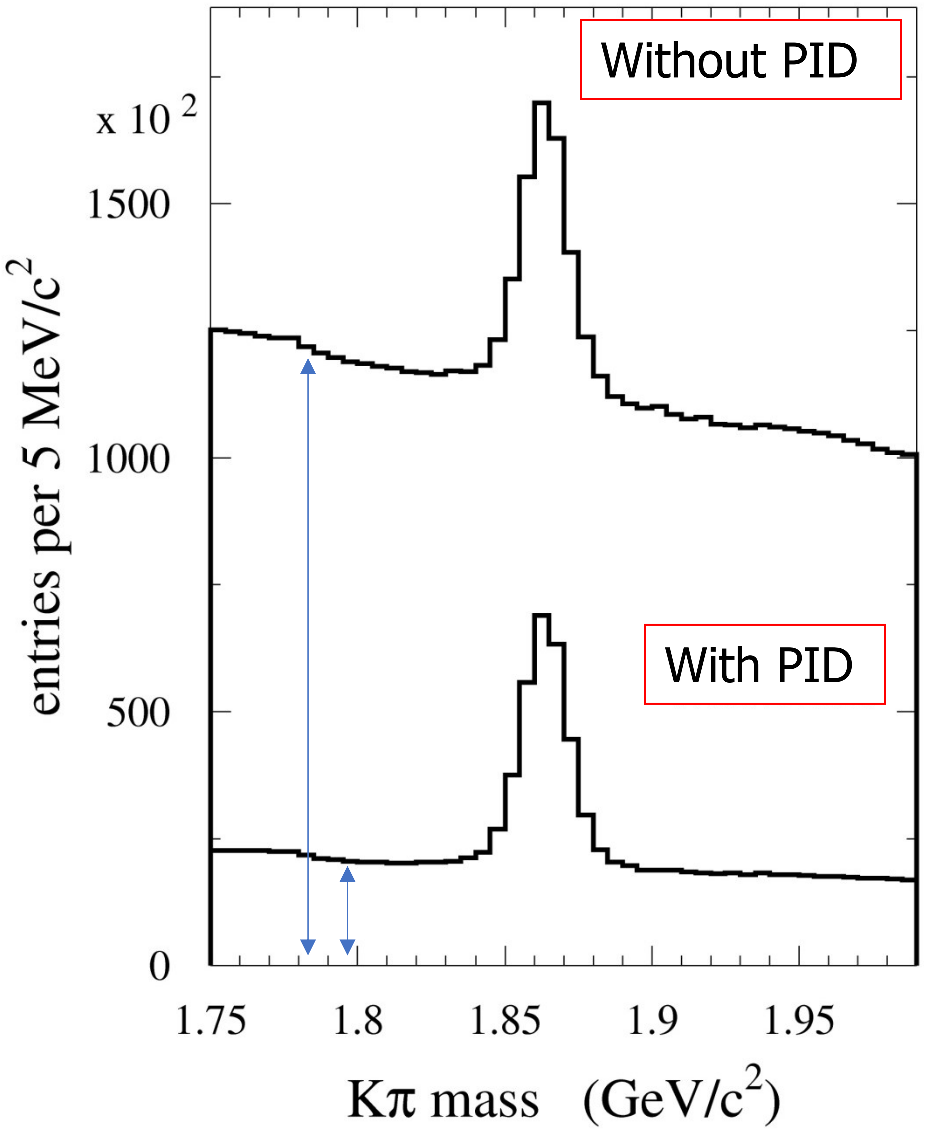
Particle Identification

Вступ: Навіщо Particle ID

- Ідентифікація частинок є важливим аспектом фізичних експериментів із елементарними, ядерними частинками, та частинками космічного випромінювання.
- Деякі фізичні величини у фізиці елементарних частинок доступні лише за допомогою складної ідентифікації частинок (B-фізика, порушення CP, рідкісні розпади, пошук екзотичних адронних станів).
- Ядерна фізика: ідентифікація кінцевого стану при пошуку кварк-глюонної плазми, поділ між ізотопами.
- Астрофізика/фізика астрочастинок: ідентифікація космічних променів – поділ між ядрами (ізотопами), зарядженими частинками проти фотонів високої енергії.

Навіщо Particle ID



Приклад 1: B factory

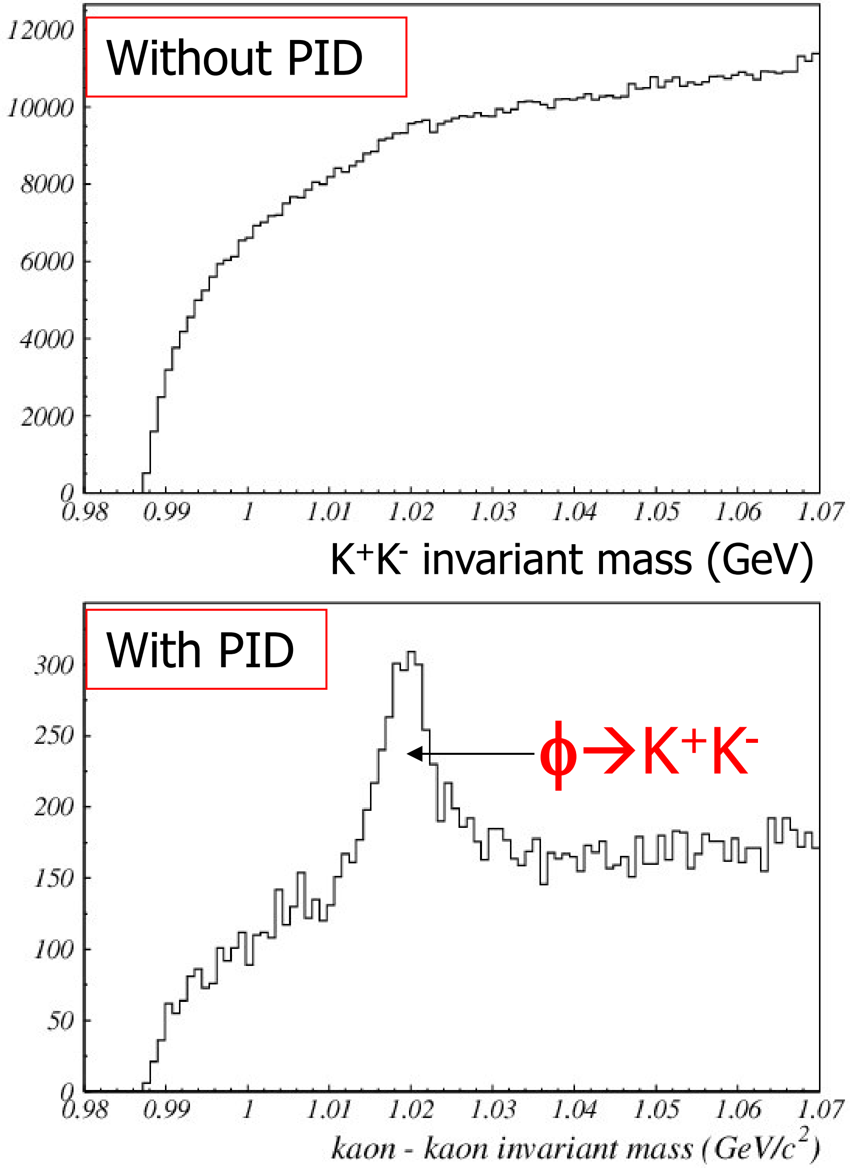
Ідентифікація частинок зменшує частку неправильних комбінацій Kπ (комбінаторний фон) на ~5x

Пошук розпаду D мезона в Kπ:
З виміряних треків піона та каона розраховуємо інваріантну масу системи: (i= K,π):

$$Mc^2 = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2 c^2}$$

Кандидати на розпад D→Kπ decay дають пік в розподілі на фоні з неправильних комбінацій (комбінаторний фон)

Навіщо Particle ID



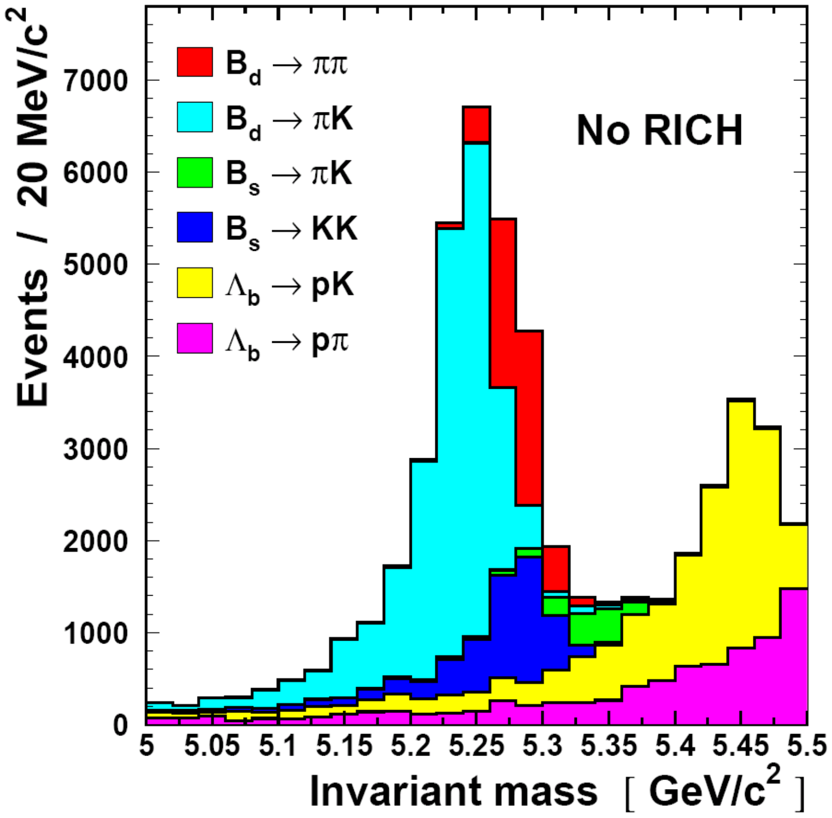
Приклад 2: HERA-B

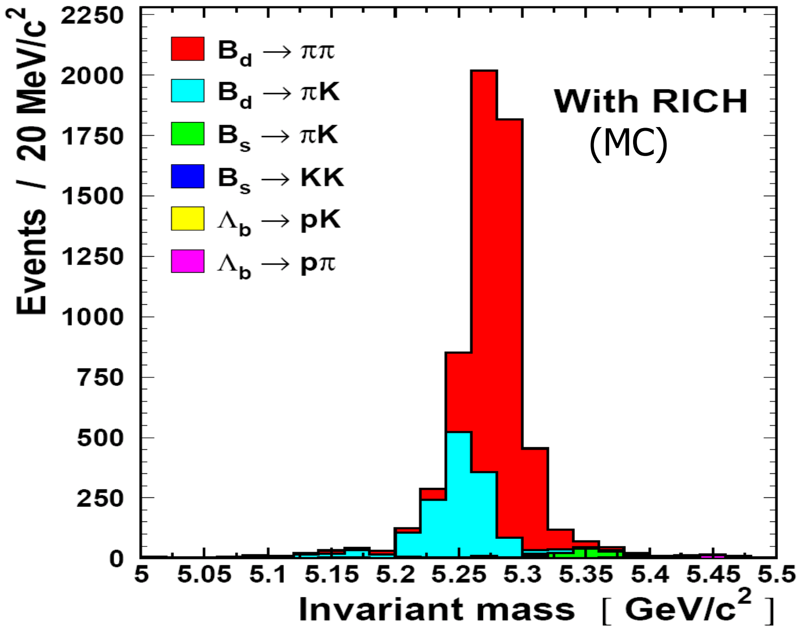
Інваріантна маса K^+K^-

Інклюзивний розпад $\phi \rightarrow K^+K^-$ стає видимим лише тоді, коли використана ідентифікація частинок (інакше пік тоне в комбінаторному фоні)

Навіщо Particle ID

Приклад 3: LHCb





Потрібно відрізняти $B_d \rightarrow \pi\pi$ від інших 2-body розпадів зі схожою топологією та розрізняти B і анти-B за допомогою «тагу» від Каону.

Навіщо Particle ID

PID також потрібен у:

- Експерименти на LHC загального призначення: кінцеві стани з електронами та мюонами.

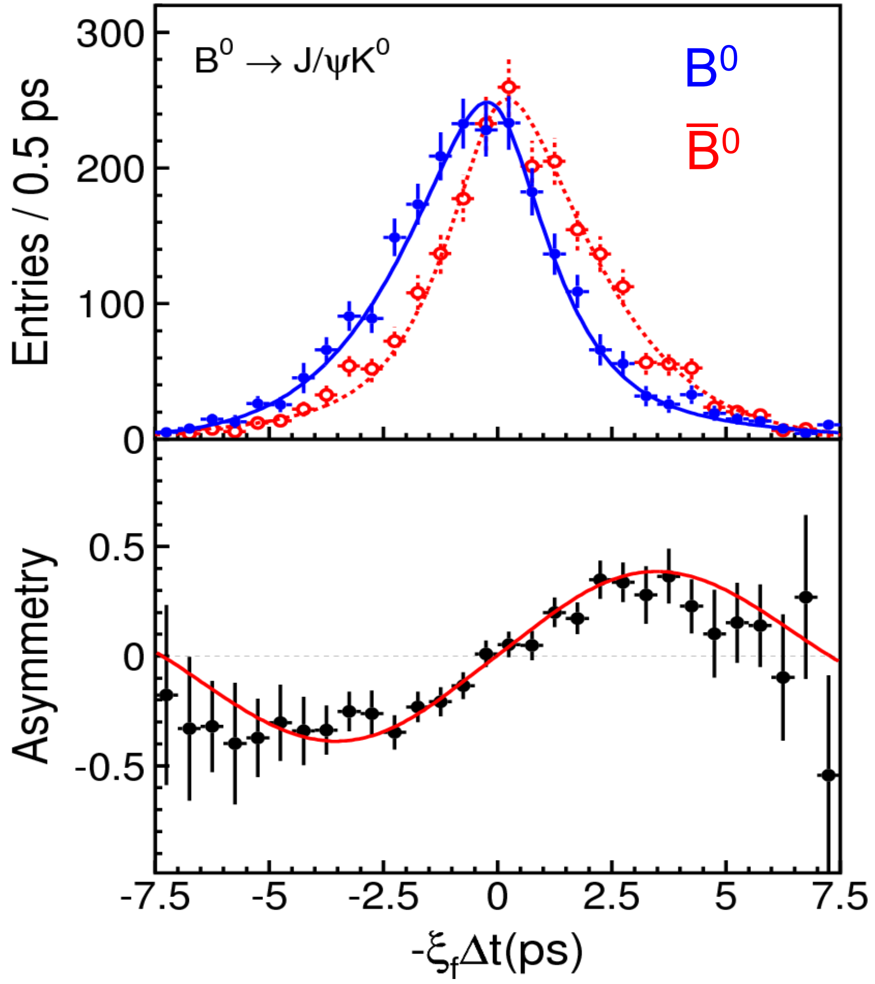
- Пошуки екзотичних станів матерії (кварк-глюонна плазма)

- Спектроскопія та пошуки екзотичних адронних станів.

Навіщо Particle ID

Ідентифікація частинок на B-фабриках (Belle і BaBar):

мала важливе значення для спостереження порушення CP у B-мезонній системі.

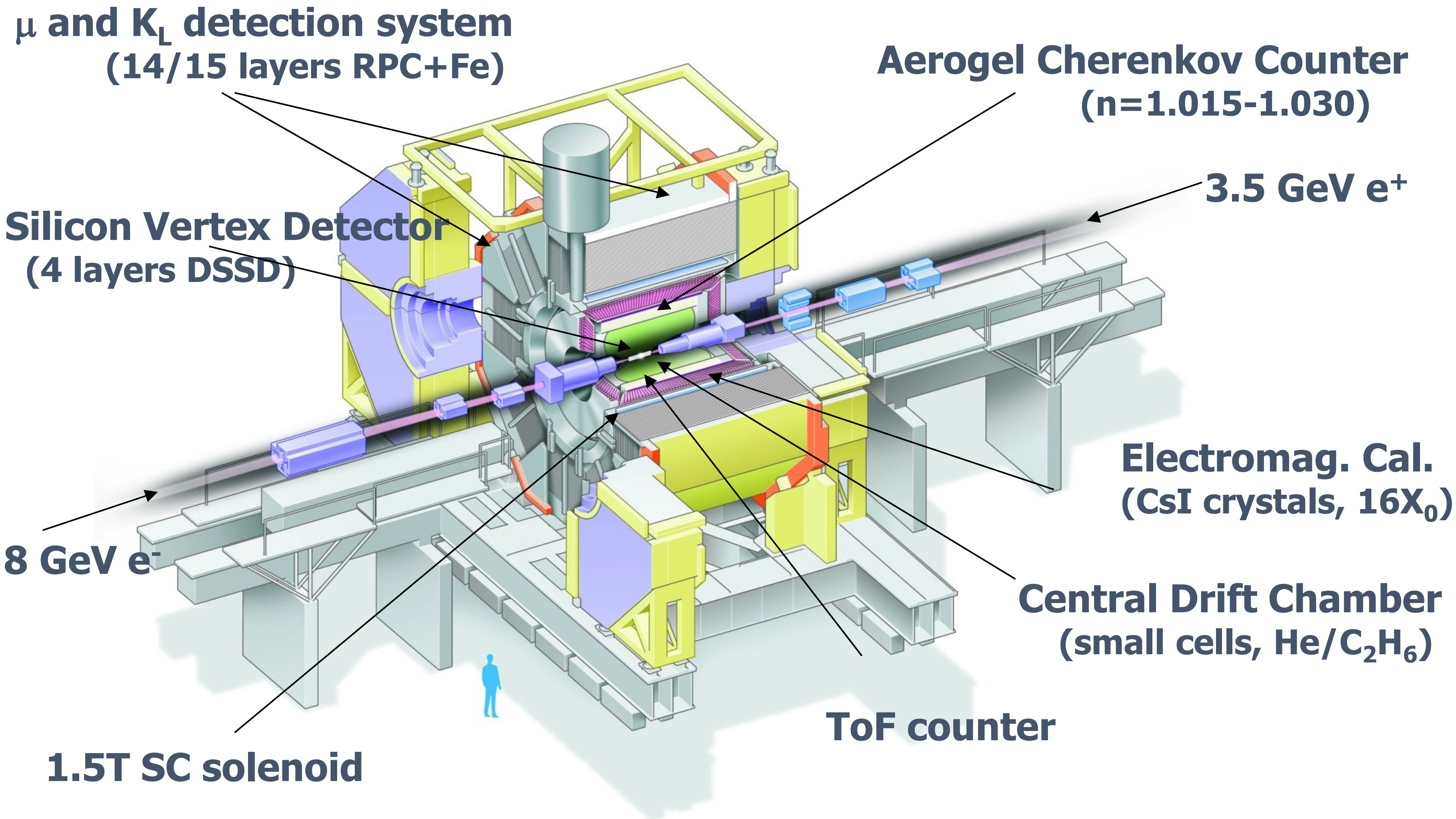


B^0 та його анти-частинка розпадаються по різному в однаковий кінцевий стан $J/\psi\ K^0$

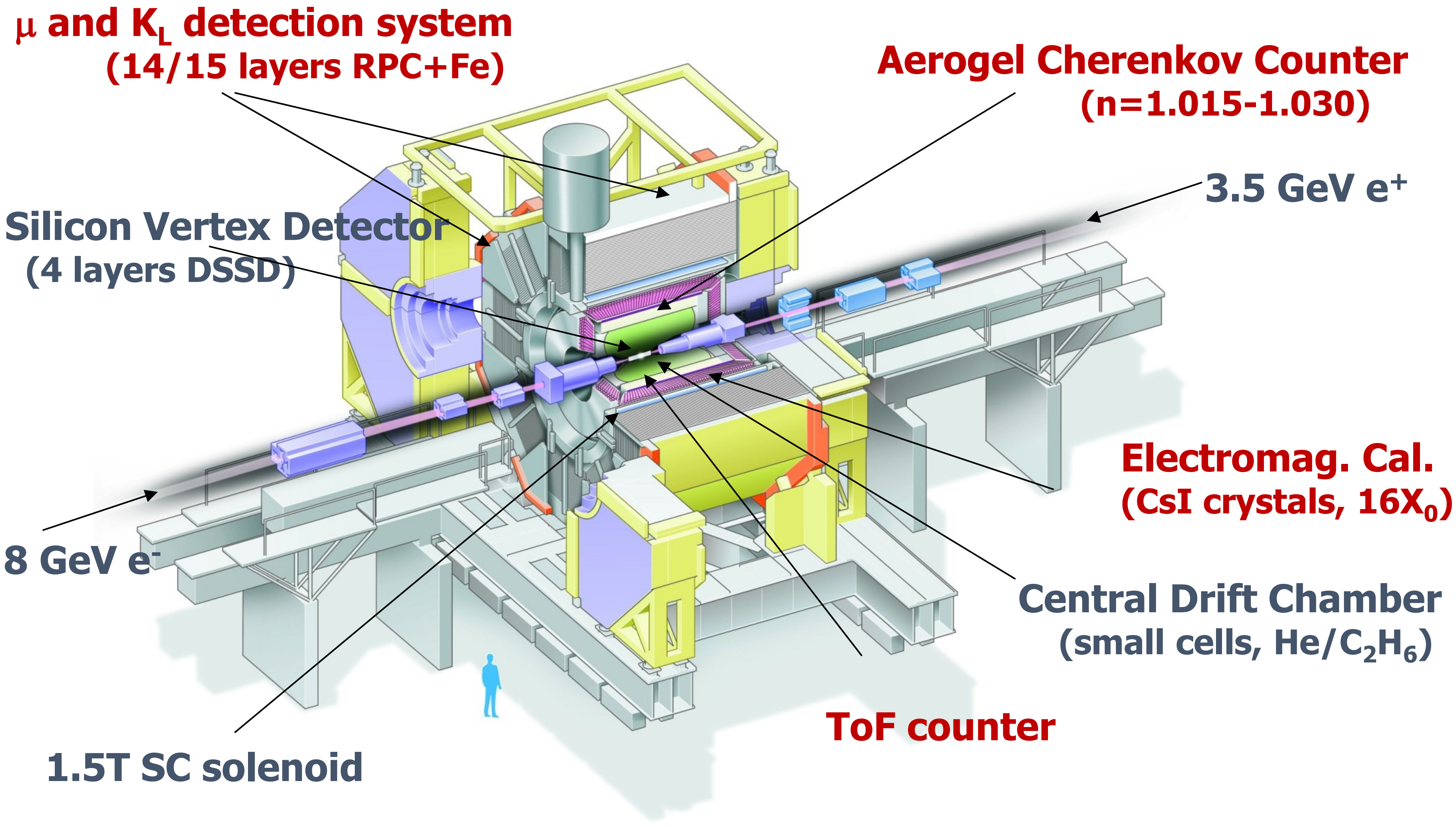
Флейвор B: з продуктів розпаду іншого B: заряд каону, електрона, мюона...

→particle ID є обов'язковим

Приклад: Belle



Системи ідентифікації в Belle



Ідентифікація заряджених частинок

- Частинки ідентифікуються за їх масою або за способом взаємодії.

- Визначення маси: із співвідношення між імпульсом і швидкістю, $p=\gamma mv$ (p відомий - радіус кривизни в магнітному полі)

→ Виміряти швидкість:

- час польоту (time of flight)
- іонізаційні втрати dE/dx
- Кут черенковських фотонів (і/або вихід)
- перехідне випромінювання (transition radiation)

В основному використовується для ідентифікації адронів.

Ідентифікація через взаємодію: електрони та мюони

→ калориметри, мюонні системи

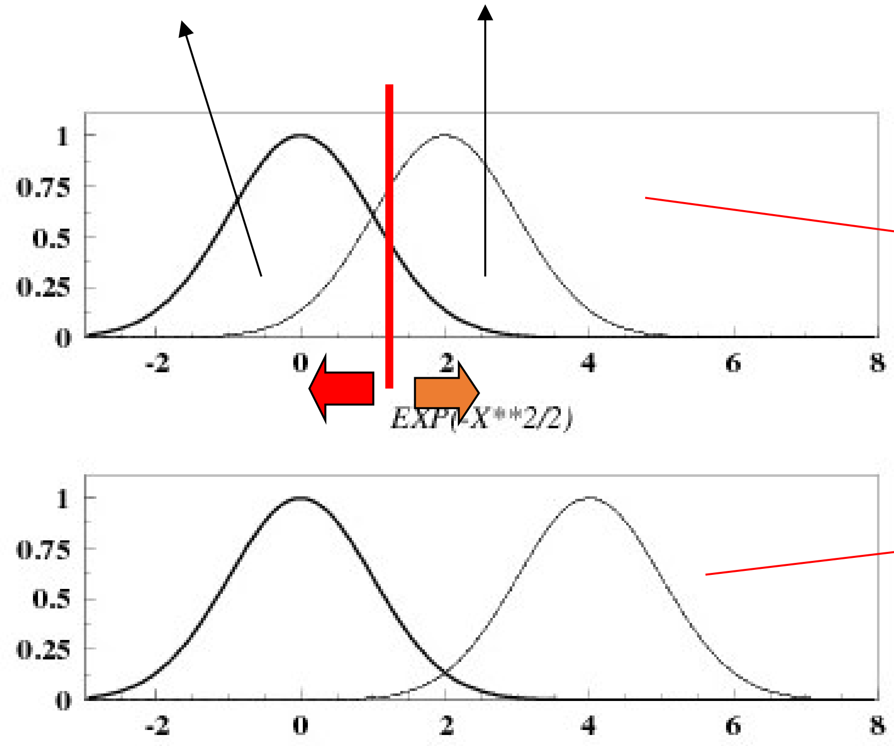
Efficiency and purity in particle identification

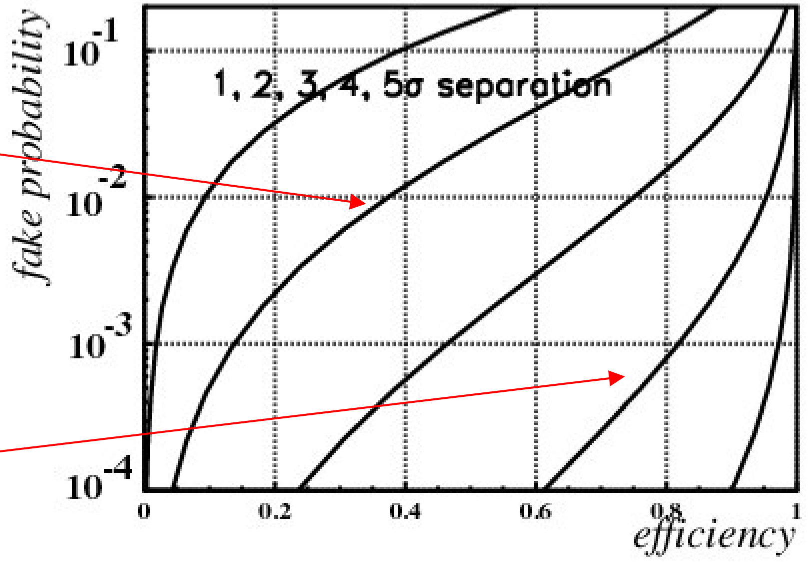
Efficiency and purity are tightly coupled!

Two examples:

частинка тип 1 тип 2

eff. vs fake probability





Певна дискримінуюча змінна

Time-of-flight measurement (TOF)

Measure time difference over a known distance, determine velocity

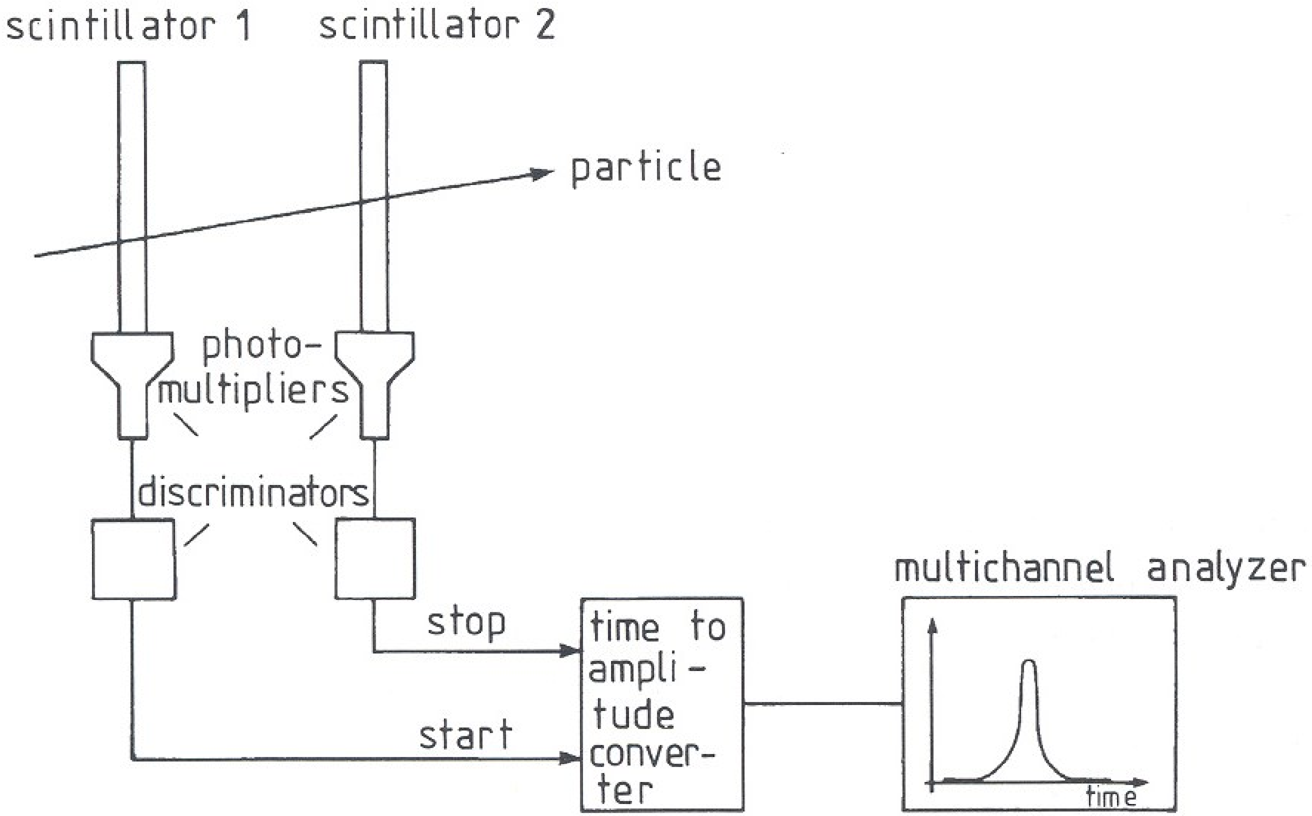


Fig. 6.5. Working principle of time-of-flight measurement.

Time-of-flight measurement 2

Required resolution, example:

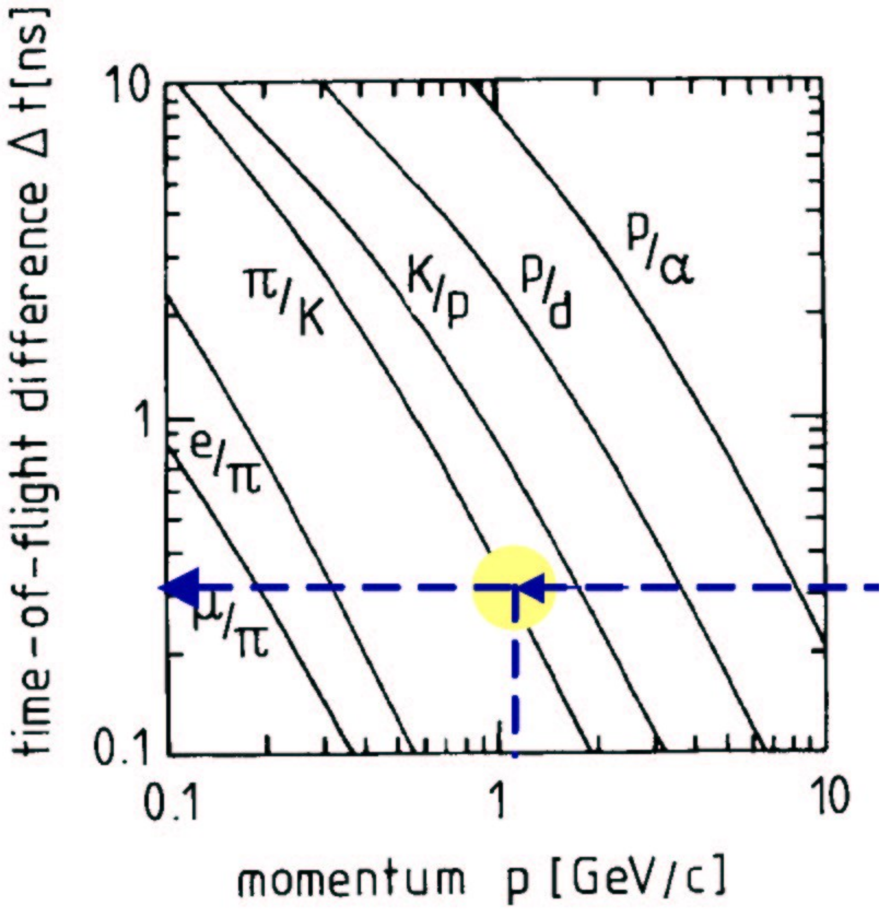
π/K difference at 1GeV/c: 300ps

For a 3σ separation need σ(TOF)=100ps

Resolution contributions:

- PMT: transient time spread (TTS)
- Path length variation
- Momentum uncertainty
- Decay time of the scintillator

Time difference between two particle species for path length=1m



Time-of-Flight (TOF) counters

Traditionally: plastic scintillator + PMTs

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

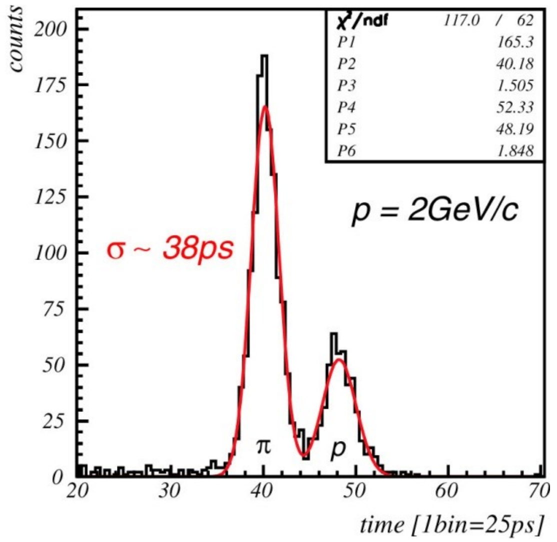
To go beyond that: need faster detectors:
→use Cherenkov light (prompt) instead of scintillations
→use a fast gas detector (Multi gap RPC)

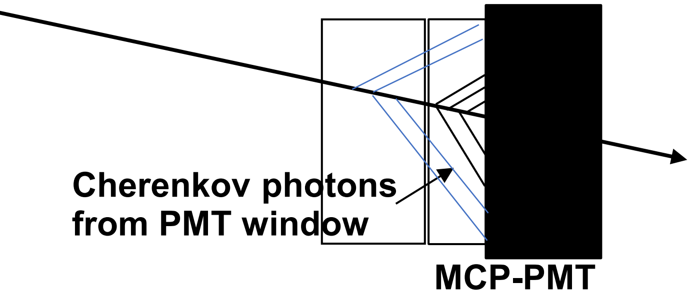
However: make sure you also know the interaction time very precisely...

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.





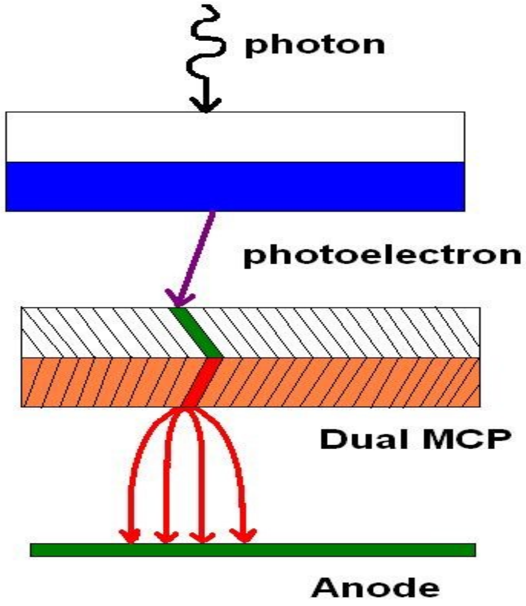
Proof of principle: beam test with pions and protons at 2 GeV/c.

