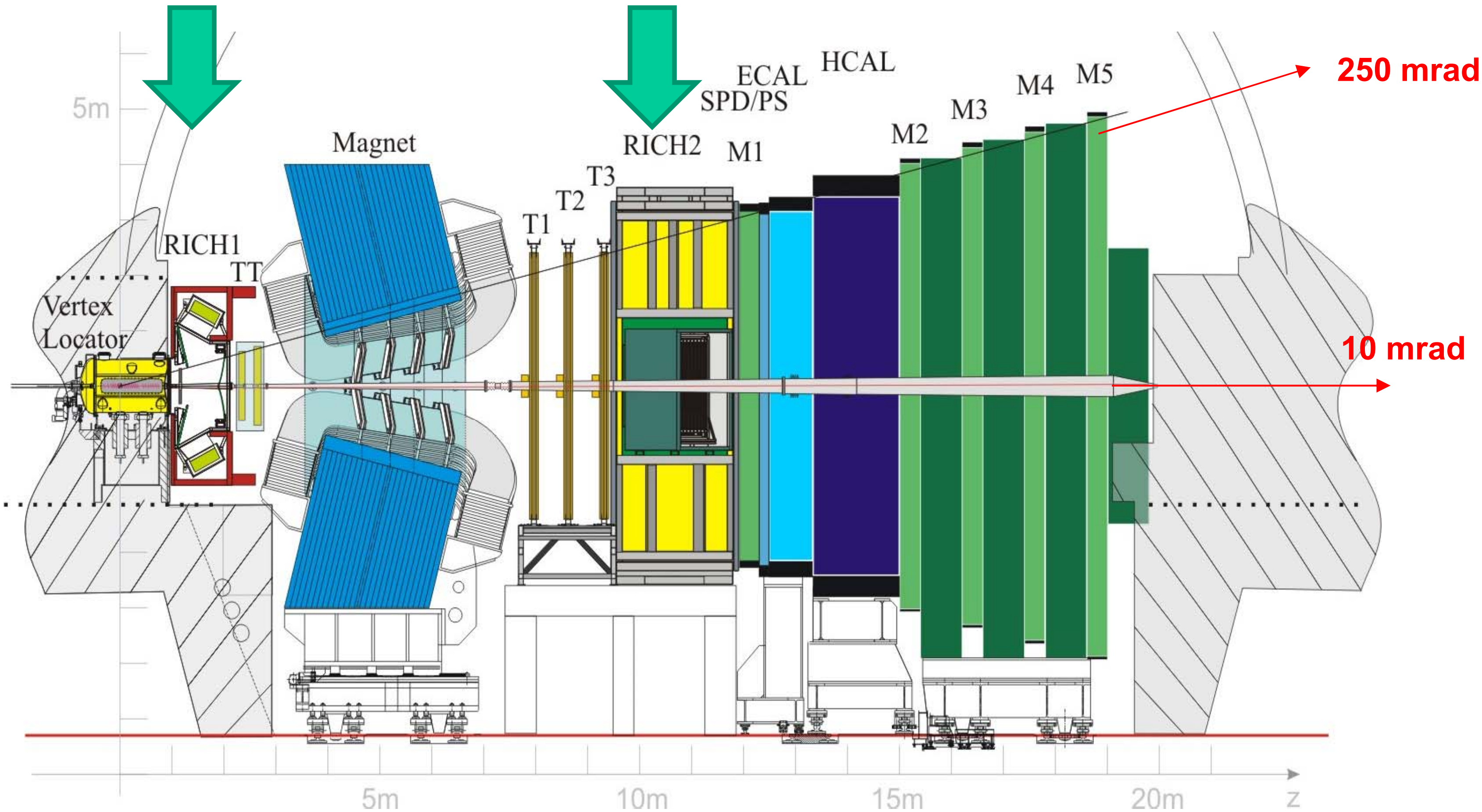
RICHes with several radiators

Extending the kinematic range → need more than one radiator

- DELPHI, SLD (liquid +gas)
- HERMES (aerogel+gas)



The LHCb RICH counters



Vertex reconstruction:	**Trigger:**	**PID:**	**Kinematics:**
VELO	**Muon Chambers**	**RICHes**	**Magnet**
	Calorimeters	**Calorimeters**	**Tracker**
	Tracker	**Muon Chambers**	**Calorimeters**

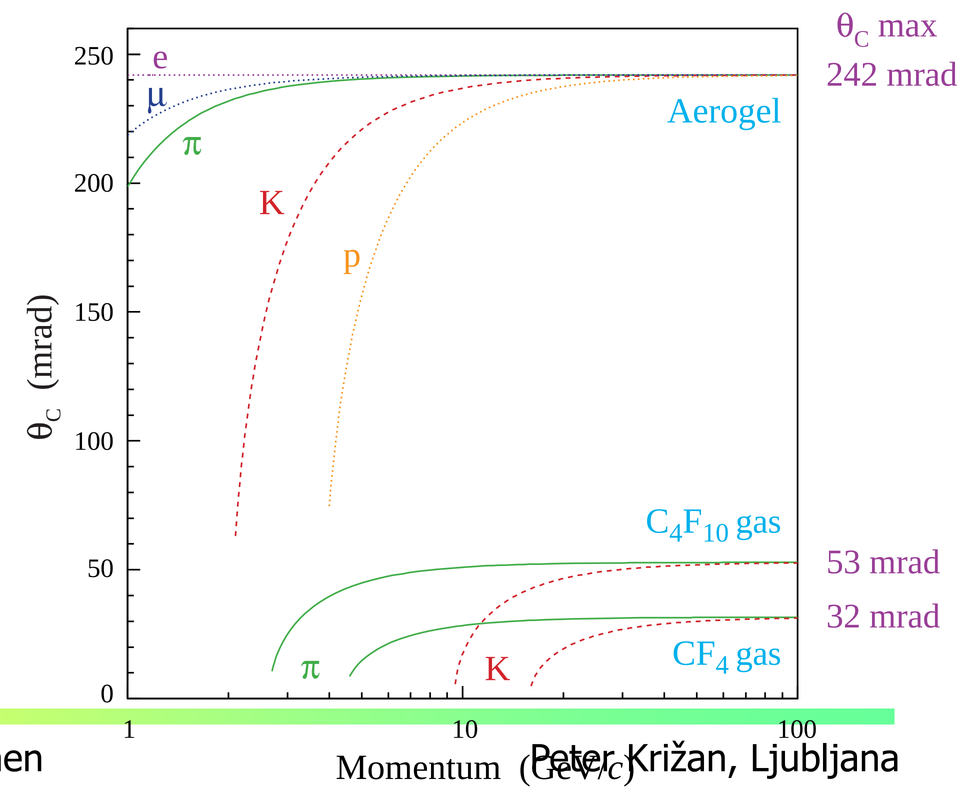
LHCb RICHes

Need:

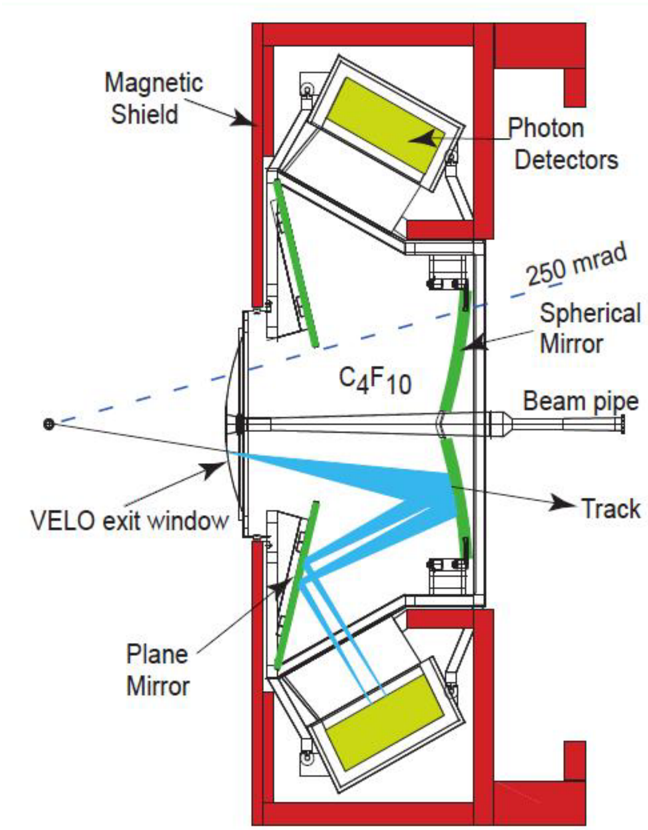
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm²
- Large area (2.8m²) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

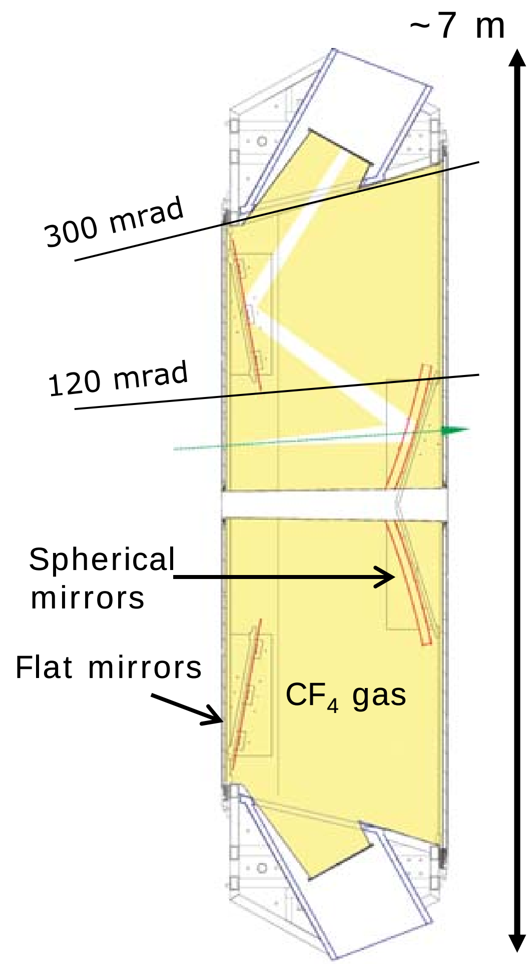
→3 radiators

- Aerogel
- C_4F_{10} gas
- CF_4 gas



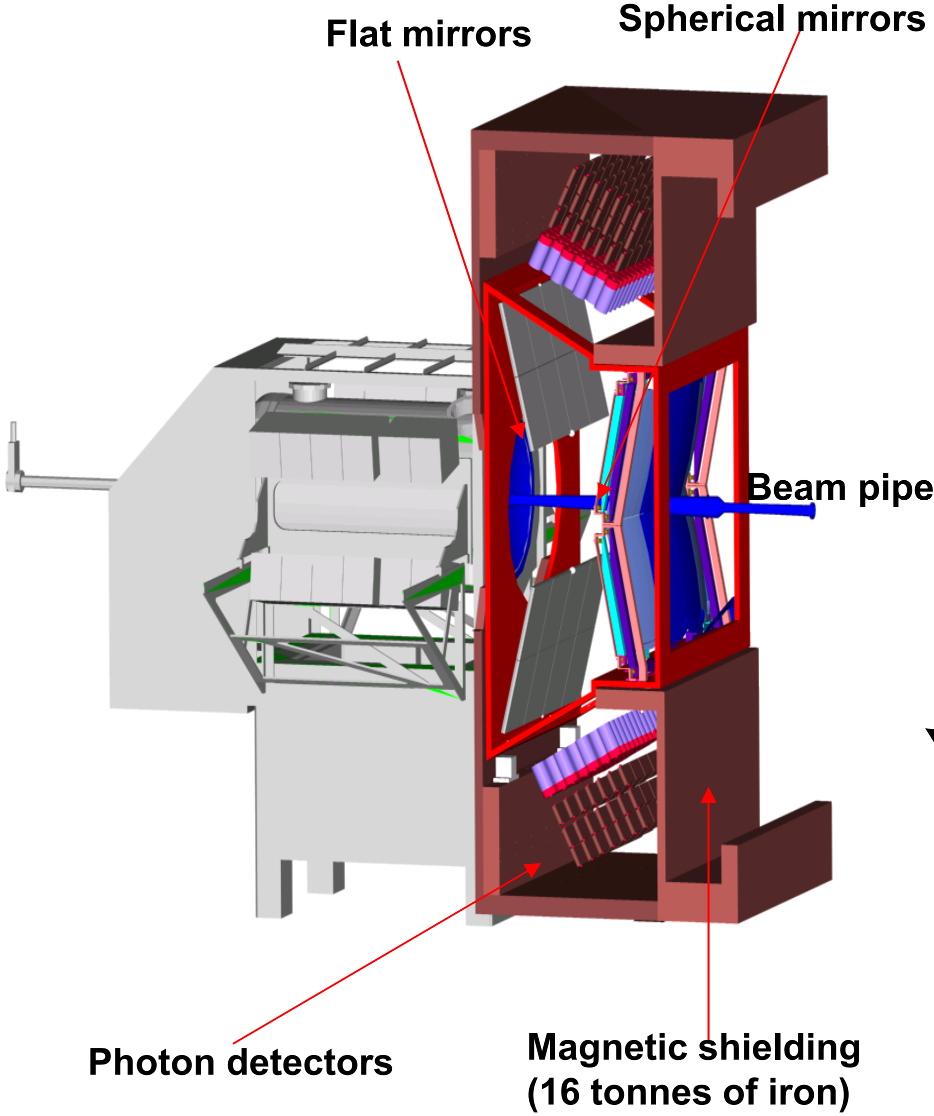
LHCb RICHes

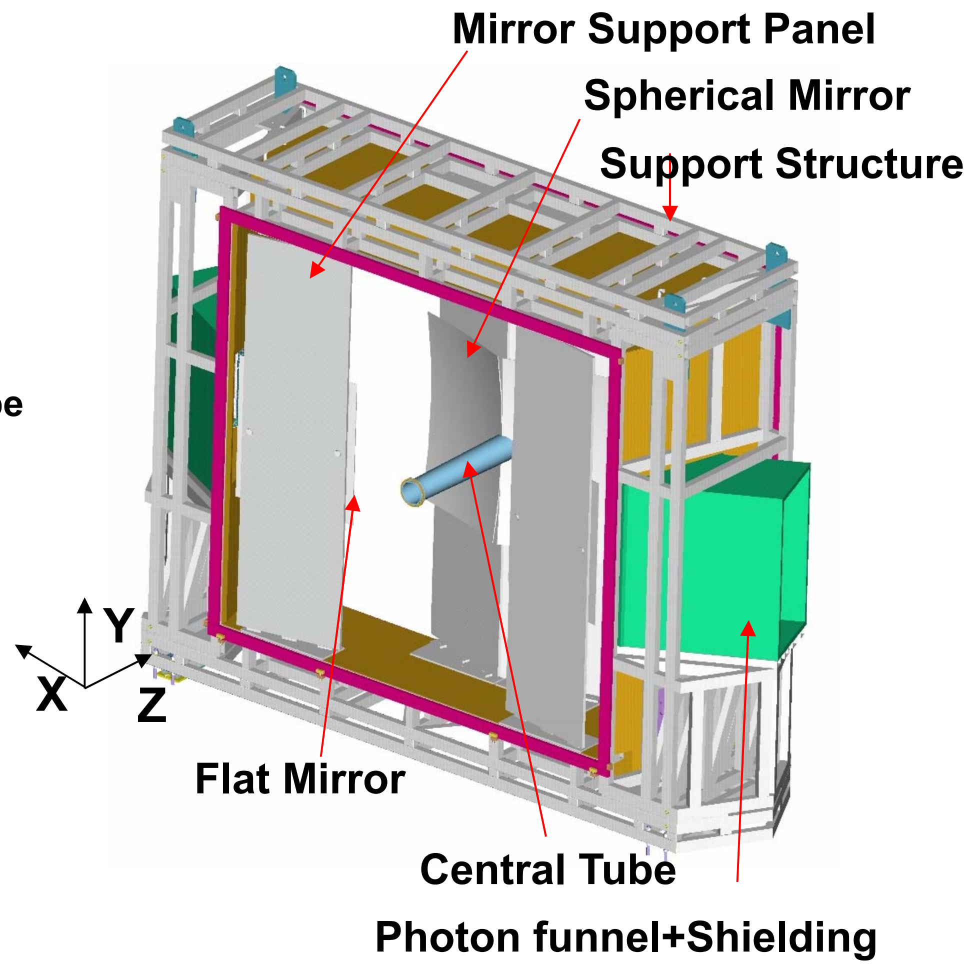




RICH 1 + 2

LHCb RICHes

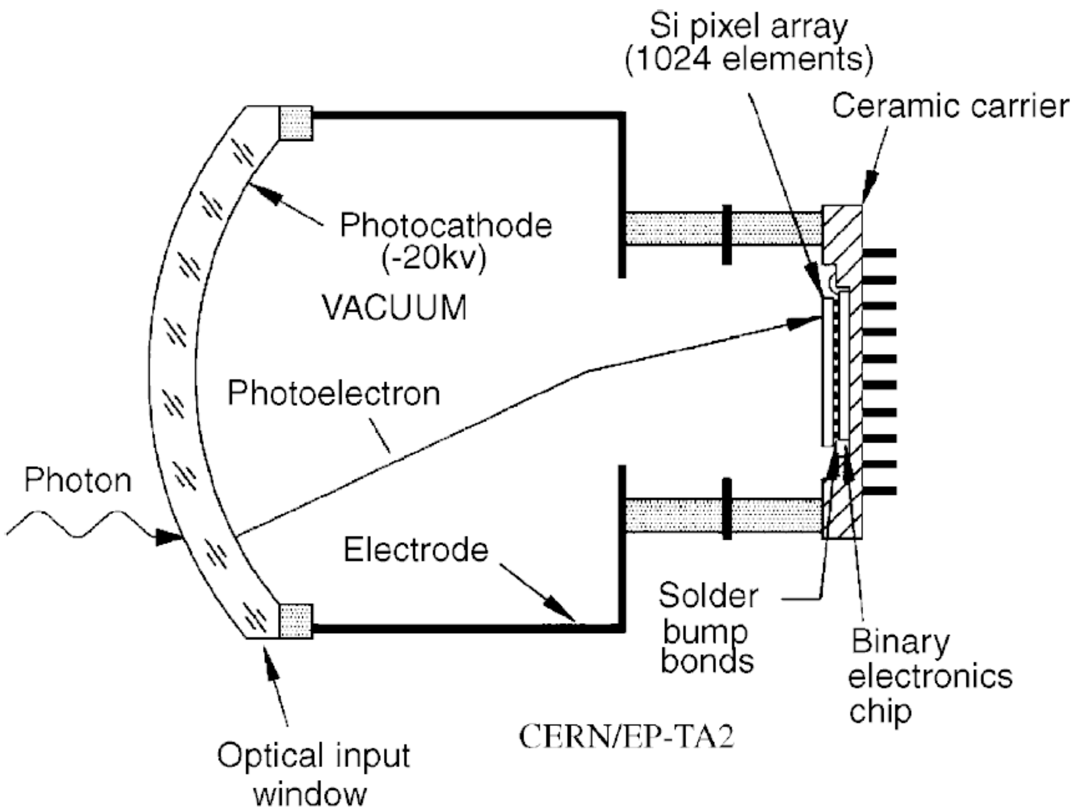

Flat mirrors
Spherical mirrors
Beam pipe
Photon detectors
Magnetic shielding
(16 tonnes of iron)


Mirror Support Panel
Spherical Mirror
Support Structure
Y
X
Z
Flat Mirror
Central Tube
Photon funnel+Shielding

LHCb RICHes

Photon detector: hybrid PMT (R+D with DEP) with 5x demagnification (electrostatic focusing).

Hybrid PMT: accelerate photoelectrons in electric field (~20kV), detect it in a pixelated silicon detector.



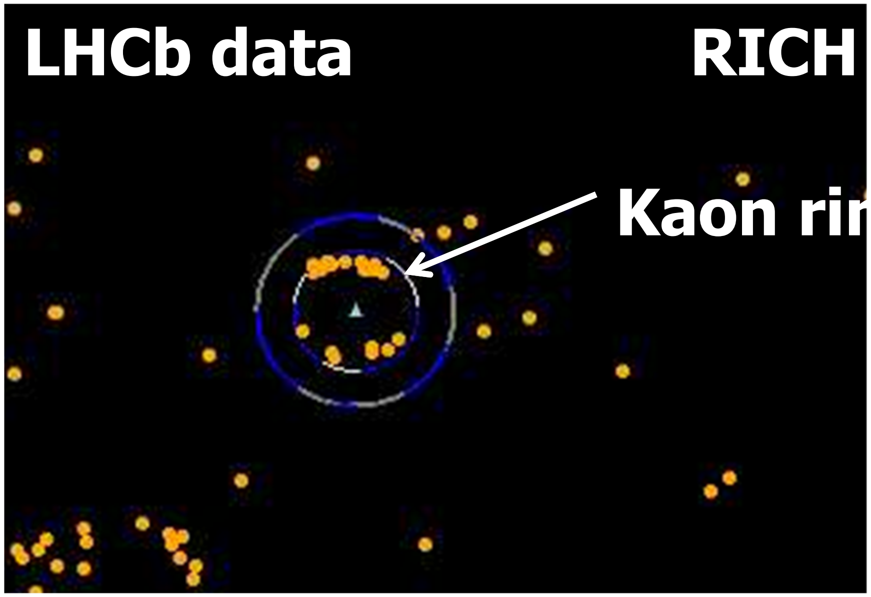
NIM A553 (2005) 333

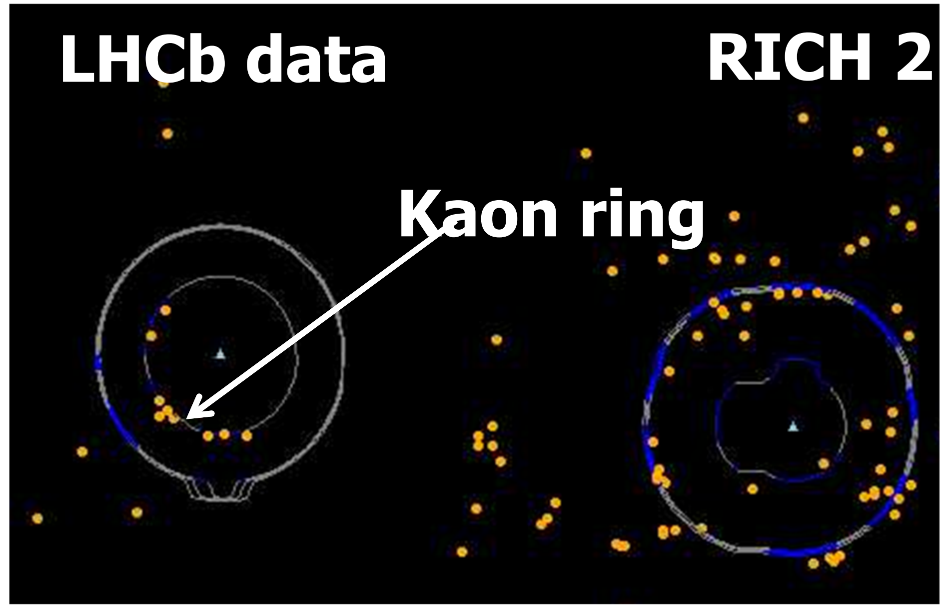
LHCb Event Display

RICH1

Early data, Nov/Dec 2009
LHC beams $\sqrt{s}$ = 900 GeV

RICH2



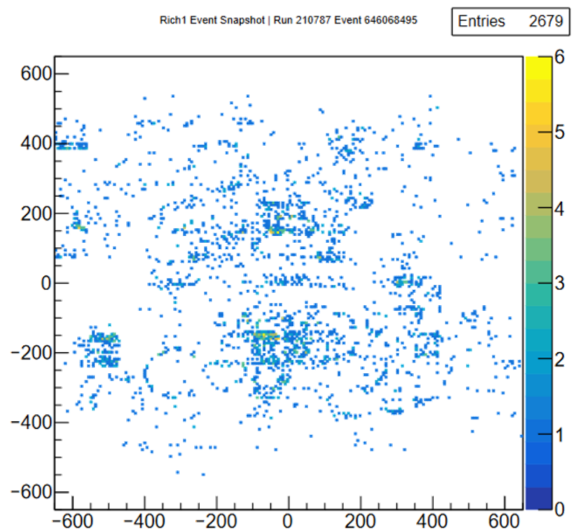


- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

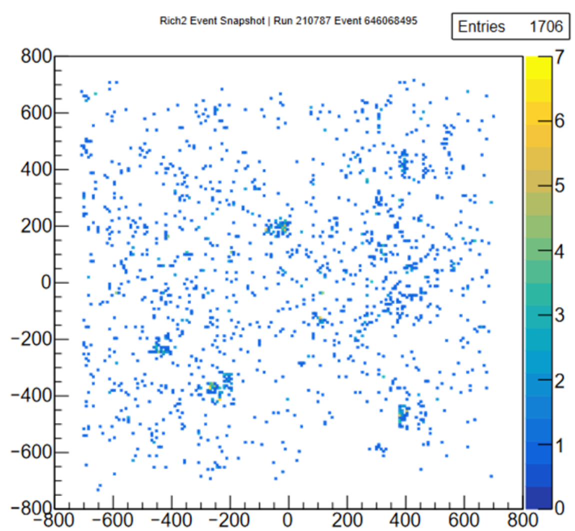
More on LHCb

Single event

RICH 1

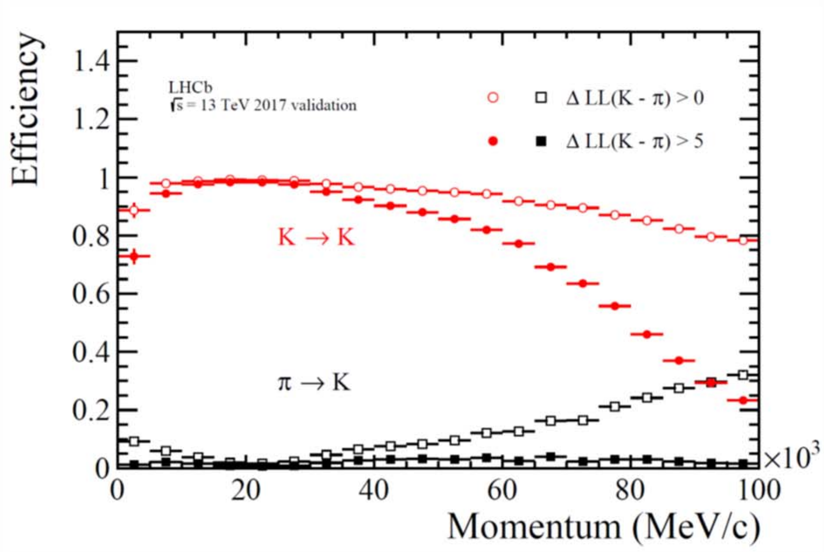


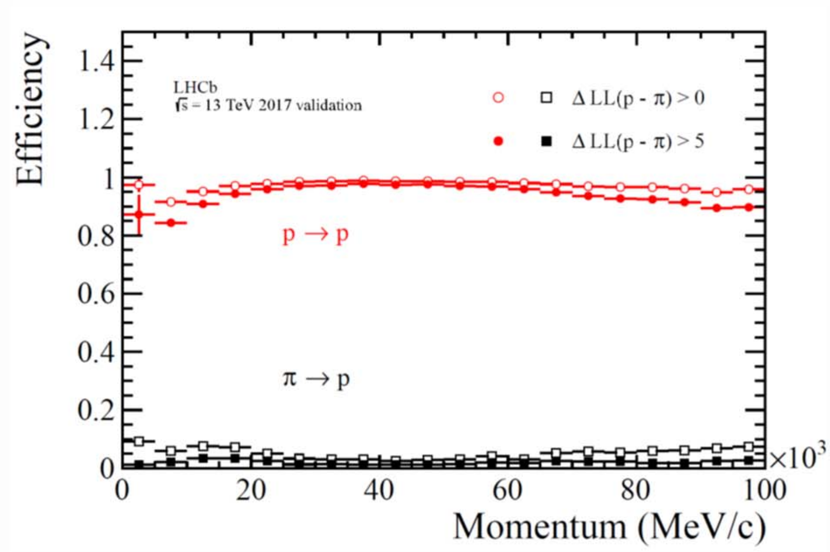
RICH 2

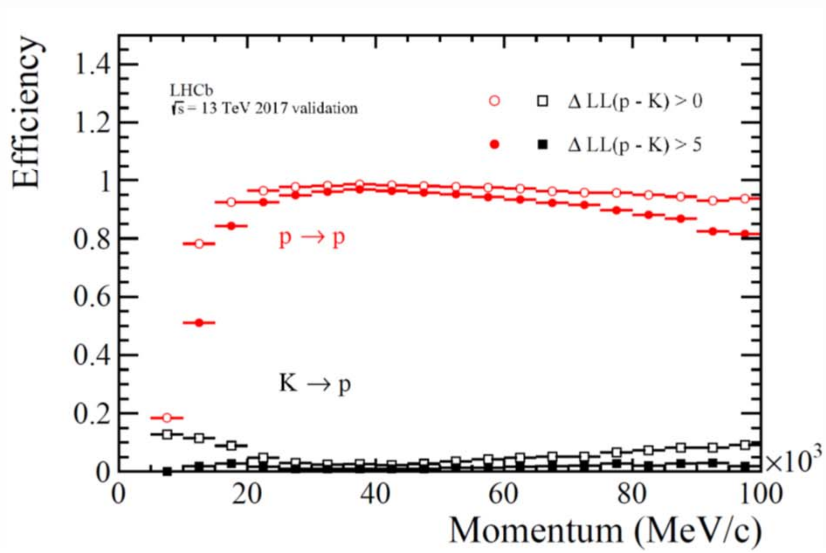


RICH-1 carbon fibre mirrors

LHCb RICHes: performance



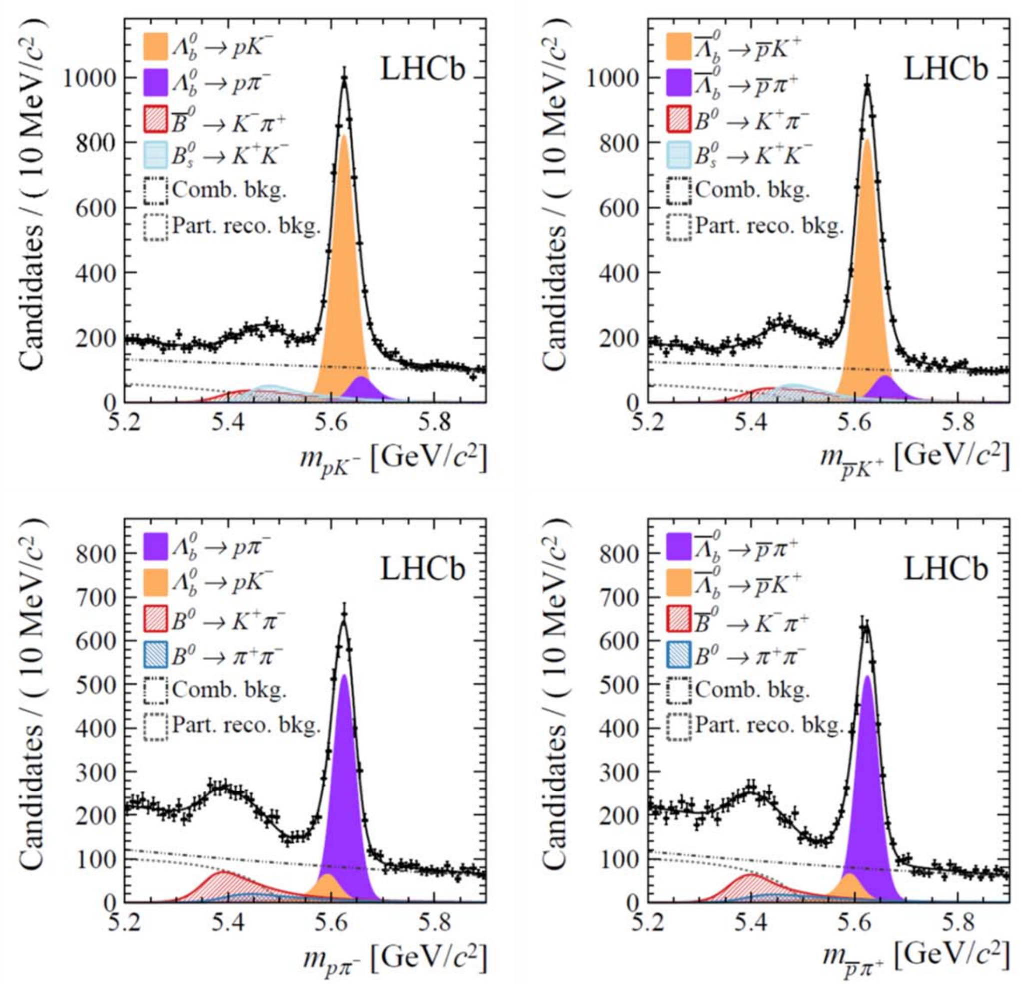




LHCb RICHes: performance

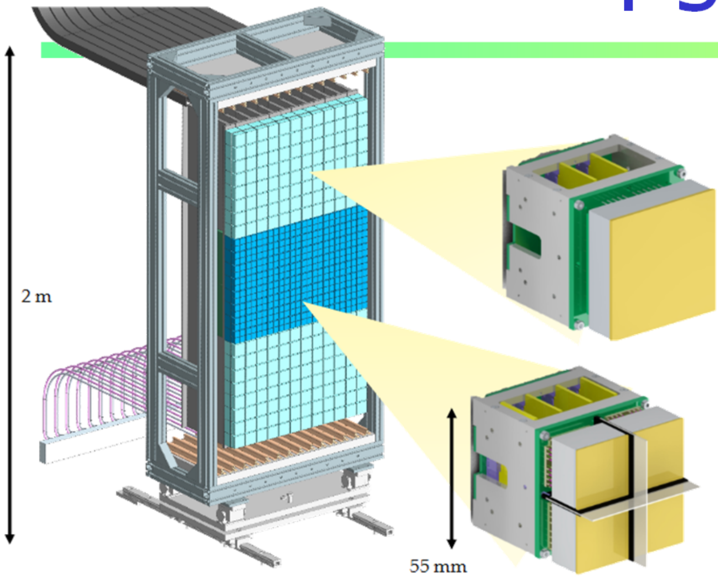
LHCb RICH detectors successfully and stably operating since 2010

Key ingredient to the successful physics program delivered by LHCb

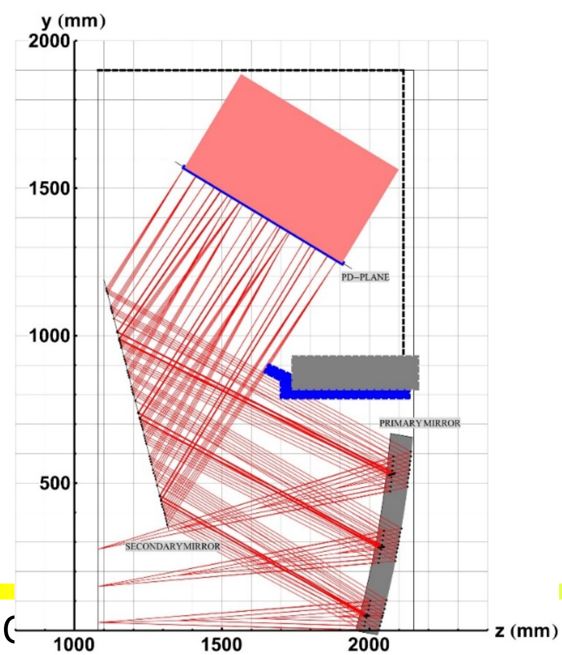


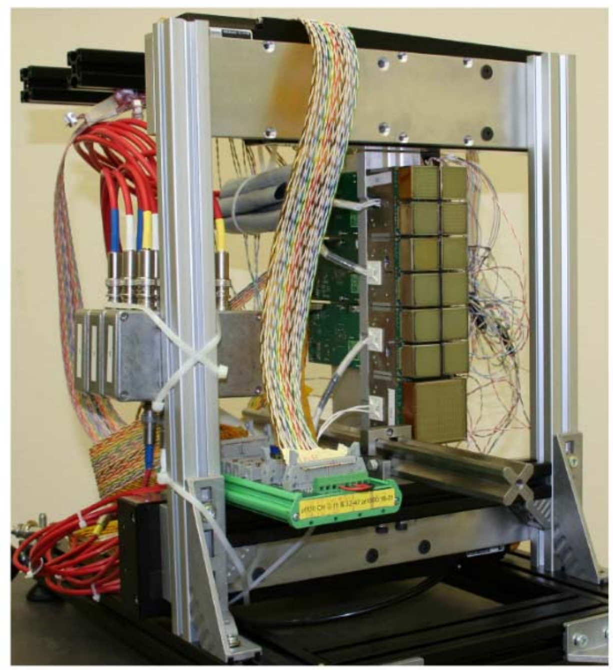
"Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays"
[LHCb-PAPER-2018-025]

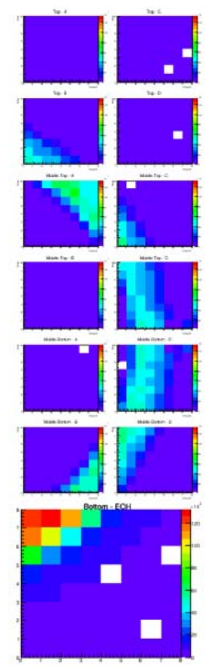
LHCb Upgrade (under way)



- New optics layout for RICH 1
- New photon detectors: Hamamatsu R13743 (H12700) and R13742 (R11265)
- New electronics working at 40 MHz readout rate

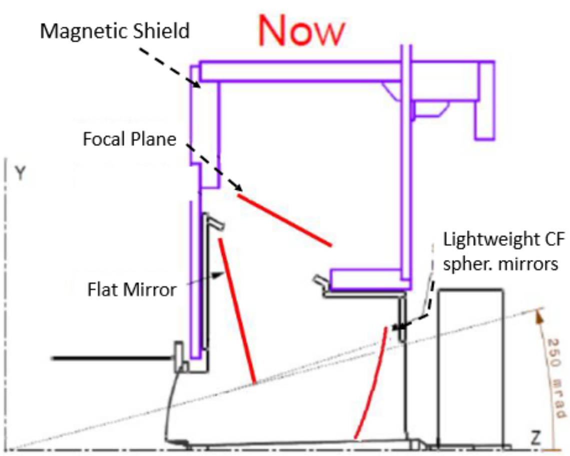


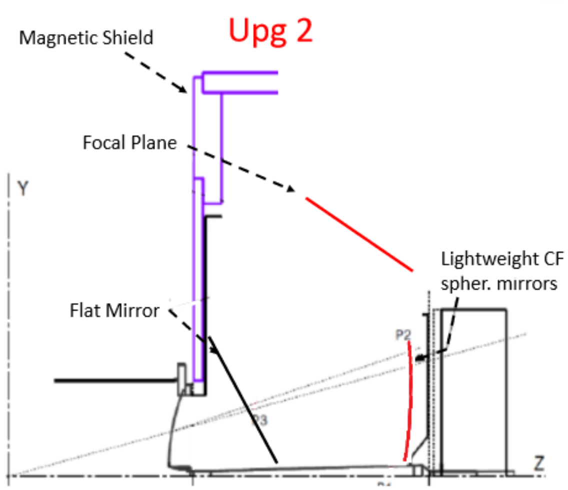




Future LHCb Upgrade

- Provide PID at p-p luminosity of 10^{34} in the forward region
- Incremental improvements in:
  - Cherenkov angle resolution
    - More photons in the green
  - Reduced event complexity with timing
  - Enhanced number of photons

