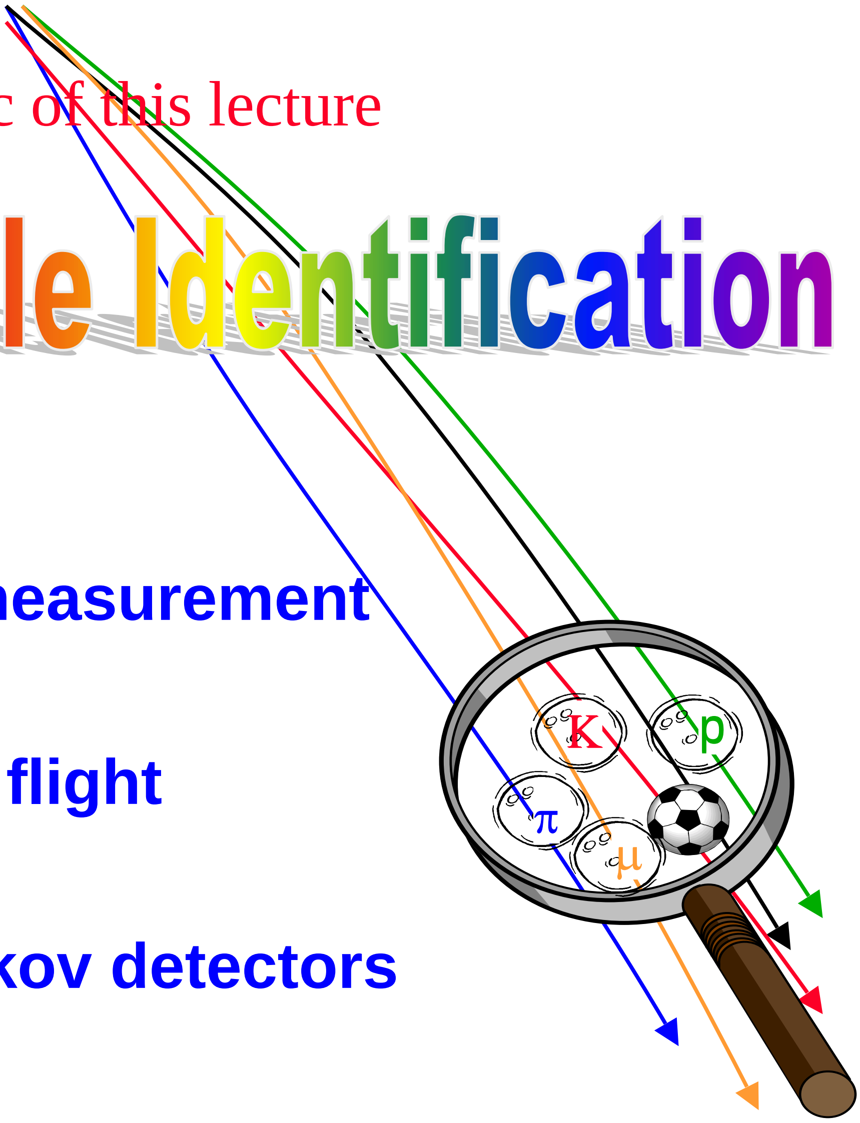
Topic of this lecture

Particle Identification



- **dE/dx measurement**
- **Time of flight**
- **Cherenkov detectors**
- **Transition radiation detectors**

Particle Identification

Particle identification is an important aspect of high energy physics experiments.

Some physical quantities are only accessible with sophisticated particle identification (B-physics, CP violation, rare exclusive decays).

One wants to discriminate: π/K, K/p, e/π, γ/π^0 ….

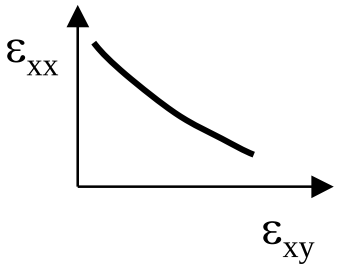
The applicable methods depend strongly on the interesting energy domain.

Depending on the physics case either ε_{xx} or ε_{xy} has to be optimized:

Efficiency: $\varepsilon_{xx} = N_x^{tag} / N_x$

Misidentification: $\varepsilon_{xy} = N_y^{x-tag} / N_y$

Rejection: $R_{xy} = \varepsilon_{xx} / \varepsilon_{xy}$



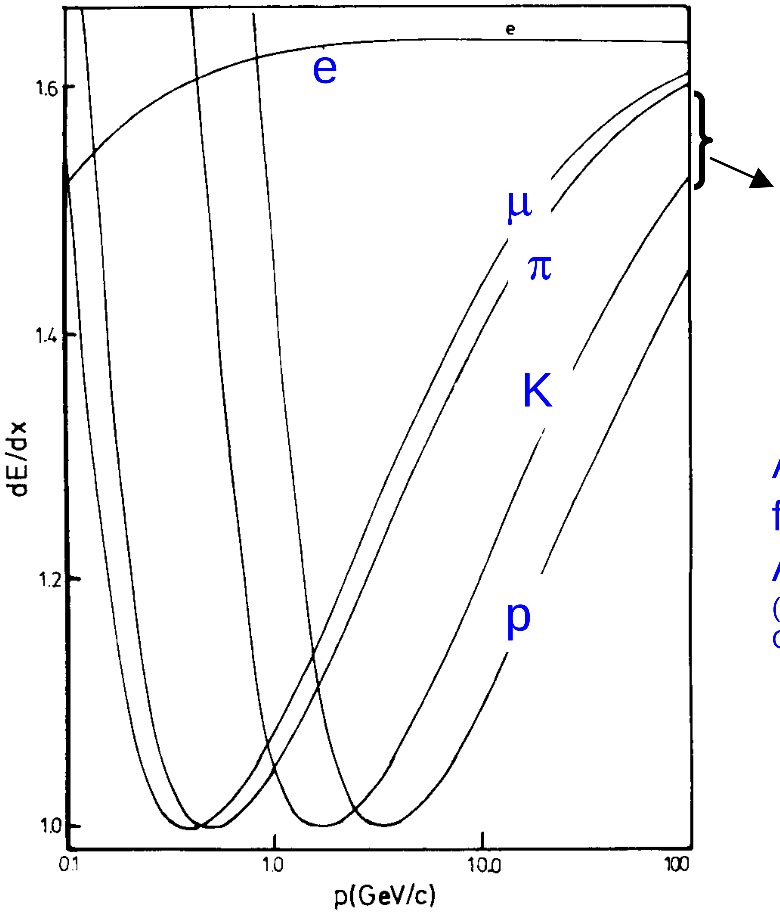
The performance of a detector can be expressed in terms of the resolving power $D_{x,y} = \dfrac{Q_x - Q_y}{\sigma_Q}$

Particle ID using the specific energy loss dE/dx

$$p = m_0 \beta\gamma$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2}\ln\left(\beta^2\gamma^2\right)$$

Simultaneous measurement of p and dE/dx defines mass m, hence the particle identity



π/K separation (2σ) requires a dE/dx resolution of < 5%

Average energy loss for e,μ,π,K,p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

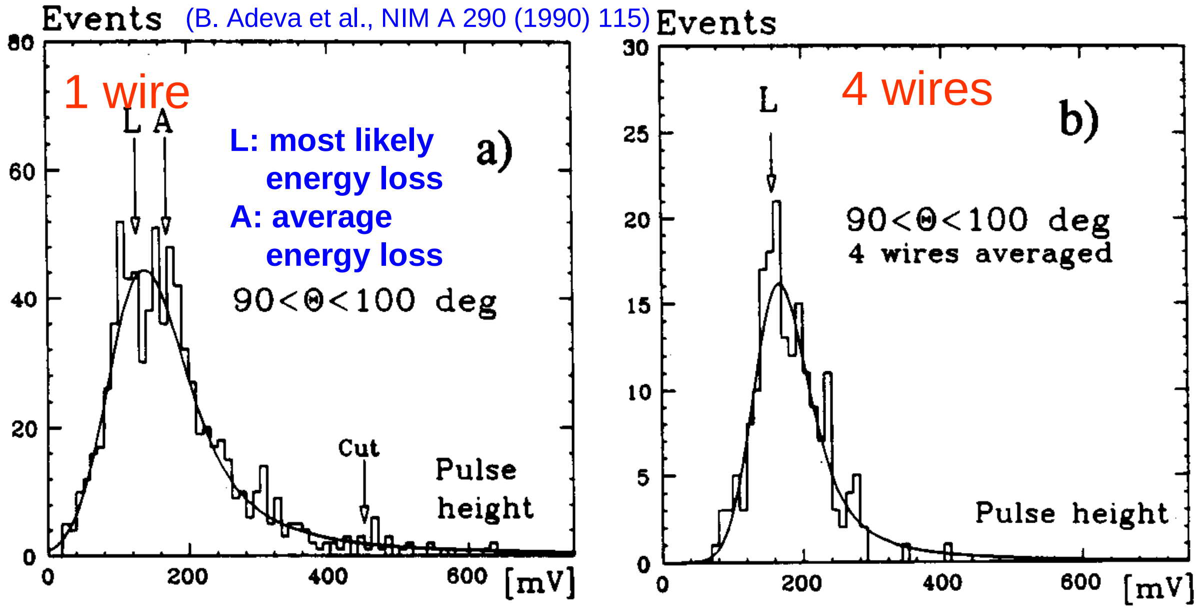
But: Large fluctuations + Landau tails !

Specific energy loss (backup)

Improve dE/dx resolution and fight Landau tails

- Chose gas with high specific ionization
- Devide detector length L in N gaps of thickness T.
- Sample dE/dx N times

(B. Adeva et al., NIM A 290 (1990) 115)



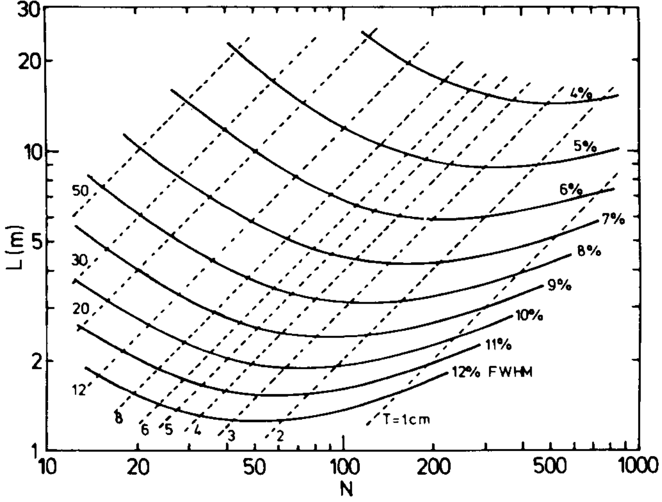
1 wire

4 wires

L: most likely energy loss

A: average energy loss

(M. Aderholz, NIM A 118 (1974), 419)



Don't cut the track into too many slices !
There is an optimum for each total detector length L.