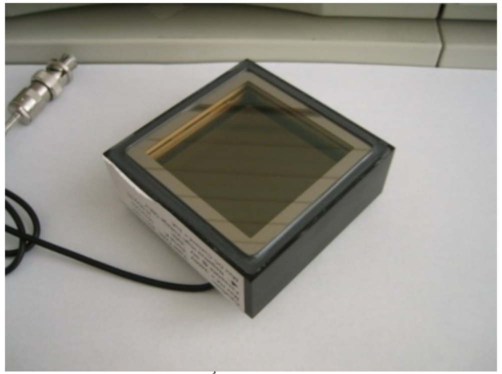
Only photons from the window

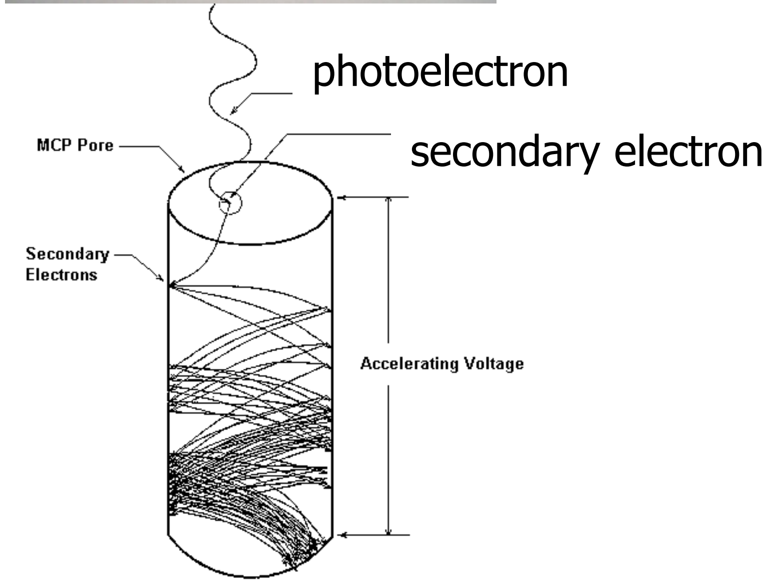
Distance between start counter and MCP-PMT was only 65cm

Very fast: MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: multi-anode PMT with two MCP stages







→ very fast (σ=40ps for single photons)

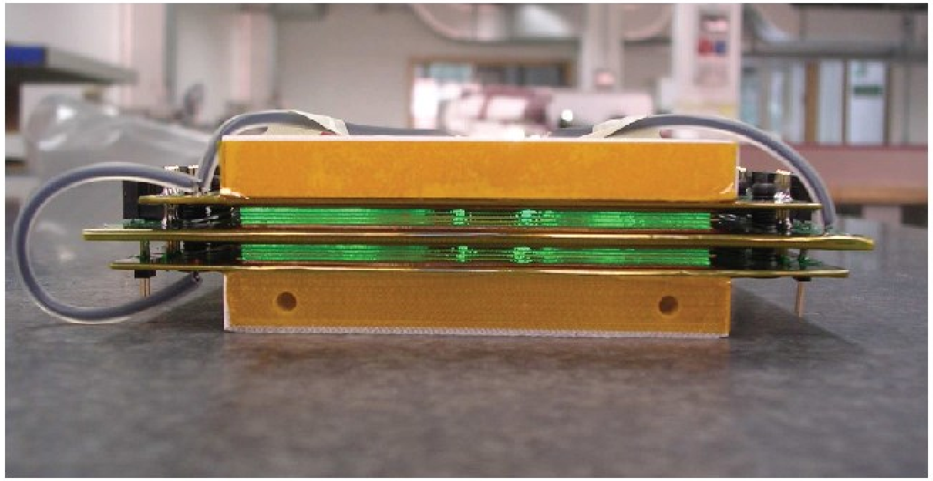
ALICE TOF

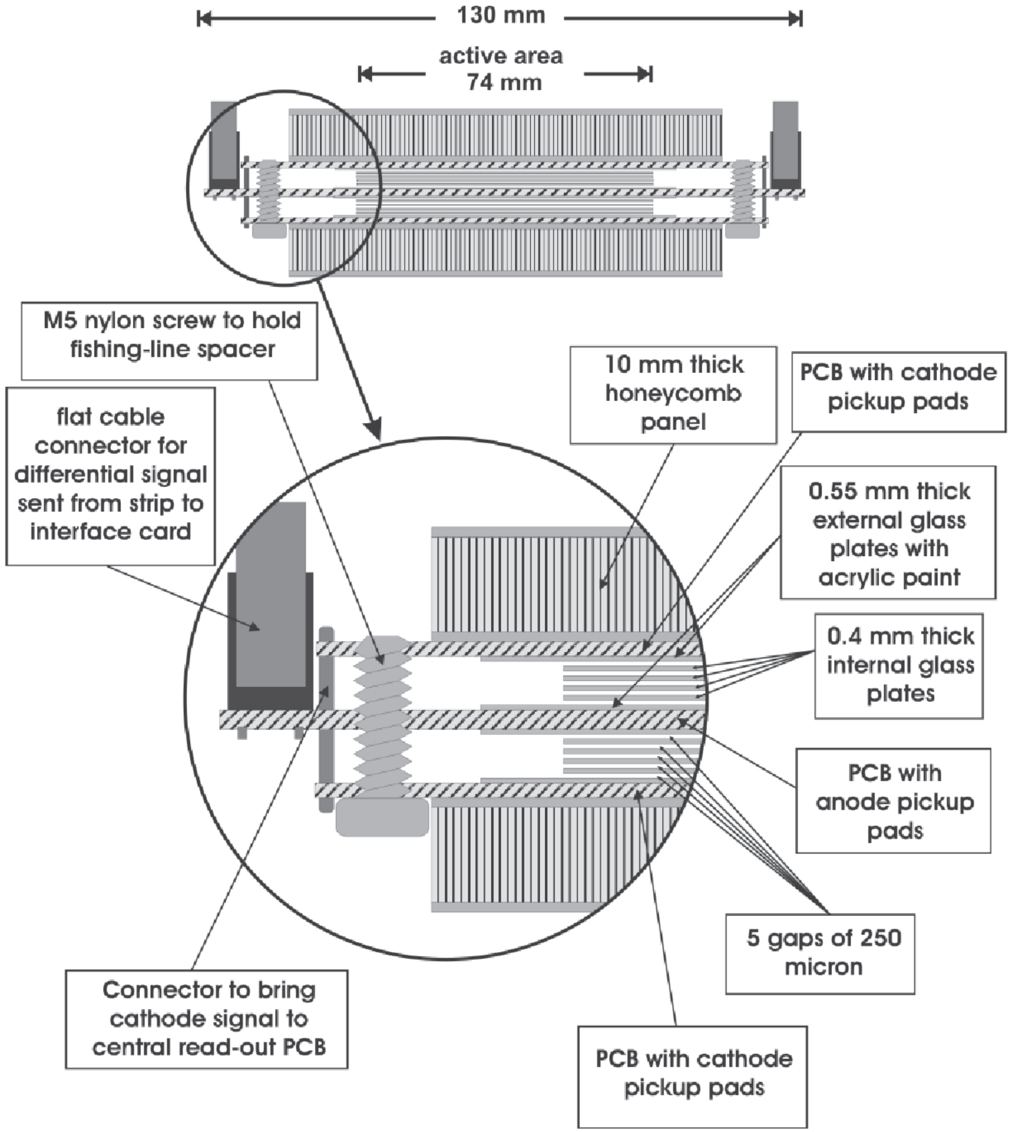
Very fast large area (140m^2) particle detector:

→MRPC, multi-gap RPC

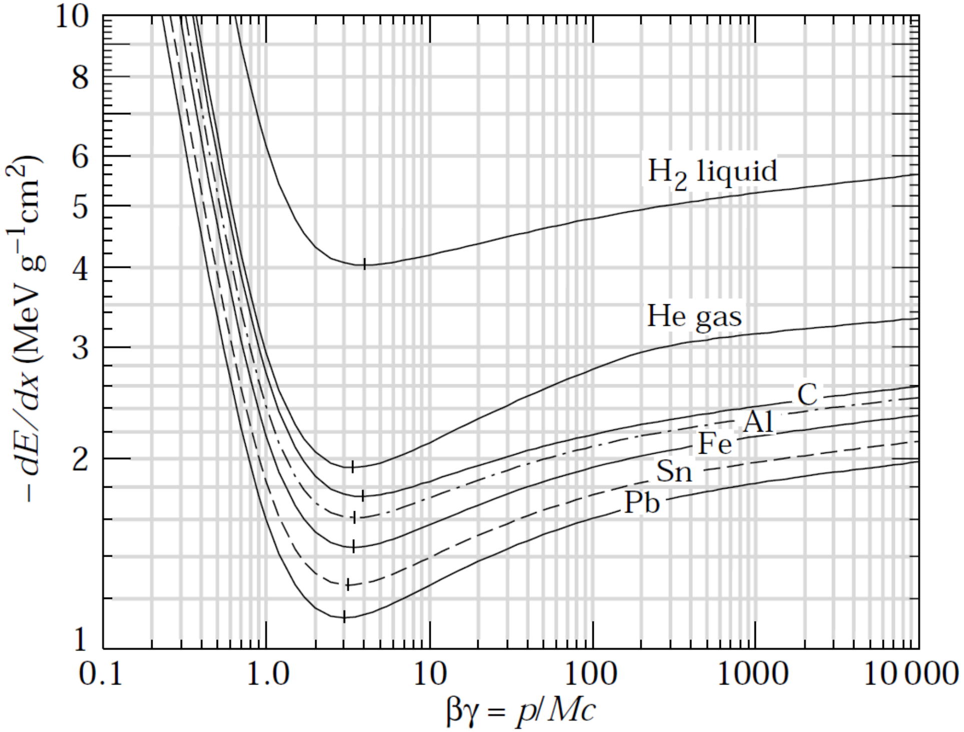
σ=50ps (incl. read-out)

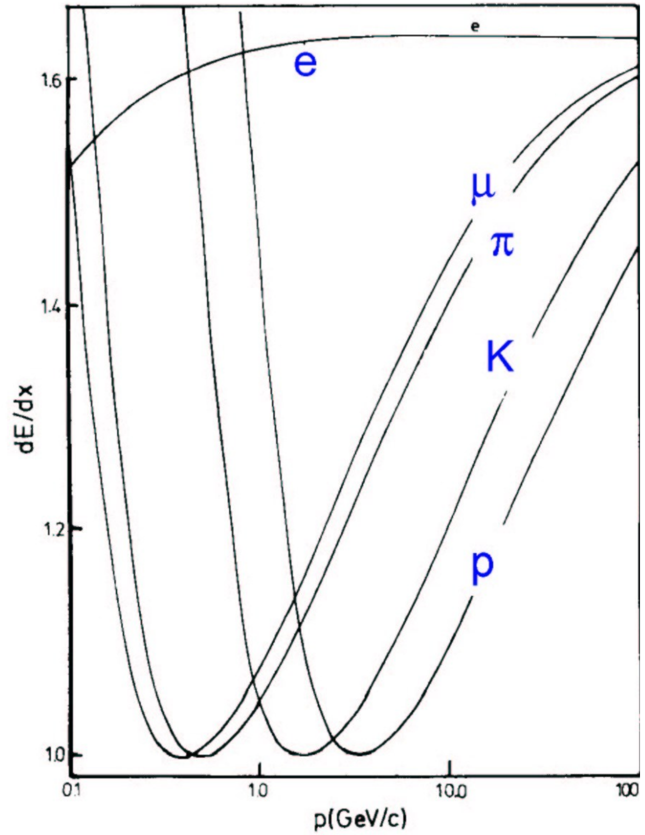
π/K separation (3σ) up to 2.5 GeV/c at large track densities





Identification with dE/dx measurement





dE/dx is a function of velocity β

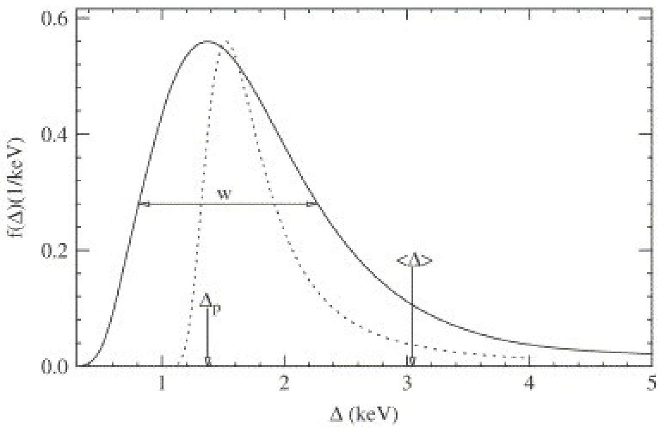
For particles with different mass the Bethe-Bloch curve gets displaced if plotted as a function of p

For good separation: resolution should be ~5%

Identification with dE/dx measurement

Problem: long tails (not Gaussian!)

Energy loss distribution for particles with βγ=3.6 traversing 1.2 cm of Ar gas (solid line).



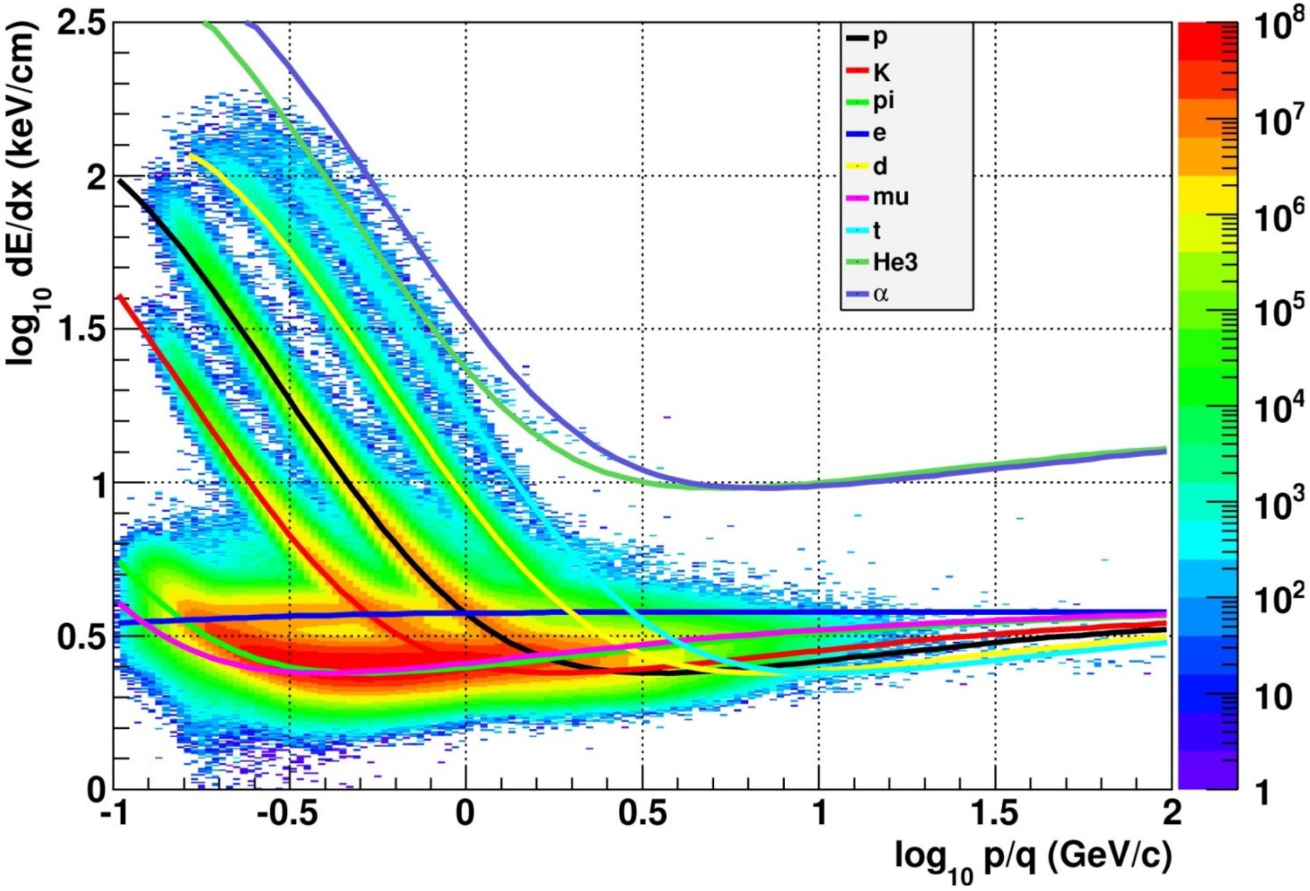
Parameters describing f(Δ) are the most probable energy loss $\Delta_p(x;\beta\gamma)$ = the position of the maximum at 1371 eV, and ***w***, the full-width-at-half-maximum (FWHM) of 1463 eV. The mean energy loss is 3044 eV. Dotted line: the original Landau function.

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

Identification with dE/dx measurement

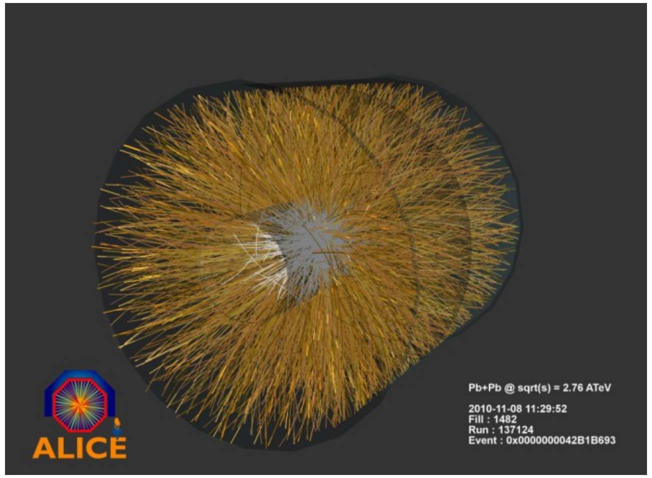
dE/dx performance in the STAR TPC

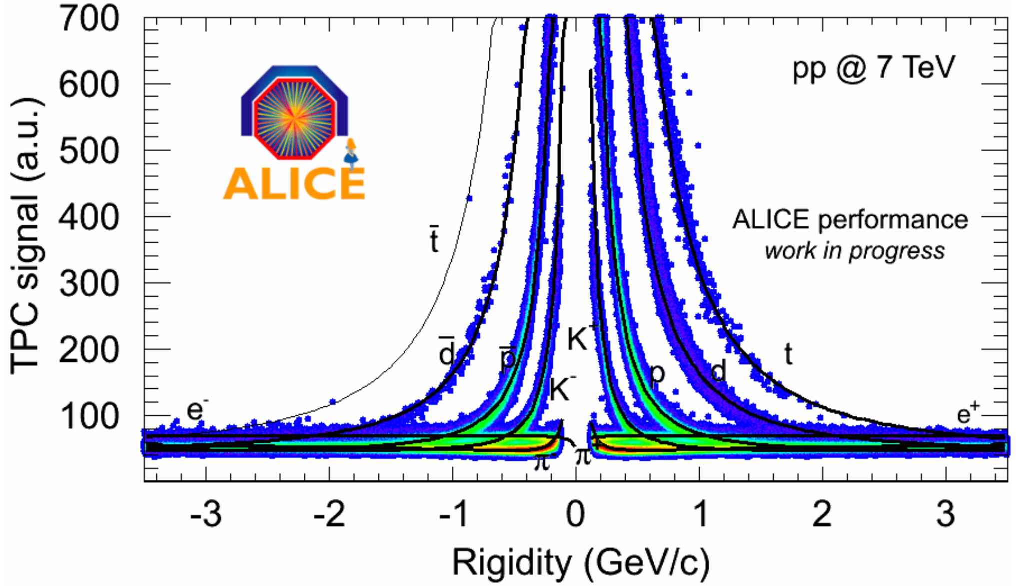
gold-gold
collisions



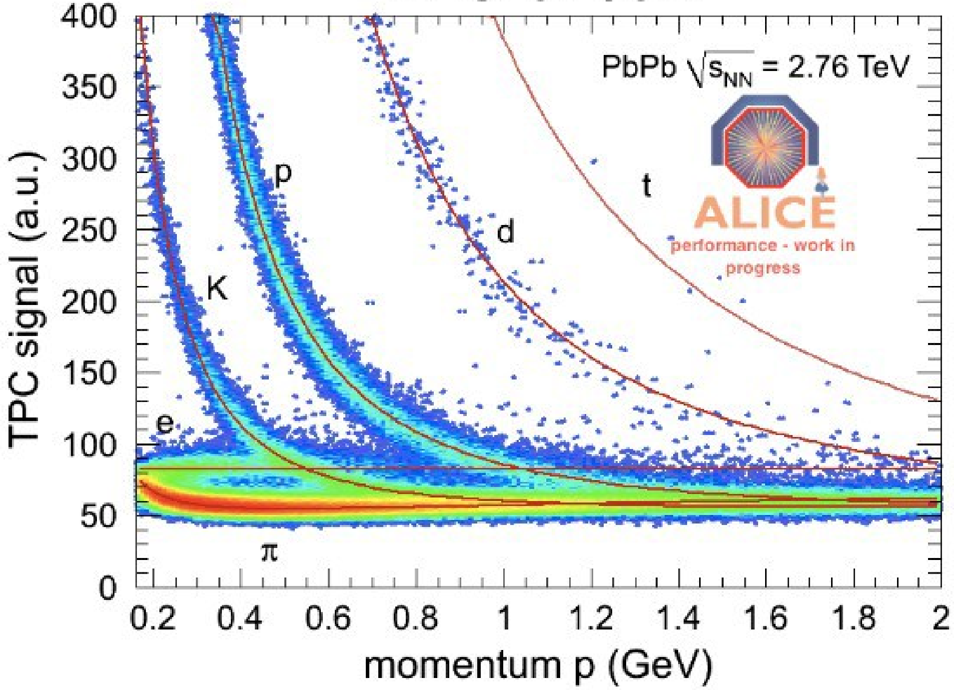
Energy loss in the STAR TPC: truncated mean as a function of momentum. The curves are Bichsel model predictions.

dE/dx in ALICE

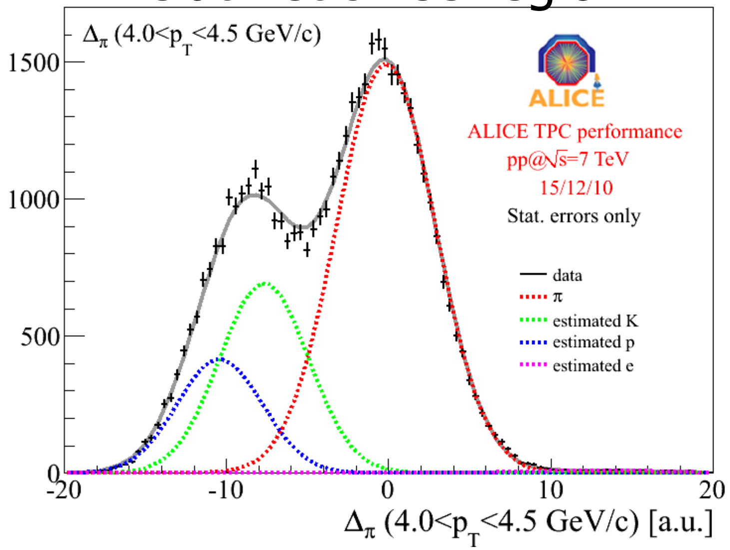




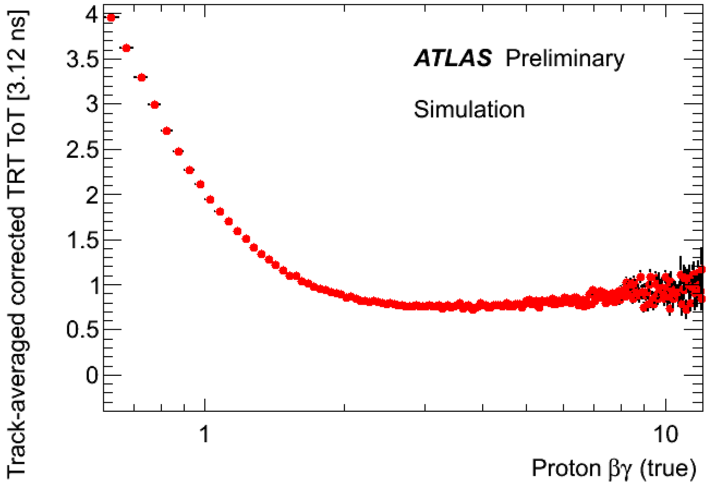
TPC dE/dx



relativistic rise region

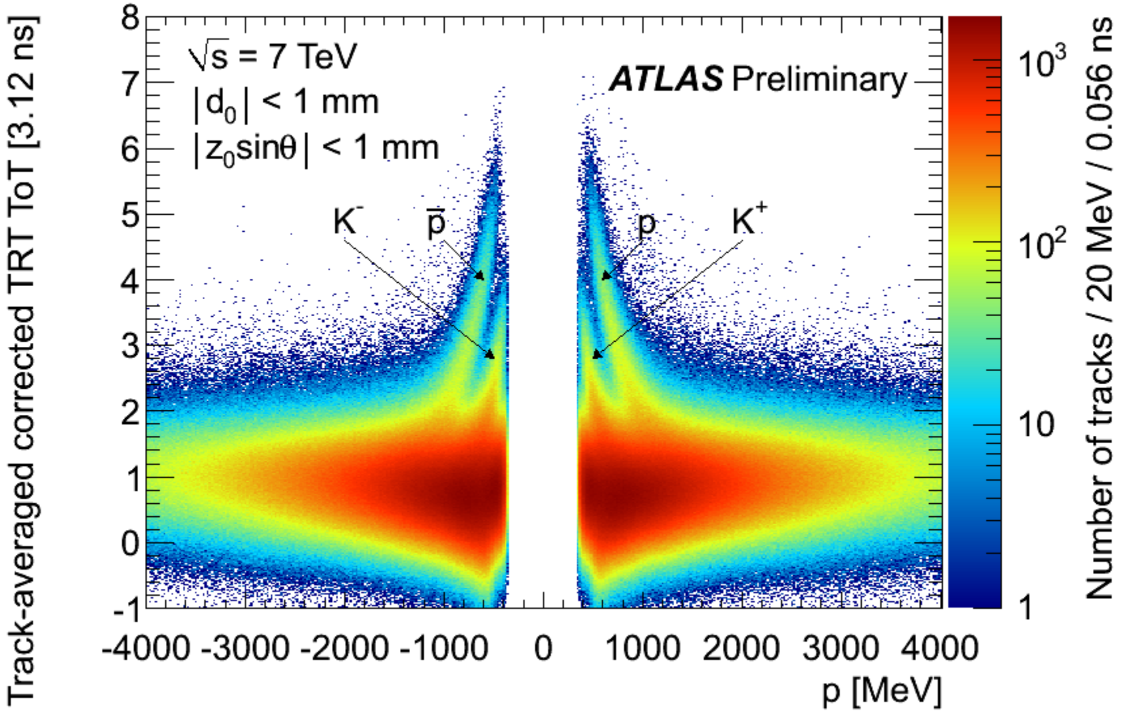


Time-over-Threshold (ToT): dE/dx in ATLAS TRT



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

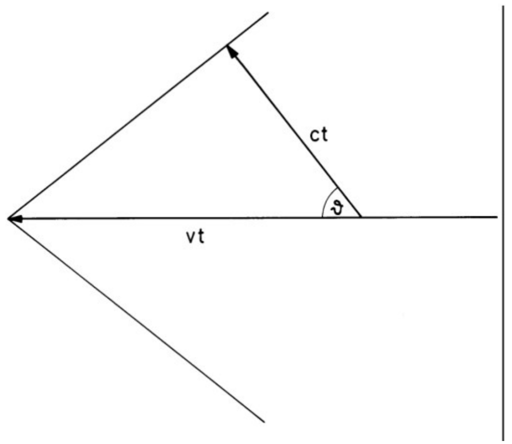
2010 data: The track-averaged ToT distribution as a function of the track momentum.



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,

$$\cos(\theta) = \frac{c}{nv} = \frac{1}{n\beta}$$



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***:

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

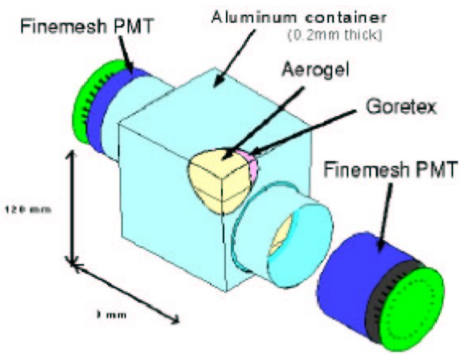
→Few detected photons

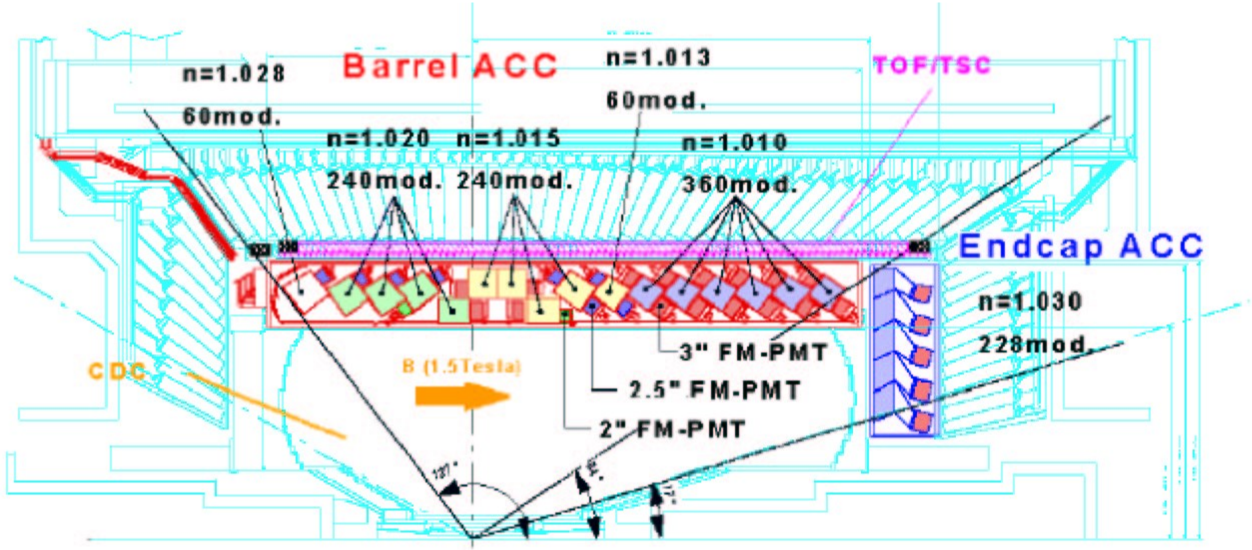
Belle: threshold Cherenkov counter

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’)

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

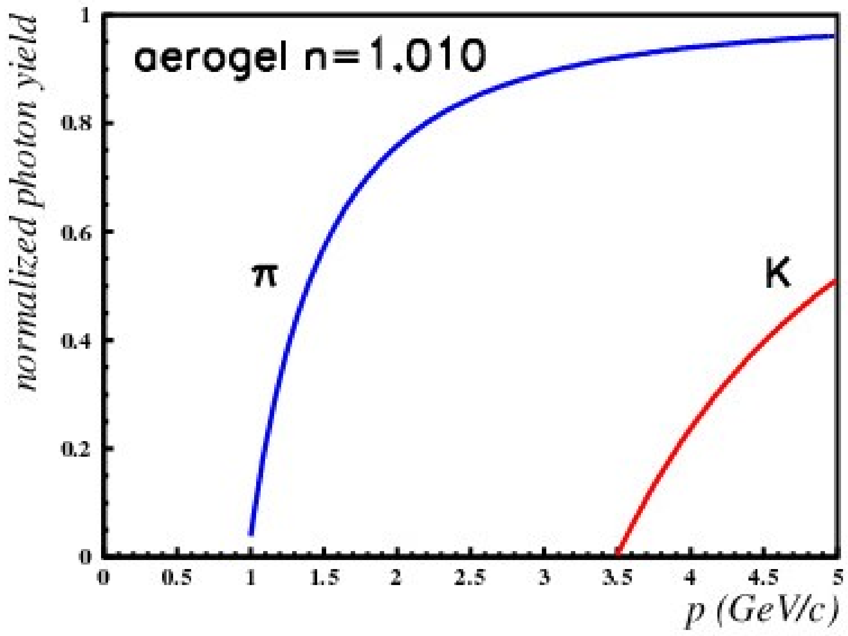




Fine-mesh PMT: works in high B fields (1.5 T)

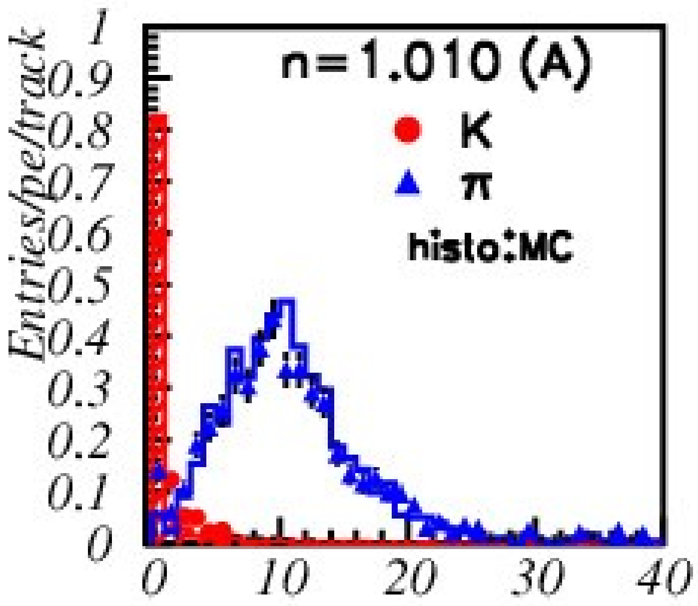
Belle ACC : threshold Cherenkov counter

expected yield vs p



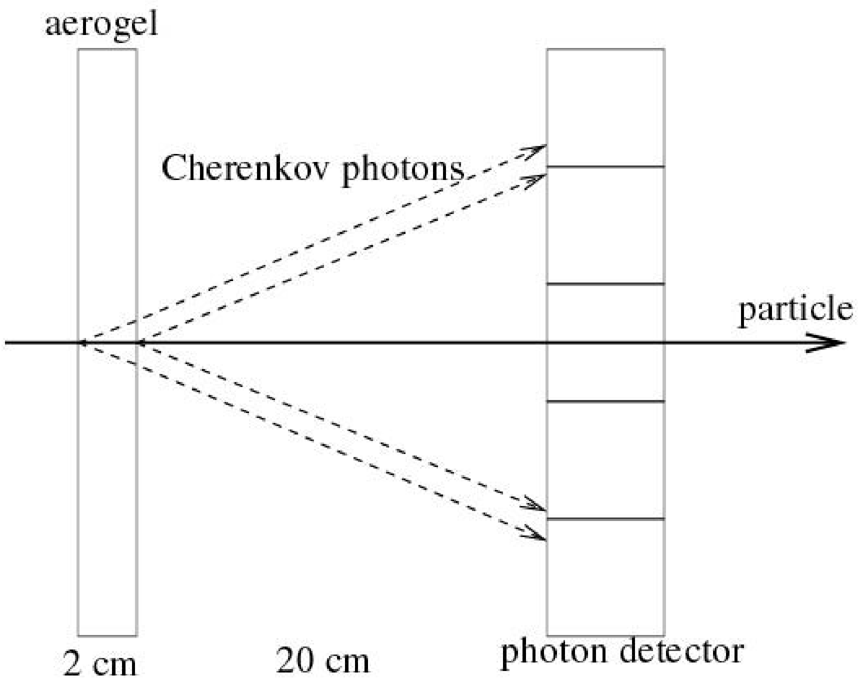
NIM A453 (2000) 321

yield for 2GeV<p<3.5GeV:
expected and measured
number of hits



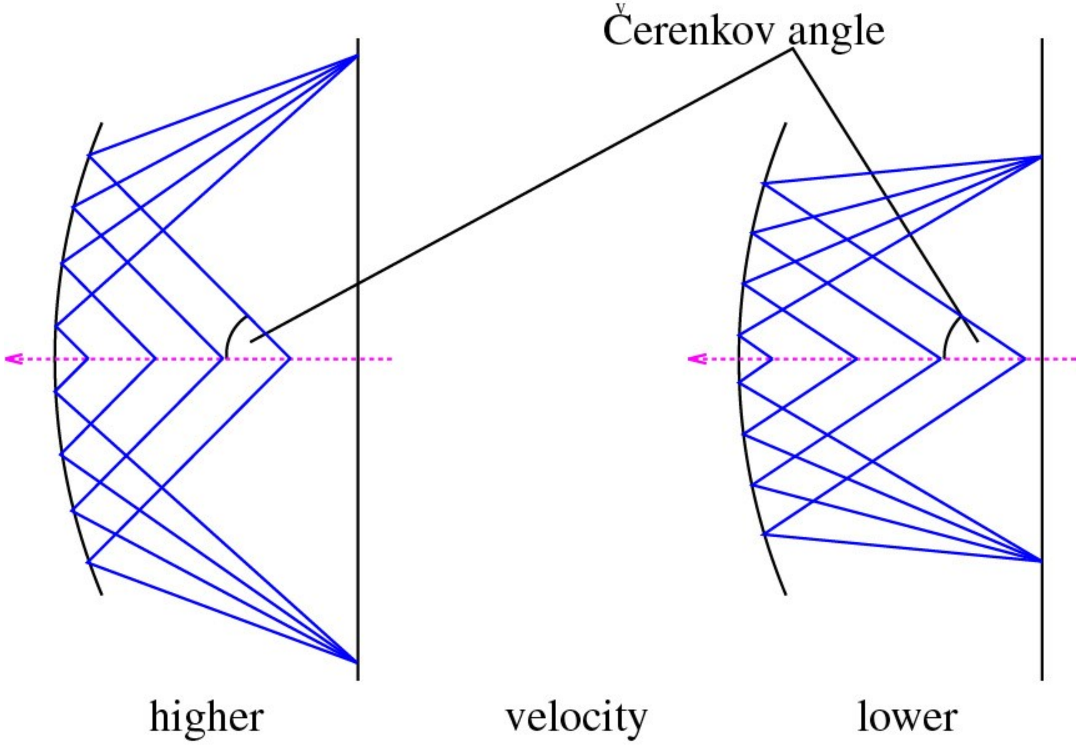
→Good separation between pions (light) and kaons (no light) between ~1.5 GeV/c and 3.5 GeV/c