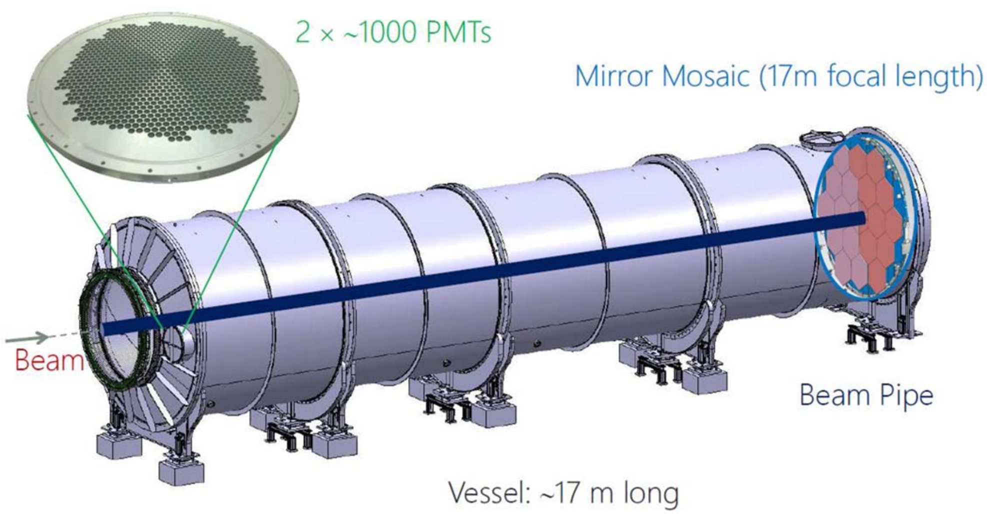


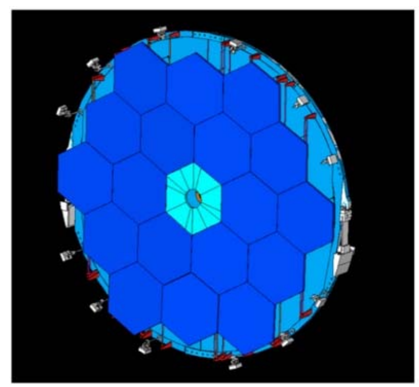


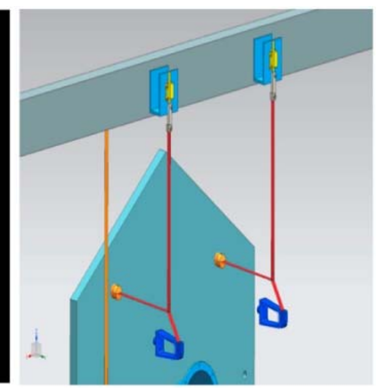
Radiator	C_4F_{10}			CF_4	
Detector Version	RICH 1 Current (HPD)	RICH 1 UPG1	**RICH 1 UPG2**	RICH 2 UPG1	**RICH 2 UPG2**
Average Photoelectron Yield	30	40	**60–30**	22	**30**
Single Photon Errors (mrad)					
Chromatic	0.84	0.58	**0.24–0.12**	0.31	**0.1**
Pixel	0.9	0.44	**0.15**	0.20	**0.07**
Emission Point	0.8	0.37	**0.1**	0.27	**0.05**
Overall	1.47	0.82	**0.3–0.2**	0.46	**0.13**

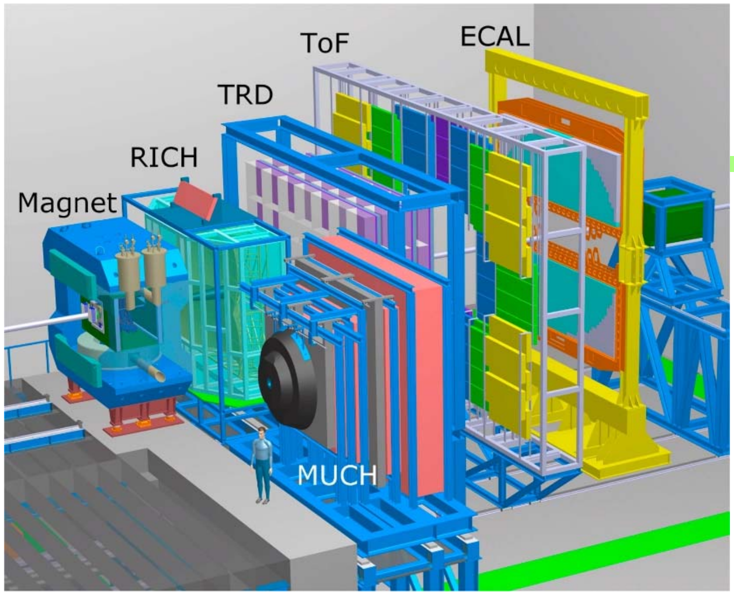
NA62 RICH

- 200m^3, 17m long, cylindrical vacuum proof tank with Neon radiator
- Operational since 2014
- Photon detectors: 2000 PMTs (16mm, 8mm active, with Winstone cone light guides)
- Mirror alignment ~30 μrad
- Single photon resolution: ~140 μrad
- Operation 15-35 GeV/c

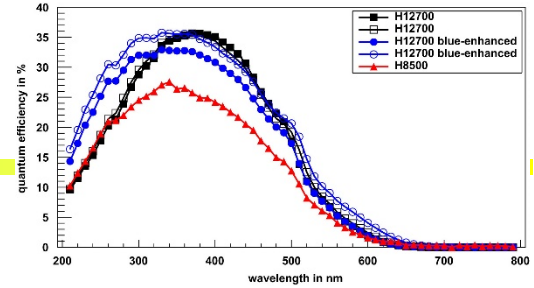




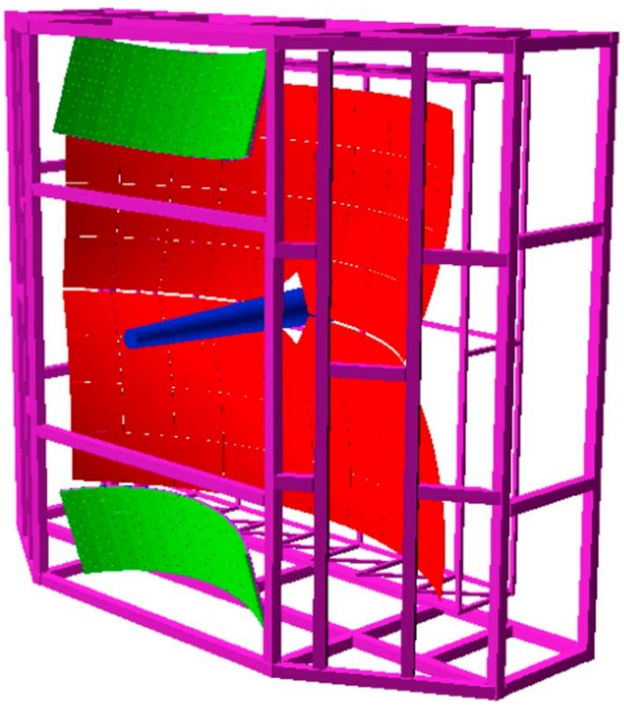


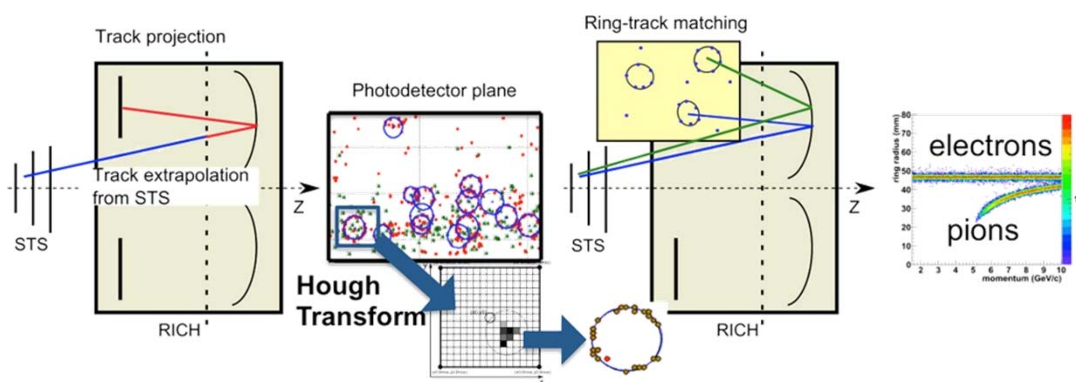


CBM

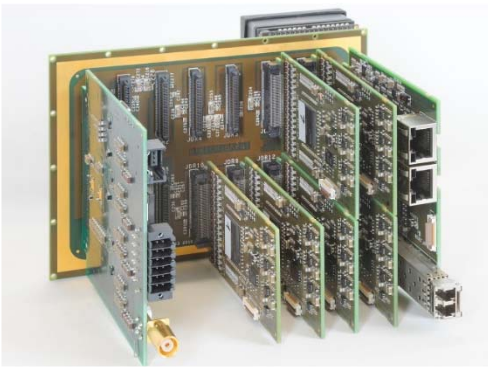


- RICH with CO_2 radiator
- MaPMTs: Hamamatsu H12700
- Cylindrical photon detection surface
- Extensive testing of MaPMTs for radiation damage
- Up to 1000 tracks per event
- Momentum up to 8 GeV/c
- Pion suppression factor ~5000 (with TRD)

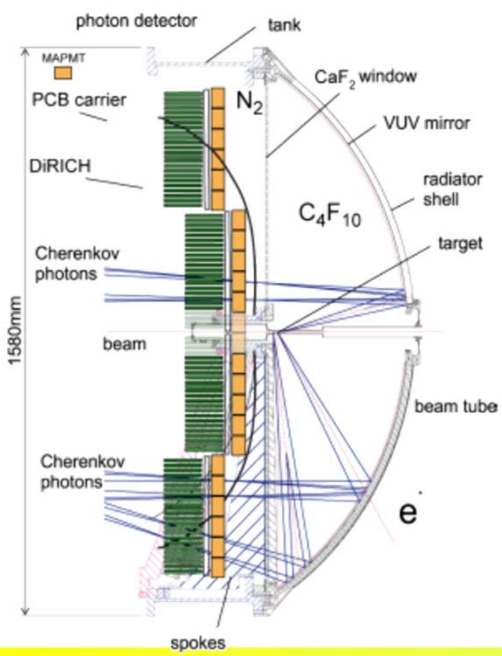


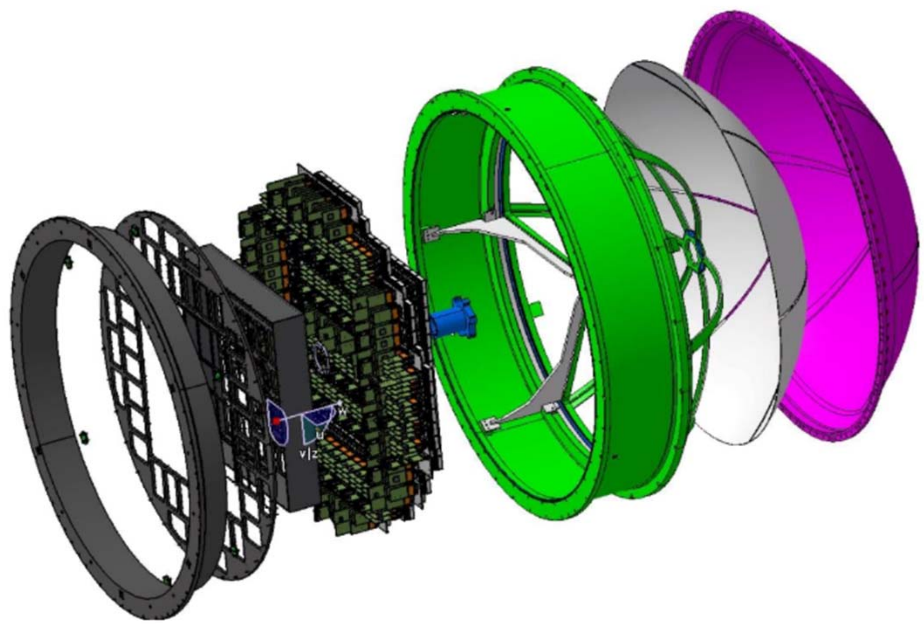


HADES Upgrade

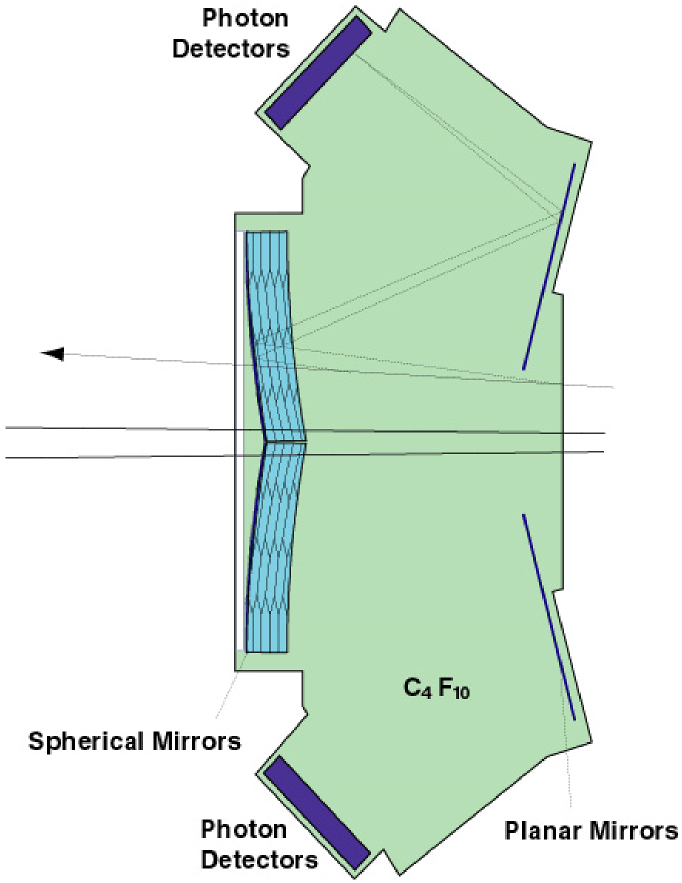


- Replace CsI-MWPCs with MaPMTs
  - Hamamatsu H12700
  - Same as for CBM-RICH
  - Also share electronics

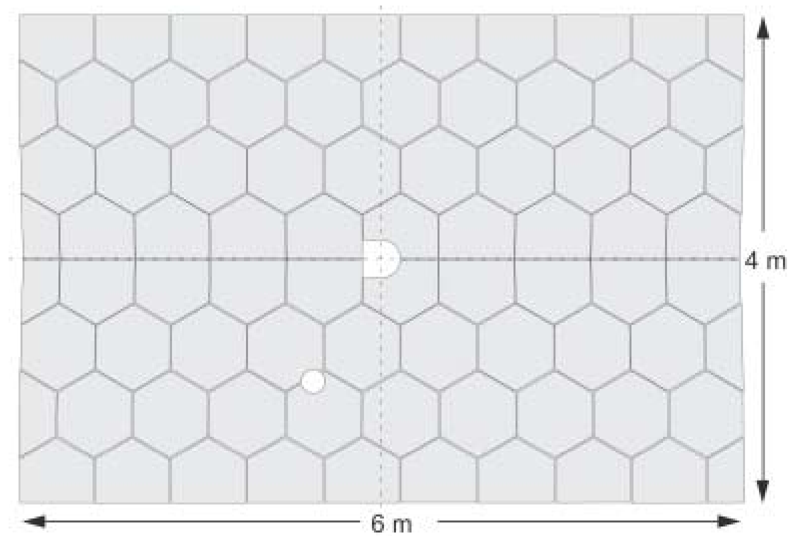




Mirror alignment



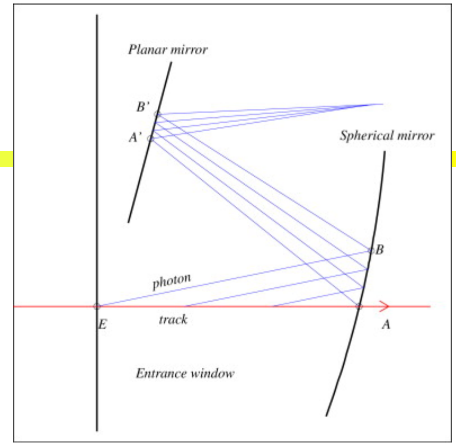
Gas radiator RICHes: large mirrors → tens of segments → need relative alignment



- Spherical mirror: 80 hexagonal segments
- Planar mirrors: 2x 18 rectangular segments

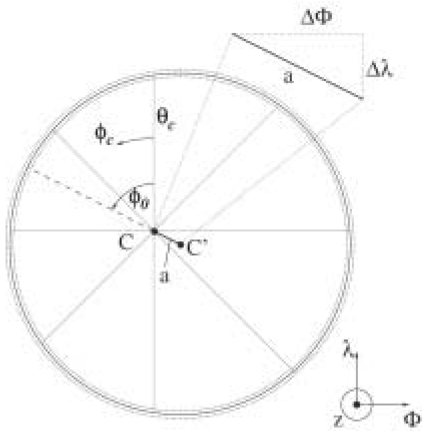
Aligning pairs of spherical and planar segments by using unambiguous photons.

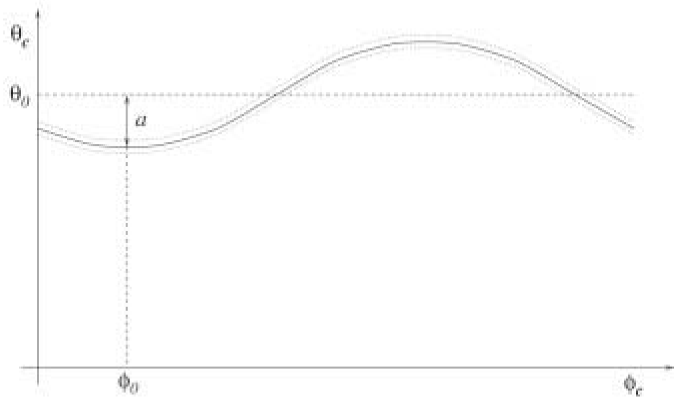
Mirror alignment

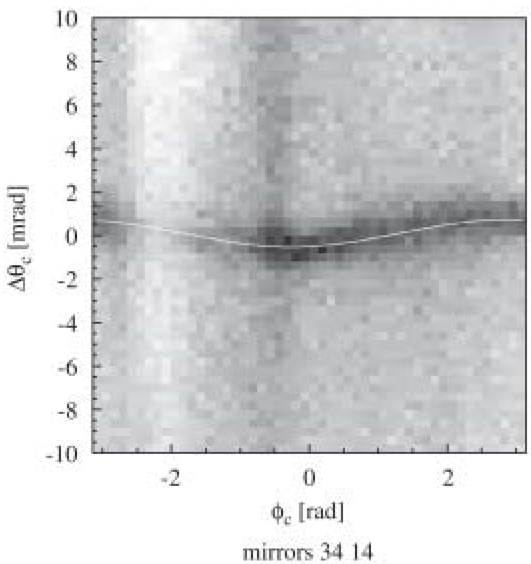


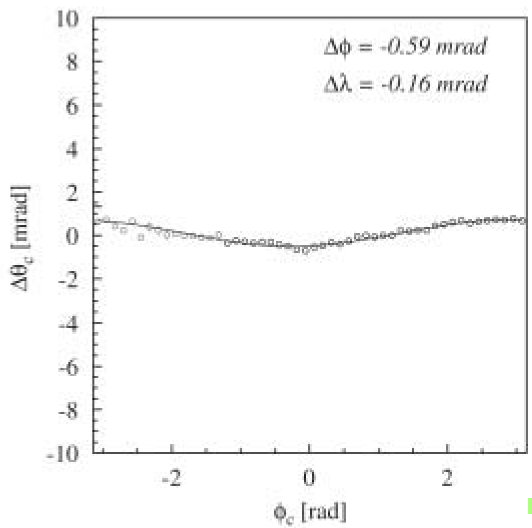
Misalignment: Cherenkov angle depends on the azimuthal angle around the track

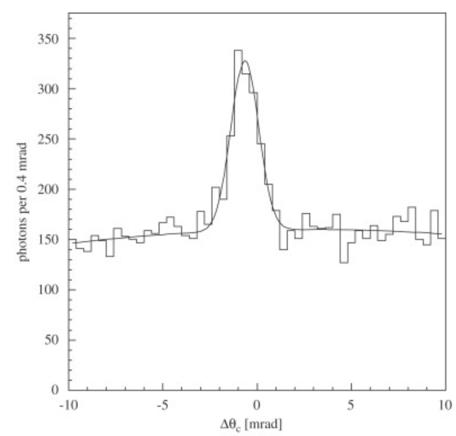
Use unambiguos photons.











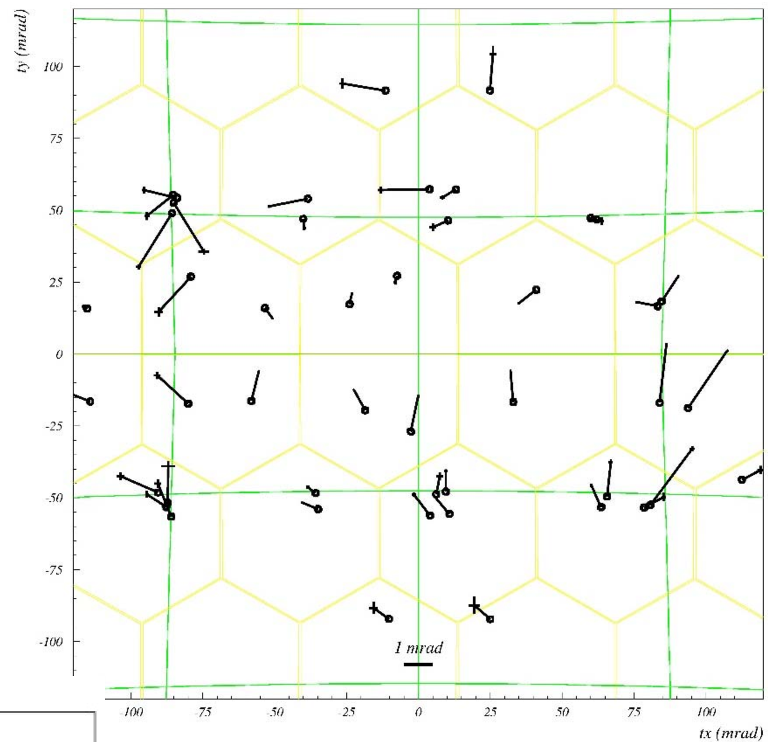
Slice in ϕ_c

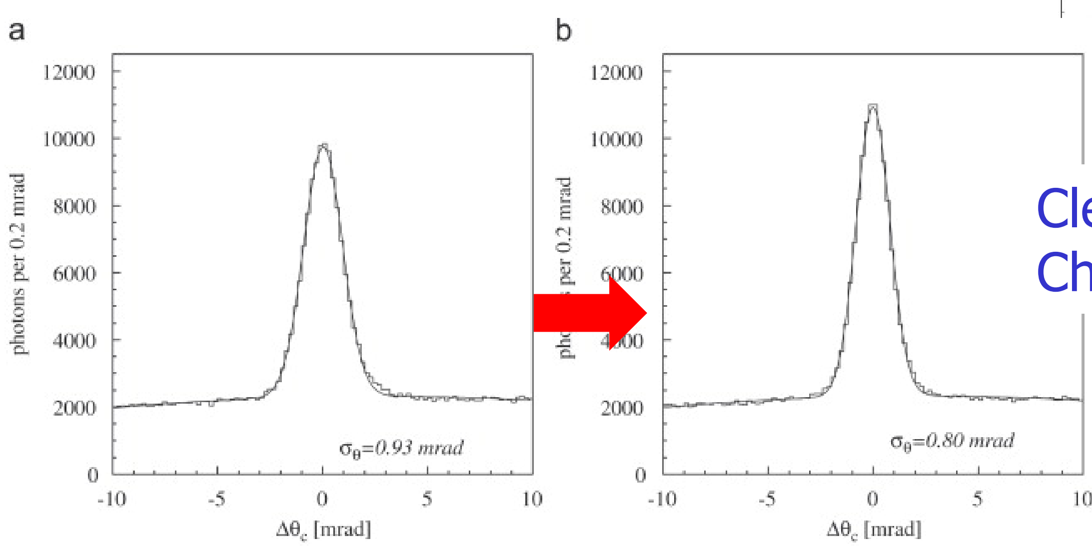
Mirror alignment

Initial mirror system alignment: with optical methods, theodolite.

Alignment with data: tells you the ultimate truth…

Combine all alignment data for all (possible) pairs of segments → solve a system of linear equations

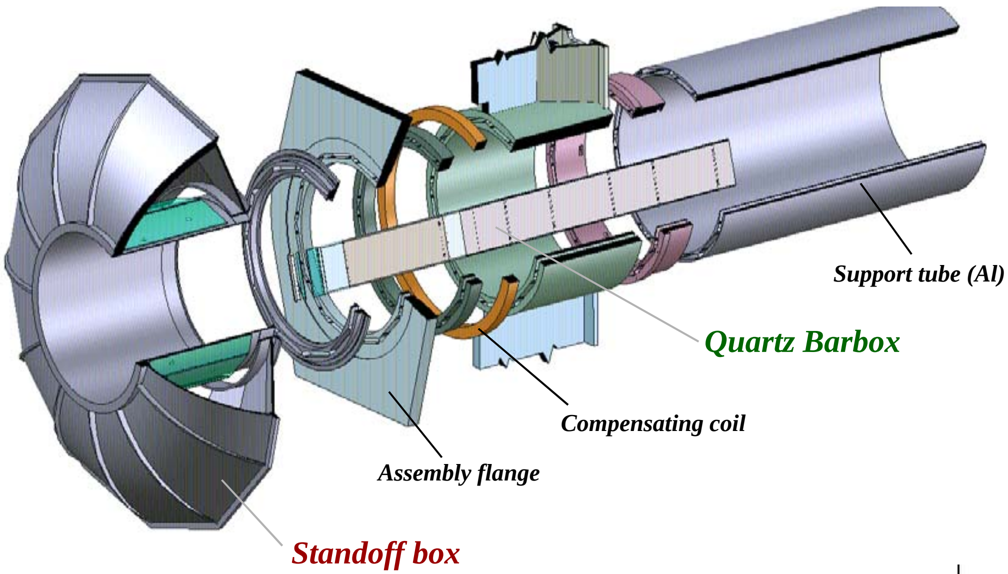


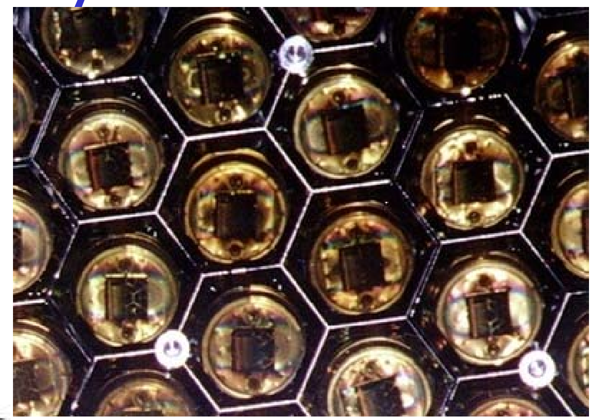


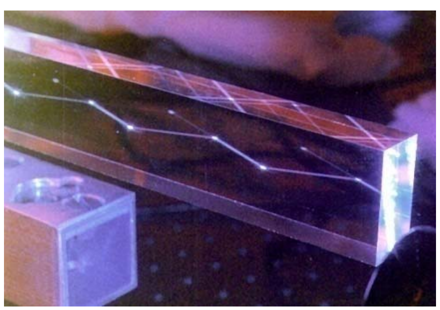
Clear improvement in Cherenkov angle resolution

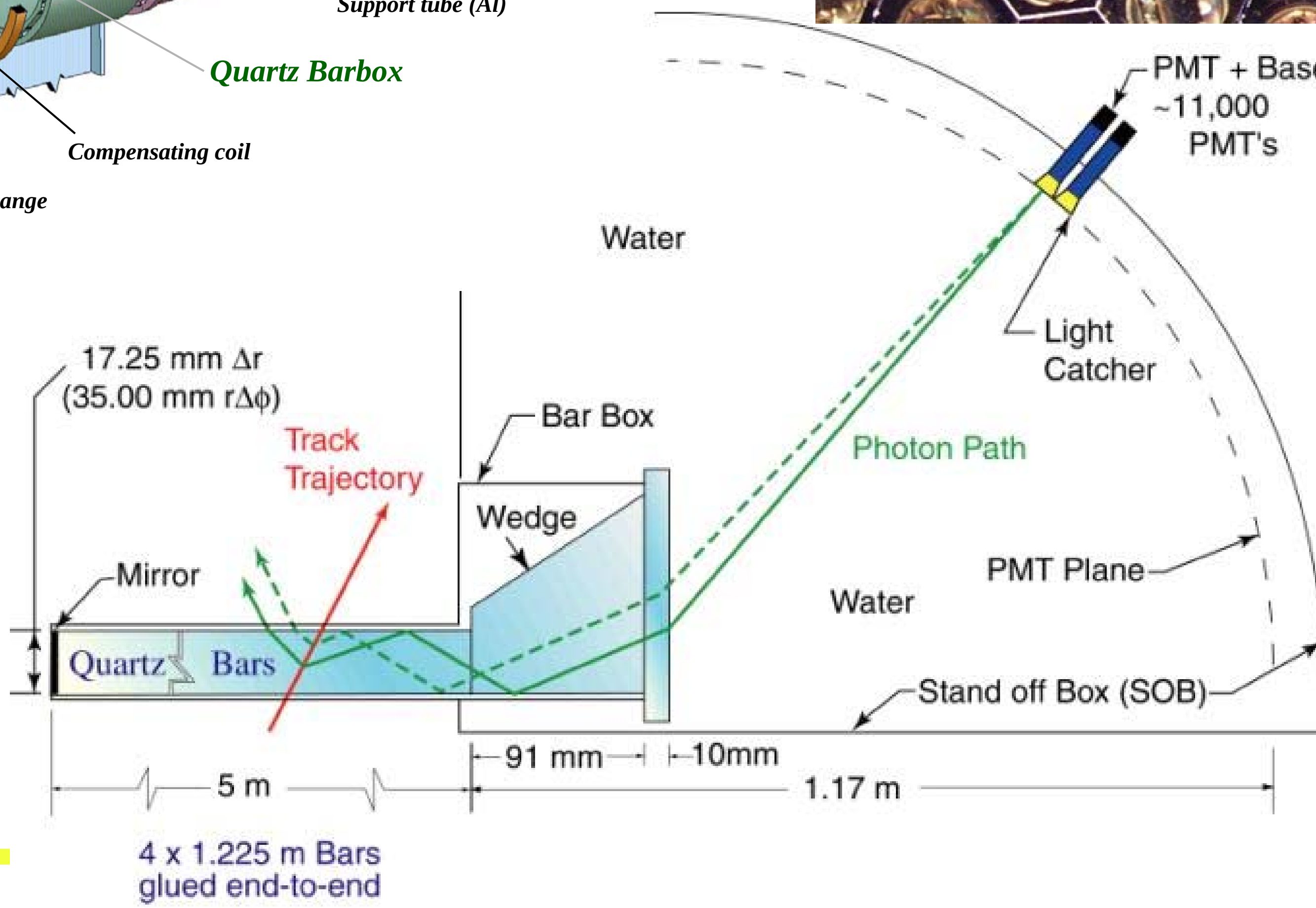
→NIMA 586 (2008) 174

DIRC (@BaBar) - detector of internally reflected Cherenkov light



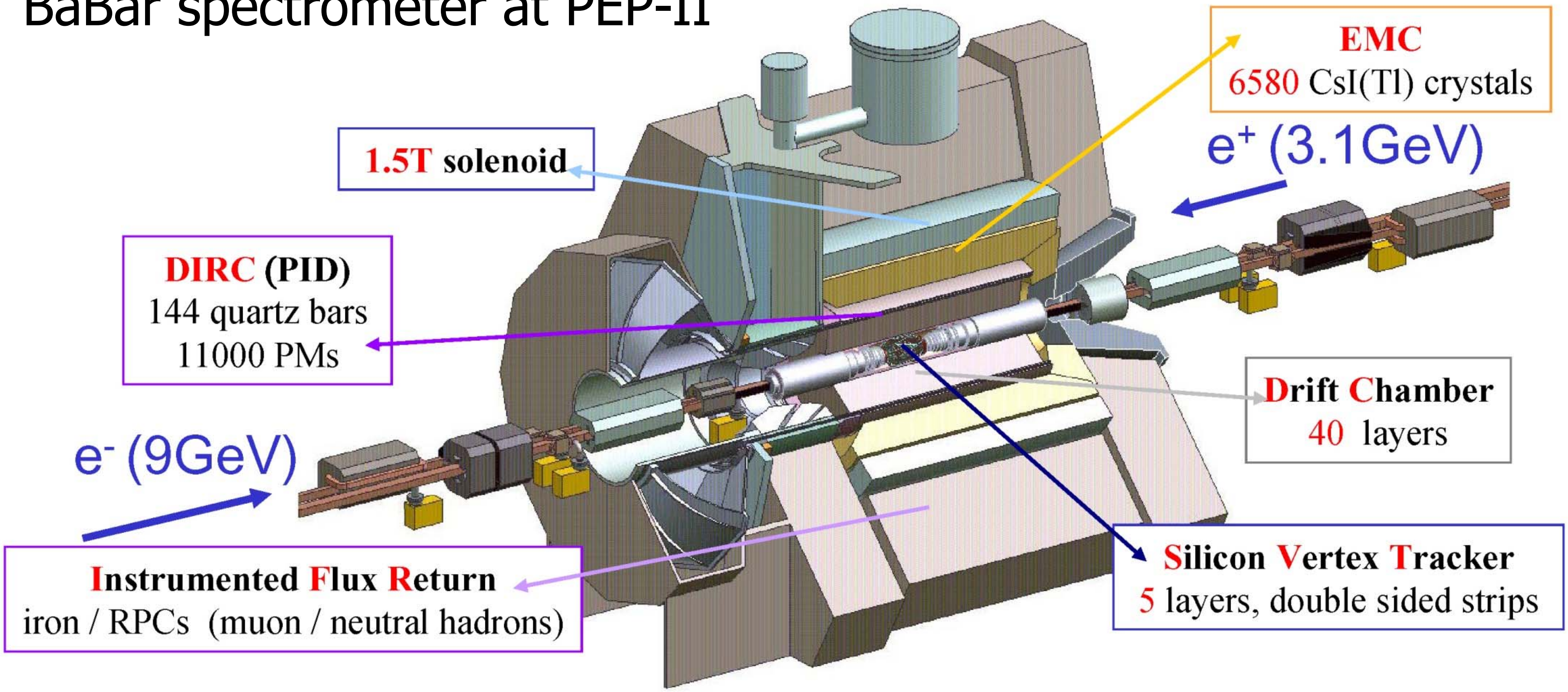




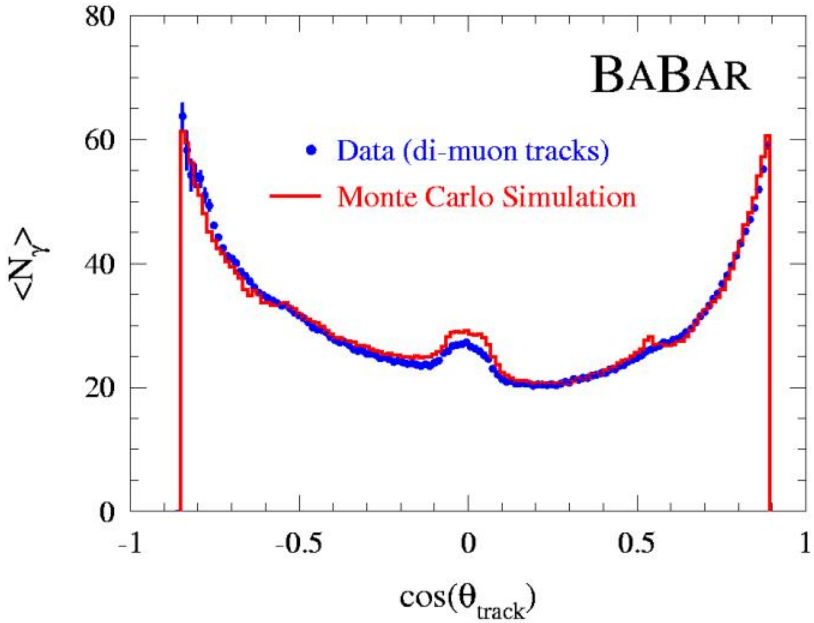


DIRC - detector of internally reflected Cherenkov light

BaBar spectrometer at PEP-II

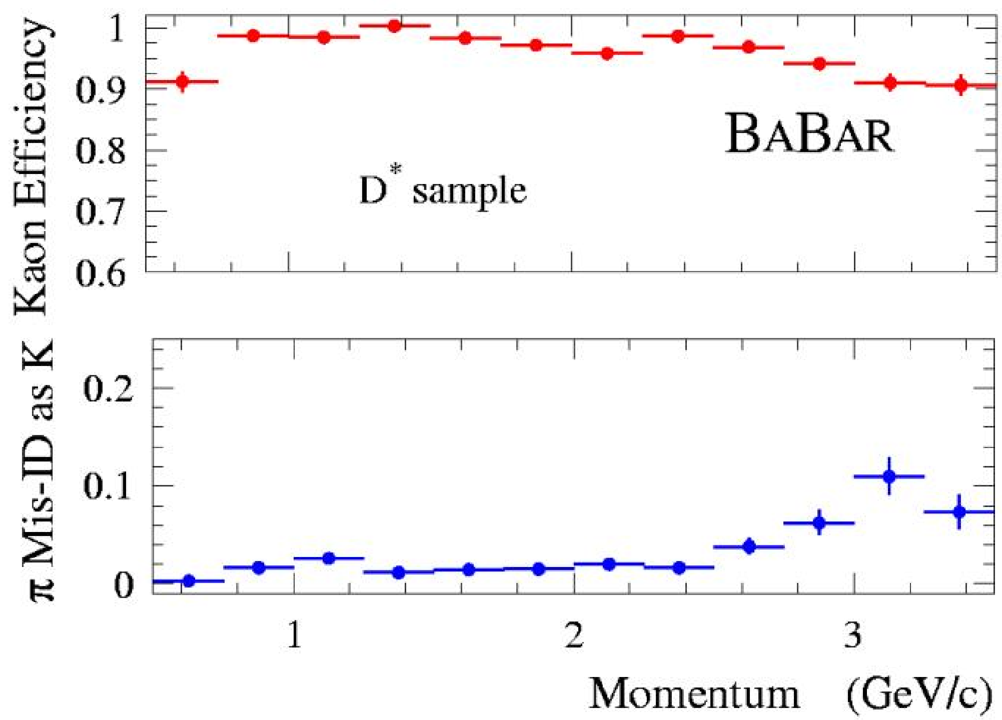


DIRC performance



← Lots of photons!

