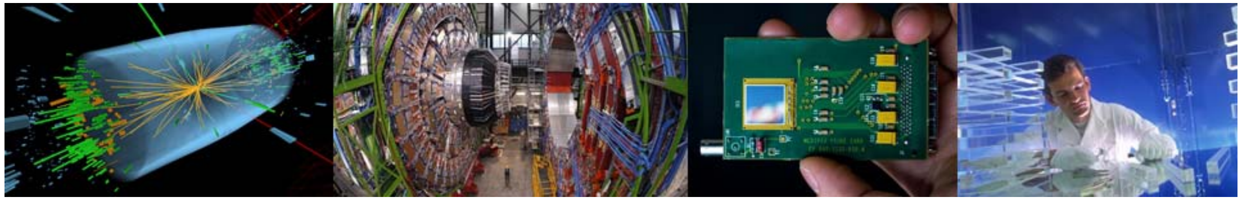
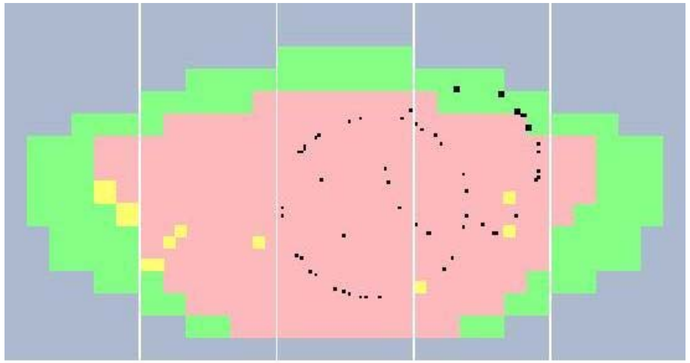


XII ICFA SCHOOL ON INSTRUMENTATION IN ELEMENTARY PARTICLE PHYSICS
BOGOTÁ, November 25th – December 6th, 2013



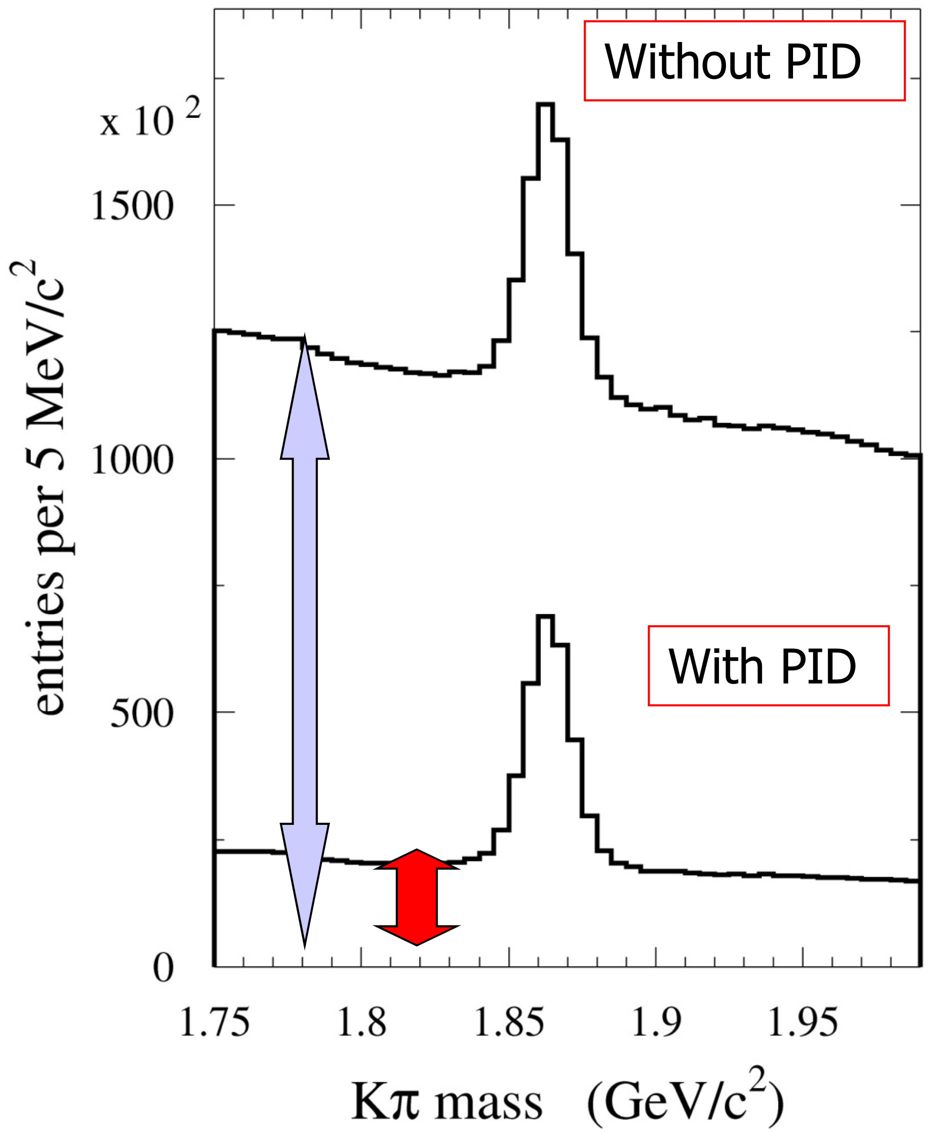
Particle Identification

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

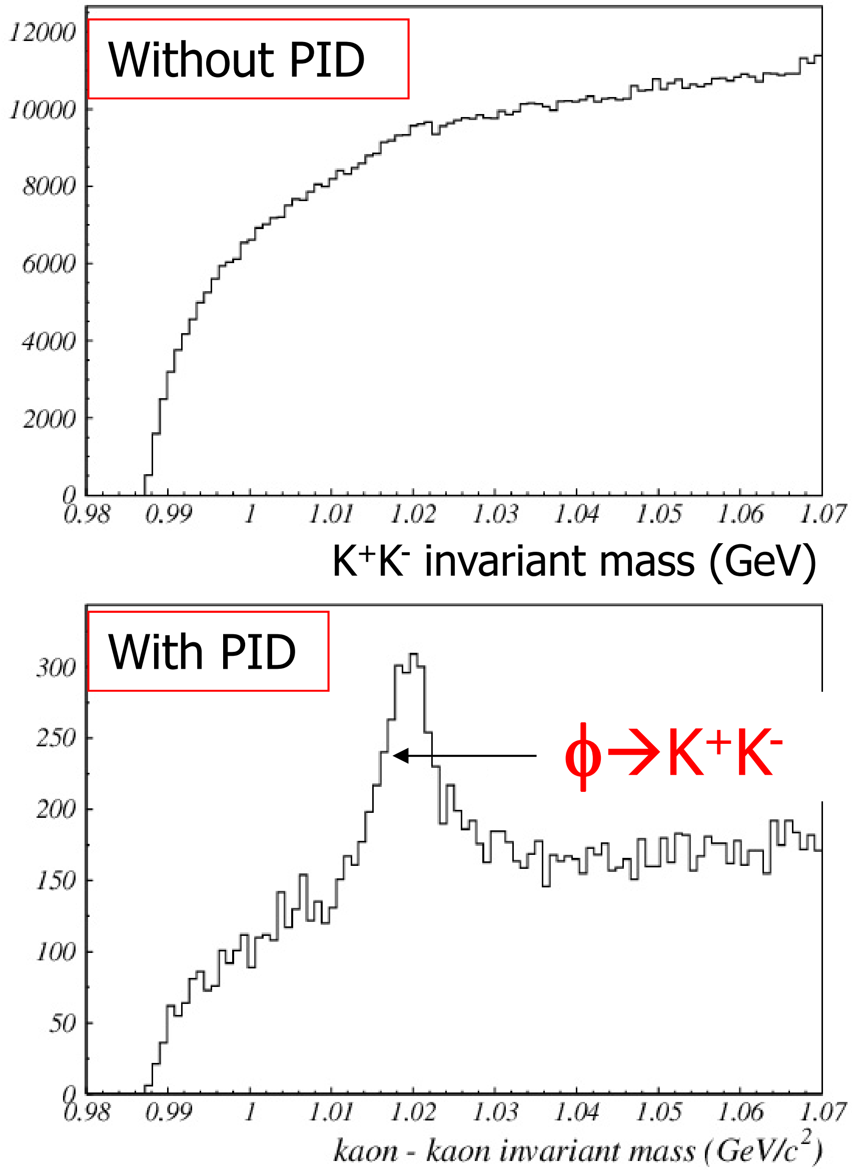
Why particle ID?



Example 1: B factory

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

Why particle ID?

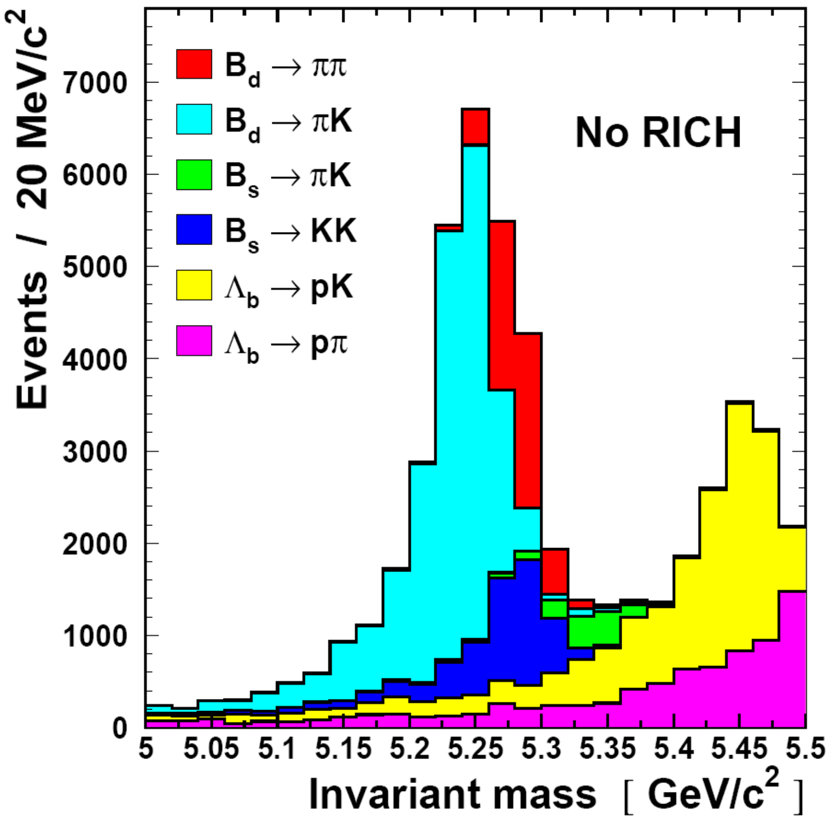


Example 2: HERA-B

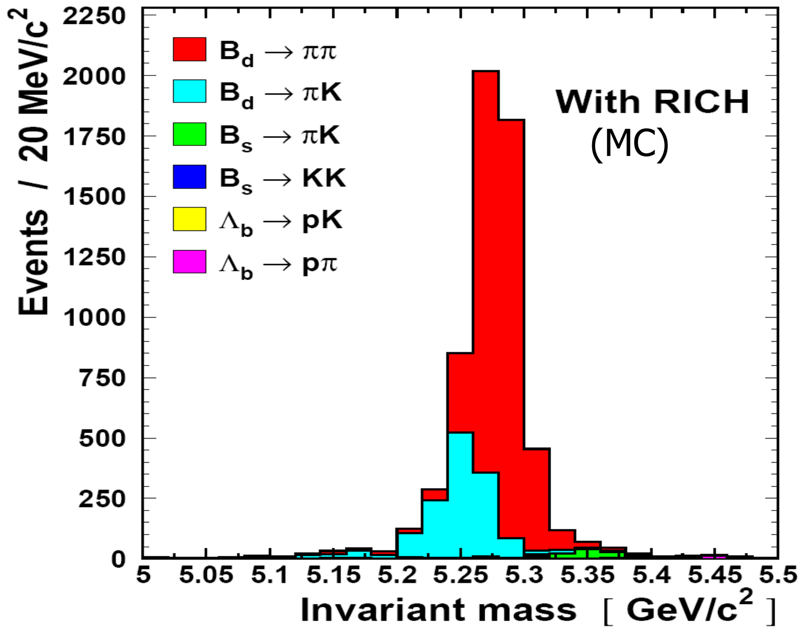
K^+K^- invariant mass.

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

Why particle ID?



Example 3: LHCb



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

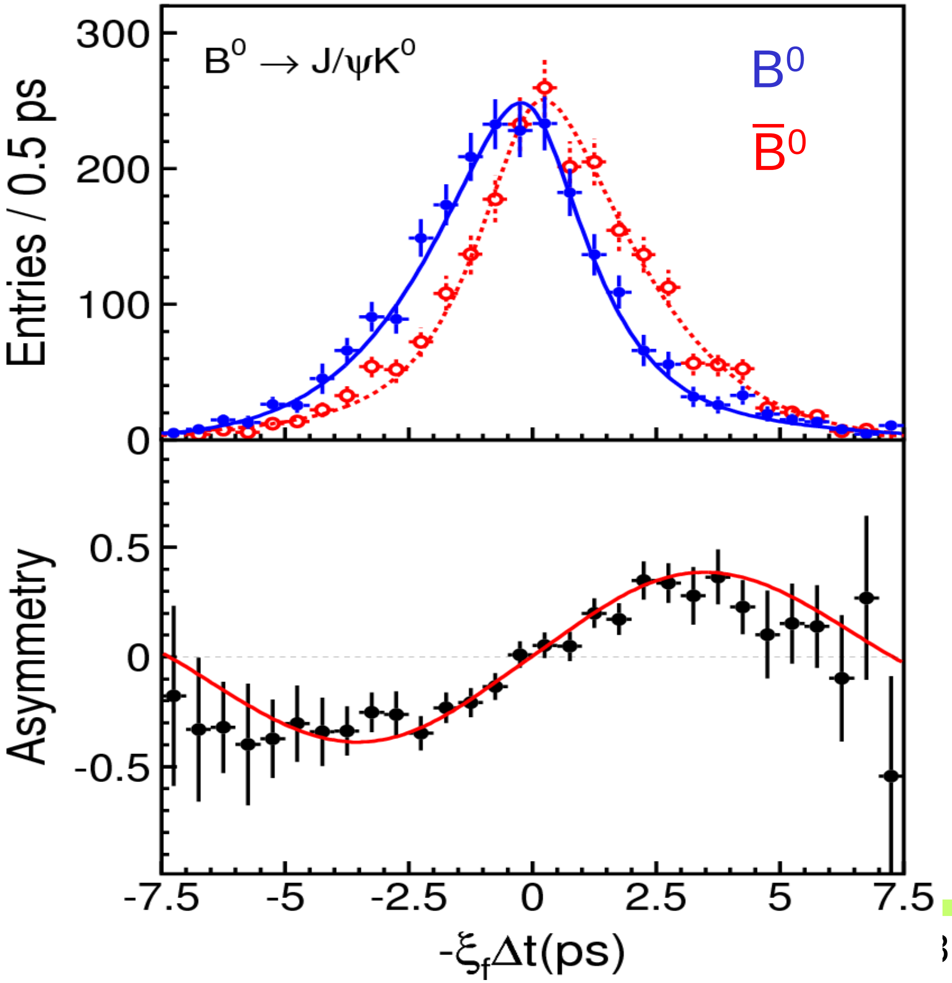
Why particle ID?

PID is also needed in:

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

Why particle ID?

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

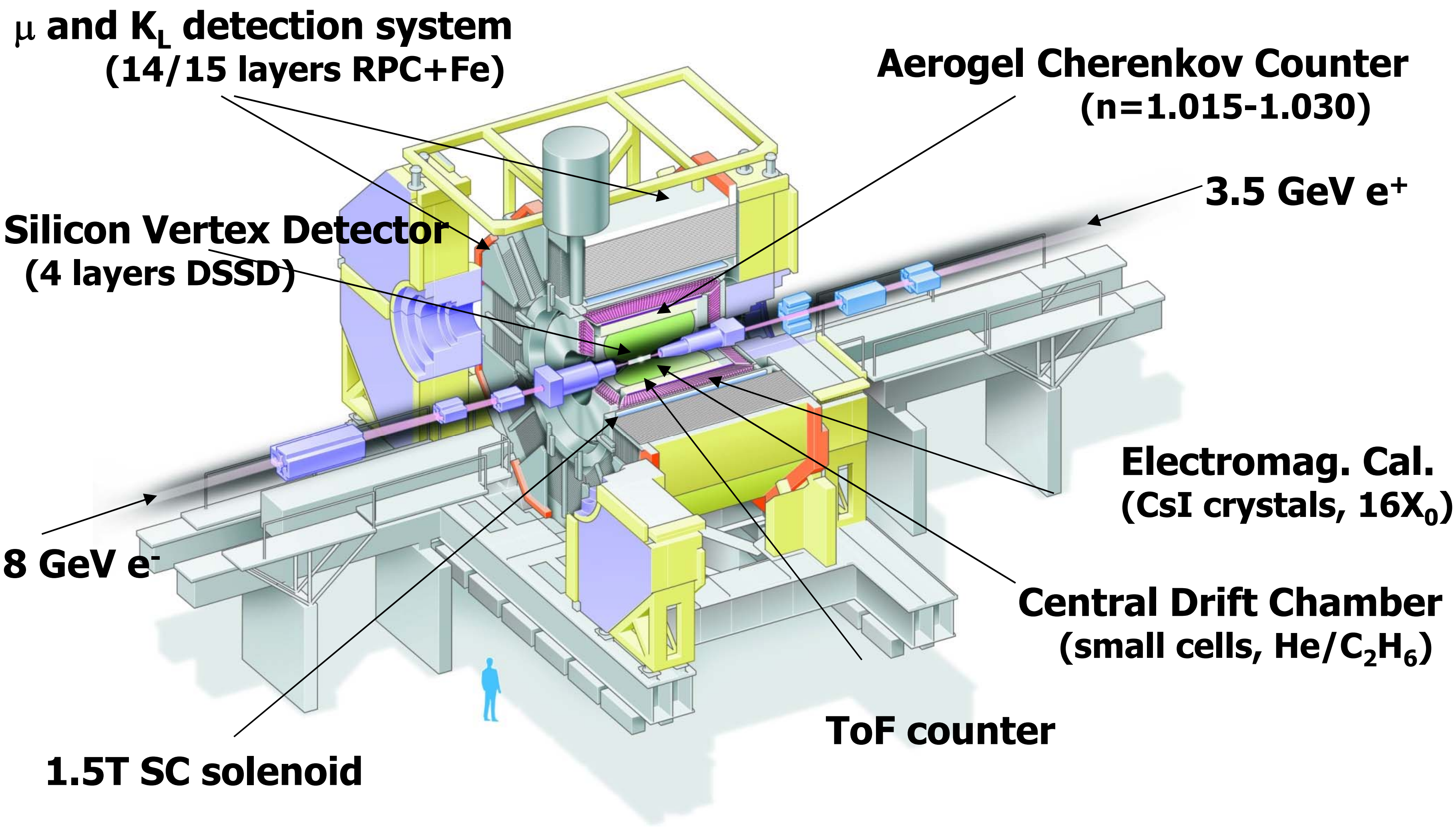


B^0 and its anti-particle decay differently to the same final state $J/\psi\ K^0$

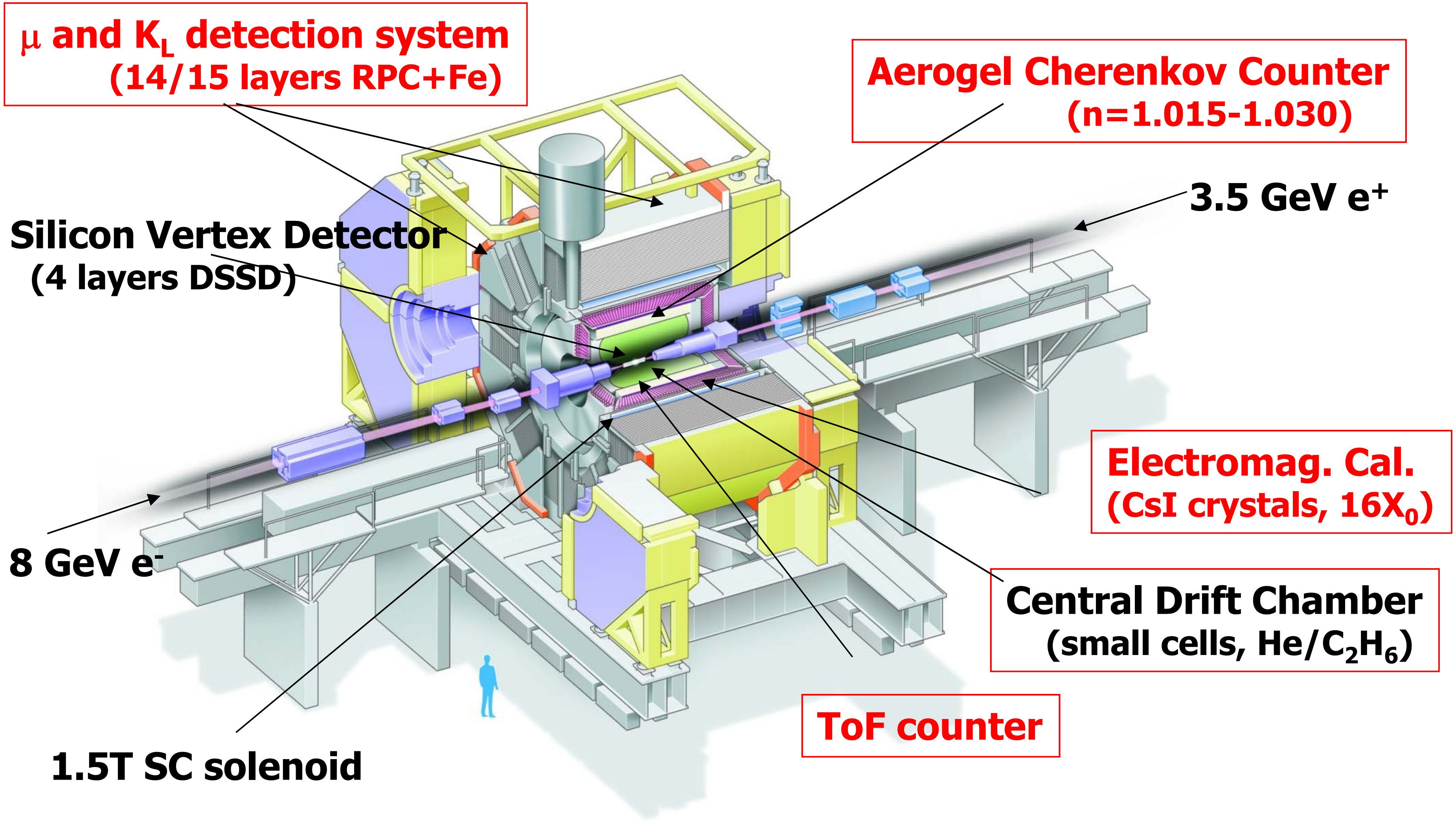
Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

→particle ID is compulsory

Example: Belle

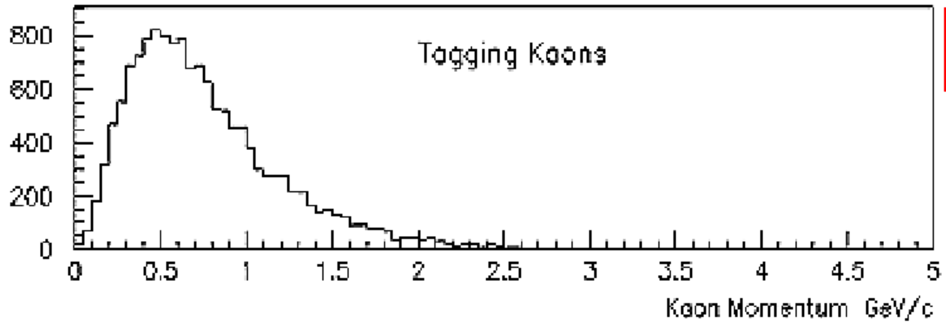


Particle identification systems in Belle



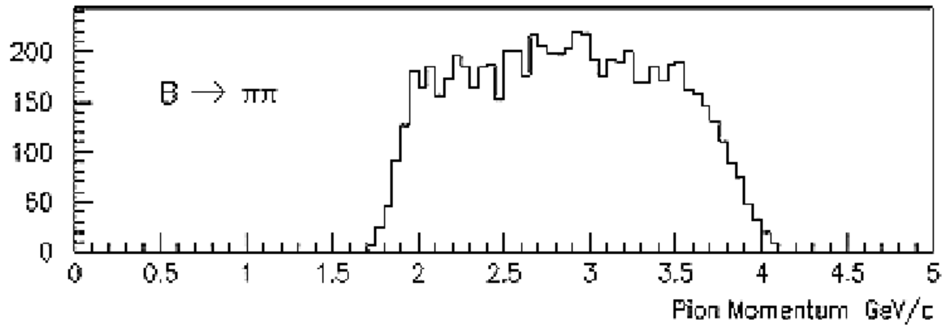
Particle identification methods depend on the requirements (physics channel, kinematics)

Example: B factory, pion/kaon separation



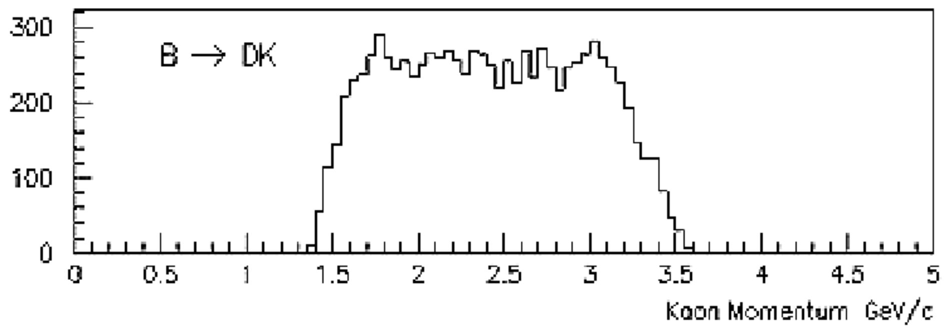
Tagging Kaons

Relatively soft, ms dominated for tracking



$B \to \pi\pi$

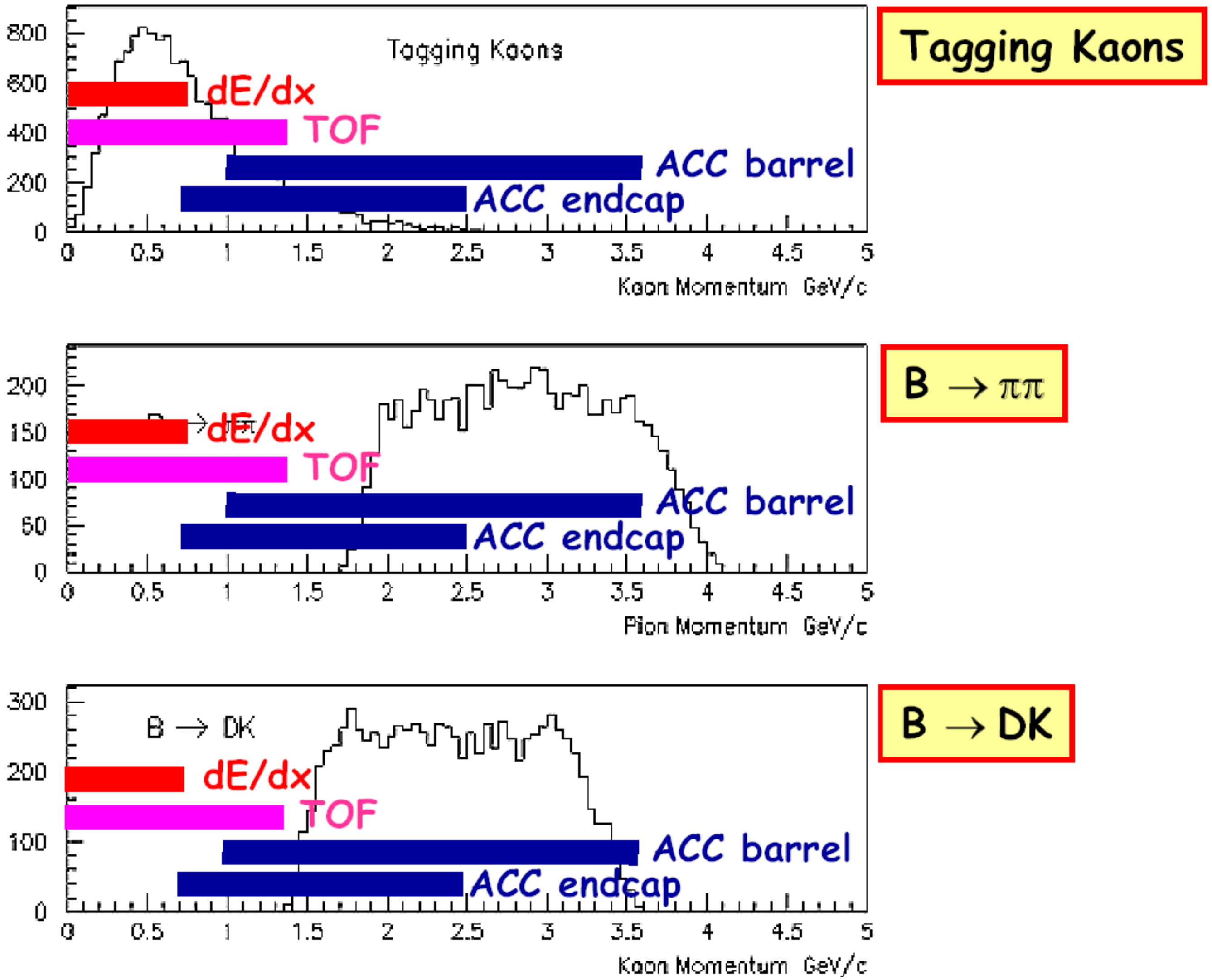
Requires dedicated PID



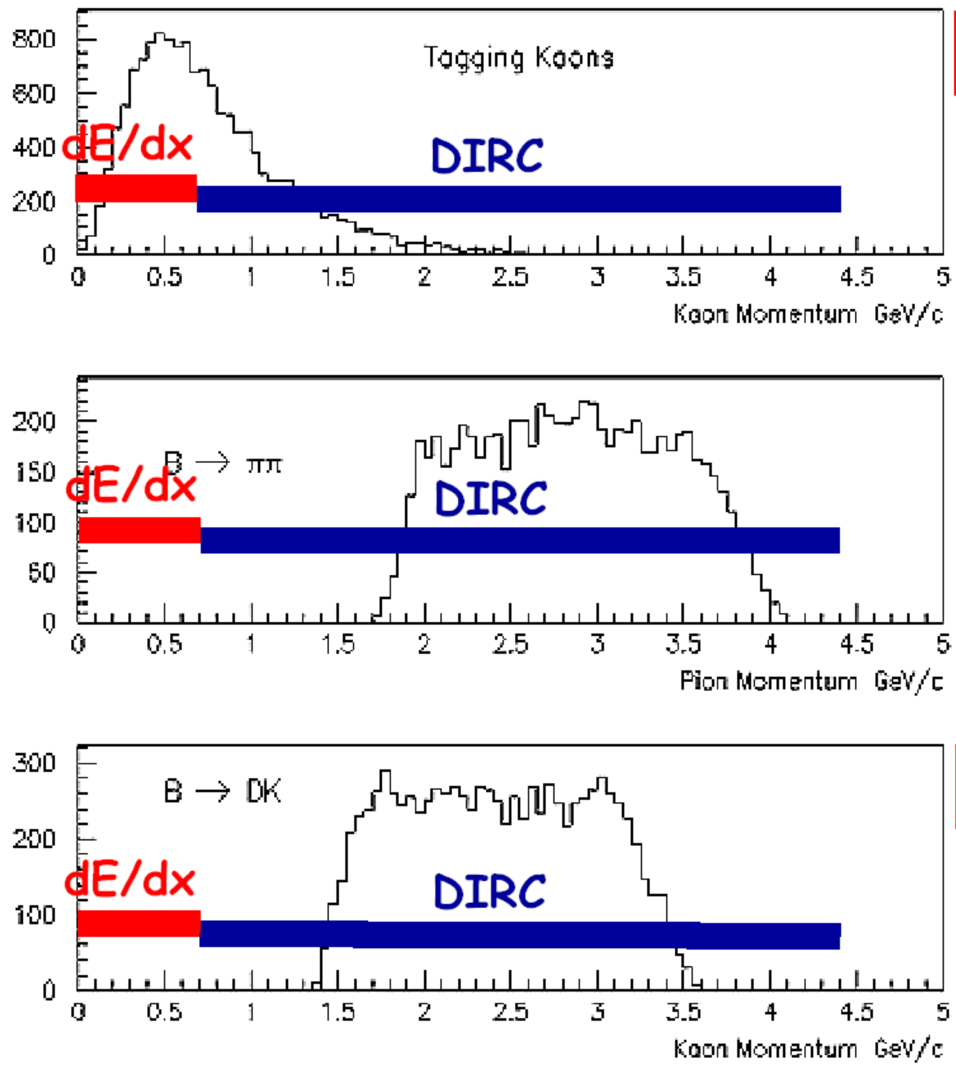
$B \to DK$

Requires dedicated PID

PID coverage of kaon/pion spectra in Belle



PID coverage of kaon/pion spectra in BaBar



Tagging Kaons

$B \to \pi\pi$

$B \to DK$

Identification of charged particles

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

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

→Measure velocity by:

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

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters (→lectures by Francesco Lanni)

Lectures

Because my lectures fortunately come rather late in this school, you are already well equipped for understanding a lecture on particle identification:

» Interaction of charged particles with matter (C. Joram)
» Detection of light (C. Joram)
» Gas detectors (M. Capeans)
» Silicon detectors (M. Krammer)
» Physics motivation and requirements (L. Rolandi, Z. Doležal)

Some of you already had lab courses related to this lecture (Cherenkov detectors, SiPMs, gas detectors)

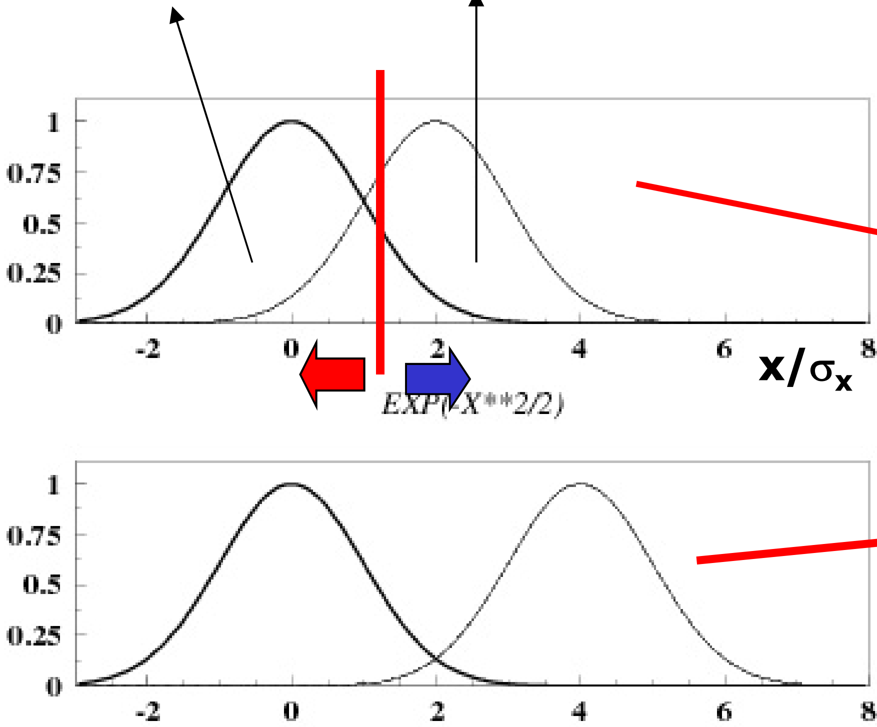
Efficiency and purity in particle identification

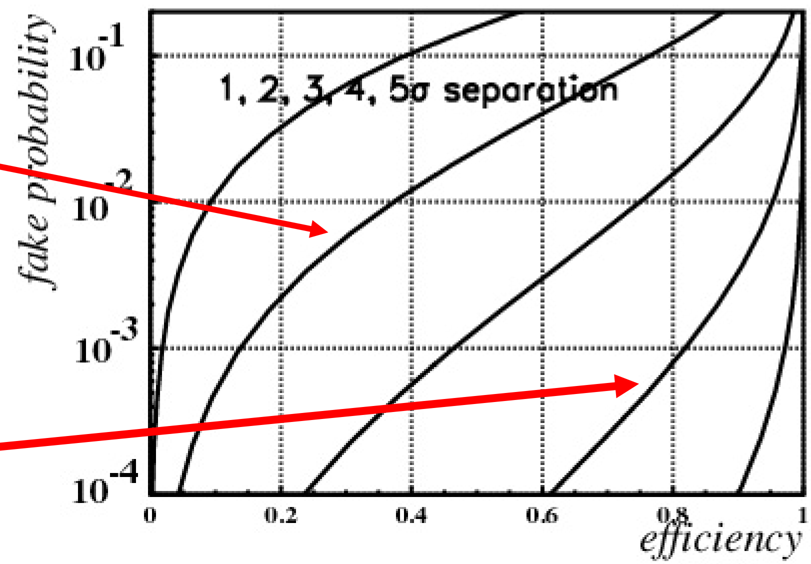
Efficiency and purity are tightly coupled!

Two examples:

particle type 1 type 2

eff. vs fake probability
(for Gaussian distributions)





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

Identification of charged particles

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Identification through interaction: electrons and muons

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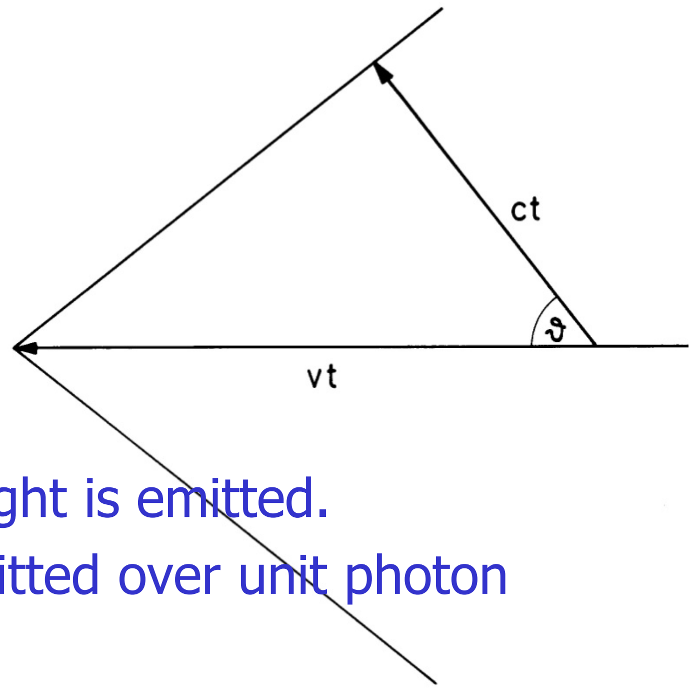
Cherenkov radiation

A charged track with velocity $v=\beta c$ 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:

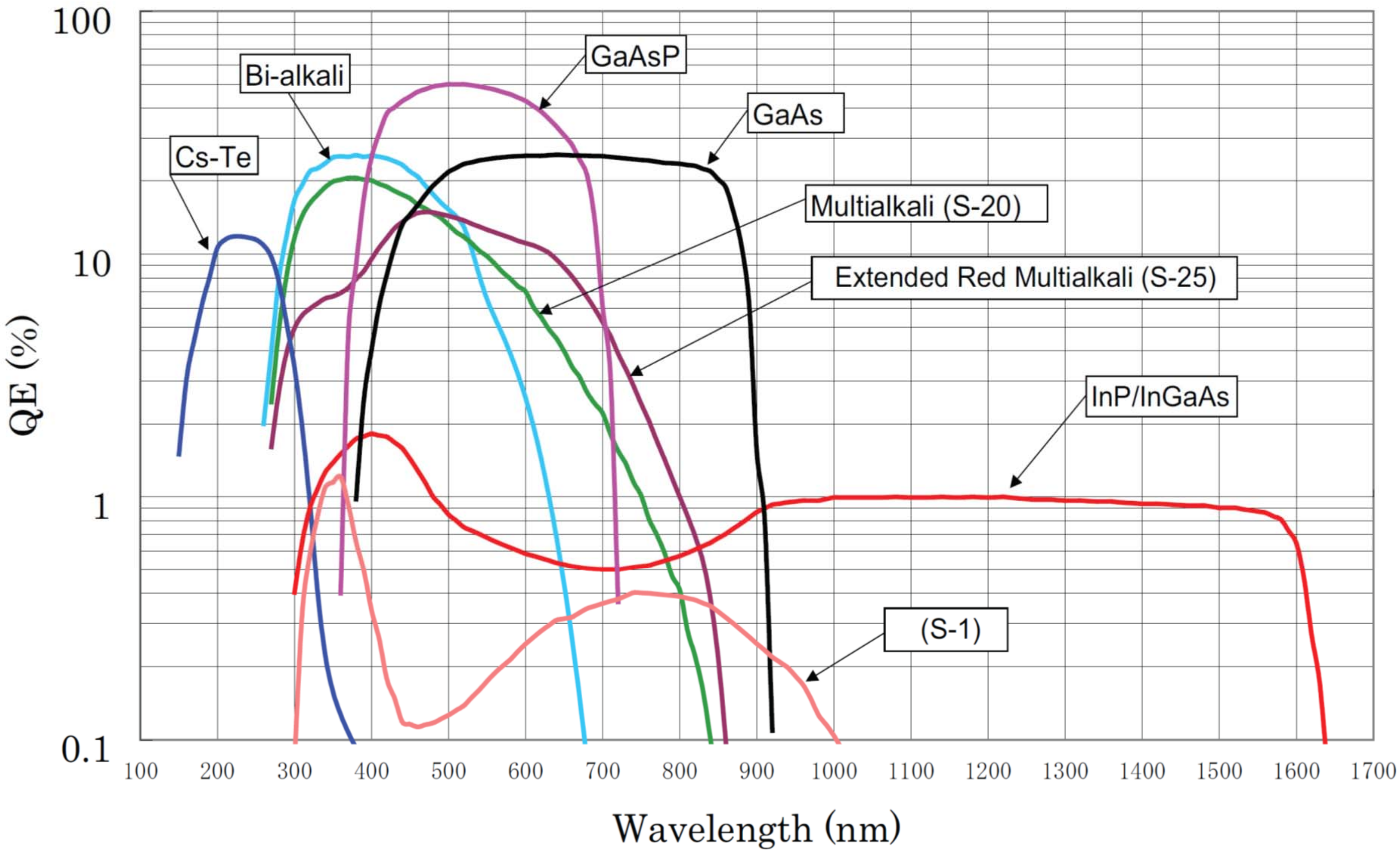
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

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

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

→Few detected photons

Quantum efficiency



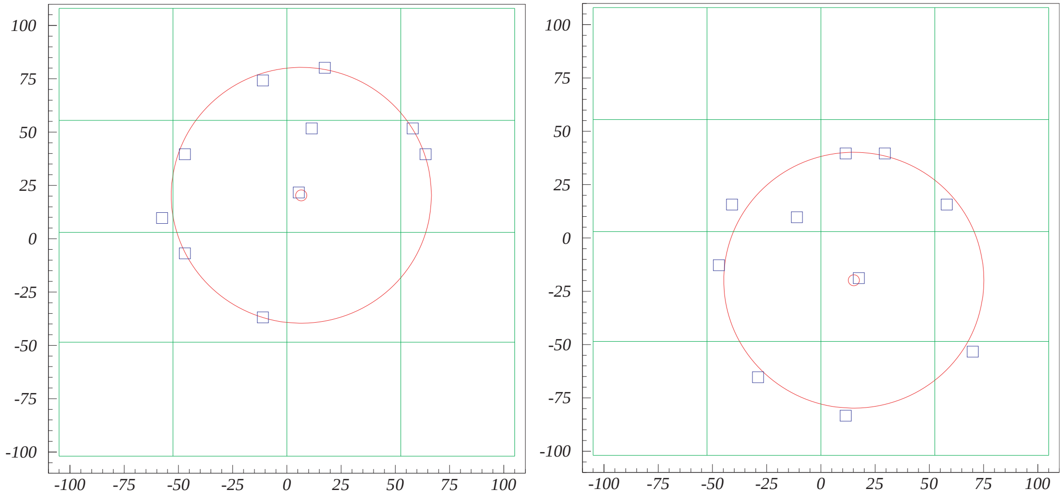
Number of detected photons

Example: in 1m of air (n=1.00027) a track with $\beta=1$ 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

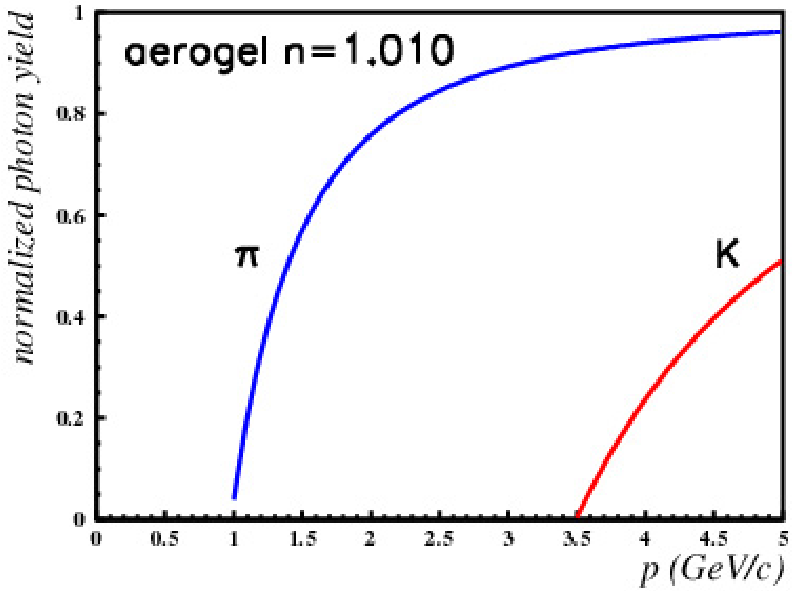
→Important to have a low noise detector



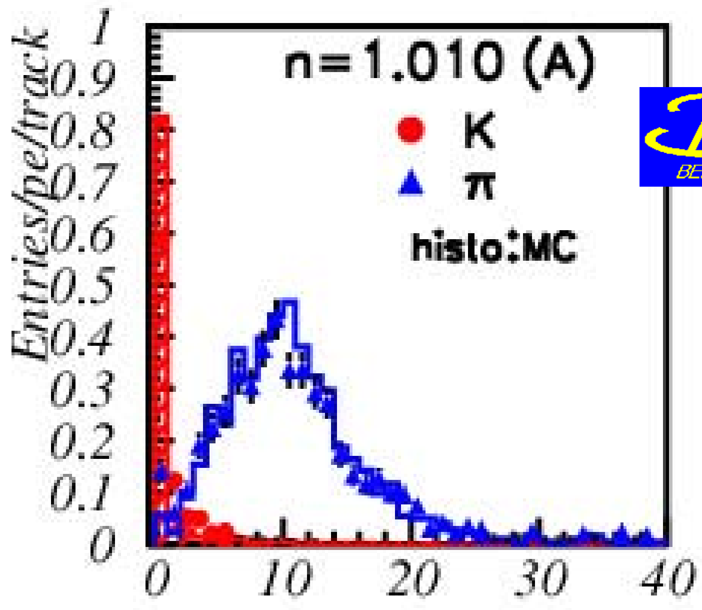
Threshold Cherenkov counter

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

Photon yield vs p



Choice of n: depends on the momentum range.

