# Outline

- **Lecture 1 - Introduction** C. Joram, L. Ropelewski
- **Lecture 2 - Tracking Detectors** L. Ropelewski, M. Moll
- **Lecture 3 - Scintillation and Photodetection** C. D'Ambrosio, T. Gys
- **Lecture 4 – Calorimetry** C. Joram
- **Lecture 5a - Particle Identification** C. Joram
  - dE/dx measurement
  - Time of flight
  - Cherenkov detectors
  - Transition radiation detectors
- **Lecture 5b - Detector Systems/ Design** C. D'Ambrosio

# Particle Identification

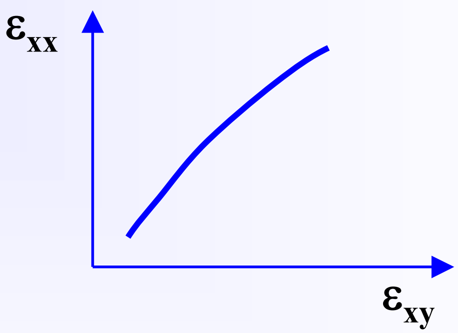
Particle identification is an important aspect of high energy physics experiments.

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

One wants to discriminate: $\pi$/K, K/p, e/$\pi$, $\gamma/\pi^0$ ….

The applicable methods depend strongly on the interesting energy domain.

Depending on the physics case either $\varepsilon_{xx}$ or $\varepsilon_{xy}$ 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 $D_{x,y}$

$$D_{x,y} = \frac{S_x - S_y}{\sigma_S}$$

$S_x$ and $S_y$ are the signals provided by the detector for particles of types $x$ and $y$ with a resolution $\sigma_S$.

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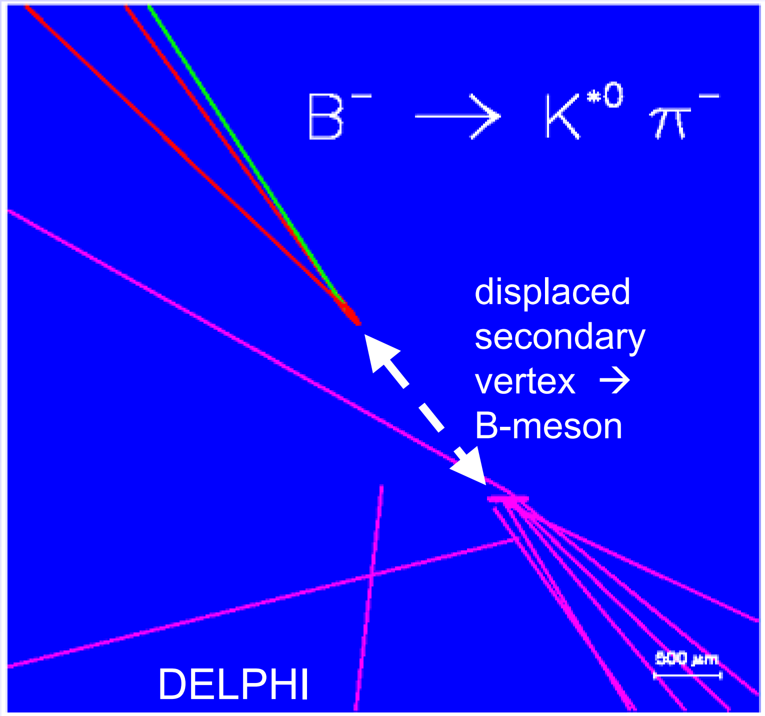
# Particle Identification - an example

A 'charmless' B decay:

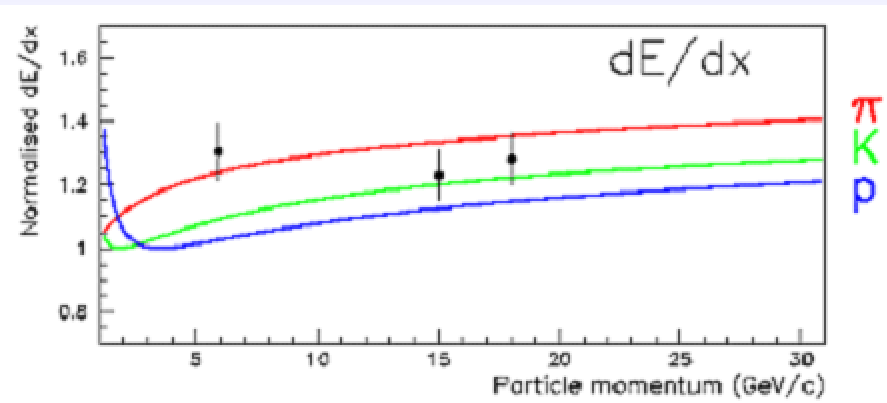
$$B^- \rightarrow K^* \pi^-$$
$$K^* \downarrow K\pi$$

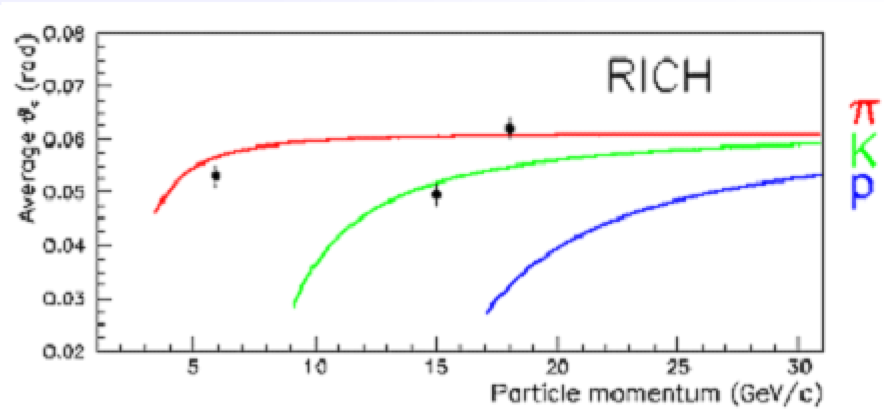
1 K + 2 π

in final state




Who is who ?

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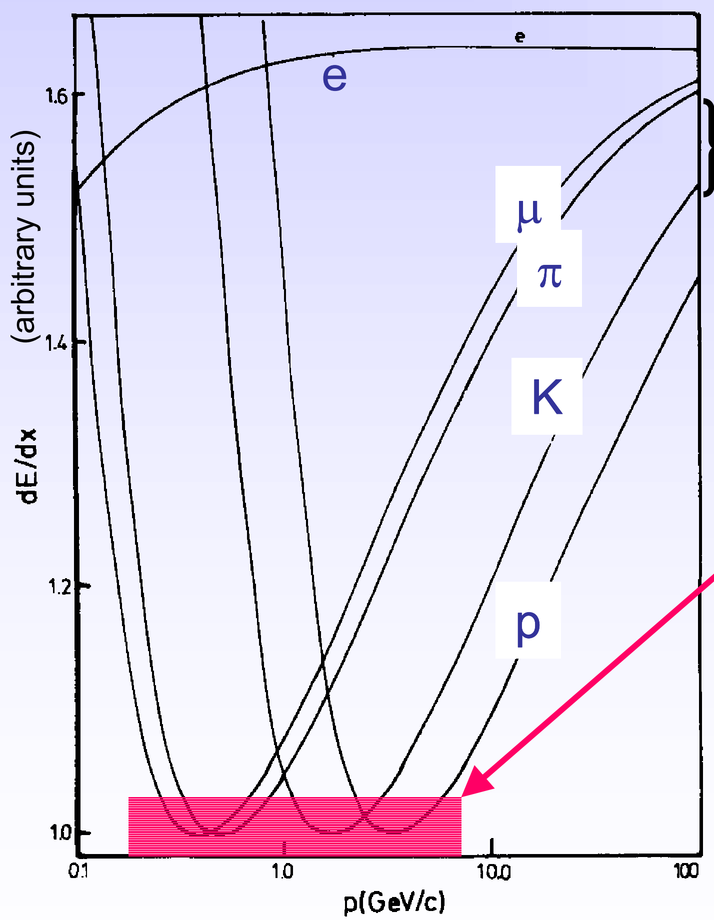
# Particle ID through dE/dx

$$p = m_0 \beta\gamma c$$

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

Simultaneous measurement of *p* and *dE/dx* defines mass $m_0$, hence the particle identity




$\pi/K$ separation ($2\sigma$) requires a *dE/dx* resolution of < 5%

Not so easy to achive !

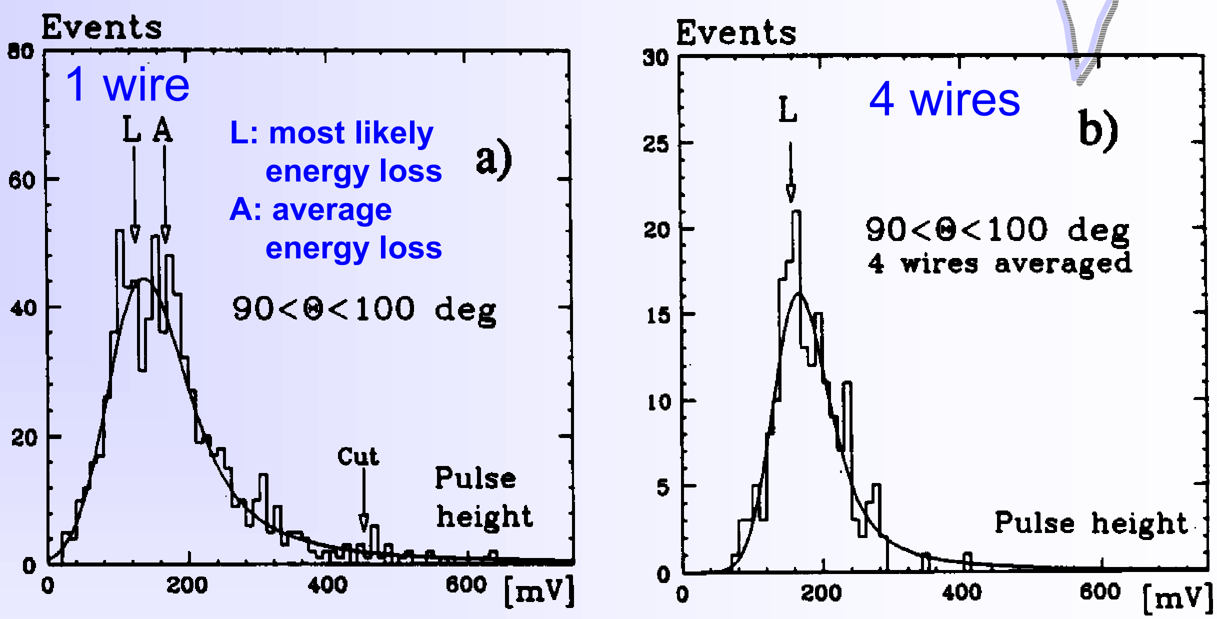
- dE/dx is very similar for minimum ionising particles.
- Energy loss fluctuates and shows Landau tails.