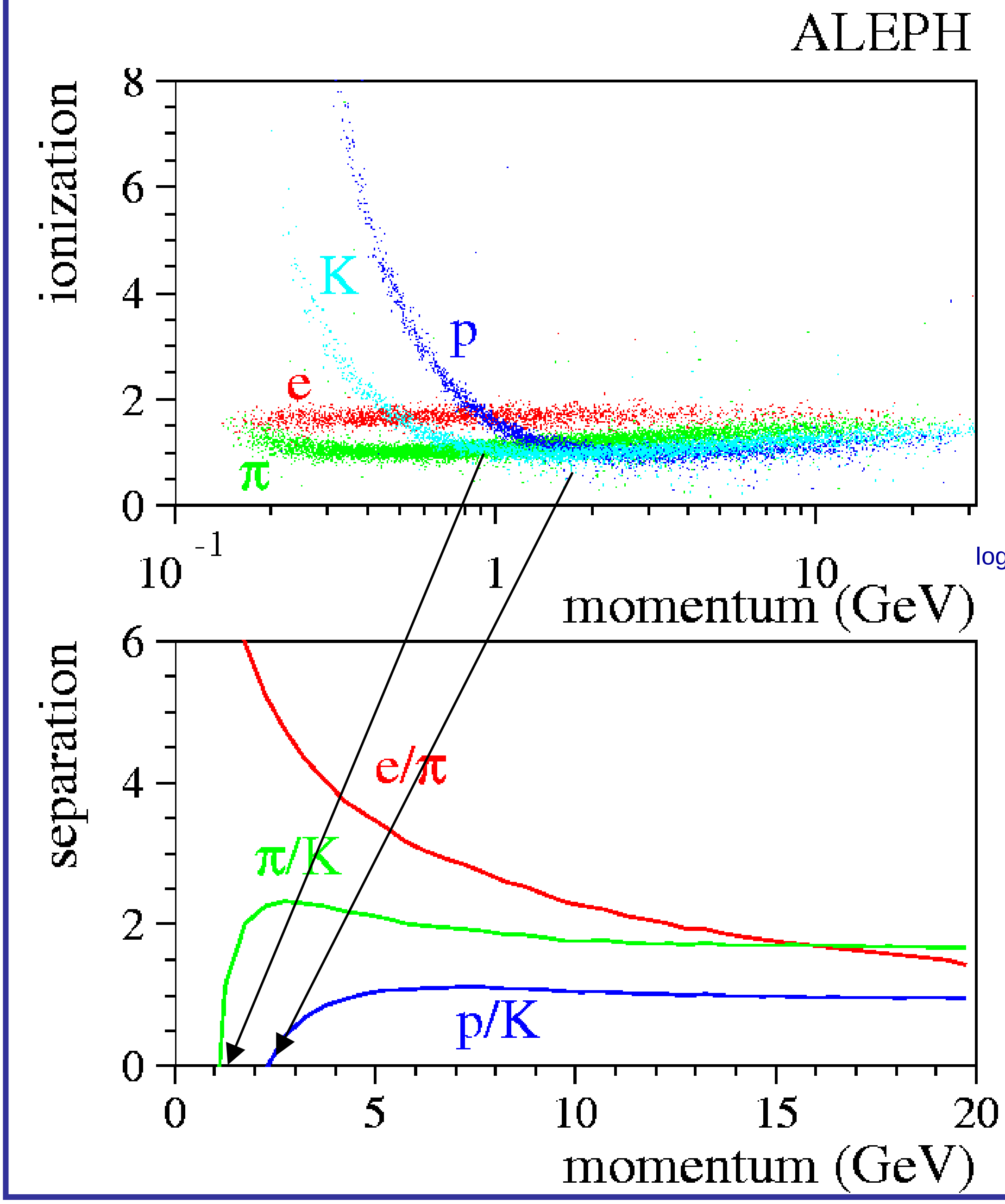
- calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values
- Also pressure increase can improve resolution, but reduced rel. rise due to density effect !

Example ALPEPH TPC

Gas: Ar/CH$_4$ 90/10

N$_{\text{samples}}$ = 338, wire spacing 4 mm

dE/dx resolution: 4.5% for Bhabhas, 5% for m.i.p.'s



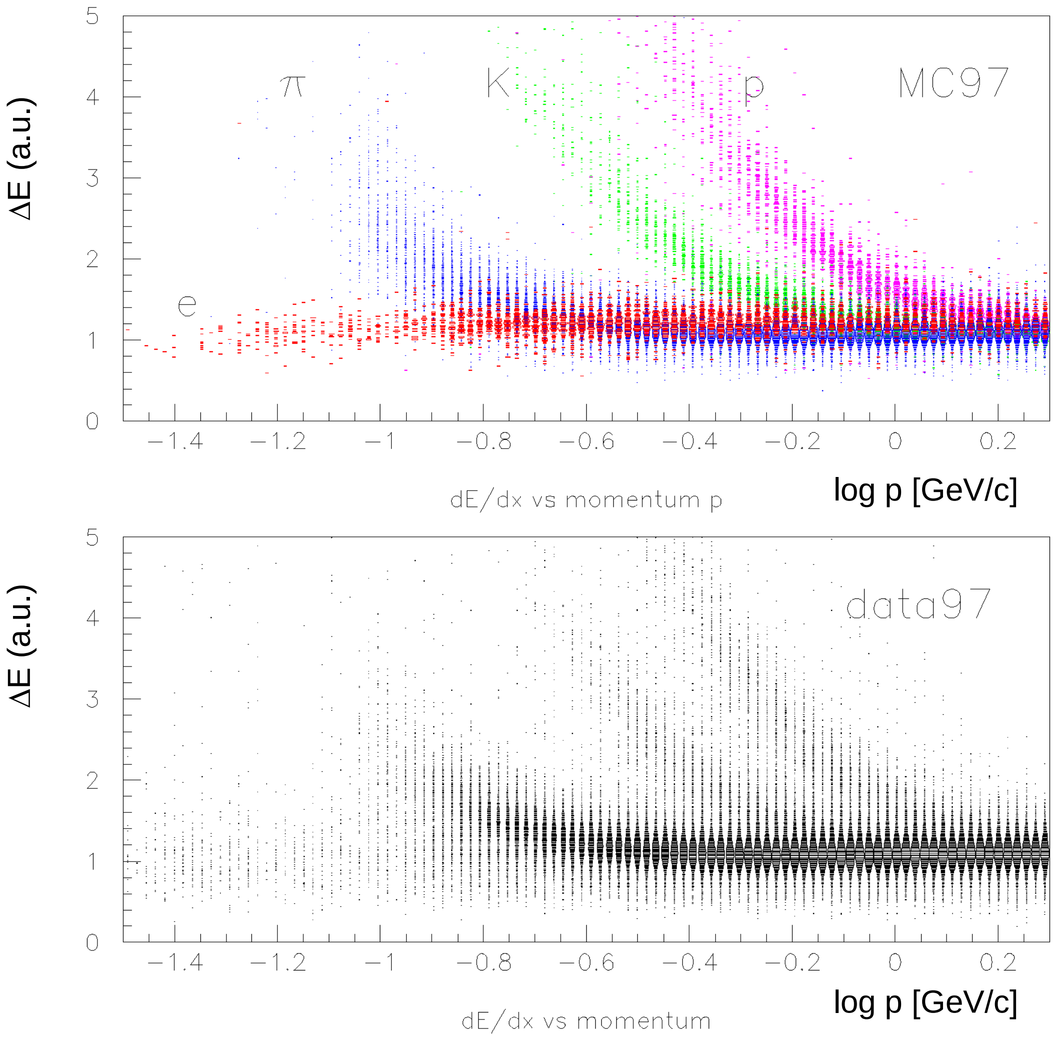
log scale !

linear scale !

Specific energy loss

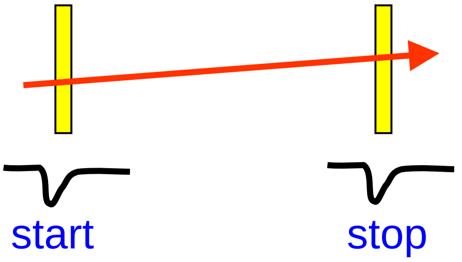
dE/dx can also be used in Silicon detectors

Example DELPHI microvertex detector (3 x 300 μm Silicon)



Particle ID using Time Of Flight (TOF)

$$t = \frac{L}{\beta c}$$



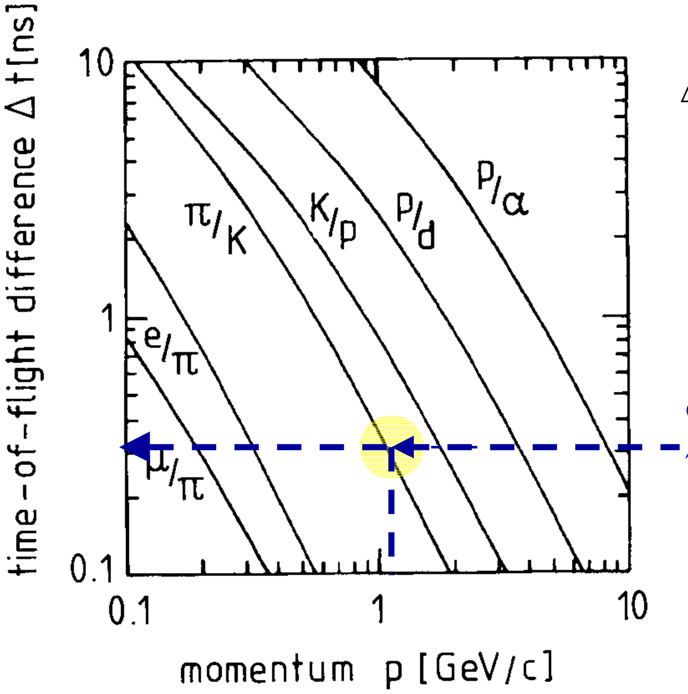
Combine TOF with momentum measurement $(p = m_0 \beta\gamma)$

$$m = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

Mass resolution $$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

TOF difference of 2 particles at a given momentum

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

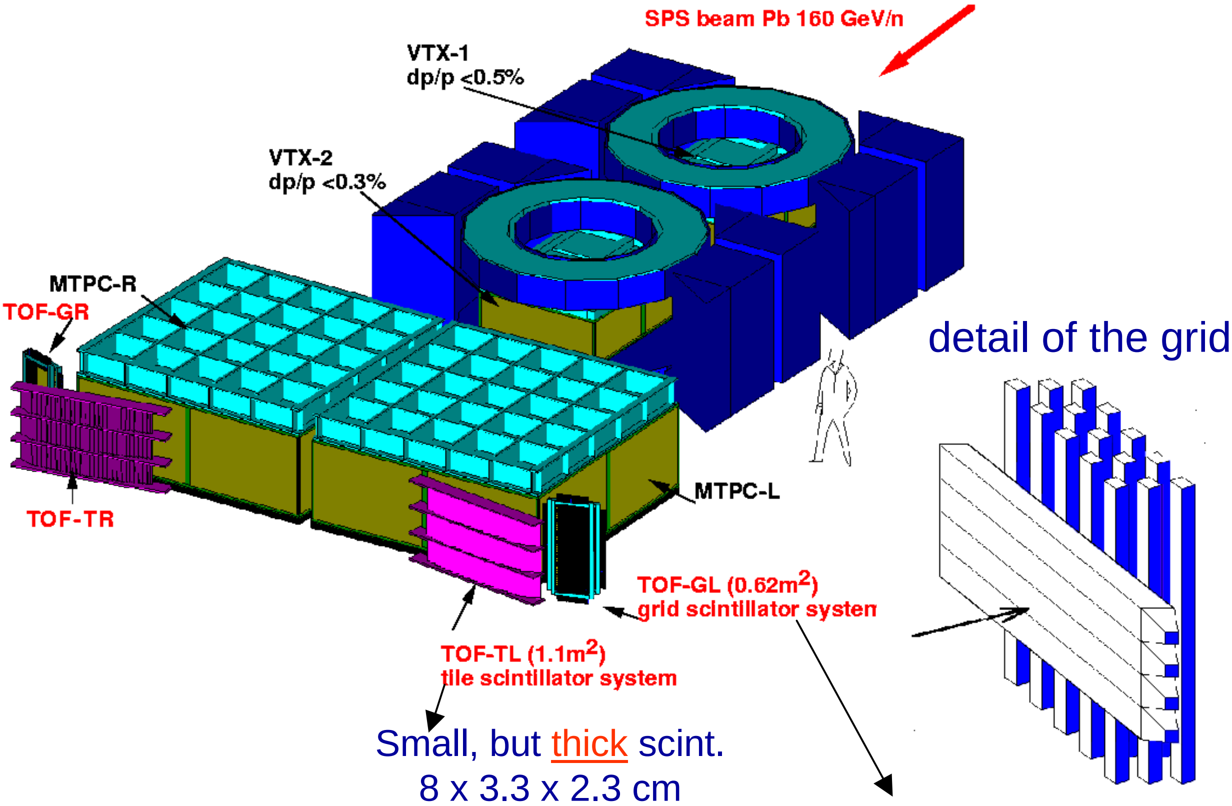


Δt for L = 1 m path length

σ_t = 300 ps
π/K separation up to
1 GeV/c

Example: CERN NA49 Heavy Ion experiment

Na 49 experimental setup (part)