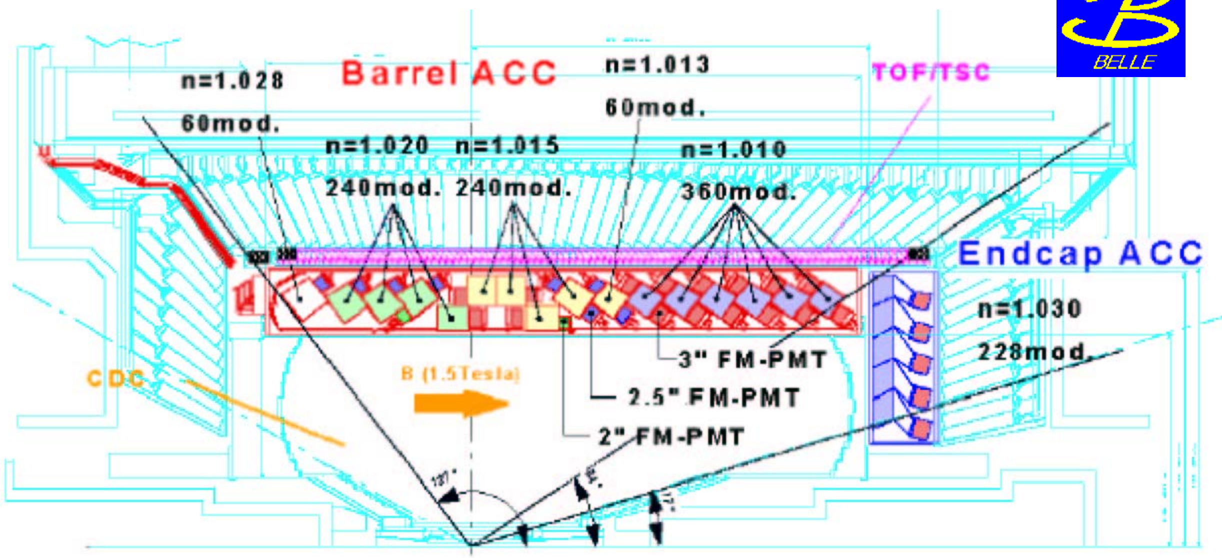


→ Good separation between pions (light) and kaons (no light) between ~1.5 GeV/c and 3.5 GeV/c

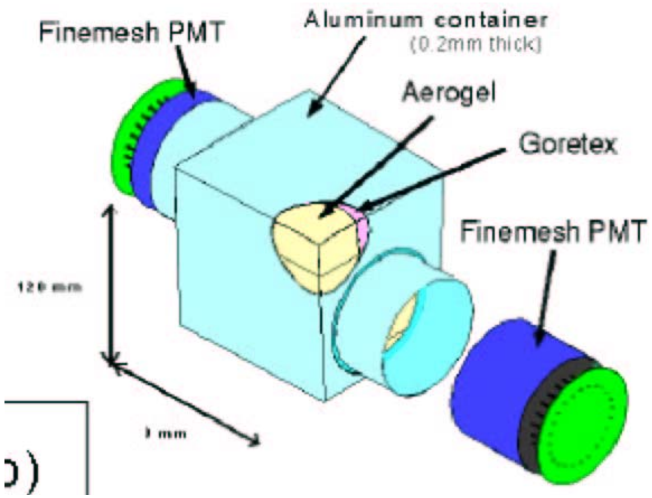
Belle: Threshold Cherenkov counter, ACC (aerogel Cherenkov counter)

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

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



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



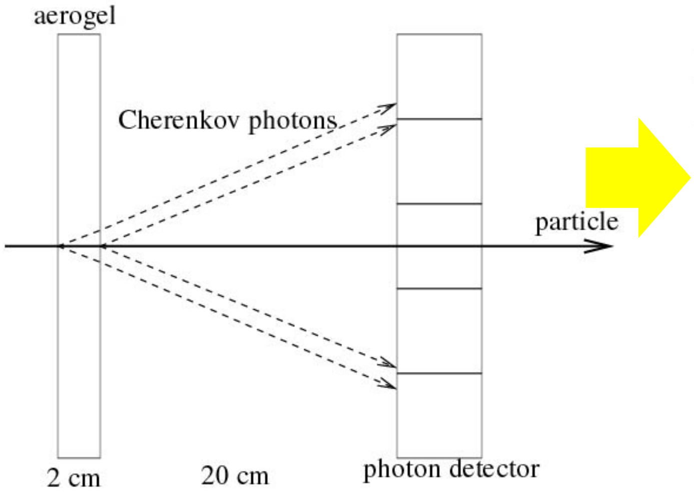
Fine-mesh PMT: works in high B fields (1.5 T)

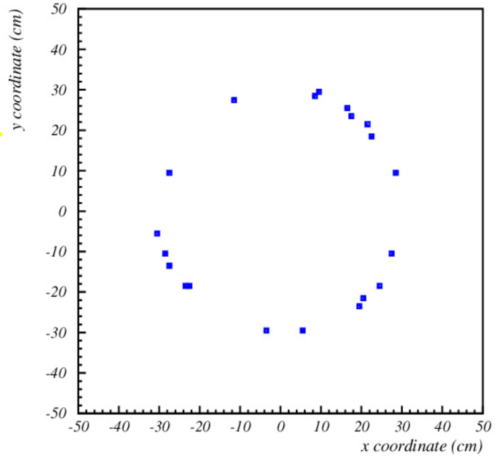
Measuring the Cherenkov angle

Particles above threshold: measure θ

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

→ Ring Imaging Cherenkov (RICH) counter

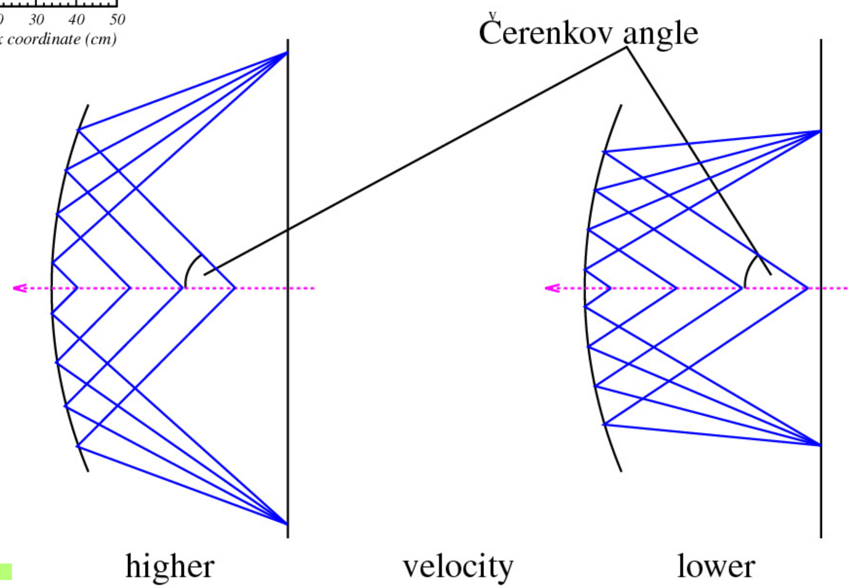




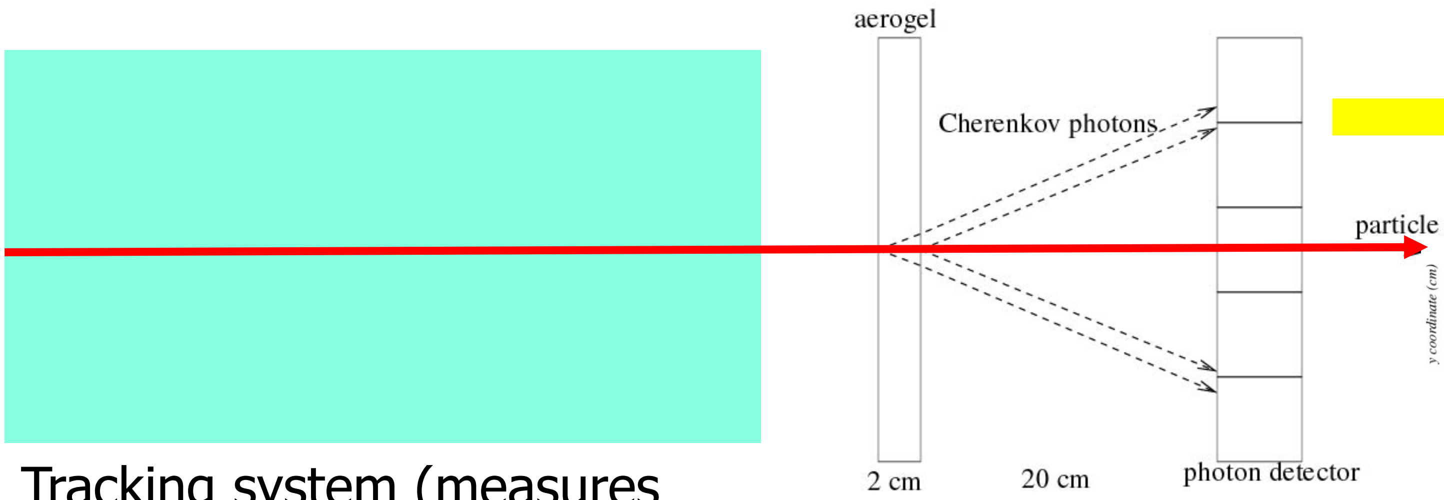
Proximity focusing RICH

RICH with a

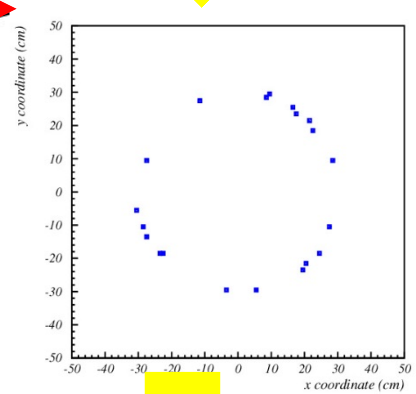
focusing mirror



Measuring the Cherenkov angle

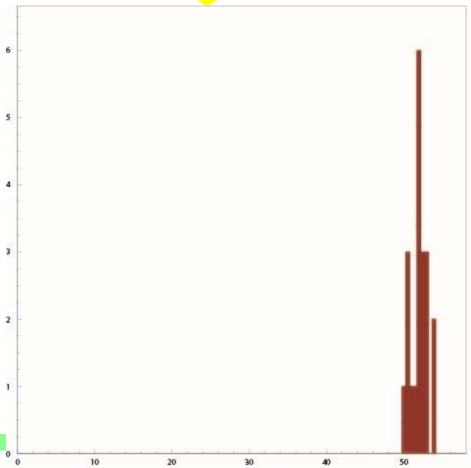


Tracking system (measures direction of the particle)

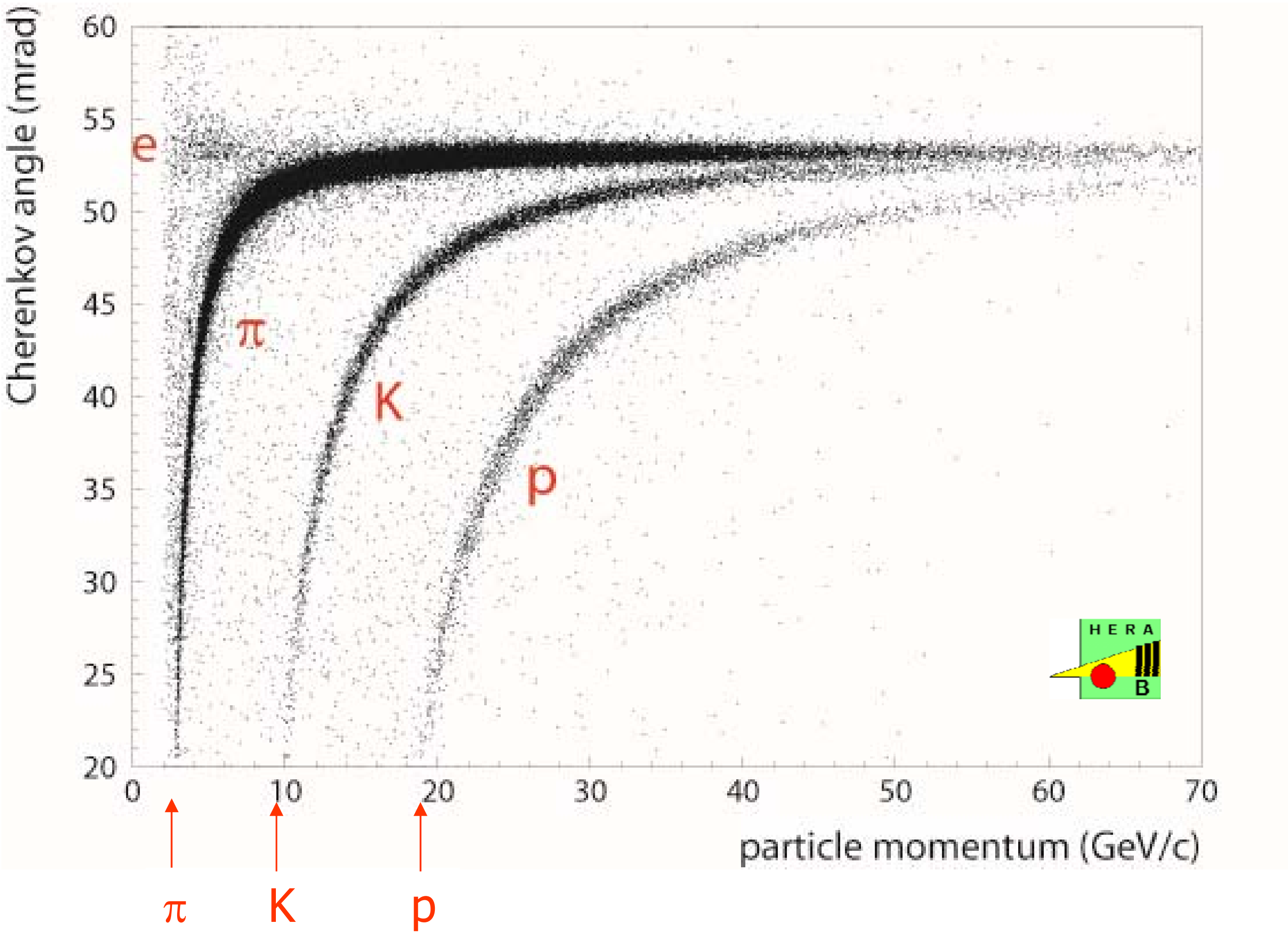


Tracking system tells us where the particle hit the radiator, and at which angle.

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



Measuring Cherenkov angle



thresholds

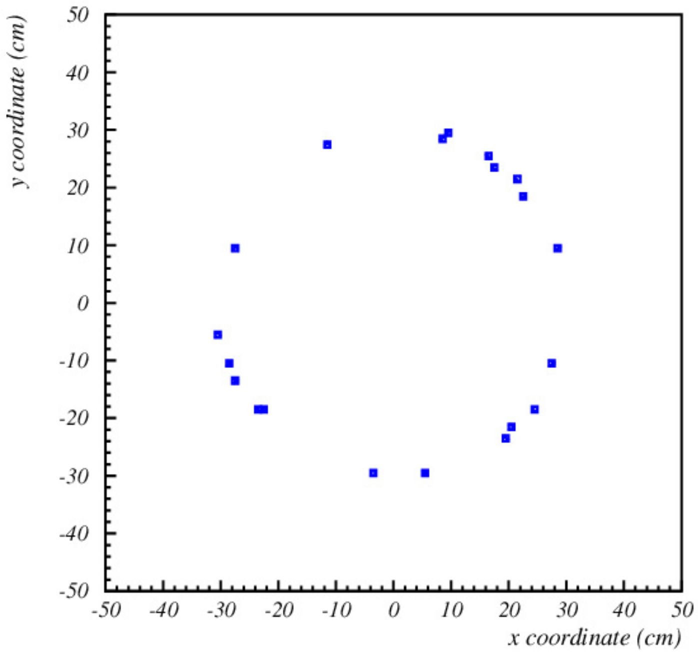
Radiator:
C_4F_{10} gas

Photon detection in RICH counters

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

→ detection of single photons with

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



Special requirements:

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

Photon detector is the most crucial element of a RICH counter

Resolution of a RICH counter

Determined by:

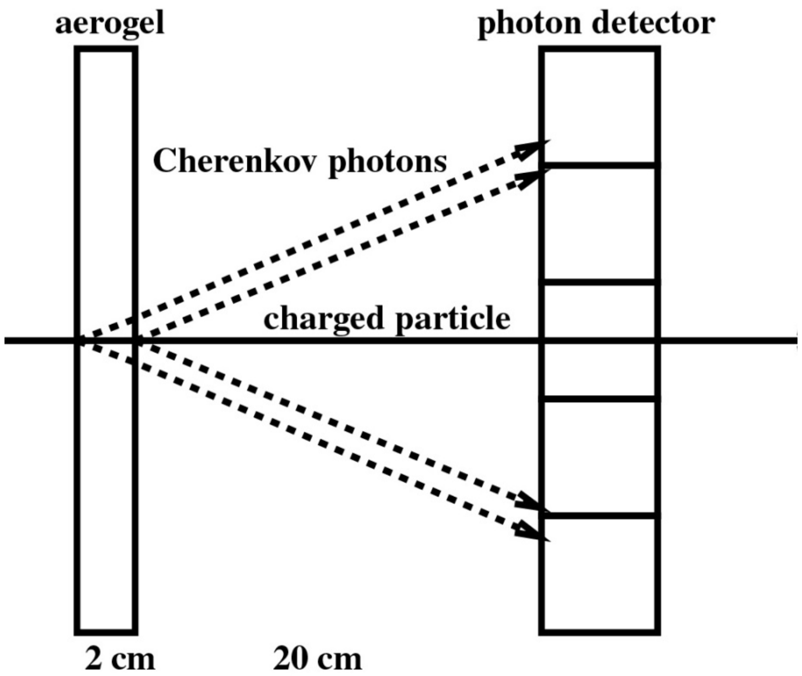
•Photon impact point resolution (~photon detector granularity)

•Emission point uncertainty (not in a focusing RICH)

•Dispersion: $1/\beta = n(\lambda)\cos\theta$

•Errors of the optical system

•Uncertainty in track parameters



Resolution per track:

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

single photon resolution

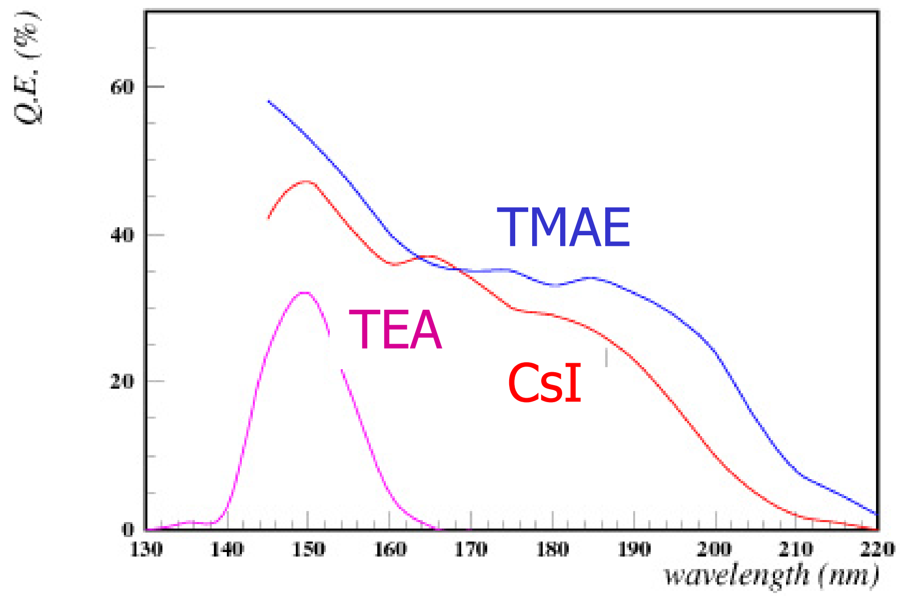
# of detected photons

(in the case of low background)

First generation of RICH counters

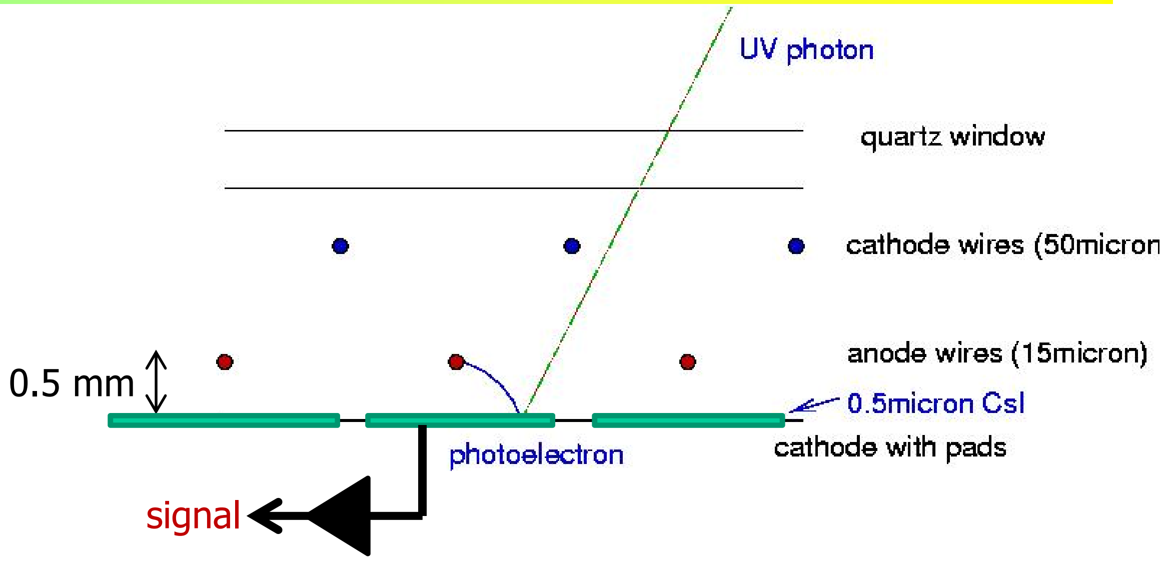
DELPHI, SLD, OMEGA RICH counters: all employed wire chamber based photon detectors (UV photon → photo-electron → detection of a single electron in a TPC)

Photosensitive component:
TMAE added to the gas mixture



Fast RICH counters with wire chambers

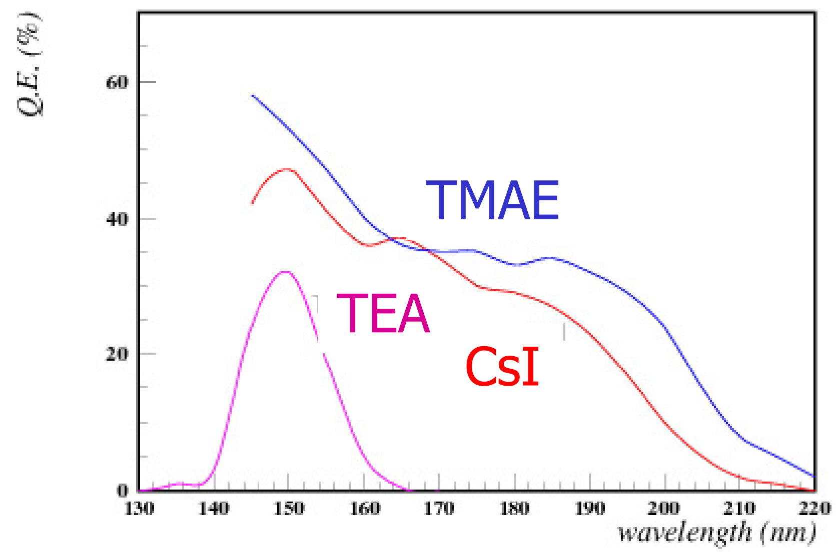
Multiwire chamber with
cathode pad read-out:
→ short drift distances,
fast detector



Photosensitive component:

•in the gas mixture (TEA):
CLEOIII RICH

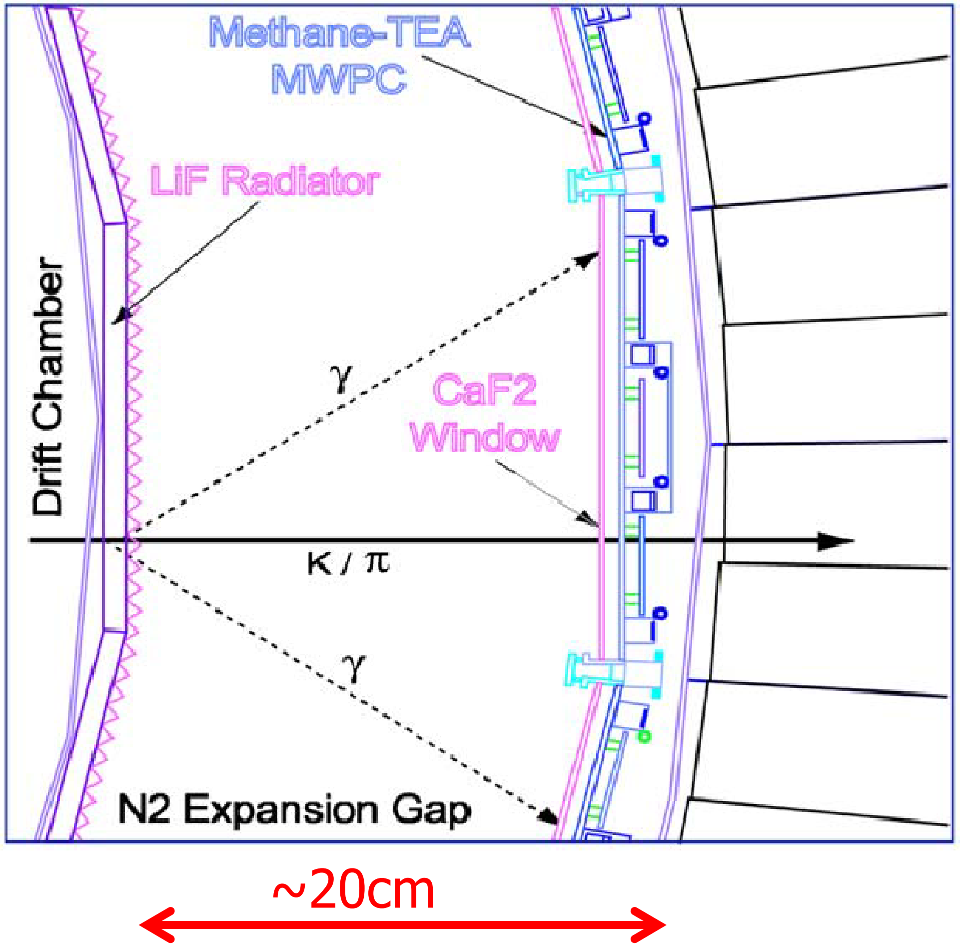
•or a layer on one of the cathodes (CsI on the printed circuit cathode with pads) →



Works in high magnetic field!

CLEOIII RICH

Photon detection in a wire chamber with a methane+TEA mixture. Technique pioneered by T. Ypsilantis and J. Seguinot

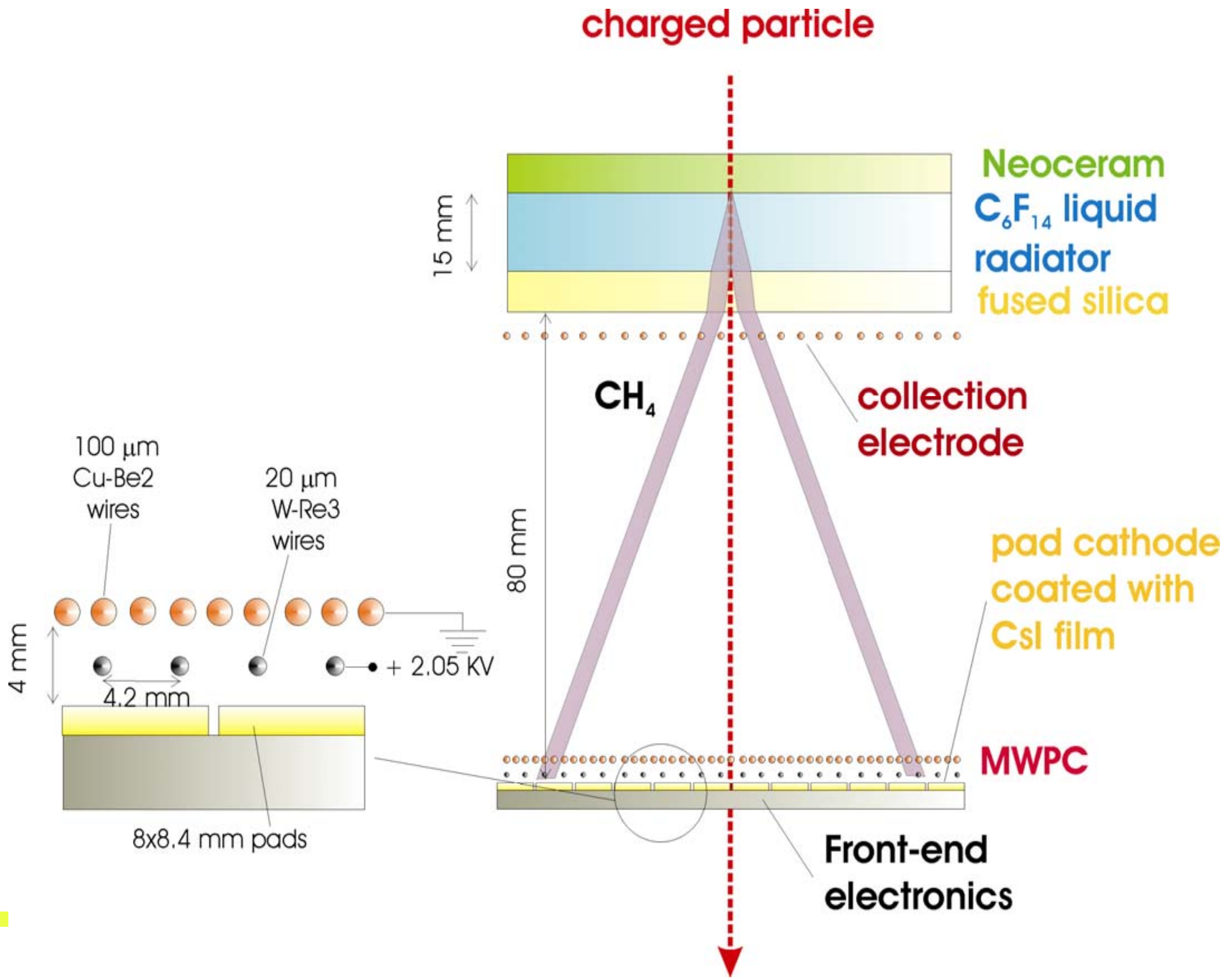


CsI based RICH counters: HADES, COMPASS, ALICE

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

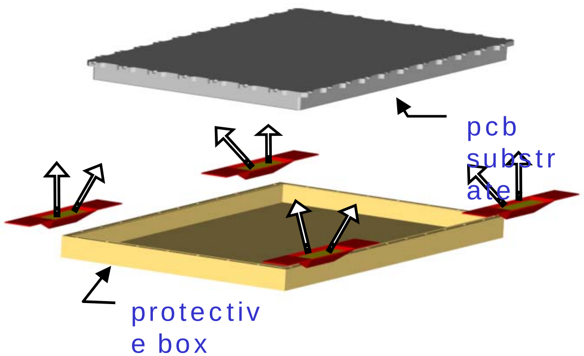
ALICE:

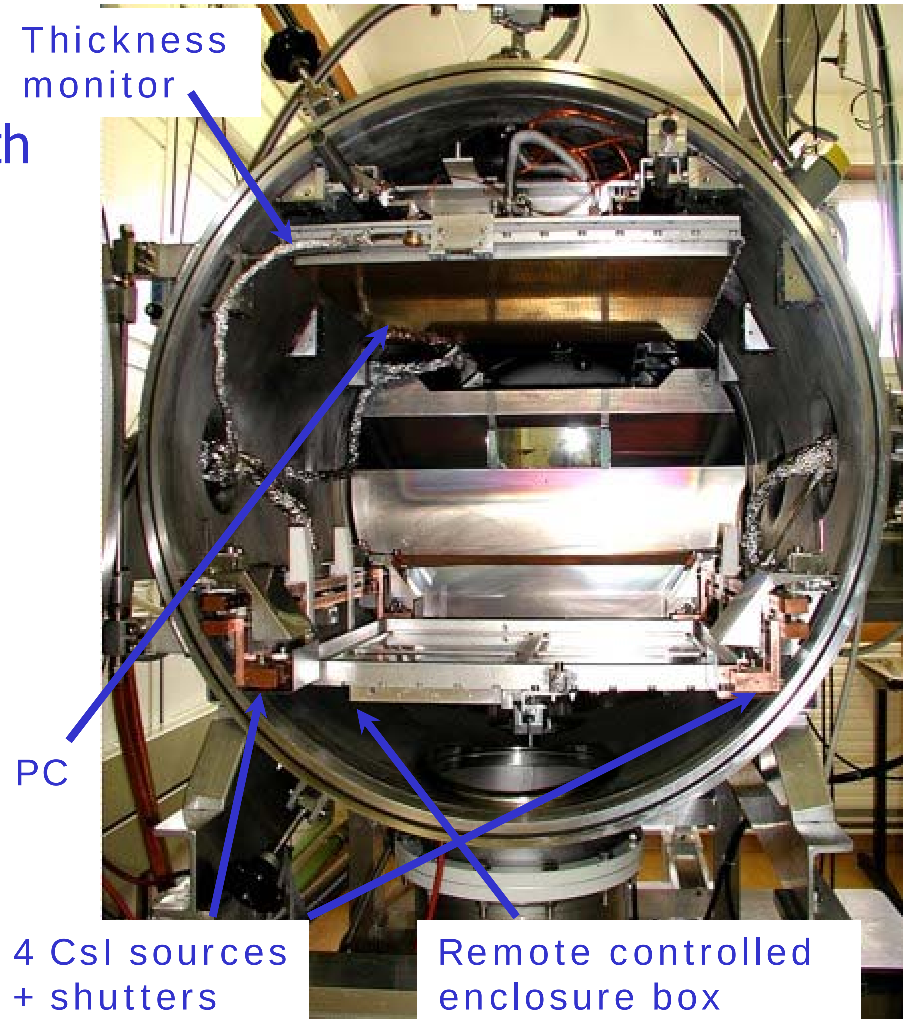
- liquid radiator
- proximity focusing



CERN CsI deposition plant

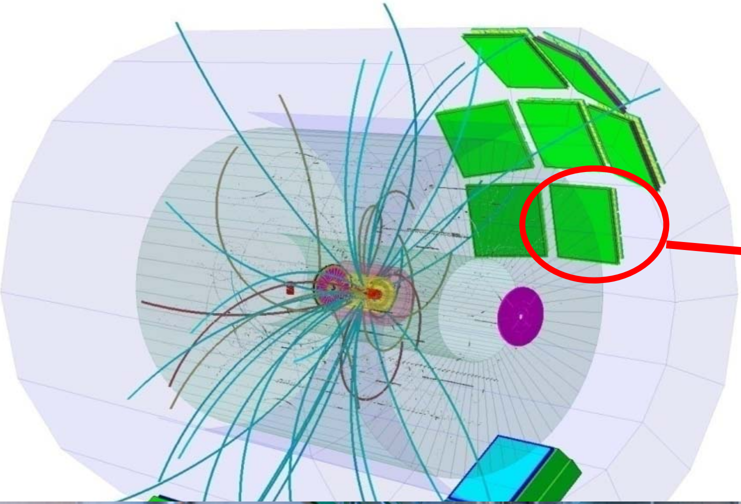
Photocathode produced with a well defined, several step procedure, with CsI vaccum deposition and subsequent heat conditioning



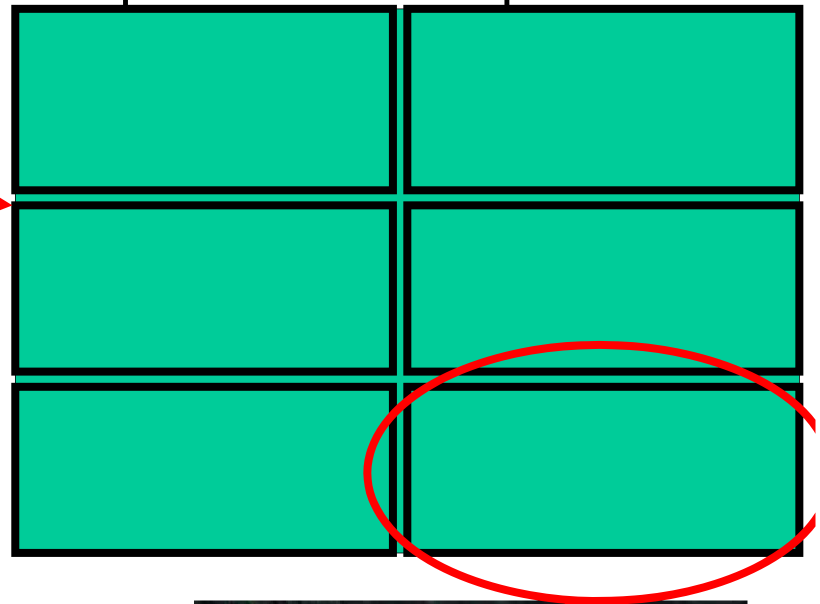


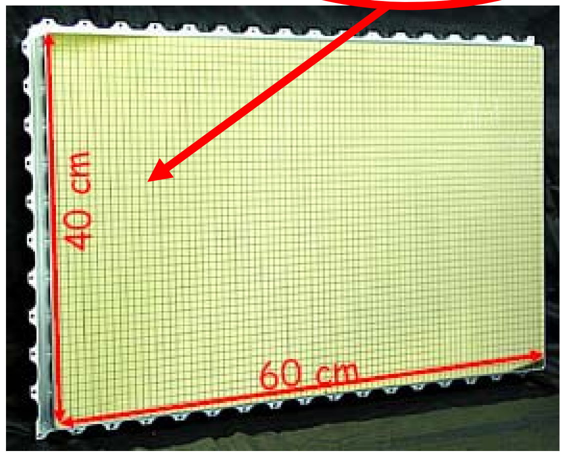
ALICE RICH = HMPID

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



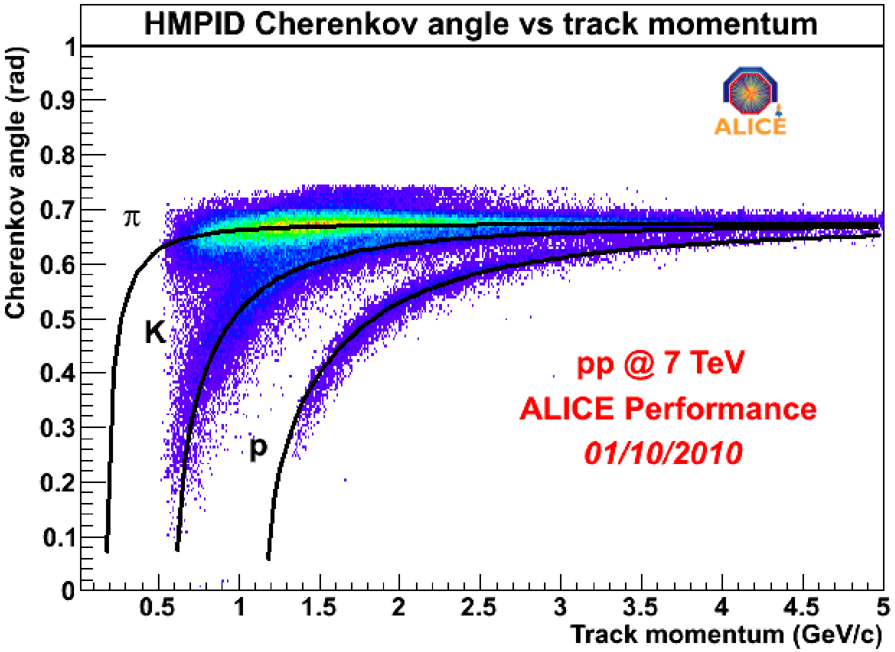
Six photo-cathodes per module

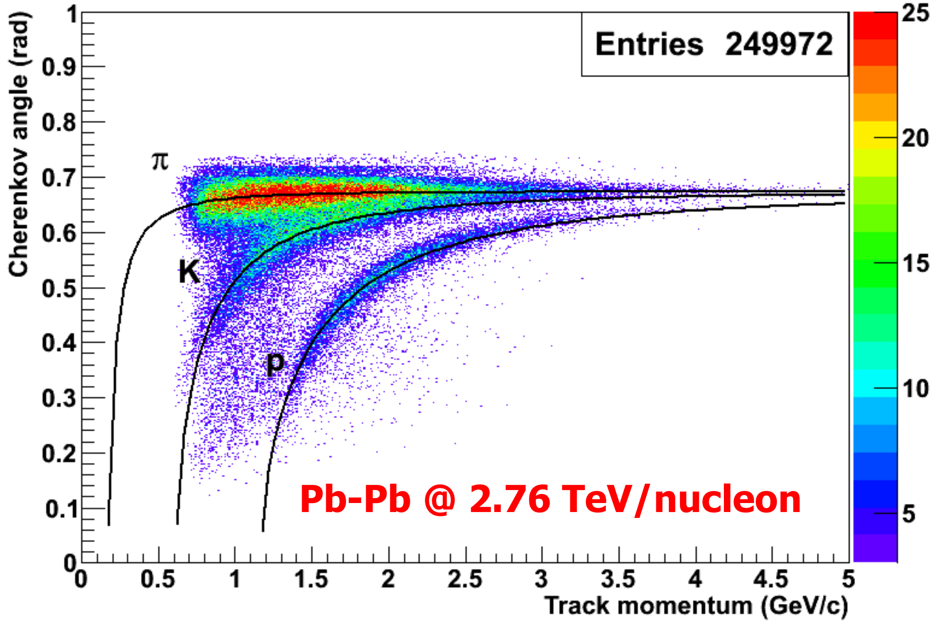


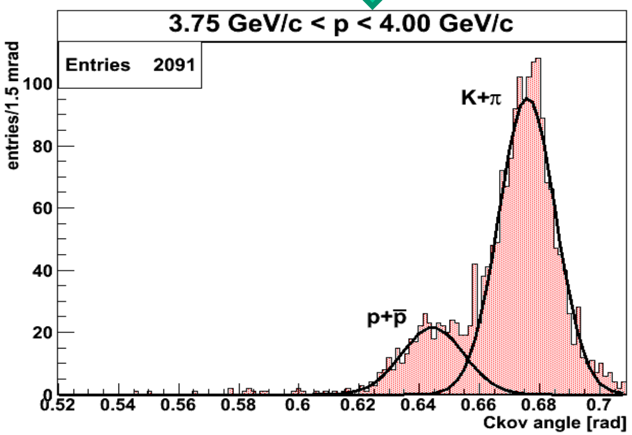


CsI photo-cathode is segmented in 0.8x0.84 cm pads

ALICE HMPID performance







Cherenkov counters with vacuum based photodetectors

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

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

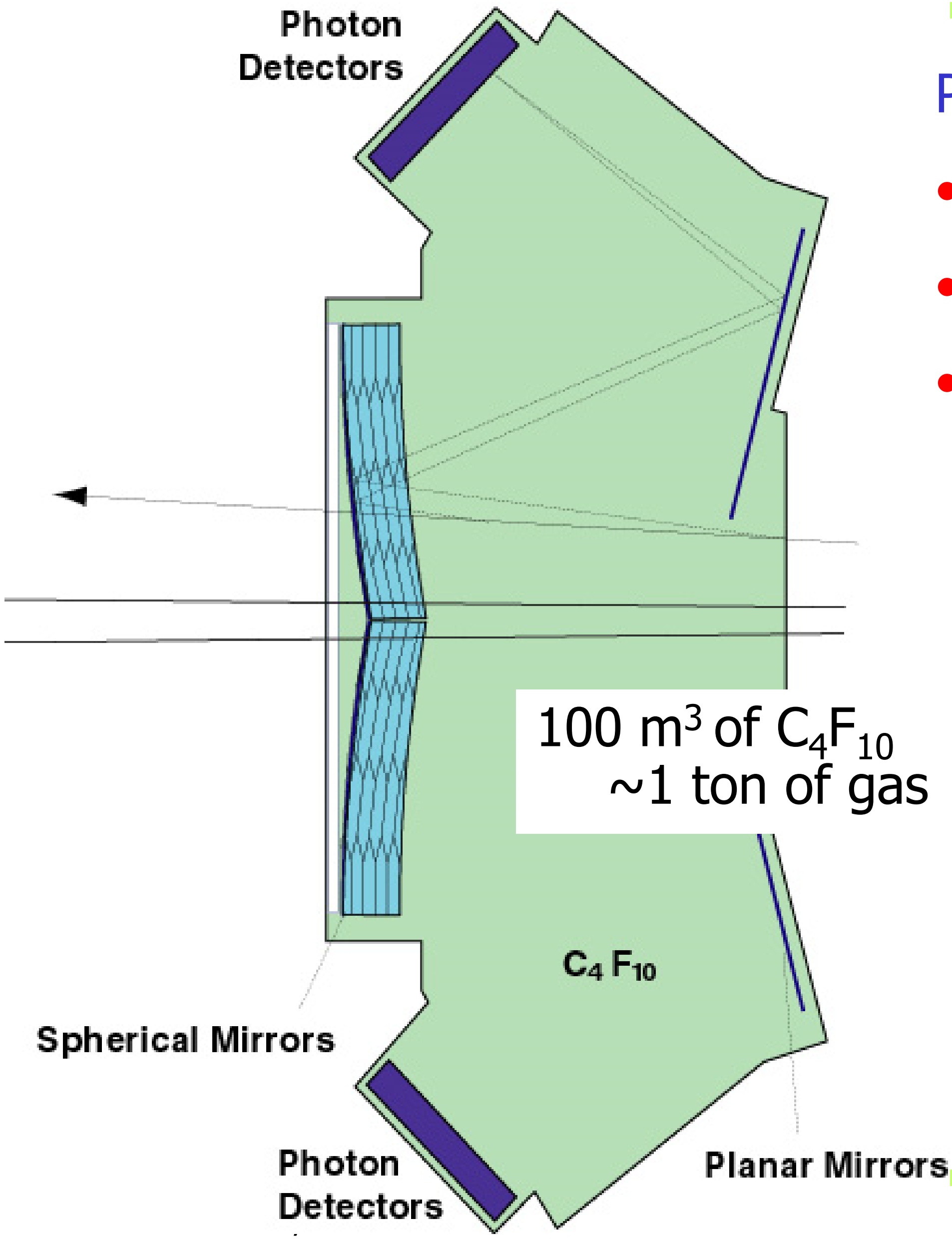
Good spacial resolution (pads with ~5 mm size)

→ Need multianode PMTs

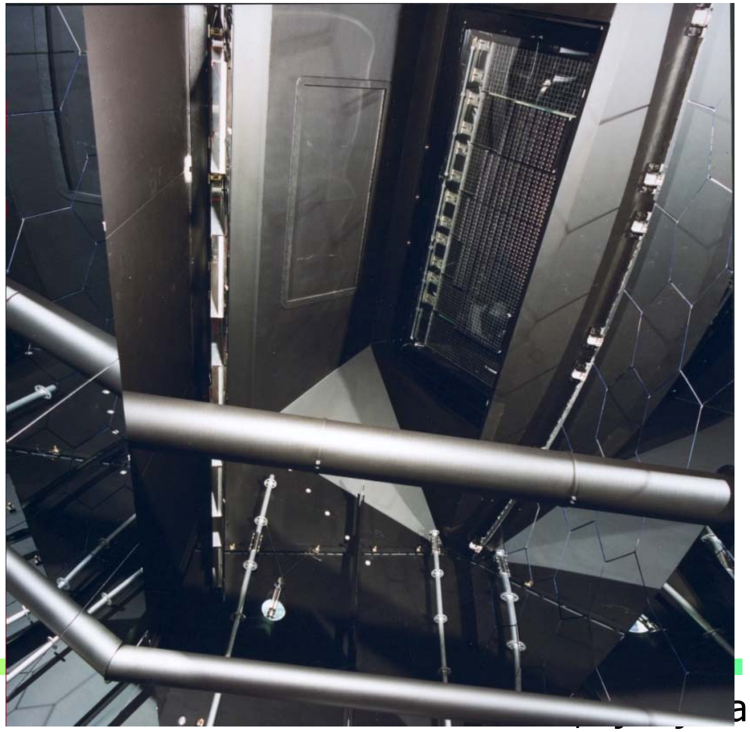
HERA-B RICH

Photon detector requirements:

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



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



Multianode PMTs

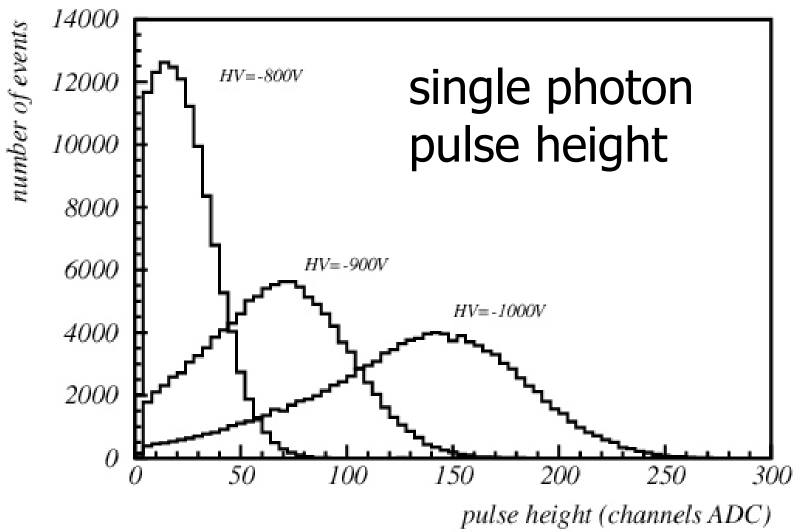
Multianode PMTs with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

→Excellent single photon pulse height spectrum

→Low noise (few Hz/ch)

→Low cross-talk (<1%)