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

# Particle ID through dE/dx

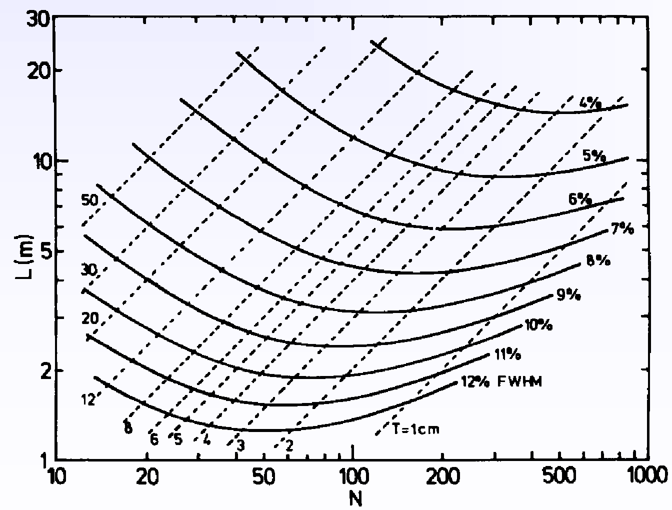
How to reduce fluctuations ?

- subdivide track in several dE/dx samples
- calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values




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

- Also increased gas pressure can improve resolution (→ higher primary statistics), but it reduces the rel. rise due to density effect !

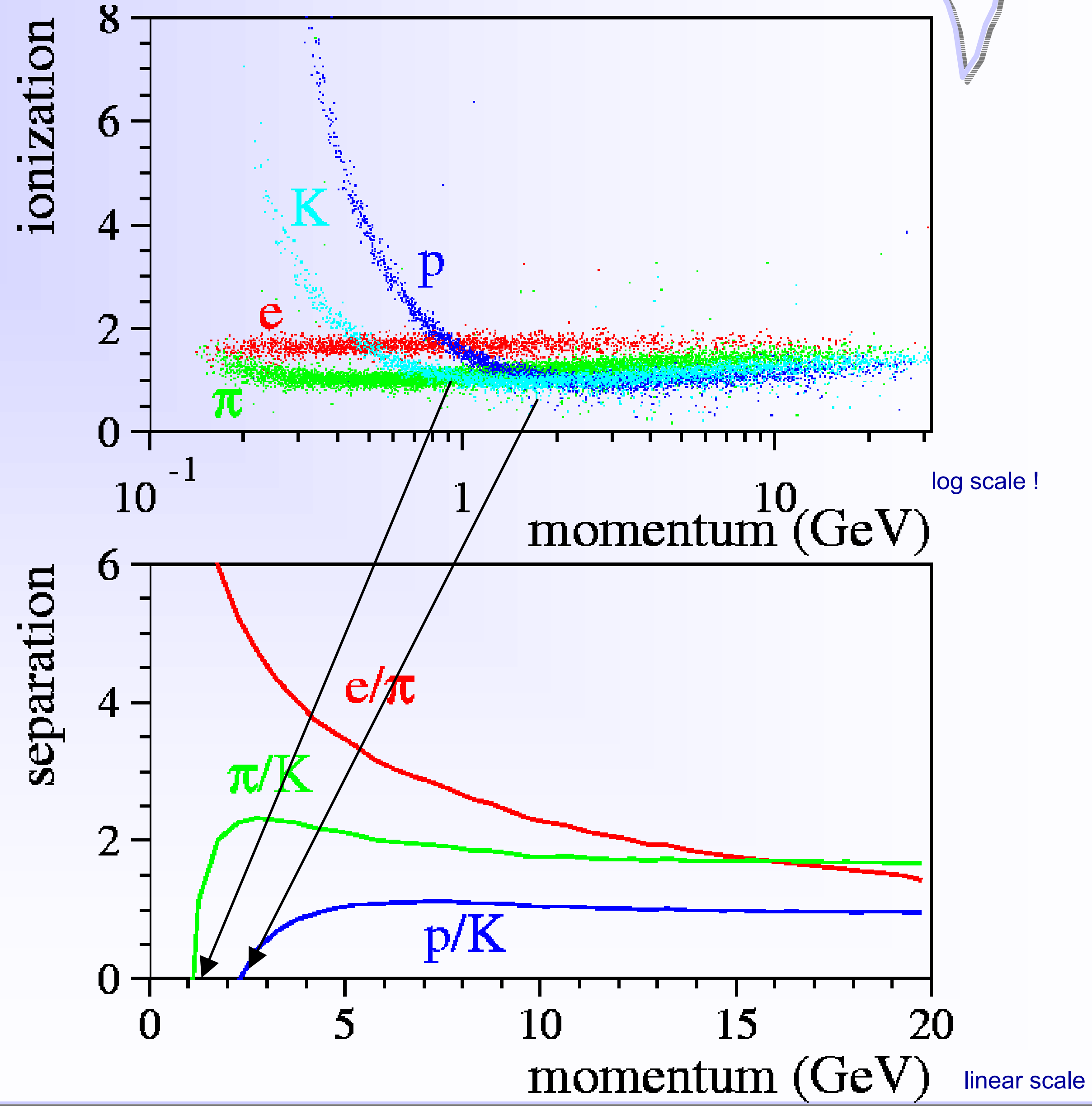



(M. Aderholz, NIM A 118 (1974), 419)

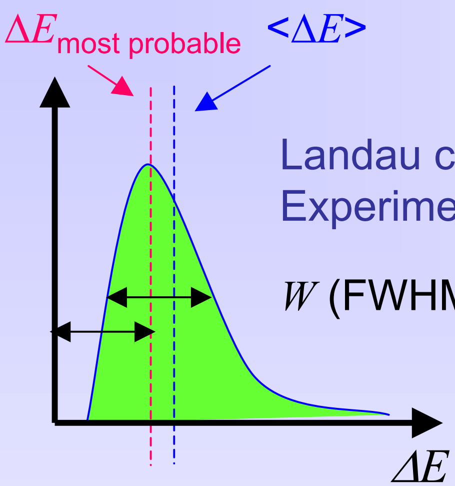
Don't cut the track into too many slices ! There is an optimum for a given track length L.

# Example ALEPH TPC

- Gas: Ar/CH4 90/10
- $N_{samples}$ = 338
- wire spacing 4 mm
- dE/dx resolution
  ~5% for m.i.p.'s



# High resolution dE/dx by cluster counting



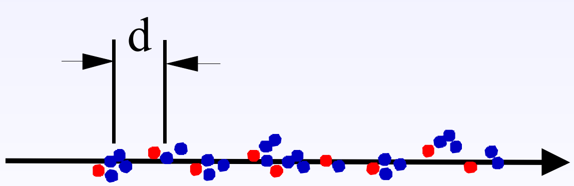

Landau curve
Experimental observation (first order)

$W$ (FWHM) $\approx \Delta E_{\text{m.p.}}$

Remember (lecture 2a): the number of primary electron - ion pairs is Poisson distributed !
What would be the resolution in $\Delta E$ if we could count the clusters ?

1 cm Ar $\rightarrow n_{primary} \approx 28$

$$\frac{W}{\Delta E_{m.p.}} = 2.35\frac{\sqrt{n_{primary}}}{n_{primary}} = 0.44$$



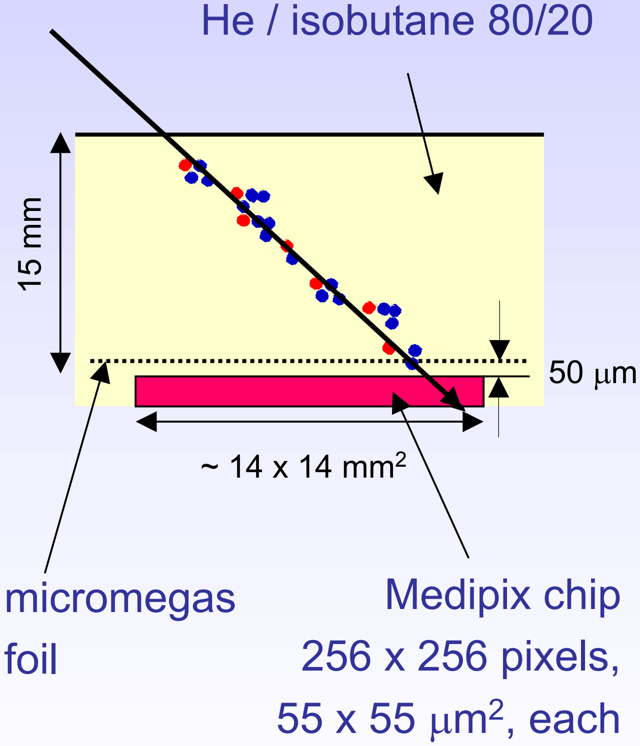

Average distance d ≈ 360 μm $\rightarrow \Delta t = d/v_{\text{drift}} \approx$ few ns

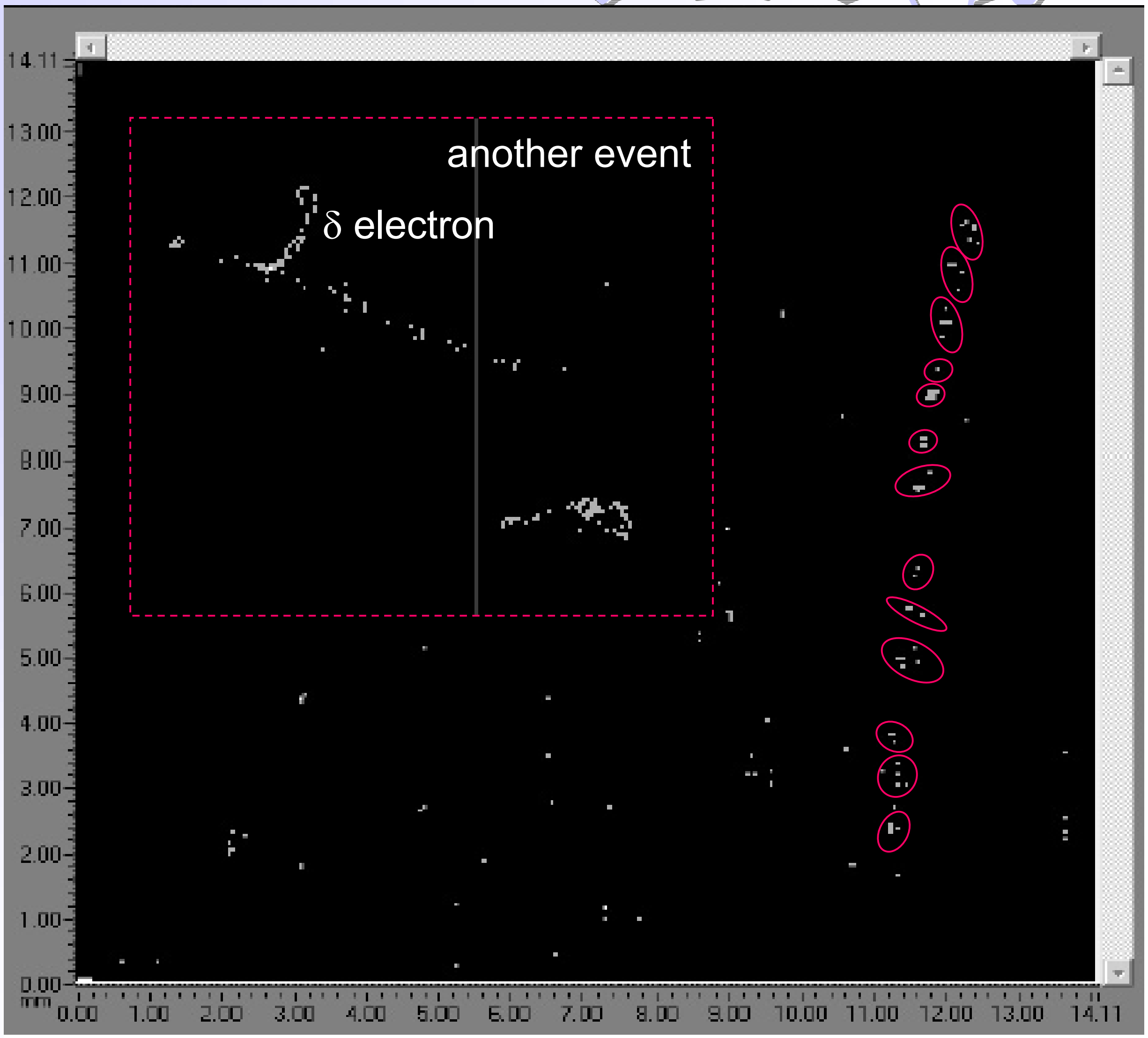
In addition diffusion → washes out clusters

