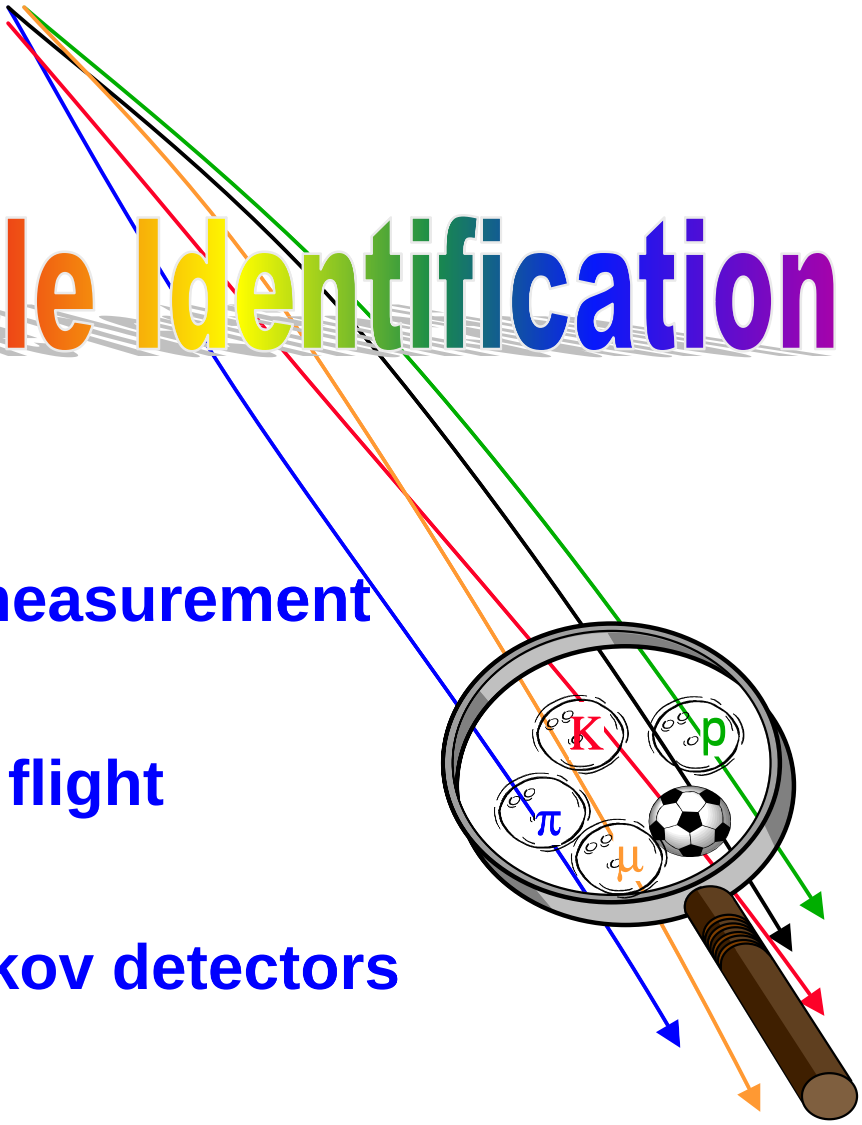
Particle Identification



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

Why particle ID ?

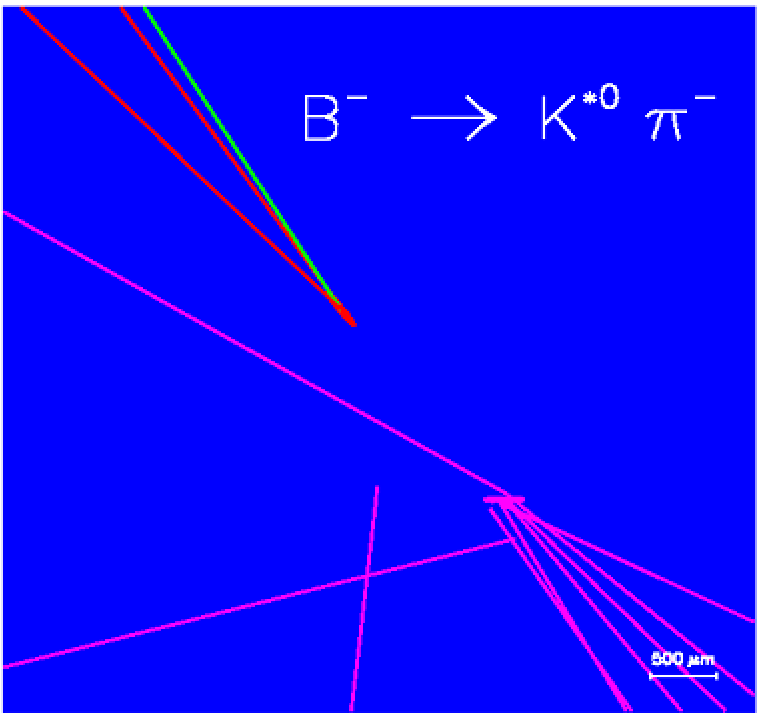
DELPHI

A 'charmless' B decay:

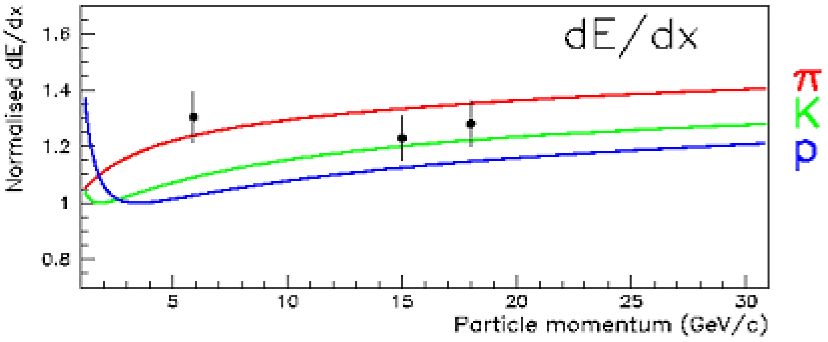
$$\begin{array}{c} B^- \rightarrow K^* \pi^- \\ \downarrow \\ K\pi \end{array}$$

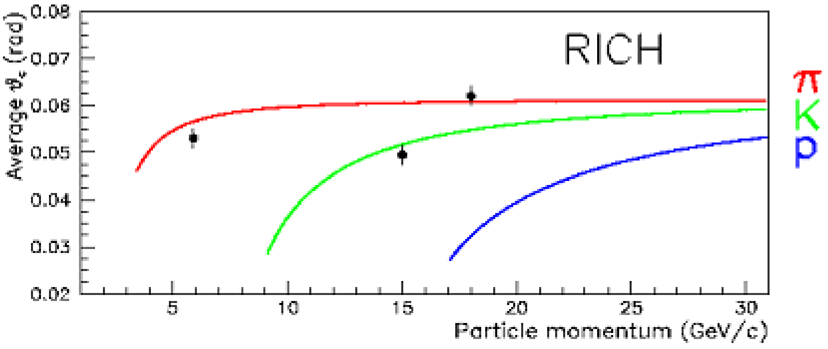
1 K + 2 π

in final state



Who is who ?

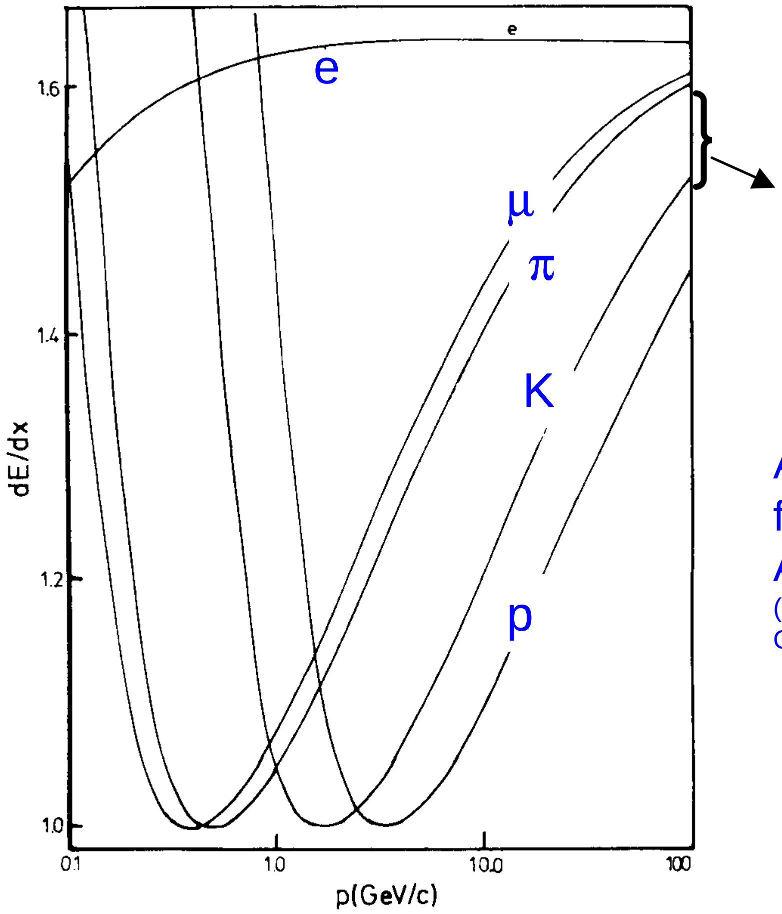




Particle ID using the specific energy loss dE/dx

$$\left.\begin{array}{l} p = m_0 bg \\ \dfrac{dE}{dx} \propto \dfrac{1}{b^2}\ln\left(b^2 g^2\right) \end{array}\right\}$$

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)

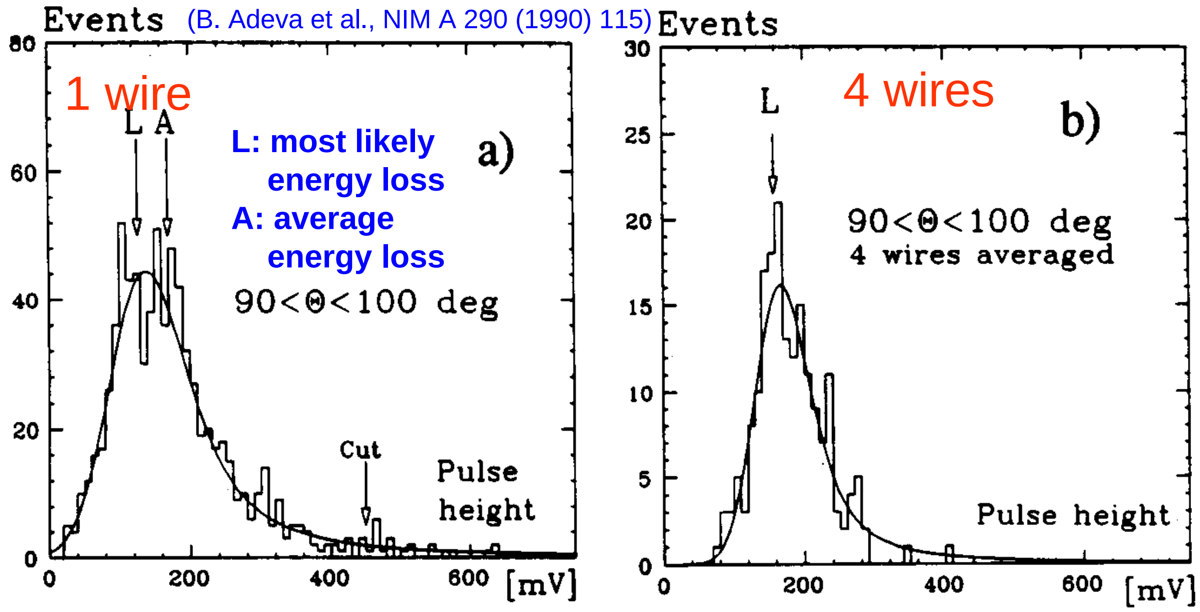
(J.N. Marx, Physics today, Oct.78)

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)

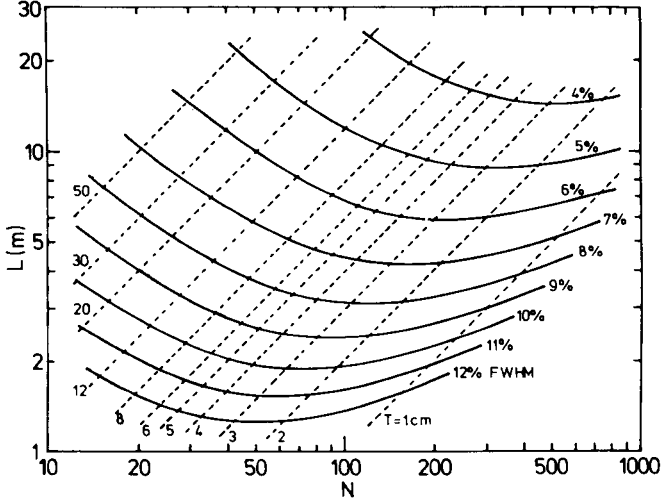
1 wire

L: most likely energy loss

A: average energy loss

4 wires

(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.