detail of the grid

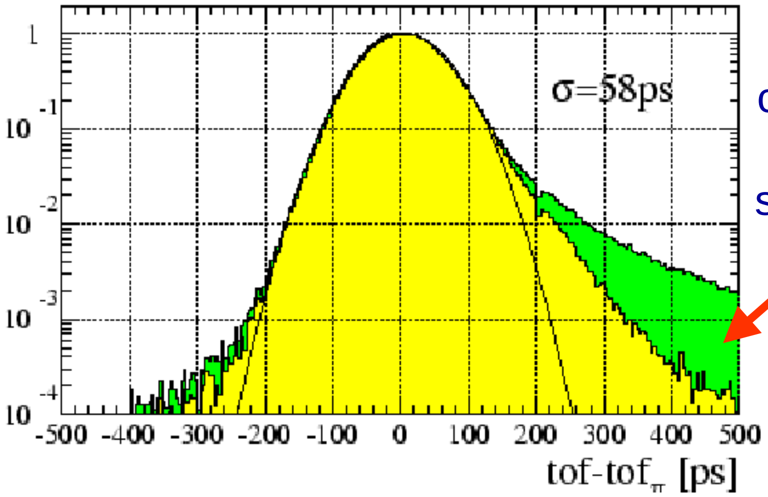
Small, but thick scint.
8 x 3.3 x 2.3 cm

Long scint. (48 or 130 cm),
read out on both sides

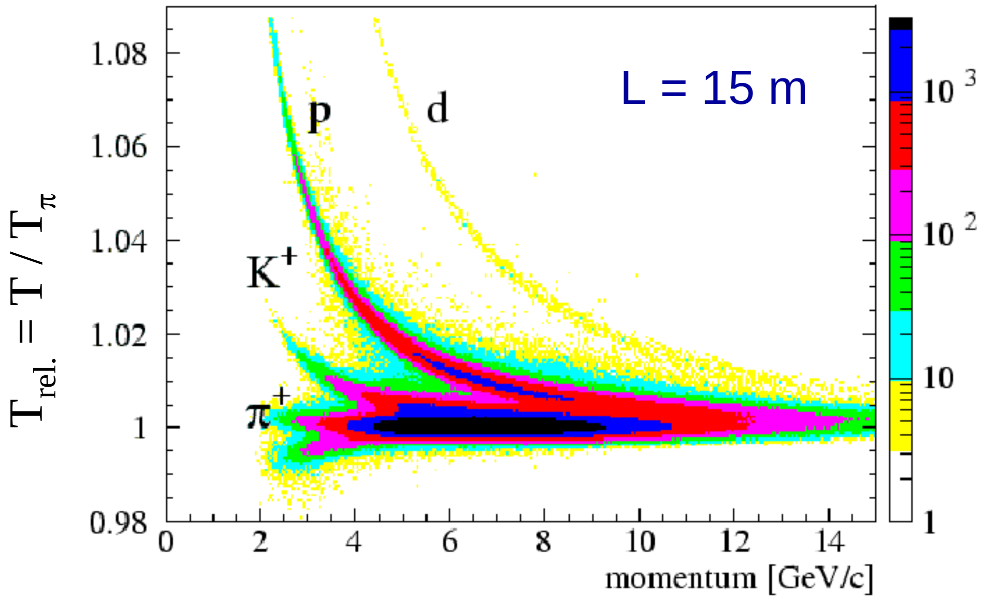
TOF requires fast detectors (plastic scintillator, gaseous detectors), approporiate signal processing (constant fraction discrimination, corrections + continuous stability monitoring.

Time of flight

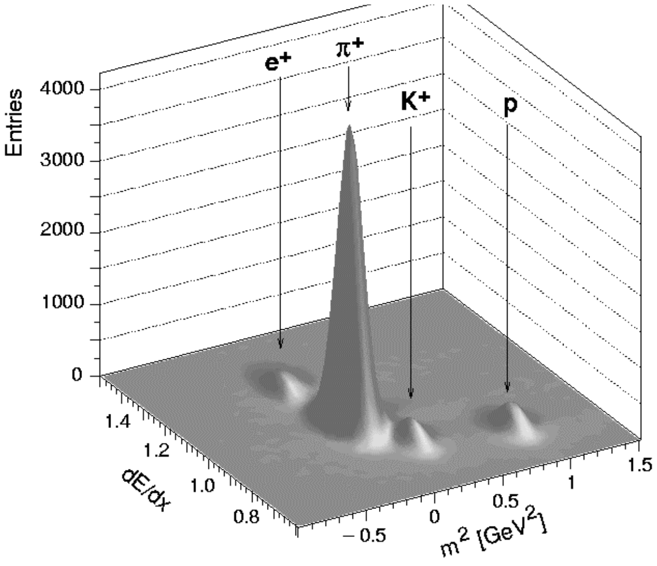
System resolution of the tile stack



From γ conversion in scintillators

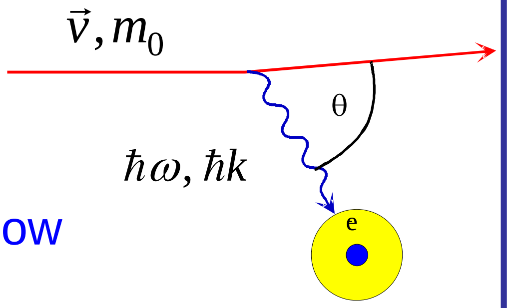


NA49 combined particle ID: TOF + dE/dx (TPC)



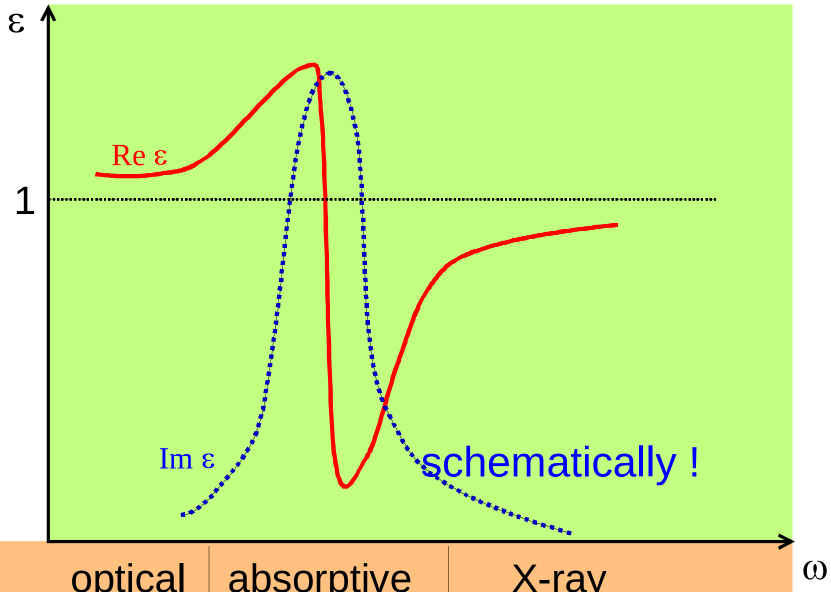
Remember energy loss due to ionisation…

There are other ways of energy loss !



- A photon in a medium has to follow the dispersion relation

$$\omega = 2\pi\nu = 2\pi \frac{c/n}{\lambda} = k\frac{c}{n} \qquad \omega^2 - \frac{k^2c^2}{\varepsilon} = 0 \qquad \varepsilon = n^2$$



regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

- For soft collisions + energy and momentum conservation → real photons:

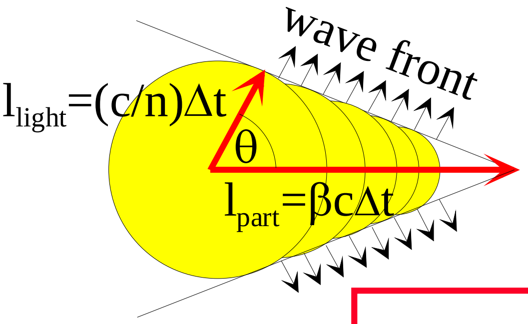
$$\omega \cong \vec{v}\cdot\vec{k} = v\cdot k\cos\theta \quad \rightarrow \quad \cos\theta = \frac{\omega}{vk} = \frac{1}{n\beta} = \frac{1}{\beta\sqrt{\varepsilon}}$$

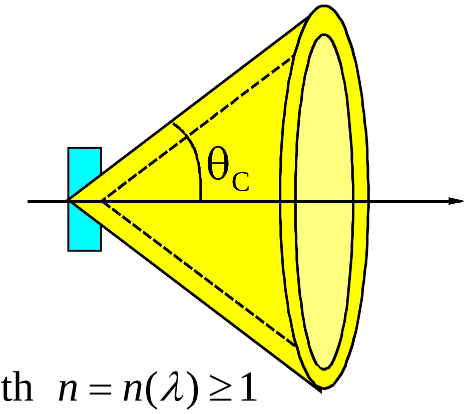
→ Emission of Cherenkov photons if $\beta \geq 1/n$

Cherenkov radiation

Cherenkov radiation is emitted when a charged particle passes a dielectric medium with velocity

$$\beta \geq \beta_{thr} = \frac{1}{n} \quad n: \text{refractive index}$$



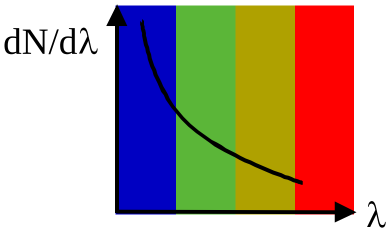


$$\boxed{\cos\theta_C = \frac{1}{n\beta}} \quad \text{with} \quad \underline{n = n(\lambda) \geq 1}$$

$$\beta_{thr} = \frac{1}{n} \quad \rightarrow \quad \theta_C \approx 0$$ threshold

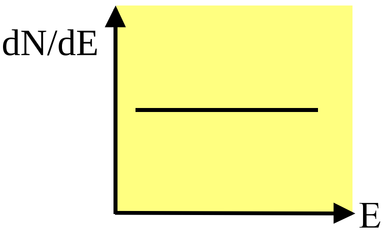
$$\theta_{\max} = \arccos\frac{1}{n}$$ ‘saturated’ angle (β=1)

Number of emitted photons per unit length and unit wavelength interval



$$\frac{d^2N}{dx d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dx d\lambda} \propto \frac{1}{\lambda^2} \quad \text{with} \quad \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dx dE} = const.$$



Cherenkov detectors

medium	n	θ_{max} ($\beta=1$)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

Energy loss by Cherenkov radiation small compared to ionization (≈1%)

Number of detected photo electrons

$$N_{p.e.} = L \sin^2\theta \frac{\alpha}{\hbar c} \int_{E_1}^{E_2} \varepsilon_Q(E) \prod_i \varepsilon_i(E) dE$$

$$N_0 = 370 \cdot eV^{-1} \cdot cm^{-1} \langle \varepsilon_{total} \rangle \Delta E$$

$\Delta E = E_2 - E_1$ is the width of the sensitive window of the photodetector (photomultiplier, photosensitive gas detector...)