Principle of cluster counting has been demonstrated to work - Time Expansion Chamber - but never successfully applied in a particle physics experiment. (A.H. Walenta, IEEE NS-26, 73 (1979))

# High resolution dE/dx by cluster counting

Cluster counting with a hybrid gas detector: pixel readout chip + micromegas

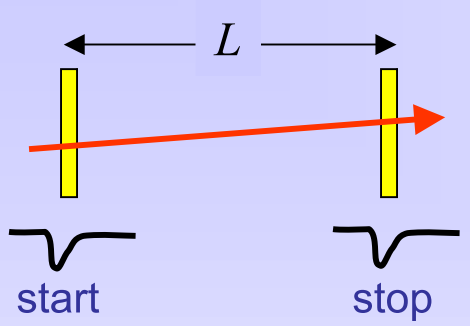



M. Campbell et al., NIM A 540 (2005) 295

track by cosmic particle (mip): 0.52 clusters / mm, ~3 e⁻/cluster

# Particle ID using Time Of Flight (TOF)




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

Combine TOF with momentum measurement

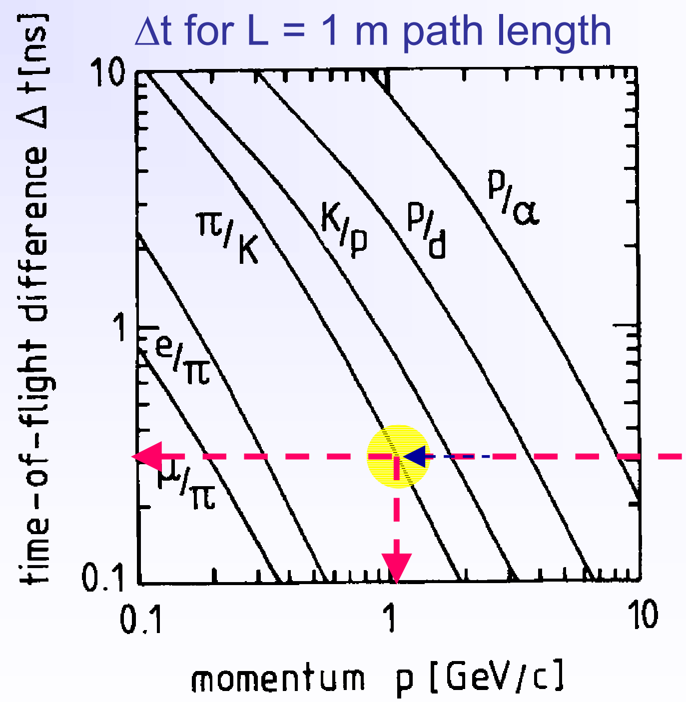
$$p = m_0 \beta\gamma \longrightarrow m_0 = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

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

TOF difference of 2 particles as *f(p)*

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

$\Delta$t for L = 1 m path length




$\sigma_t$ = 300 ps
$\pi$/K separation up to 1 GeV/c

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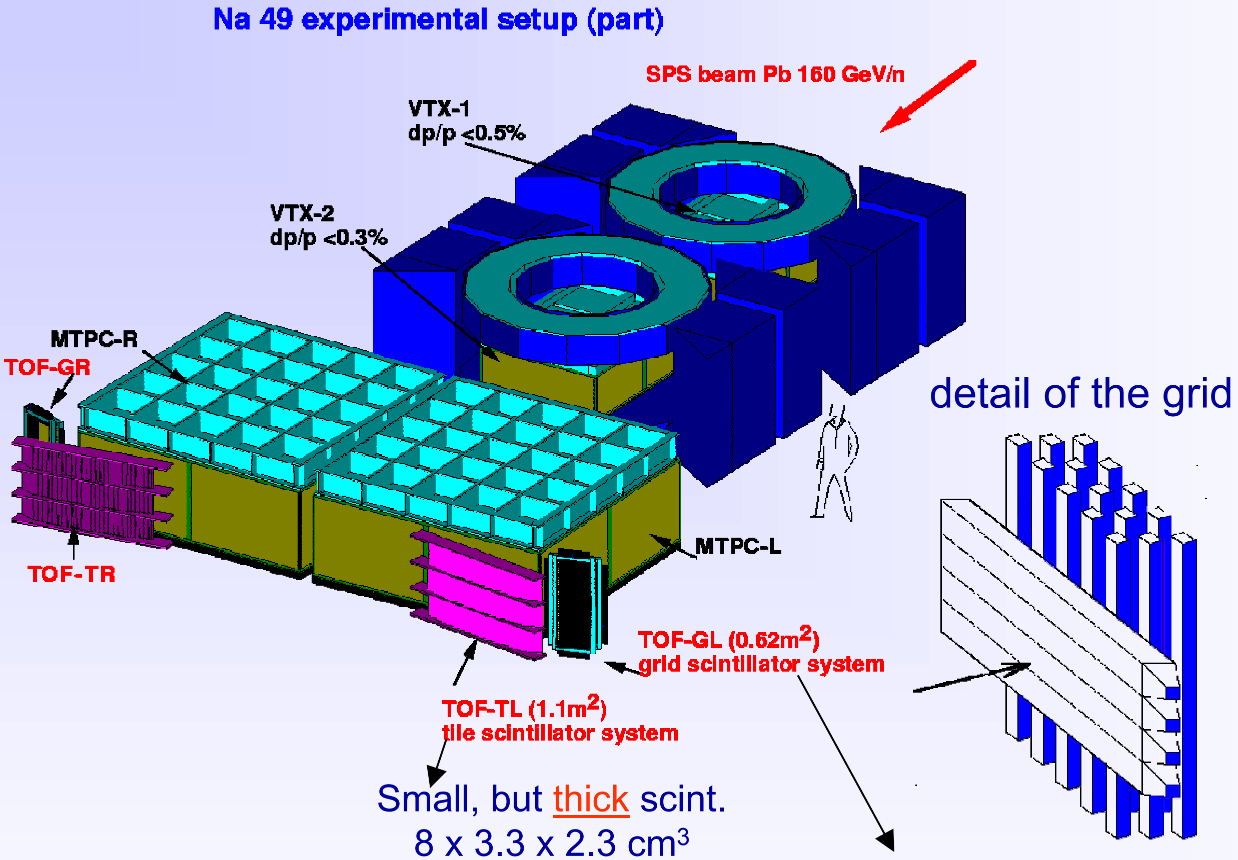
# Example: NA49 Heavy Ion experiment




Small, but thick scint.
8 x 3.3 x 2.3 cm$^3$

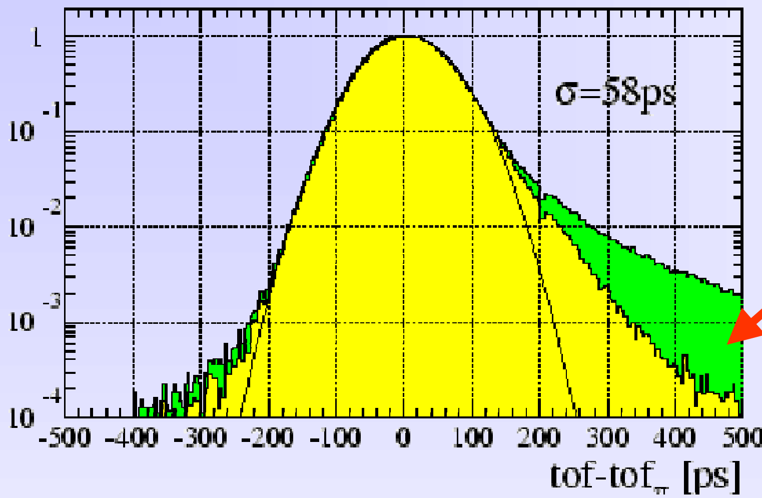
Long scint. (48 or 130 cm), read out on both sides

High resolution TOF requires

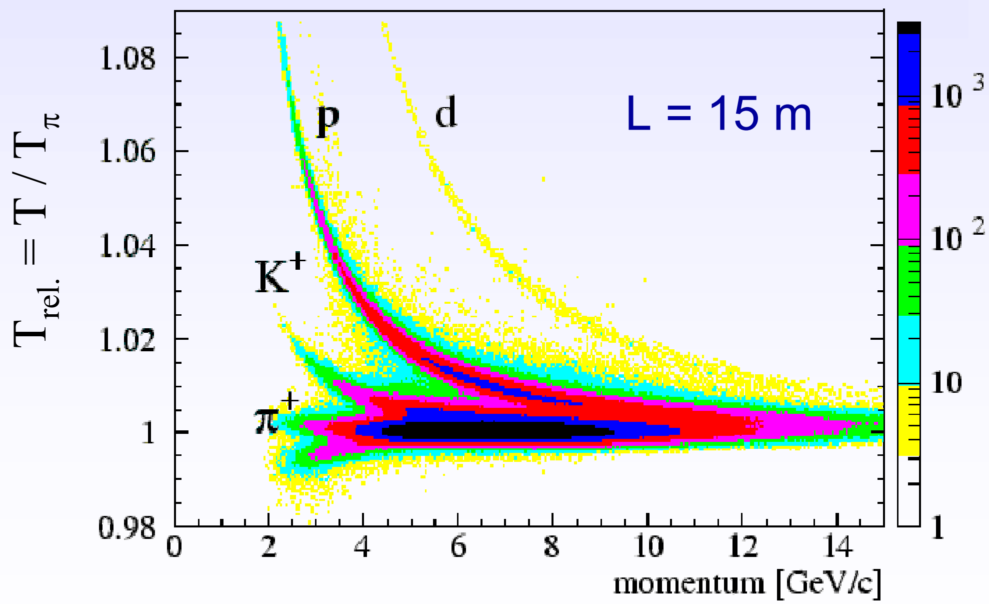
- fast detectors (plastic scintillator, gaseous detectors, e.g. RPC (ALICE)),
- appropriate signal processing (constant fraction discrimination, corrections)
- continuous stability monitoring.