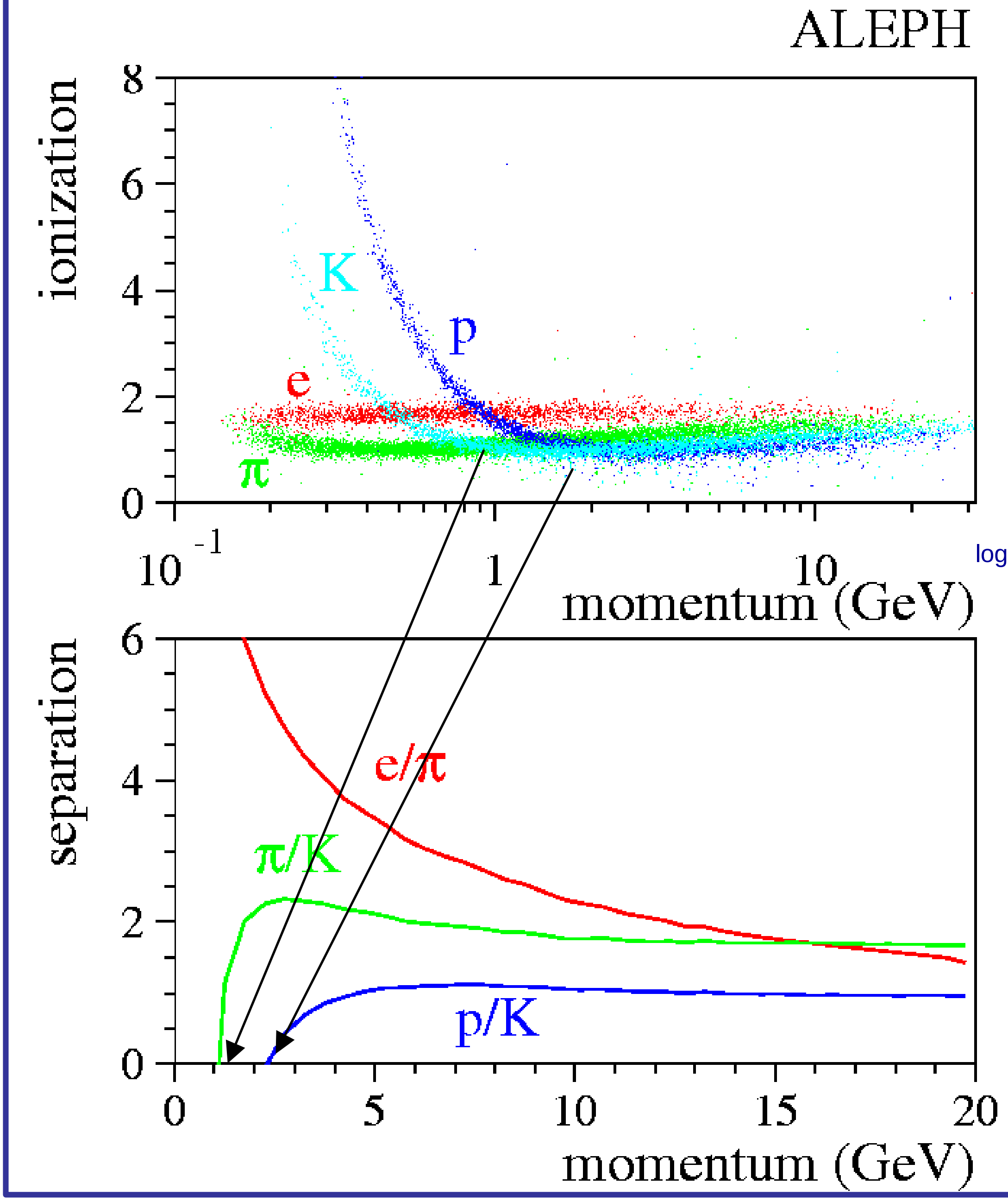
- calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values
- Also pressure increase can improve resolution, but reduced rel. rise due to density effect !

Example ALPEPH TPC

Gas: Ar/CH_4 90/10

$N_{samples}$ = 338, wire spacing 4 mm

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



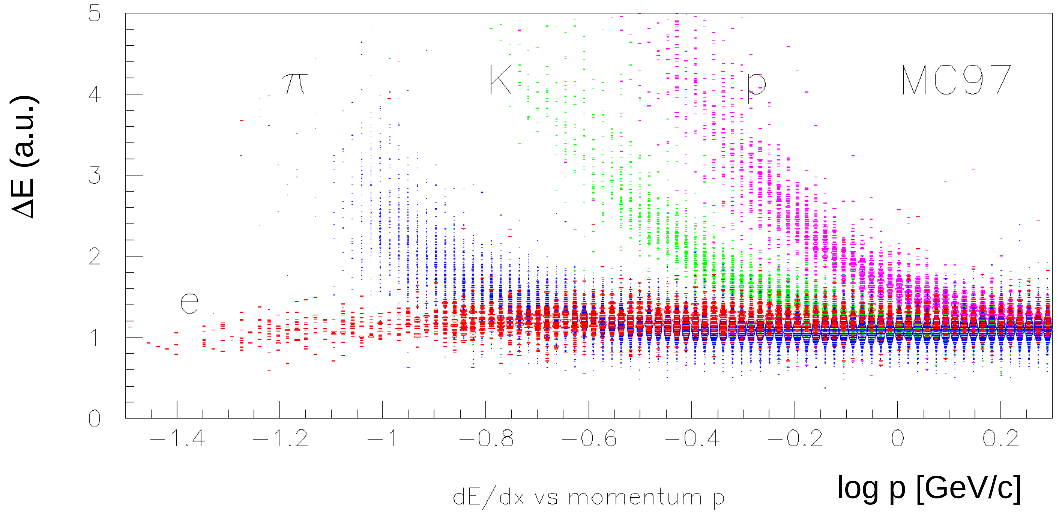
log scale !

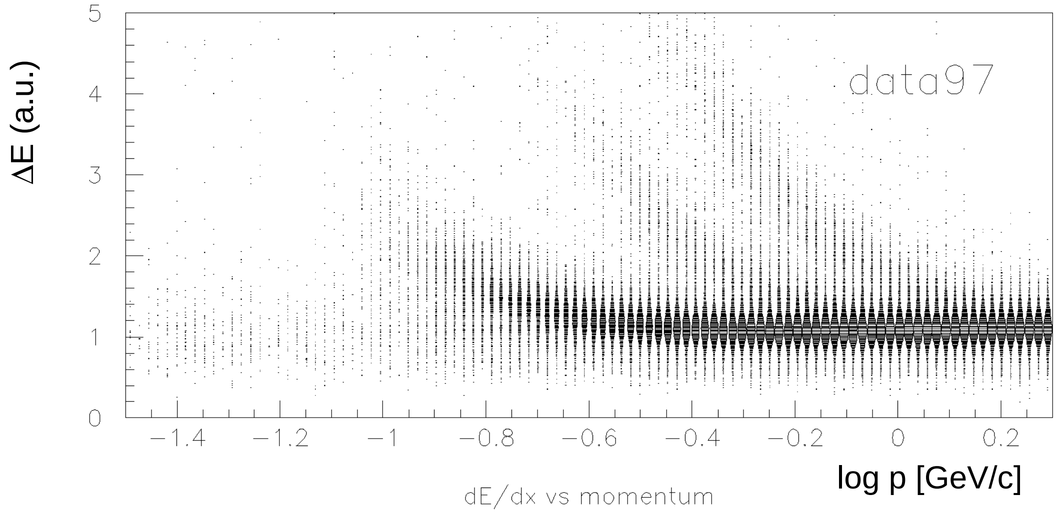
linear scale !

Specific energy loss

dE/dx can also be used in Silicon detectors

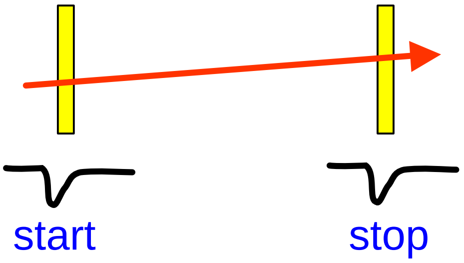
Example DELPHI microvertex detector (3 x 300 µm Silicon)





Particle ID using Time Of Flight (TOF)

$$t = \frac{L}{bc}$$



Combine TOF with momentum measurement $(p = m_0 bg)$

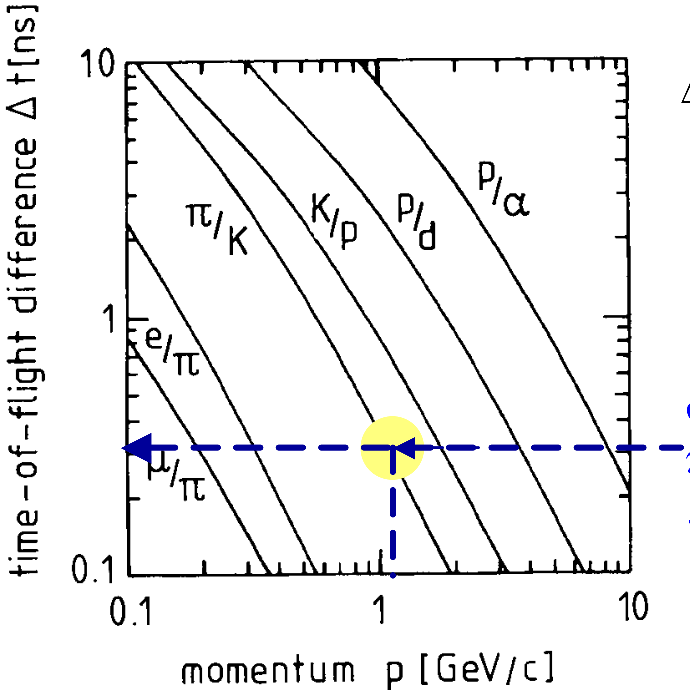
$$m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$$