→ NIM A394 (1997) 27

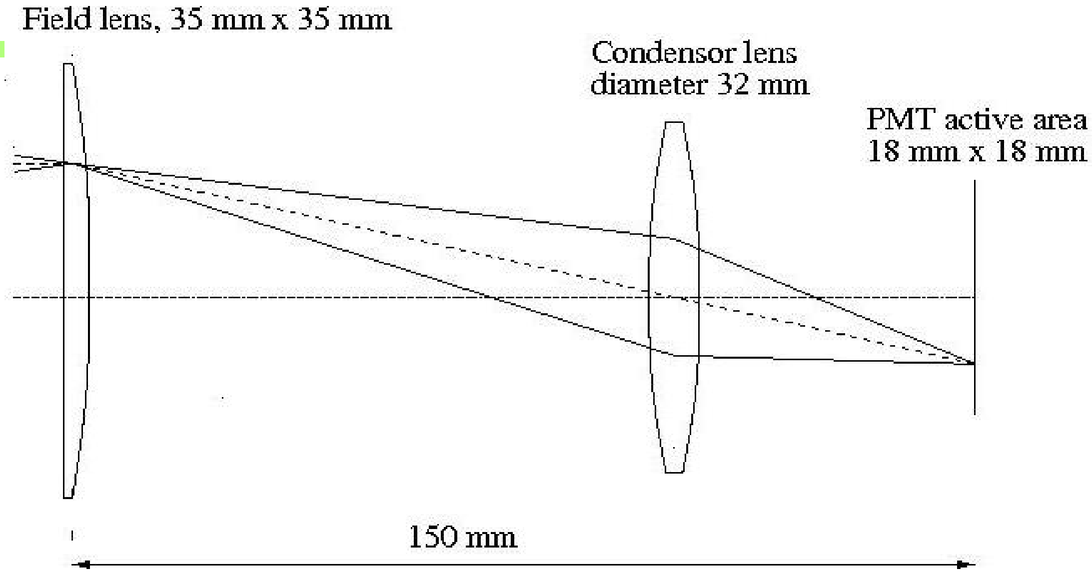


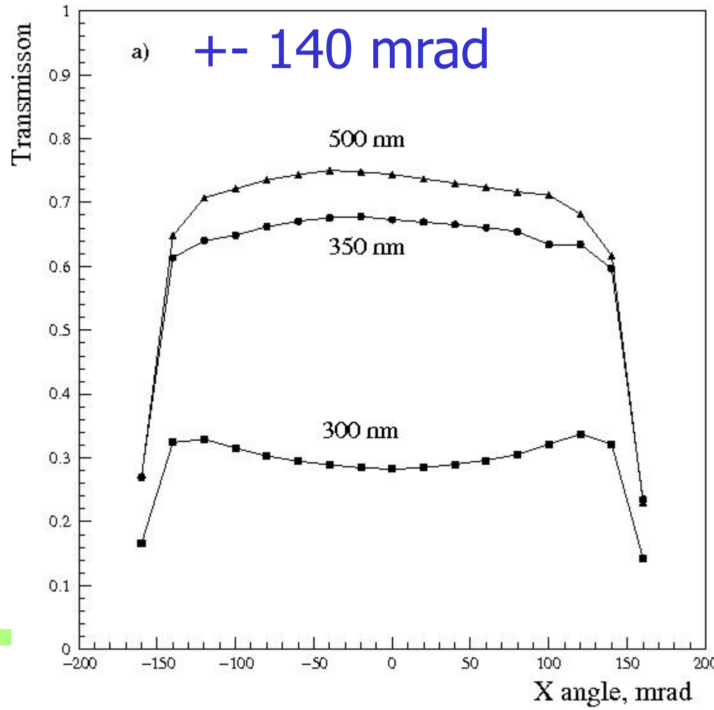
HERA-B RICH photon detector

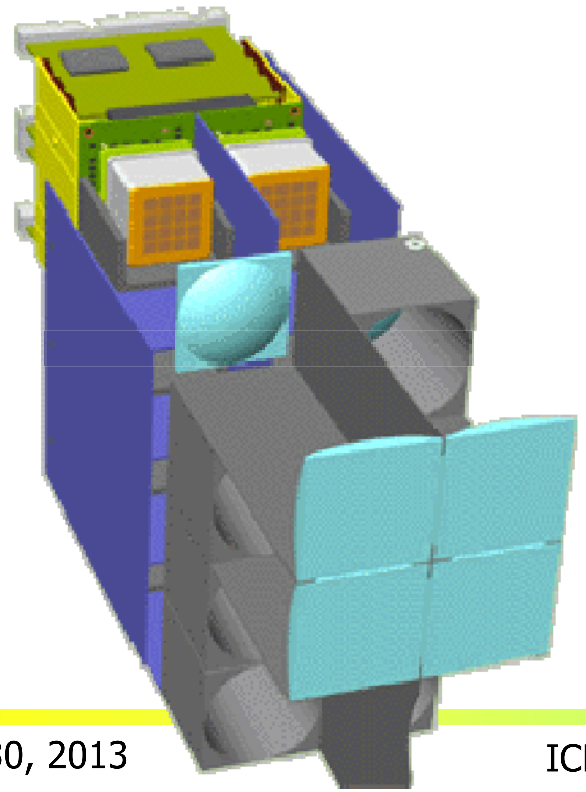
Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size







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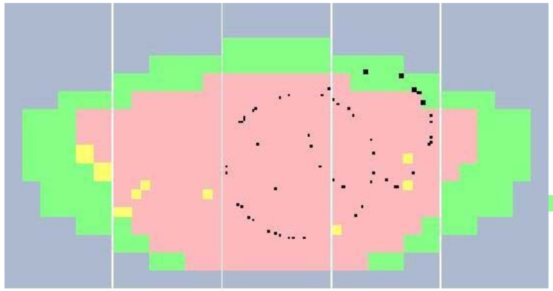
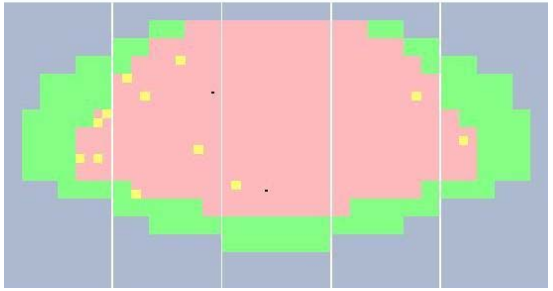
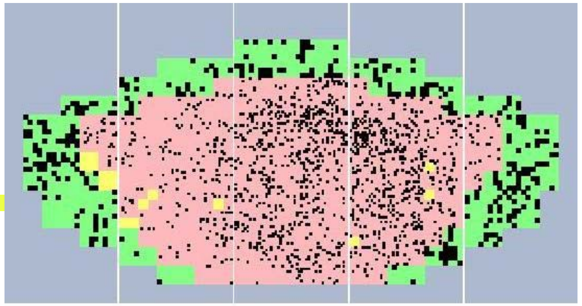
HERA-B RICH

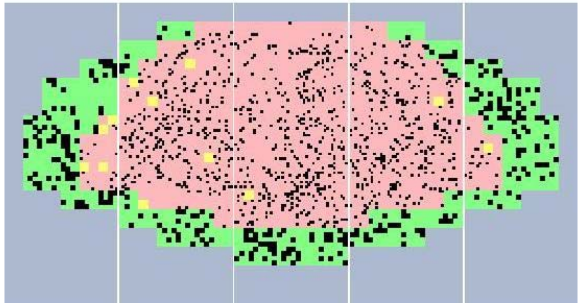




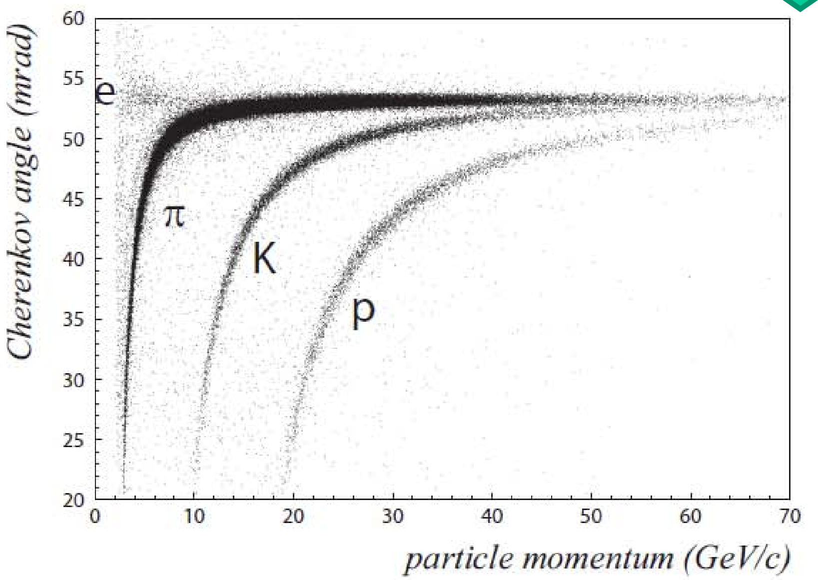
← Little noise, ~30 photons per ring

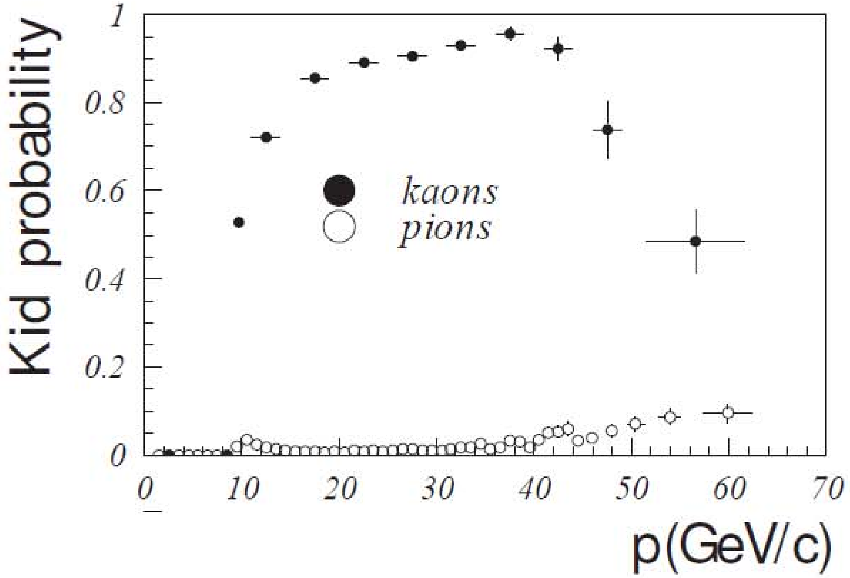
Typical event →





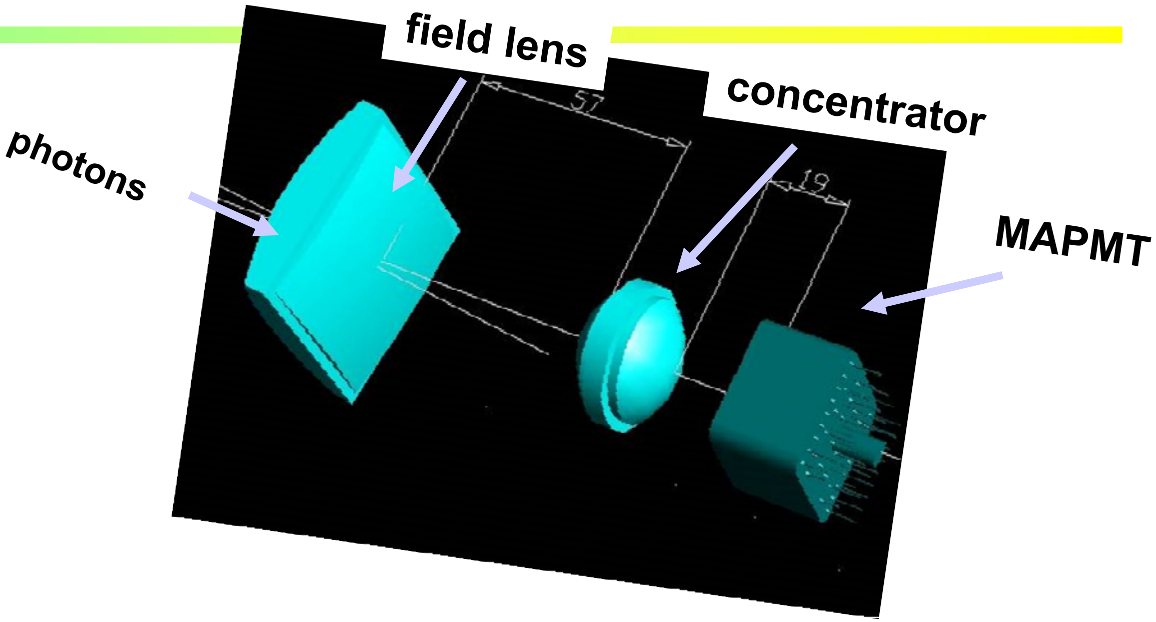
Worked very well!





Kaon efficiency and pion fake probability

Photon detector for the COMPASS RICH-1

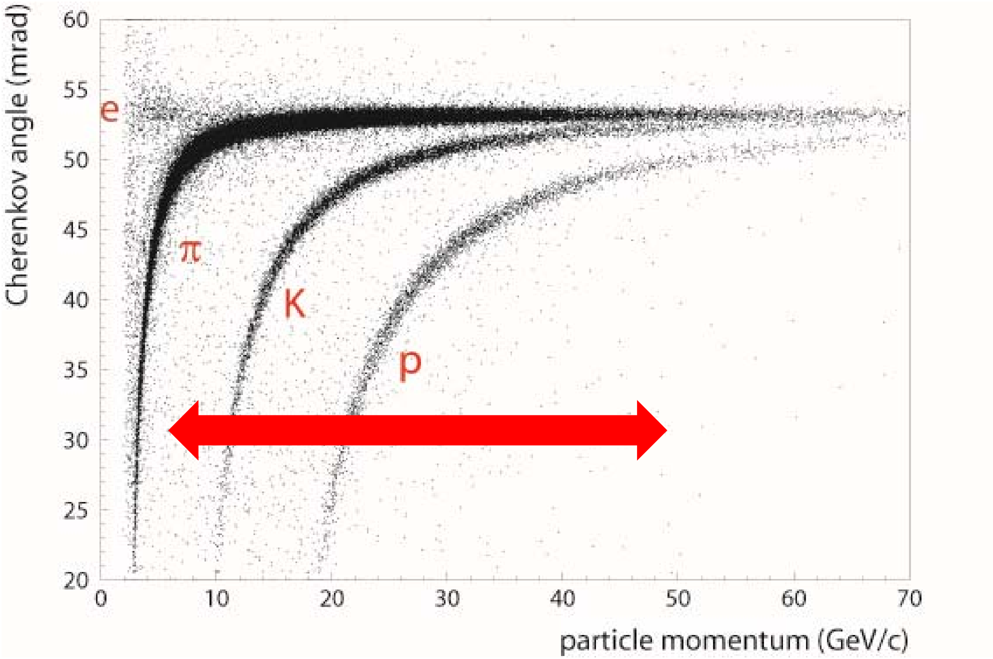


Upgraded COMPASS RICH-1:
similar concept as in the HERA-B RICH

New features:

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

Kinematic range of a RICH counter



Example: kinematic range for kaon/pion separation

Kinematic range for separation of two particle types:

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

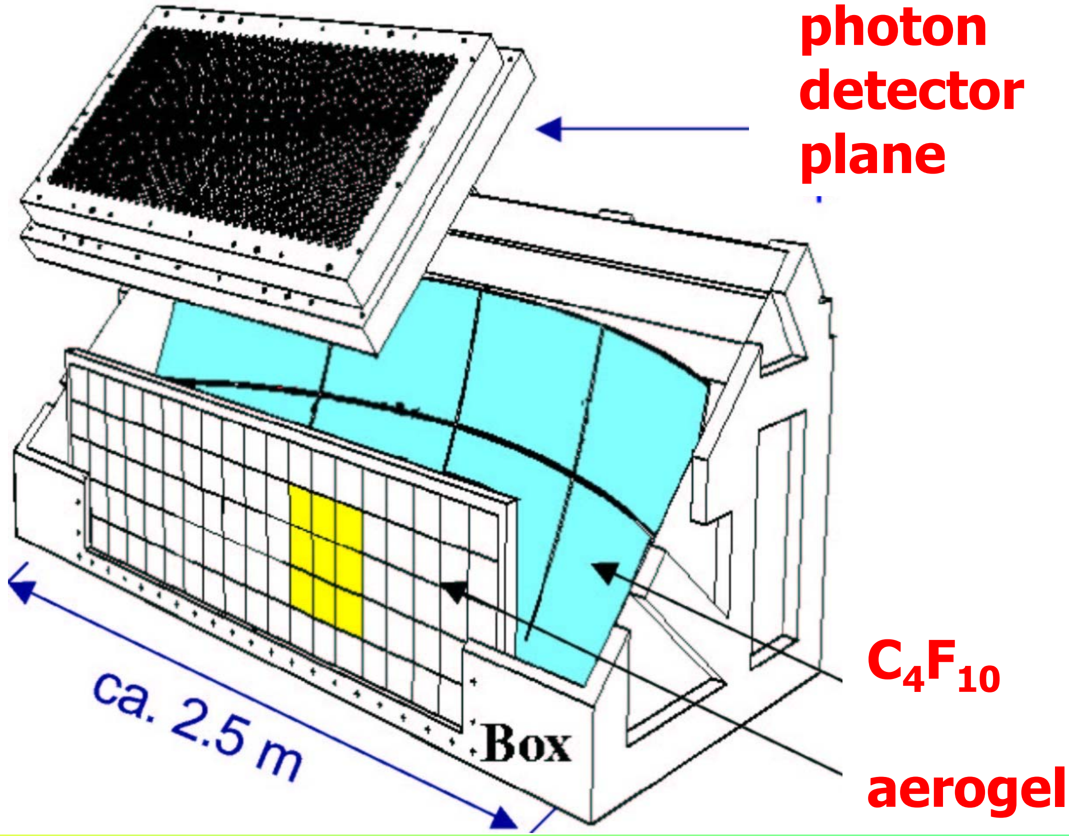
•Upper limit p_{max}: given by Cherenkov angle resolution – overlap of the two bands

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

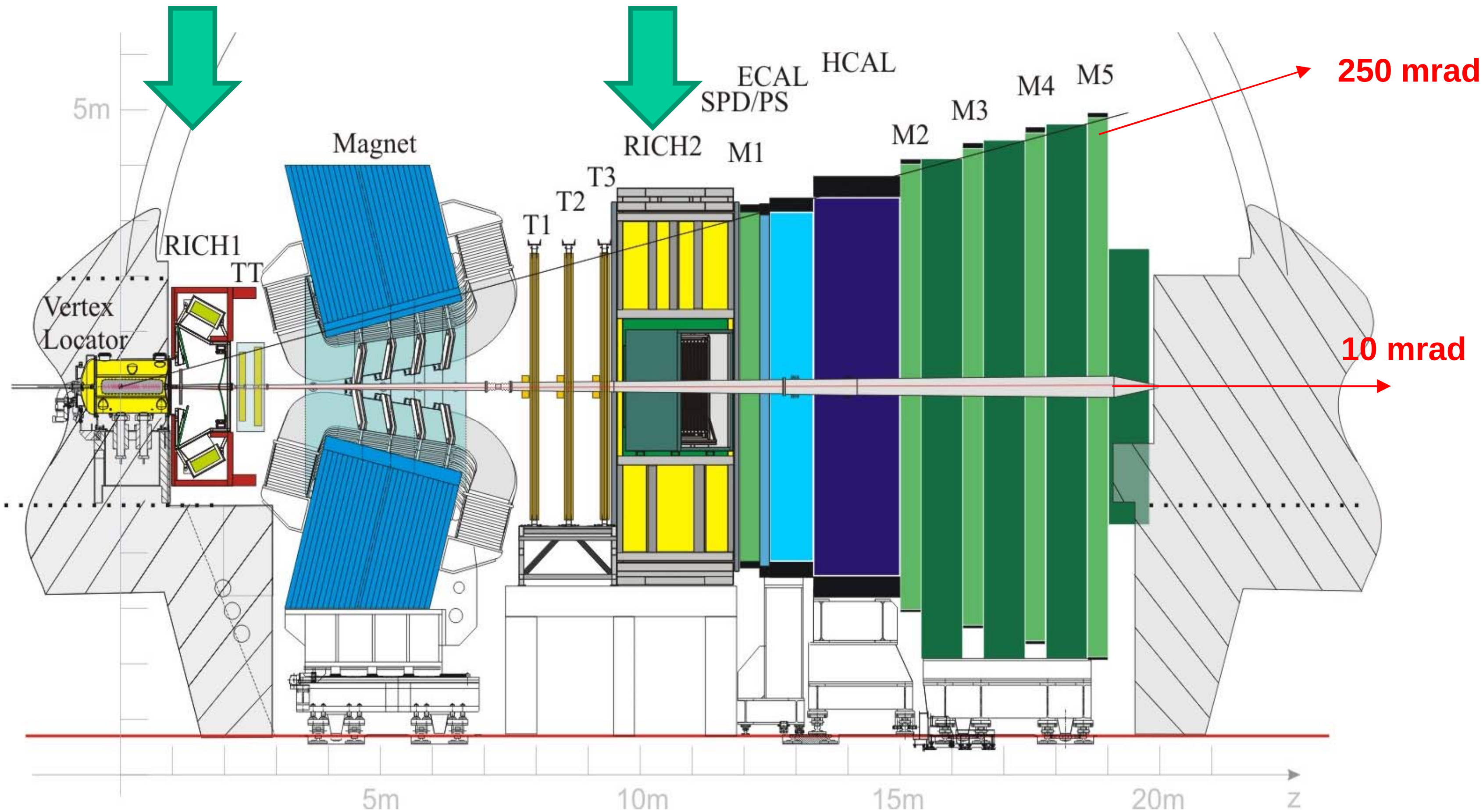
RICHes with several radiators

Extending the kinematic range → need more than one radiator

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



The LHCb RICH counters



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

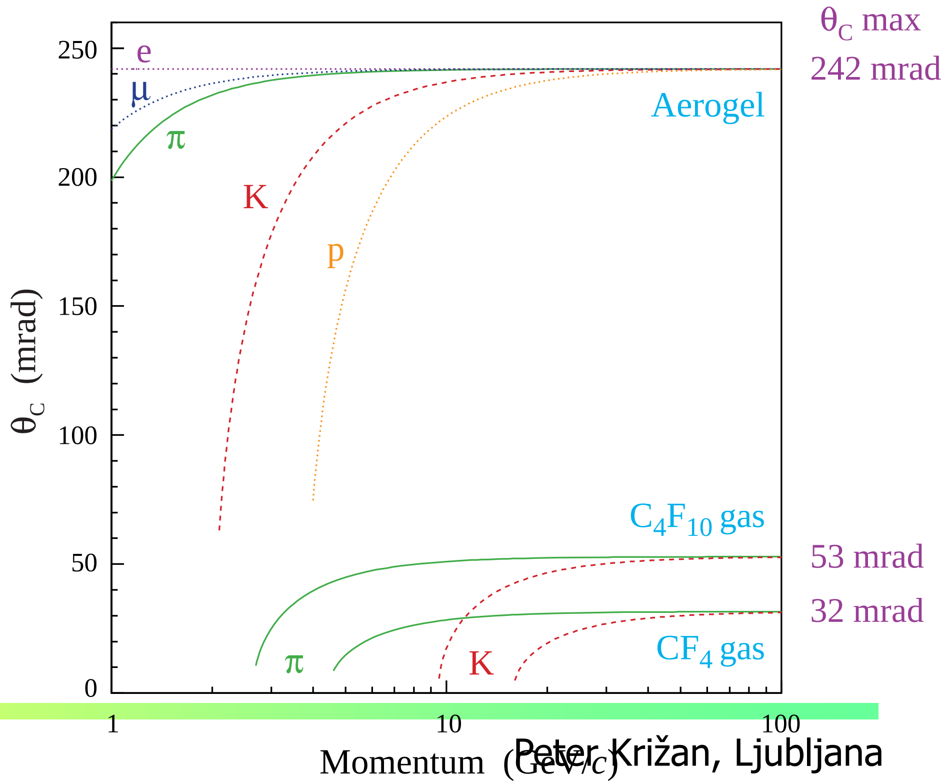
LHCb RICHes

Need:

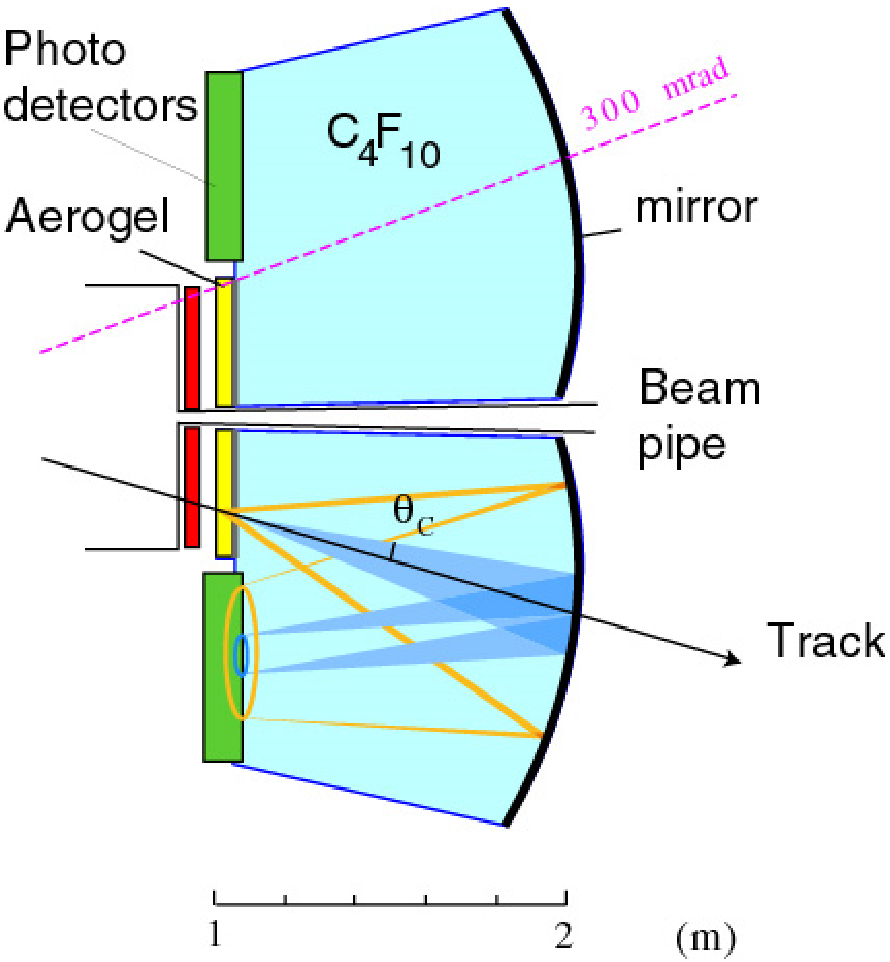
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

→3 radiators

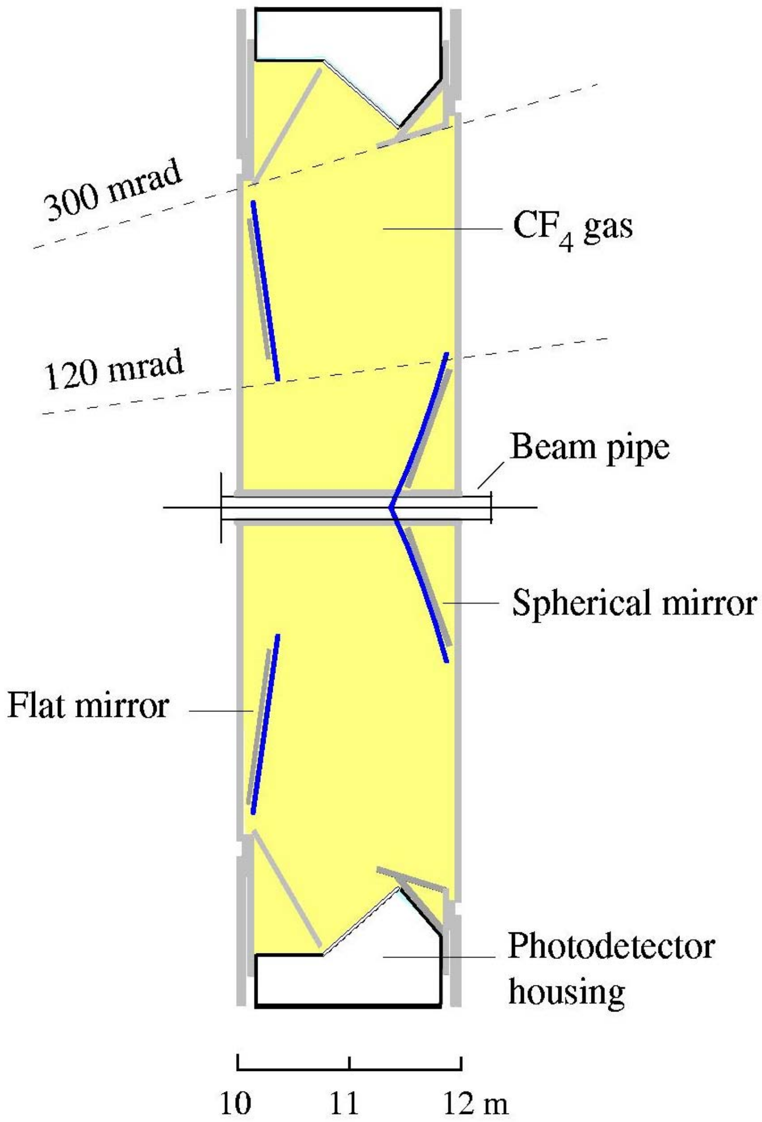
- Aerogel
- C_4F_{10} gas
- CF_4 gas



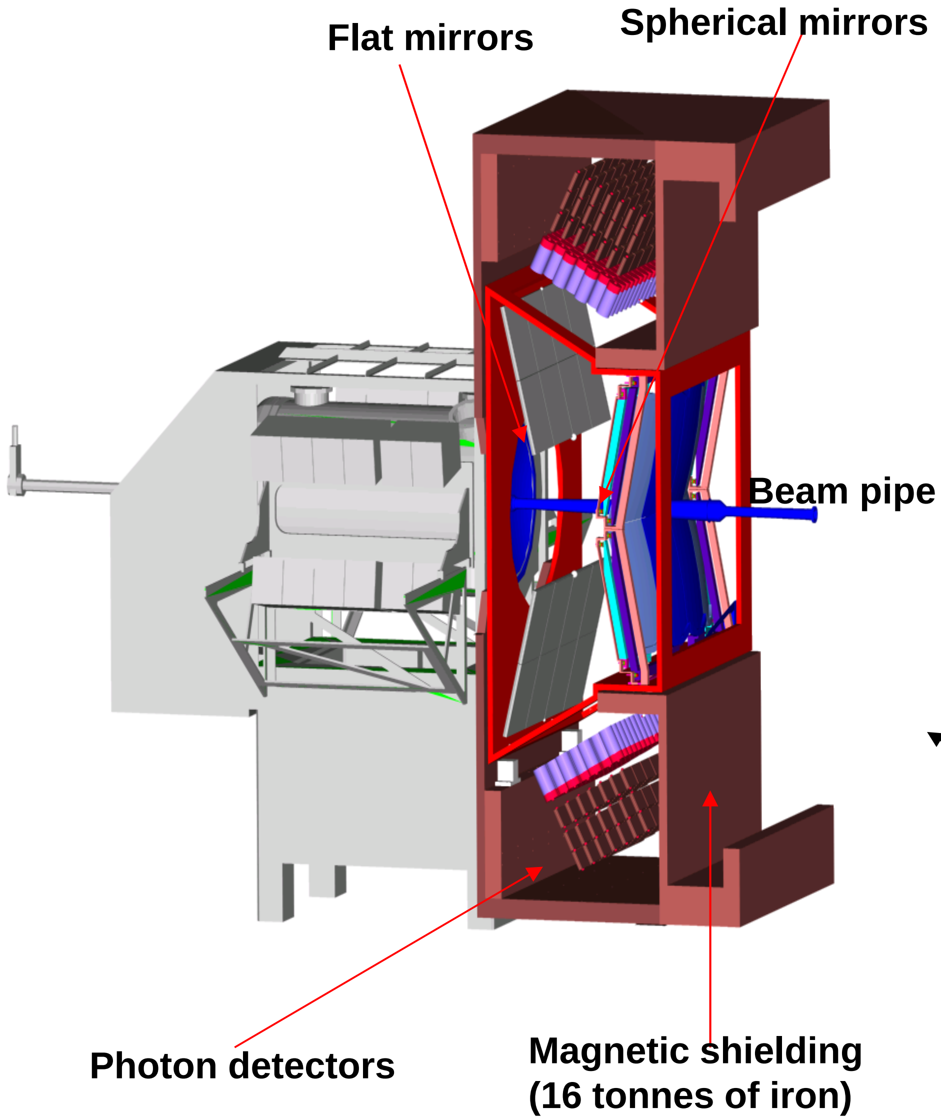
LHCb RICHes

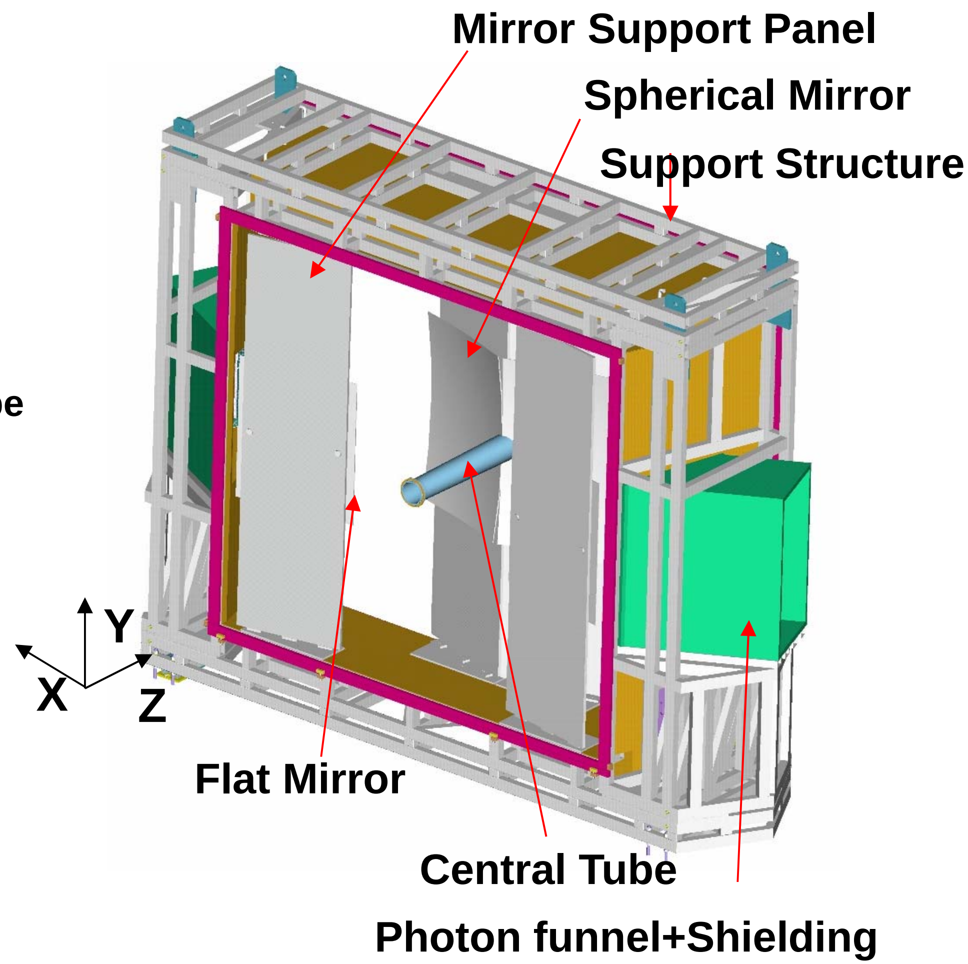


RICH 1 + 2



LHCb RICHes

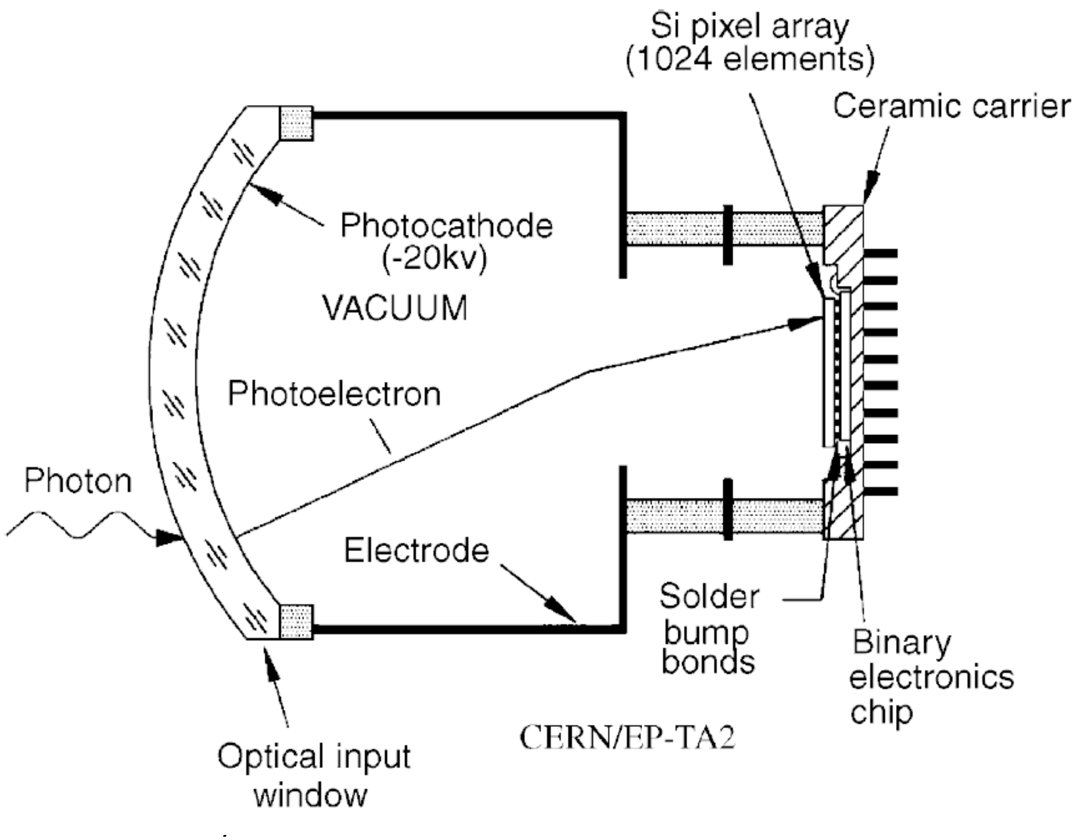

Flat mirrors
Spherical mirrors
Beam pipe
Photon detectors
Magnetic shielding
(16 tonnes of iron)


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

LHCb RICHes

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

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



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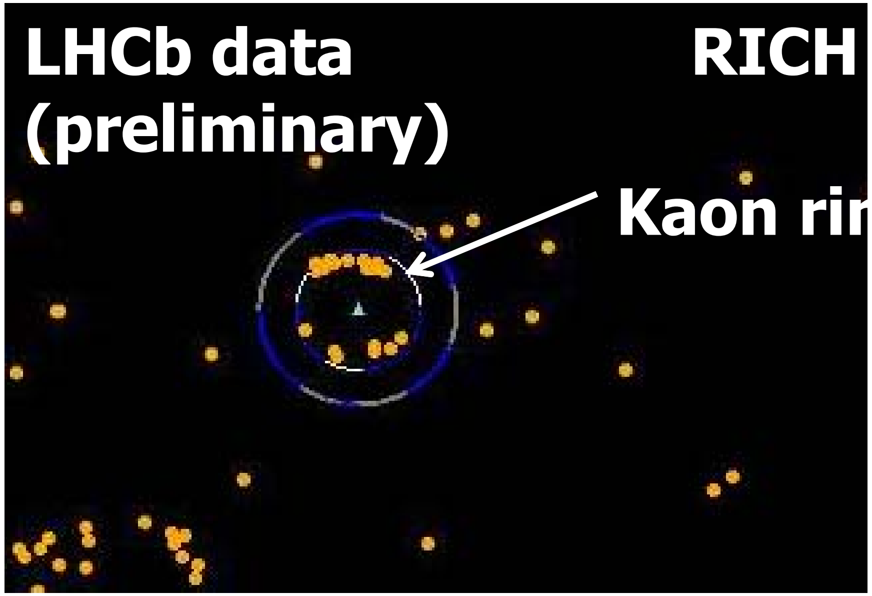
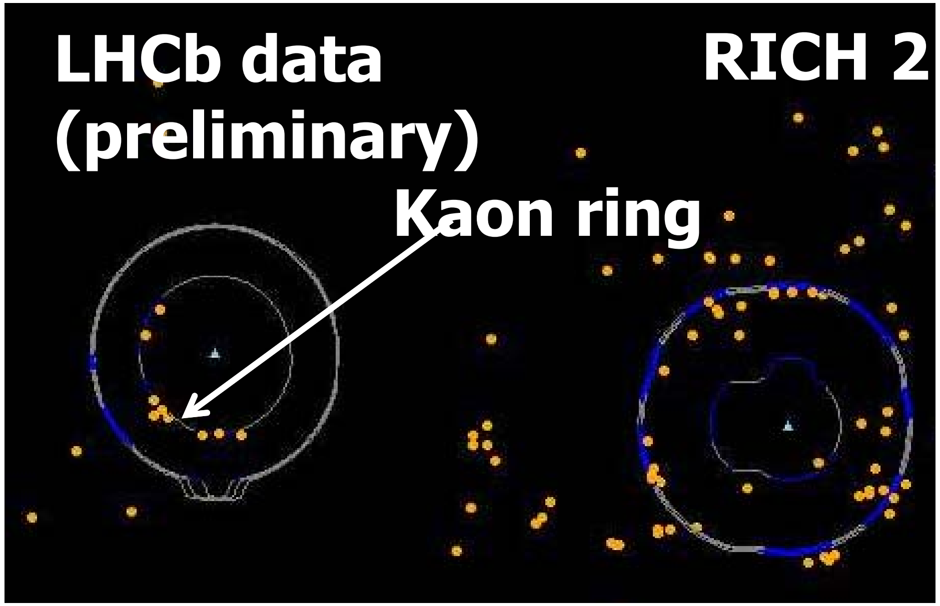
LHCb Event Display

RICH1

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

RICH2

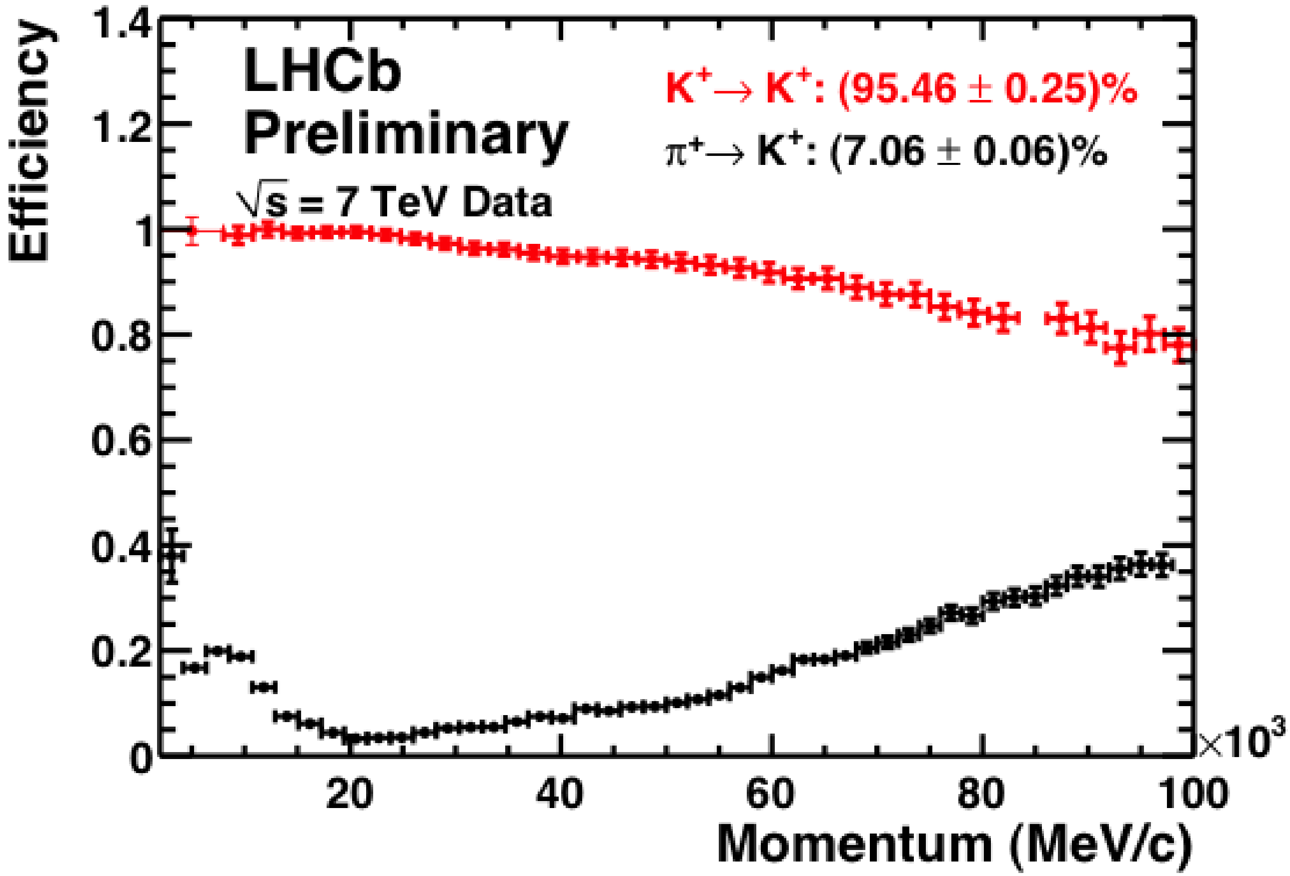


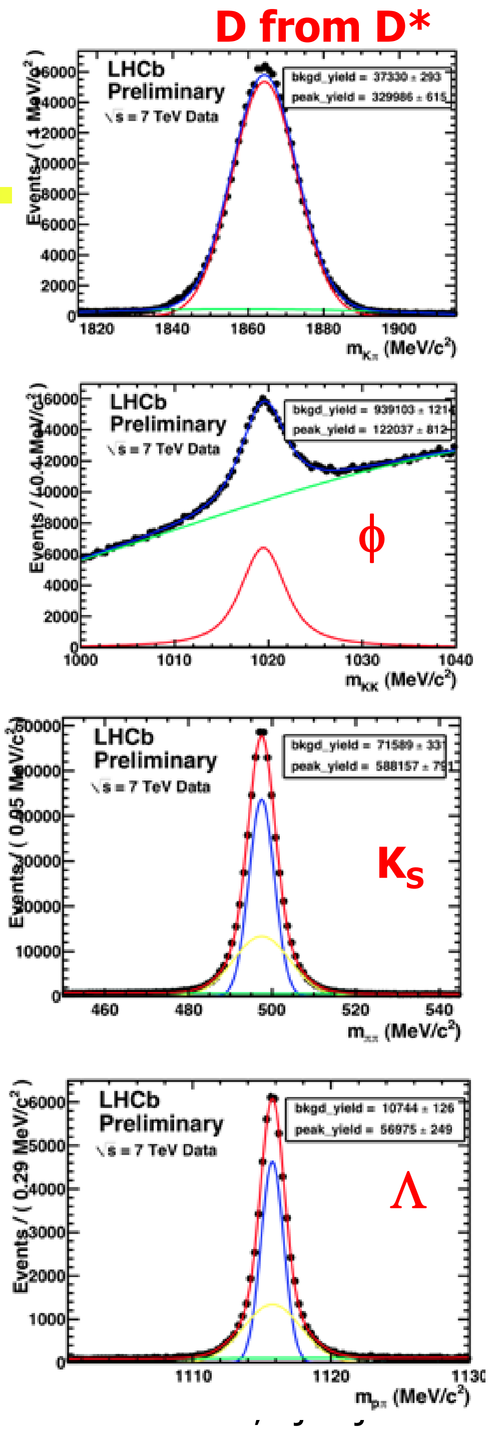


- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

F. Muheim, RICH 2010

LHCb RICHes: performance

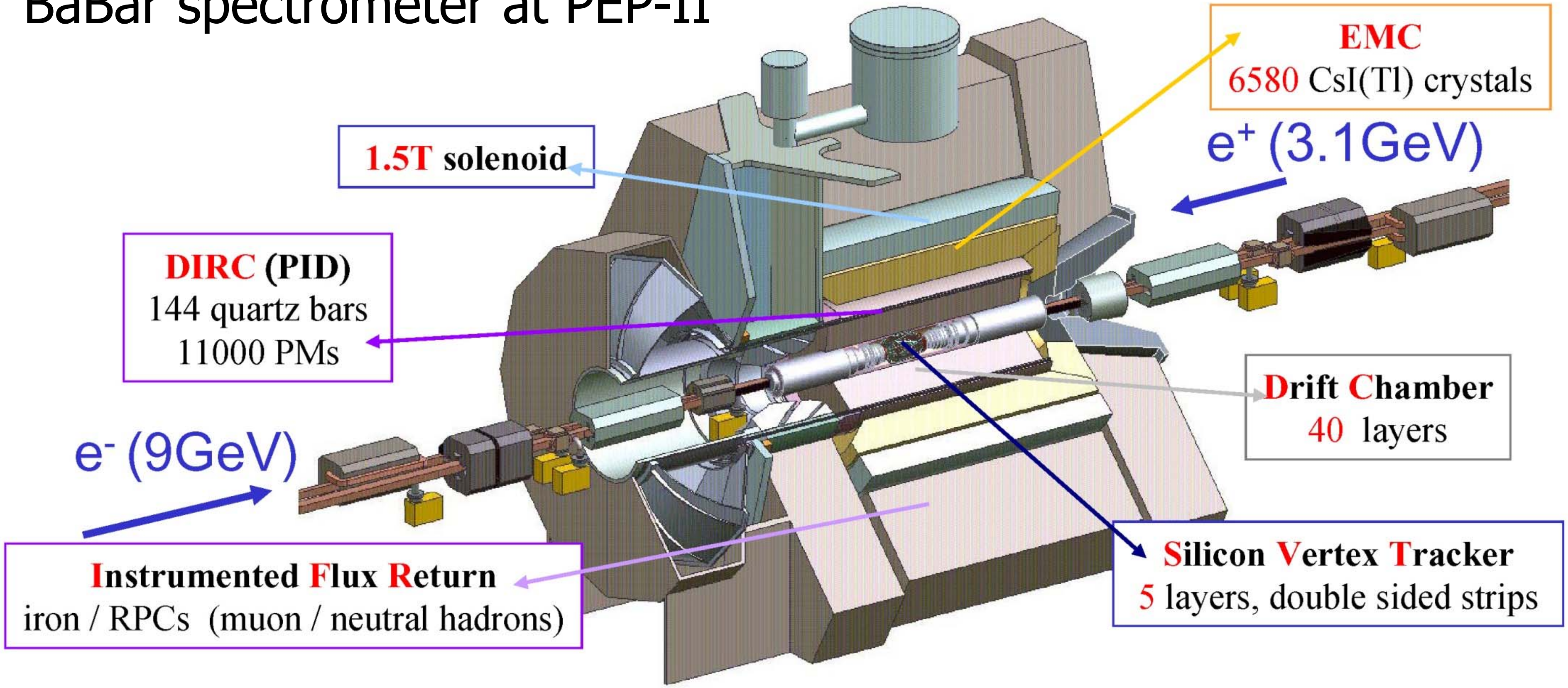




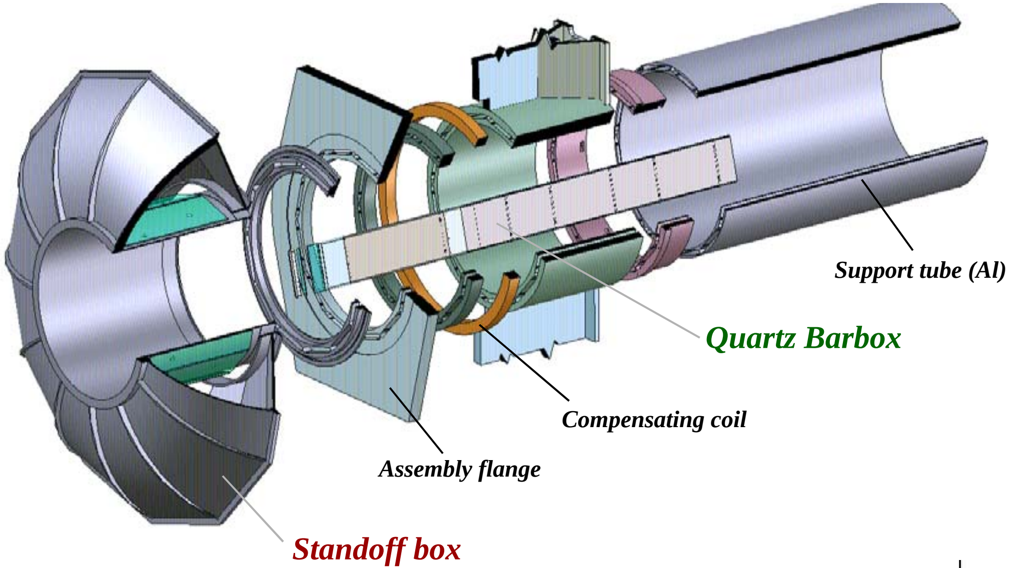
Efficiency and purity from data → excellent agreement with MC