Measuring Cherenkov angle



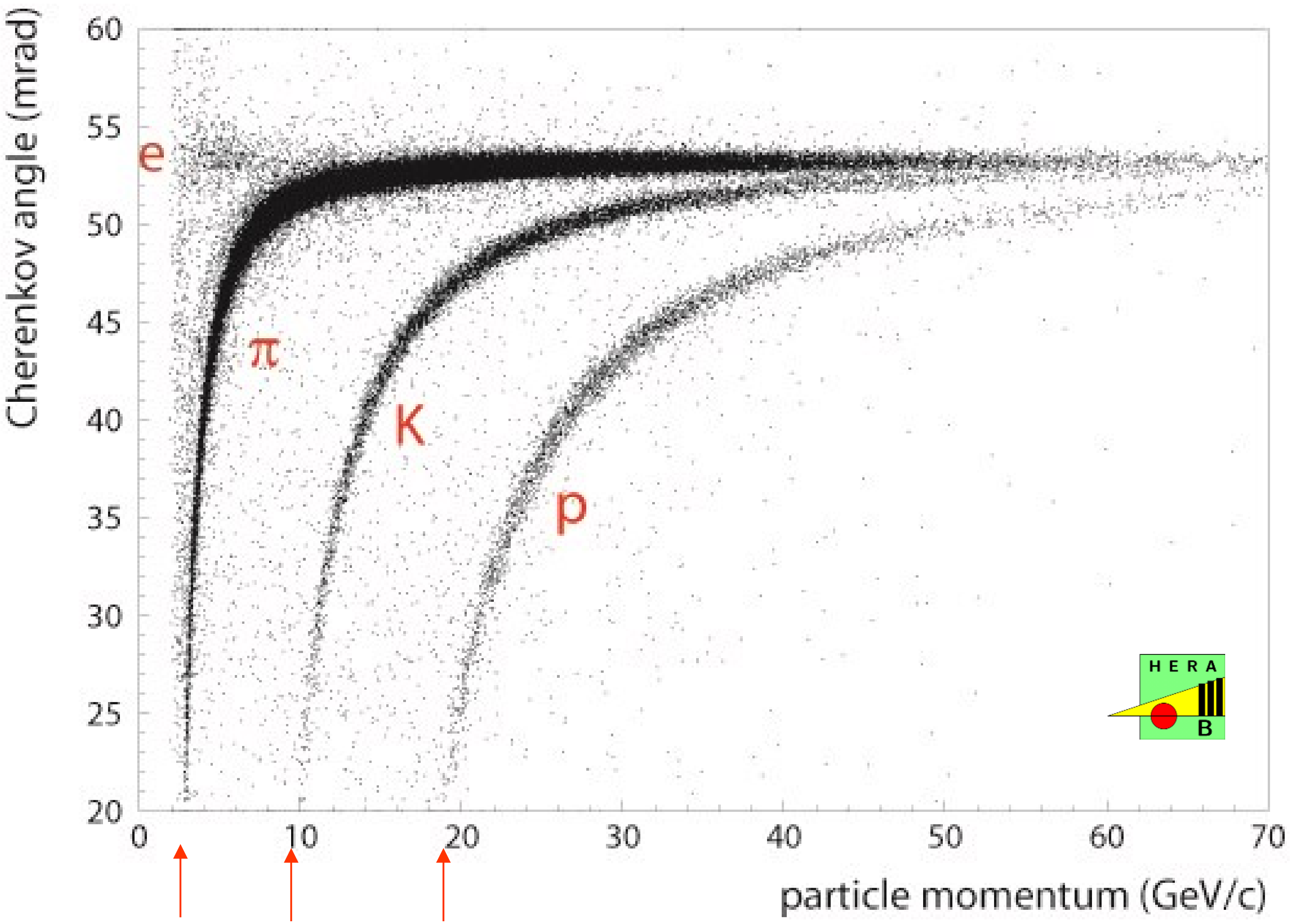
Proximity focusing RICH

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



RICH with a focusing mirror

Measuring Cherenkov angle



π K p

thresholds

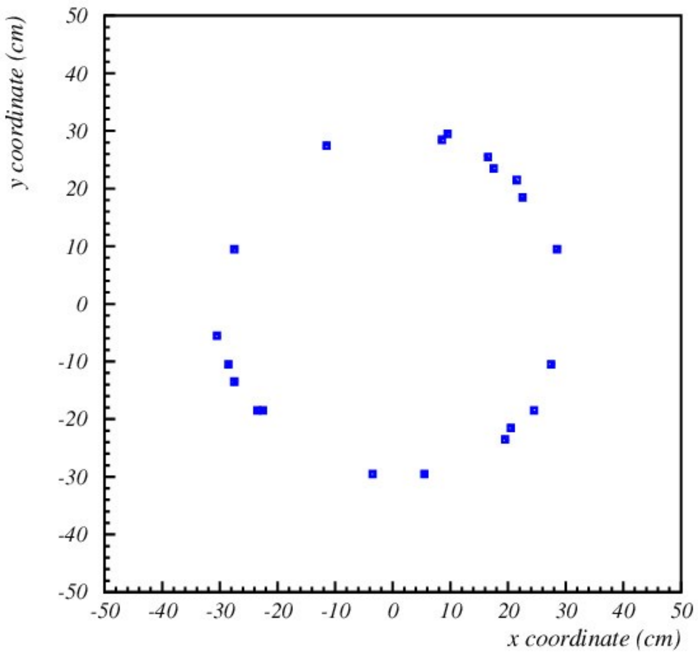
Radiator:
C_4F_{10} gas

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)

Resolution of a RICH counter

Determined by:

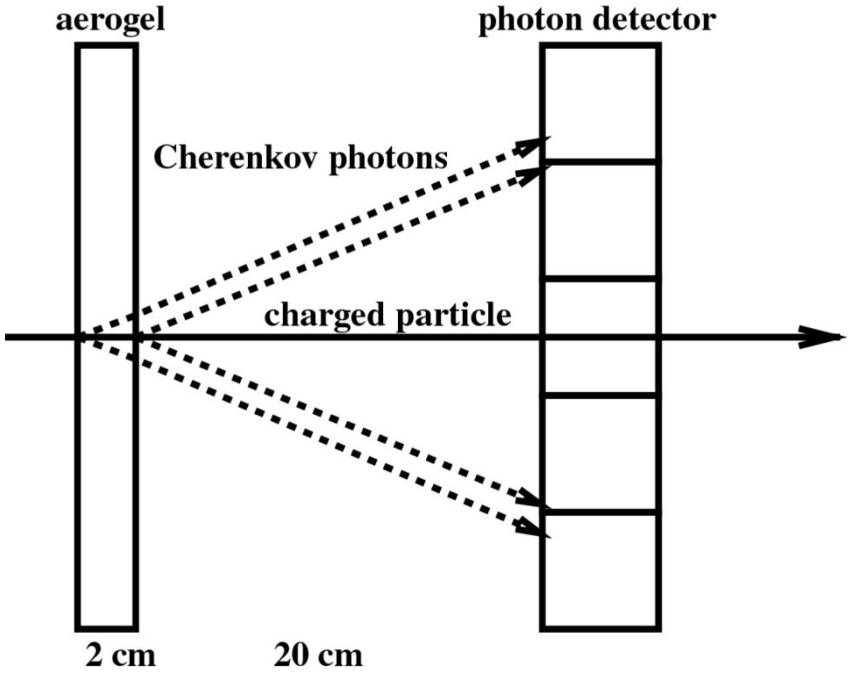
•Photon impact point resolution (~photon detector granularity)

•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:

single photon resolution

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

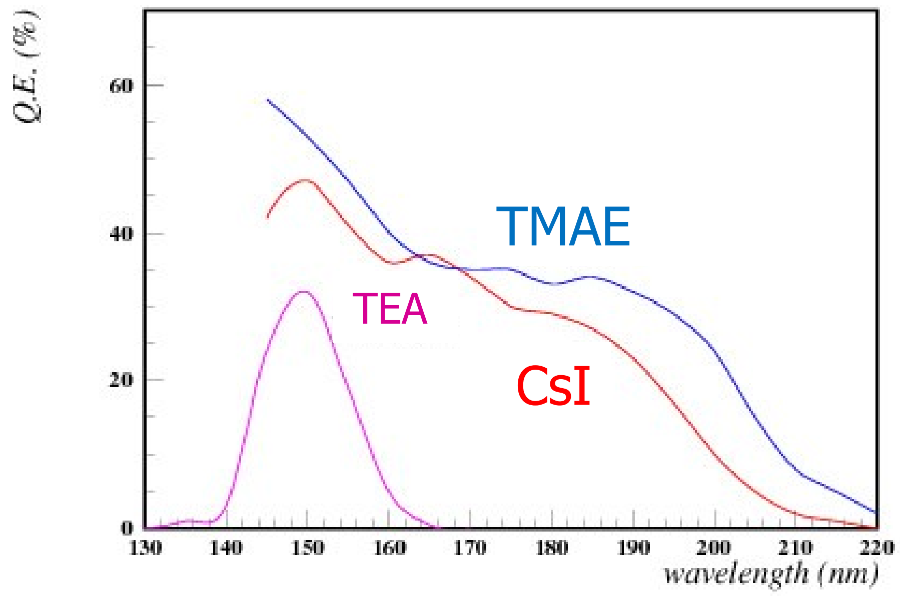
# of detected photons

(in the case of low background)

First generation of RICH counters

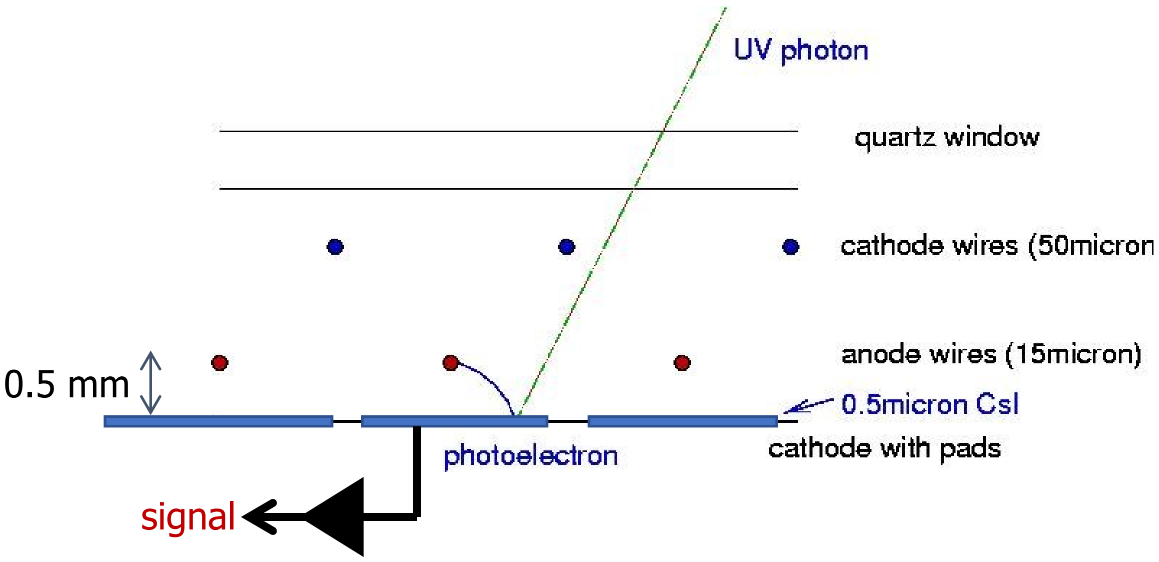
DELPHI, SLD, OMEGA RICH counters: all employed wire chamber based photon detectors (UV photon → photo-electron → detection of a single electron in a TPC)

Photosensitive component:
TMAE added to the gas mixture



Fast RICH counters with wire chambers

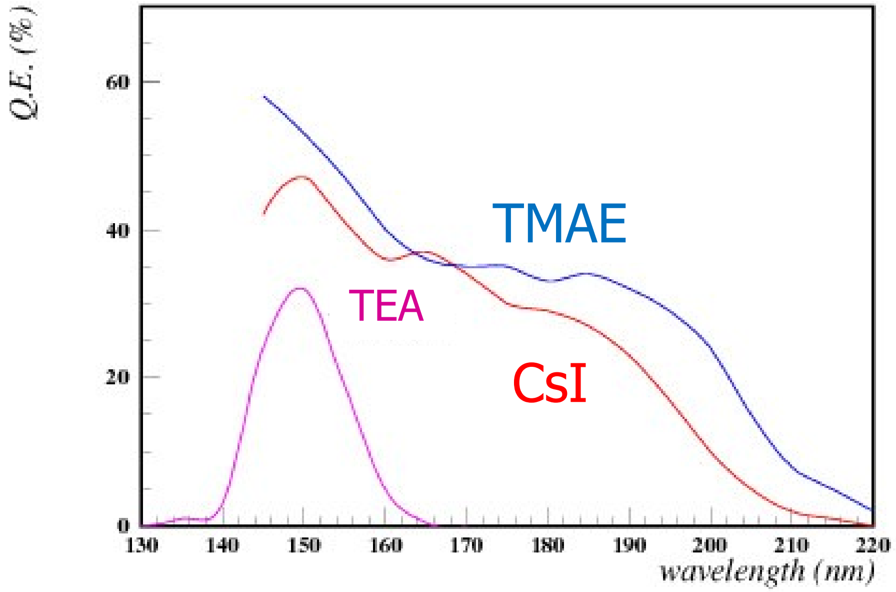
Multiwire chamber with cathode pad read-out: → short drift distances, fast detector



Photosensitive component:

•in the gas mixture (TEA): CLEOIII RICH

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



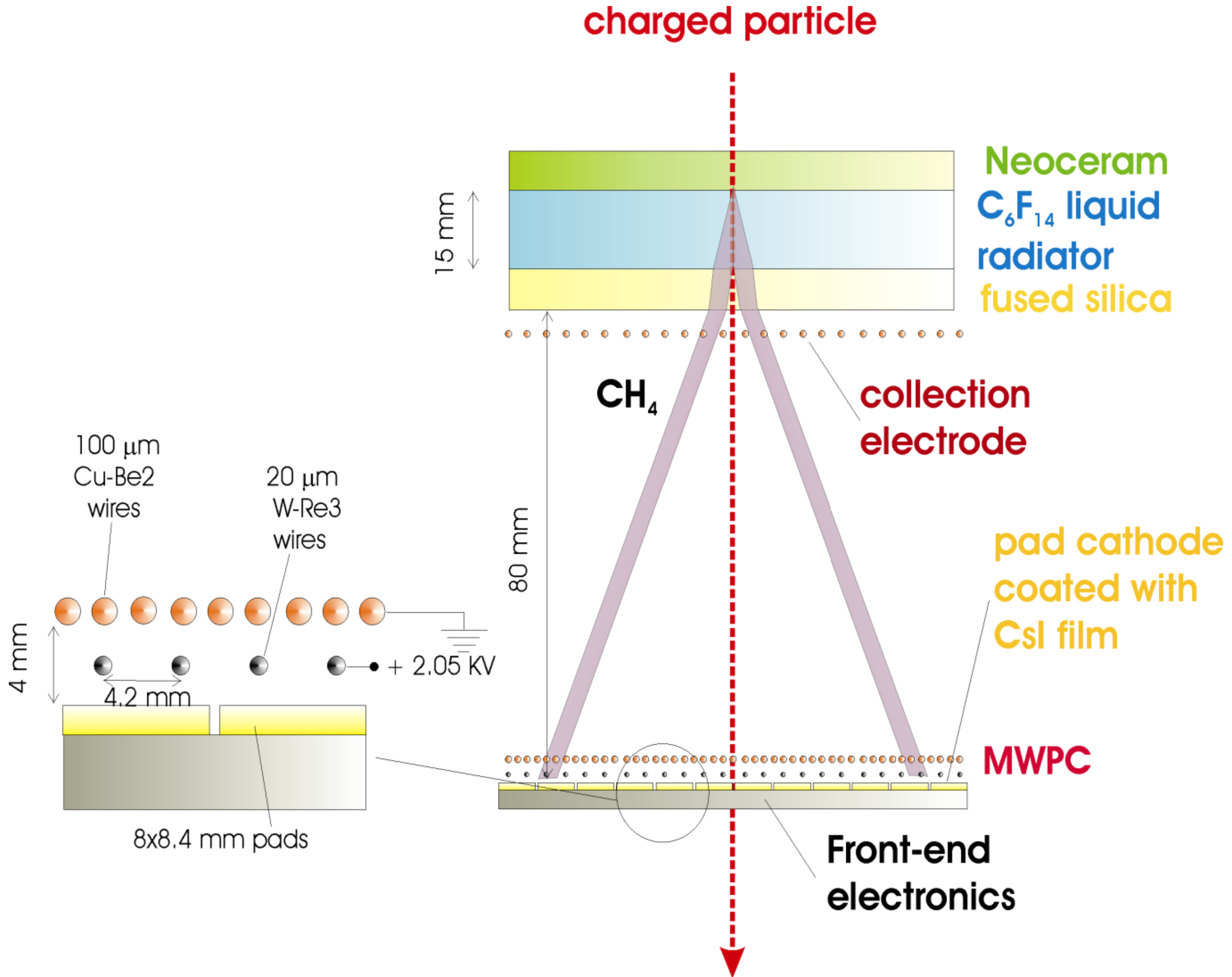
Works in high magnetic field!

CsI based RICH counters: HADES, COMPASS, ALICE

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

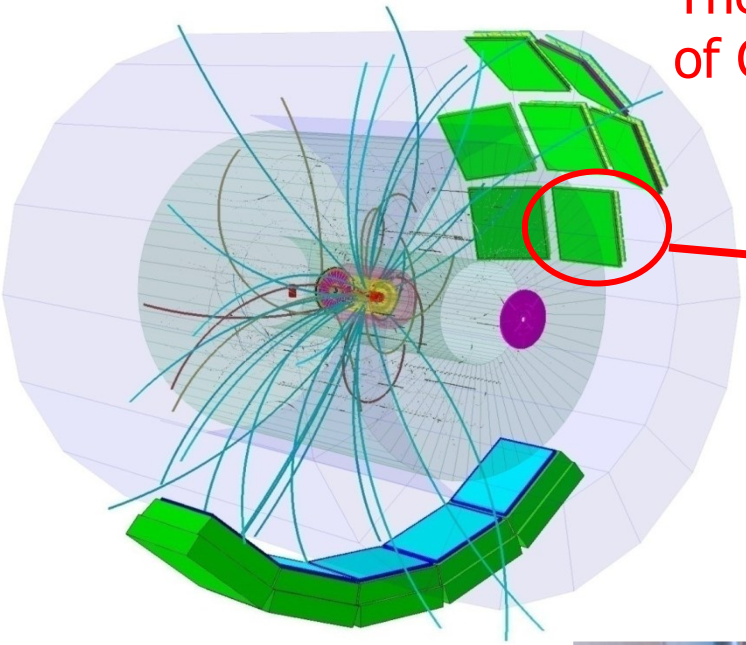
ALICE:

- liquid radiator
- proximity focusing

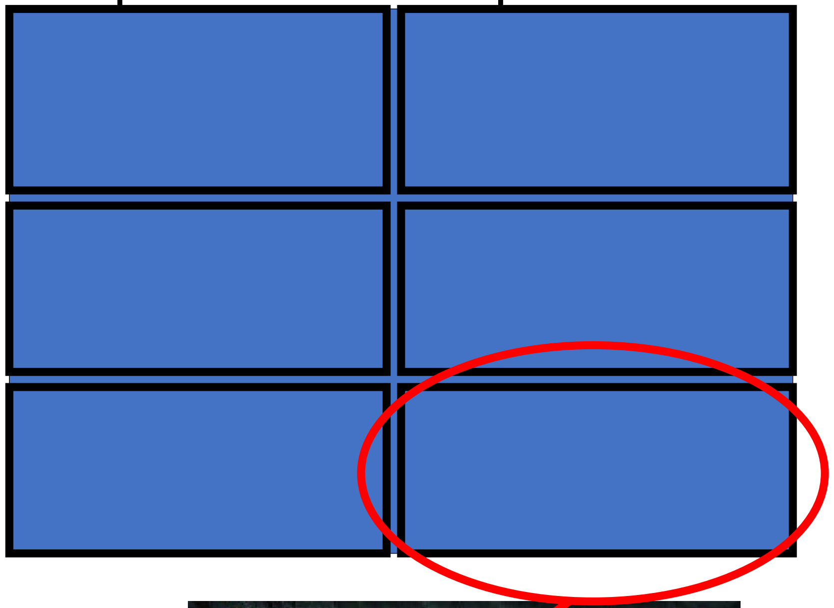


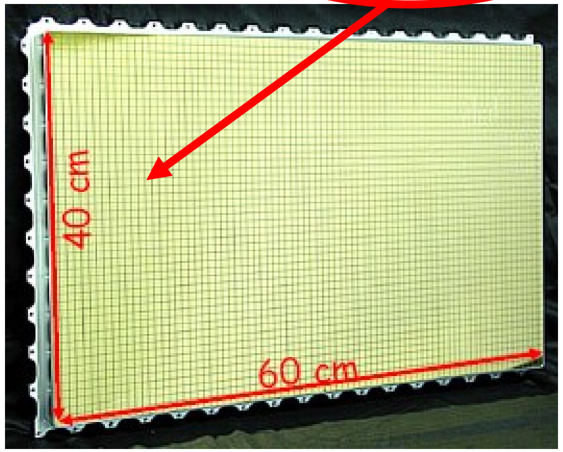
ALICE RICH = HMPID

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



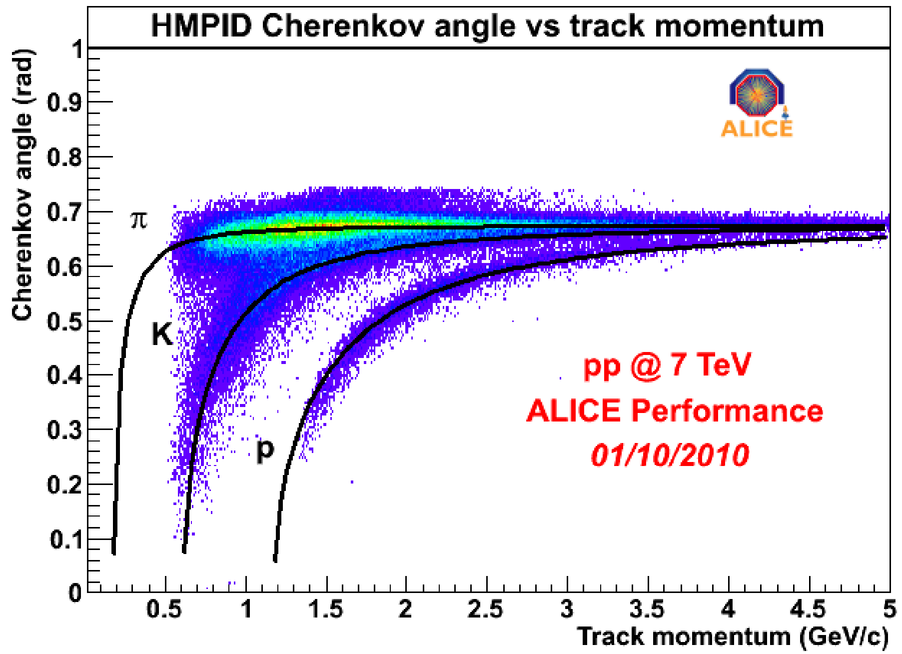
Six photo-cathodes per module

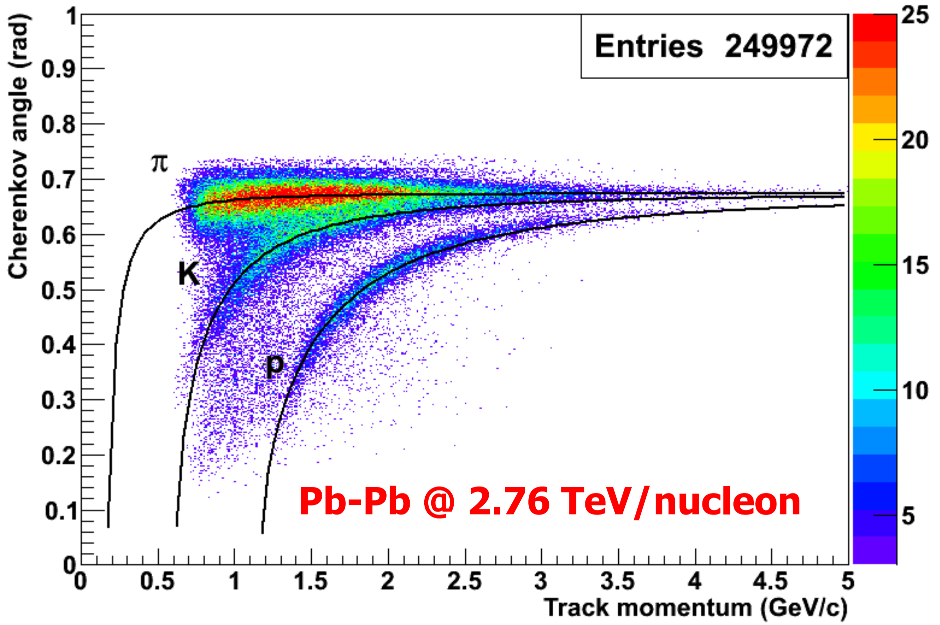


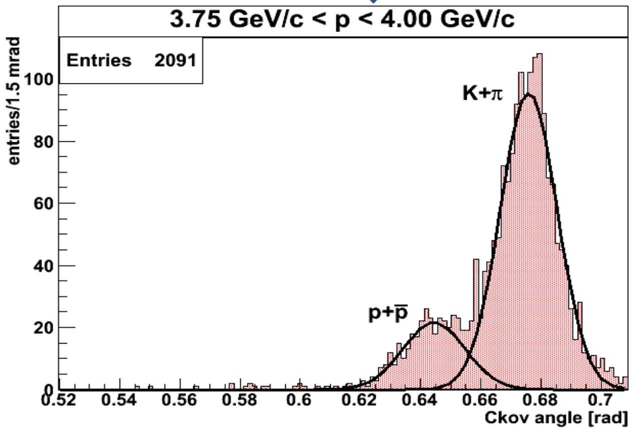


CsI photo-cathode is segmented in 0.8x0.84 cm pads

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 vaccum based photon detectors (e.g. PMTs)

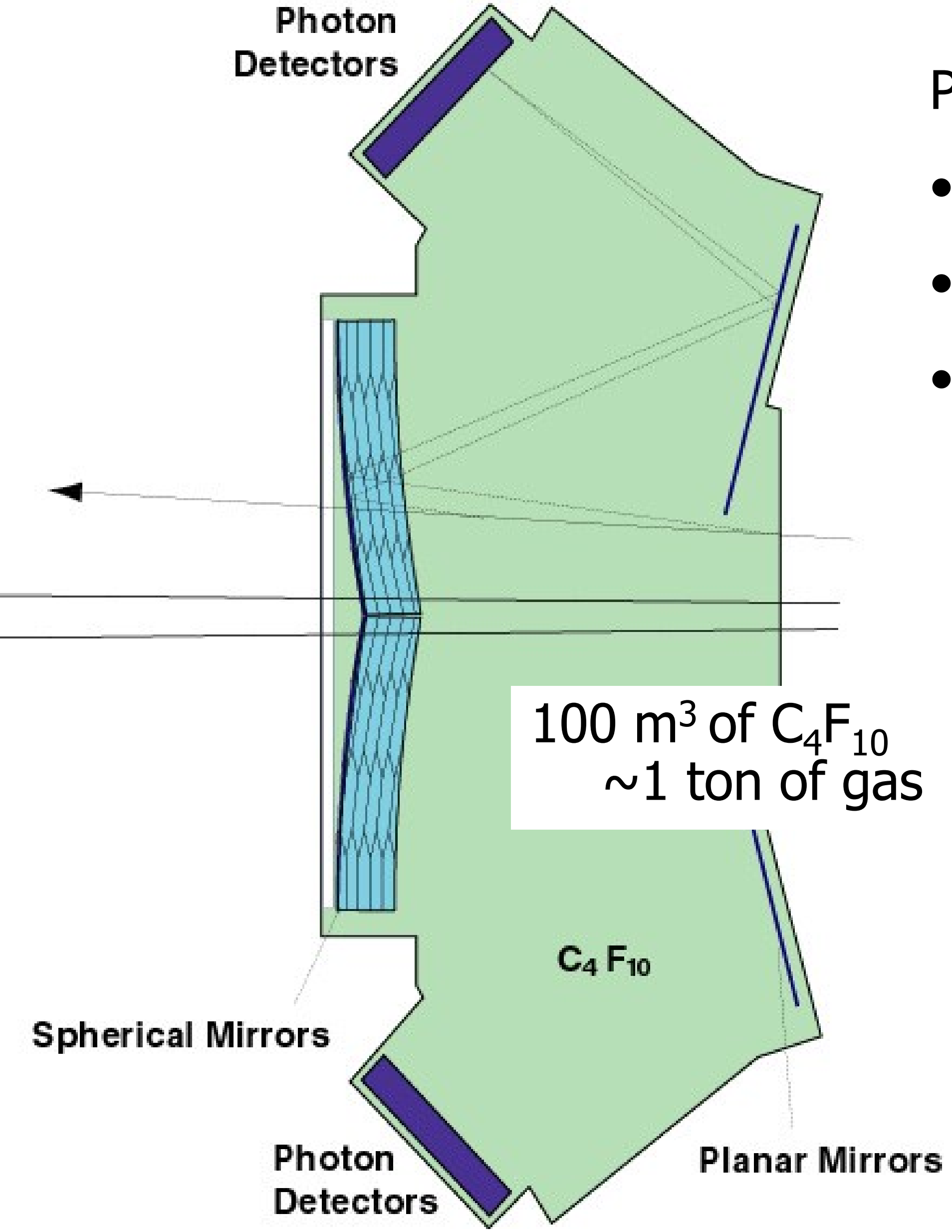
Good spacial resolution (pads with ~5 mm size)

→ Need multianode PMTs

HERA-B RICH

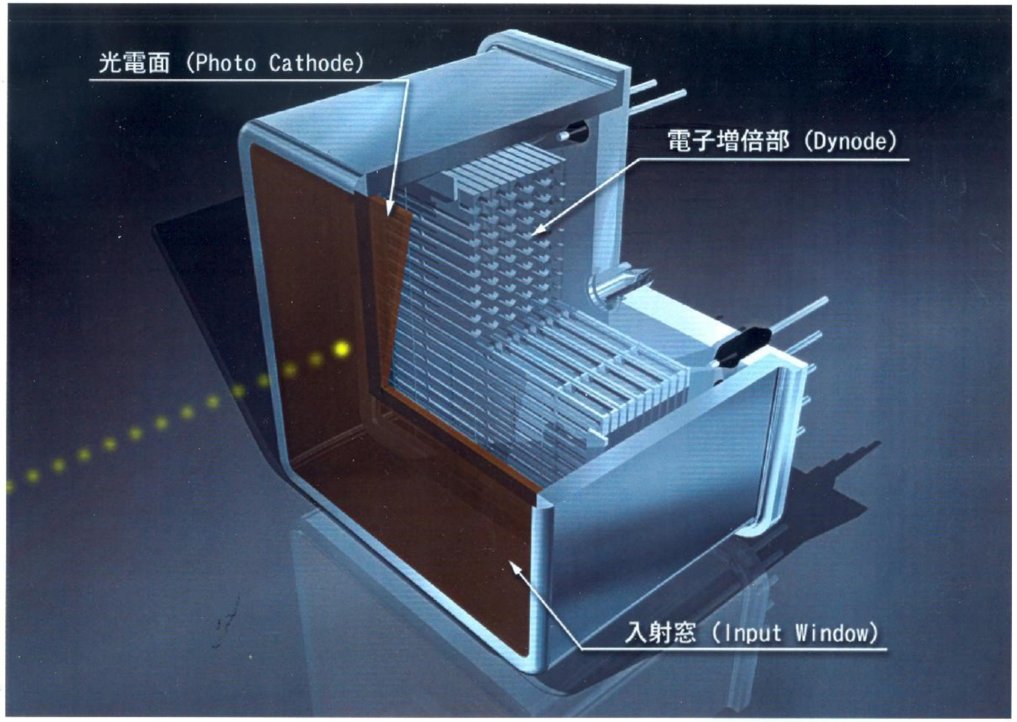
Photon detector requirements:

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



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

Multianode PMTs



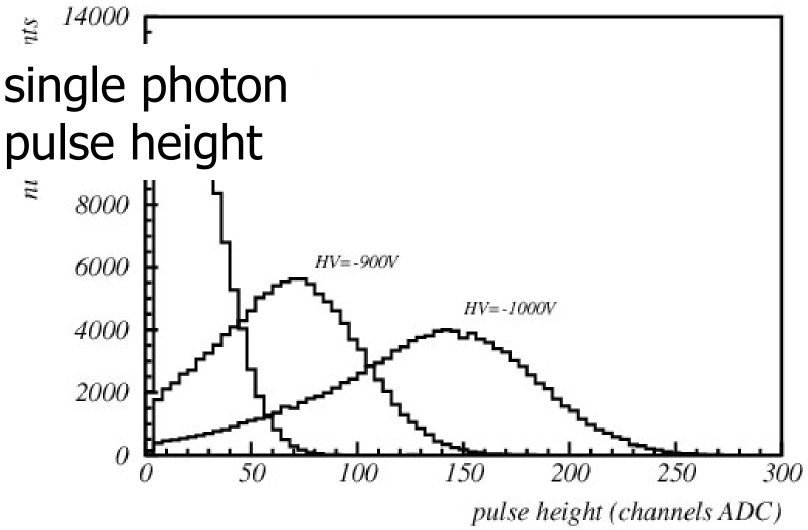
Multianode PMTs with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

→Excellent single photon pulse height spectrum

→Low noise (few Hz/ch)

→Low cross-talk (<1%)

→ NIM A394 (1997) 27

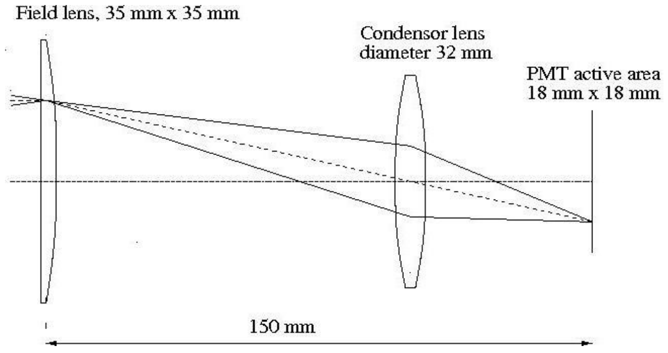


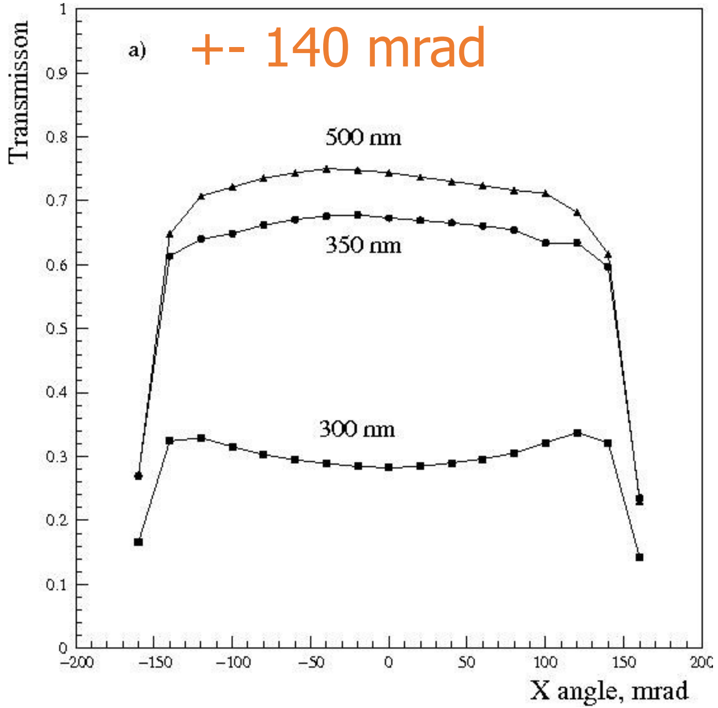
HERA-B RICH photon detector

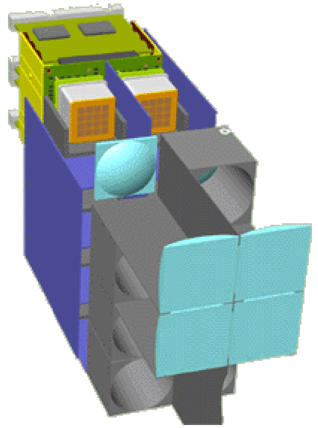
Light collection system (imaging!) to:

- Eliminate dead areas

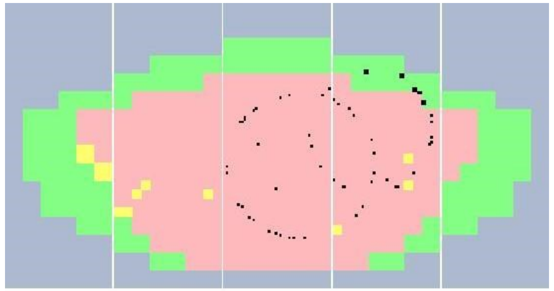
- Adapt the pad size



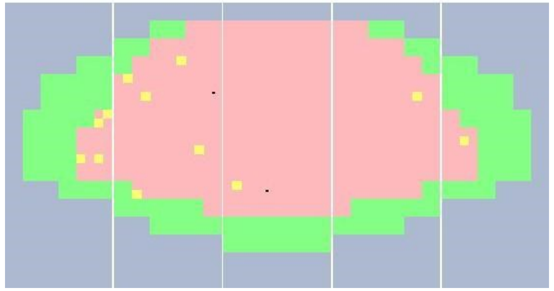




HERA-B RICH

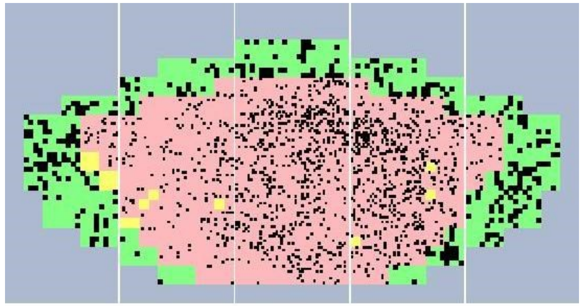


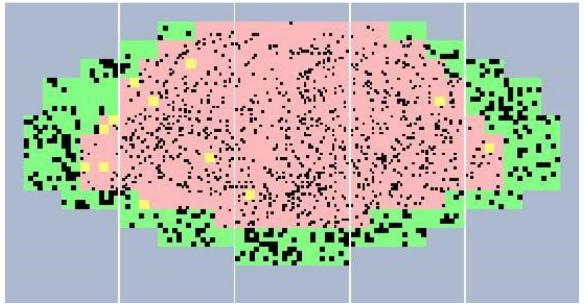
← Little noise, ~30 photons per ring

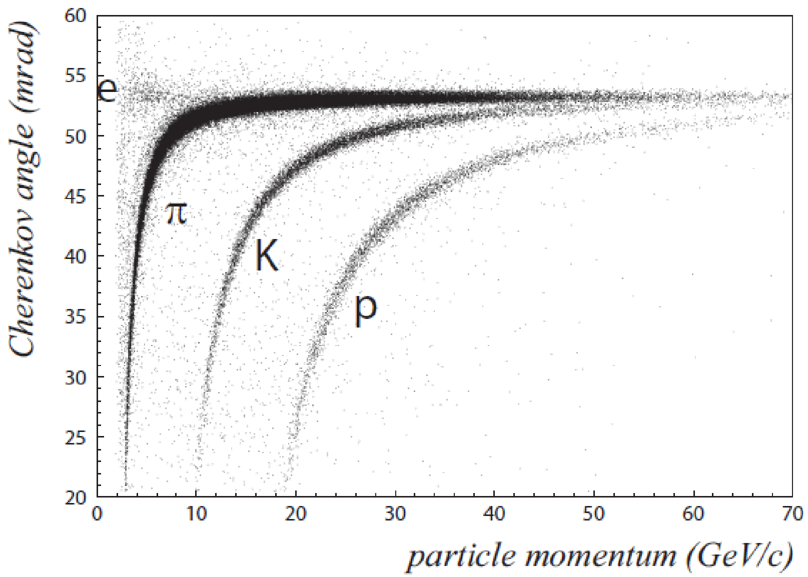


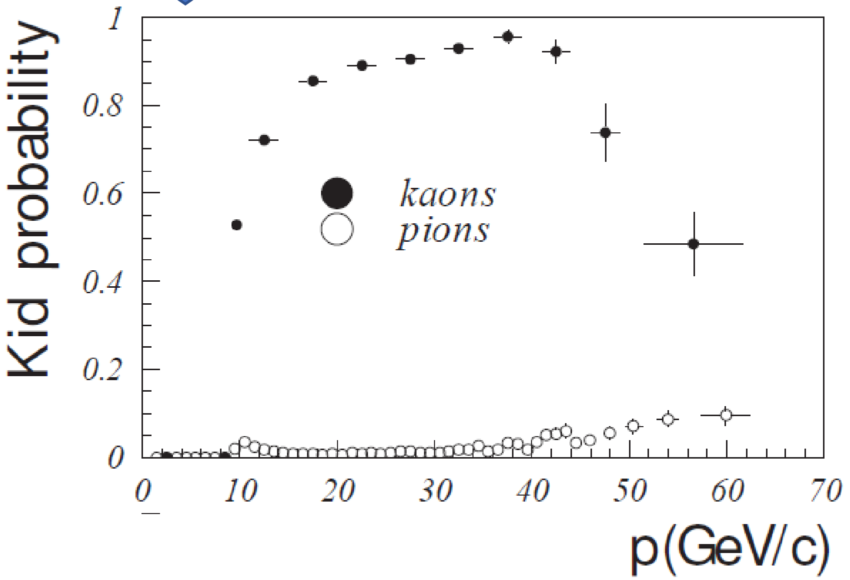
Worked very well!