Mass resolution

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

TOF difference of 2 particles at a given momentum

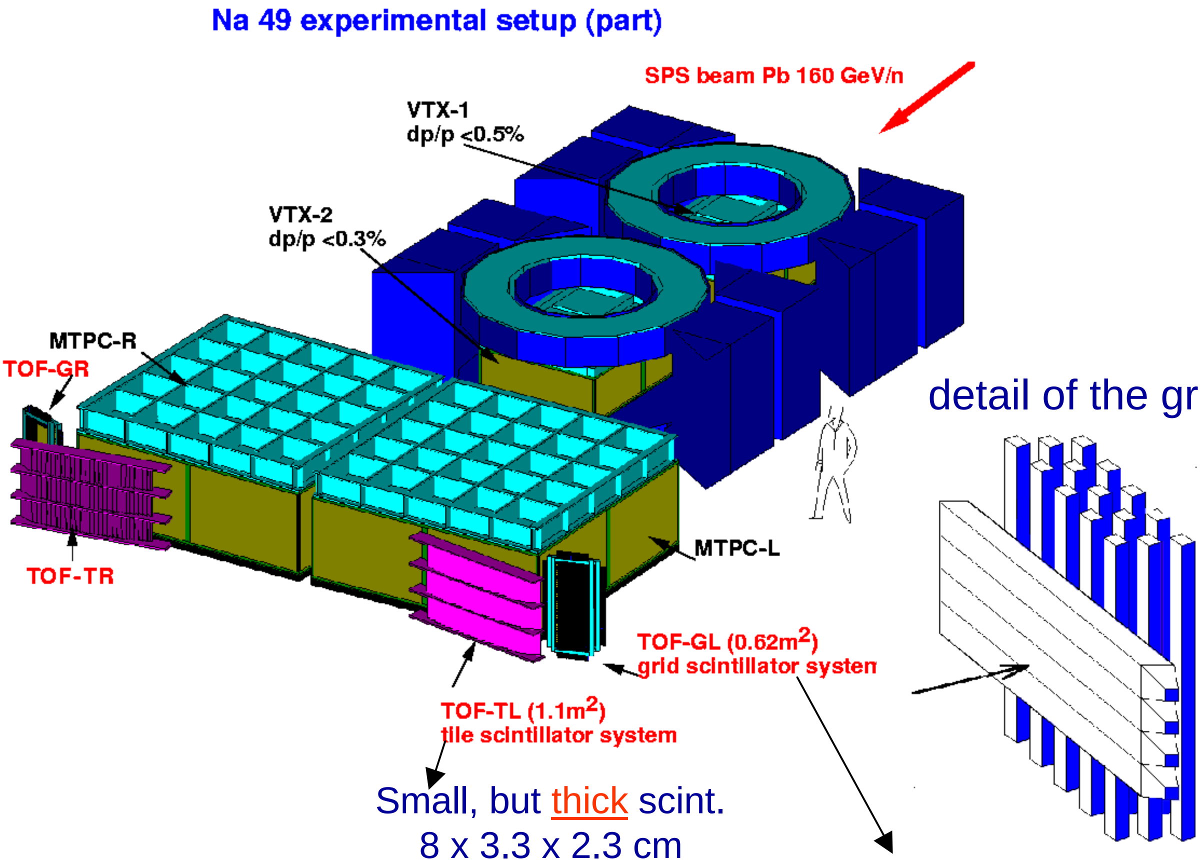
$$\Delta t = \frac{L}{c}\left(\frac{1}{b_1} - \frac{1}{b_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2c^2/p^2} - \sqrt{1 + m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$



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



detail of the grid

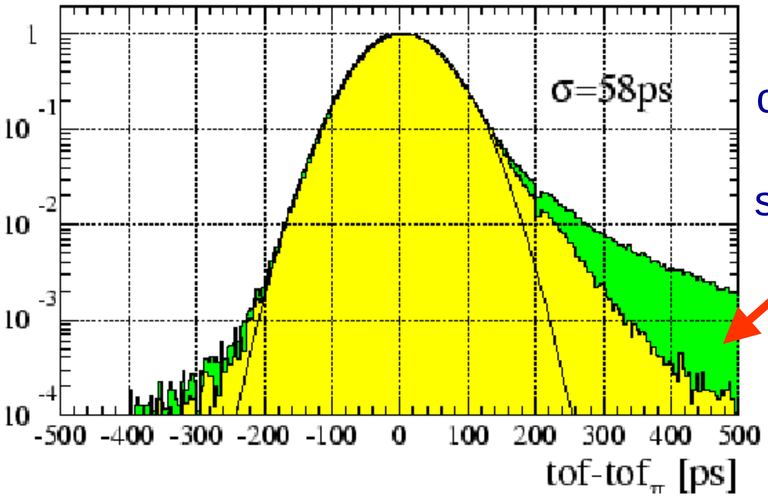
Small, but thick scint.
8 x 3.3 x 2.3 cm

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

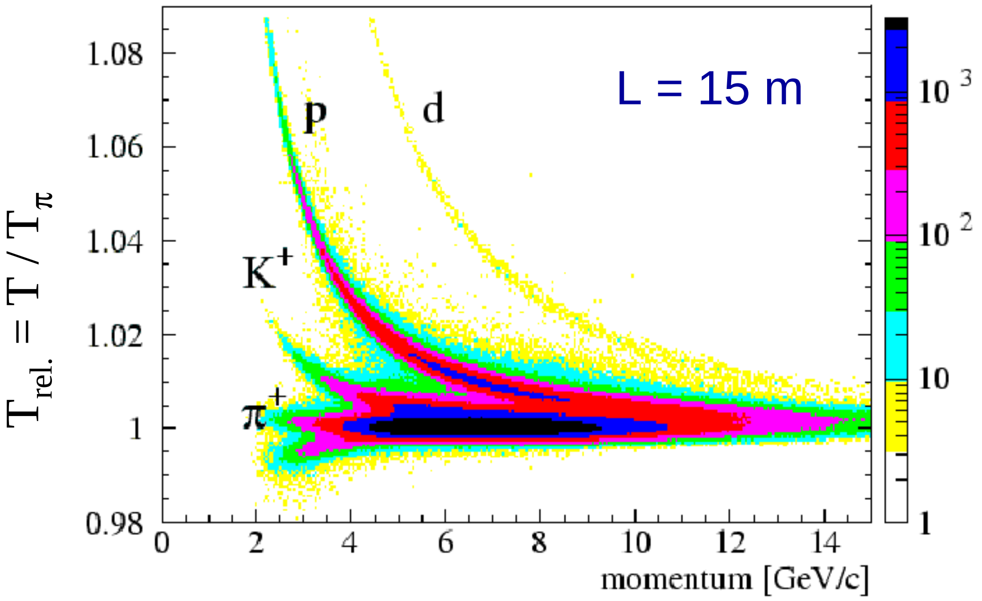
TOF requires fast detectors (plastic scintillator, gaseous detectors), approporiate signal processing (constant fraction discrimination, corrections + continuous stability monitoring.

Time of flight

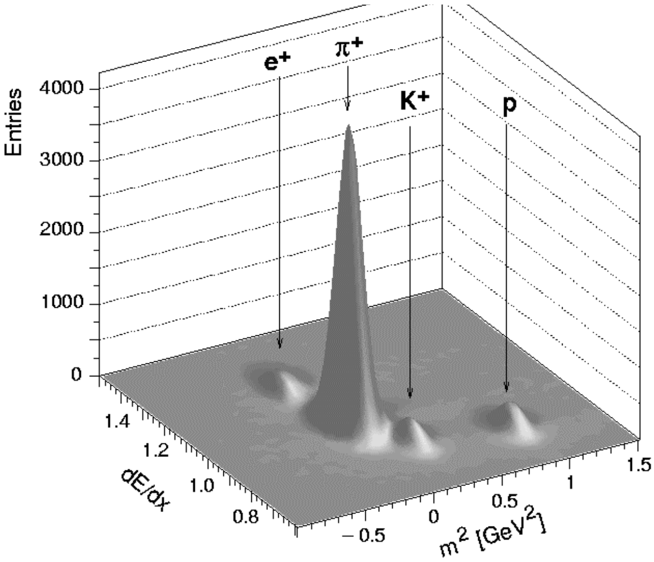
System resolution of the tile stack



From γ conversion in scintillators

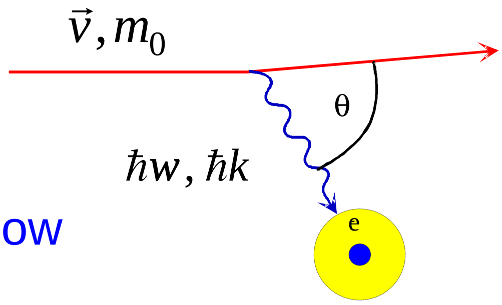


NA49 combined particle ID: TOF + dE/dx (TPC)



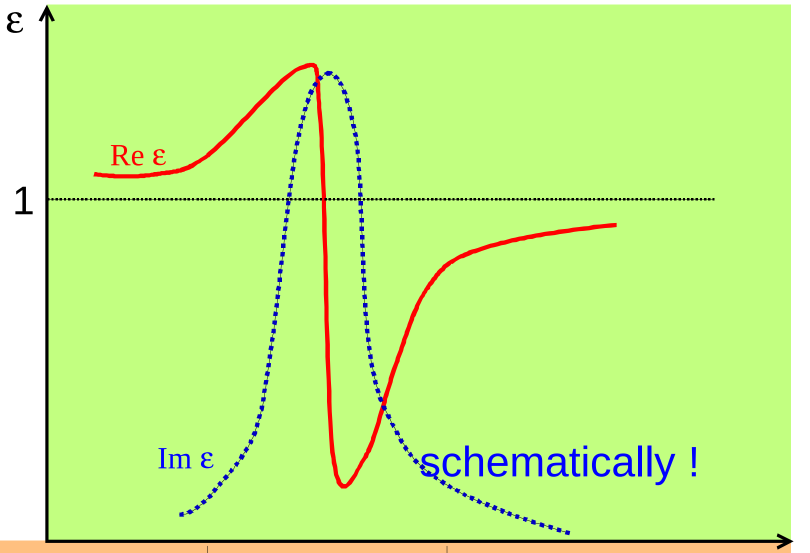
Remember energy loss due to ionisation…

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:

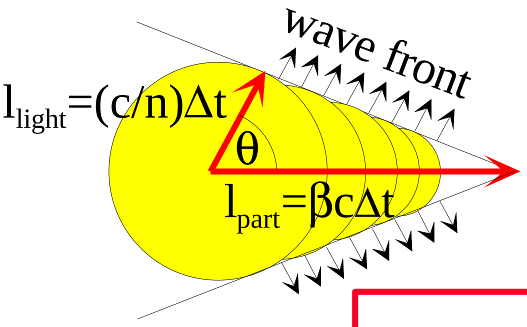
$$\omega \cong \vec{v}\cdot\vec{k} = v\cdot k\cos\theta \quad \rightarrow \quad \cos\theta = \frac{\omega}{vk} = \frac{1}{n\beta} = \frac{1}{\beta\sqrt{\varepsilon}}$$

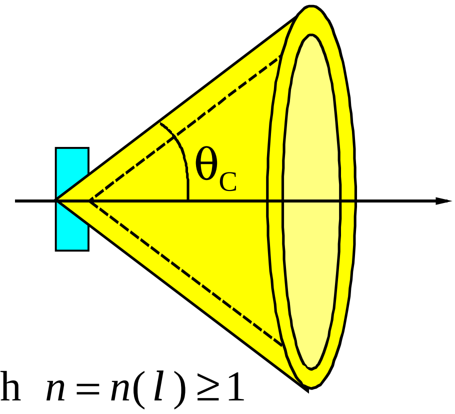
→ Emission of Cherenkov photons if $\beta \geq 1/n$

