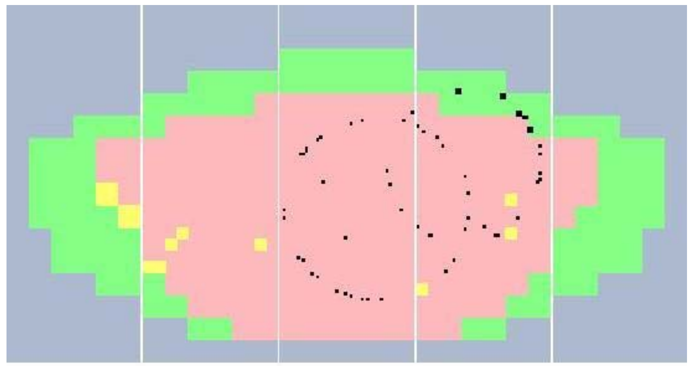
Instrumentation for Colliding Beam Physics (INSTR-20)
February 24 – February 28, 2020
Budker Institute of Nuclear Physics, Novosibirsk



Recent advances in particle identification methods

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dE/dx and TOF

Transition radiation detectors

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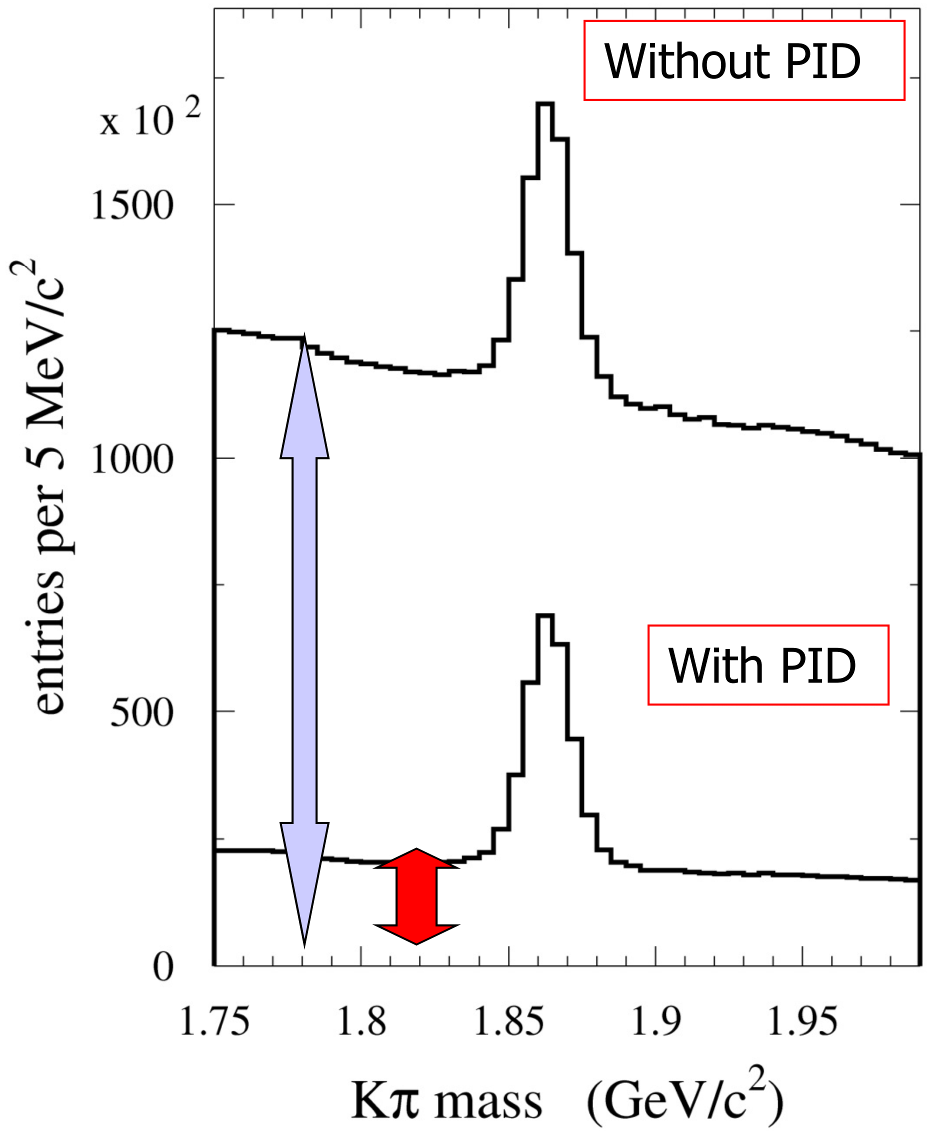
Why particle ID?

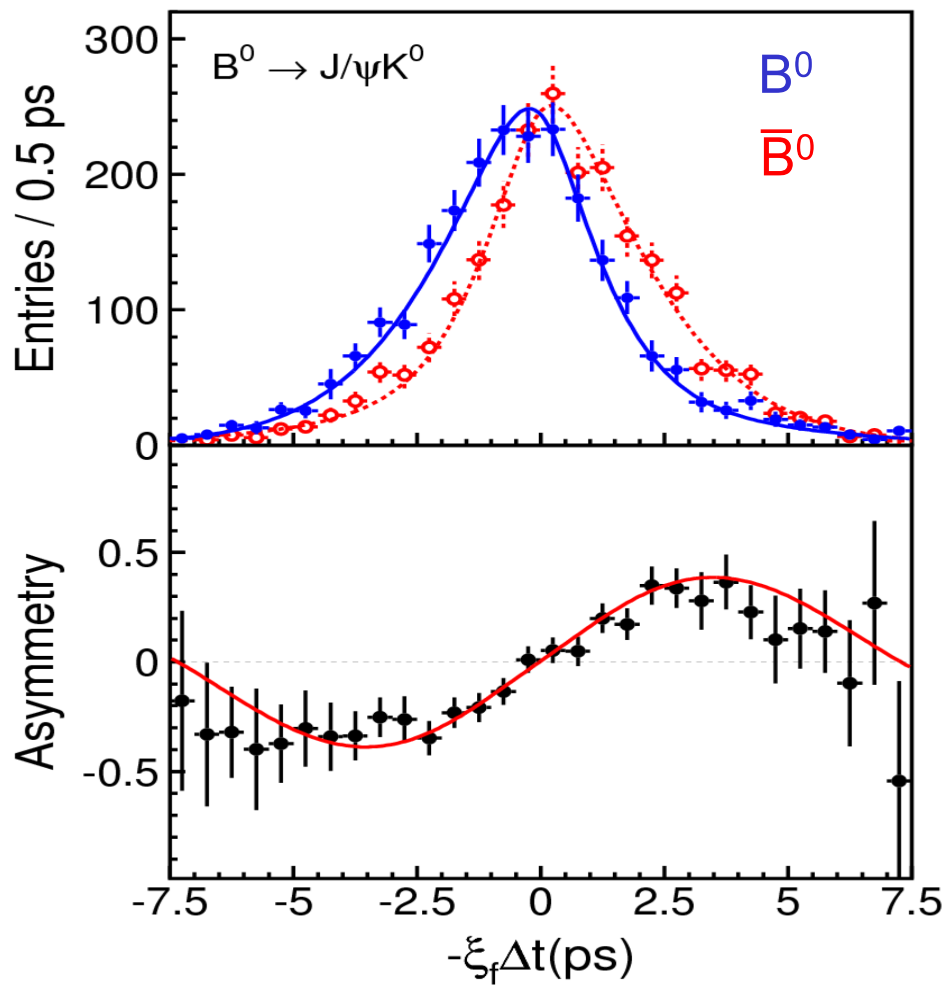


Example 1: BaBar (B factory)

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

Why particle ID?

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

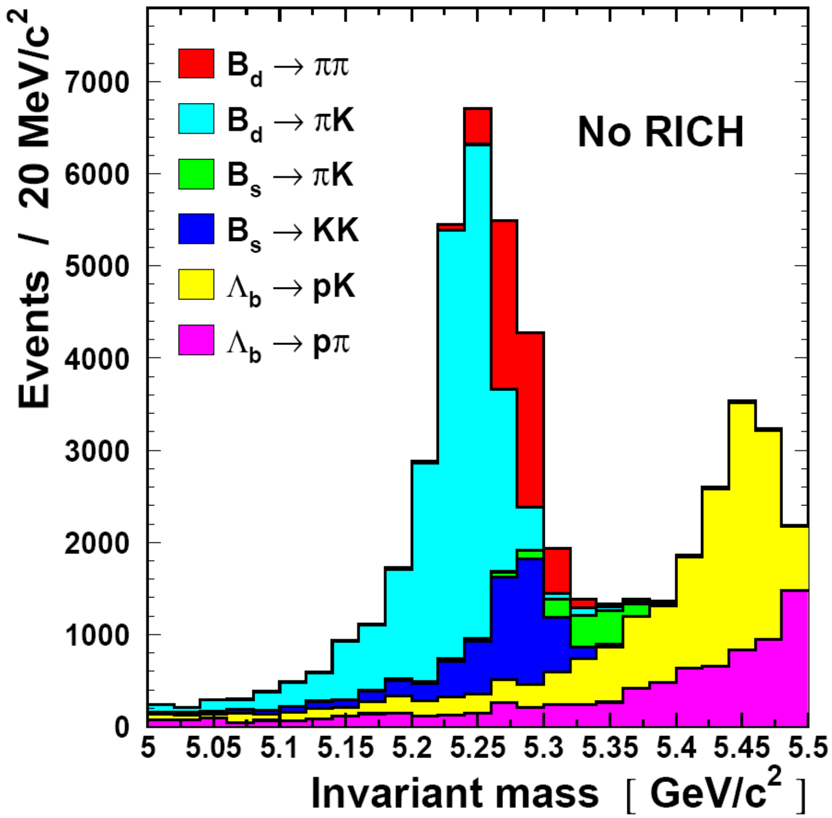


B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

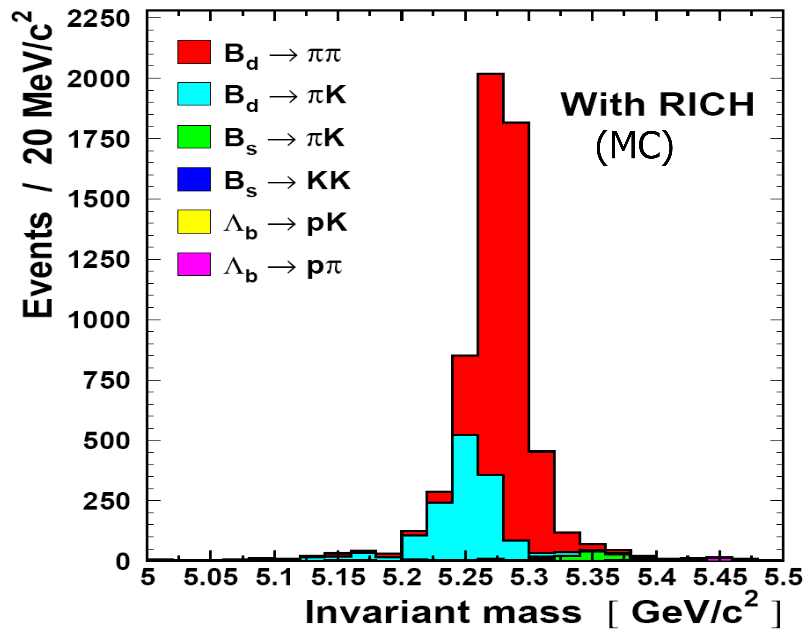
Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

→particle ID is compulsory

Why particle ID?

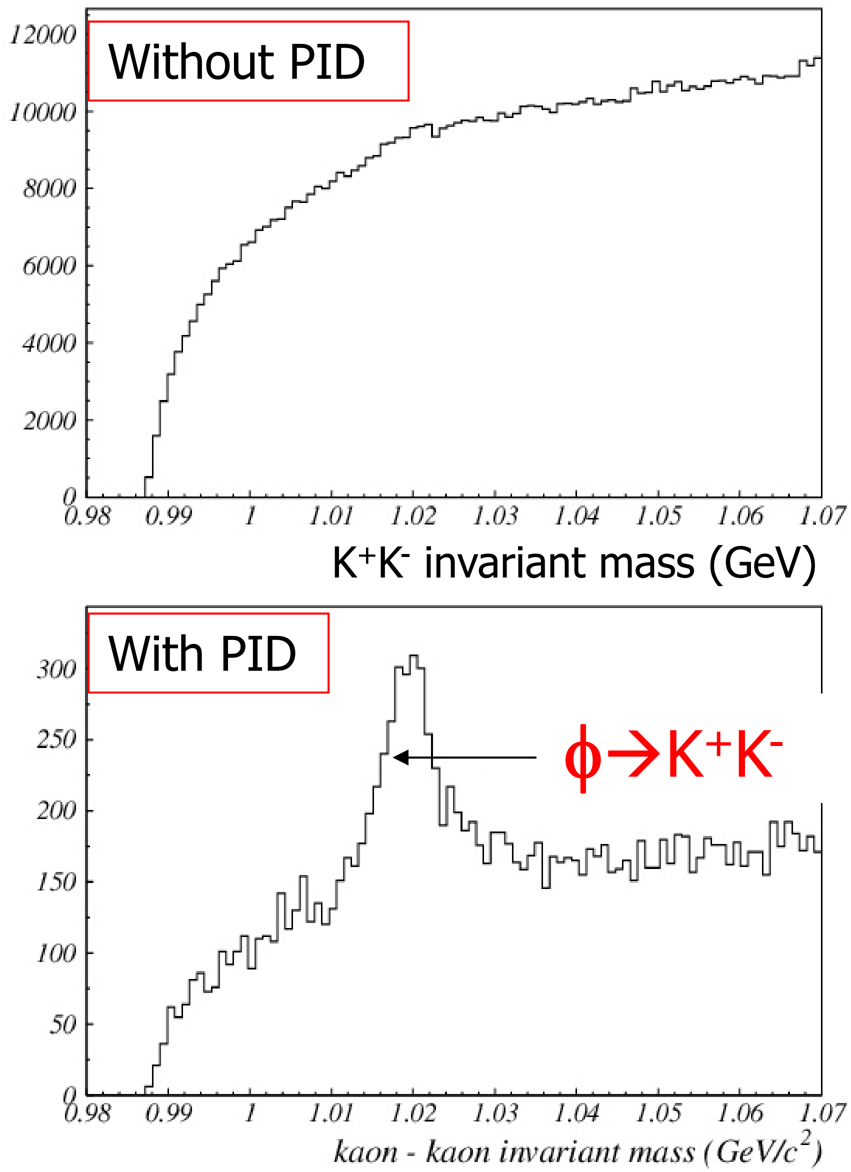


Example 2: LHCb



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:

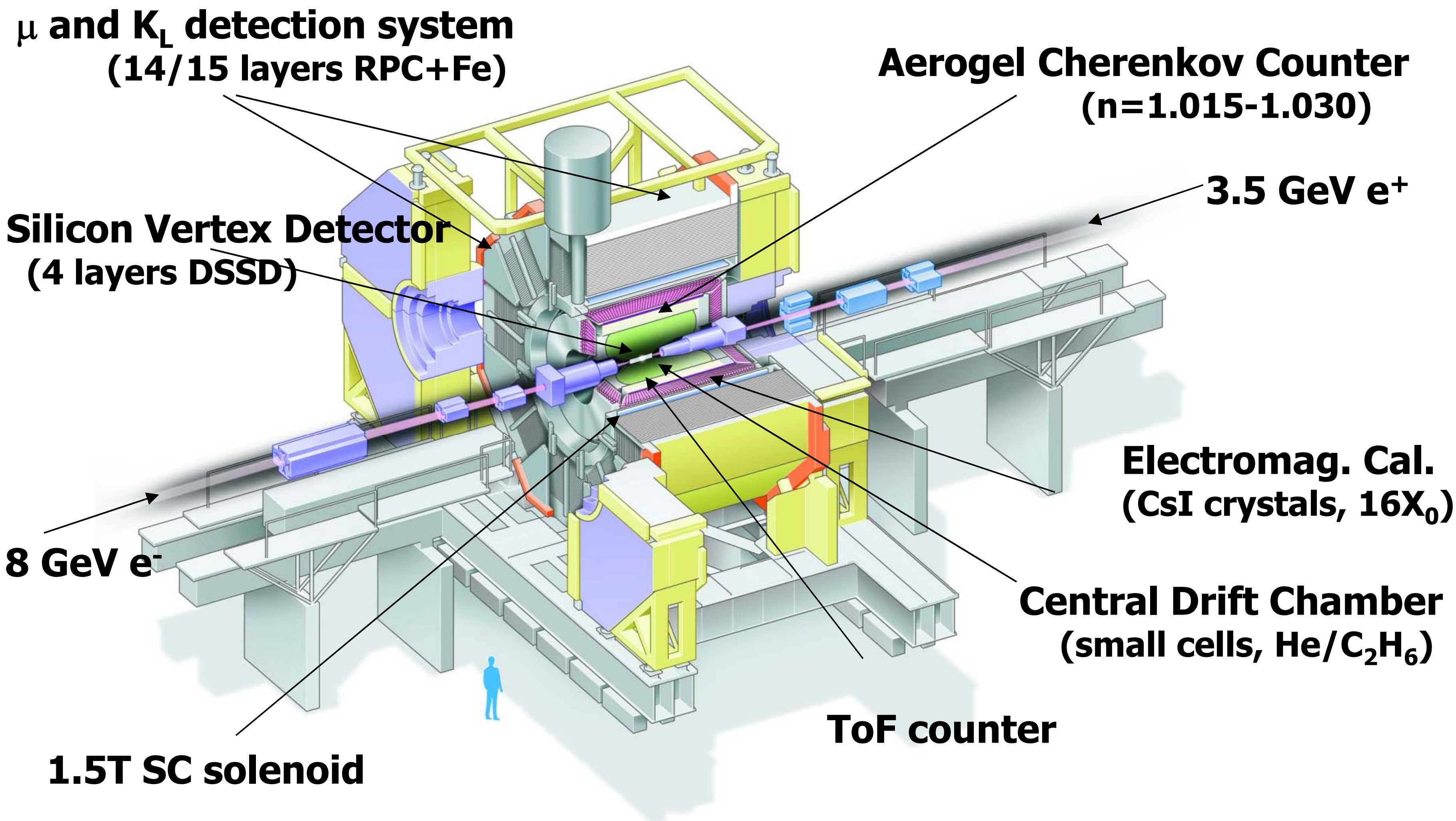
•General purpose LHC experiments: final states with electrons and muons

•Searches for exotic states of matter (quark-gluon plasma)

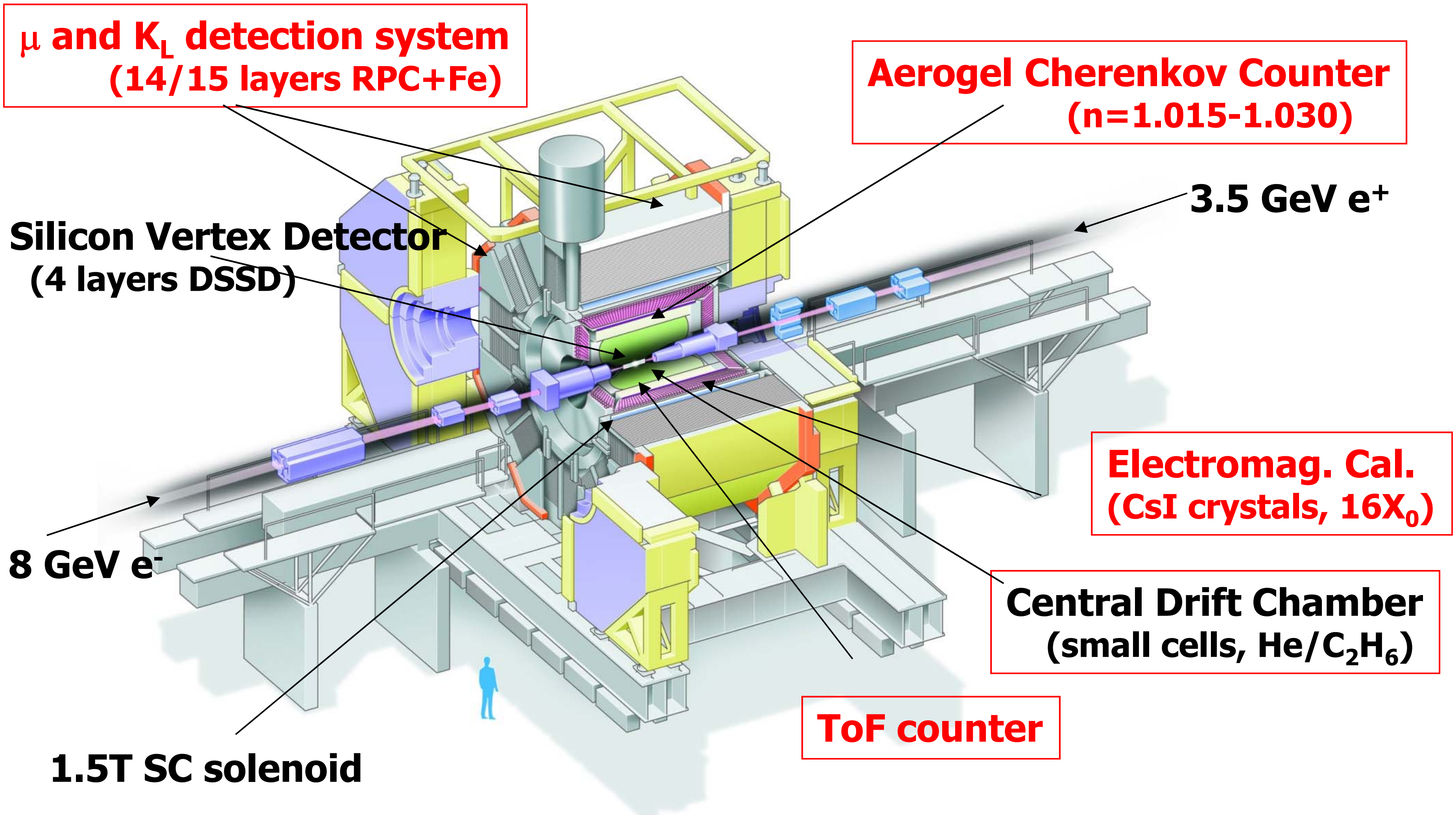
•Spectroscopy and searches for exotic hadronic states

•Studies of fragmentation functions

Example: Belle

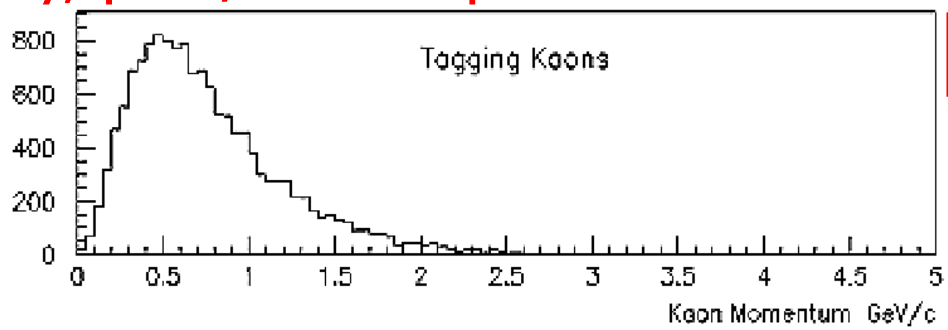


Particle identification systems in Belle



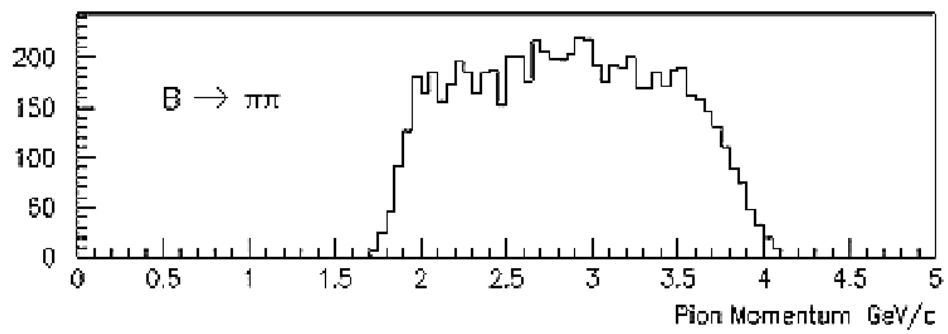
Particle identification methods depend on the requirements (physics channel, kinematics)

Example: B factory, pion/kaon separation



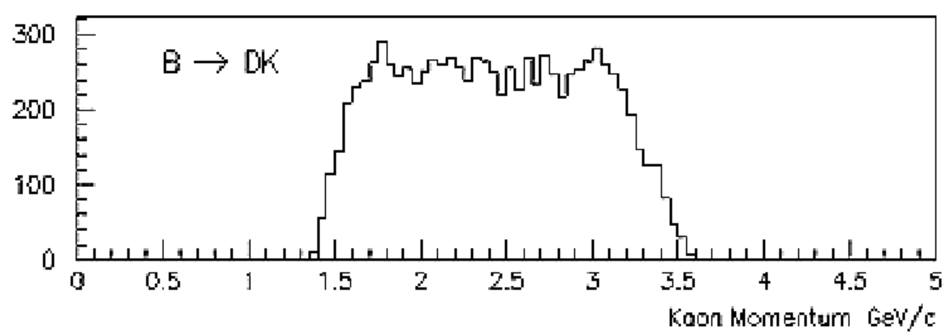
Tagging Kaons

Relatively soft, ms dominated for tracking



$B \to \pi\pi$

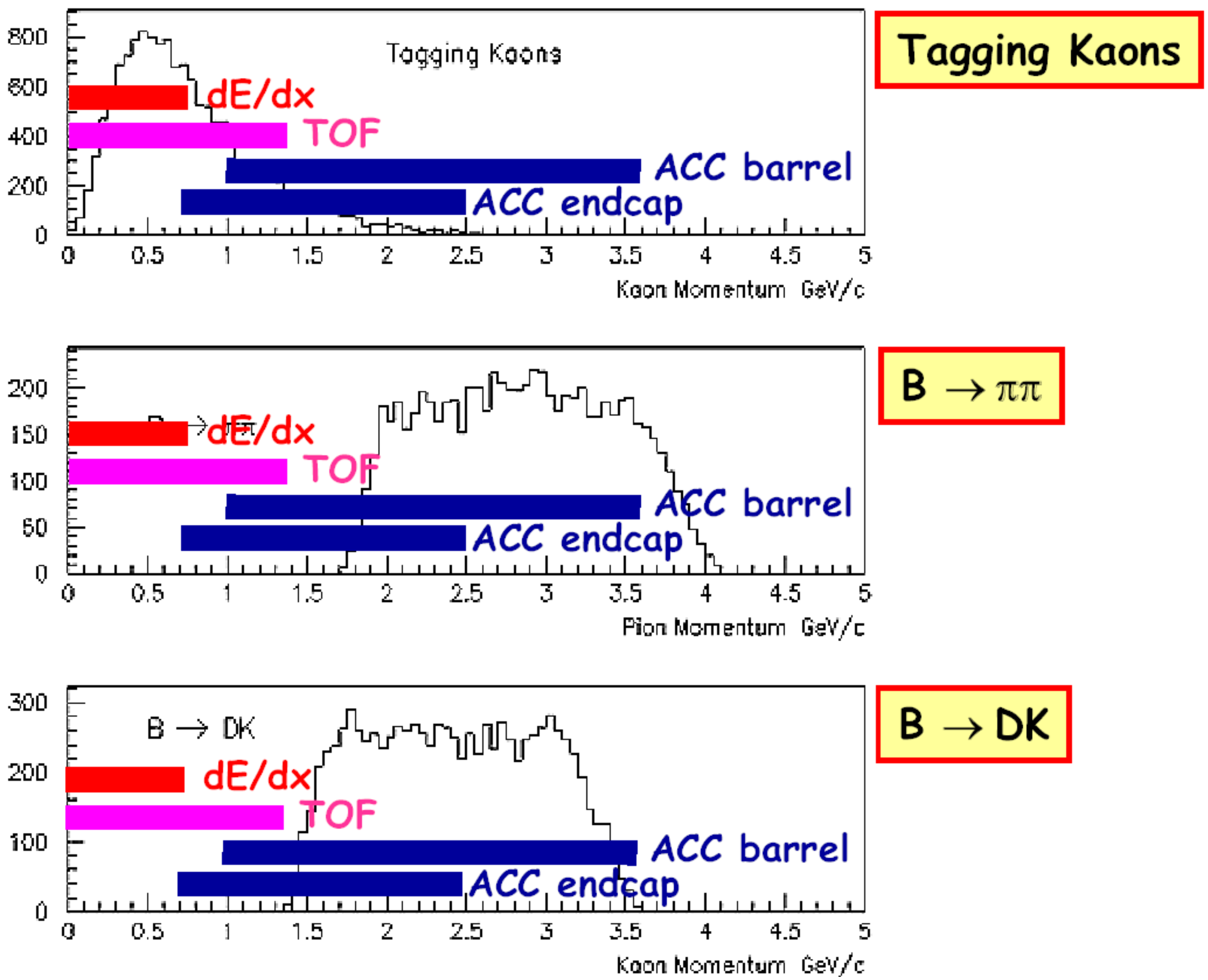
Requires dedicated PID



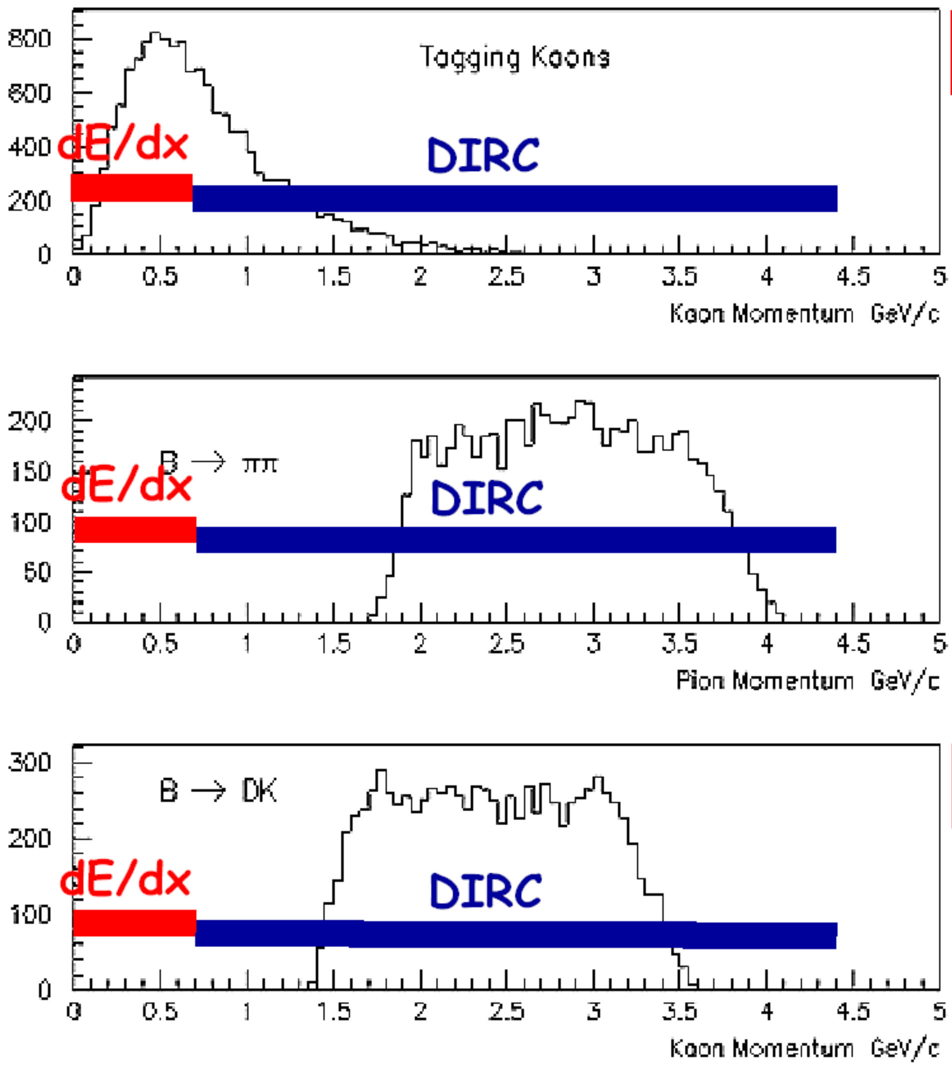
$B \to DK$

Requires dedicated PID

PID coverage of kaon/pion spectra in Belle



PID coverage of kaon/pion spectra in BaBar



Tagging Kaons

$B \to \pi\pi$

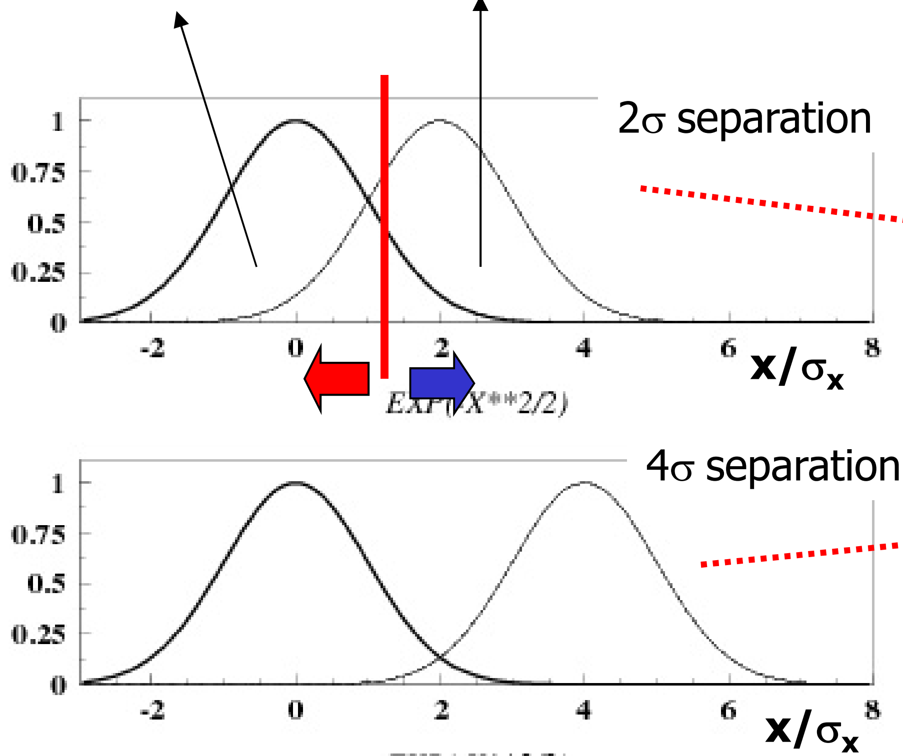
$B \to DK$

Efficiency and purity in particle identification

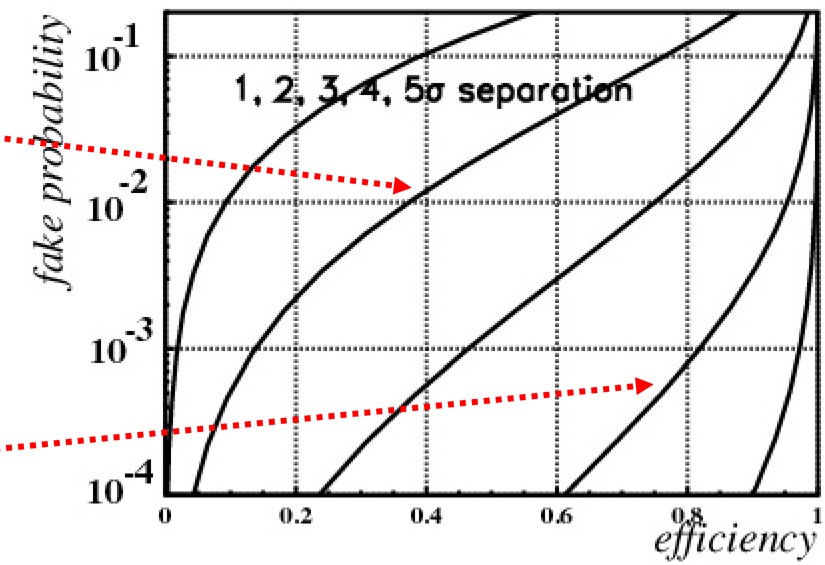
Efficiency and purity are tightly coupled!

Two examples:

particle type 1   type 2



efficiency vs fake probability
(for Gaussian distributions)



some discriminating variable **x**, scaled to the resolution σ_x

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 the 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

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Identification through interaction: electrons and muons

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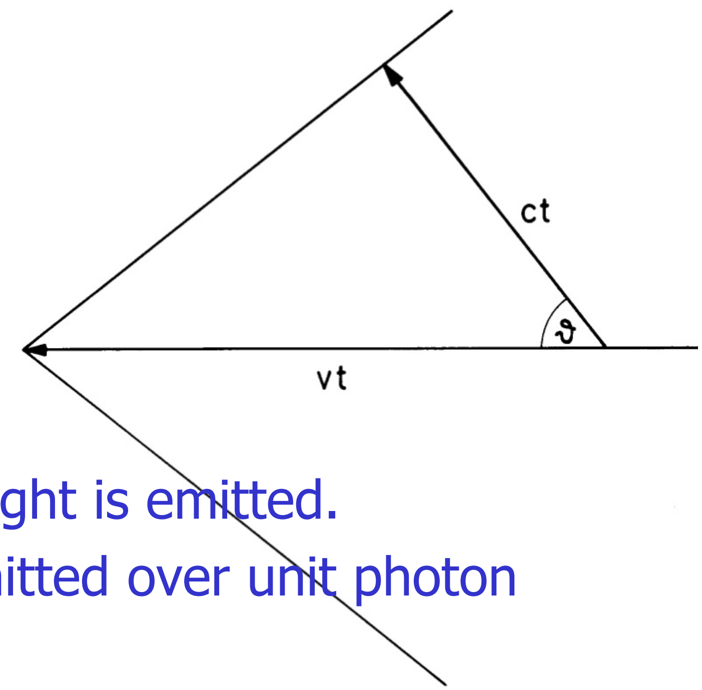
Cherenkov radiation

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.

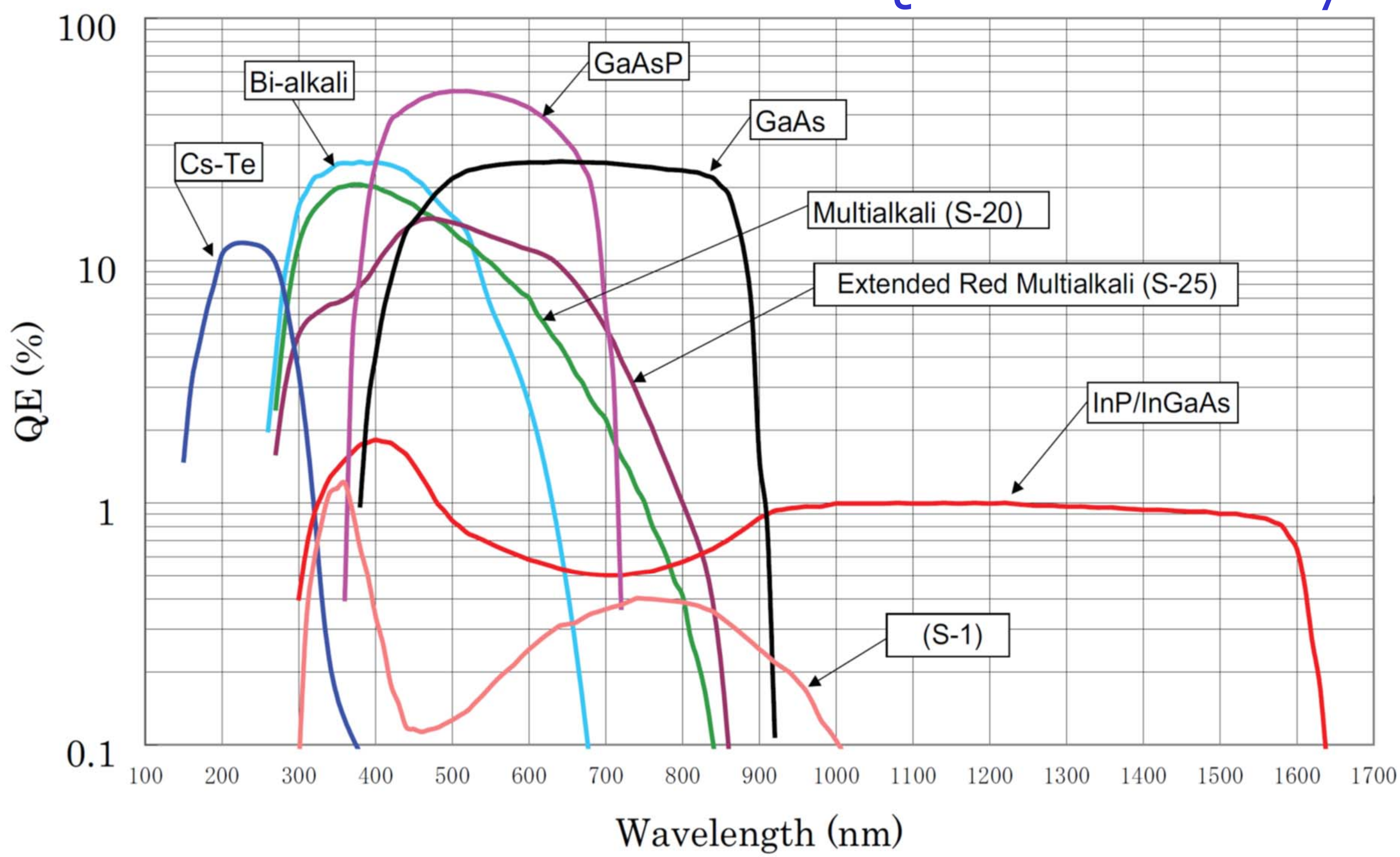
→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

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

→Few detected photons

Photon detection efficiency

Quantum efficiency



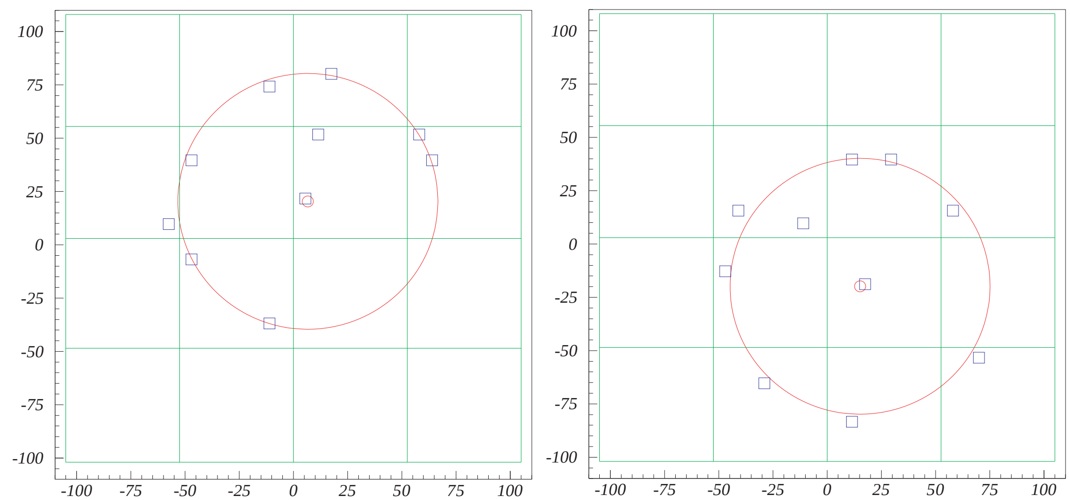
Number of detected photons

Example: in 1m of air ($n=1.00027$) a track with $\beta=1$ emits N=41 photons in the spectral range of visible light ($\Delta E \sim 2$ eV).

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

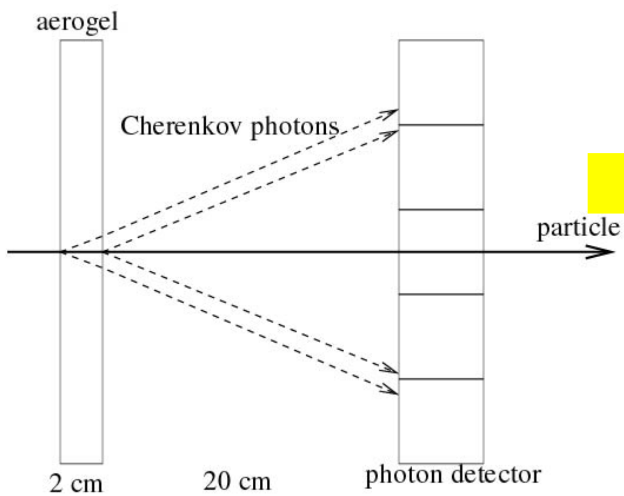
Few photons detected

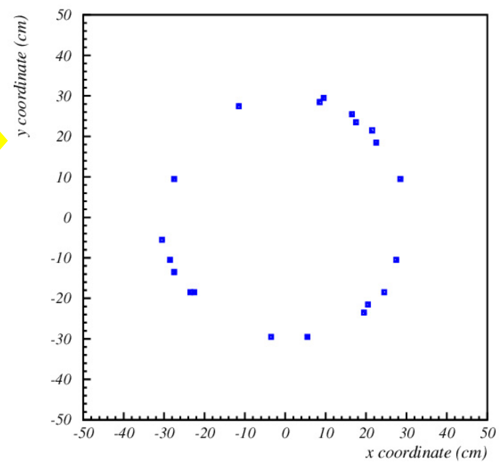
→Important to have a low noise detector



Measuring the Cherenkov angle

Particles above threshold: measure θ



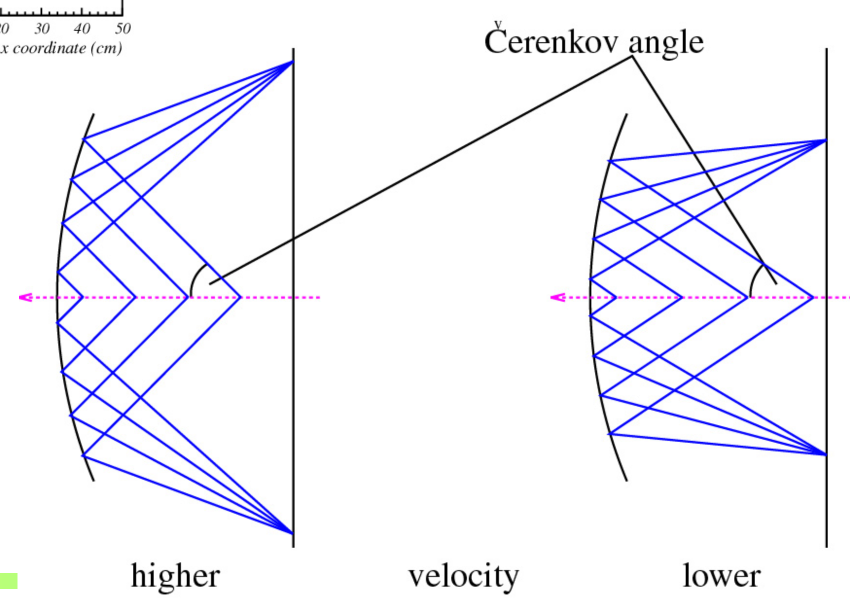


Idea: transform the direction into a coordinate → ring on the detection plane

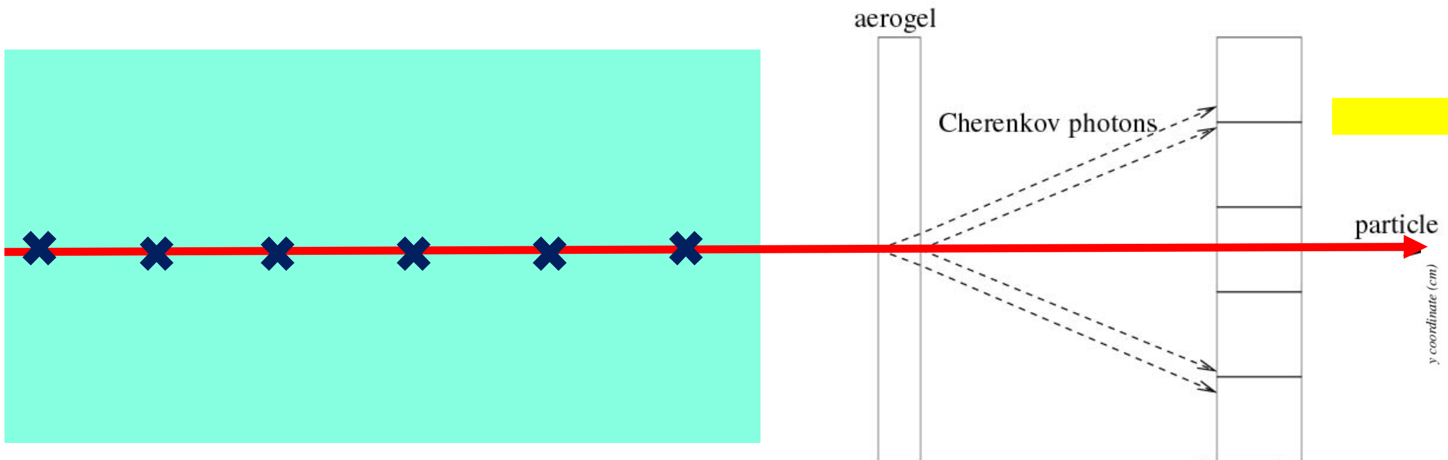
→ Ring Imaging Cherenkov (RICH) counter

Proximity focusing RICH

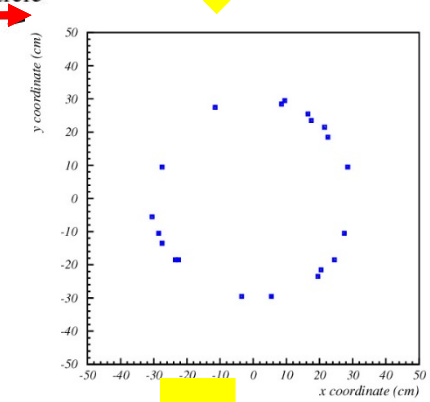
RICH with a focusing mirror

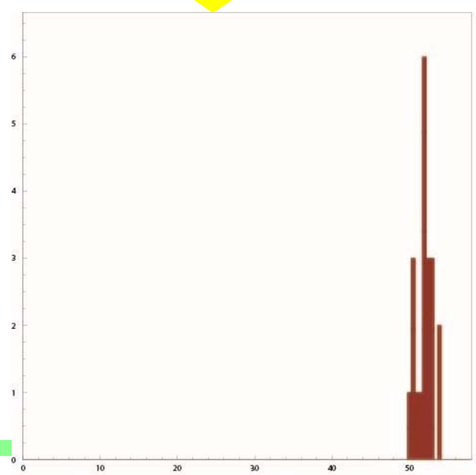


Measuring the Cherenkov angle



Tracking system (measures the direction of the particle)



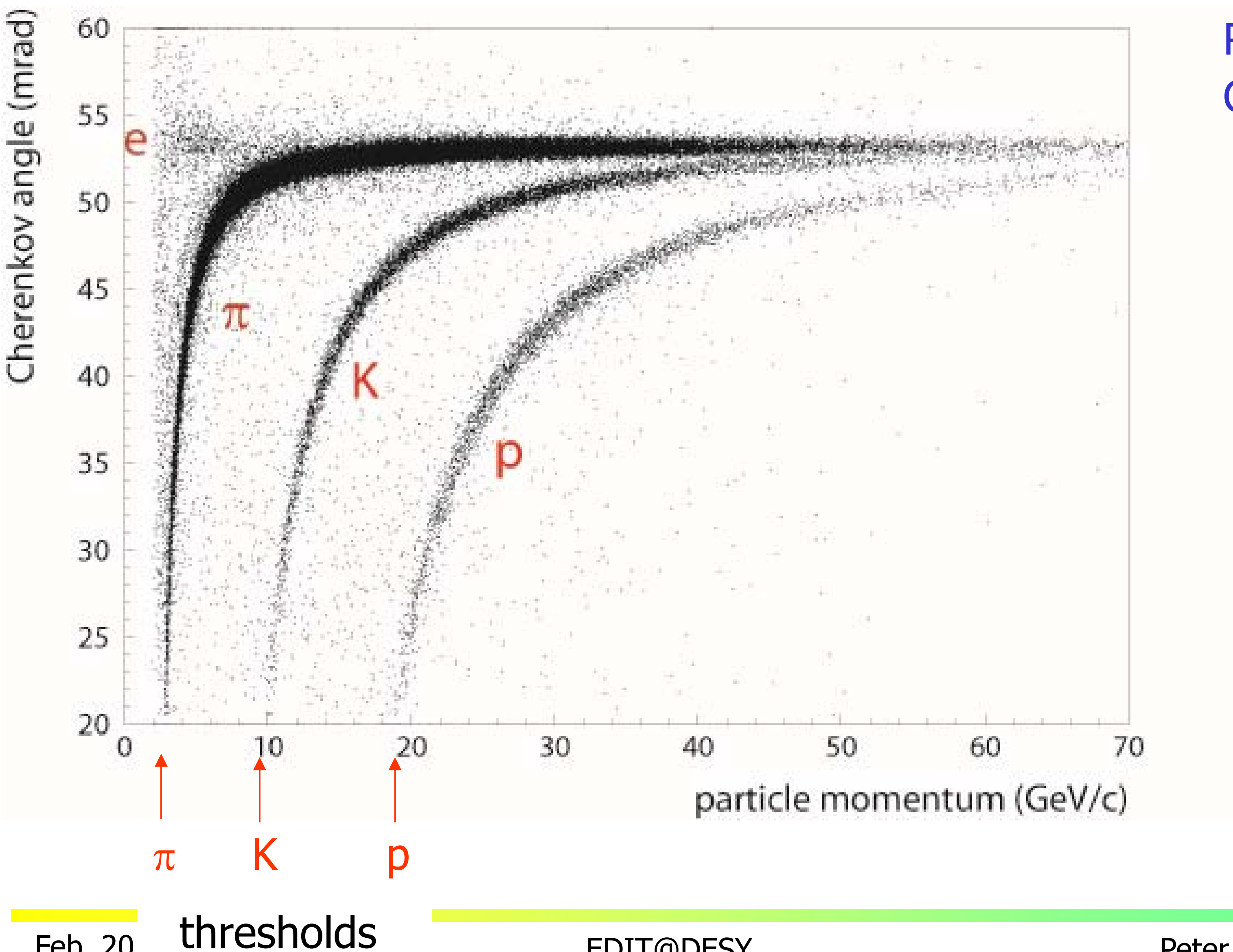


Cherekov angle distribution (mradian)

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

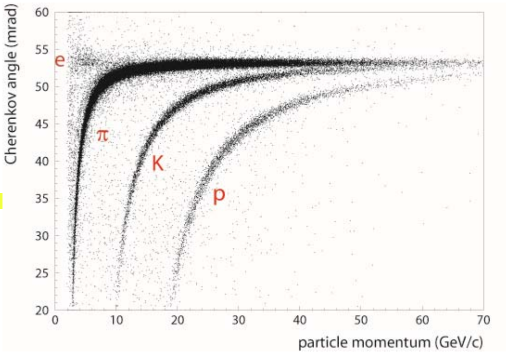
Use this information to calculate the Cherenkov angle for each individual detected photon

Measuring Cherenkov angle



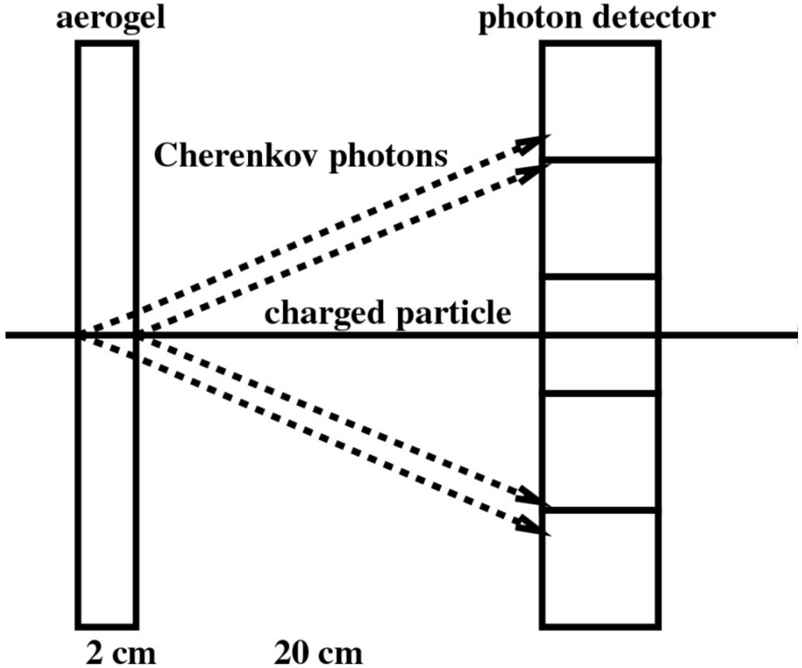
Radiator:
C_4F_{10} gas

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

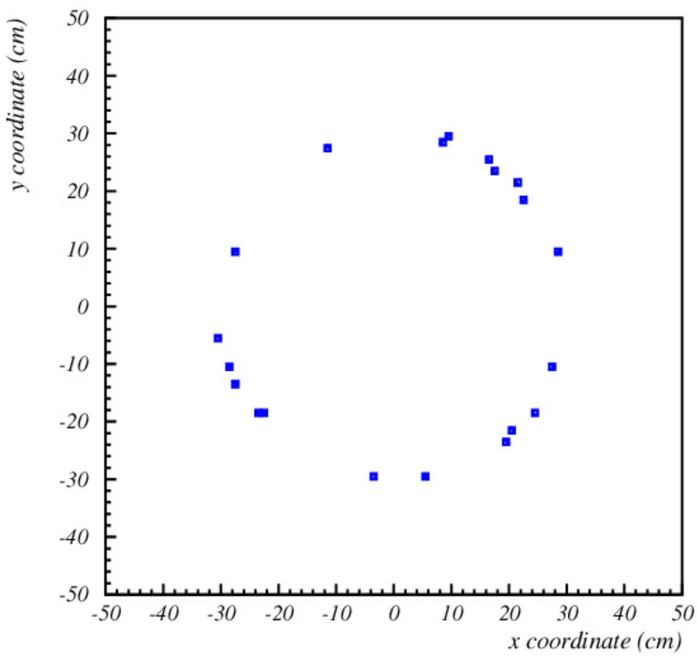
(in the case of low background)

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)



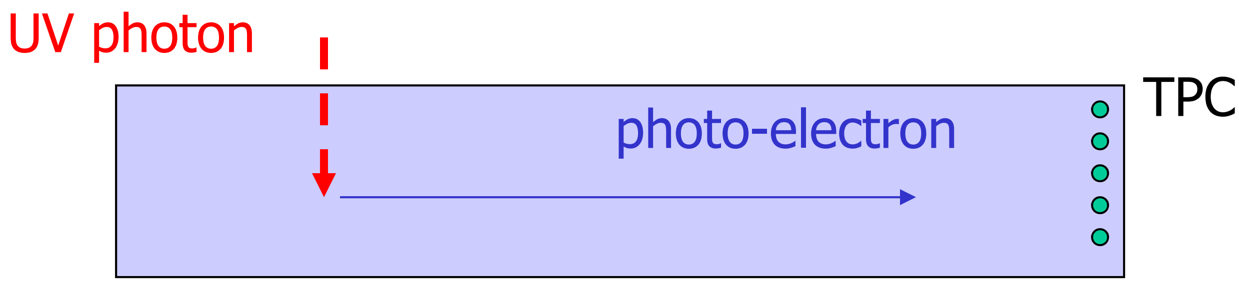
Special requirements:

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

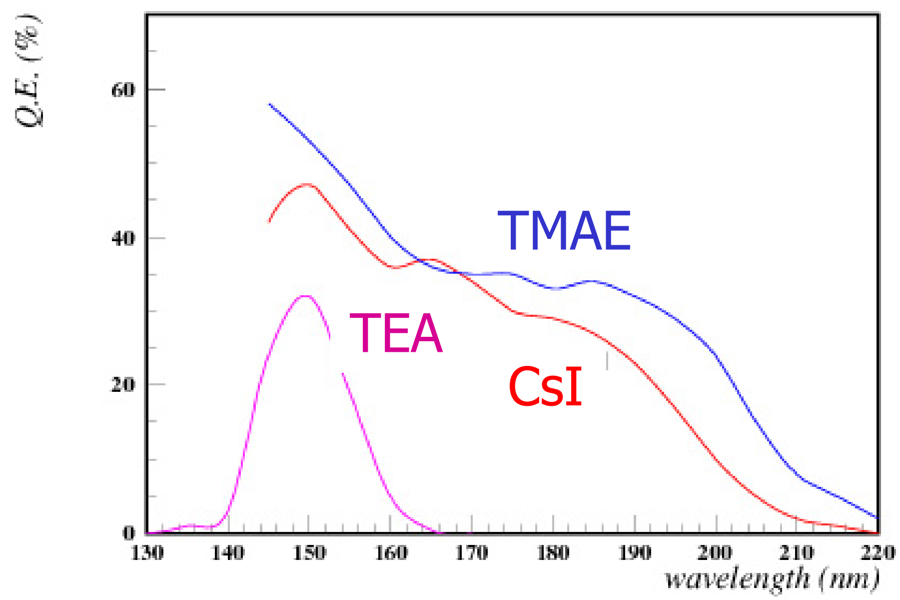
Photon detector is the most crucial element of a RICH counter

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)

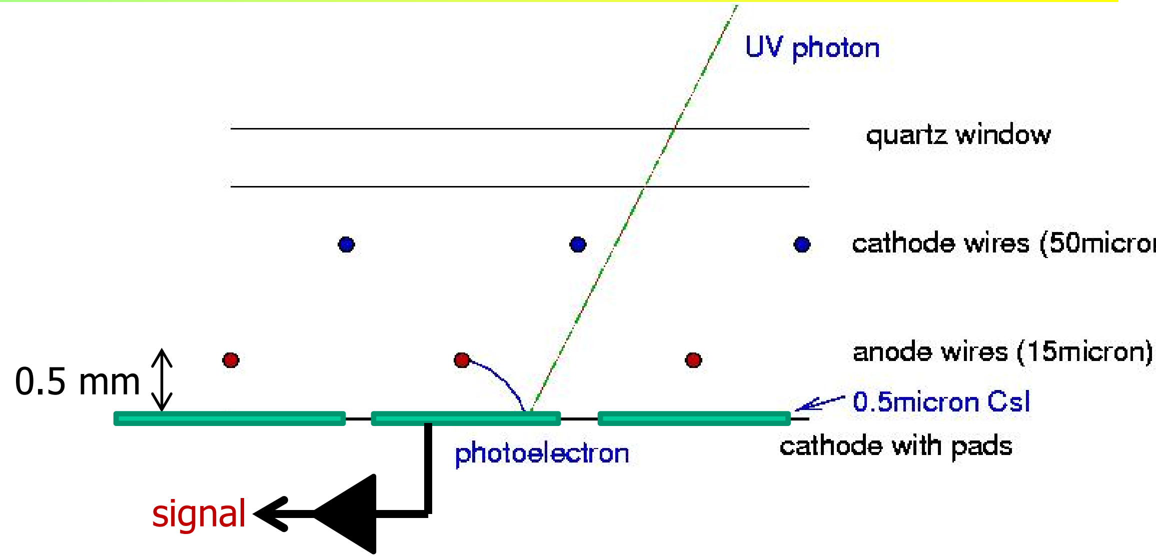


Photosensitive component:
TMAE added to the gas mixture



Fast RICH counters with wire chambers

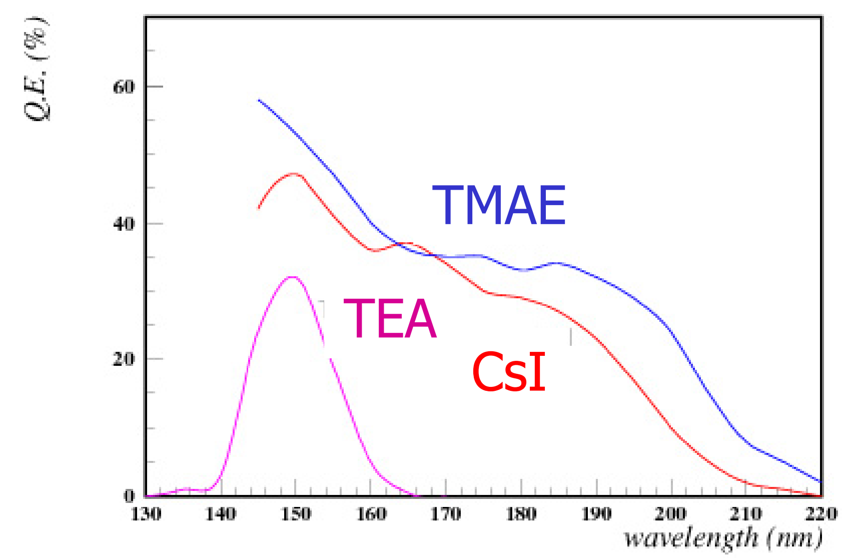
Multiwire chamber with
cathode pad read-out:
→ short drift distances,
fast detector



Photosensitive component:

•in the gas mixture (TEA):
CLEOIII RICH

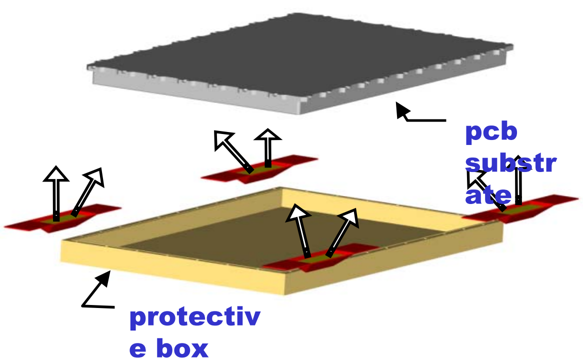
•or a layer on one of the cathodes (CsI on the printed circuit cathode with pads) HADES, COMPASS, ALICE

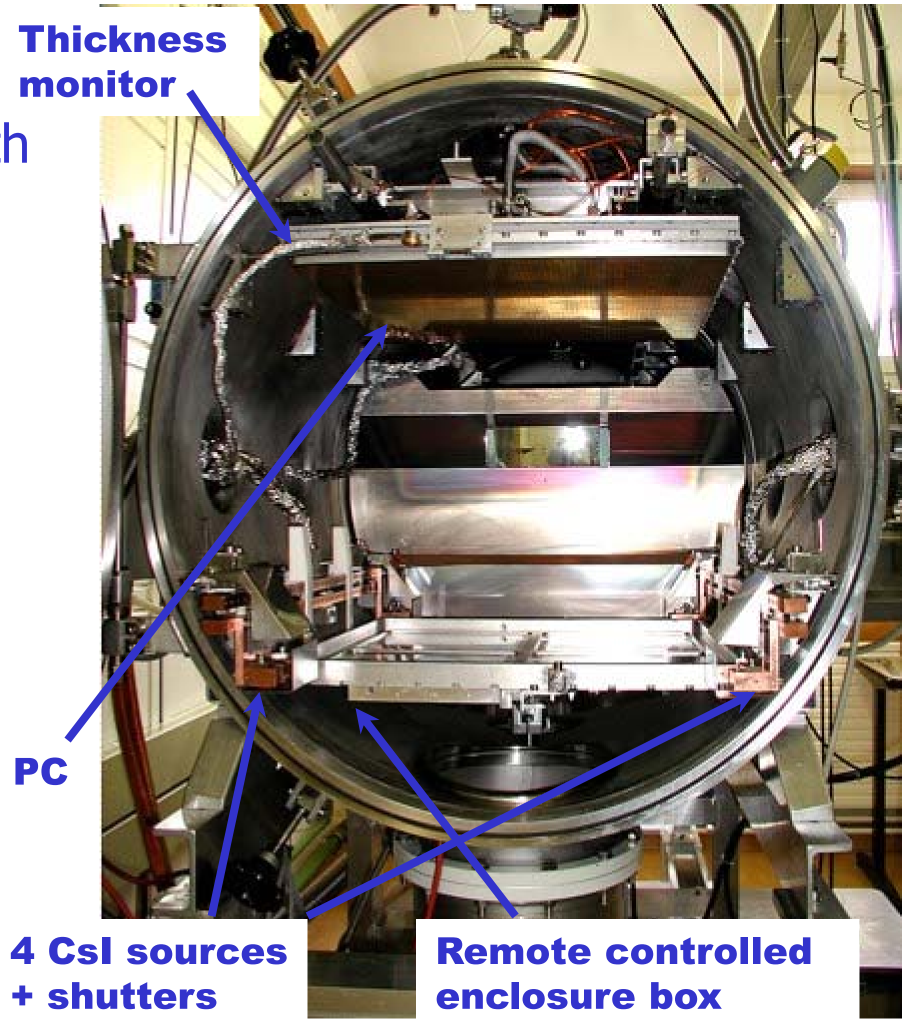


Works in high magnetic field!