Typical event →









Kaon efficiency and pion fake probability

Limits of the RICH technique

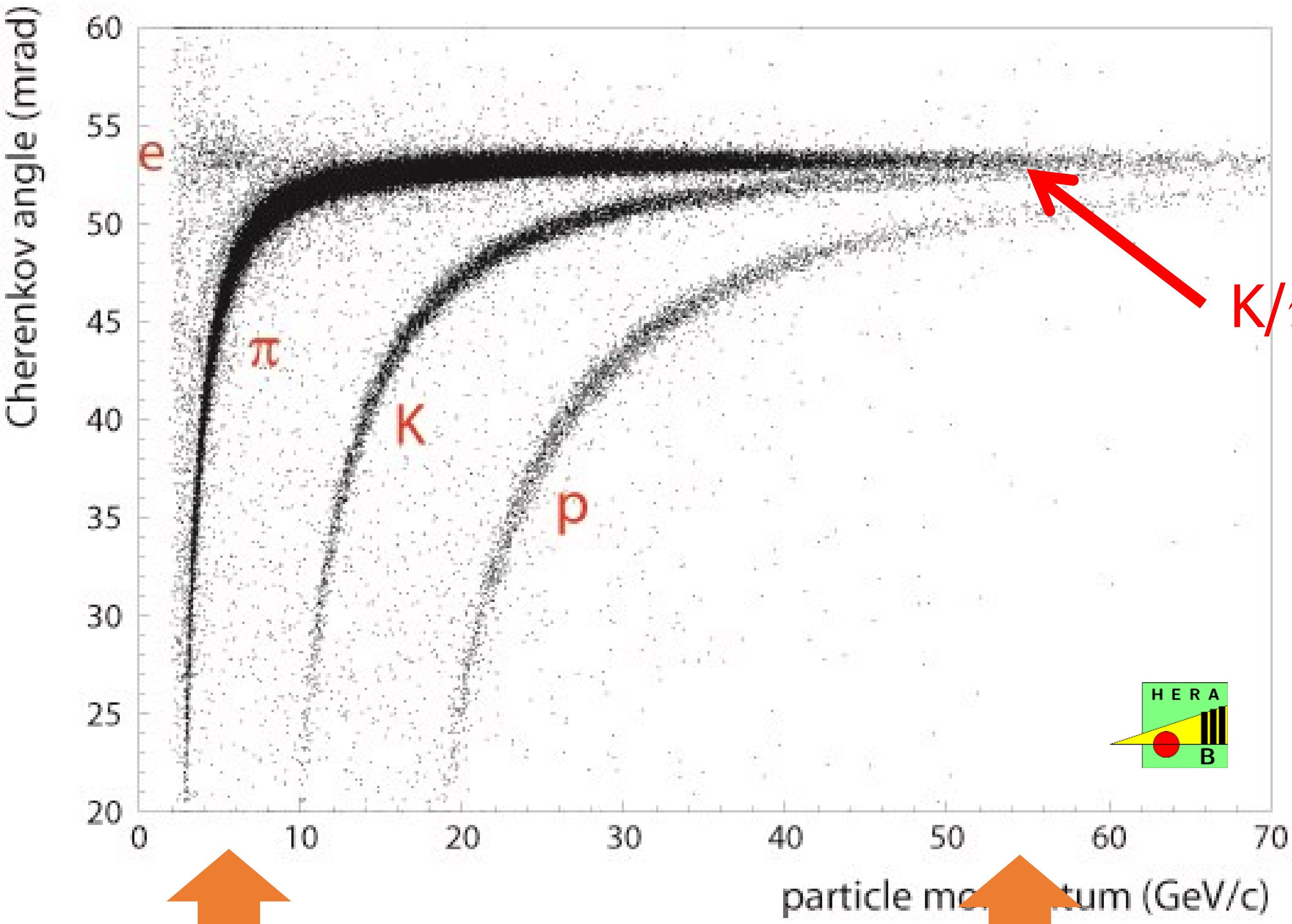
The choice of RICH radiator medium in case of a specific experiment depends on the particles we would like to identify, and their kinematics:

- the threshold momentum for the lighter of the two particles we want to separate: $\mathbf{p_t = \beta_t \gamma_t m c, \beta_t = 1/n}$ should coincide with the lower limit of momentum spectrum p_{min}. Typically

  $$\mathbf{p_{min} = sqrt\ 2\ p_t}$$

- the resolution in Čerenkov angle should allow for a separation up to the upper limits of kinematically allowed momenta $\mathbf{p_{max}}$

Limits of a RICH detector



Radiator: C_4F_{10} gas

K/π overlap

$\mathbf{P_{min}}$ for K/π separation

$\mathbf{P_{max}}$ for K/π separation

π/K separation example:

Limiting performance at the high momentum side: irreducible contribution to the resolution - dispersion.

radiator	LiF solid	C_6F_{14} liquid	C_5F_{12} gas	N_2 gas	He gas
σ_θ (mrad)	7.0	3.9	0.45	0.40	0.13
σ_N (mrad)	2.2	1.2	0.14	0.13	0.04
p_{max} (GeV/c) for 3σ π/K	3.5	6.9	50	100	330
p_{min} (GeV/c)	0.6	0.9	11	28	83

photon detector: TMAE, 10 det. photons assumed

Summary:

$$\mathbf{p_{max} / p_{min} \sim 4\text{-}7}$$

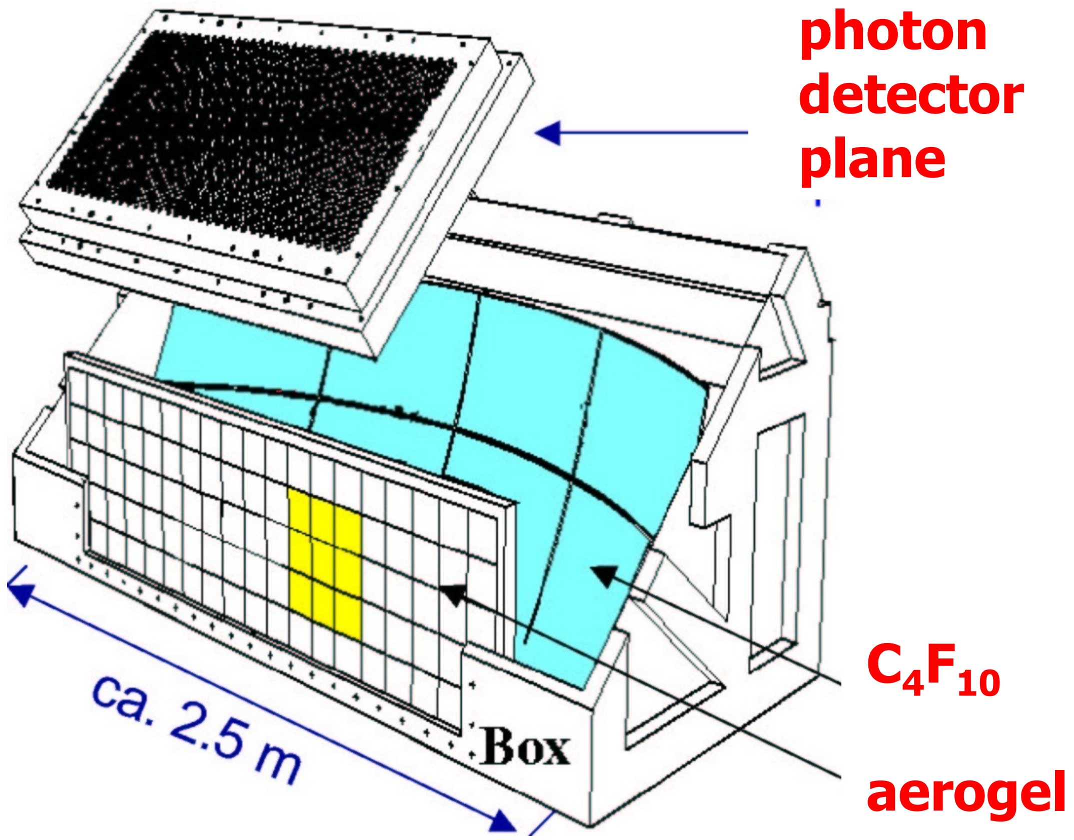
for a 3σ separation between the two particles

For a larger kinematic region **2 radiators are needed!**

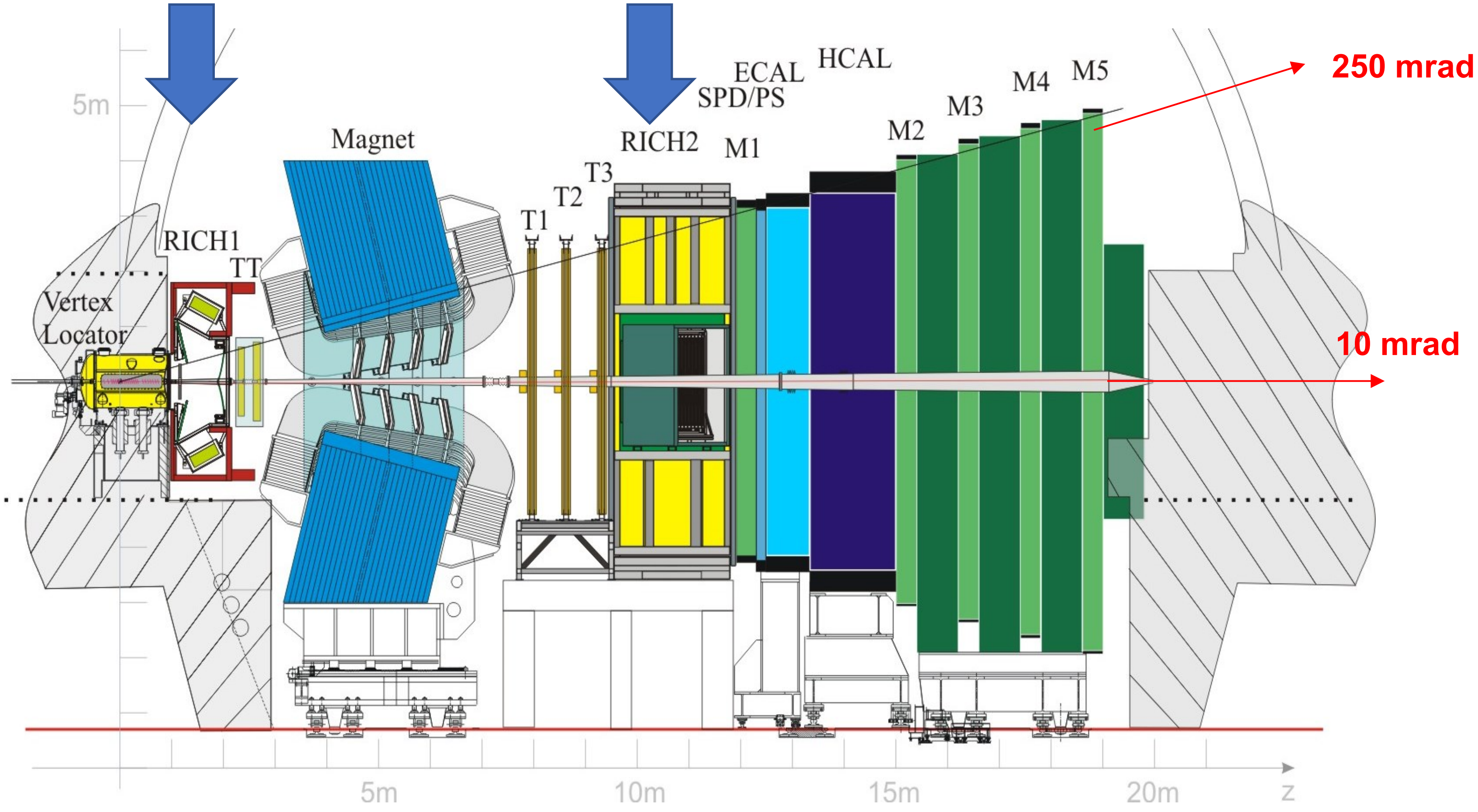
RICHes with several radiators

Extending the kinematic range → need more than one radiator

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



The LHCb RICH counters



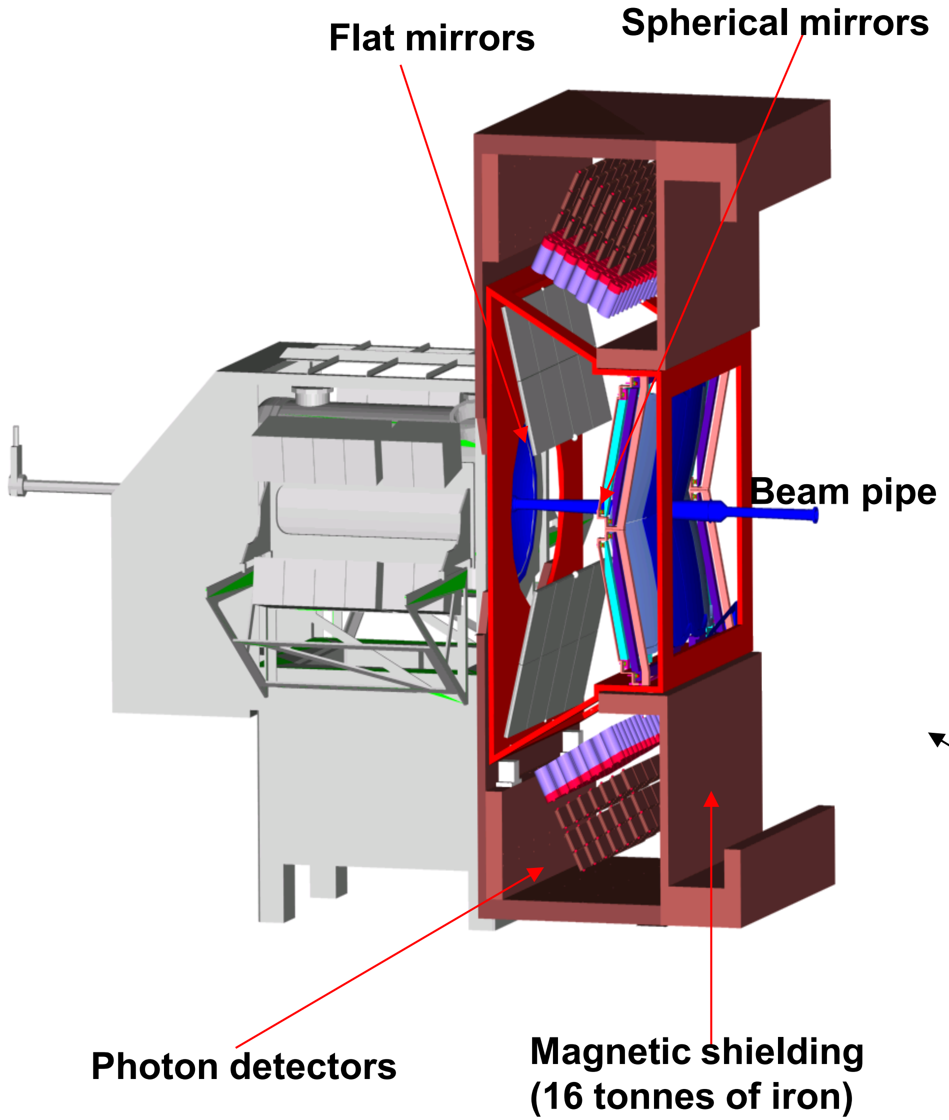
Vertex reconstruction:
VELO

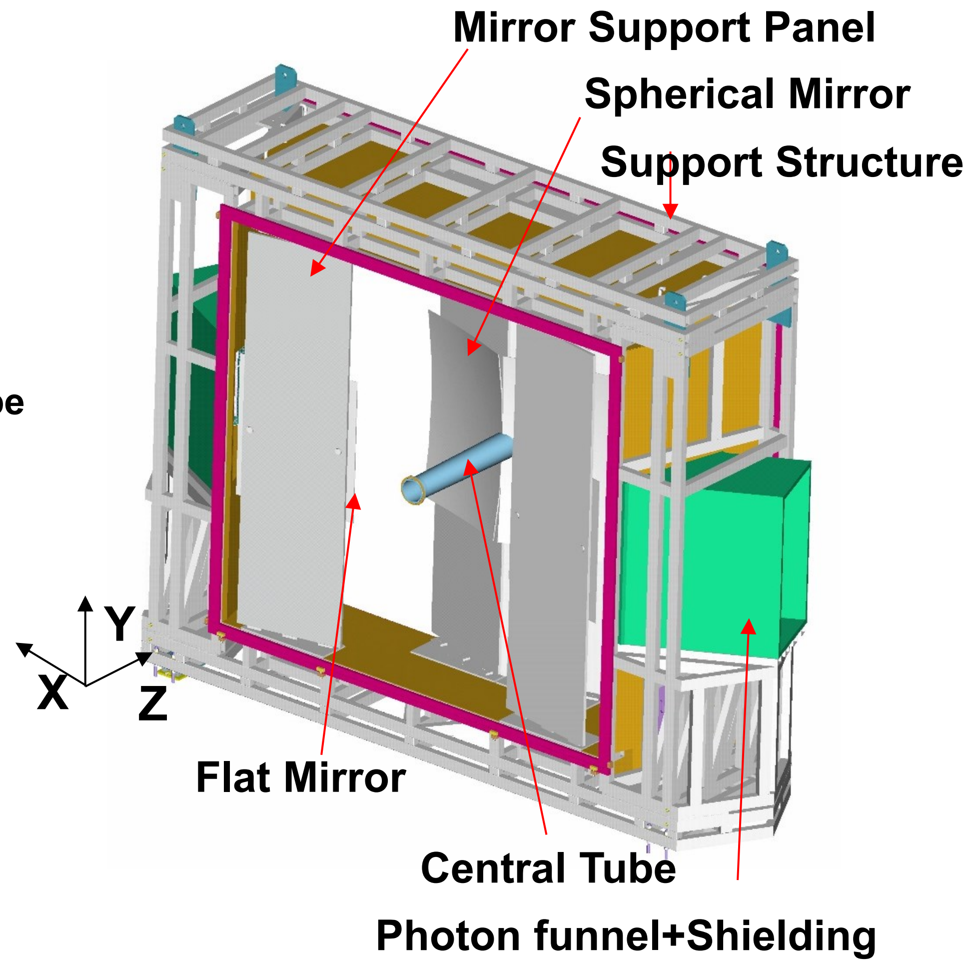
Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

LHCb RICHes


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

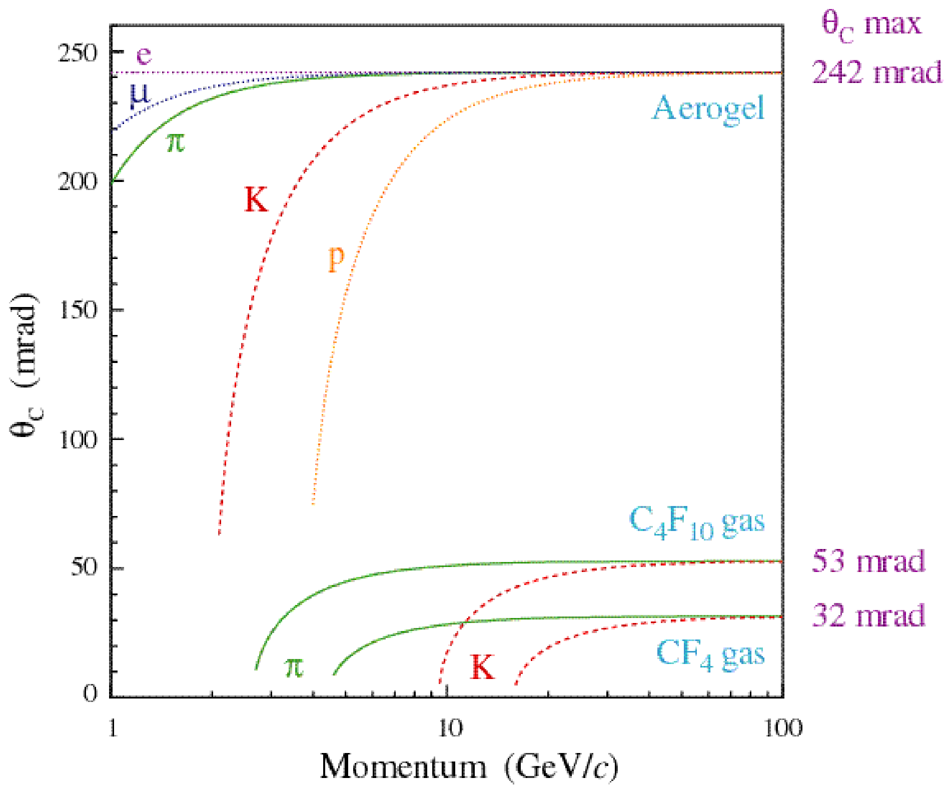
LHCb RICHes

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

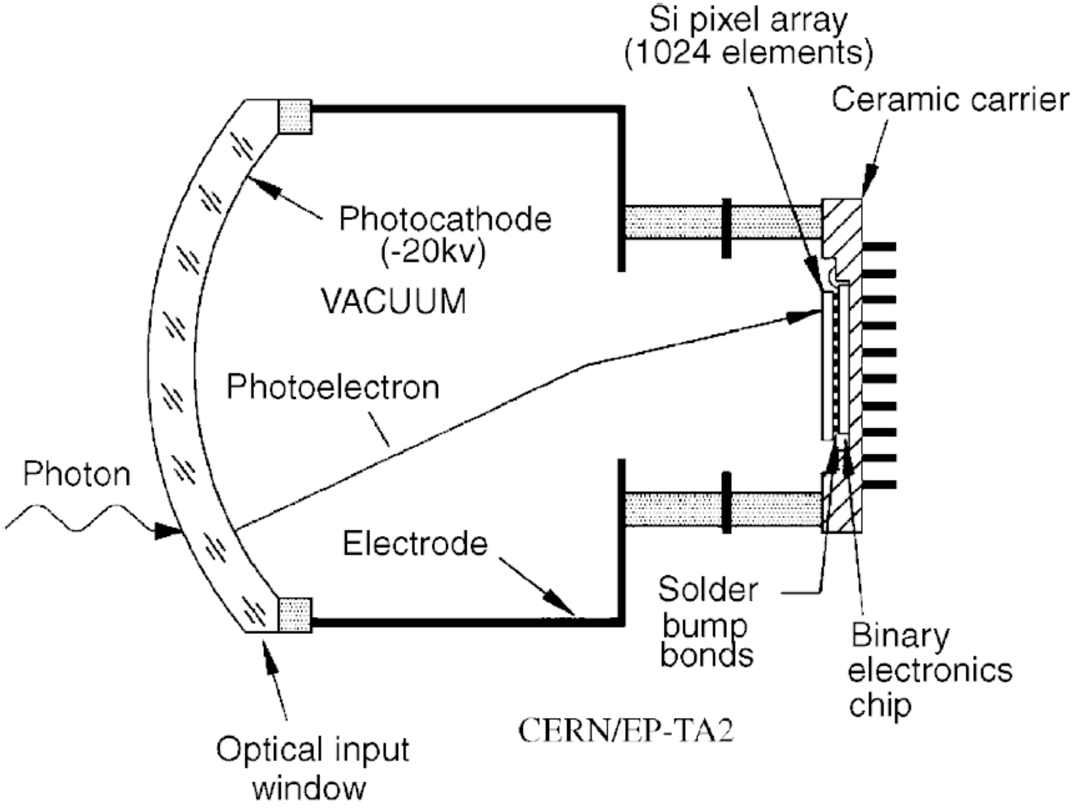
- Aerogel
- C_4F_{10}
- CF_4



LHCb RICHes

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

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



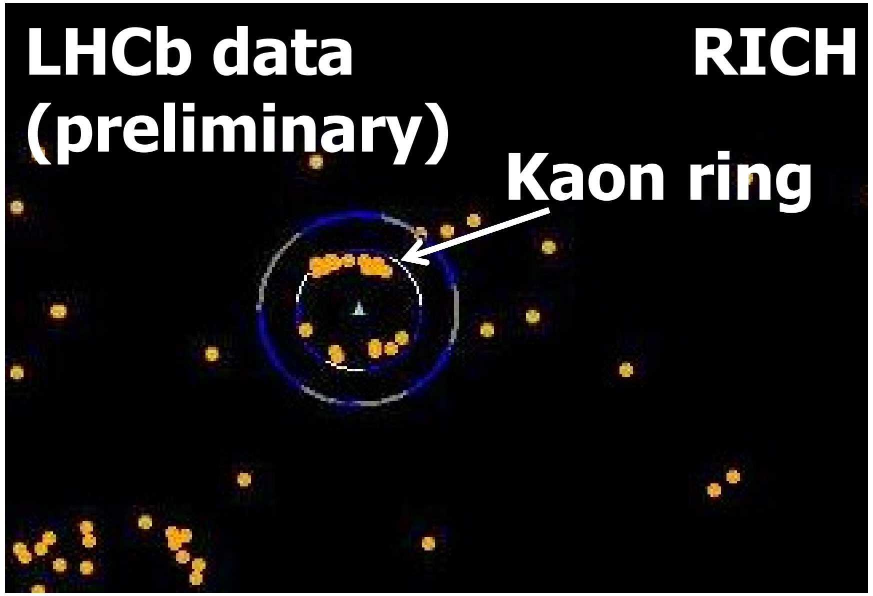
NIM A553 (2005) 333

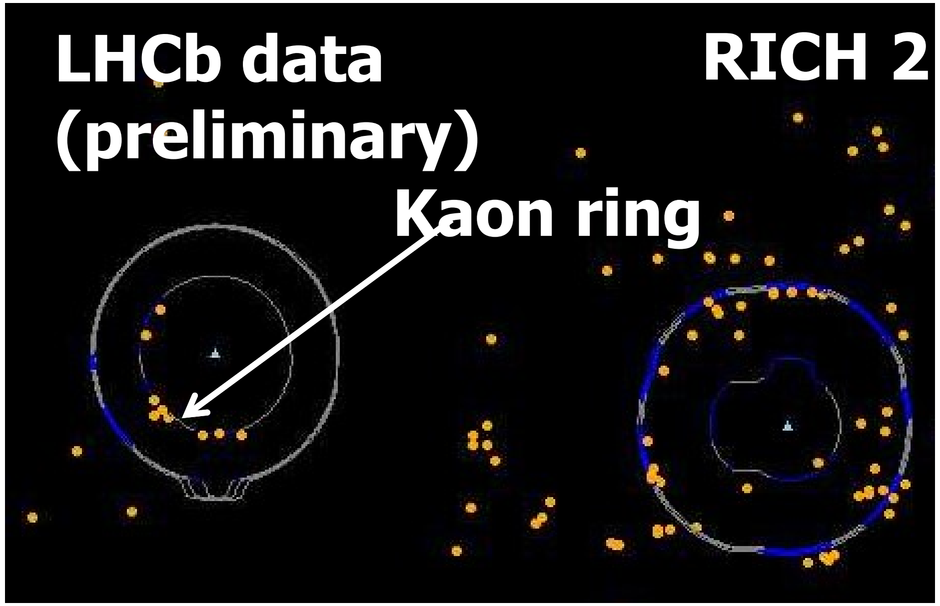
LHCb Event Display

RICH1

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

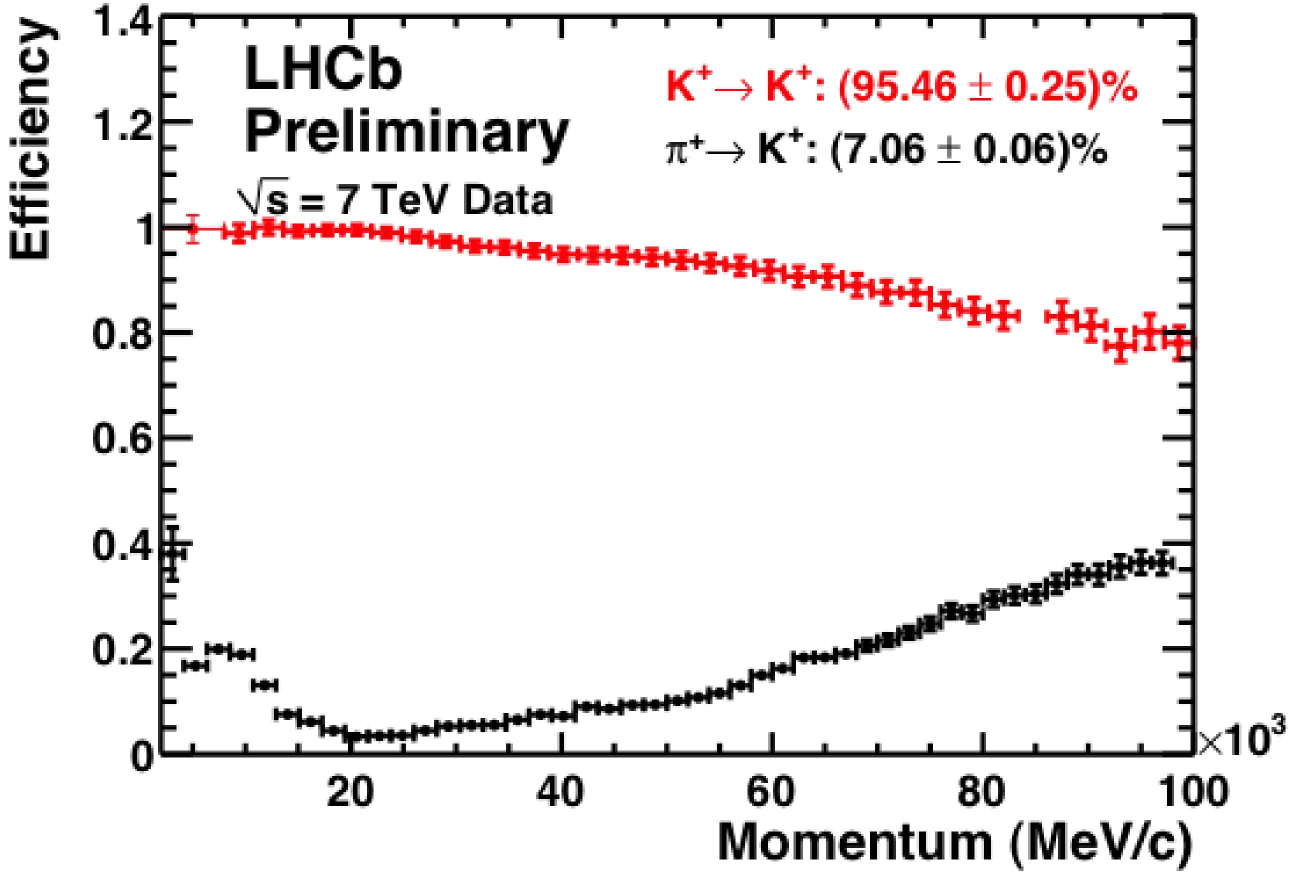
RICH2

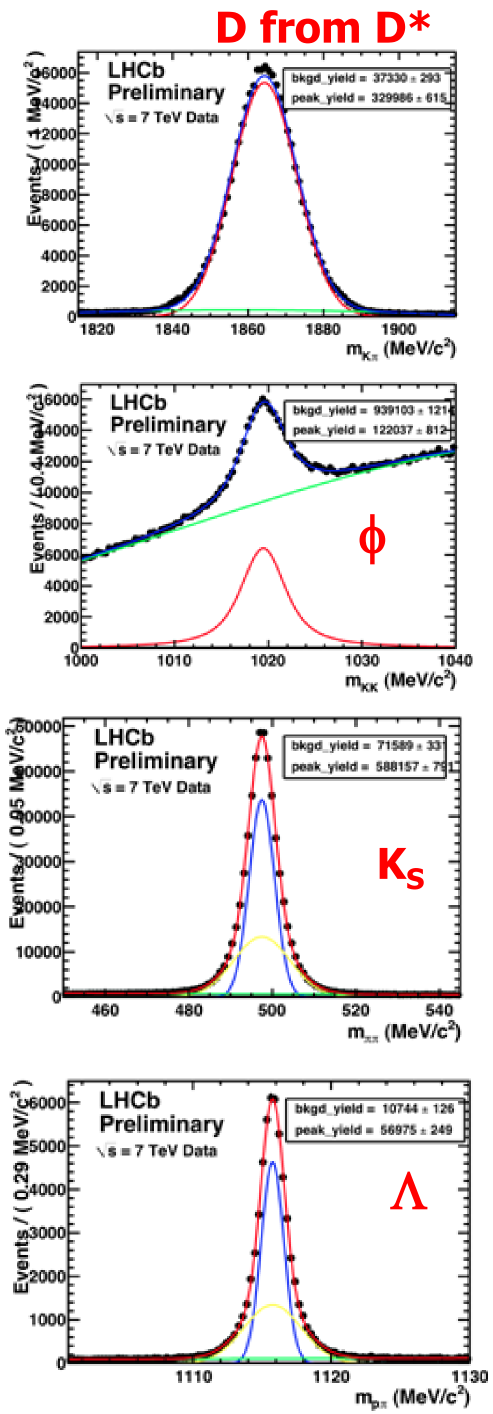




- ➢ Orange points → photon hits
- ➢ Continuous lines → expected distribution for each particle hypothesis

LHCb RICHes: performance

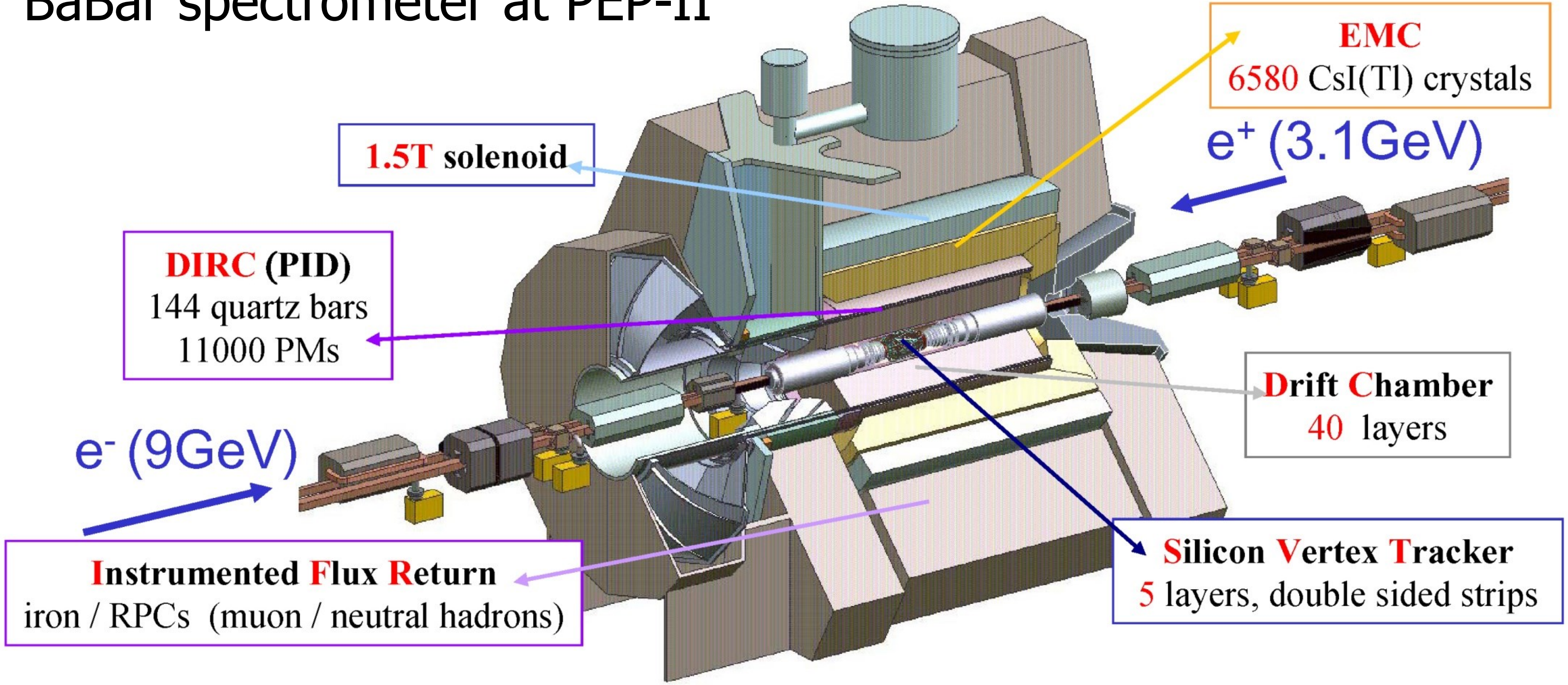




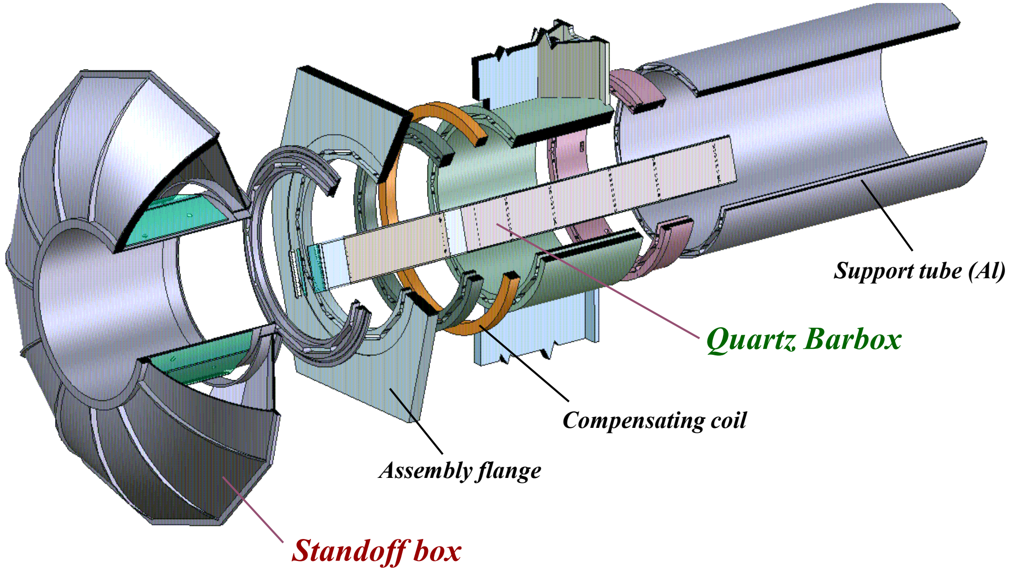
DIRC

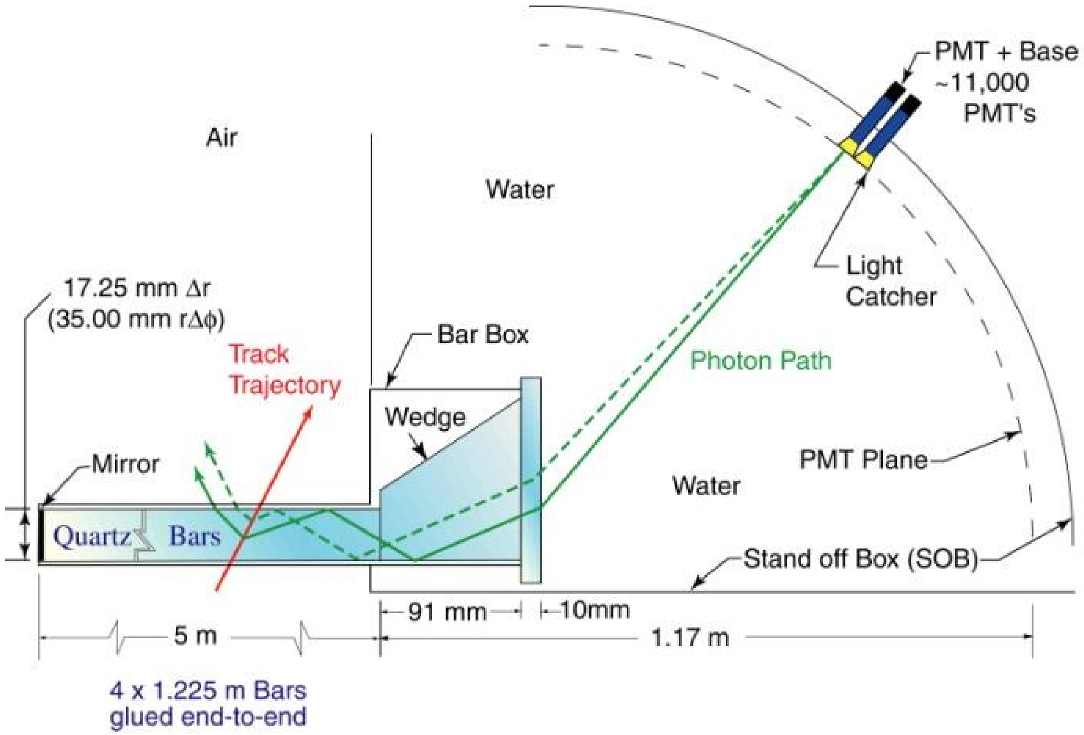
- detector of internally reflected Cherenkov light