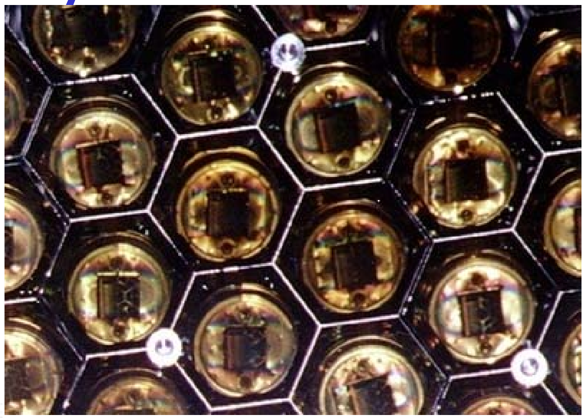
DIRC - detector of internally reflected Cherenkov light

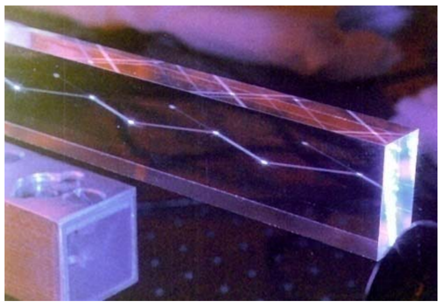
BaBar spectrometer at PEP-II

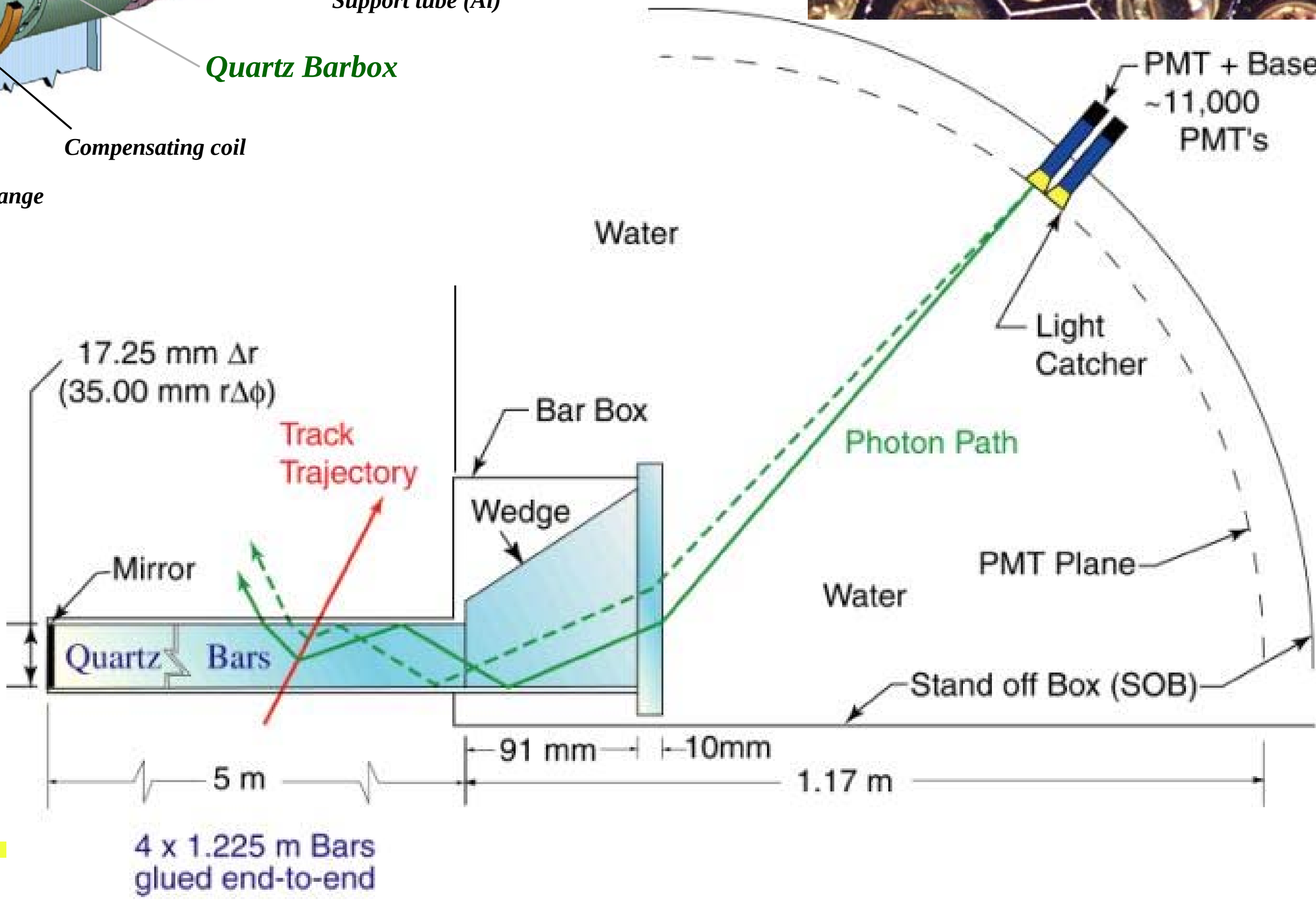


DIRC (@BaBar) - detector of internally reflected Cherenkov light

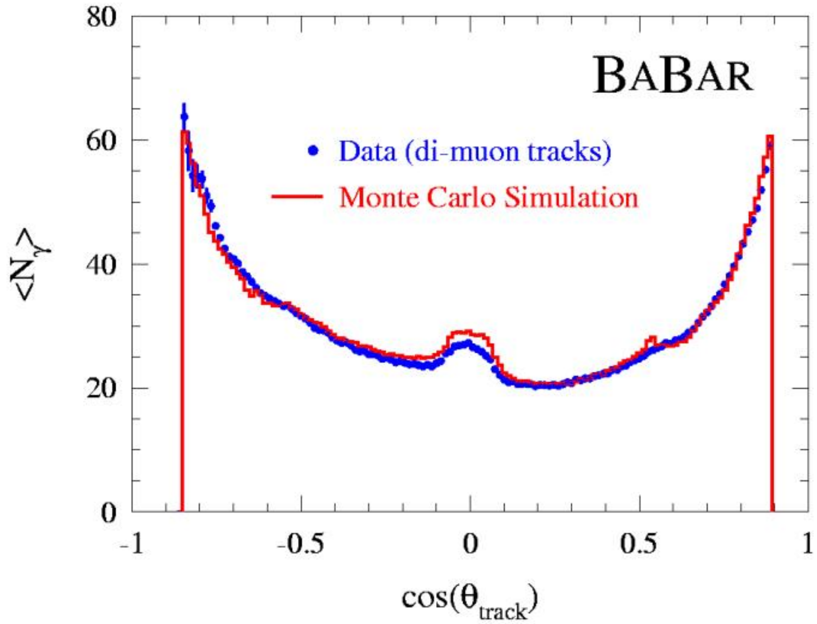






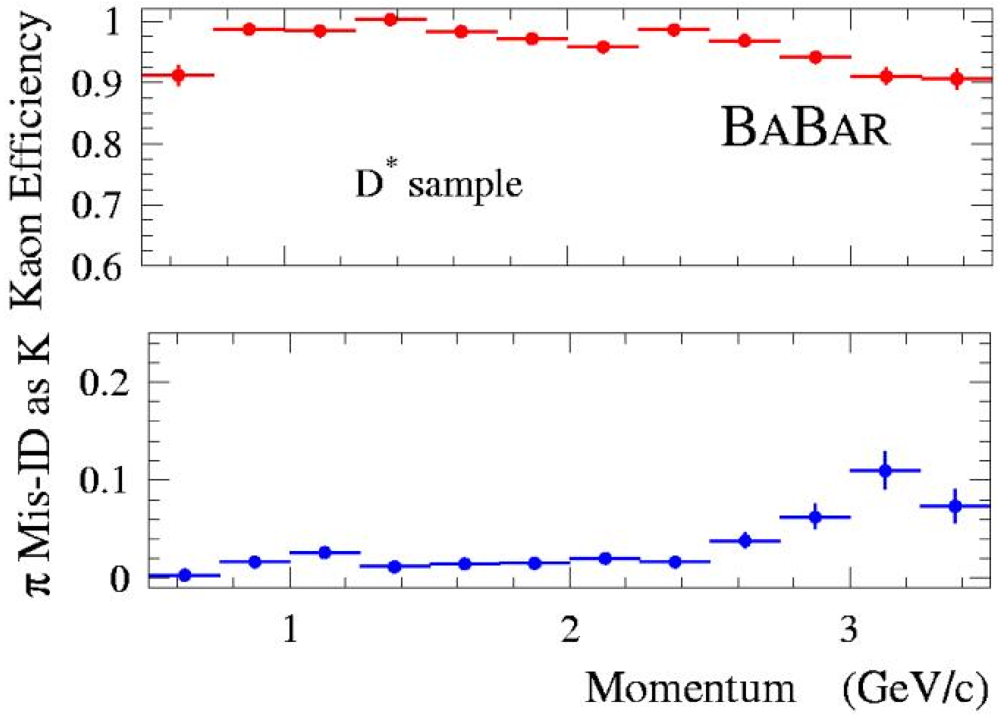


DIRC performance



← Lots of photons!

Excellent π/K separation



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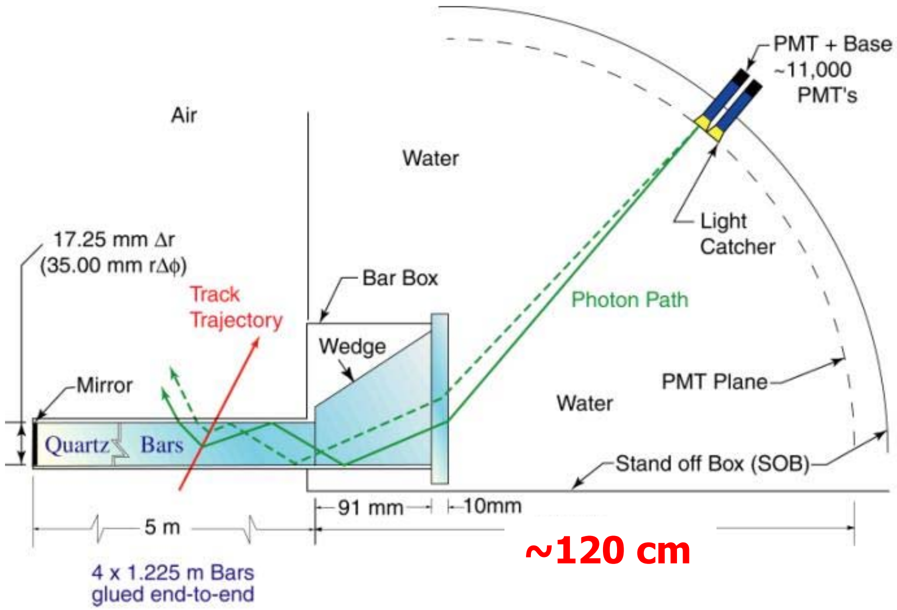
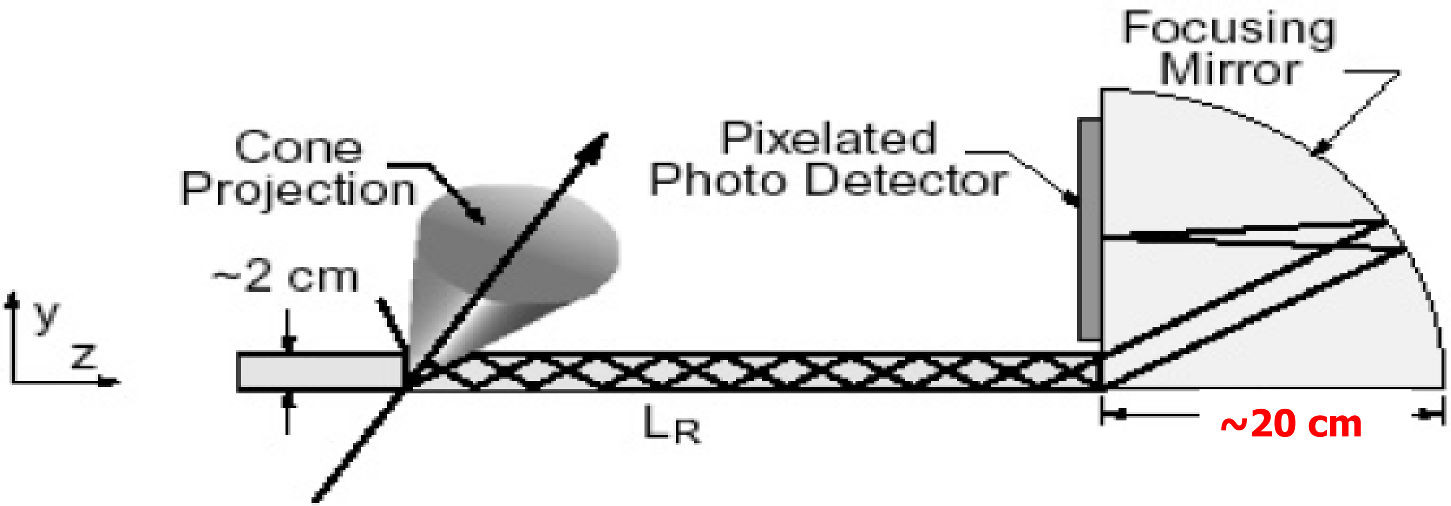
Focusing DIRC

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





Focusing DIRC

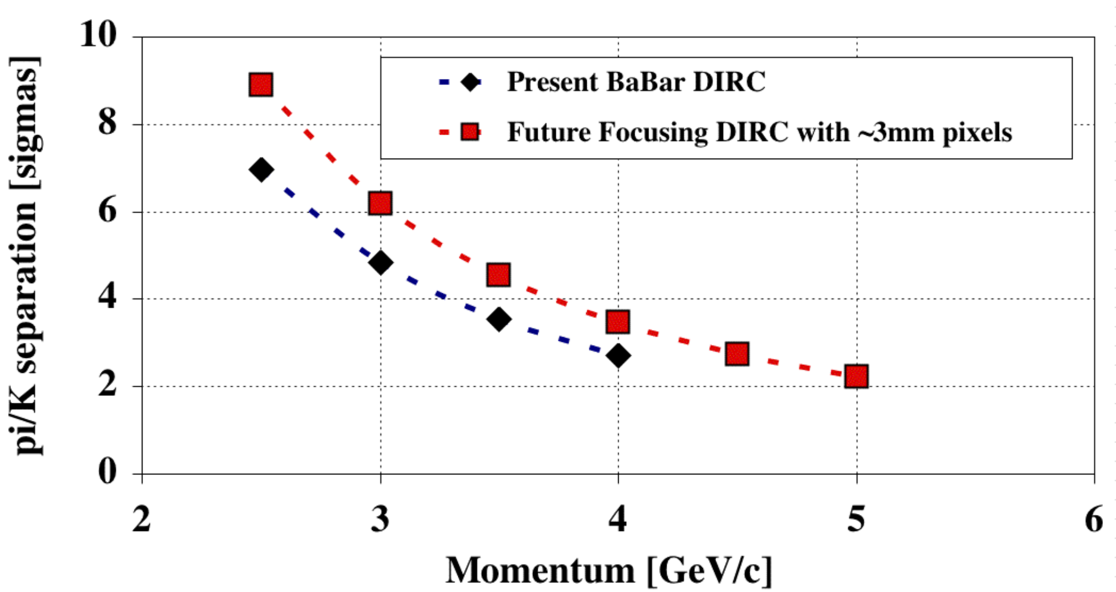
Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

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

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

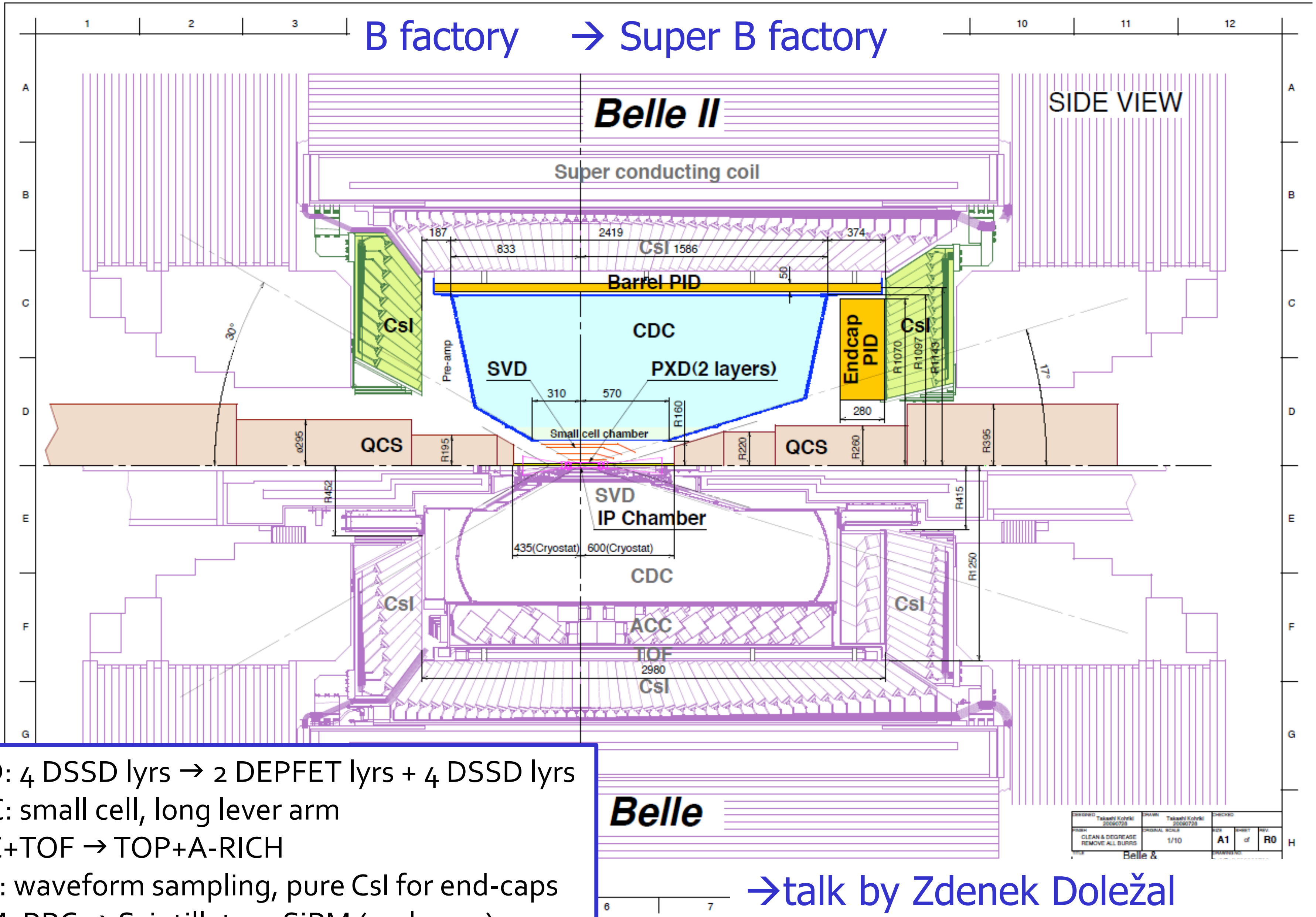
Photon detector:

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



Belle → Belle II

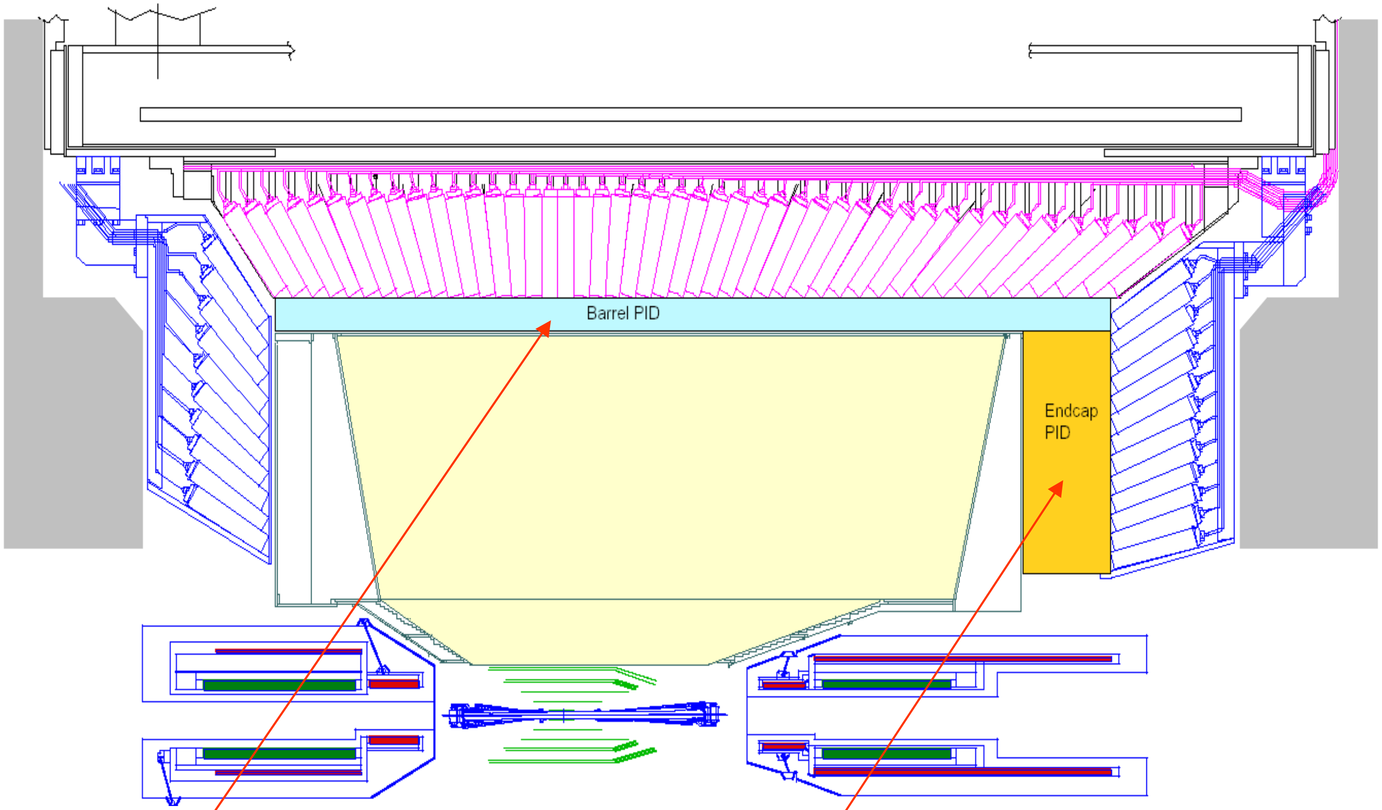
B factory → Super B factory



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 end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

→talk by Zdenek Doležal

Belle II PID systems – side view

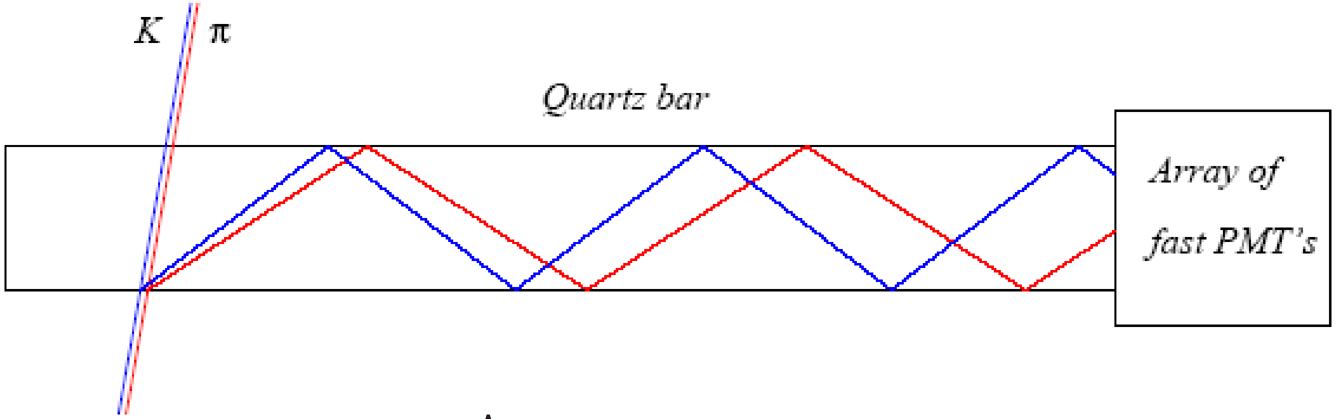


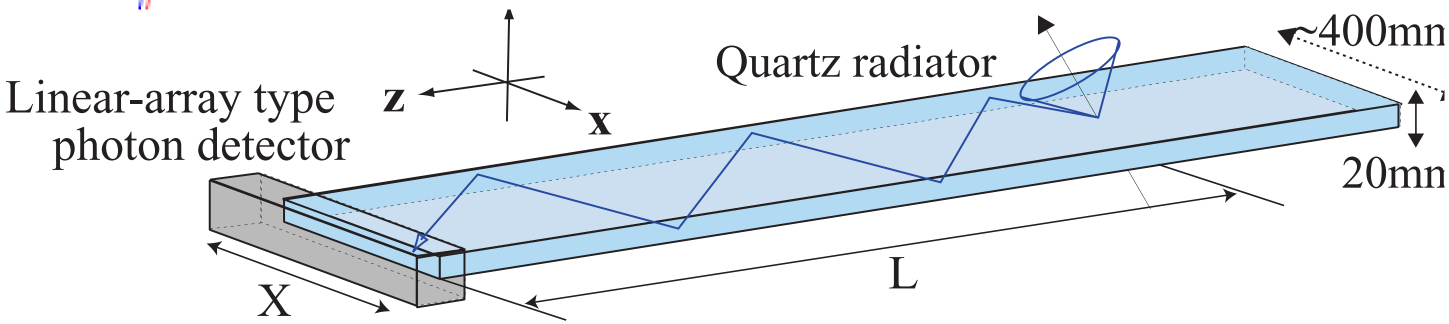
Two new particle ID devices, both RICHes:

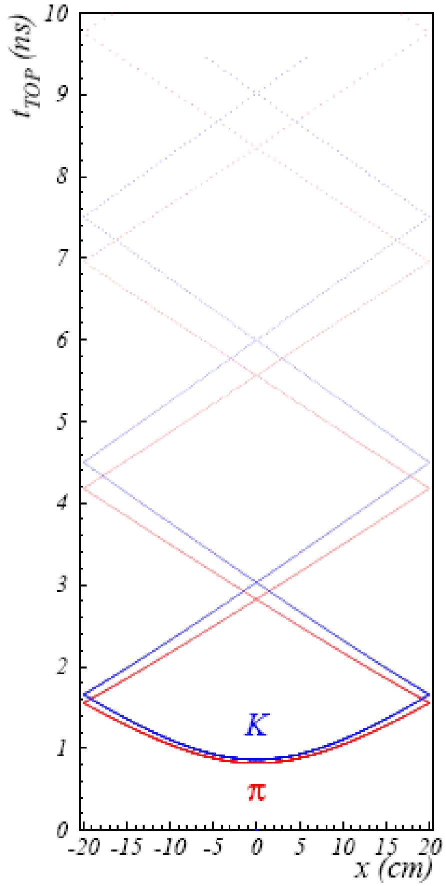
Barrel: time-of-propagation (TOP) counter

Endcap: proximity focusing RICH

Time-Of-Propagation (TOP) counter



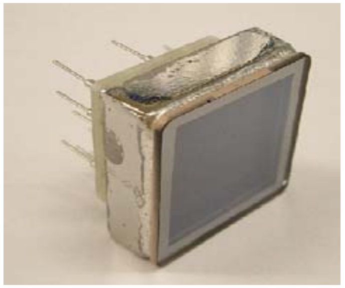




Similar to DIRC, but instead of two coordinates measure:

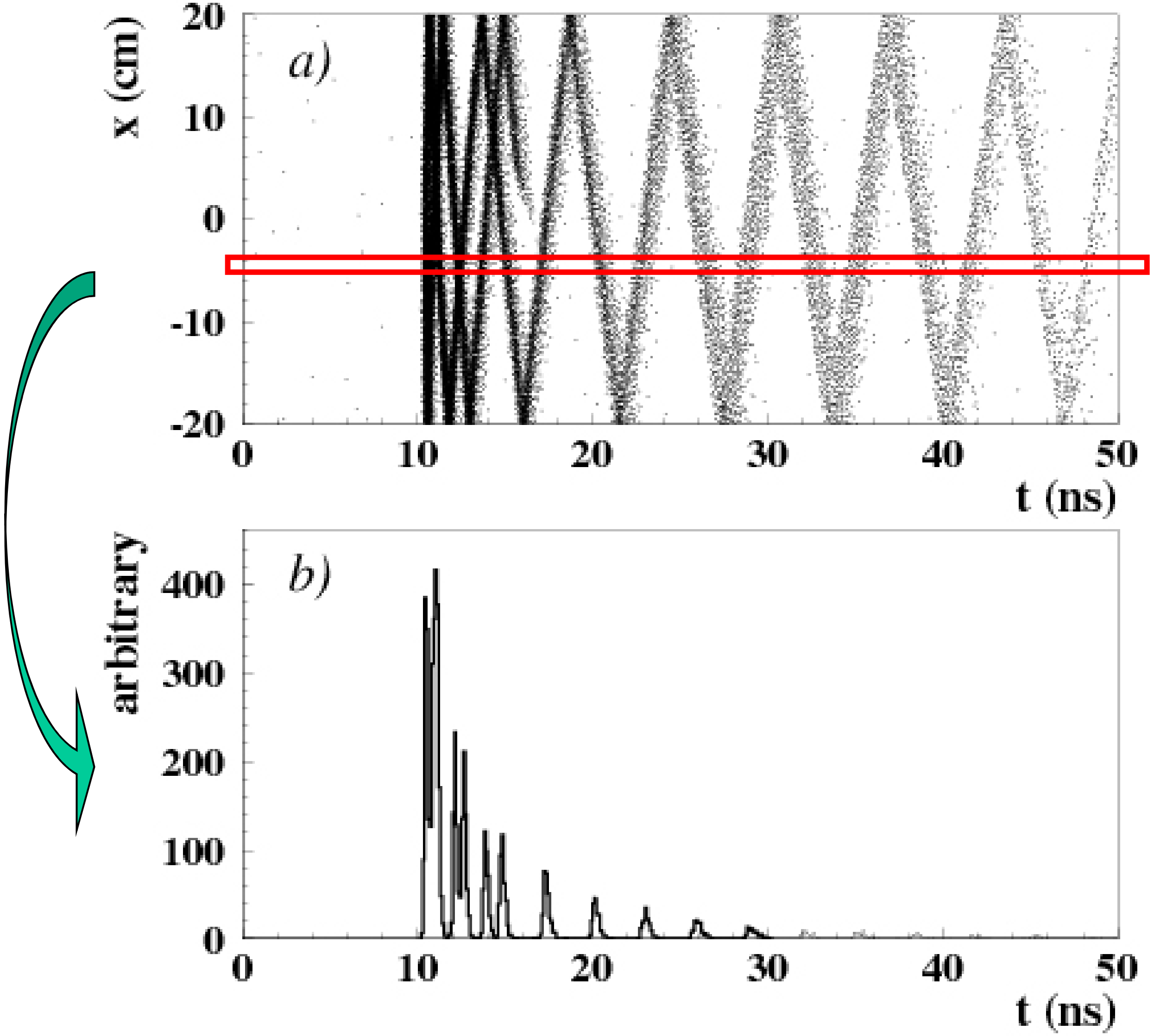
- One (or two coordinates) with a few mm precision
- Time-of-arrival

→ Excellent time resolution < ~40ps required for single photons in 1.5T B field



Hamamatsu SL10 MCP-PMT

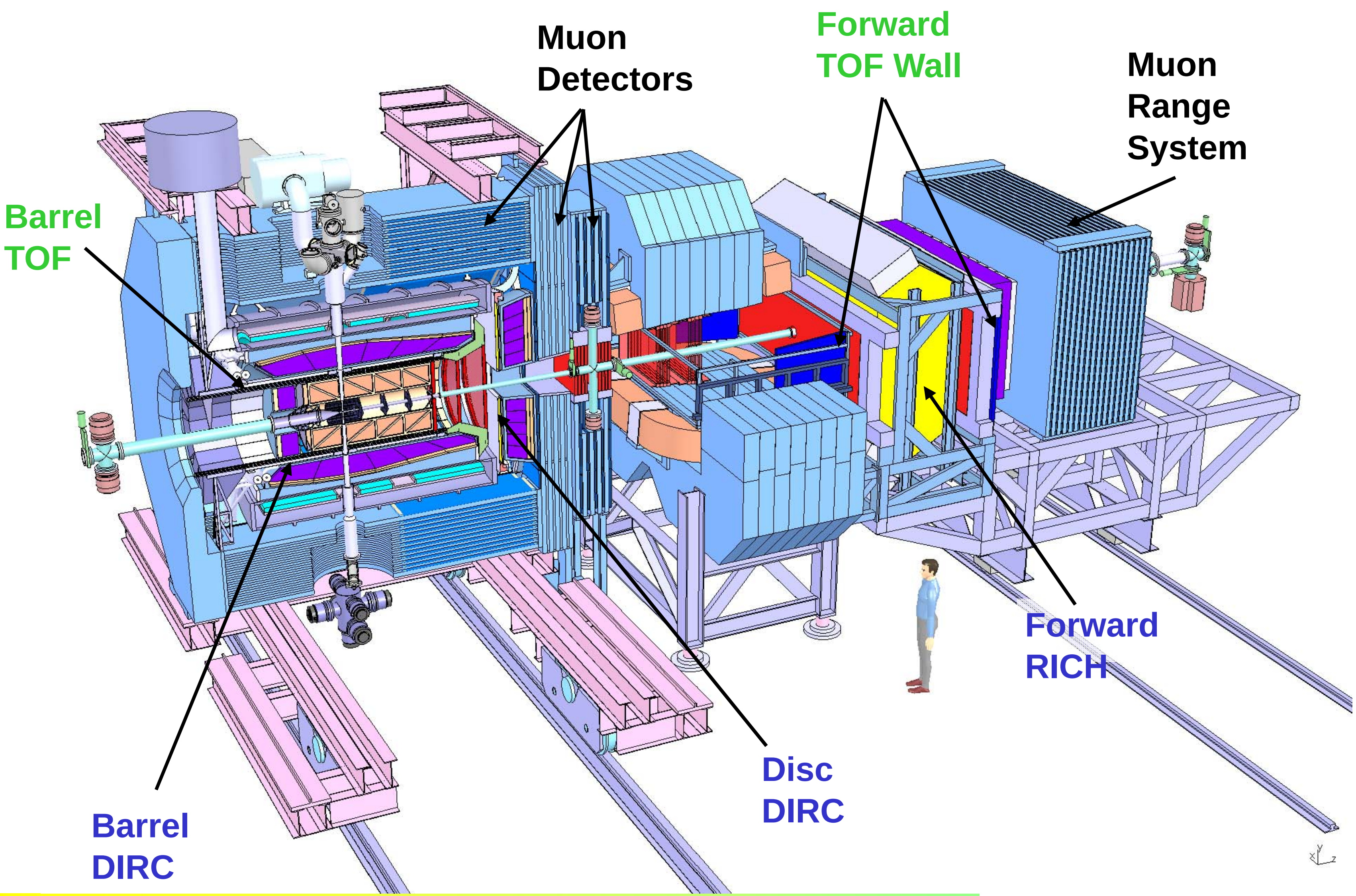
TOP image



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

Time distribution of signals recorded by one of the PMT channels: different for π and K

PID for PANDA

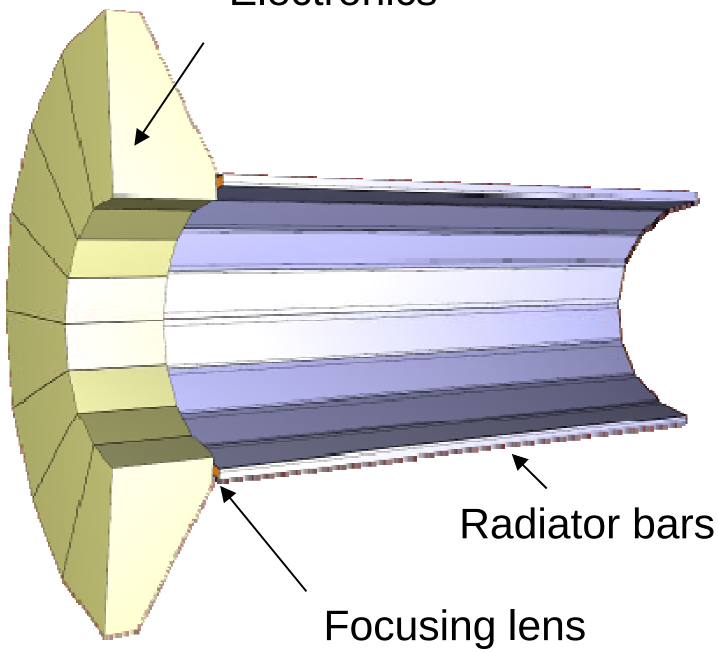


J. Smyrski @ TIPP2011

Barrel DIRC

- Similar to BaBar DIRC
- π/K separation 0.5 < *p* < 4 GeV/c
- Inner radius: 48 cm
- Radiator: 96 bars, fused silica (n=1.47), size: 17mm (T) x 33mm(W) x 2500mm (L)
- Compact photon detector: array of MCP-PMT (Burle Planacon) in magnetic field 0.5 -1 T

  total 7000-10000 channels
- Time of propagation → dispersion corrections (3D-DIRC concept – *x,y,t*)
- Focusing optics



J. Smyrski @ TIPP2011

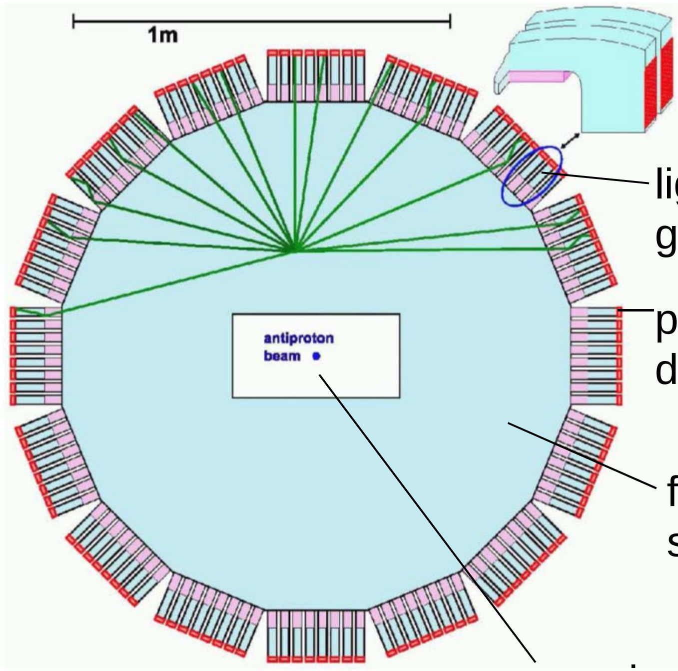
Disc DIRC

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

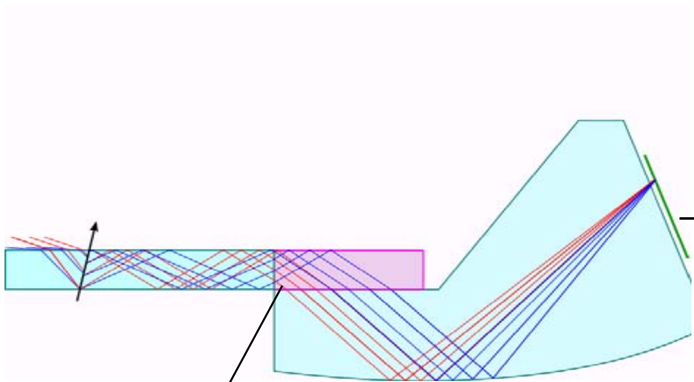
π/K separation up to 4 GeV/c

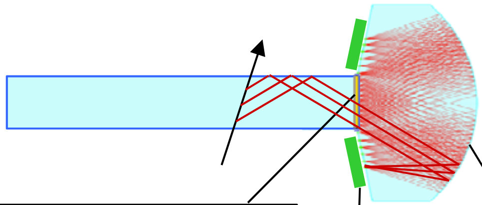
Focusing light guide

Photon detector in ~1T field
capable of rates 0.75 MHz/cm^2
(MCP-PMTs or dSiPMs)



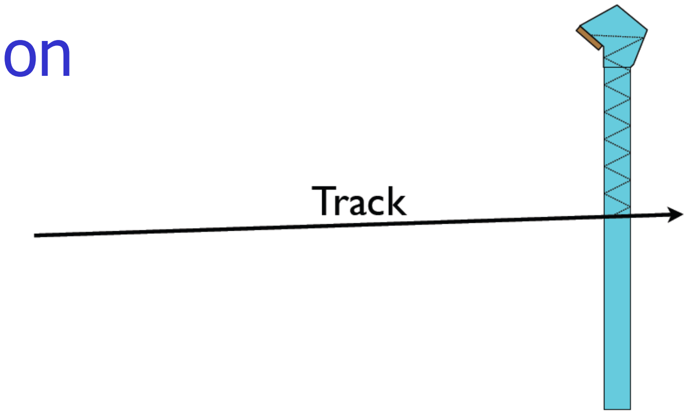
Two options for light guides

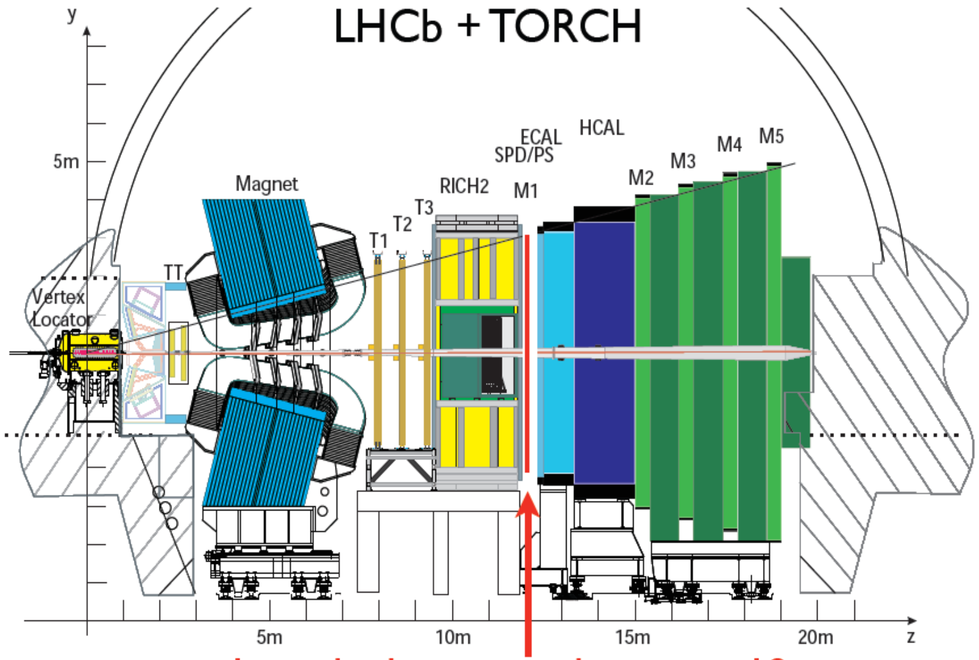




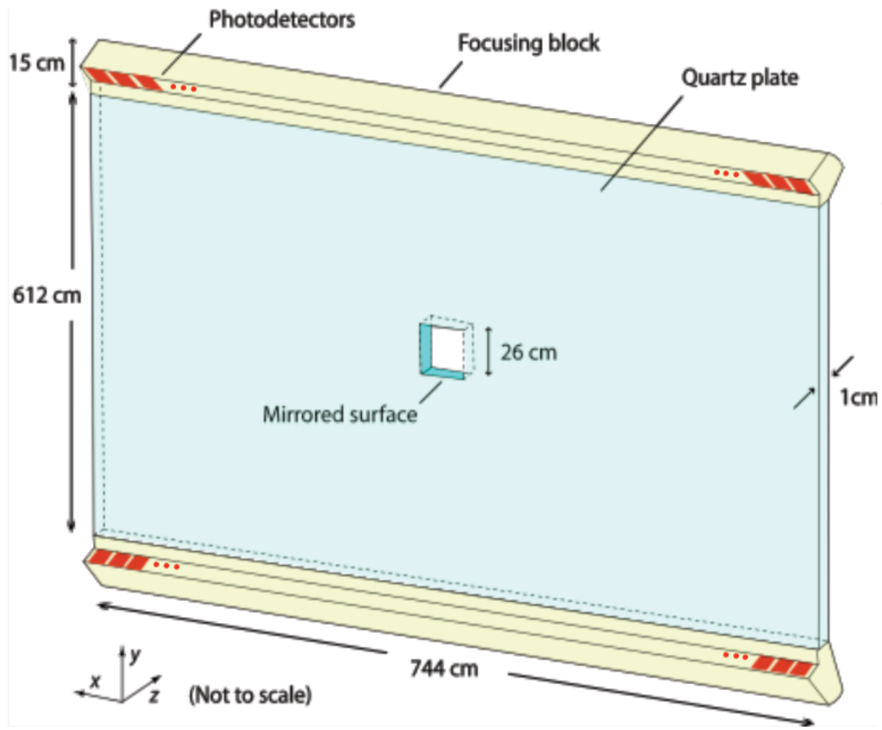
LHCb PID upgrade: TORCH

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



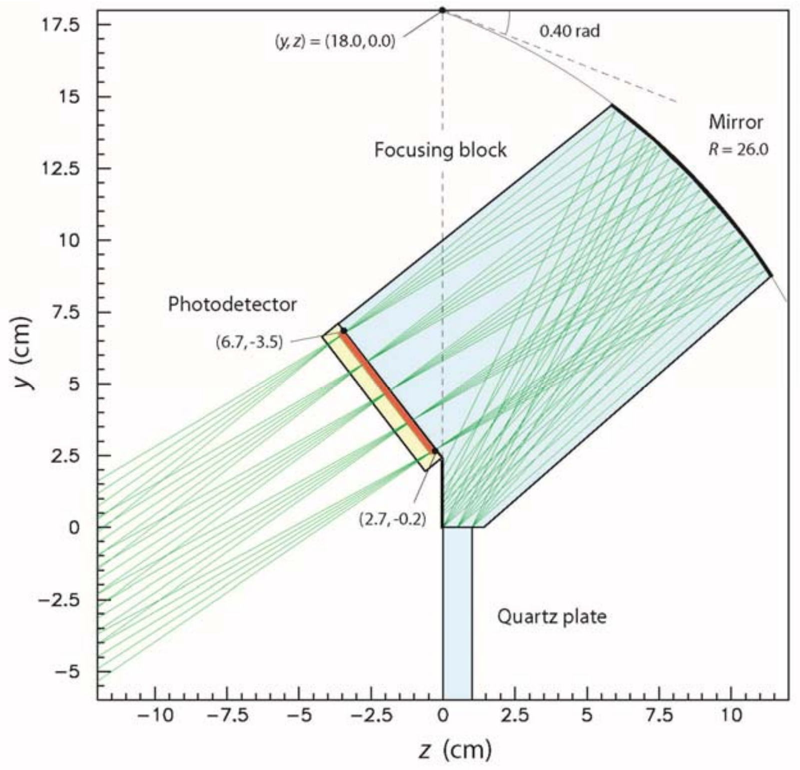


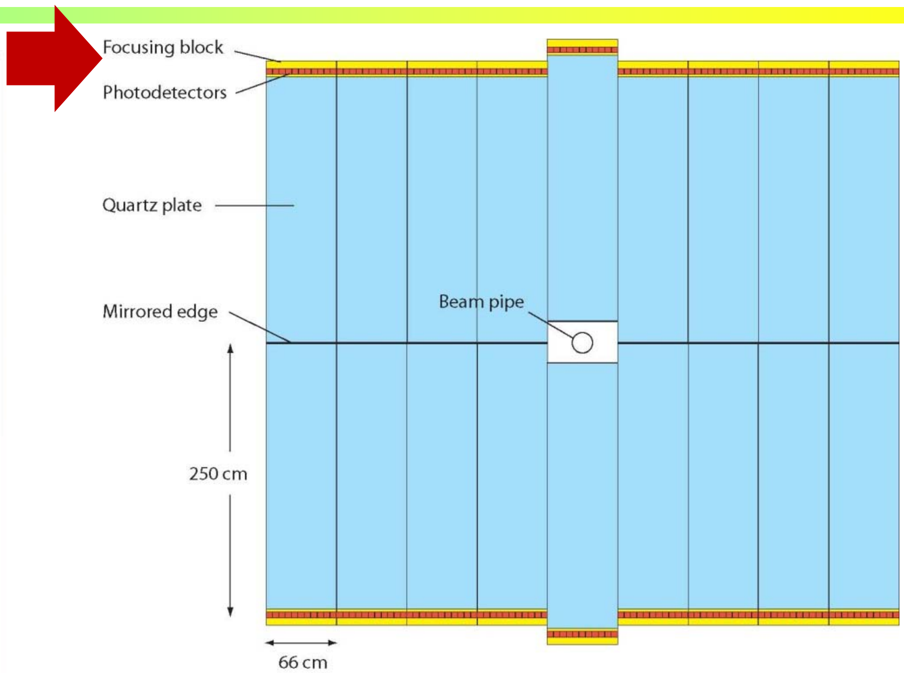
1cm-thick quartz plate at z=12m



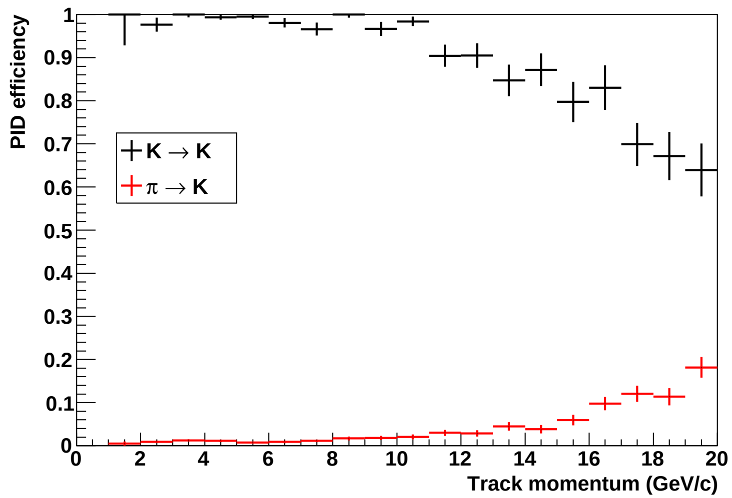
Sides are instrumented too (not shown)