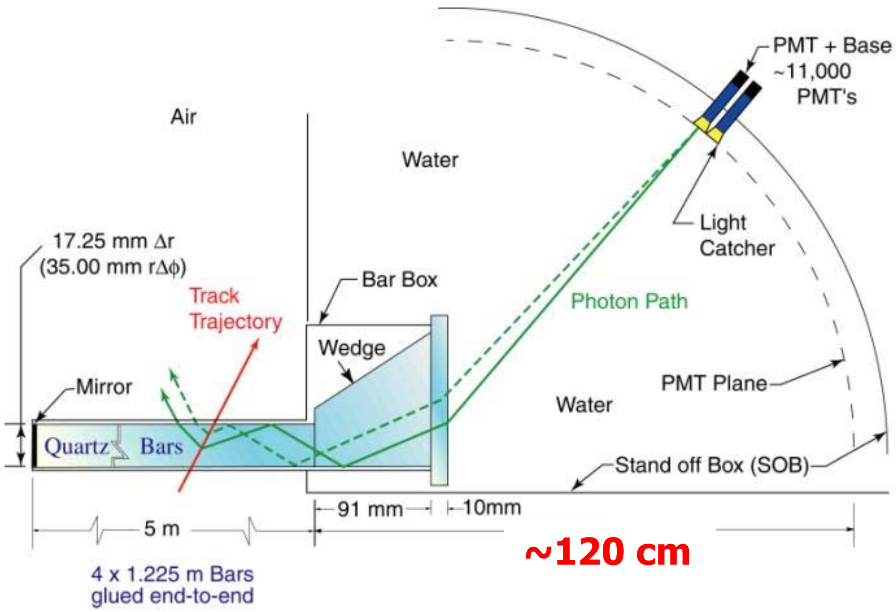
Excellent π/K separation

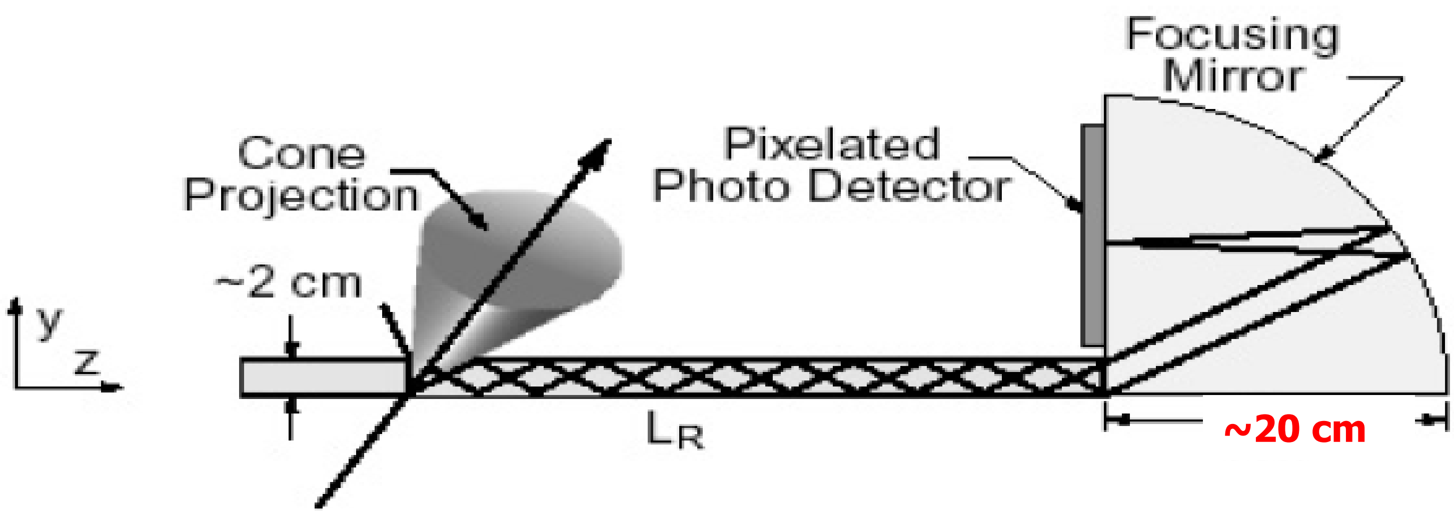


NIM A553 (2005) 317

Focusing DIRC

Upgrade idea: step further, remove the stand-off box →





Focusing DIRC

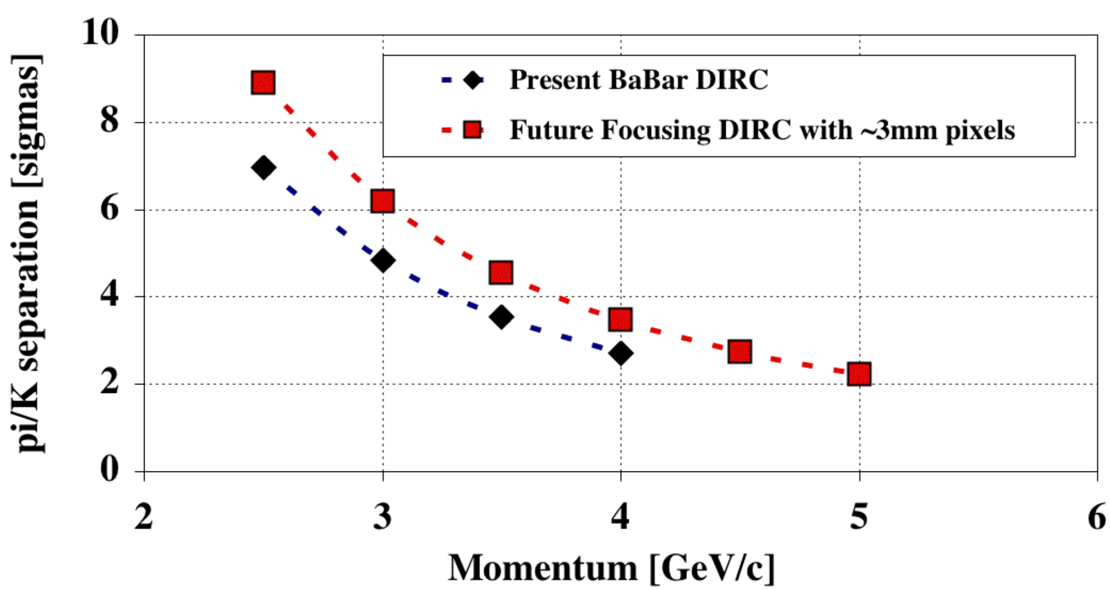
Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10

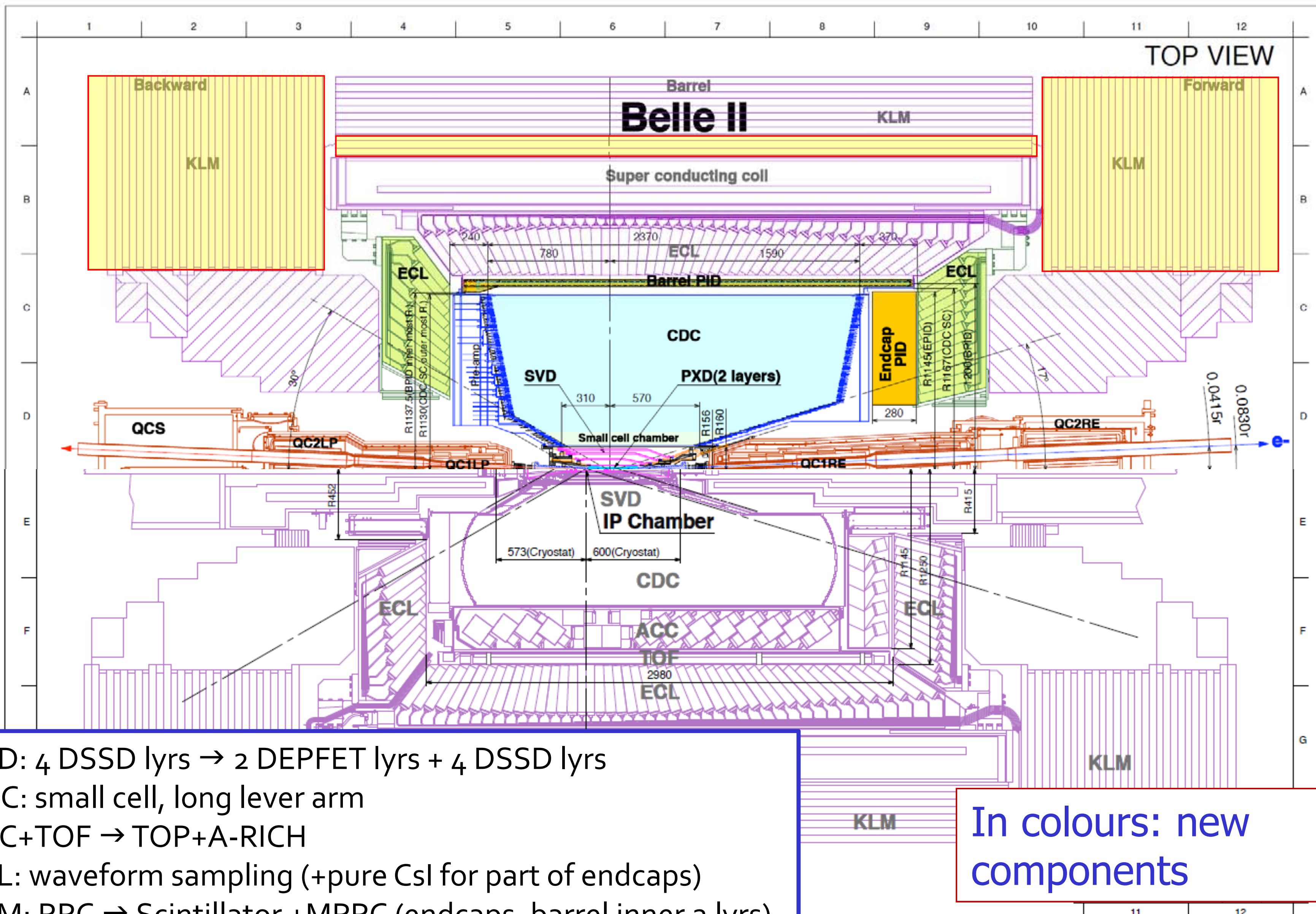
Timing resolution improvement: σ ~1.7ns (BaBar DIRC) → $\sigma \leq$150-200ps (~10x better) allows a measurement of the photon group velocity $c_g(\lambda)$ to correct the chromatic error of θ_c.

Photon detector:

- Pad size <5mm
- Time resolution ~50-100ps



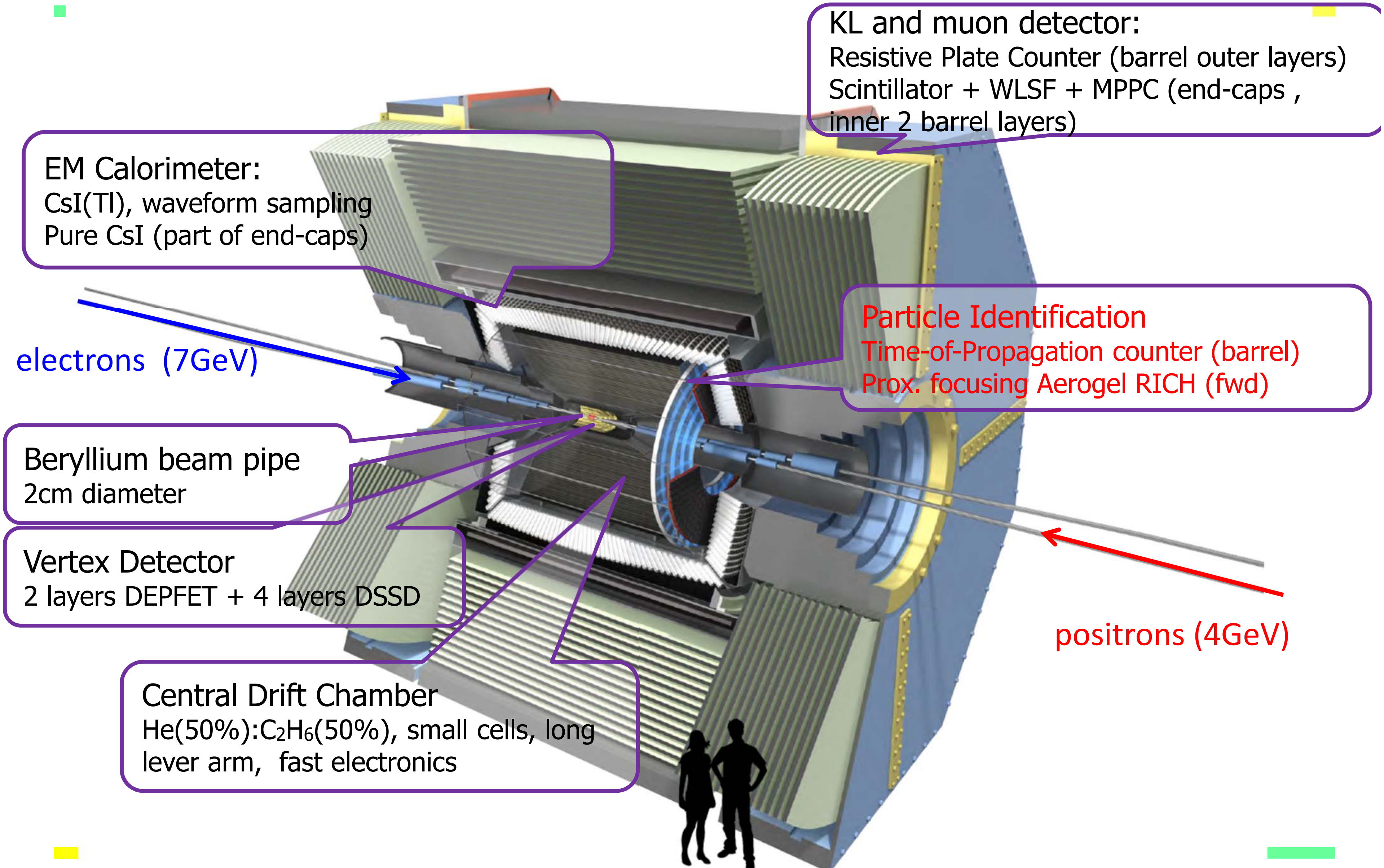
Belle II Detector (compared to Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for part of endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

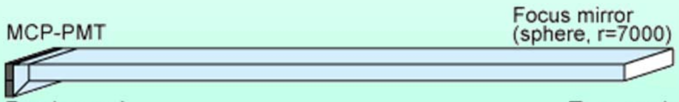
Belle II Detector



bljana

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



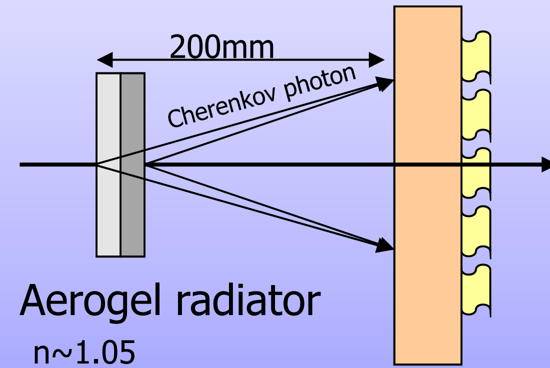
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

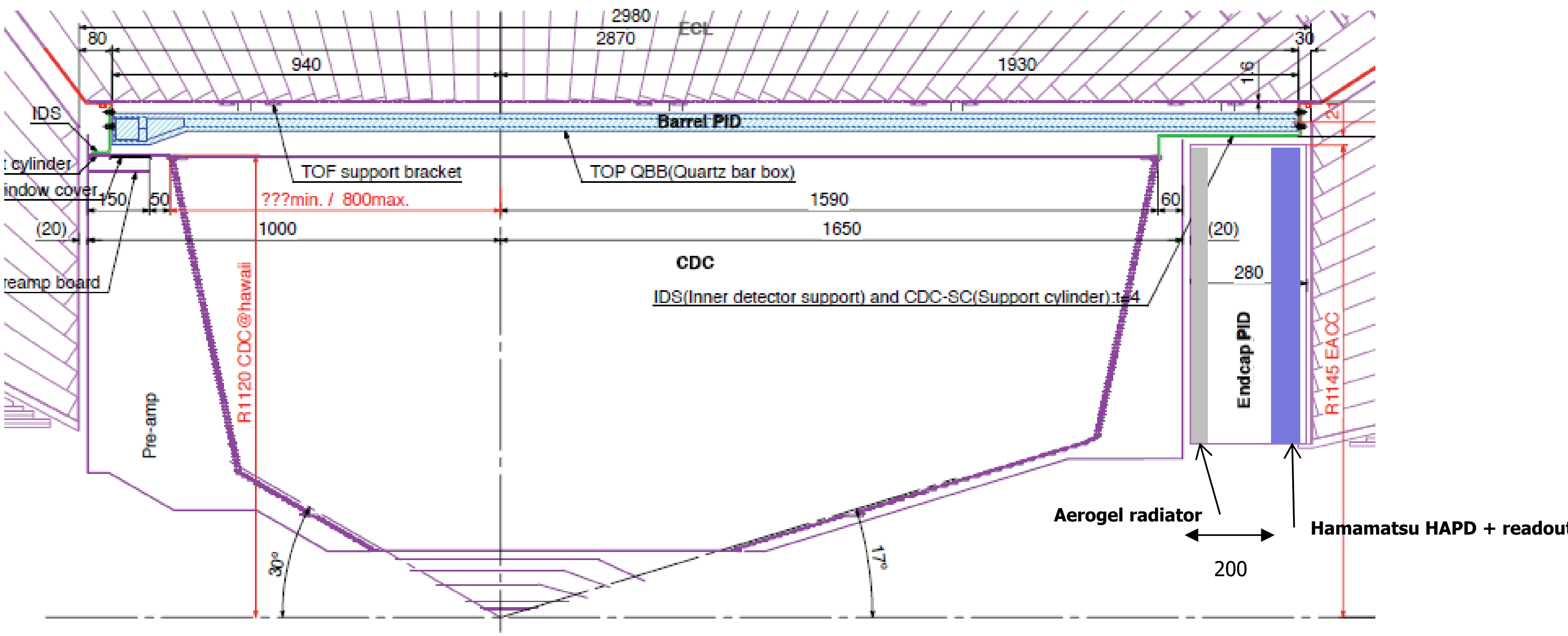


Aerogel radiator

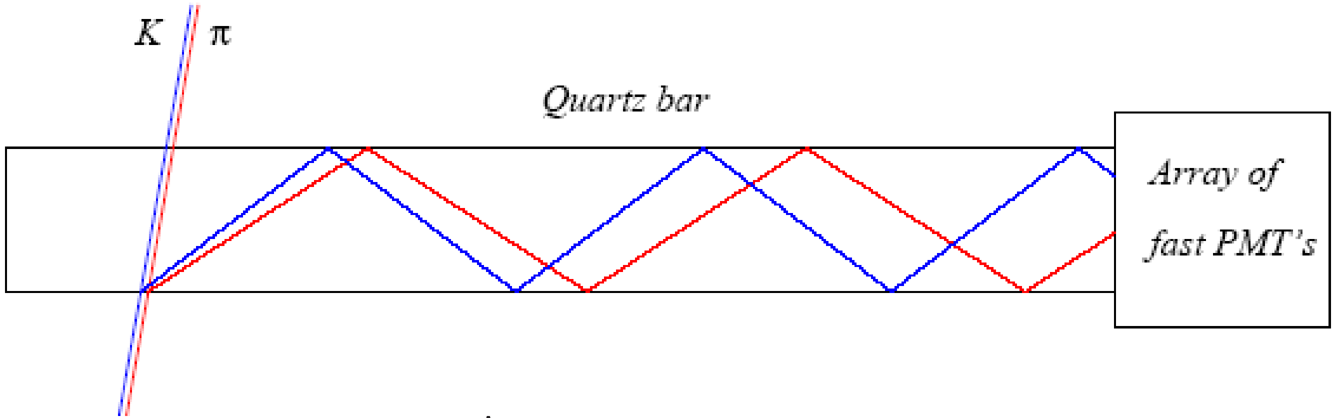
n~1.05

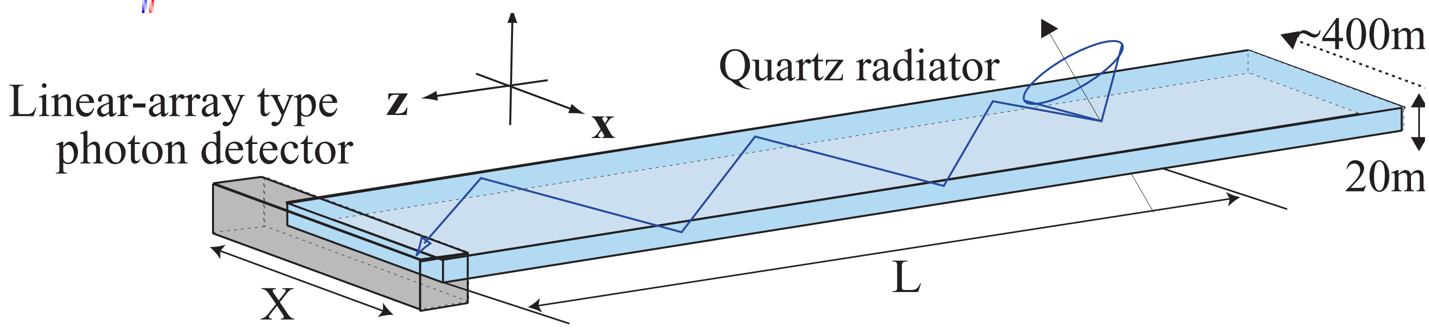
Hamamatsu HAPD

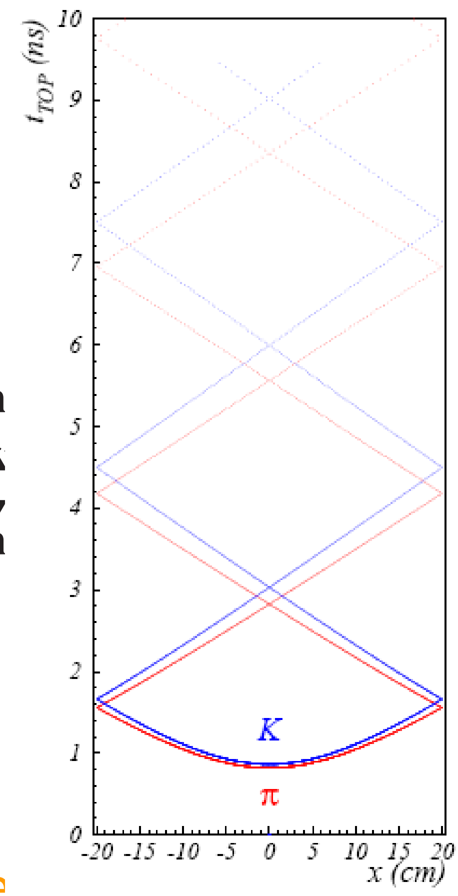
+ new ASIC



Time-Of-Propagation (TOP) counter



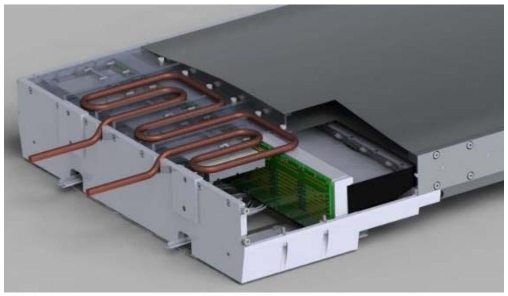


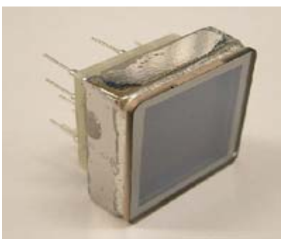


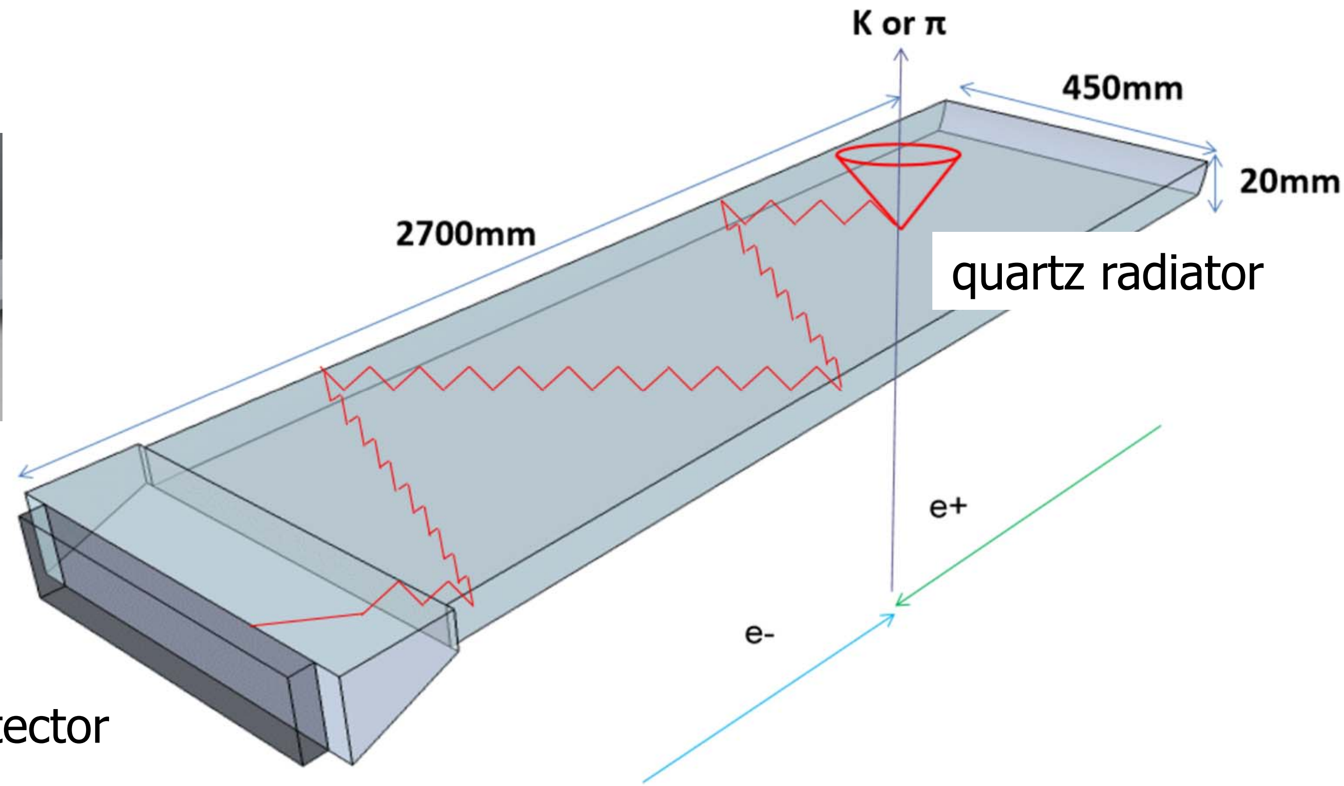
Similar to DIRC, but instead of two coordinates measure

- One (or two coordinates) with a few mm precision
- Time-of-arrival

Belle II Barrel PID: Time of propagation (TOP) counter



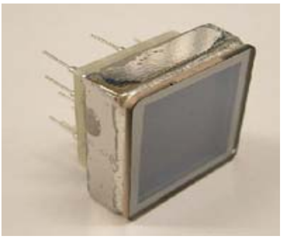


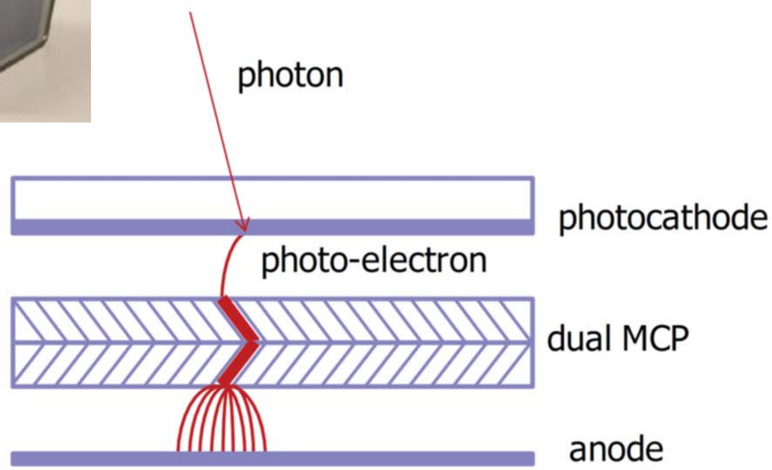


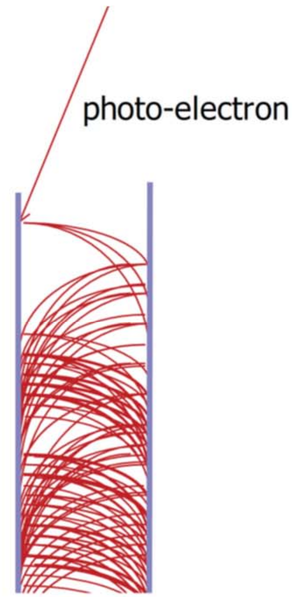
Photon detector

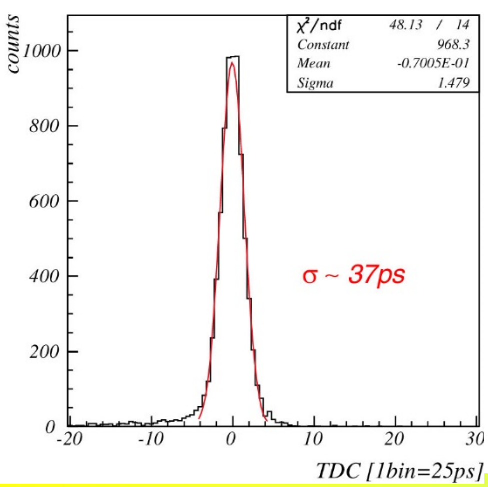
- Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity at 1.5 T

MCP PMTs for a very fast timing





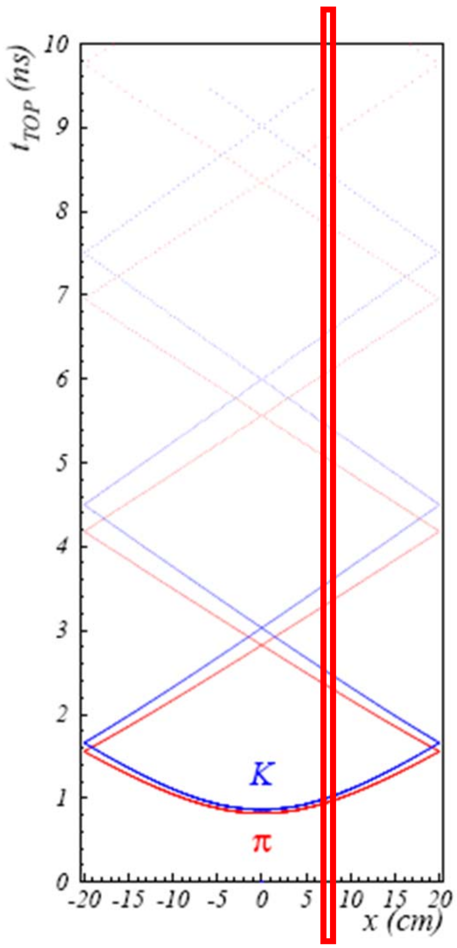




Micro-channel plate PMTs:

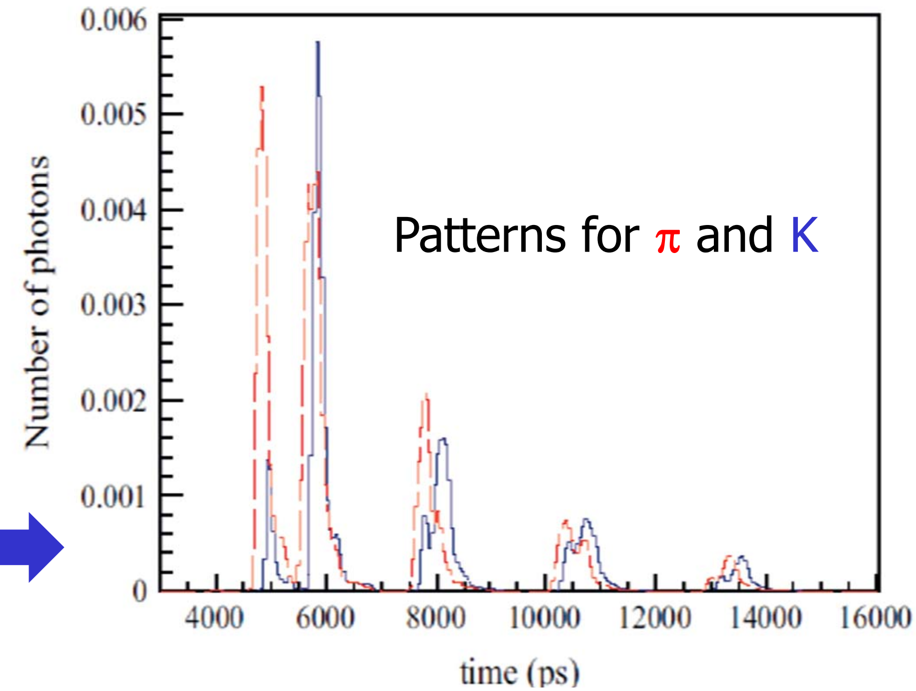
Single photon resolution: typically 20ps – 40ps

TOP image reconstruction



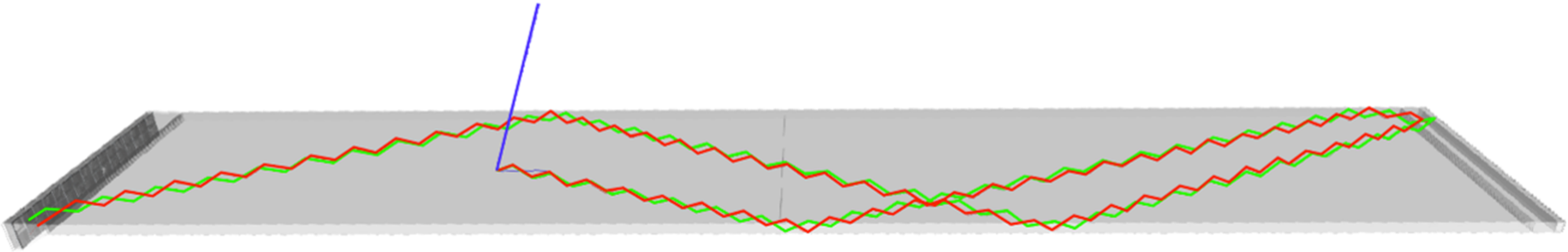
Pattern in the coordinate-time space ('ring') of a pion and kaon hitting a quartz bar

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

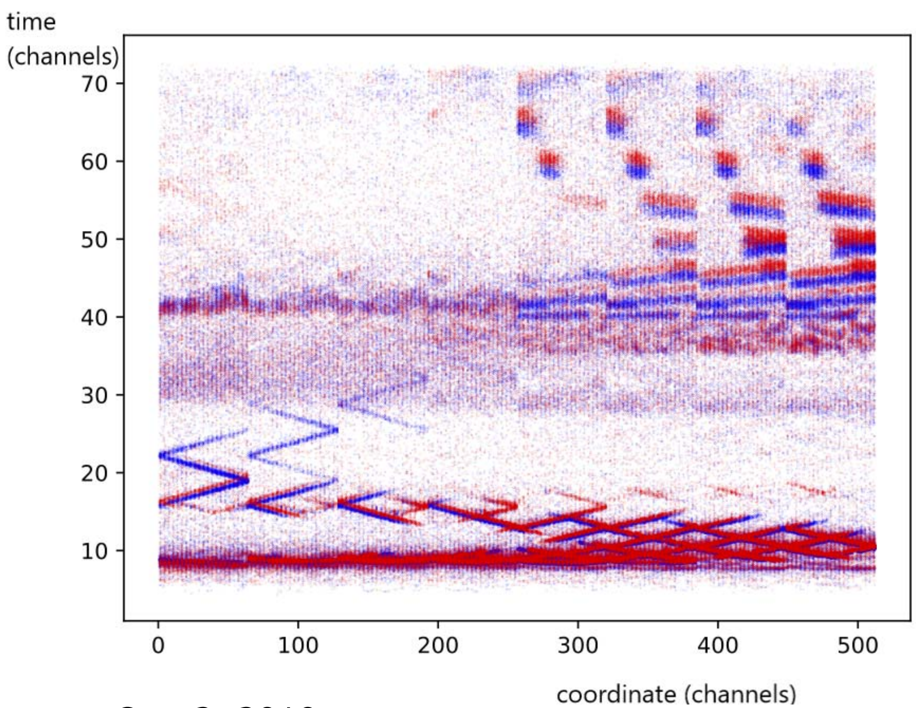


The name of the game: analytic expressions for the 2D likelihood functions →M. Starič et al., NIMA A595 (2008) 252-255

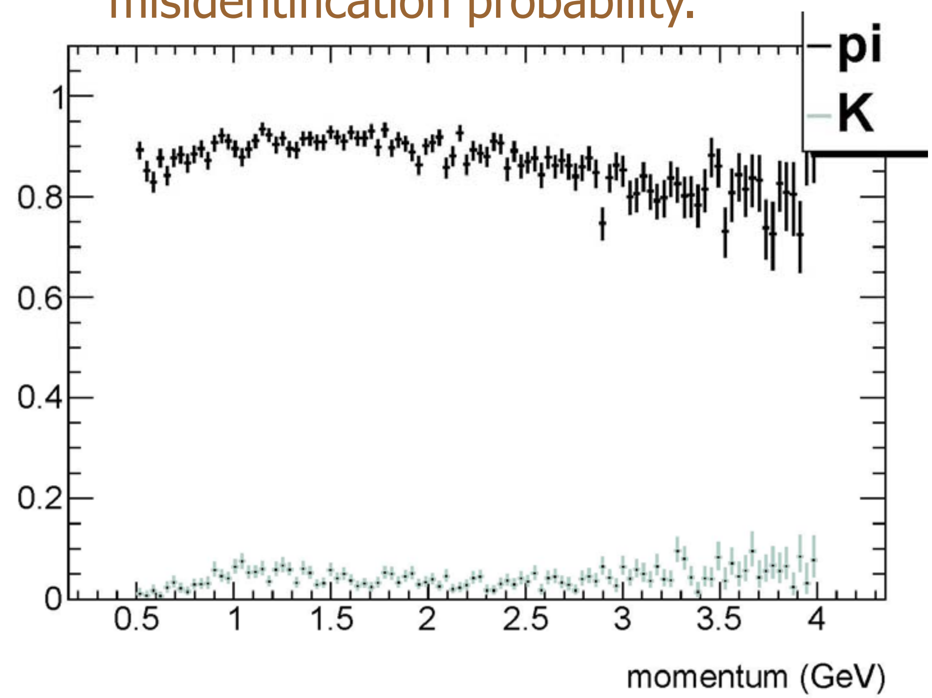
Separation of kaons and pions



Pions vs kaons in TOP:
different patterns in the time vs PMT impact point coordinate

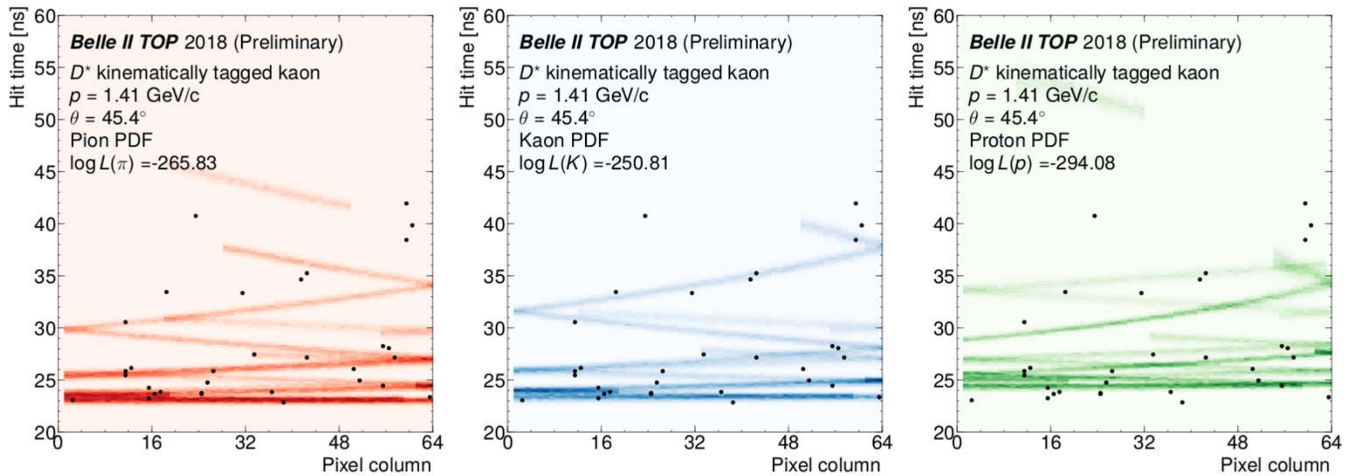


Pions vs kaons:
Expected PID efficiency and misidentification probability.