# Example: NA49 Heavy Ion experiment

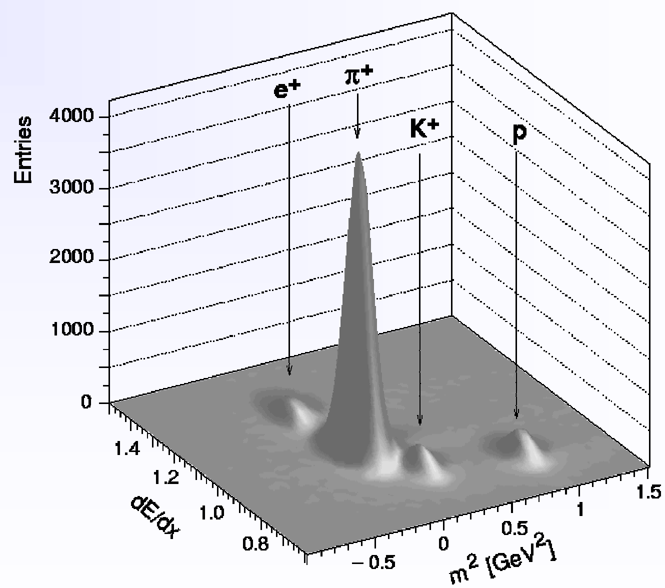
System resolution of the tile stack




From γ conversion in scintillators




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

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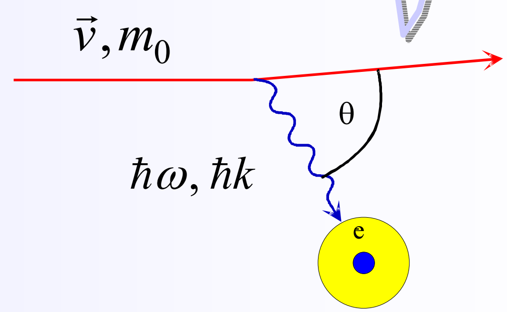
# back to ... Interaction of charged particles

Remember energy loss due to ionisation…

There are other ways of energy loss !




A photon in a medium has to follow the dispersion relation

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

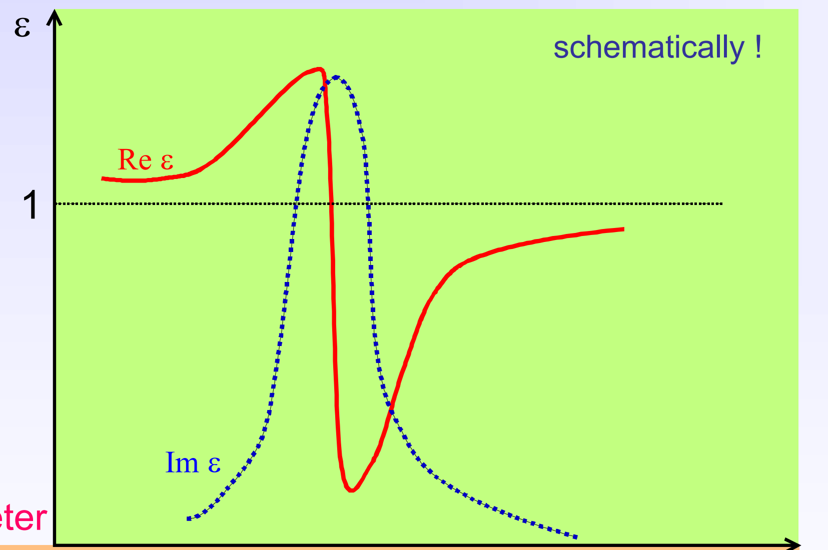
Optical behaviour of medium is characterized by the dielectric constant ε

$\mathrm{Re}\sqrt{\varepsilon} = n$

Refractive index

$\mathrm{Im}\,\varepsilon = k$

Absorption parameter




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

Assuming soft collisions + energy and momentum conservation → emission of real photons:

$$\omega \cong \vec{v} \cdot \vec{k} = v \cdot k \cos\theta$$

$$\rightarrow \quad \cos\theta = \frac{\omega}{vk} = \frac{1}{n\beta} = \frac{1}{\beta\sqrt{\varepsilon}}$$

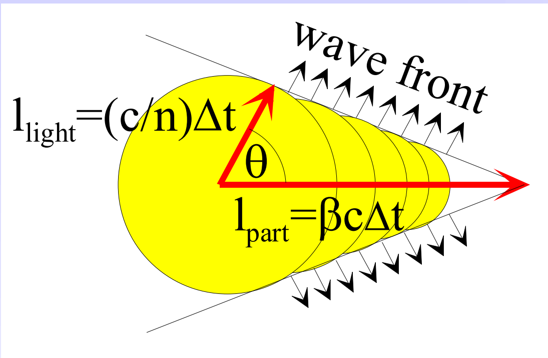
Emission of photons if

$$\beta = 1/n \cdot \cos\theta \qquad \beta \geq 1/n$$

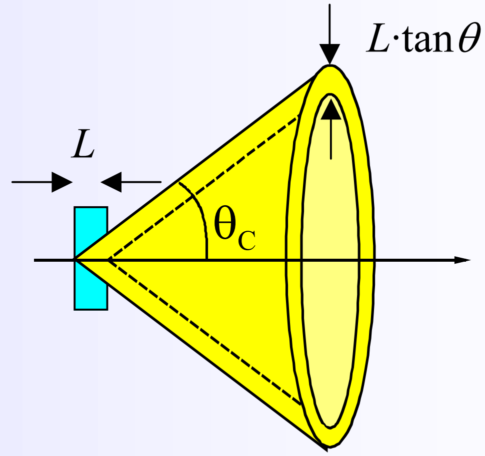
A particle emits real photons in a dielectric medium if its speed $\beta \cdot c$ is greater than the speed of light in the medium c/n

# Cherenkov radiation

Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$ $n$: refractive index




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

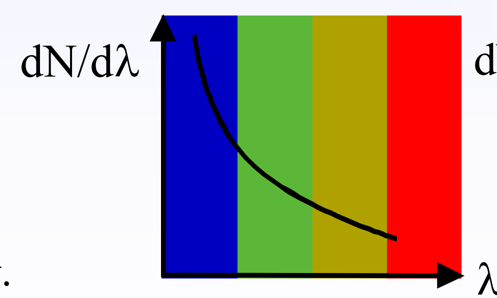


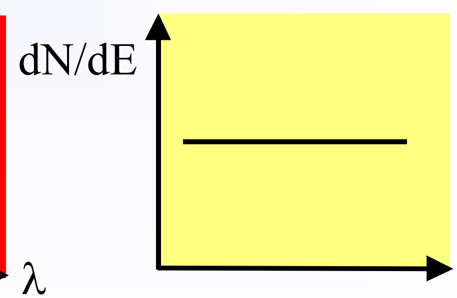

- $\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$ Cherenkov threshold
- $\theta_{max} = \arccos\frac{1}{n}$ 'saturated' angle (β=1)

Number of emitted photons per unit length and unit wavelength interval

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

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

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# Cherenkov detectors

| medium | n | $\theta_{max}$ (deg.) | $N_{ph}$ ($eV^{-1}$ $cm^{-1}$) |
|---|---|---|---|
| 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 |

*NTP

- Energy loss by Cherenkov radiation small compared to ionization (≈0.1%)
- Cherenkov effect is a very weak light source

→ need highly sensitive photodetectors

Number of detected photo electrons $$N_{p.e.} = L \sin^2\theta \underbrace{\frac{\alpha}{\hbar c} \int_{E_1}^{E_2} \varepsilon_Q(E) \prod_i \varepsilon_i(E) dE}_{N_0 = 370 \cdot eV^{-1} \cdot cm^{-1} \langle \varepsilon_{total} \rangle \Delta E}$$

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

$N_0$ is also called figure of merit ( ~ performance of the photodetector)

Example: for a detector with $\langle \varepsilon_{total} \rangle \cdot \Delta E = 0.2 \cdot 1\, eV$ $\quad L = 1\, cm$

and a Cherenkov angle of $\theta_C = 30^\circ$

one expects $N_{p.e.} = 18$ photo electrons

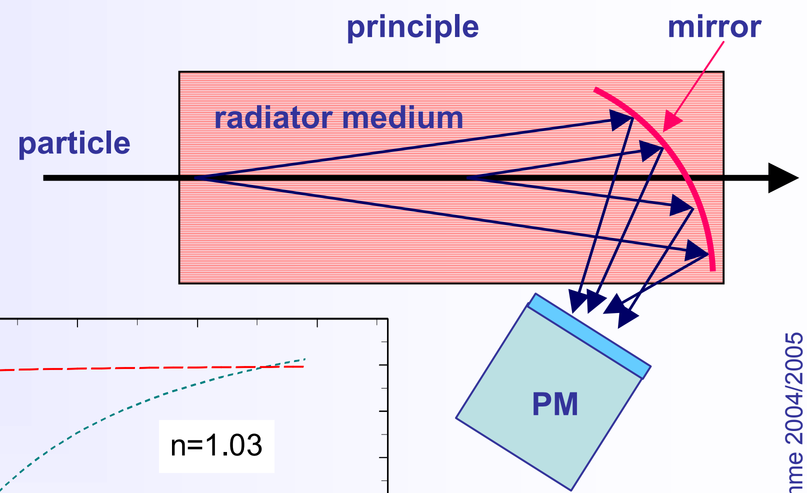
# Cherenkov detectors

Detectors can exploit ...