Example: for a detector with $\langle \varepsilon_{total} \rangle \Delta E = 0.2 \cdot 1\, eV$ $\quad L = 1\, cm$
and a Cherenkov angle of $\theta_C = 30^\circ$
one expects $N_{p.e.} = 18$ photo electrons

Particle ID with Cherenkov detectors

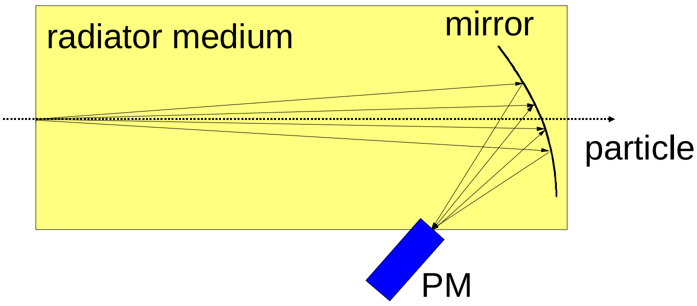
Detectors can exploit ...

- $N_{ph}(\beta)$: threshold detector (do not measure θ_C)
- $\theta(\beta)$: differential and
  Ring Imaging Cherenkov detectors “RICH”

Threshold Cherenkov detectors

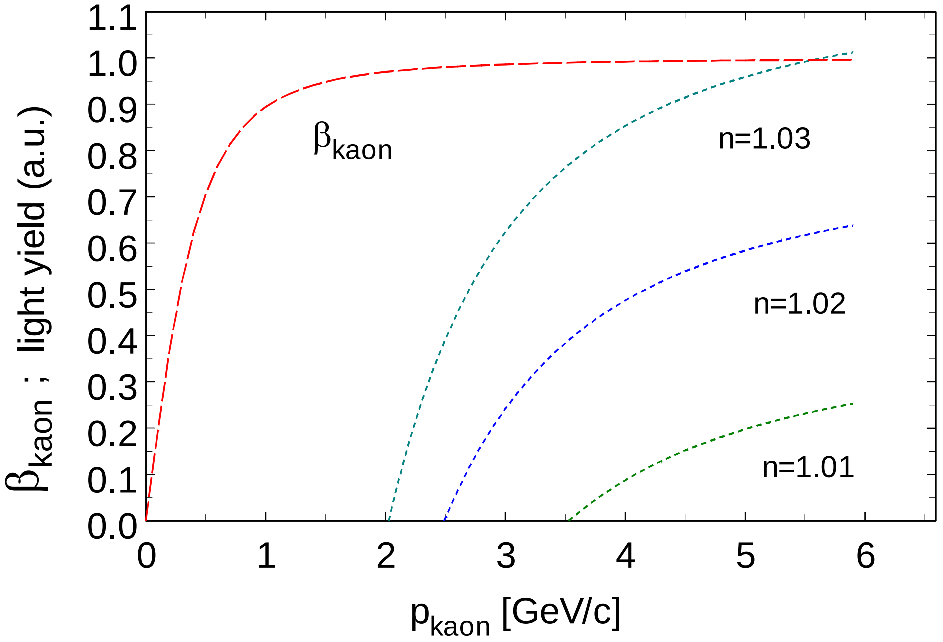
$$N \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\cdot\left(1 + m^2/p^2\right)$$

principle

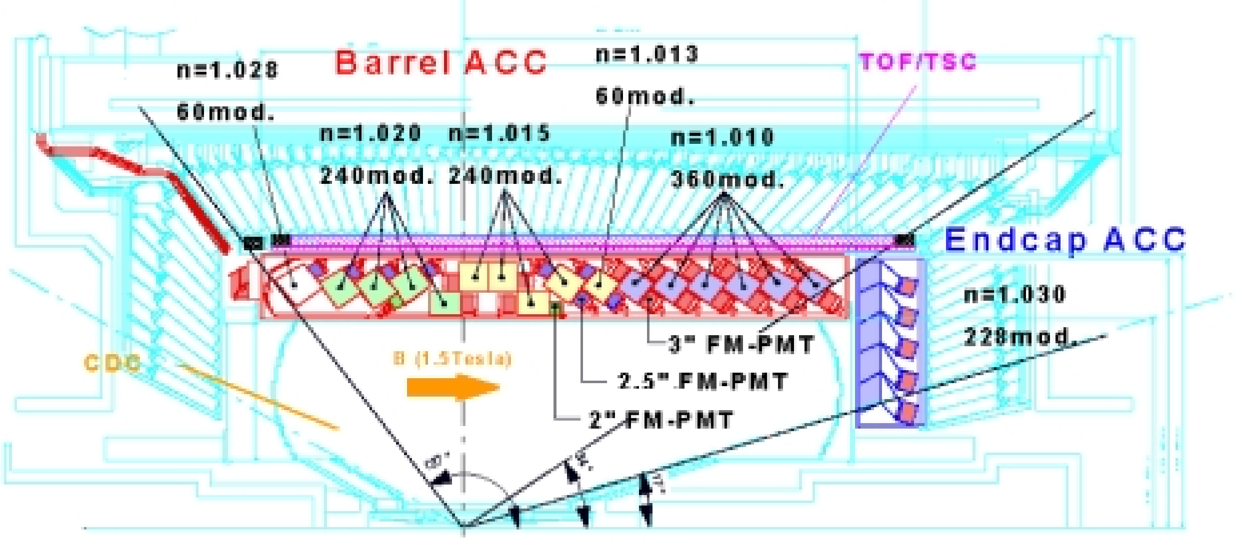


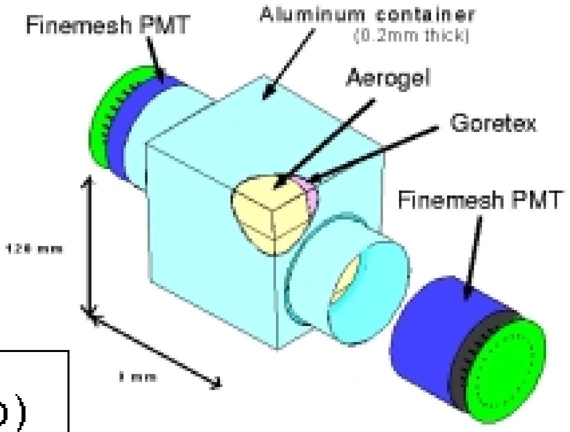
Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

Goal: π/K separation

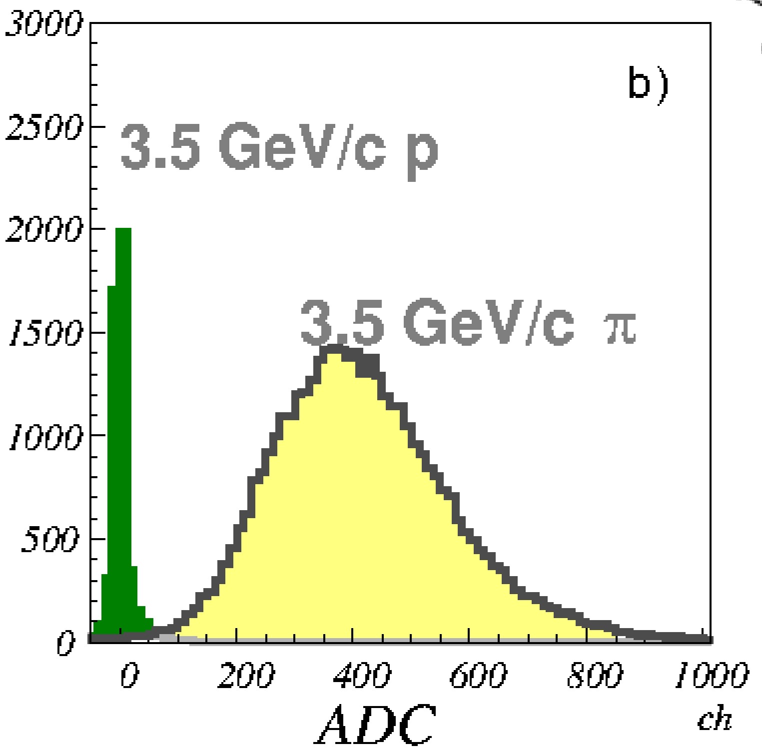


Cherenkov detectors





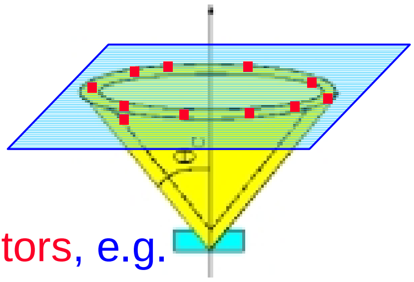
The Belle Detector
edited by S. Mori
KEK Progress Report 2000-4.



Ring Imaging Cherenkov detectors (RICH)

(J. Seguinot, T. Ypsilantis, NIM 142 (1977) 377)

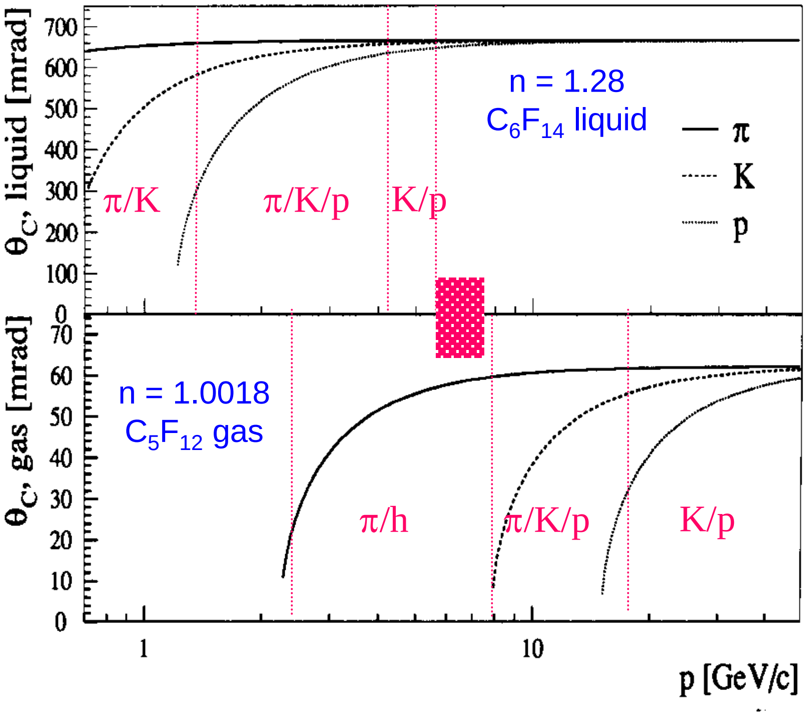
RICH detectors determine θ_C by intersecting the Cherenkov cone with a photosensitive plane



→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right) = \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$