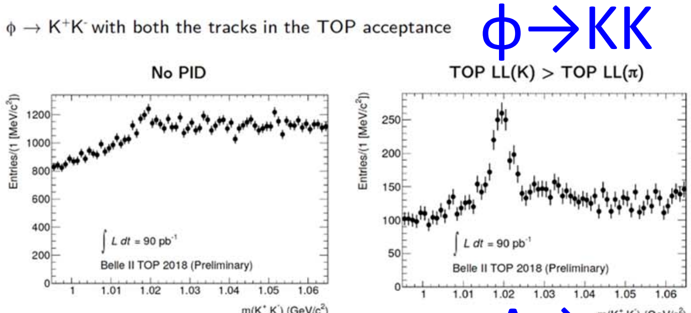


TOP first events

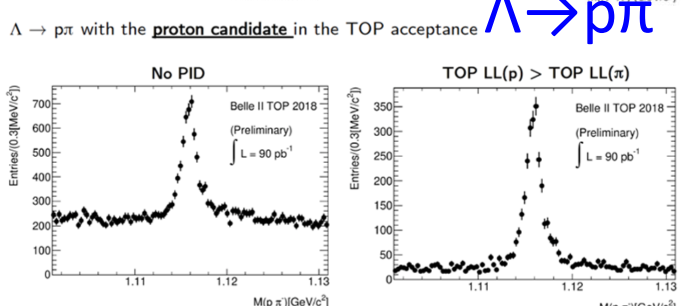
The early data demonstrated that the TOP principle is working



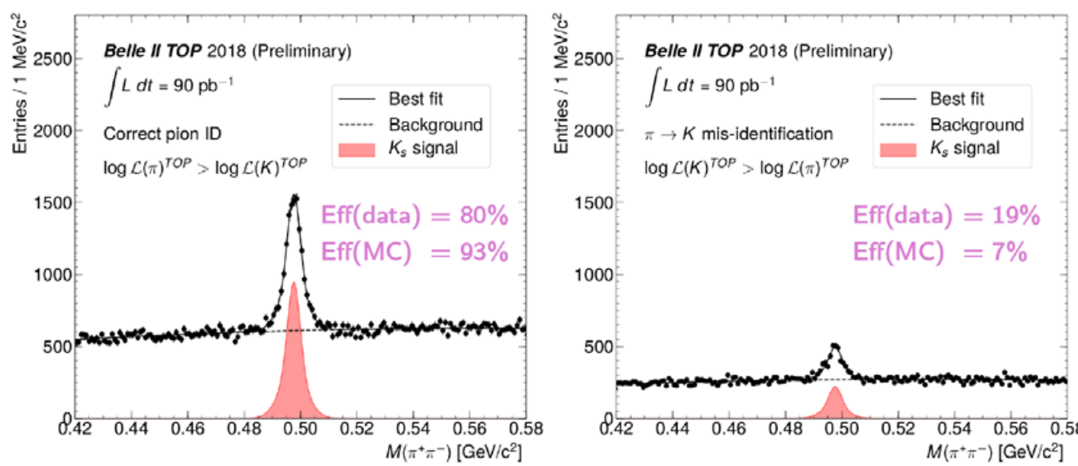
ϕ→KK



Λ→pπ

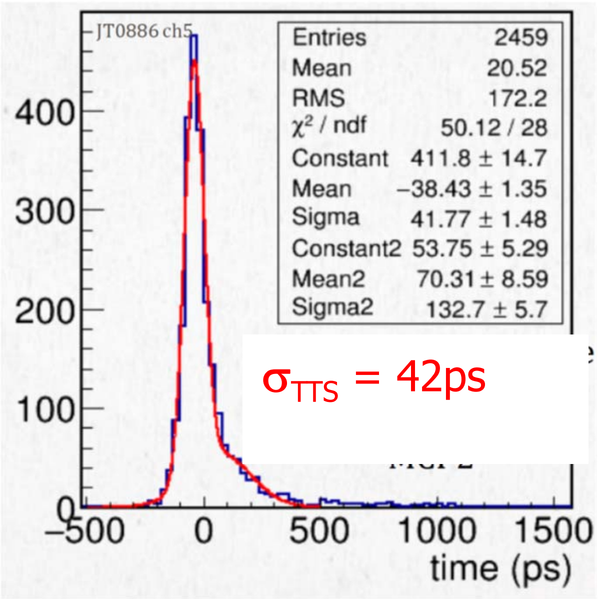


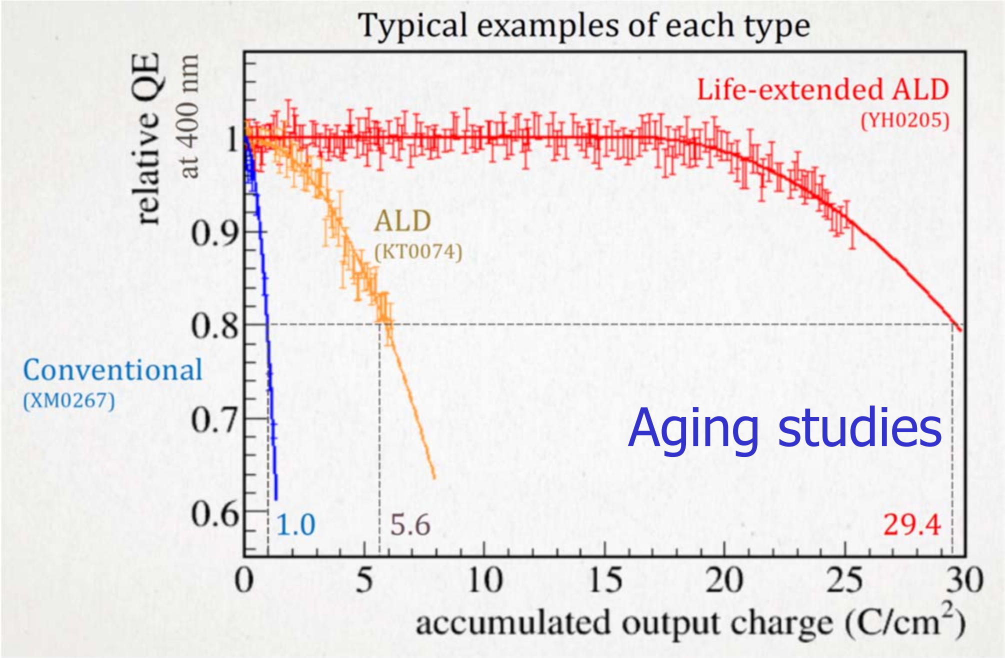
$K_s \rightarrow \pi\pi$



TOP R+D areas

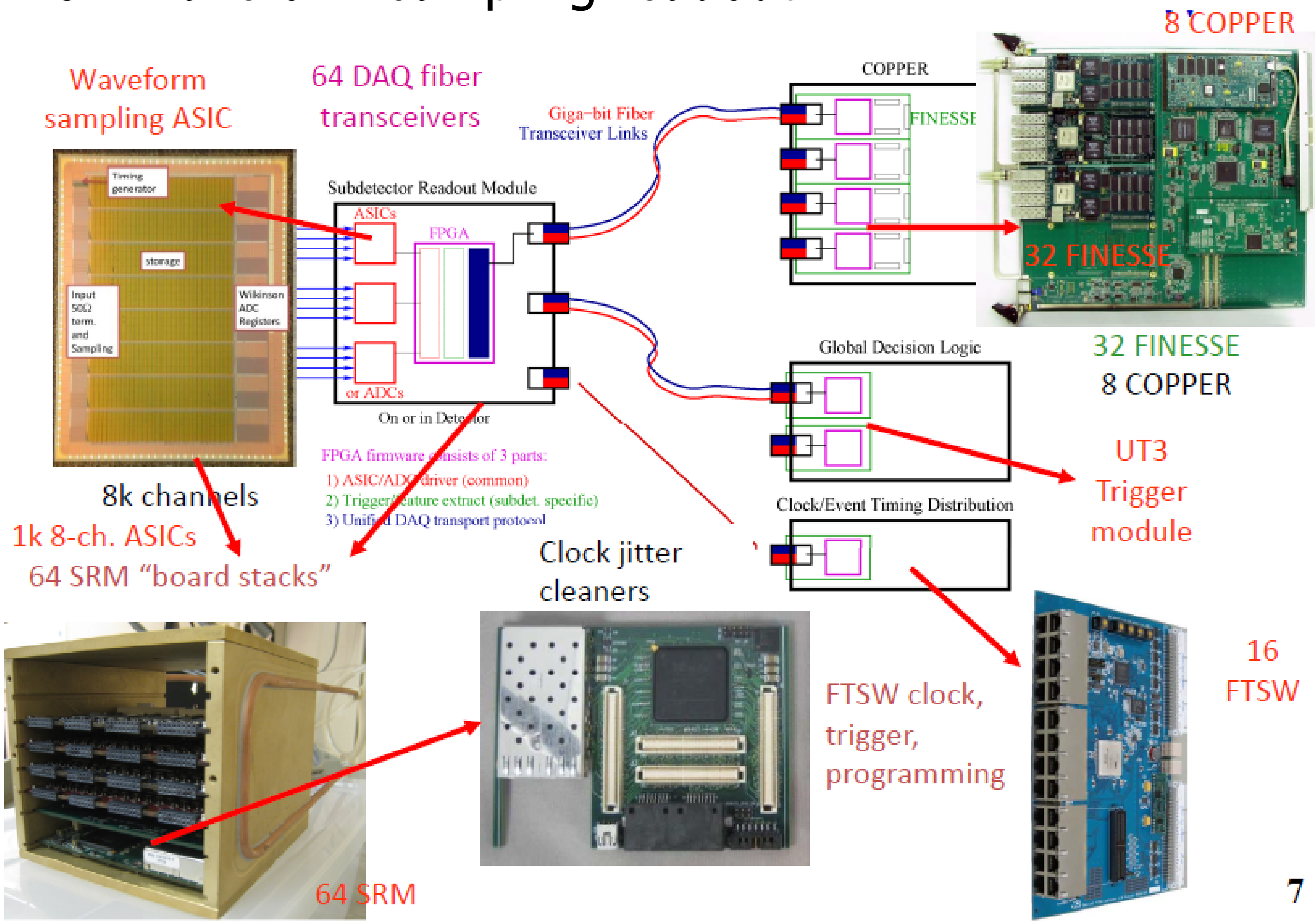
- Very fast photosensors for operation in 1.5 T field (MCP PMTs)
- R+D to mitigate aging of photocathodes in MCP PMTs (ALD)





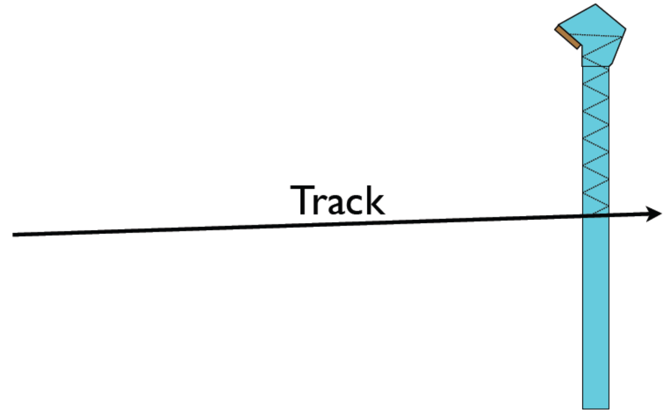
- Very fast and compact readout electronics with waveform sampling for a precise time measurement →
- Production of large quartz pieces, construction of modules, mechanics and installation methods
- Analytic expressions for the very complex 2D likelihood functions.

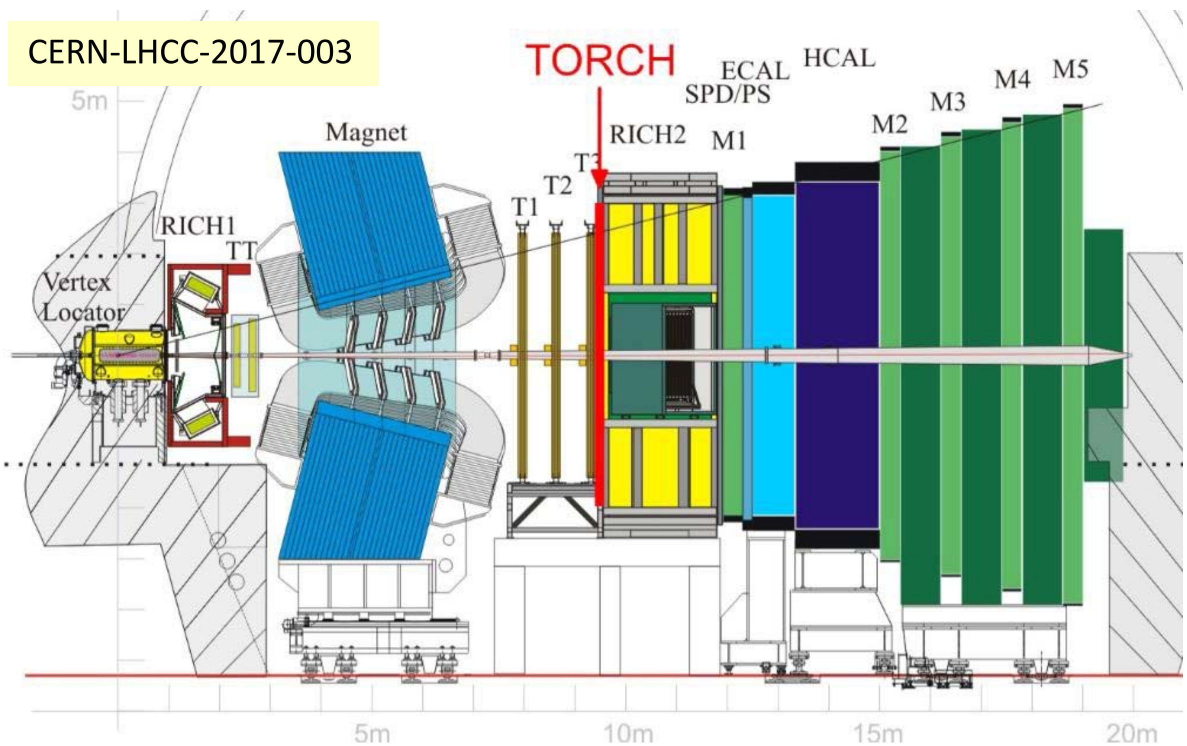
TOP Waveform sampling readout



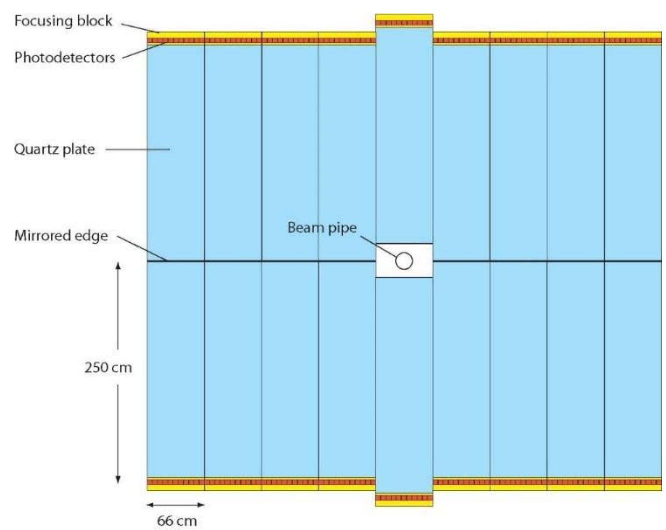
LHCb PID upgrade: TORCH

A special type of Time-of-Propagation counter for the LHCb upgrade

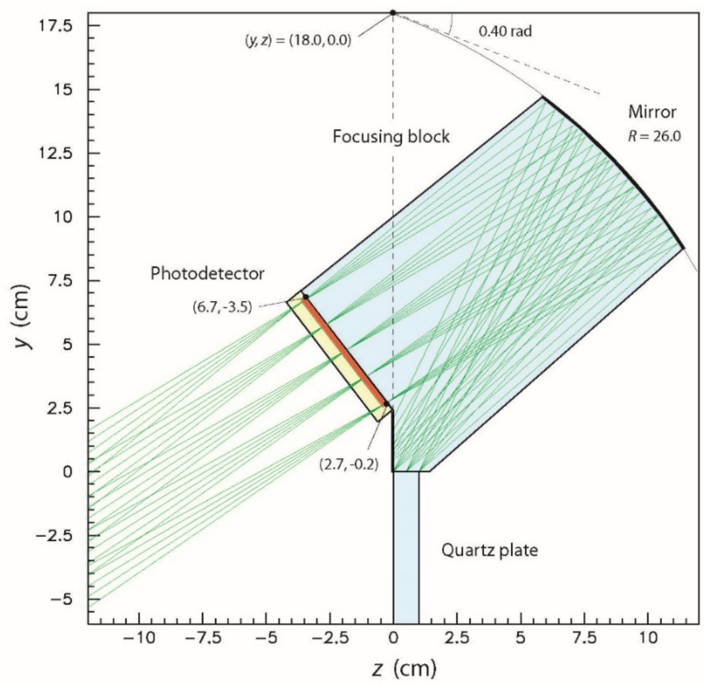




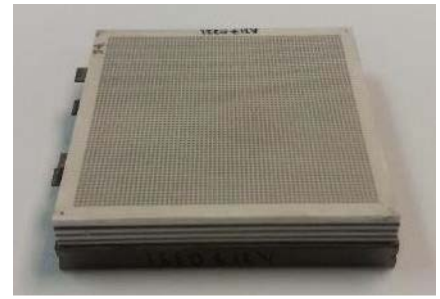
- TORCH area 5 x 6 m^2
- 18 module system
- 11 MCPs per module



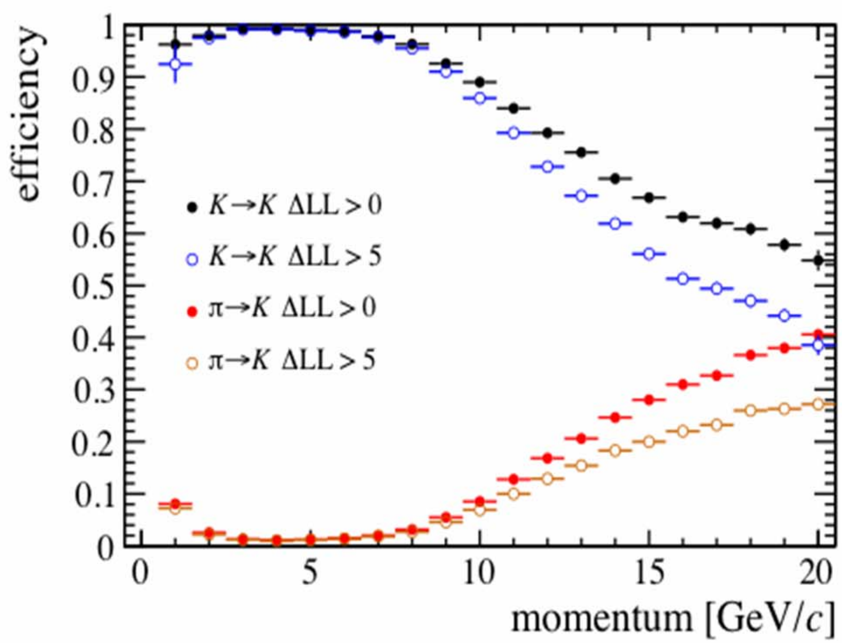
LHCb PID upgrade: TORCH

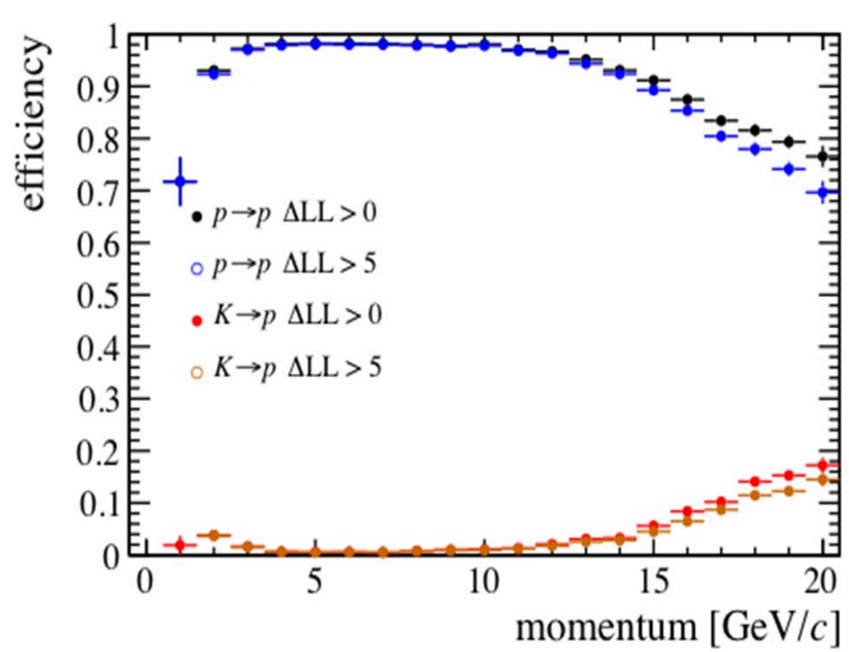


Focusing block with light sensors (MCP PMTs from Photek)

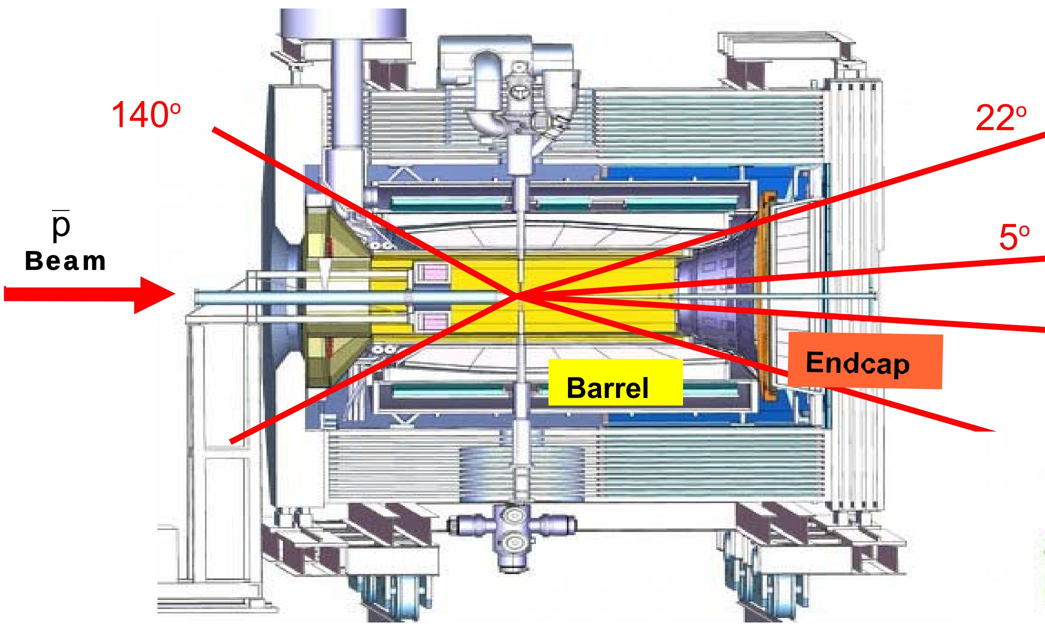


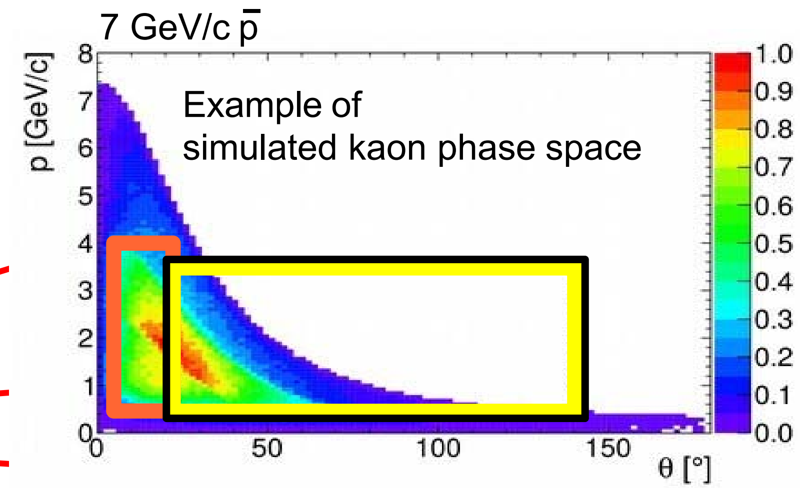
Expected performance





PANDA DIRC counters



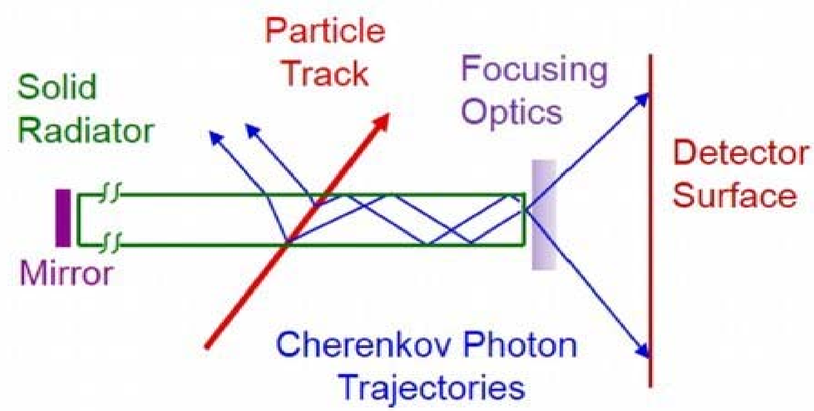


Barrel DIRC

Goal: 3 s.d. π/K separation up to 3.5 GeV/c

Endcap Disc DIRC

Goal: 3 s.d. π/K separation up to 4 GeV/c

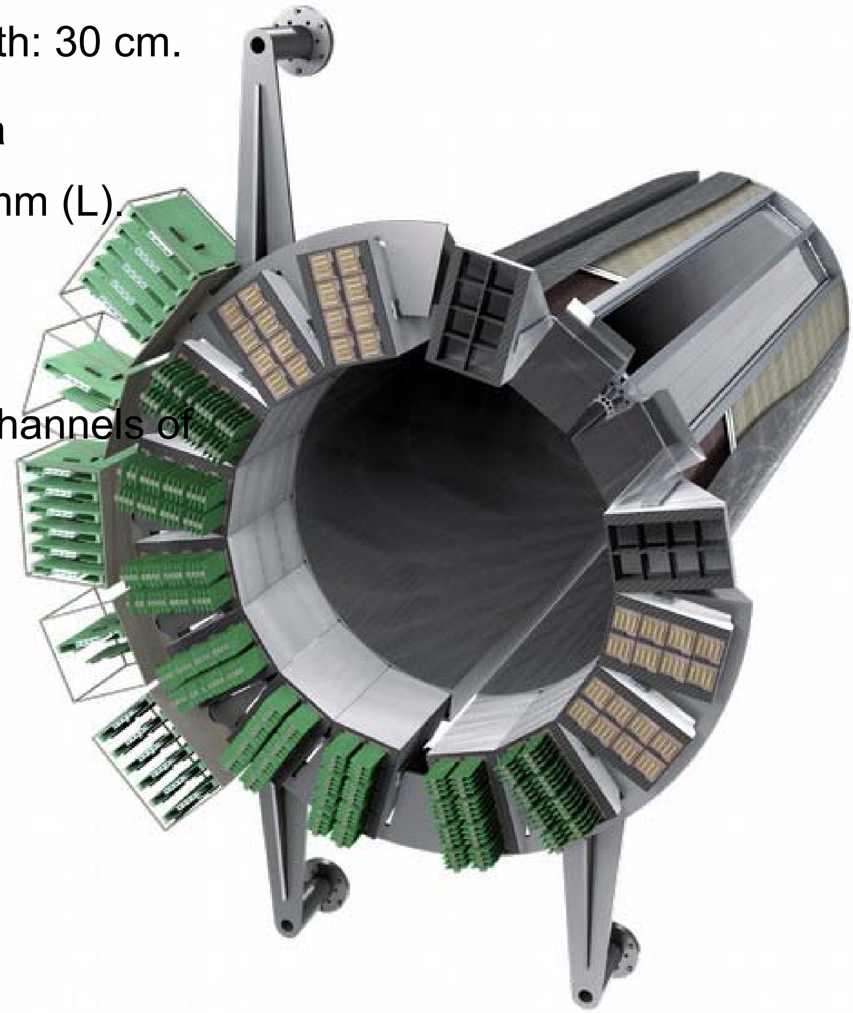


Magnitude of photon angles in radiator preserved

PANDA Barrel DIRC

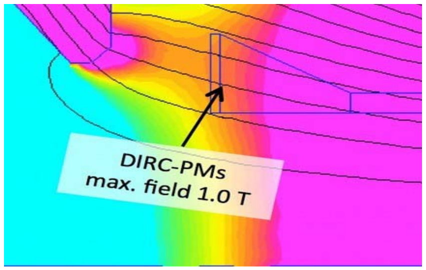
Design: based on BABAR DIRC and SuperB FDIRC with key improvements

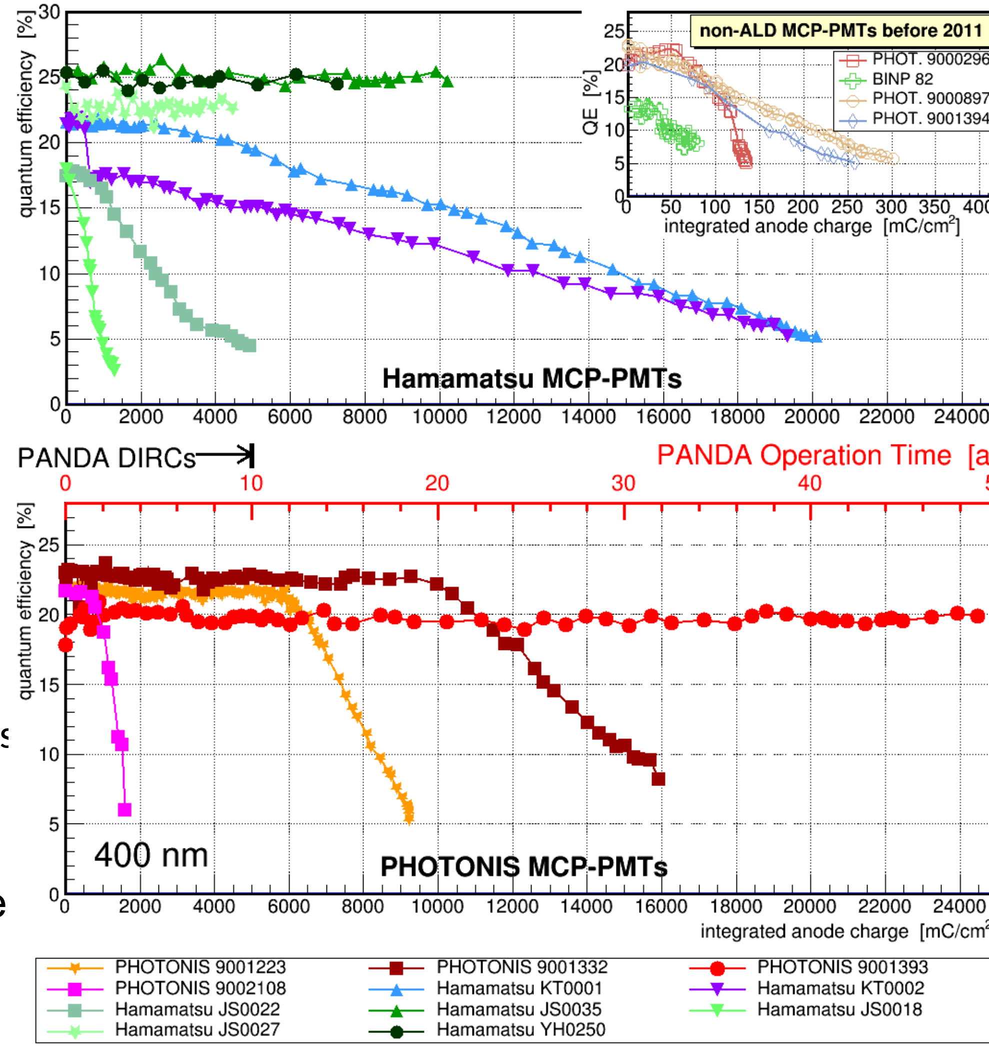
- Barrel radius ~48 cm; expansion volume depth: 30 cm.
- 48 narrow radiator bars, synthetic fused silica
  17 mm (T) x 53 mm (W) x 2400 mm (L).