CERN CsI deposition plant

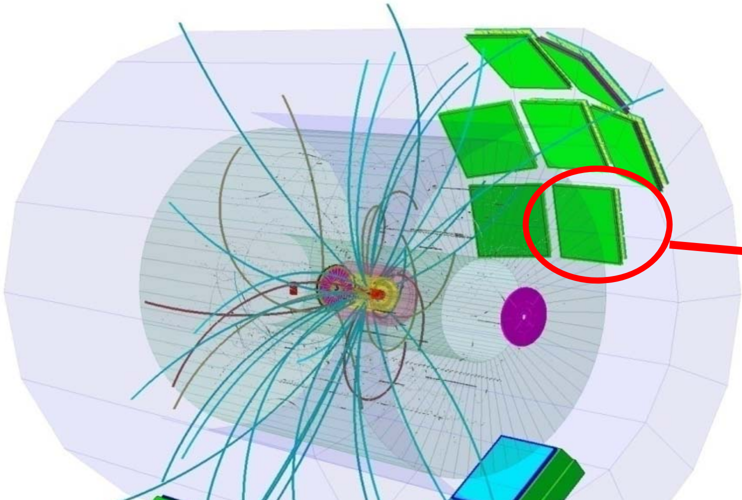
Photocathode produced with a well defined, several step procedure, with CsI vaccum deposition and subsequent heat conditioning

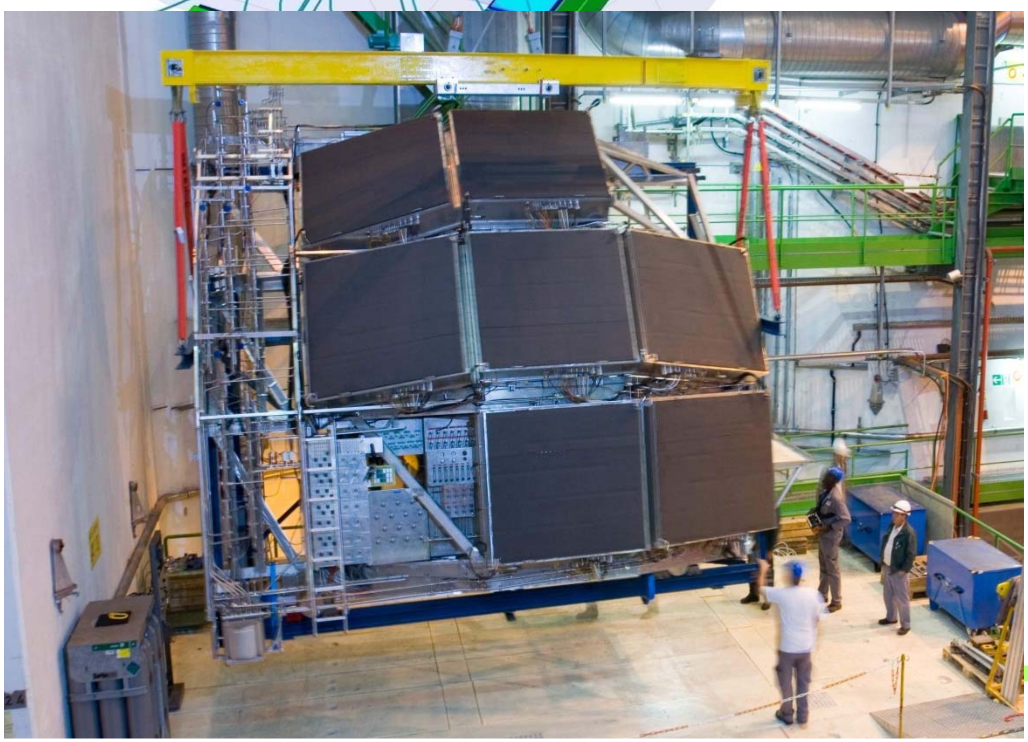




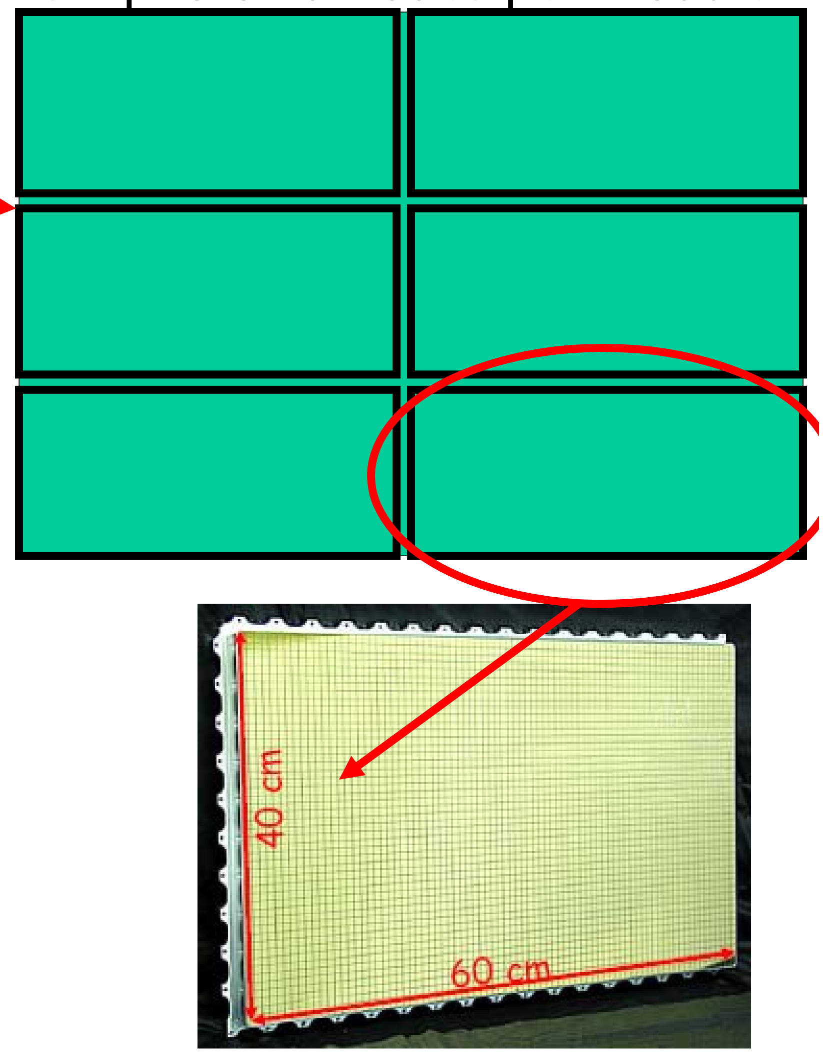
ALICE RICH = HMPID

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

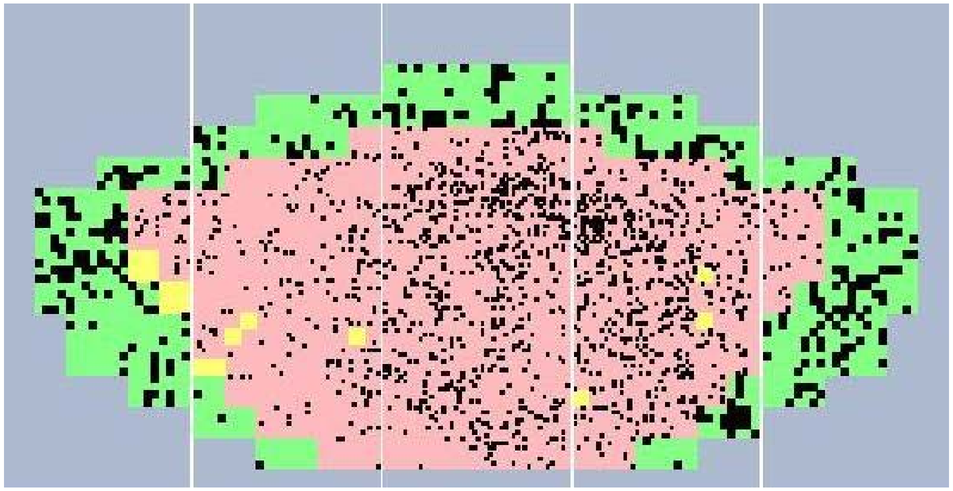
Cherenkov counters with vacuum based photodetectors

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)

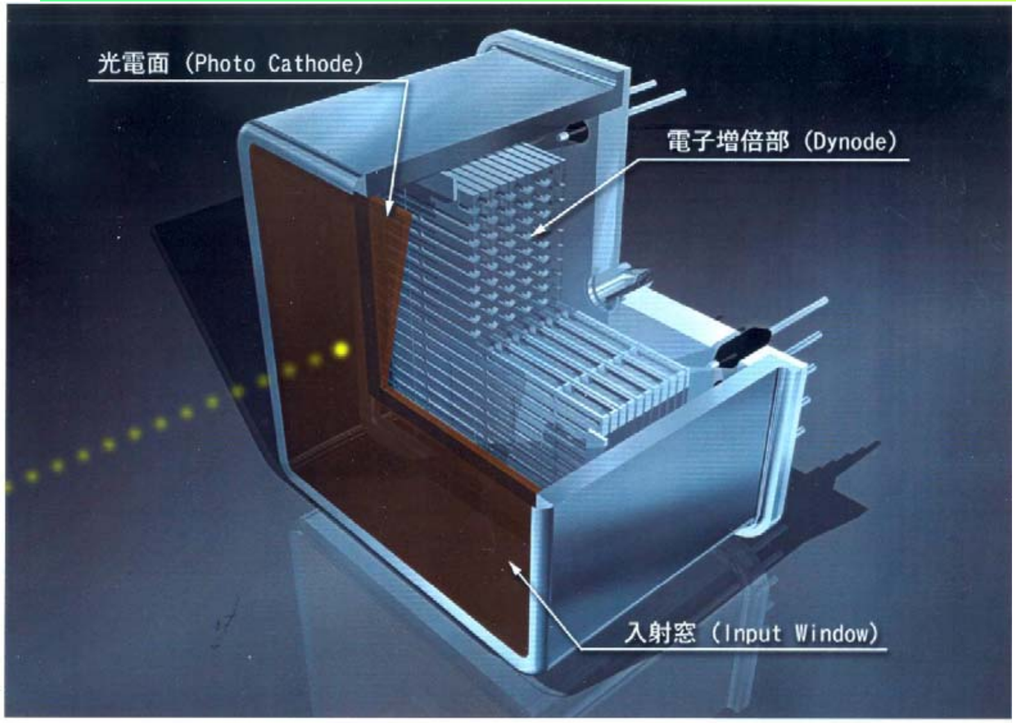
→ Need vacuum based photon detectors (e.g. PMTs)

Good spacial resolution (pads with ~5 mm size)

→ Solution: multianode PMTs (MaPMTs)



Multianode PMTs



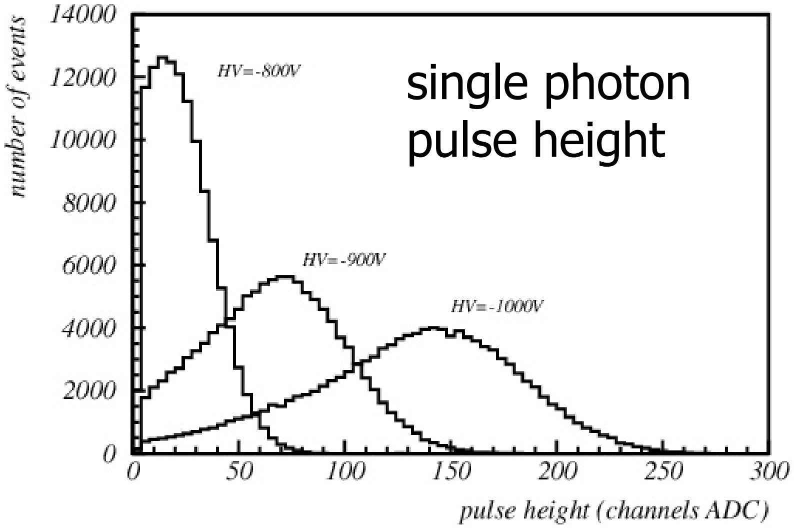
Multianode PMTs (MaPMTs) with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

→Excellent single photon pulse height spectrum

→Low noise (few Hz/ch)

→Low cross-talk (<1%)

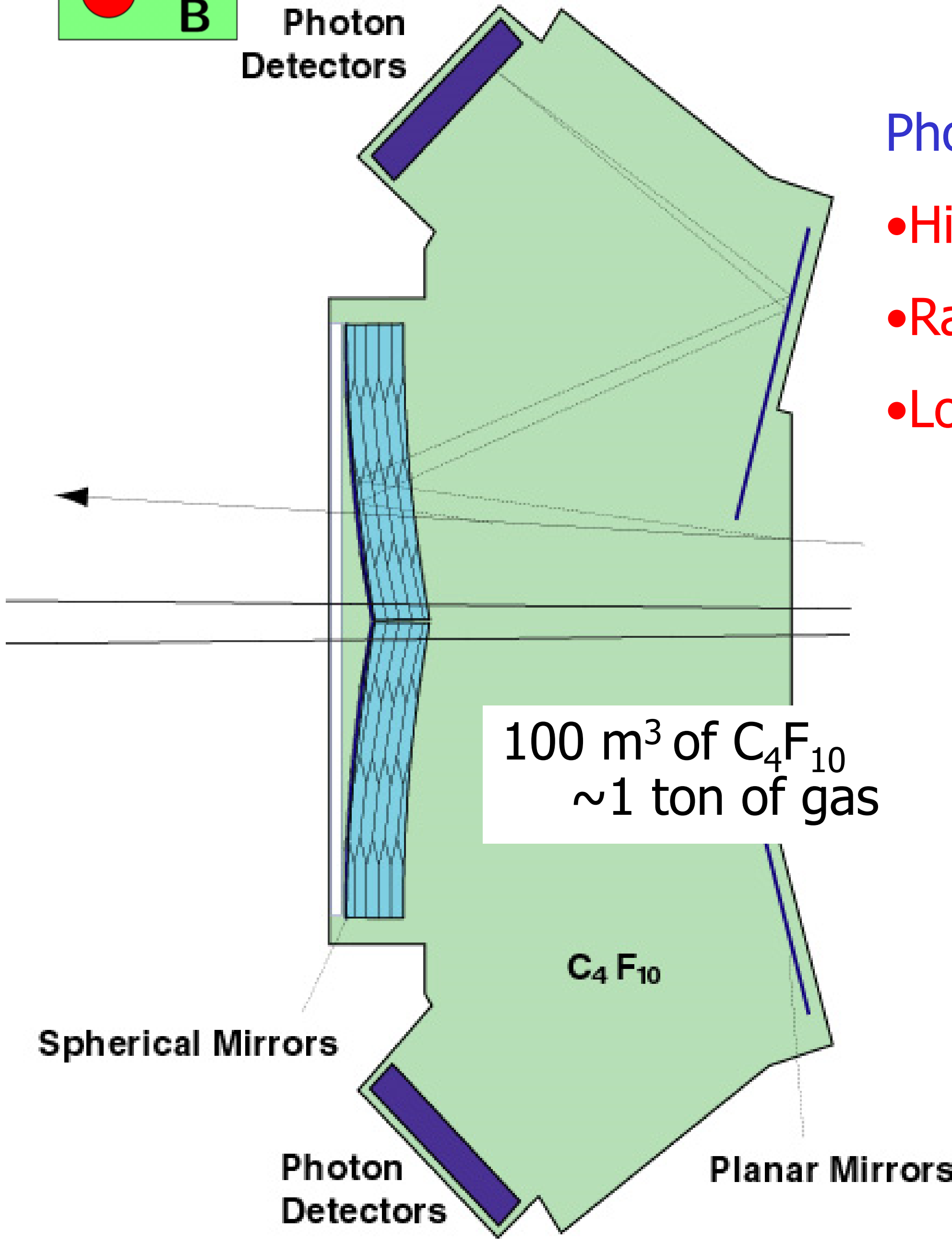
→ NIM A394 (1997) 27

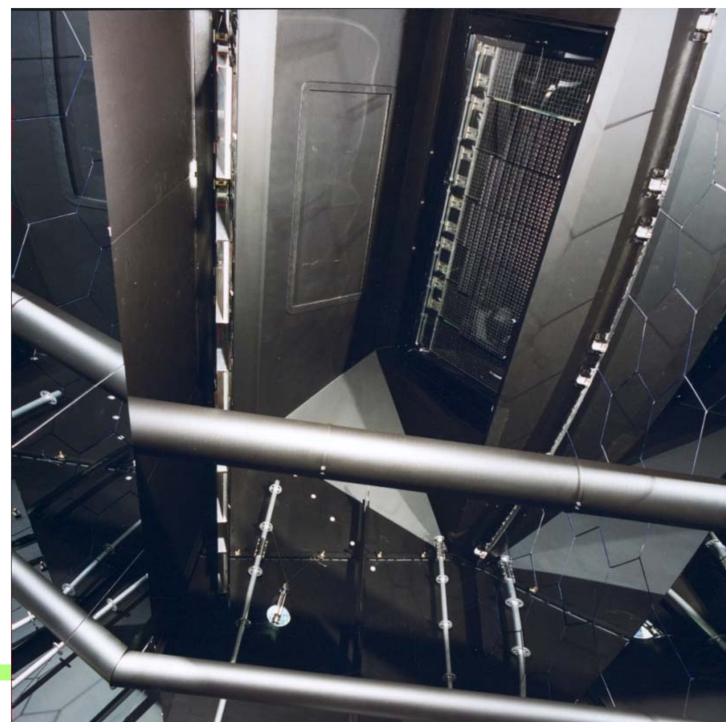


HERA-B RICH

Photon detector requirements:

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



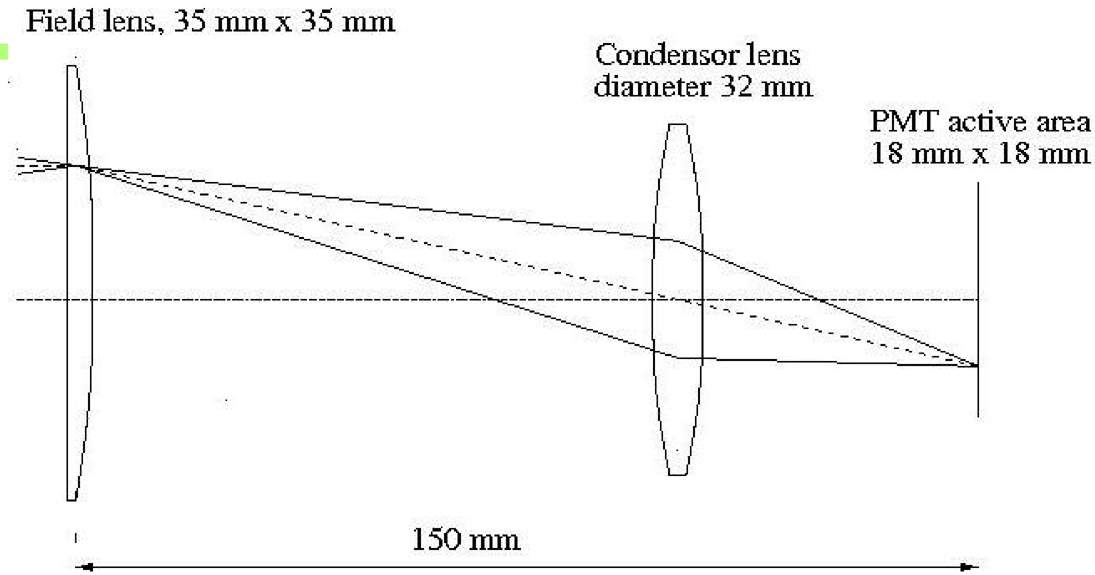


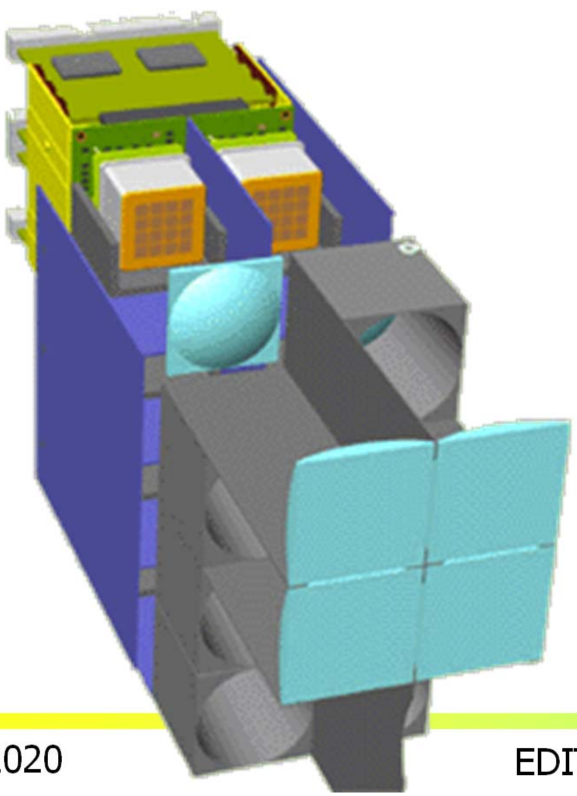
HERA-B RICH photon detector

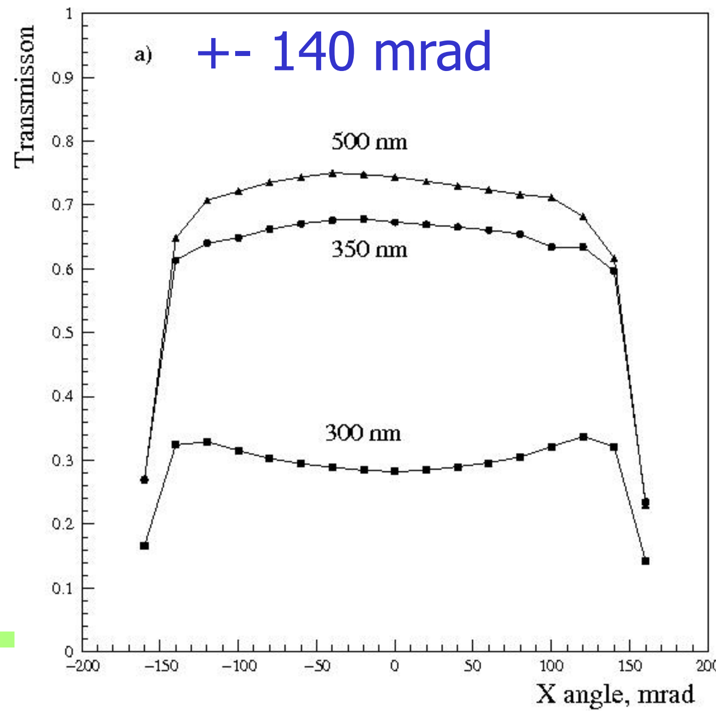
Light collection system (imaging!) to:

-Eliminate dead areas

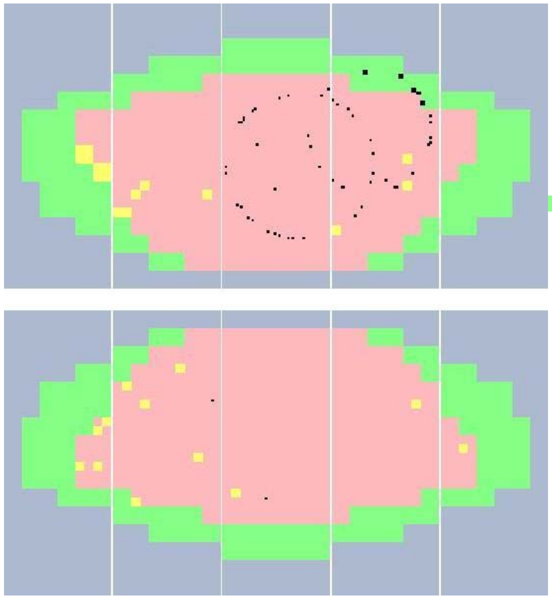
-Adapt the pad size





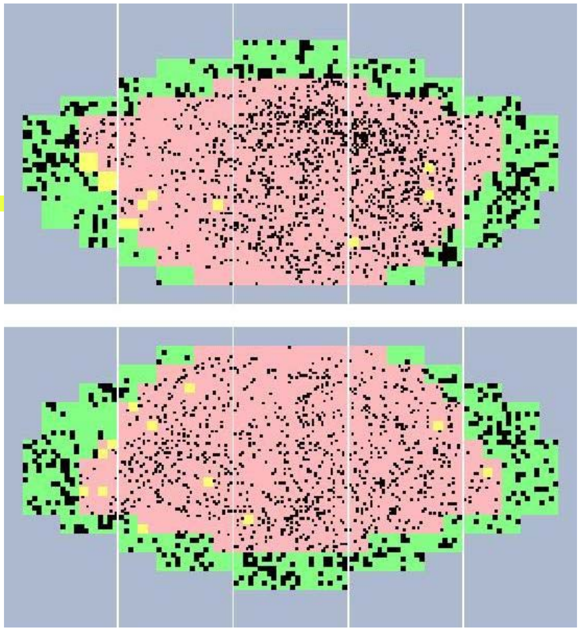


HERA-B RICH

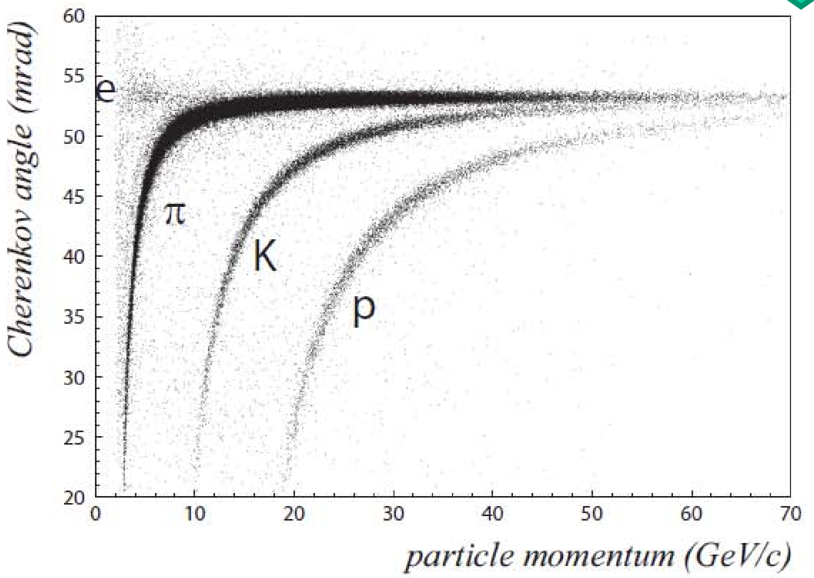


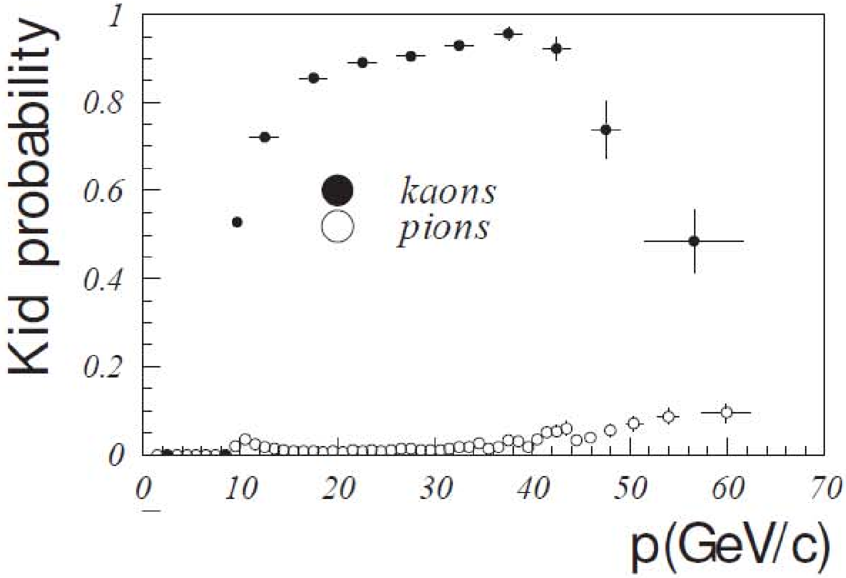
← Little noise, ~30 photons per ring

Typical event →



Worked very well!

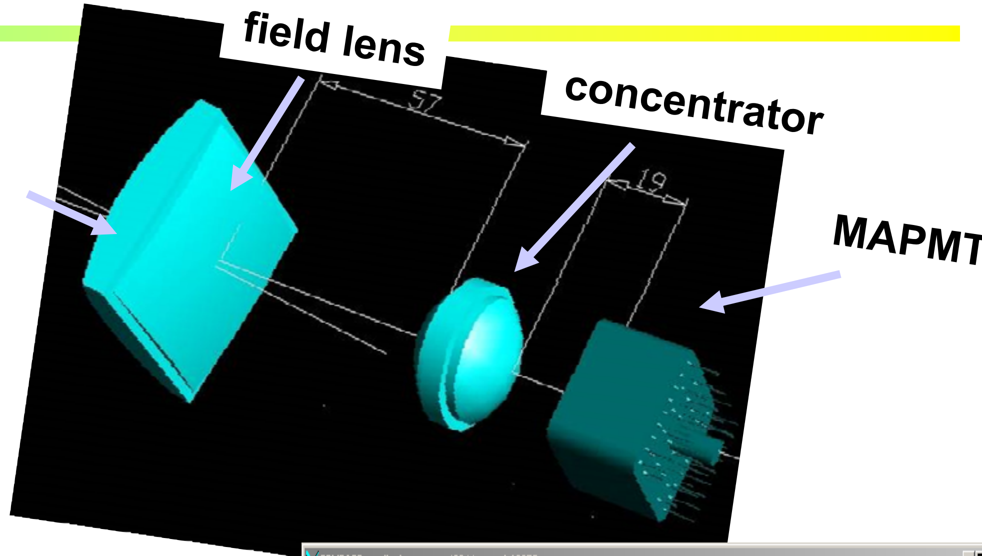




Kaon efficiency and pion fake probability

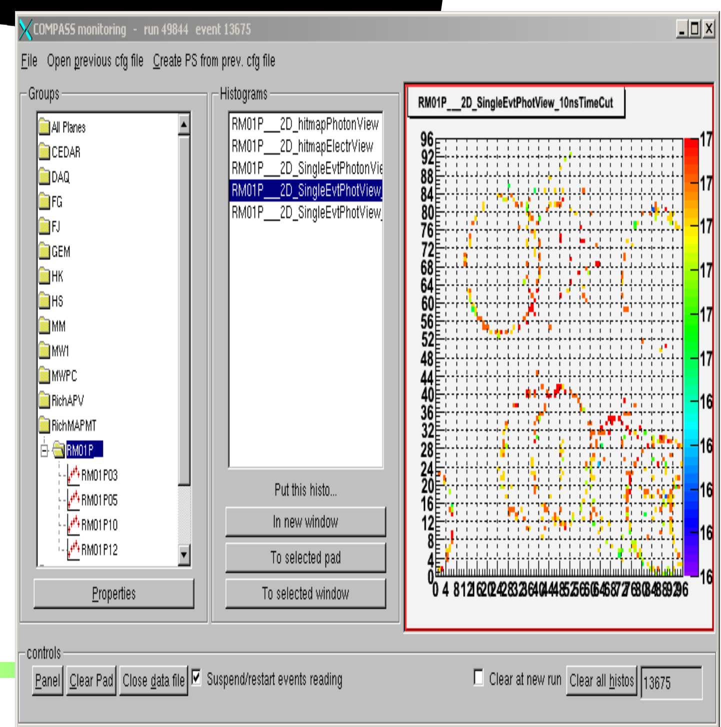
Photon detector for the COMPASS RICH-1

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

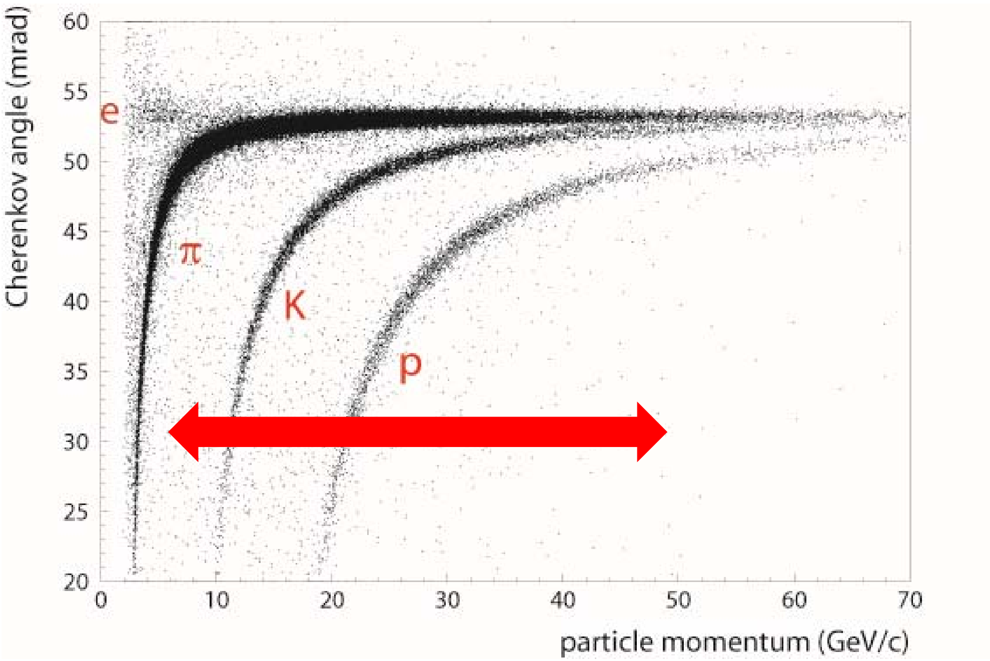


New features:

- 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

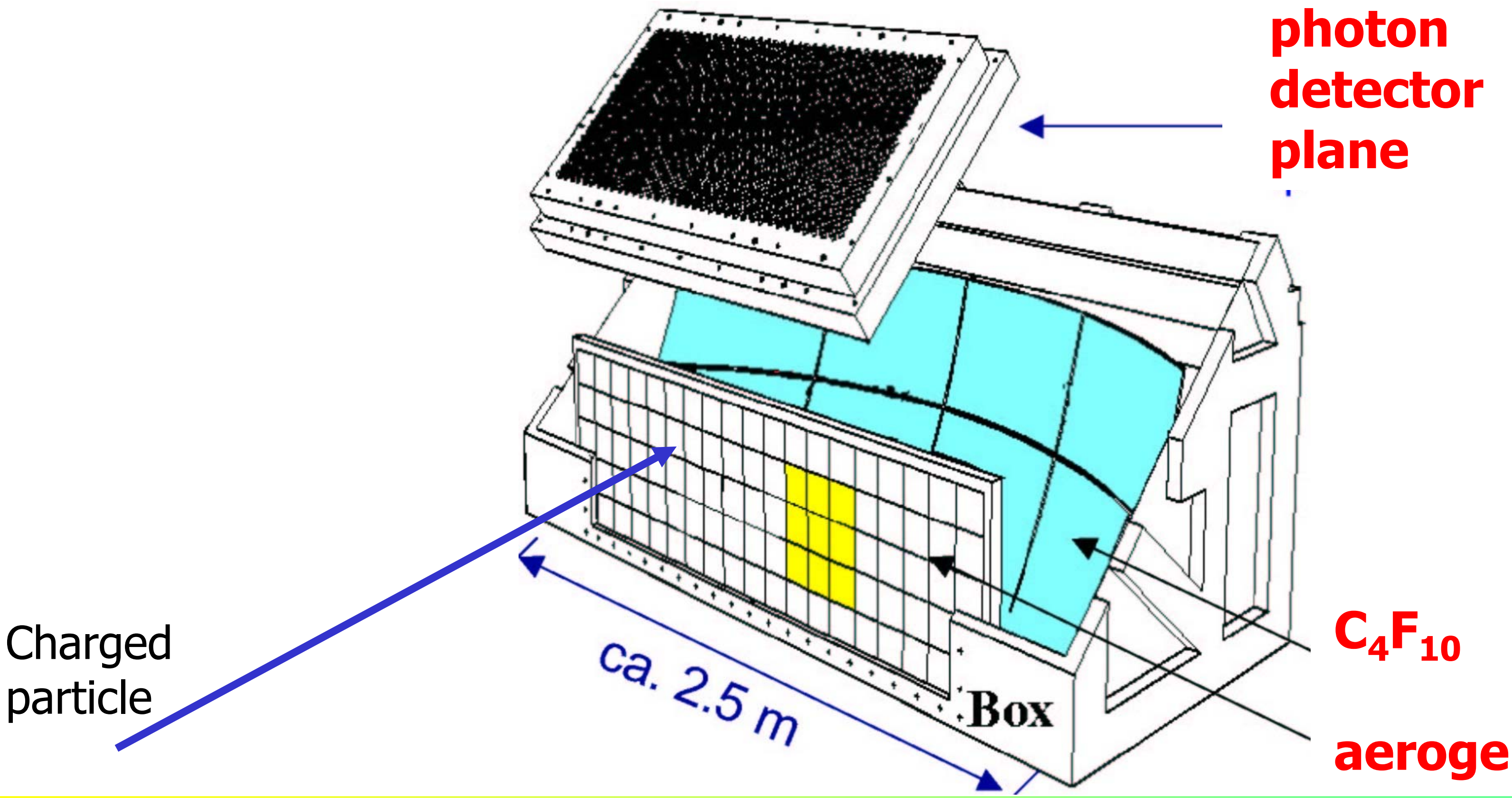
•Upper limit p_{max}: given by Cherenkov angle resolution – overlap of the two bands

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

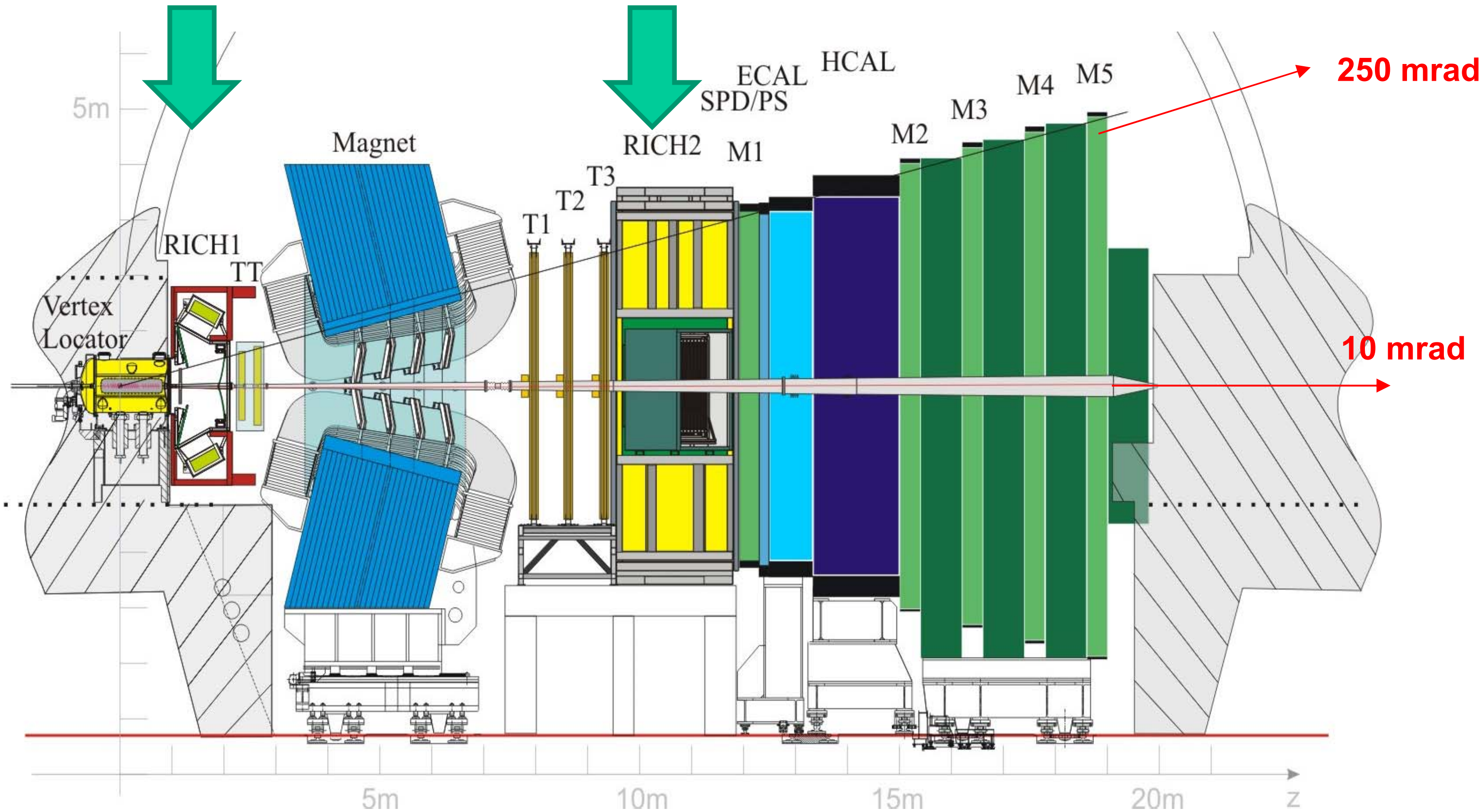
RICHes with several radiators

Extending the kinematic range → need more than one radiator

- DELPHI at LEP, SLD at SLC (liquid +gas)
- HERMES at HERA (aerogel+gas)



The LHCb RICH counters



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

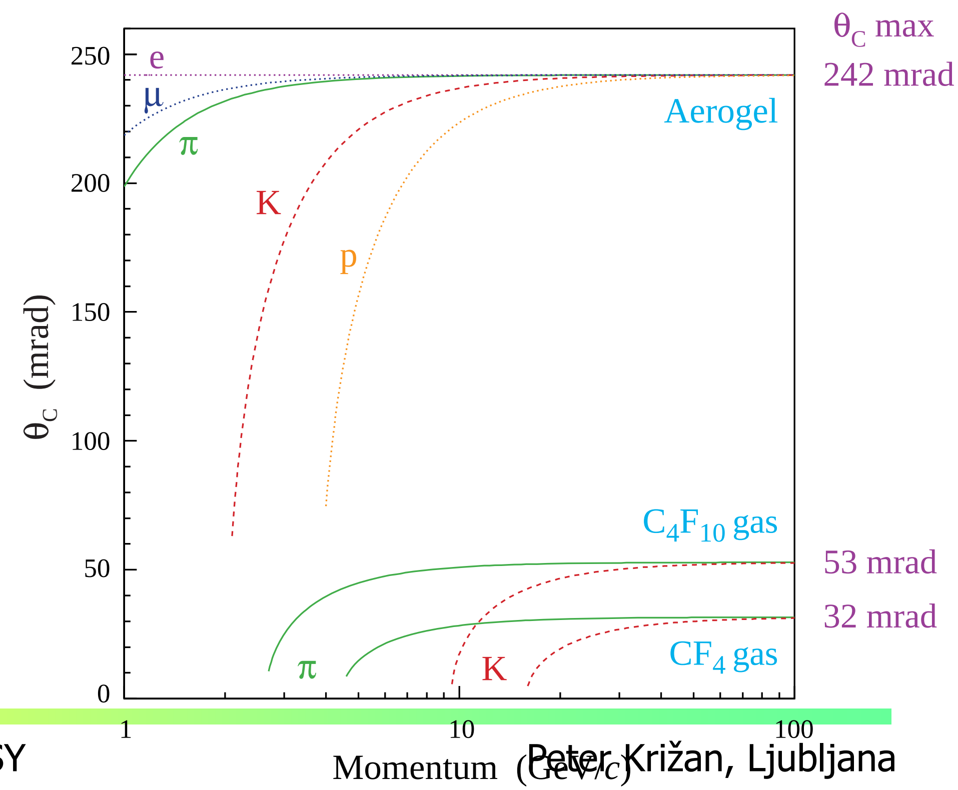
LHCb RICHes

Need:

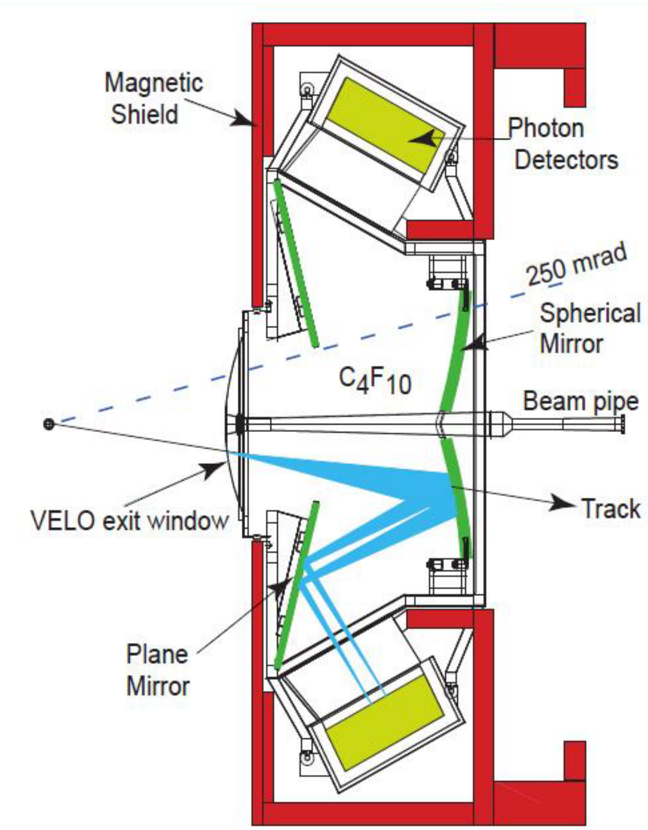
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

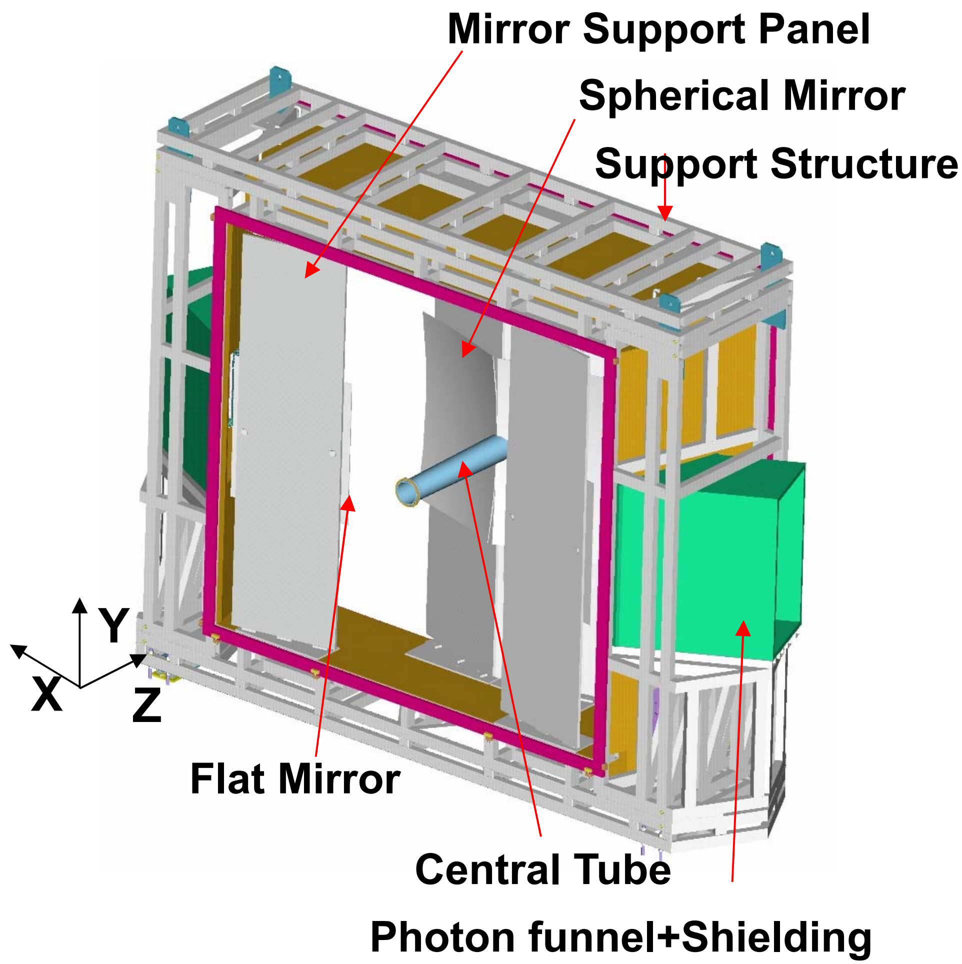
→3 radiators

- Aerogel
- C_4F_{10} gas
- CF_4 gas



LHCb RICHes

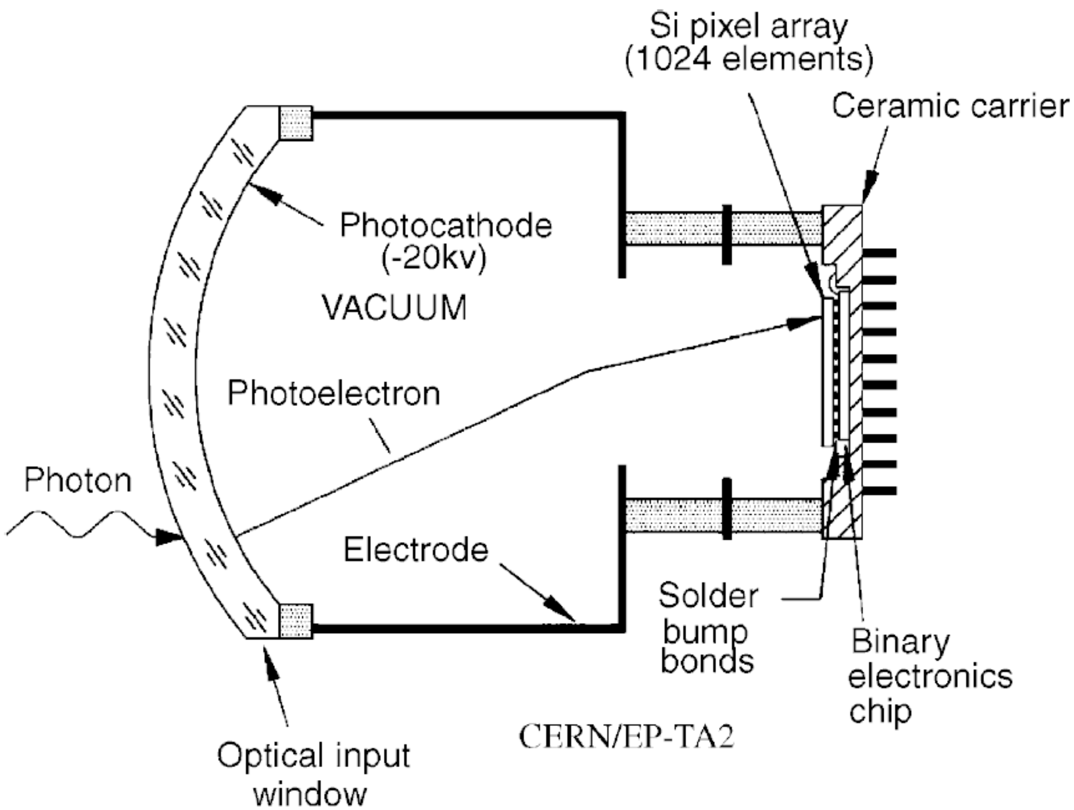

Magnetic Shield
Photon Detectors
250 mrad
Spherical Mirror
C_4F_{10}
Beam pipe
VELO exit window
Track
Plane Mirror


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 them in a pixelated silicon detector.