DELPHI

$$\frac{\sigma_\beta}{\beta} = \tan\theta\cdot\sigma_\theta$$

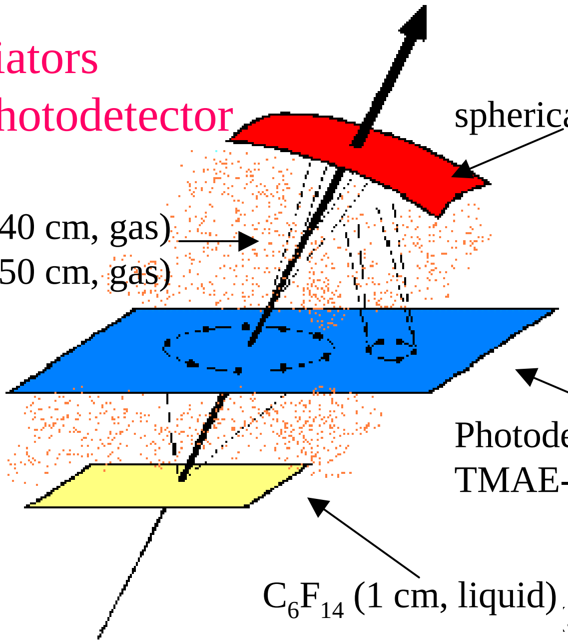
Detect N photons (p.e.) → $\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$

→ minimize σ_θ

→ maximize $N_{p.e.}$

Principle of operation of a RICH detectors

DELPHI RICH



2 radiators
+ 1 photodetector

spherical mirror

C_5F_{12} (40 cm, gas)
C_4F_{10} (50 cm, gas)

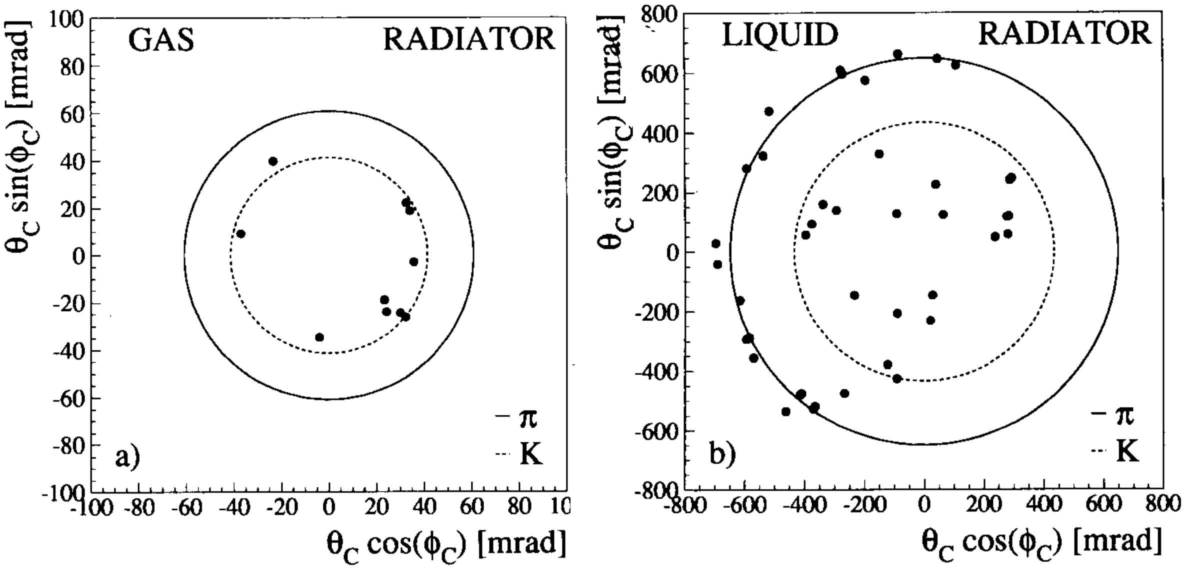
Photodetector
TMAE-based

C_6F_{14} (1 cm, liquid)

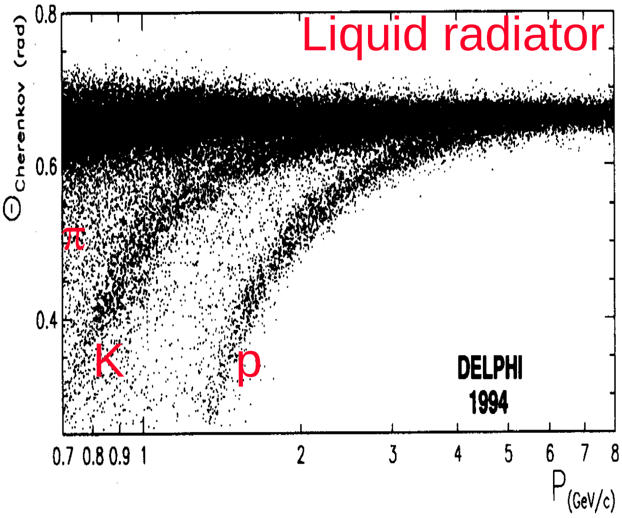
1996) 240)

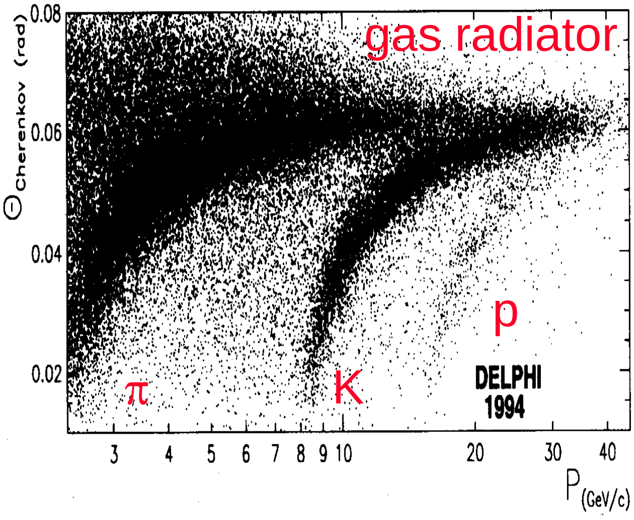
A RICH with two radiators to cover a large momentum range. π/K/p separation 0.7 - 45 GeV/c: DELPHI and SLD

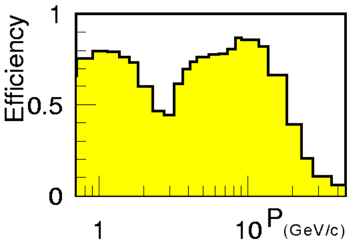
Two particles from a hadronic jet (Z-decay) in the DELPHI gas and liquid radiator + hypothesis for π and K



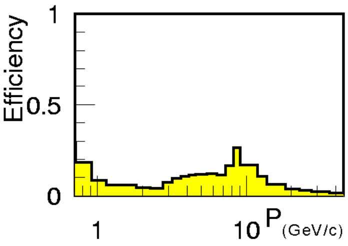
Performance of DELPHI RICH (barrel) in hadronic Z decays



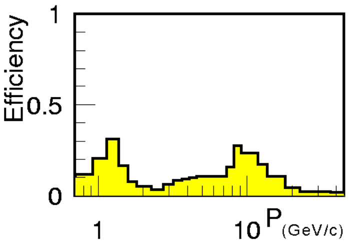




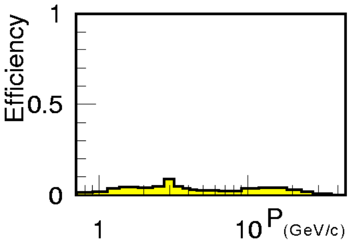
π tagged as π



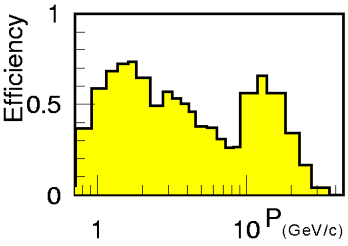
K tagged as π



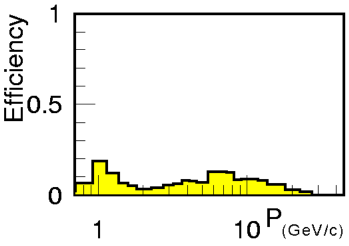
p tagged as π



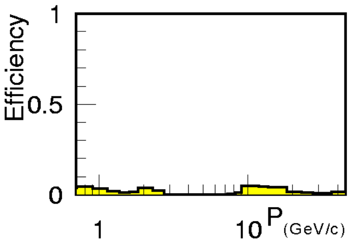
π tagged as K



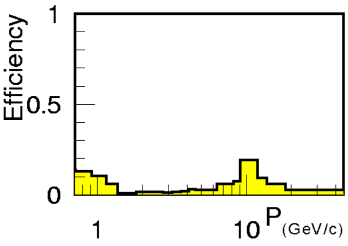
K tagged as K



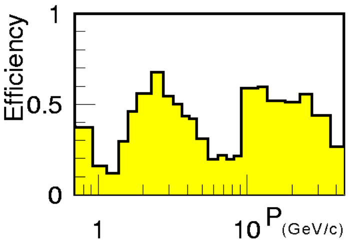
p tagged as K



π tagged as p



K tagged as p



p tagged as p

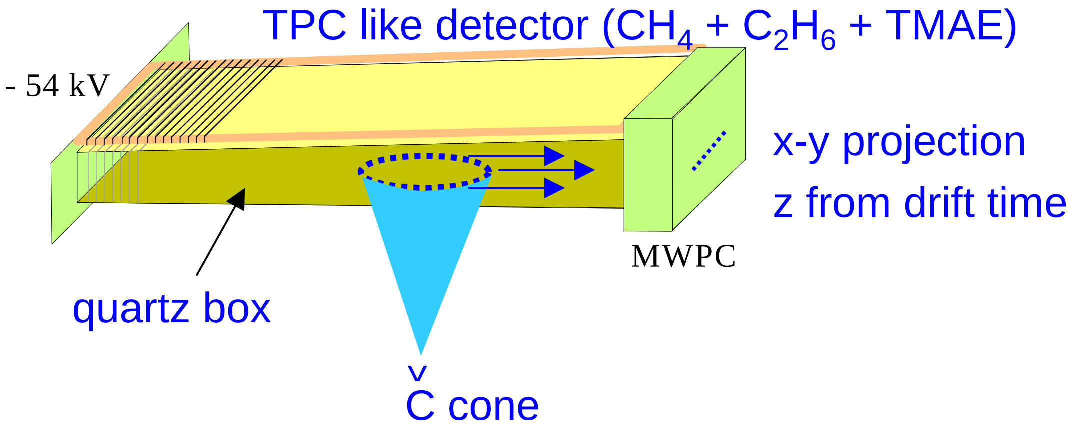
(E. Schyns, PhD thesis, Wuppertal University 1997)

Photo detectors for RICH counters

- Gas based detectors

  Admix photosensitive agent (TEA, TMAE) to detector gas

  example DELPHI:

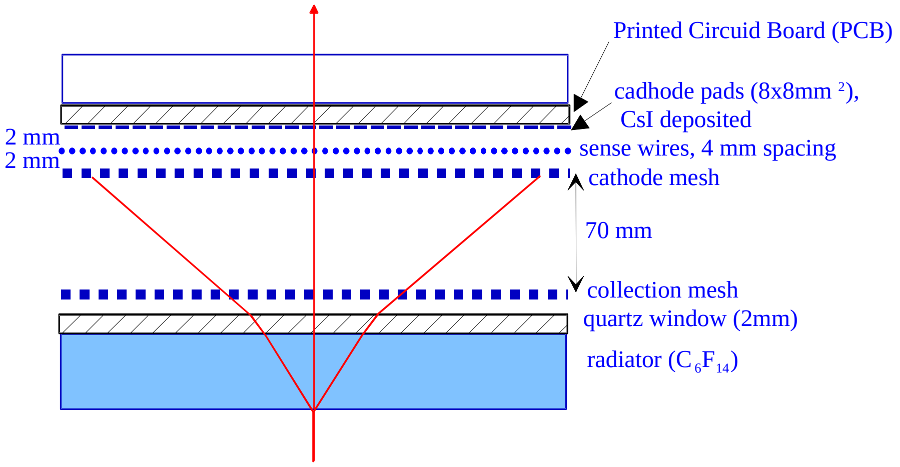


Drawbacks:

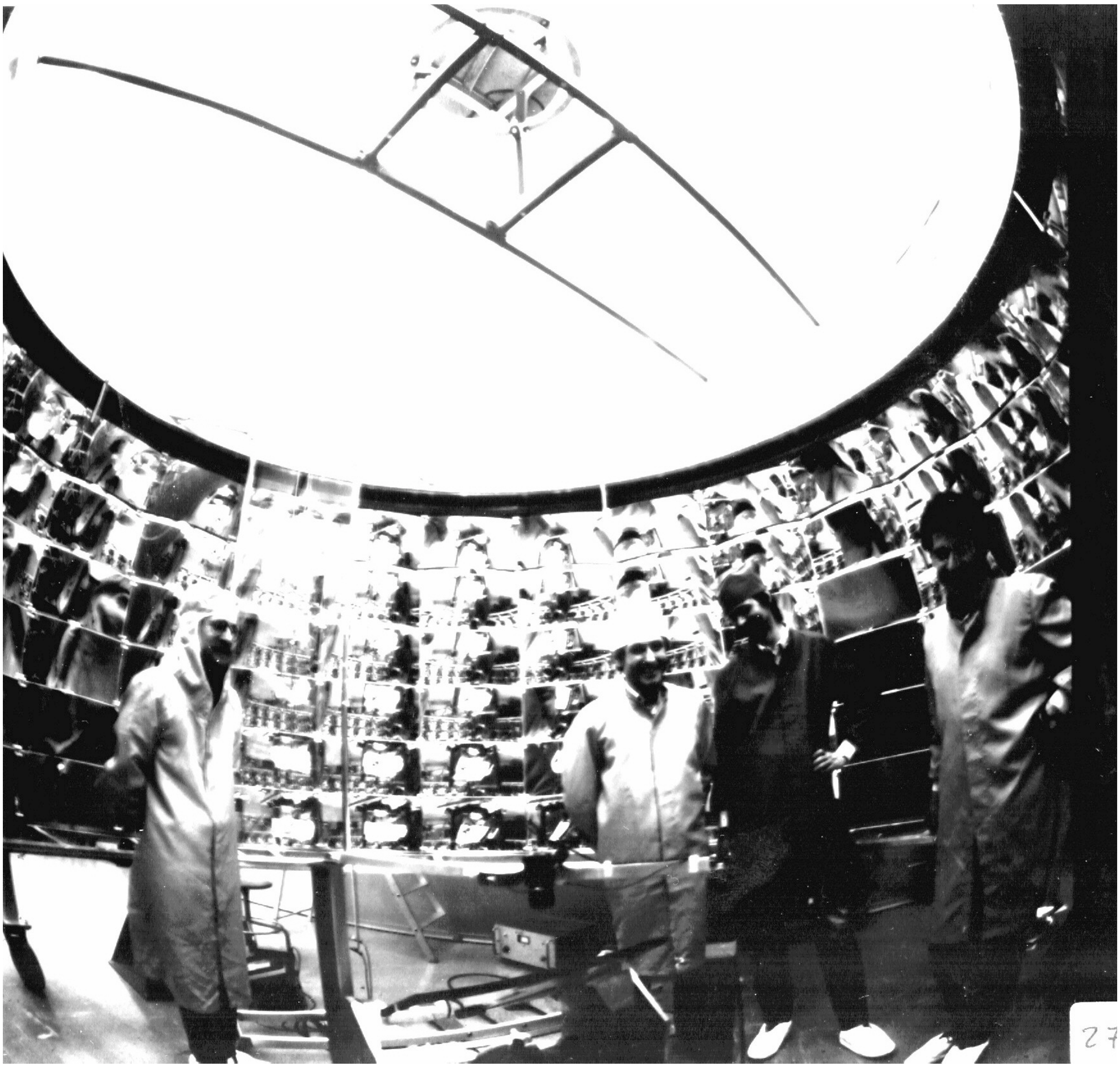
- slow response because of long drift times (many μs)

- λ_{thr}(TMAE) = 220 nm => only sensitive to UV light

example ALICE: A MWPC with CsI deposited cathode pads

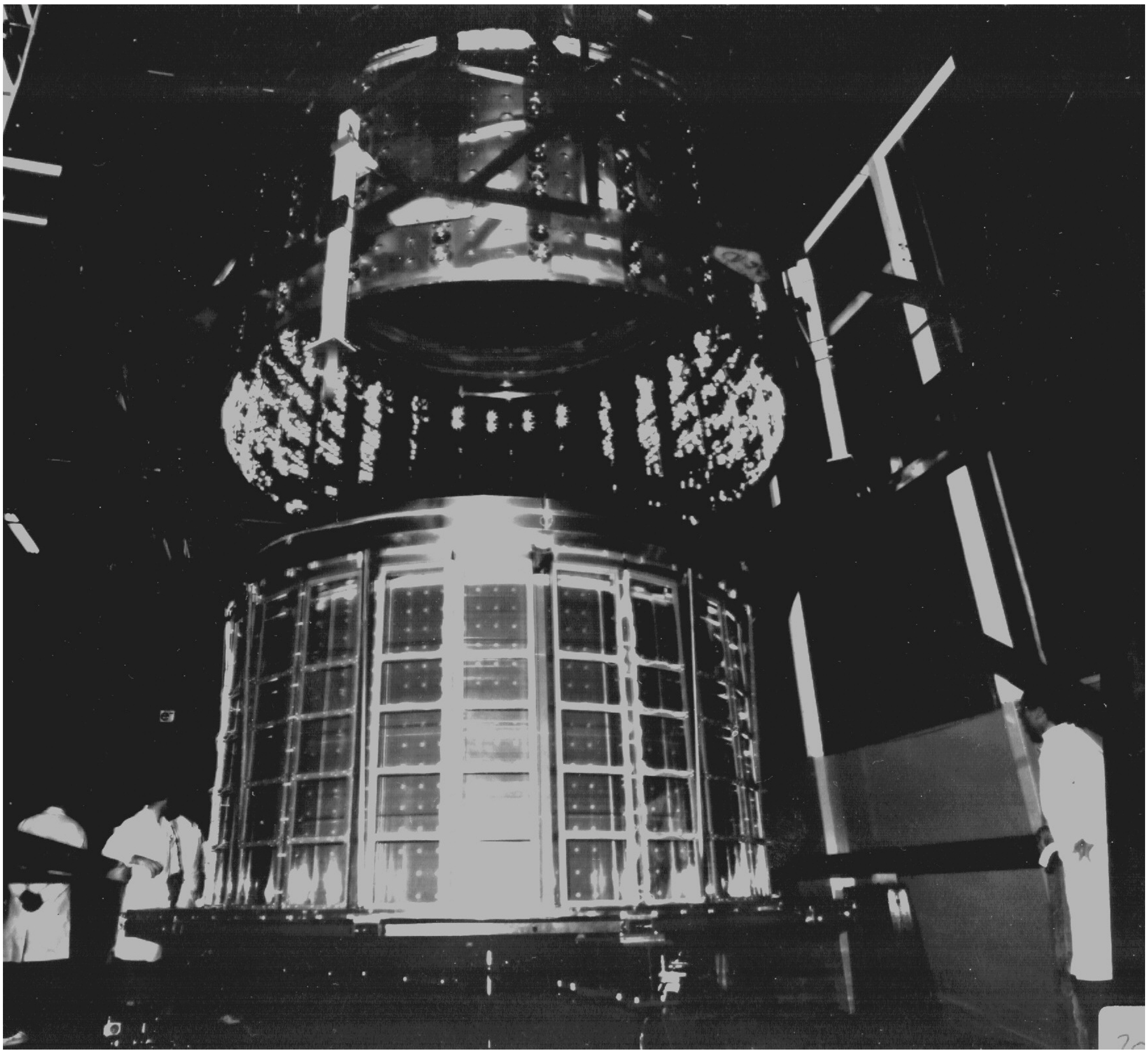


Fast response (<100 ns), but still only sensitive to UV light



The mirror cage of the DELPHI Barrel RICH (288 parabolic mirrors)

Cherenkov detectors

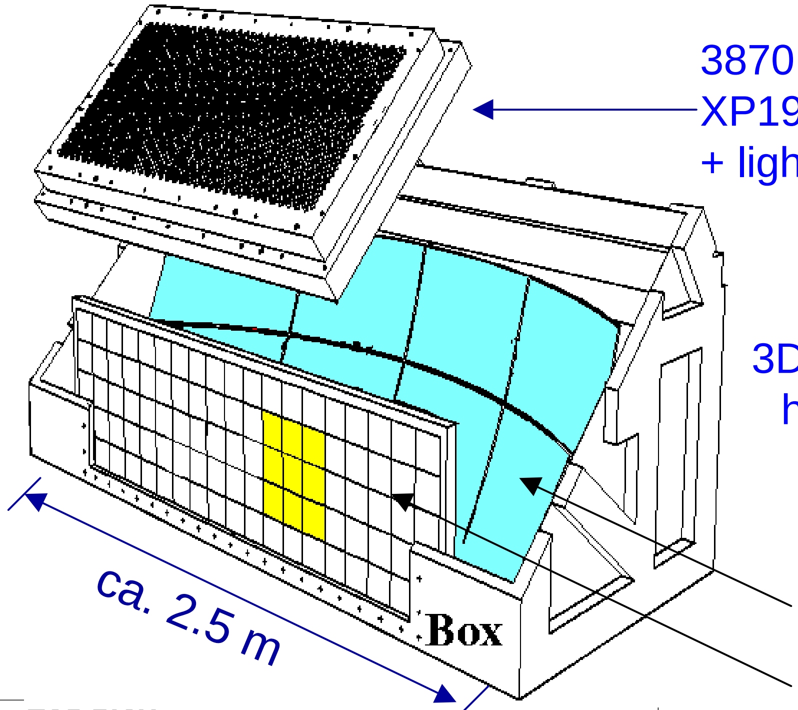


“Marriage” of mirror cage and central detector part of the DELPHI Barrel RICH.