- Compact photon detector:
  30 cm fused silica expansion volume 8192 channels of MCP-PMTs
  in ~1T B field
- Focusing optics: spherical lens system
- Fast photon detection:
  fast TDC plus TOT electronics,
  → 100-200 ps timing

Photon detector





Requirements:

- **few mm** spatial resolution
- **~100 ps** timing resolution

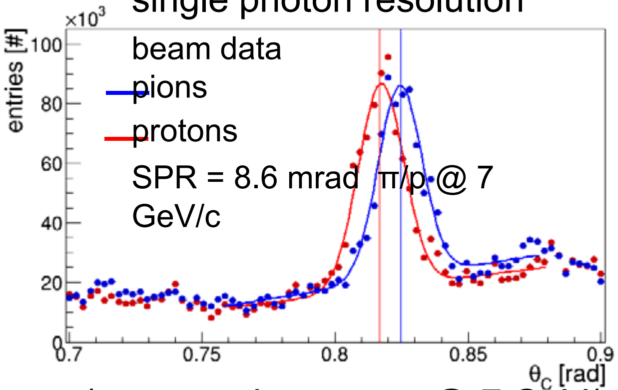
Bar-box:

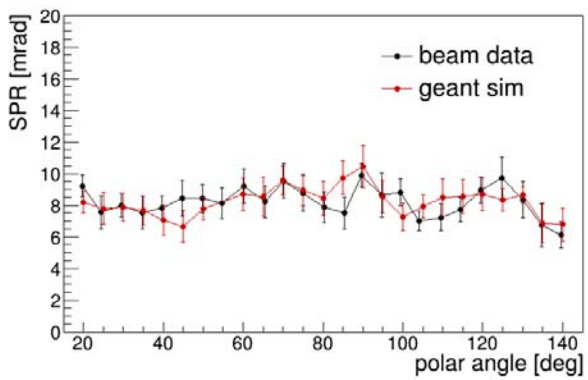
8 MCP-PMT, 512 pixels (total 8 k readout channels
survive **10 years** of PANDA (aging)

Most sensors with **ALD coated** MCPs have

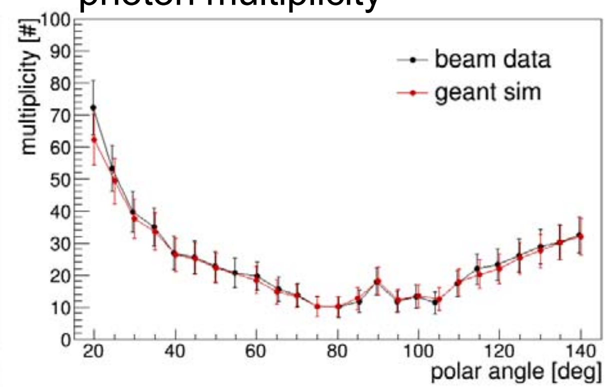
Beam Test at CERN 2018

single photon resolution

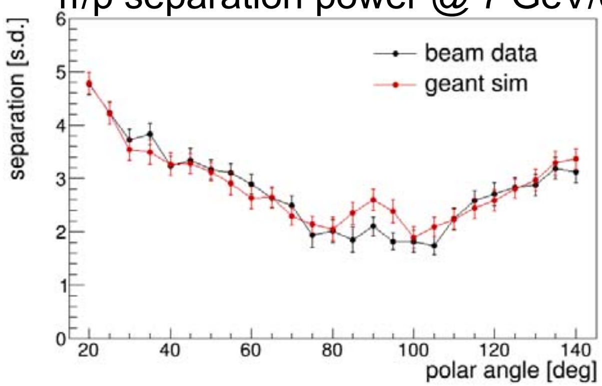




photon multiplicity



π/p separation power @ 7 GeV/c



Good performance
Good agreement with Geant simulations

Panda Disc DIRC

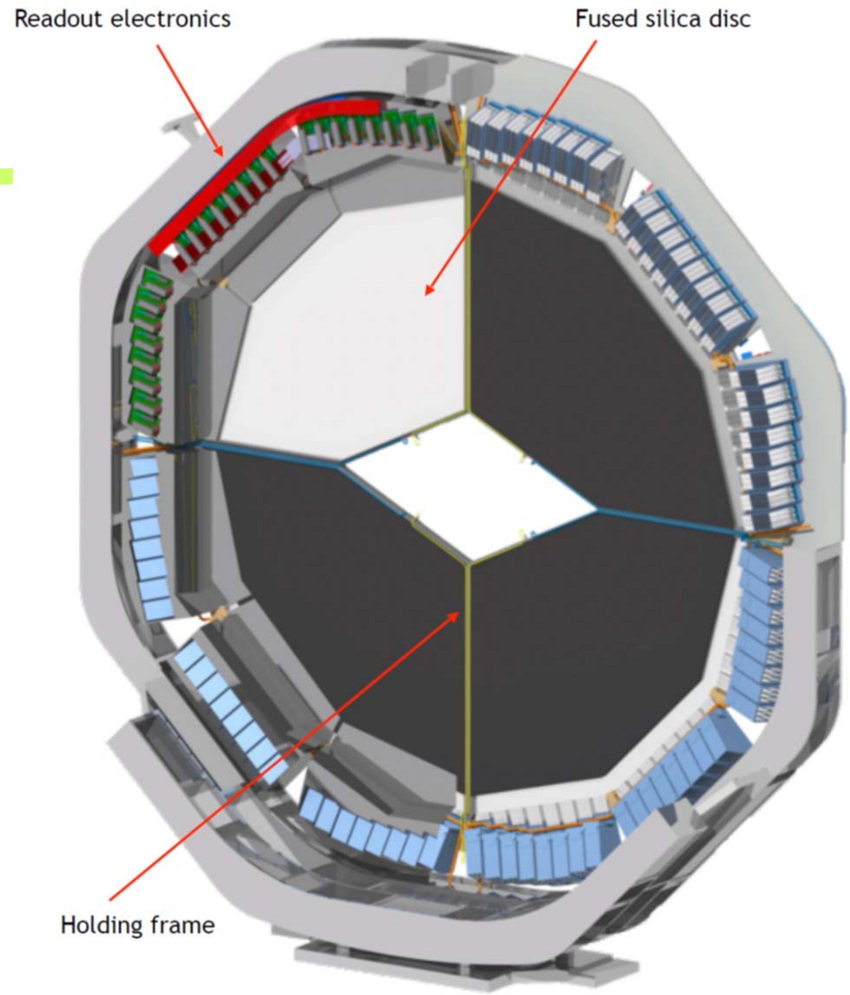
Radiator: fused silica 20 mm thick, *R* =1m

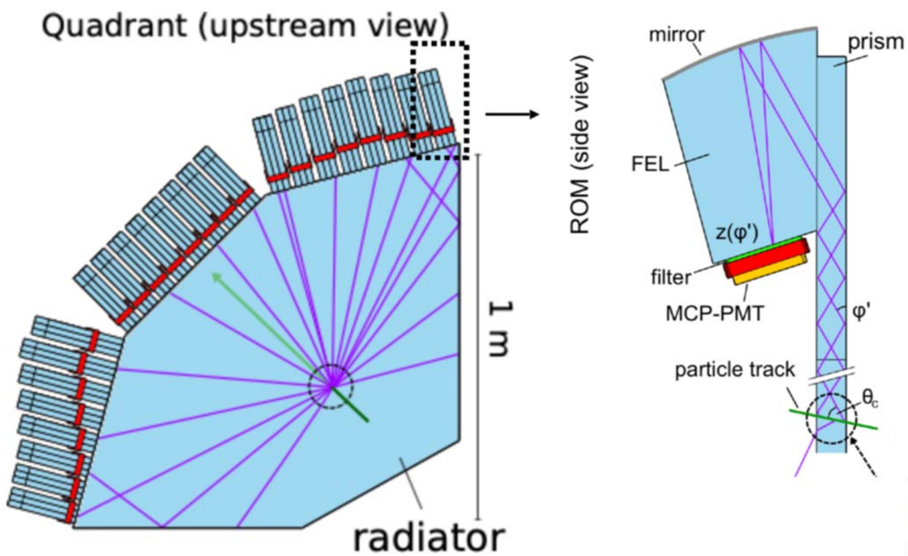
π/K separation up to 4 GeV/c

Focusing optics

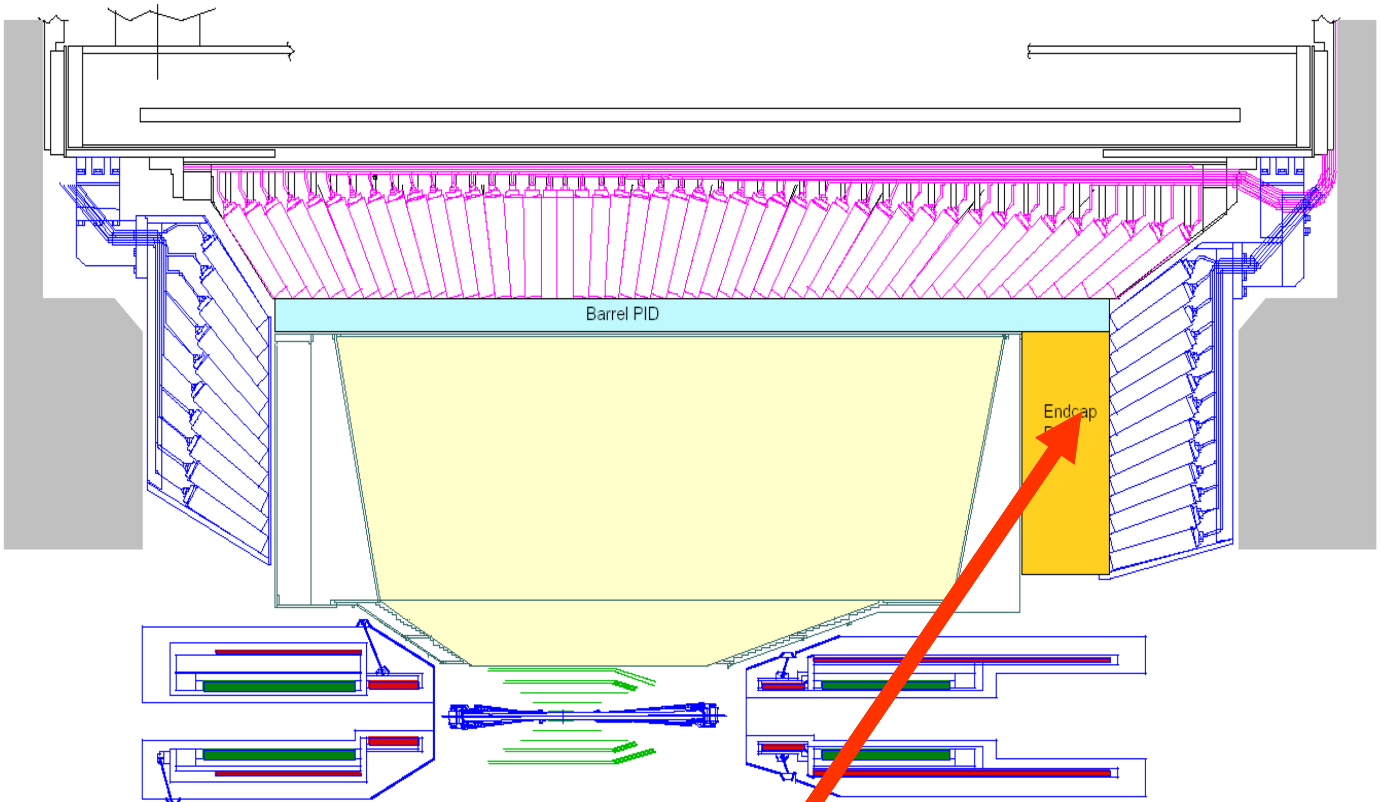
Photon detector in ~1T field:

- 96 MCP PMTs with a highly segmented anode, TofPET2 readout ASIC





Belle II PID system

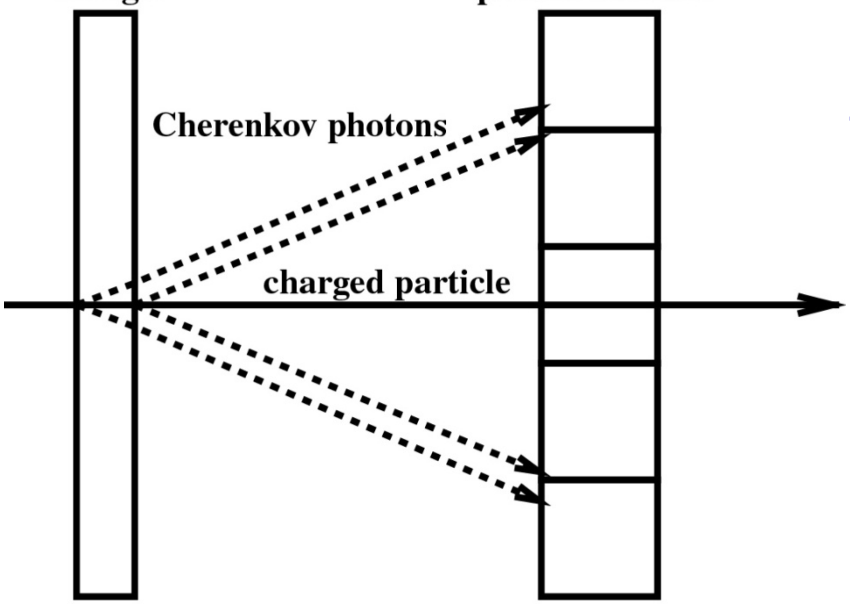


Two novel particle ID devices, both RICHes:

Barrel: Time-of-propagation counter (TOP) counter

Endcap: proximity focusing RICH

Endcap: Proximity focusing RICH



K/π separation at 4 GeV/c:
$\theta_c(\pi)$ ~ 308 mrad (n = 1.05)
$\theta_c(\pi)$– $\theta_c(K)$ ~ 23 mrad

For single photons: $\delta\theta_c$(meas.)=σ_0 ~ 14 mrad,
typical value for a 20mm thick radiator and 6mm PMT pad size

Per track:

$$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

Separation: $[\theta_c(\pi)-\theta_c(K)]/\sigma_{track}$

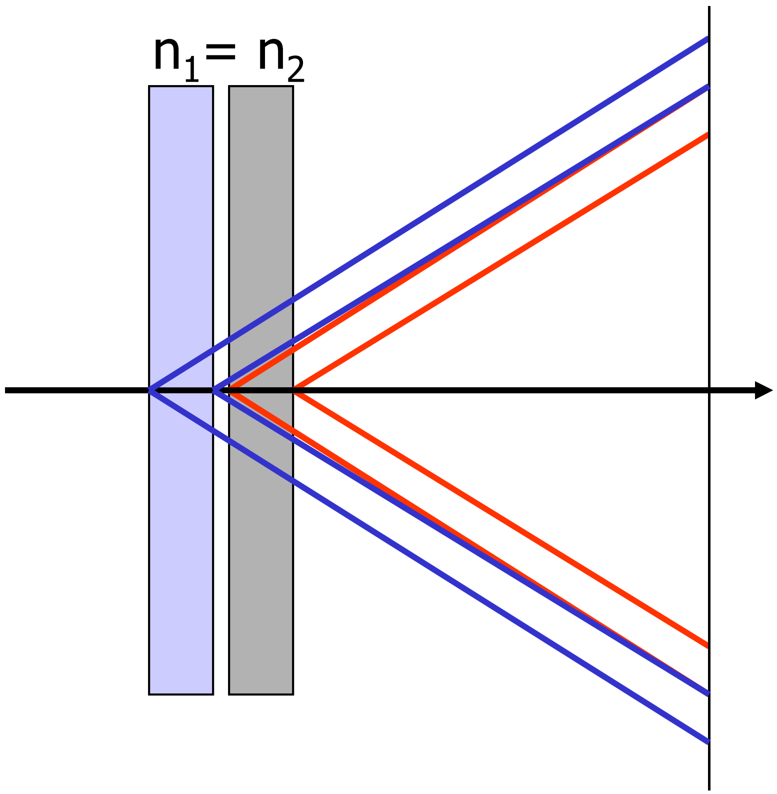
→ 5σ separation with N_{pe}~10

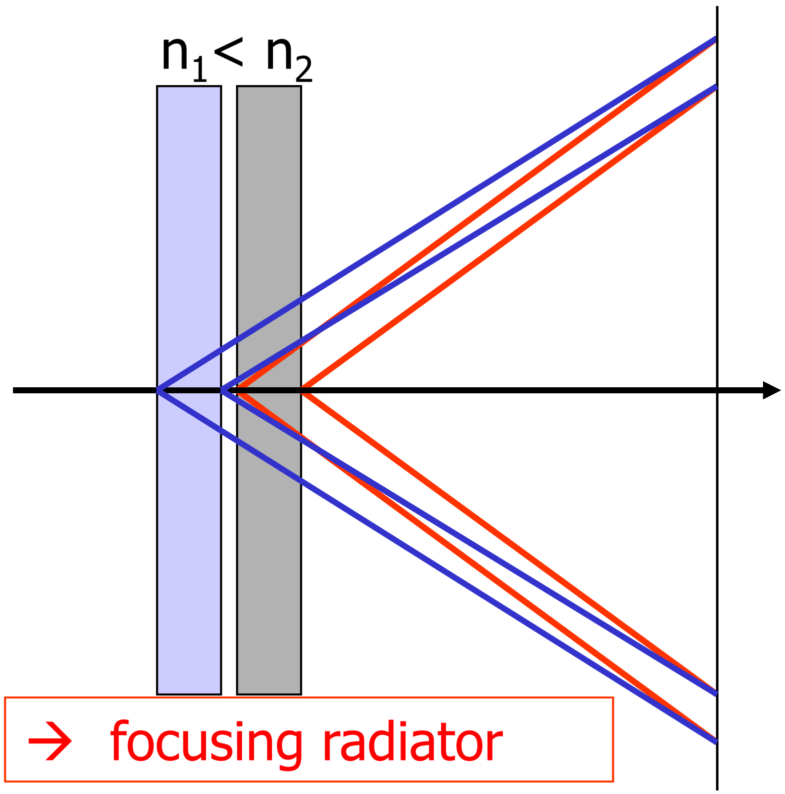
Radiator with multiple refractive indices

Small number of photons from aerogel → need a thick layer of aerogel.
How to improve the resolution by keeping the same number of photons?

→ stack two tiles with different refractive indices:
"focusing" configuration

normal

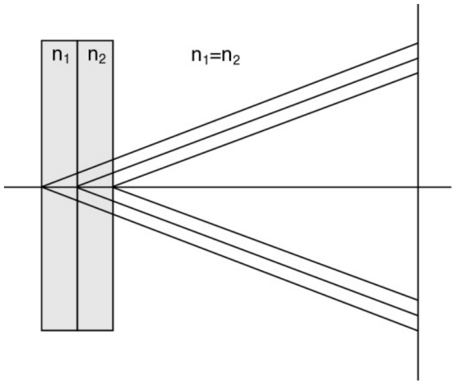


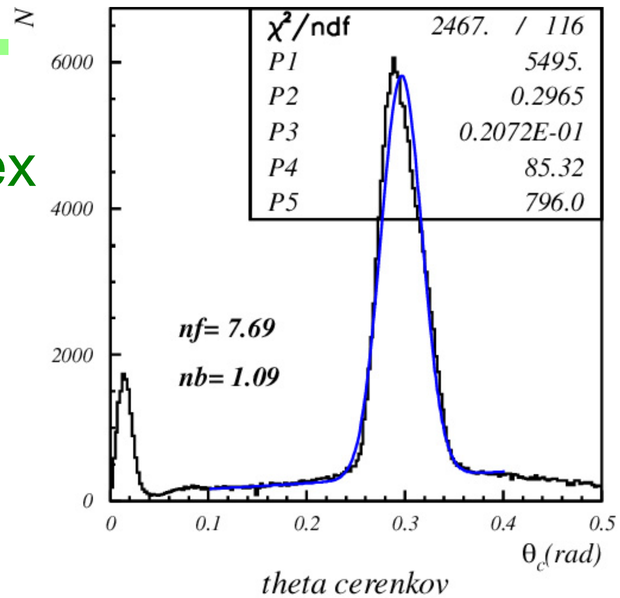


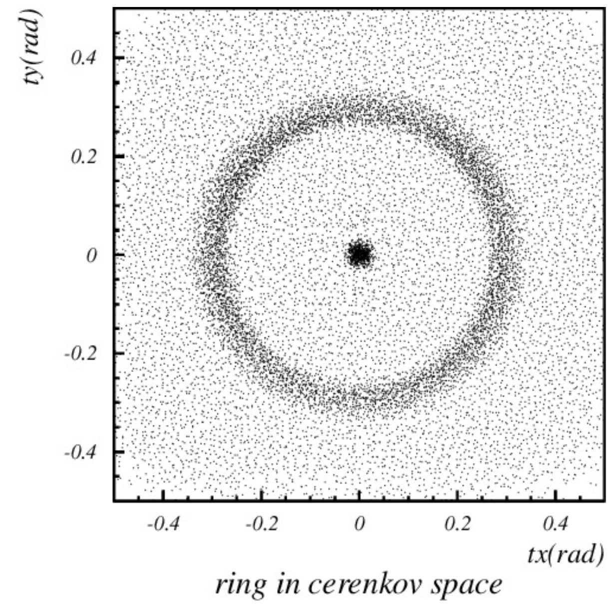
→ focusing radiator

Focusing configuration – data

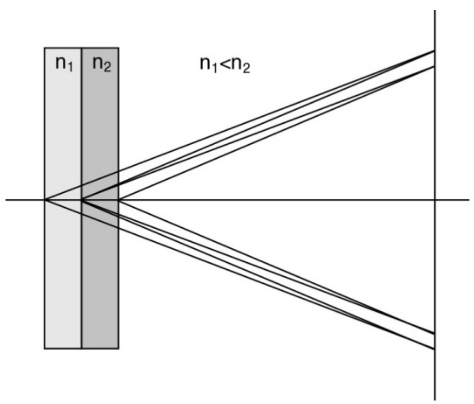
4cm aerogel single index

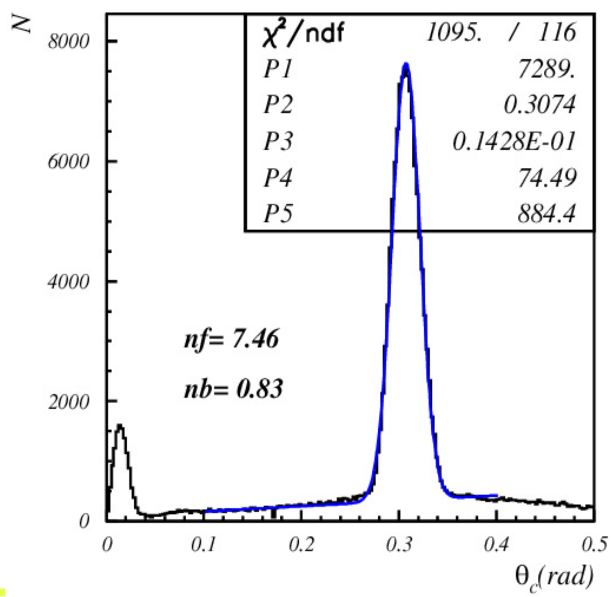


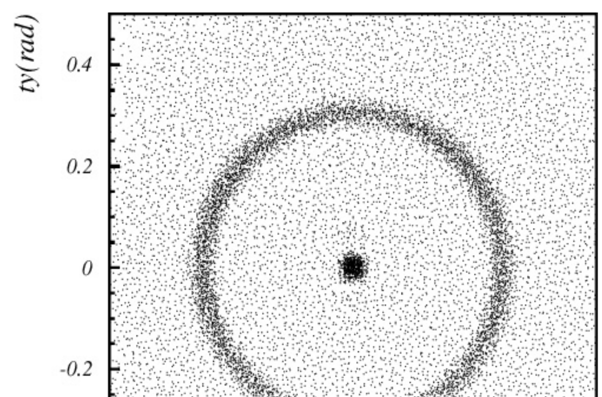


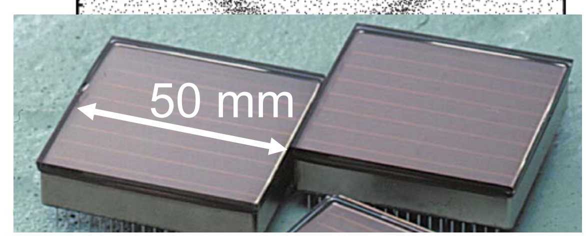


2+2cm aerogel







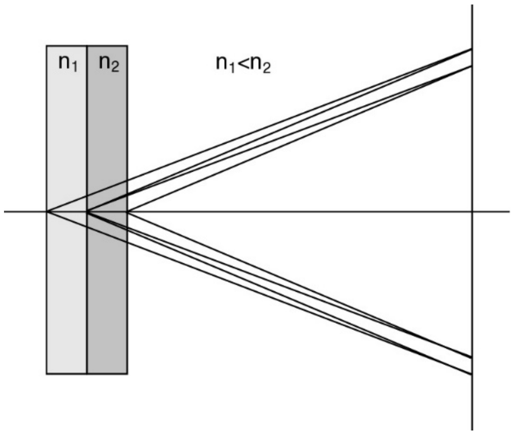


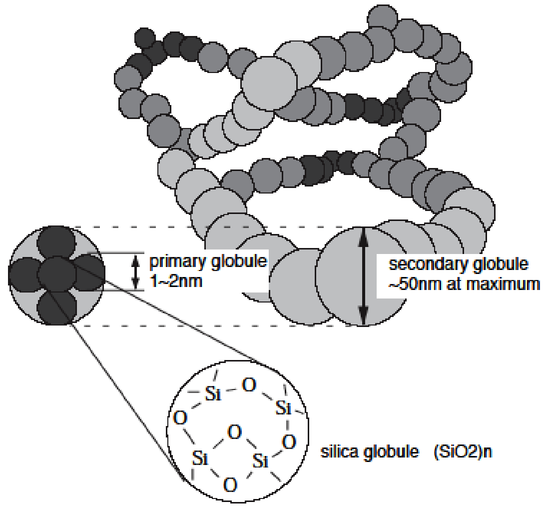
4x4 array of flat pannel MAPMTs

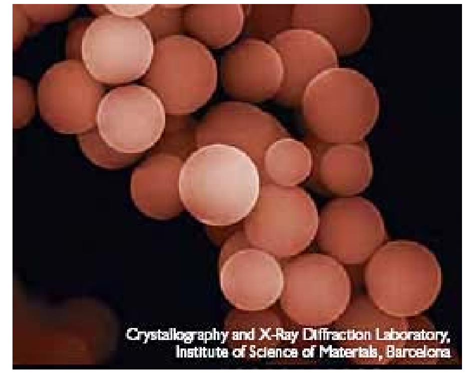
→NIM A548 (2005) 383, NIMA 565 (2006) 457

Radiator with multiple refractive indices 2

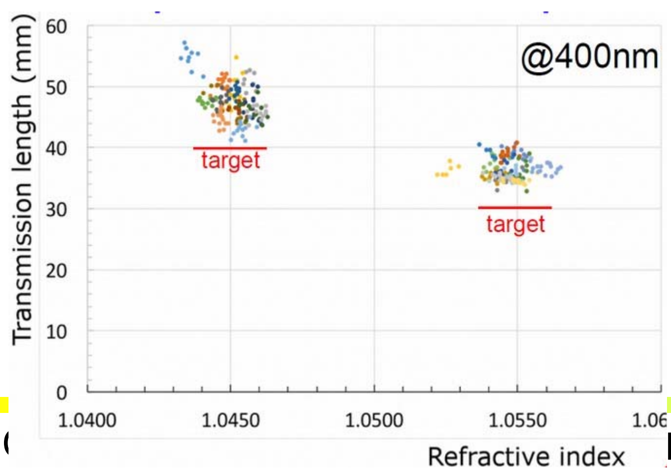
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.

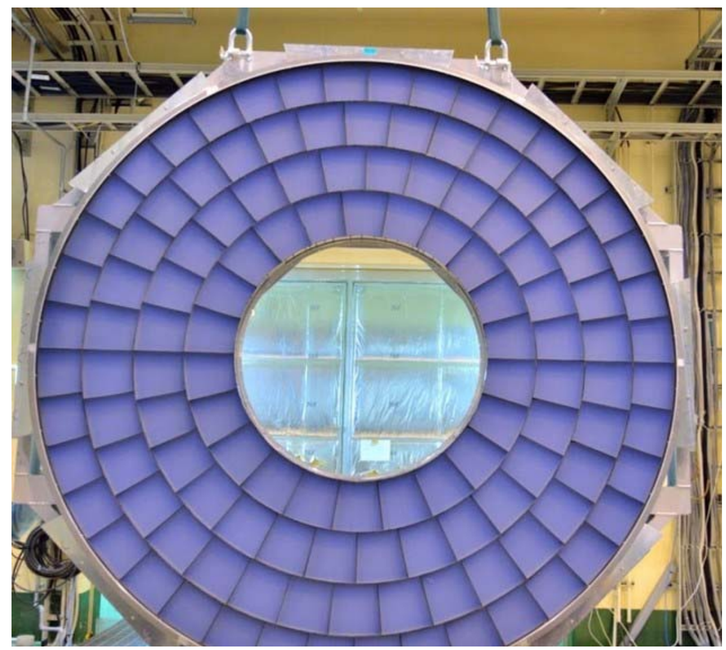






Requires aerogel with high transparency





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

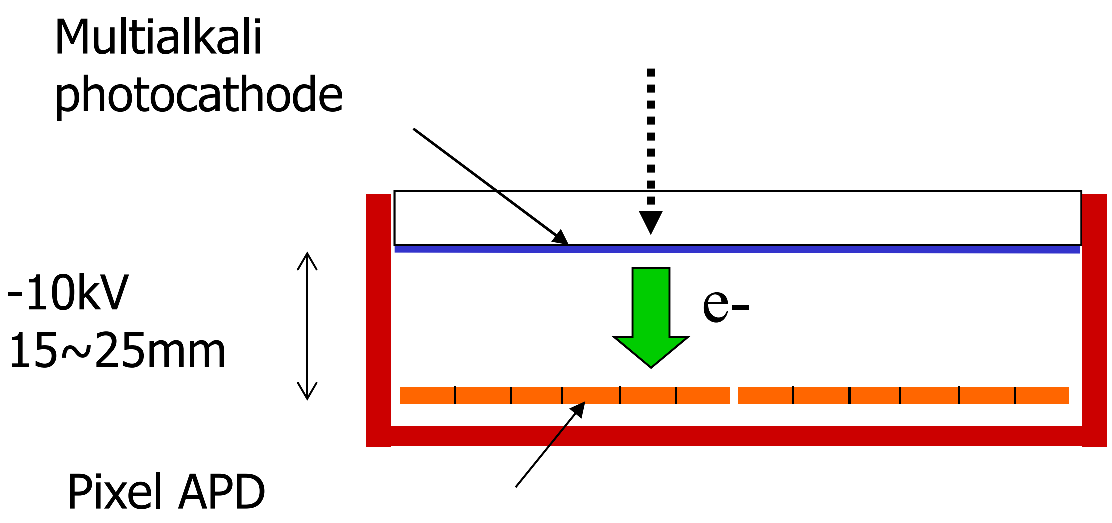
Photon detectors for the aerogel RICH requirements and candidates

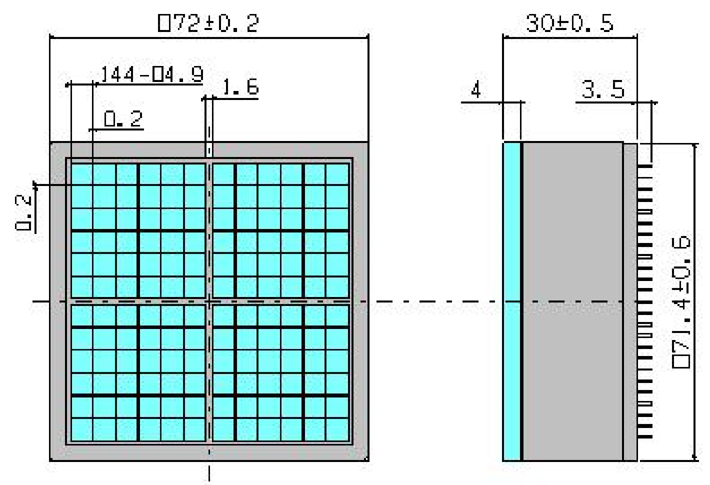
Need: Operation in a high magnetic field (1.5 T)

Pad size ~5-6mm

Final choice: large active area HAPD of the proximity focusing type

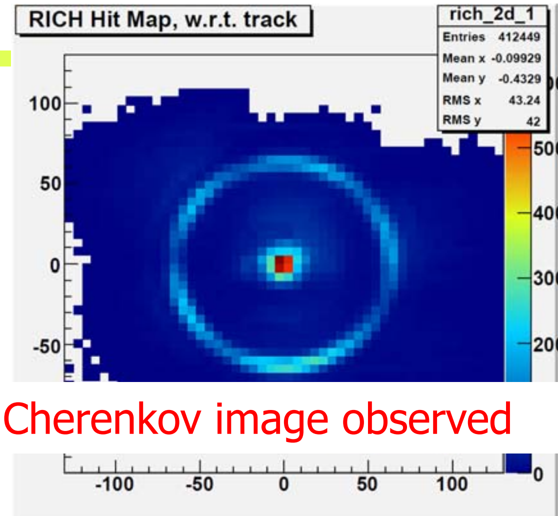
Candidates: MCP PMT (Photonis/Burle 85011, SiPMs)



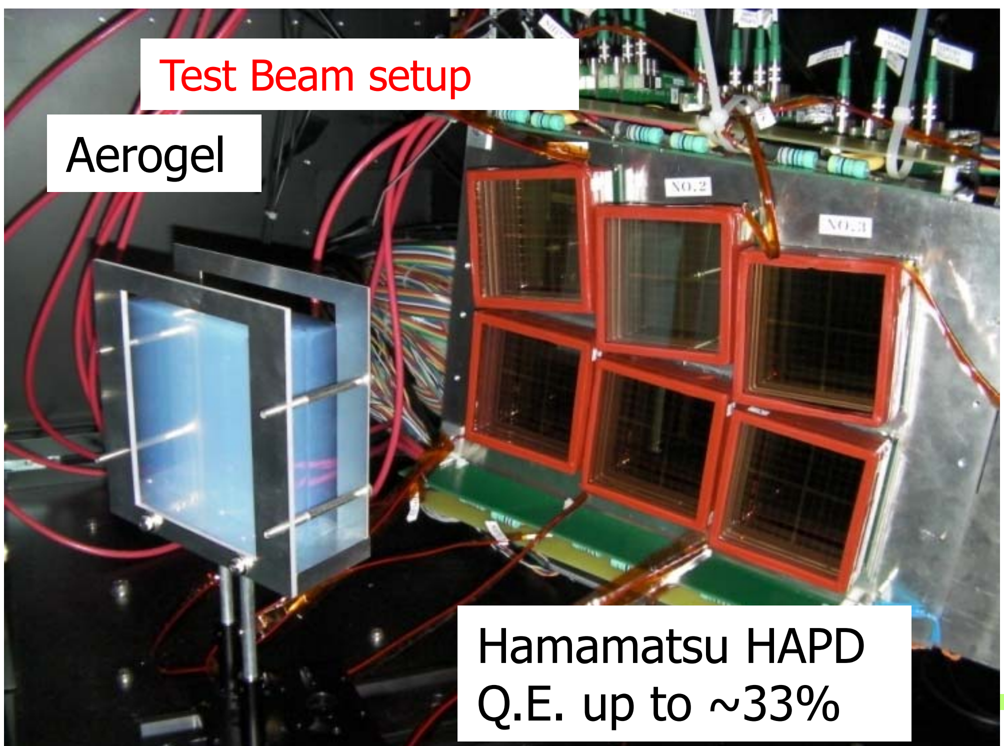


HAPD R&D project in collaboration with HPK.

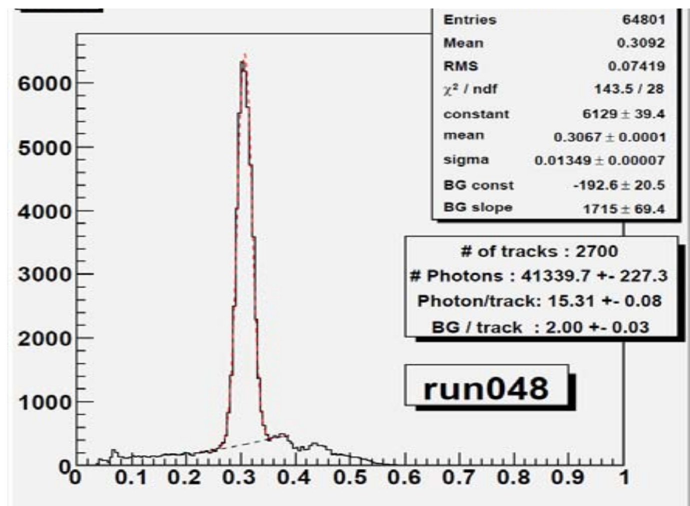
HAPD as the Aerogel RICH photon detector



Clear Cherenkov image observed



Cherenkov angle distribution

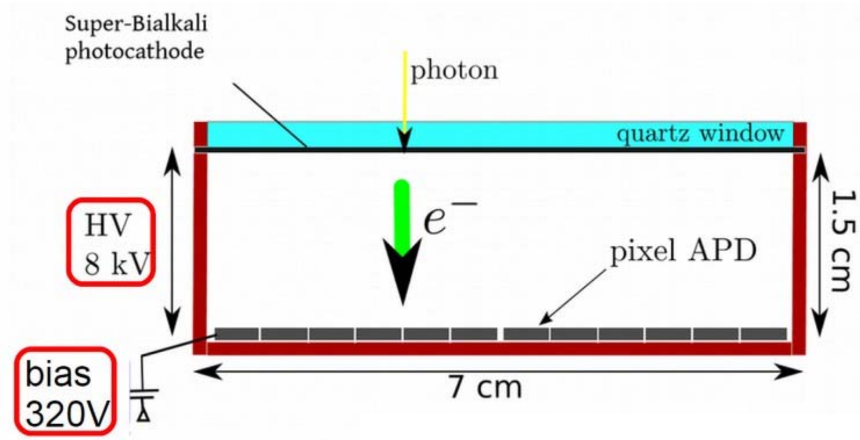


6.6 σ p/K at 4GeV/c !