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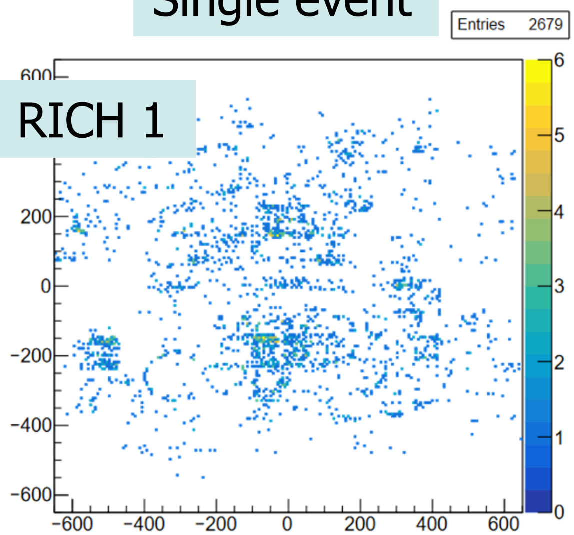
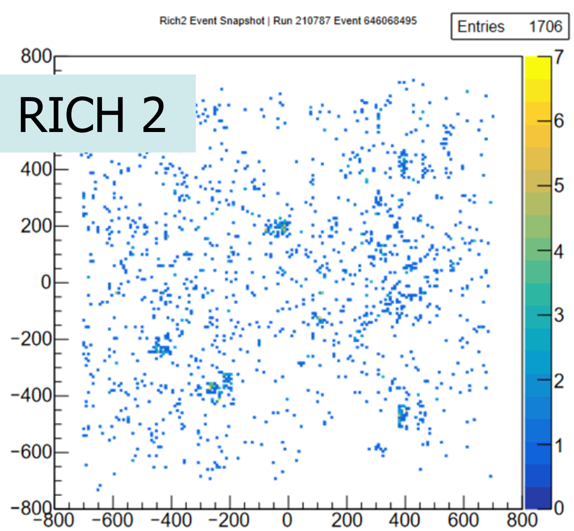
Performance of LHCb RICHes

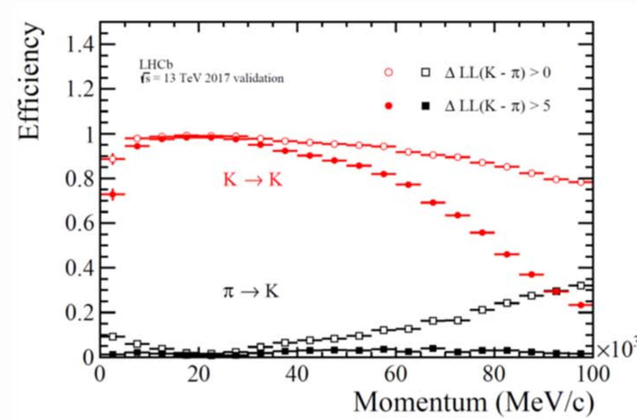
Single event

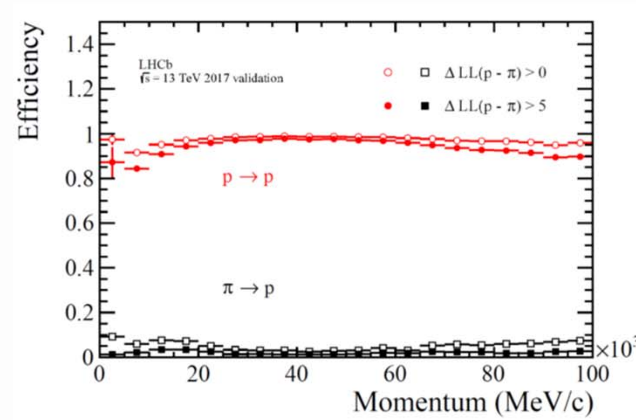
RICH 1

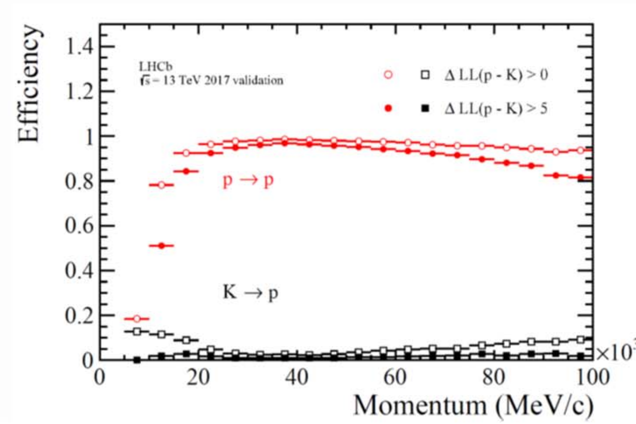


RICH 2

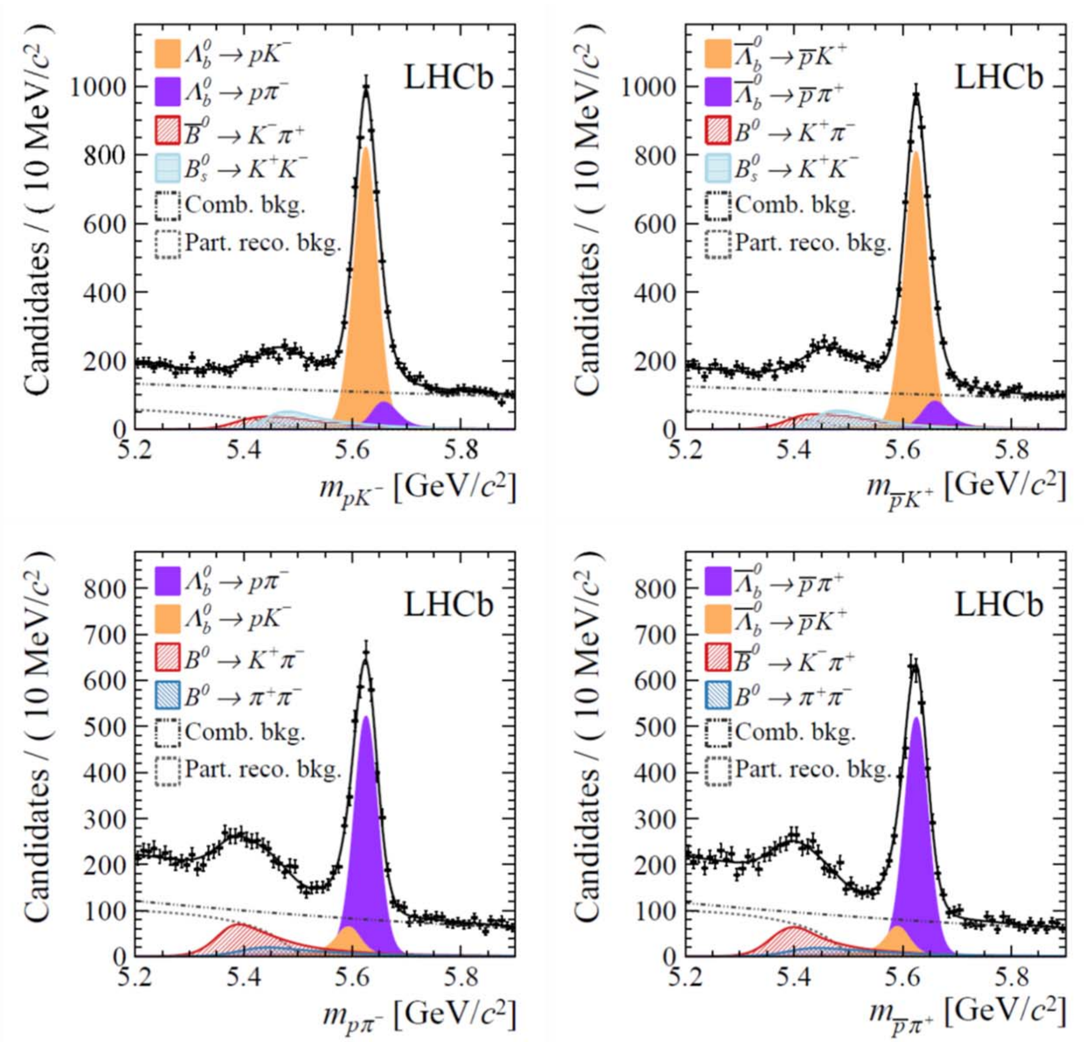






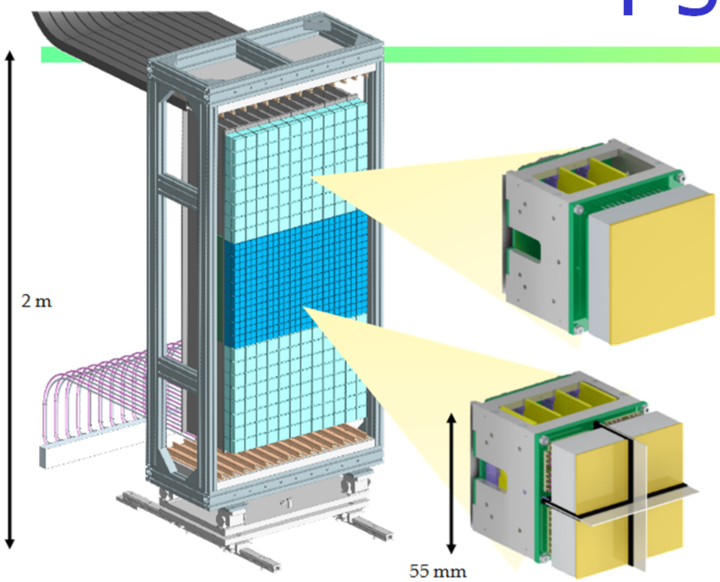


LHCb RICHes: performance

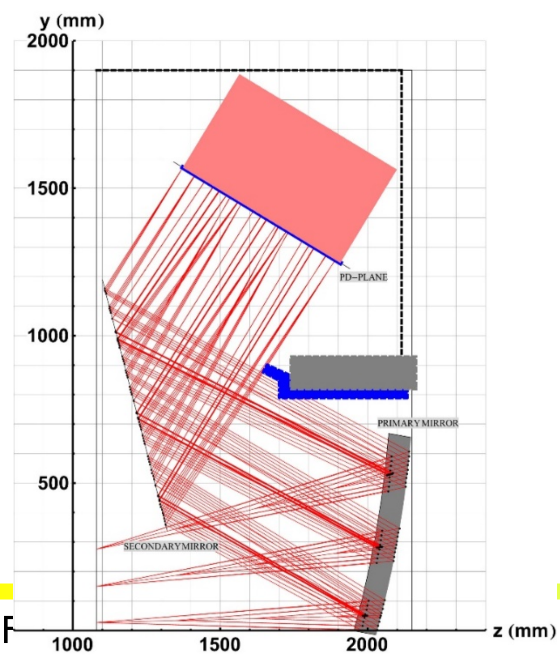


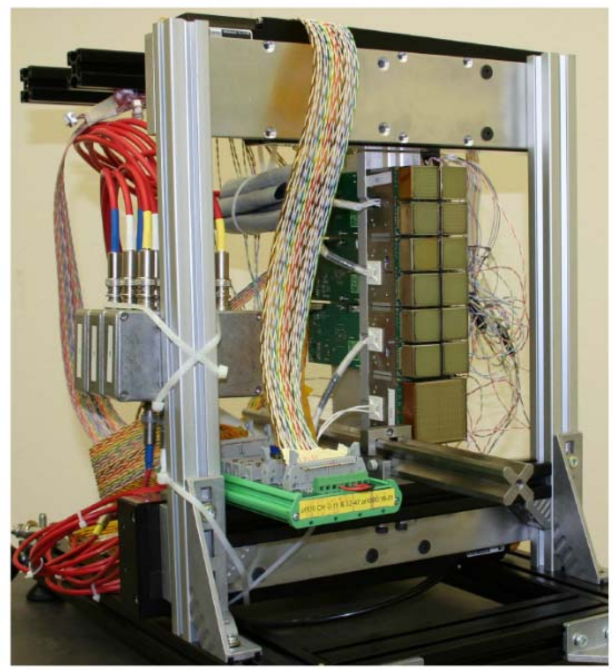
"Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays"
[LHCb-PAPER-2018-025]

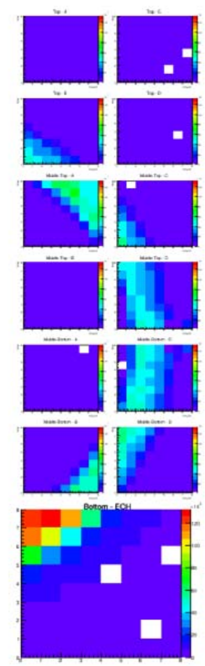
LHCb Upgrade (under way)



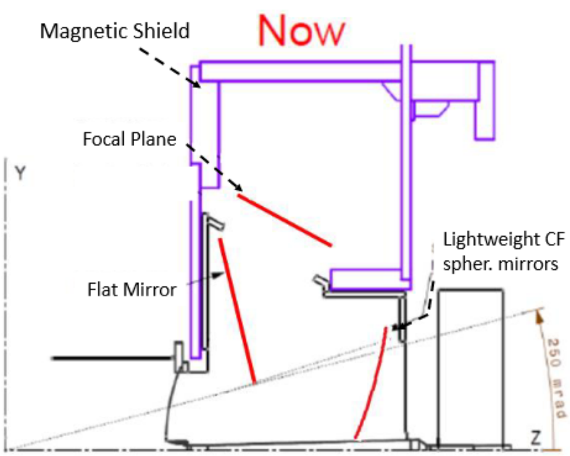
- New photon detectors: MaPMTs Hamamatsu R13743 (H12700) and R13742 (R11265)
- New electronics working at 40 MHz readout rate
- New optics layout for RICH 1

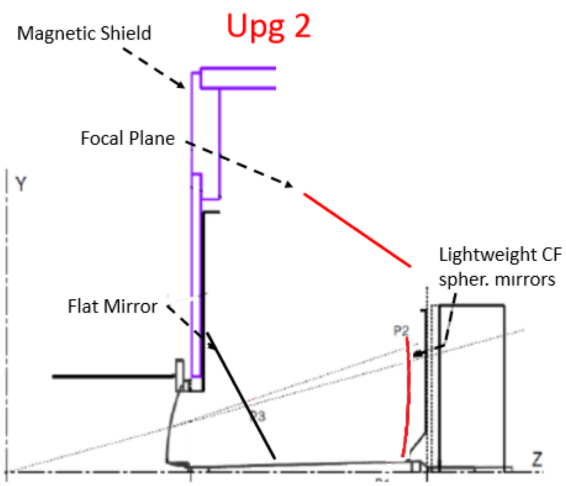






Future LHCb Upgrade



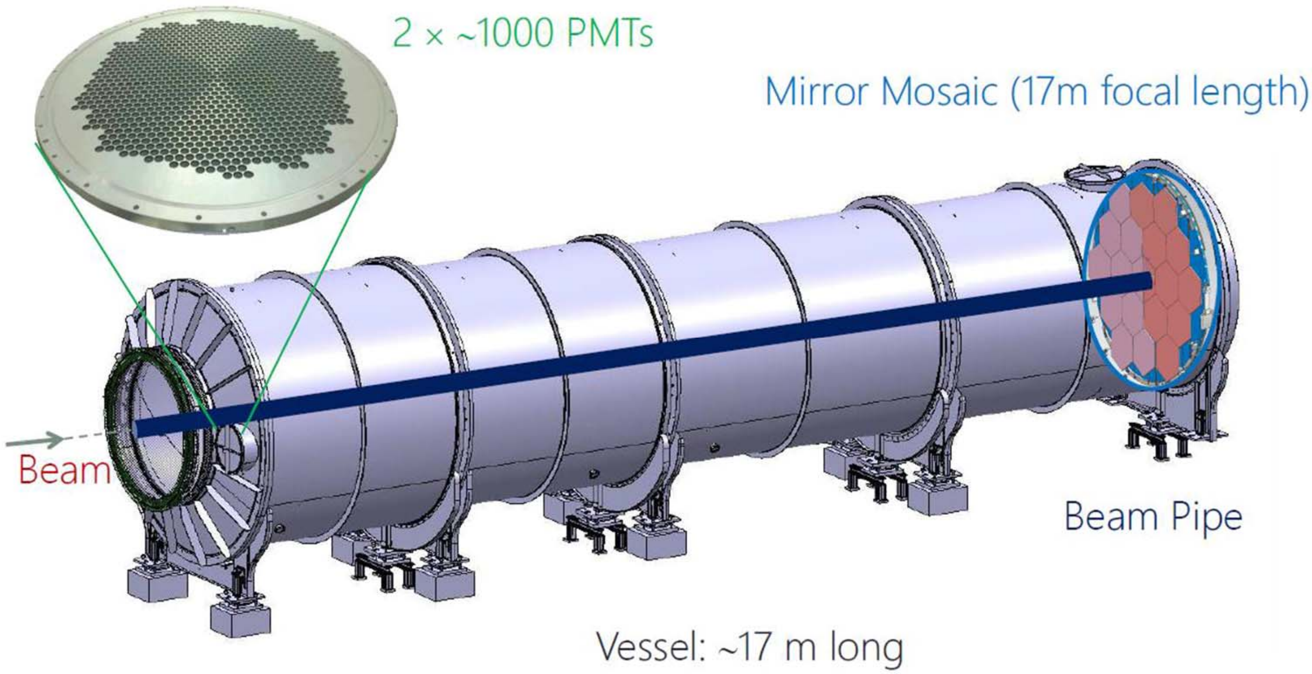


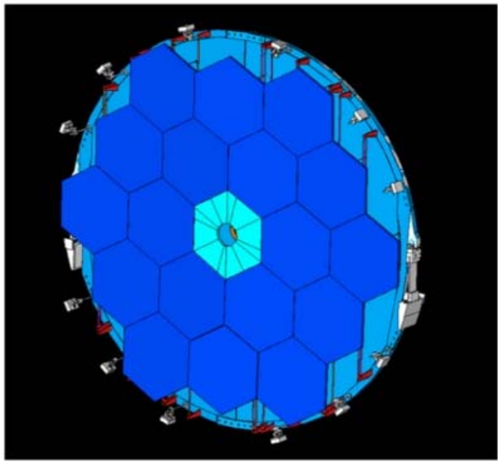
- Provide PID at p-p luminosity of 10^{34} in the forward region
- Incremental improvements in:
  - Improve Cherenkov angle resolution
    - More photons in the green → lower chromatic error
  - Reduced event complexity with timing
  - Enhanced number of photons

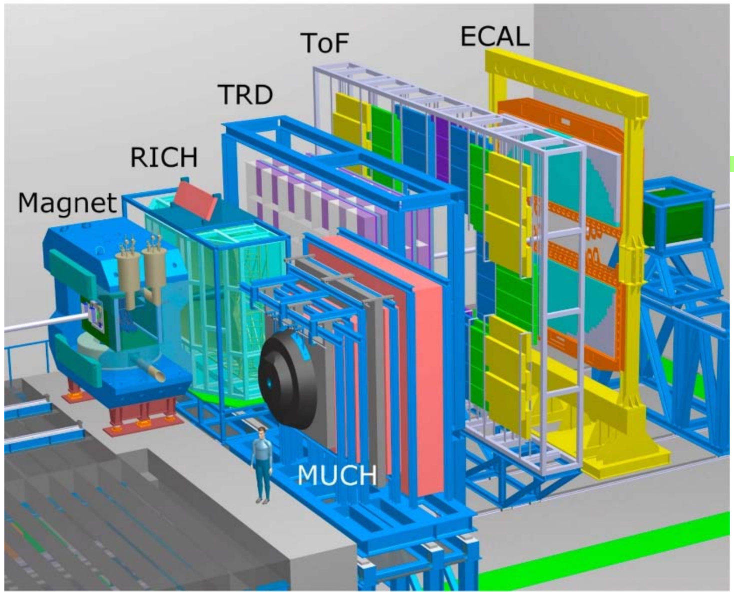
Radiator	C_4F_{10}			CF_4	
Detector Version	RICH 1 Current (HPD)	RICH 1 UPG1	**RICH 1 UPG2**	RICH 2 UPG1	**RICH 2 UPG2**
Average Photoelectron Yield	30	40	**60–30**	22	**30**
Single Photon Errors (mrad)					
Chromatic	0.84	0.58	**0.24–0.12**	0.31	**0.1**
Pixel	0.9	0.44	**0.15**	0.20	**0.07**
Emission 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

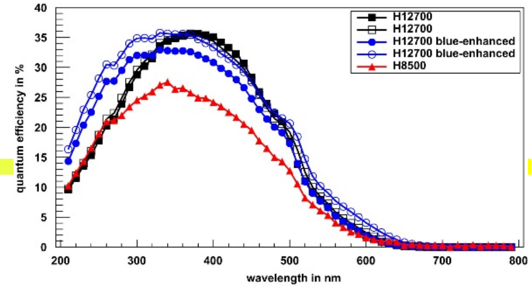
- Momentum range 15-35 GeV/c
- 17m long, 200m^3 cylindrical vacuum proof tank with Neon radiator
- Photon detectors: 2000 PMTs (16mm, 8mm active, with Winstone cone light guides)
- Mirror alignment ~30 μrad
- Single photon resolution: ~140 μrad
- Operational since 2014



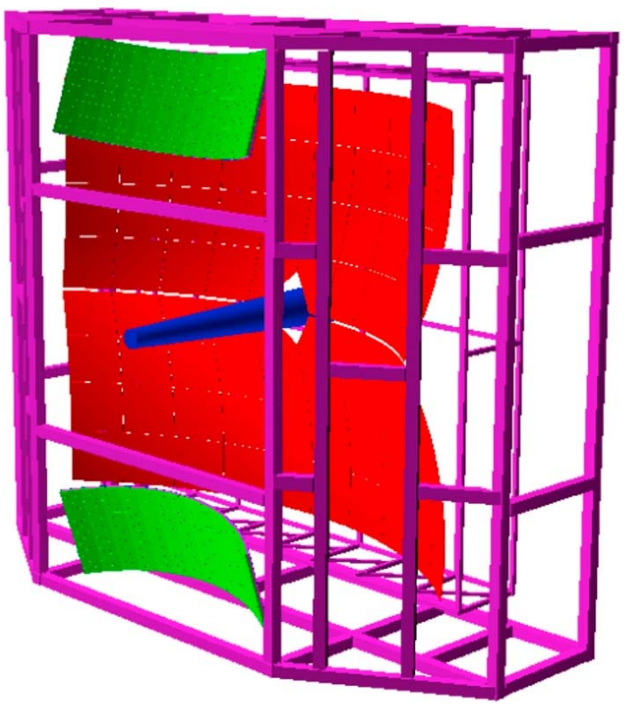


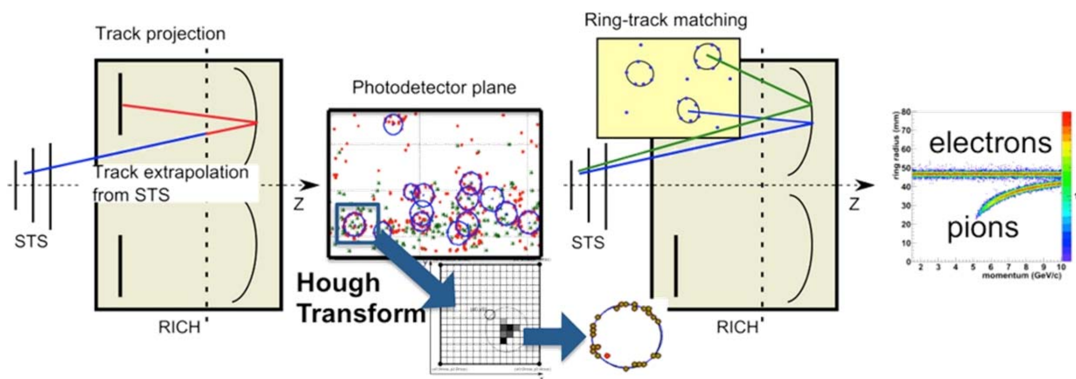


CBM

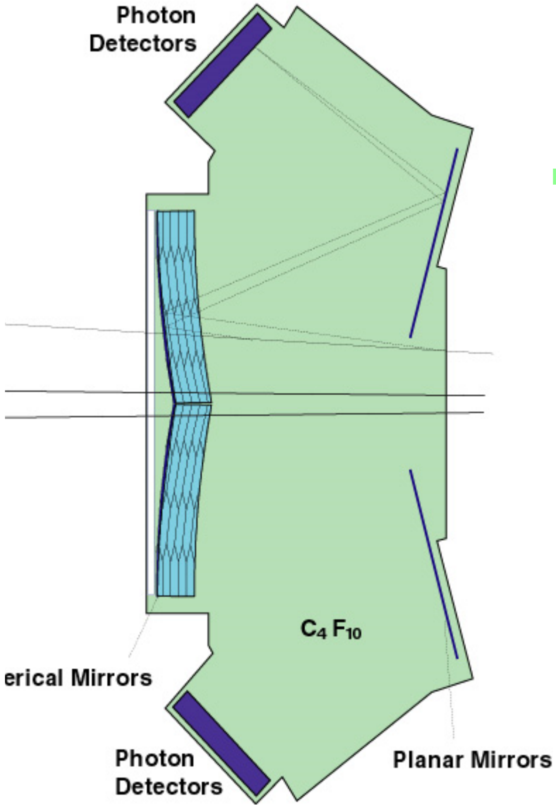


- RICH with CO_2 radiator
- MaPMTs: Hamamatsu H12700
- Cylindrical photon detection surface
- Extensive testing of MaPMTs for radiation damage
- Up to 1000 tracks per event
- Momentum up to 8 GeV/c
- Pion suppression factor ~5000 (with TRD)

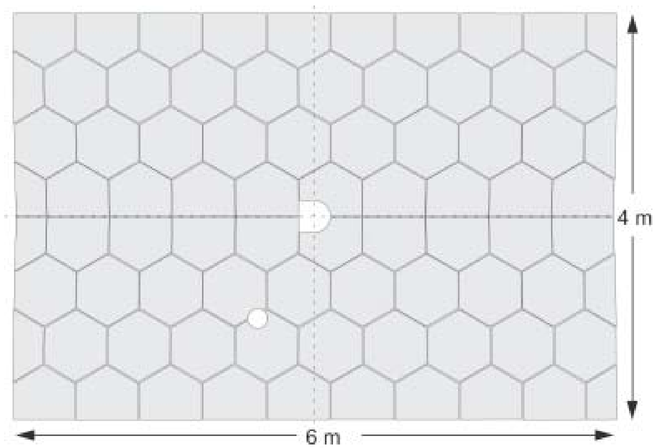




Mirror alignment

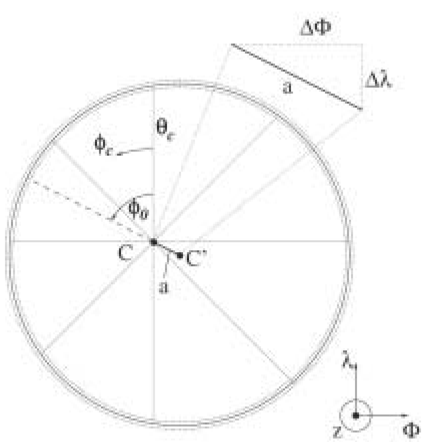


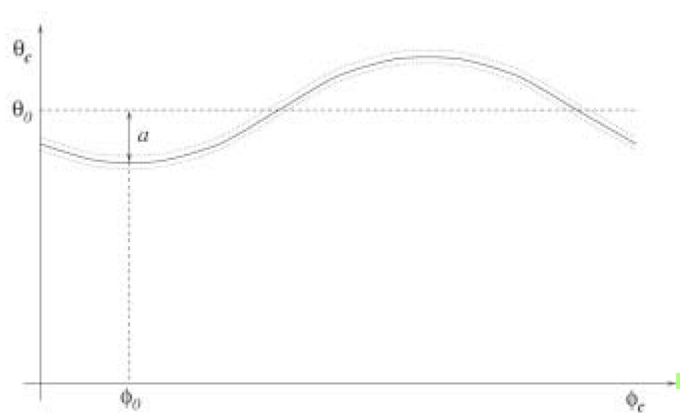
Gas radiator RICHes: large mirrors → tens of segments → need relative alignment



- Spherical mirror: 80 hexagonal segments
- Planar mirrors: 2x18 rectangular segments

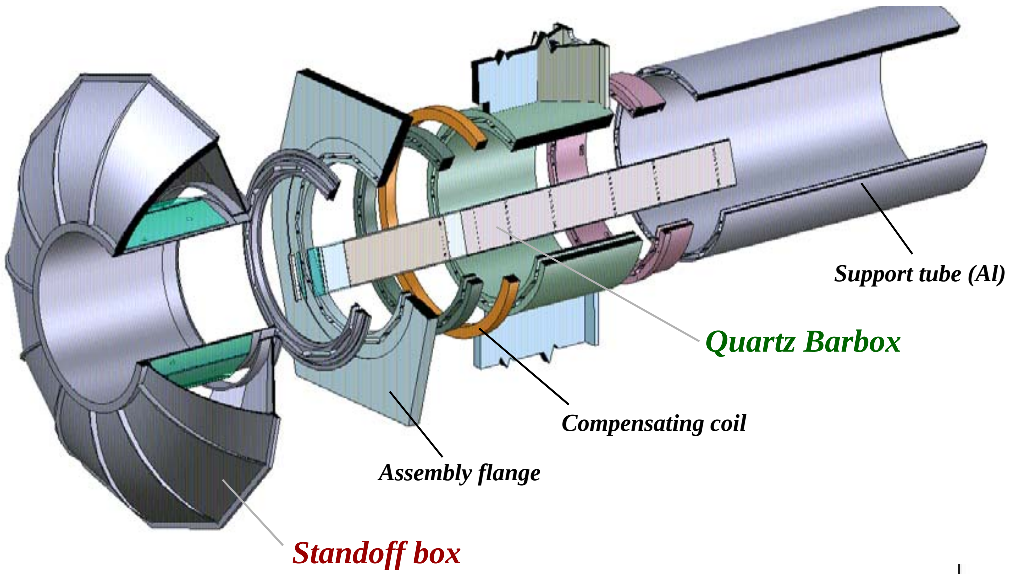
Aligning pairs of spherical and planar segments.

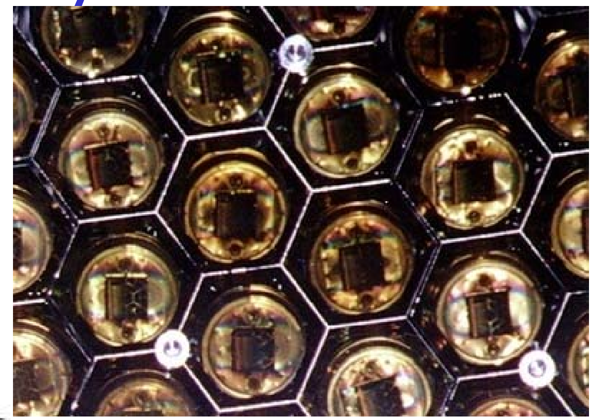


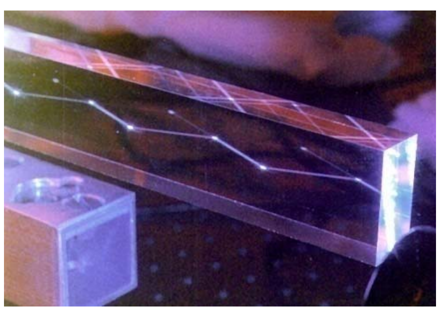


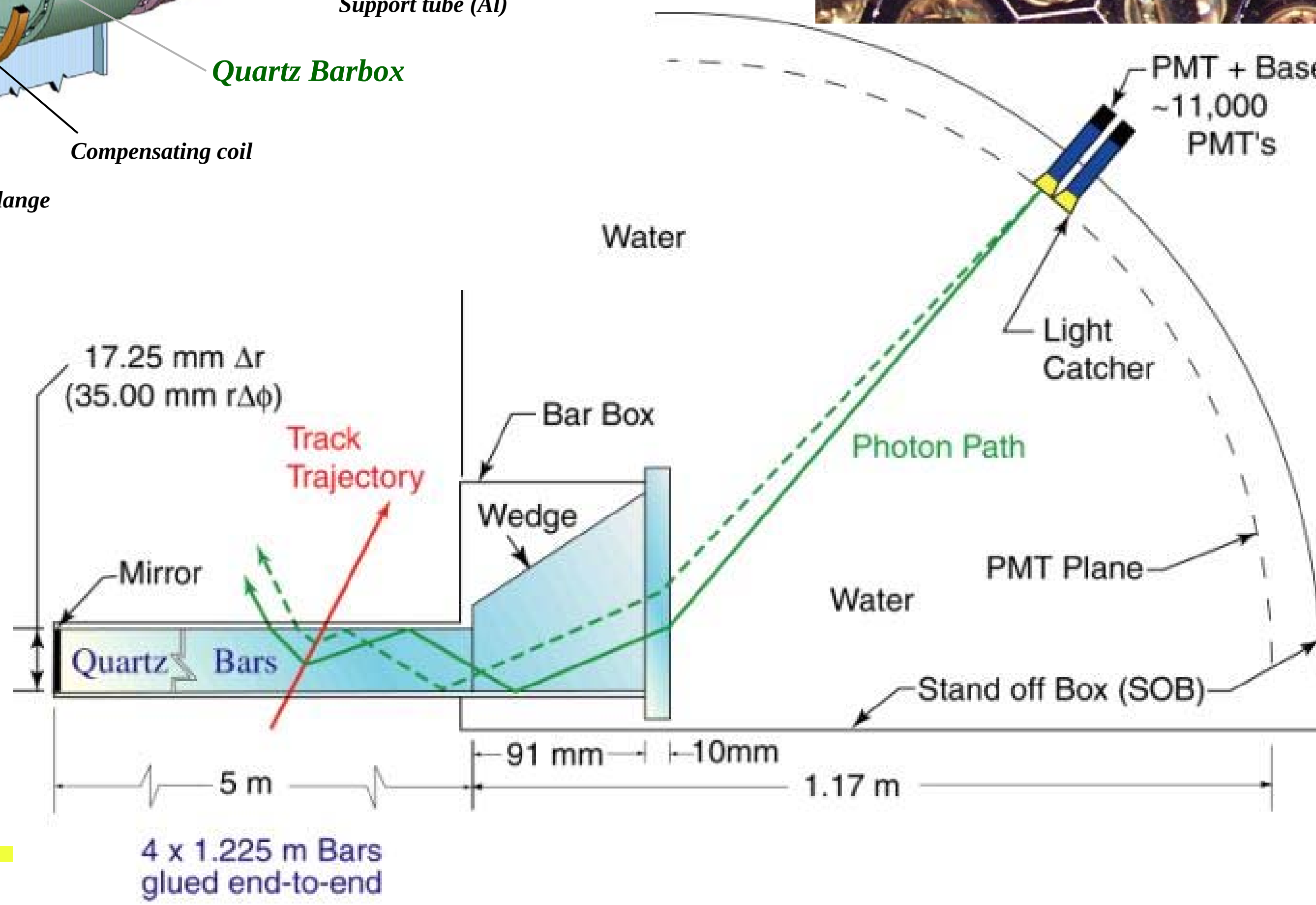
Misalignment: Cherenkov angle depends on the azimuthal angle around the track

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



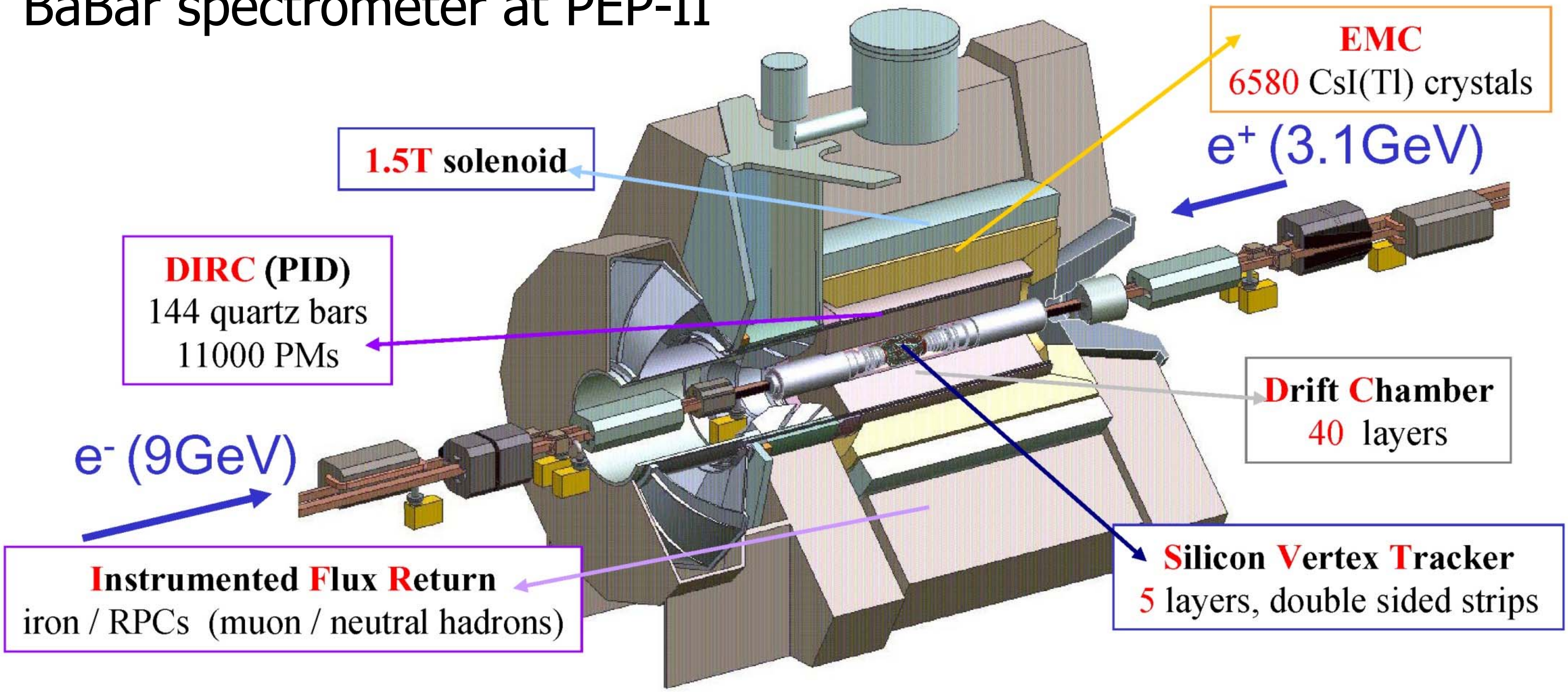




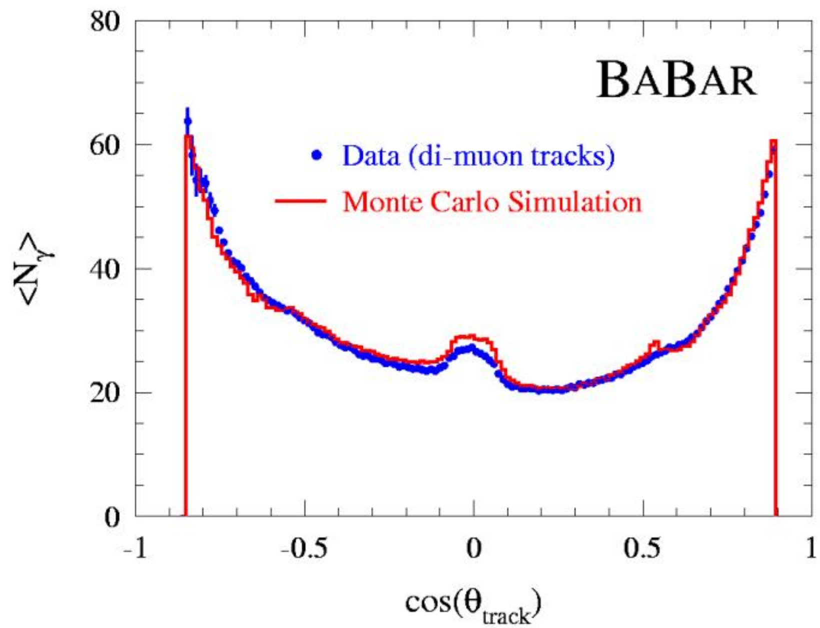


DIRC - detector of internally reflected Cherenkov light

BaBar spectrometer at PEP-II

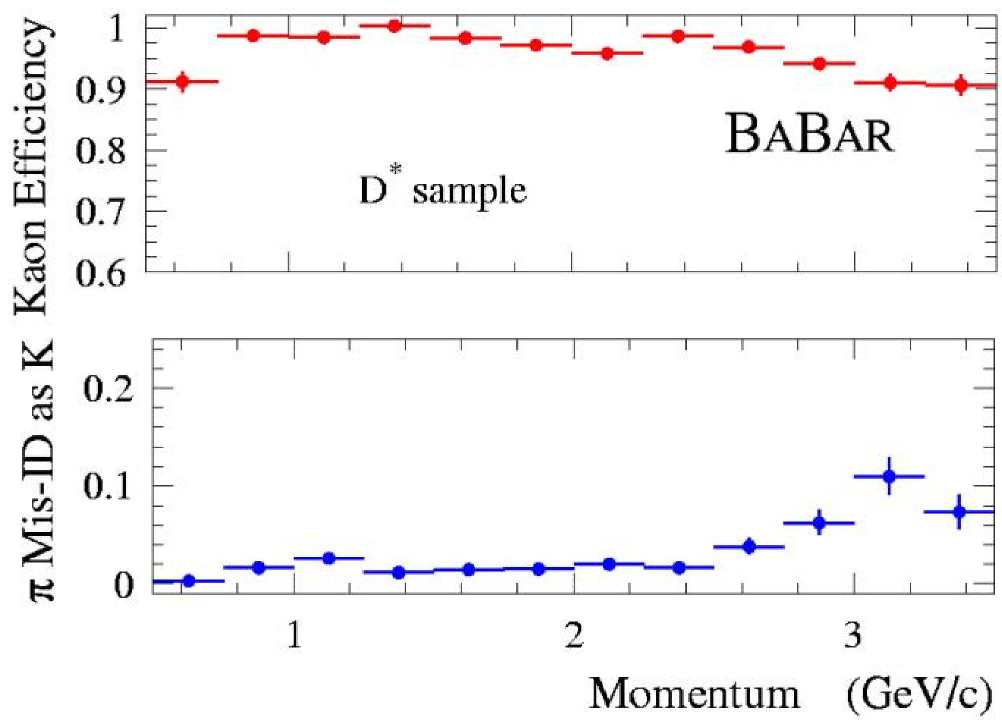


DIRC performance



← Lots of photons!

Excellent π/K separation



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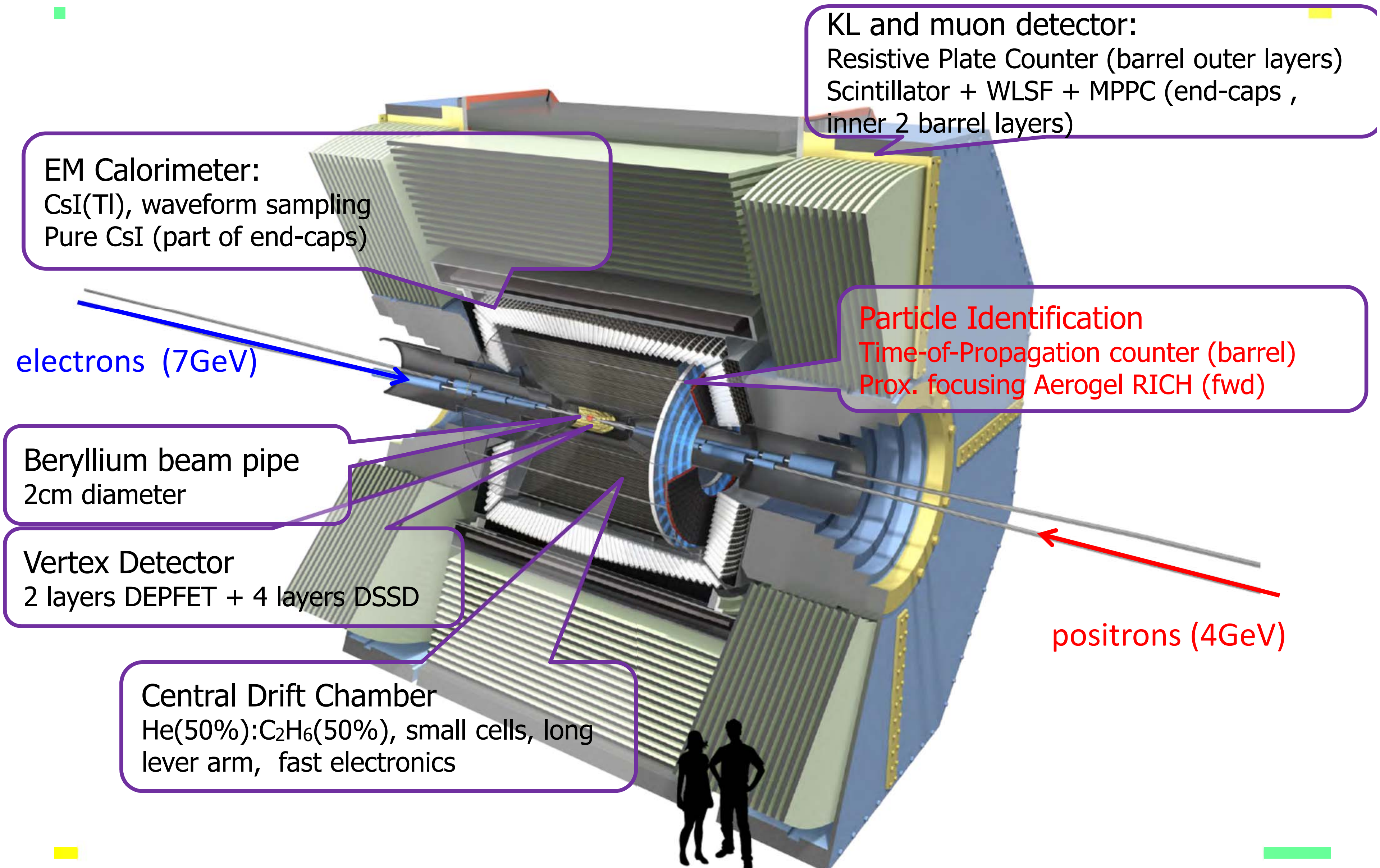
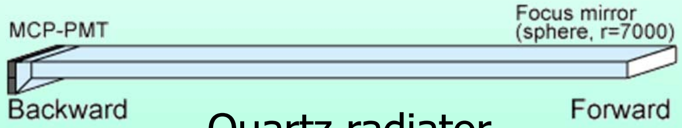
EDIT

Hadron PID in the Belle II Detector



Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



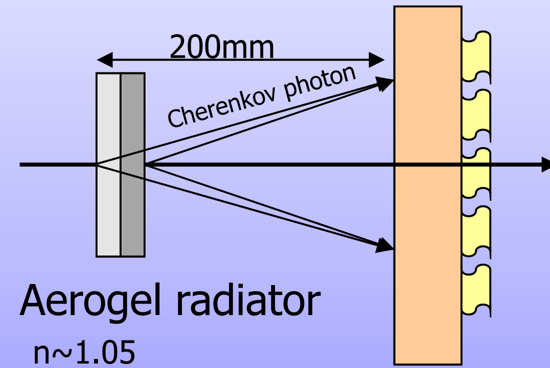
Quartz radiator

Focusing mirror

Small expansion block

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

Endcap PID: Aerogel RICH (ARICH)

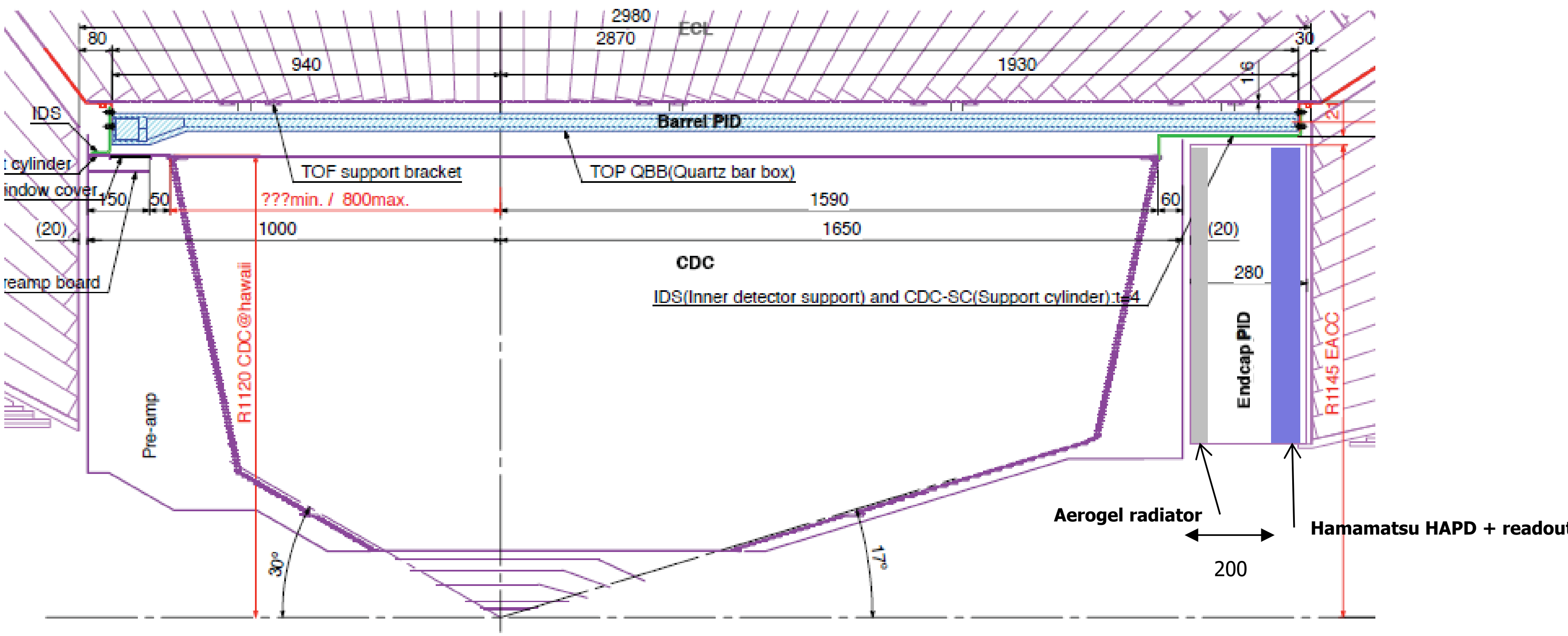


Aerogel radiator

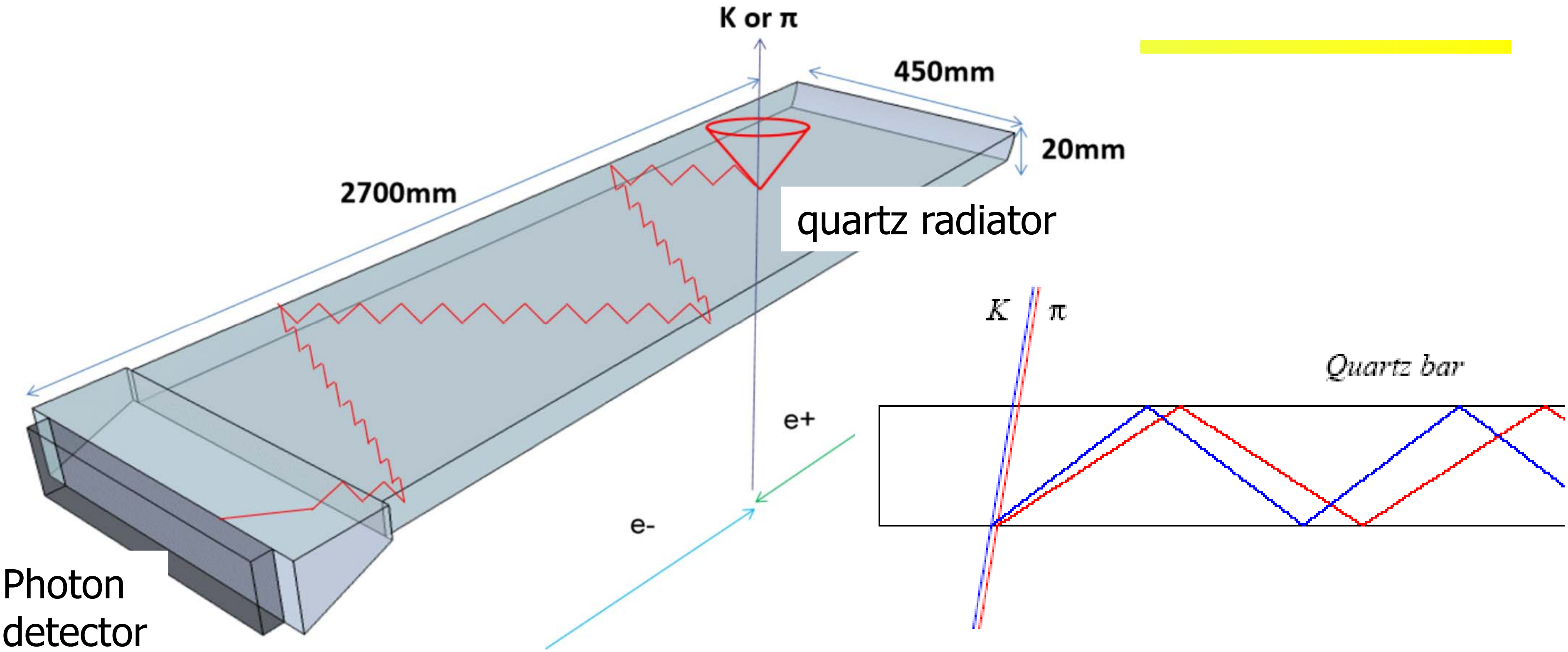
n~1.05

Hamamatsu HAPD

+ new ASIC

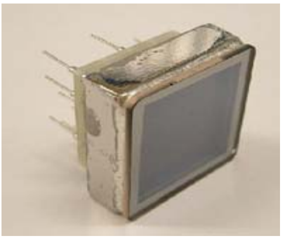


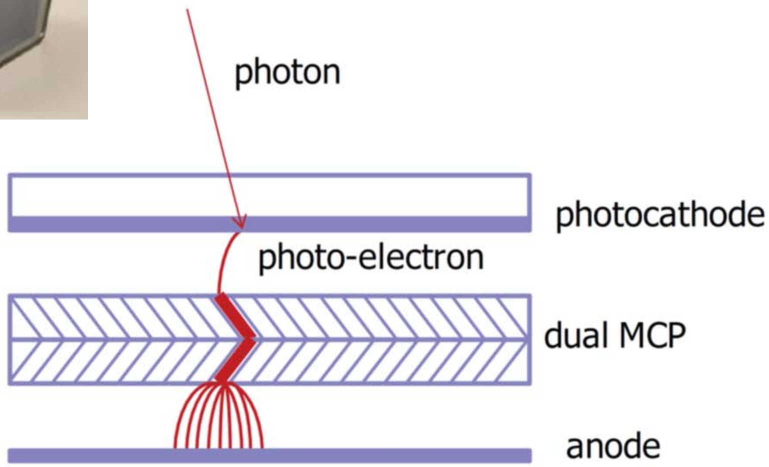
Belle II Barrel PID: Time of propagation (TOP) counter

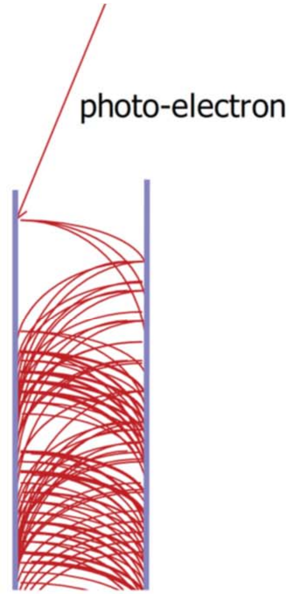


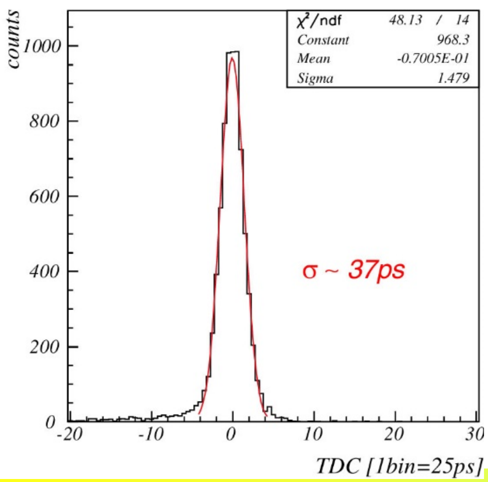
- Similar to the DIRC, Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity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

MCP PMTs for a very fast timing





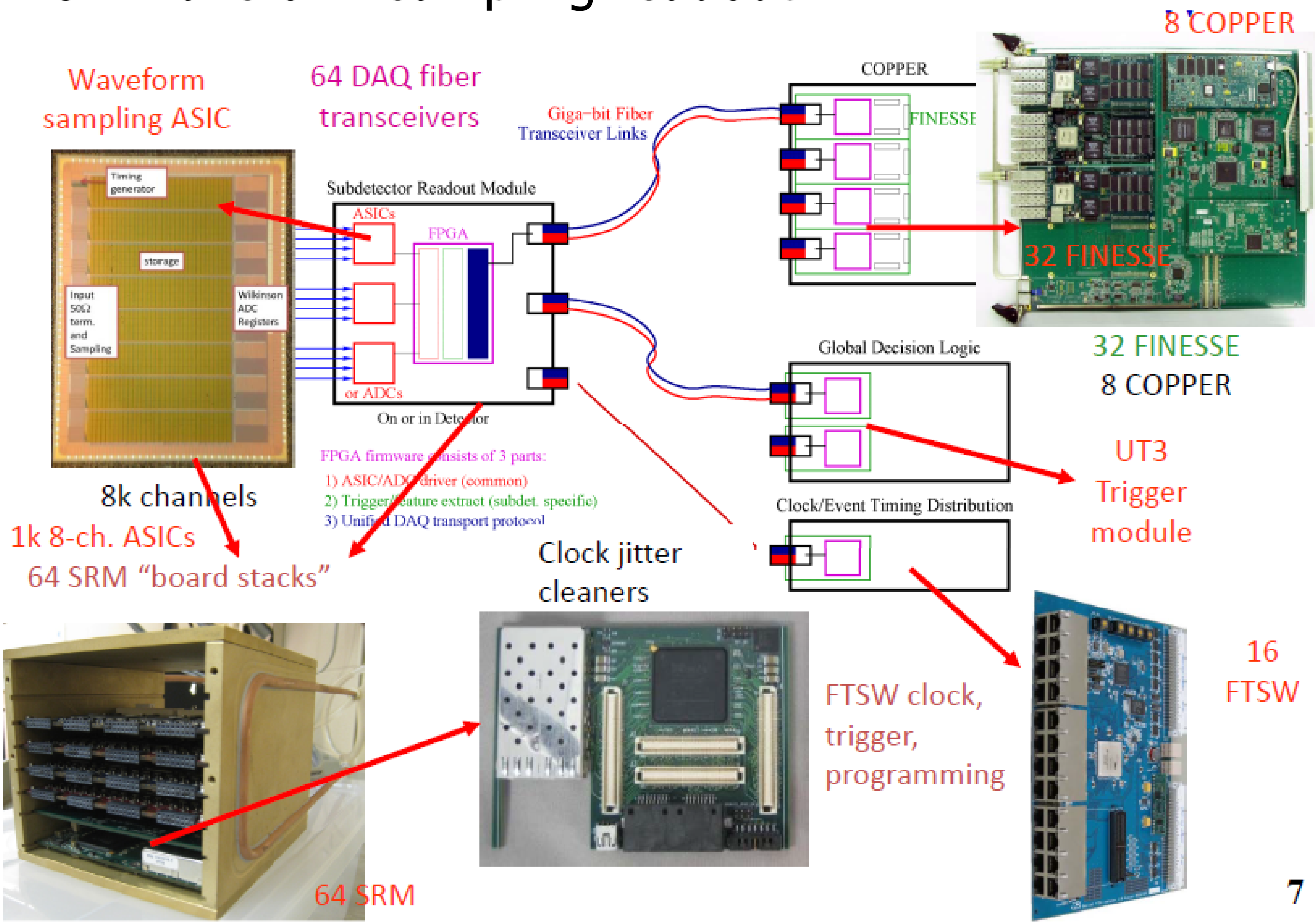


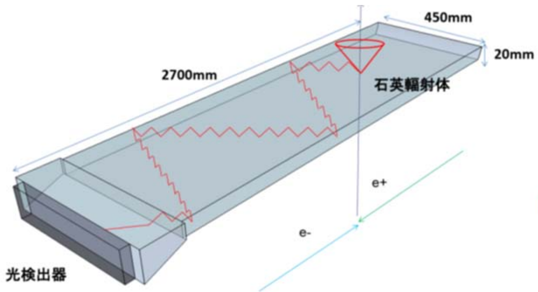


Micro-channel plate PMTs:

Single photon resolution: typically 20ps – 40ps

TOP Waveform sampling readout

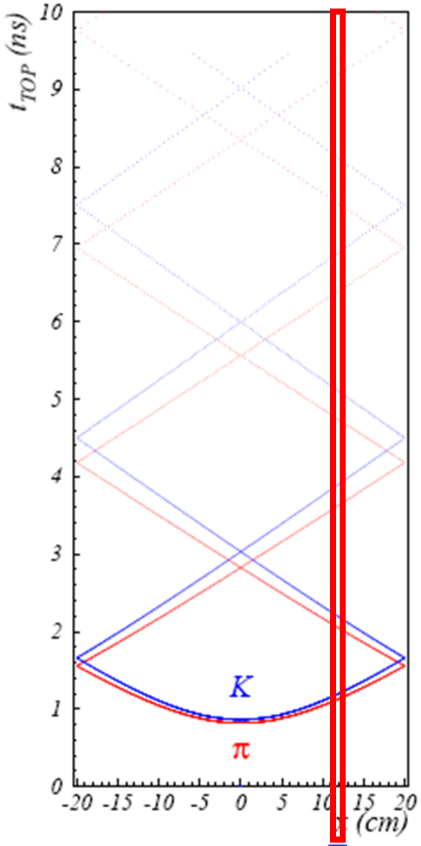


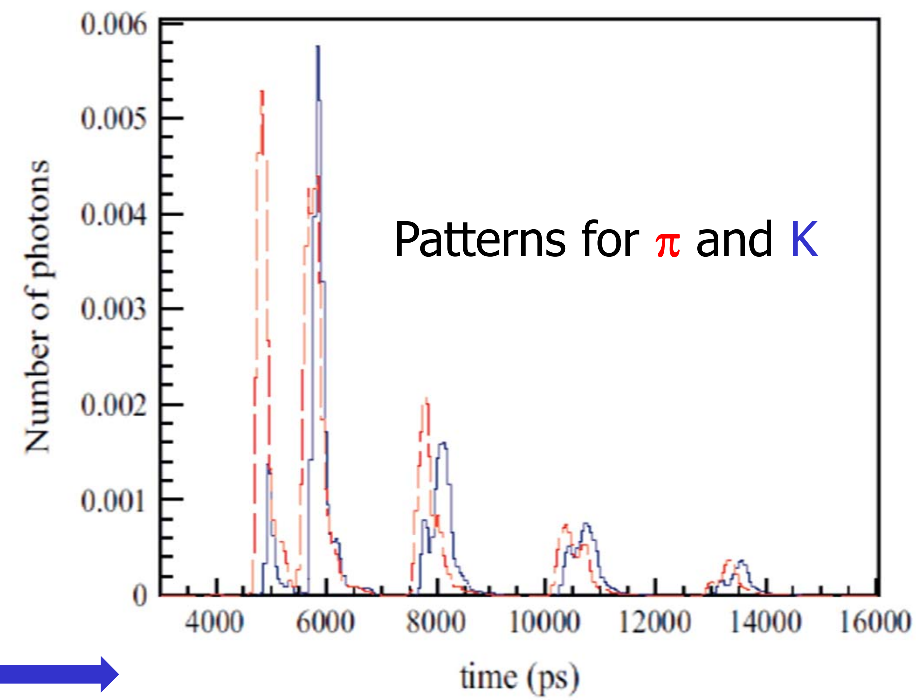


TOP image reconstruction

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

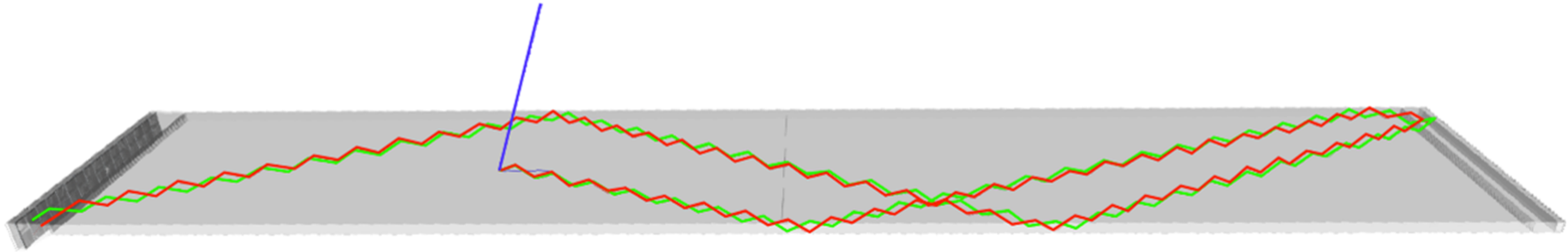
Time distribution of signals recorded by one of the PMT channels (slice in x): different for π and K (~shifted in time)



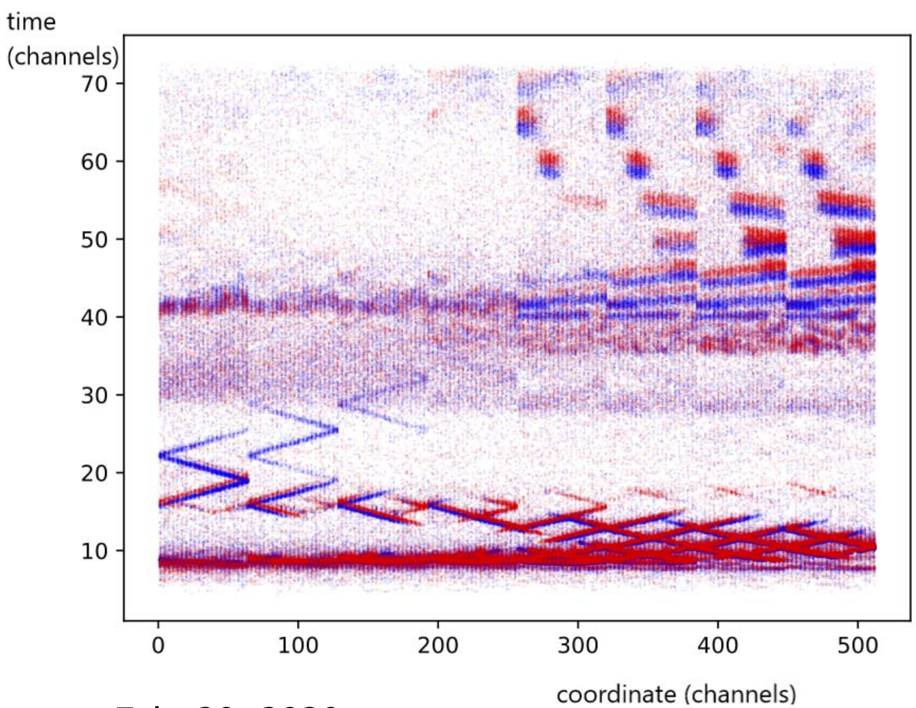


The name of the game: analytic expressions for the 2D likelihood functions
→M. Starič et al., NIMA A595 (2008) 252-255

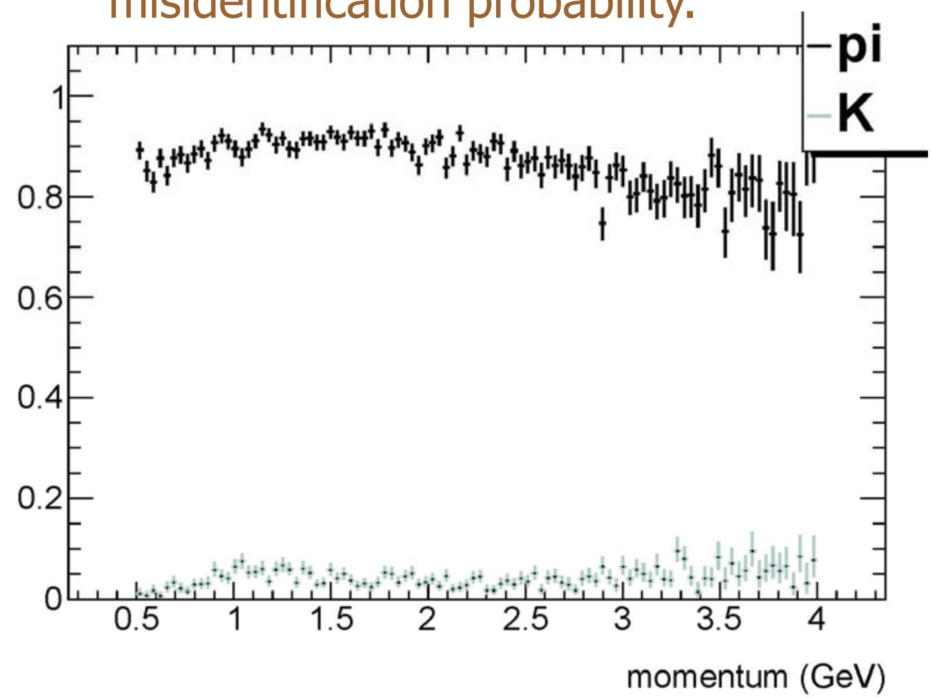
Separation of kaons and pions



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

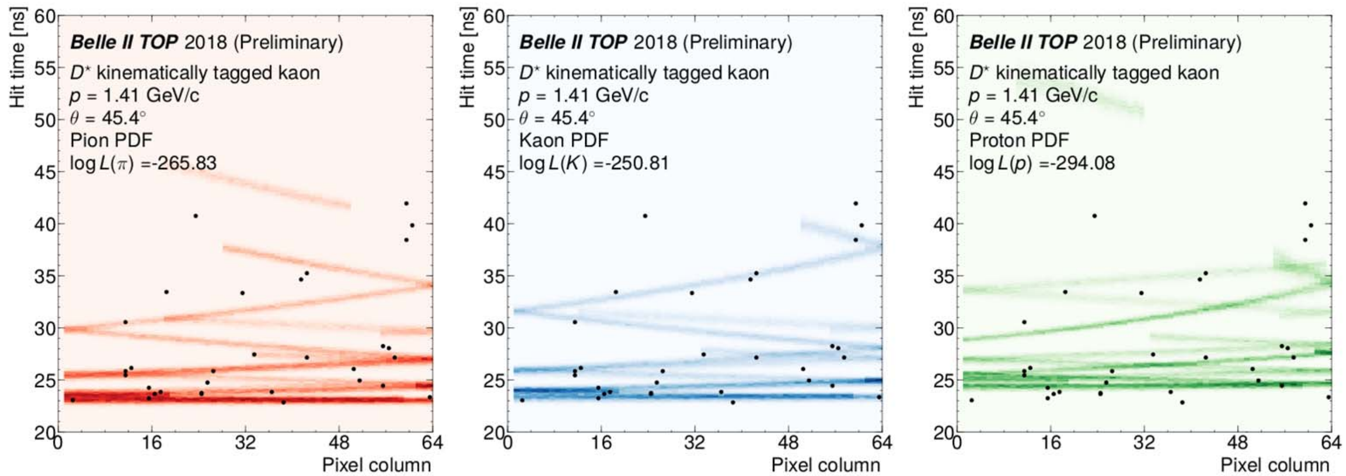


Pions vs kaons:
Expected PID efficiency and misidentification probability.