LHCb PID upgrade: TORCH

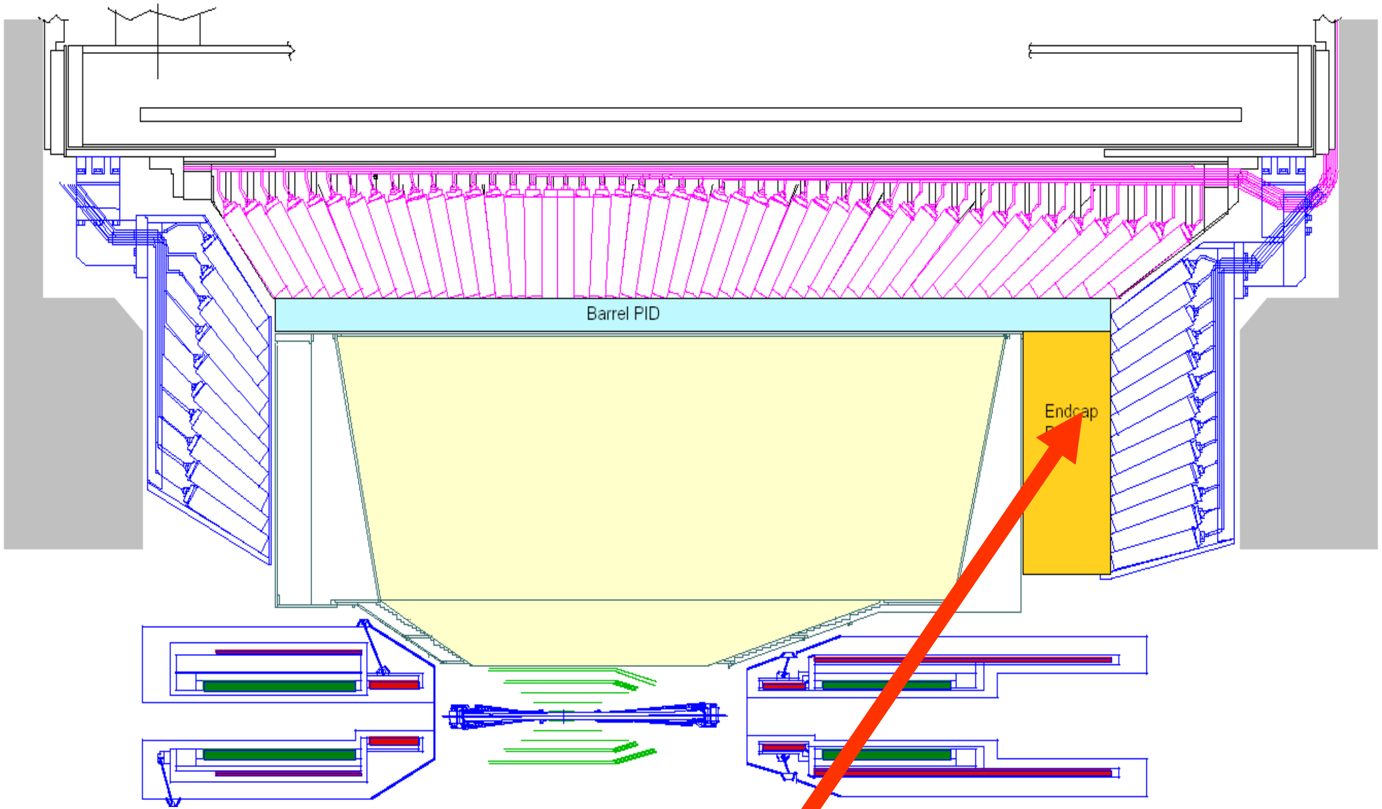




Expected performance with Photonis Planacon MCP PMTs



Belle II PID system

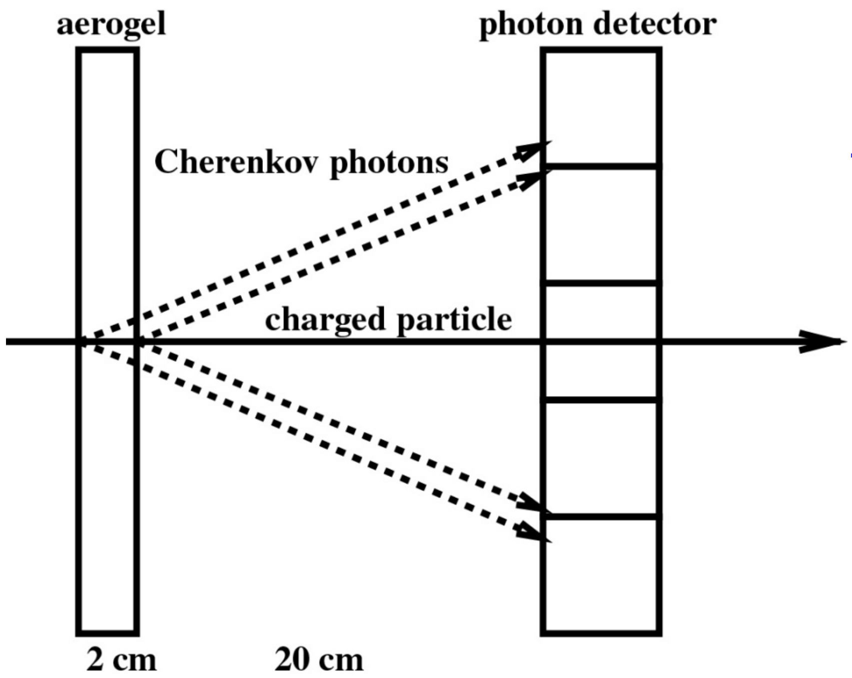


Two new particle ID devices, both RICHes:

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

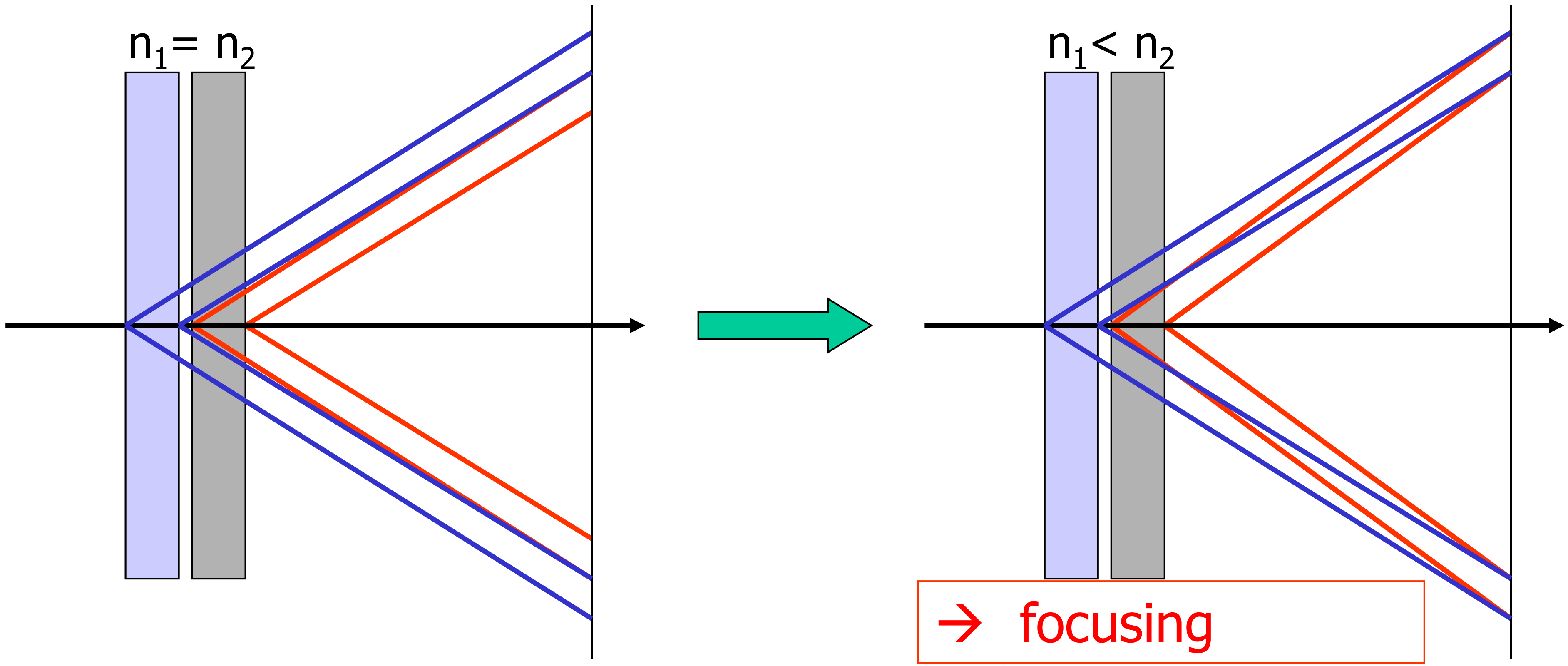
→ 5σ separation with N_{pe}~10

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal

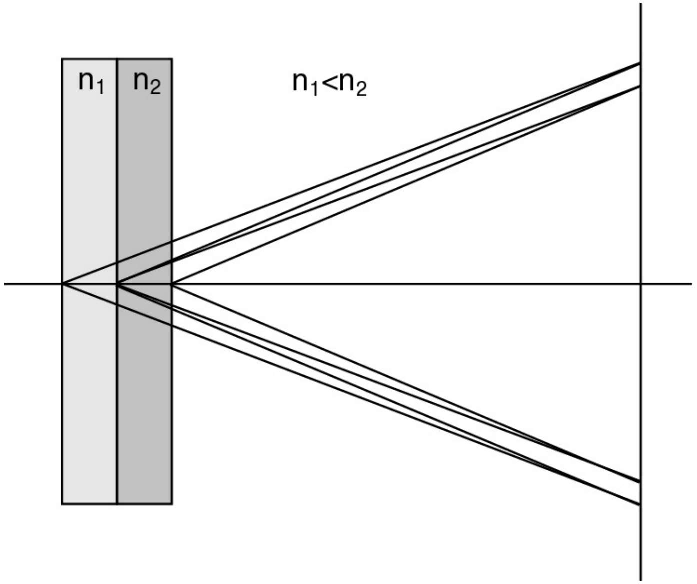
→ stack two tiles with different refractive indices: "focusing" configuration

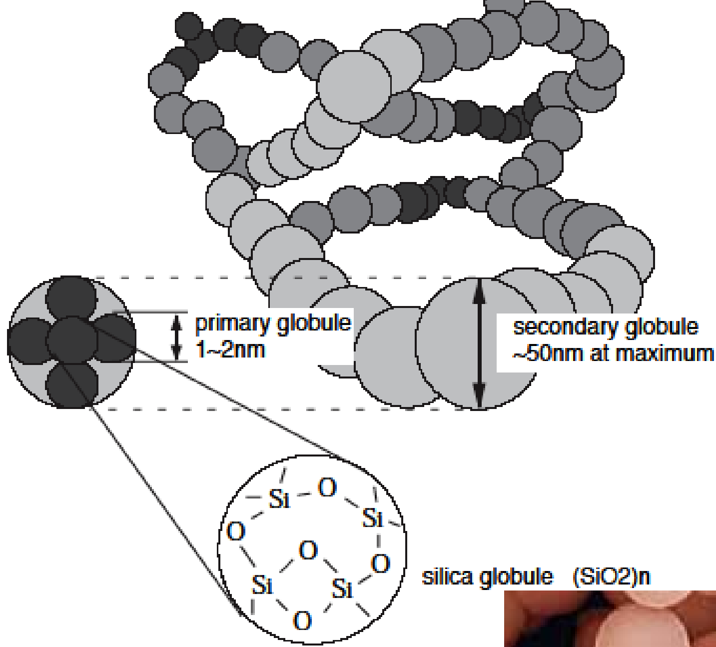


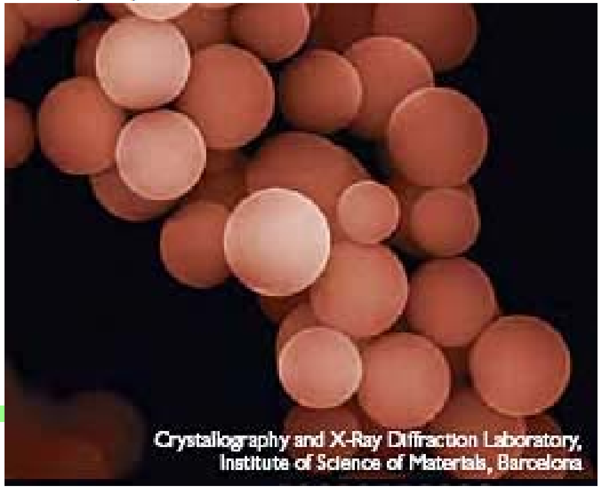
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

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.

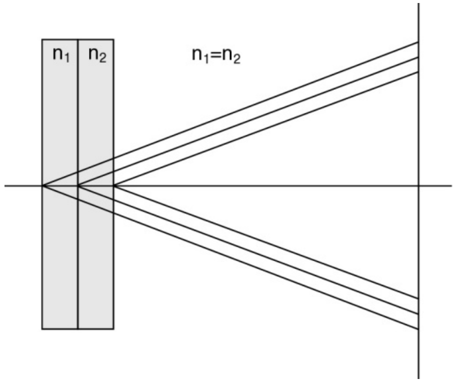


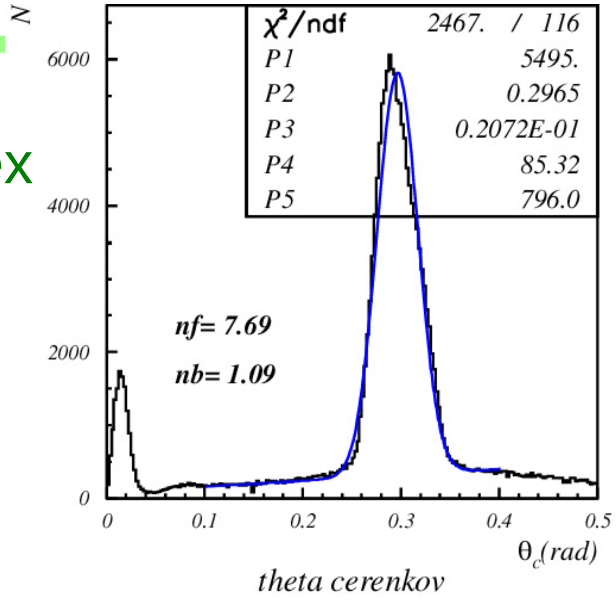


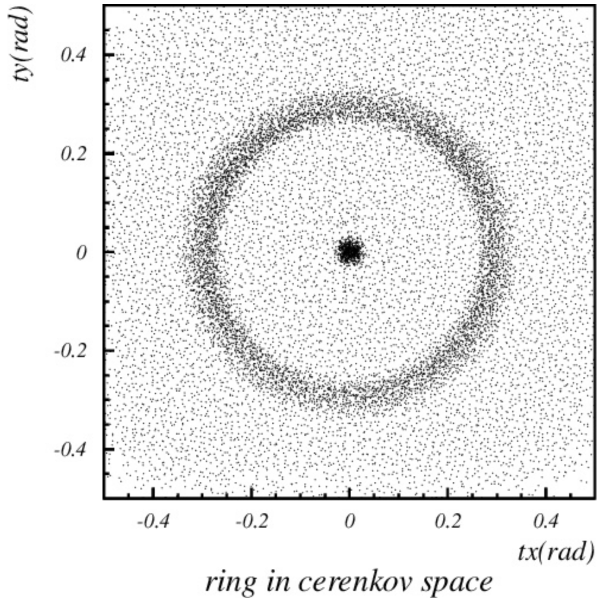


Focusing configuration – data

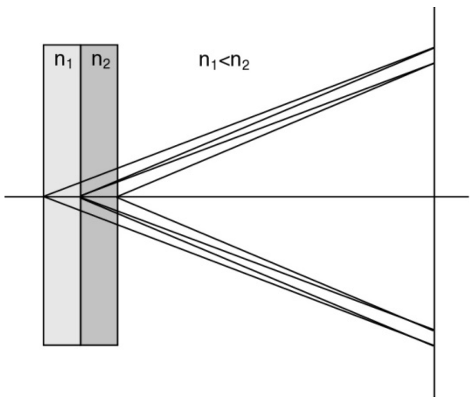
4cm aerogel single index

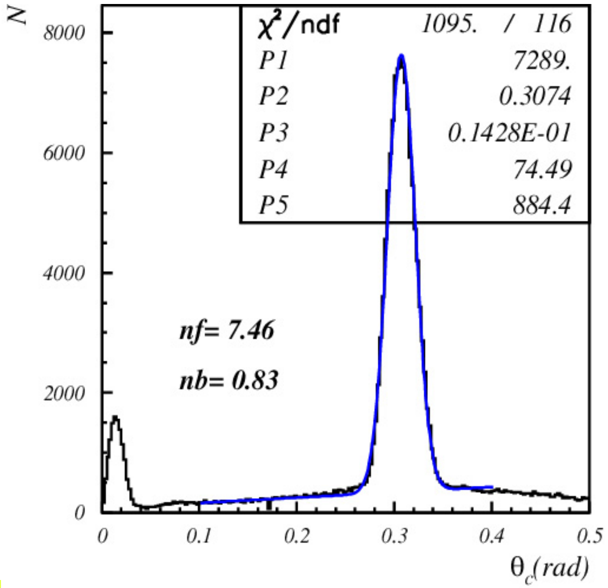


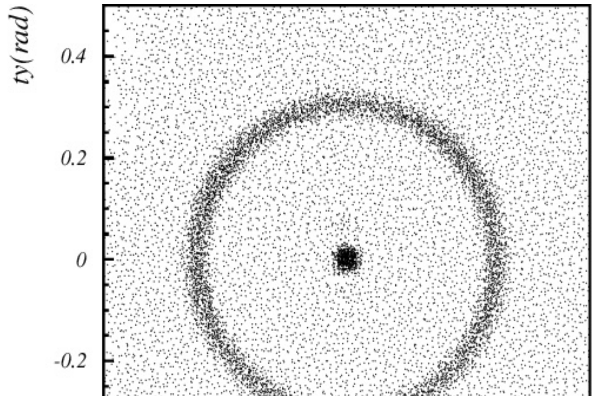


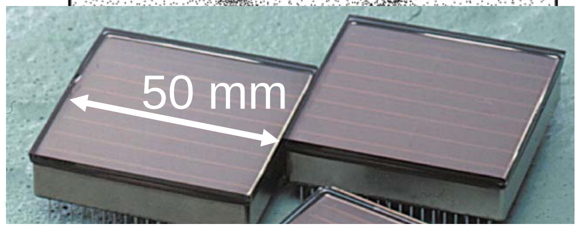


2+2cm aerogel









4x4 array of flat pannel MAPMTs

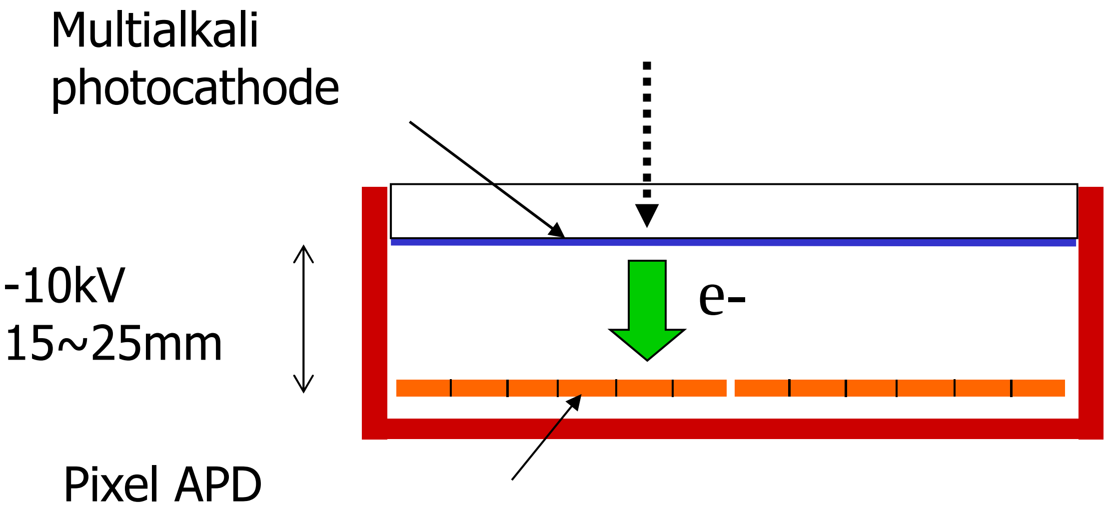
→NIM A548 (2005) 383, NIMA 565 (2006) 457

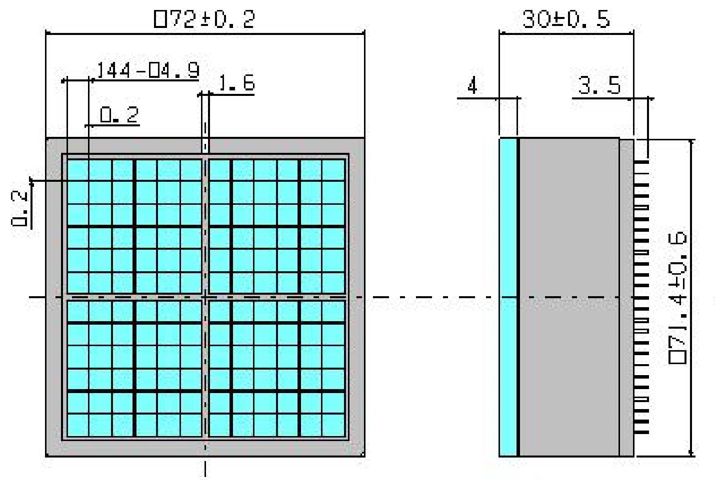
Photon detectors for the aerogel RICH requirements and candidates

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

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

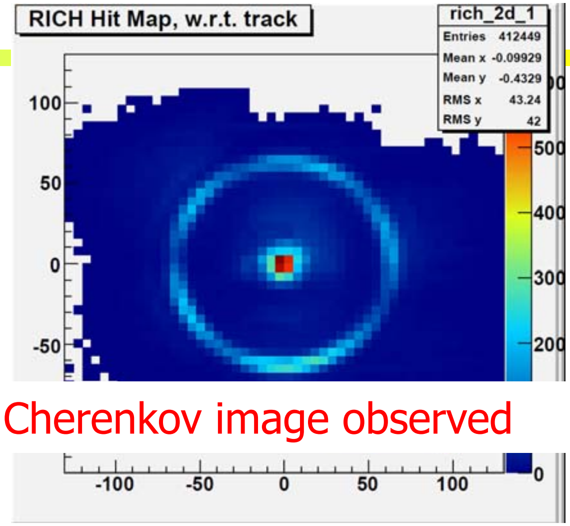
Candidates: MCP PMT (Photonis/Burle 85011, SiPMs)



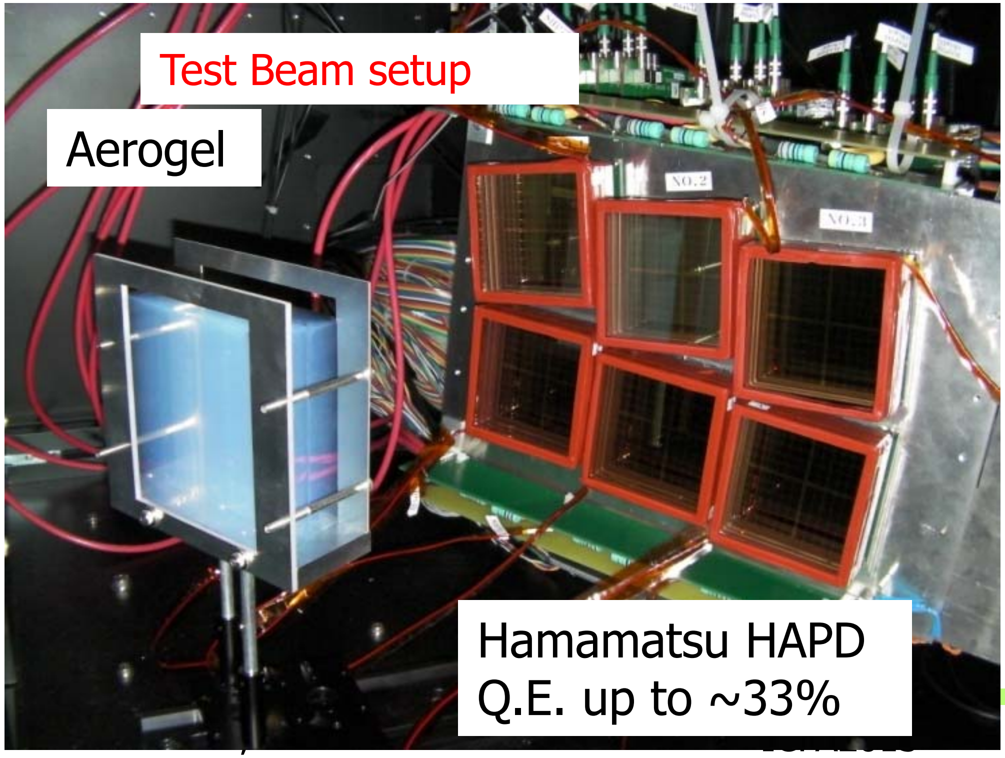


HAPD R&D project in collaboration with HPK.

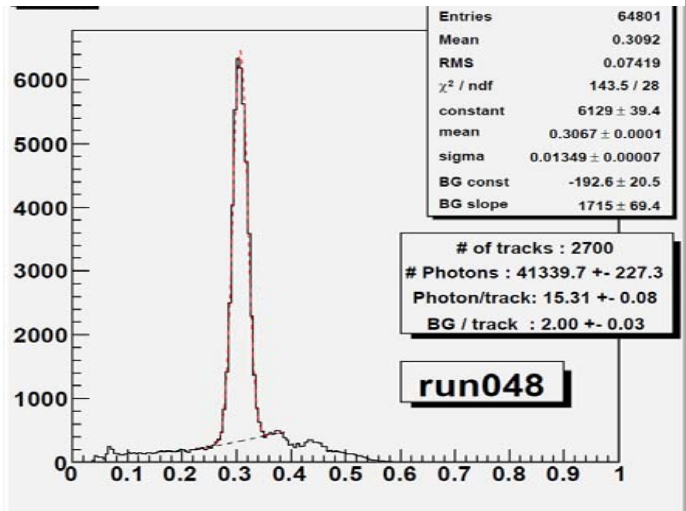
HAPD as the Aerogel RICH photon detector



Clear Cherenkov image observed



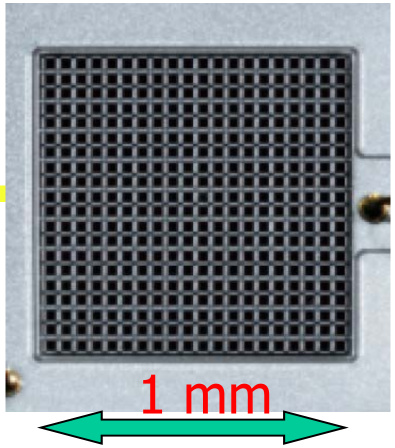
Cherenkov angle distribution



6.6 σ p/K at 4GeV/c !

→ NIM A595 (2008) 180

SiPMs as photon detectors?

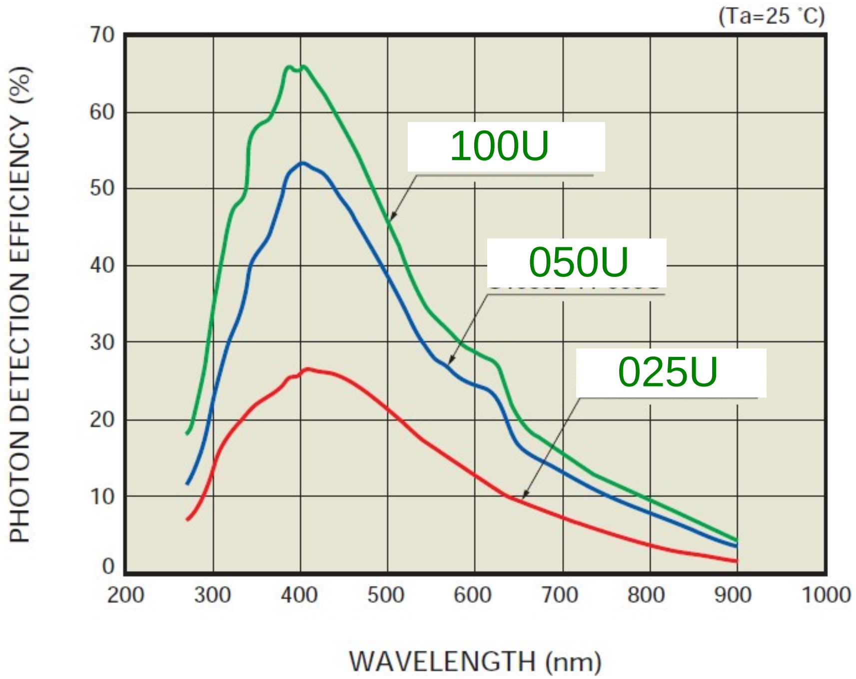


SiPM is an array of APDs operating in Geiger mode. Characteristics:

- 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)

→ Talk by C. Joram



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

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

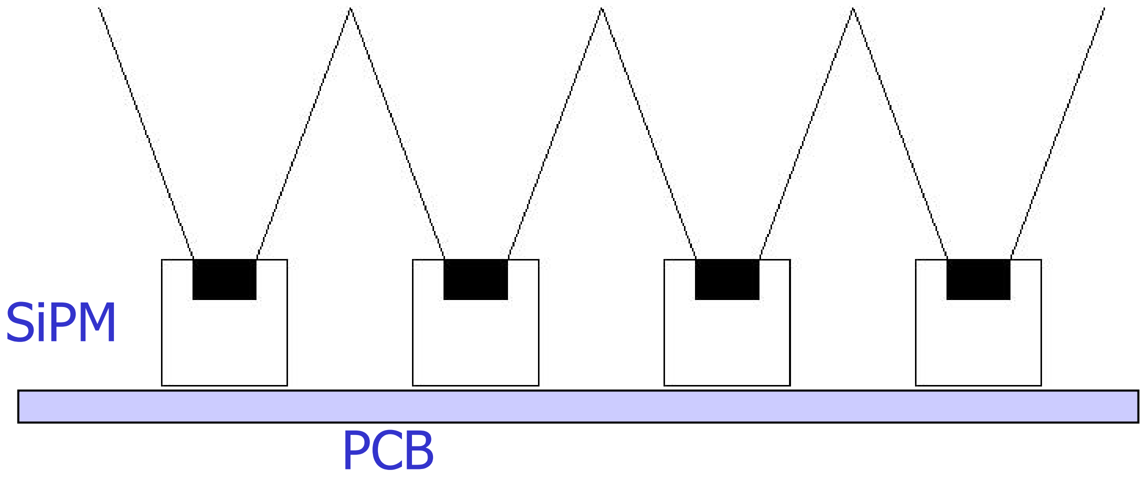
SiPM as photosensor for a RICH counter

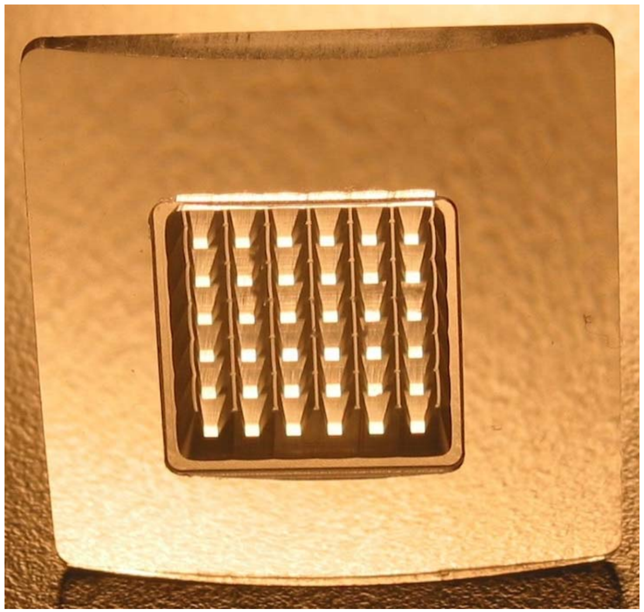
Improve the signal to noise ratio:

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

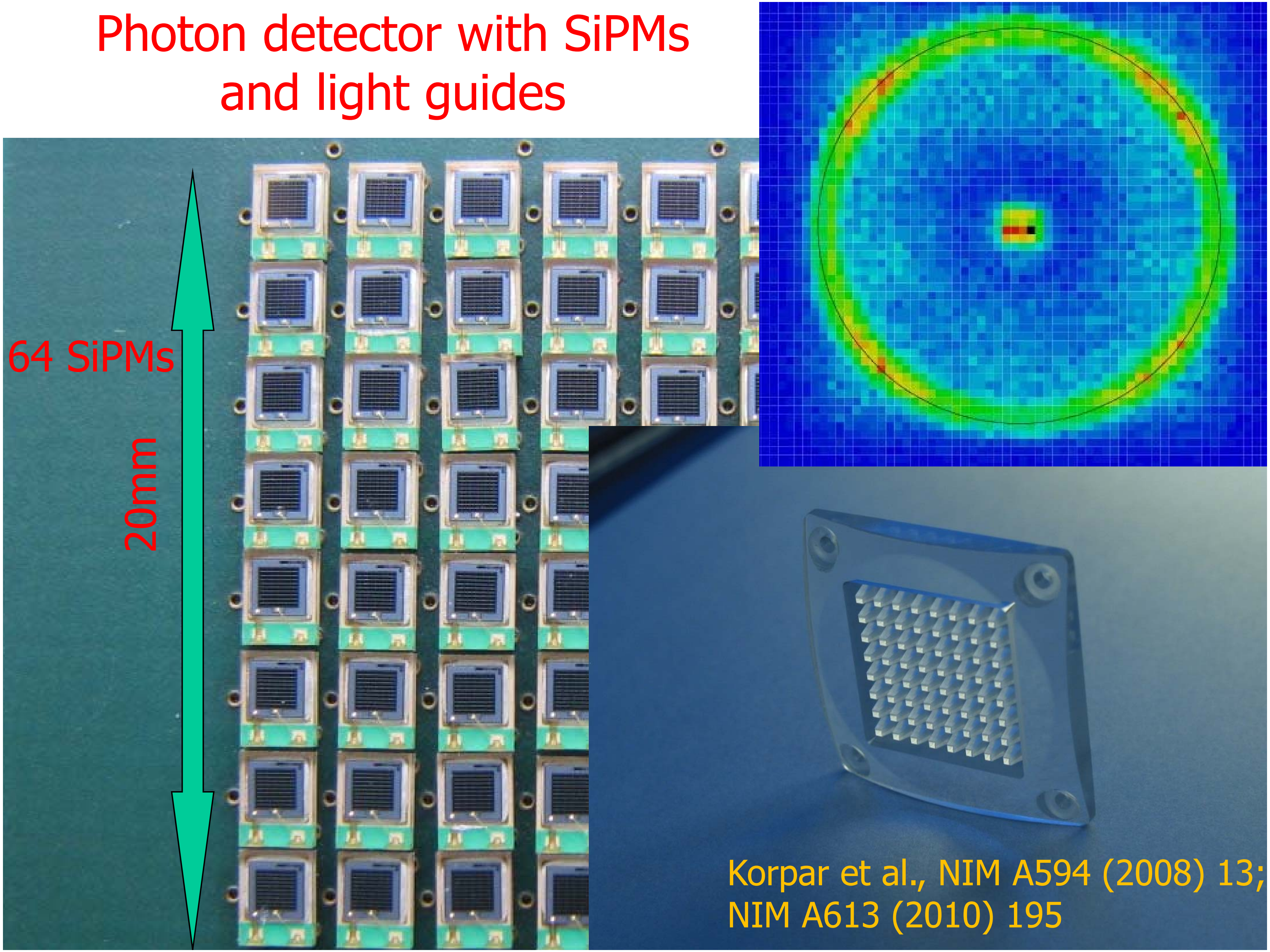
•Increase the number of signal hits per single sensor by using light collectors

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





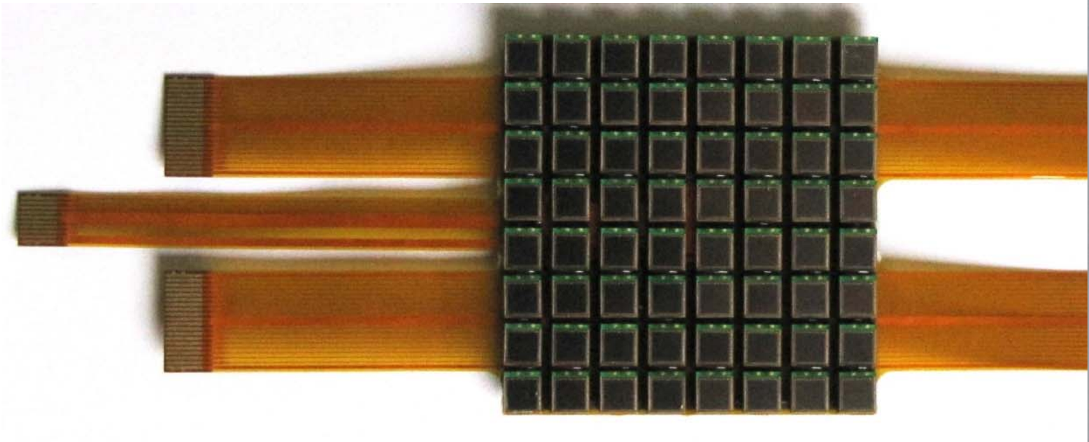
Photon detector with SiPMs and light guides

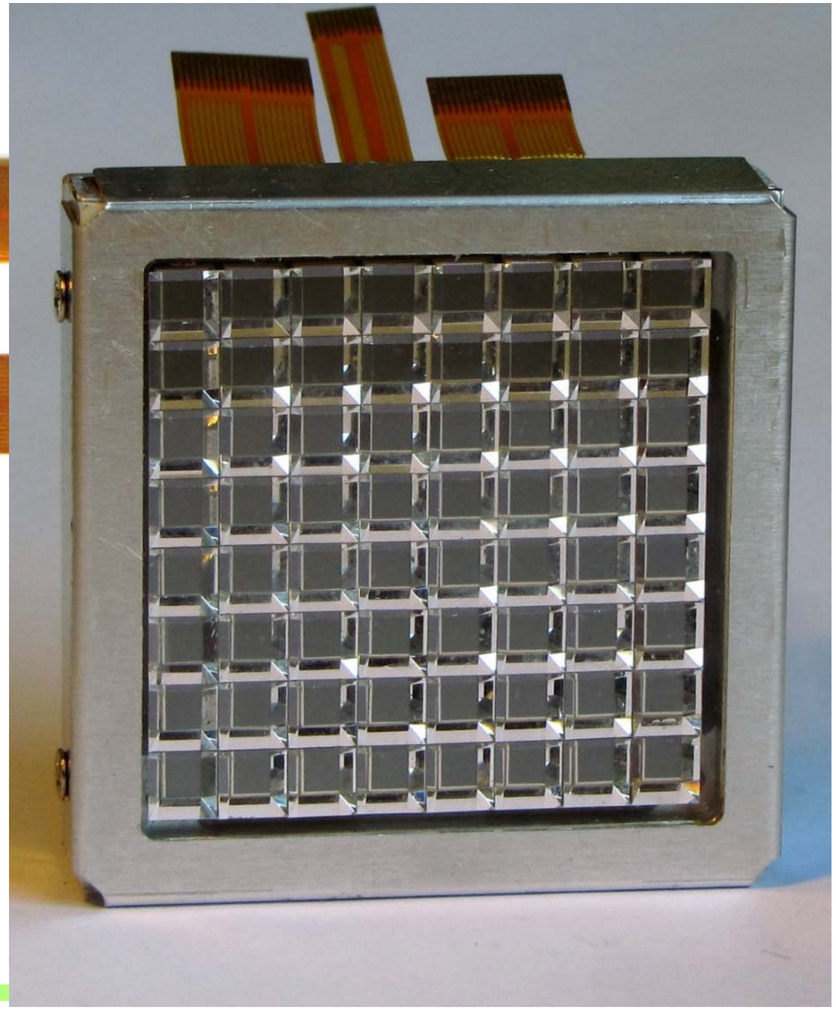


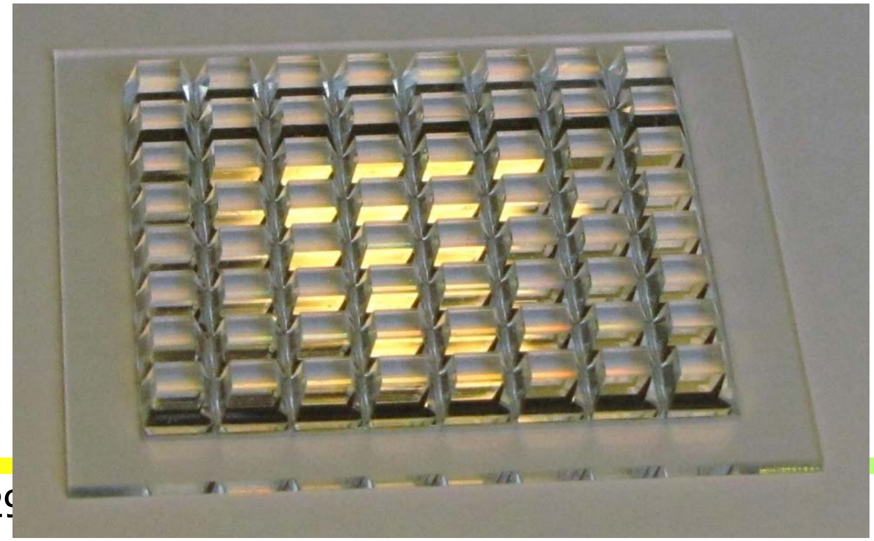
Next step: use arrays of SiPMs

Example: Hamamatsu MPPC S11834-3388DF

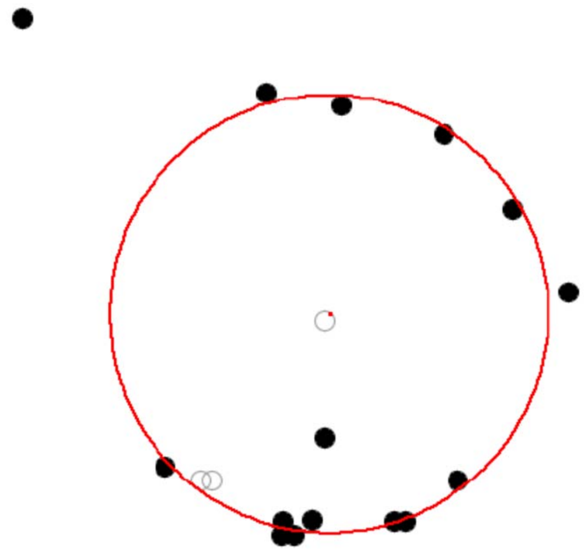
- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2







Digital SiPM



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

→ Lectures by C. Joram

Square matrix 20x20 cm^2

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

S. Kononov, VCI2013

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 (→lectures by Francesco Lanni)

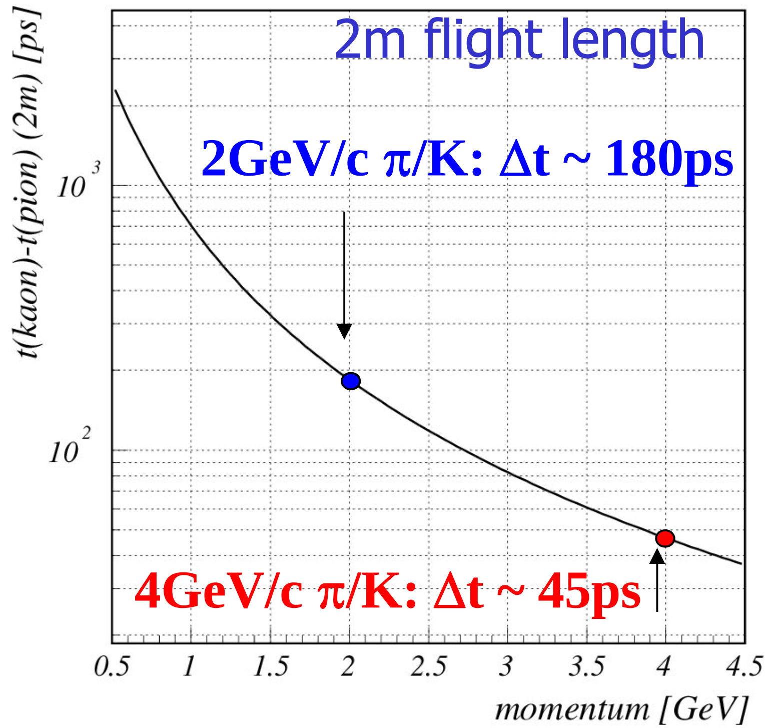
Time-of-Flight (TOF) counters

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

Traditionally: plastic scintillator + PMTs

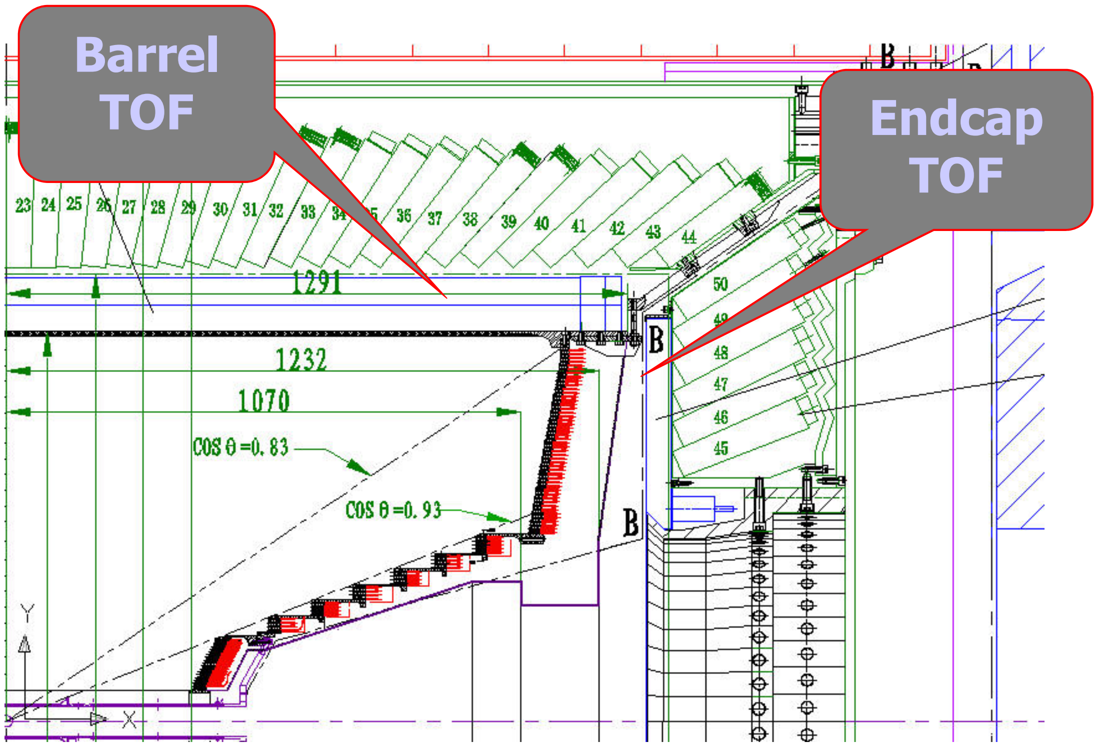
Typical resolution: ~100 ps → π/K separation up to ~1GeV.