→ NIM A595 (2008) 180

ARICH photo sensor: HAPD

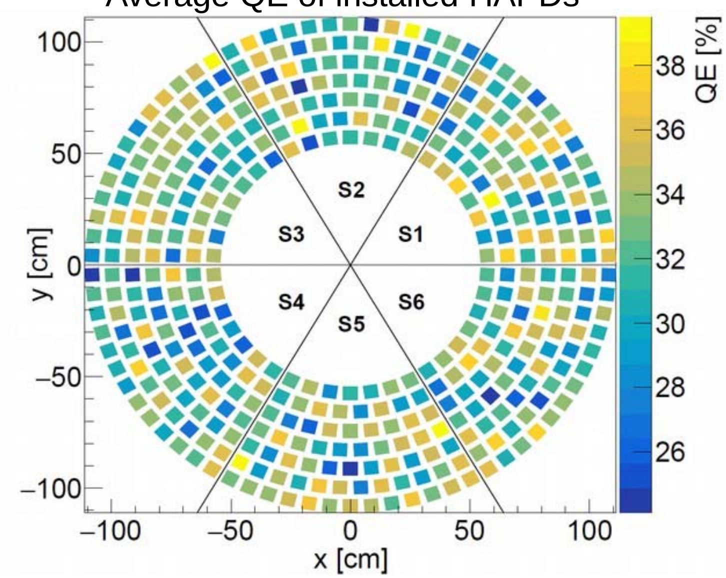
- HAPD – Hybrid Avalanche Photo-Detector

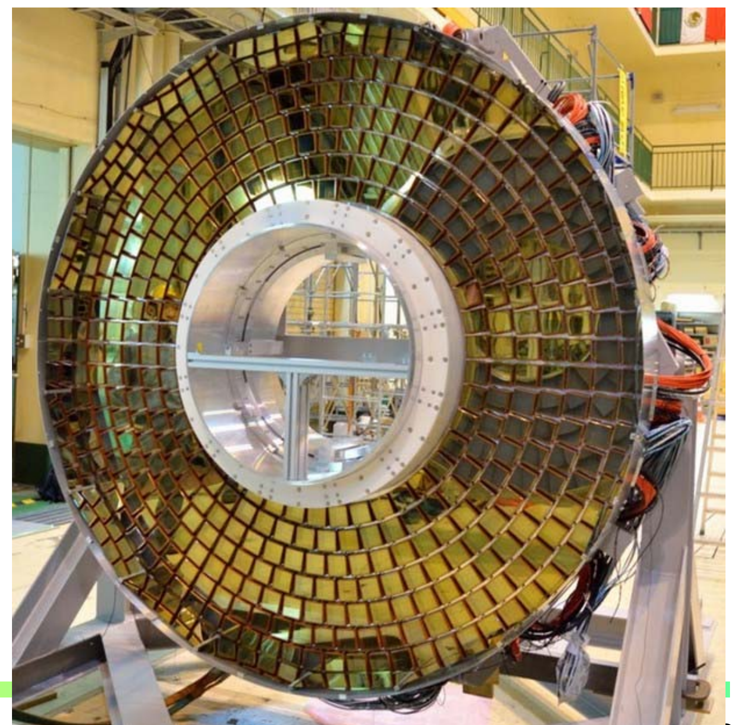


Size	73x73 mm
# of channels	144 (36-ch APDx4)
Total gain	>60000 (1500 x 40)
Peak QE	~30%
Active area	64%
Weight	220g

- 420 modules to cover the detector plane

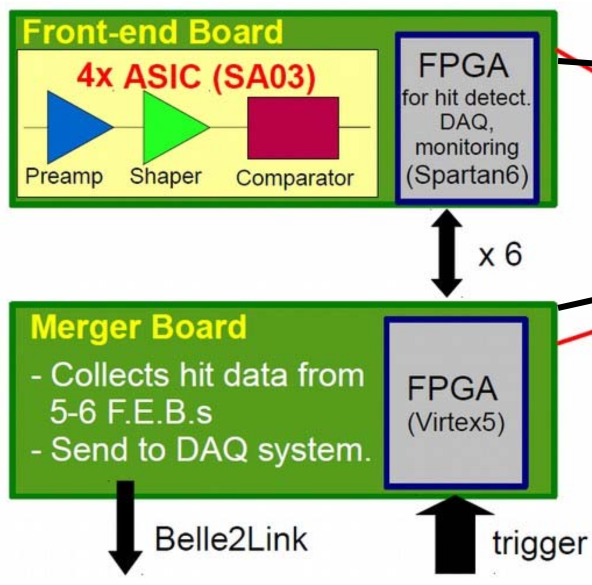
Average QE of installed HAPDs

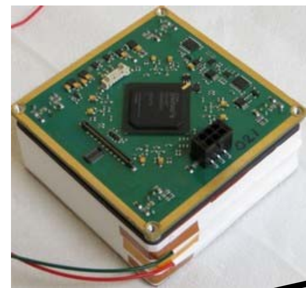


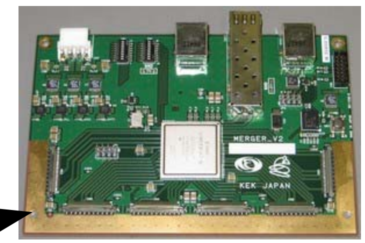


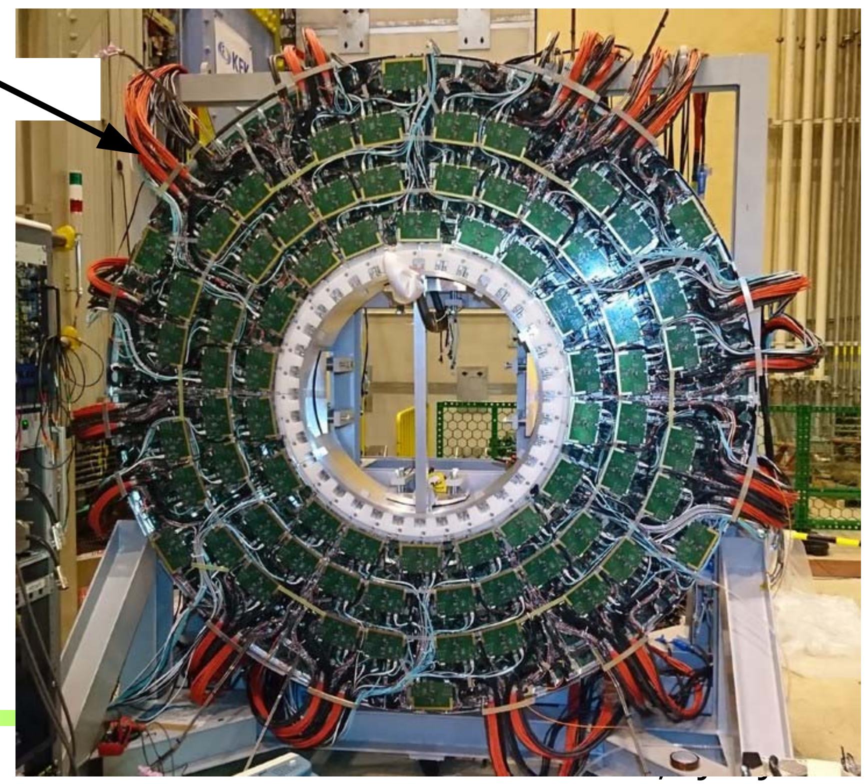
ARICH read-out electronics

- In total ~60k channels
- Limited space of 5cm behind HAPDs





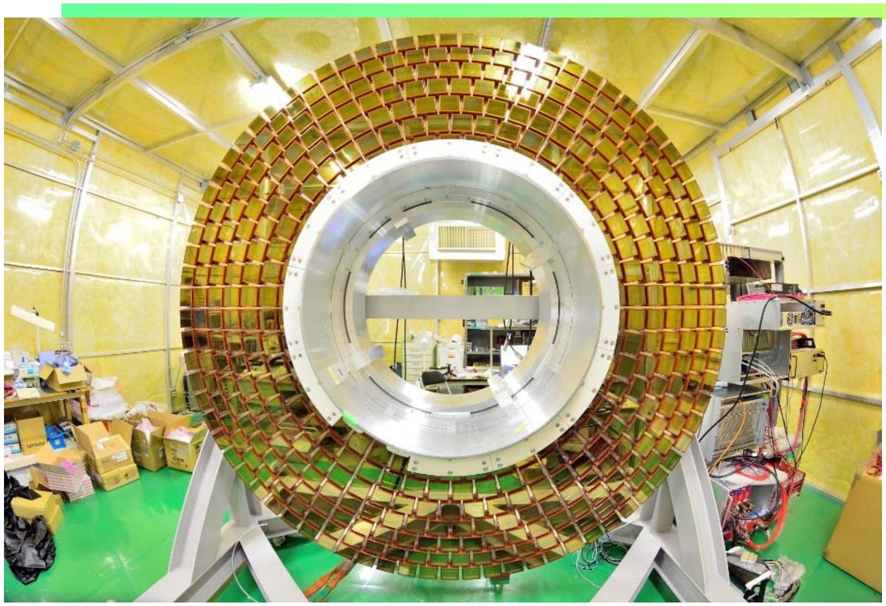


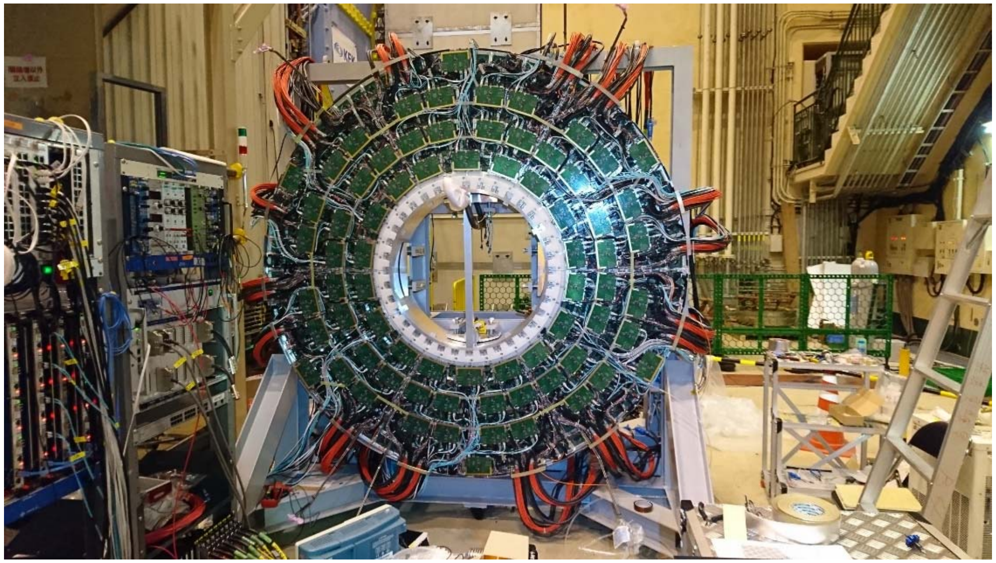


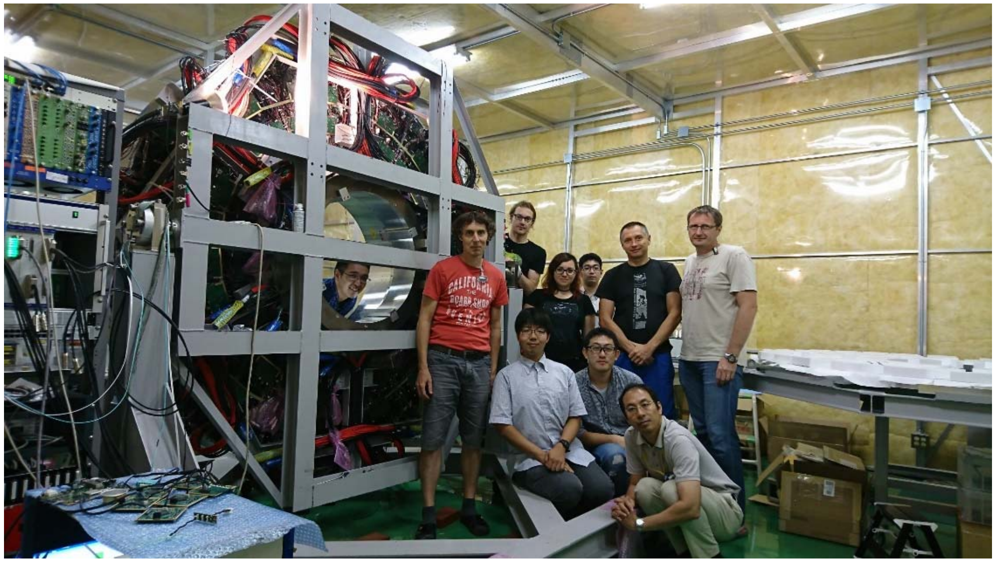
- Variable gain (3.1-12.5 V/pC), shaping time (100-200 ns)

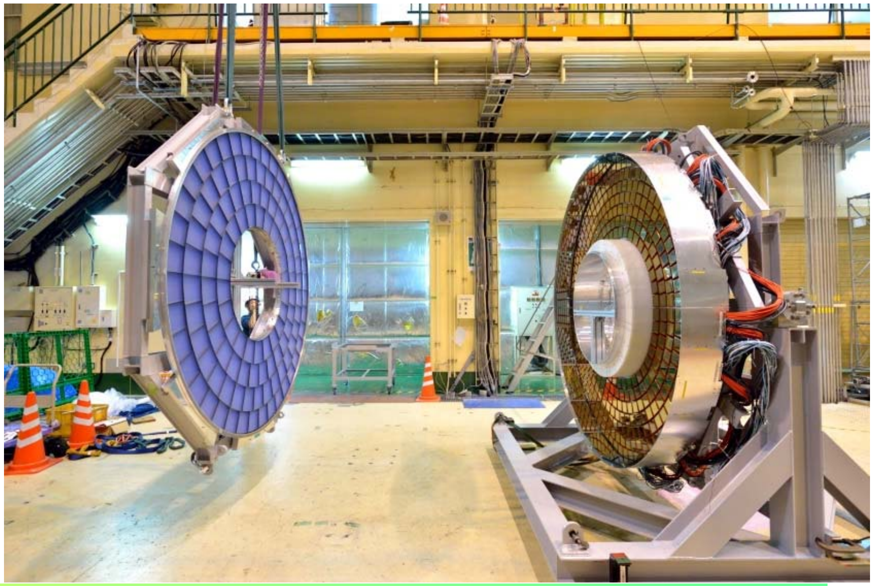
  → optimization for increased noise levels

The big eye of ARICH

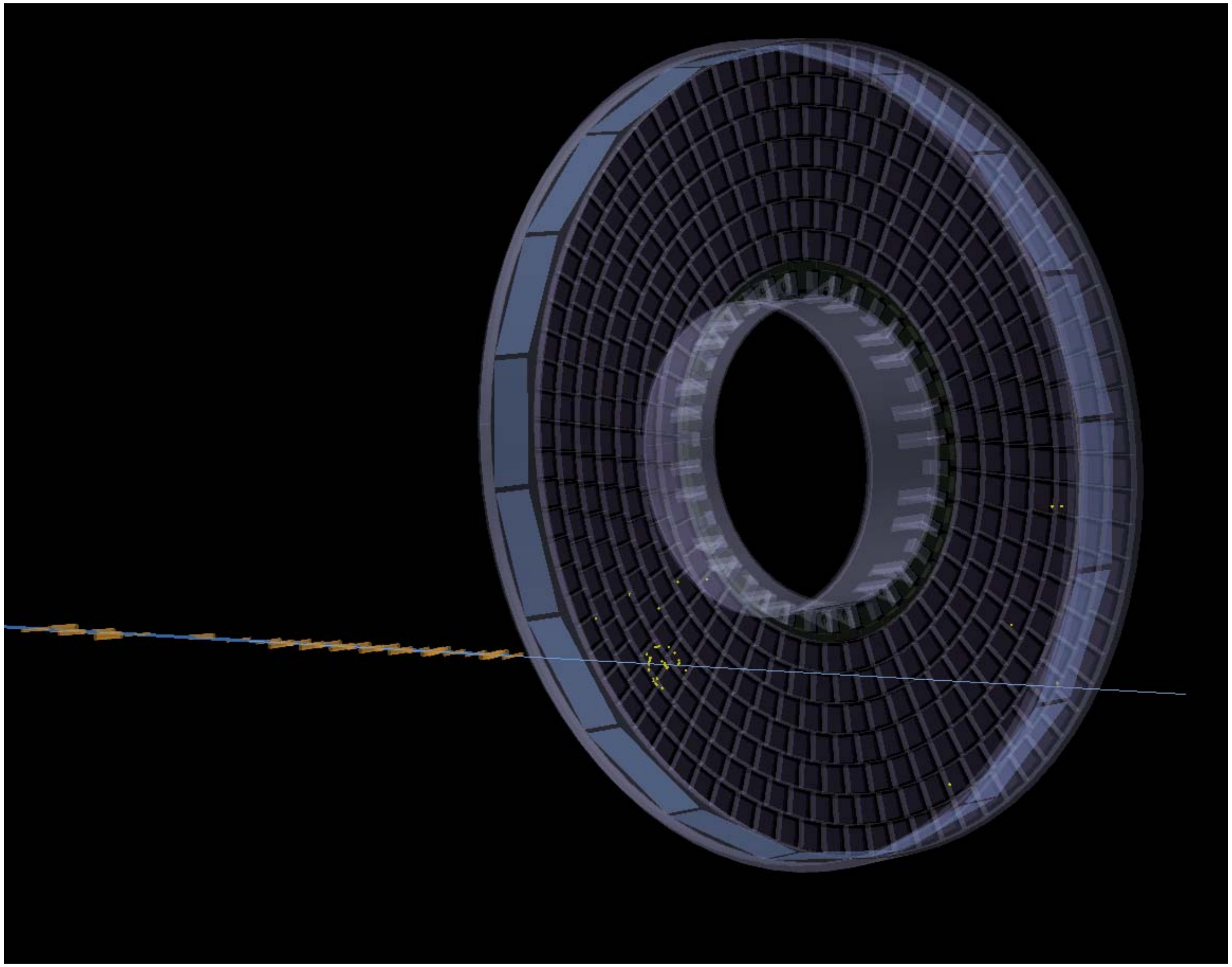








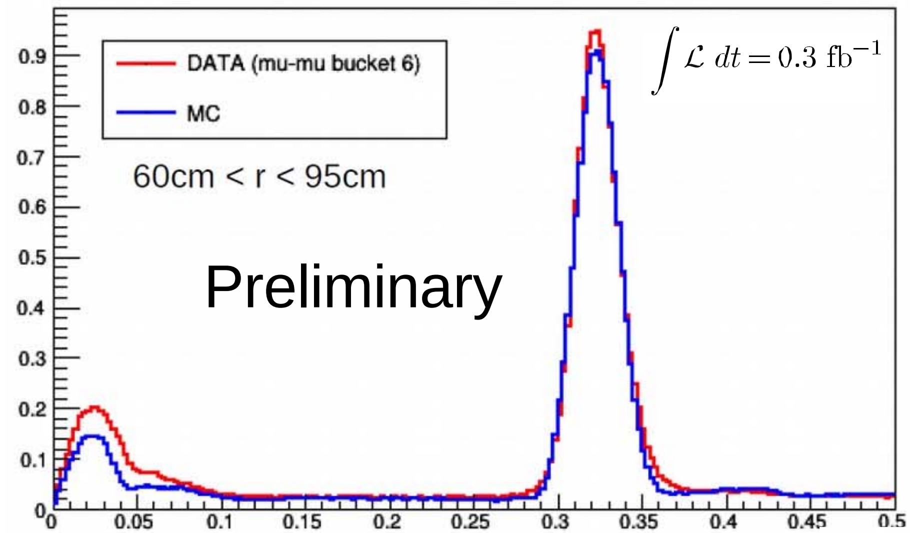
ARICH: Rings from cosmic ray muons



First events recorded in the fully instrumented ARICH.

Performance in the early Belle II data

Cherenkov angle distribution in $e^+e^- \to \mu^+\mu^-$



DATA

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

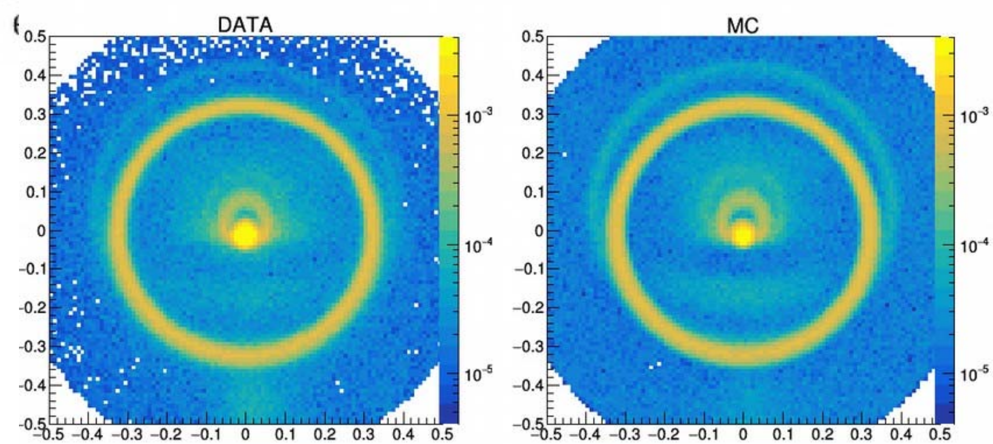
$\sigma_c = 12.7\ \mathrm{mrad}$

MC

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

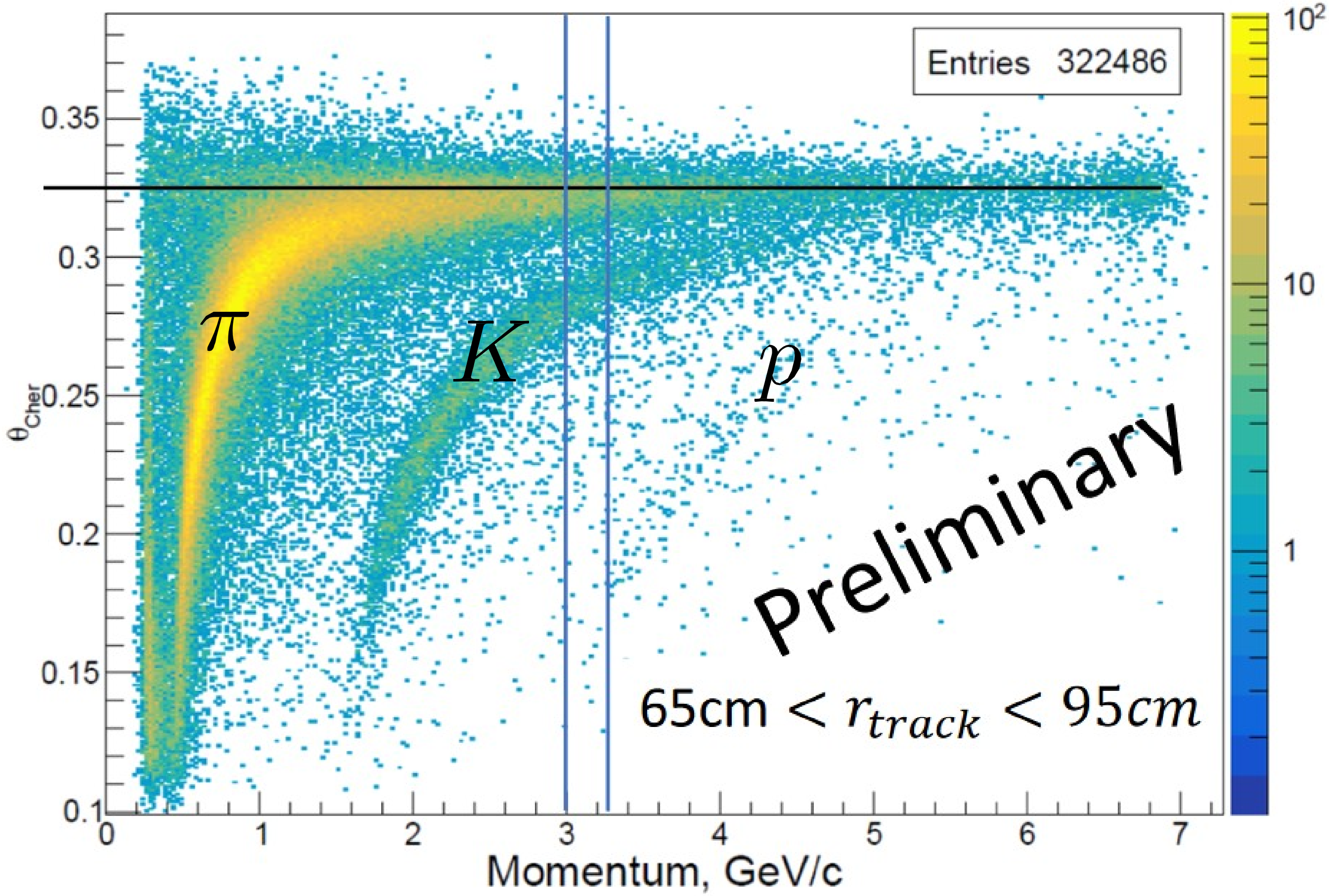
$\sigma_c = 12.75\ \mathrm{mrad}$

Overall a very good DATA/MC agreement !



Chrenkov ring (accumulated)

Cherenkov angle vs momentum in hadronic events



Average Cherenkov angle for tracks from hadronic events

Estimation of π/K separation power using $D^{*\pm}$ decays

- Identify $K,\ \pi$ based on track charge in association with the charge of π_{slow}

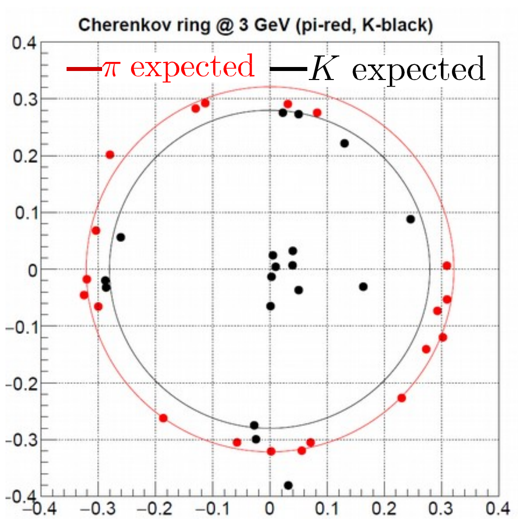
$D^{*+} \to D^0\ \pi^+_{\text{slow}}$, $D^0 \to K^-\ \pi^+$

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

- Apply selection criteria on

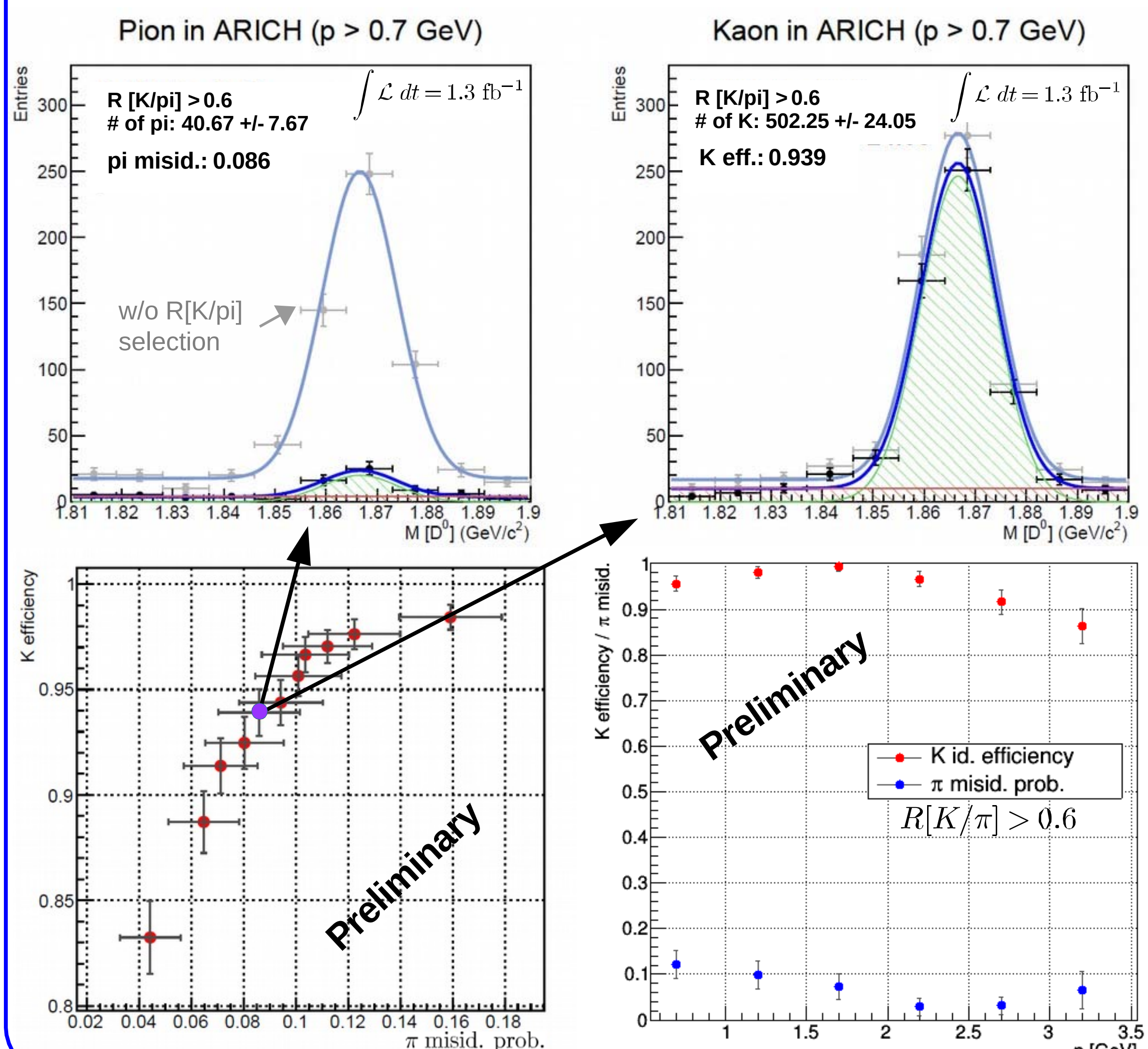
$$R[K/\pi] = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

$\mathcal{L}$ - likelihood for given id. hypothesis



- Only coarse/preliminary calibrations included
  → further improvements expected

D^0 mass peak

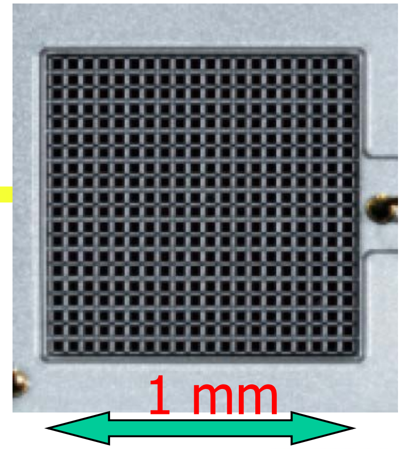


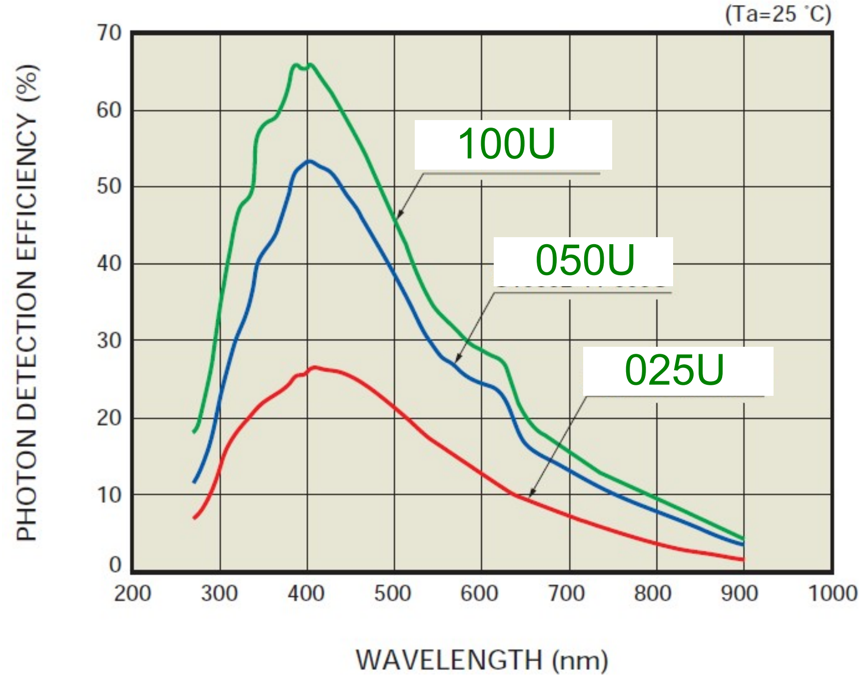
SiPMs as photon detectors?

SiPM is an array of APDs operating in Geiger mode. Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)





Not trivial to use in a RICH where we have to detect single photons!

Dark counts have single photon pulse heights (rate 0.1-1 MHz)

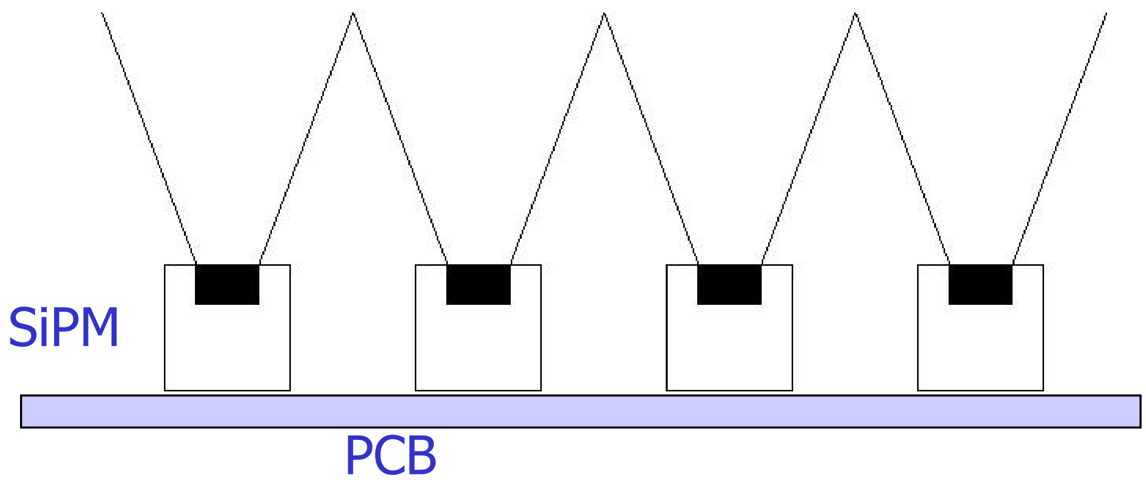
SiPM as photosensor for a RICH counter

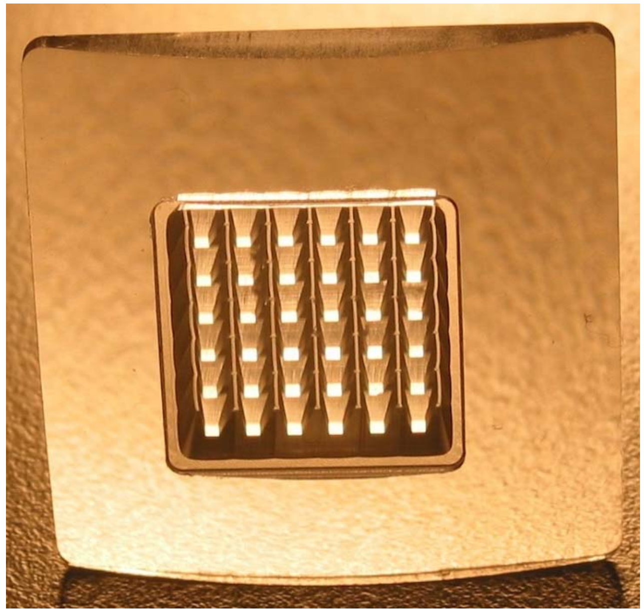
Improve the signal to noise ratio:

•Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)

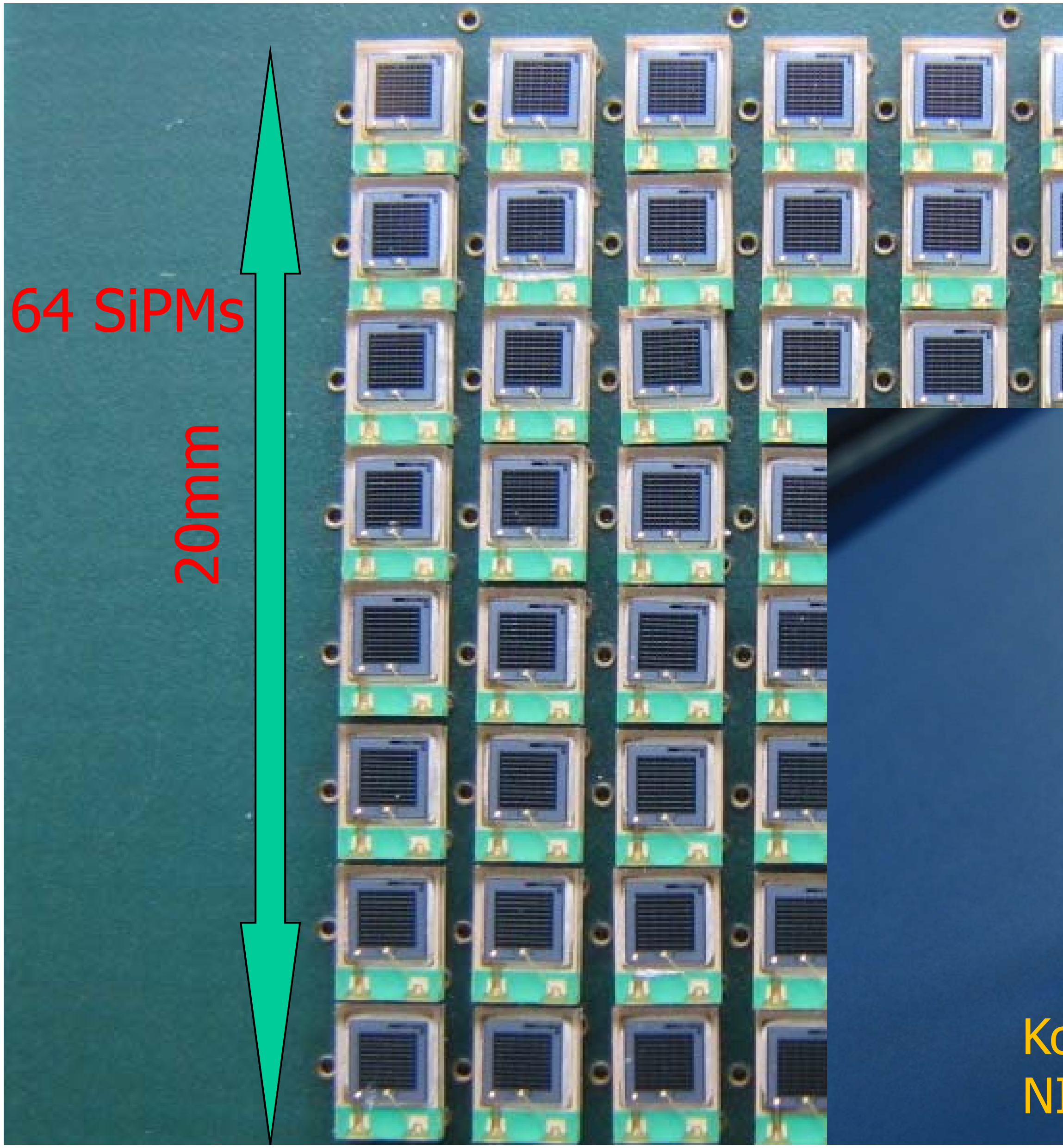
•Increase the number of signal hits per single sensor by using light collectors

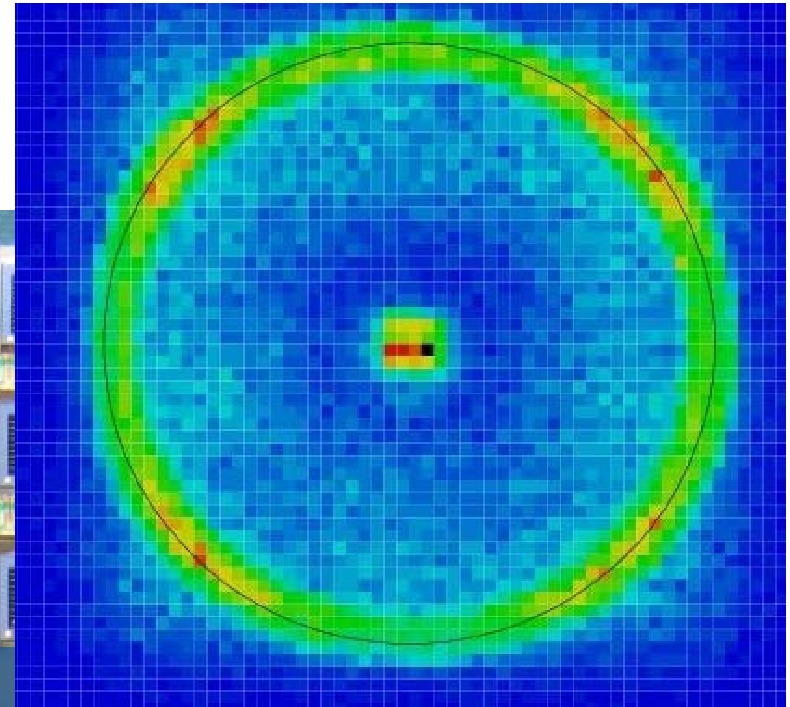
E.g. light collector with reflective walls or plastic light guide