1. $N_{ph}(\beta)$ → threshold detector (do not measure $\theta_C$)
2. $\theta(\beta)$ → differential and Ring Imaging Cherenkov detectors "RICH"

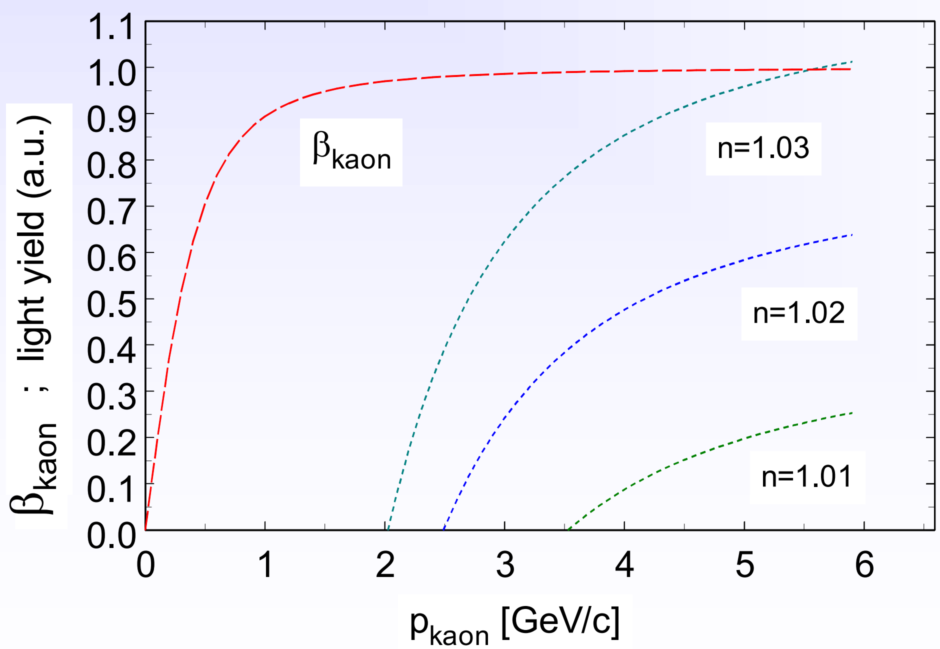
## Threshold Cherenkov detectors

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




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

Goal: $\pi$/K separation

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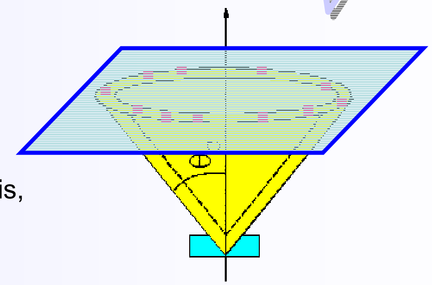
# Ring Imaging Cherenkov detectors (RICH)



RICH detectors determine $\theta_C$ by intersecting the Cherenkov cone with a photosensitive plane

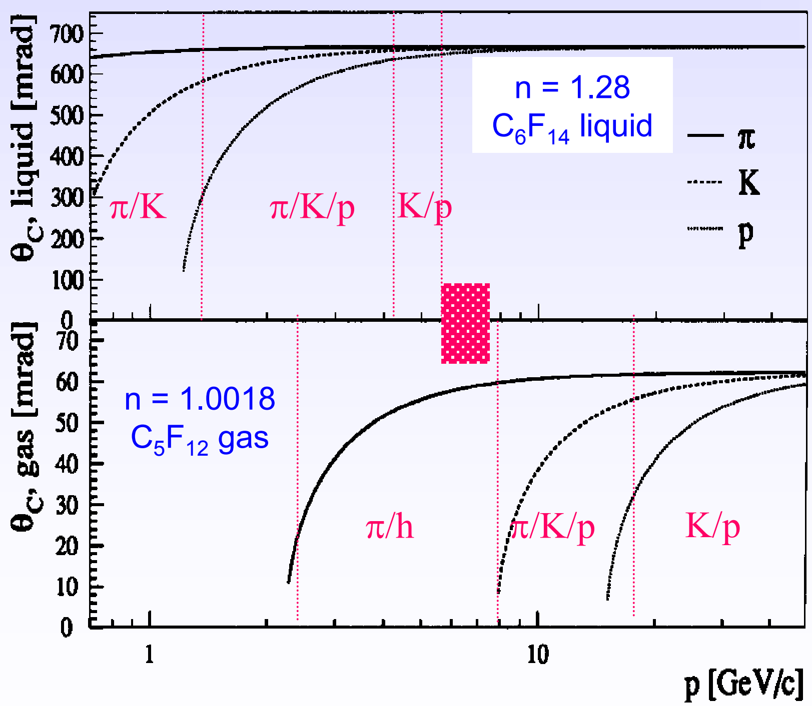


→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

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

DELPHI




$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right)$$

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

$$\cos\theta_C = \frac{1}{n\beta} \quad \rightarrow \quad \frac{\sigma_\beta}{\beta} = \tan\theta\cdot\sigma_\theta$$

Detect $N_{p.e.}$ photons (photoelectrons) →

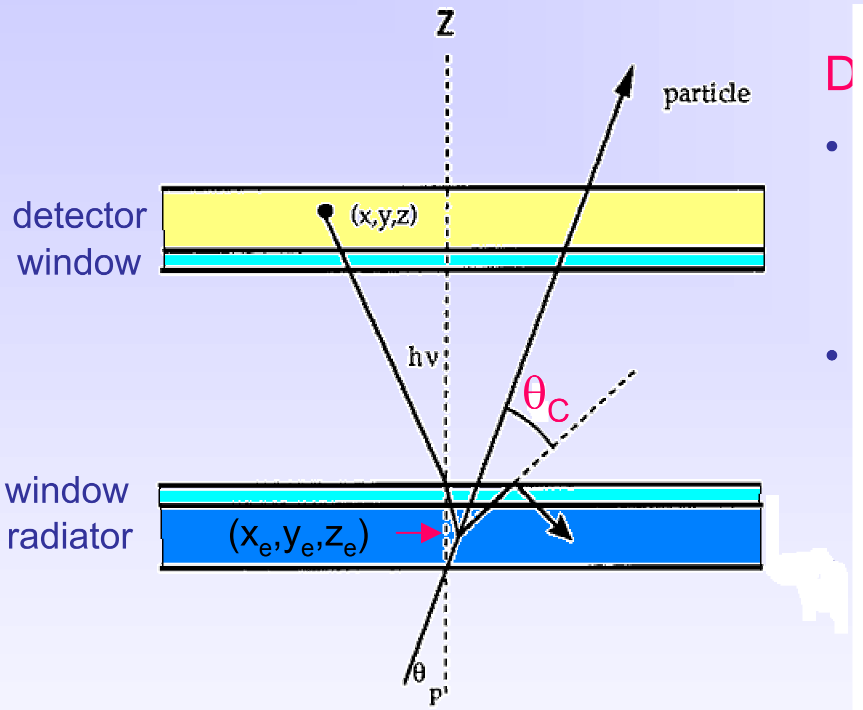
$$\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$$

→ minimize $\sigma_\theta^{p.e.}$

→ maximize $N_{p.e.}$

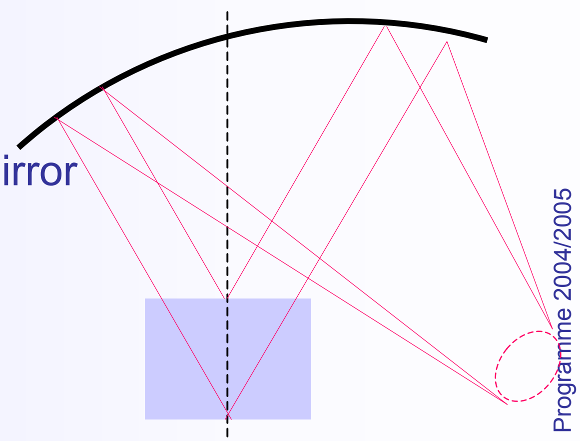
# Ring Imaging Cherenkov detectors (RICH)

## Reconstruction and resolution of Cherenkov angle

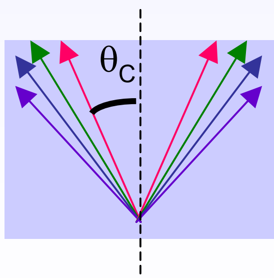



**Determination of $\theta_C$ requires:**

- space point of the detected photon (x,y,z)
  - ► photodetector granularity ($\sigma_x$, $\sigma_y$), depth of interaction ($\sigma_z$)
- emission point ($x_e$,$y_e$,$z_e$)
  - ► keep radiator thin or use focusing mirror
- particle direction $\theta_p$, $\phi_p$
  - ► RICH requires good tracker



- the chromatic error - an 'irreducible' error




$$n_{rad} = n(E)$$

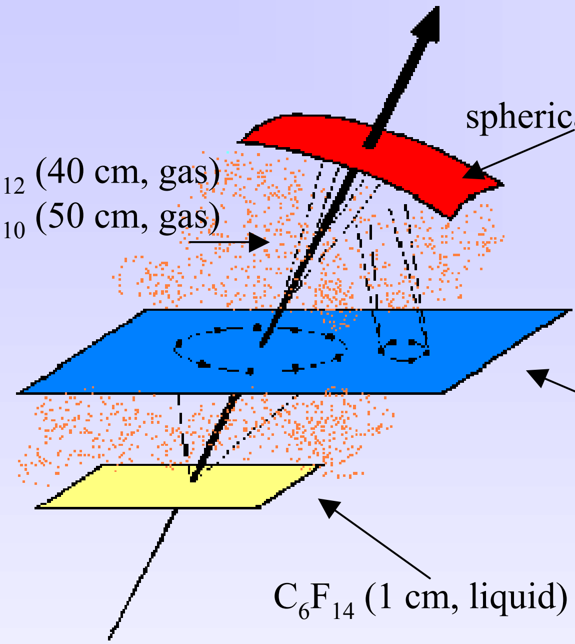
$$\sigma_\theta^c = \frac{1}{n\tan\theta}\sigma_n = \frac{1}{n\tan\theta}\frac{dn}{dE}\sigma_E$$

$\sigma_E$ is related to the sensitivity range of the photodetector $\Delta E$

$\Delta E \uparrow \;\rightarrow\; N_{pe}\uparrow$ good $\quad \sigma_E \uparrow$ bad

$\Delta E \downarrow \;\rightarrow\; N_{pe}\downarrow$ bad $\quad \sigma_E \downarrow$ good

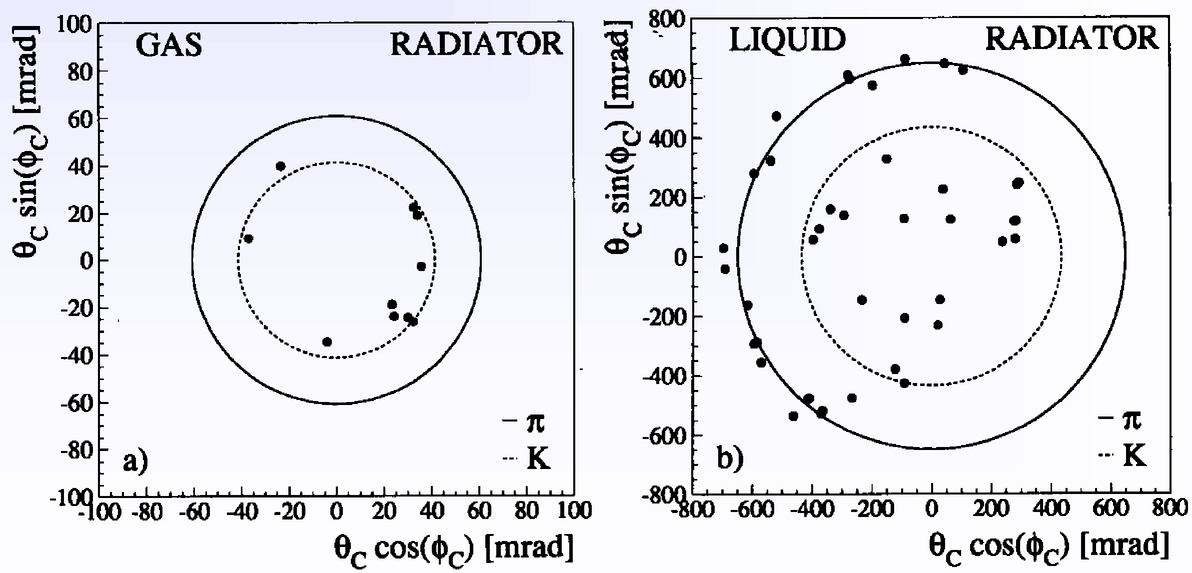
# Ring Imaging Cherenkov detectors (RICH)