Cherenkov radiation

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

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



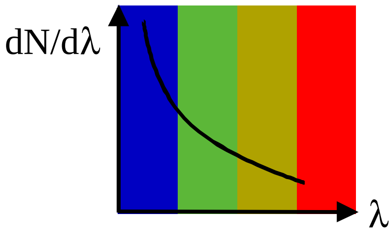


$$\boxed{\cos\theta_C = \frac{1}{n\beta}} \quad \text{with} \quad \underline{n = n(\lambda) \geq 1}$$

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

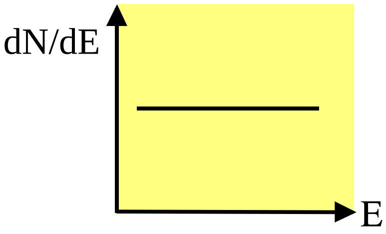
$$\theta_{\max} = \arccos\frac{1}{n}$$ 'saturated' angle (β=1)

Number of emitted photons per unit length and unit wavelength interval



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

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



medium	n	θ_{max} (β=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

$$N_{p.e.} = L \sin^2 q \, \frac{a}{\hbar c} \int_{E_1}^{E_2} e_Q(E) \prod_i e_i(E) \, dE$$

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

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

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

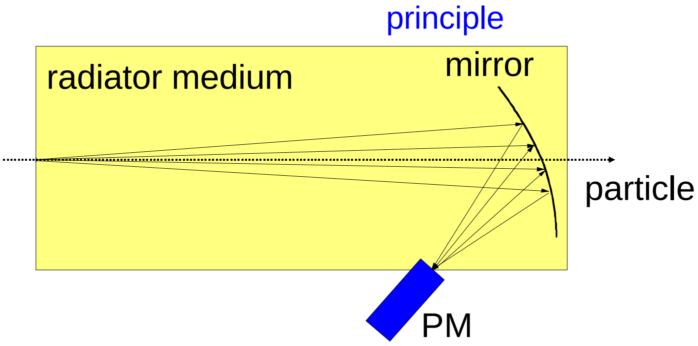
Particle ID with Cherenkov detectors

Detectors can exploit ...

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

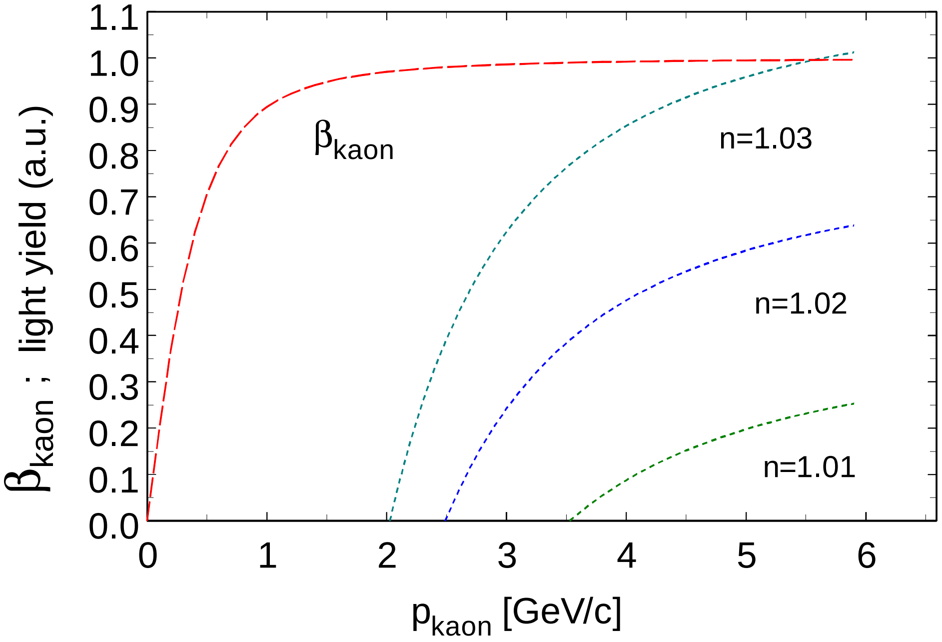
Threshold Cherenkov detectors

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

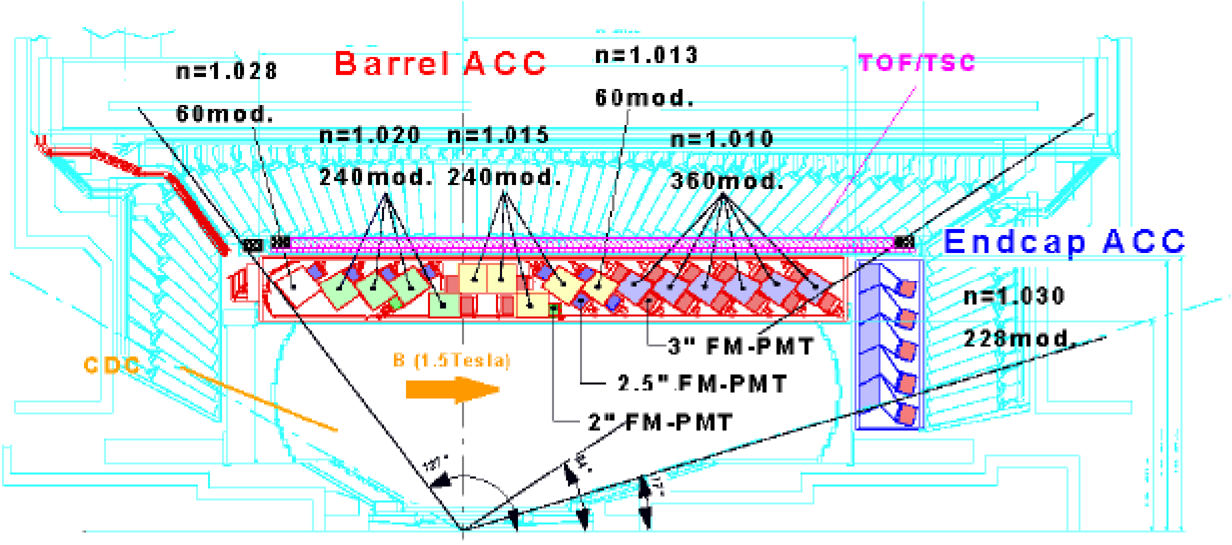


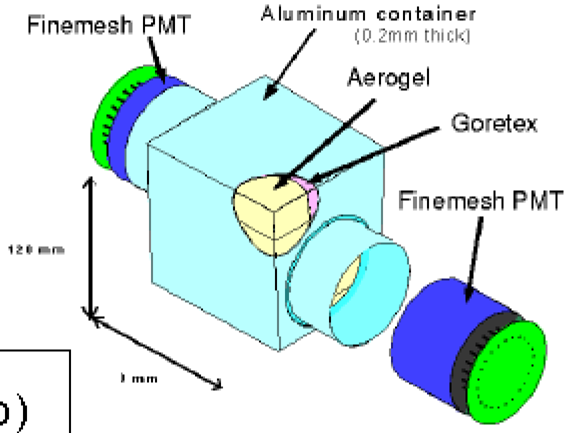
Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

Goal: π/K separation

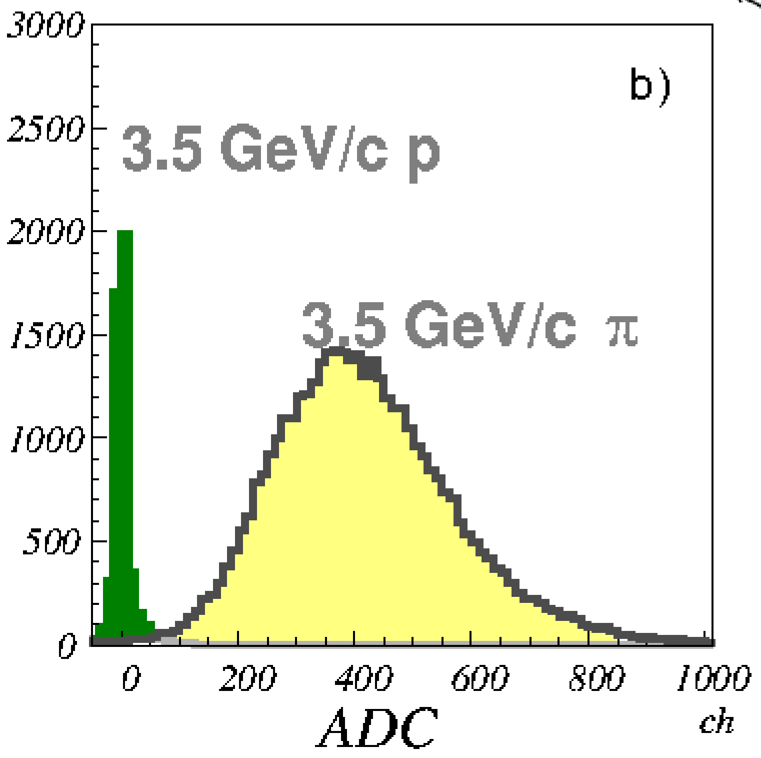


Cherenkov detectors





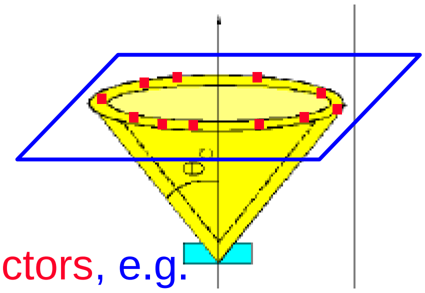
The Belle Detector
edited by S. Mori
KEK Progress Report 2000-4.



Ring Imaging Cherenkov detectors (RICH)

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

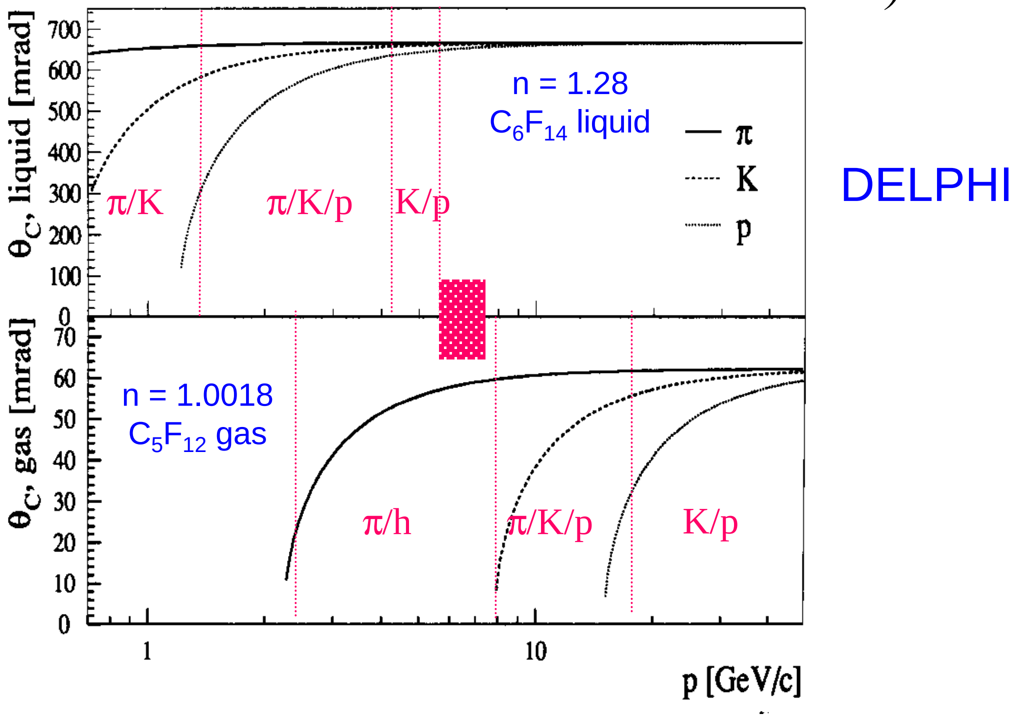
RICH detectors determine θ_C by intersecting the Cherenkov cone with a photosensitive plane