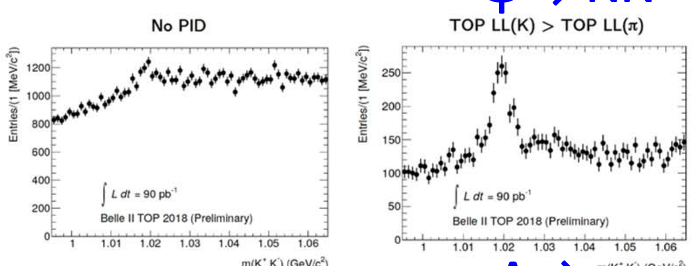
TOP first events

The early data demonstrated that the TOP principle is working



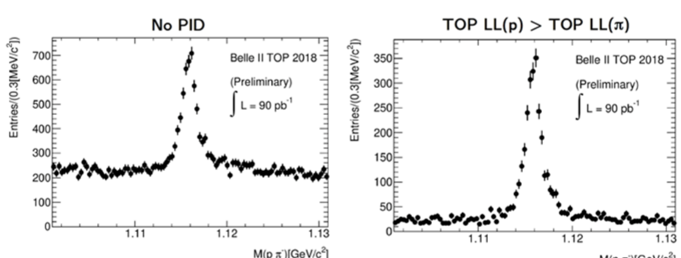
$\phi \rightarrow K^+K^-$ with both the tracks in the TOP acceptance

$\phi \rightarrow KK$

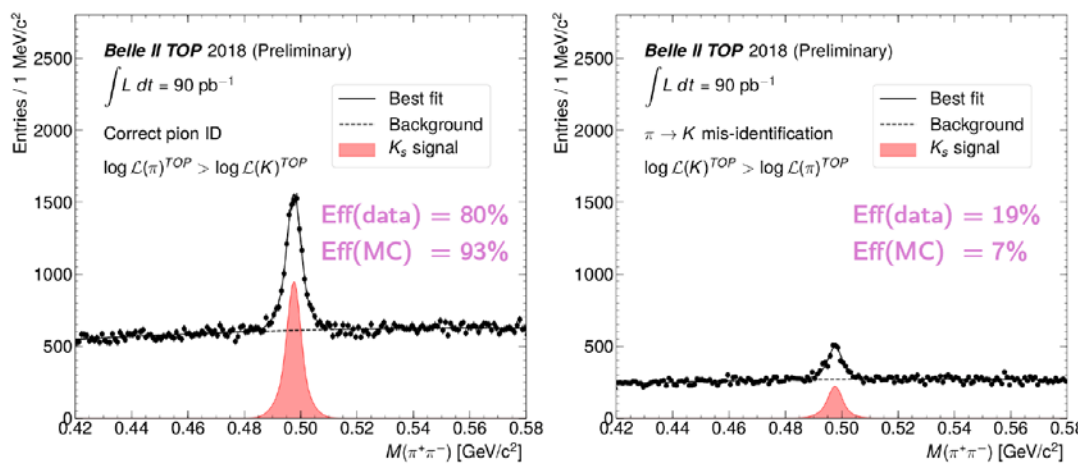


$\Lambda \rightarrow p\pi$ with the **proton candidate** in the TOP acceptance

$\Lambda \rightarrow p\pi$

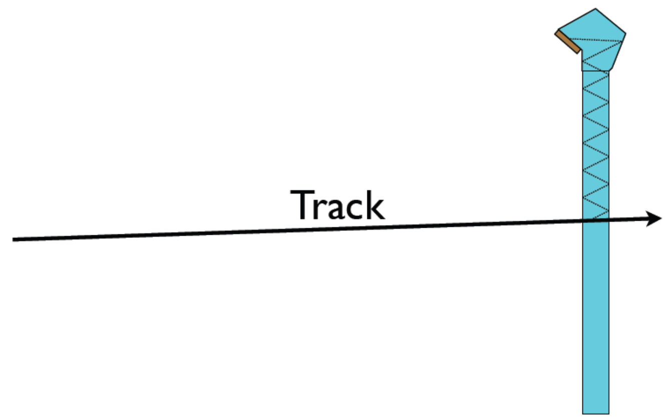


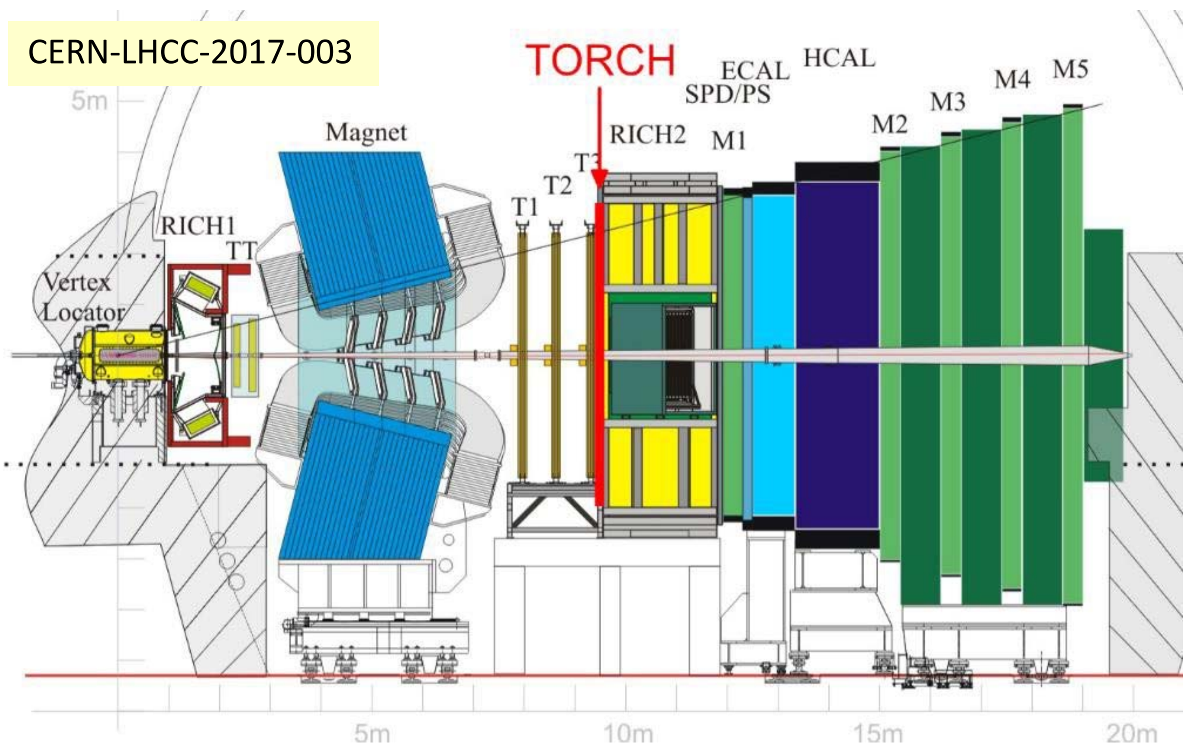
$K_s \rightarrow \pi\pi$



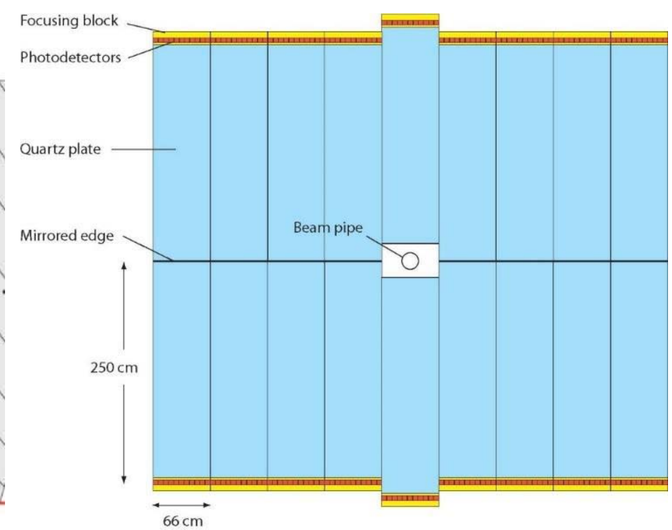
LHCb PID upgrade: TORCH

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

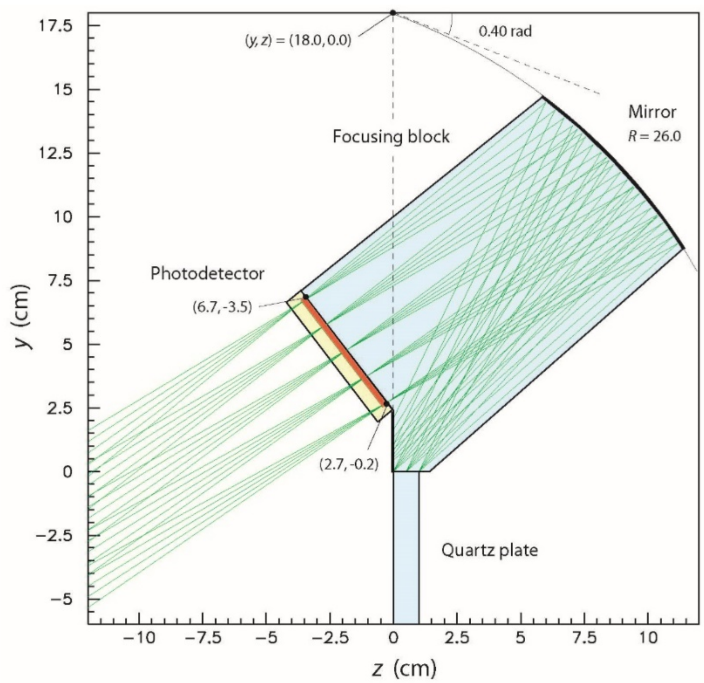




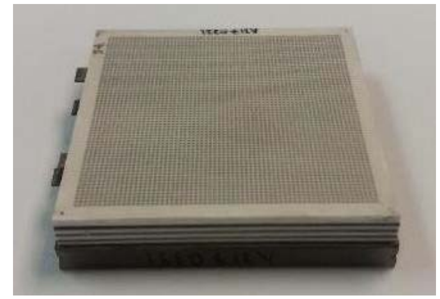
- TORCH area 5 x 6 m^2
- 18 module system
- 11 MCPs per module



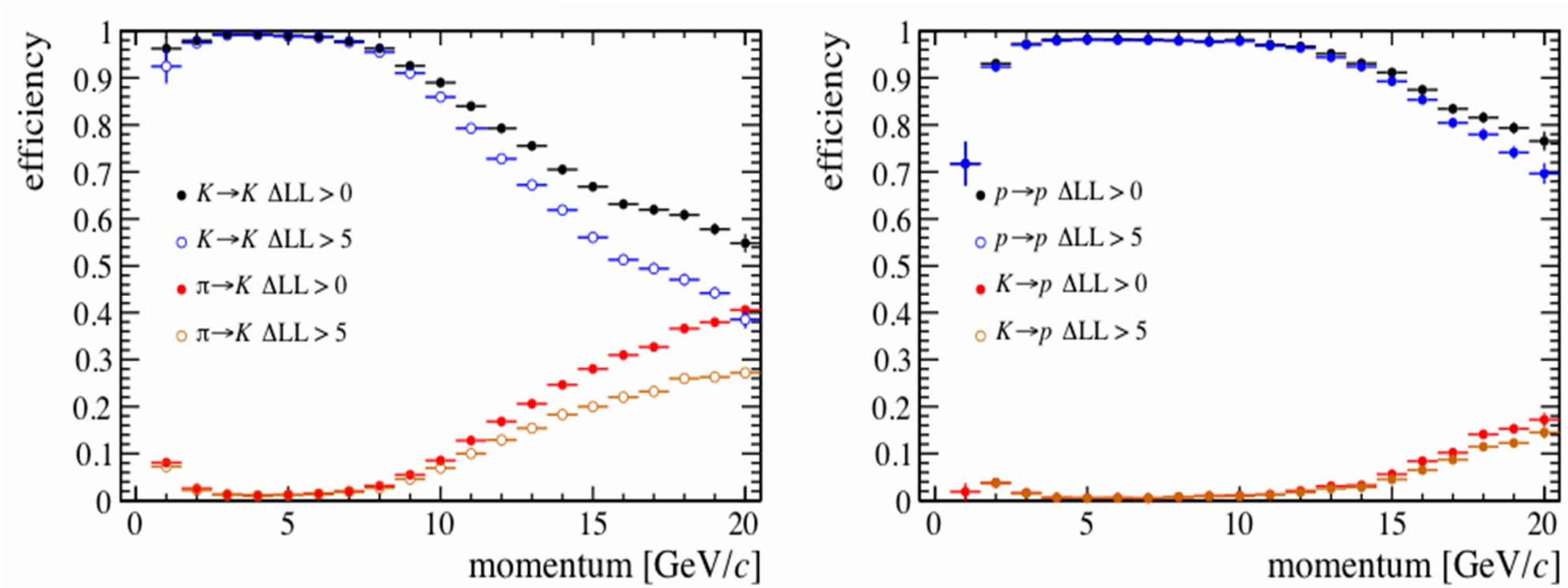
LHCb PID upgrade: TORCH



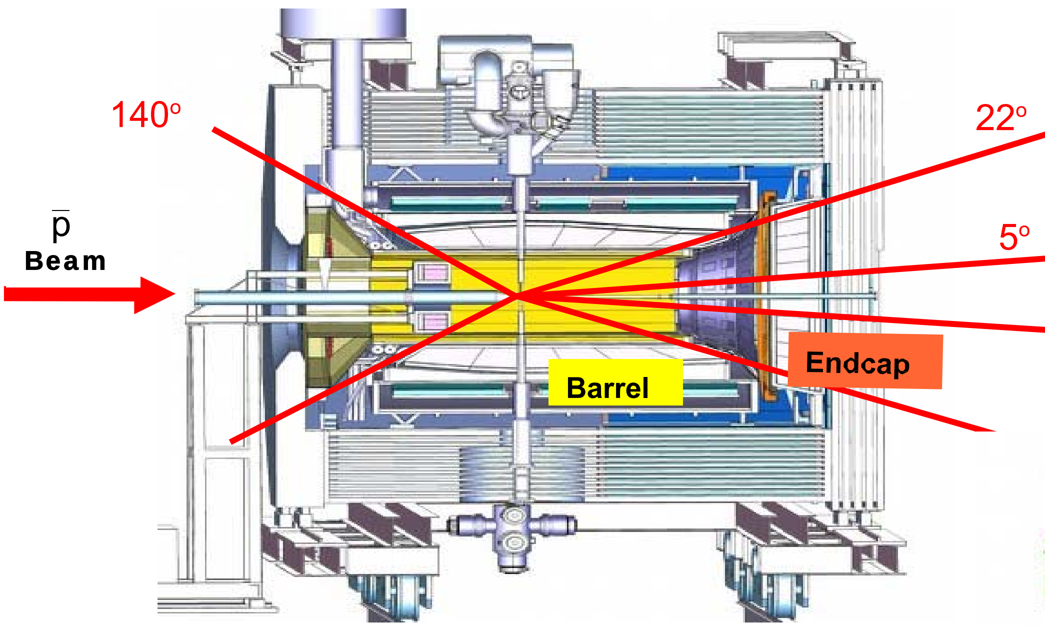
Focusing block with light sensors (MCP PMTs from Photek)

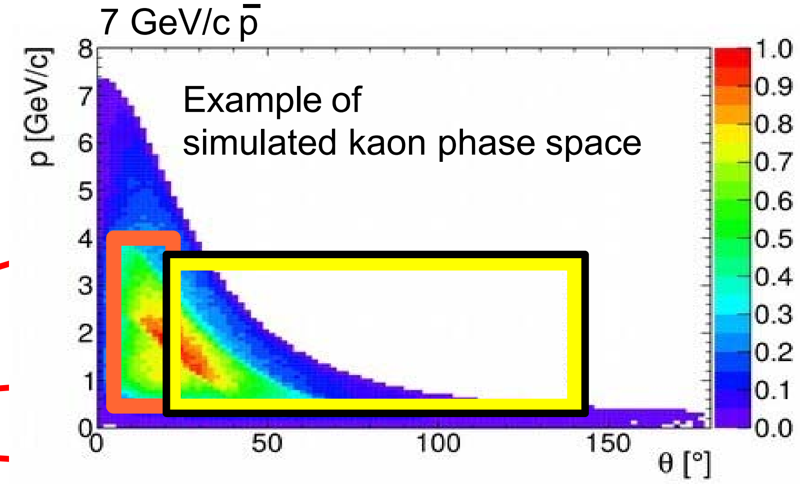


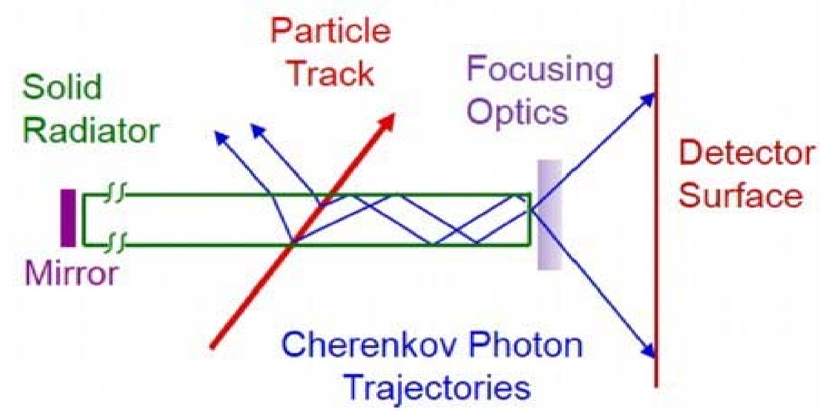
Expected performance



PANDA DIRC counters







Magnitude of photon angles
in radiator preserved

Barrel DIRC

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

Endcap Disc DIRC

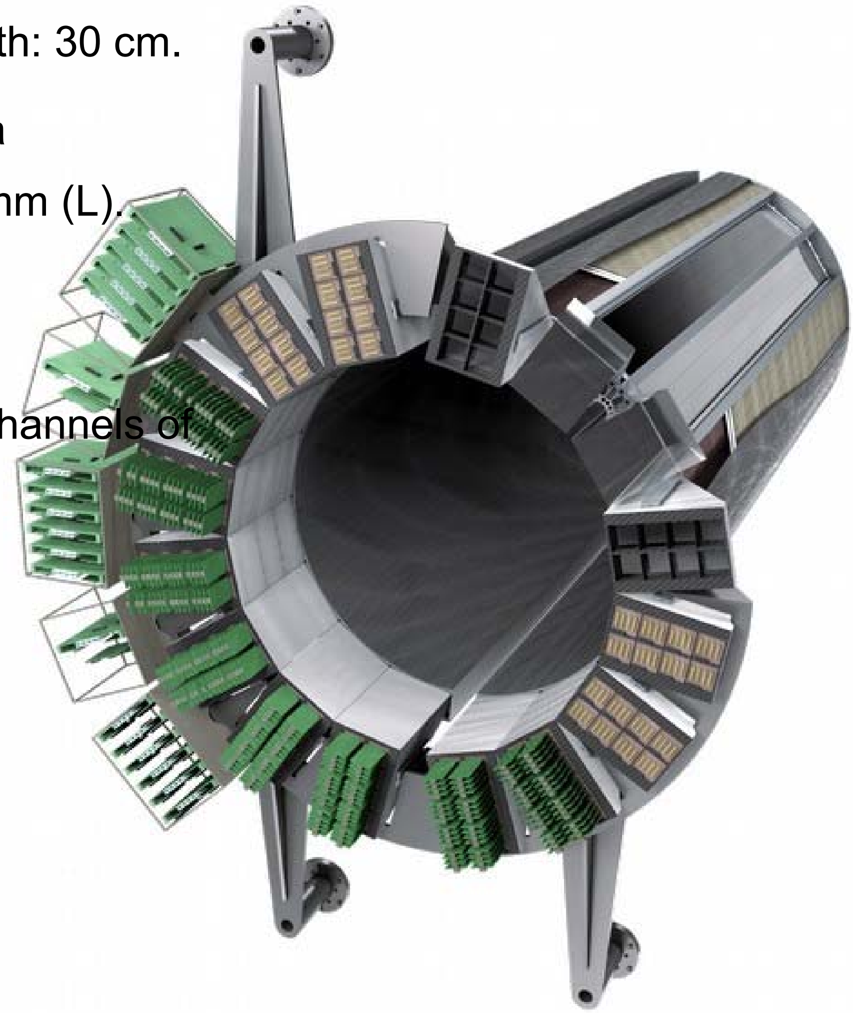
Goal: 3 s.d. π/K
separation up to
4 GeV/c

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).

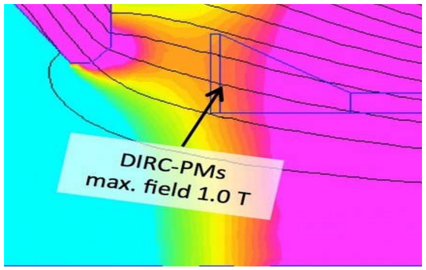


- Compact photon detector:
  30 cm fused silica expansion volume 8192 channels of MCP-PMTs
  in ~1T B field
- Focusing optics: spherical lens system
- Fast photon detection:

  fast TDC plus TOT electronics,

  → 100-200 ps timing

Photon detector



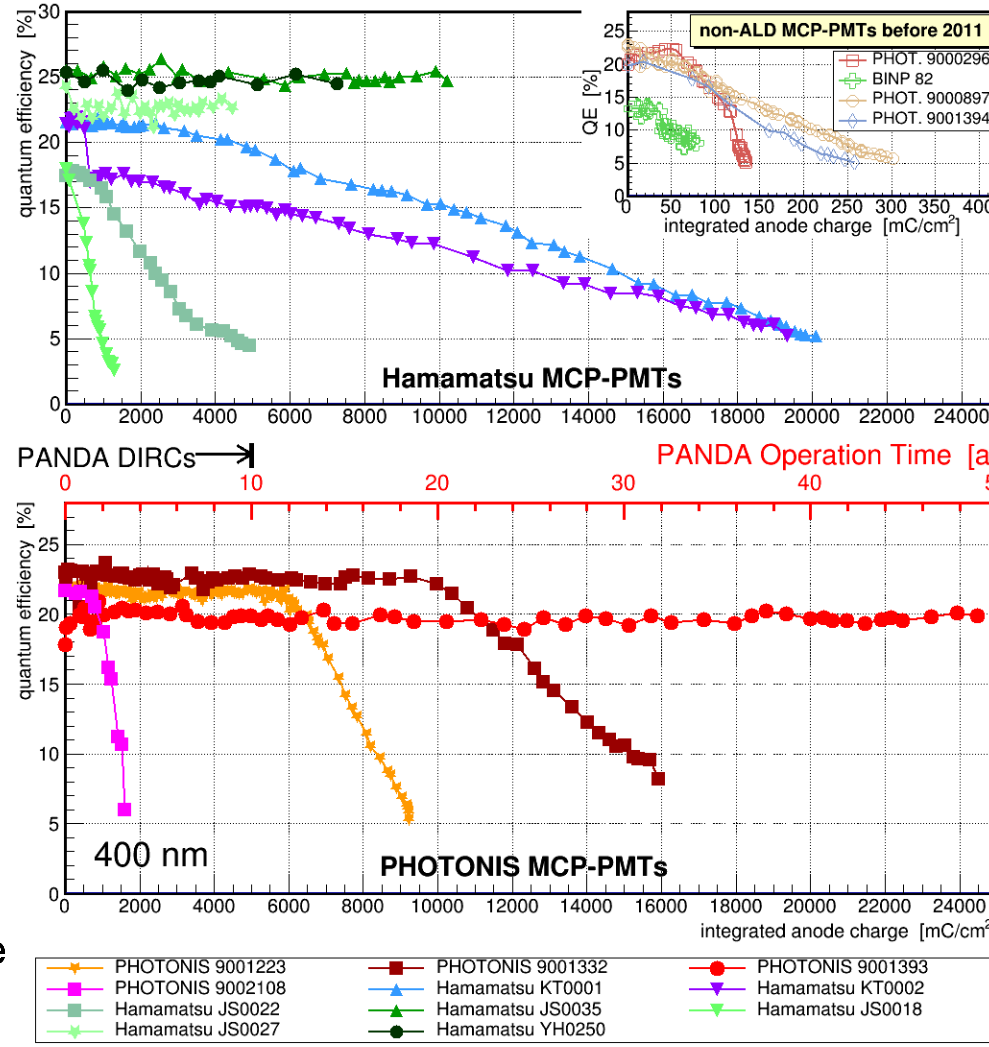
Requirements:

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

Bar-box:

8 MCP-PMT, 512 pixels (total 8 k readout channels) with **pixel size 6 x 6 mm²** work in **1T magnetic field** survive **10 years** of PANDA (aging)

Most sensors with **ALD coated** MCPs have **lifetime > 5 C/cm²**



Panda Disc DIRC

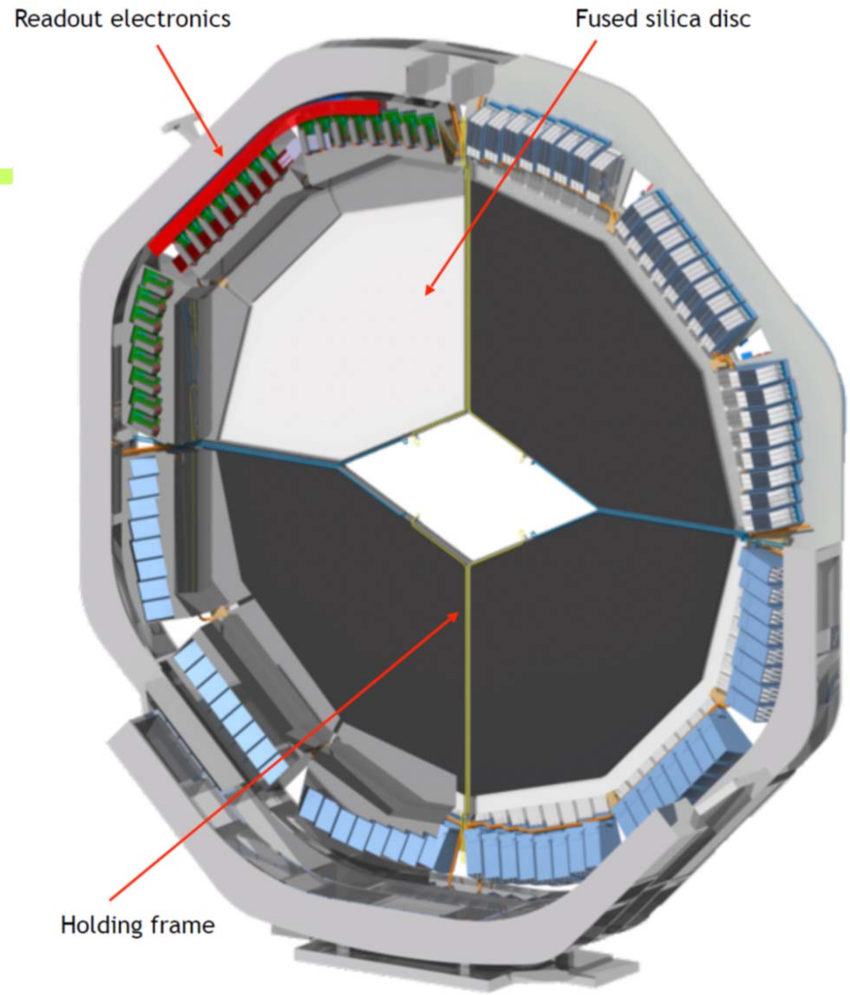
Radiator: fused silica 20 mm thick, R =1m

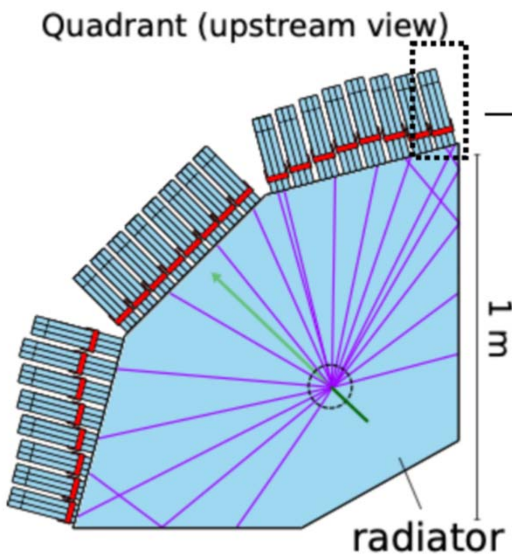
π/K separation up to 4 GeV/c

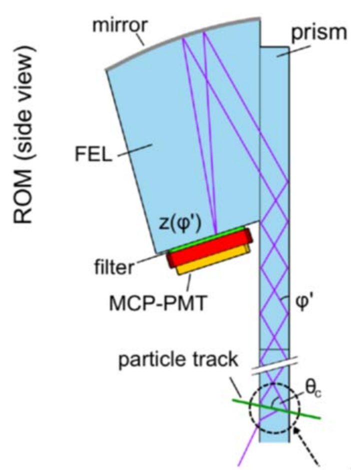
Focusing optics

Photon detector in ~1T field:

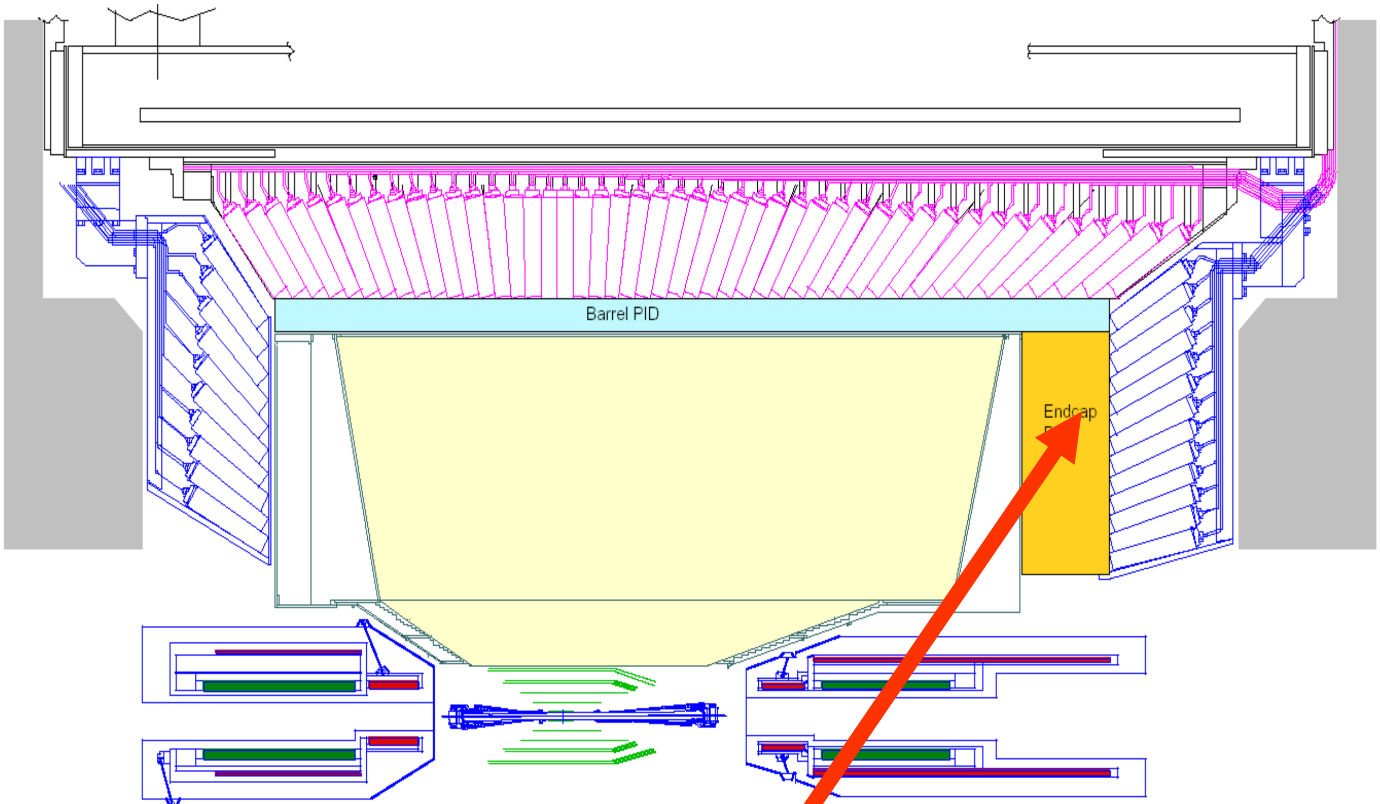
- 96 MCP PMTs with a highly segmented anode, TofPET2 readout ASIC







Belle II PID system

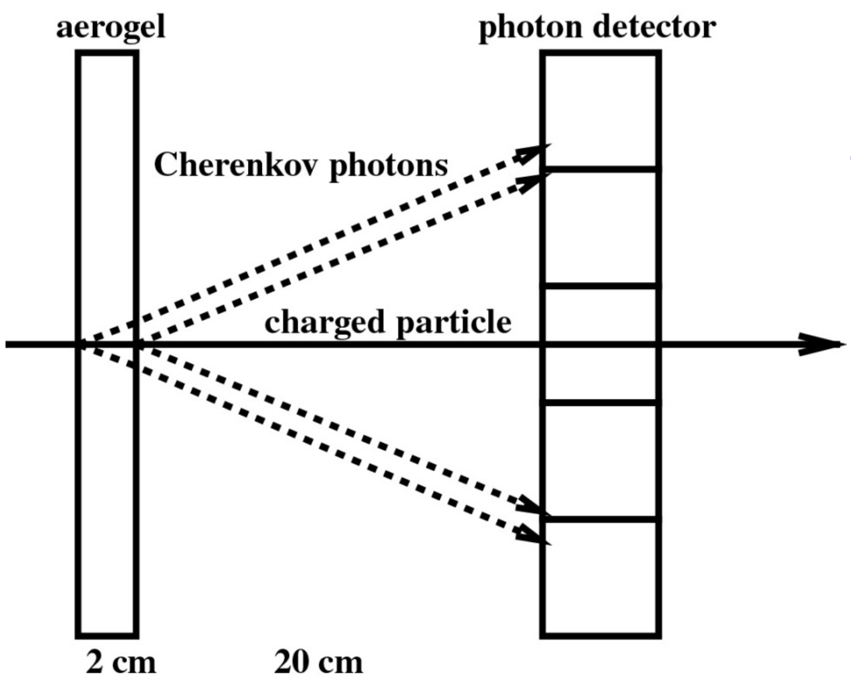


Two novel particle ID devices, both RICHes:

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

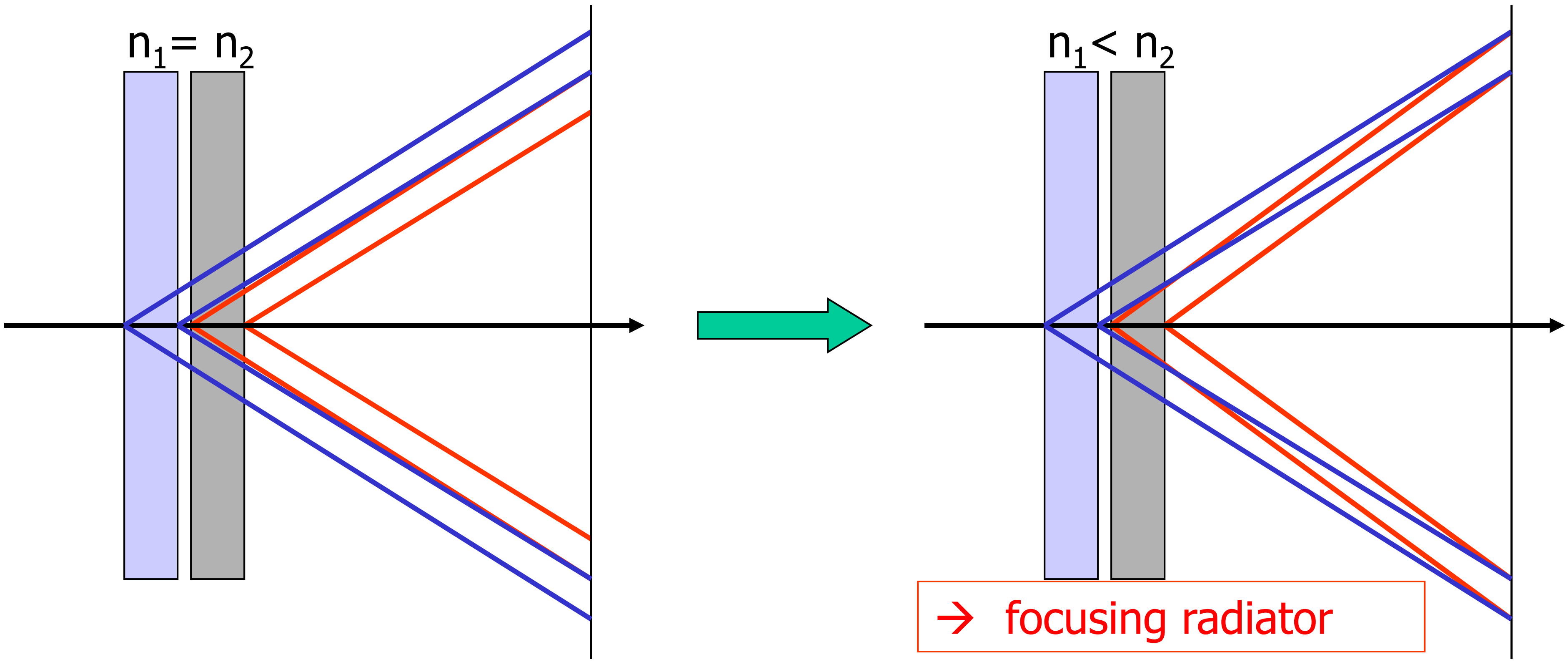
→ 5σ separation with N_{pe}~10

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?

normal

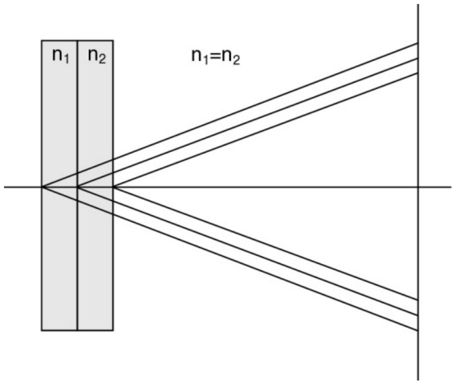
→ stack two tiles with different refractive indices: "focusing" configuration

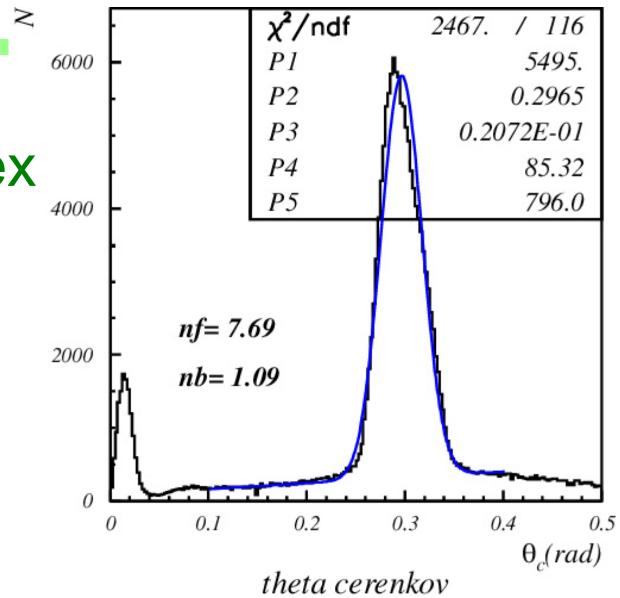


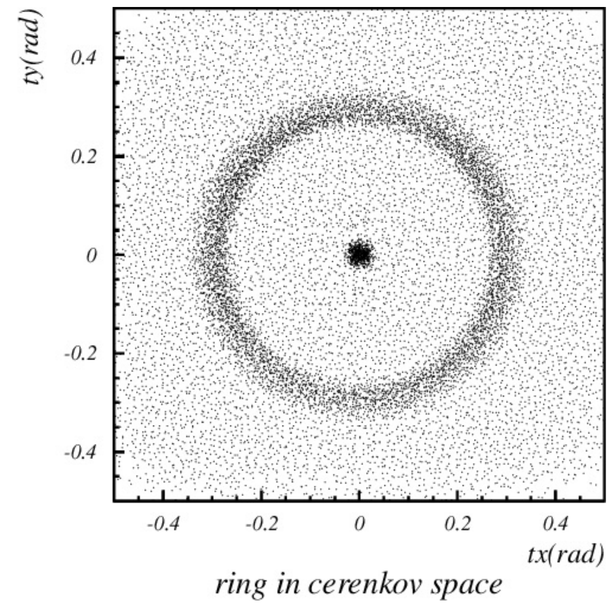
→ focusing radiator

Focusing configuration – data

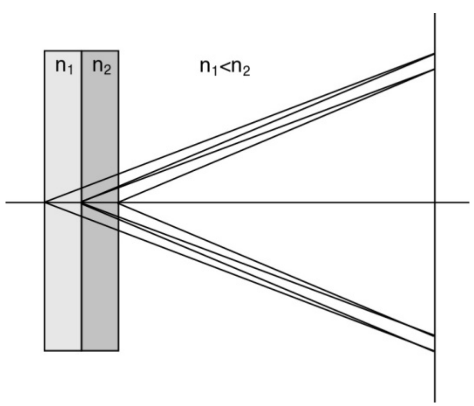
4cm aerogel single index

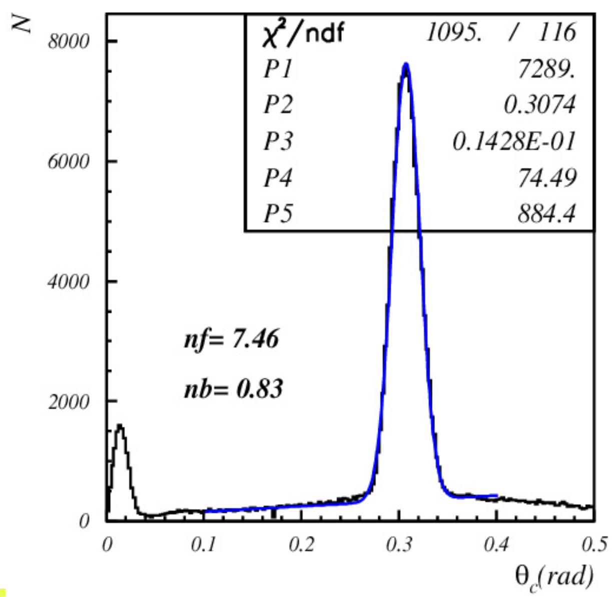


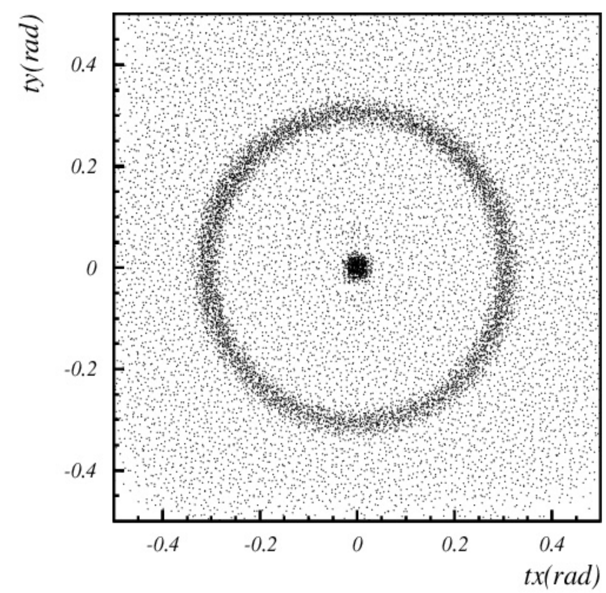




2+2cm aerogel





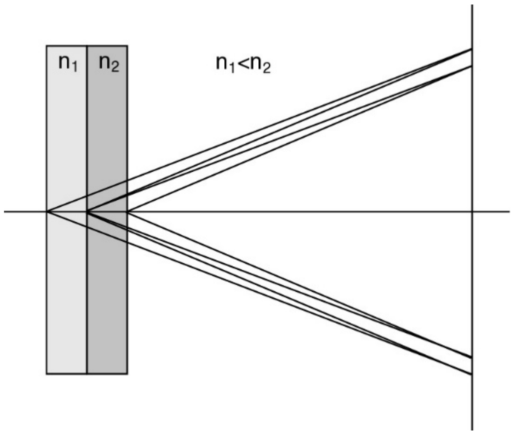


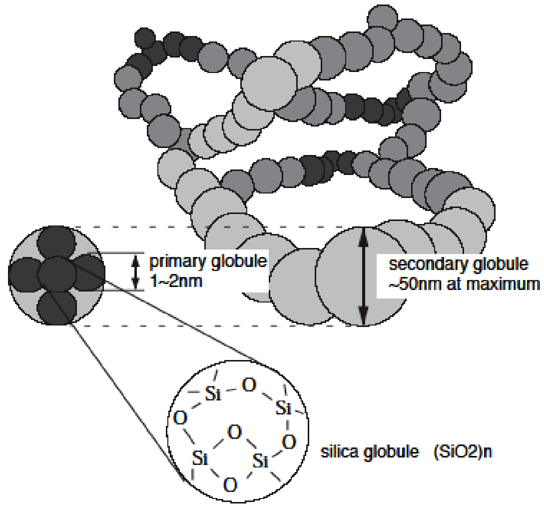
→NIM A548 (2005) 383, NIMA 565 (2006) 457

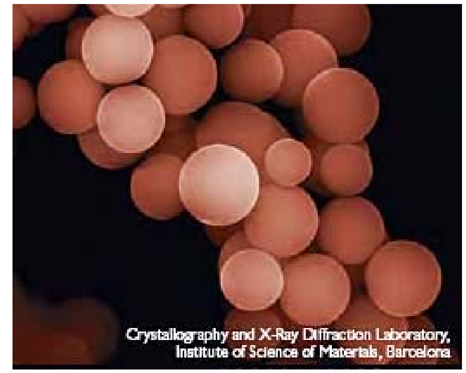
4x4 array of flat pannel MAPMTs

Radiator with multiple refractive indices 2

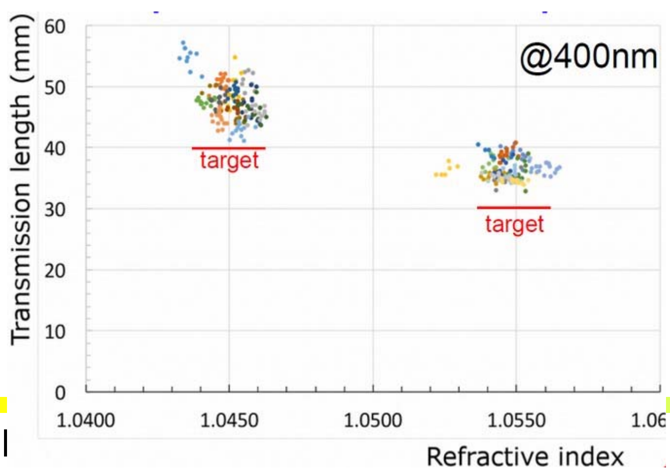
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.

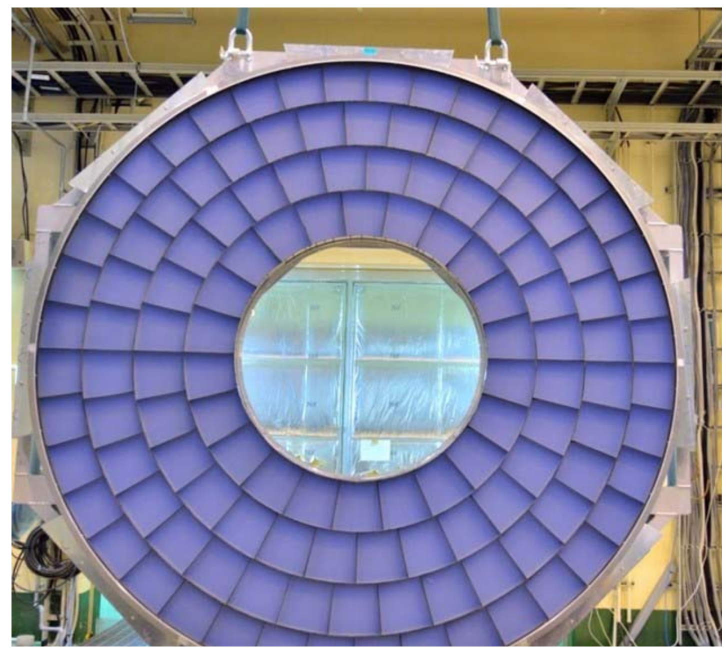






Requires aerogel with high transparency





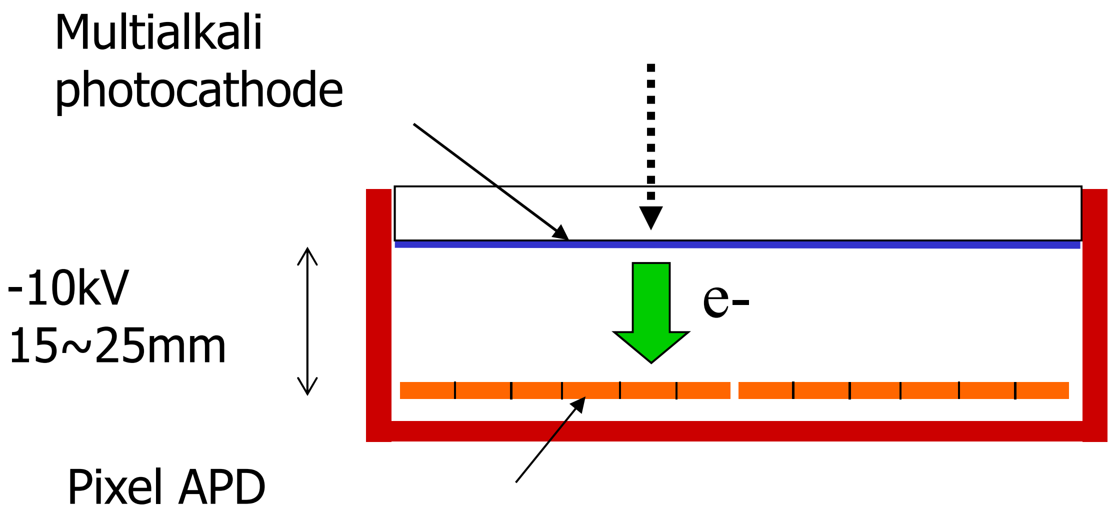
Detector plane covered with 2 x 124 tiles water-jet cut tiles (~ 17x17cm)

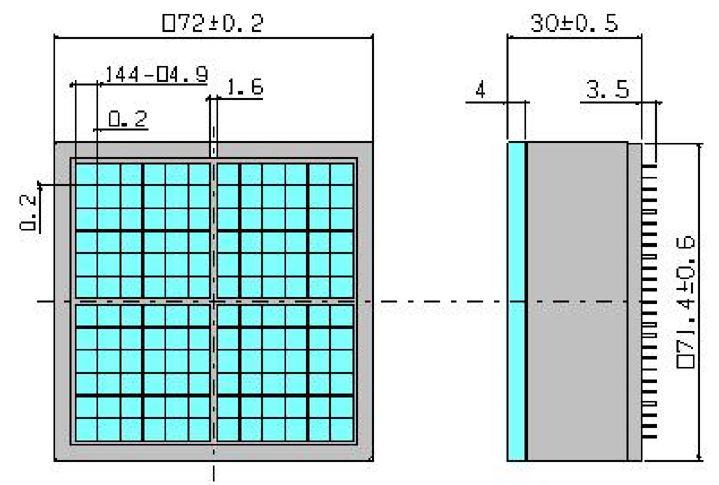
Photon detectors for the aerogel RICH requirements and candidates

Need: Operation in a high magnetic field (1.5 T)
Pad size ~5-6mm

Final choice: large active area HAPD (hybrid avalanche photon detector) of the proximity focusing type

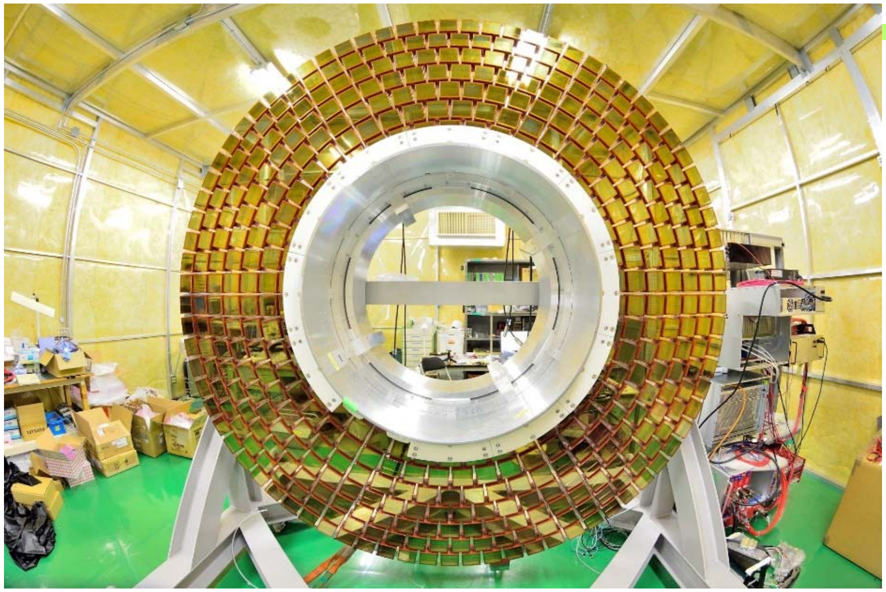
Other candidates: MCP PMT (Photonis 85011), SiPMs

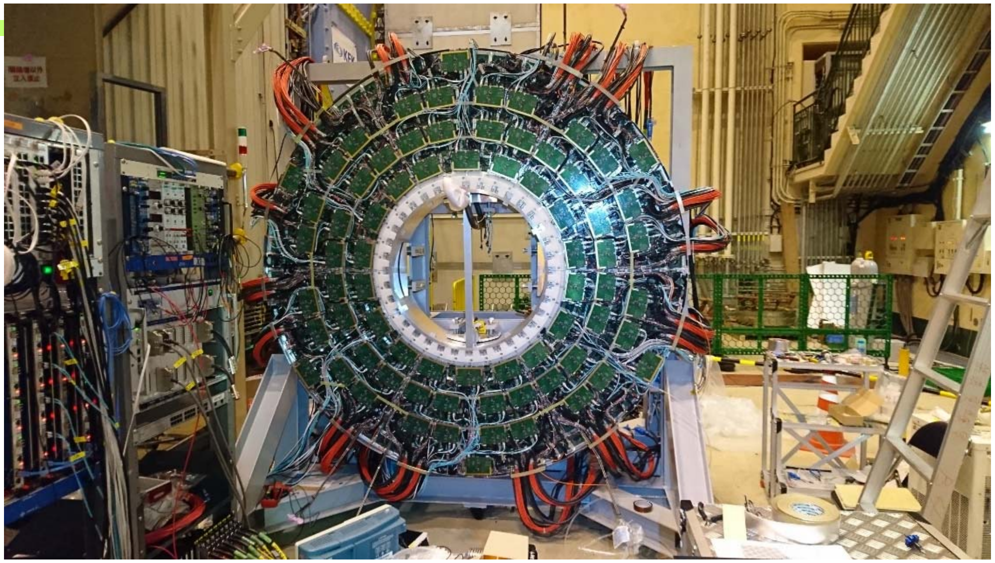


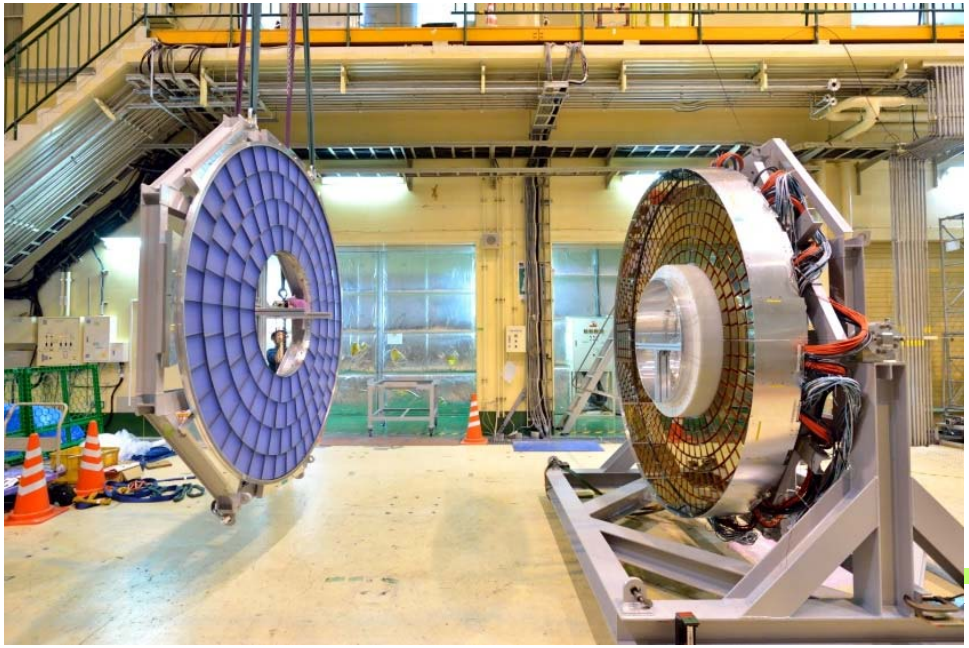


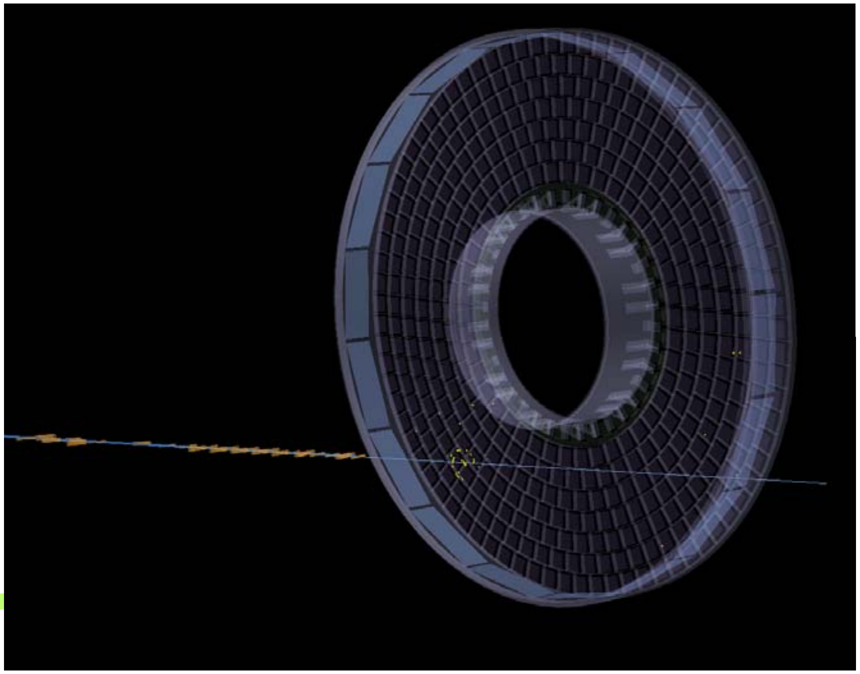
HAPD R&D project in collaboration with HPK.