DELPHI and SLD:
A RICH with two radiators and a common photodetector plane
→ covers a large momentum range.
→ $\pi$/K/p separation 0.7 - 45 GeV/c:

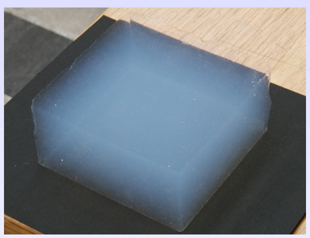
(W. Adam et al. NIM A 371 (1996) 240)

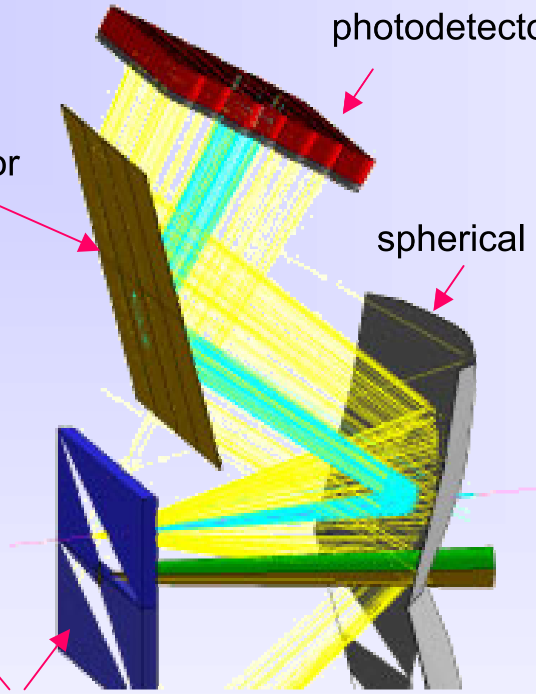
Two particles from a hadronic jet (Z-decay) in the DELPHI gas and liquid radiator.
Circles show hypotheses for $\pi$ and K



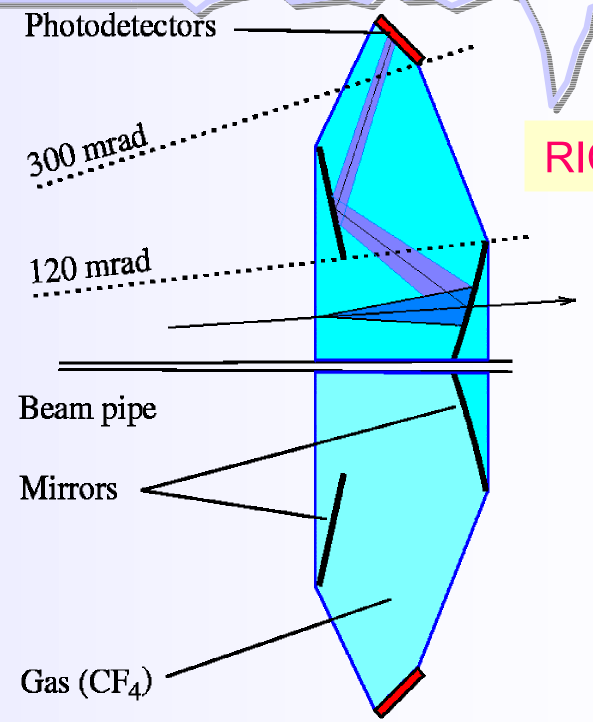
# 2 RICH detectors in LHCb

RICH 1





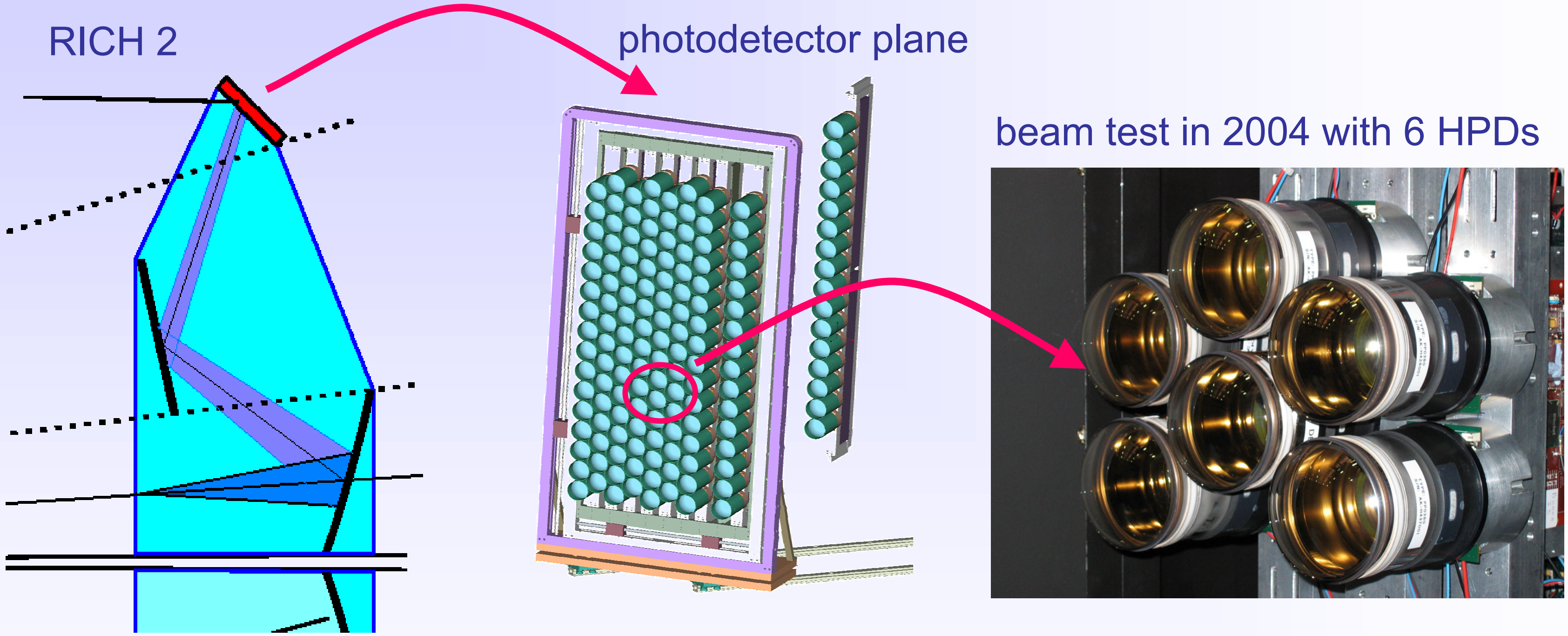

RICH 2




| radiator | $C_4F_{10}$ | aerogel |
|---|---|---|
| θ | 3.03° | 13.8° |
| n | 1.0014 | 1.03 |
| $p_{thresh}$ (π) | 2.6 | 0.6 GeV/c |
| $N_{p.e.}$ | 31 | 6.8 |
| $\sigma_\theta$ | 1.29 | 2.19 mrad |
| $p$ (3σ) | 56 | 13.5 GeV/c |

| radiator | $CF_4$ |
|---|---|
| θ | 1.8° |
| n | 1.0005 |
| $p_{thresh}$ (π) | 4.4 GeV/c |
| $N_{p.e.}$ | 23 |
| $\sigma_\theta$ | 0.6 mrad |
| $p$ (3σ) | 98.5 GeV/c |