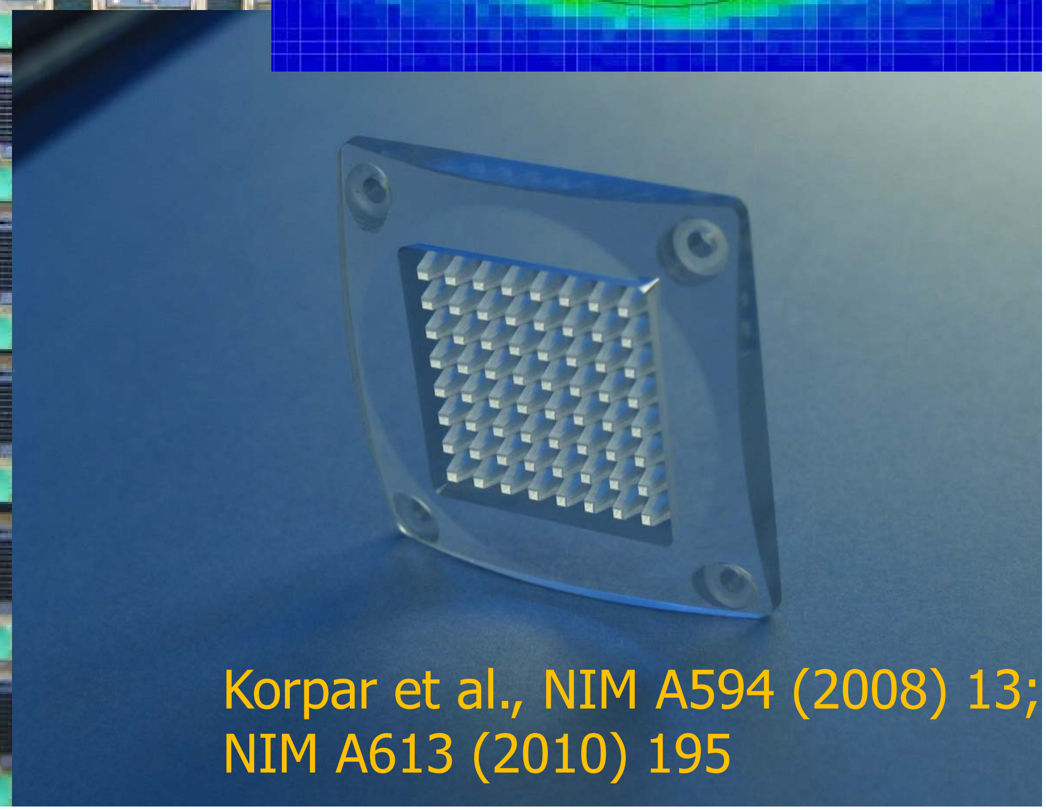




Photon detector with SiPMs and light guides



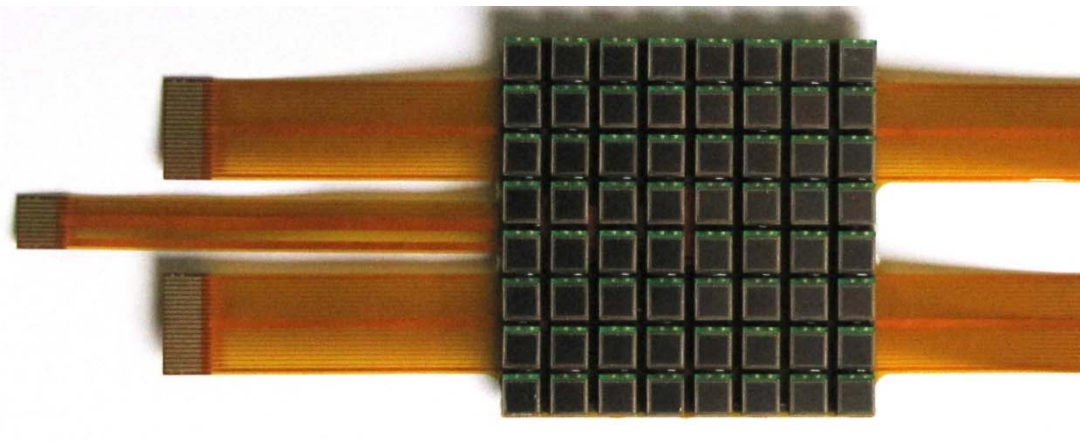


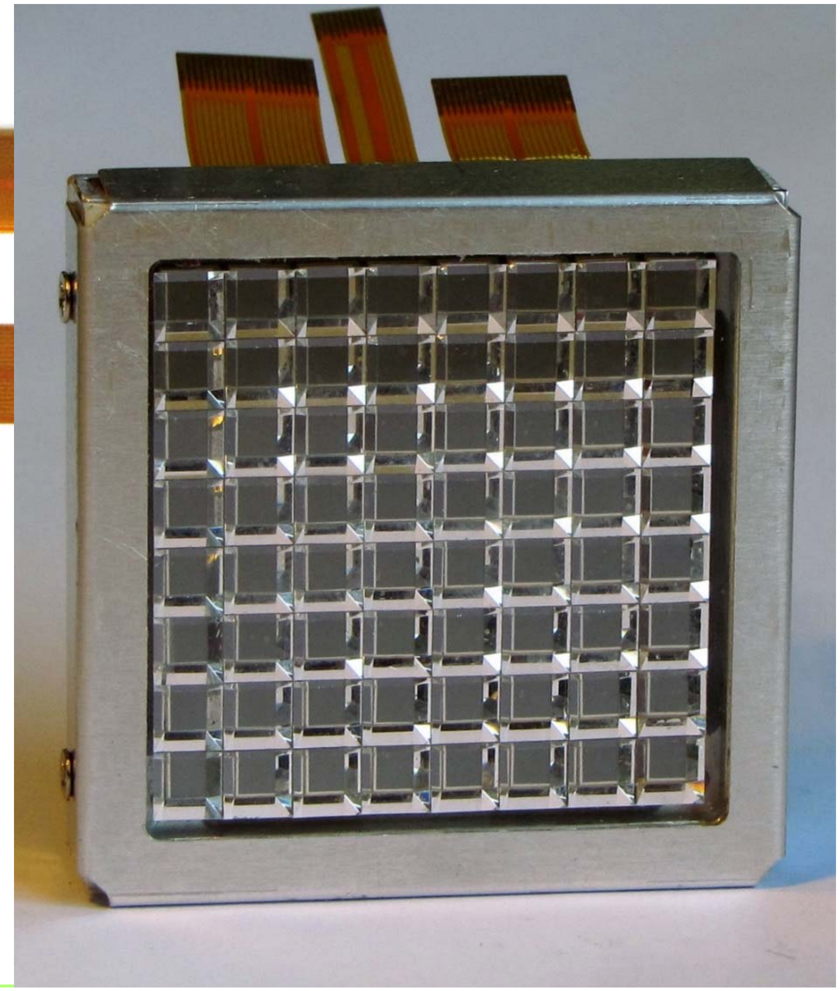


Next step: use arrays of SiPMs

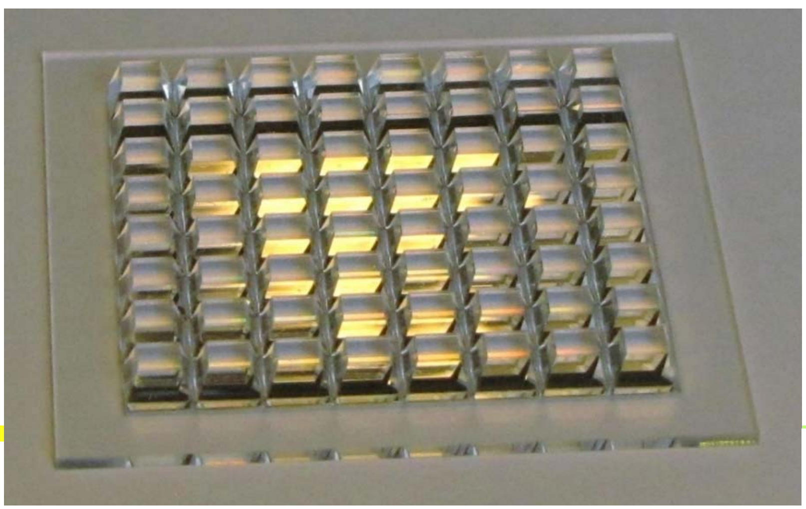
Example: Hamamatsu MPPC S11834-3388DF

- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2



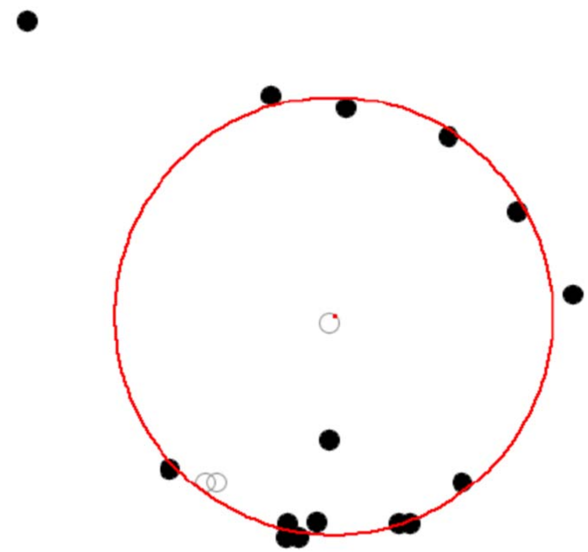


+ array of quartz light collectors



E. Tahirović et al., NIM A787 (2015) 203

Digital SiPM



Digital SiPM (Philips): instead of an analog sum of signals from all cells of a single SiPM, use on board lectrons for a digital sum + time stamp

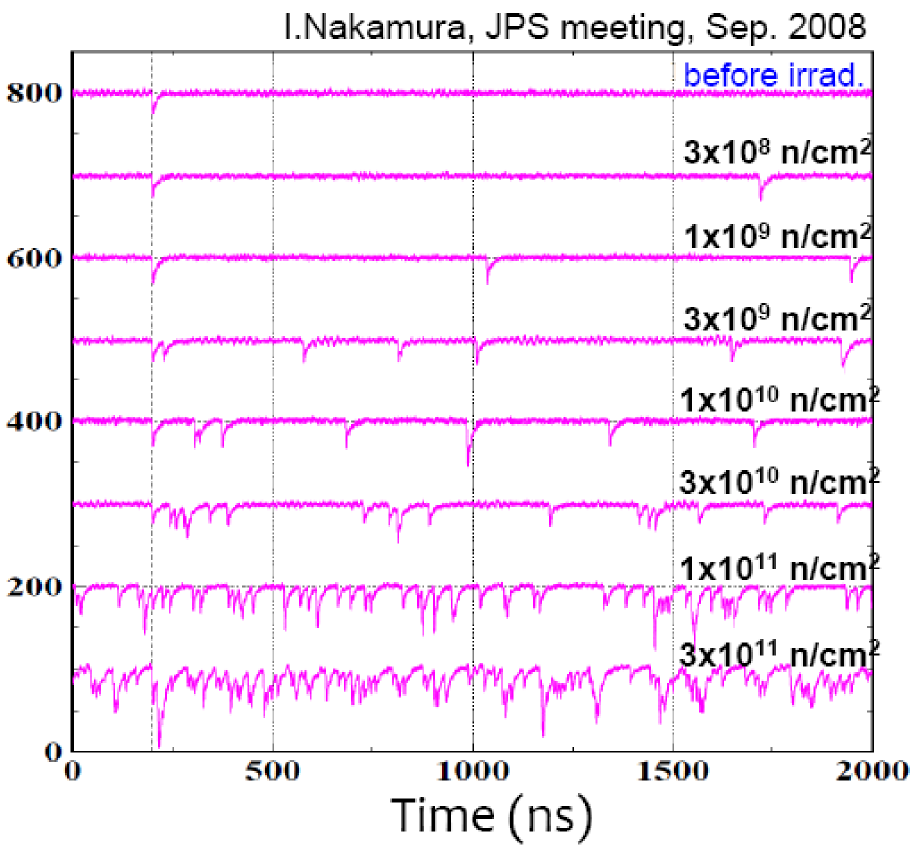
Square matrix 20x20 cm^2

- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 time channels
- 2304 amplitude (position) channels
- 4 levels of FPGA readout: tiles, modules, bus boards, test board

S. Kononov, VCI2013

13/02/2013 VCI 2013 10

SiPMs: Radiation damage



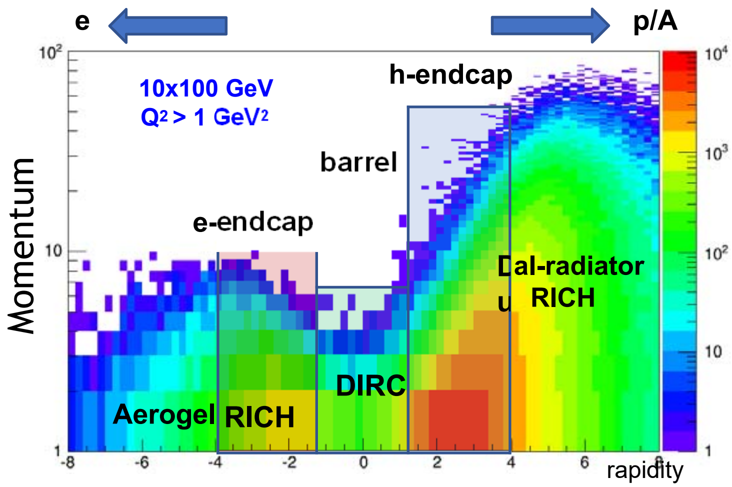
Expected fluence at 50/ab at Belle II:
2-20 10^{11} n cm^{-2}

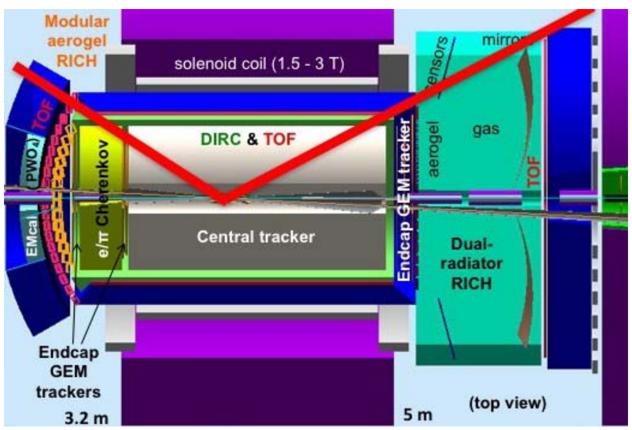
→ Worst than the lowest line

→Need cooling of sensors and wave-form sampling readout electronics

… and more radiation resistant SiPMs…

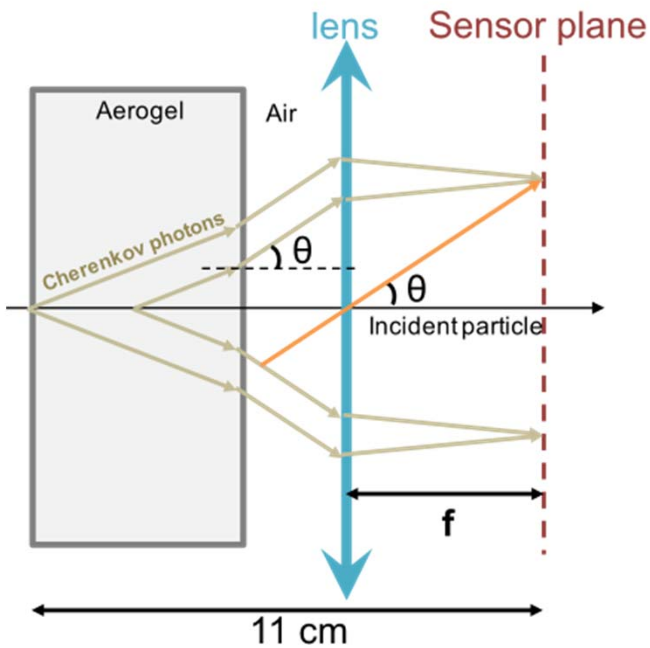
PID Strategies for the Electron Ion Collider

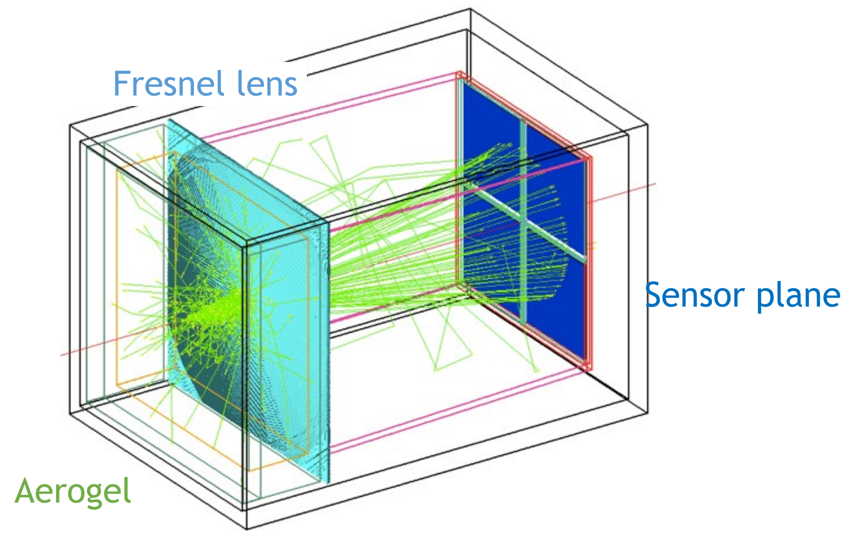




- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K separation up to ~50 GeV/c **dRICH**
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K separation up to ~10 GeV/c **mRICH**
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  π/K separation up to ~6-7 GeV/c **DIRC**
- **TOF (and/or dE/dx in TPC)**: can cover lower momenta.

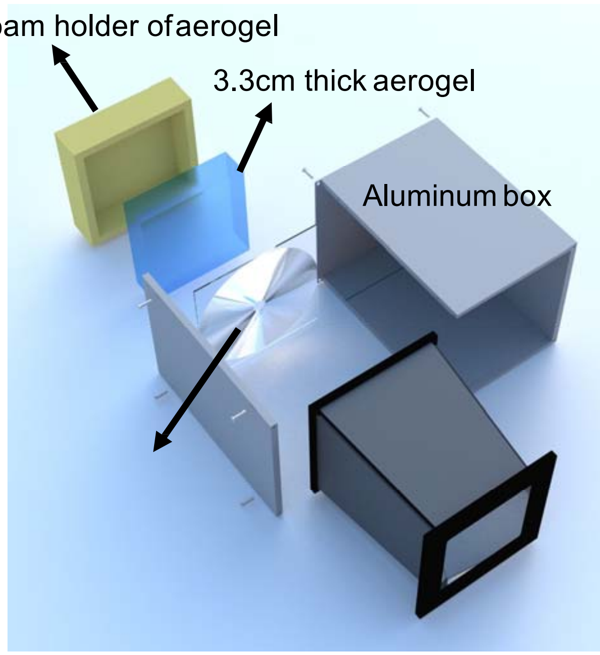
EIC mRICH – Working Principle

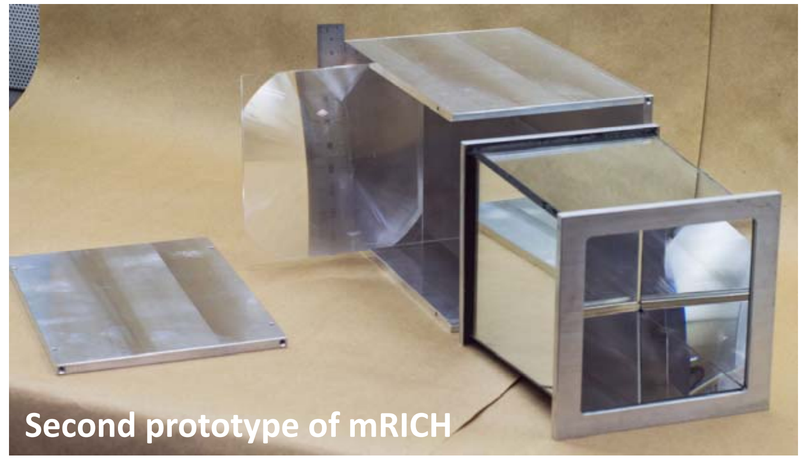




Geant4 Simulation

2nd mRICH Prototype - Verify the PID Capability





6” focal length Fresnel lens

mirror set

1.Longer focal length (Fresnel lens)
2.Smaller pixel size sensors

Identification of charged particles

Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

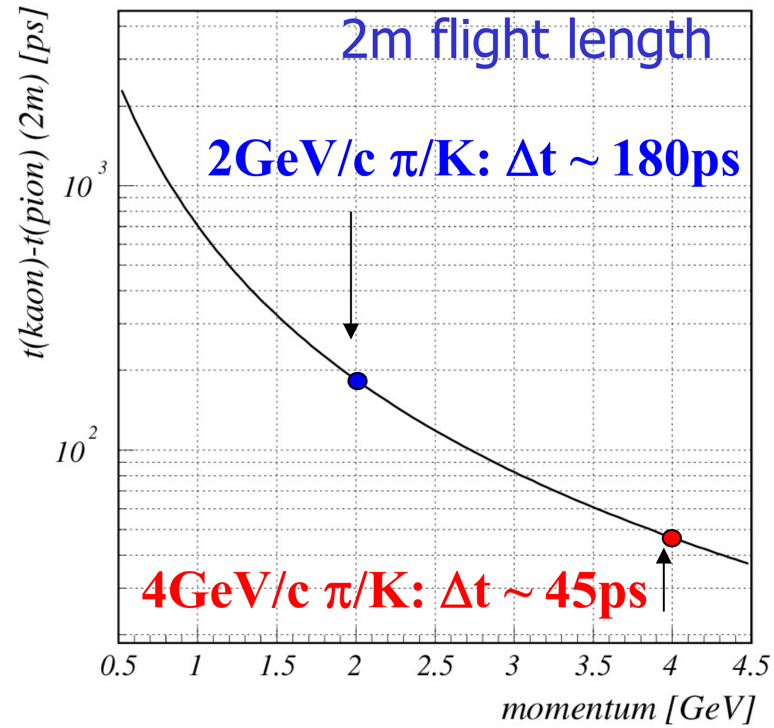
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters

Time-of-Flight (TOF) counters

Time difference between π and K:



Measure velocity by measuring the time between the interaction and the passing of the particle through the TOF counter.

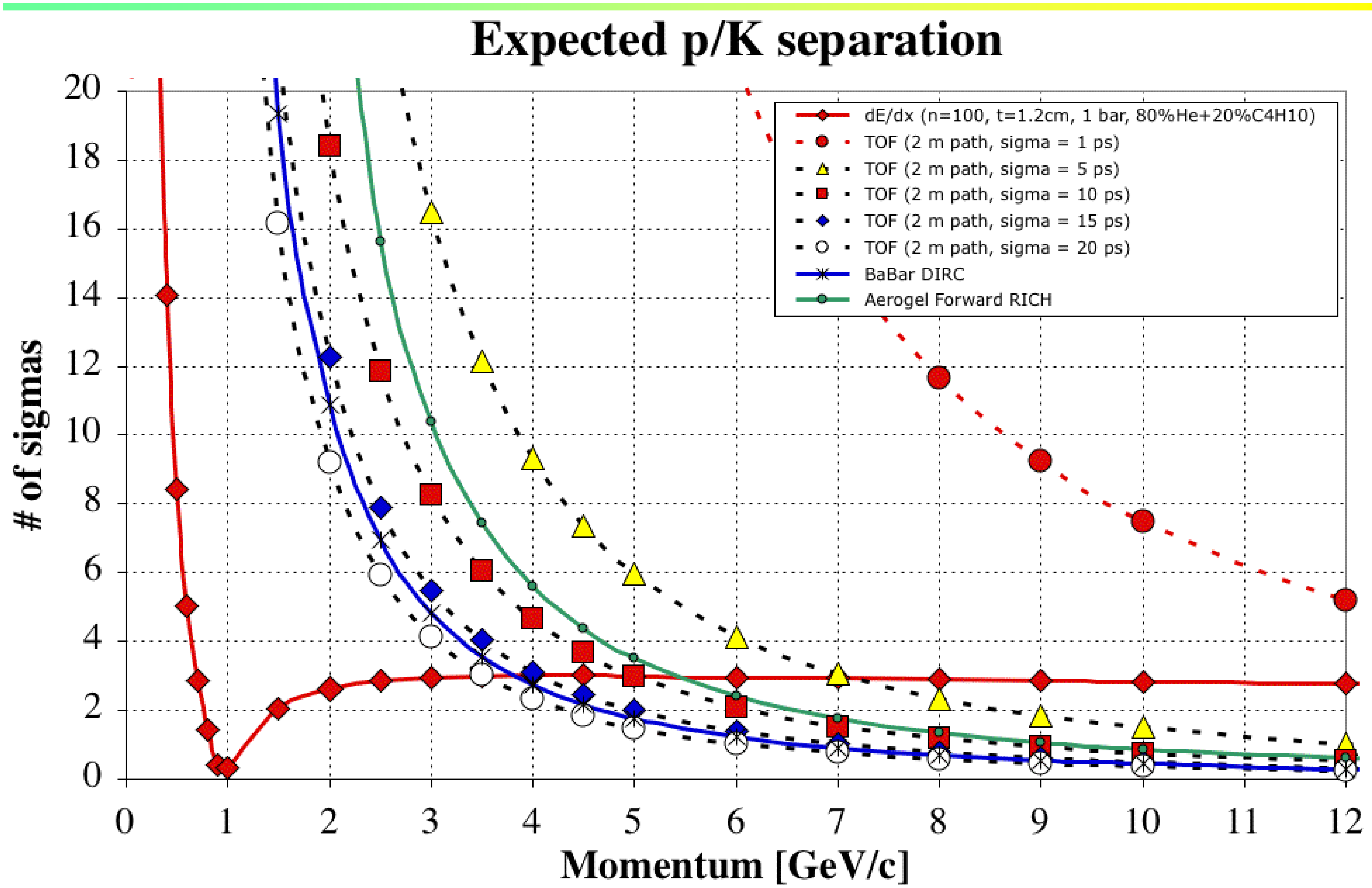
Traditionally: plastic scintillator + PMTs

Typical resolution: ~100 ps →π/K sepration up to ~1GeV.

To go beyond that: need faster detectors:
One possibility:
→use Cherenkov light (prompt) instead of scintillations

However: make sure you also know the interaction time very precisely...

Time-of-flight with fast photon detectors

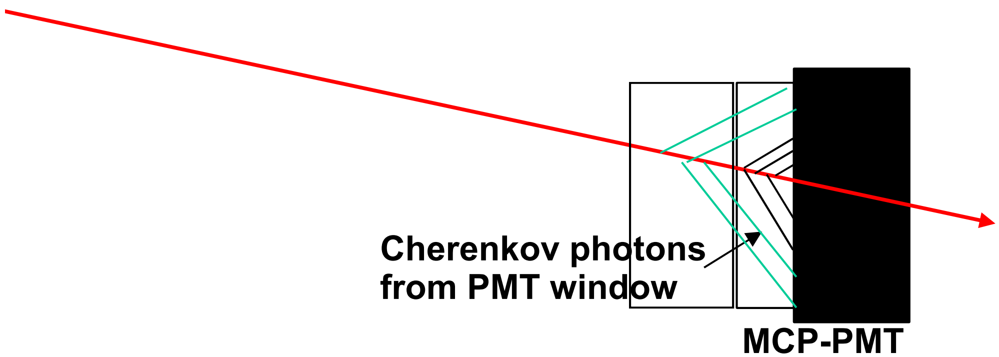


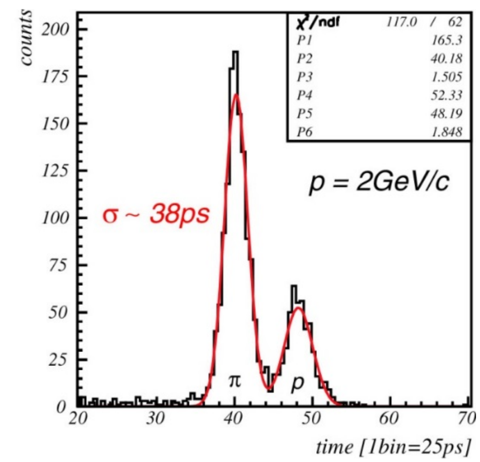
J. Va'vra, slides shown at RICH07

TOF with Cherenkov light

Idea: detect Cherenkov light with a very fast photon detector (MCP PMT).

Cherenkov light is produced in a quartz plate in front of the MCP PMT and in the PMT window.





Proof of principle: beamt test with pions and protons at 2 GeV/c.

Recent results:

→resolution ~5ps measured

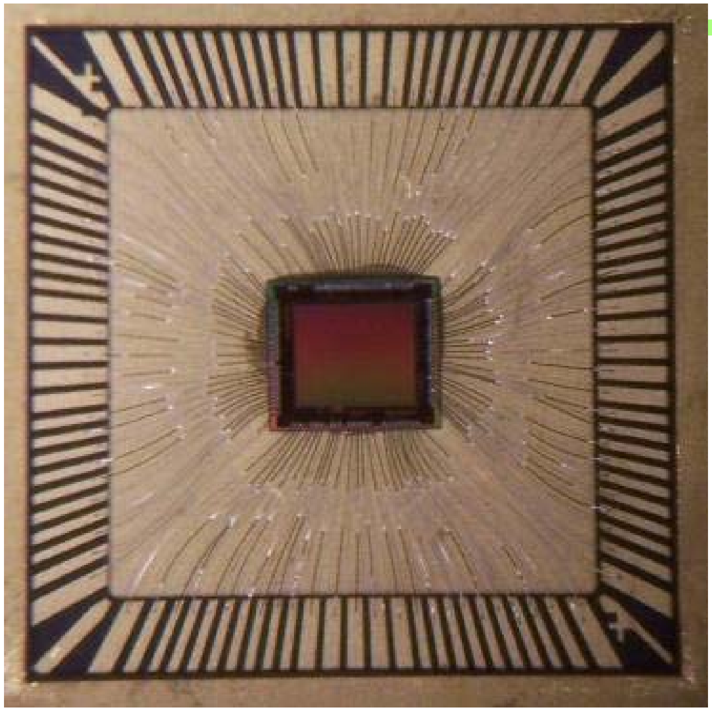
•K. Inami NIMA 560 (2006) 303

•J. Va'vra NIMA 595 (2008) 270

Open issues:

- read-out
- start time

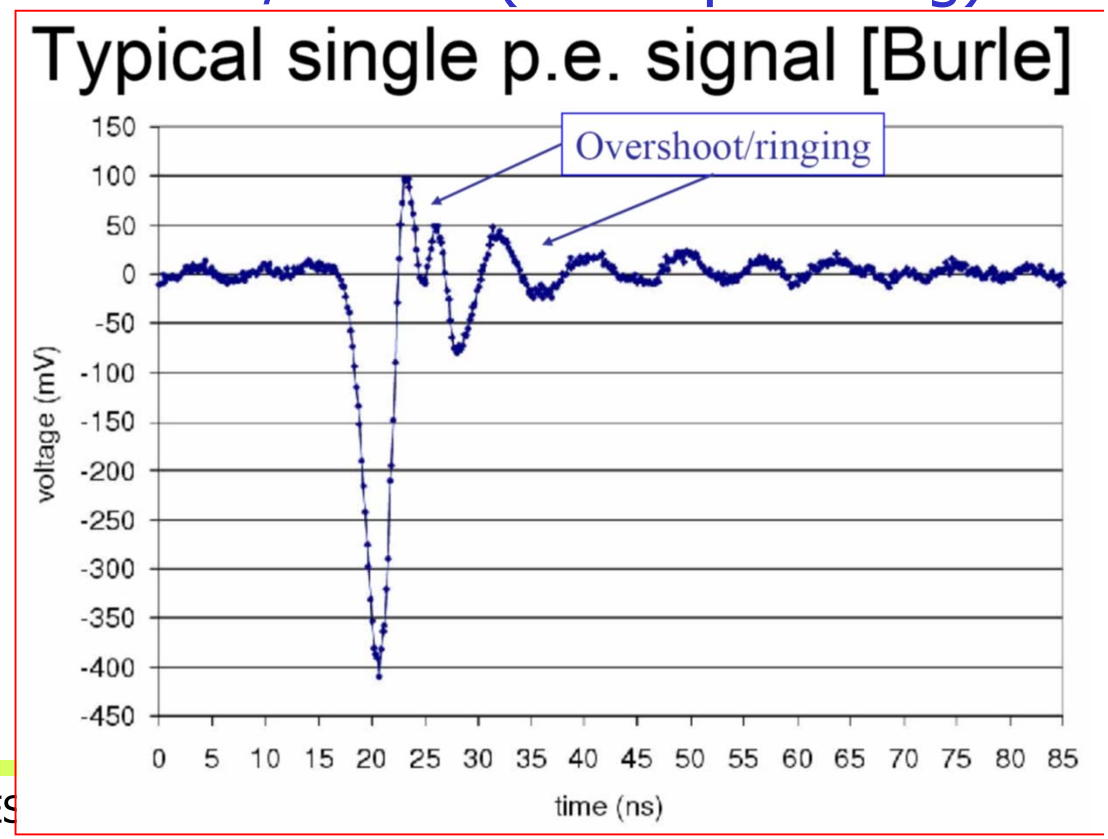
Time walk correction: waveform sampling



Gary Varner (Hawaii)

Variant of the LABRADOR 3

Successfully flew on ANITA in Dec 06/Jan 07 (<= 50ps timing)



3mm x 2.8mm, TSMC 0.25um

- 64k samples deep
- Multi-MSa/s to Multi-GSa/s

RICH for muon identification at low momenta at Belle II

Hot topic in flavour physics, lepton flavour universality tests: muon momentum spectra

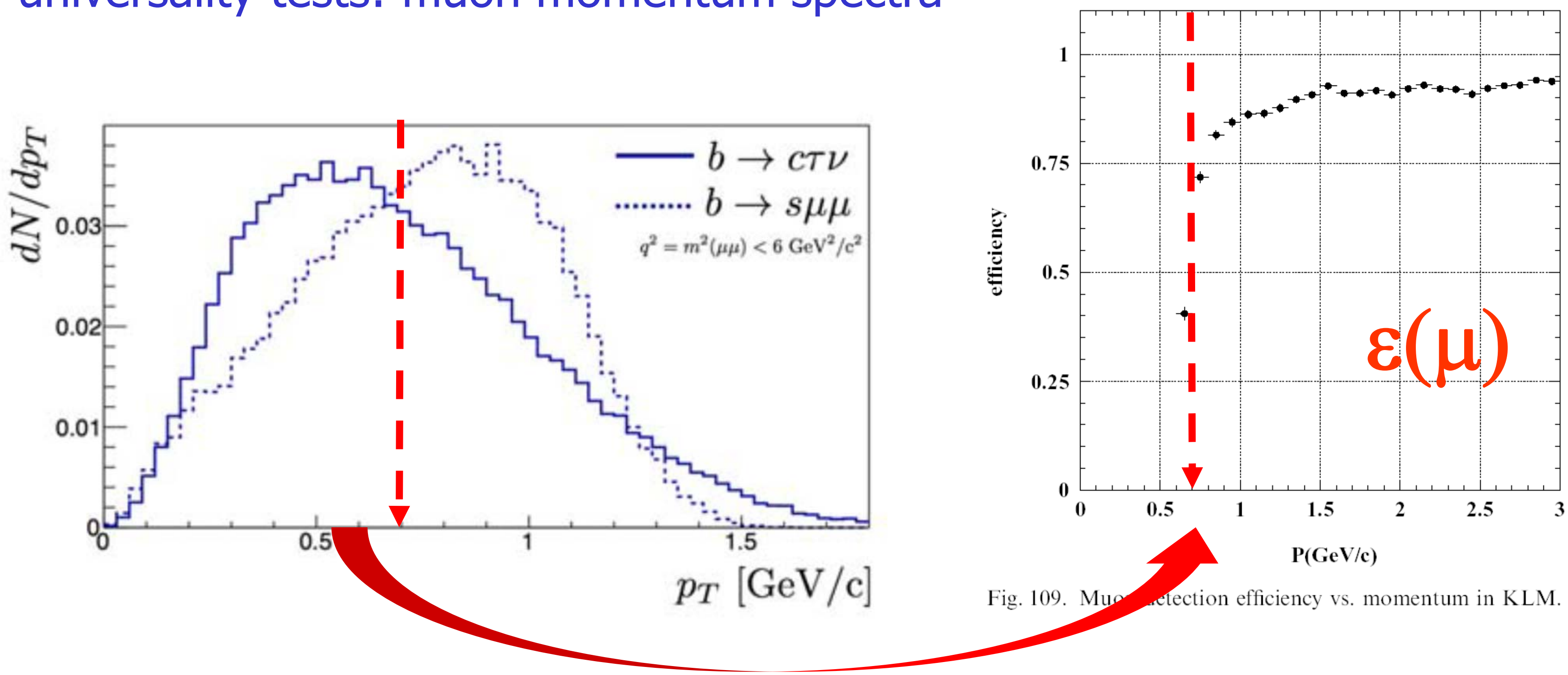


Fig. 109. Muon detection efficiency vs. momentum in KLM.

→ Muons cannot be efficiently separated from pions at low momenta – because they do not make it to the muon system

RICH for muon identification at low momenta at Belle II

Cherenkov angle for single Cherenkov photons from pions, muons, and electrons as measured in a 0.5 GeV/c test beam by a ring imaging Cherenkov detector prototype; with typically about 10 photons per muon as expected in such a counter, the muon and pion peaks would be well separated.

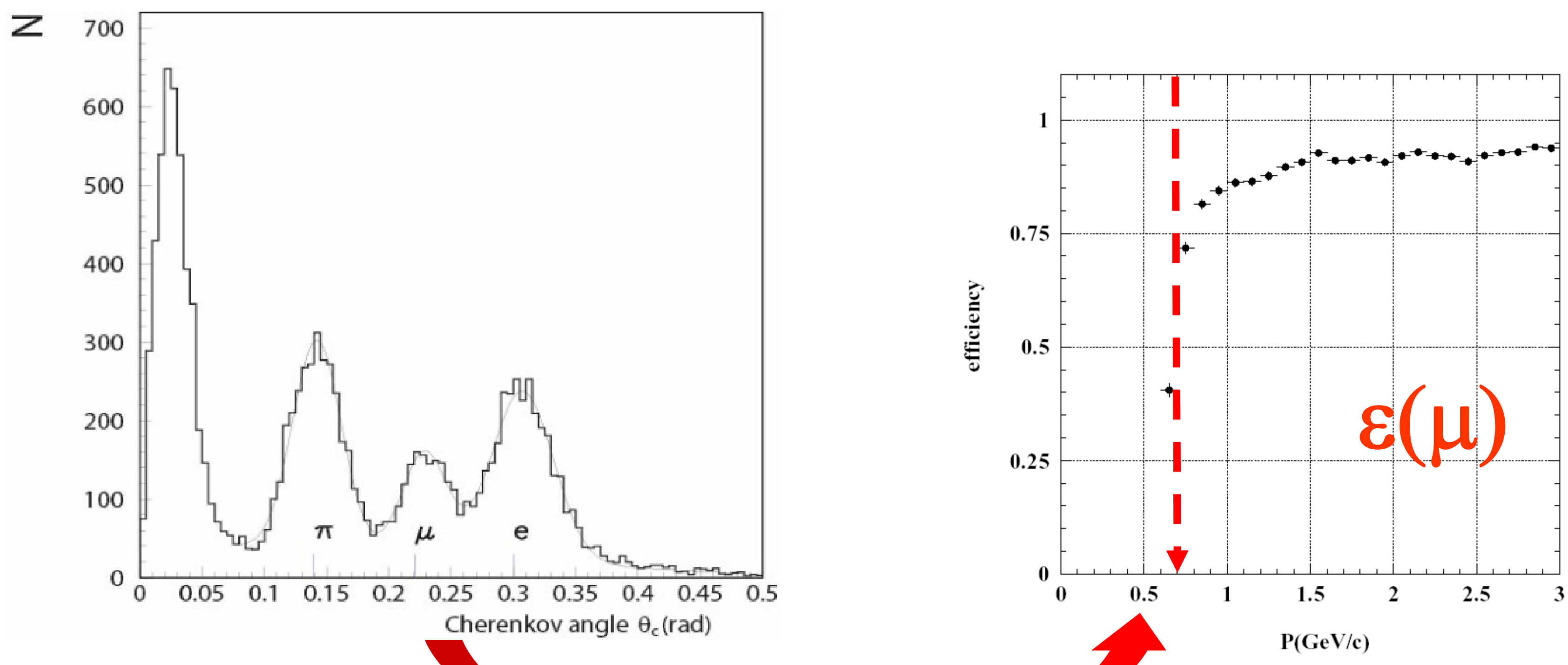


Fig. 109. M n detection efficiency vs. momentum in KLM.