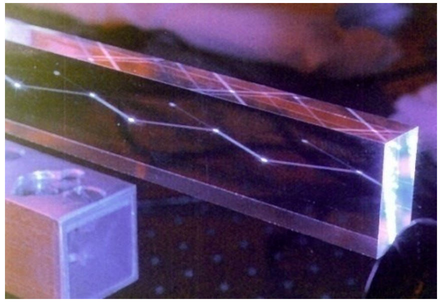
BaBar spectrometer at PEP-II



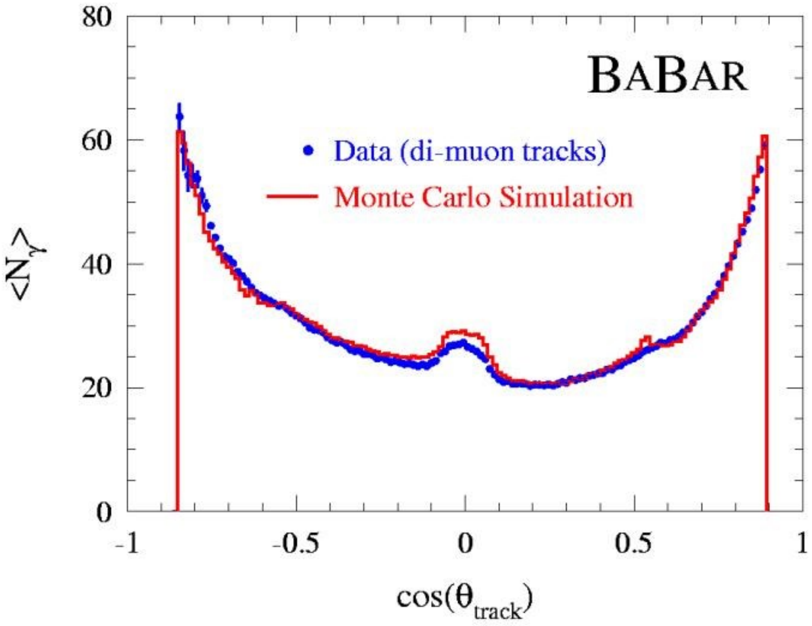
DIRC (@BaBar) - detector of internally reflected Cherenkov light





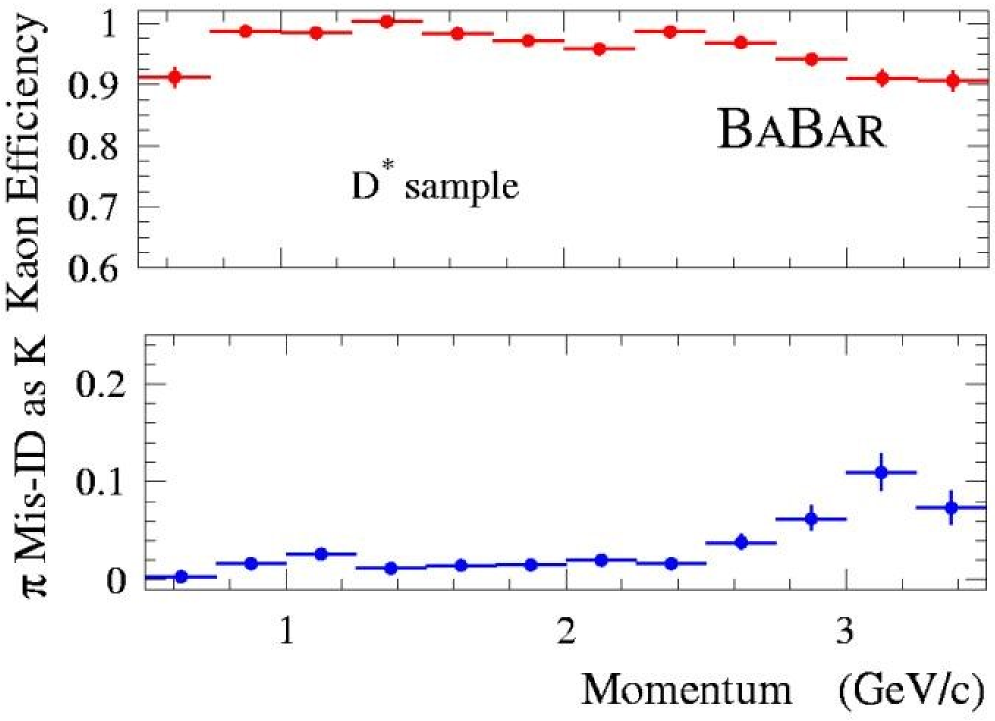


DIRC performance

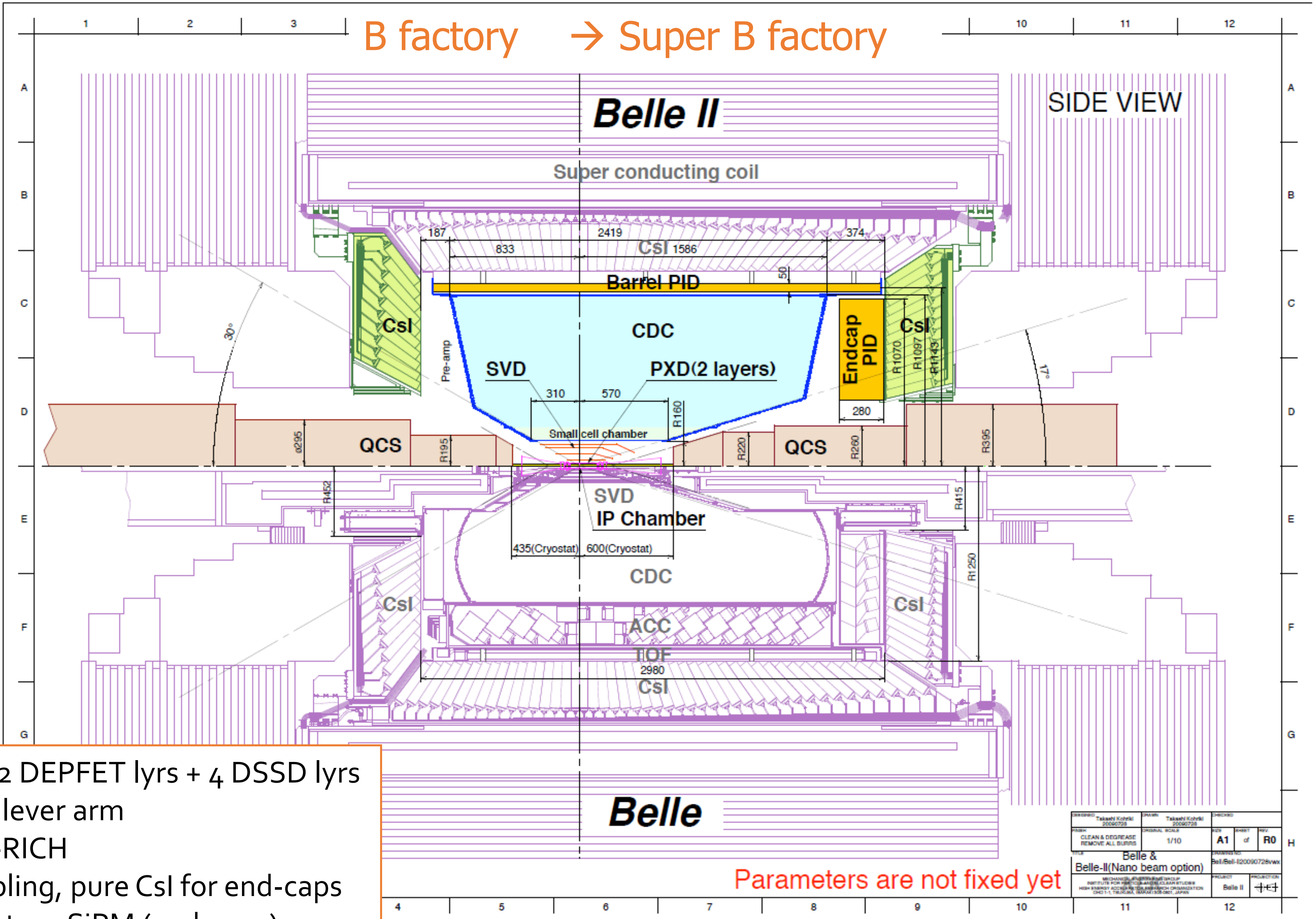


←Lots of photons!

Excellent π/K separation

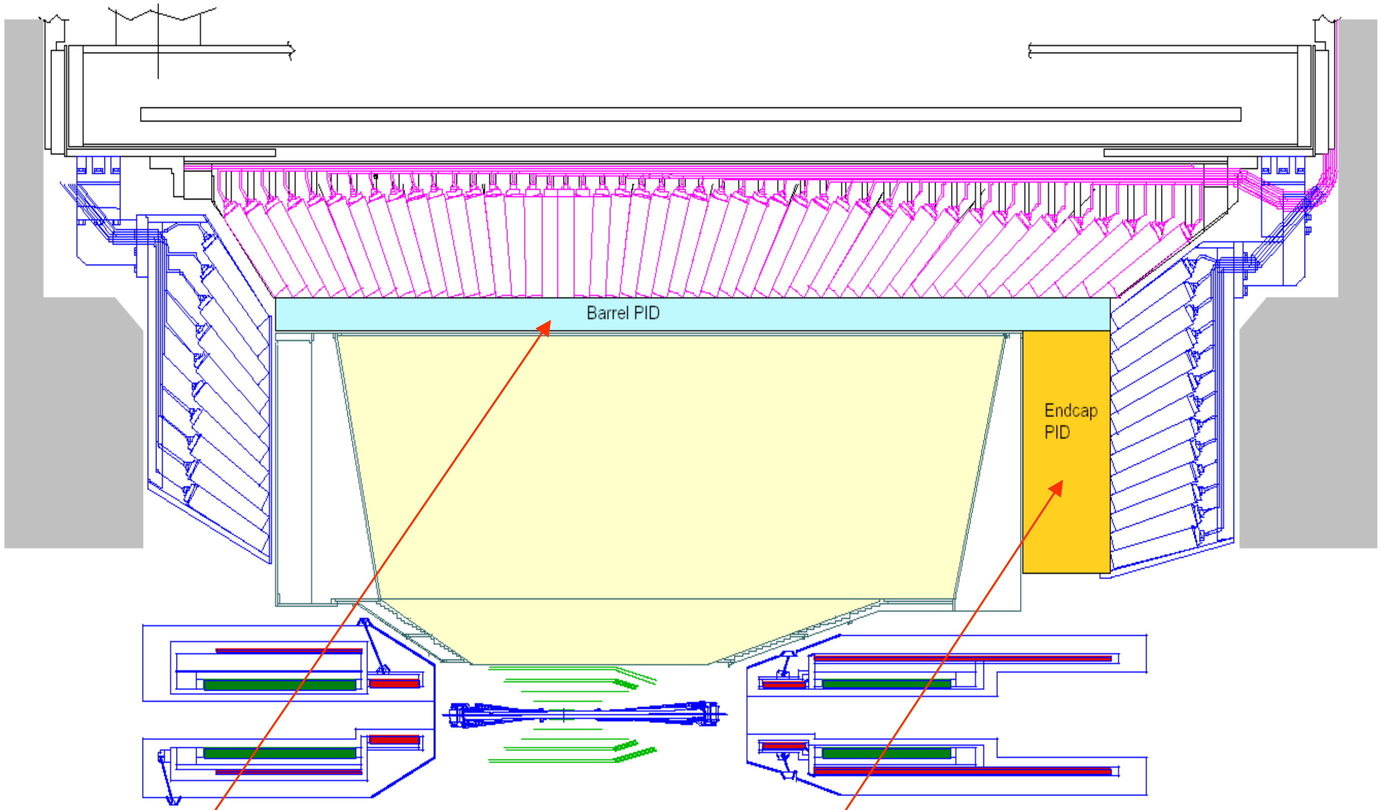


Belle → Belle II



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)

Belle II PID systems – side view

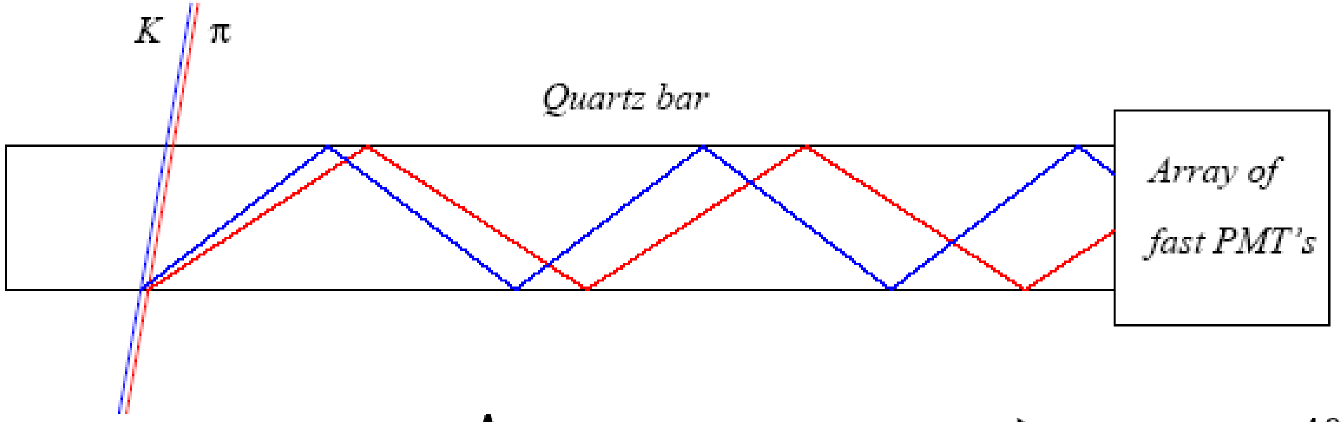


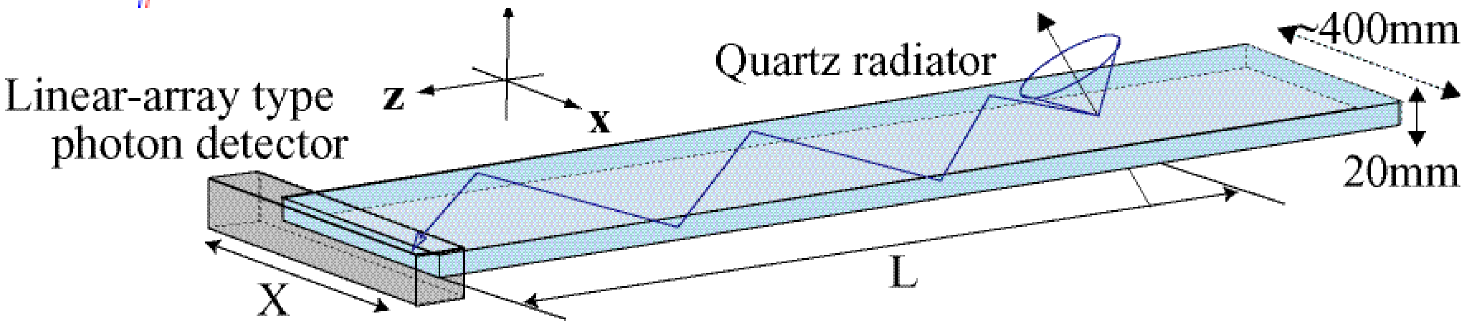
Two new particle ID devices, both RICHes:

Barrel: time-of-propagation (TOP) counter

Endcap: proximity focusing RICH

Time-Of-Propagation (TOP) counter

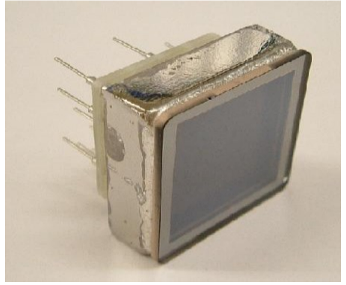




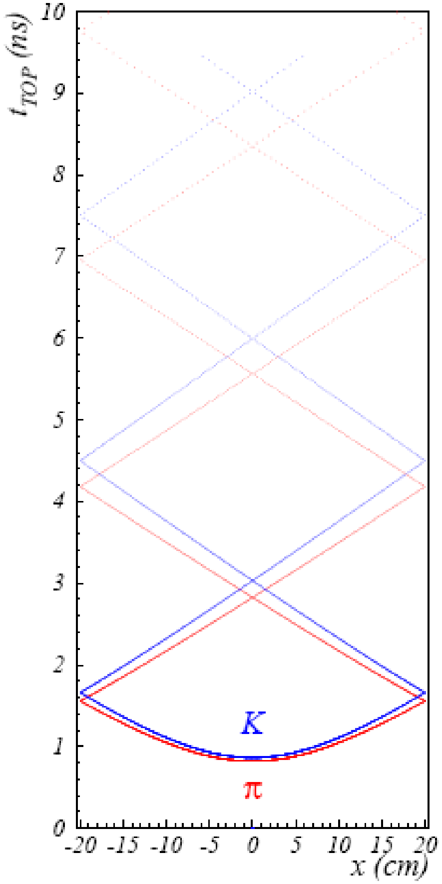
Similar to DIRC, but instead of two coordinates measure:

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

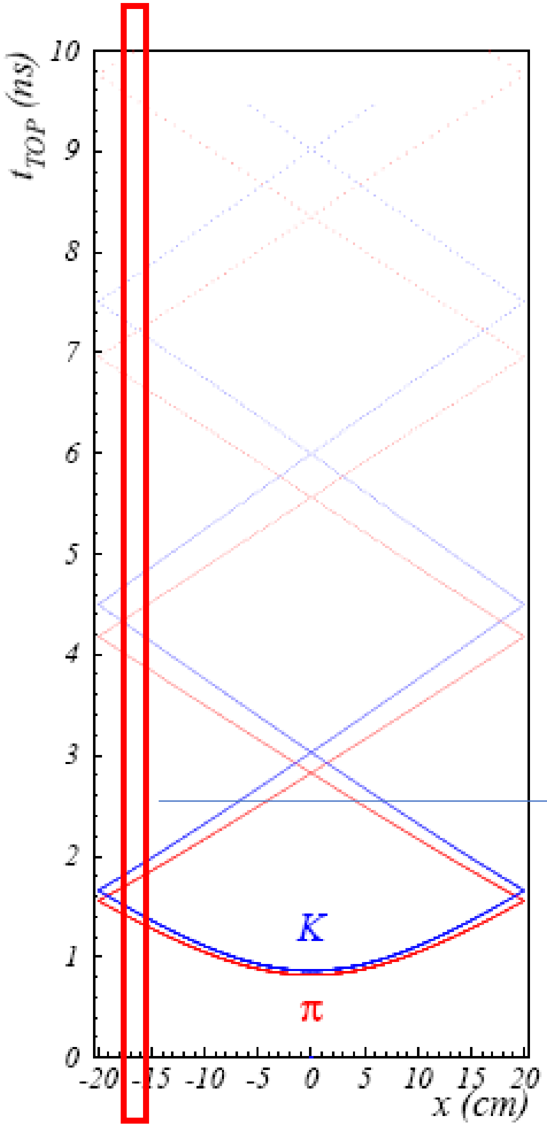
→ Excellent time resolution < ~40ps required for single photons in 1.5T B field



Hamamatsu
SL10 MCP-PMT

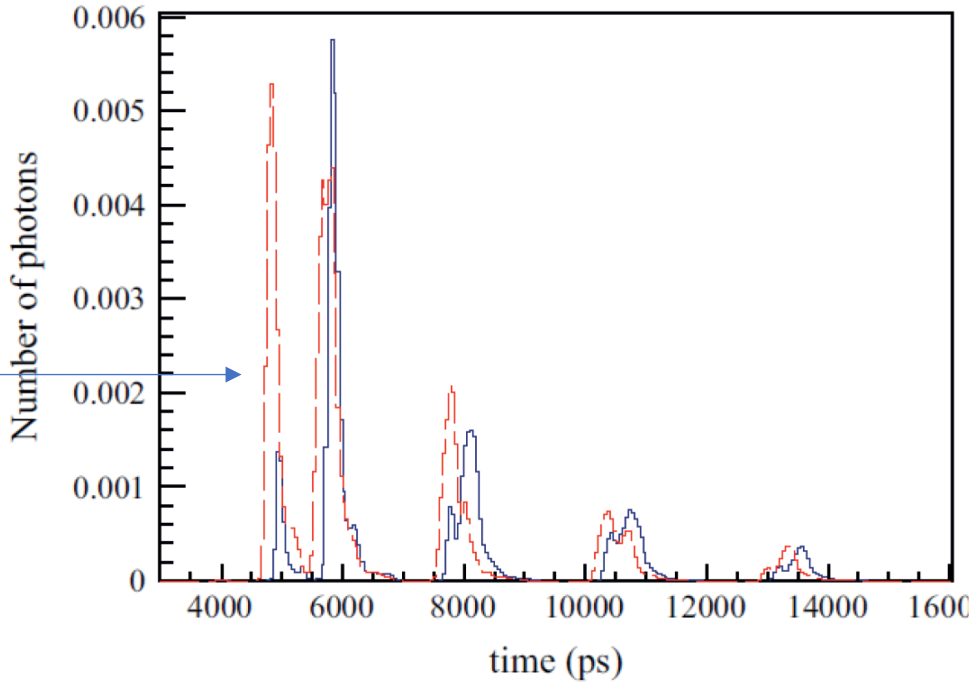


TOP image

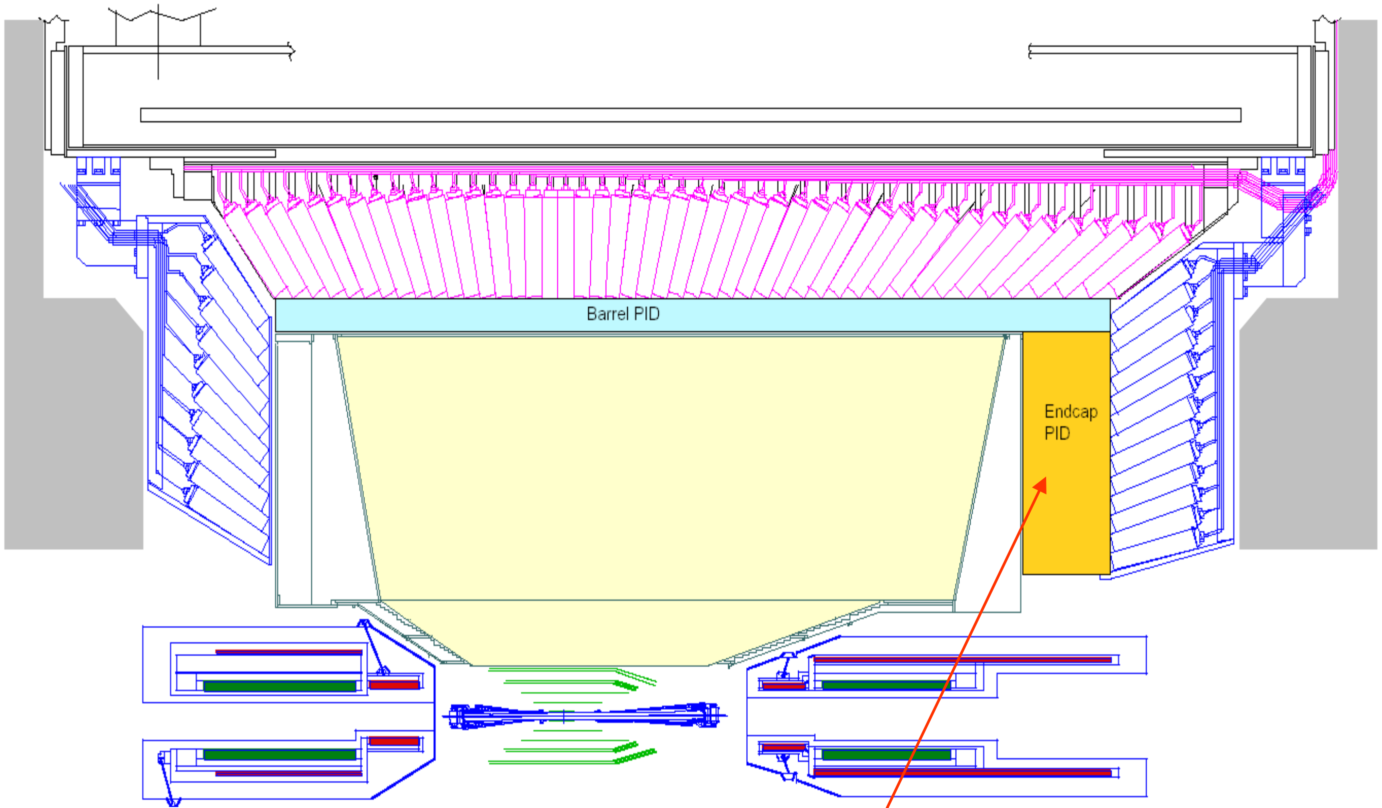


Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

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



Belle II PID system – side view

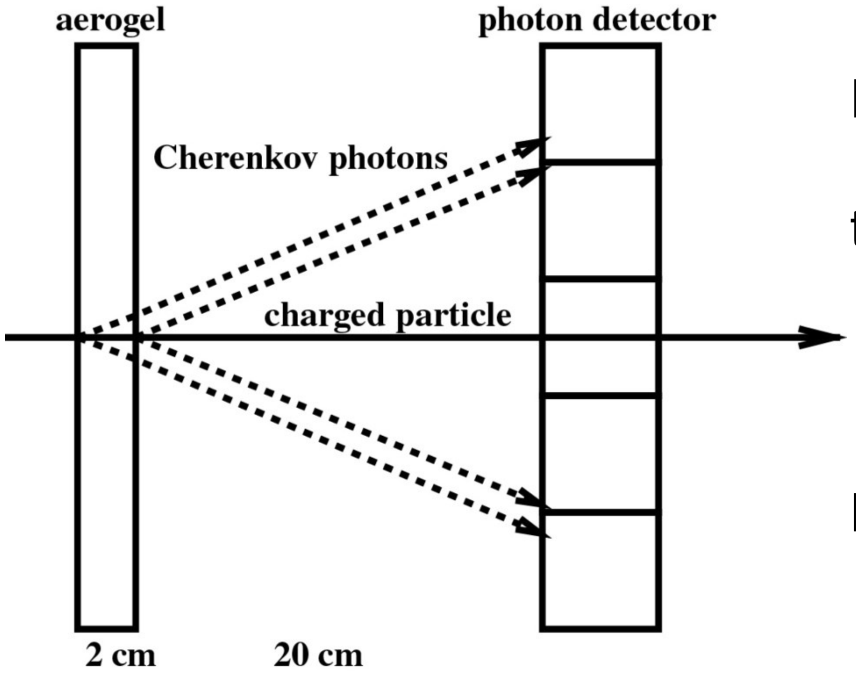


Two new particle ID devices, both RICHes:

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: $\delta\theta_c(\text{meas.}) = \sigma_0$ ~ 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: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

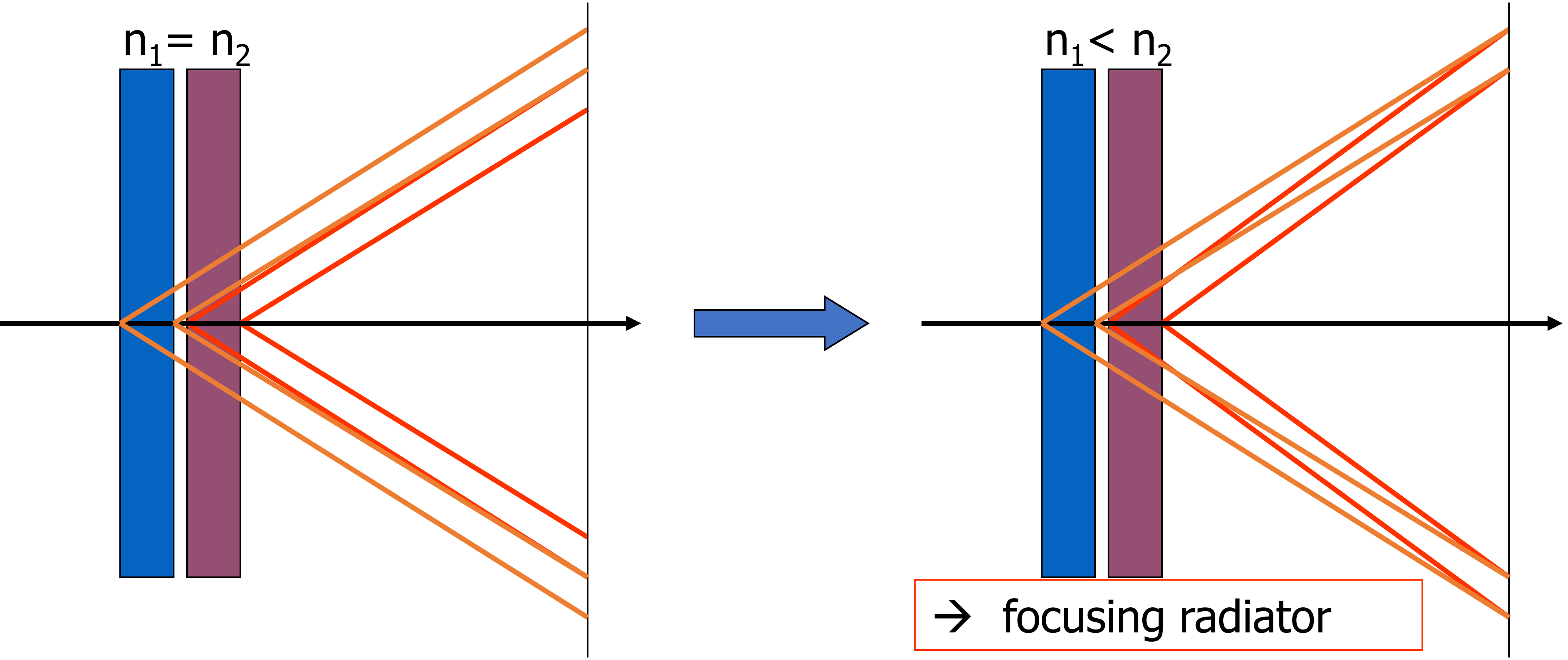
→ 5σ separation with N_{pe}~10

Radiator with multiple refractive indices

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

normal

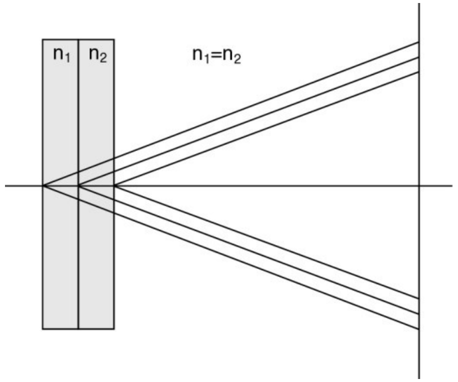
→ stack two tiles with different refractive indices: "focusing" configuration

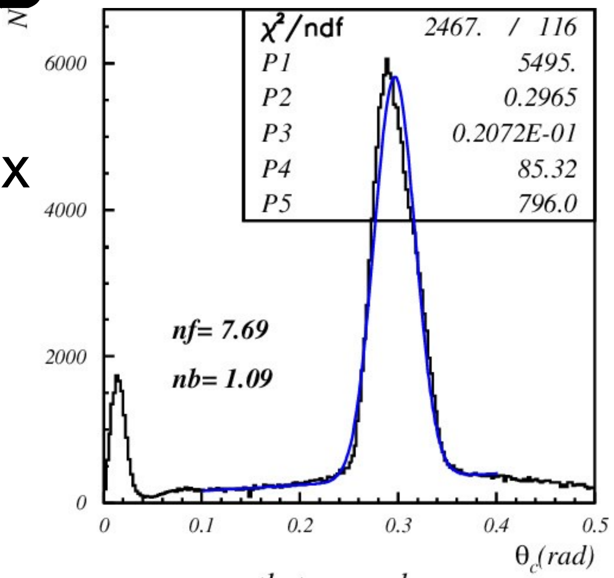


Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

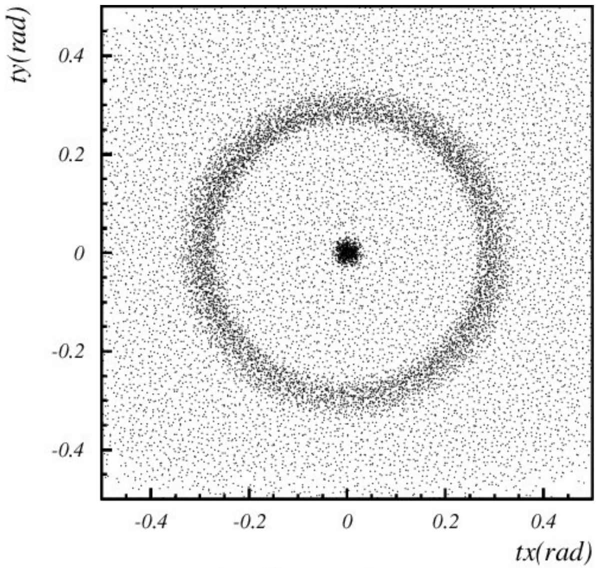
Focusing configuration – data

4cm aerogel single index



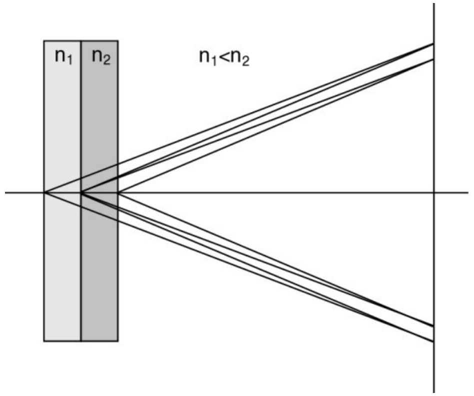


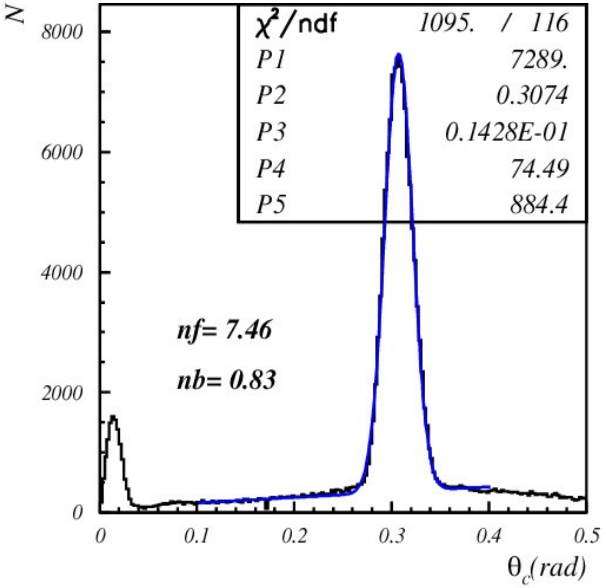
theta cerenkov

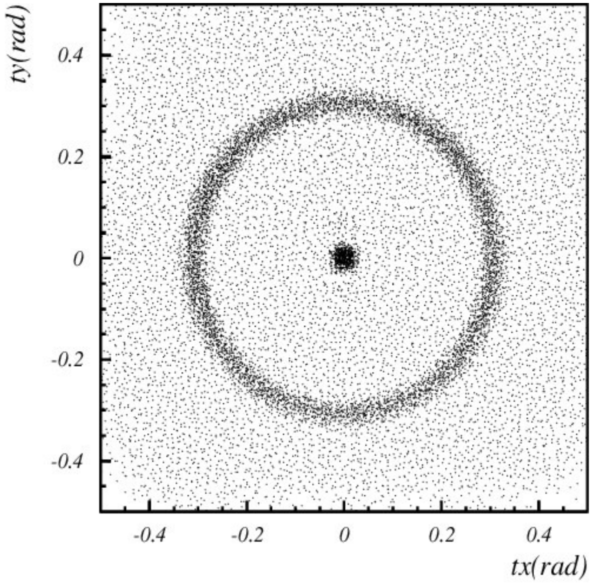


ring in cerenkov space

2+2cm aerogel







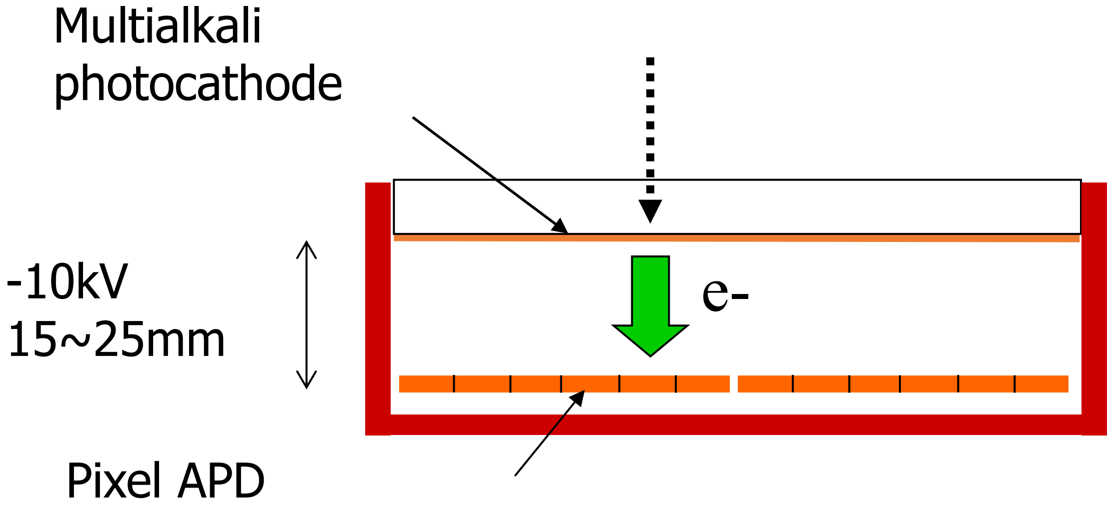
→NIM A548 (2005) 383, NIMA 565 (2006) 457