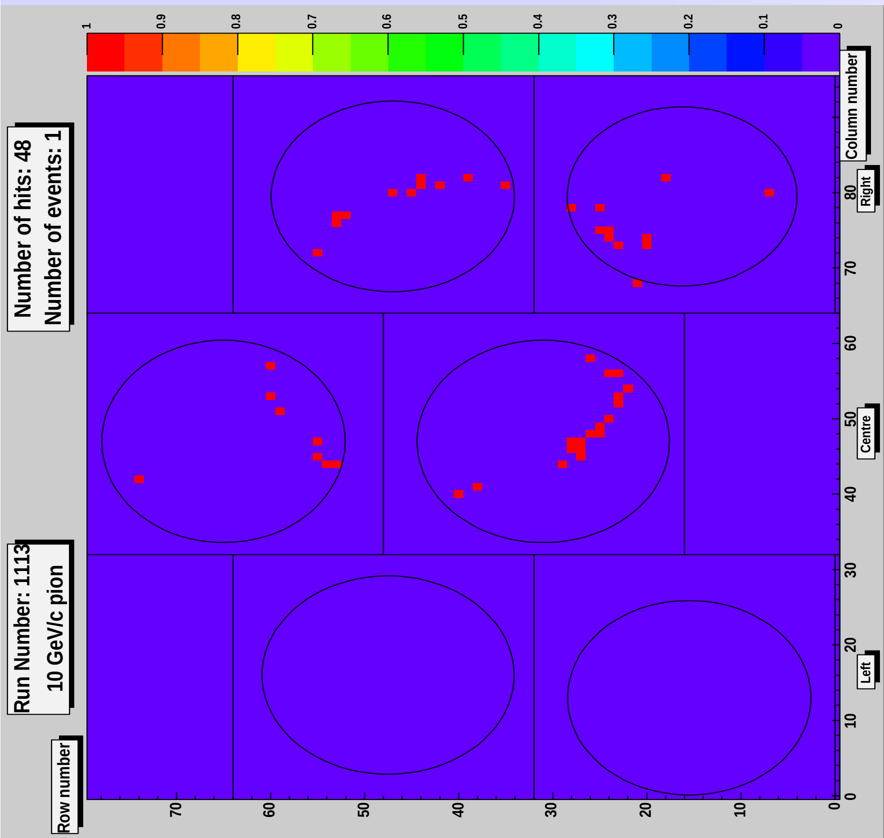
# 2 RICH detectors in LHCb



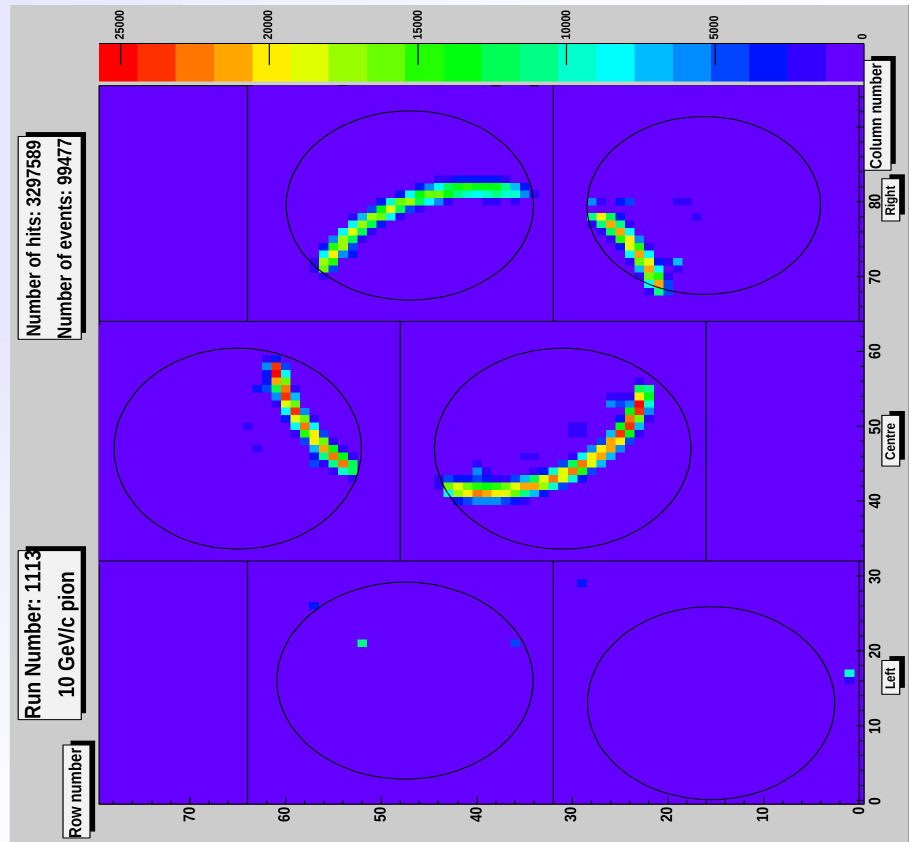
# 2 RICH detectors in LHCb

Beam test results with $C_4F_{10}$ radiator gas (autumn 2004).

Single pion (10 GeV/c)




Superimposed events (100 k pions, 10 GeV/c)



# Particle ID by Transition radiation

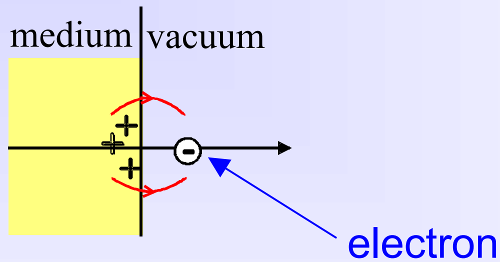
(there is an excellent review article by B. Dolgoshein (NIM A 326 (1993) 434))

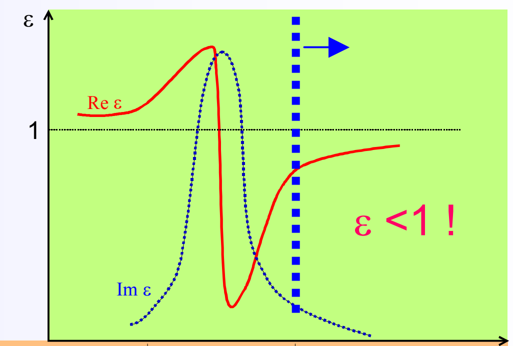
Transition Radiation was predicted by Ginzburg and Franck in 1946

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

TR is also called
sub-threshold
Cherenkov radiation

A (too) simple picture




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

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 energetic $e^{\pm}$ emit TR of detectable intensity.
→ particle ID

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

# Particle ID by Transition radiation

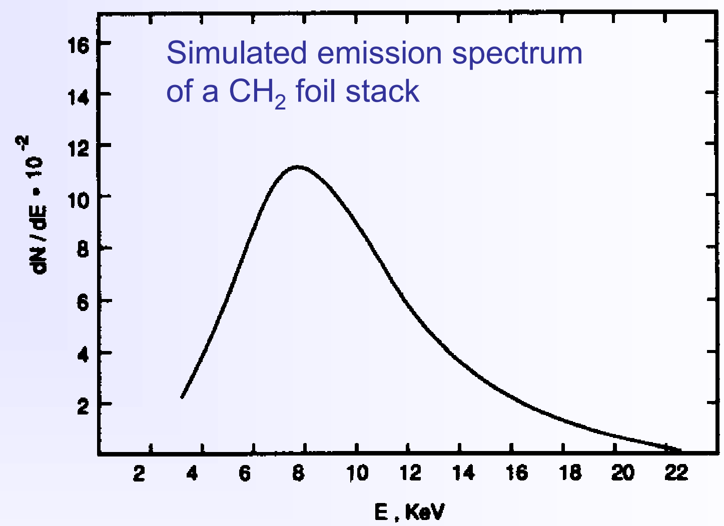
- Number of emitted photons / boundary is small $N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$

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

- Emission spectrum of TR = f(material, γ)

  Typical energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

  → photons in the keV range




- X-rays are emitted with a sharp maximum at small angles $\theta \propto 1/\gamma$

  → TR stay close to track

- Particle must traverse a minimum distance, the so-called formation zone $Z_f$, in order to efficiently emit TR.

$$Z_f = \frac{2c}{\omega(\gamma^{-2} + \theta^2 + \xi^2)}, \quad \xi = \omega_p / \omega$$

$Z_f$ depends on the material ($\omega_p$), TR frequency ($\omega$) and on $\gamma$.

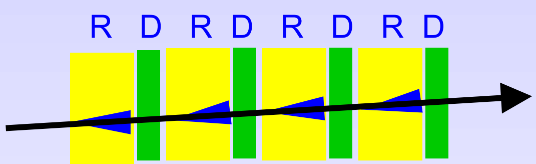
$Z_f(air)$ ~ mm, $Z_f(CH_2)$ ~ 20 μm → important consequences for design of TR radiator.

# Particle ID by Transition radiation

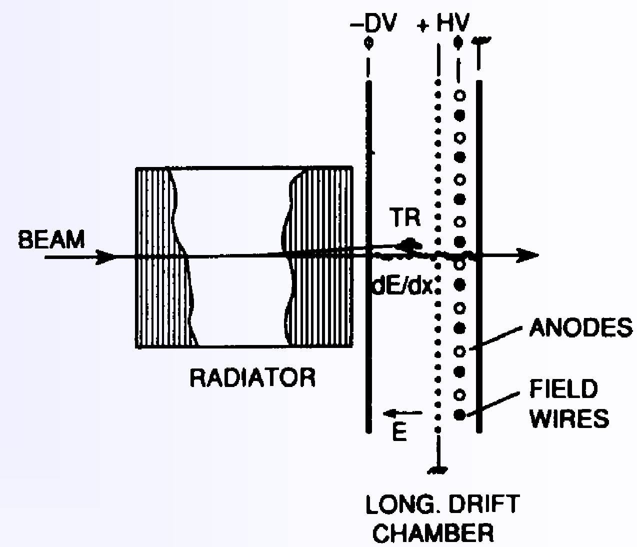
## TR Radiators:

- stacks of thin foils made out of $CH_2$ (polyethylene), $C_5H_4O_2$ (Mylar)
- hydrocarbon foam and fiber materials

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



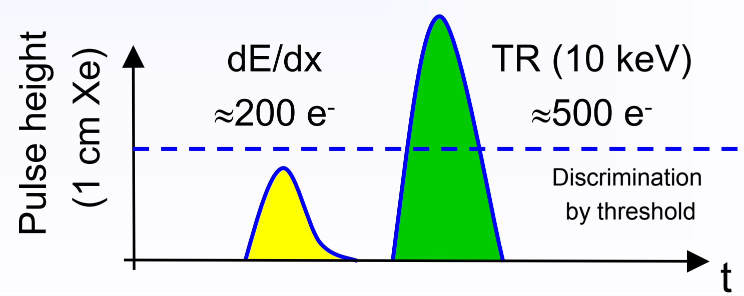

alternating arrangement of radiators stacks and detectors
→ minimizes reabsorption




## TR X-ray detectors:

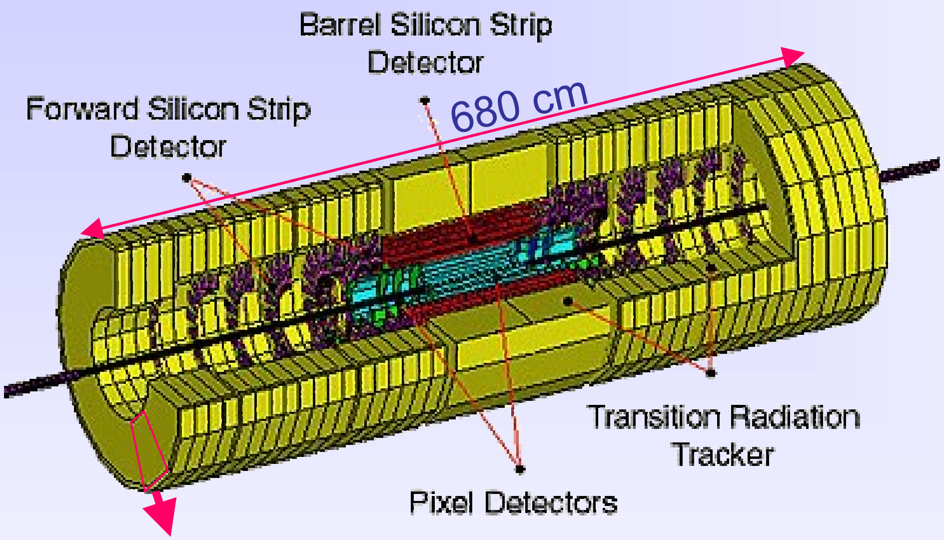
- Detector should be sensitive for $3 \le E_\gamma \le 30$ keV.
- Mainly used: Gas detectors: MWPC, drift chamber, straw tubes…
- Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

  → gas with high Z required, e.g. Xenon (Z=54)
- Intrinsic problem: detector "sees" TR and dE/dx

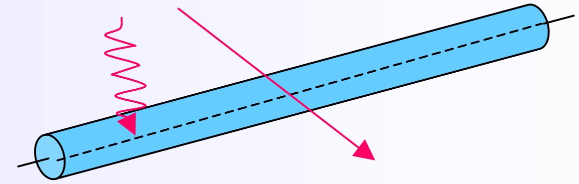


# Particle ID by Transition radiation

## The ATLAS Transition Radiation Tracker (TRT)




Straw tubes (d = 4mm) based tracking chamber with TR capability for electron identification.