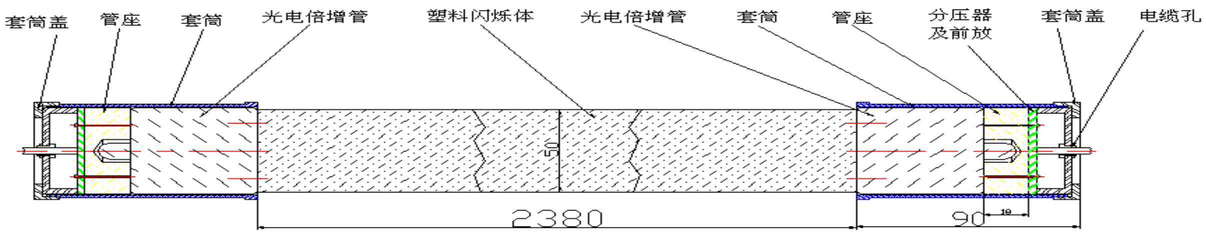
Time difference between π and K:



→ BESSIII

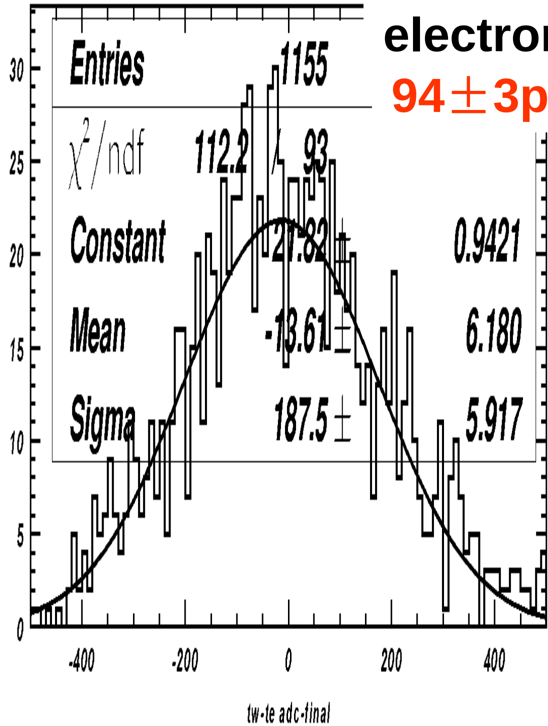
BESIII: Time-Of-Flight counters





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

Beam test results: two TOF modules



electrons
94±3ps

Time-of-Flight (TOF) counters

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

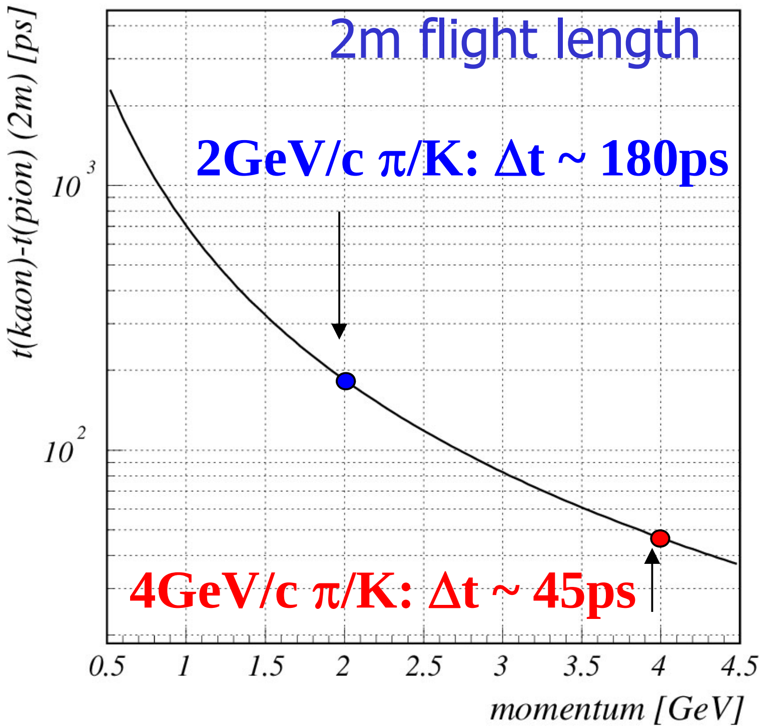
Traditionally: plastic scintillator + PMTs

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

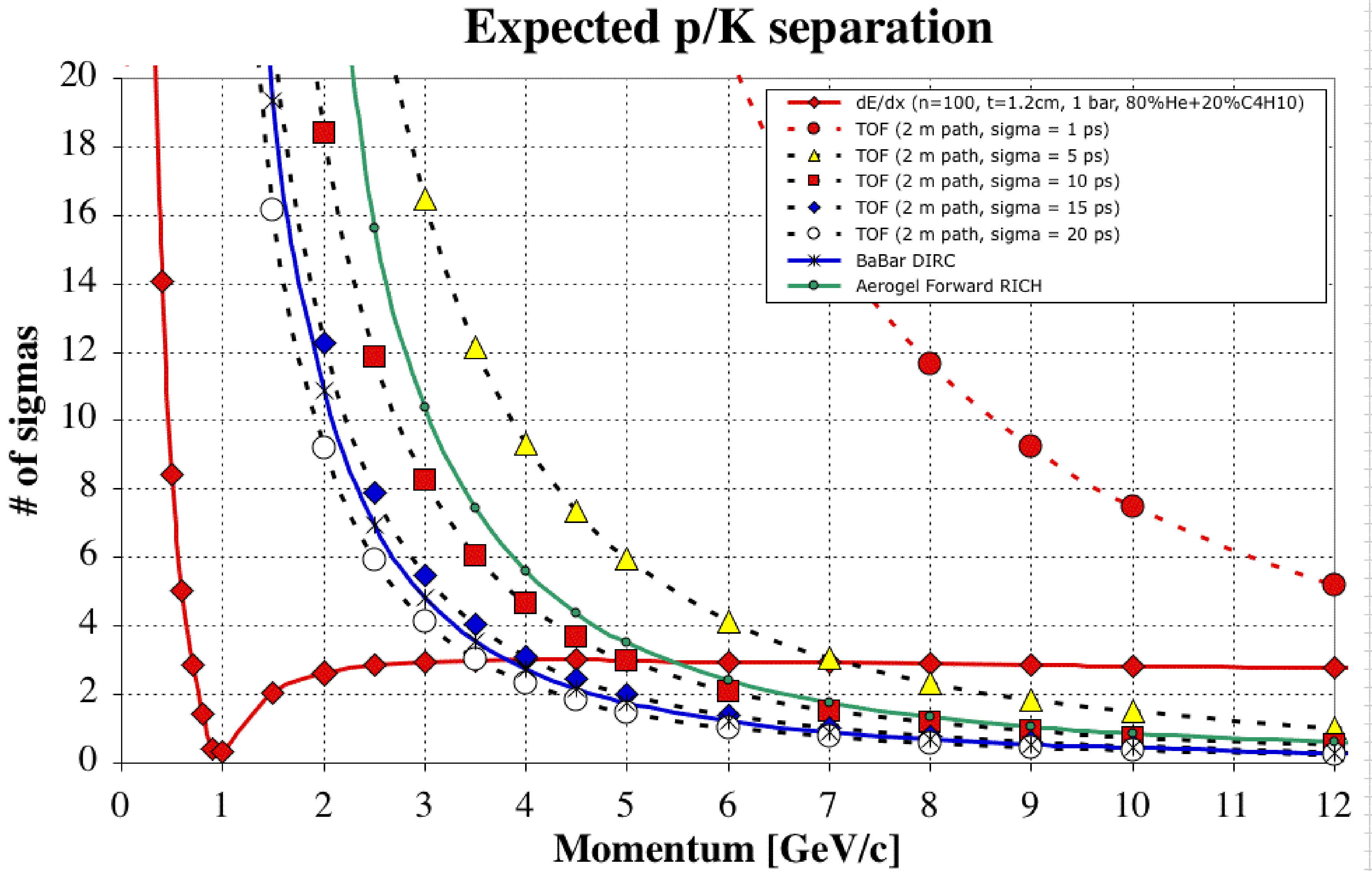
To go beyond that: need faster detectors:
→use Cherenkov light (prompt) instead of scintillations
→use a fast gas detector (Multi gap RPC)

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

Time difference between π and K:



Time-of-flight with fast photon detectors



J. Va'vra, slides shown at RICH07

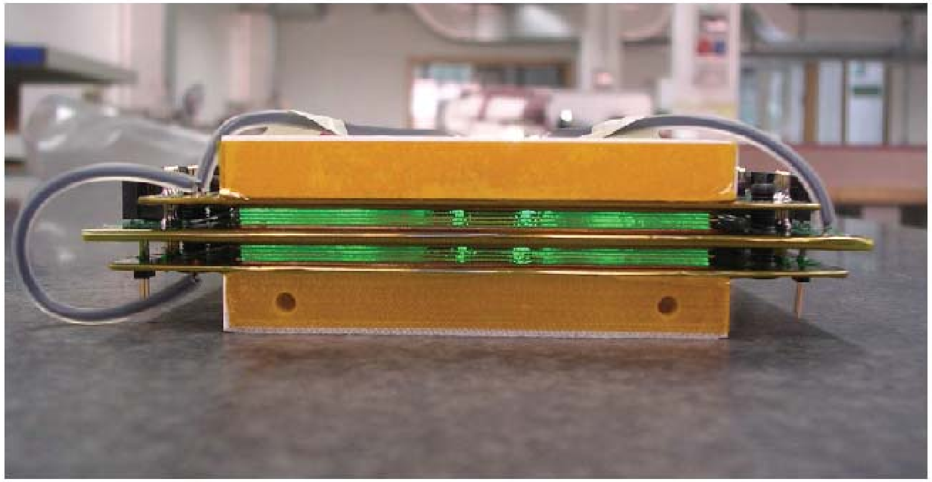
ALICE TOF

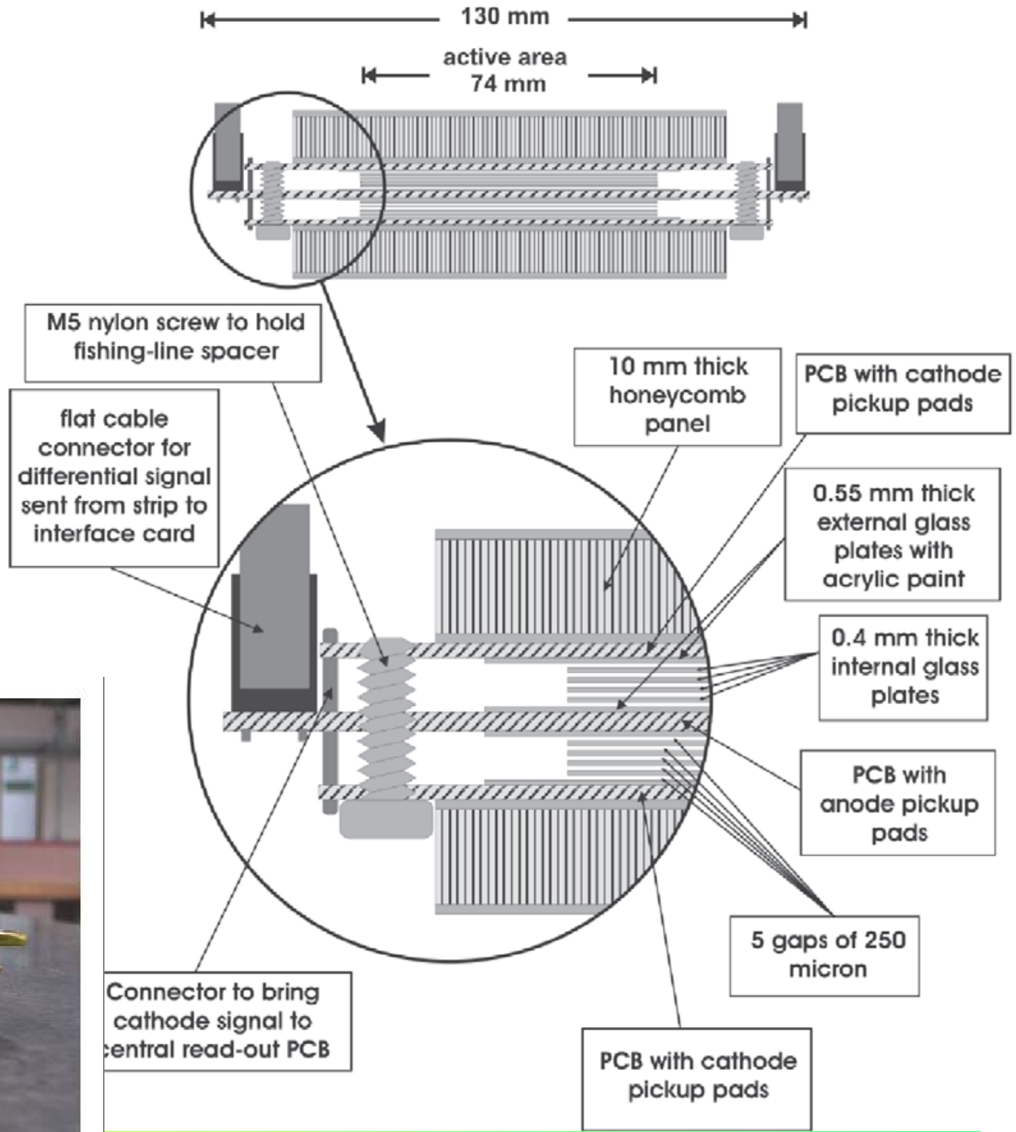
Very fast large area (140m^2) particle detector:

→ MRPC, multi-gap RPC

σ=50ps (incl. read-out)

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

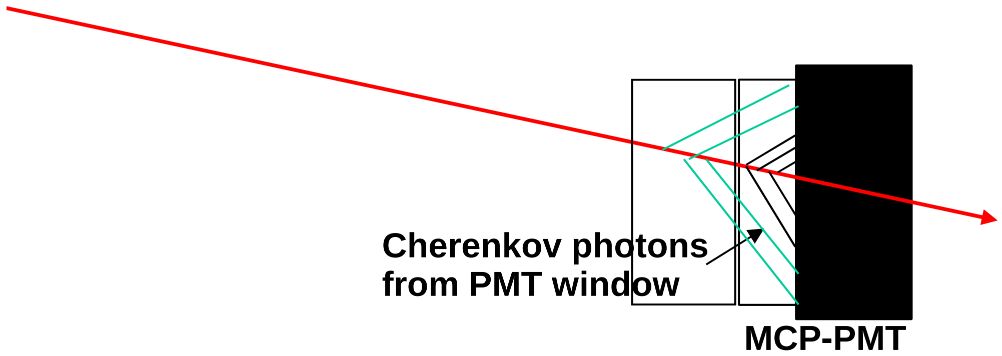


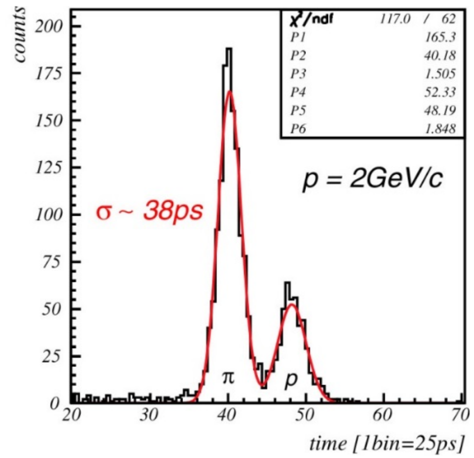


TOF with Cherenkov light

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.

Recent results:

→resolution ~5ps measured

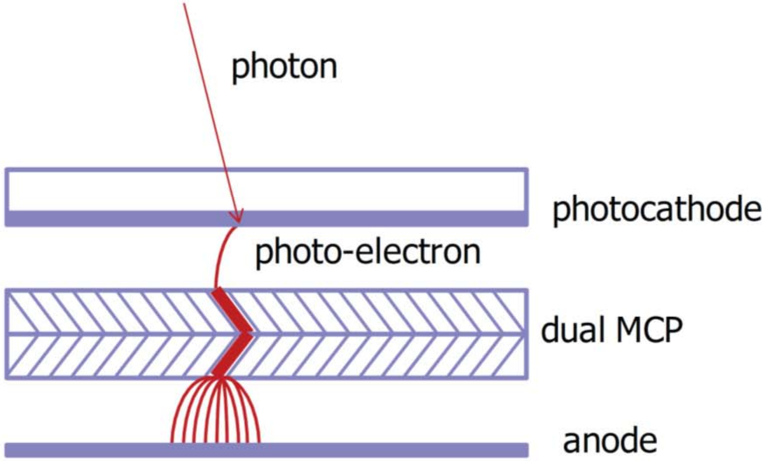
•K. Inami NIMA 560 (2006) 303

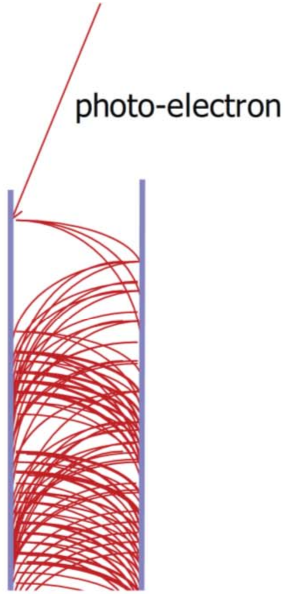
•J. Va'vra NIMA 595 (2008) 270

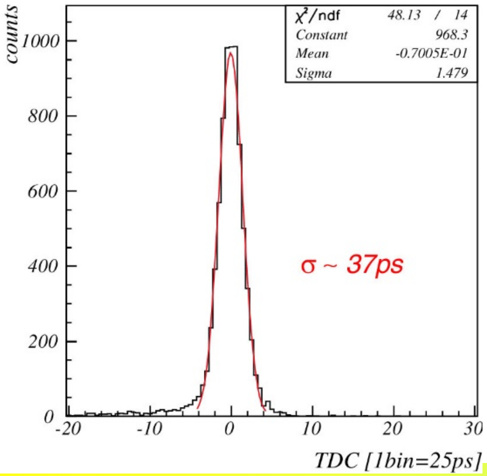
Open issues:

- read-out
- start time

MCP PMTs for a very fast timing



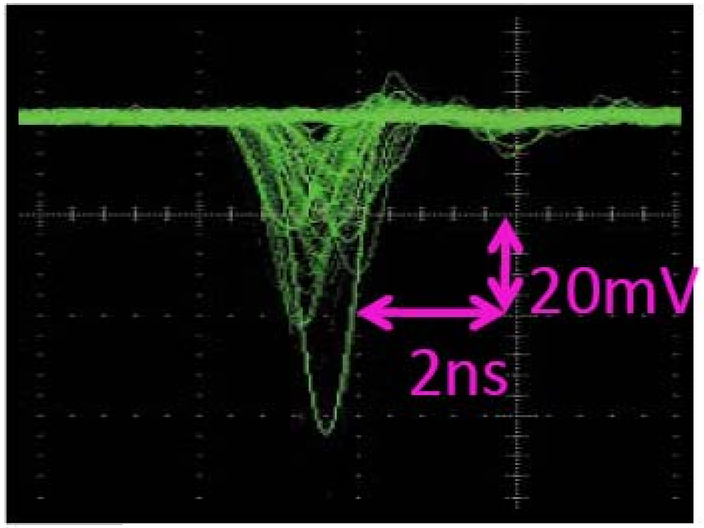


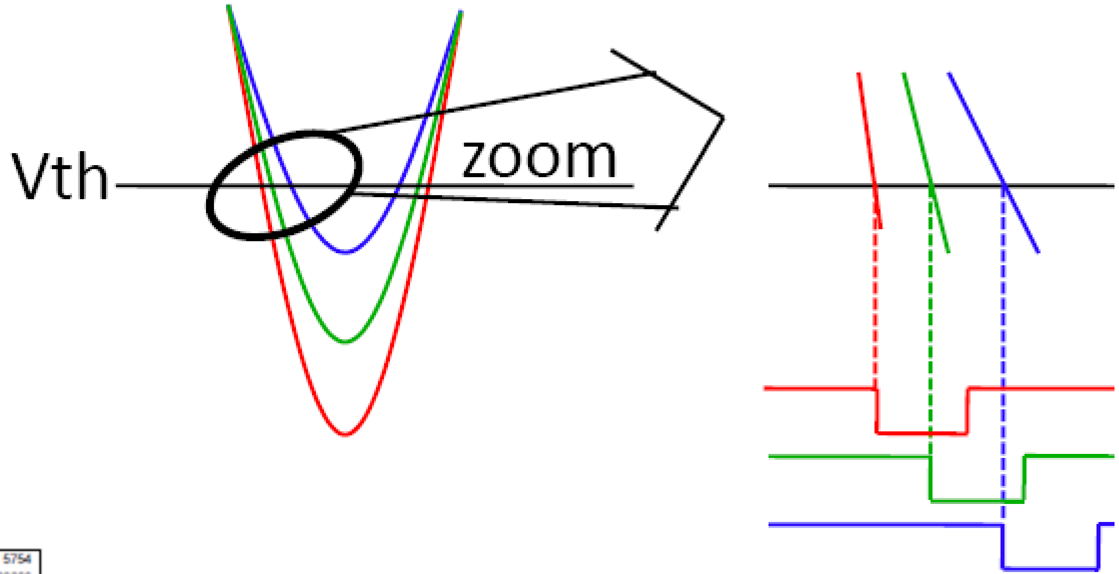


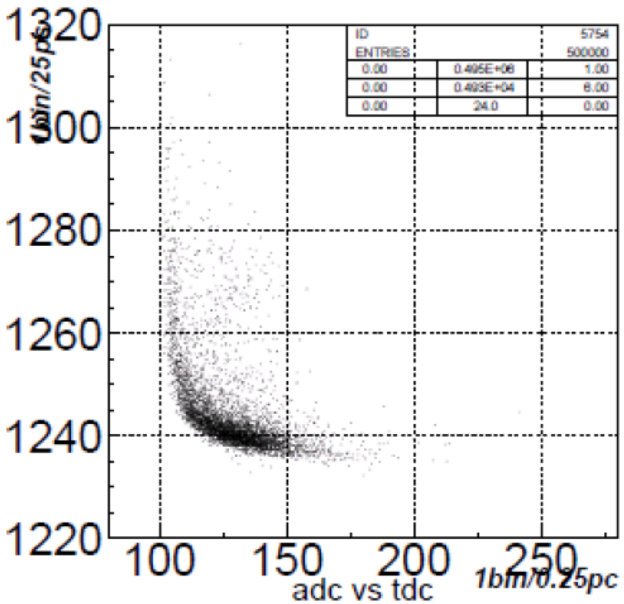
Micro-channel plate PMTs:

Single photon resolution: typically 20ps – 40ps

Read out: time walk with a leading edge discriminator



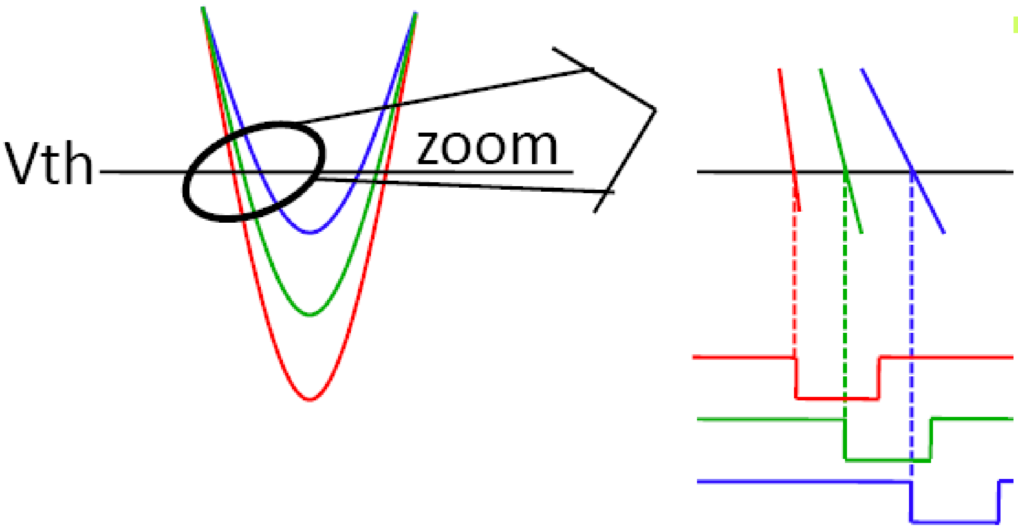


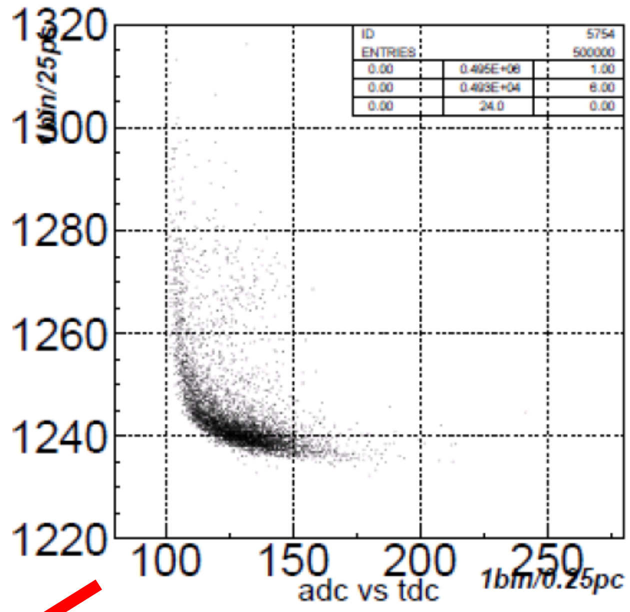


Variation of time determined with a leading edge discriminator: smaller pulses give a delayed signal

→ Has to be corrected!

Time walk correction 1

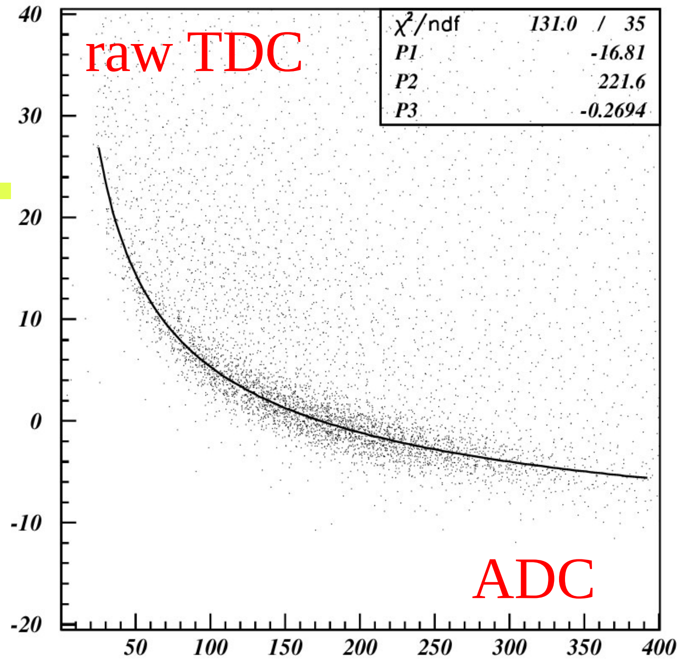




One possibility: measure both time (TDC) and amplitude (ADC)

→ Correct time of arrival by using a ΔT(ADC) correction

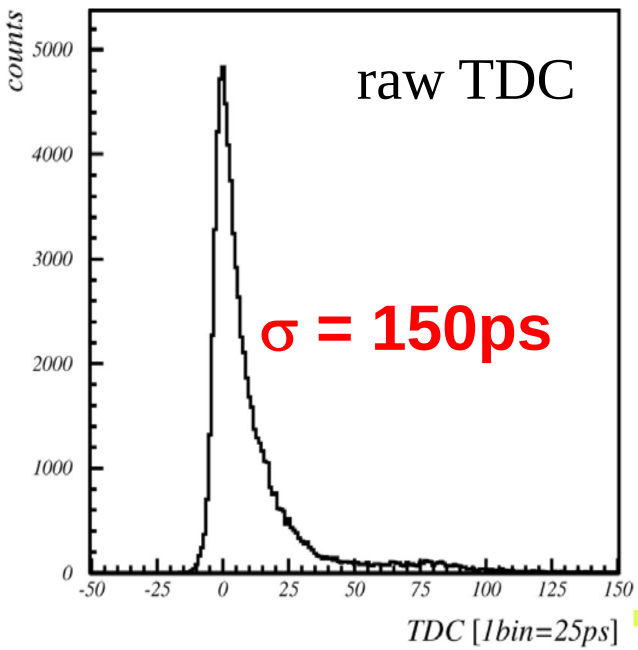
Time walk correction

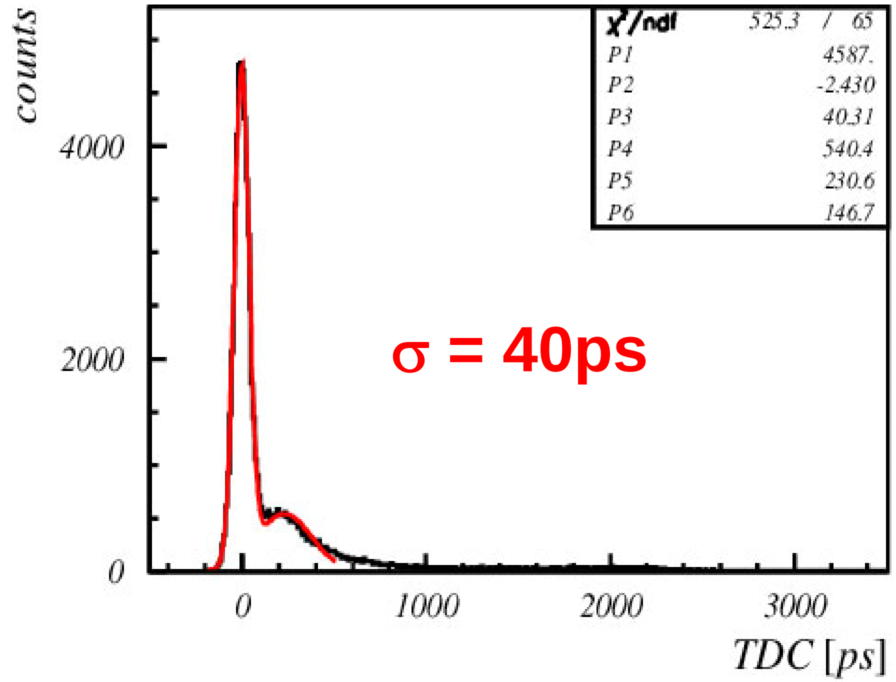


TDC vs. ADC correlation is fitted with

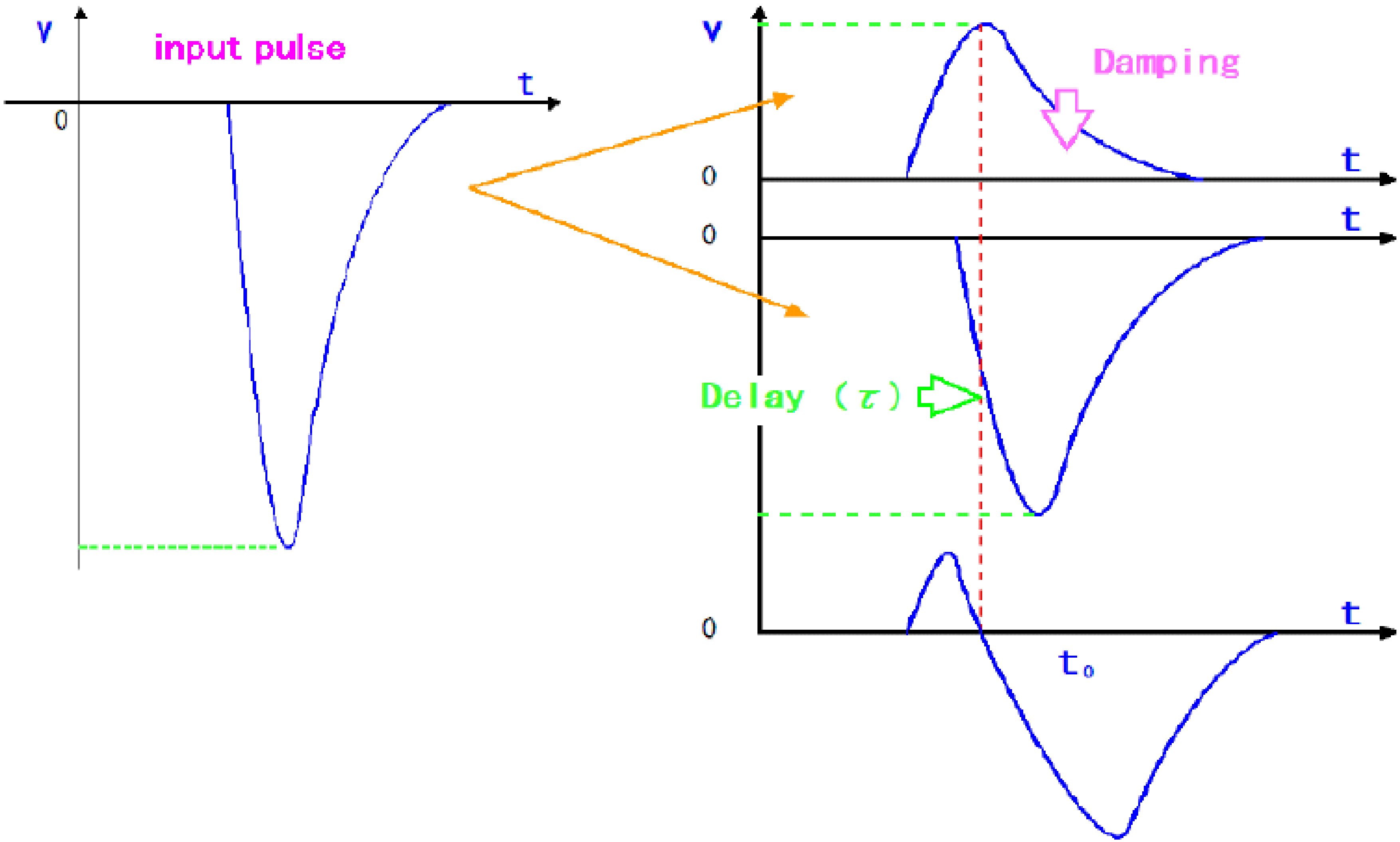
$$TDC = P1 + \sqrt{\frac{P2}{ADC - P3}}$$

and used for TDC correction

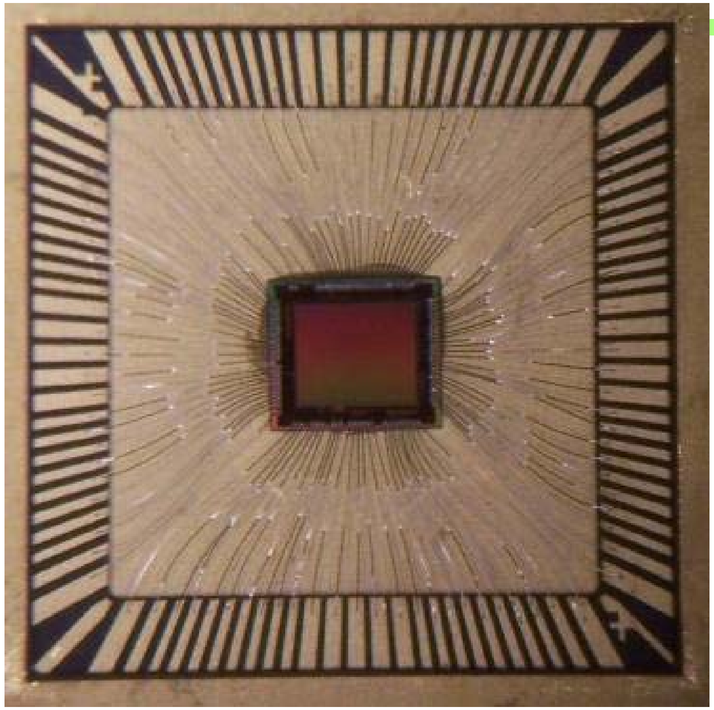




Time walk correction 2: constant fraction discriminator (CFD)



Time walk correction 3: waveform sampling



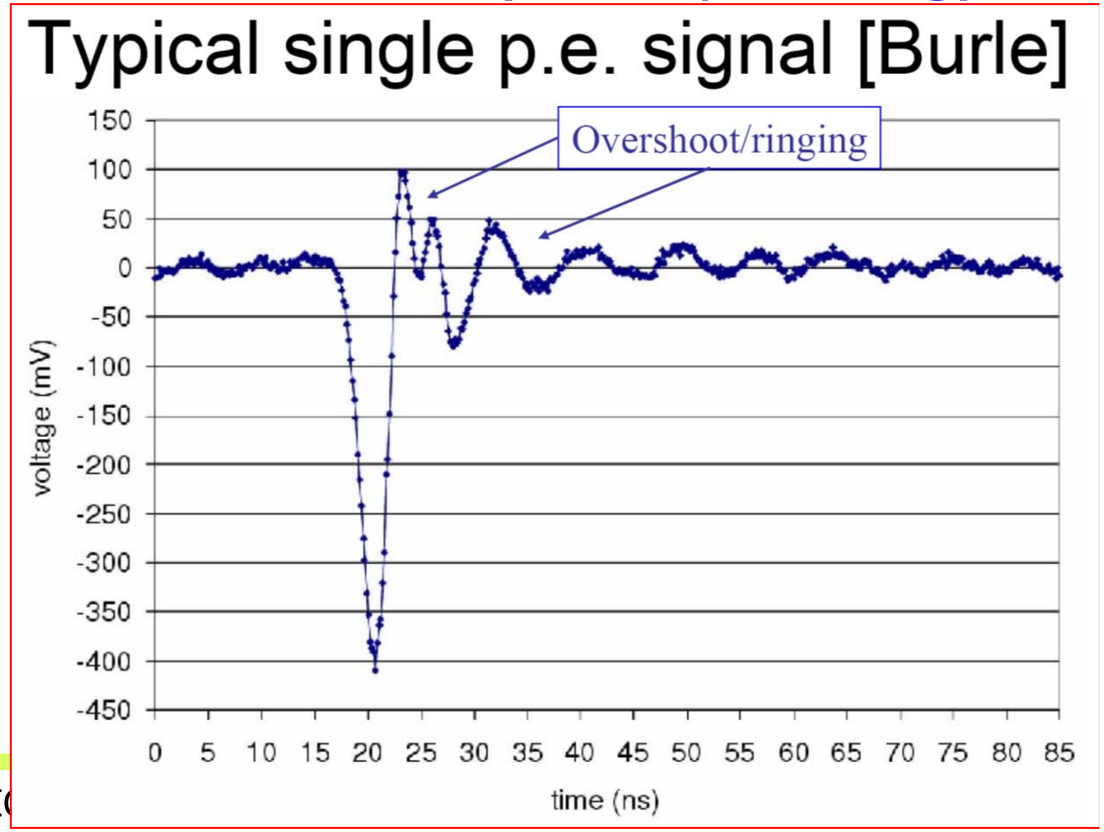
3mm x 2.8mm, TSMC 0.25um

- 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)



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)
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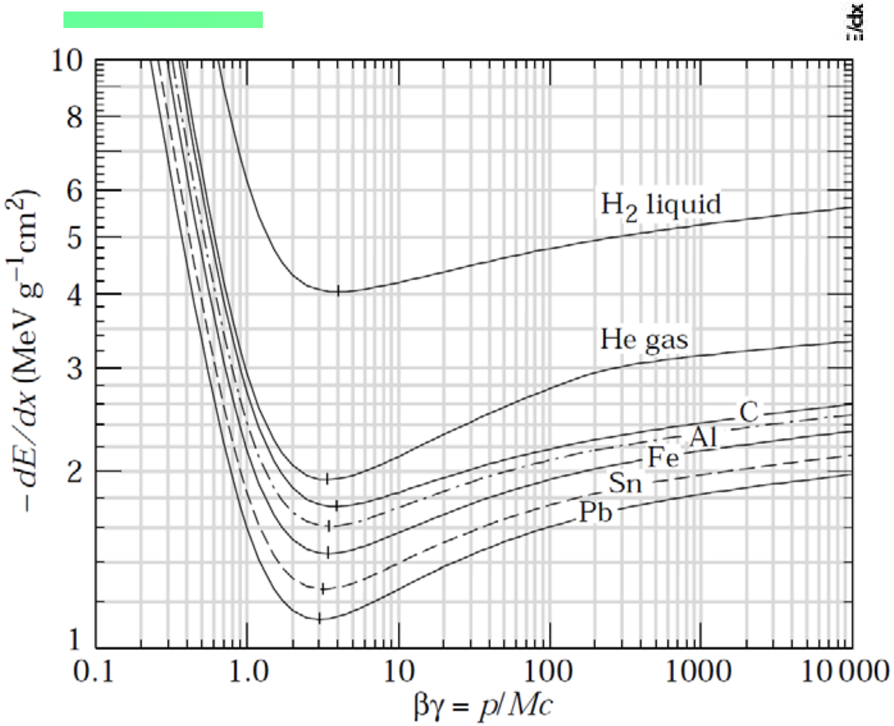
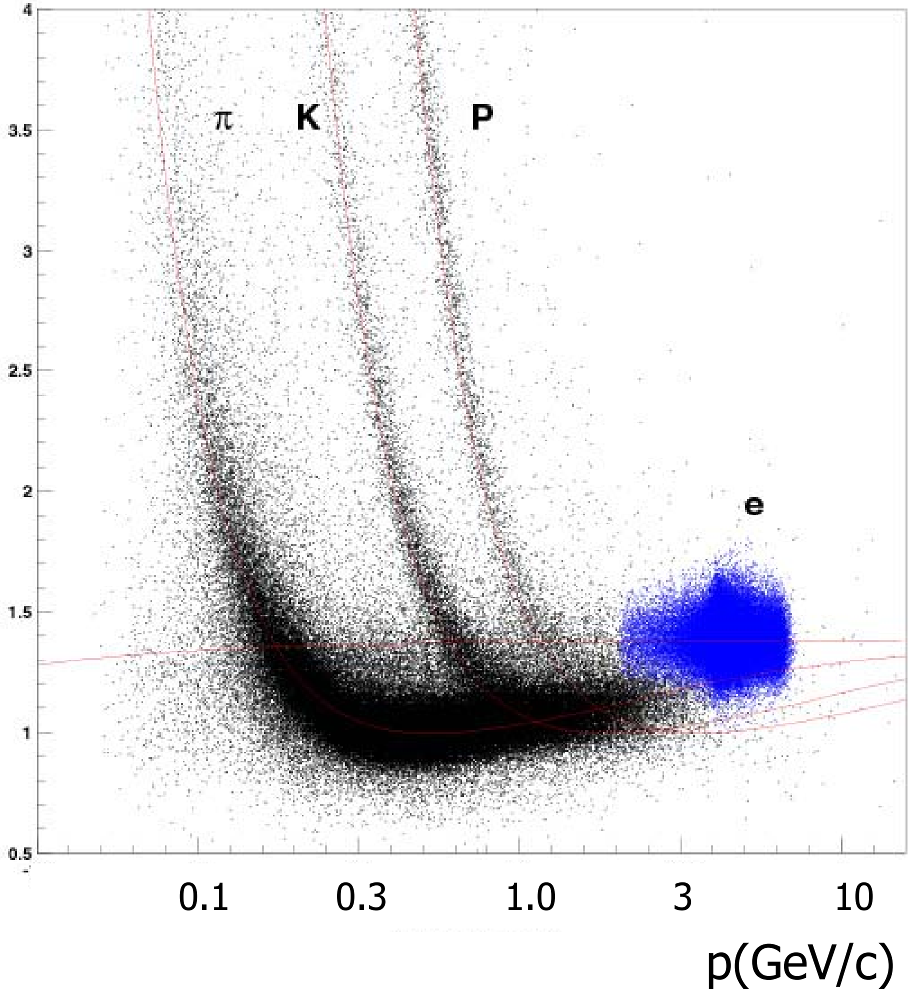
Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

- muon systems
- calorimeters (→lectures by Francesco Lanni)

Identification with the dE/dx measurement





dE/dx is a function of velocity β

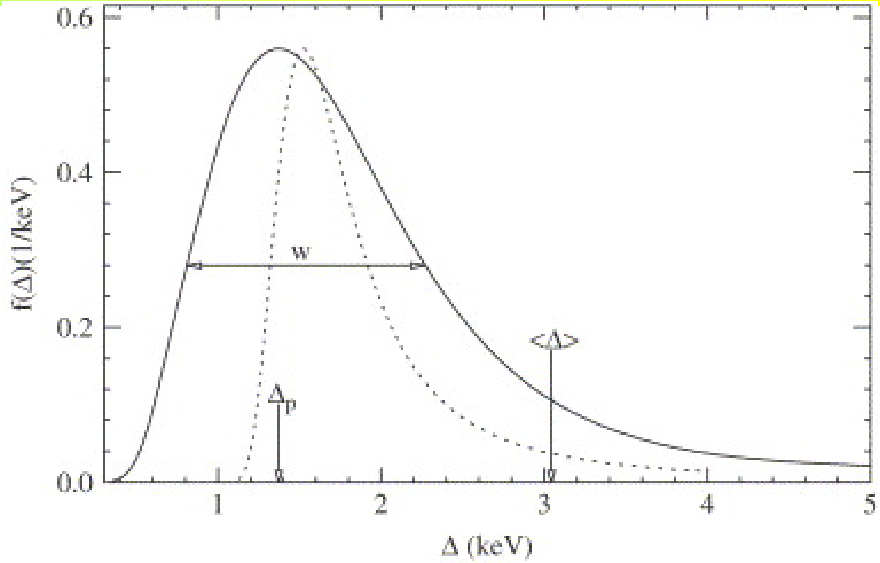
For particles with different mass the Bethe-Bloch curve gets displaced if plotted as a function of p

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.