Identification of charged particles

Particles (e, μ, π, K, p) in the final state are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, $p=\gamma mv$ (p is known - radius of curvature in magnetic field)

→Measure velocity by:

- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

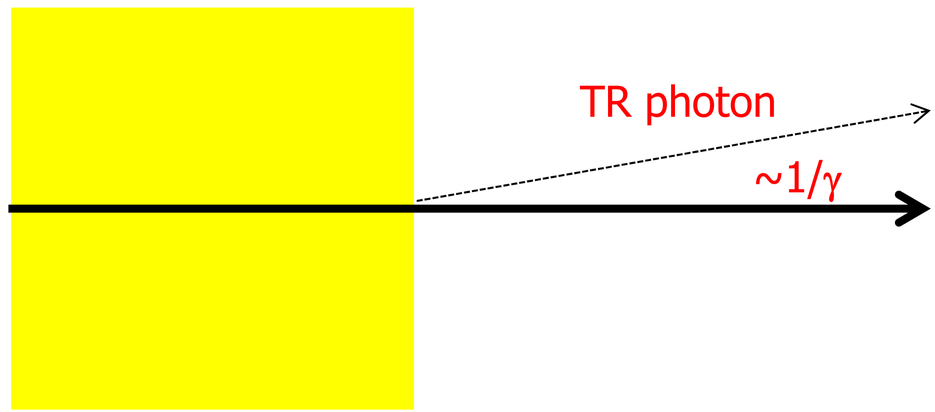
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters

Transition radiation

E.M. radiation emitted by a charged particle at the boundary of two media with different refractive indices



Analogy:

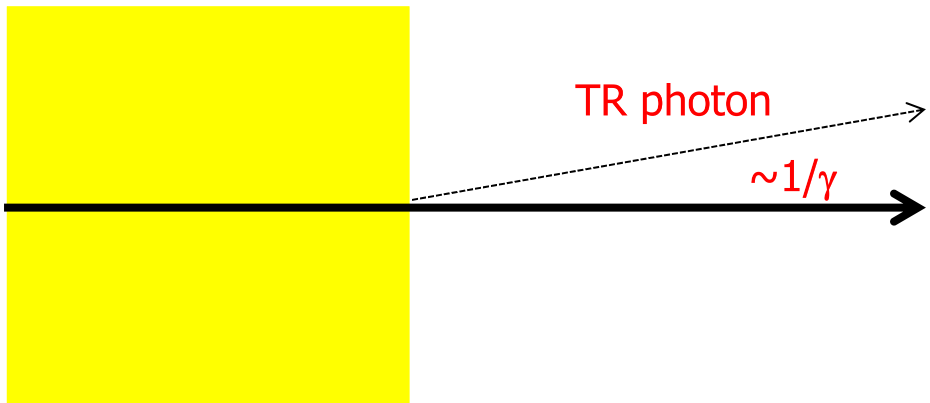
- Accelerated particle emits E.M. radiation
- Transition radiation: particle has a constant velocity, but the phase velocity of the medium changes abruptly at the boundary → radiation

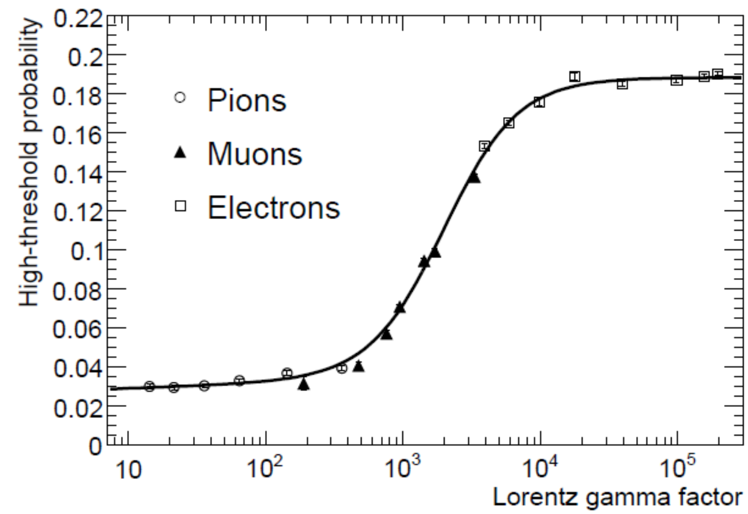
→B. Dolgoshein, NIM A326 (1993) 434-469; J.D. Jackson, Classical Electrodynamics.

→H. Kolanoski, N. Wermes, Teilchendetektoren, Springer.

Transition radiation

E.M. radiation emitted by a charged particle at the boundary of two media with different refractive indices





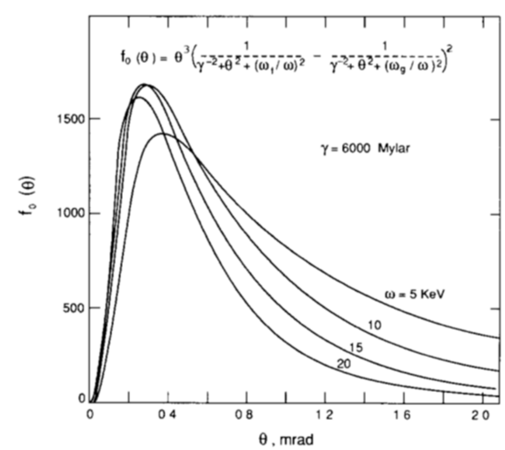
Emission rate depends on γ (Lorentz factor): becomes important at γ~1000

- Electrons at 0.5 GeV
- Pions above 140 GeV

Emission probability per boundary ~α = 1/137

Emission angle ~1/γ

Typical photon energy: ~10 keV → X rays



Transition radiation - detection

Emission probability per boundary $\sim\alpha = 1/137$

→ Need many boundaries

- Stacks of thin foils or
- Porous materials – foam with many boundaries of individual 'bubbles'

Typical photon energy: ~10 keV → X rays

→ Need a wire chamber with a high Z gas (Xe) in the gas mixture

Emission angle $\sim 1/\gamma$

→ Hits from TR photons along the charged particle direction

- Separation of X ray hits (high energy deposit on one place) against ionisation losses (spread out along the track)
- Two thresholds: lower for ionisation losses, higher for X ray detection

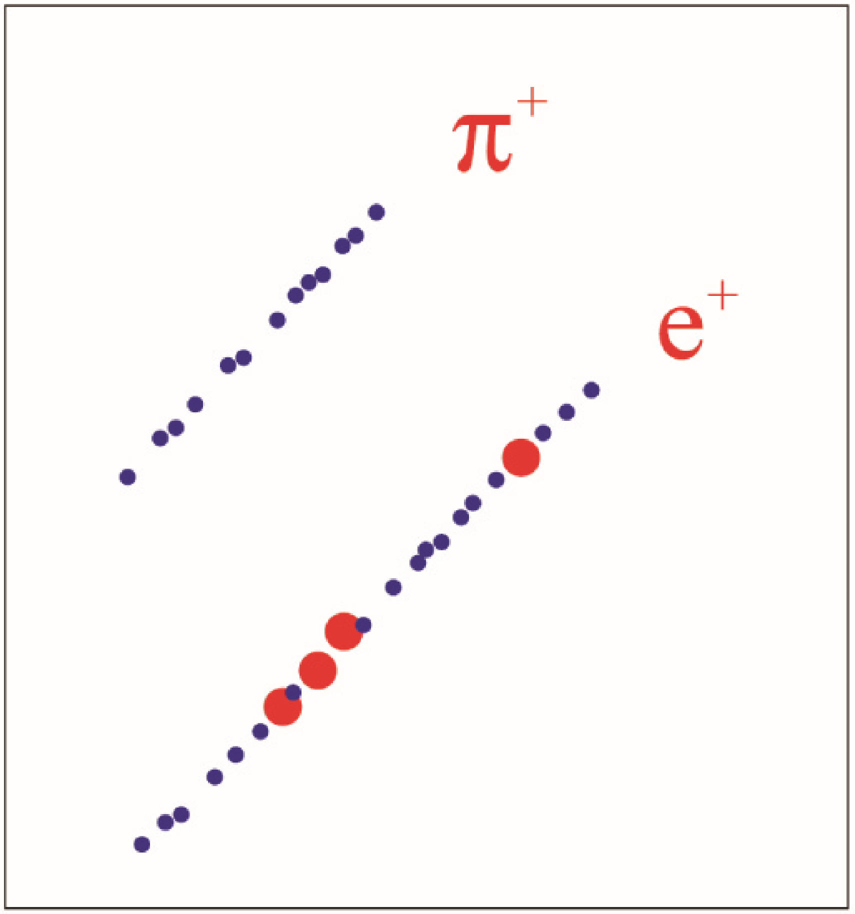
Transition radiation - detection

→ Hits from TR photons along the charged particle direction

- Separation of X ray hits (high energy deposit on one place) against ionisation losses (spread out along the track)
- Two thresholds: lower for ionisation losses, higher for X ray detection

  - Small circles: low threshold (ionisation)
  - Big circles: high threshold (X ray detection)

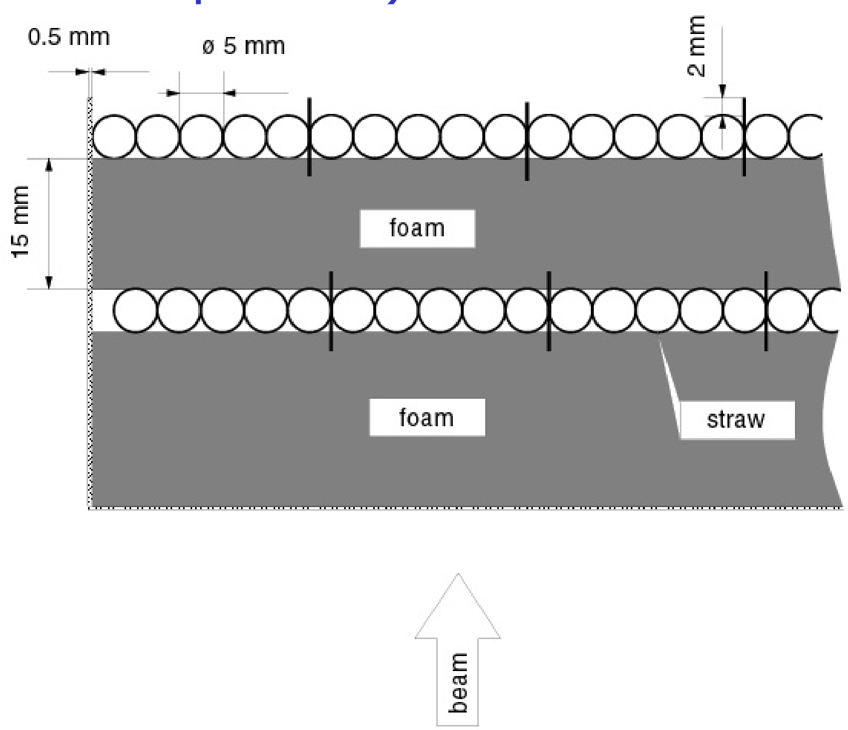
(pion below, e above the TR threshold)



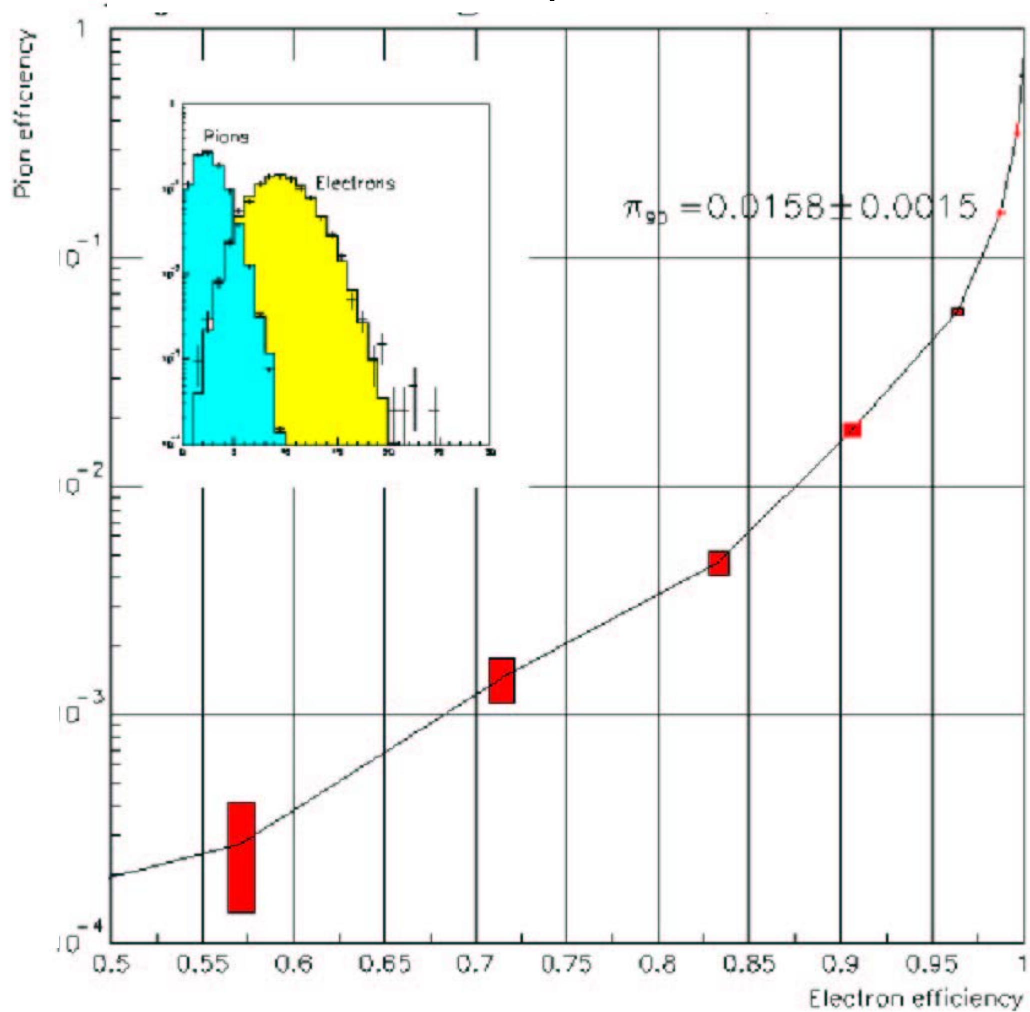
Transition radiation detectors

Example:

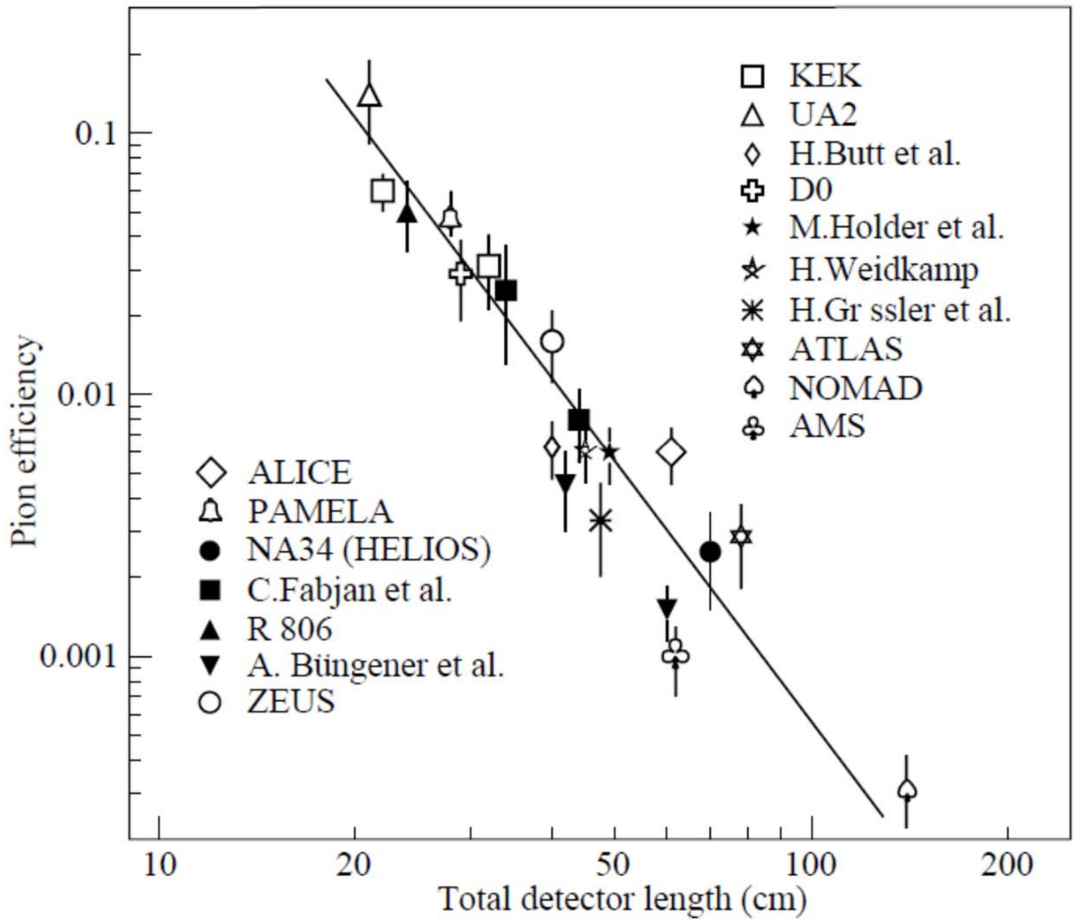
Radiator: organic foam between the detector tubes (straws made of capton foil)



Performance: pion efficiency (fake prob.) vs electron efficiency

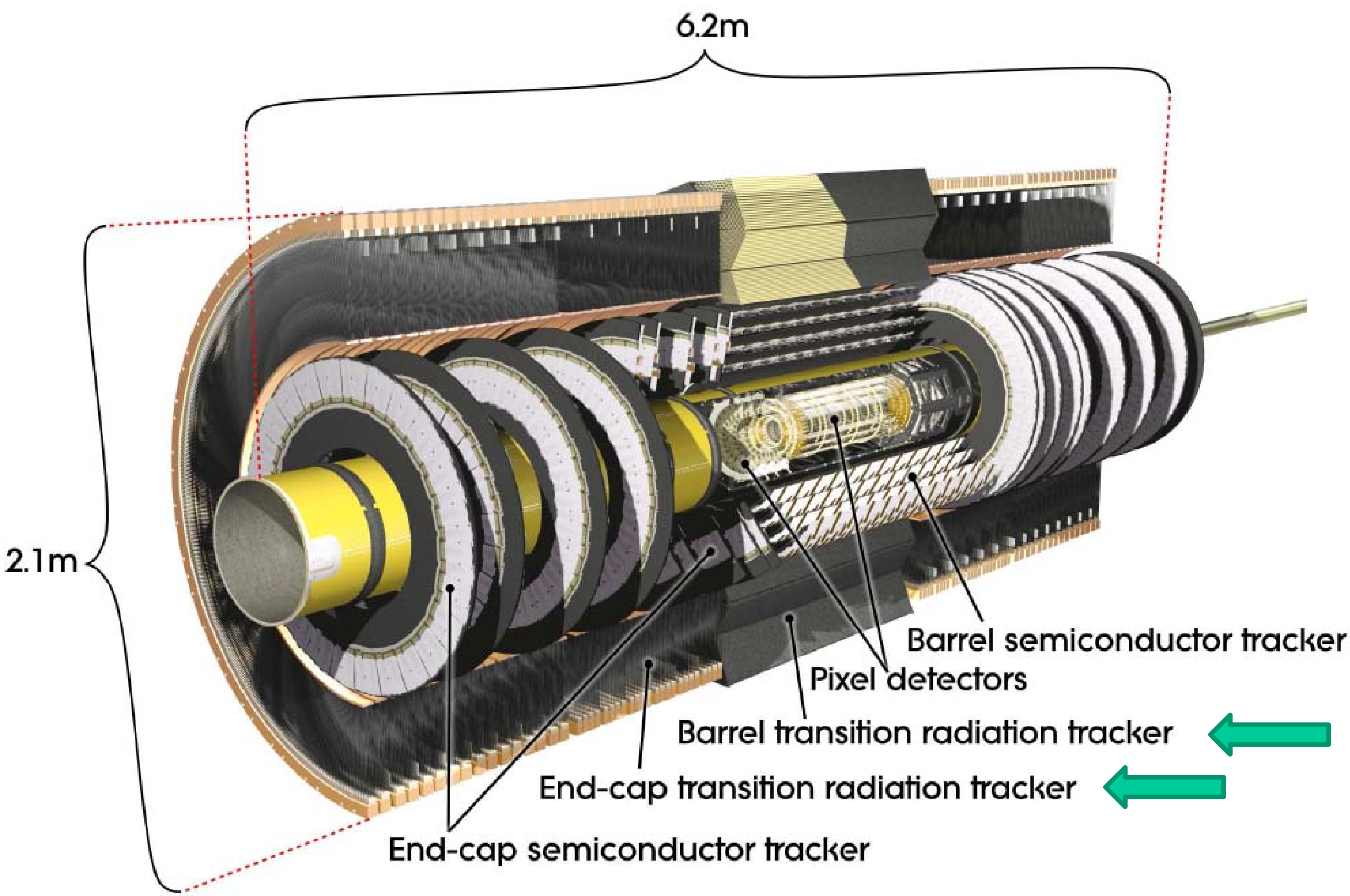


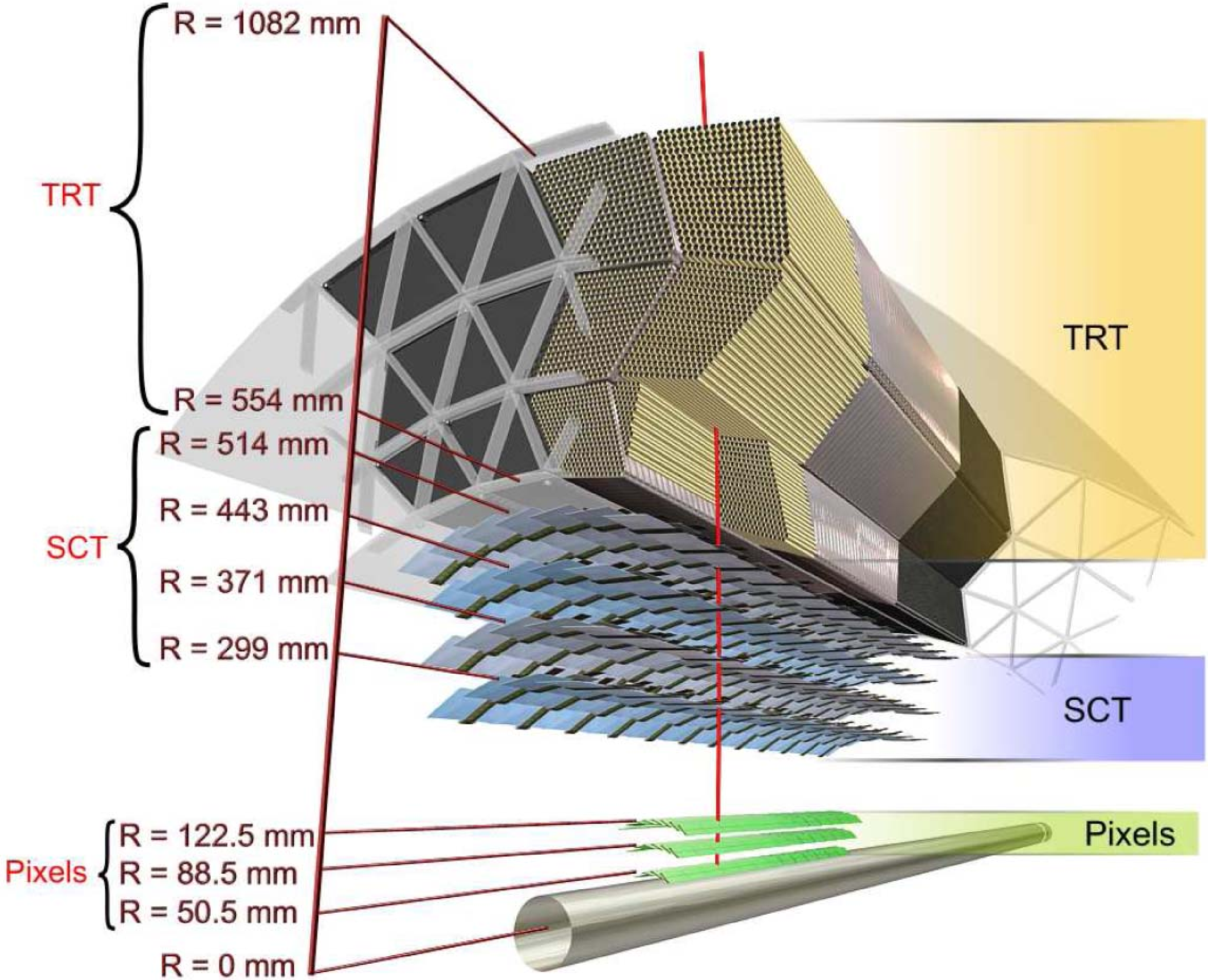
Transition radiation detectors - peformance



Performance: pion efficiency (fake prob.) vs detector length

Transition radiation detector in ATLAS: combination of a tracker and a transition radiation detector





R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels

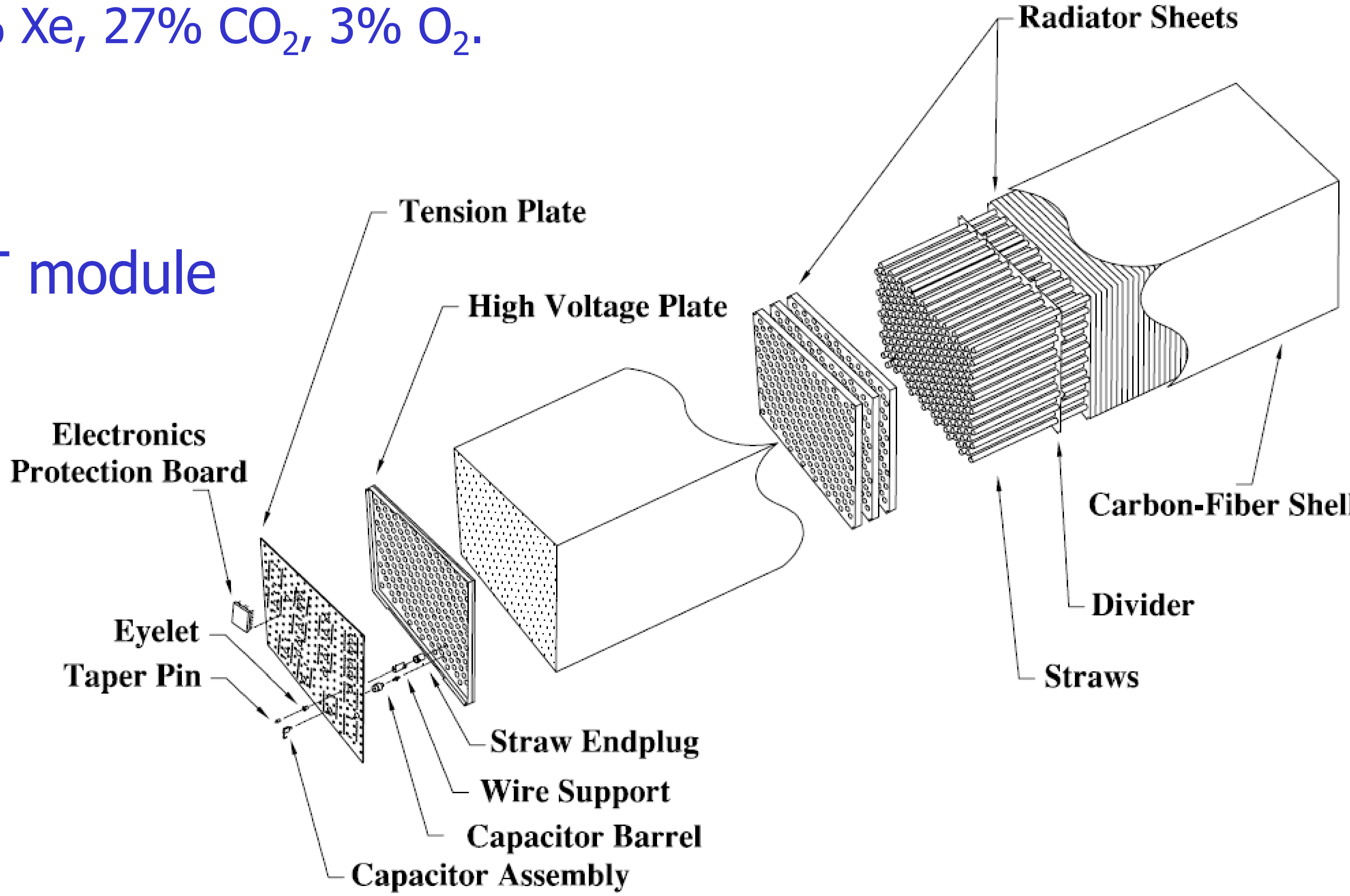
ına

ATLAS TRT

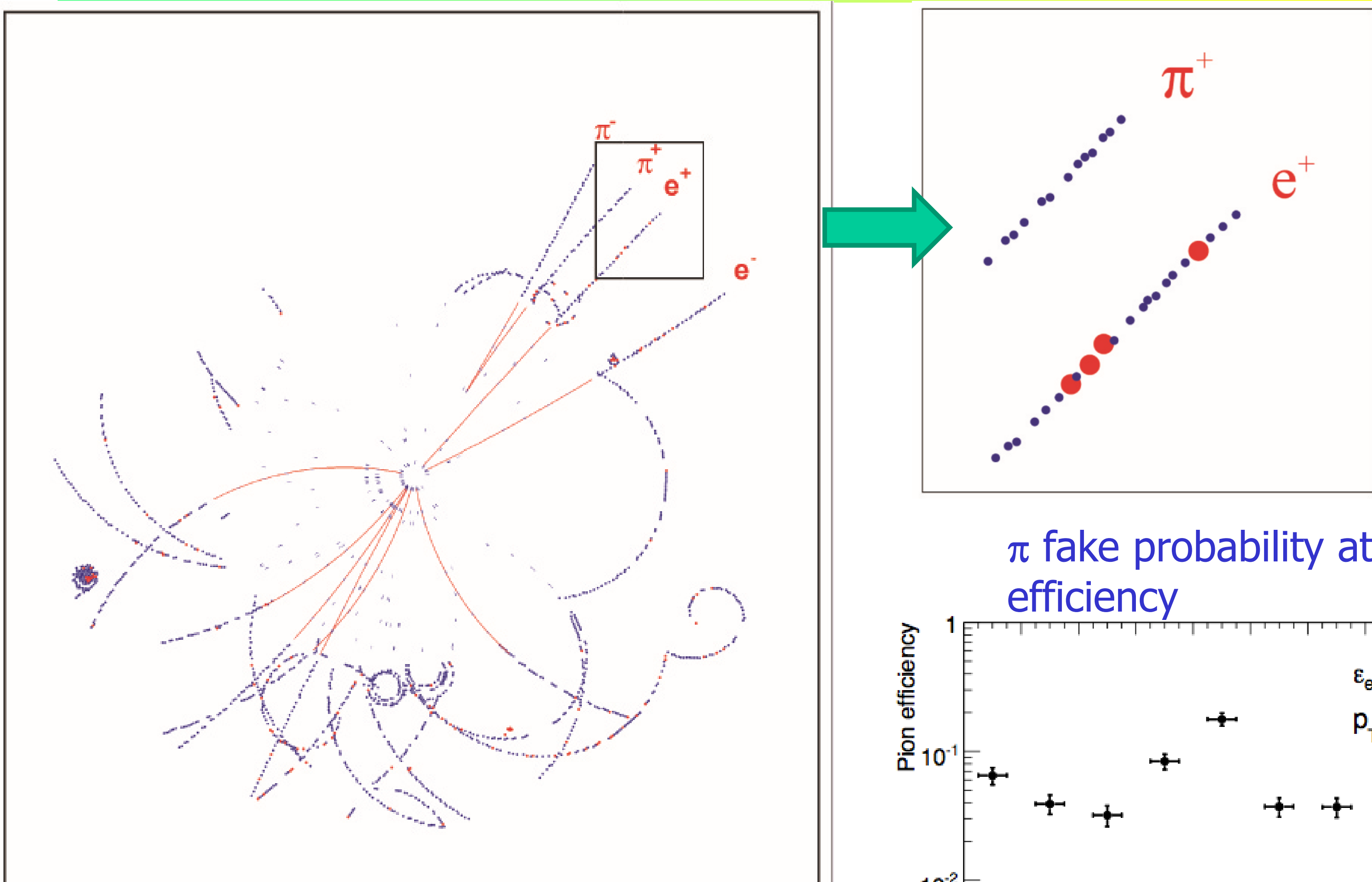
Radiator: 3mm thick layers made of polypropylene-polyethylene fibers with ~19 micron diameter, density: 0.06 g/cm^3

Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO_2, 3% O_2.

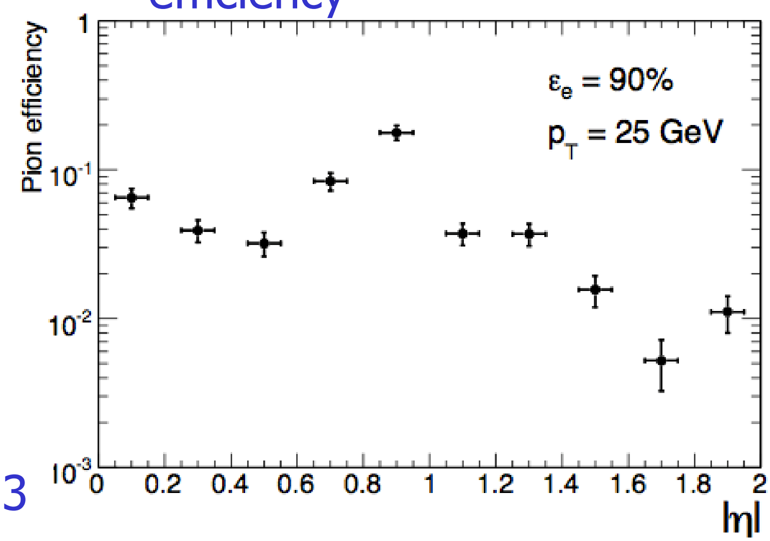
TRT module



TRT: pion-electron separation



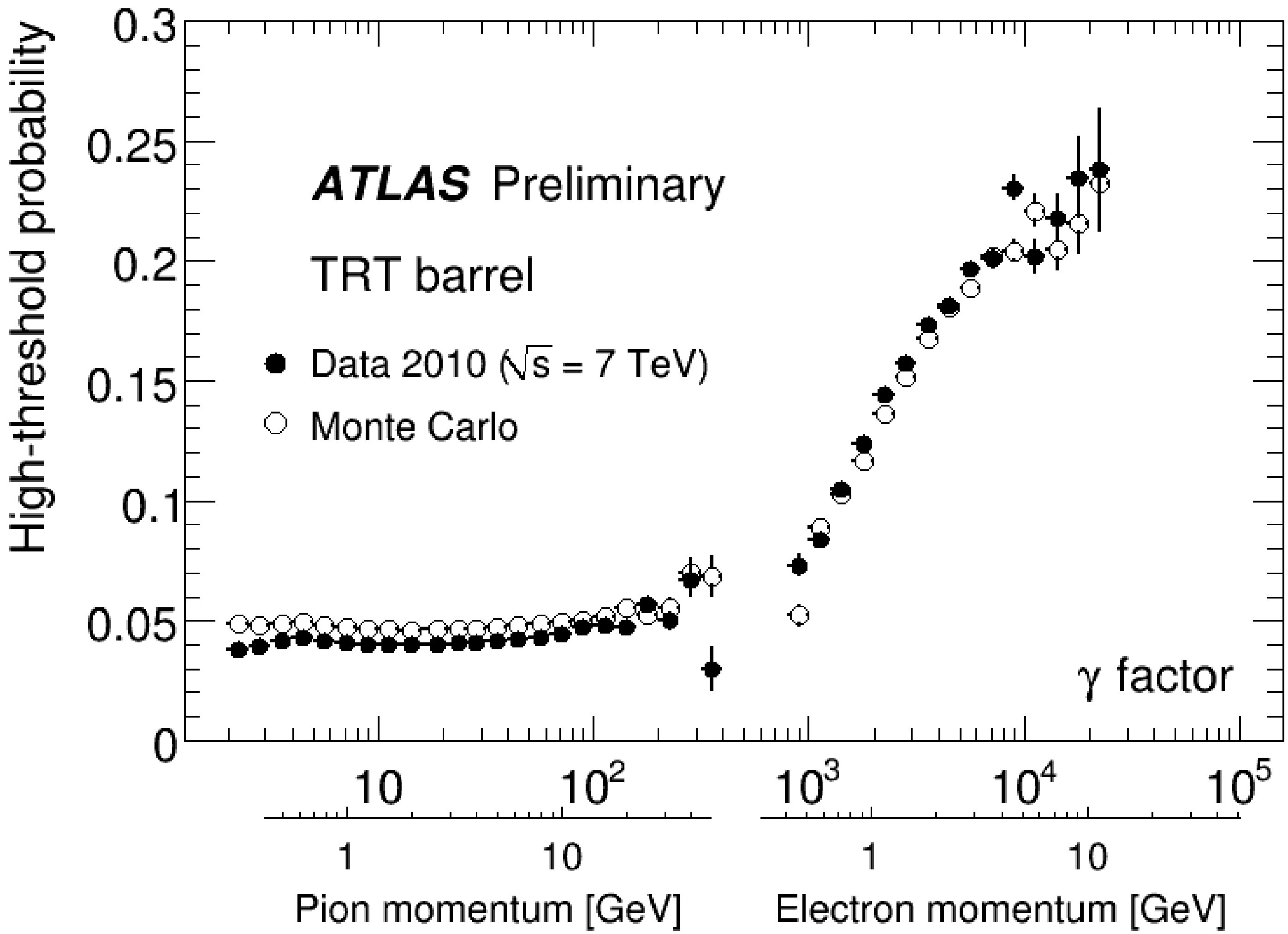
π fake probability at 90% e efficiency



→ JINST 3 (2008) S08003

TRT performance in 2010 data

e/pion separation: high threshold hit probability per straw



Summary

Particle identification is an essential part of several experiments, and has contributed substantially to our present understanding of elementary particles and their interactions, and will continue to have an important impact in searches for new physics.

A large variety of techniques has been developed for differnt kinematic regions and different particles, based on Cherenkov radiation and transition radiation.

New concepts and detectors are being studied → this is a very active area of detector R+D.