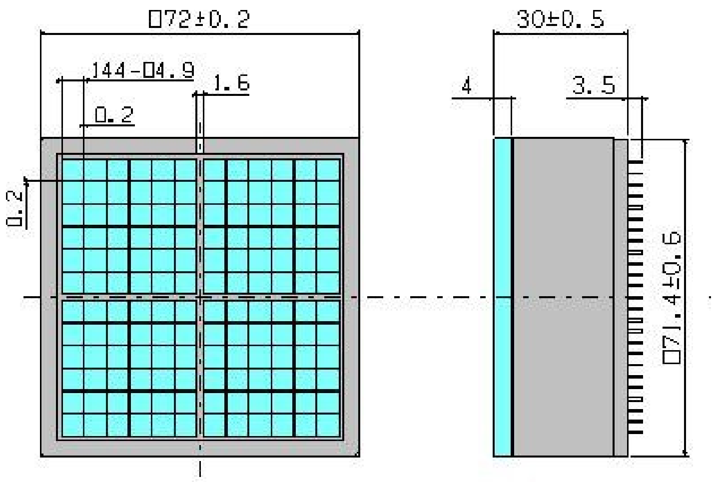
Aerogel RICH requirements and candidates

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)

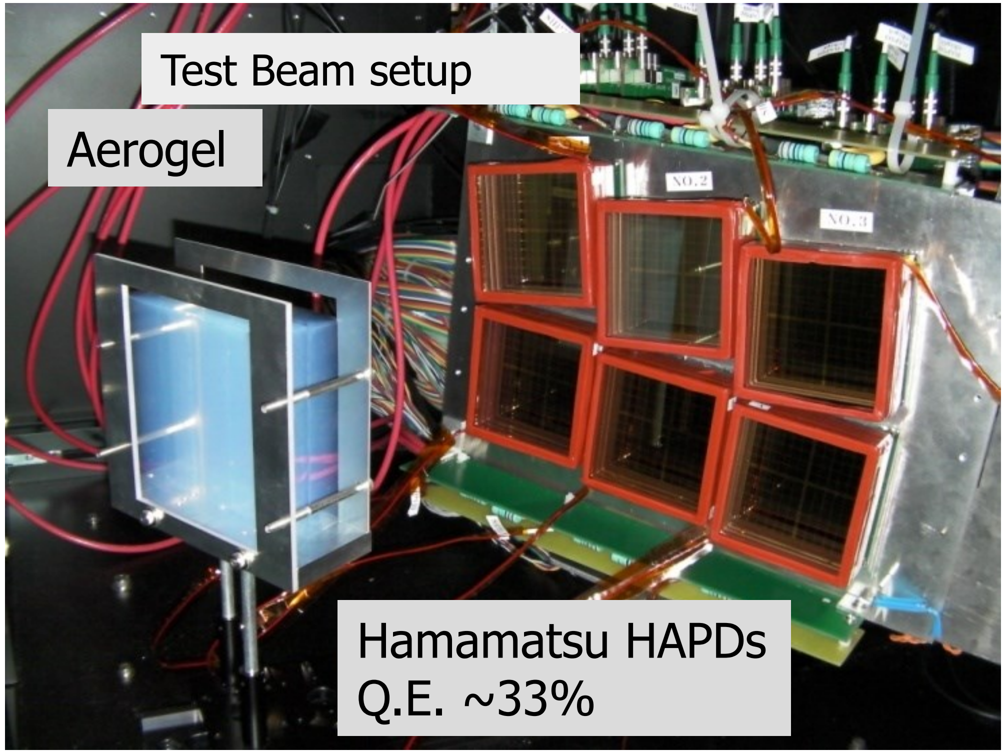




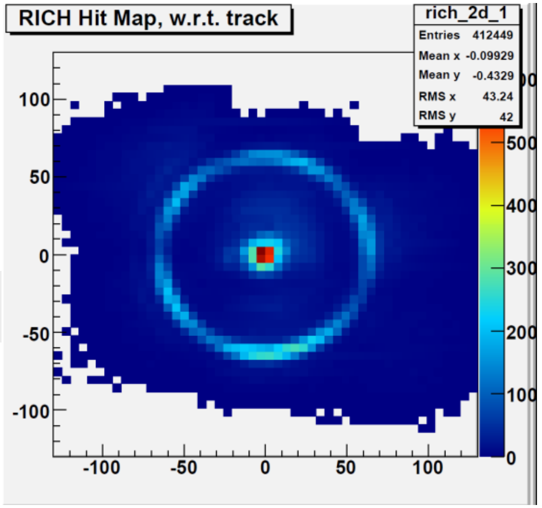
Aerogel RICH photon detectors

Need:
Operation in 1.5 T magnetic field
Pad size ~5-6mm

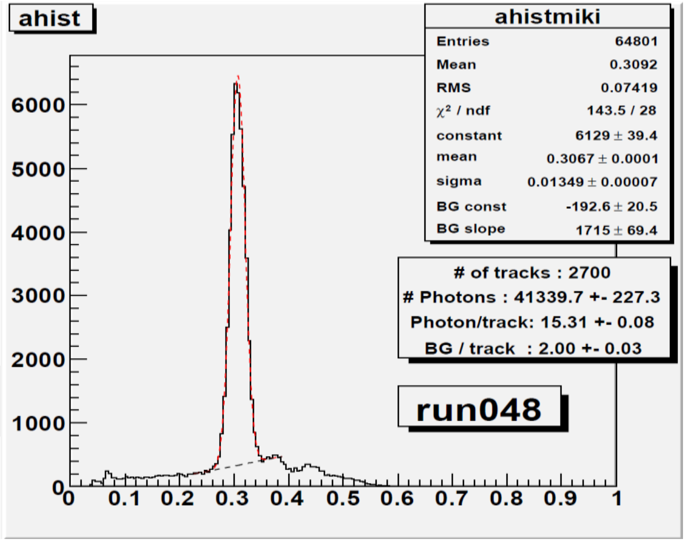
Baseline option: large active area HAPD of the proximity focusing type



Clear Cherenkov image observed

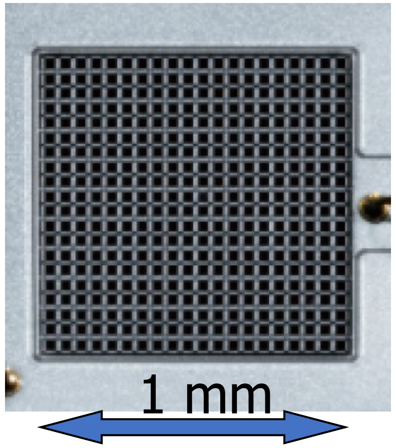


Cherenkov angle distribution



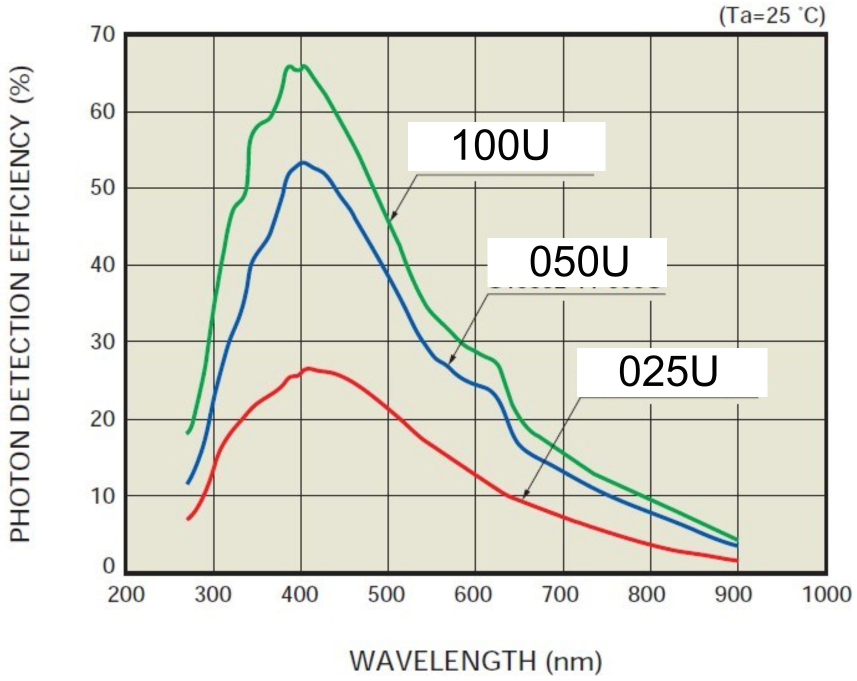
6.6 σ p/K at 4GeV/c !

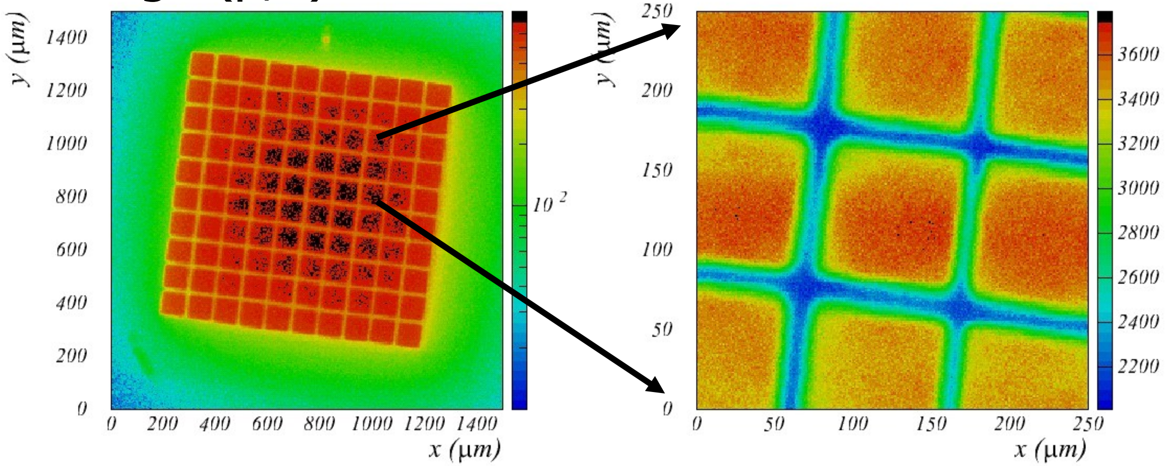
SiPMs as photon detectors?



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

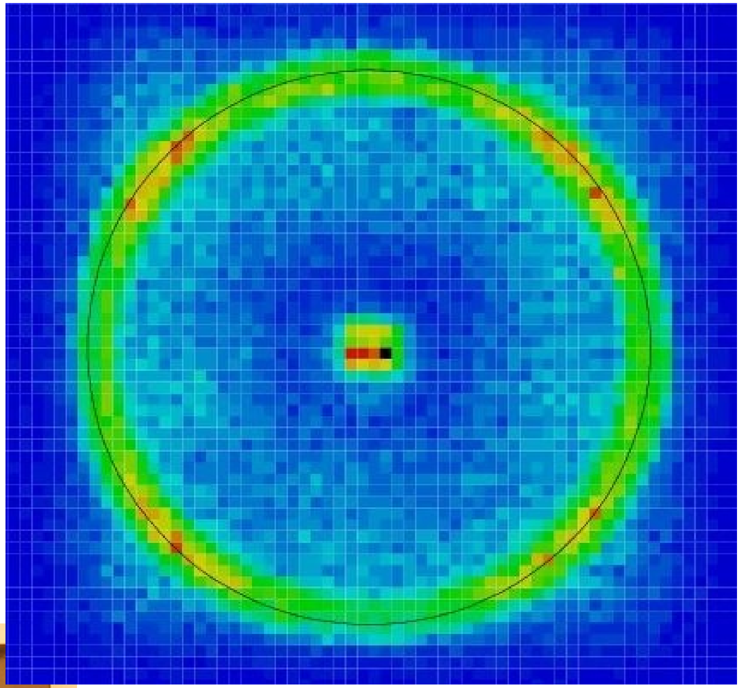
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)





Never before tested in a RICH where we have to detect single photons. ← Dark counts have single photon pulse heights (rate 0.1-1 MHz)

Can such a detector work?

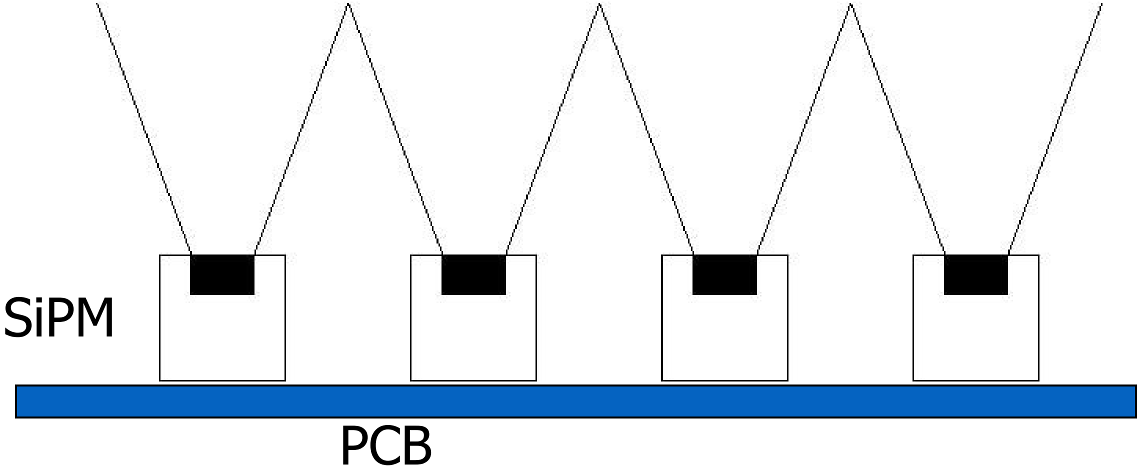


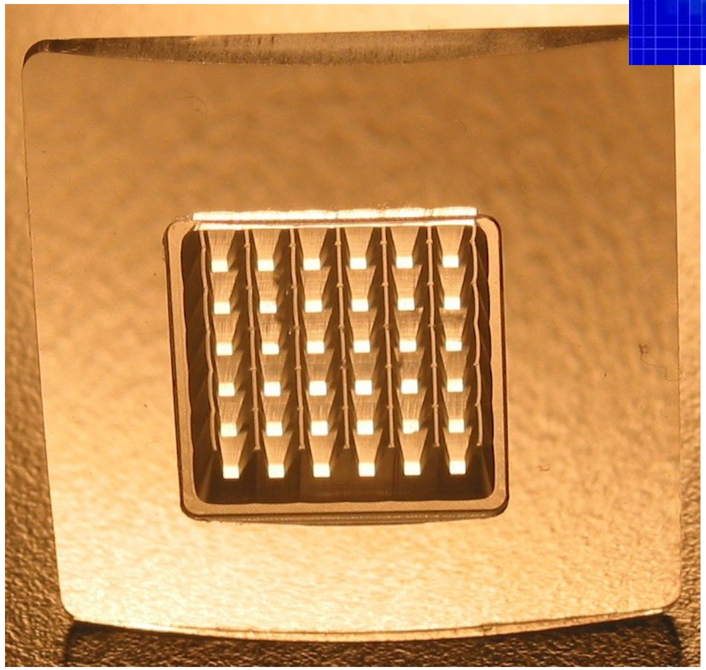
Improve the signal to noise ratio:

•Reduce the noise by a narrow (<10ns) time window

•Increase the number of signal hits per single sensor by using light collectors and by adjusting the pad size to the ring thickness

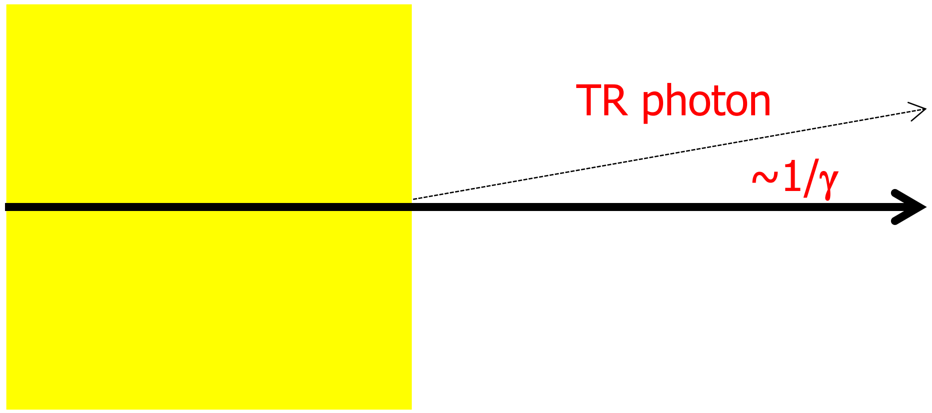
E.g. light collector with reflective walls or plastic light guide

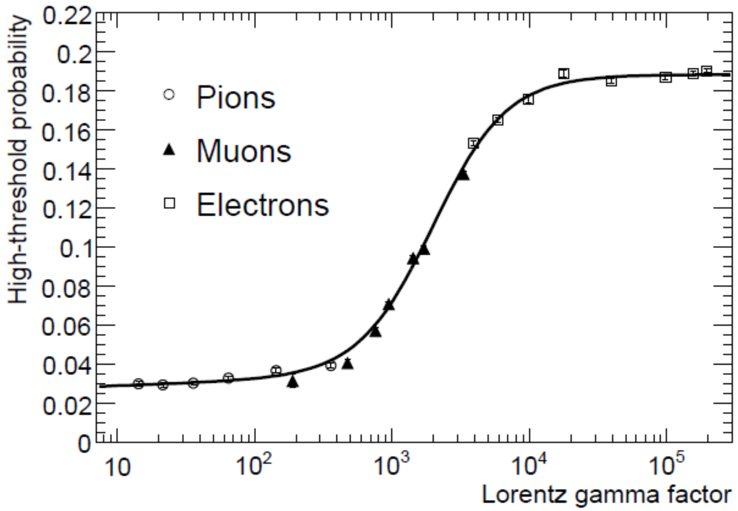




Transition radiation

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 $\gamma\sim1000$

- 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

Transition radiation - detection

Emission probability per boundary ~α = 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 ~$1/\gamma$

→Hits from TR photons along the charged particle direction

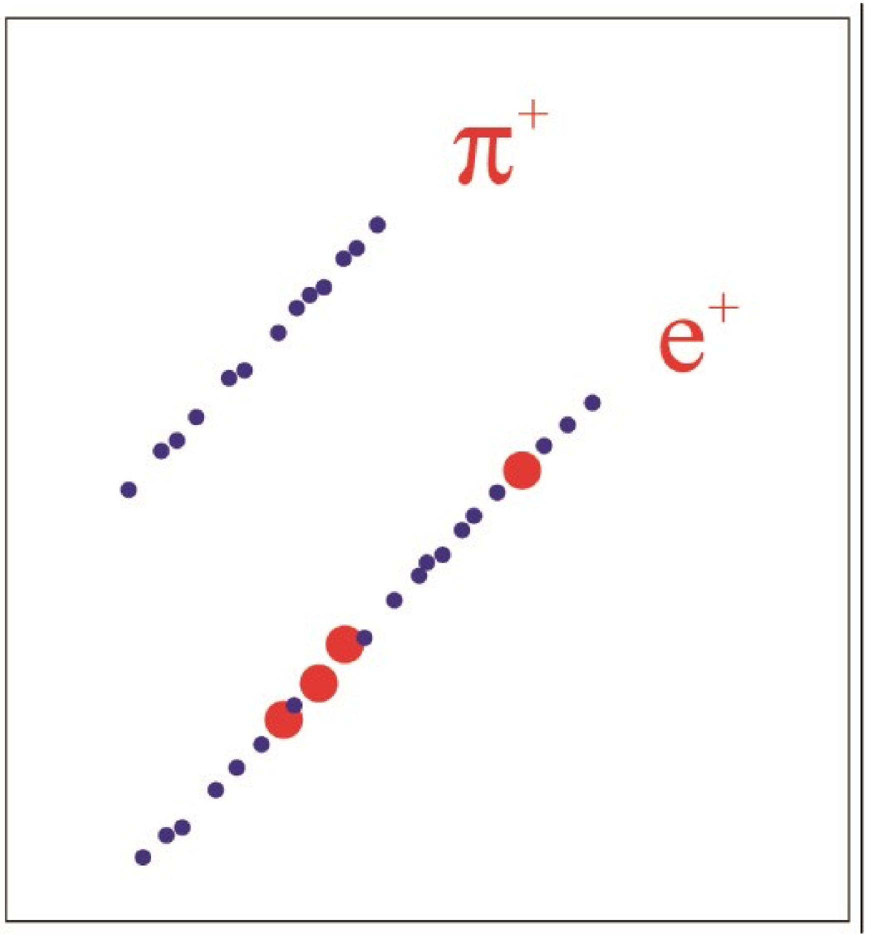
- Separation of X ray hits (high energy deposit on one place) against ionisation losses (spread out along the track)
- Two thresholds: lower for ionisation losses, higher for X ray detection

Transition radiation - detection

→Hits from TR photons along the charged particle direction

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

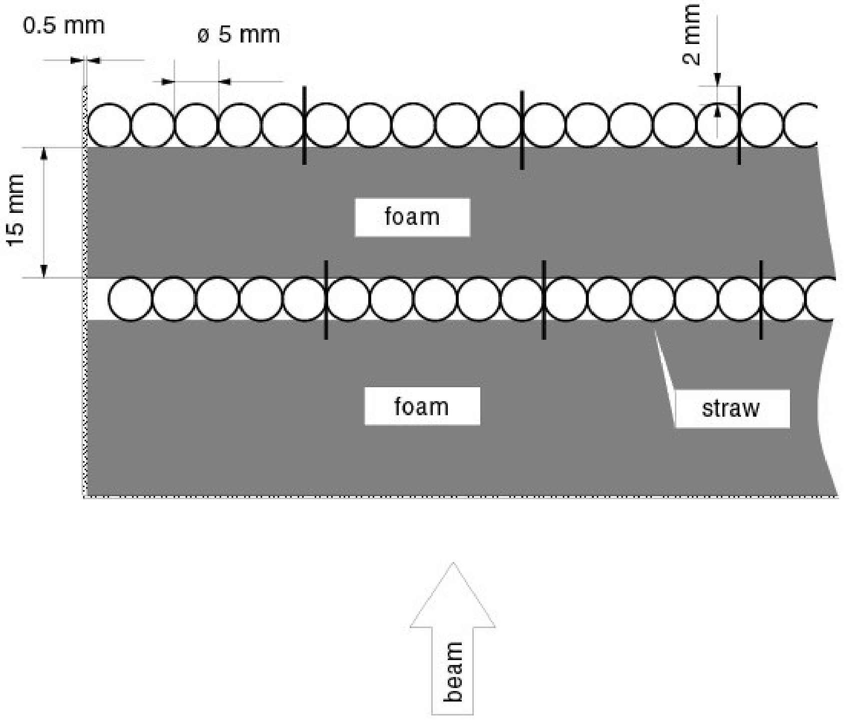
- Small circles: low threshold (ionisation)
- Big circles: high threshold (X ray detection)



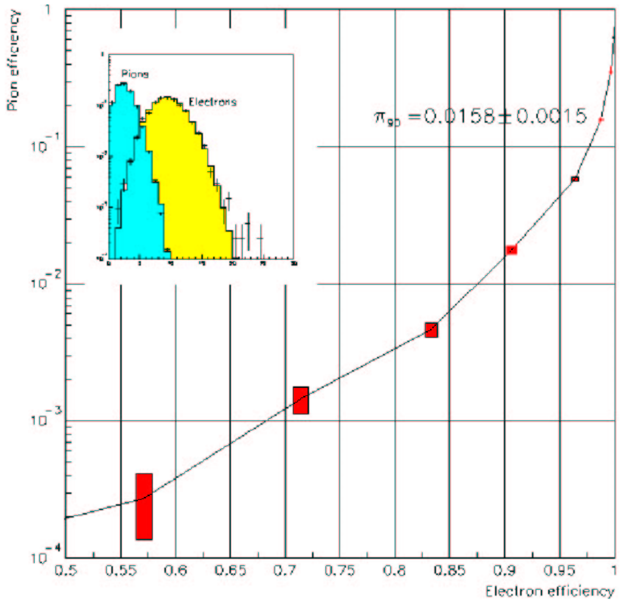
Transition radiation detectors

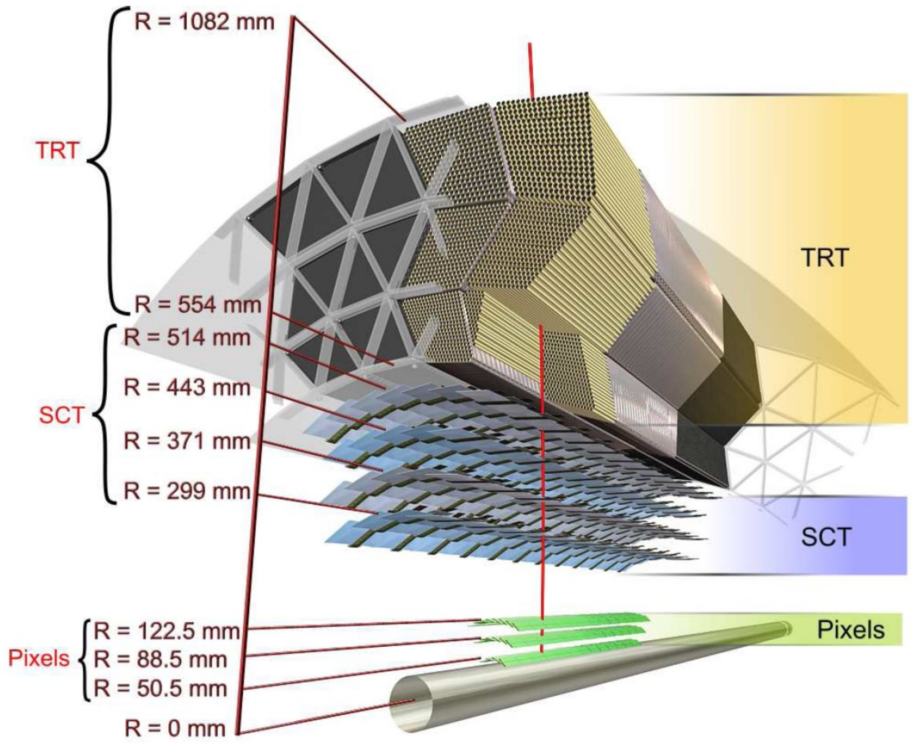
Example:

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



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

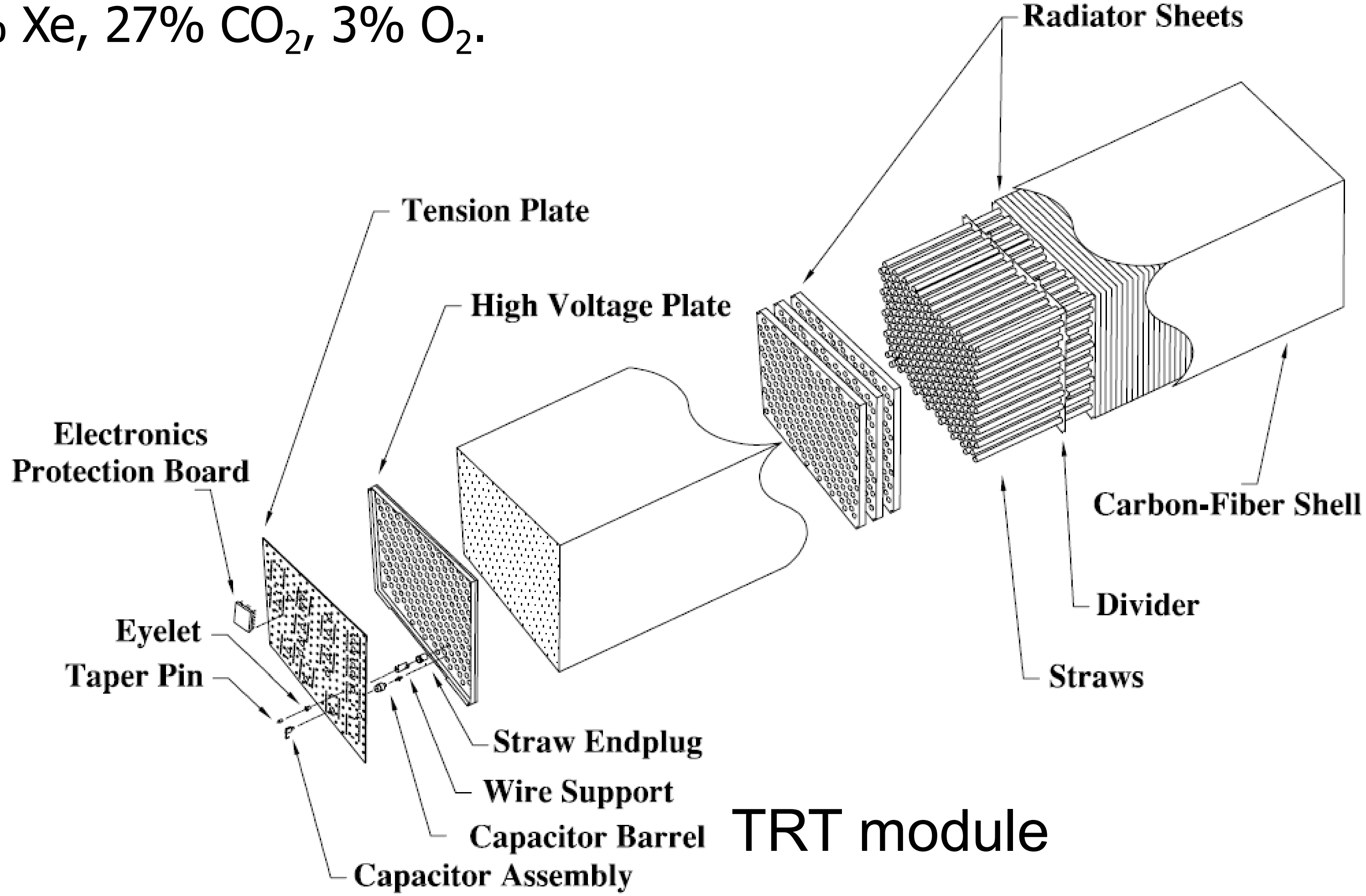




ATLAS TRT

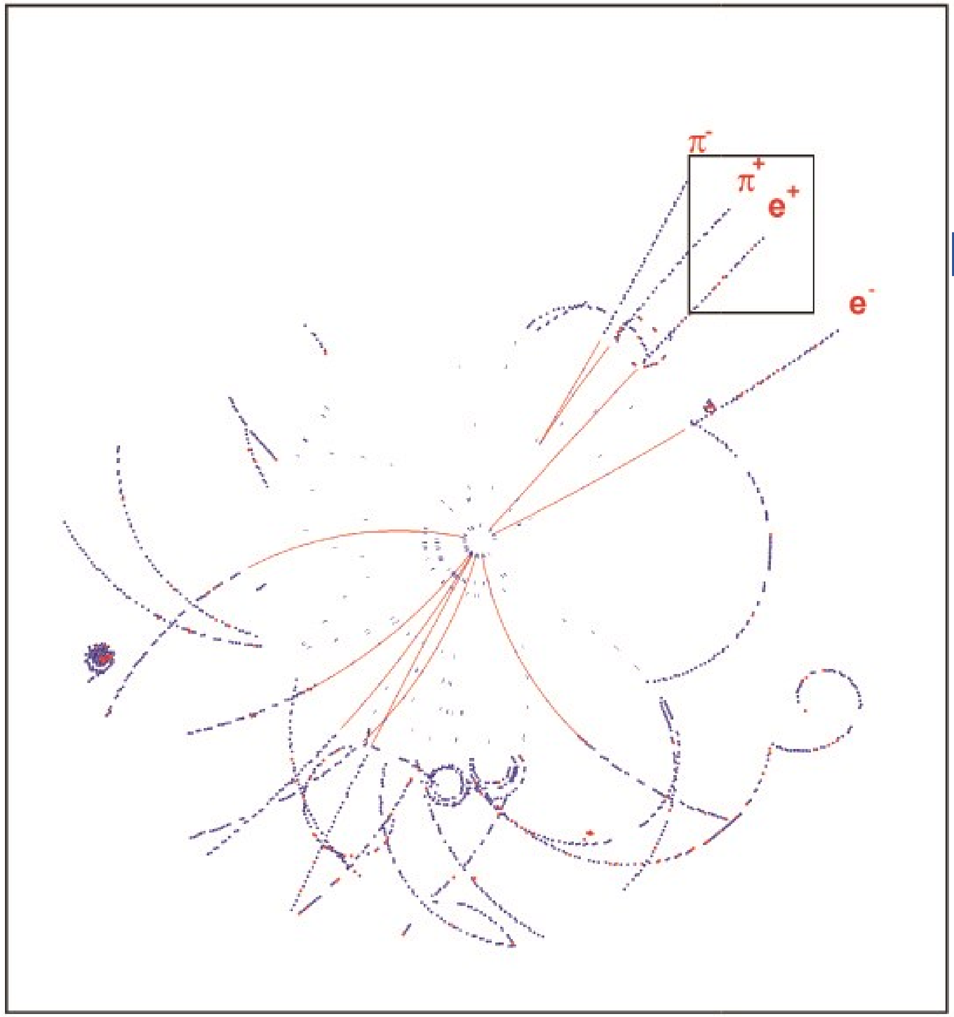
Radiator: 3mm thick layers made of polypropylene-polyethylene fibers with ~19 micron diameter, density: 0.06 g/cm^3

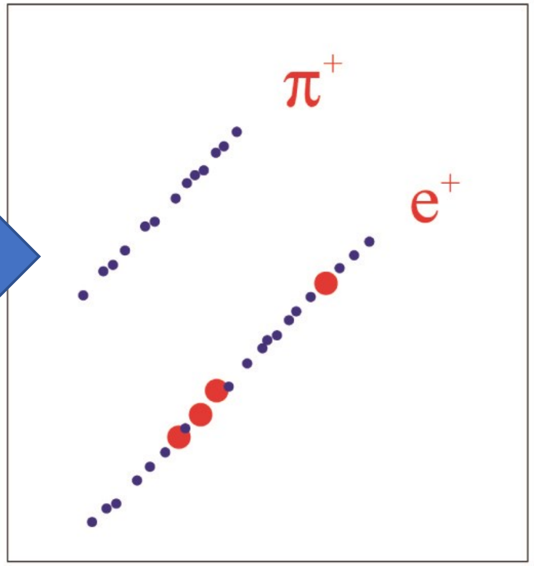
Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO_2, 3% O_2.