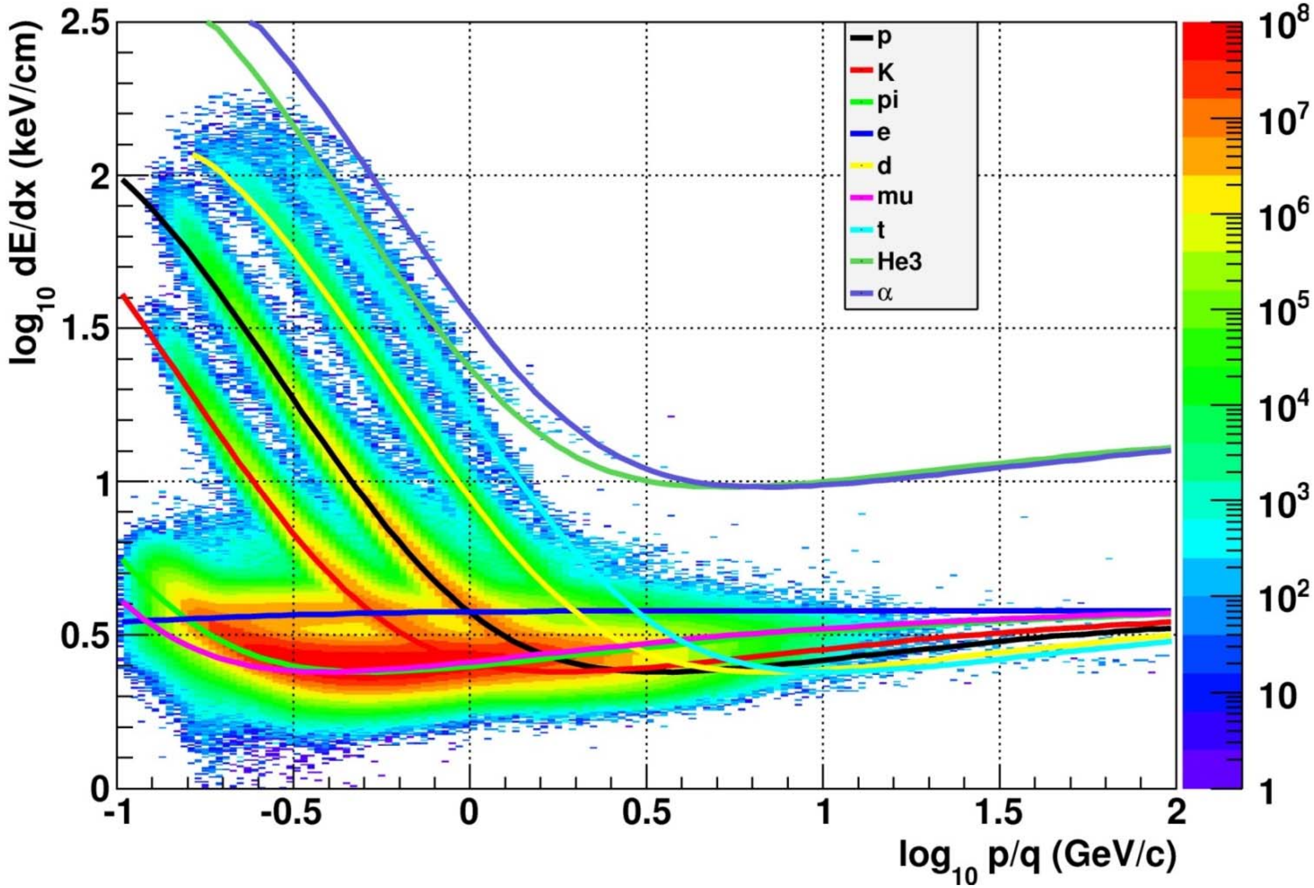
→Many samples along the track (~100 in ALICE TPC), remove the largest ~40% values (reduce the influence of the ling tail) → truncated mean

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

Identification with dE/dx measurement

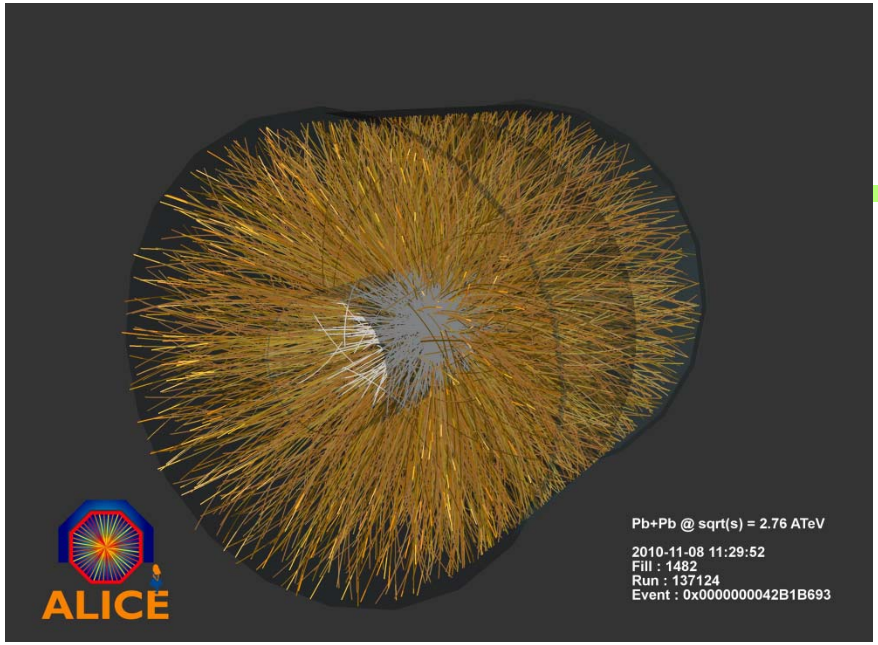
dE/dx performance in the STAR TPC

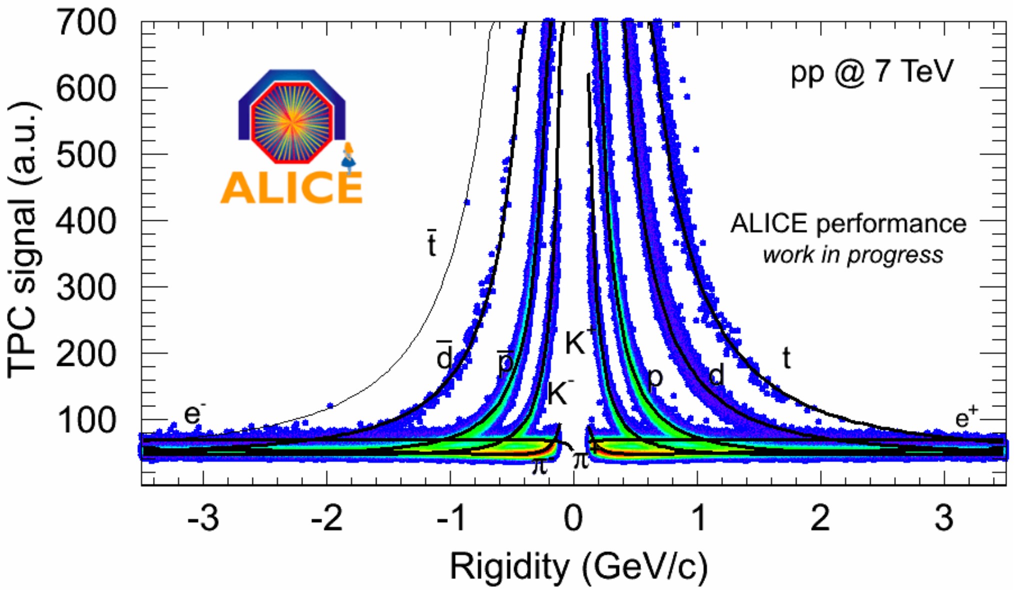
gold-gold collisions



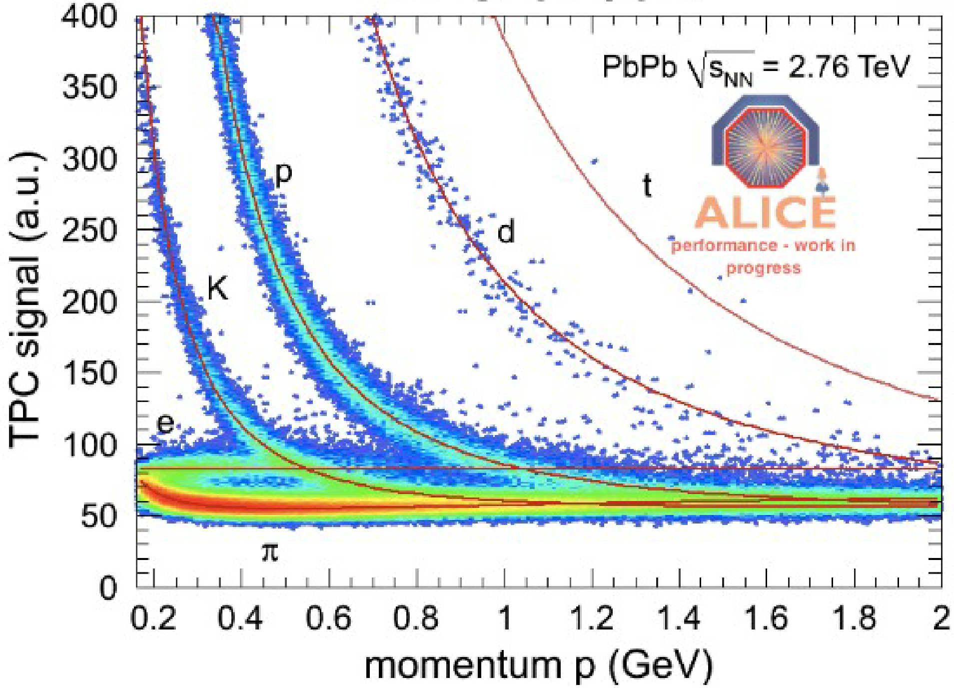
Energy loss in the STAR TPC: truncated mean as a function of momentum. The curves are Bichsel model predictions.

dE/dx in ALICE

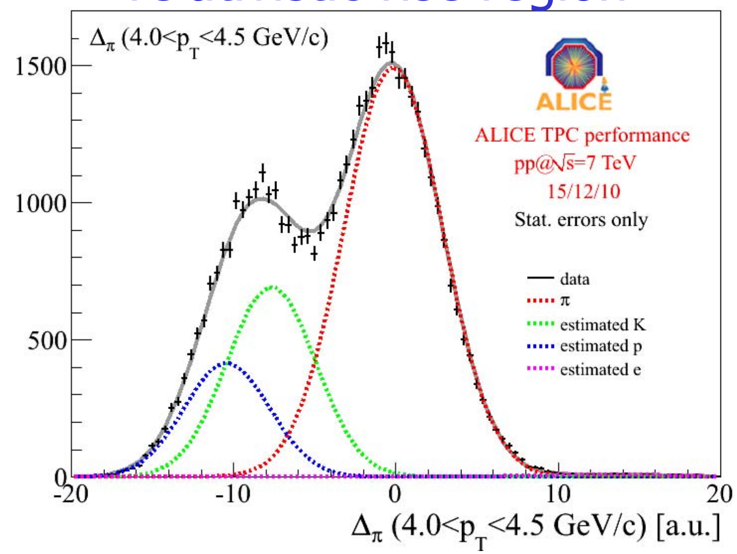




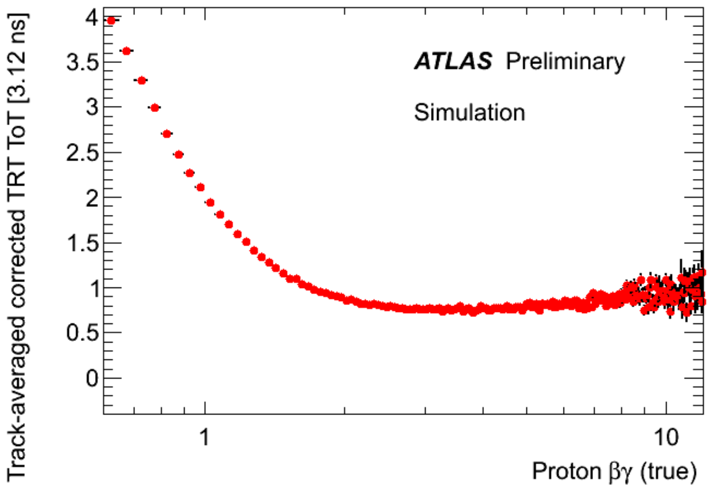
TPC dE/dx



relativistic rise region

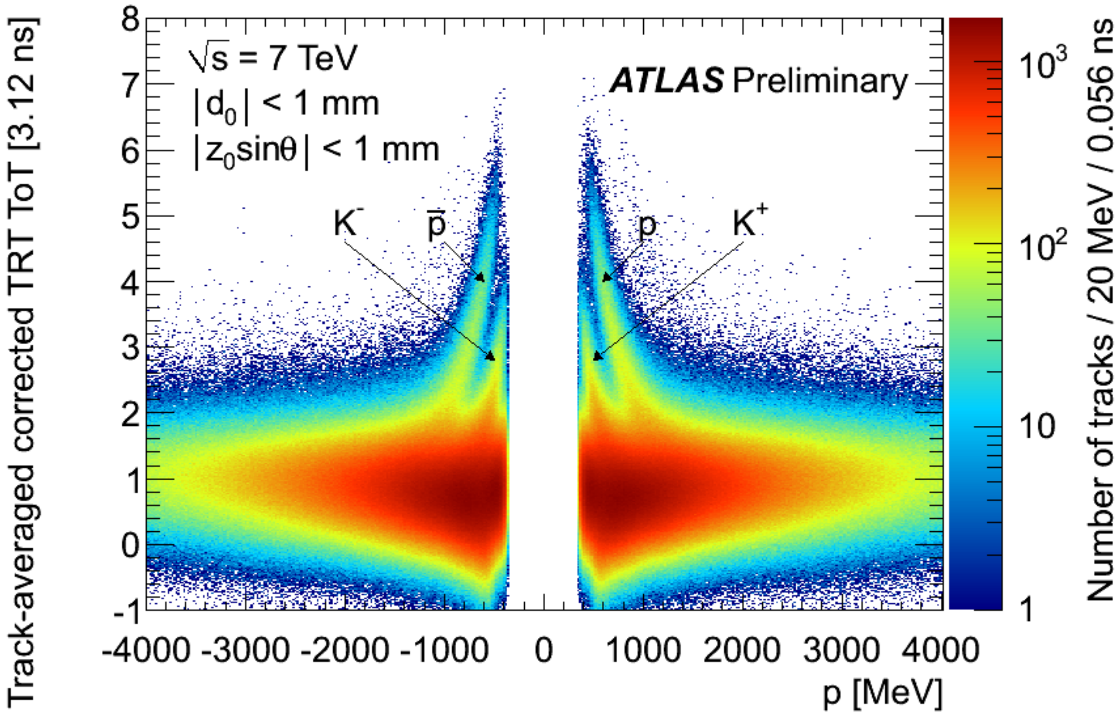


Time-over-Threshold (ToT): dE/dx in ATLAS TRT



The relation between the track ToT measurement and the track βγ, obtained from MC studies.

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



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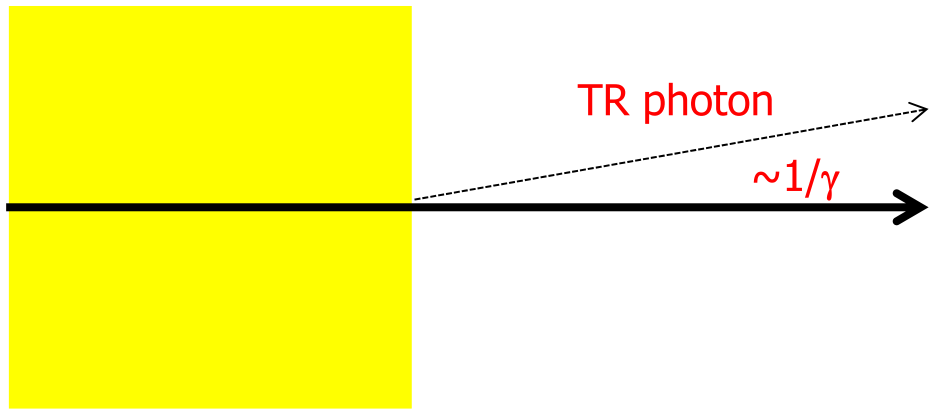
Transition radiation

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



Analogy:

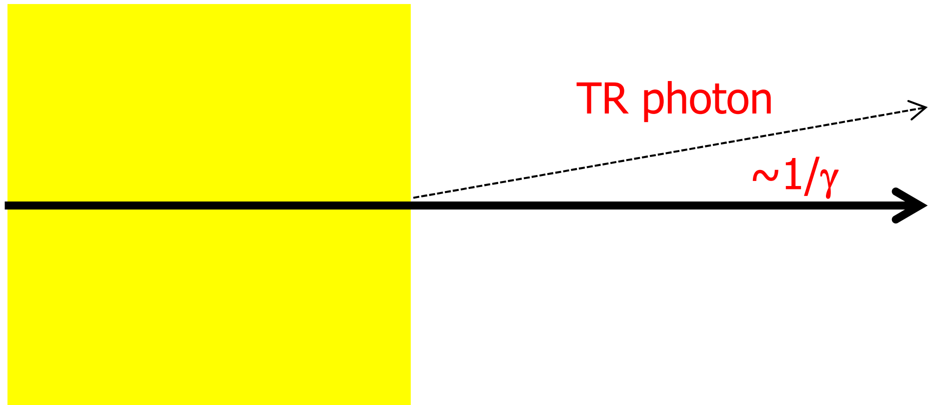
- Accelerated particle emits E.M. radiation
- Transition radiation: particle has a constant velocity, but the phase velocity of the medium changes abruptly at the boundary → radiation

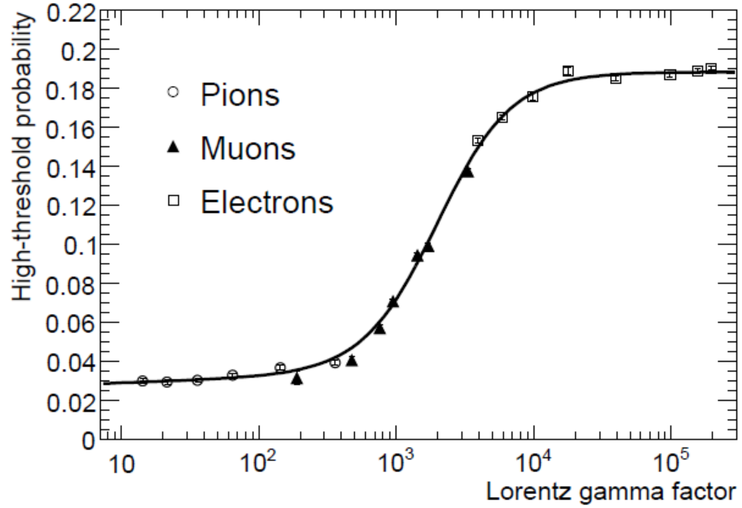
→B. Dolgoshein, NIM A326 (1993) 434-469

J.D. Jackson, Classical Electrodynamics.

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 $\gamma \sim 1000$

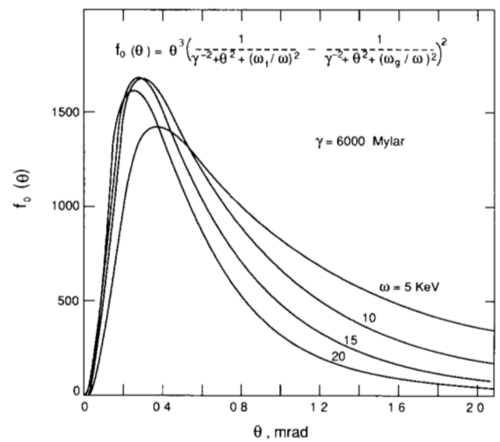
- Electrons at 0.5 GeV
- Pions above 140 GeV

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

Emission angle $\sim 1/\gamma$

Typical photon energy: ~10 keV → X rays

→ Lectures by C. Joram



Transition radiation - detection

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

→ Need many boundaries

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

Typical photon energy: ~10 keV → X rays

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

Emission angle $\sim 1/\gamma$

→ Hits from TR photons along the charged particle direction

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

Transition radiation - detection

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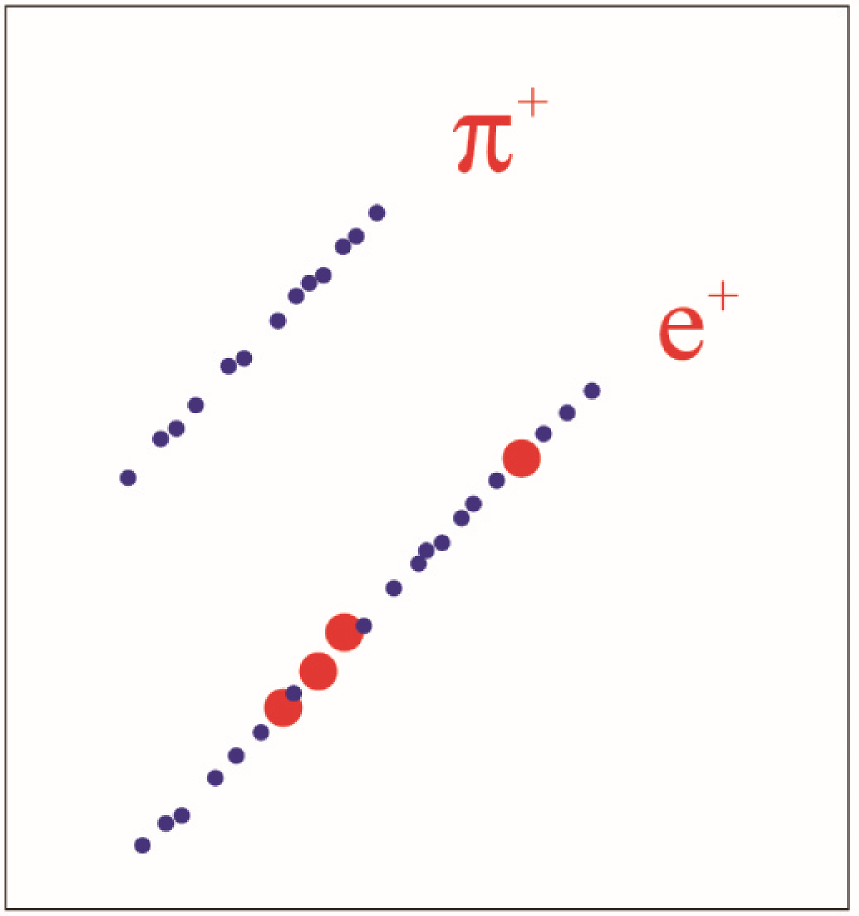
- Separation of X ray hits (high energy deposit on one place) against ionisation losses (spread out along the track)
- Two thresholds: lower for ionisation losses, higher for X ray detection



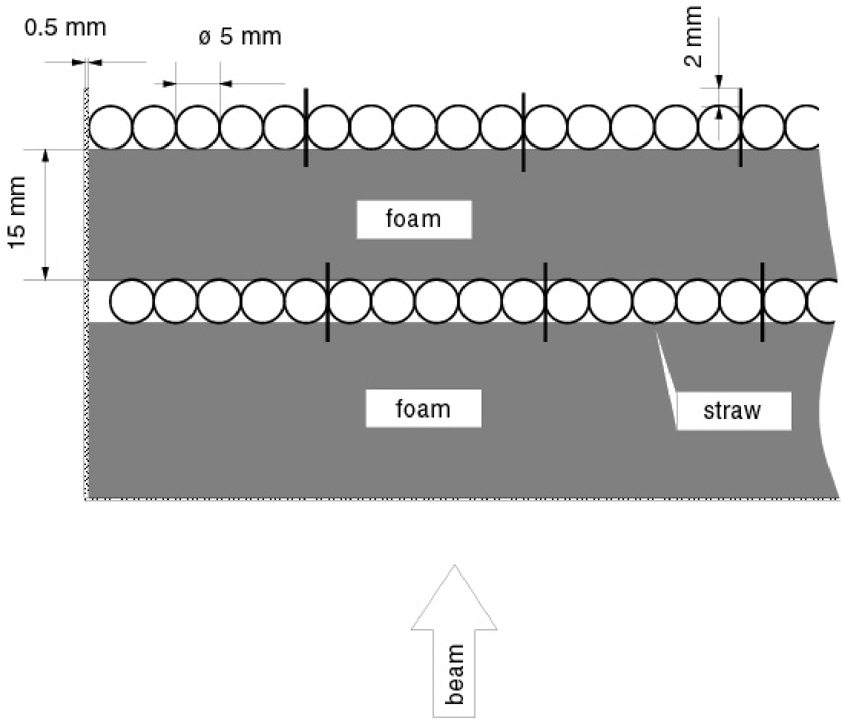
- Small circles: low threshold (ionisation)
- Big circles: high threshold (X ray detection)

(pion below, e above the TR threshold)

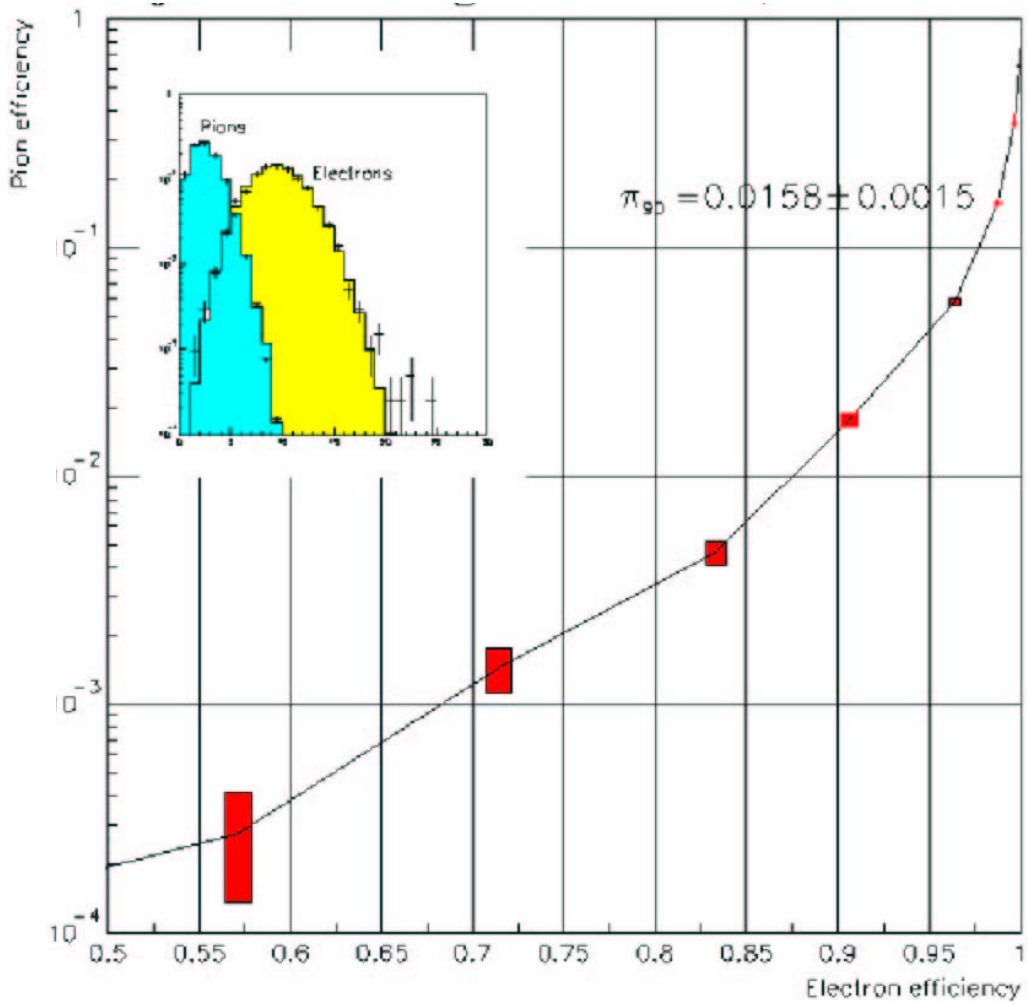
Transition radiation detectors

Example:

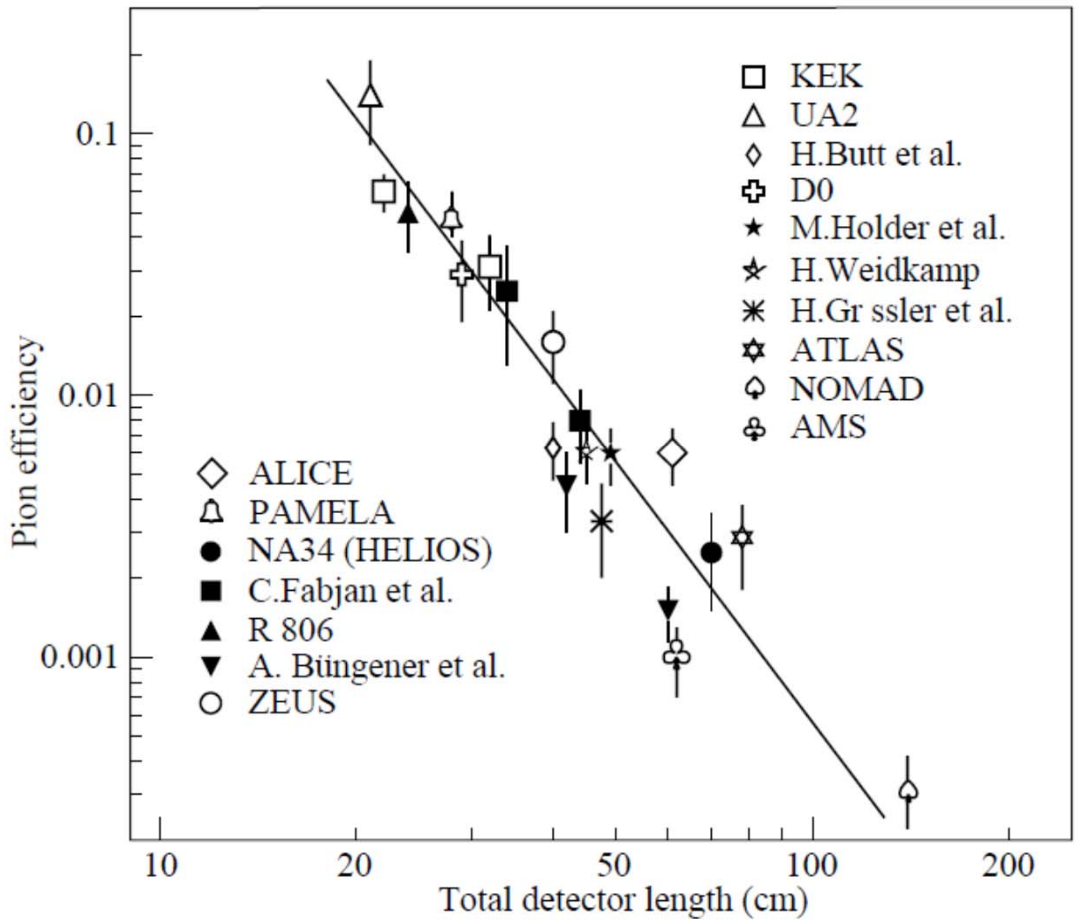
Radiator: organic foam between the detector tubes (straws made of capton foil)



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

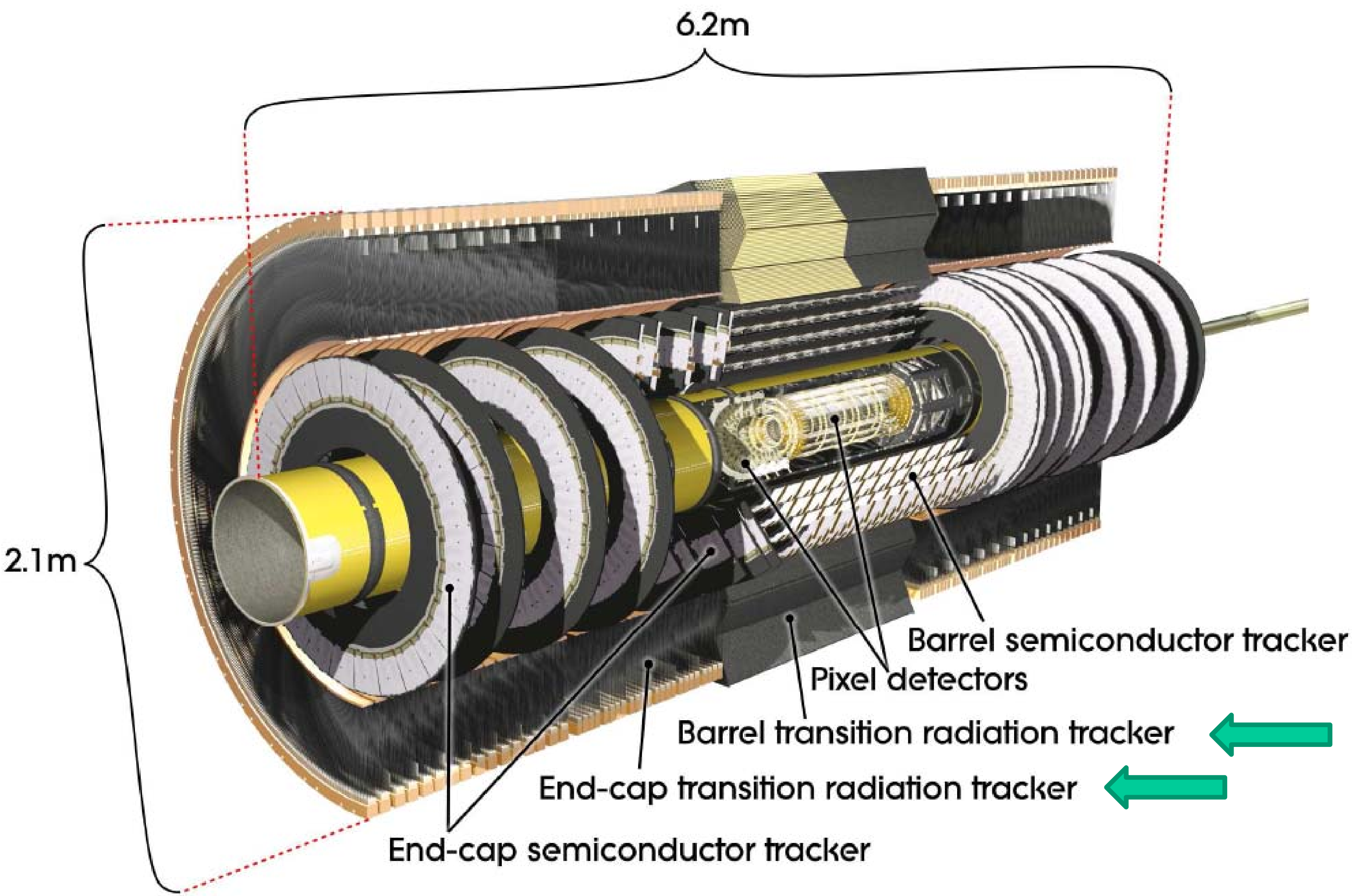


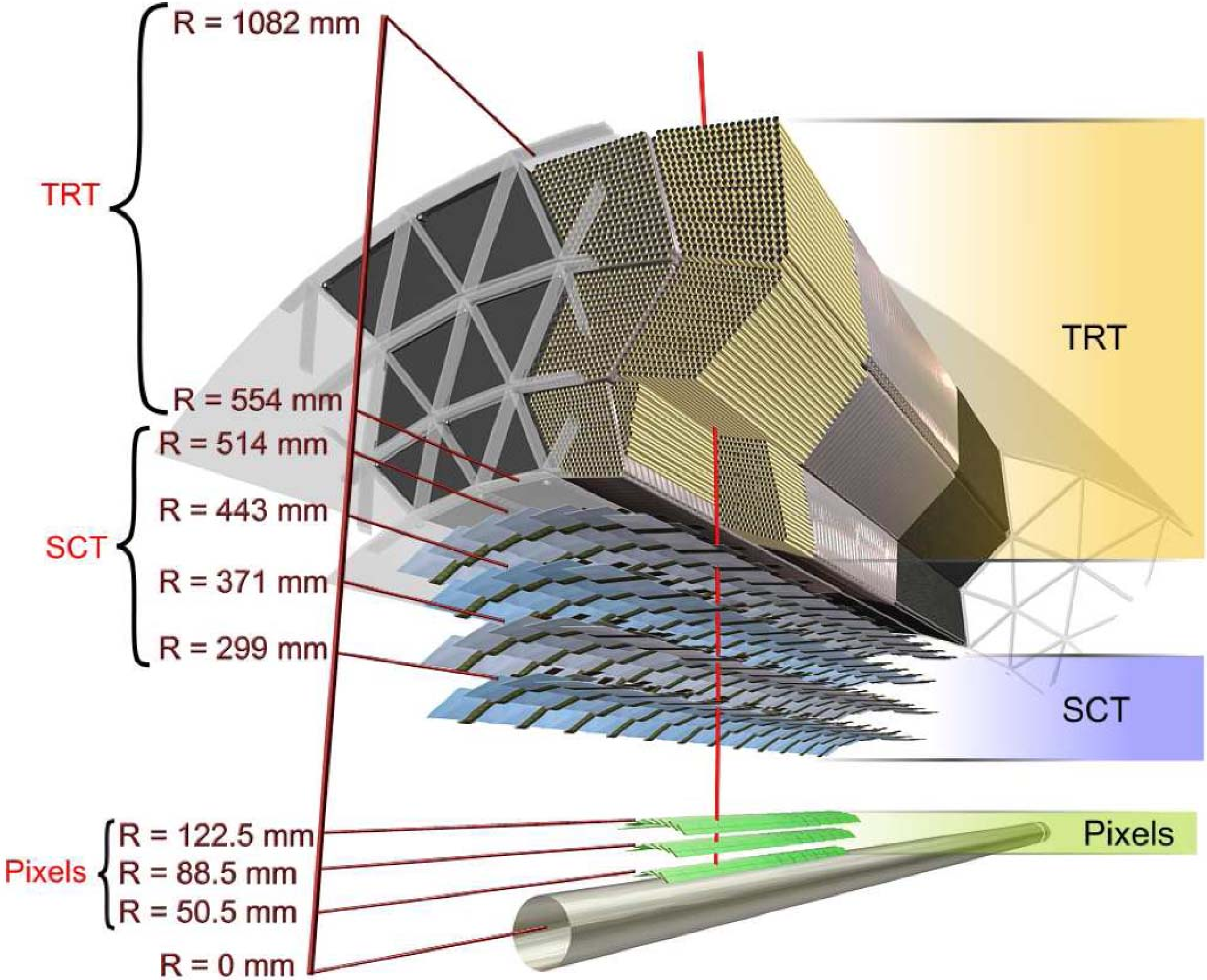
Transition radiation detectors - peformance



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

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



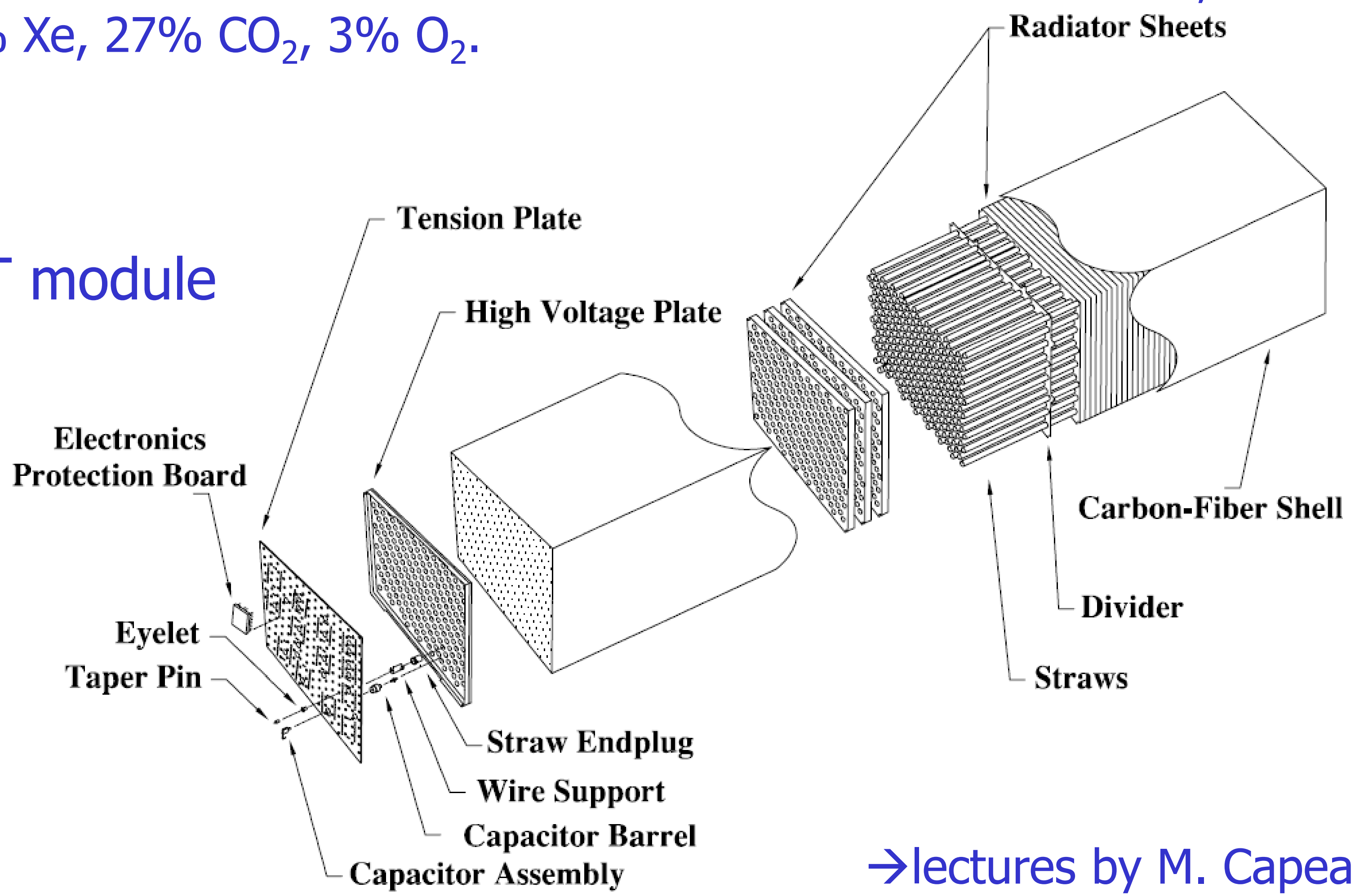

R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels

ATLAS TRT

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

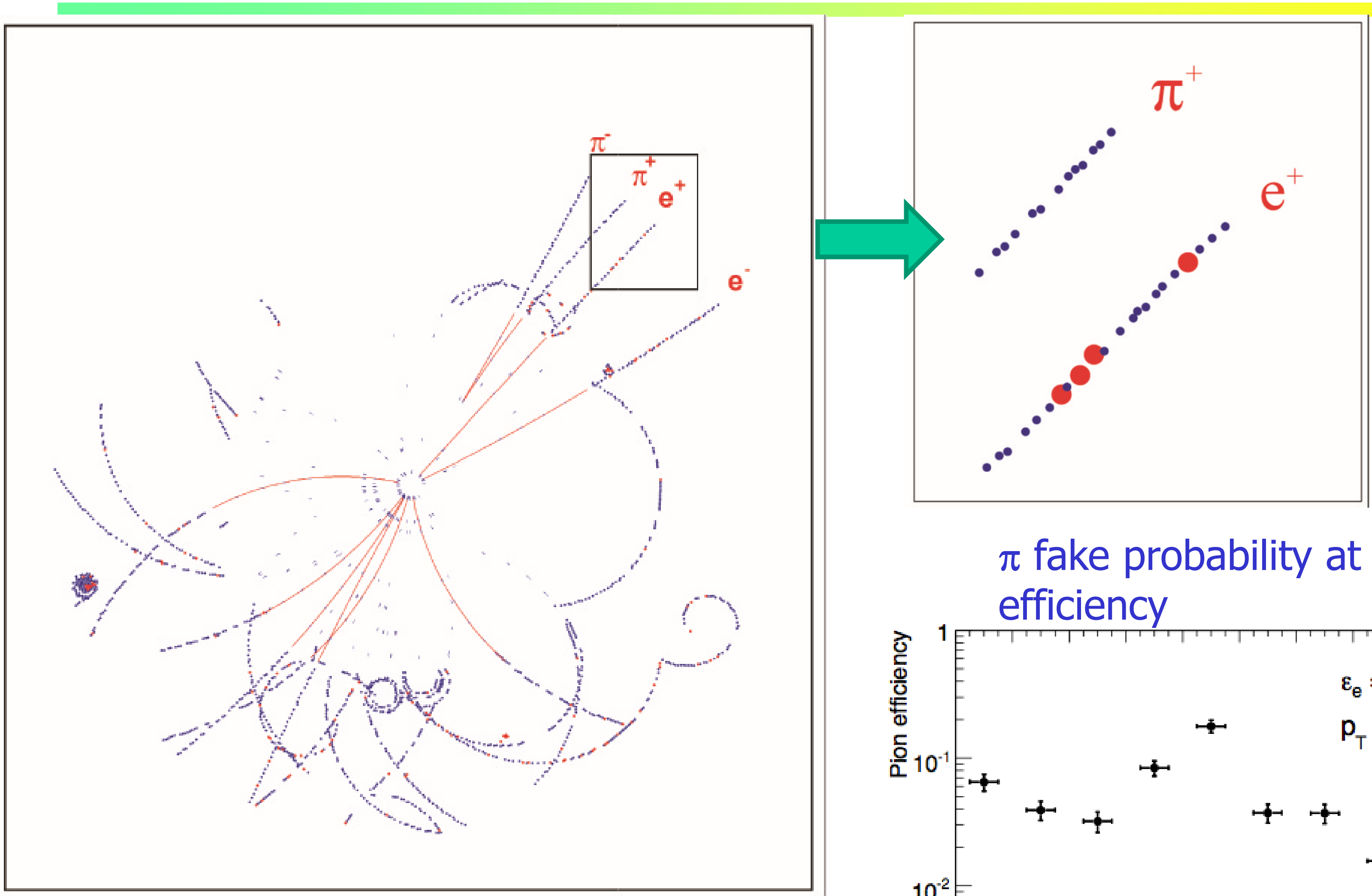
Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO_2, 3% O_2.

TRT module

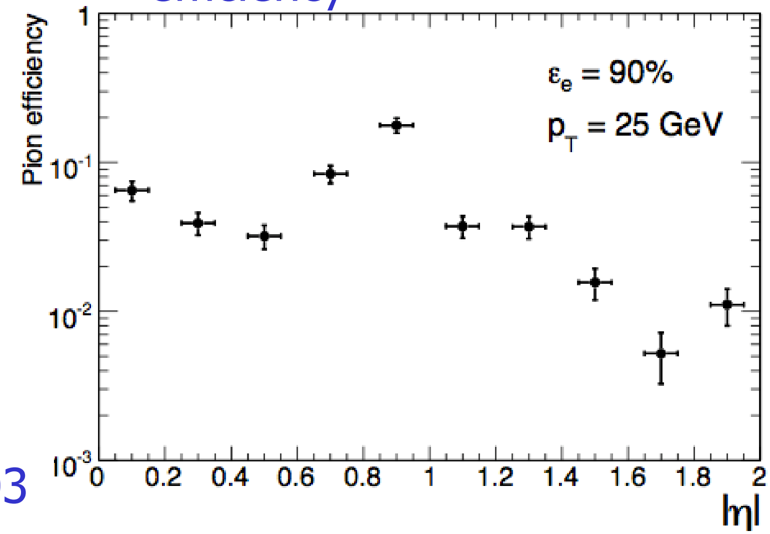


→lectures by M. Capeans

TRT: pion-electron separation



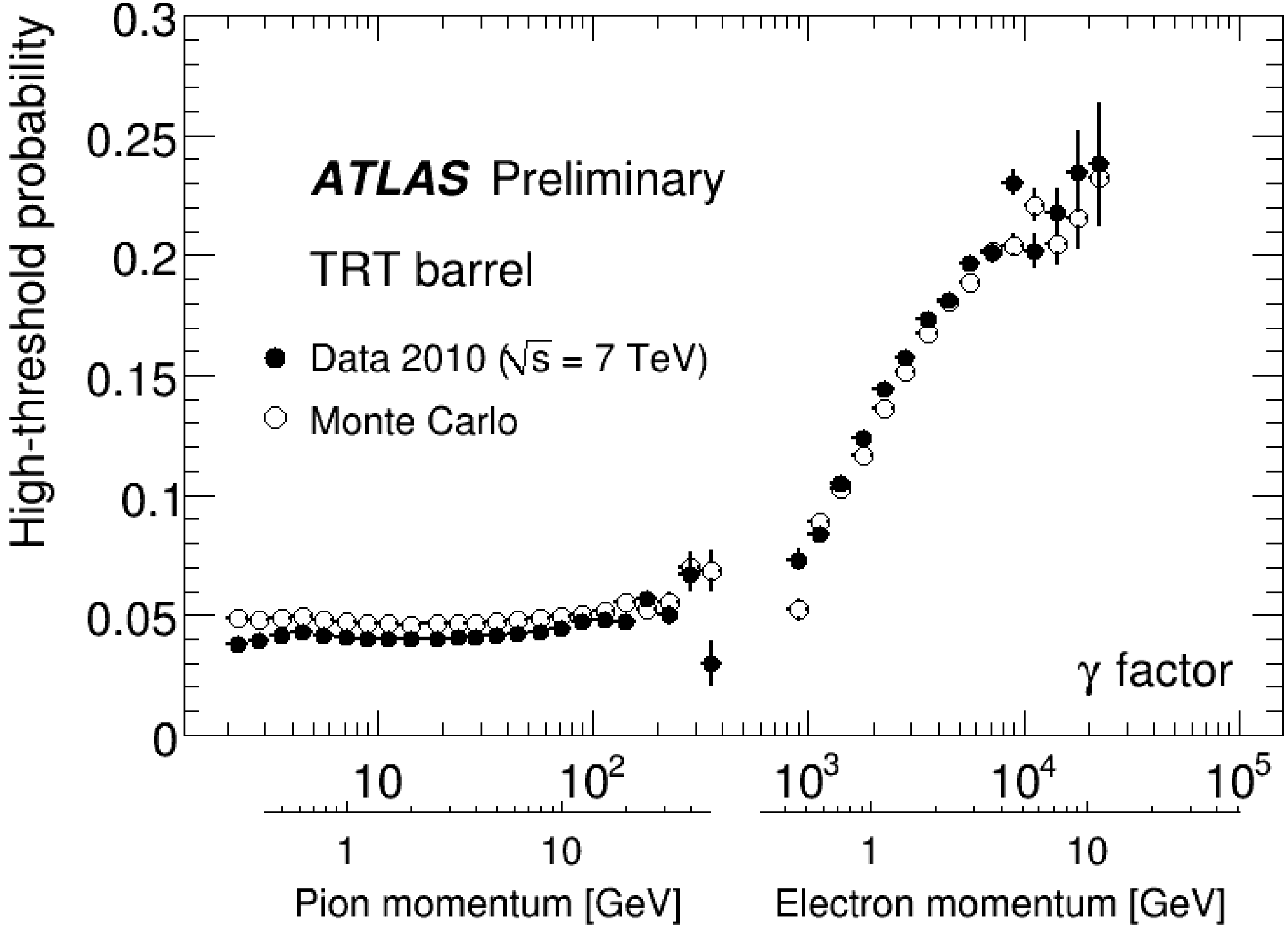
π fake probability at 90% e efficiency



→ JINST 3 (2008) S08003

TRT performance in 2010 data

e/pion separation: high threshold hit probability per straw



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 (→lectures by Francesco Lanni)

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).