The big eye of ARICH – and one of the first rings



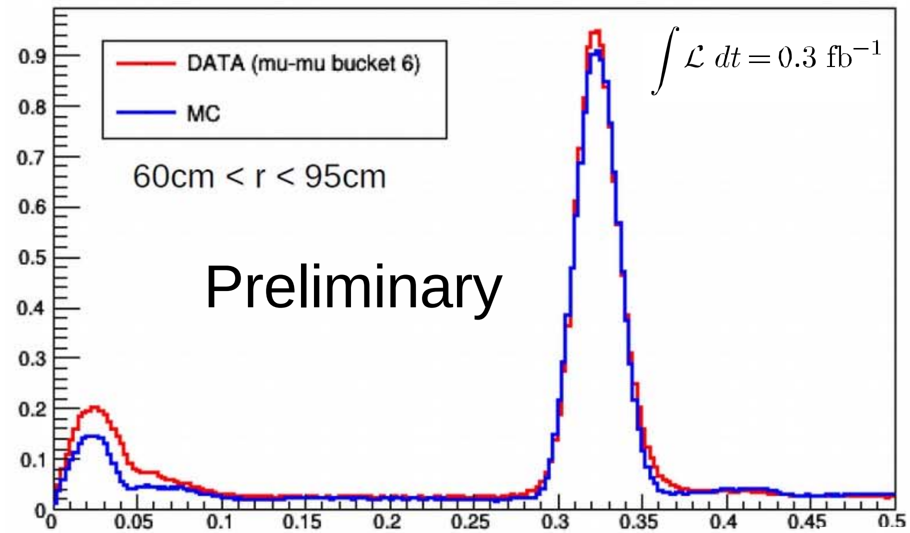






Performance in the early Belle II data

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



DATA

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

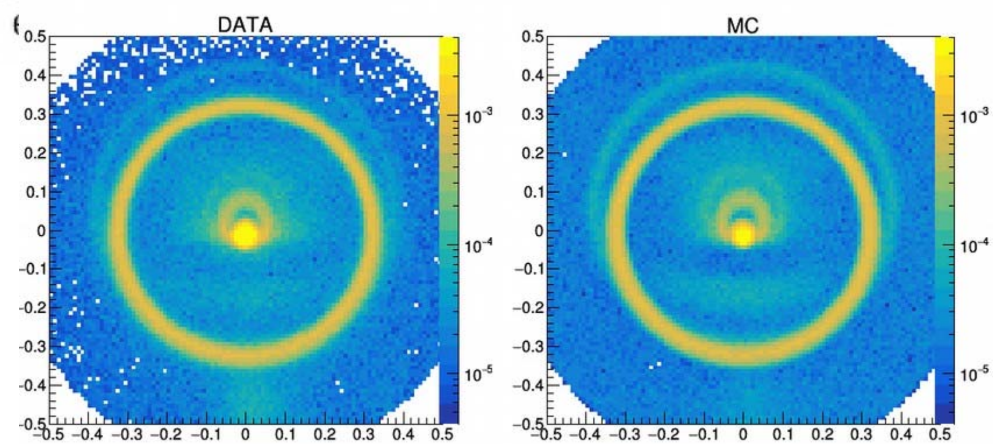
$\sigma_c = 12.7\ \mathrm{mrad}$

MC

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

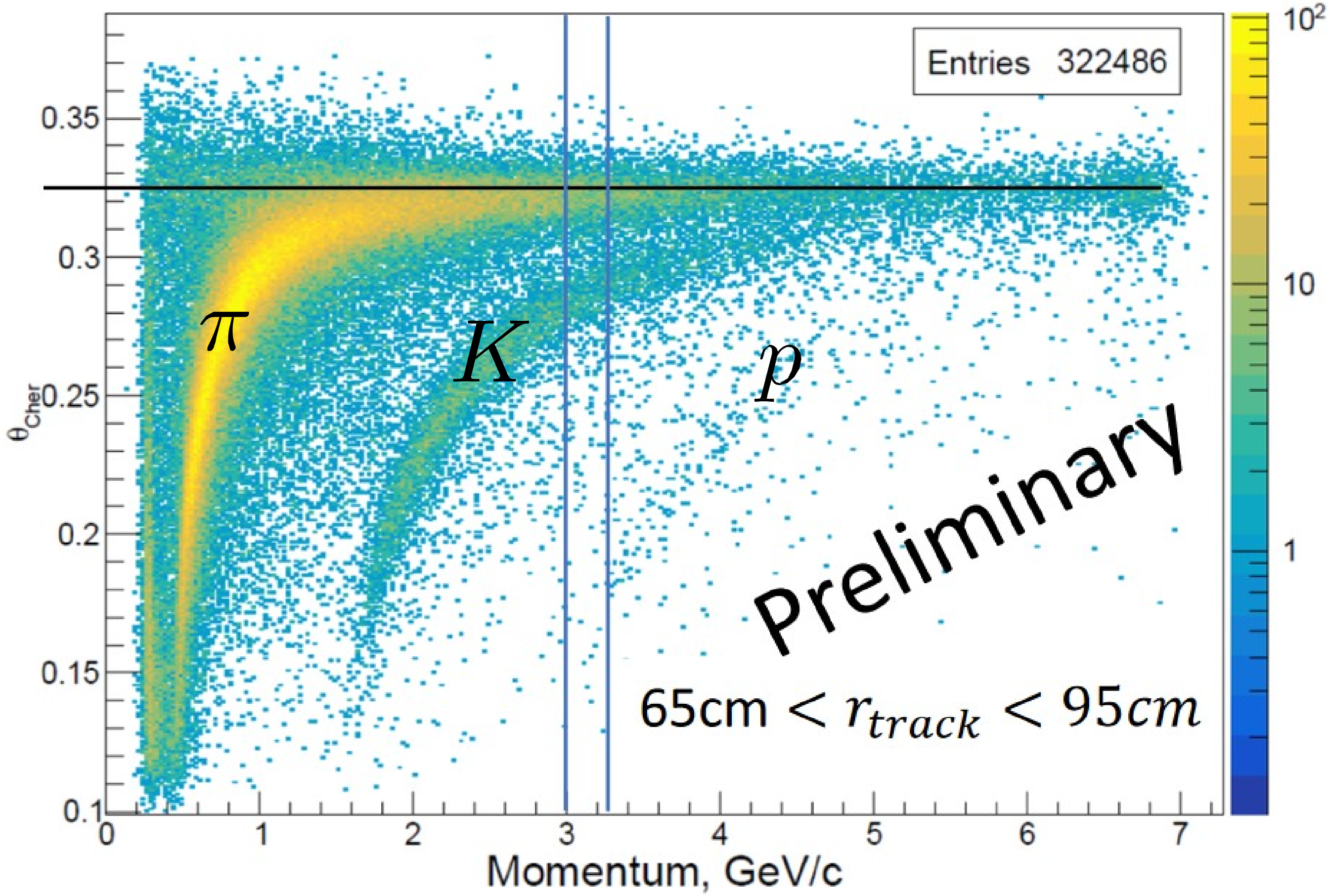
$\sigma_c = 12.75\ \mathrm{mrad}$

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}

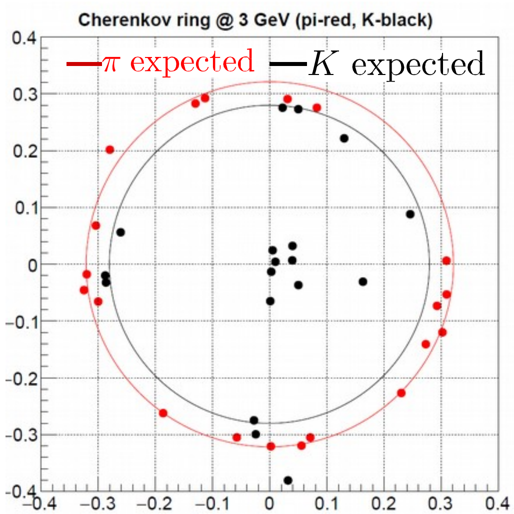
$$D^{*+} \to D^0\ \pi^+_{\mathrm{slow}}, \quad D^0 \to K^-\ \pi^+$$

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

- Apply selection criteria on

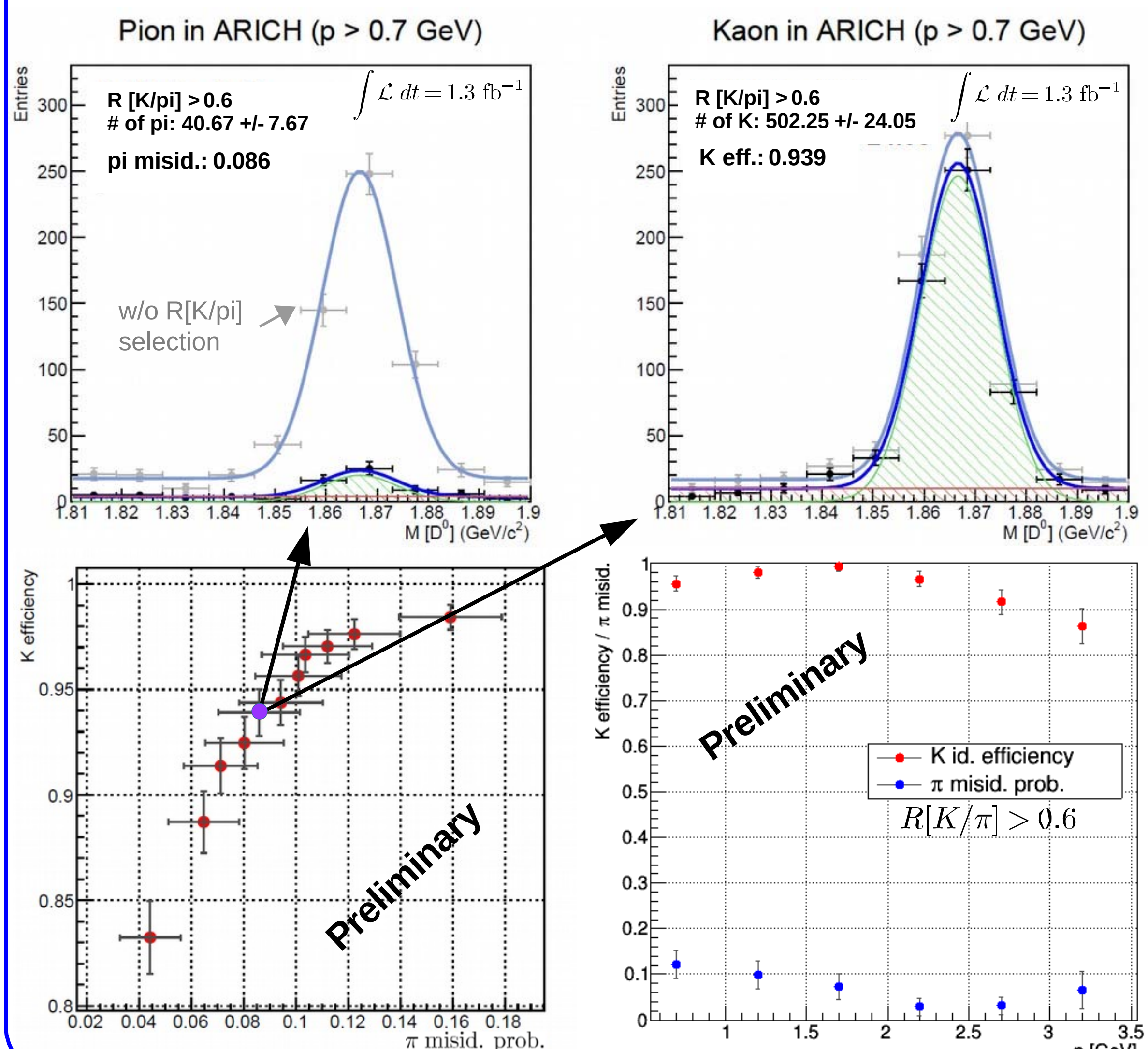
$$R[K/\pi] = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

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

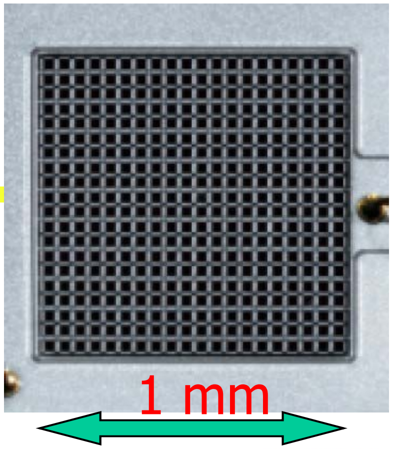


- Only coarse/preliminary calibrations included
  → further improvements expected

D^0 mass peak



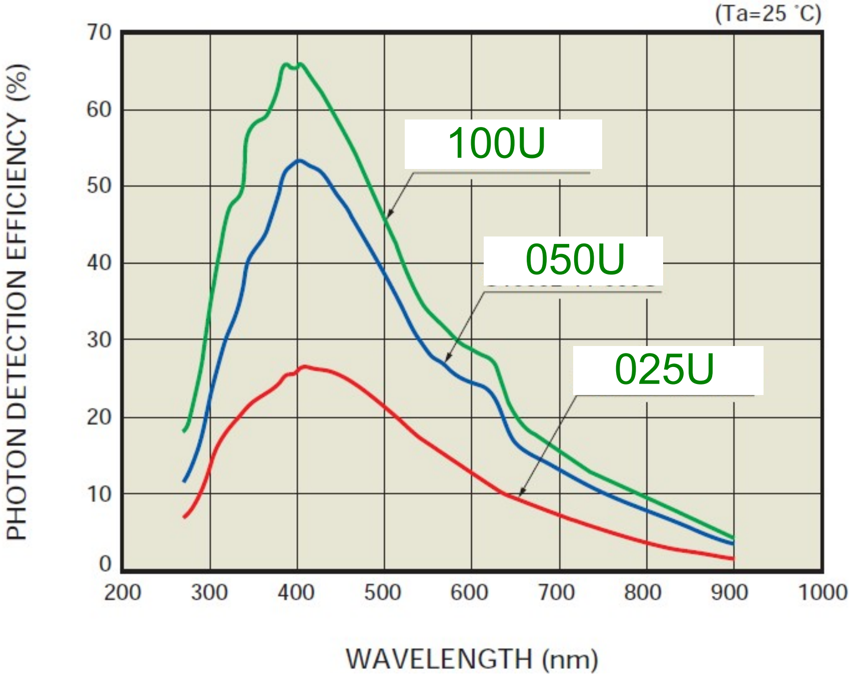
SiPMs as photon detectors?



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 per mm^2)

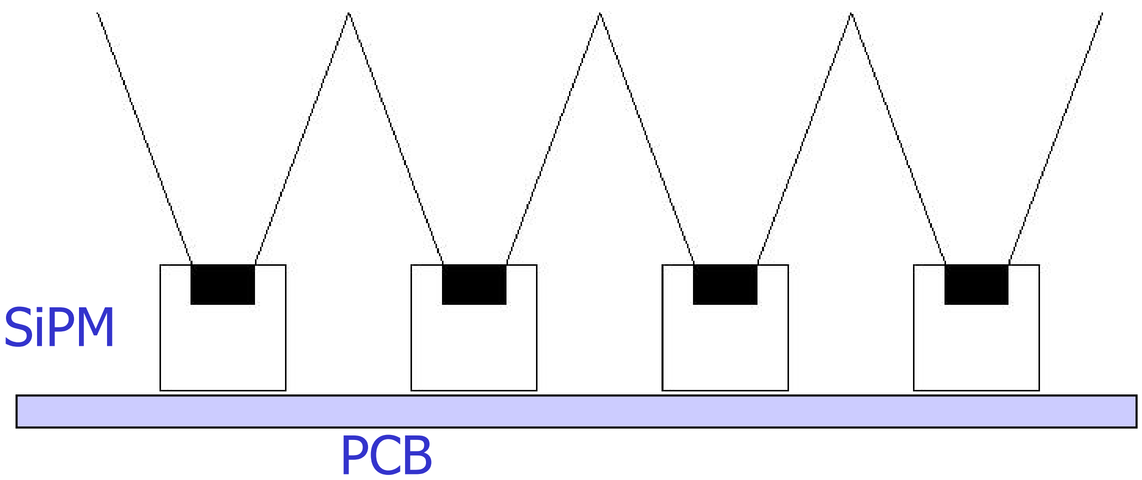
SiPM as photosensor for a RICH counter

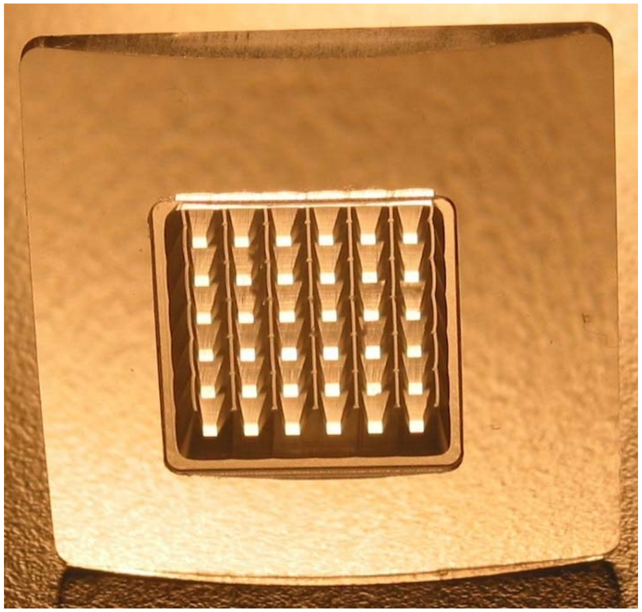
Improve the signal to noise ratio:

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

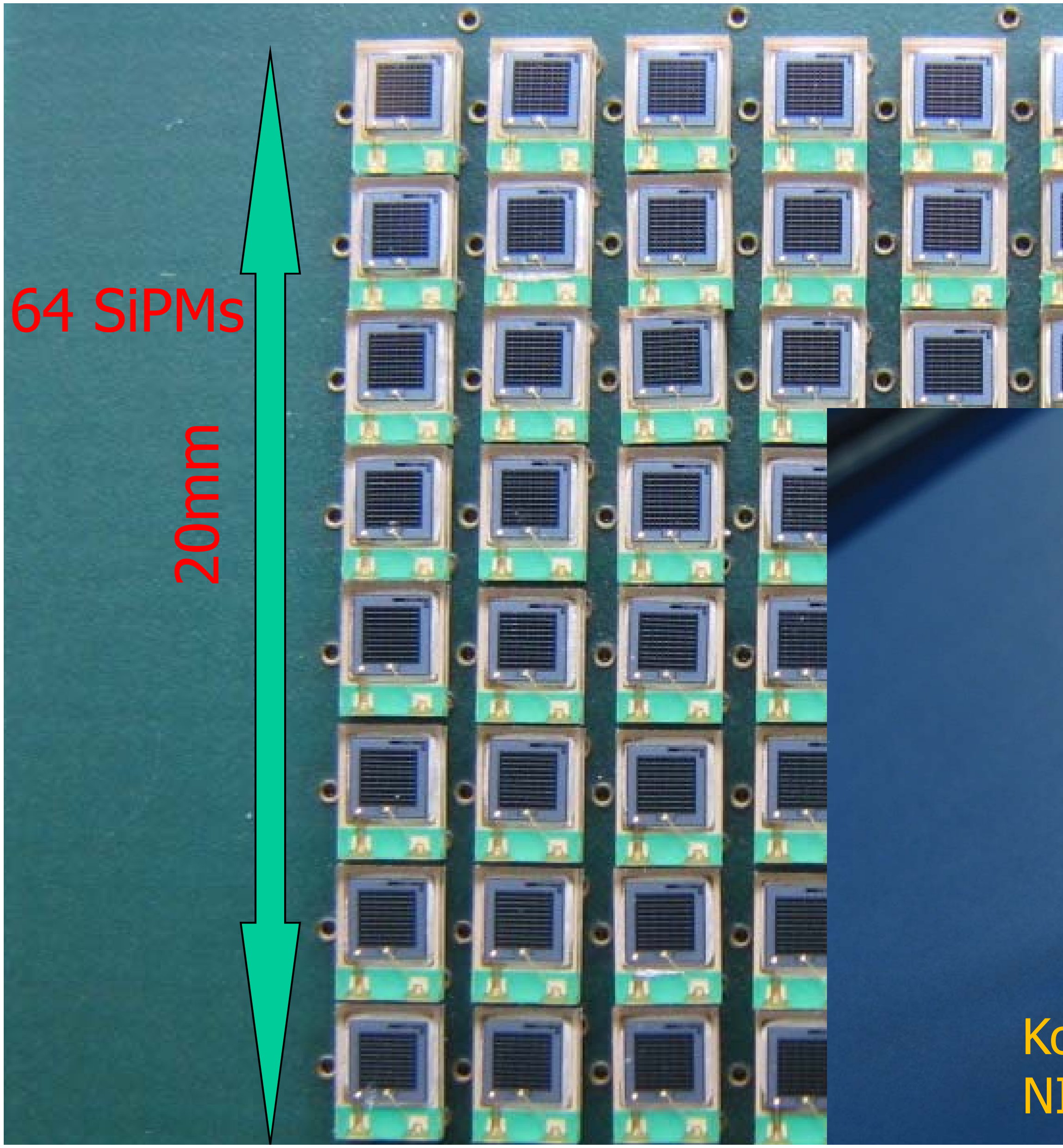
•Increase the number of signal hits per single sensor by using light collectors

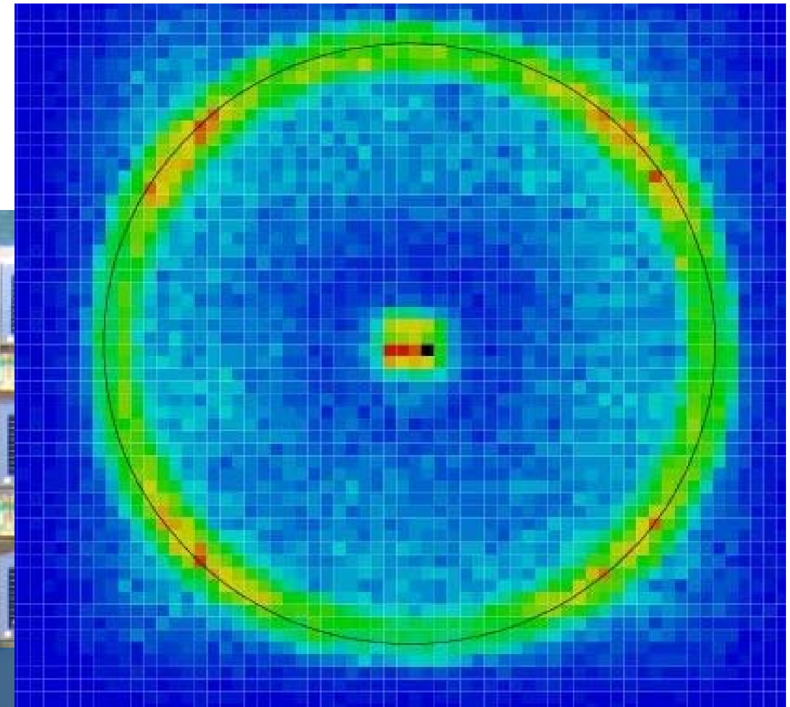
E.g. light collector with reflective walls or plastic light guide

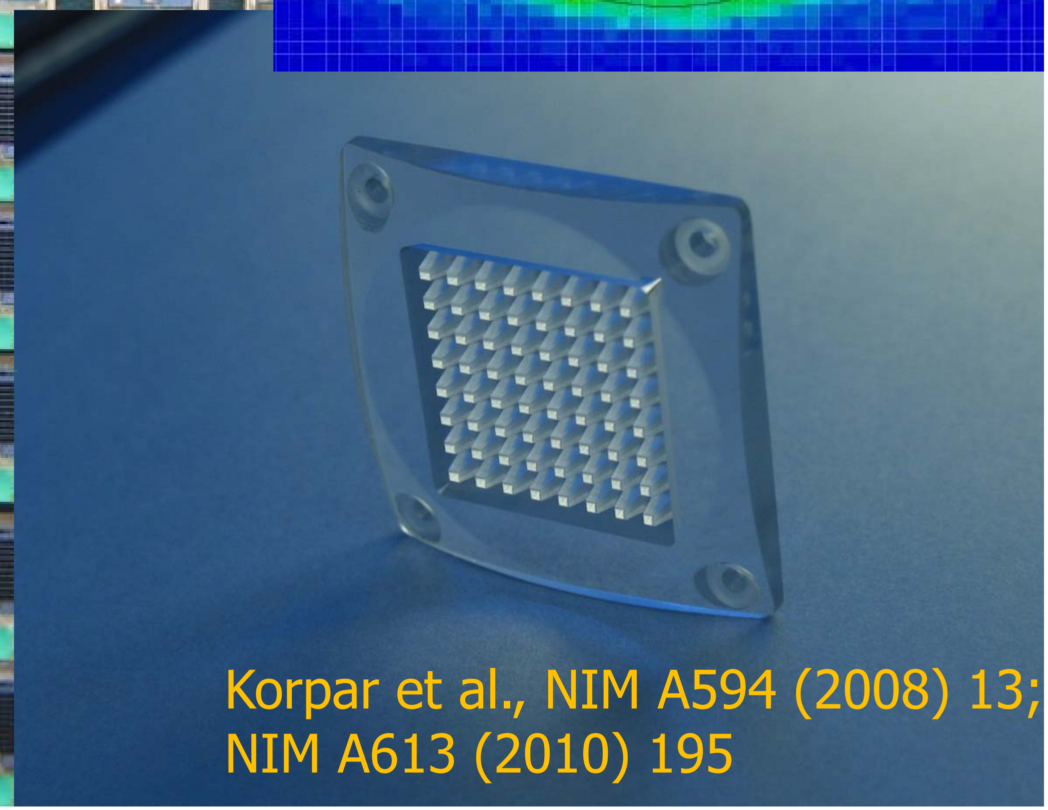




Photon detector with SiPMs and light guides





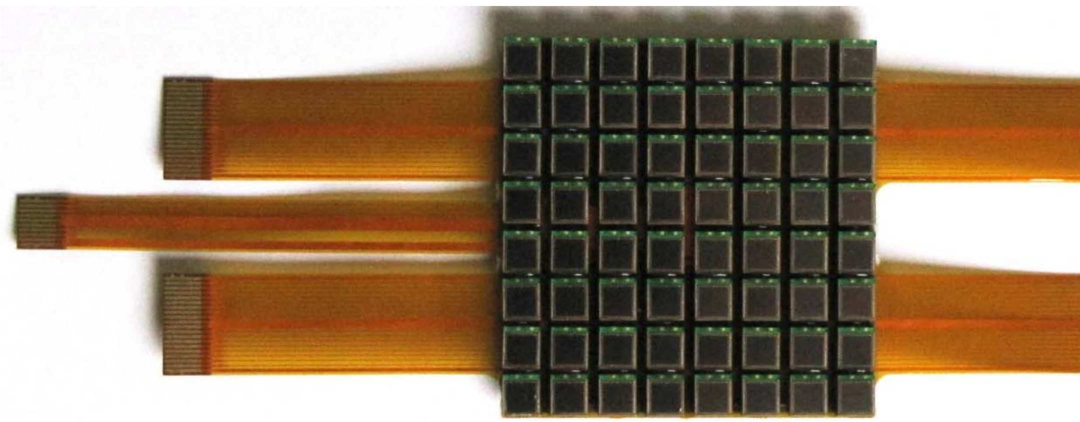


Korpar et al., NIM A594 (2008) 13;
NIM A613 (2010) 195

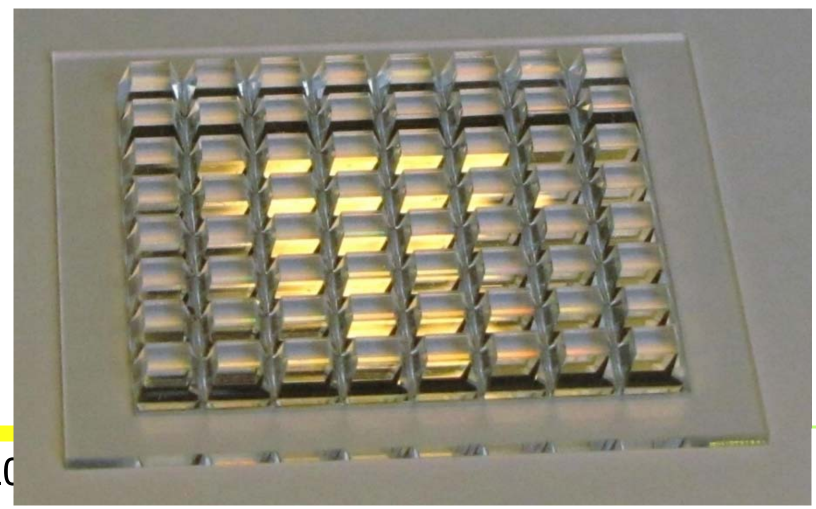
Next step: use arrays of SiPMs

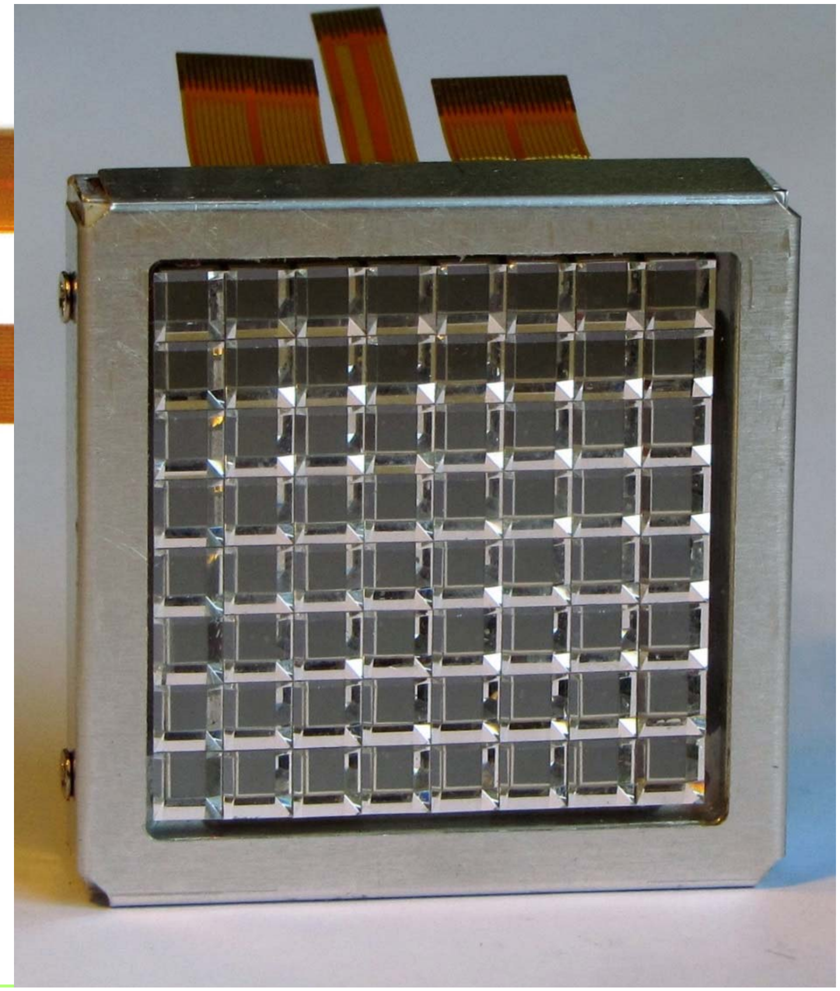
Example: Hamamatsu MPPC S11834-3388DF

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



+ array of quartz light collectors

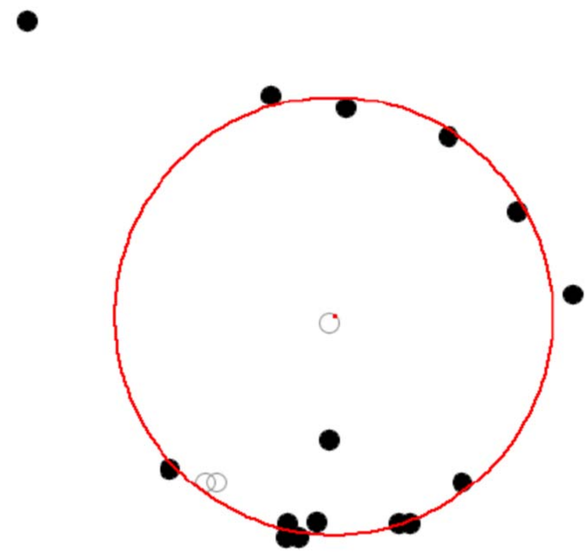




E. Tahirović et al., NIM A787 (2015) 203

Digital SiPM

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

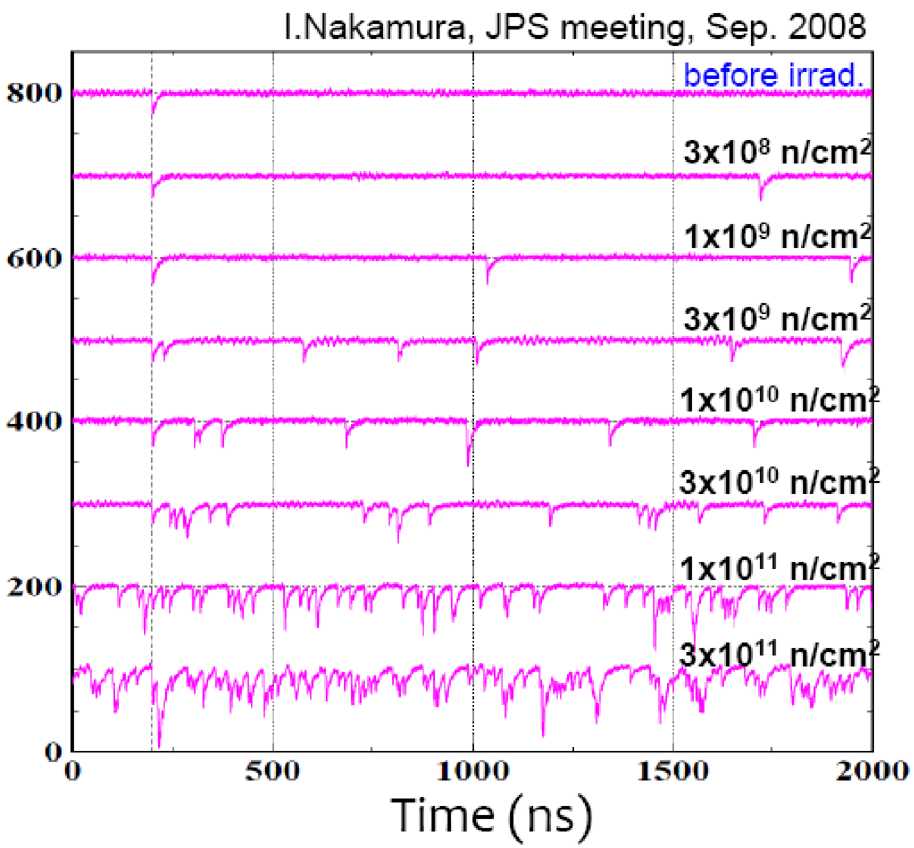


Square matrix 20x20 cm^2

- 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

→ A.Y. Barnyakov et al., NIM A732 (2013) 352

SiPMs: Radiation damage



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

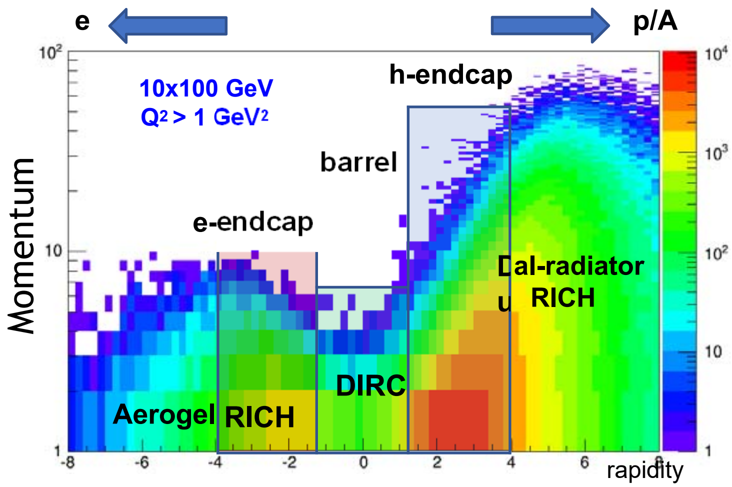
→ Worst than the lowest line

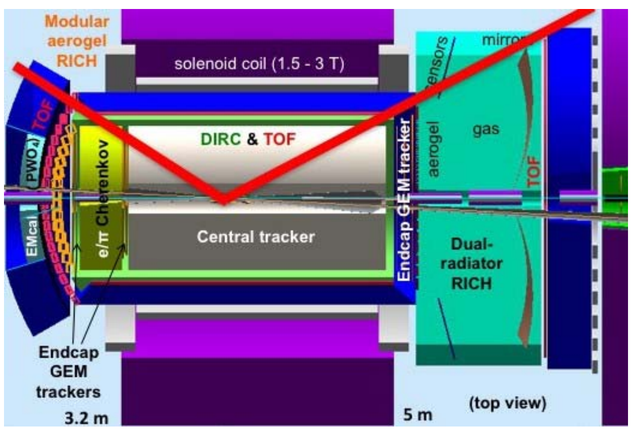
→Need cooling of sensors and wave-form sampling readout electronics

→Annealing?

… and more radiation resistant SiPMs…

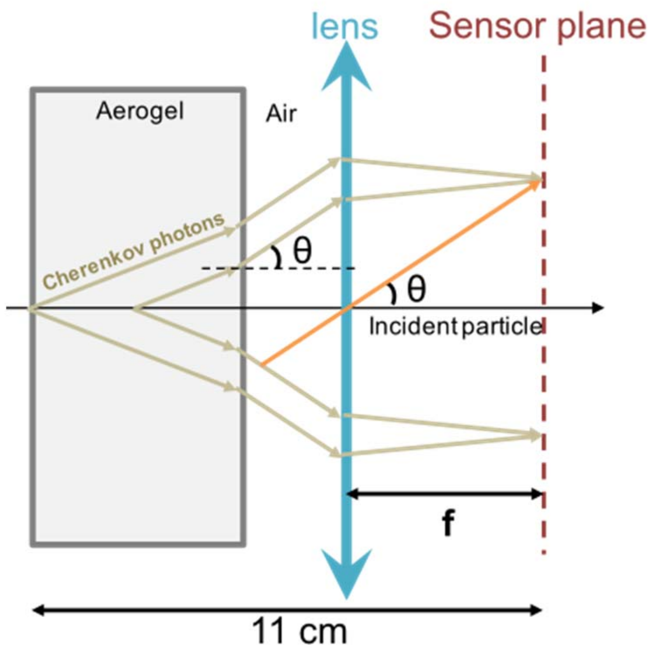
PID Strategies for the Electron Ion Collider

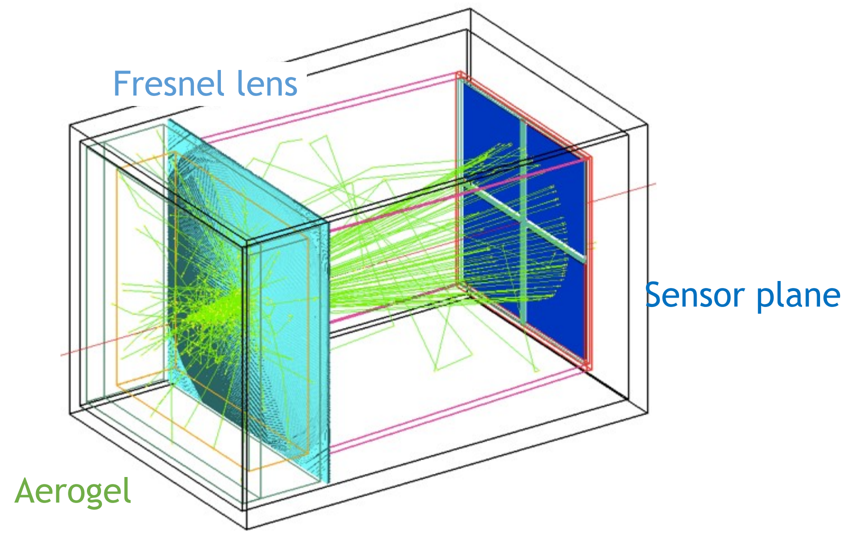




- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K separation up to ~50 GeV/c **dRICH**
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K separation up to ~10 GeV/c **mRICH**
- **barrel**: A high-performance DIRC provides a compact and cost-effective way 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

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

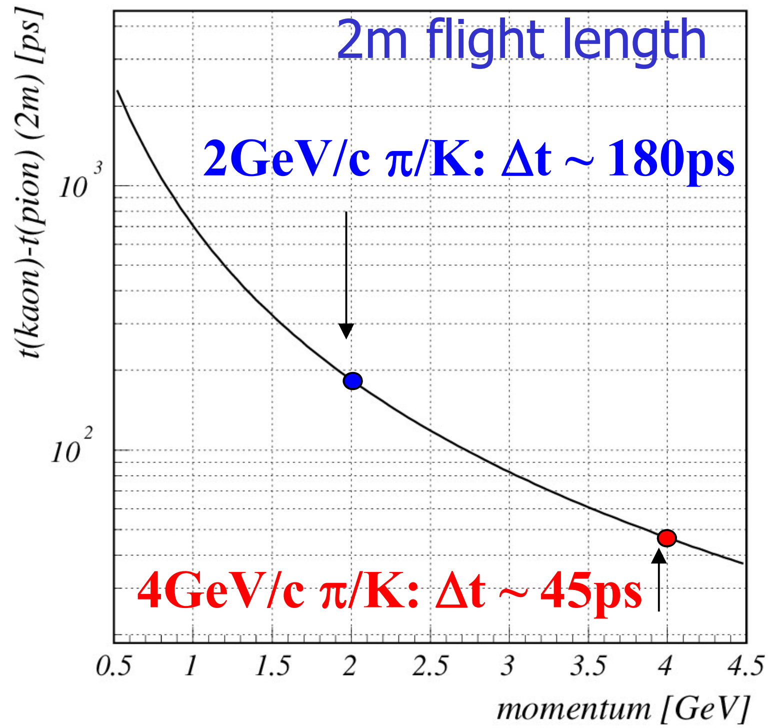
Time-of-Flight (TOF) counters

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

Traditionally: plastic scintillator + PMTs

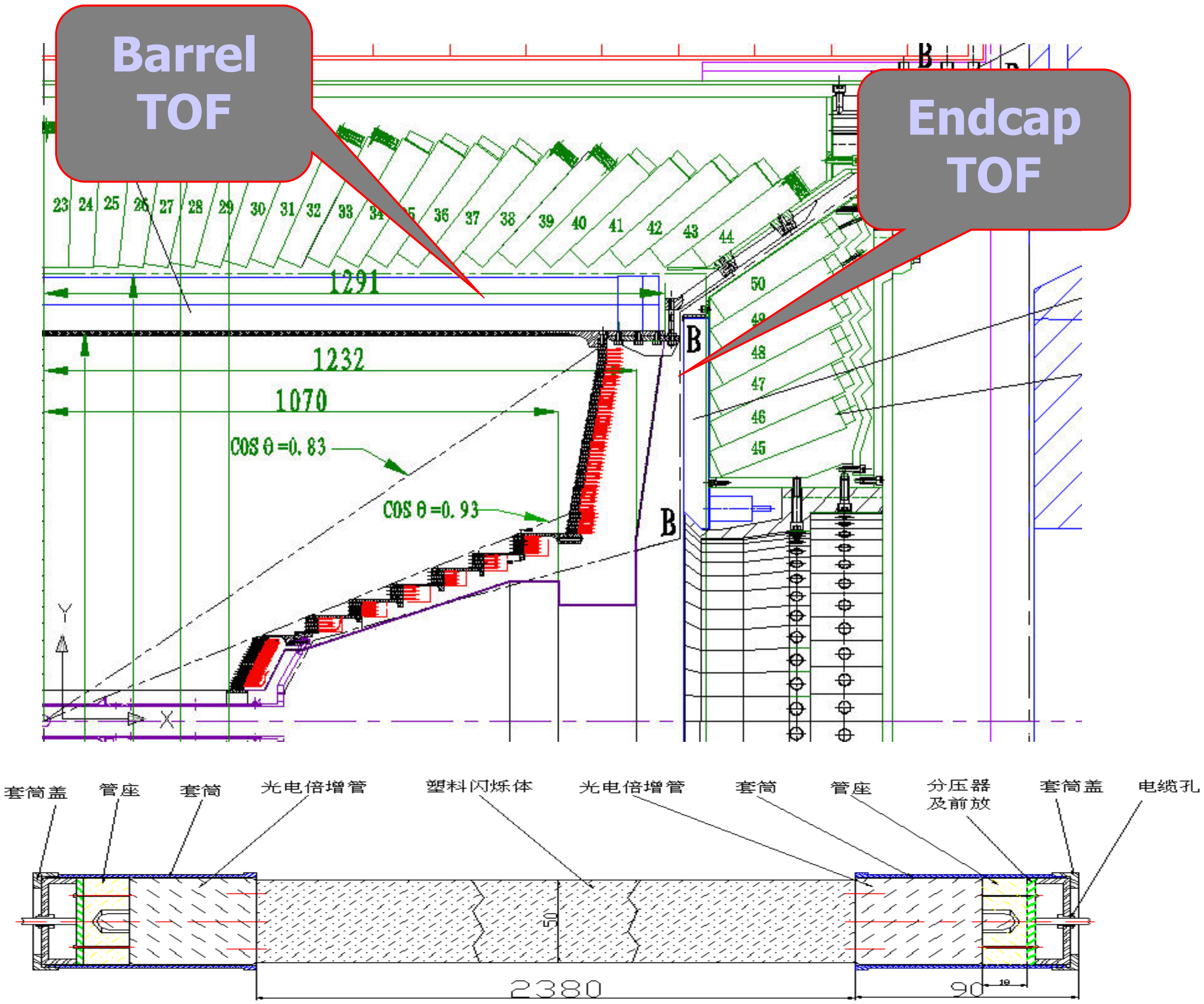
Typical resolution: ~100 ps →π/K separation up to ~1GeV.

Time difference between π and K:

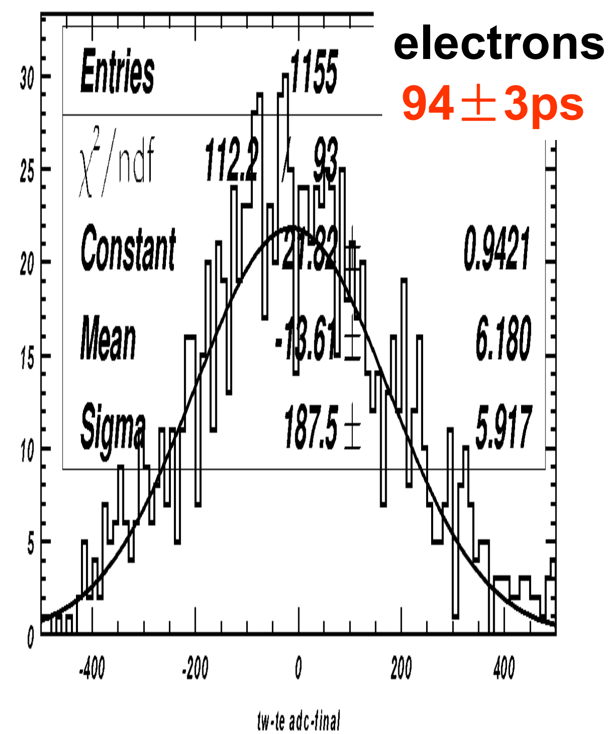


→ BESSIII

BESIII: Time-Of-Flight counters



Beam test results: two TOF modules



TOF module: high quality plastic scintillator: 2.4 m long, 5cm thick, two PMTs with preamplifiers

Time-of-Flight (TOF) counters

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

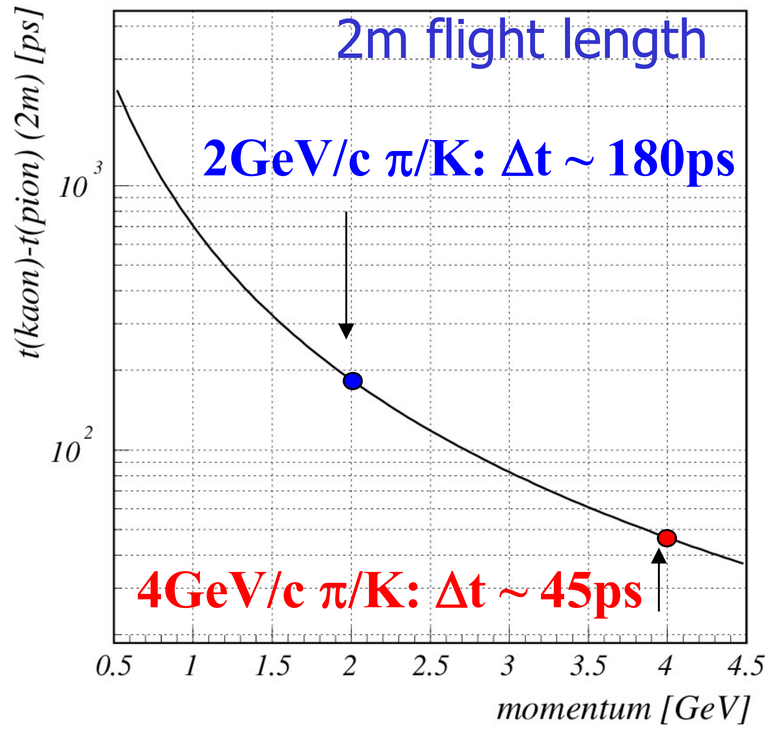
Traditionally: plastic scintillator + PMTs

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

To go beyond that: need faster detectors:
→use Cherenkov light (prompt) instead of scintillations
→use a fast gas detector (Multi gap RPC)

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

Time difference between π and K:



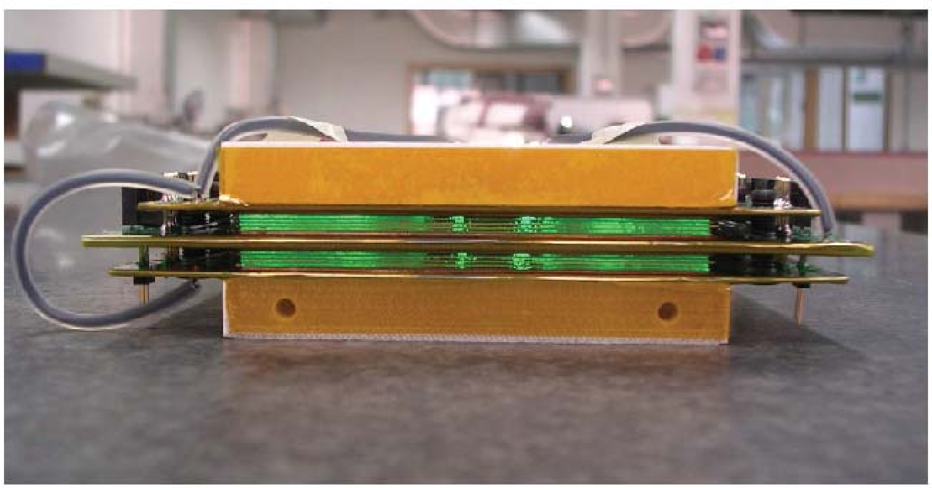
ALICE TOF

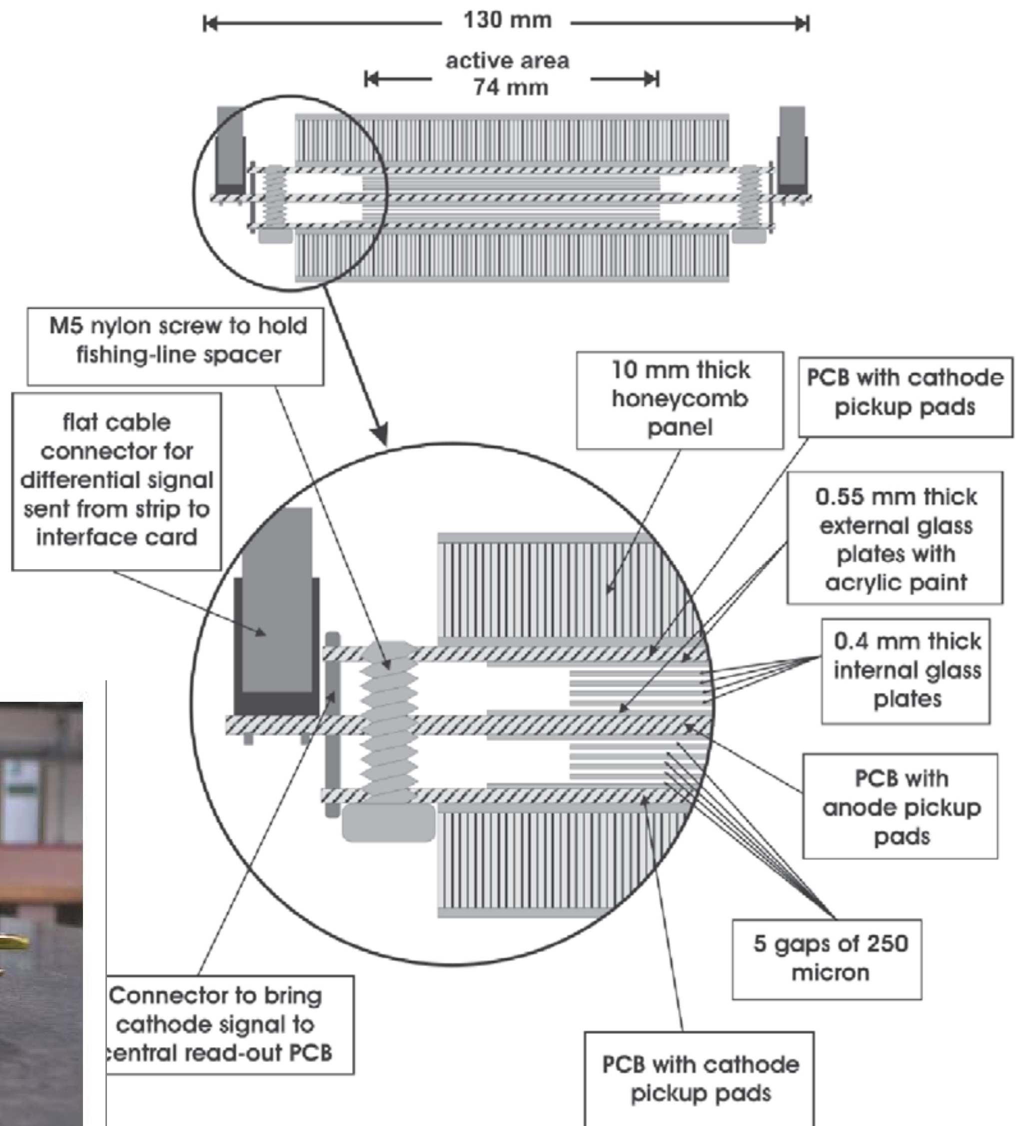
Very fast large area (140m^2) particle detector:

→ MRPC, multi-gap RPC

σ=50ps (incl. read-out)

π/K separation (3σ) up to 2.5 GeV/c at large track densities

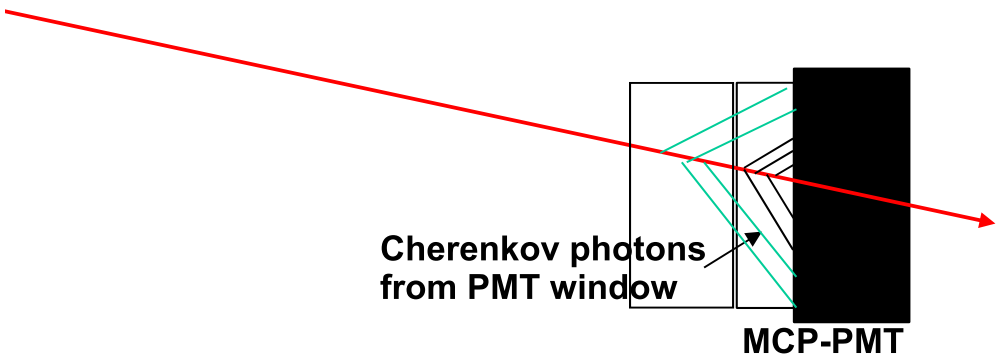


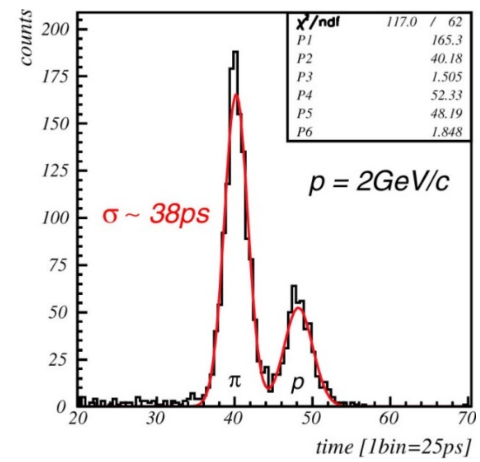


TOF with Cherenkov light

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.

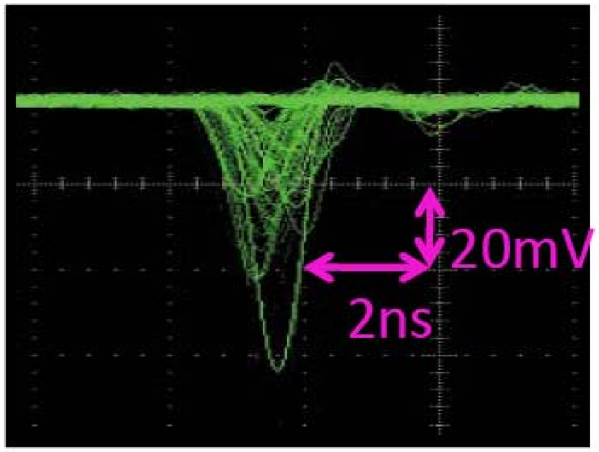
→resolution ~5ps measured

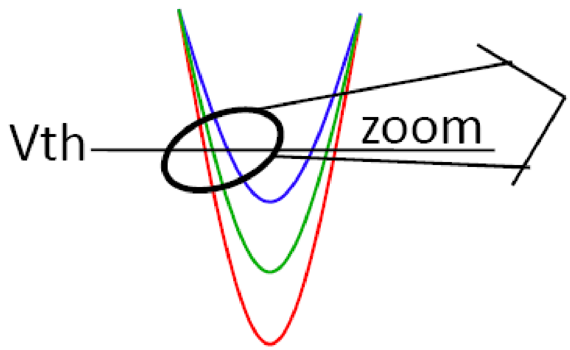
- K. Inami NIMA 560 (2006) 303
- J. Va'vra NIMA 595 (2008) 270

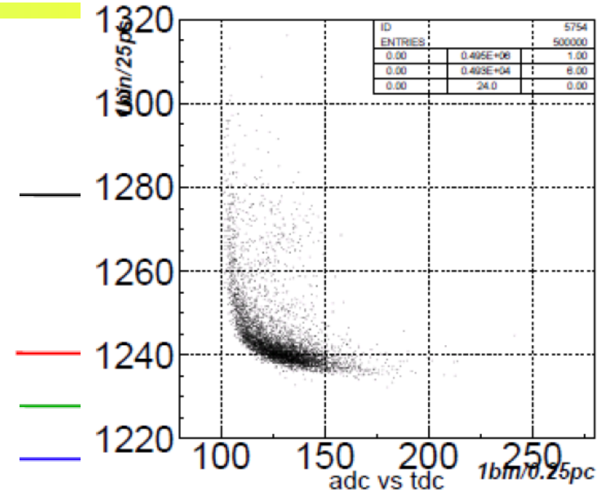
Open issues:

- read-out
- start time

Read out: for precise timing mitigate time walk

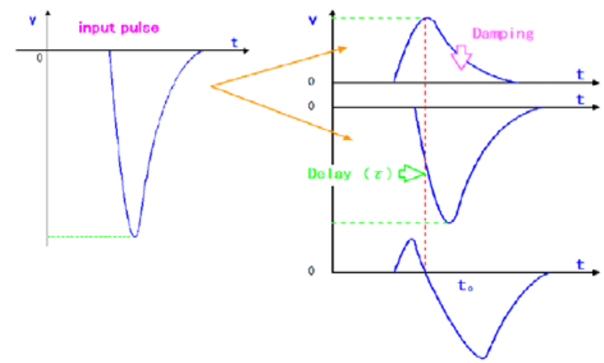


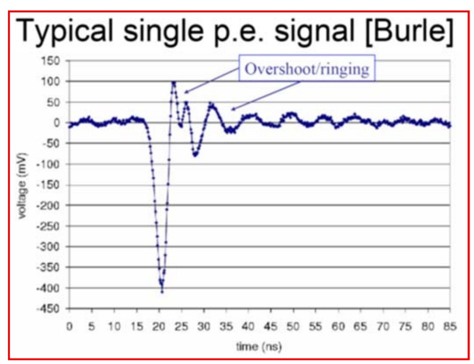




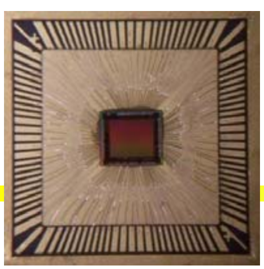
Variation of time determined with a leading edge discriminator: smaller pulses give a delayed signal.→ Has to be corrected!