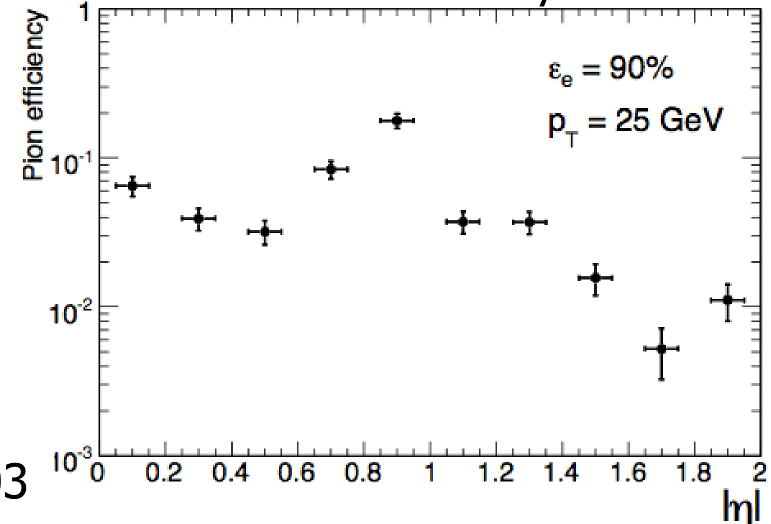
TRT module

TRT: pion-electron separation





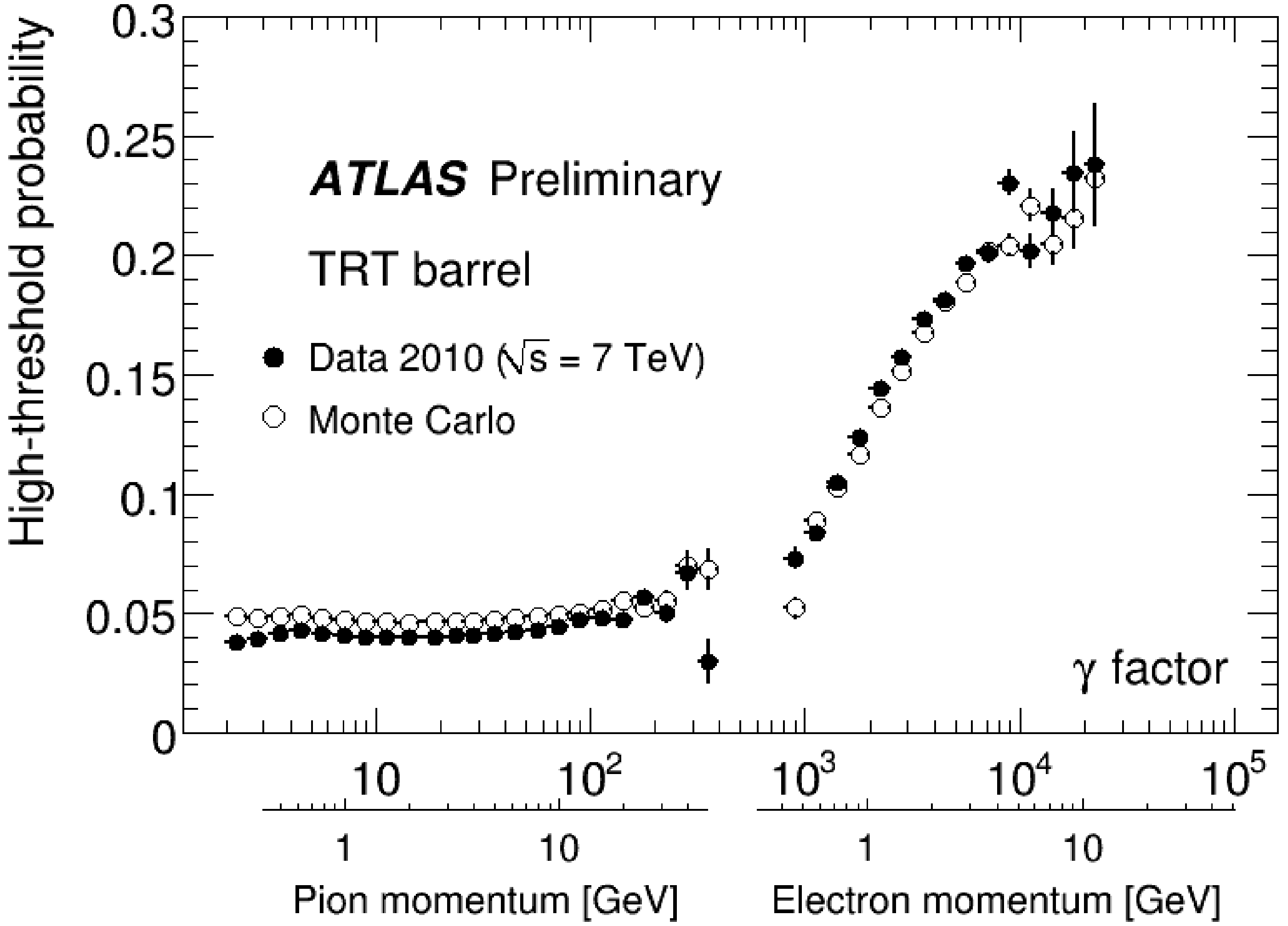
Expected π fake probability at 90% e efficiency



→ JINST 3 (2008) S08003

TRT performance in 2010 data

e/pion separation: high threshold hit probability per straw



Muon and K_L detector at B factories

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 muon if it penetrates the material.

Detect K_L interaction (cluster): again need a few interaction lengths.

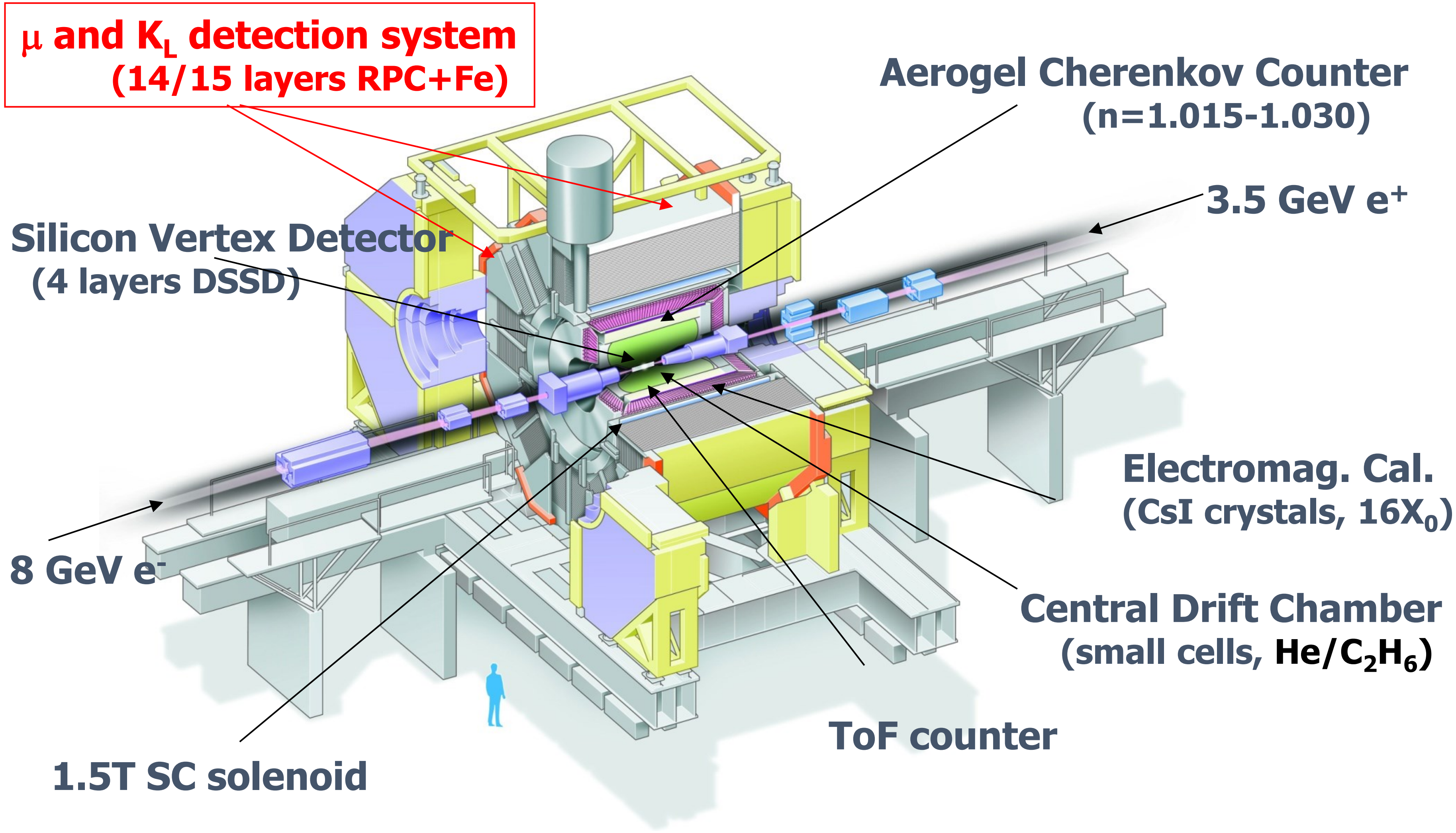
Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

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

Example: Muon and K_L detection at Belle



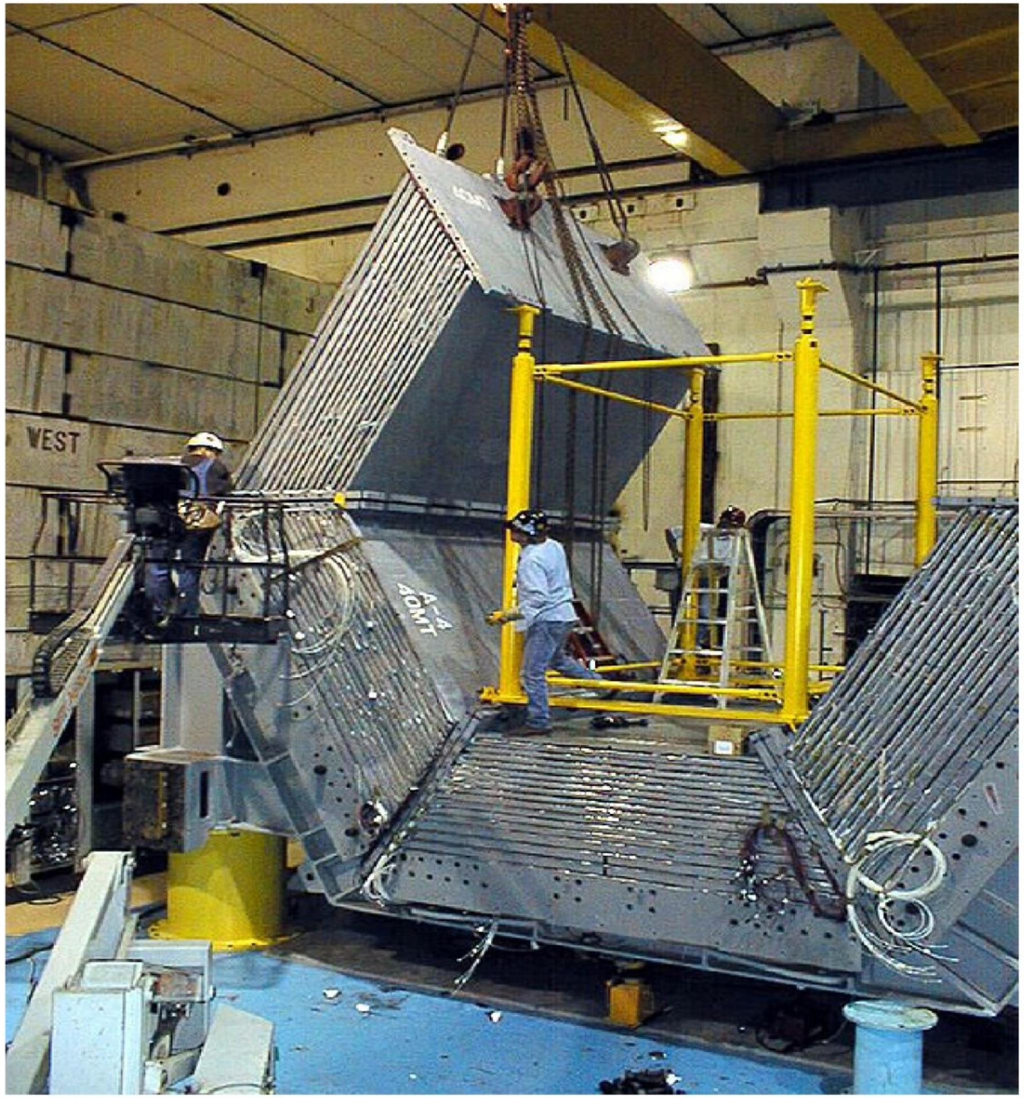
Muon and K_L detector

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

Bakelite RPCs at BABAR

Glass RPCs at Belle

(better choice)



Muon and K_L detector

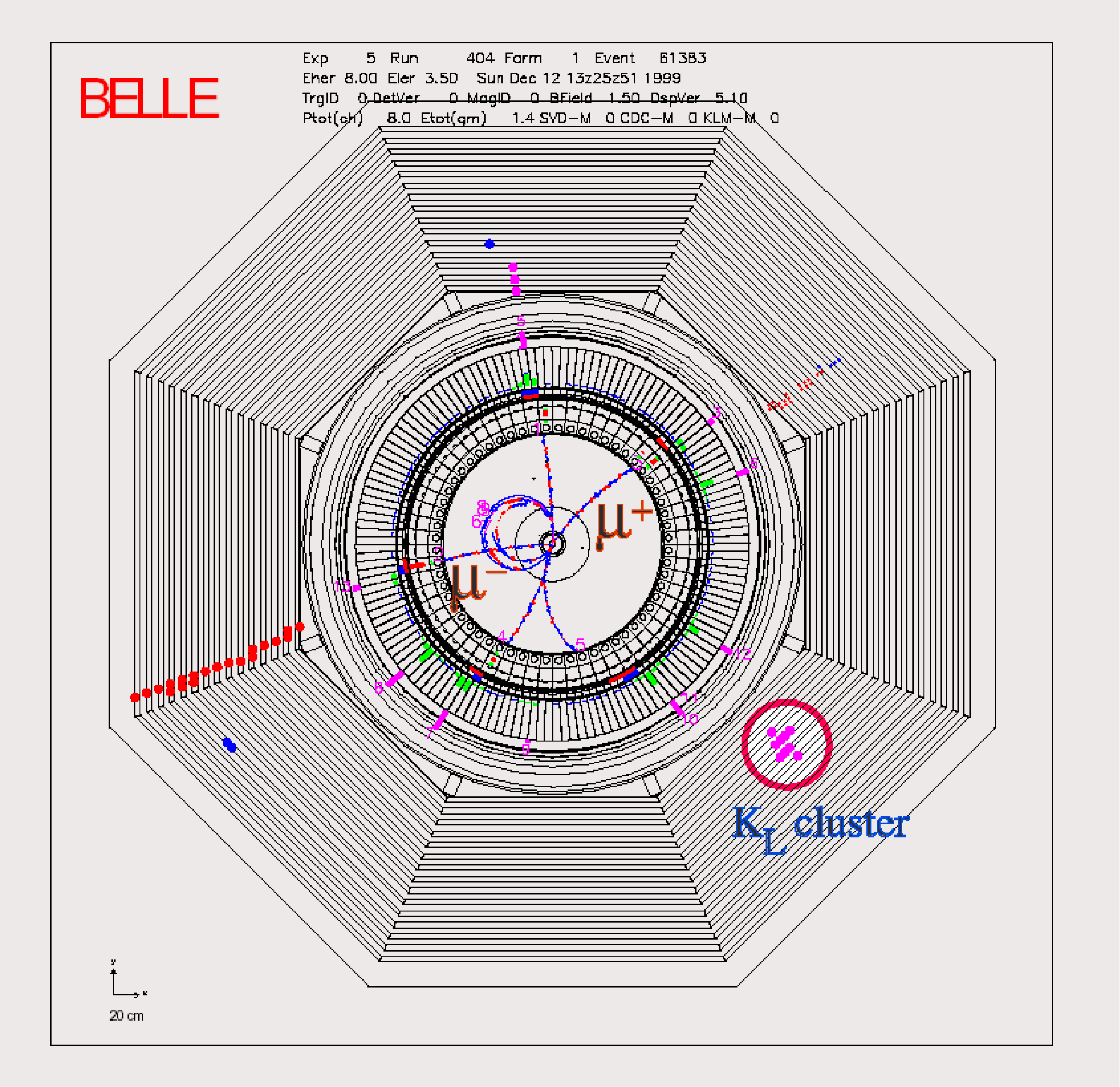
Example:

event with

•two muons and a

K_L

and a pion that partly penetrated



Muon and K_L detector performance

Muon identification: efficient for p>800 MeV/c

efficiency

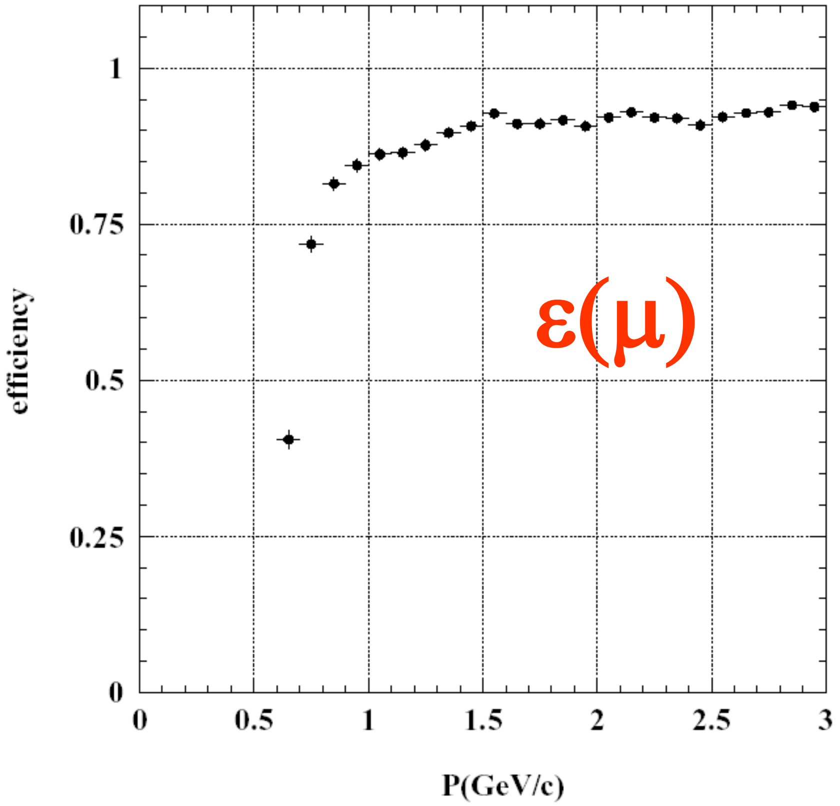


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

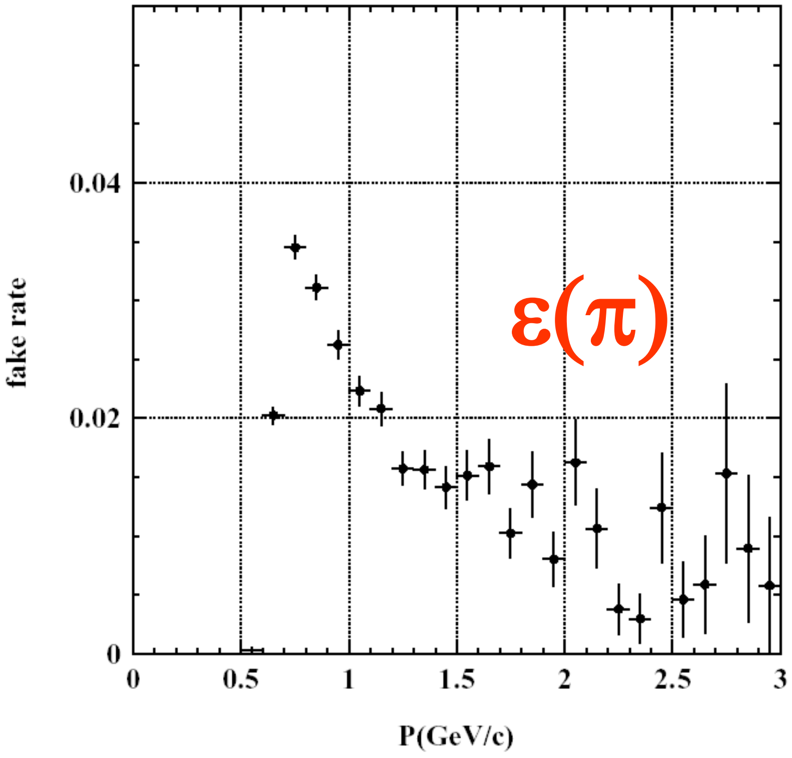


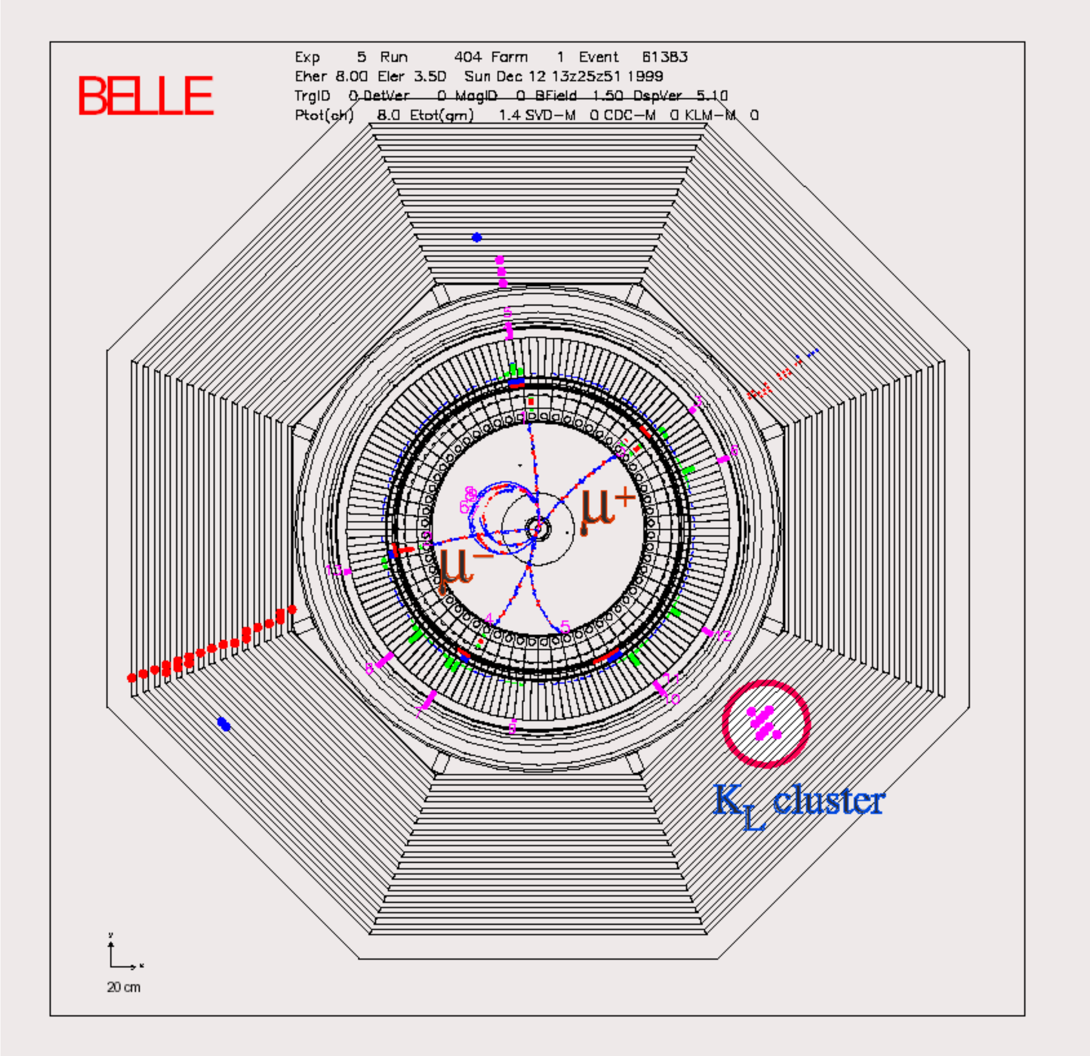
Fig. 110. Fake rate vs. momentum in KLM.

K_L detector

K_L: neutral particle, long lifetime (would decay weakly to 3 pions far from the detector)

interacts with strong interaction in the detector

→ need enough material with active detection layers



Muon and K_L detector performance

K_L detection: resolution in direction →

K_L detection: also with possible with electromagnetic calorimeter (0.8 interactin lengths)

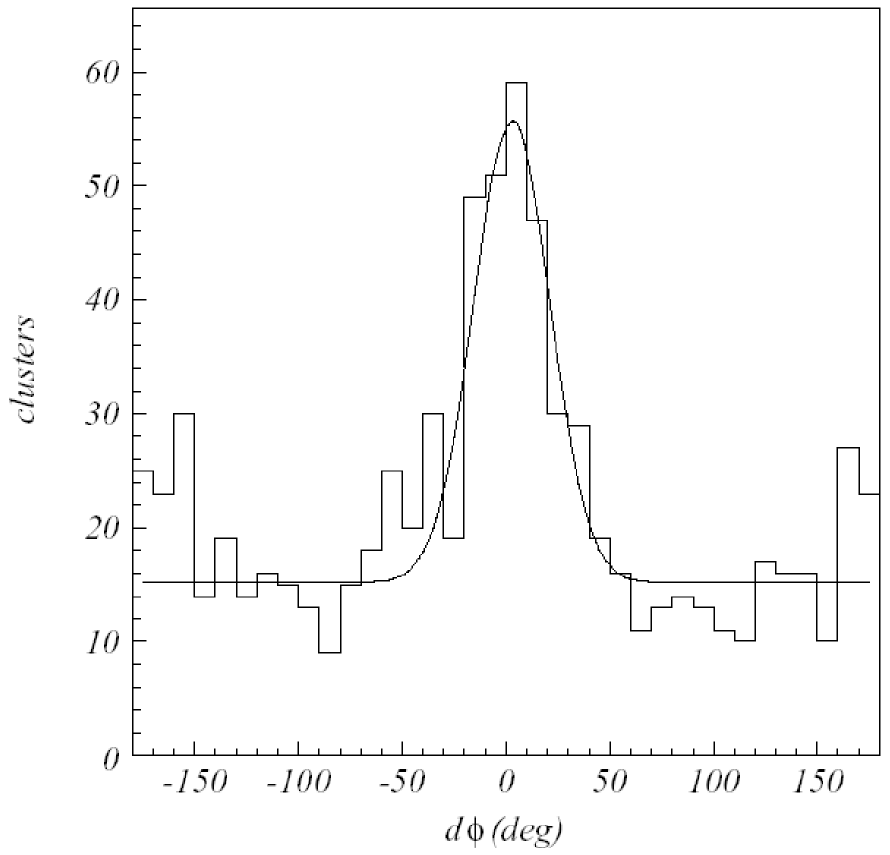
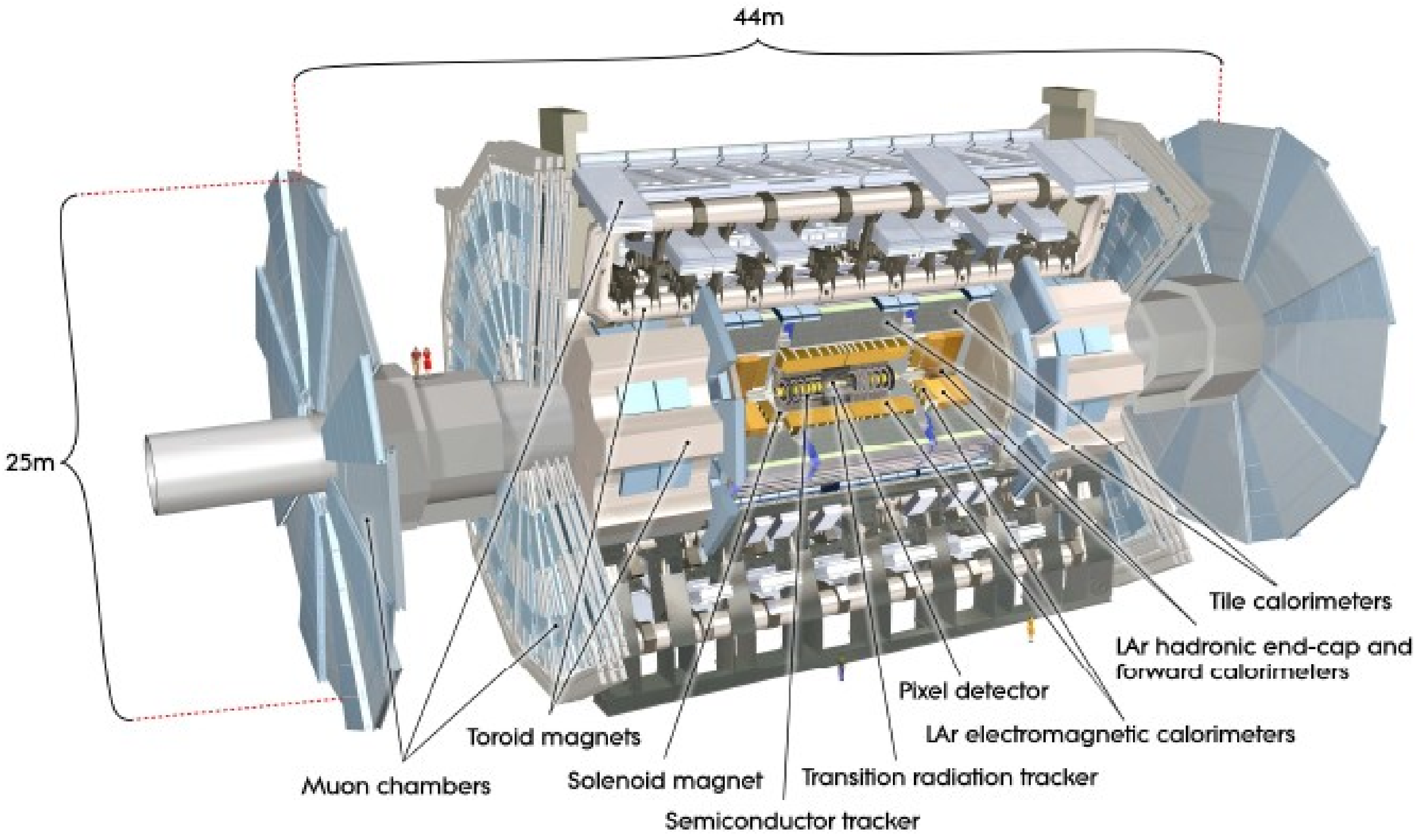


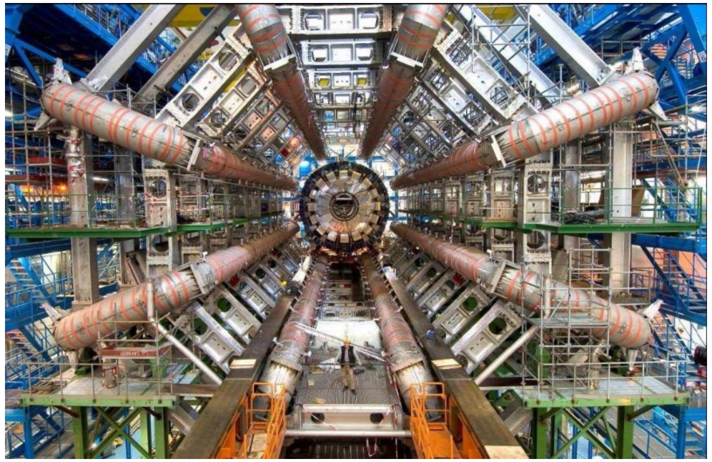
Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