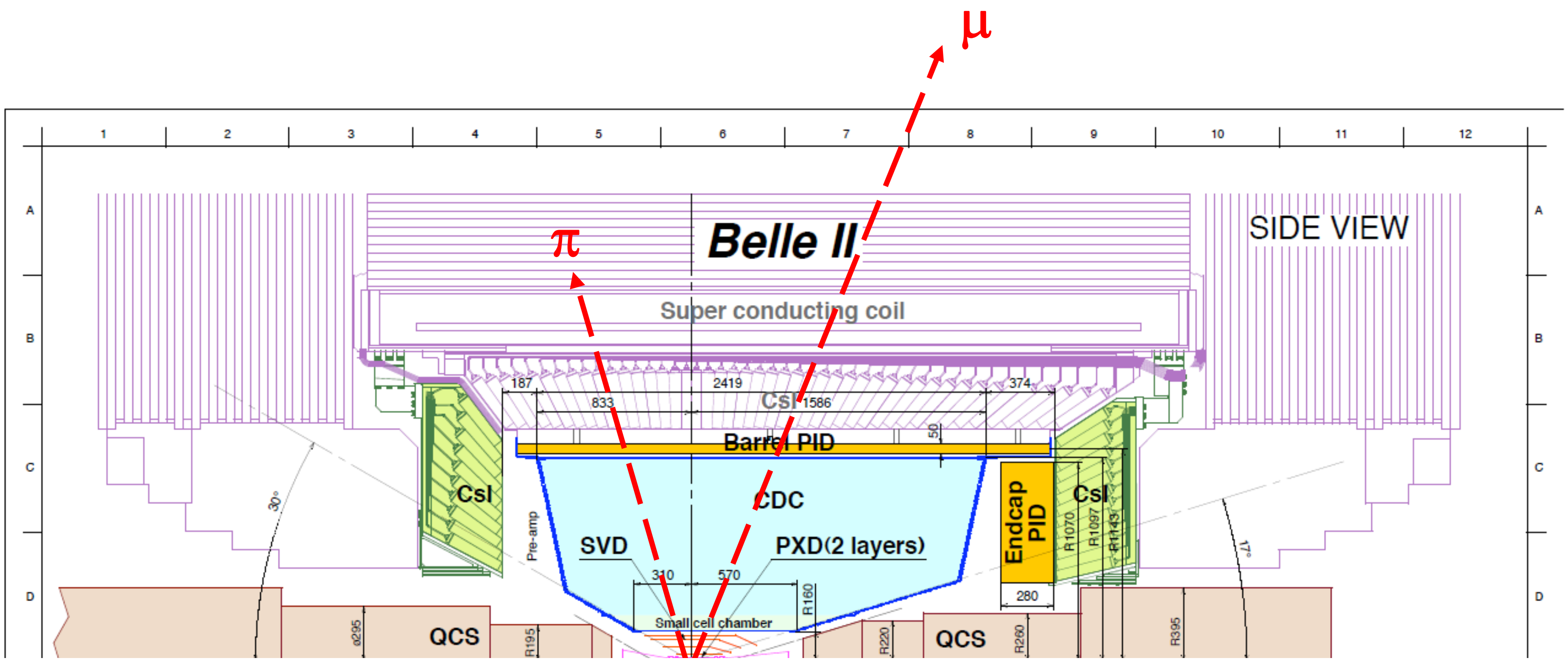
→ **A particle is identified as a muon if it penetrates the material.**

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).



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).

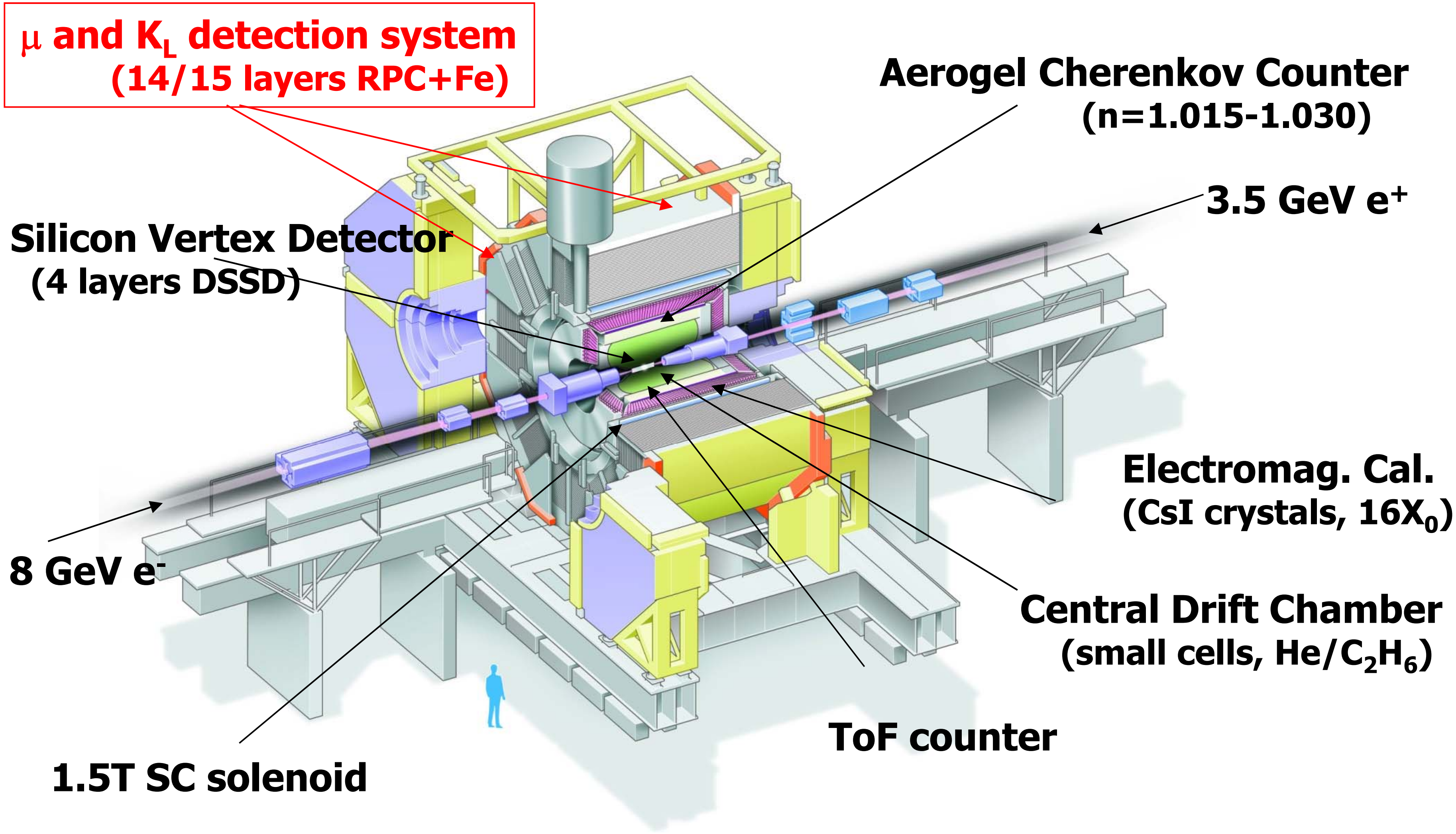
Some relevant numbers:

- Calorimeter (CsI): ~20 rad. lengths → 0.8 interaction length
- Magnet return yoke (iron): 3.9 interaction lengths
- Interaction length: iron 132 g/cm^2, CsI 167 g/cm^2
- $(dE/dx)_{min}$: iron 1.45 MeV/(g/cm^2), CsI 1.24 MeV/(g/cm^2)

→ ΔE_{min} = (0.36+0.11) GeV = 0.47 GeV → reliable identification of muons possible above ~600 MeV

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



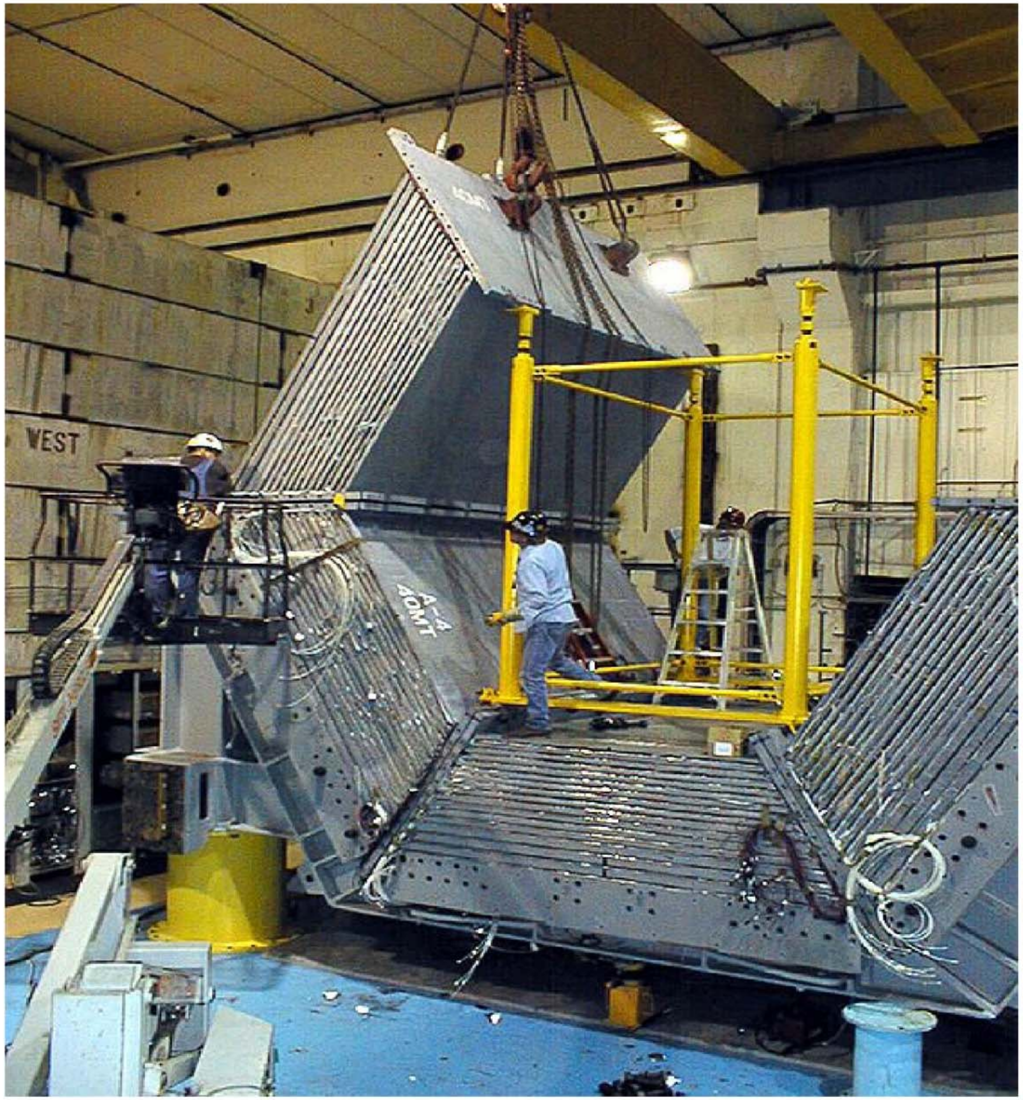
Muon and K_L detector

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

Bakelite RPCs at BABAR

Glass RPCs at Belle

(better choice because of ageing effects)



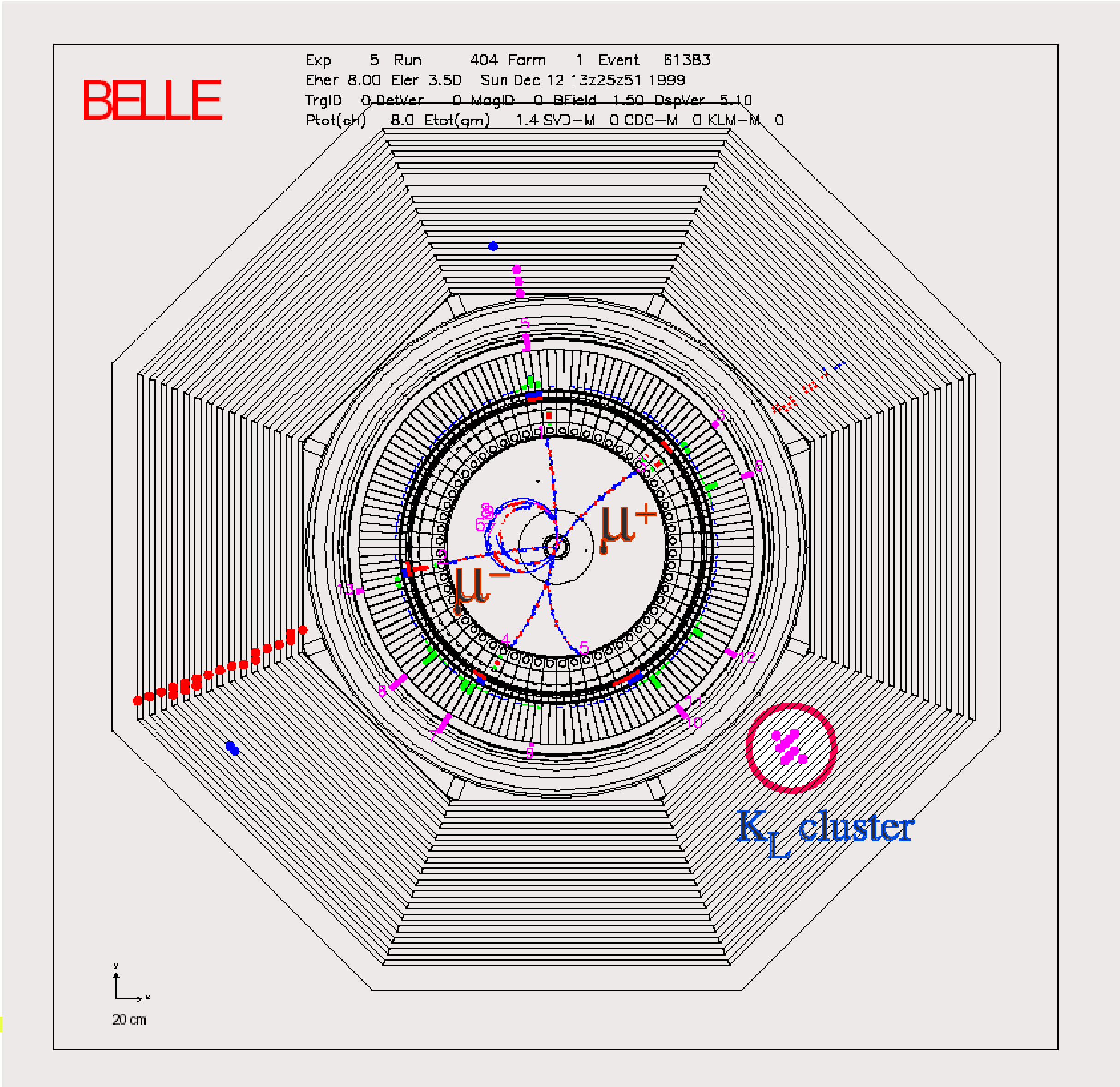
Muon and K_L detector

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

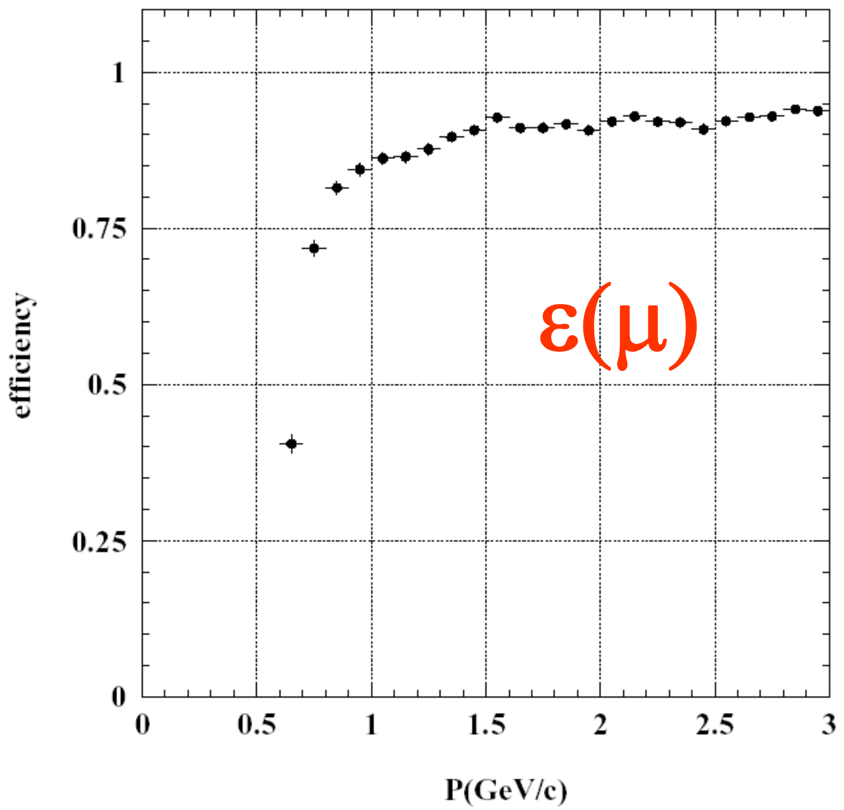


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

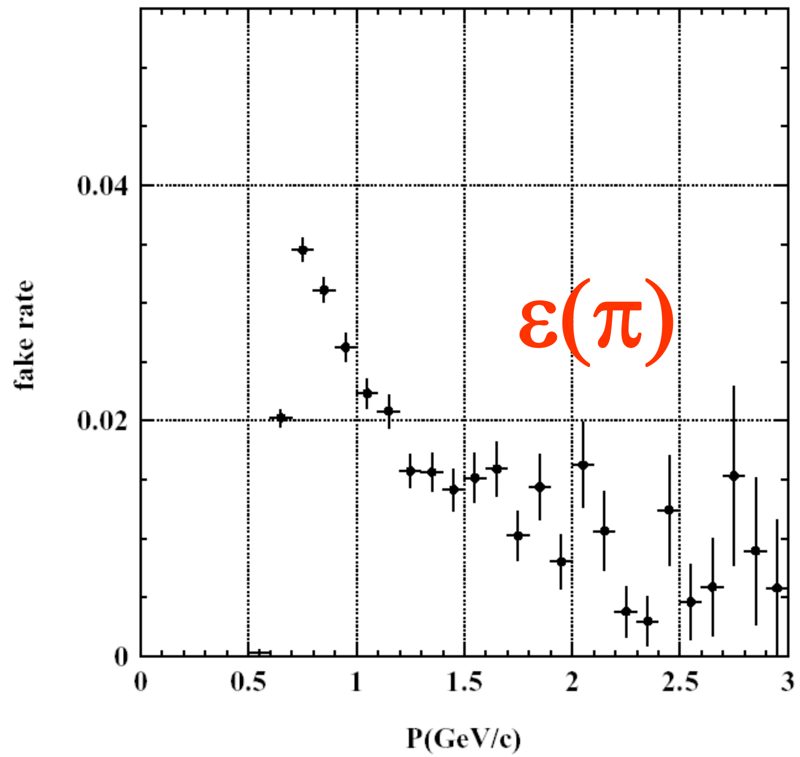
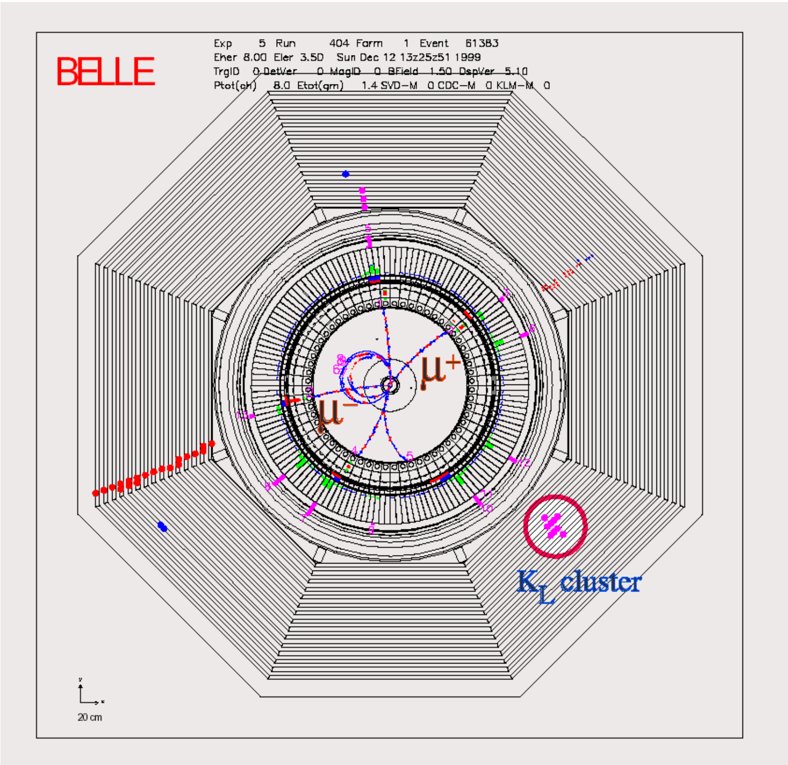


Fig. 110. Fake rate vs. momentum in KLM.

K_L detection performance



K_L detection: resolution in K_L direction

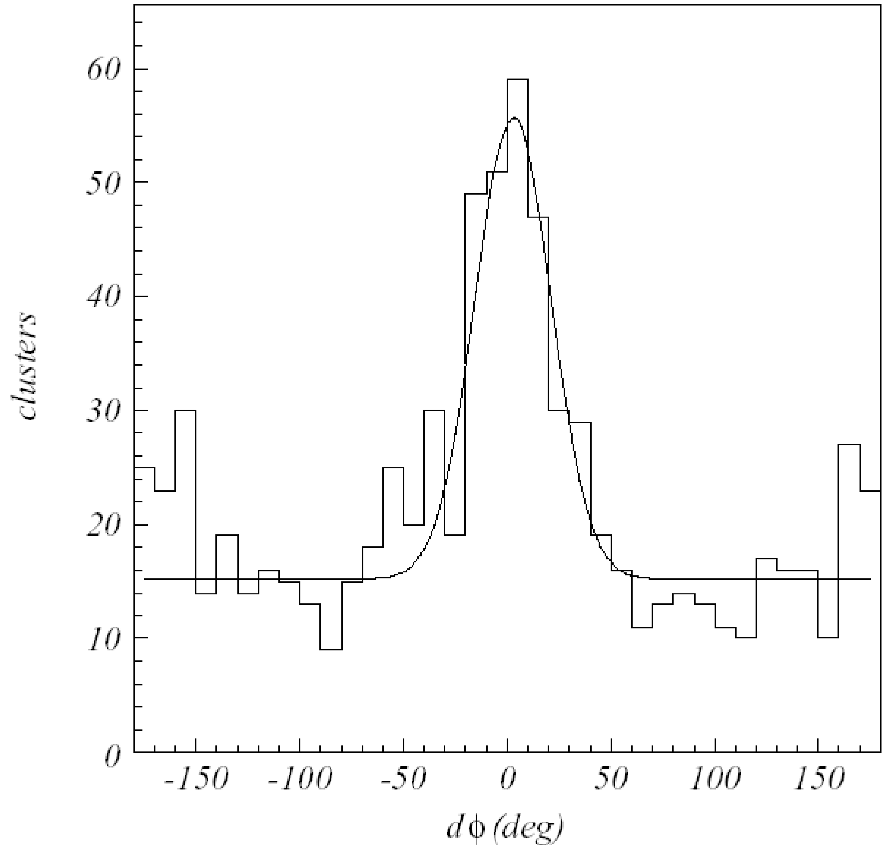
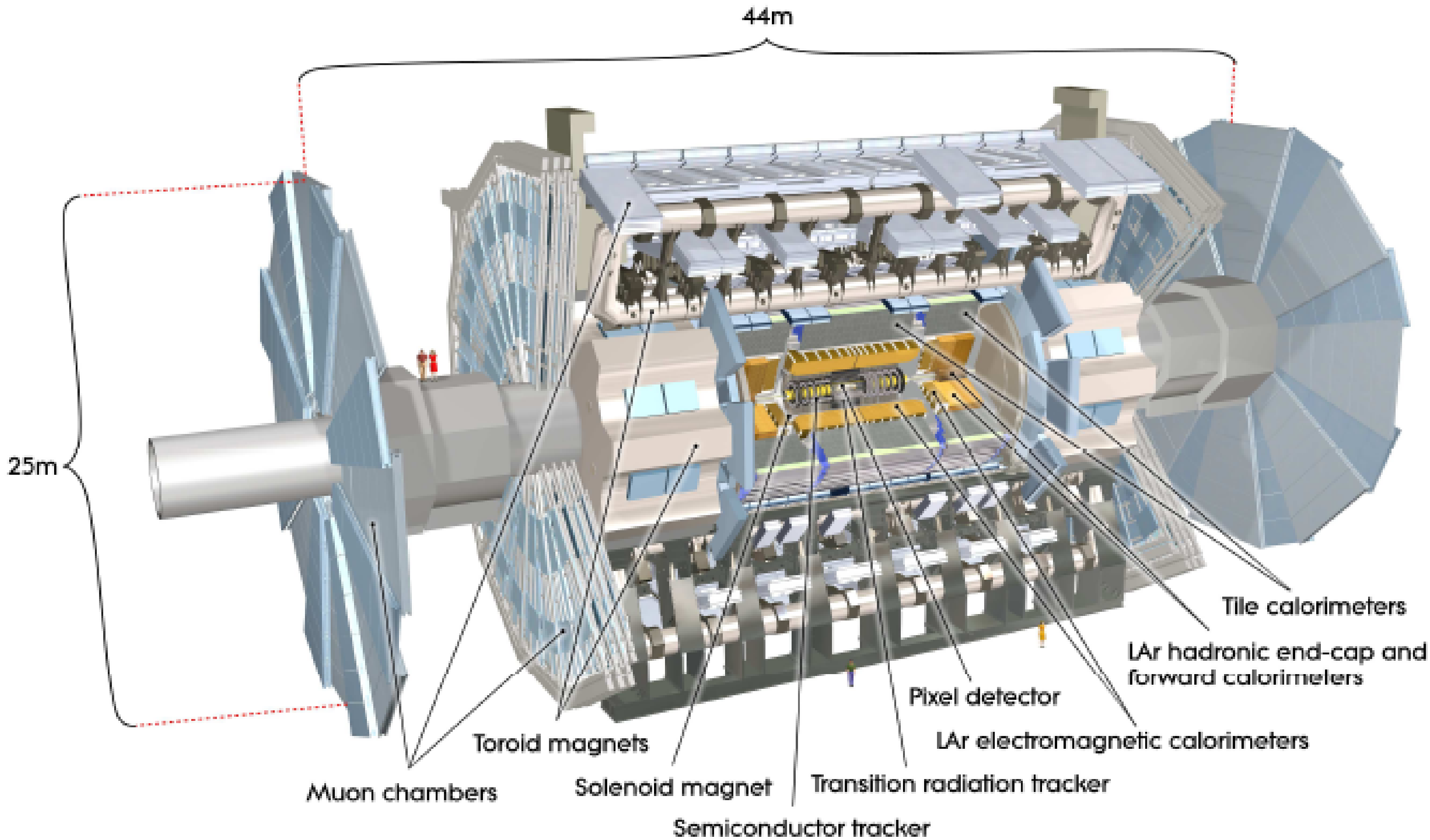
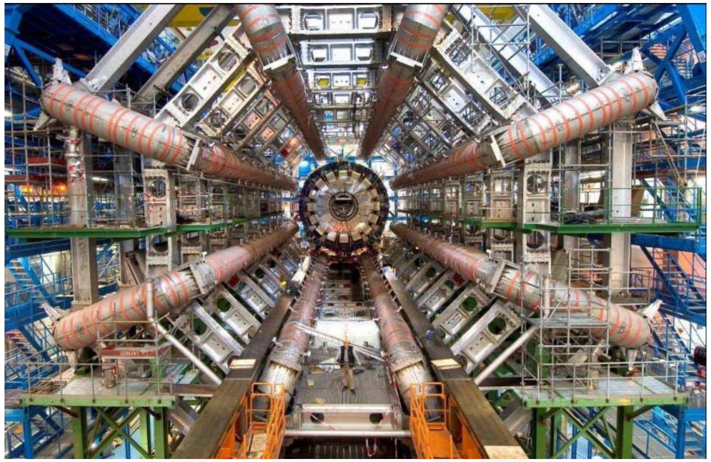


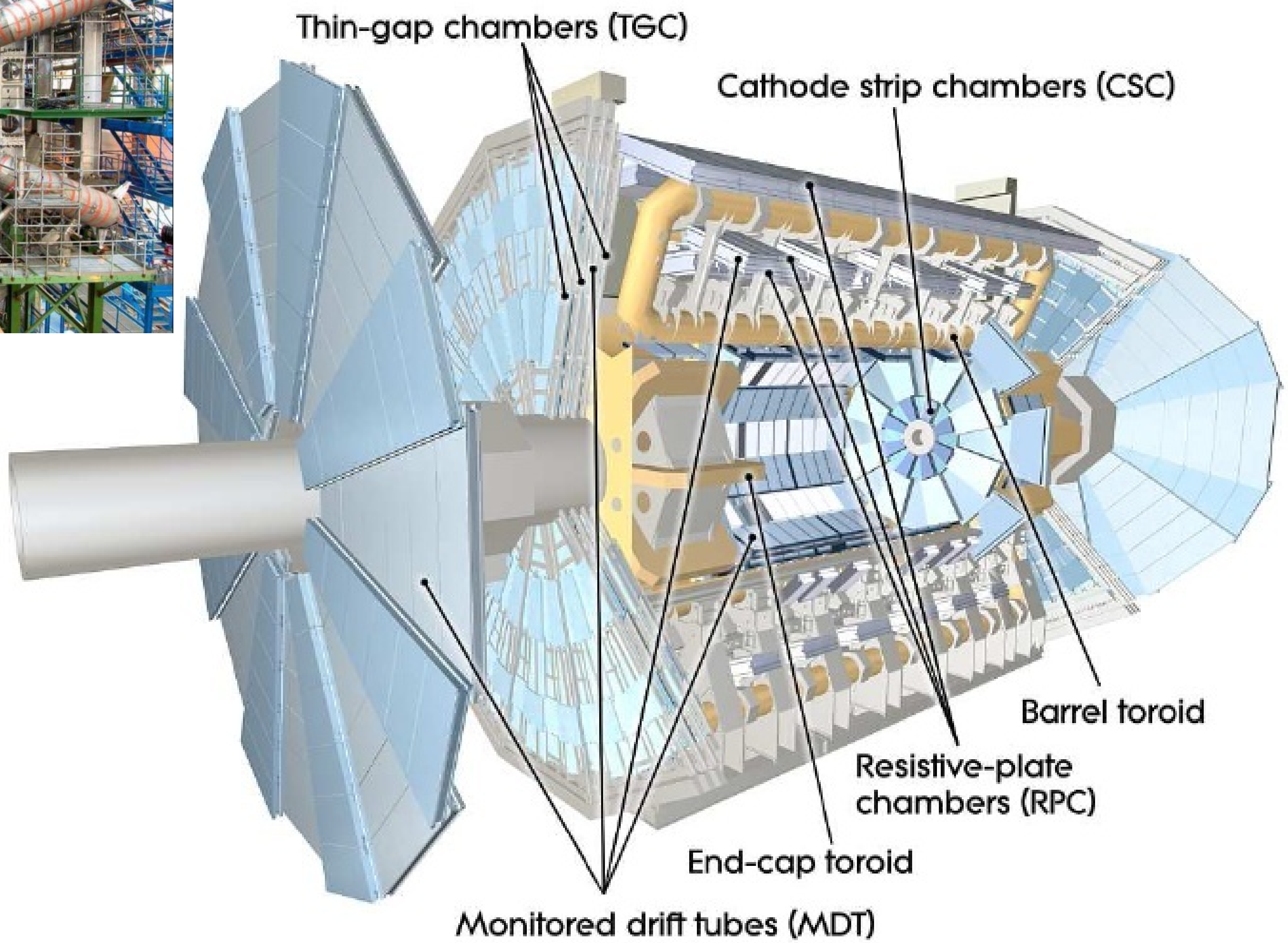
Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

Identification of muons at LHC - example ATLAS



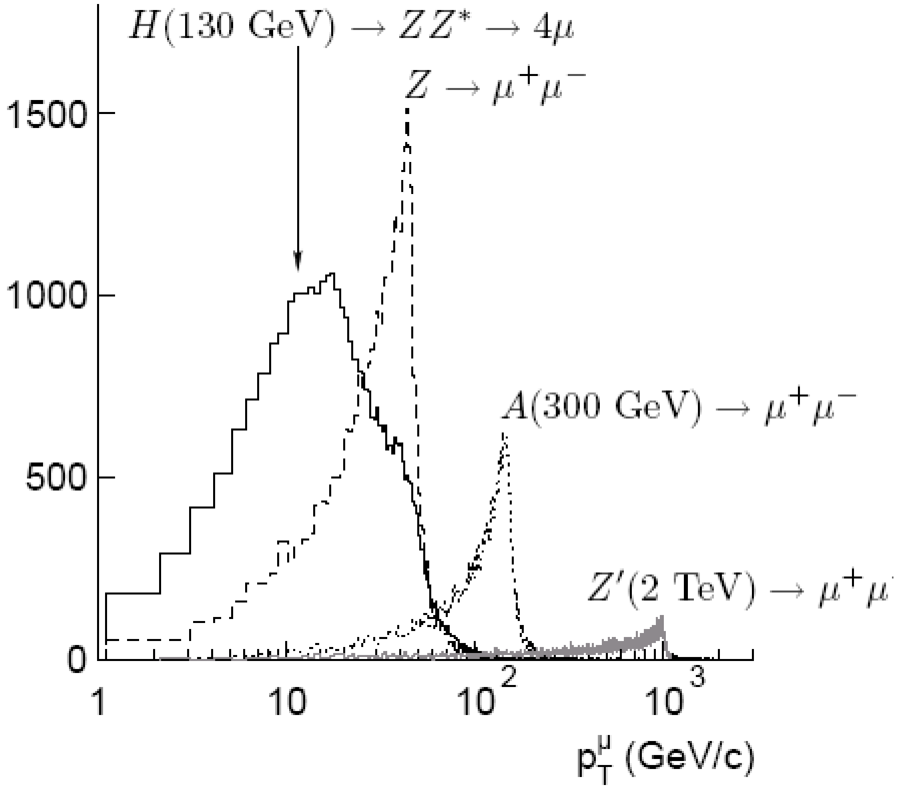
Identification of muons in ATLAS

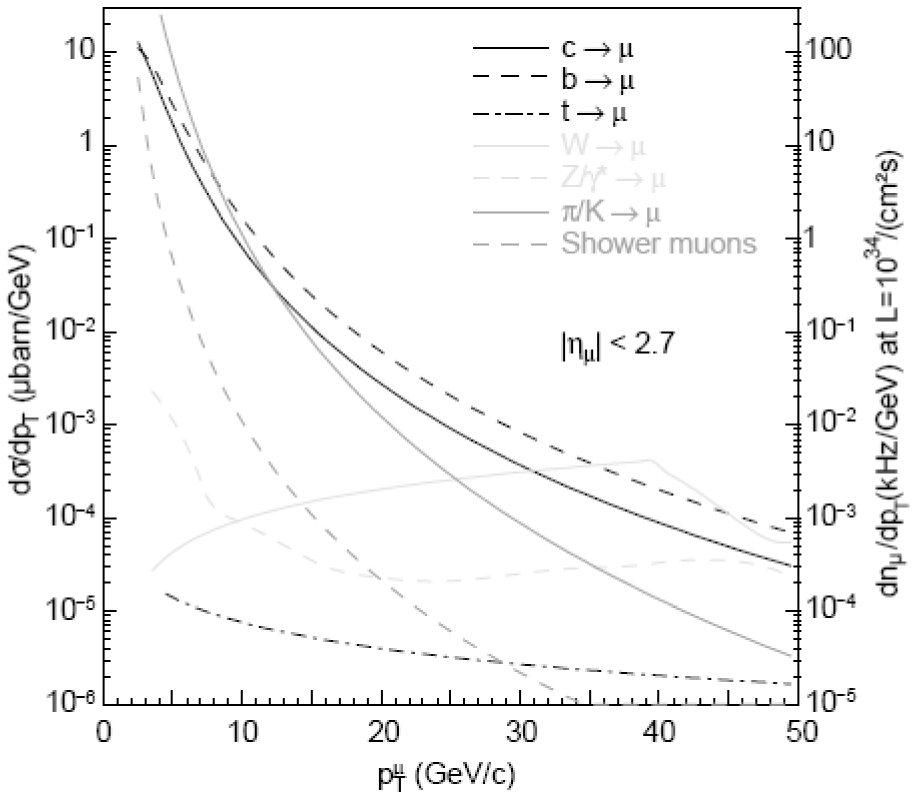




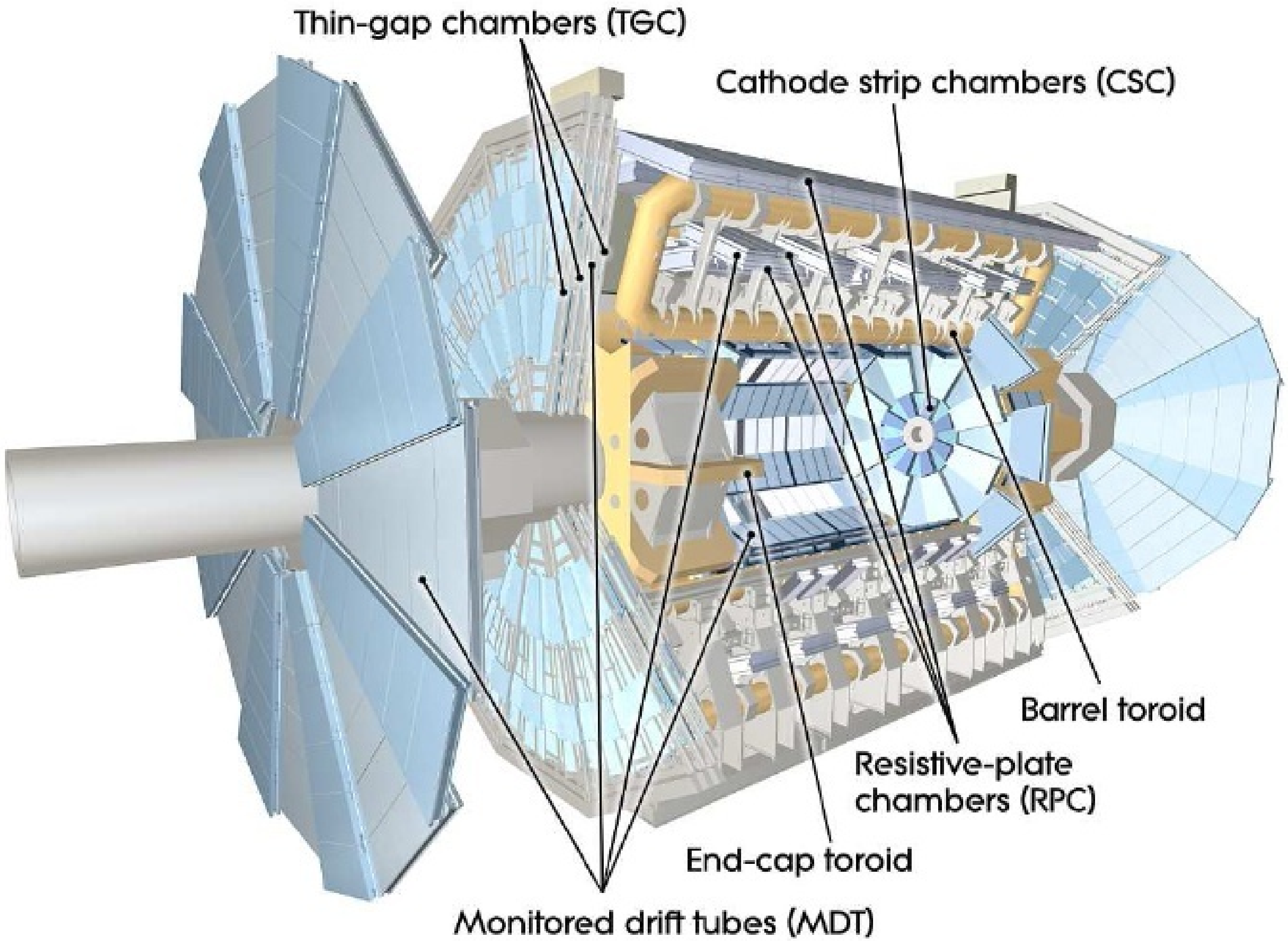
- Identify muons
- Measure their momentum

Muon spectrum

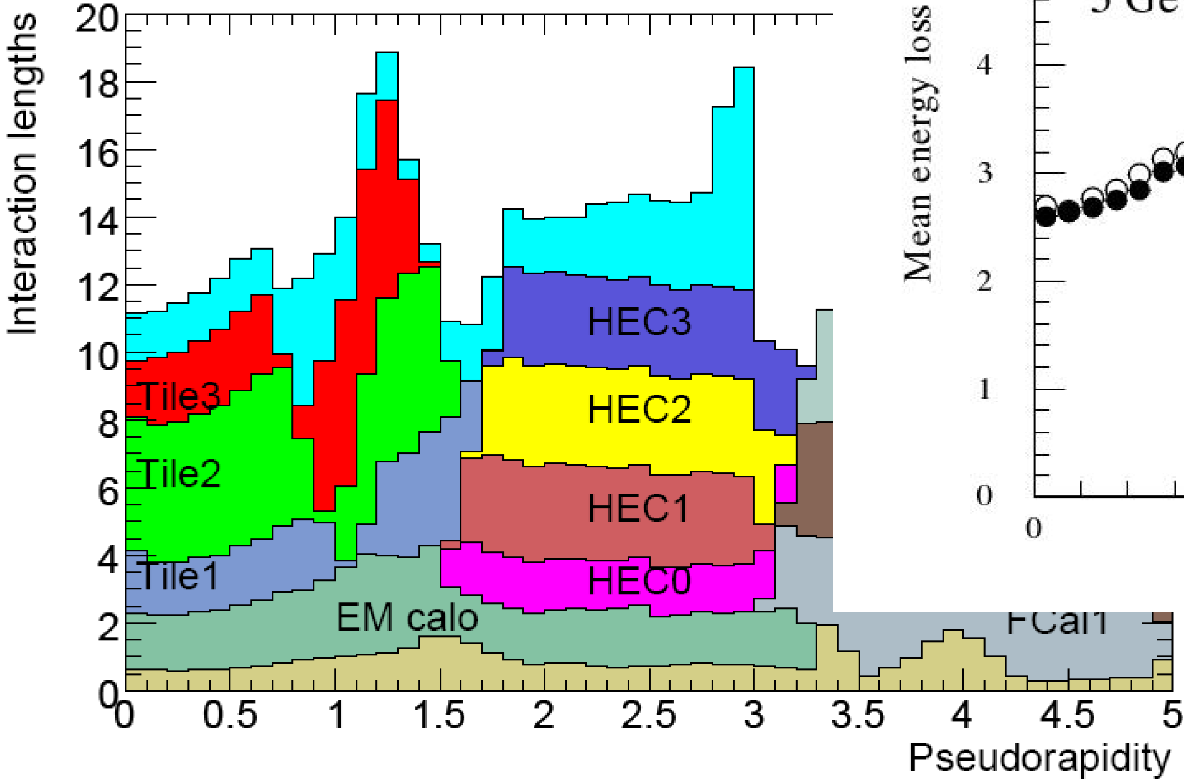


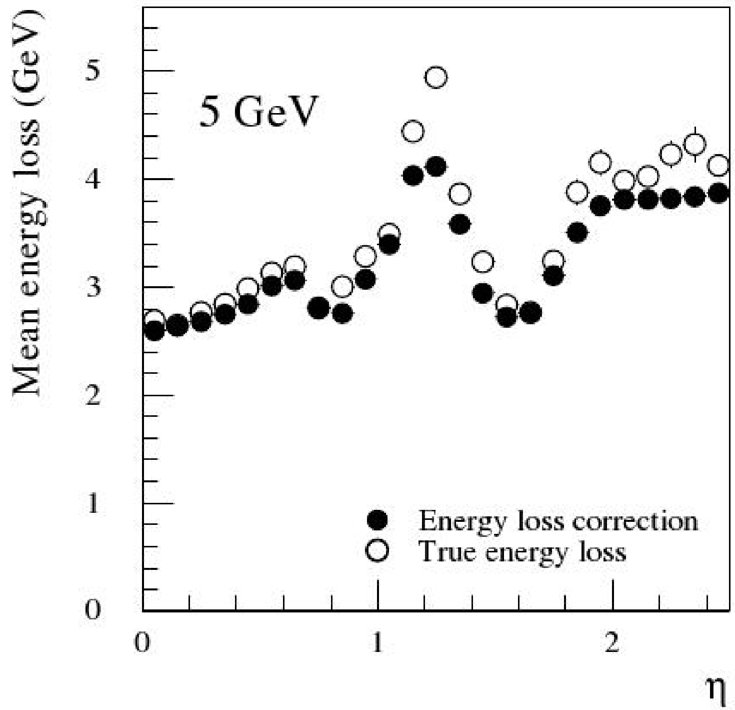


Detection of muons in ATLAS



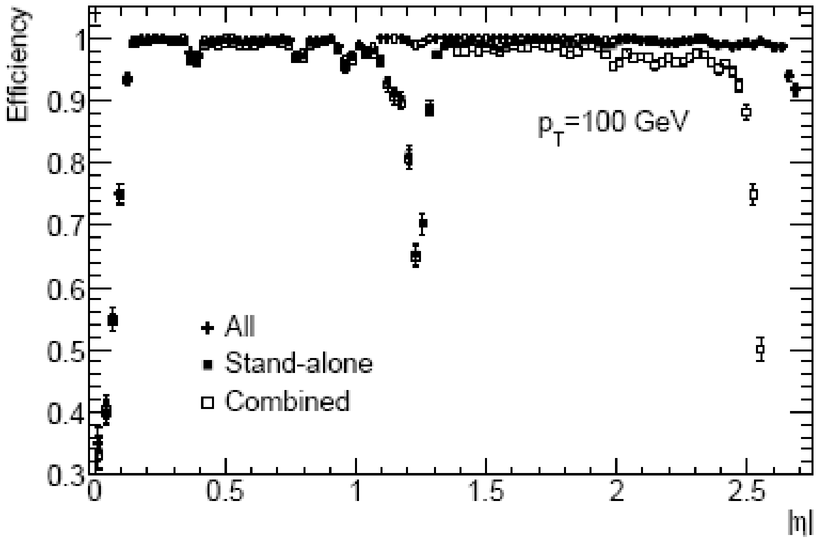
Muon identification in ATLAS



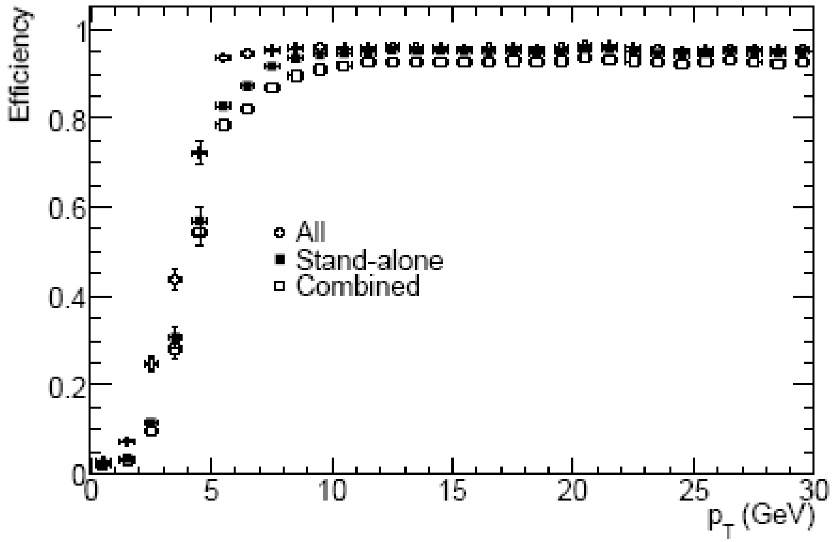


Material in front of the muon system

Muon identification efficiency



Efficiency for 100 GeV muons



Efficiency vs p_T

Muon fake probability

Sources of fakes:

-Hadrons: punch through negligible, >10 interaction legths of material in front of the muon system (remain: muons from pion and kaon decays)

-Electromagnetic showers triggered by energetic muons traversing the calorimeters and support structures lead to low-momentum electron and positron tracks, an irreducible source of fake stand-alone muons. Most of them can be rejected by a cut on their transverse momentum (pT > 5 GeV reduces the fake rate to a few percent per triggered event); can be almost entirely rejected by requiring a match of the muon-spectrometer track with an inner-detector track.

- Fake stand-alone muons from the background of thermal neutrons and low energy γ-rays in the muon spectrometer ("cavern background"). Again: pT > 5 GeV reduces this below 2% per triggered event at 10^{33} cm^{-2} s^{-1}. Can be reduced by almost an order of magnitude by requiring a match of the muon-spectrometer track with an inner-detector track.

Summary

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

A large variety of techniques has been developed for differnt kinematic regions and different particles, based on Cherenkov radiation, TOF, dE/dx and TR.

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