- Measure both time (TDC) and amplitude (ADC), correct time of arrival by using a ΔT(ADC) correction
- Use constant fraction discriminator (CFD) →
- Wave-form sampling →





e.g. Labrador 3,
G. Varner, U Hawaii



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:

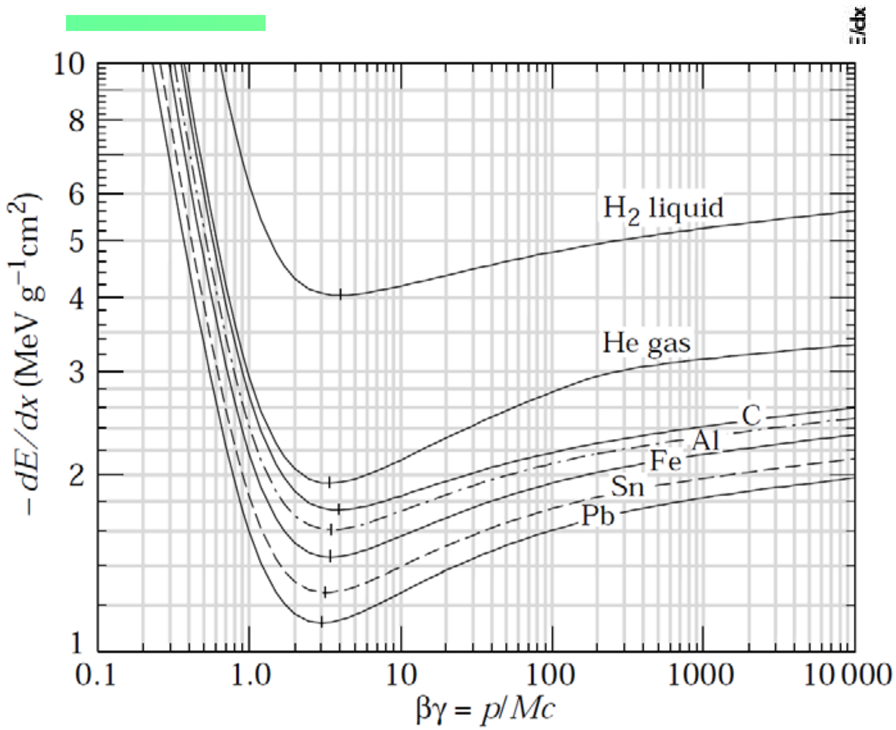
- time of flight
- ionisation losses dE/dx
- Cherenkov photon angle (and/or yield)
- transition radiation

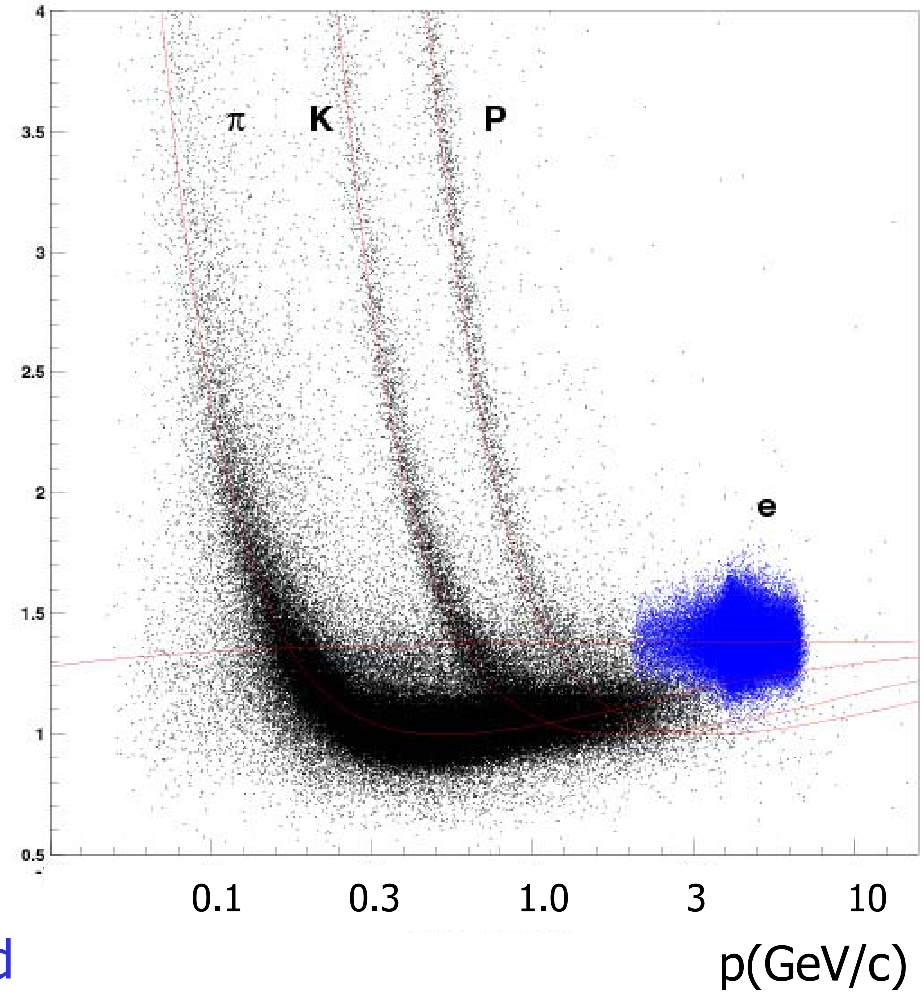
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters

Identification with the dE/dx measurement





dE/dx is a function of velocity β

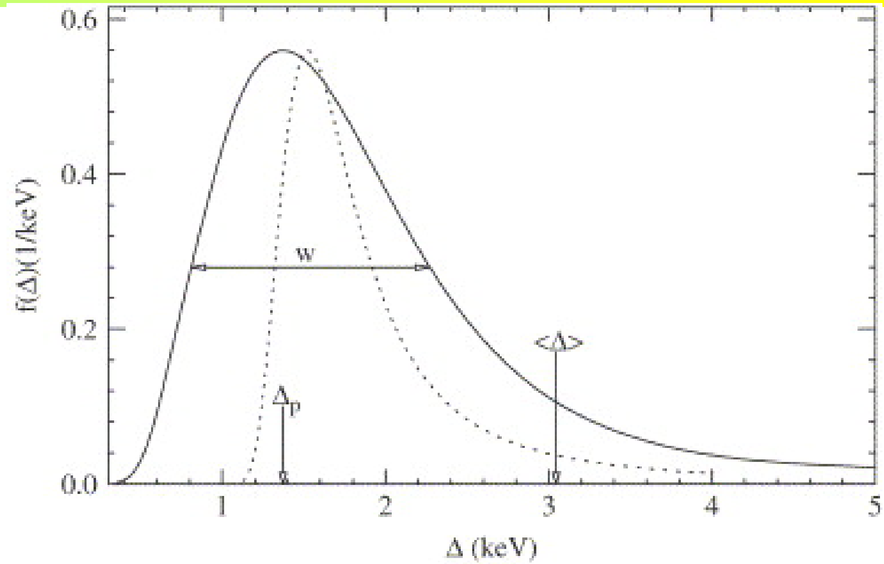
For particles with different mass the
Bethe-Bloch curve gets displaced
if plotted as a function of p

For good separation: resolution should be ~5%

Measure in each drift chamber layer – use truncated mean

Identification with dE/dx measurement

Problem: long tails (not Gaussian!)



Energy loss distribution for particles with $\beta\gamma=3.6$ traversing 1.2 cm of Ar gas (solid line).

Parameters describing ***f(Δ)*** are

$\Delta_p(x;\beta\gamma)$ **:** the most probable energy loss = the position of the maximum at 1371 eV, and

W : the full-width-at-half-maximum (FWHM) of 1463 eV. The mean energy loss is 3044 eV.

Dotted line: the original Landau function.

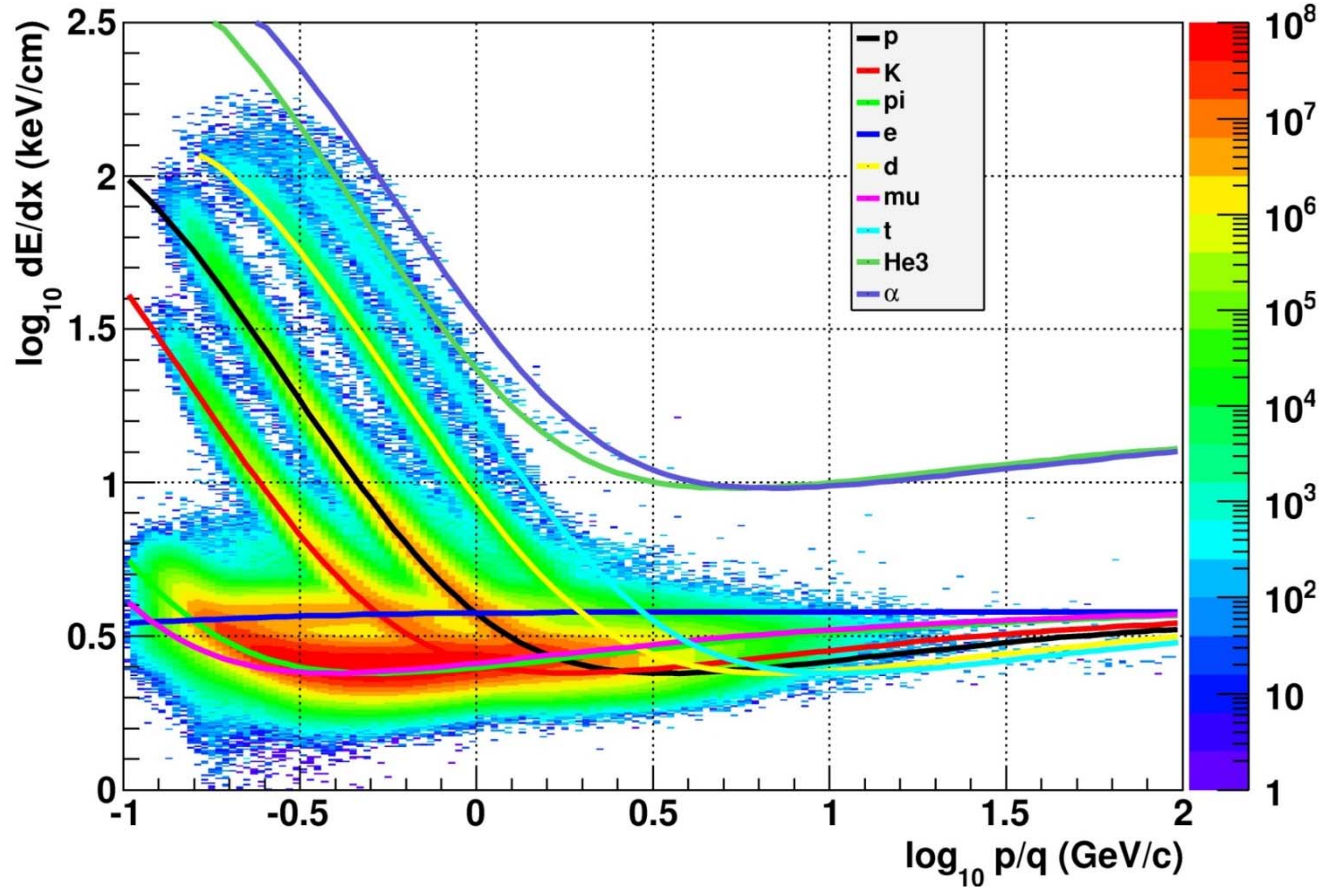
→Many samples along the track (~100 in ALICE TPC), remove the largest ~40% values (reduce the influence of the ling tail) → truncated mean

→ Hans Bichsel: A method to improve tracking and particle identification in TPCs and silicon detectors, NIM A562 (2006) 154

Identification with dE/dx measurement

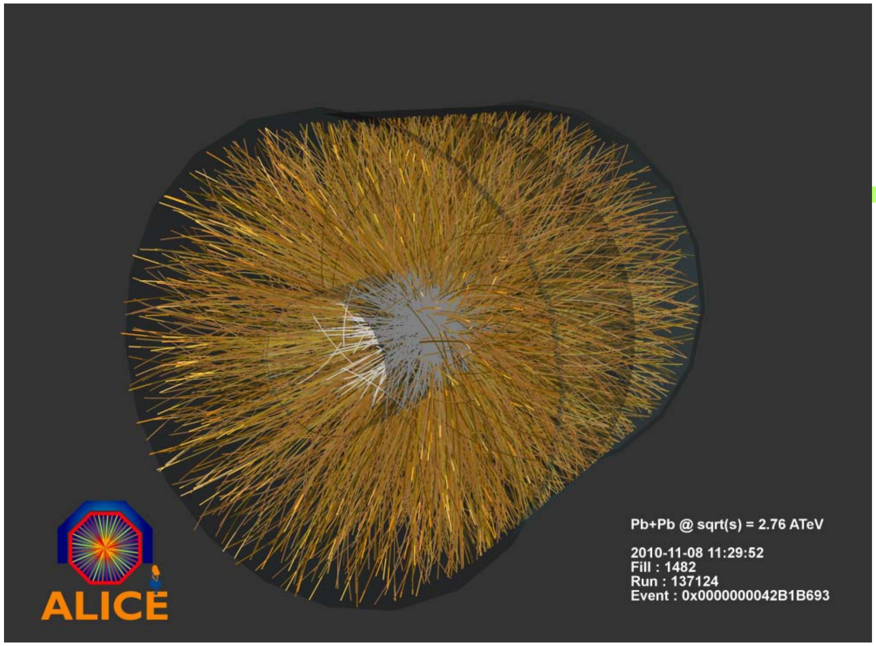
dE/dx performance in the STAR TPC

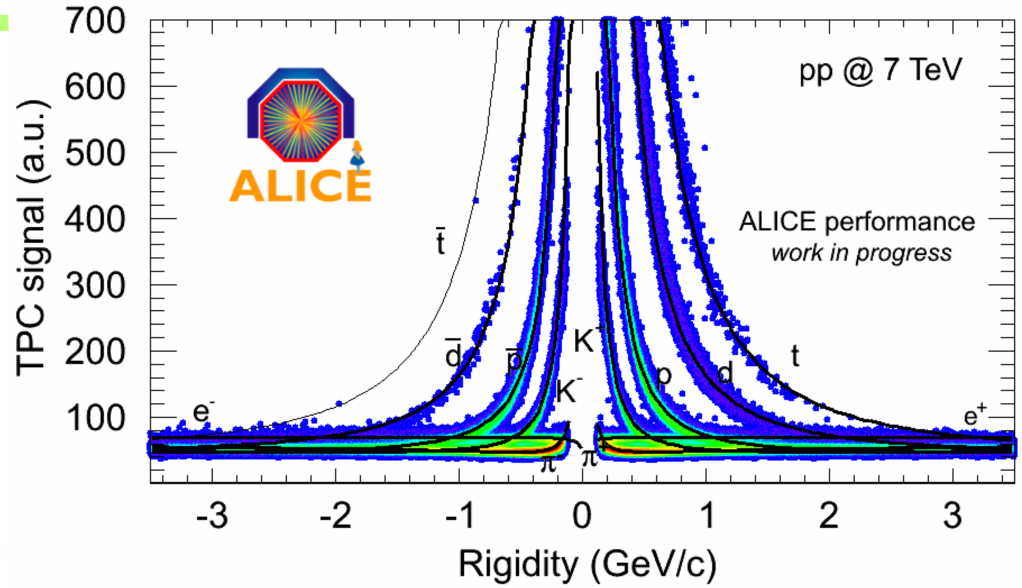
gold-gold
collisions

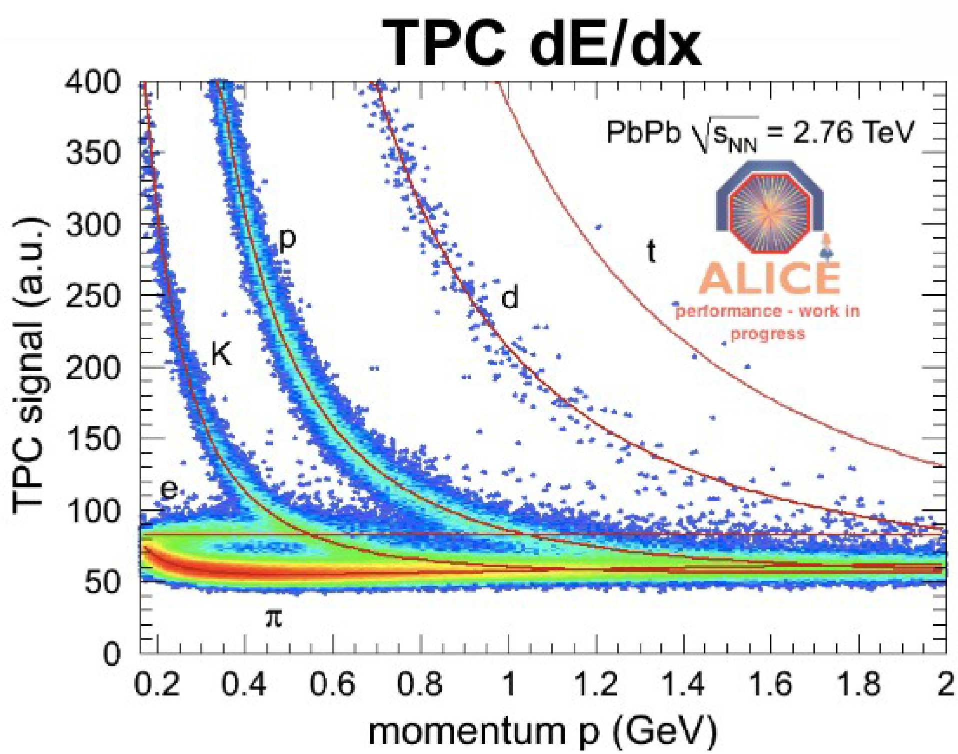


Energy loss in the STAR TPC: truncated mean as a function of momentum. The curves are Bichsel model predictions.

dE/dx in ALICE

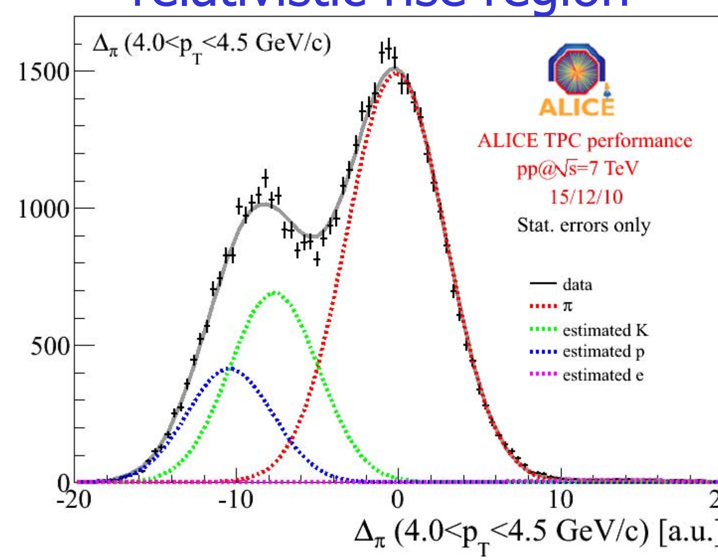






Y

relativistic rise region



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Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

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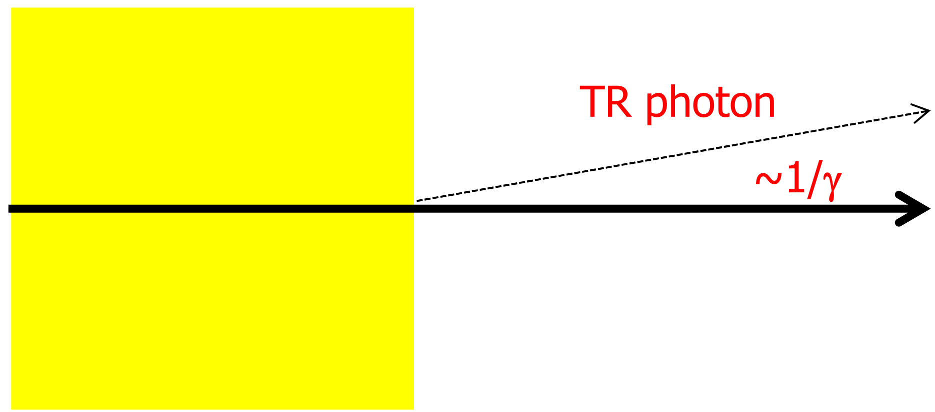
- calorimeters

Transition radiation

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

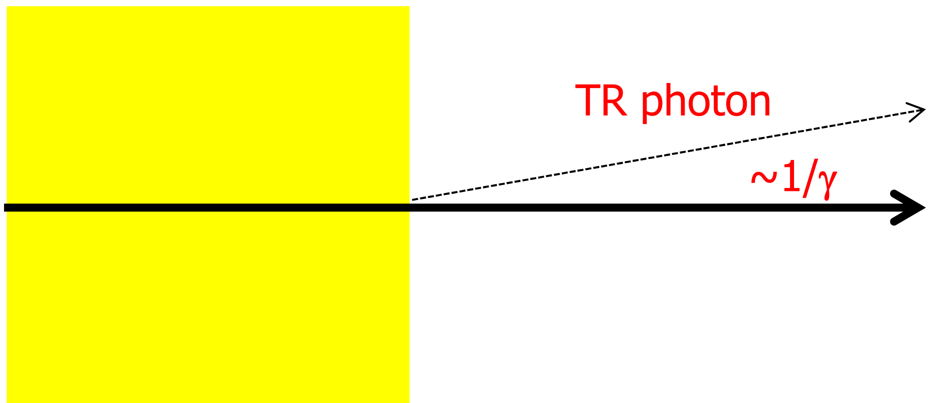


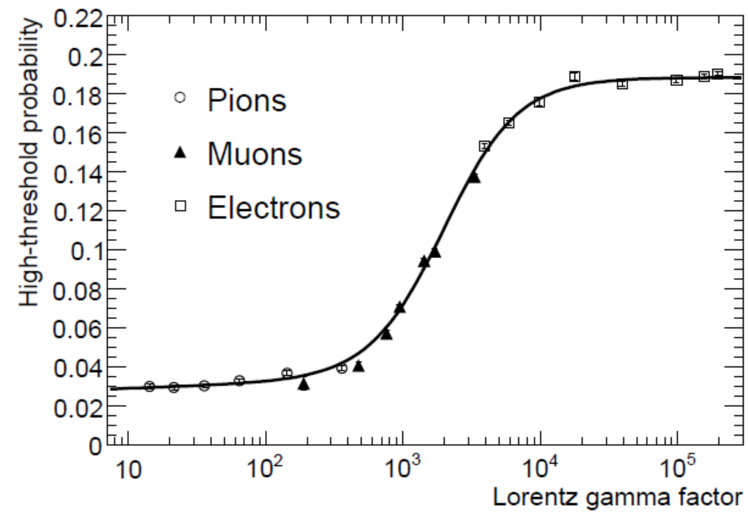
- Accelerated particle emits E.M. radiation
- Transition radiation: particle has a constant velocity, but the phase velocity of the medium changes abruptly at the boundary → radiation

→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





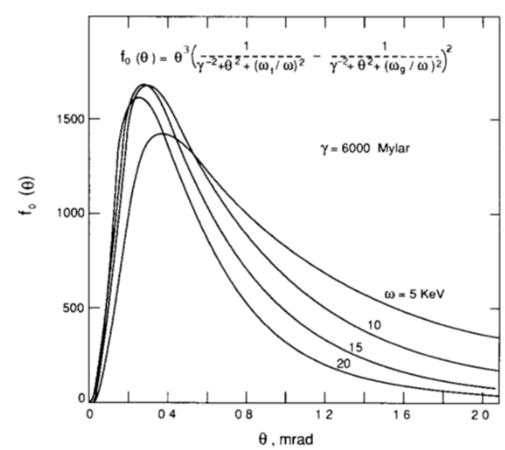
Emission rate depends on γ (Lorentz factor): becomes important at γ~1000

- 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

(=large cross section for photoeffect of X rays)

Emission angle $\sim 1/\gamma$

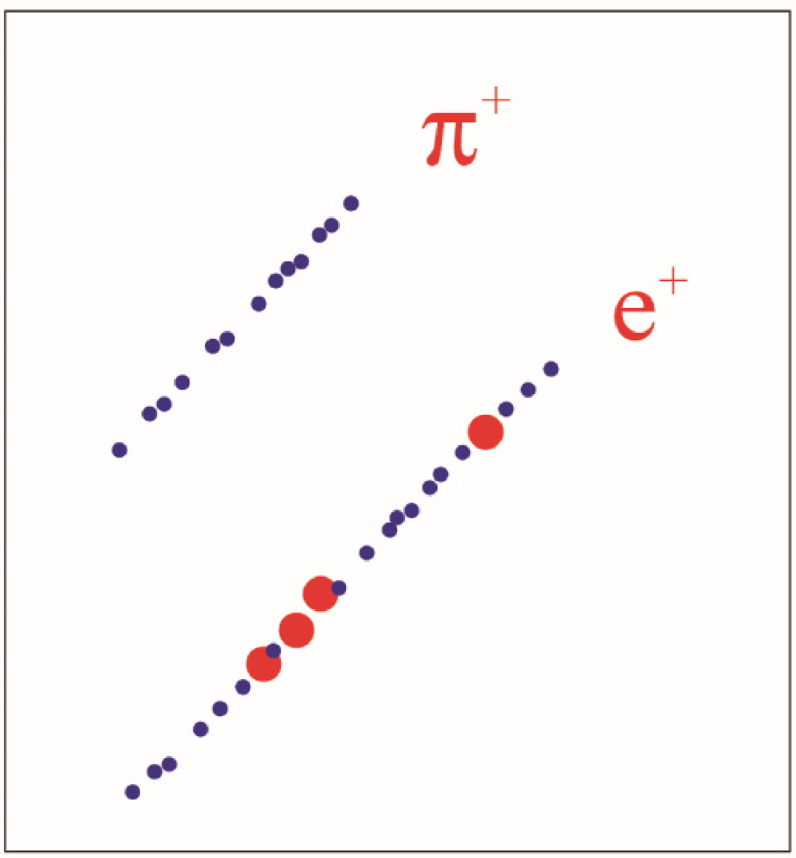
→ Hits from TR photons along the charged particle direction

- 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 to remove noise, higher to separate X ray conversions from ionisation by charged particles



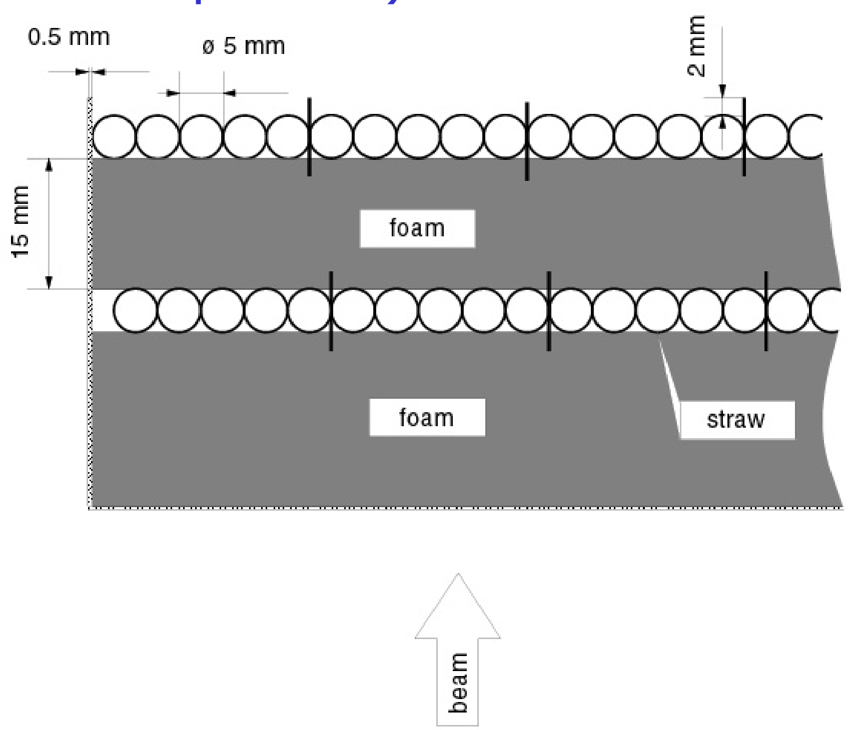
- Small circles: between low and high threshold (ionisation)
- Big circles: high threshold (X ray detection)

(pion below the TR threshold, e above the TR threshold)

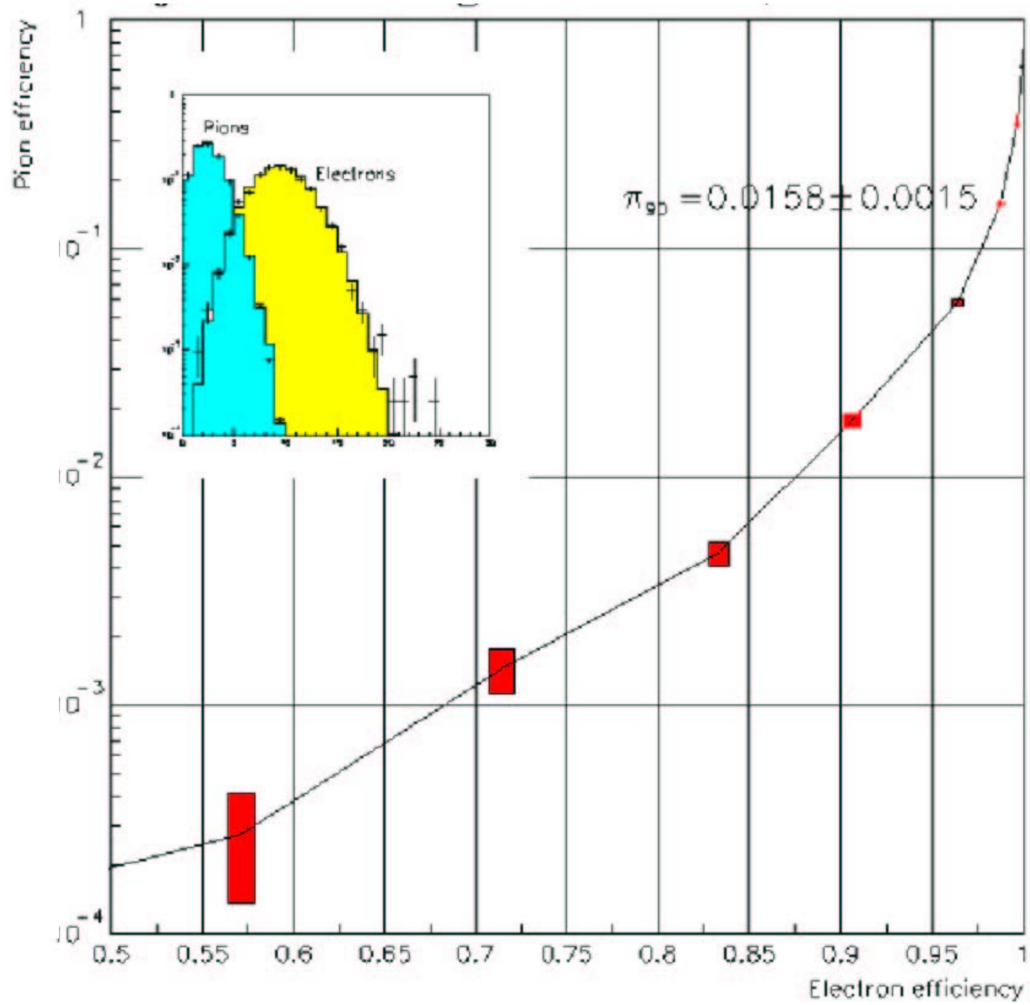
Transition radiation detectors

Example:

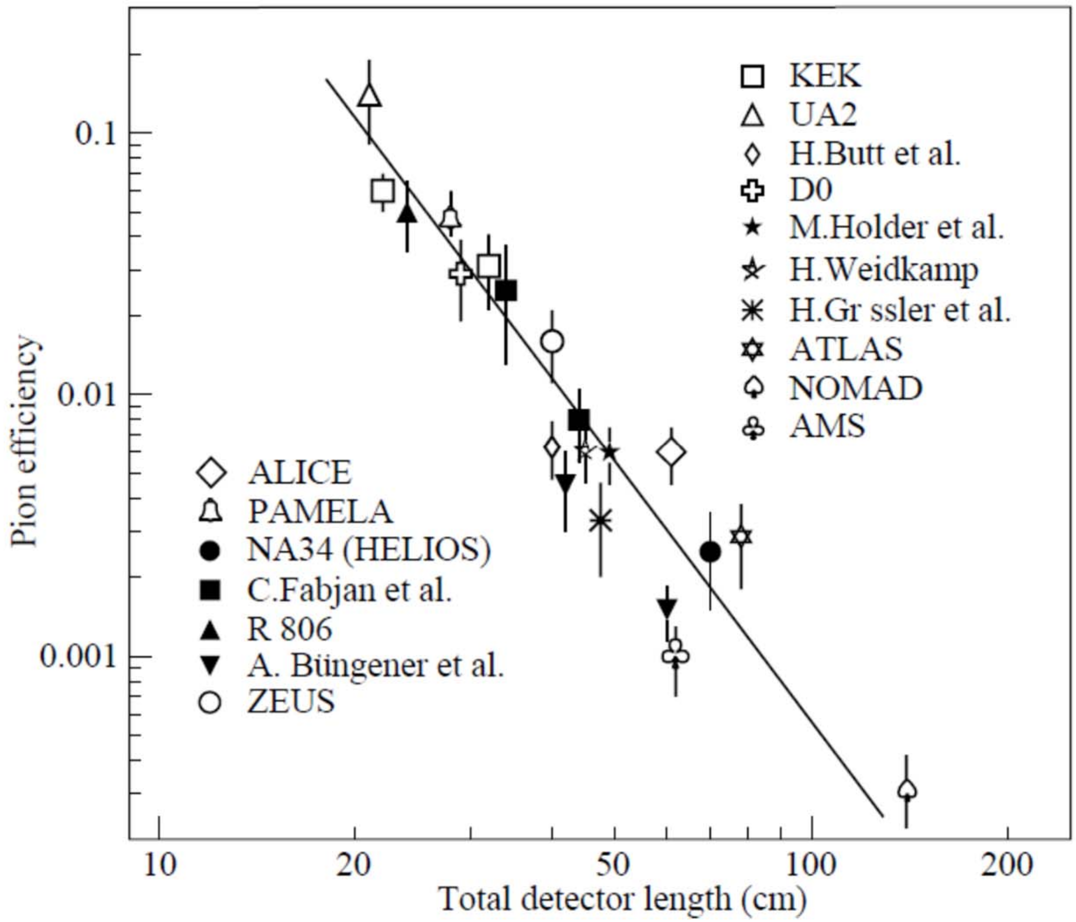
Radiator: organic foam between the detector tubes (straws made of capton foil)



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

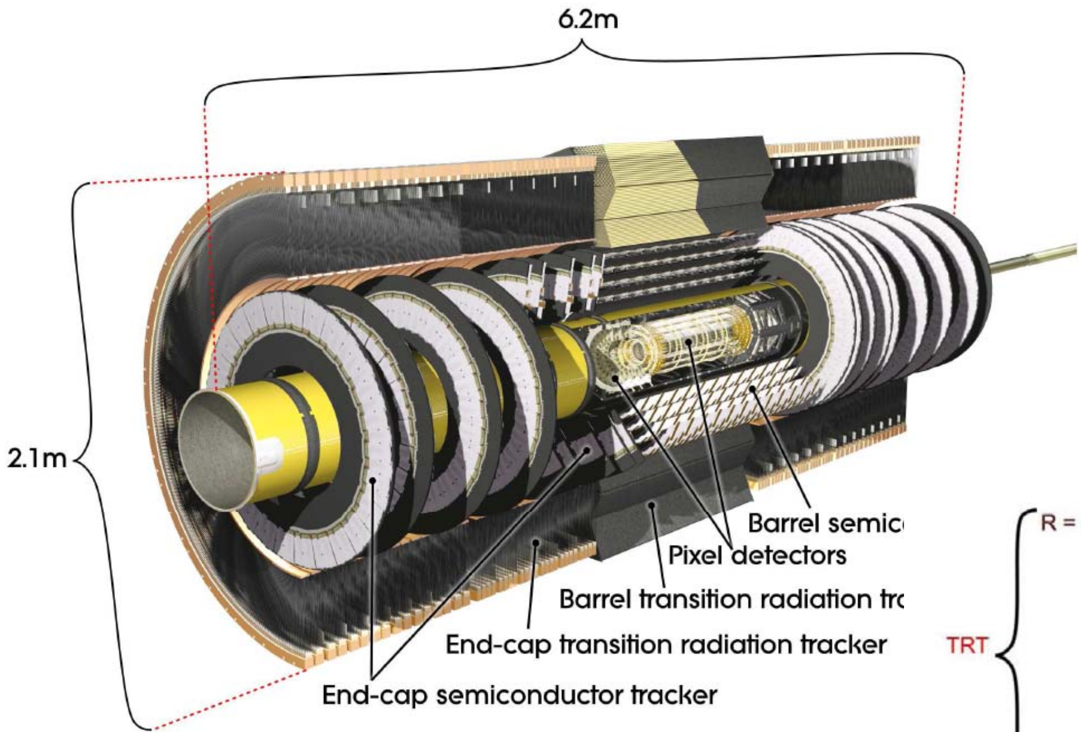


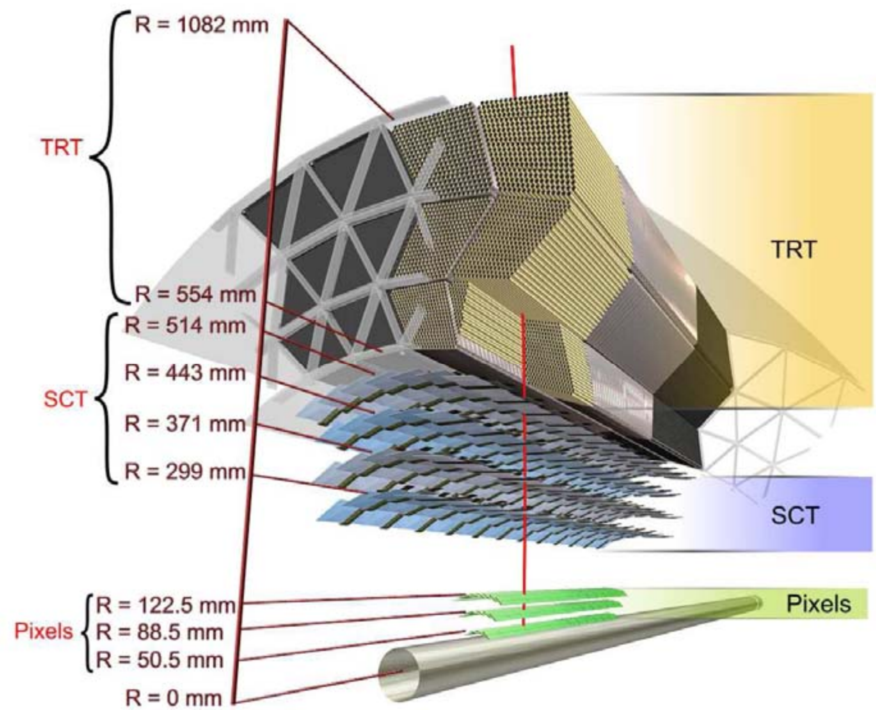
Transition radiation detectors - peformance



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

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



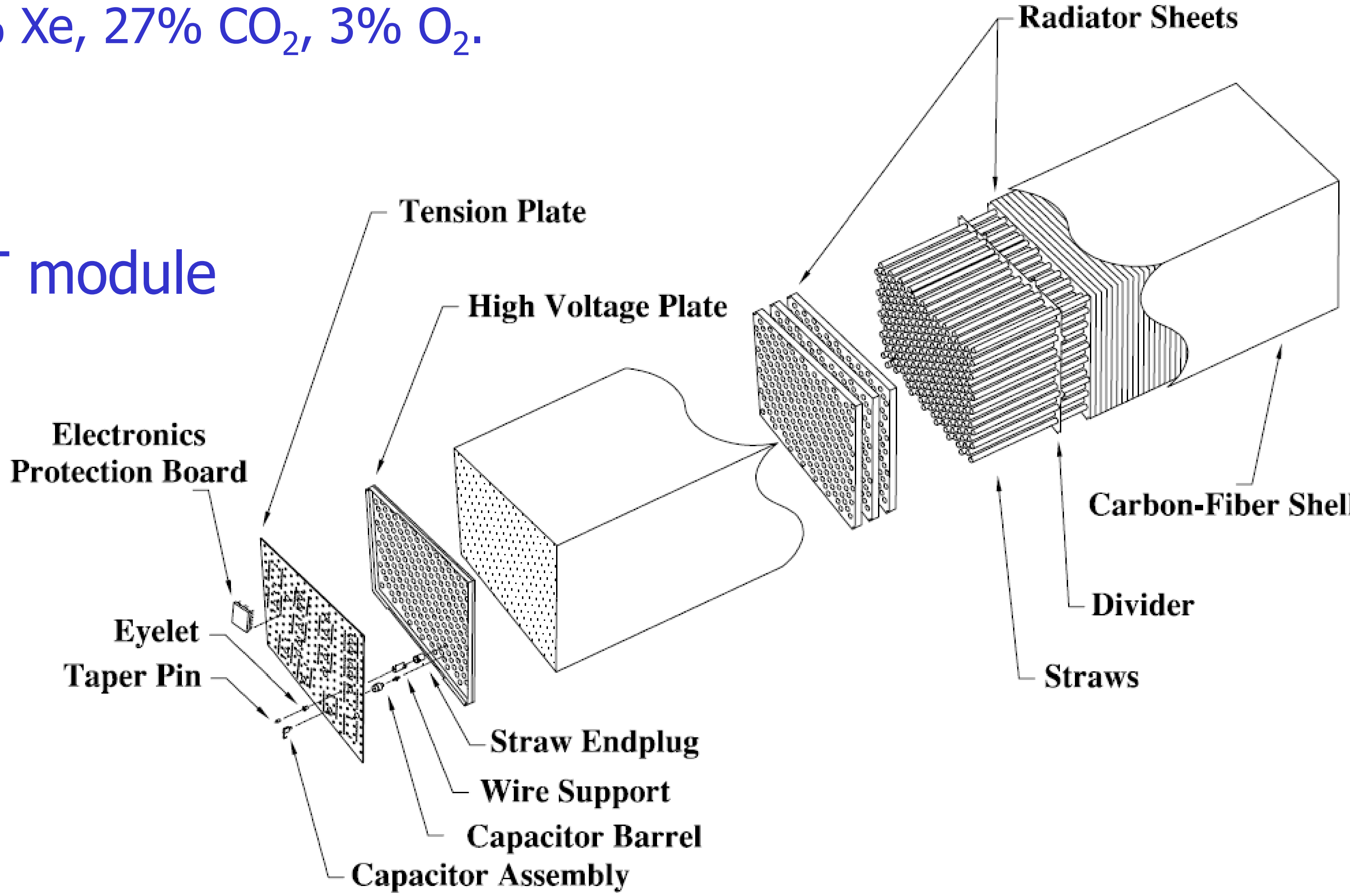


ATLAS TRT

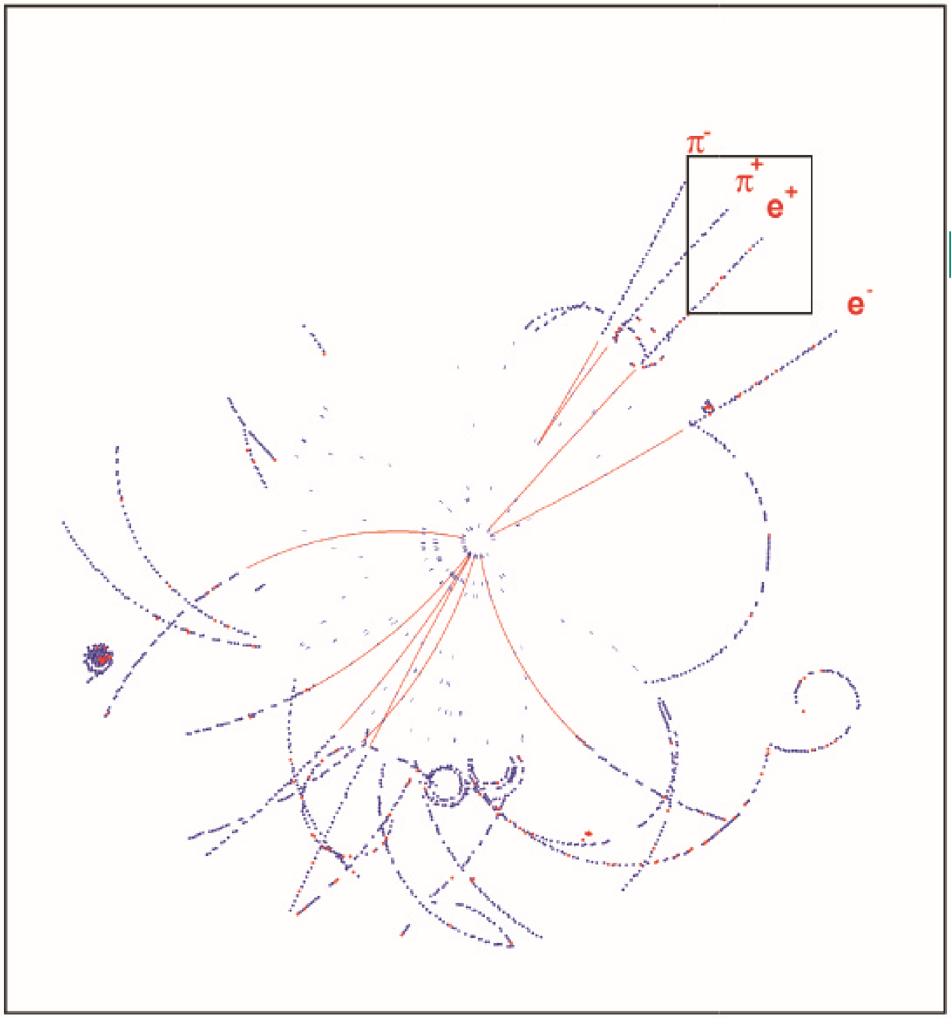
Radiator: 3mm thick layers made of polypropylene-polyethylene fibers with ~19 micron diameter, density: 0.06 g/cm^3

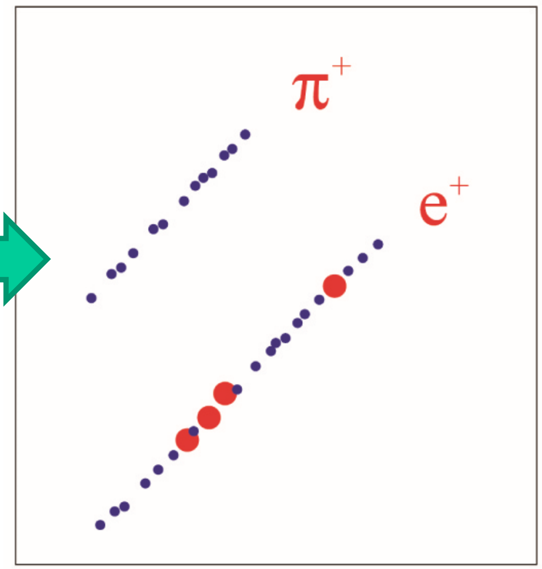
Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO_2, 3% O_2.

TRT module

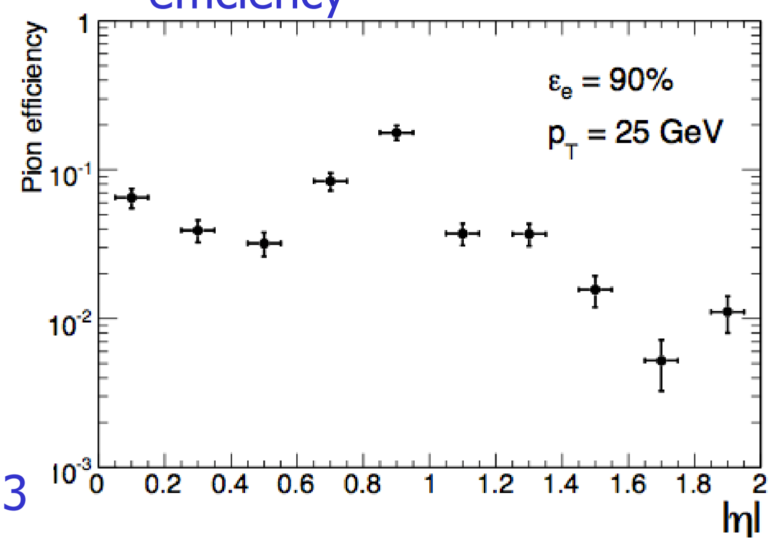


TRT: pion-electron separation





π fake probability at 90% e efficiency



→ JINST 3 (2008) S08003

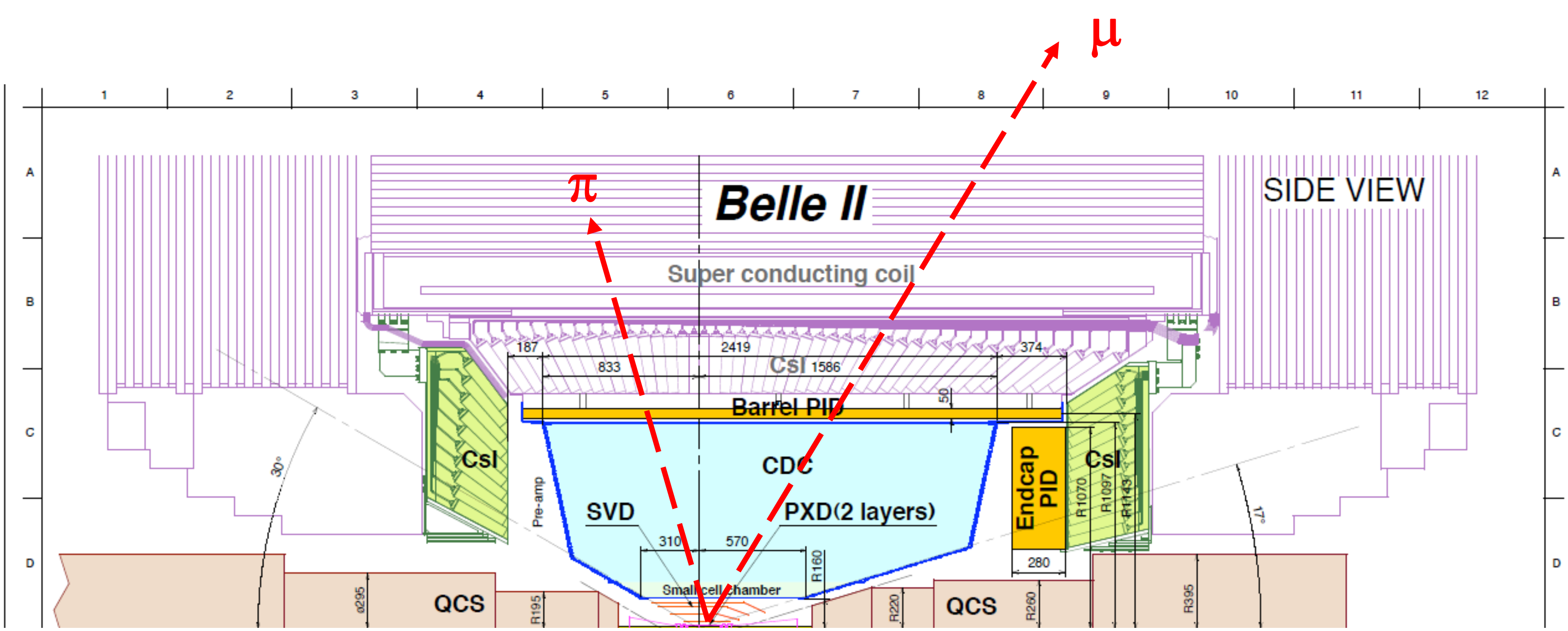
Identification of muons

Separate muons from hadrons (pions and kaons):

Exploit the fact that muons interact only electromag., while hadrons interact strongly

→ need a few interaction lengths to stop hadrons (interaction lengths = about 10x radiation length in iron, 20x in CsI).

→ **A particle is identified as a muon if it penetrates the material.**



Example: muon detection at B factories

Separate muons from hadrons (pions and kaons):

Need a few interaction lengths to stop hadrons (interaction length = about 10x radiation length in iron, 20x in CsI).

Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

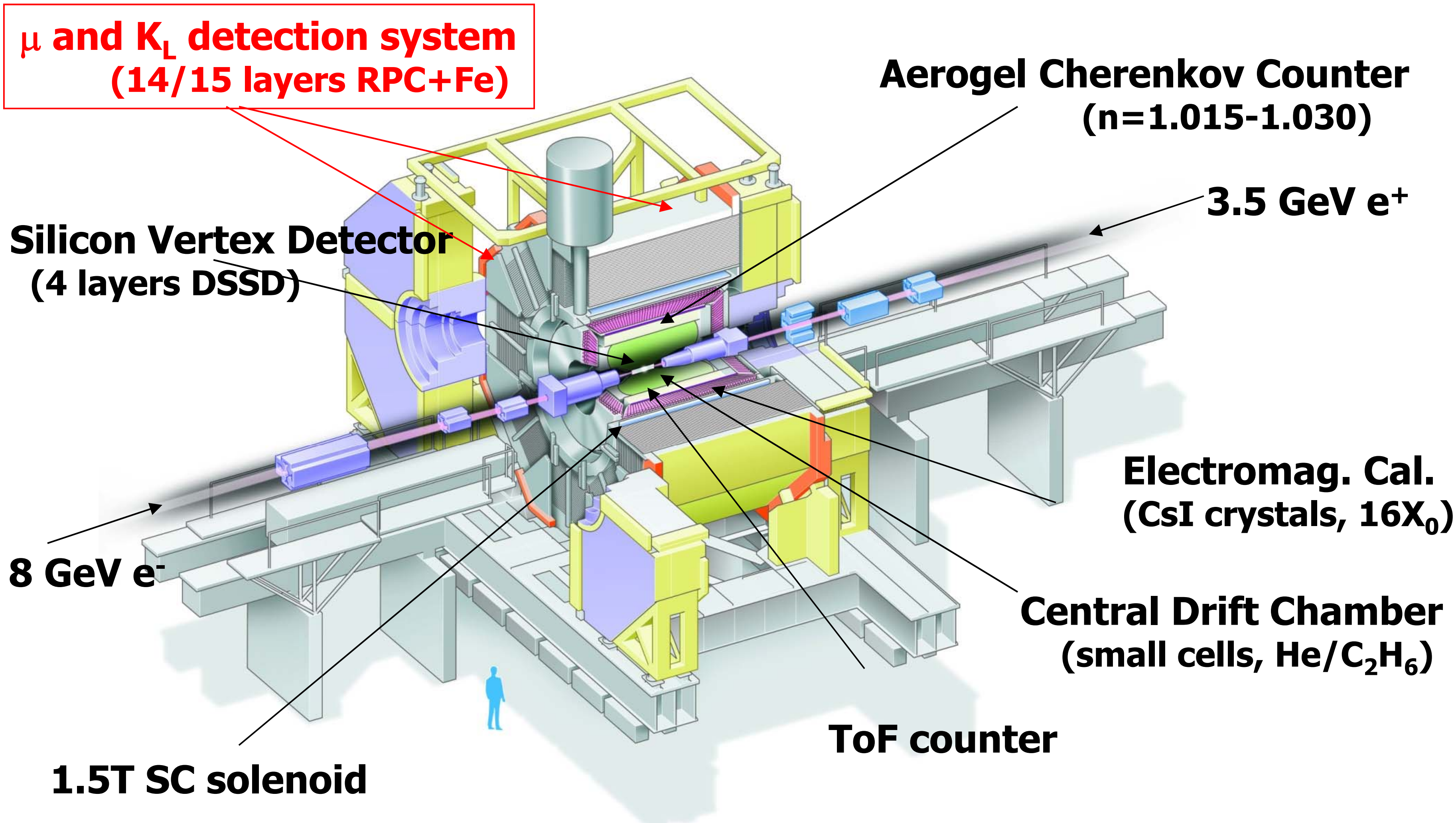
Interaction length: CsI 167 g/cm^2, iron 132 g/cm^2,

$(dE/dx)_{min}$: CsI 1.24 MeV/(g/cm^2), iron 1.45 MeV/(g/cm^2)

→ ΔE_{min} = (0.15+0.75) GeV = 0.90 GeV → reliable identification of muons possible around ~1 GeV

Detect K_L interaction (cluster): again need a few interaction lengths – the same system can be used for both – bonus!

Example: Muon and K_L detection at Belle



Muon and K_L detector

Up to 21 layers of resistive-plate chambers (RPCs) between iron plates of the flux return

Bakelite RPCs at BABAR

Glass RPCs at Belle

(glass was better choice because of ageing effects)

Scintillator strips + RPCs at Belle II

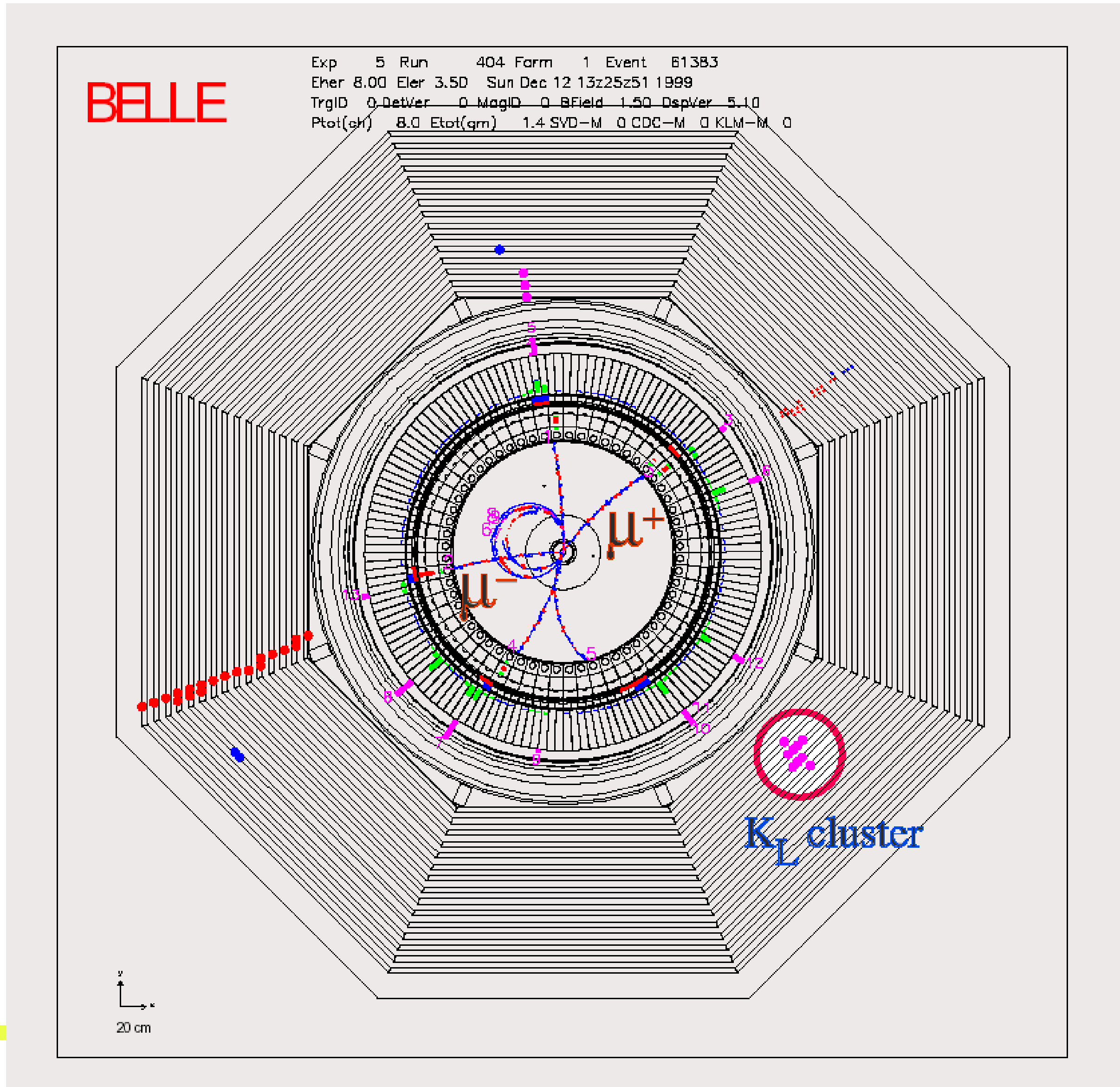
Muon and K_L detector

Example:

event with

- two muons and a
- K_L

and a pion that only partly penetrated



Muon identification performance

Muon identification: efficient for p>800 MeV/c

efficiency

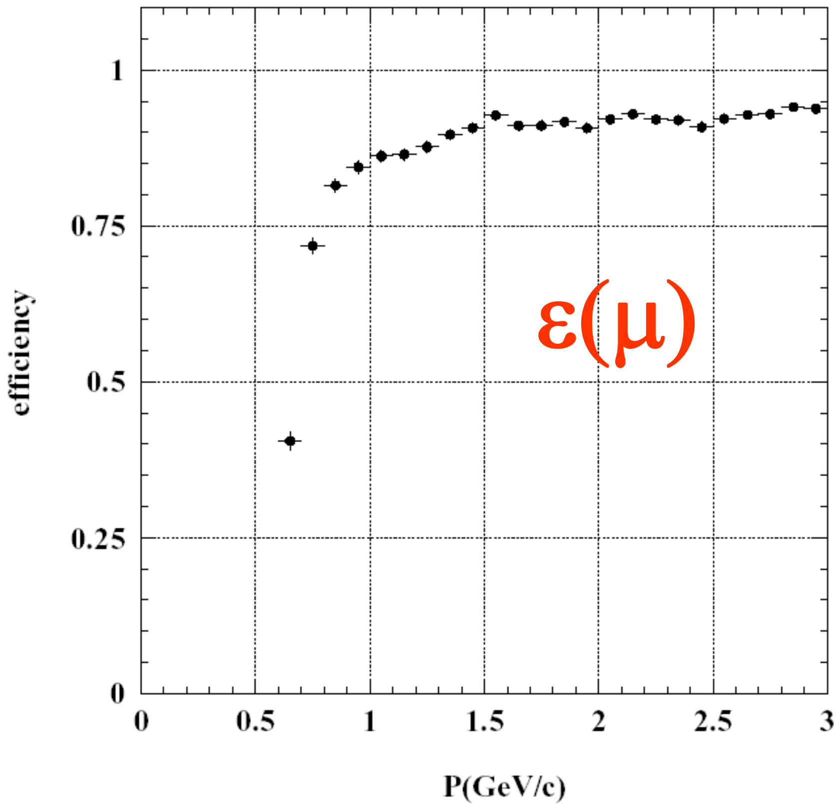


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

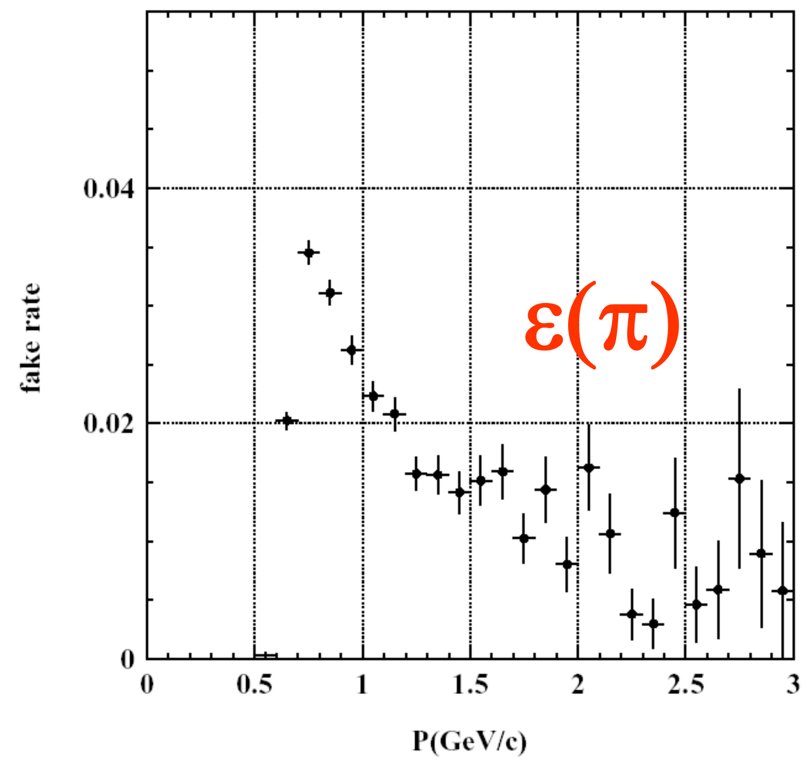
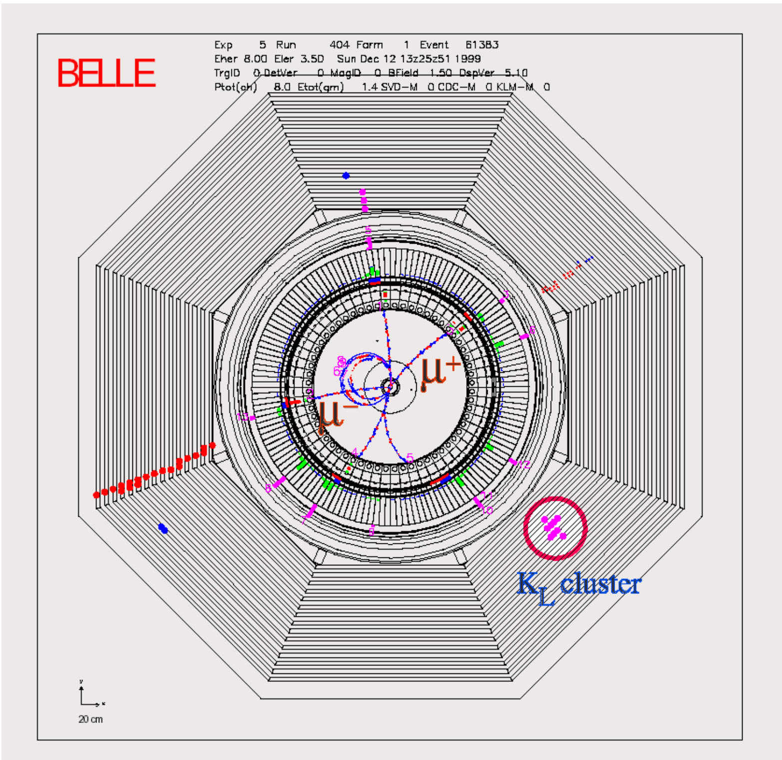


Fig. 110. Fake rate vs. momentum in KLM.