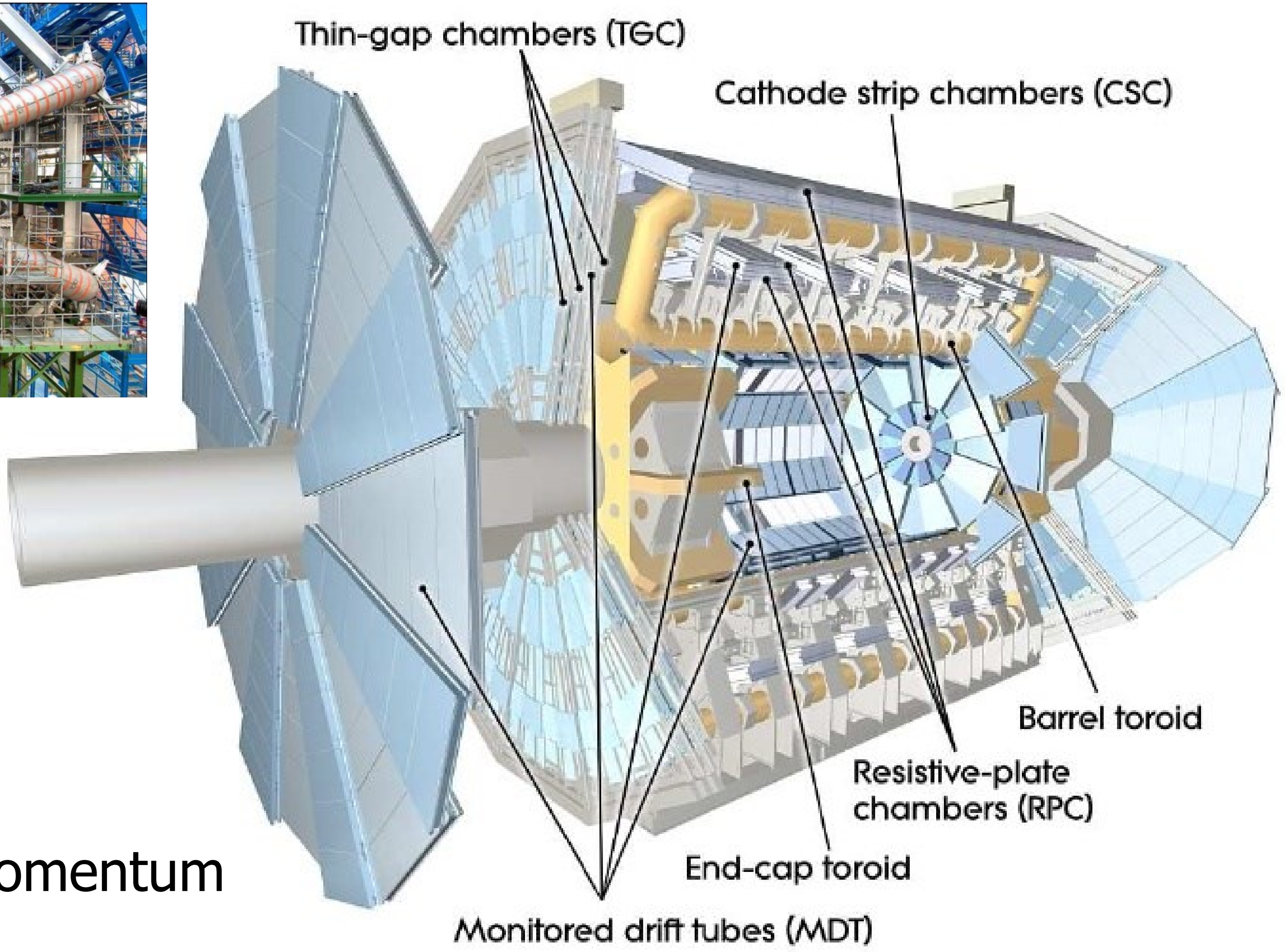
Identification of muons at LHC

- example ATLAS



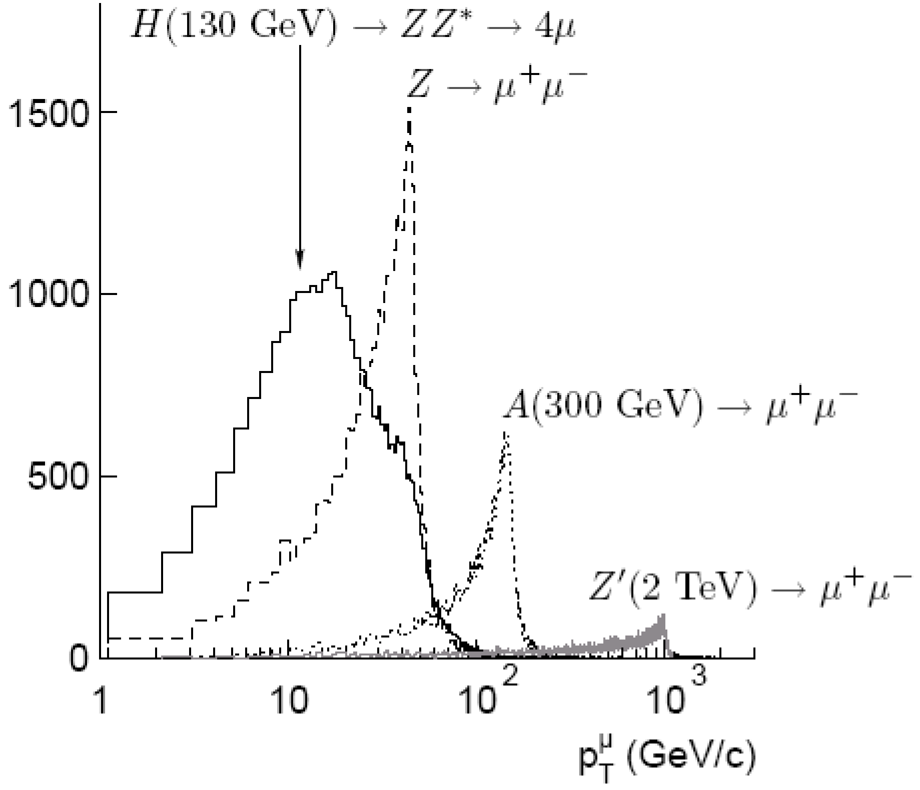
Identification of muons in ATLAS

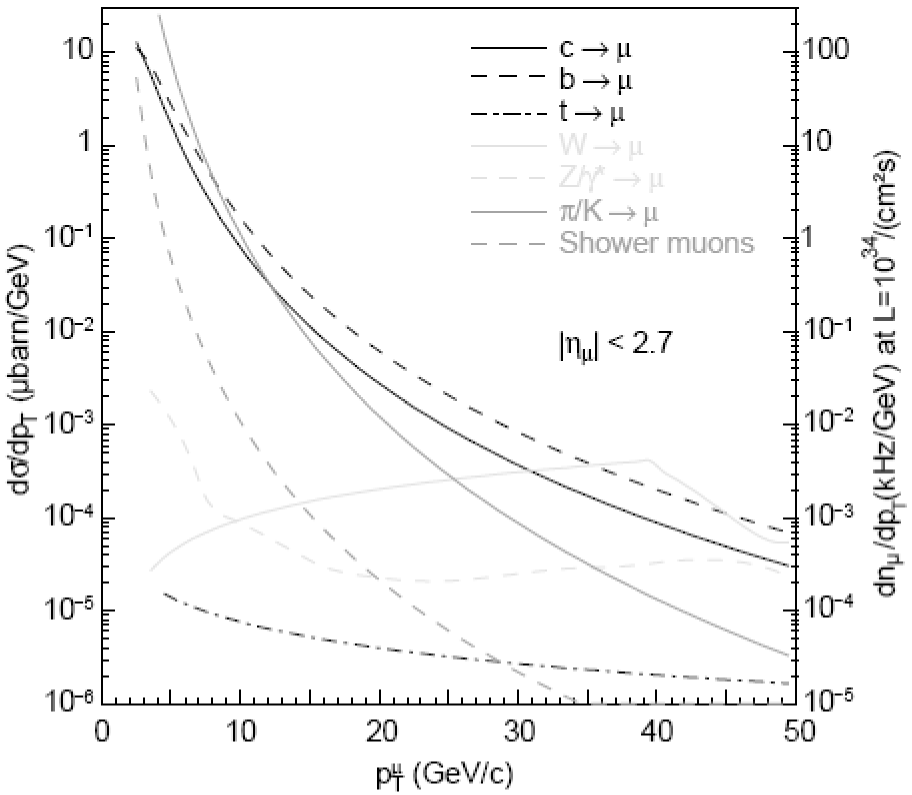




- Identify muons
- Measure their momentum

Muon sources, spectrum





Muon identification in ATLAS

Material in front of the muon system

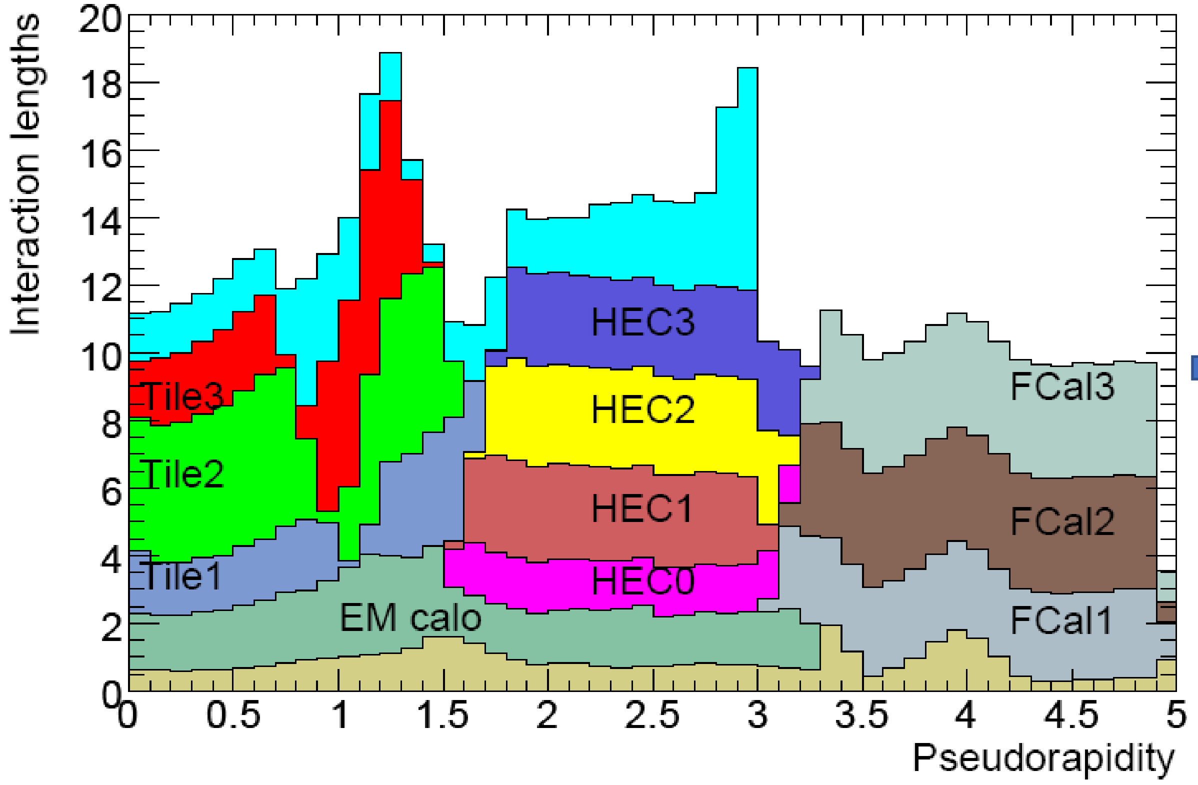
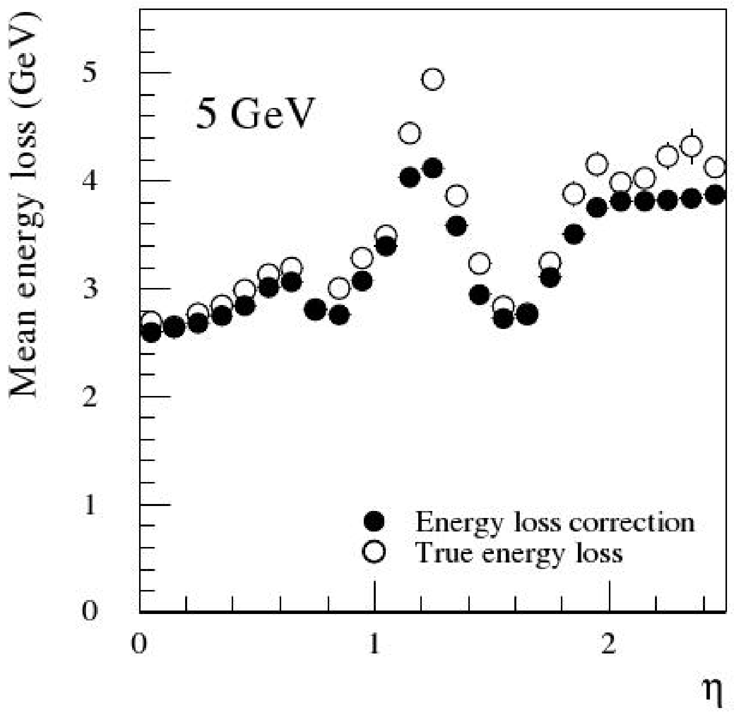
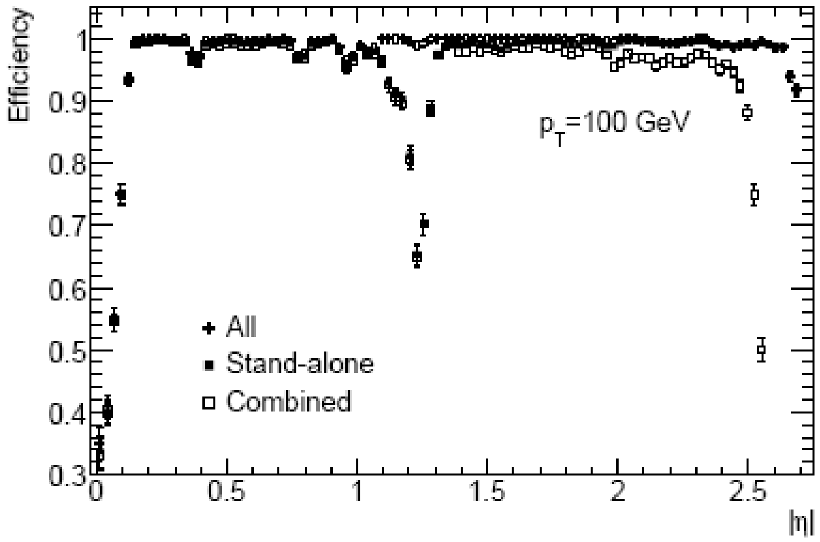


Figure 5.2: Cumulative amount of material, in units of interaction length, as a function of $|\eta|$, in front of the electromagnetic calorimeters, in the electromagnetic calorimeters themselves, in each hadronic layer, and the total amount at the end of the active calorimetry. Also shown for completeness is the total amount of material in front of the first active layer of the muon spectrometer (up to $|\eta| < 3.0$).



Muon identification efficiency



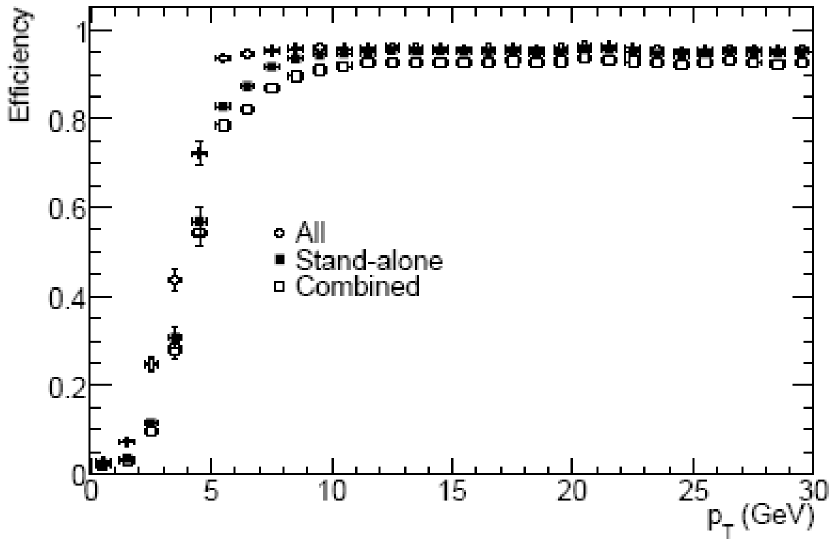


Figure 10.37: Efficiency for reconstructing muons with $p_T = 100\,\text{GeV}$ as a function of $|\eta|$. The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.

Figure 10.38: Efficiency for reconstructing muons as a function of p_T. The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.

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.

Типічний аутпут PID

- Likelihood,
- Глобальний / бінарний

Likelihood function

- Likelihood function is constructed for each of possible particle types (e,mu,pi,K,p,d)

- It is based on the comparison of the observed pattern of detected photons with the expected one assuming given track parameters (position, direction and momentum) and particle type

$$\mathcal{L}^h = \prod_i^{pixels} p_i^h(0,1)$$

$$p_i'(m_i) = e^{-n_i} n_i^{m_i}/m_i!$$

This is Poissonian!

For each particle hypothesis h

$$\ln\mathcal{L}^h = -\boxed{N^h} + \sum_{\text{hit } i}\left[\boxed{n_i^h} + \ln(1-e^{-n_i^h})\right]$$

Expected total number of hits

Expected number of hits on pixel i

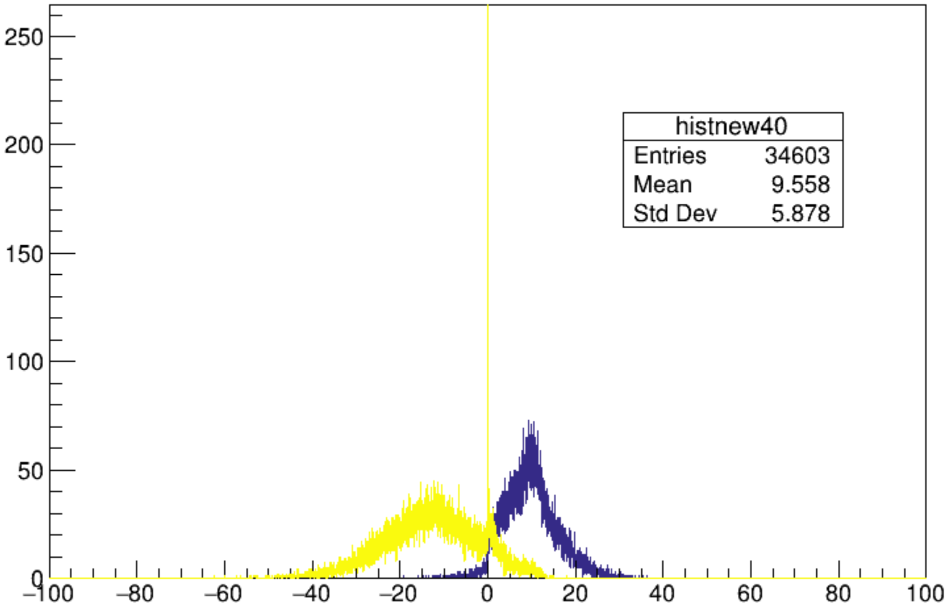
Probability of m_i photo-electrons falling on a pixel for which on average n_i photo-electrons fall.

But in our case: m_i =0 → no hit
m_i >= 1 → hit

$$p_i(0) = e^{-n_i}$$
$$p_i(1) = 1 - p_i(0) = 1 - e^{-n_i}$$

Note: n_i is not probability of pixel being hit!
$$n_i = 5 \rightarrow p_i(1) = 0.993$$

But it is true for small n_i
$$n_i = 0.01 \rightarrow p_i(1) = 0.00995$$



logL:K – logL:pi

ARICH

ARICH

Expected number of hits on pixel i

$$n_i = n_i^1 + n_i^2 + n_i^b$$

1[st] aeogel layer — 2nd — background

$$n_i^r = \epsilon_{det} \boxed{N^r} \int_{\boxed{\Omega_i}} \frac{1}{2\pi} \boxed{G(\theta, \theta_h^r, \sigma_h^r)} d\theta d\phi$$

detection efficiency

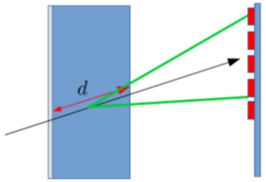
Expected cherenkov peak for given hypothesis h

expected number of photons emitted from aerogel layer r (1,2)

Solid angle covered by I-th pixel

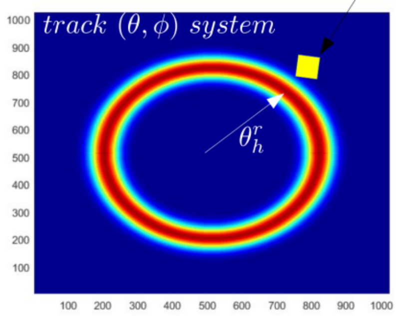
In the track internal coordinate system

$$N^r = \frac{dN_{ch}}{dx} \lambda_{abs} (1 - e^{-d/\lambda_{abs}})$$



Also possible photon loss on the edges and between aerogel tiles is taken into account to get Nr

pixel



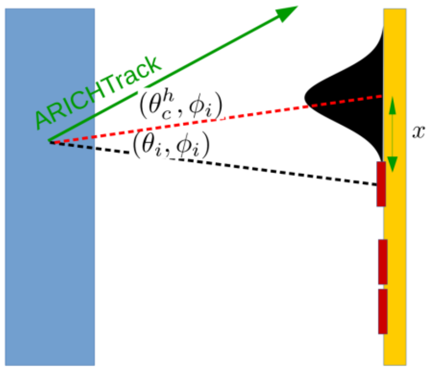
Implementation of this

We reconstruct (θ_i, ϕ_i) of photon hit, in track coordinate system (geometrically, refractions also taken into account).

Then we propagate "dummy" photon (ray tracing) from the emission point, setting its angle to (θ_c^h, ϕ_i), to the detectors plane

Expected (mean) position of cherenkov ring at ϕ_i

Expected cherenkov angle for particle type h



$$\int_{\Omega_i} \frac{1}{2\pi} G(\theta, \theta_h^r, \sigma_h^r) d\theta d\phi$$

$$\int_{S_i} G(x, 0, \sigma_x) dx dy$$

Expected total number of detected hits

$$N = \boxed{\epsilon_{acc}} \epsilon_{det} (N^1 + N^2) + N_b$$

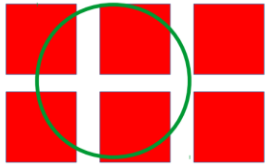
Ring geometrical acceptance

emmited from 1[st] 2[nd] aerogel

background

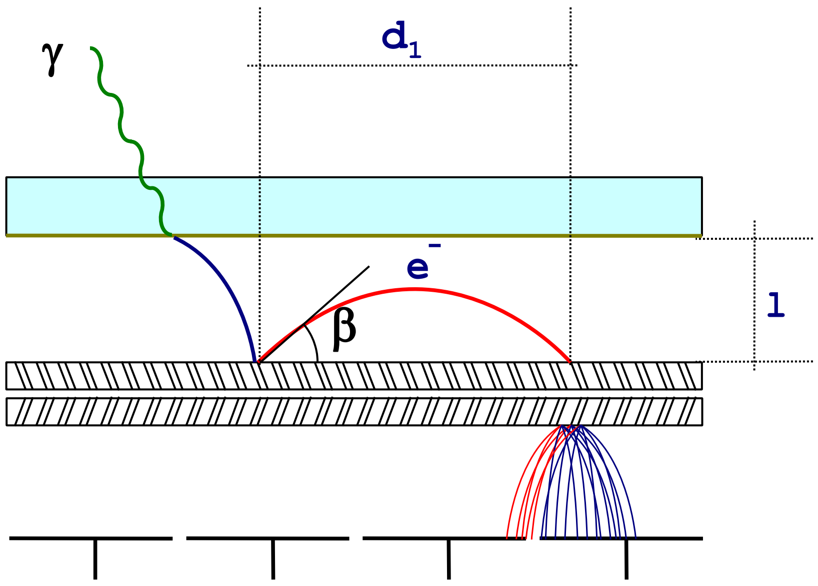
All these of course depend on particle hypothesis!
(N depends on theta_c)

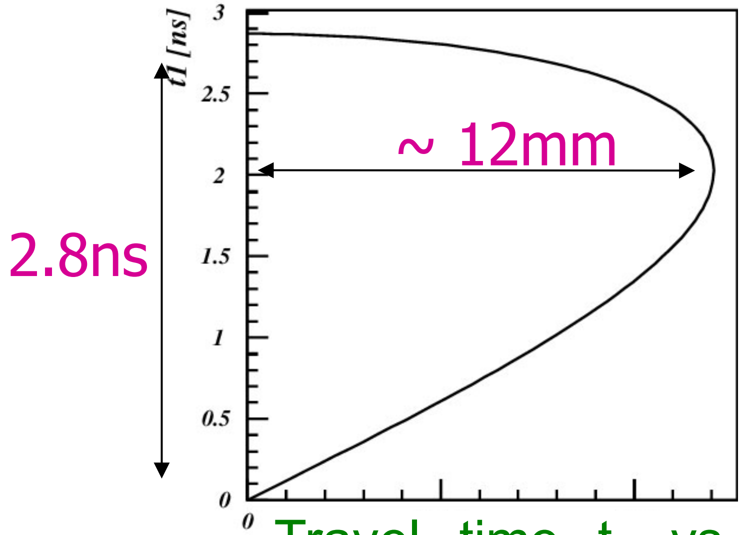
ϵ_{acc} : what fraction of expected ring falls on photo-sensitive surface?



- Створюється PDF

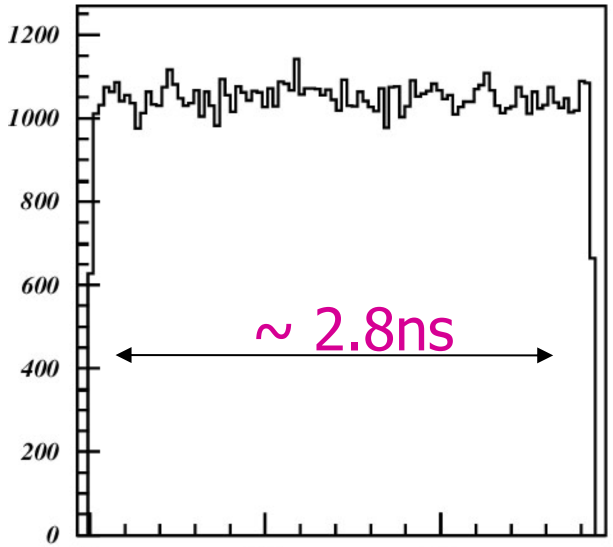
Elastic back-scattering



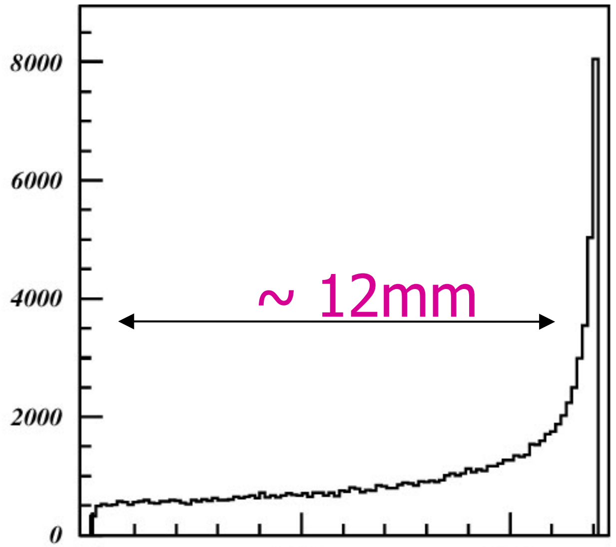


Travel time t_1 vs. travel distance d_1

Distributions assuming that back-scattering by angle β is uniform over the solid angle



$$\boxed{t_1 \approx 2t_0 \sin\beta}$$

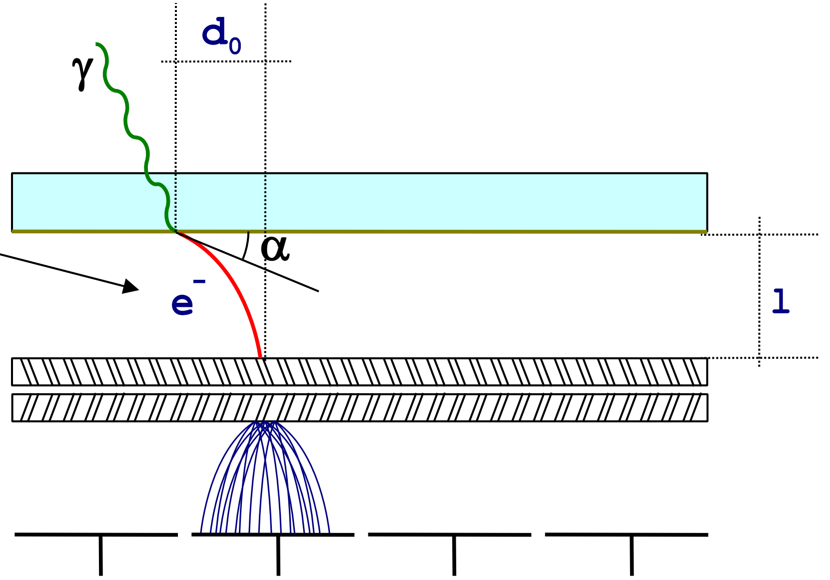


$$\boxed{d_1 \approx 2l \sin 2\beta}$$

Photon electron detection: modeling

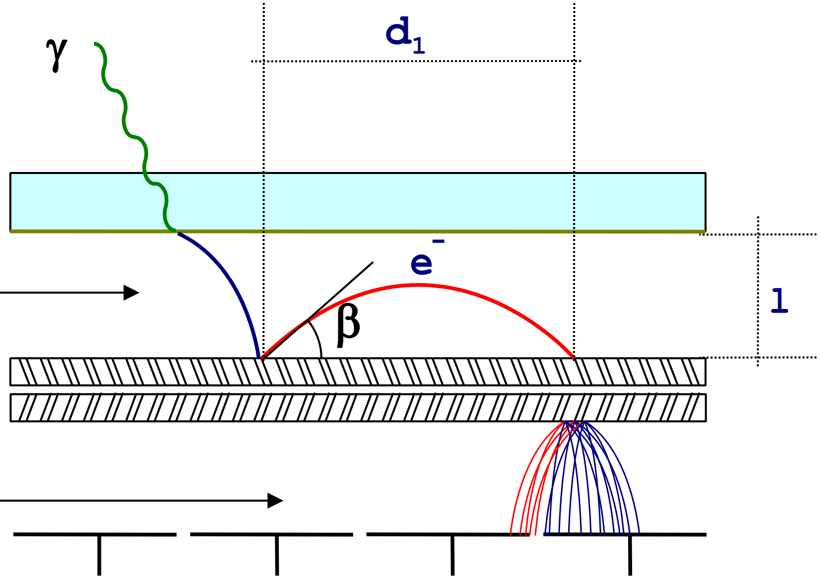
Parameters used:
- $U = 200$ V
- $l = 6$ mm
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As

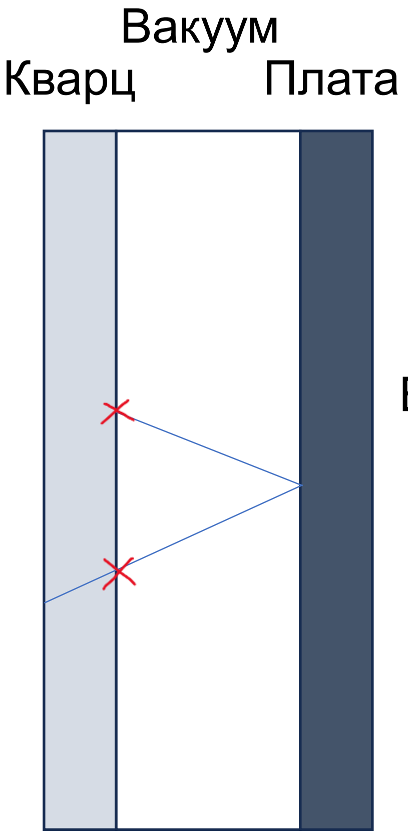
Photo-electron:
- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps



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

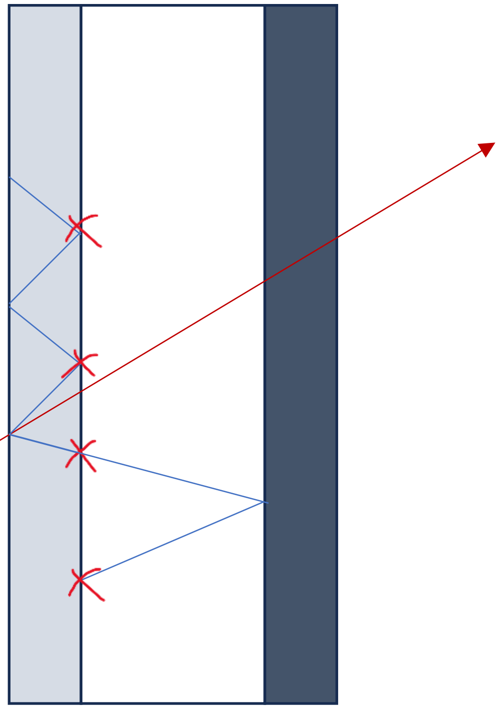
Charge sharing



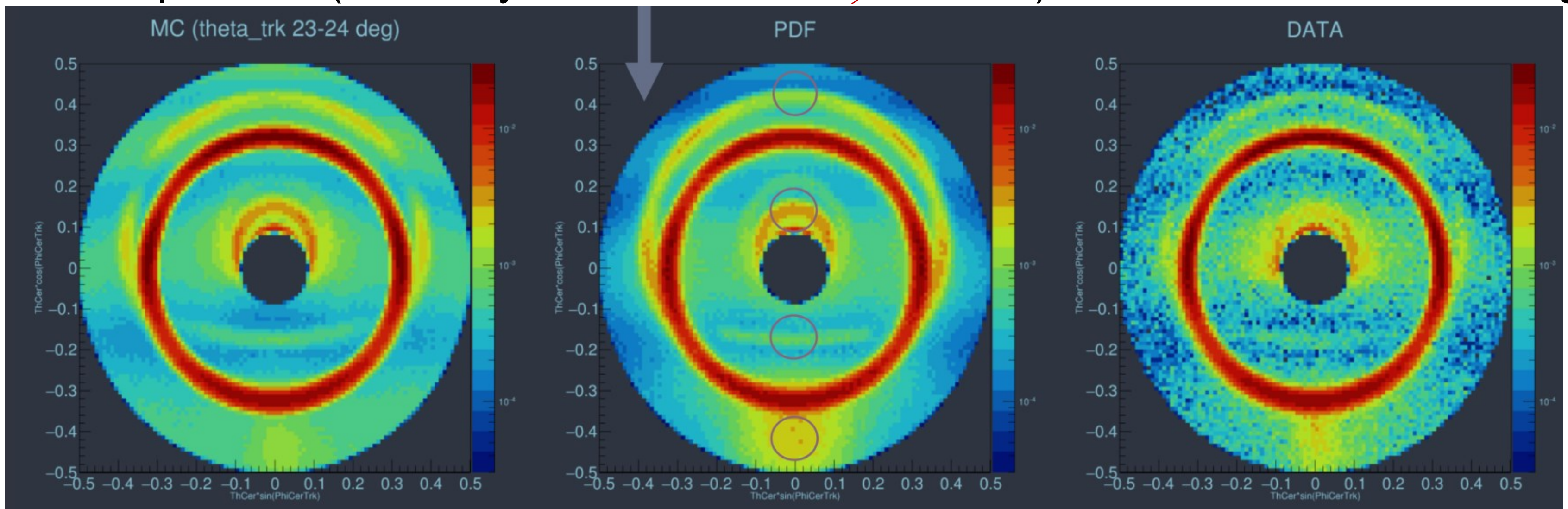


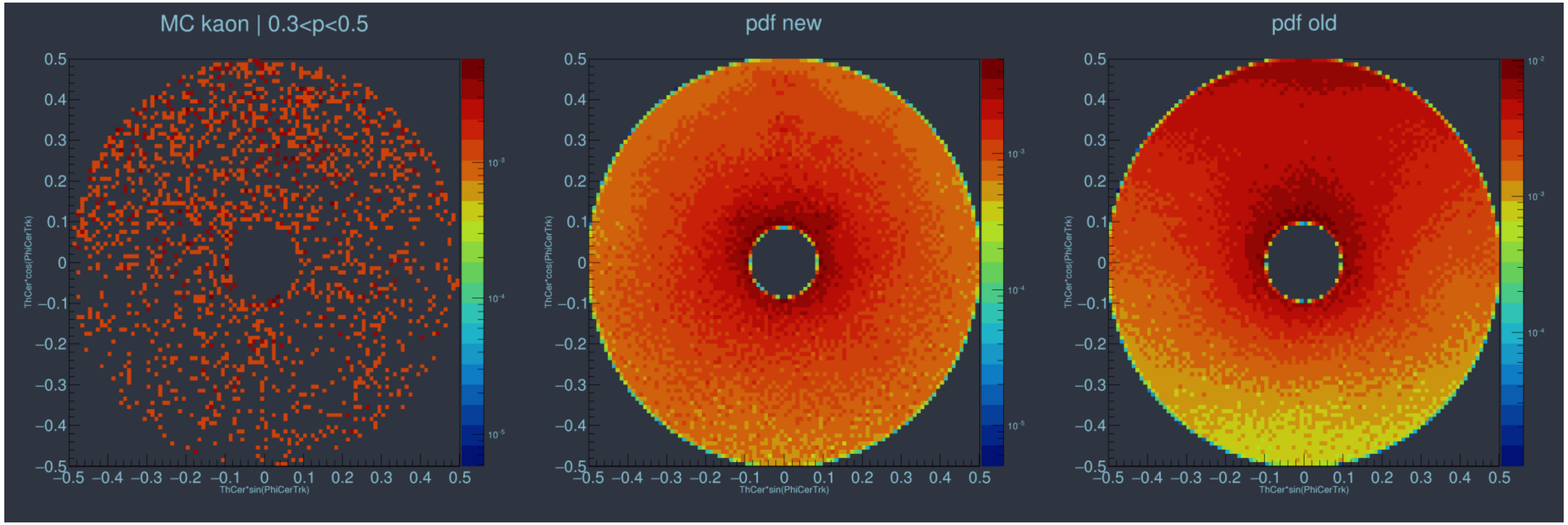
Echo ring

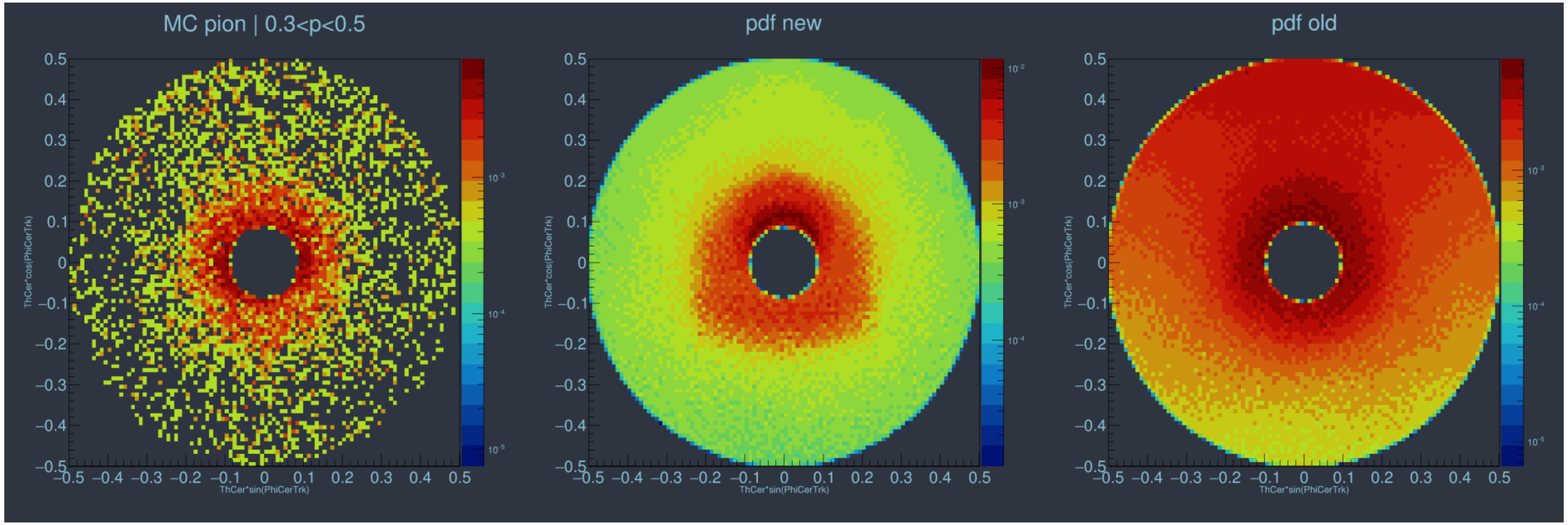
Quartz photons (internally reflected; HAPD reflected)



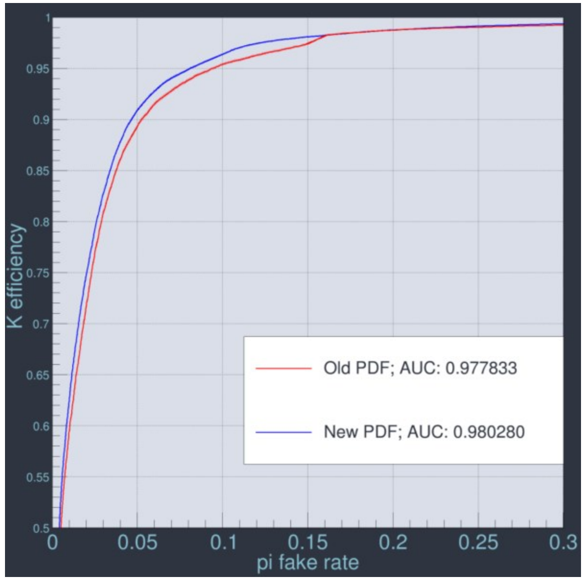
Quartz photons (internally reflected; HAPD reflected); Delta electrons; Echo ring

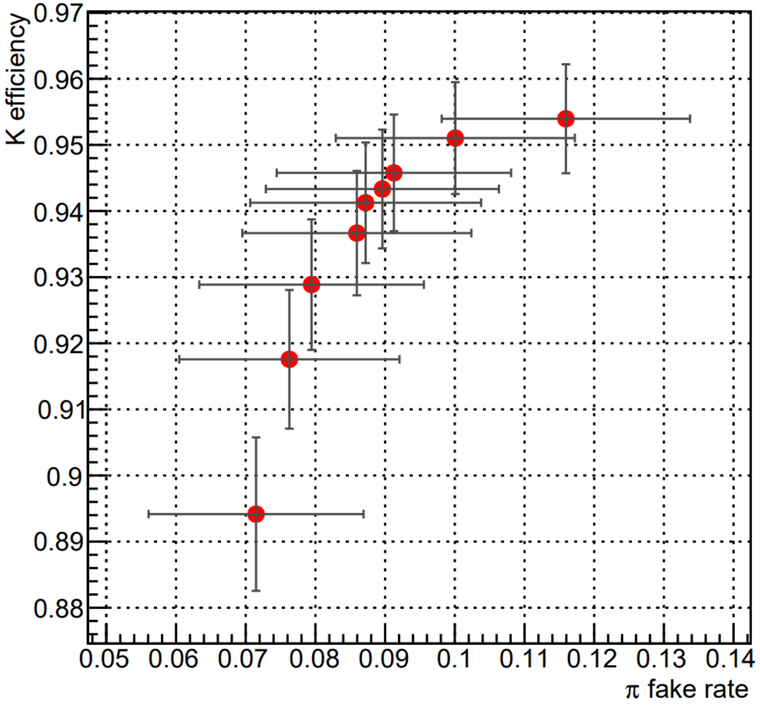


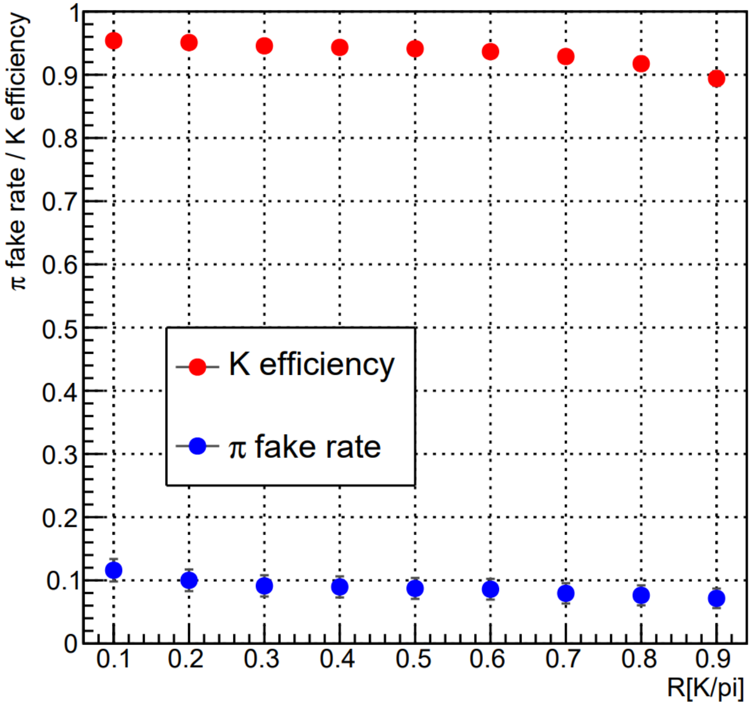




Режим як в ACC для повільних частинок


K efficiency
pi fake rate
Old PDF; AUC: 0.977833
New PDF; AUC: 0.980280


K efficiency
π fake rate


π fake rate / K efficiency
R[K/pi]
K efficiency
π fake rate

Калібрація

- Можна взяти добре відомий розпад
- Перевірити імовірність ідентифікації піона як мюона
- Перевірити імовірність ідентифікації лептона як піона (фейк)