→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

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



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

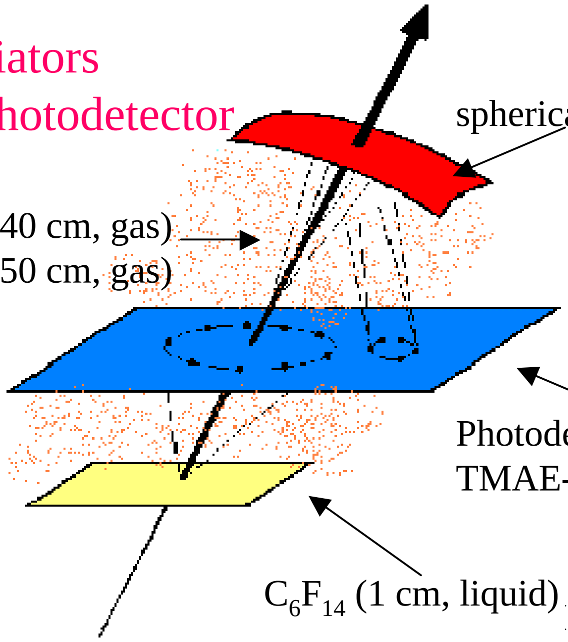
Detect N photons (p.e.) → $\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$

→ 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)

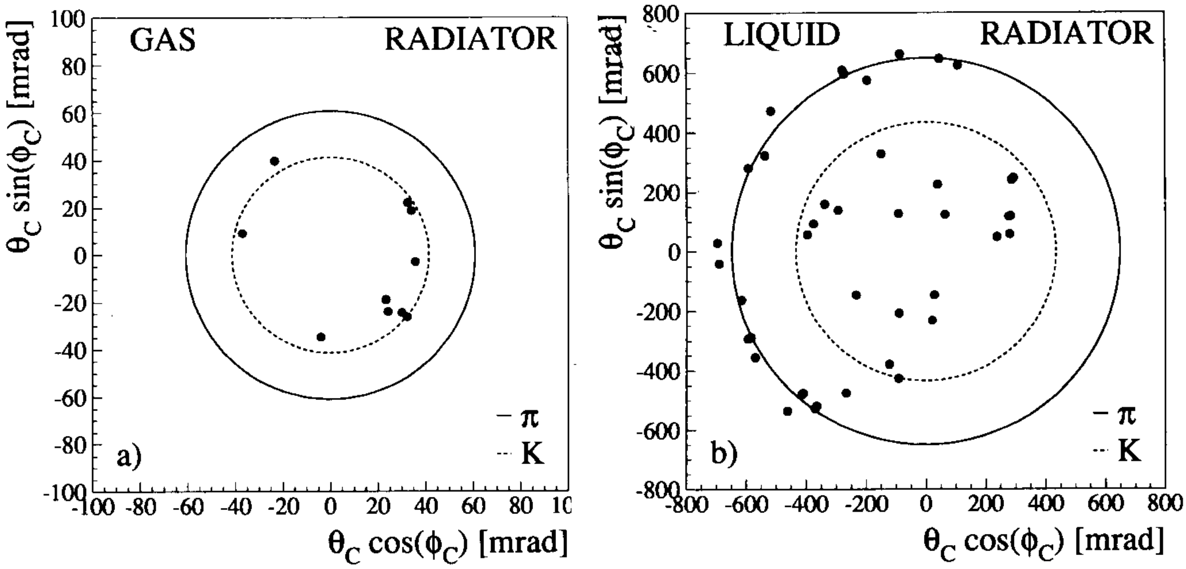
Photodetector
TMAE-based

C_6F_{14} (1 cm, liquid)

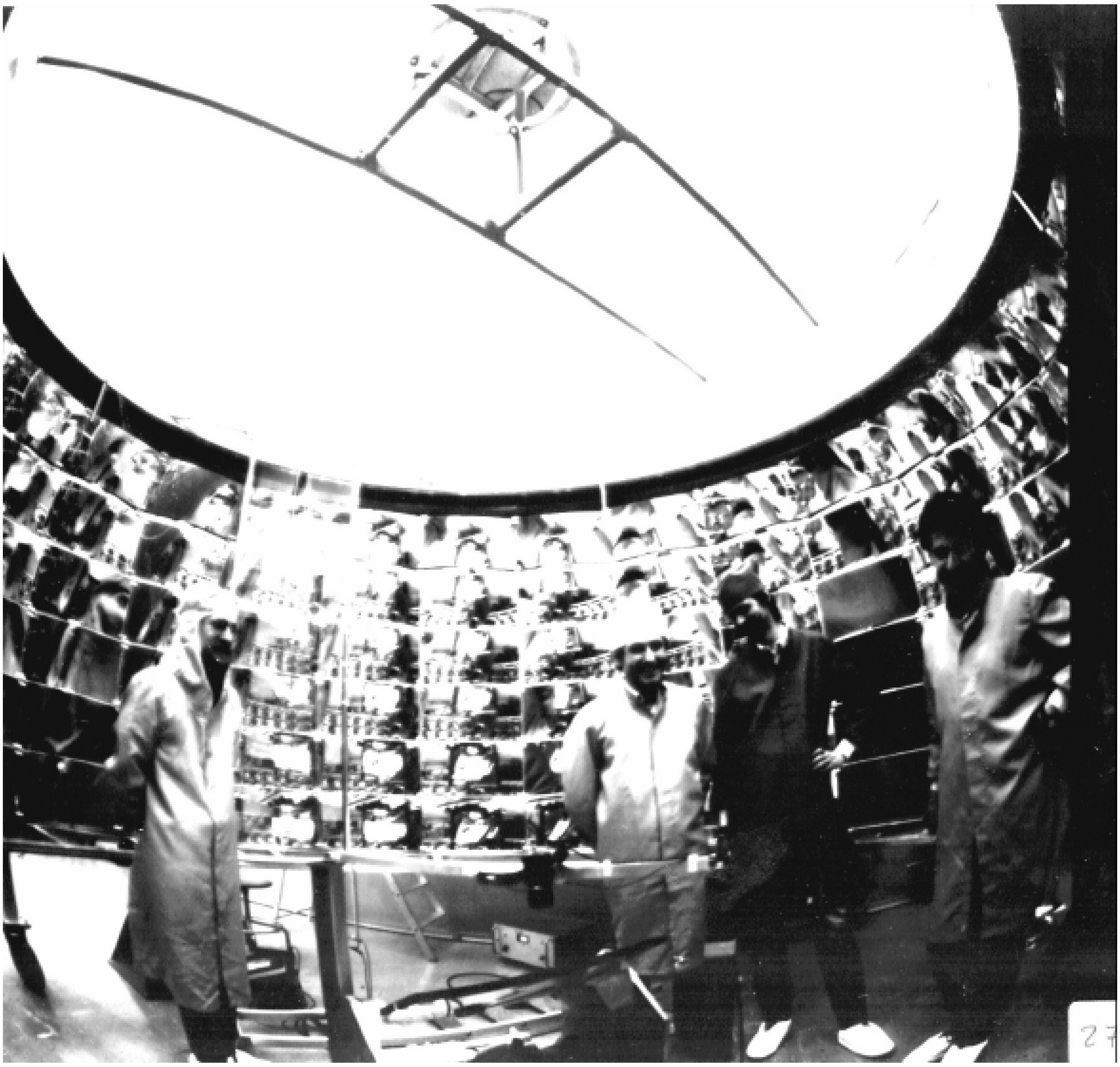
1996) 240)

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

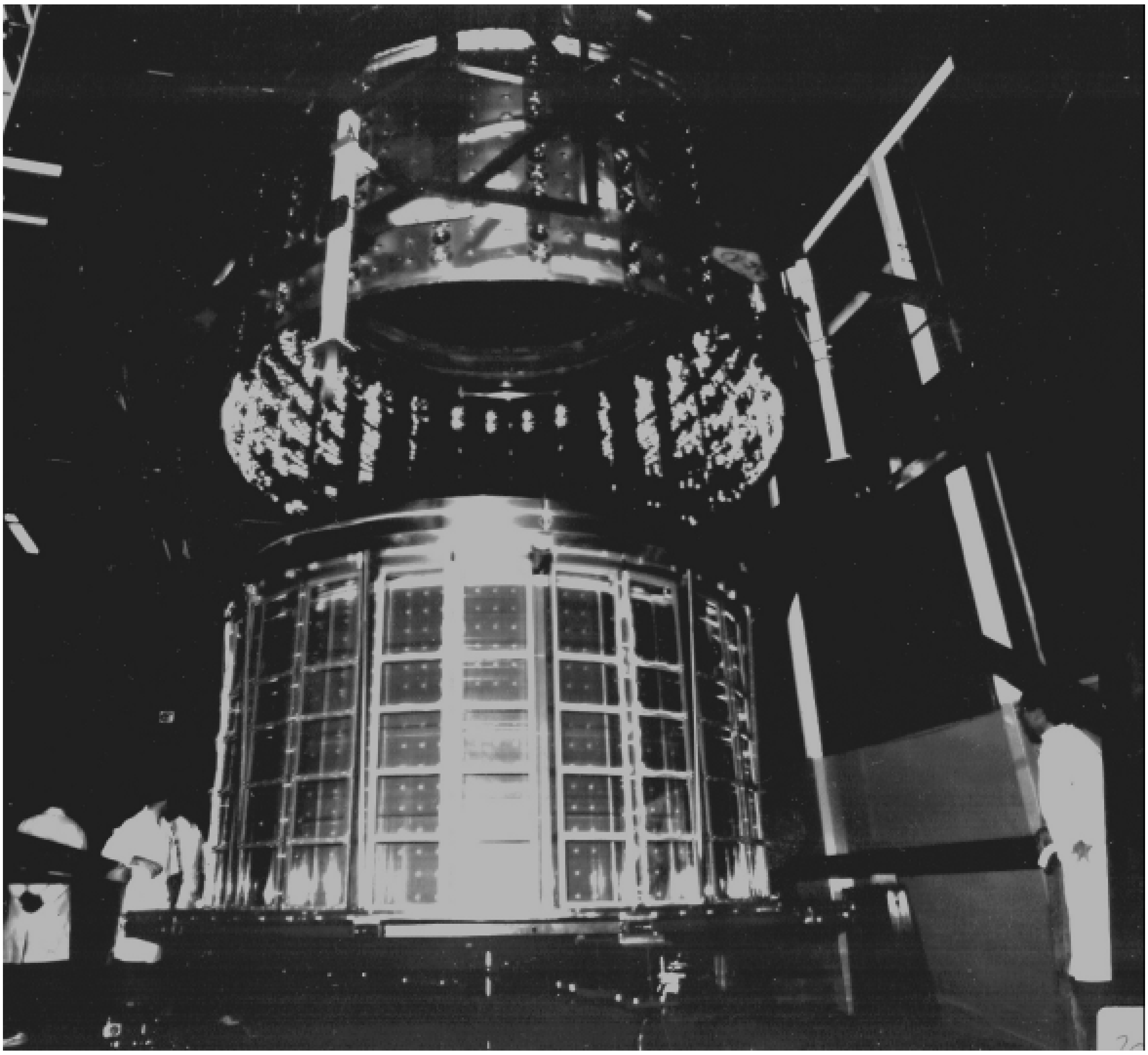
Two particles from a hadronic jet (Z-decay) in the DELPHI gas and liquid radiator + hypothesis for π and K