K_L detection performance



K_L detection: resolution in K_L direction

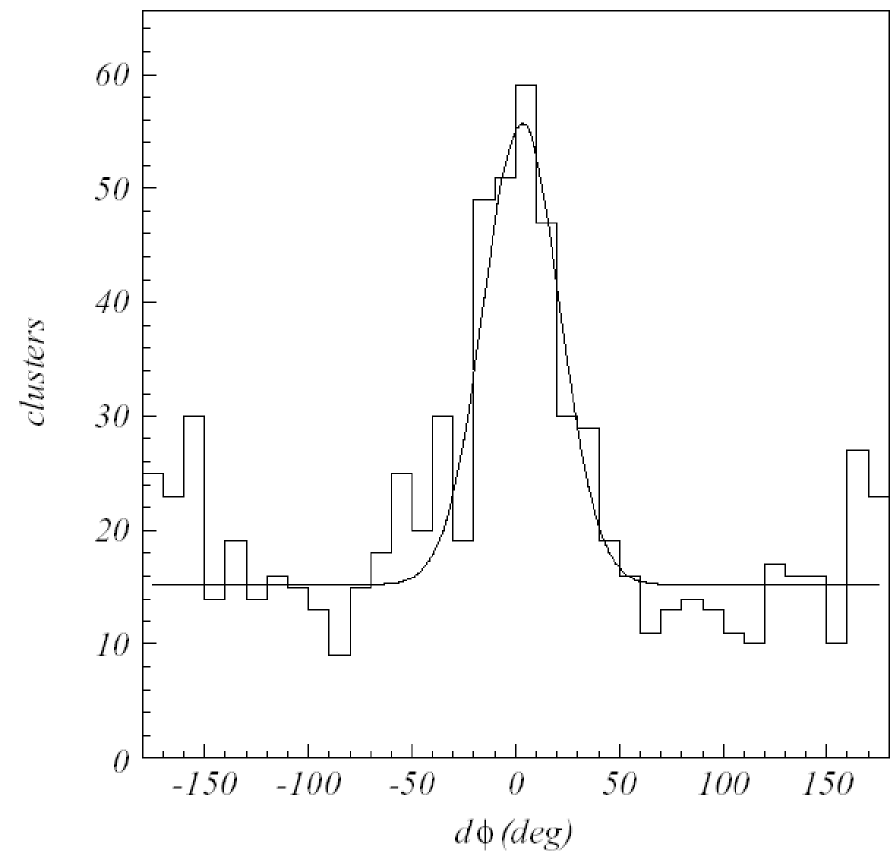
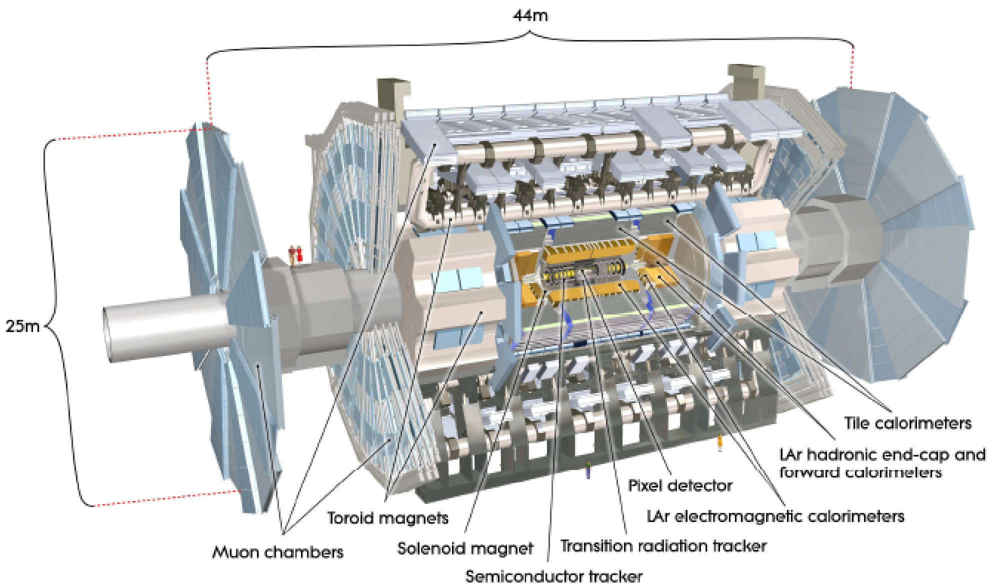
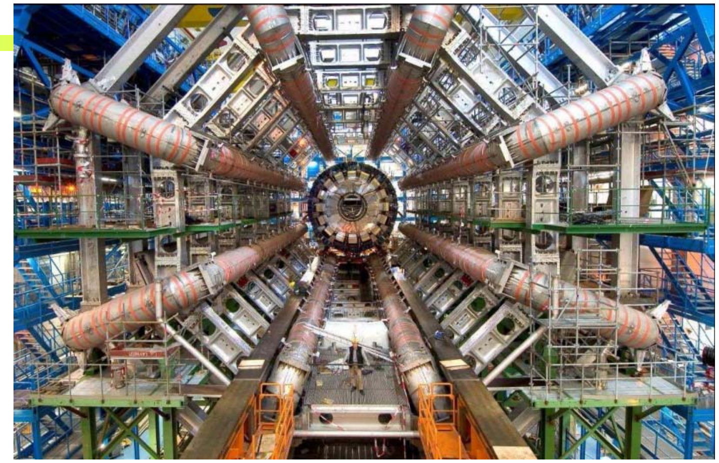


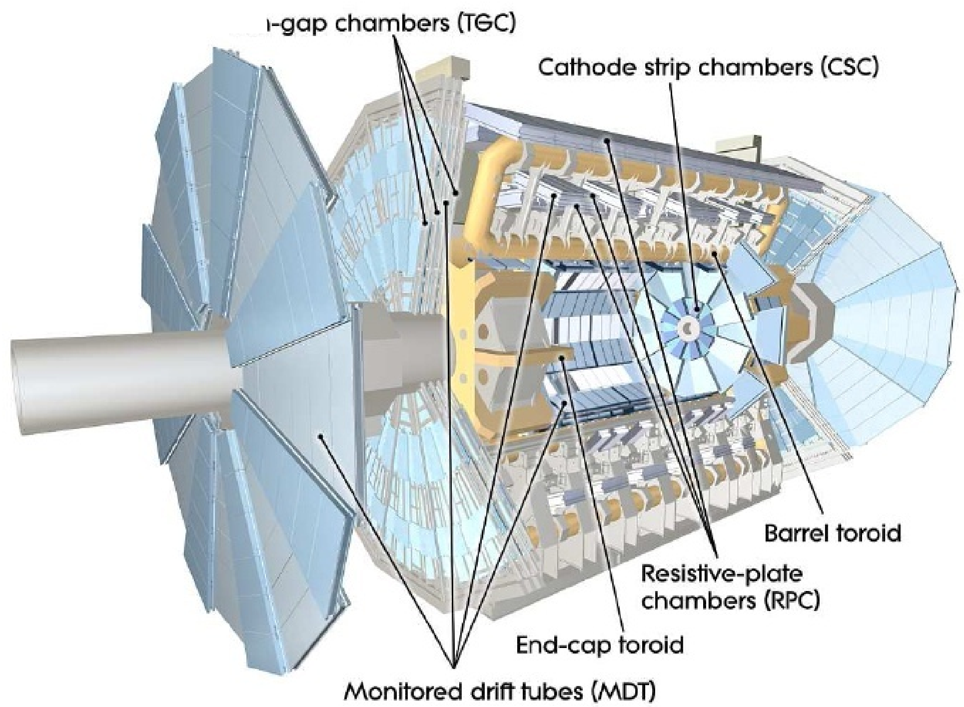
Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

Identification of muons in ATLAS

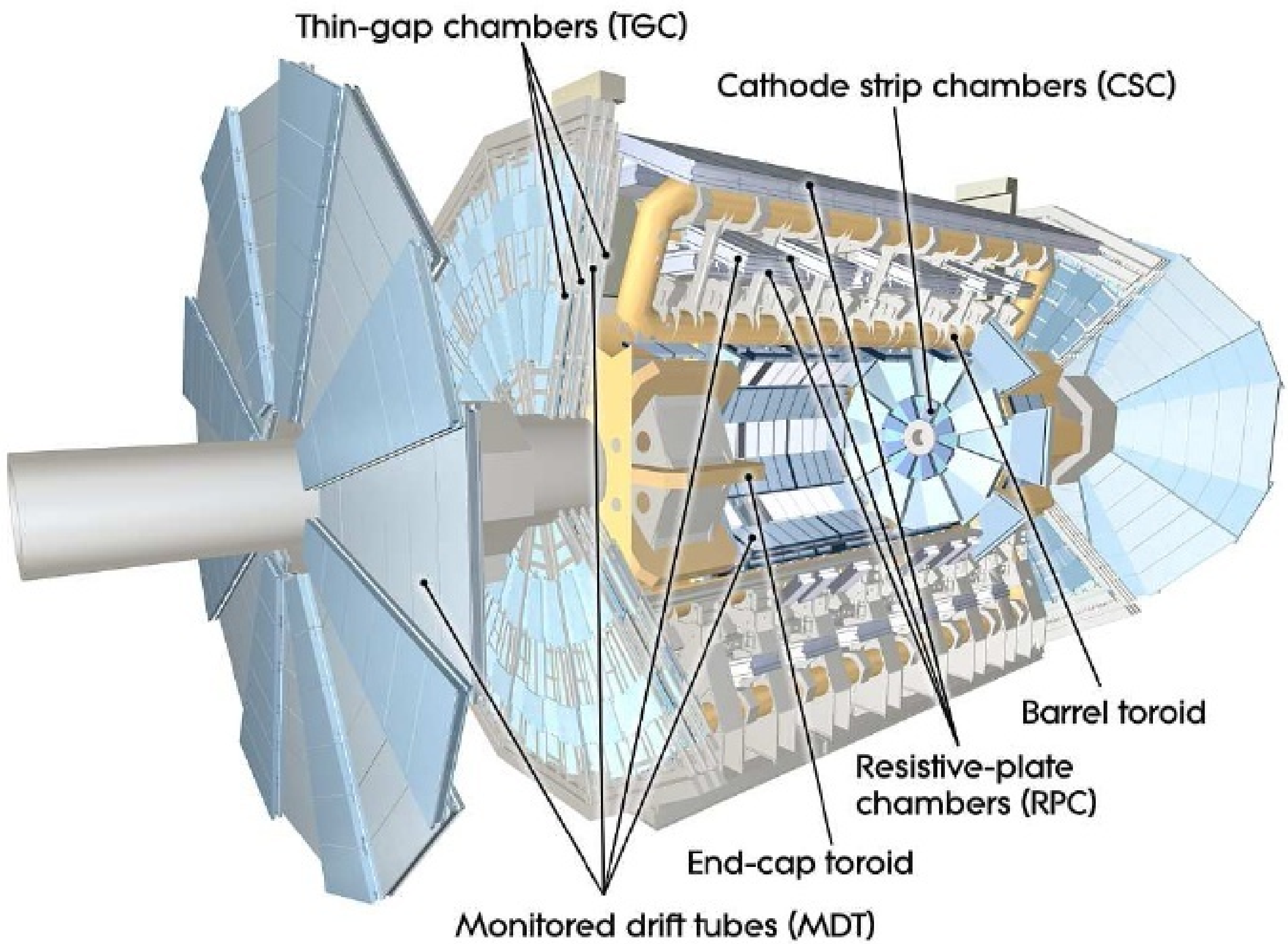




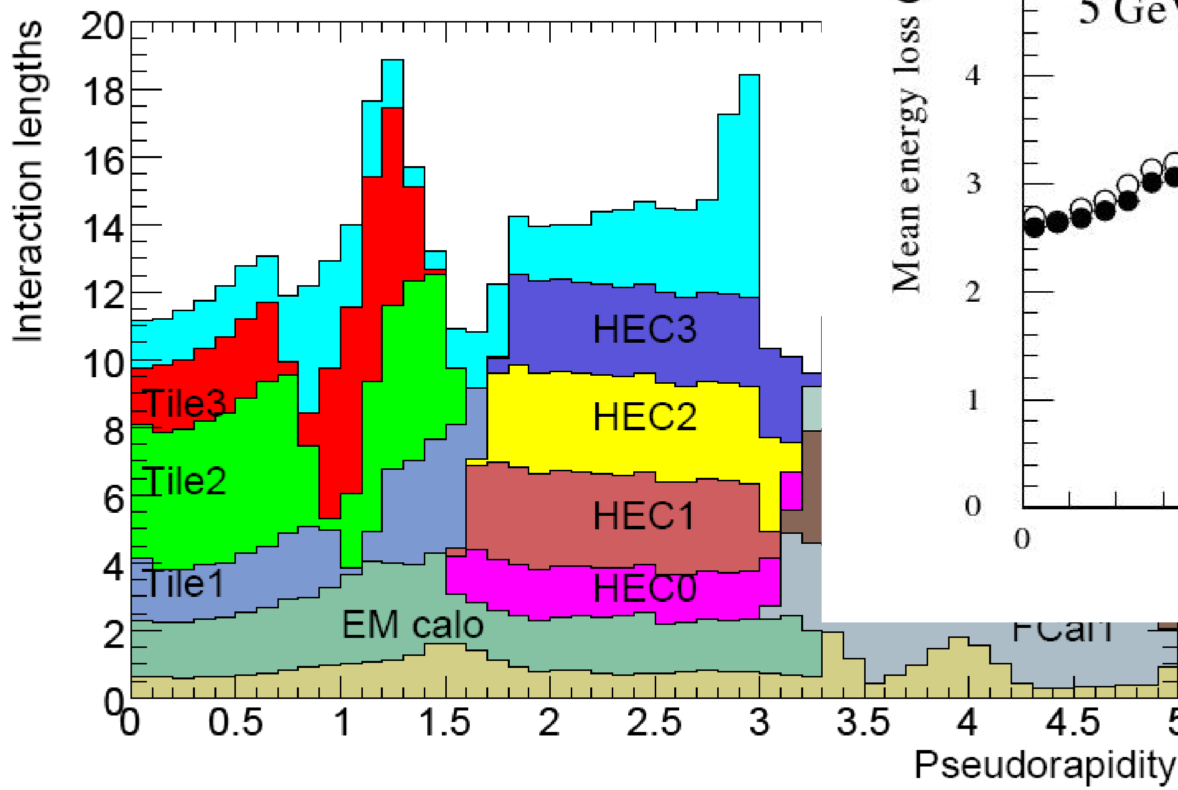
- Identify muons
- Measure their momentum

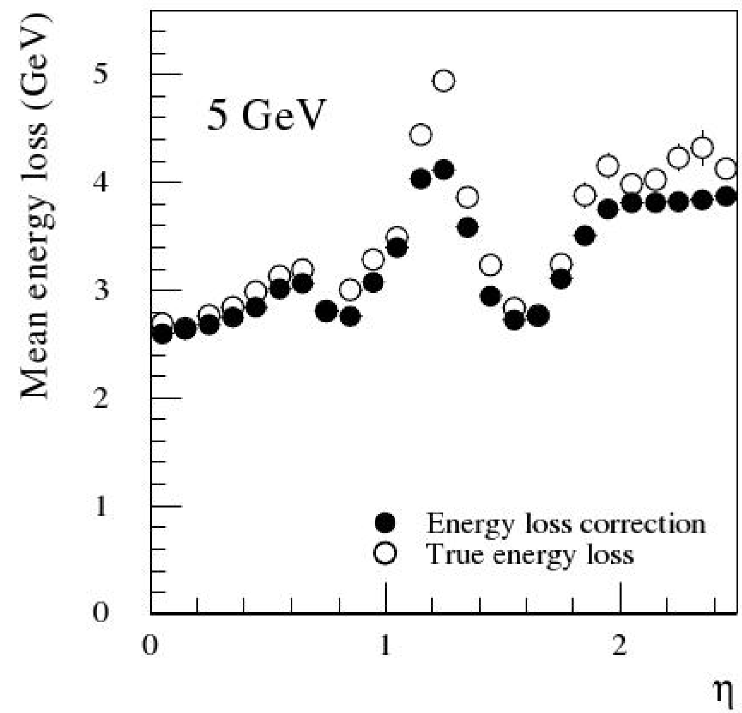


Detection of muons in ATLAS



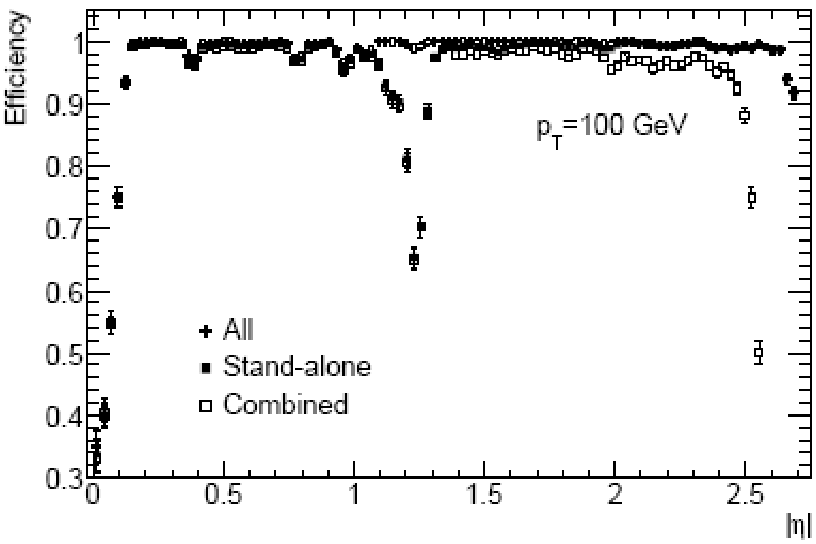
Muon identification in ATLAS

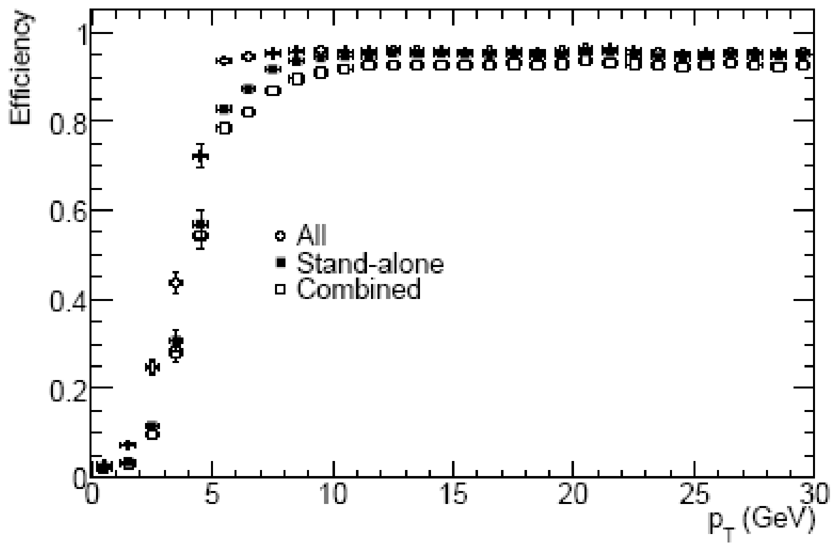




Material in front of the muon system

Muon identification efficiency





Efficiency for 100 GeV muons

Efficiency vs p_T

Summary

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

A large variety of techniques has been developed for different kinematic regions and different particles.

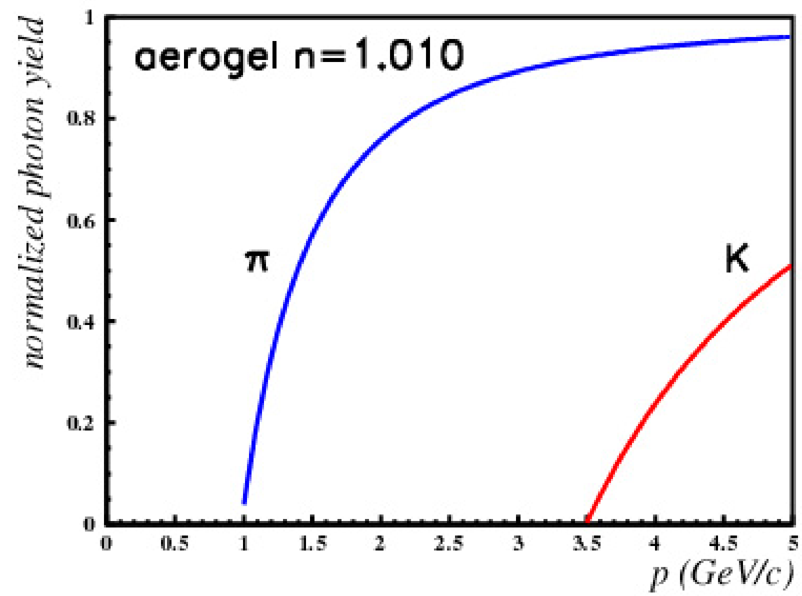
New concepts and detectors are being studied → this is a very active area of detector R+D.

Back-up slides

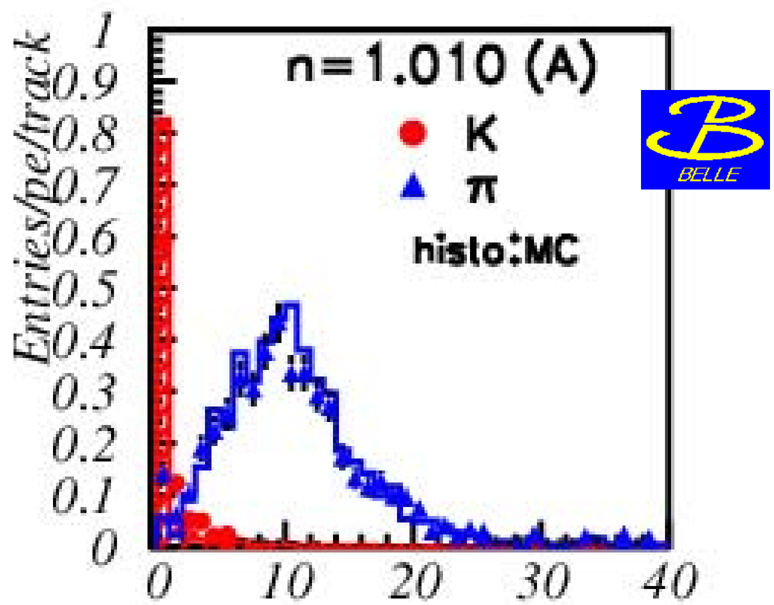
Threshold Cherenkov counter

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

Photon yield vs p



Choice of n: depends on the momentum range.



number of hits

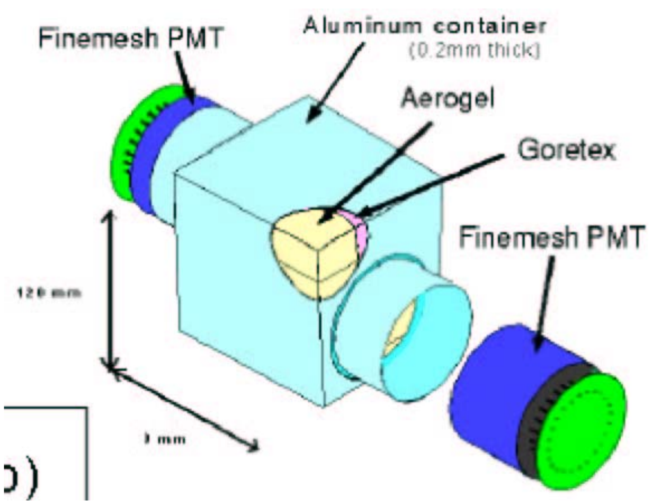
→ Good separation between pions (light) and kaons (no light) between ~1.5 GeV/c and 3.5 GeV/c

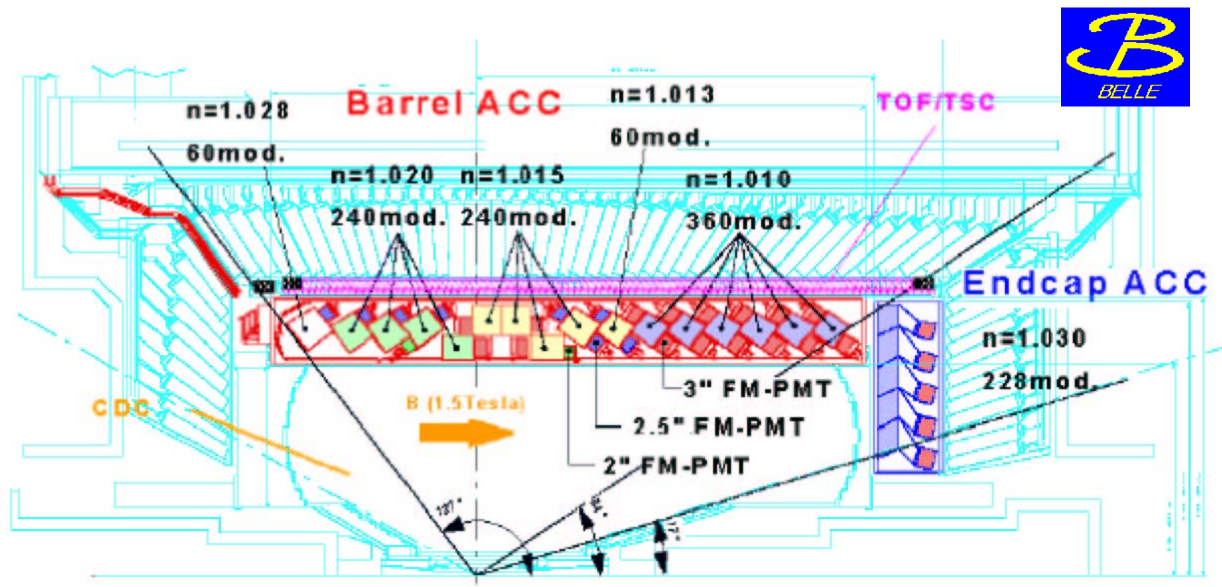
Belle: Threshold Cherenkov counter, ACC (aerogel Cherenkov counter)

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





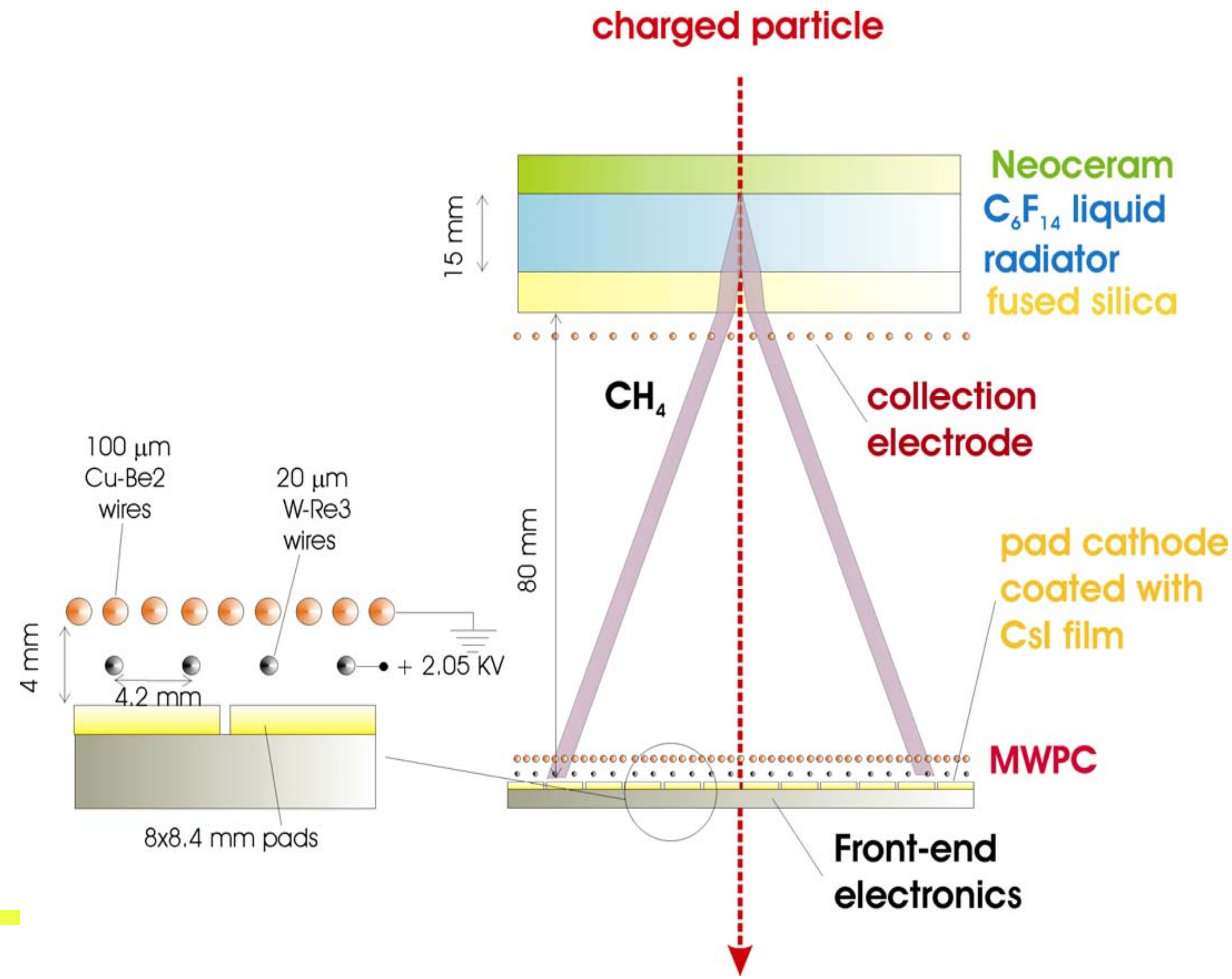
Fine-mesh PMT: works in high B fields (1.5 T)

CsI based RICH counters: HADES, COMPASS, ALICE

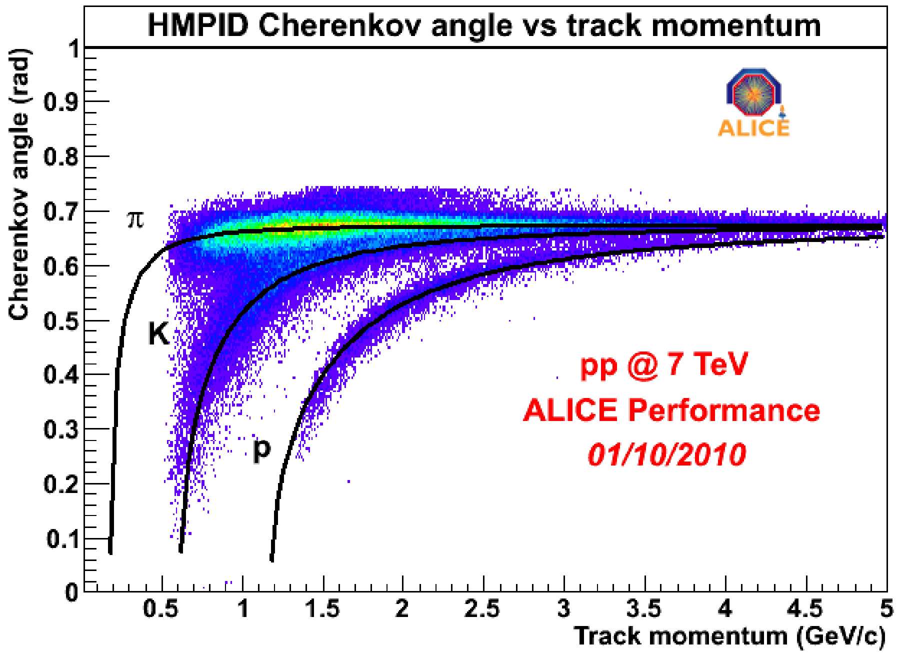
HADES and COMPASS RICH: gas radiator + CsI photocathode – long term experience in operation

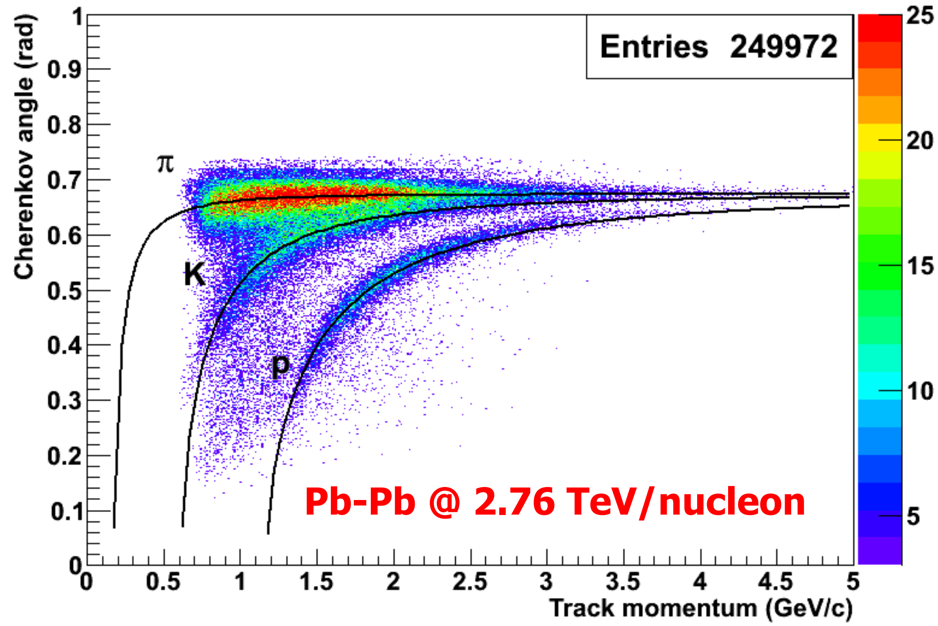
ALICE:

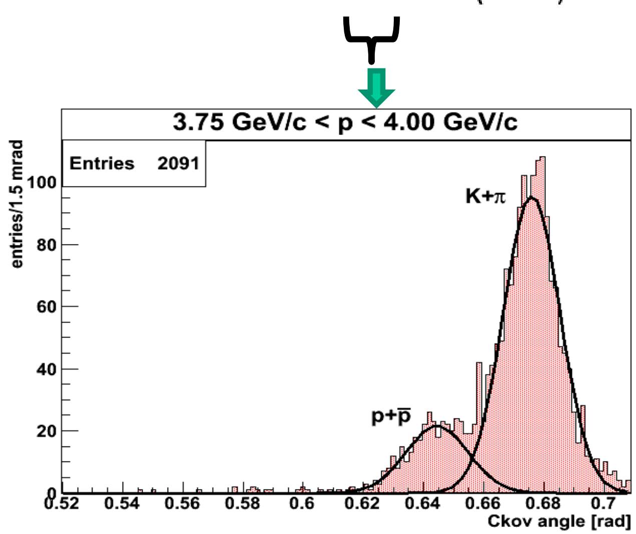
- liquid radiator
- proximity focusing



ALICE HMPID performance





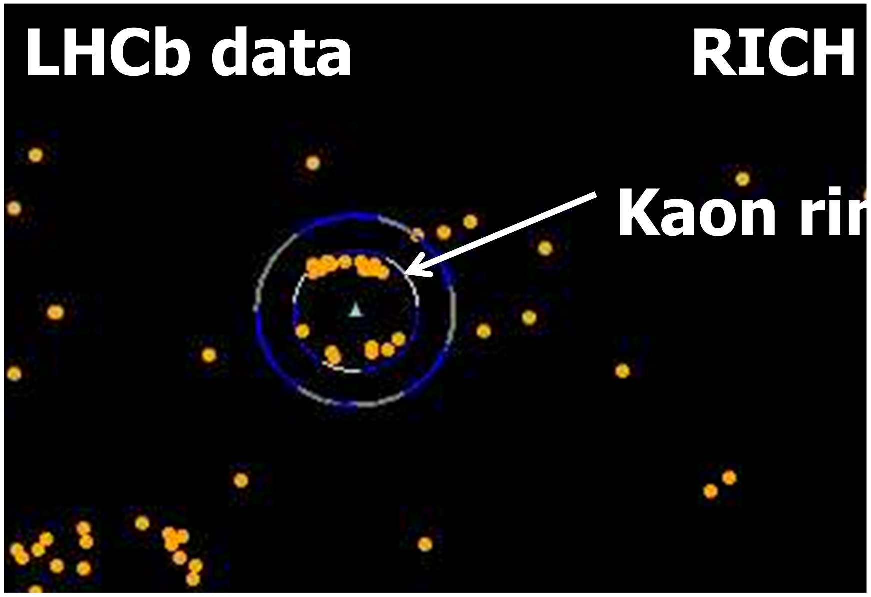


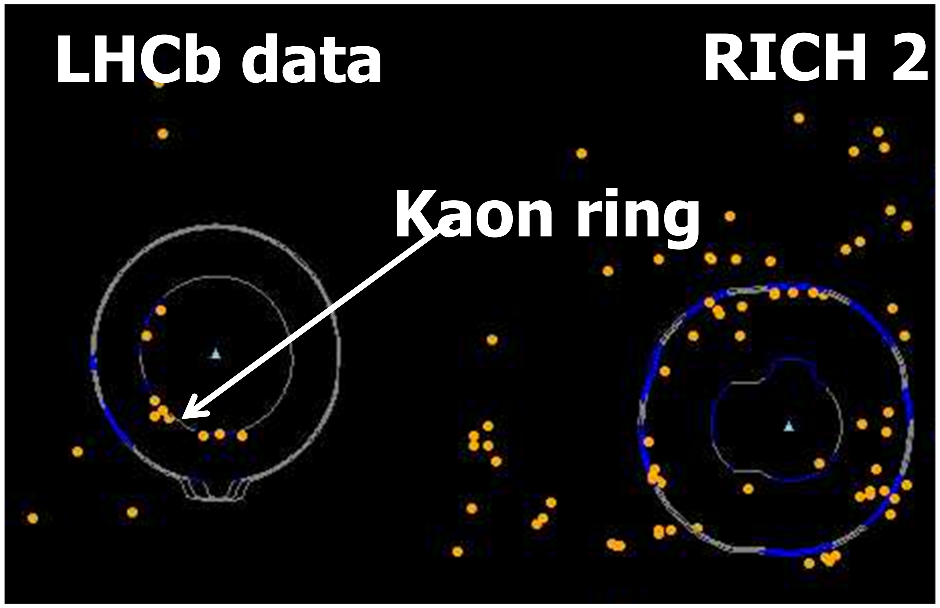
LHCb Event Display

RICH1

Early data, Nov/Dec 2009
LHC beams √s = 900 GeV

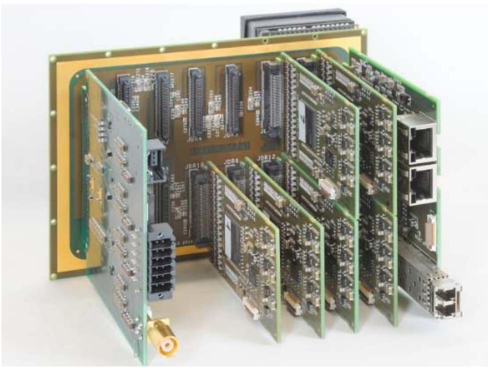
RICH2



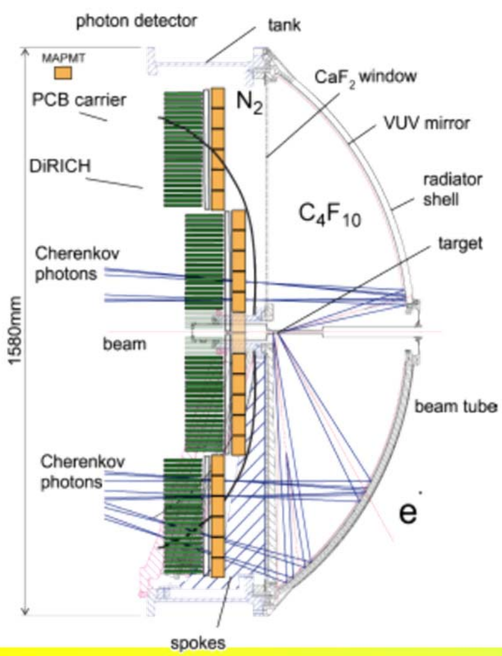


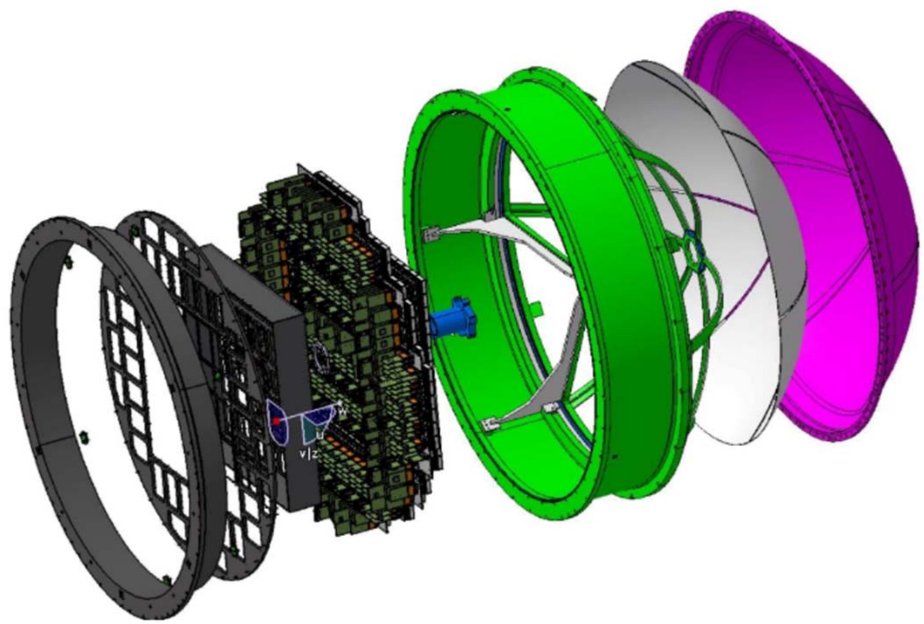
- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

HADES Upgrade

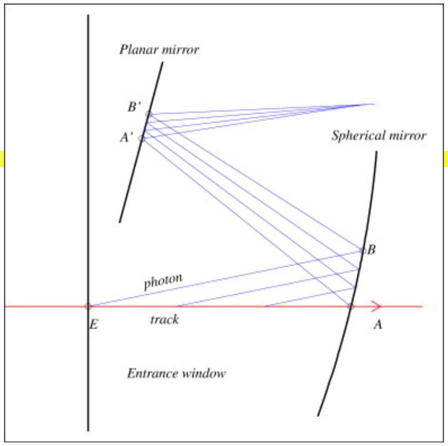


- Replace CsI-MWPCs with MaPMTs
  - Hamamatsu H12700
  - Same as for CBM-RICH
  - Also share electronics

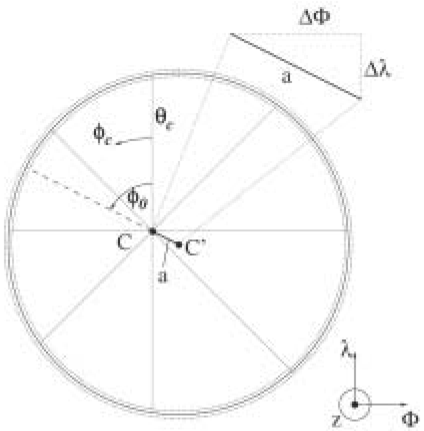


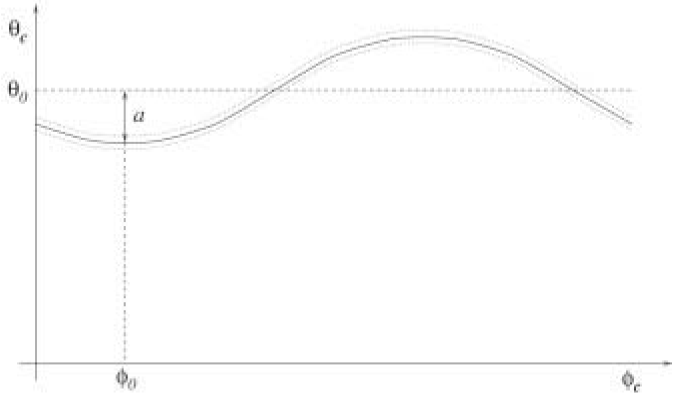


Mirror alignment

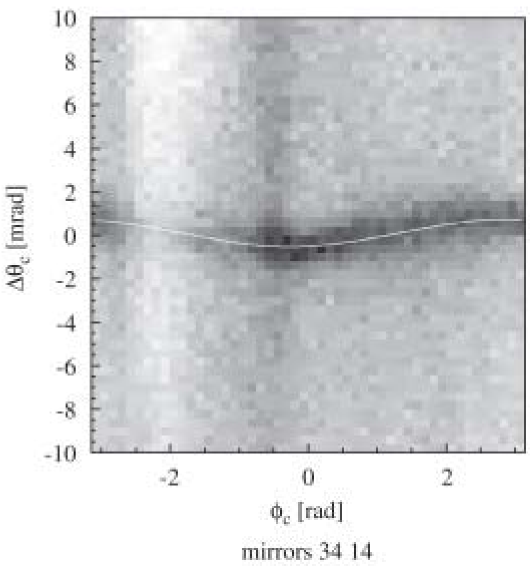


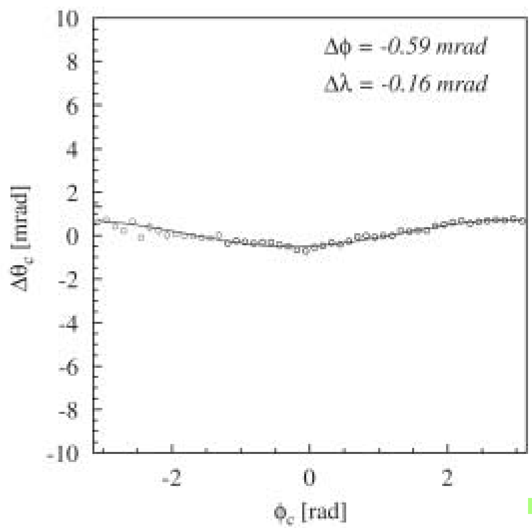
Misalignment: Cherenkov angle depends on the azimuthal angle around the track

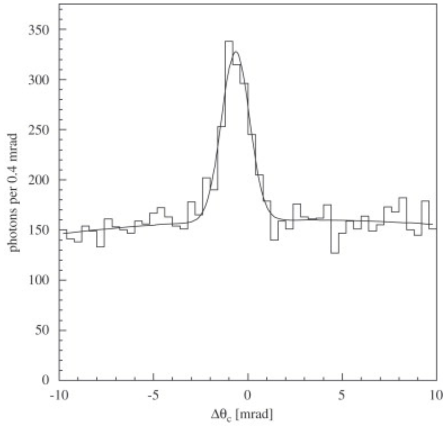




Use unambiguos photons.







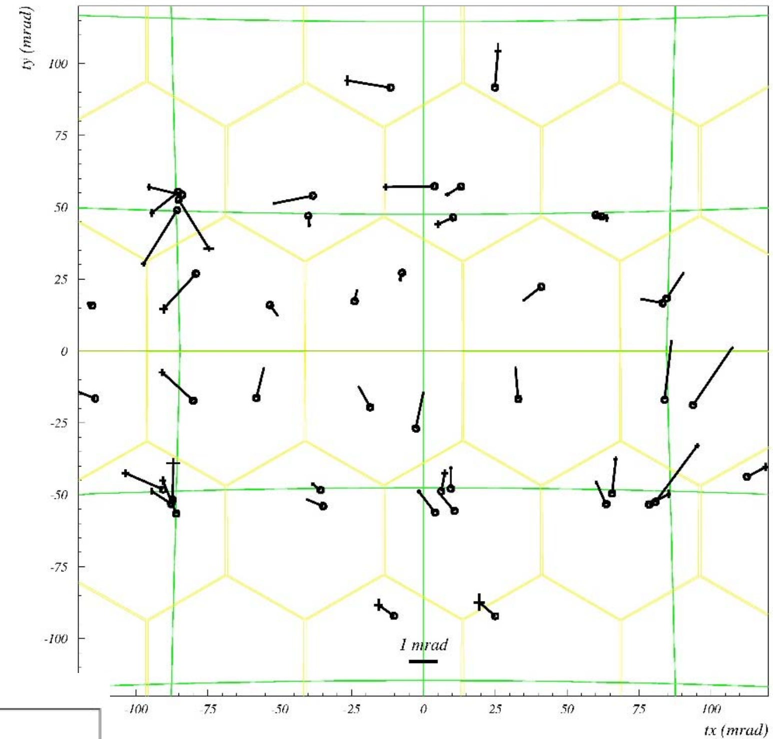
Slice in ϕ_c

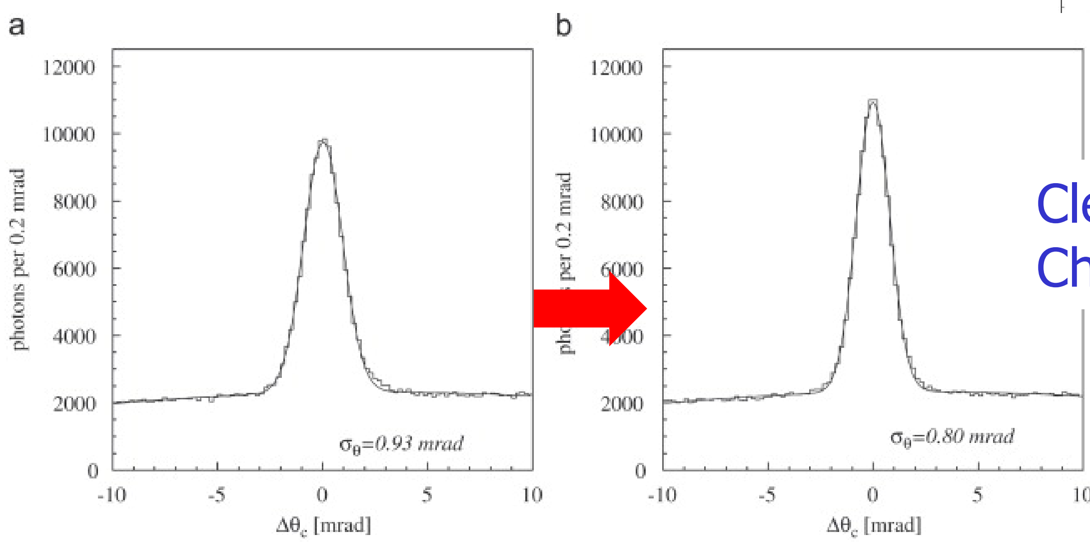
Mirror alignment

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

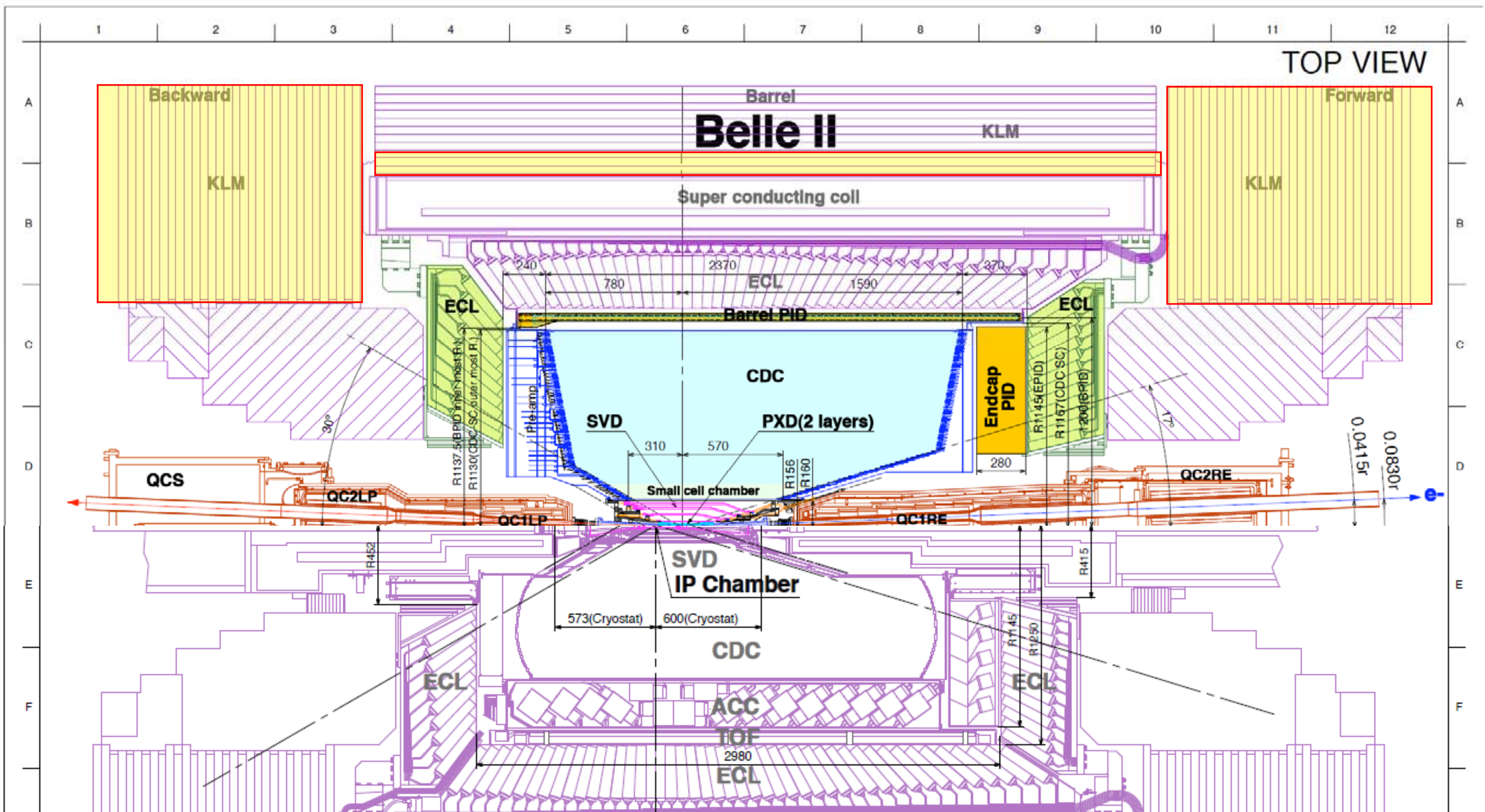




Clear improvement in Cherenkov angle resolution

→NIMA 586 (2008) 174

Belle II Detector (compared to Belle)

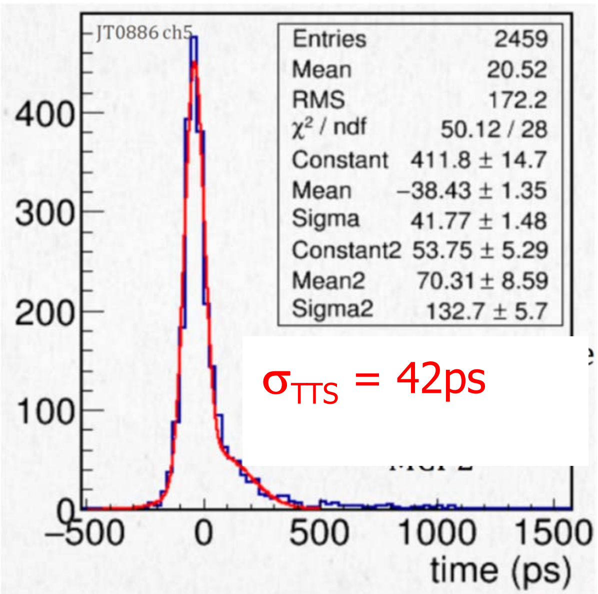


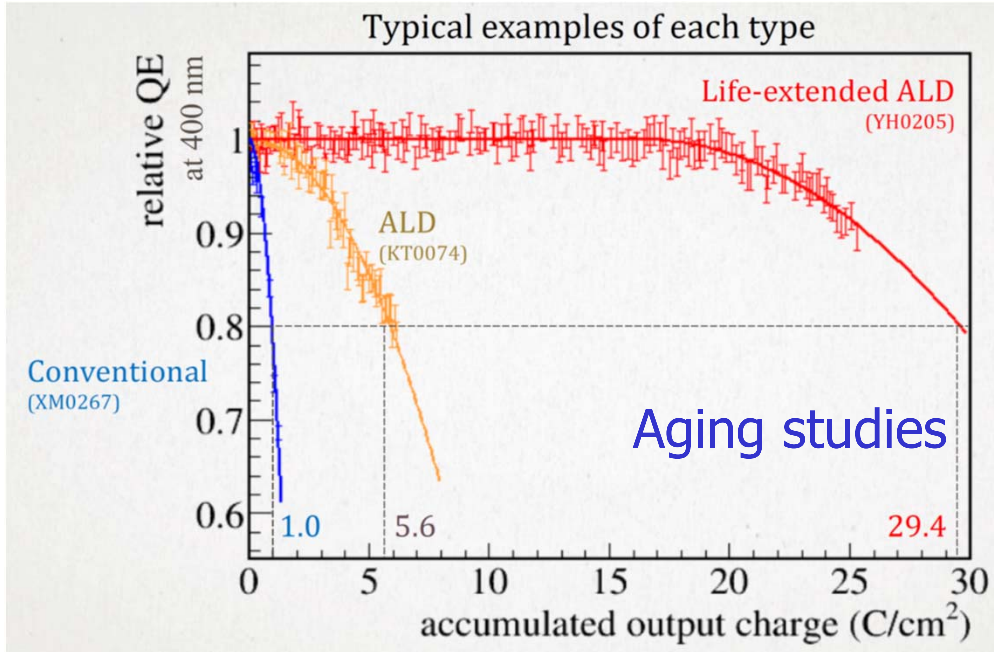
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for part of endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

TOP R+D areas

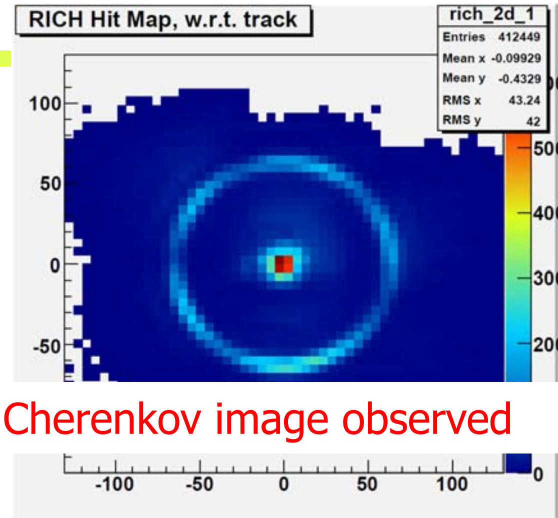
- Very fast photosensors for operation in 1.5 T field (MCP PMTs)
- R+D to mitigate aging of photocathodes in MCP PMTs (ALD)





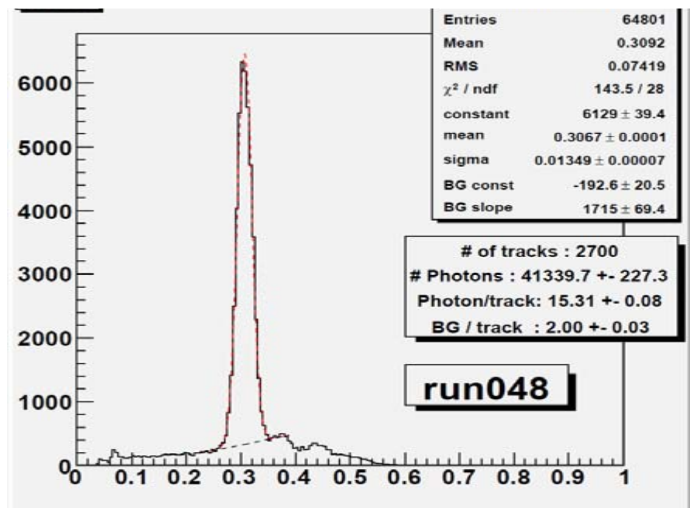
- Very fast and compact readout electronics with waveform sampling for a precise time measurement →
- Production of large quartz pieces, construction of modules, mechanics and installation methods
- Analytic expressions for the very complex 2D likelihood functions.

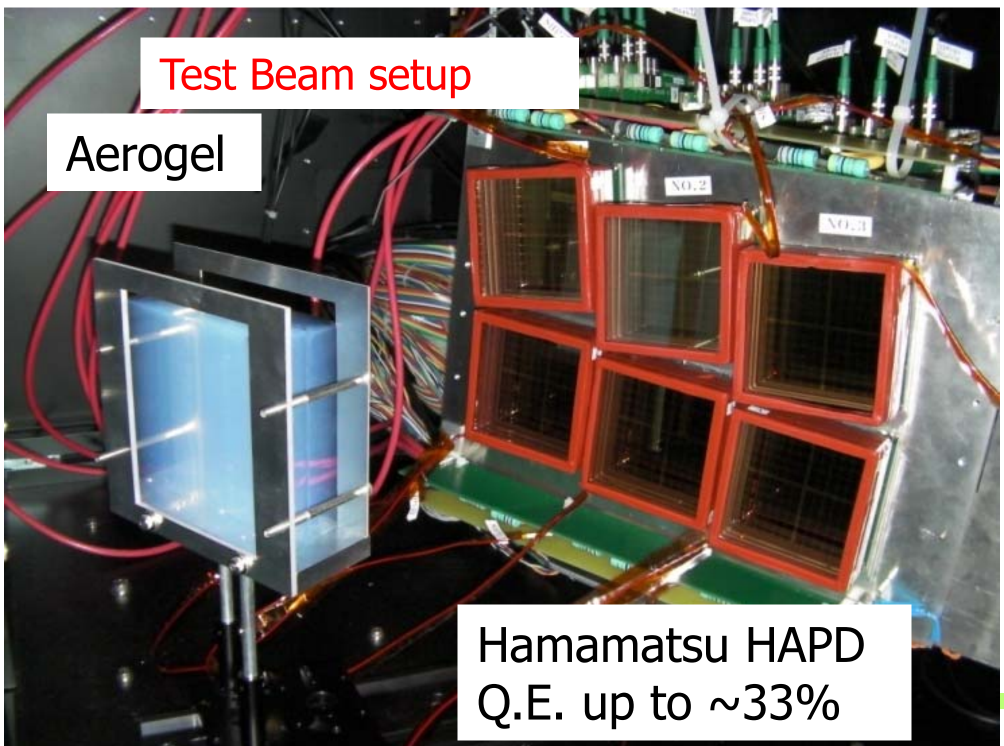
HAPD as the Aerogel RICH photon detector



Clear Cherenkov image observed

Cherenkov angle distribution



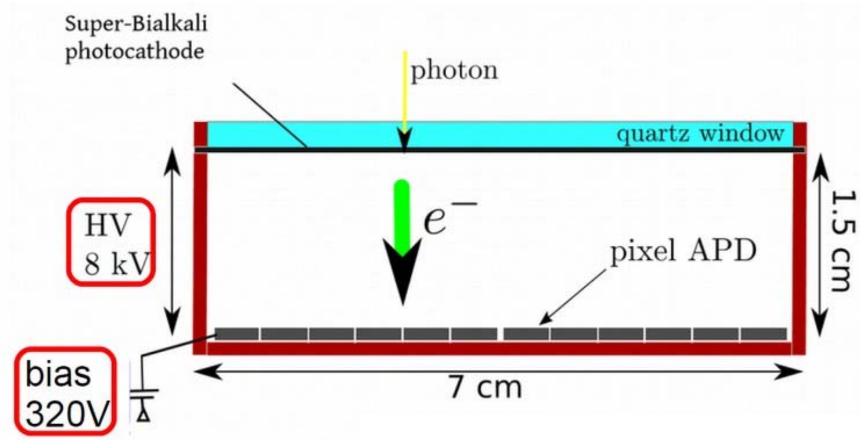


6.6 σ p/K at 4GeV/c !