- Vacuum based detectors

Photomultiplier tubes, Hybrid Photo Diodes.

example HERMES (DESY)



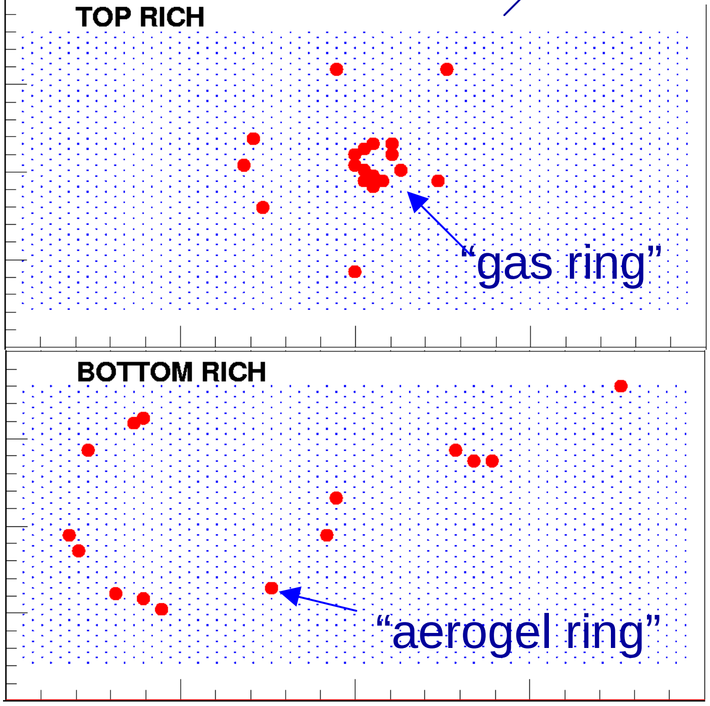
3870 PMTs, Philips XP1911/UV, Ø 3/4” + light funnels

3D view of one half detector

Double radiator

C_4F_{10} gas

Aerogel



Online Event Display

σ_θ ~ 8 mrad

$N_{p.e.}$ (aerogel) = 8

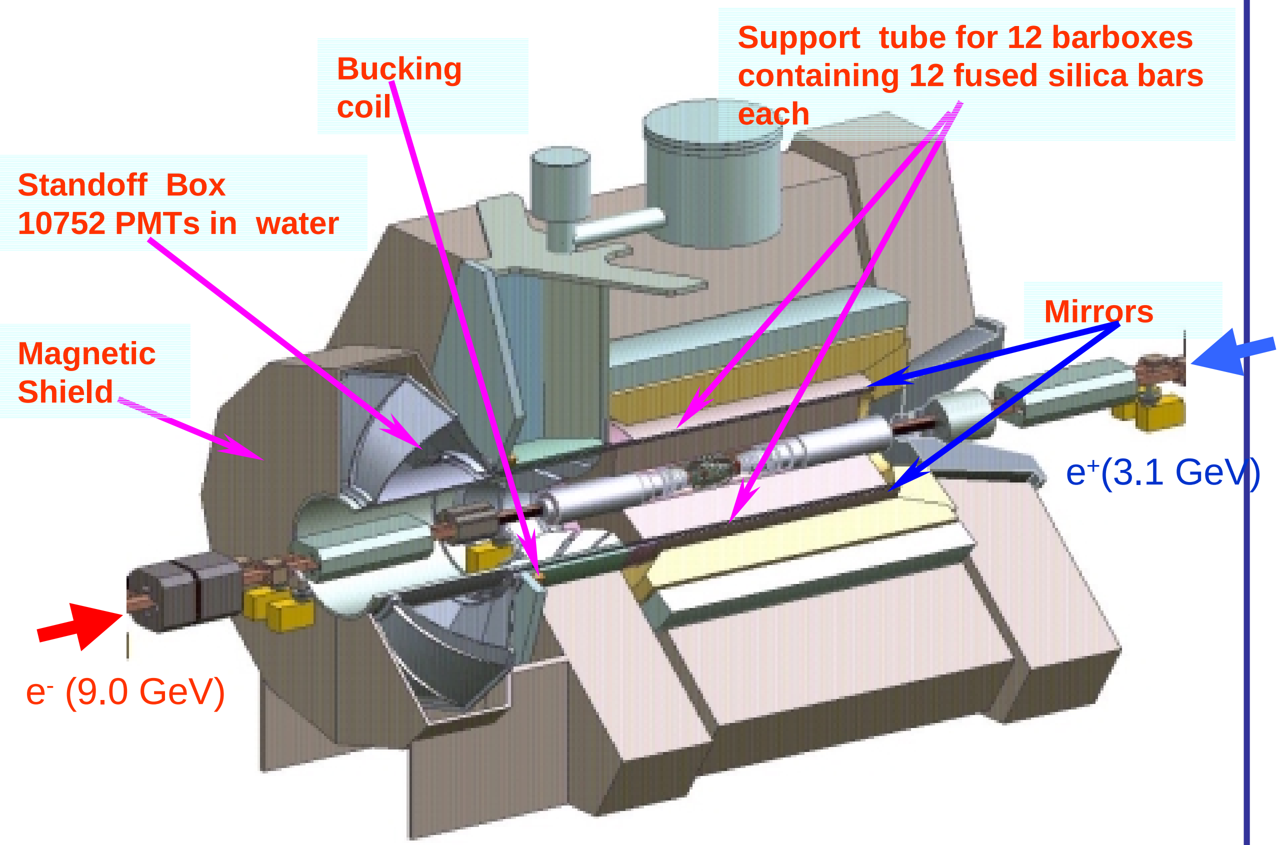
$N_{p.e.}$ (C_4F_{10}) = 12

The DIRC of BaBar

(asymmetric B-factory at SLAC)

Detector for **I**nernally **R**elfected **C**herenkov light

P. Cole et al, NIM A 343 (1999) 456
I. Adam et al., SLAC-PUB-8345



Bucking coil

Support tube for 12 barboxes containing 12 fused silica bars each

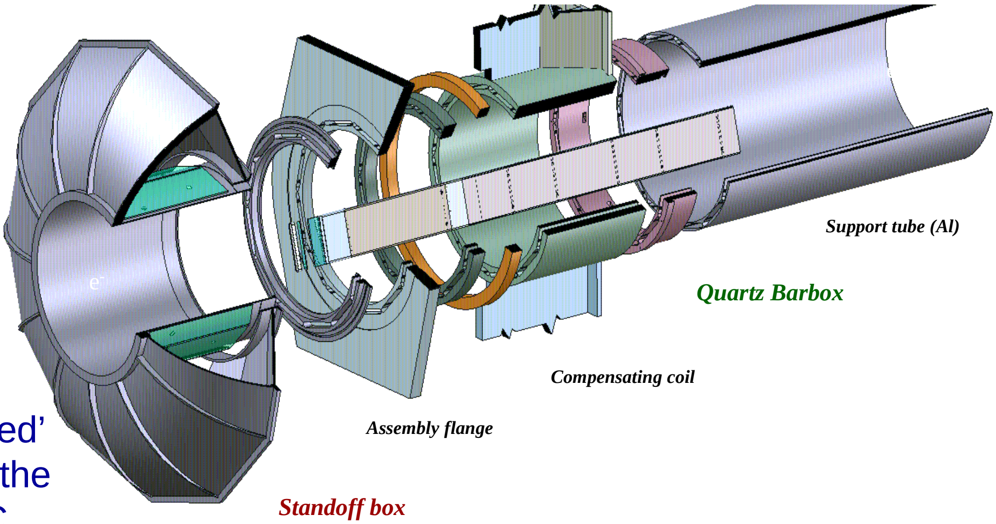
Standoff Box 10752 PMTs in water

Magnetic Shield

Mirrors

e^+(3.1 GeV)

e^- (9.0 GeV)



Support tube (Al)

Quartz Barbox

Compensating coil

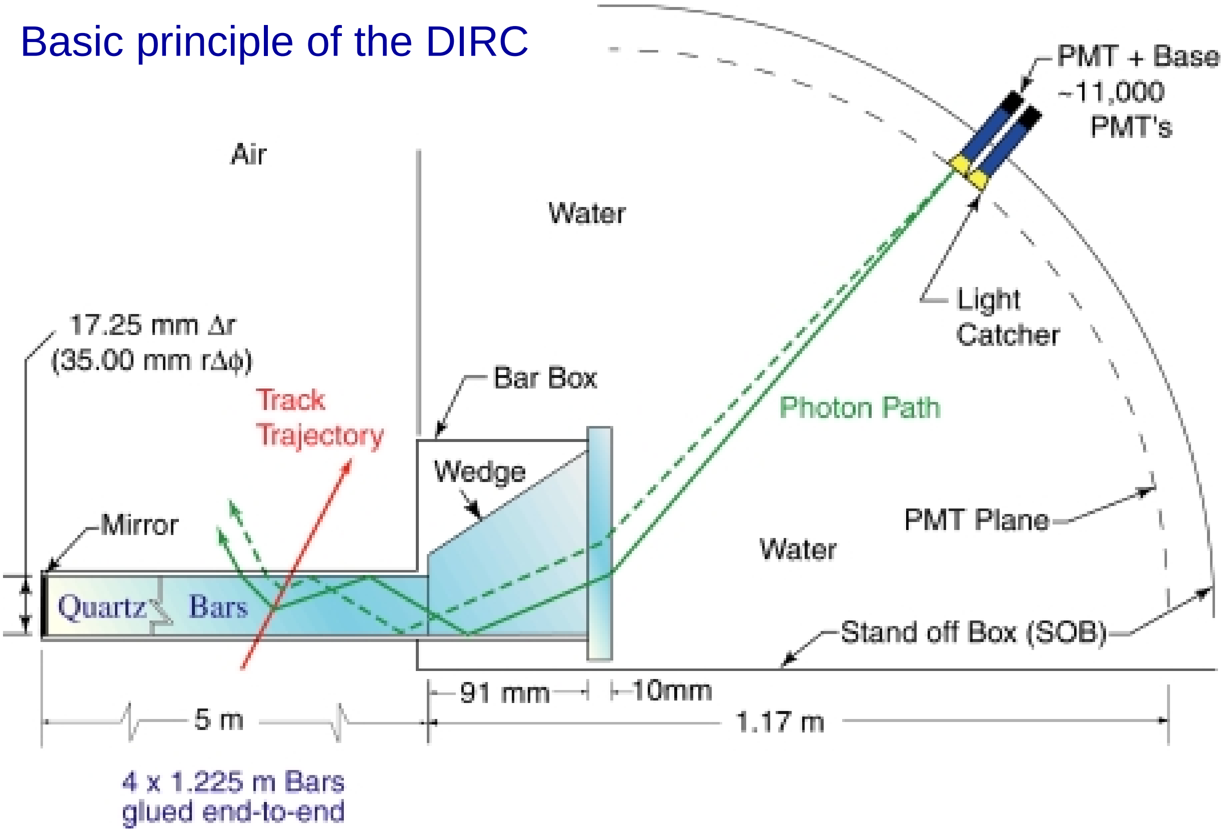
Assembly flange

Standoff box

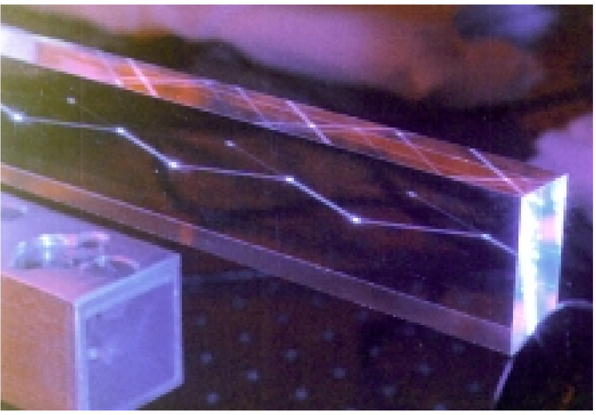
‘exploded’ view of the DIRC

Cherenkov detectors (backup)