Cherenkov detectors

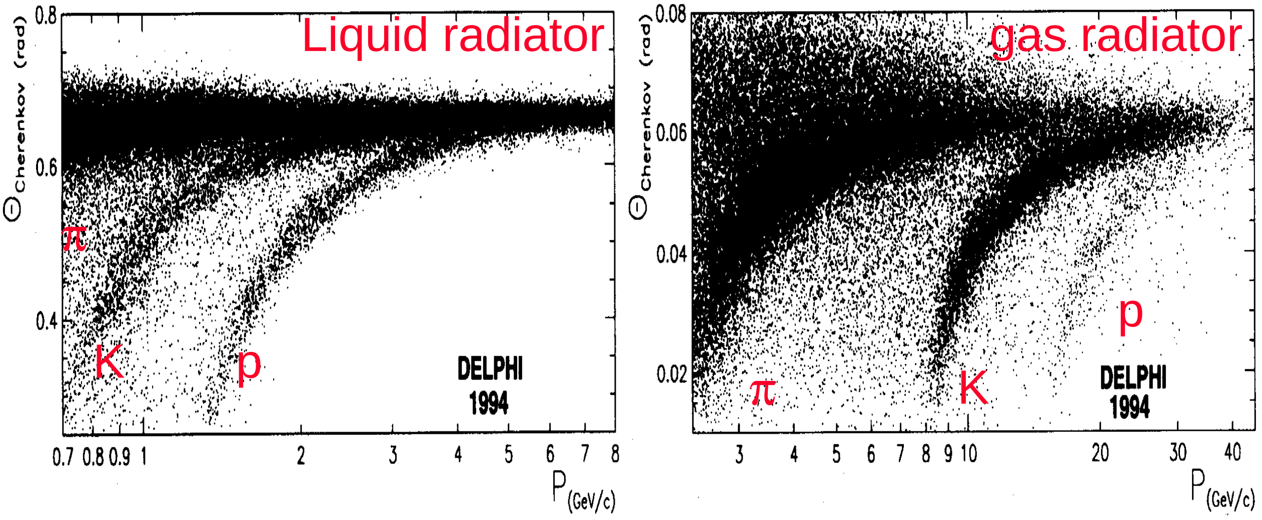


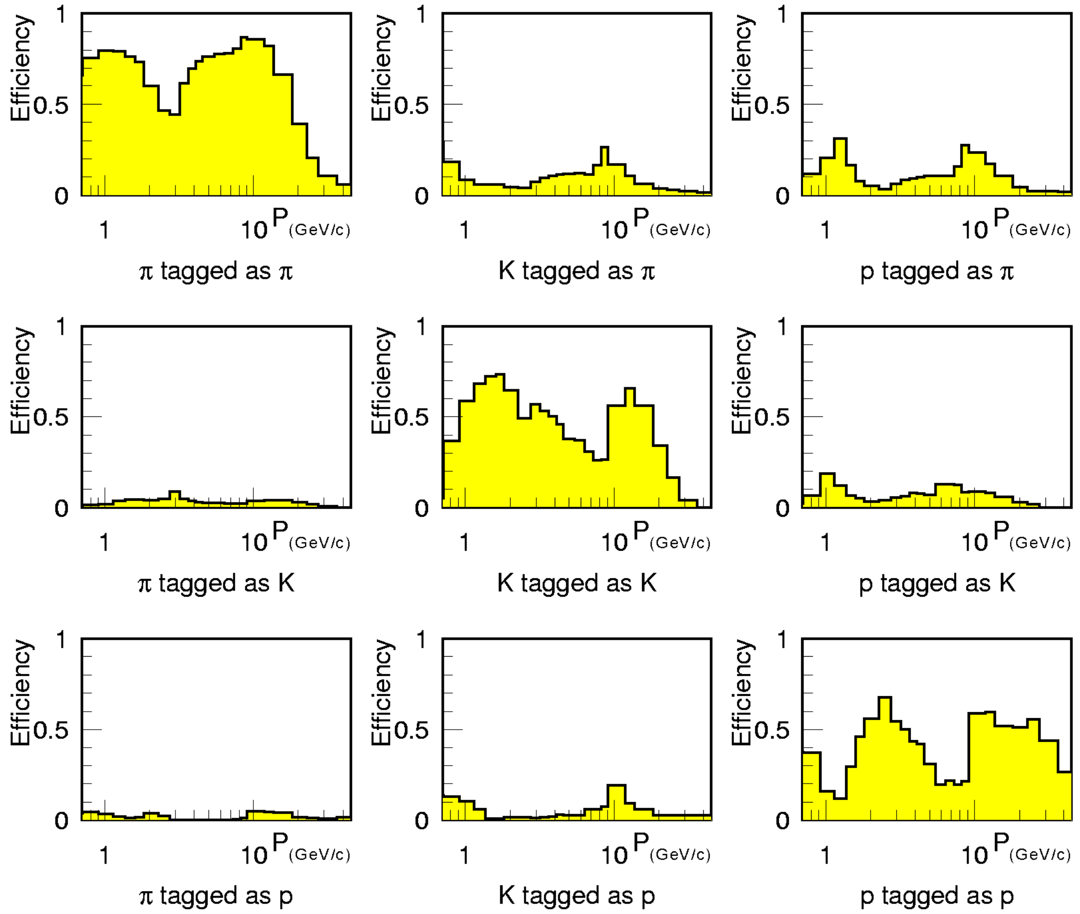
The mirror cage of the DELPHI Barrel RICH (288 parabolic mirrors)



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

Performance of DELPHI RICH (barrel) in hadronic Z decays





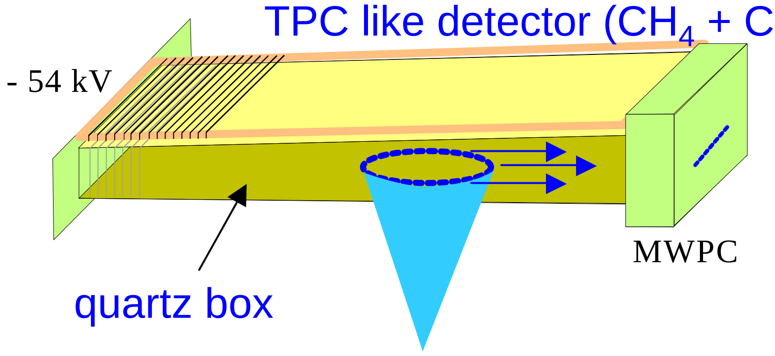
(E. Schyns, PhD thesis, Wuppertal University 1997)

Photo detectors for RICH counters

- Gas based detectors

  Admix photosensitive agent (TEA, TMAE) to detector gas

  example DELPHI:



TPC like detector (CH_4 + C_2H_6 + TMAE)

x-y projection

z from drift time

quartz box

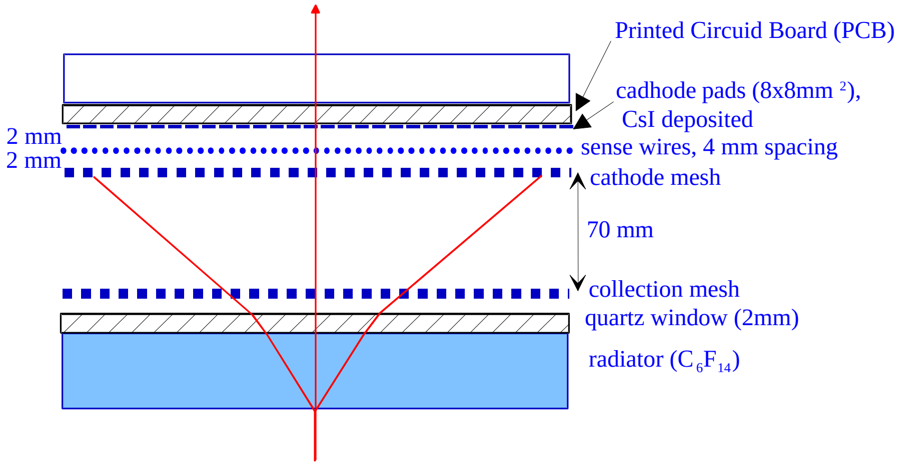
Č cone

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



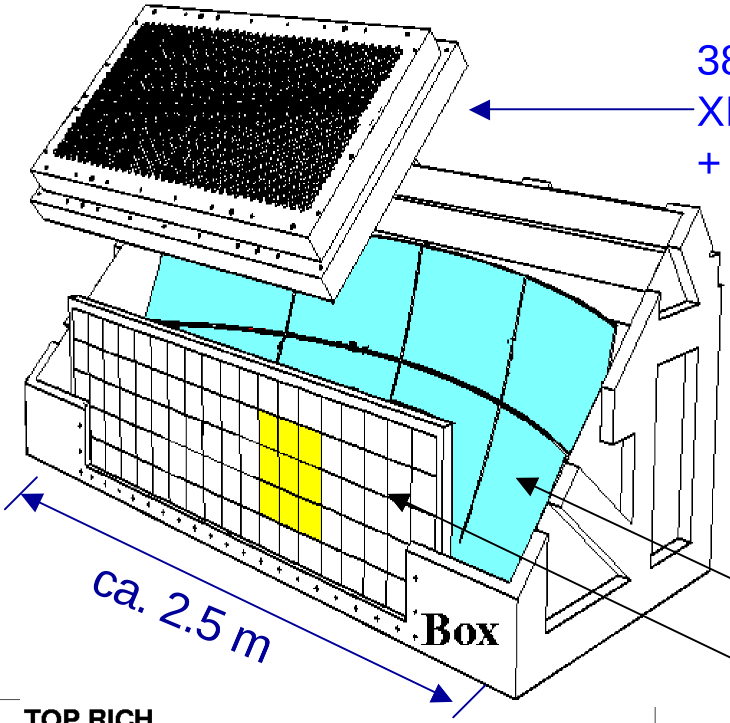
Fast response (<100 ns), but still only sensitive to UV light

Cherenkov detectors (backup)

- Vacuum based detectors

  Photomultiplier tubes, Hybrid Photo Diodes.

  example HERMES (DESY)



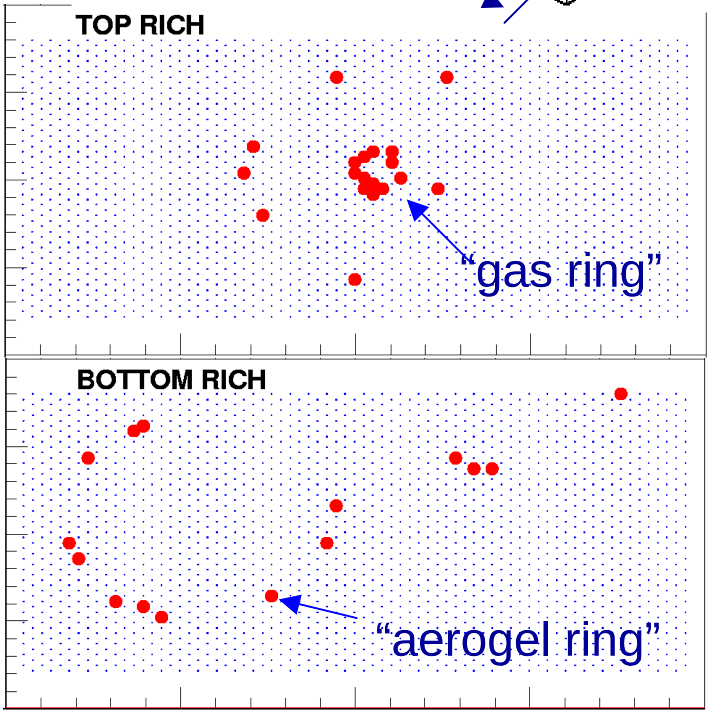
3870 PMTs, Philips XP1911/UV, Ø 3/4" + light funnels