→ NIM A595 (2008) 180

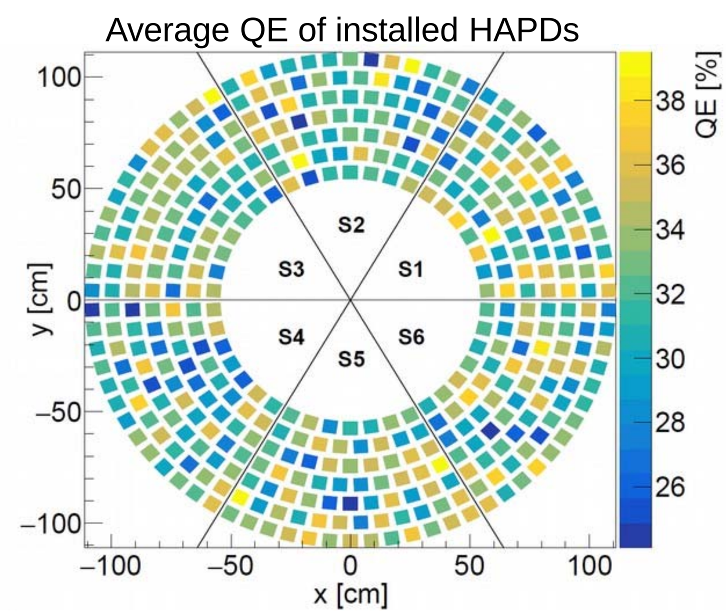
ARICH photo sensor: HAPD

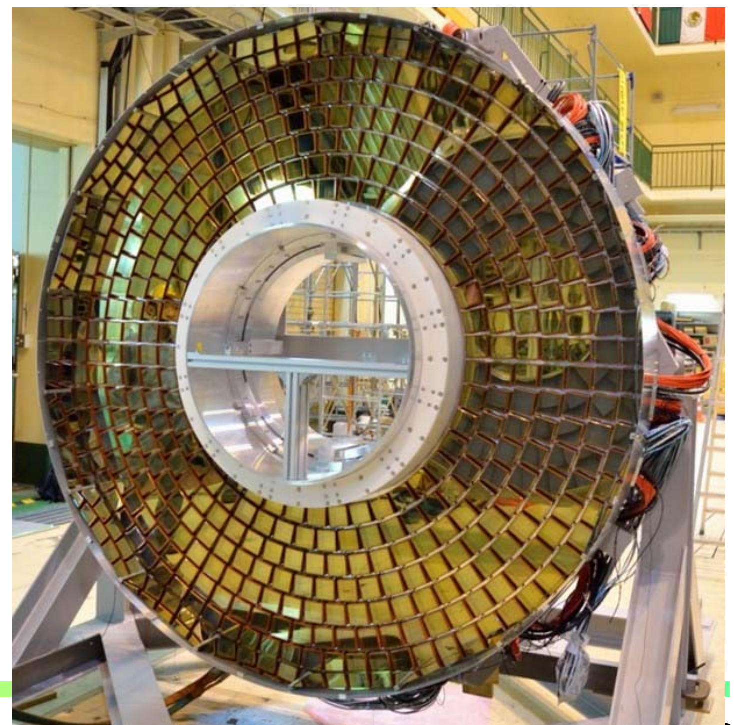
- HAPD – Hybrid Avalanche Photo-Detector



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

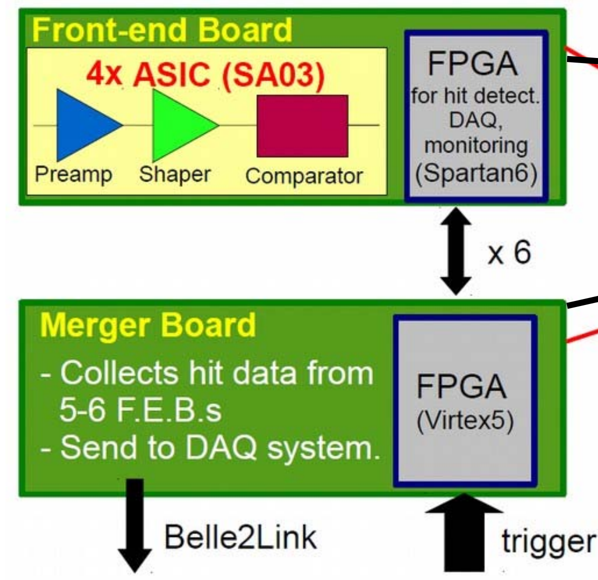
- 420 modules to cover the detector plane

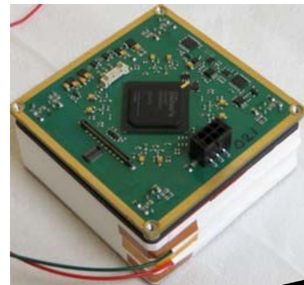


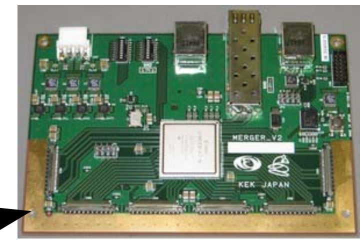


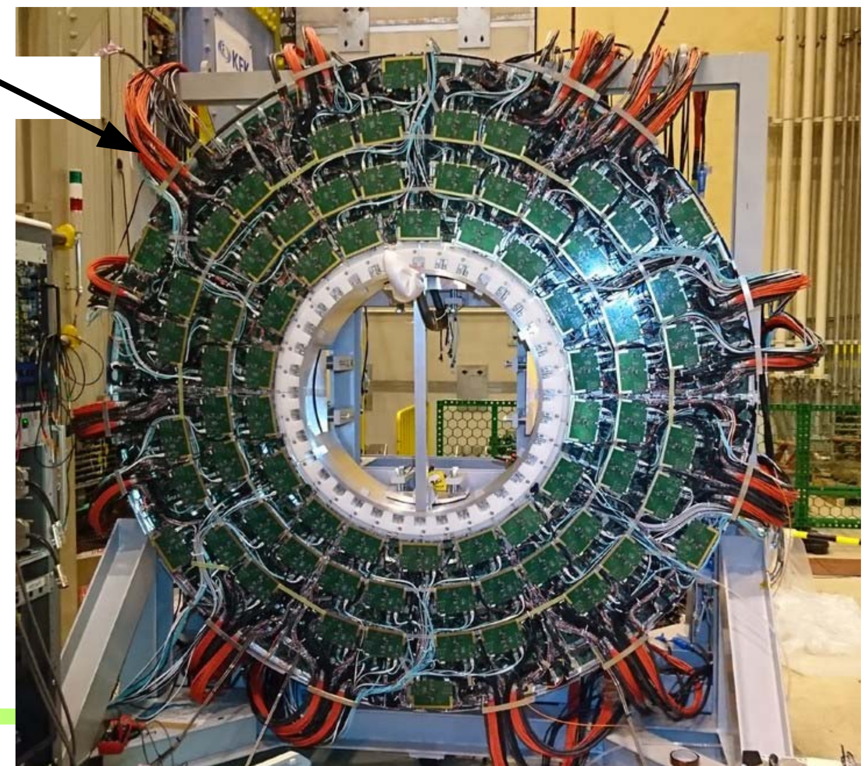
ARICH read-out electronics

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





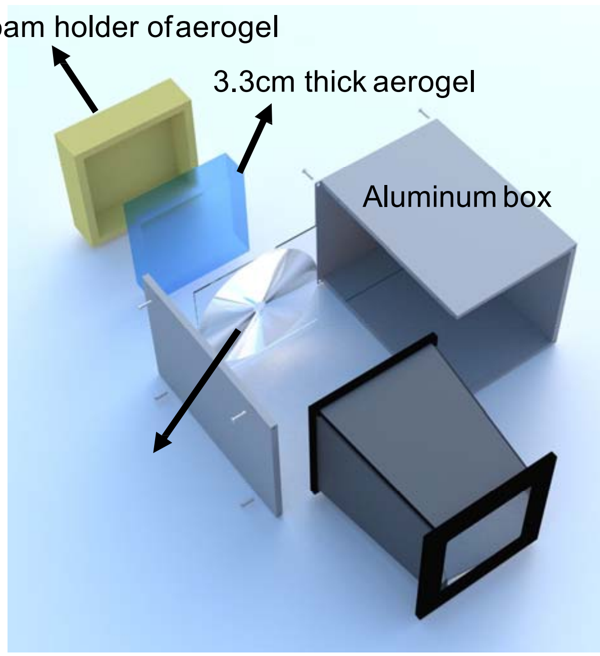


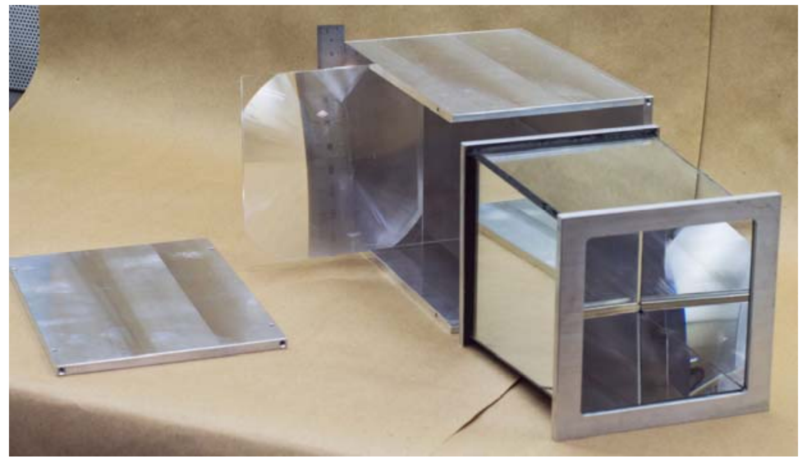


- Variable gain (3.1-12.5 V/pC), shaping time (100-200 ns)

  → optimization for
  increased noise levels

2nd mRICH Prototype - Verify the PID Capability






TECHNICAL INFORMATION

OCT. 2016

FLAT PANEL TYPE MULTIANODE PMT ASSEMBLY
H13700 SERIES

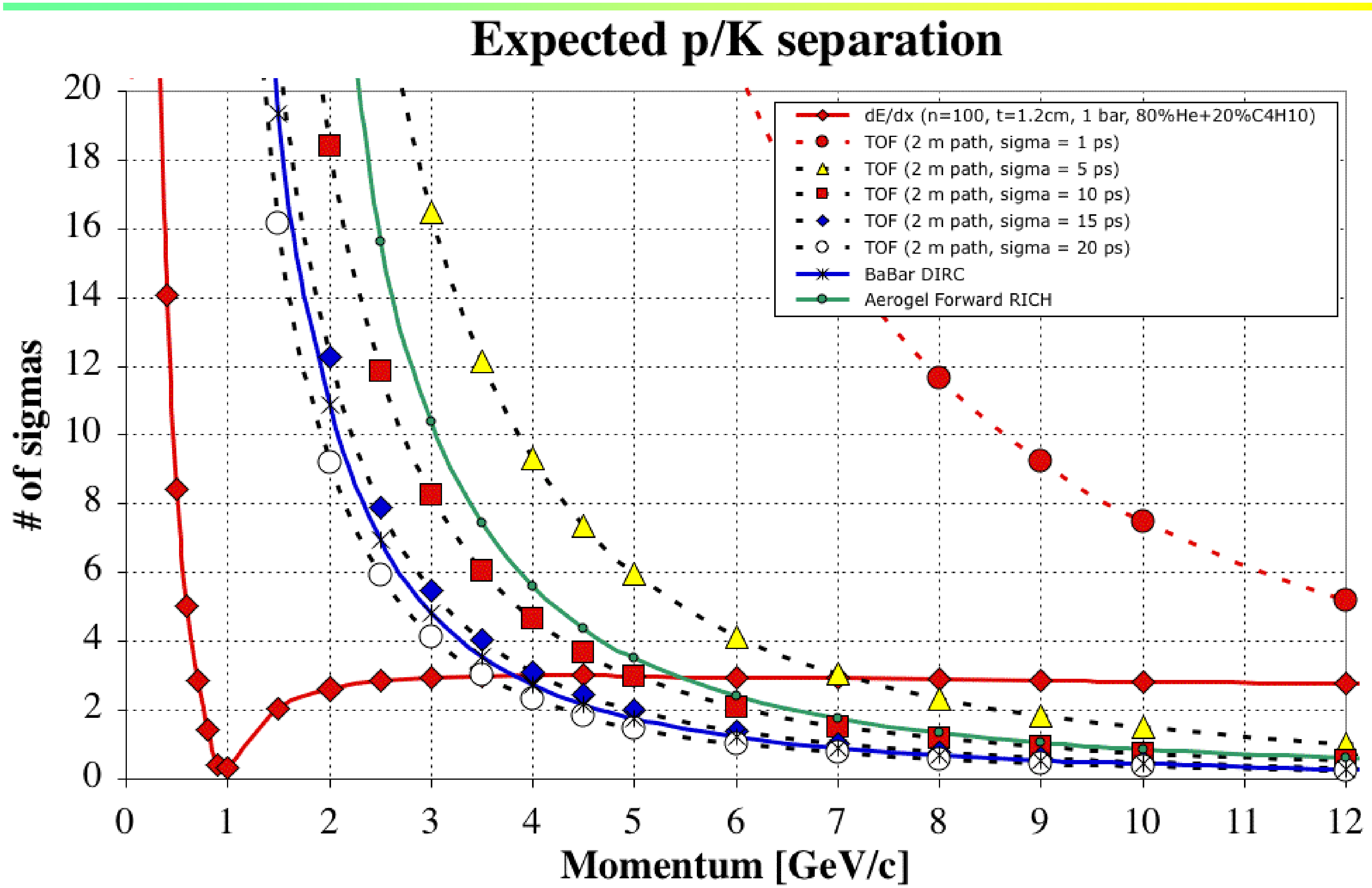
FEATURES
- High quantum efficiency: 33 % typ.
- High collection efficiency: 80 % typ.
- Single photon peaks detectable at every anode (pixel)
- Wide effective area: 48.5 mm × 48.5 mm
- 16 × 16 multianode, pixel size: 3 mm × 3 mm / anode

6” focal length Fresnel lens

mirror set

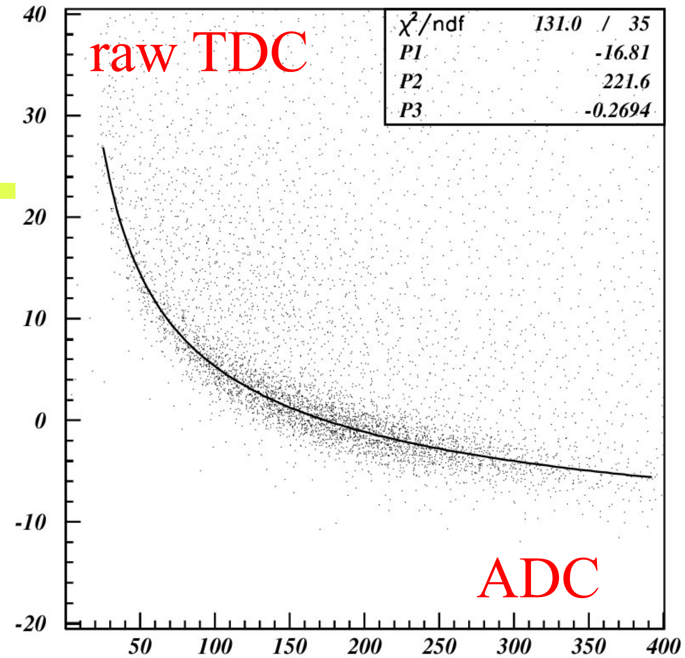
1.Longer focal length (Fresnel lens)
2.Smaller pixel size sensors

Time-of-flight with fast photon detectors



J. Va'vra, RICH07

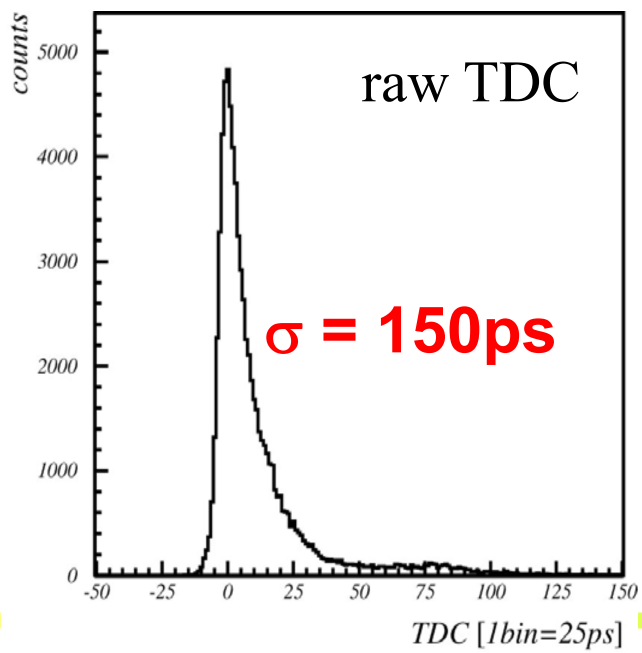
Time walk correction

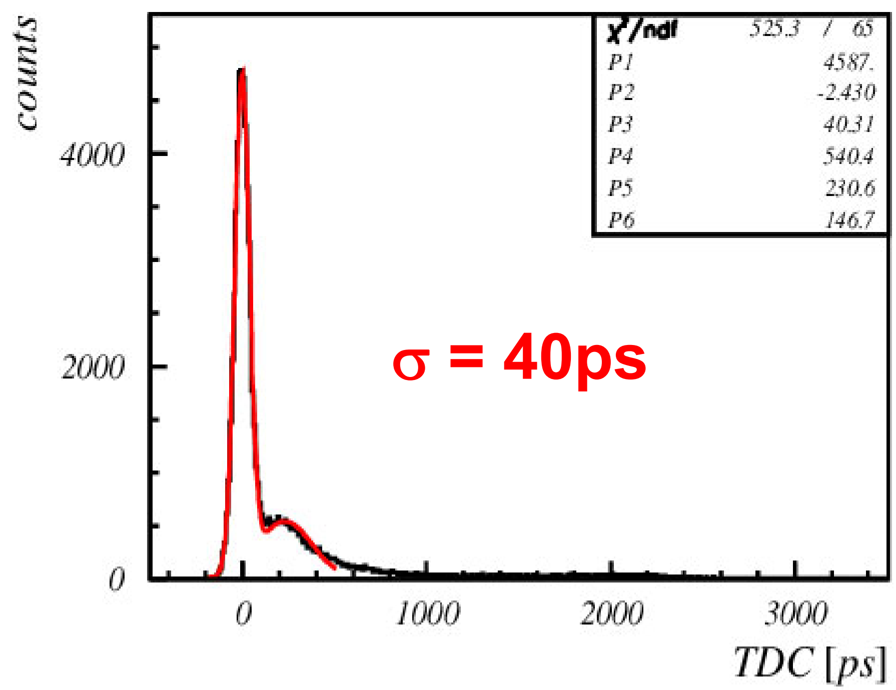


TDC vs. ADC correlation is fitted with

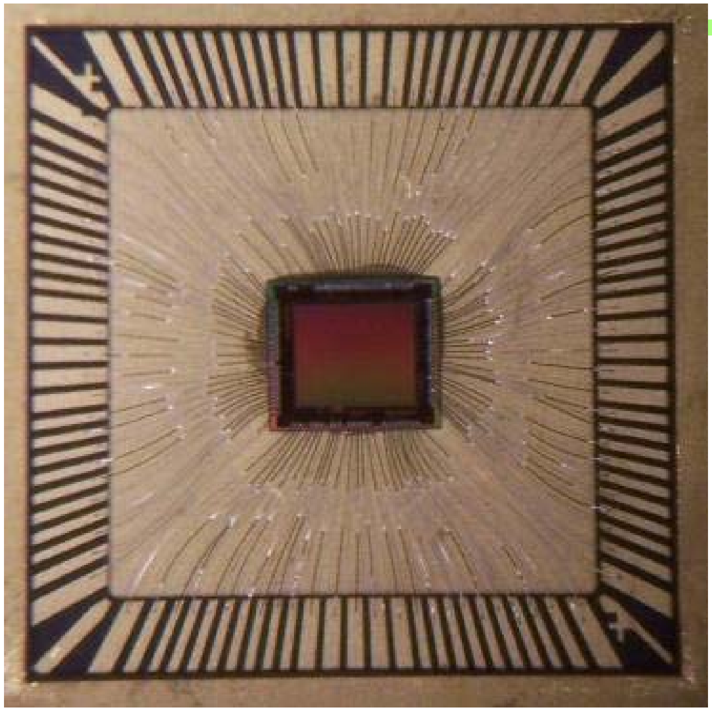
$$TDC = P1 + \sqrt{\frac{P2}{ADC - P3}}$$

and used for TDC correction





Time walk correction 3: waveform sampling



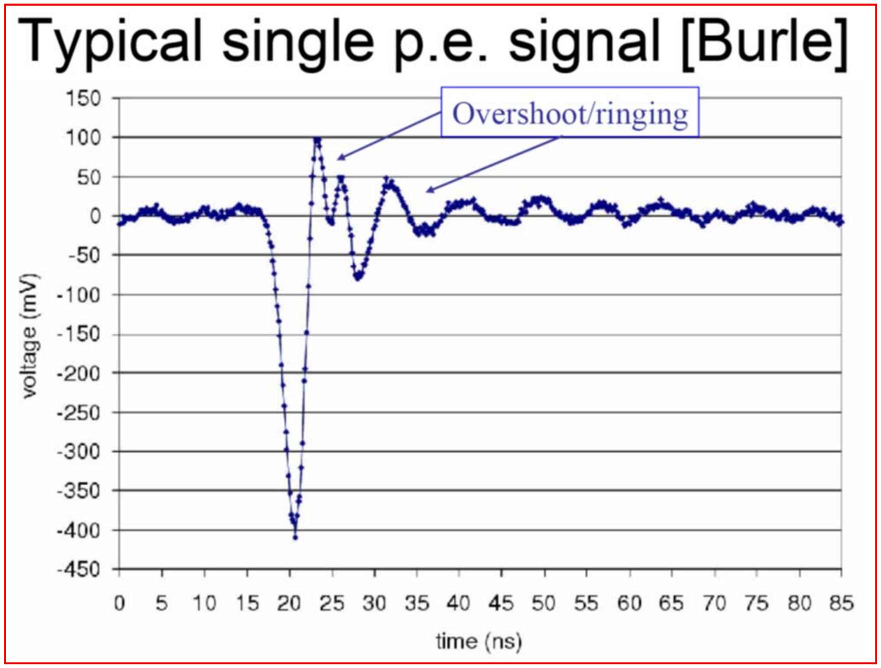
3mm x 2.8mm, TSMC 0.25um

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

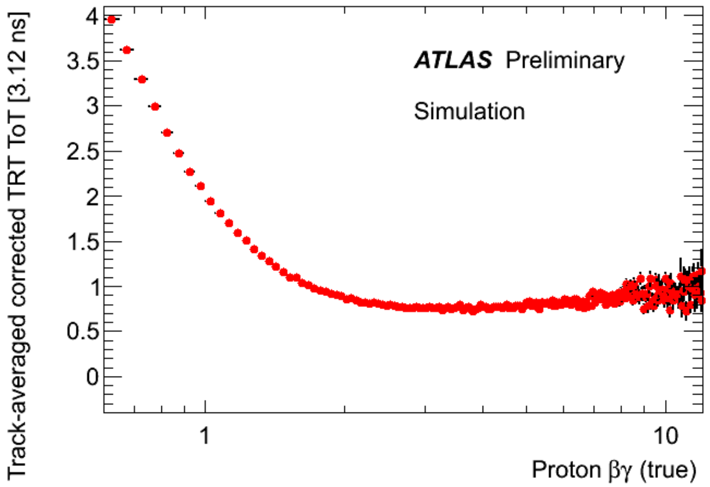
Gary Varner (Hawaii)

Variant of the LABRADOR 3

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

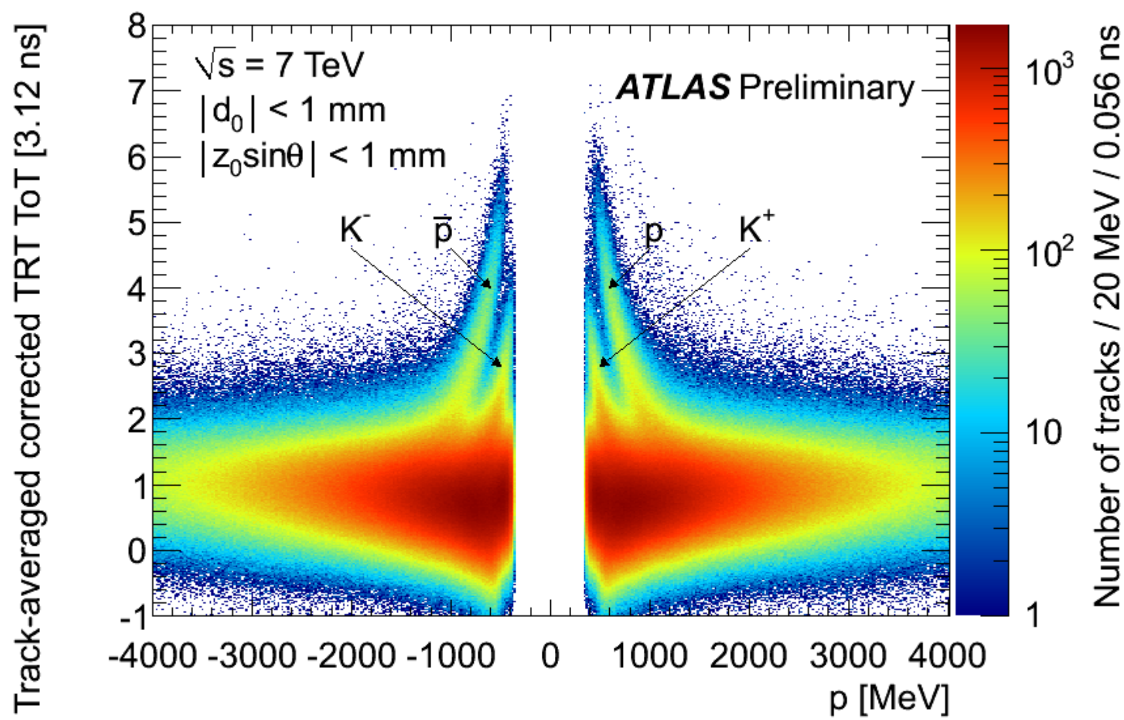


Time-over-Threshold (ToT): dE/dx in ATLAS TRT



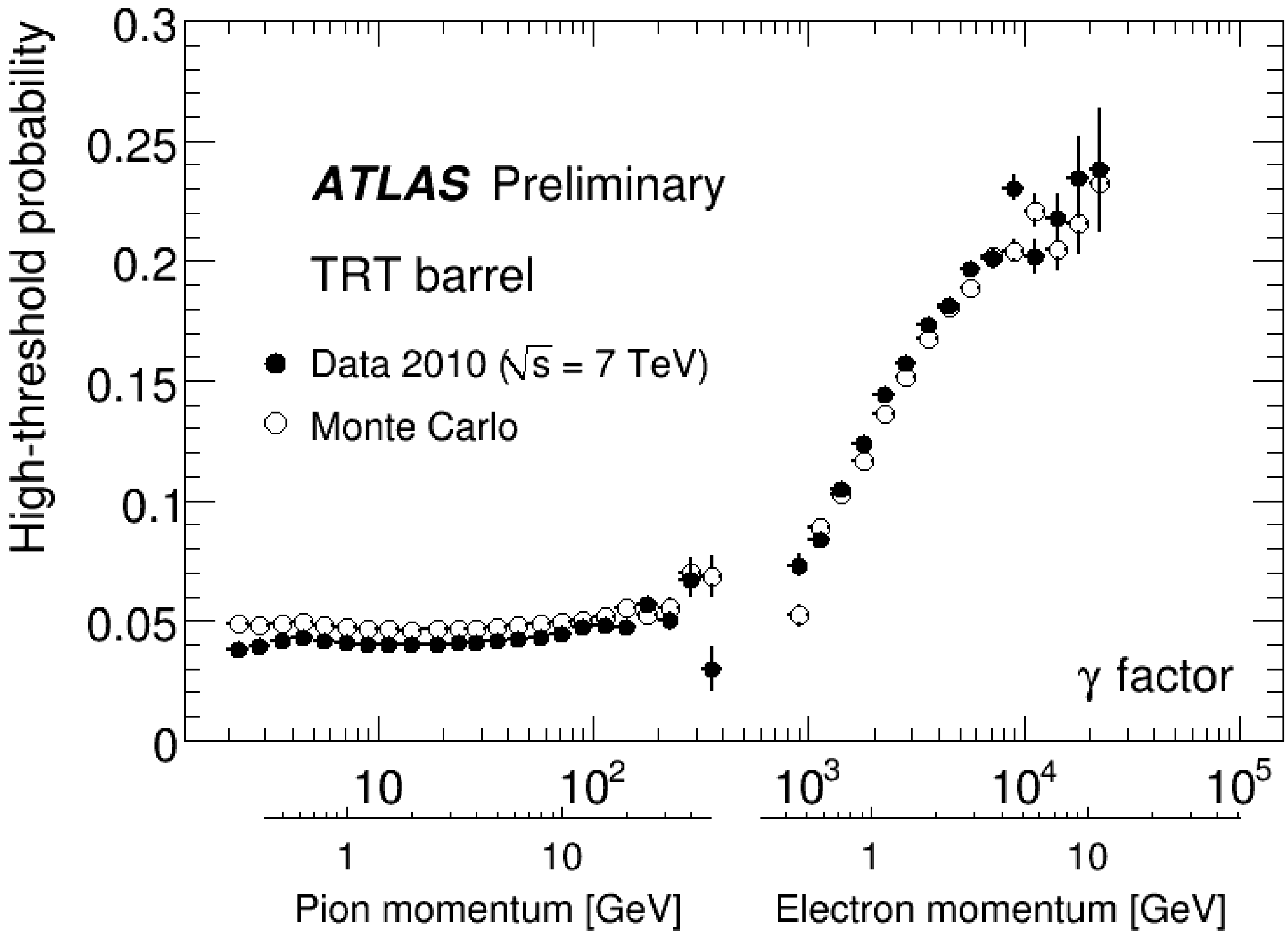
The relation between the track ToT measurement and the track $\beta\gamma$, obtained from MC studies.

Track-averaged ToT distribution as a function of the track momentum.

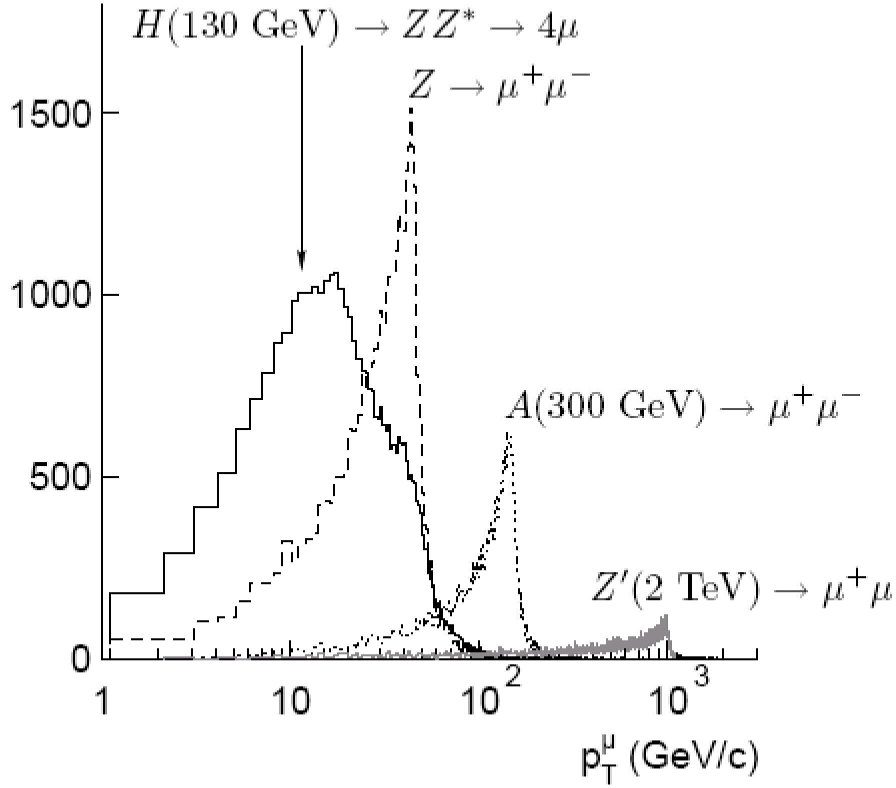


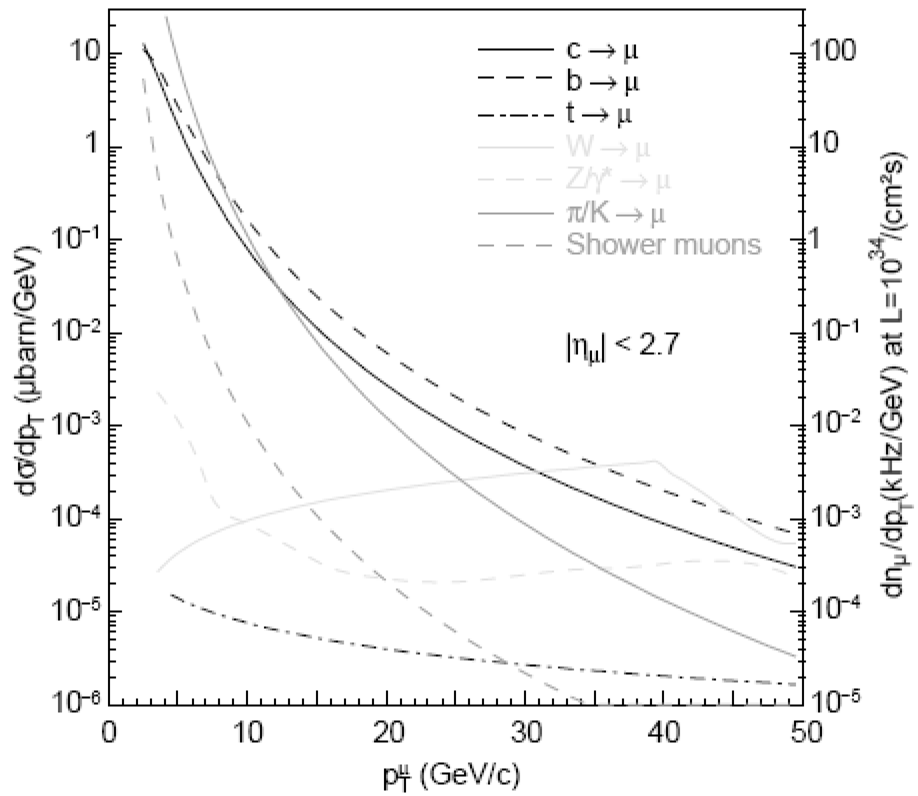
TRT performance in 2010 data

e/pion separation: high threshold hit probability per straw



Muon spectrum





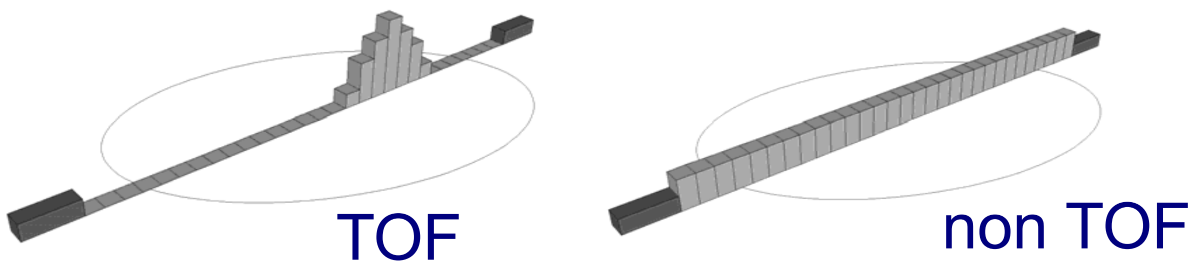
Applications in medical imaging: advances in TOF-PET

Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET

Localization of source position along the line of response:

$\Delta t \sim 66\text{ps} \rightarrow \Delta x = c_0 \Delta t/2 \sim 1\text{cm}$

Δt = coincidence resolving time, CRT



However, PET systems based on SiPM readout are reaching CRT of ~300 ps, and only with small crystals ~3x3x3 mm^3 CRT<100 ps

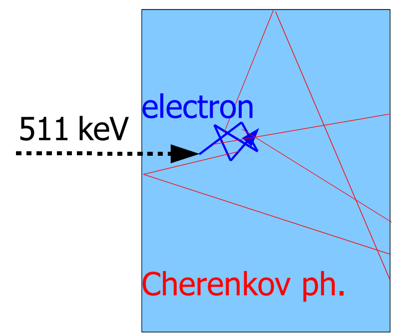
Novel photon detectors – MCP-PMTs and SiPMs – have excellent timing resolution → TOF resolution limited by the spread in photon emission and arrival time

Faster annihilation gamma detection method → a faster light emission mechanism

Annihilation gamma detection with Cherenkov light

Cherenkov light is promptly produced by a charge particle traveling through the medium with velocity higher than the speed of light c_0/n. Photoelectron emits Cherenkov light in ~1ps.

Disadvantage of Cherenkov light is the small number of Cherenkov photons produced per interaction



$$N \approx \frac{370}{eV\,cm}\, l\, \Delta E\, \sin^2_C \vartheta \approx 370 \times 0.01 \times 2 \times 0.75 \approx 8$$

→ detection at a single photon level!

Cherenkov radiator: PbF_2 an excellent candidate

- high gamma stopping power
- high fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons

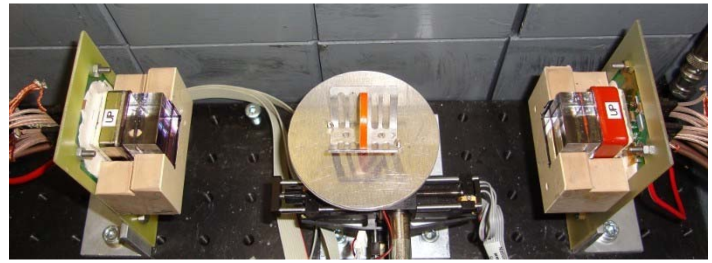
	ρ (g/cm³)	n	e⁻ Cherenkov threshold (keV)	Cutoff wavelength (nm)	Attenuation length (cm)	Photofraction
PbF_2	**7.77**	**1.82**	**101**	**250**	**0.91**	**46%**
LYSO	7.4				1.14	32%
$LaBr_3$	5.1				2.23	15%

+ high transmission in visible and near UV

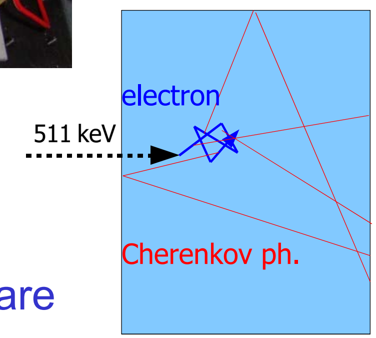
Excellent TOF PET timing with MCP PMTs

Pioneering experiment, two detectors in a back-to-back configuration: PbF_2 25x25x15 mm^3 with MCP-PMT as photodetectors

- single photon timing ~ 50 ps FWHM
- active surface 22.5x22.5 mm^2



black painted, Teflon wraped, bare



Timing resolution (black painted):

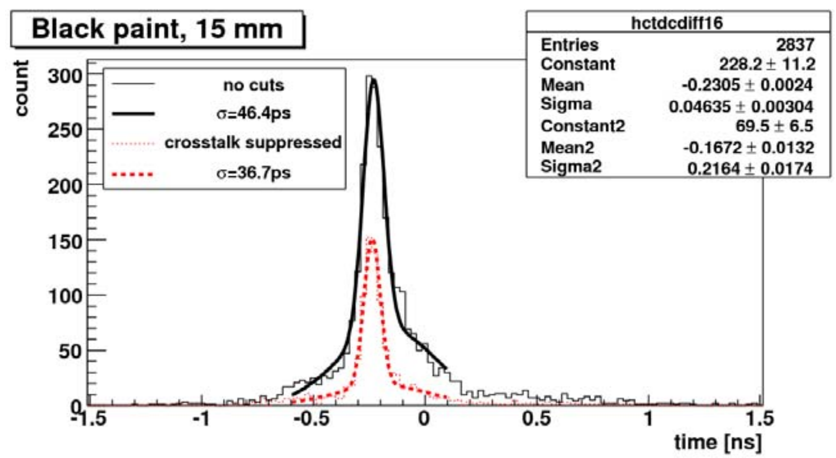
~ 70 ps FWHM, 5mm crystal

~100 ps FWHM 15mm crystal

Efficiency (Teflon wrapped):

~ 6%, single side

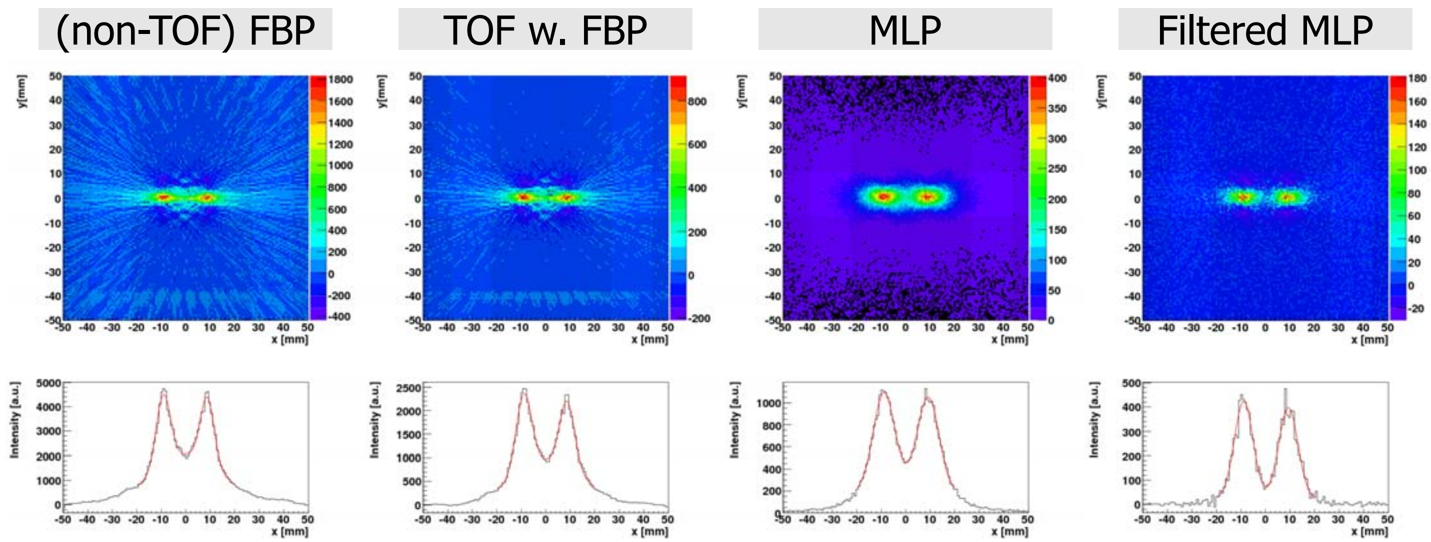
(typically ~ 30% for LSO)



NIM A654(2011)532

Reconstruction - experiment

Two ^{22}Na point sources at +10 mm and -10 mm 4x4 segmented, black painted PbF_2 radiators



→ A simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable image

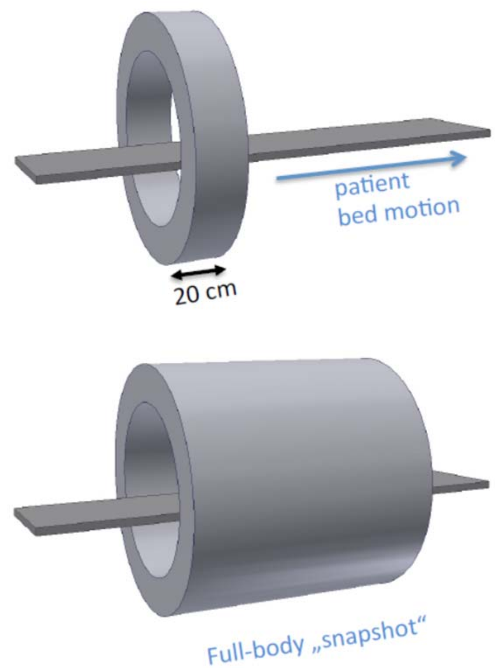
→ NIM A732 (2013) 595

Cherenkov based PET scanner?

PbF_2 not a scintillator → considerably cheaper!
Smaller attenuation length than LYSO – small parallax error

→ Cheaper normal scanner or
→ Total/half body device

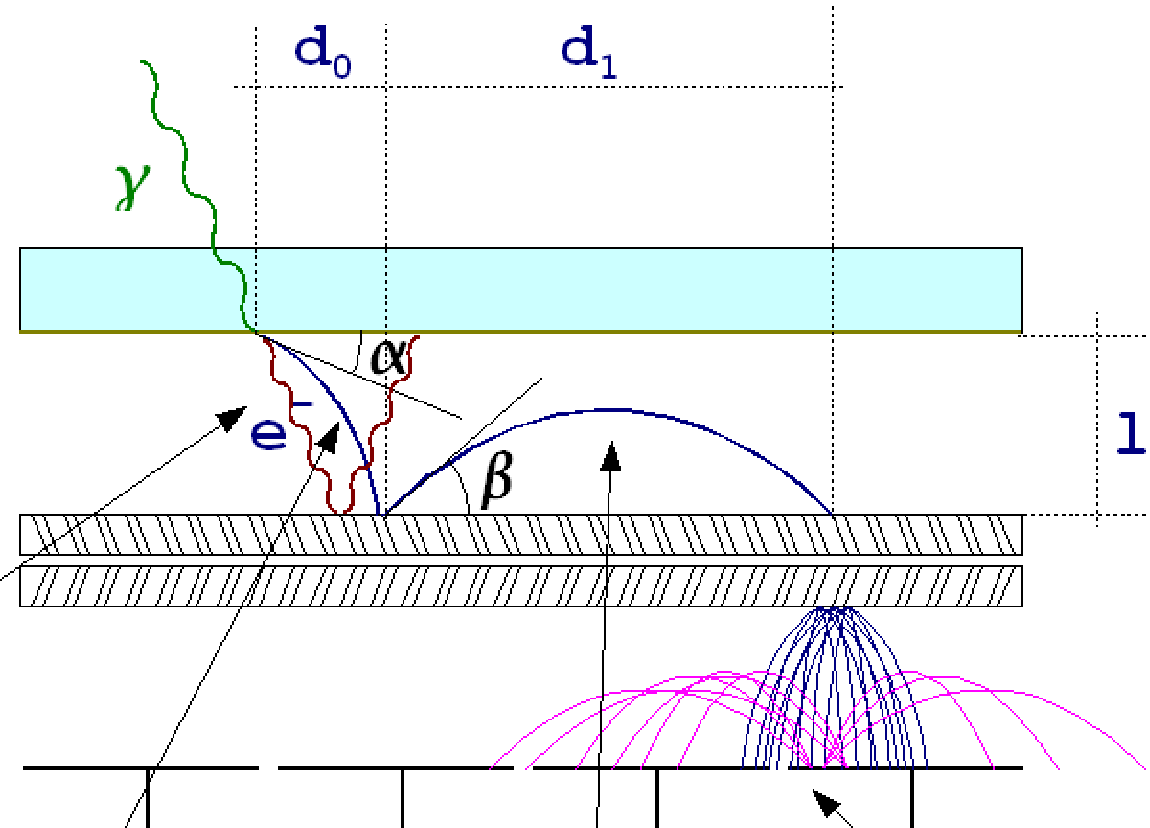
Extending axial FOV 20 cm → 200 cm:
estimated 6-fold increase in SNR →
- Better image quality
- OR Shorter scanning time
- OR Less injected activity: 8 mSv → 0.2 mSv



MCP PMT: processes involved in photon detection

Parameters used:

- $U = 200$ V
- $l = 6$ mm (K-MCP)
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As



Internal-reflection

Photo-electron:

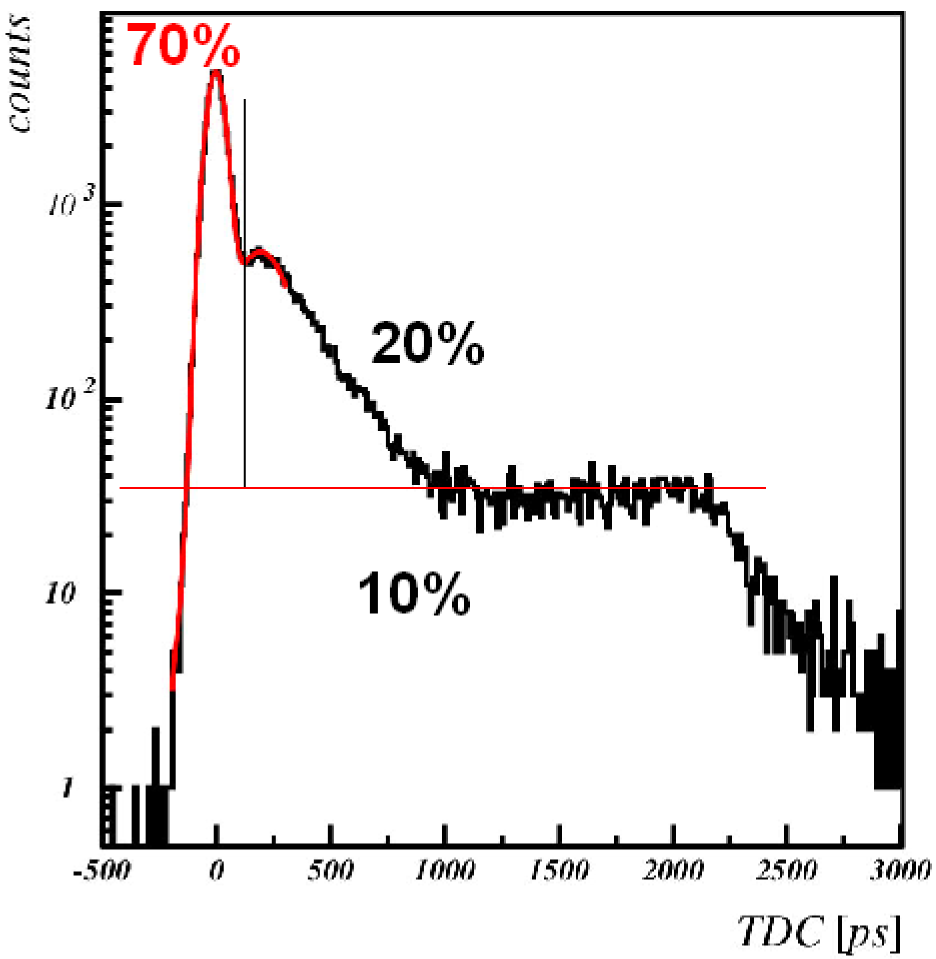
- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

Charge sharing

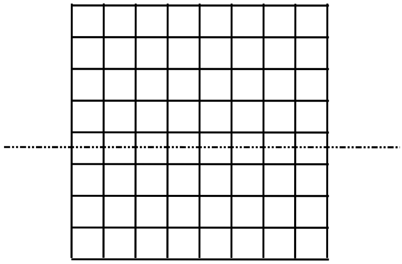
MCP PMT timing



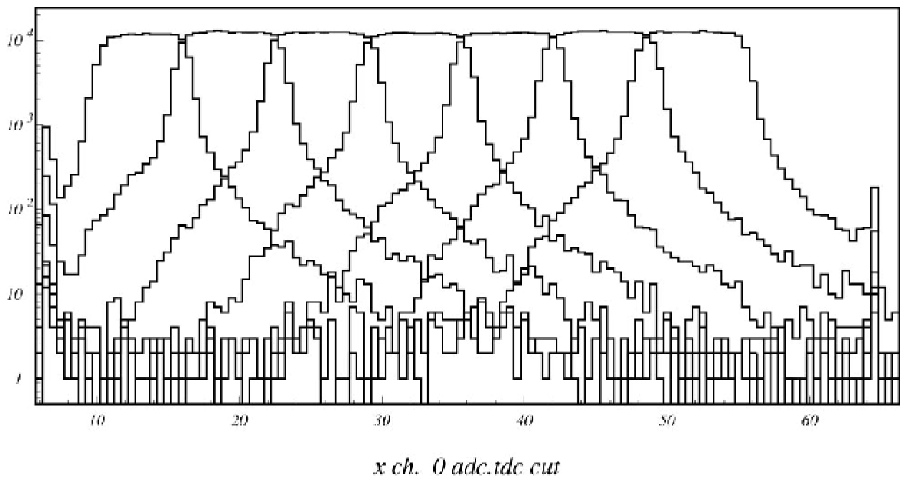
Tails understood (scattering of photoelectrons off the MCP), can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

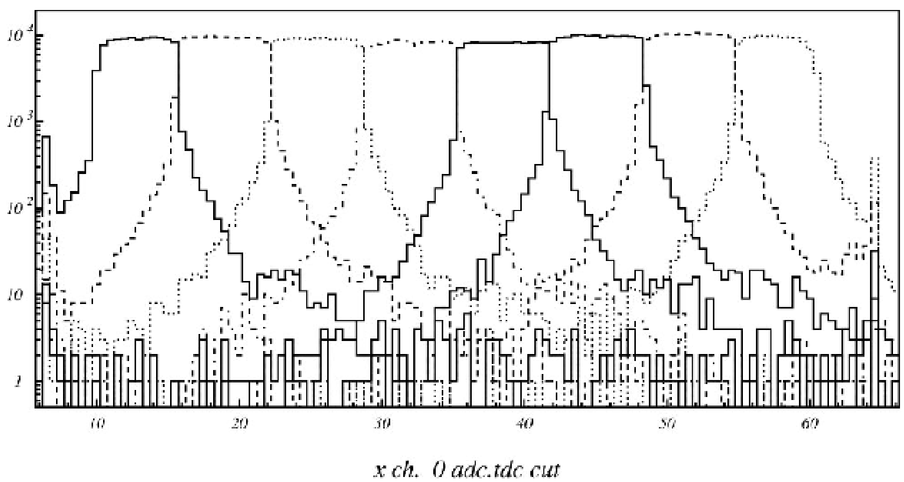


MCP PMT: sensitivity



Number of detected hits on individual channels as a function of light spot position.

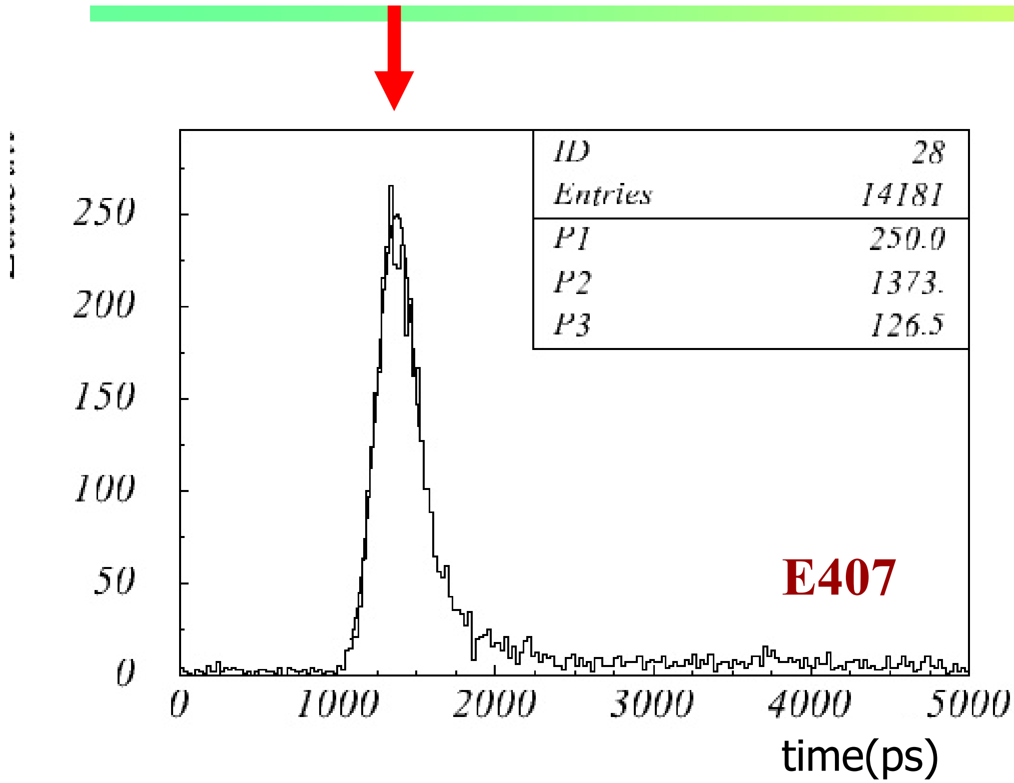
B = 0 T,
HV = 2400 V

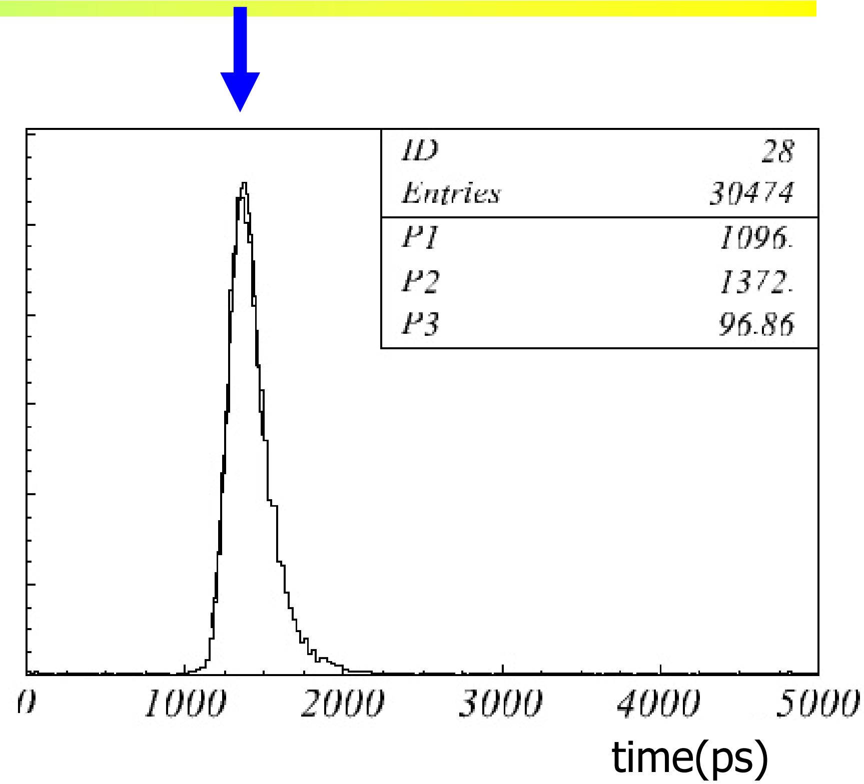


B = 1.5 T,
HV = 2500 V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

Time resolution: blue vs red



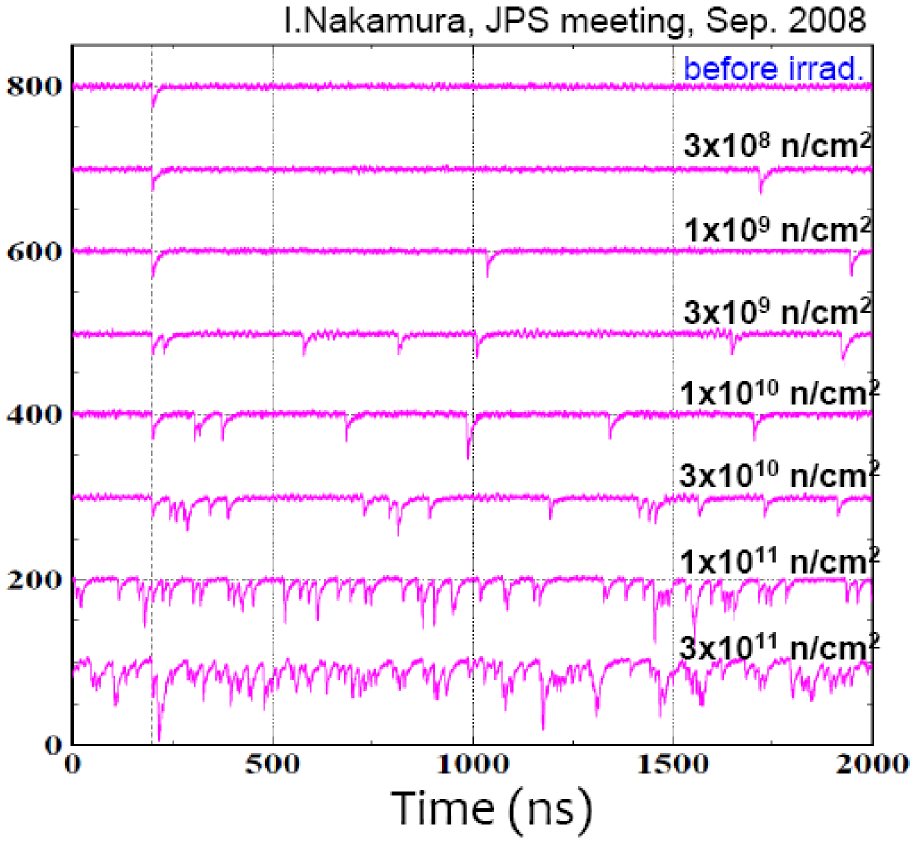


	E407	S137	H100C	H050C	H025C
σ_{red} (ps)	**127**	**182**	**145**	**212**	**154**
σ_{blue} (ps)	**97**	**151**	**136**	**358**	**135**

- $\sigma \approx 100$ ps

- $\sigma_{red} > \sigma_{blue}$

Radiation damage



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

→ Worst than the lowest line

→Very hard to use present SiPMs as single photon detectors in Belle II because of radiation damage by neutrons

→ Also: could only be used with a sofisticated electronics – wave-form sampling

COMPASS RICH-1 upgrade

Performance:

~ 60 detected photons per ring at saturation (β = 1) → N_0 ~66 cm^{-1}

σ_θ ~ 0.3 mrad → 2 σ π-K separation at ~ 60 GeV/c

K-ID efficiency ($K^\pm$ from Φ decay) > 90%

π → K misidentification ($\pi^\pm$ from K_s decay) ~ 1 %