Basic principle of the DIRC



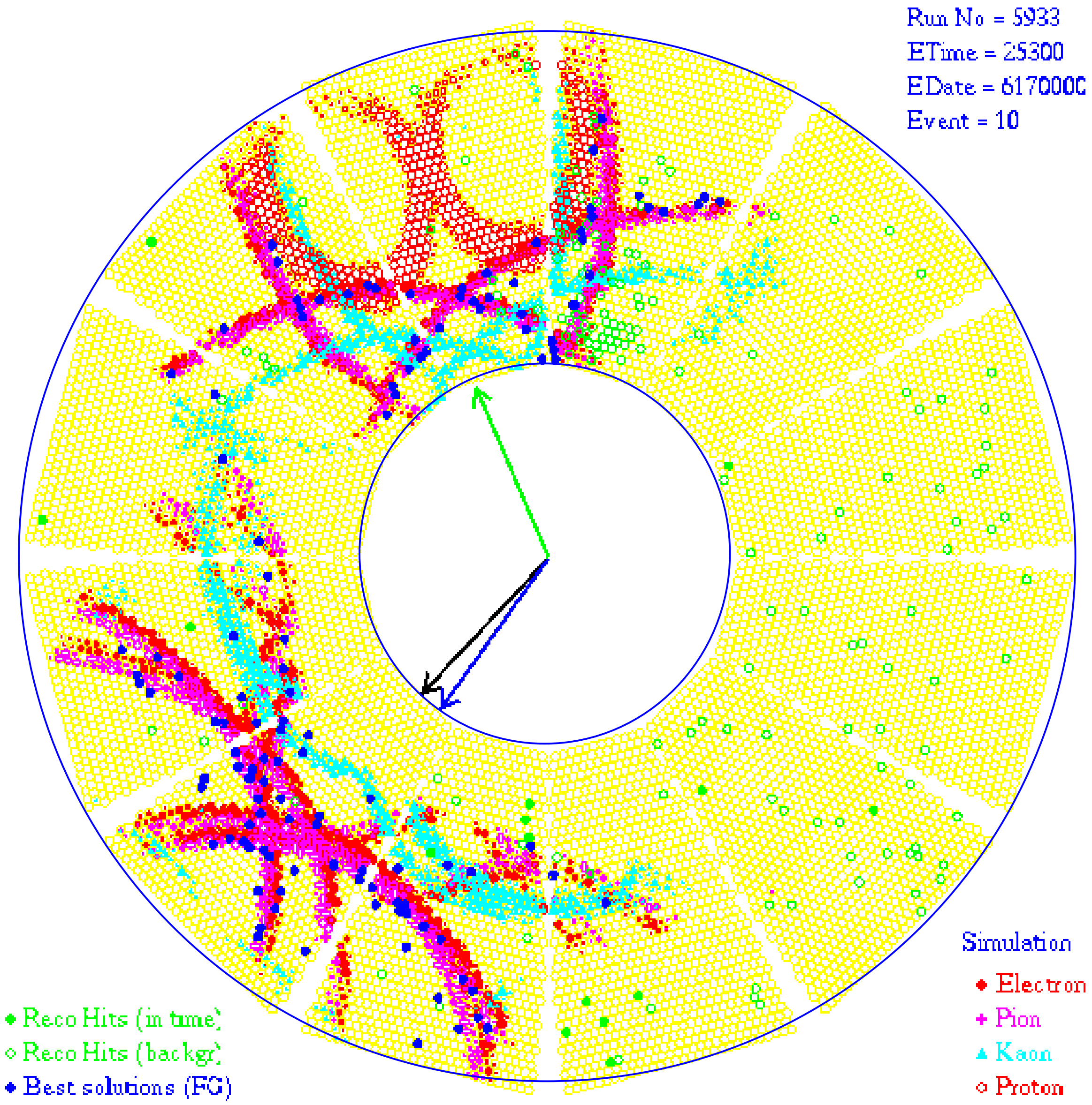
Transport of C-light by internal reflection in quartz bar. Detection by PMT array. Stand off tank filled with water for ref. index matching.



- $N_{quartz} = 1.47$,
- $\theta_{crit.} = 43^o$, $\theta_c^{max} = 47^o$
- $T = 99.9$ % / m
- $R = 99.96$ %
- ~200-400 bounces
- loss ~10-20% = $f(\theta_{dip})$

Cherenkov detectors (backup)

DIRC: Event reconstruction is a bit more difficult !
Cherenkov “ring” is decomposed into disjointed segments.



- σ_θ = 9.8 mrad, (7.0 mrad from $\varnothing_{PMT}$=28 mm, 5.4 mrad from dn/dE).
- $N_{p.e.}$ ~ 30
- π/K separation of 3.1 σ at p = 3 GeV/c

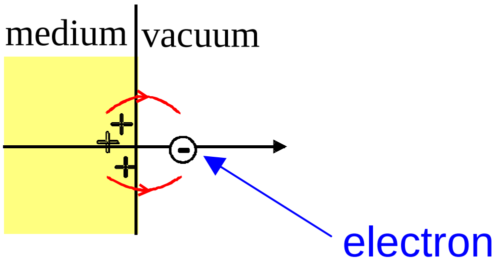
Transition radiation detectors

(there is an excellent review article by B. Dolgoshein (NIM A 326 (1993) 434))

TR predicted by Ginzburg and Franck in 1946

Electromagnetic radiation is emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

A (too) simple picture



A correct relativistic treatment shows that…

(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

- Radiated energy per medium/vacuum boundary

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \boxed{W \propto \gamma} \longrightarrow$$

Only high energy e± will emit TR. Identification of e±

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \qquad \left(\begin{array}{c}\text{plasma}\\ \text{frequency}\end{array}\right) \qquad \hbar\omega_p \approx 20\,\text{eV} \;\; \text{(plastic radiators)}$$

- X-rays are emitted with a sharp maximum at small angle

$$\theta \propto 1/\gamma$$

→ TR stay close to track

Transition radiation detectors

- Number of emitted photons / boundary is small

$$N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$$

Need many transitions → build a stack of many thin foils with gas gaps

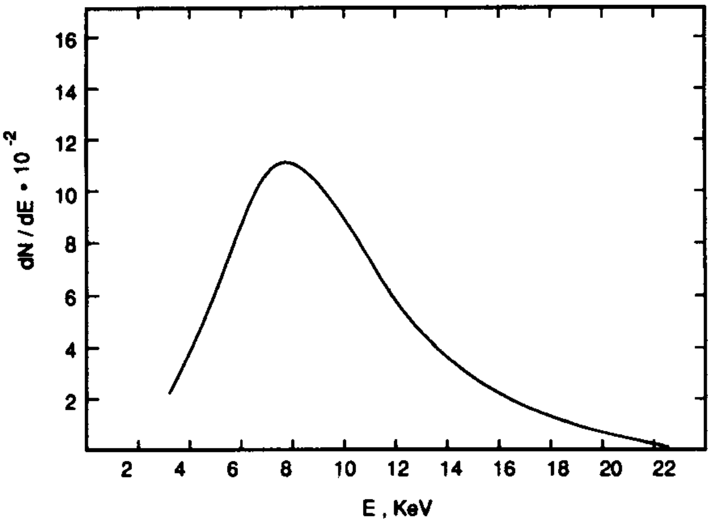
- Particle must traverse a minimum distance, the formation zone $R = c\gamma^2/\omega$, in order to efficiently emit TR.

- Emission spectrum of TR: from optical to X-ray region.

Particle detectors exploit only X-ray part.
Typical energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

→ photons in the keV range

- Simulated emission spectrum of a CH_2 foil stack

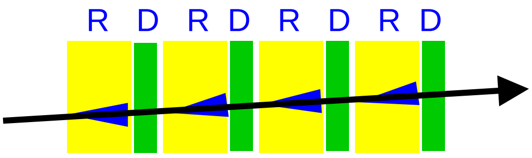


Transition radiation detectors

TR Radiators:

For practical reasons (availability, price, safety) mainly stacks of CH_2 foils are used.

Low Z material preferred to keep re-absorption small ($\propto Z^5$)



sandwich of radiator stacks and detectors

→ minimize re-absorption

Also various hydrocarbon foam and fiber materials have been used (example ATLAS Forward TRT).

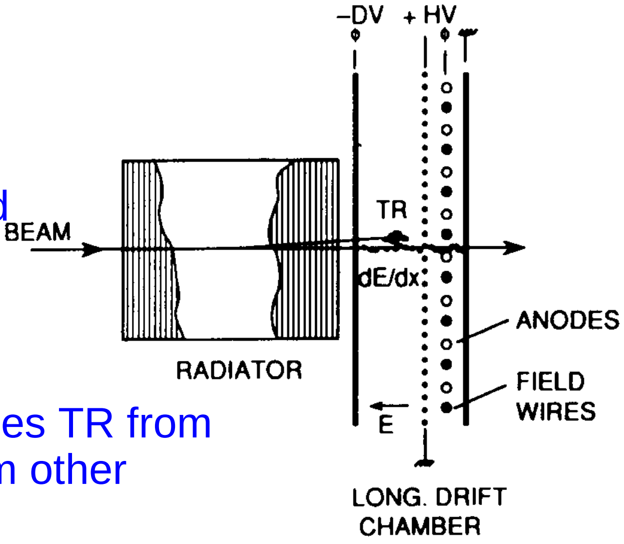
TR yield in foams are smaller than in regular stacks due to large dispersion of mean foil thickness and pore size.

TR X-ray detectors:

- Detector should be sensitive for $3 \le E_\gamma \le 30$ keV.
- Mainly used: Gaseous detectors.
  MWPC, drift chamber, straw tubes…
- Detector gas:

  $\sigma_{\text{photo effect}} \propto Z^5$

  → gas with high Z required
  Xenon (Z=54) is a good candidate



Intrinsic problem: detector sees TR from electrons, but also dE/dx from other particles.

ATLAS **Transition** **Radiation** **Tracker**

A prototype endcap “wheel”.

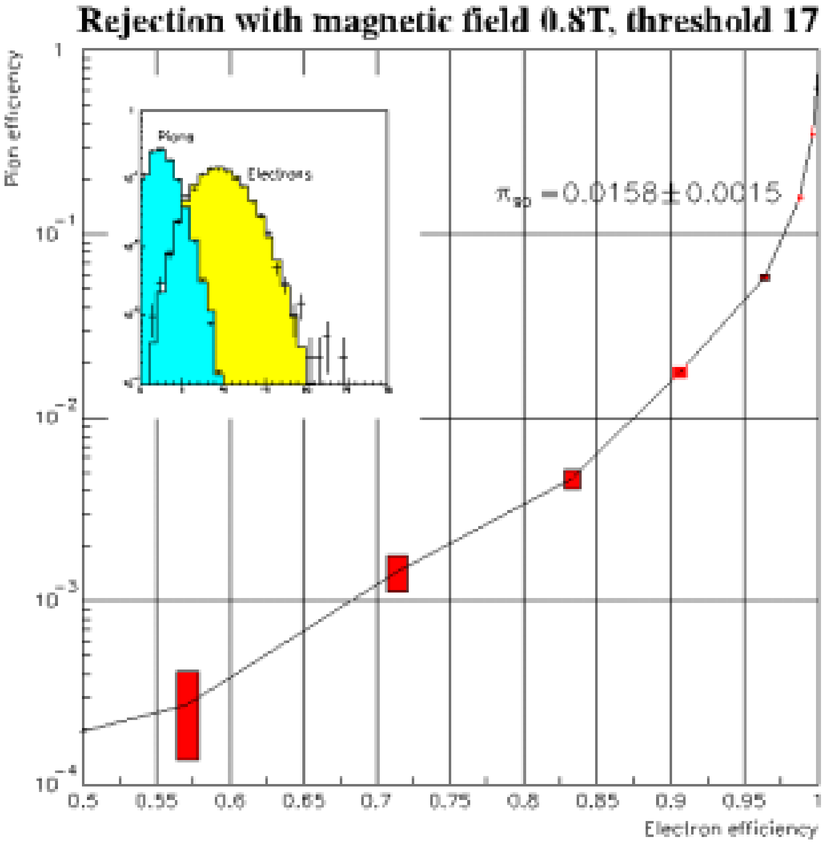
X-ray detector:
straw tubes (4mm)
(in total ca. 400.000 !)

Xe based gas

TRT protoype performance

Pion fake rate at 90% electron detection efficiency:

π_{90} = 1.58 %



Summary:

- A number of powerful methods are available to identify particles over a large momentum range.
- Depending on the available space and the environment, the identification power can vary significantly.

A very coarse plot ….