3D view of one half detector

Double radiator

C_4F_{10} gas

Aerogel



Online Event Display

$\sigma_\theta \sim 8$ mrad

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

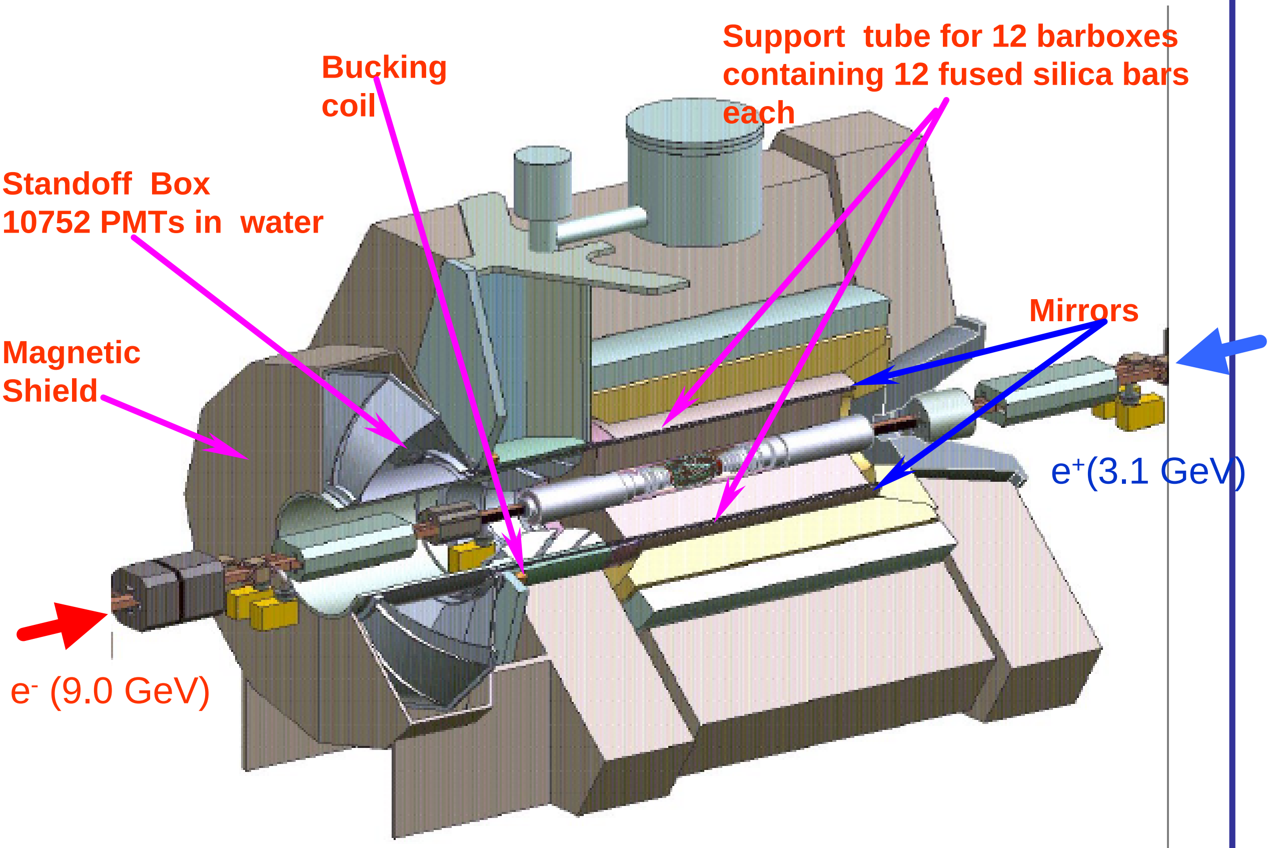
$N_{p.e.}$ (C_4F_{10}) = 12

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



Support tube for 12 barboxes containing 12 fused silica bars each

Bucking coil

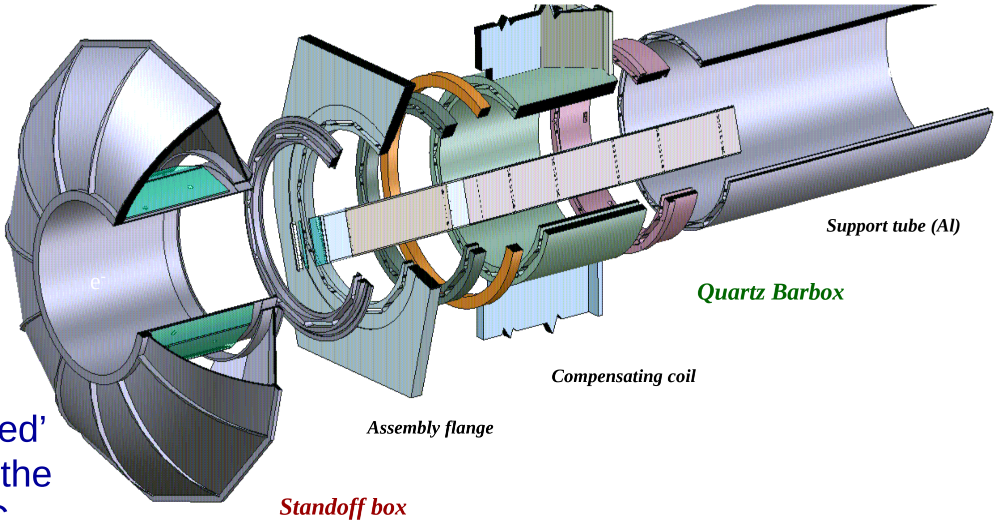
Standoff Box 10752 PMTs in water

Magnetic Shield

Mirrors

e^+(3.1 GeV)

e^- (9.0 GeV)



Support tube (Al)

Quartz Barbox

Compensating coil

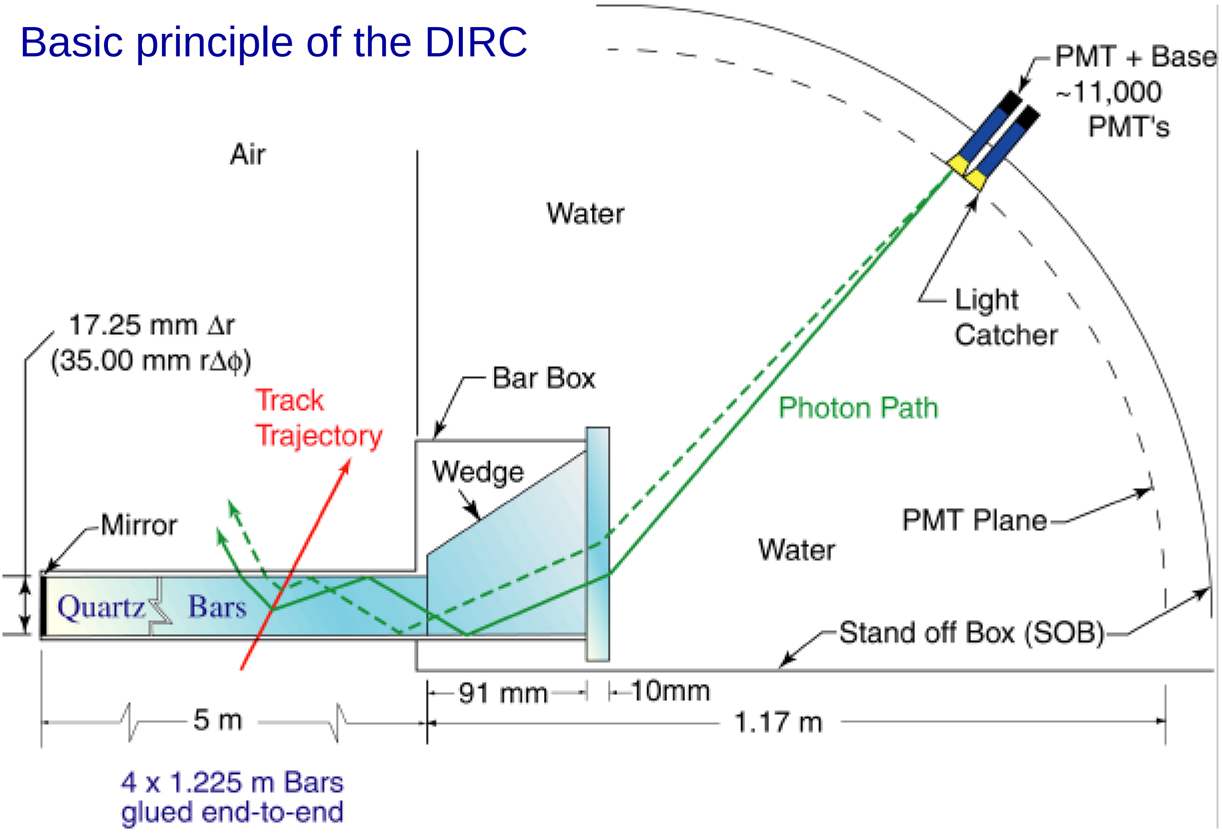
Assembly flange

Standoff box

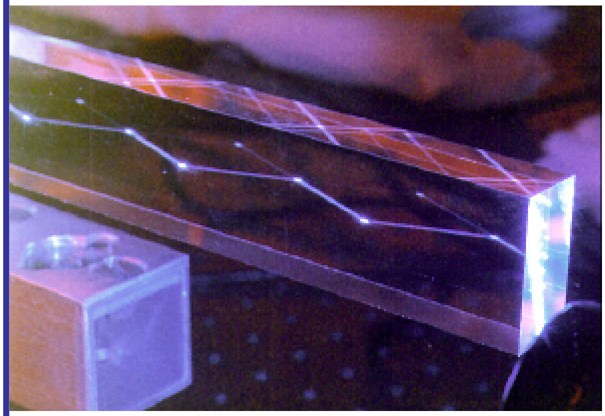
‘exploded’ view of the DIRC

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.

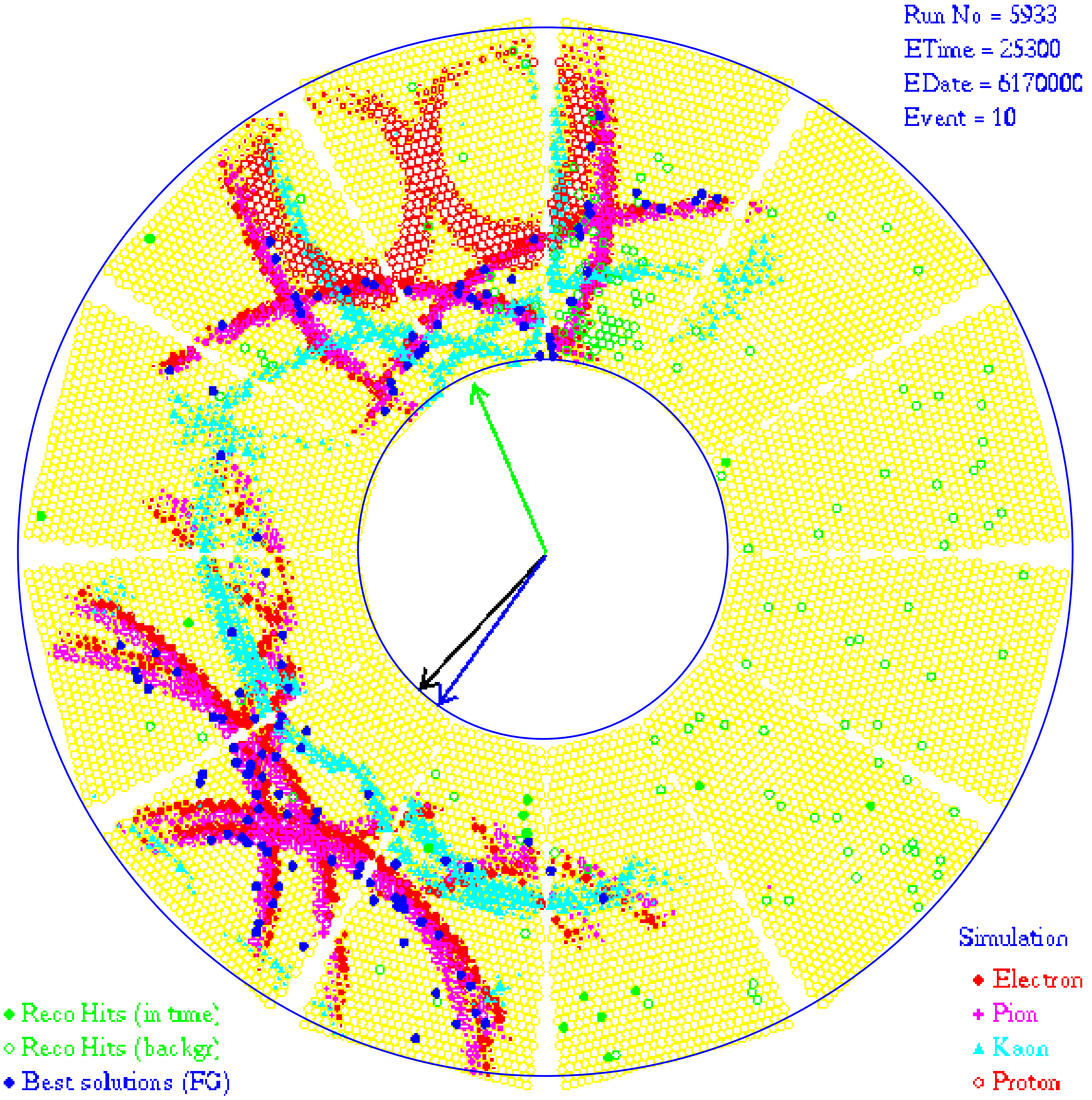


- $N_{quartz} = 1.47$,
- $\theta_{crit.} = 43^o$, $\theta_c^{max} = 47^o$
- T = 99.9 % / m
- R = 99.96 %
- ~200-400 bounces
- loss ~10-20% = $f(\theta_{dip})$

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

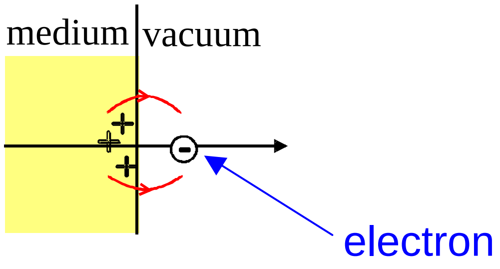
Transition radiation detectors

(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±

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

Transition radiation detectors

- Number of emitted photons / boundary is small

$$N_{ph} \approx \frac{W}{\hbar w} \propto a \approx \frac{1}{137}$$

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

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

$$q \propto 1/g$$

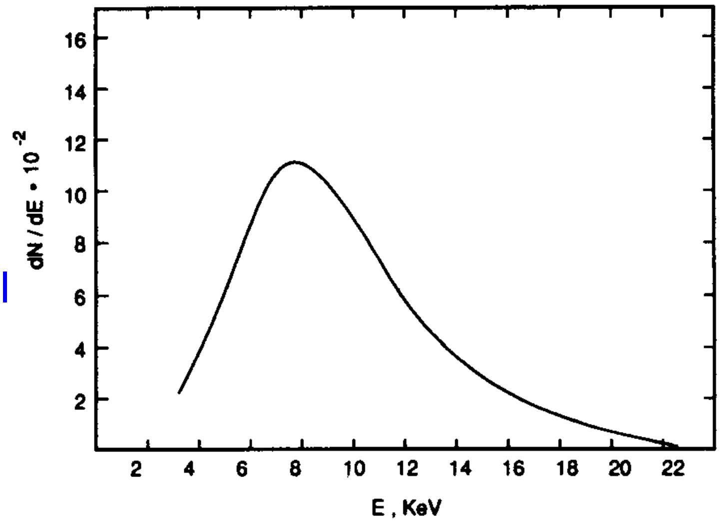
→ TR stay close to track

- Emission spectrum of TR

Typical energy: $\hbar w \approx \frac{1}{4}\hbar w_p g$

→ photons in the keV range

- Simulated emission spectrum of a CH_2 foil stack

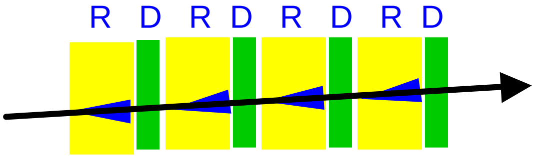


Transition radiation detectors

TR Radiators:

- stacks of CH_2 foils are used
- hydrocarbon foam and fiber materials

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



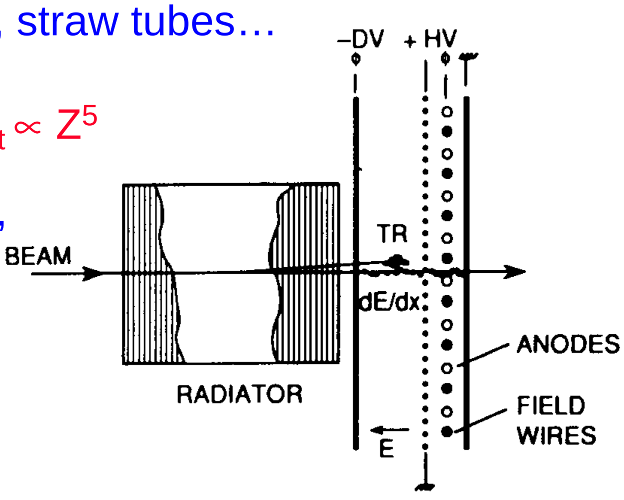
sandwich of radiator stacks and detectors

→ minimize re-absorption

TR X-ray detectors:

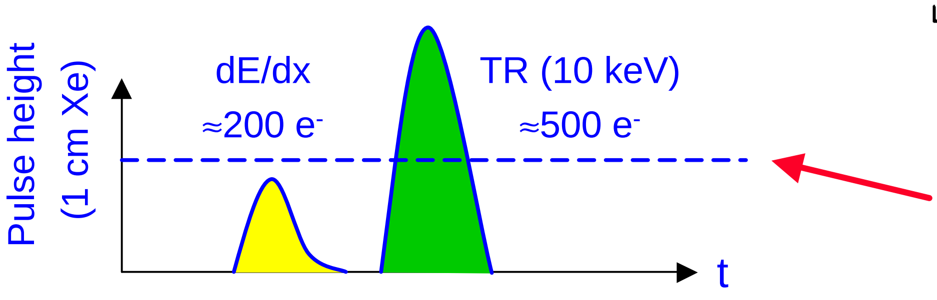
- Detector should be sensitive for $3 \le E_\gamma \le 30$ keV.
- Mainly used: Gaseous detectors: MWPC, drift chamber, straw tubes…
- Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

→ gas with high Z required, e.g. Xenon (Z=54)



Intrinsic problem:

detector “sees” TR and dE/dx



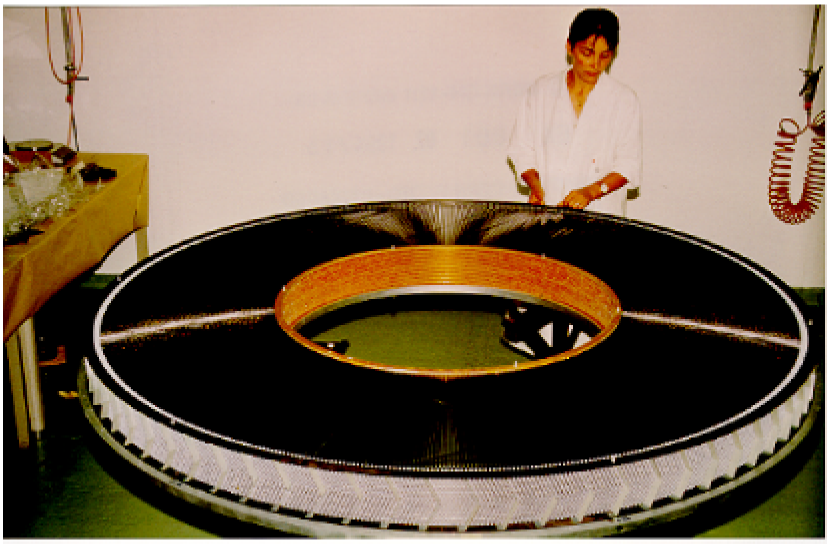
Discrimination by threshold

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

A prototype endcap “wheel”.

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

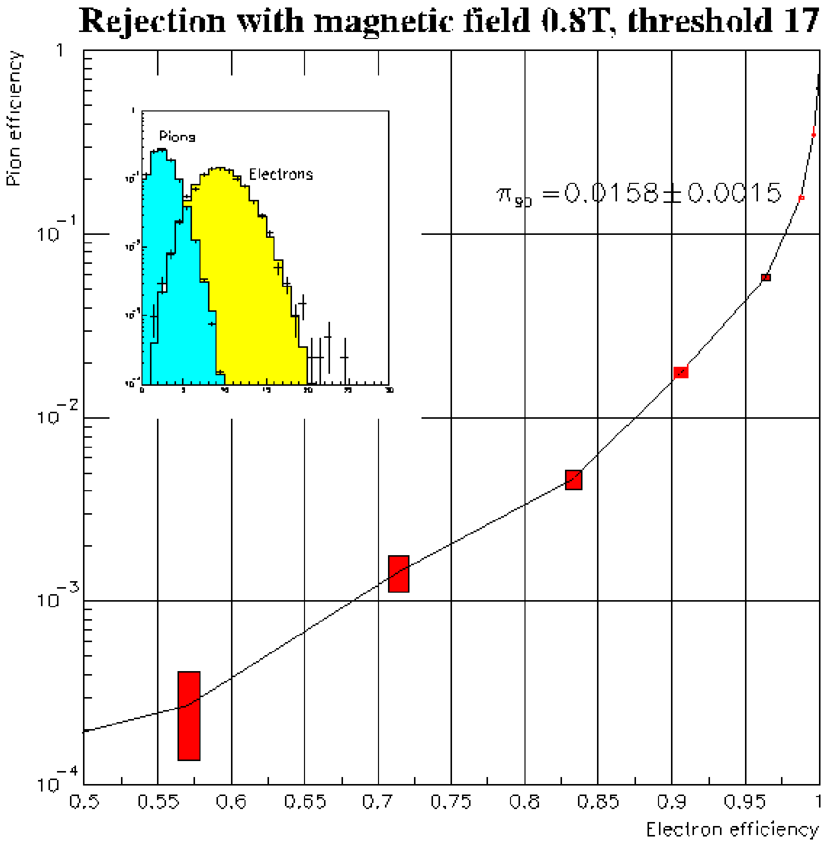
Xe based gas



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 ….