Active gas is $Xe/CO_2/O_2$ (70/27/3) operated at ~$2x10^4$ gas gain; drift time ~ 40ns ( fast!)

Radiators

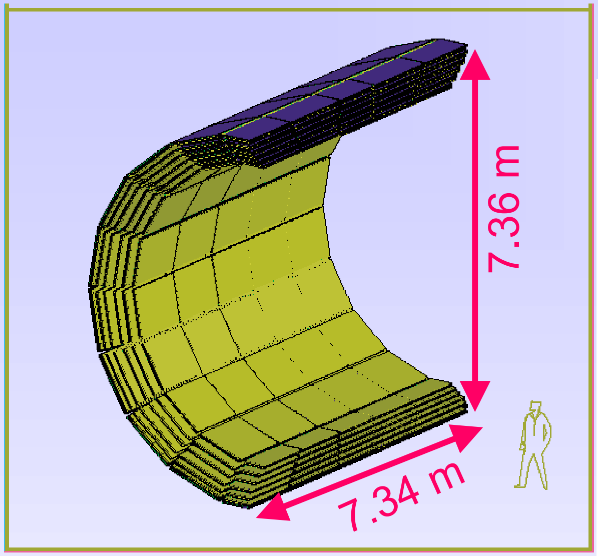
- Barrel: Propylen fibers
- Endcap: Propylen foils
  d=15 $\mu$m with 200 $\mu$m spacing.

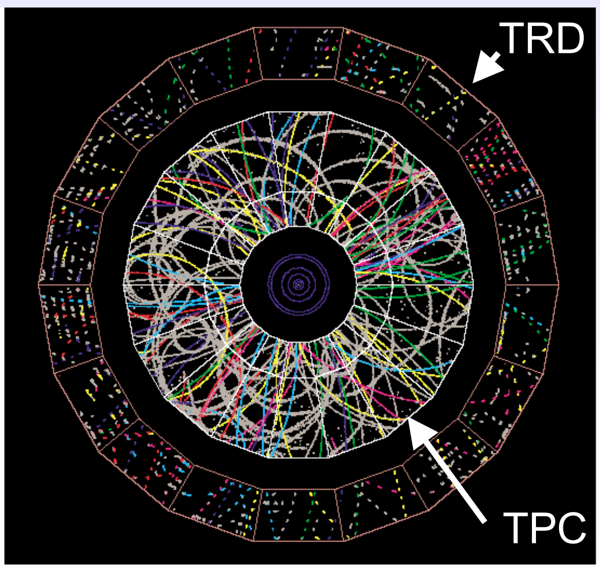
photo of an endcap TRT sector.

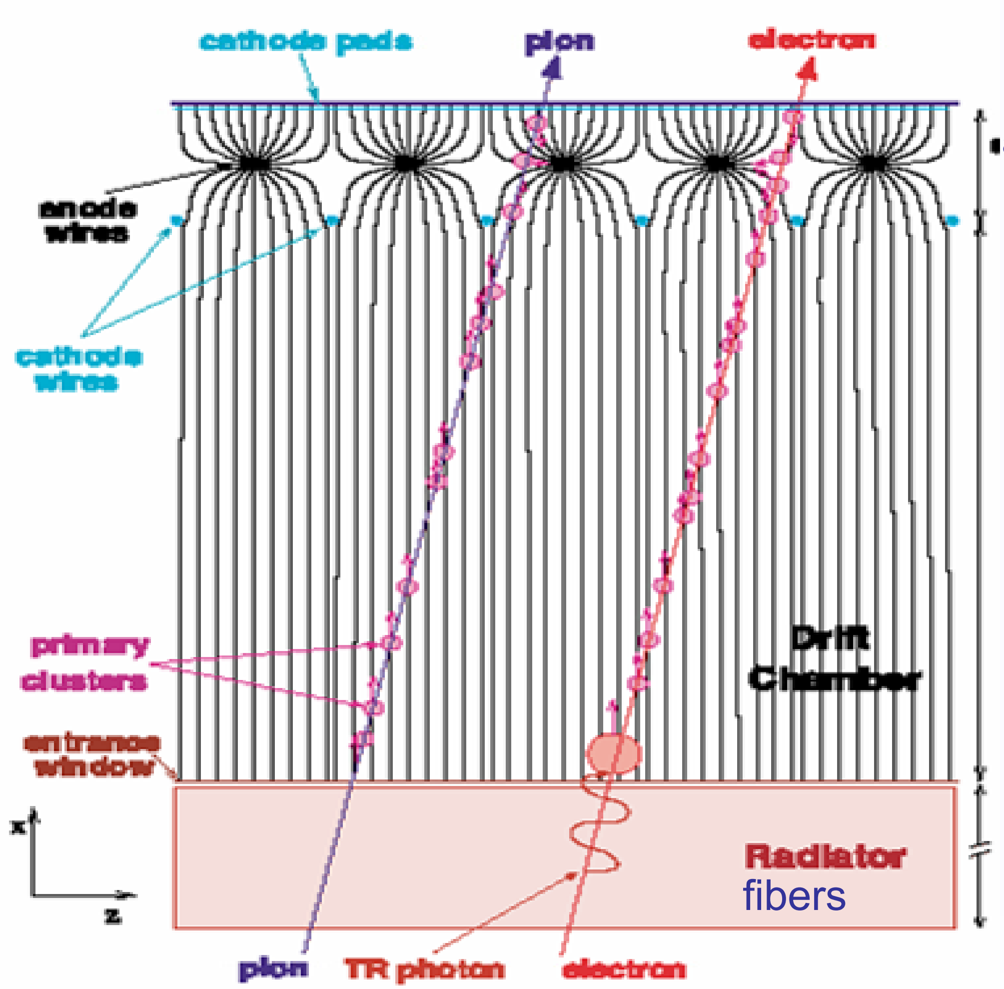
Counting rate ~ 6-18 MHz at LHC design luminosity $10^{34}$ $cm^{-2}s^{-1}$

# ALICE TRD

Time Expansion Chamber with Xe/$CO_2$ gas (85%-15%)



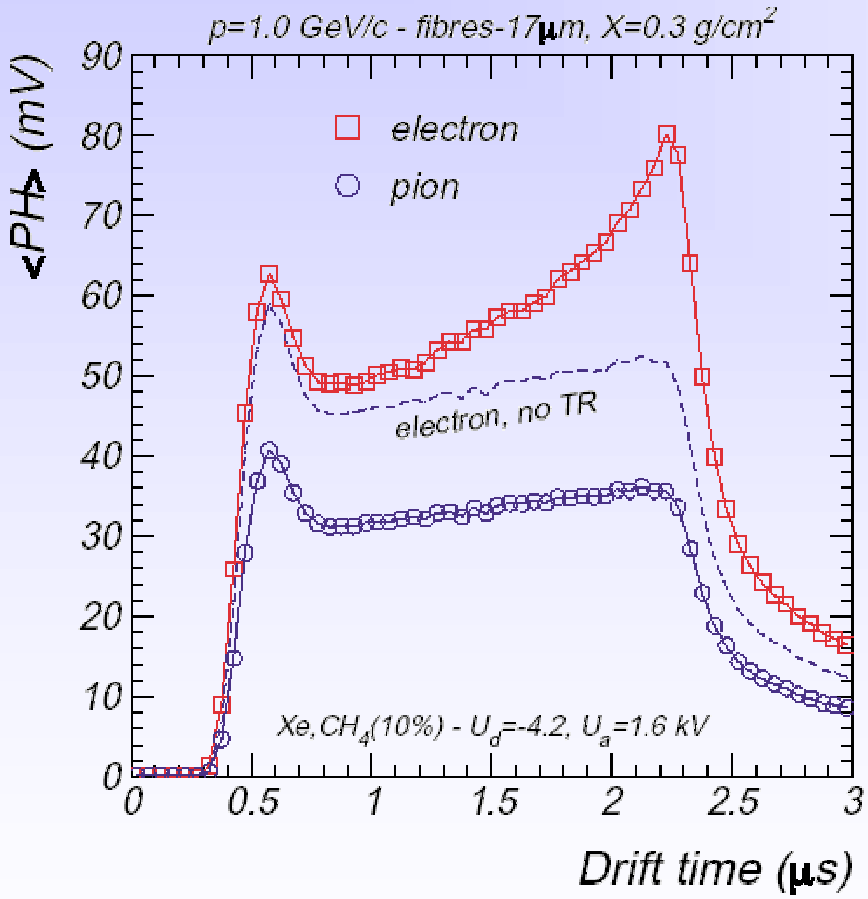



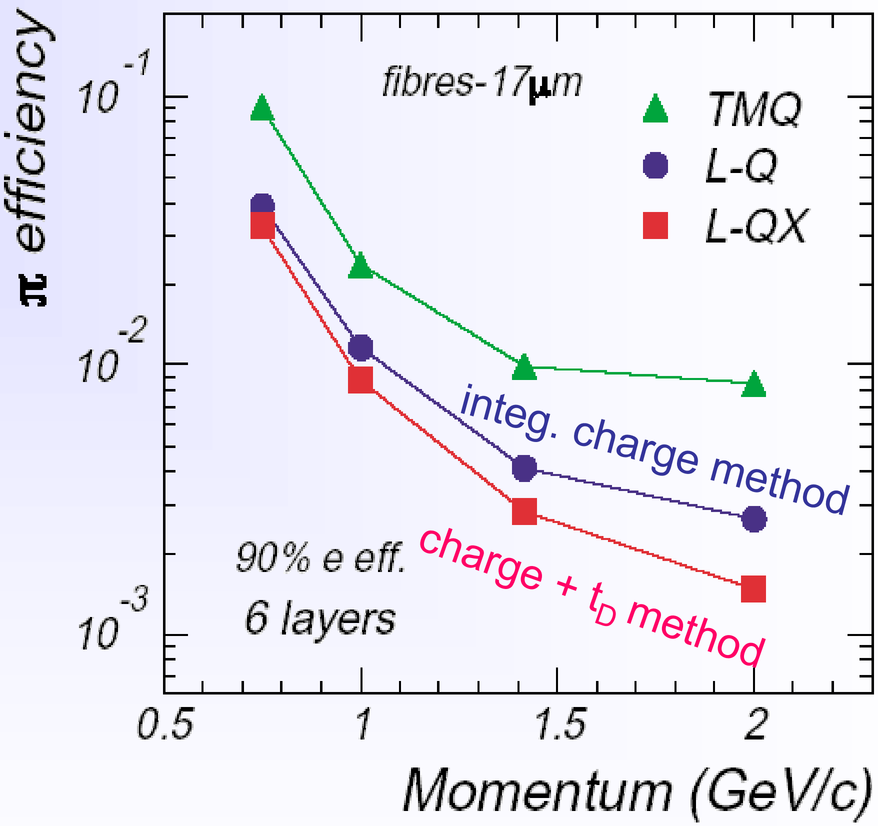




amplification region 5mm

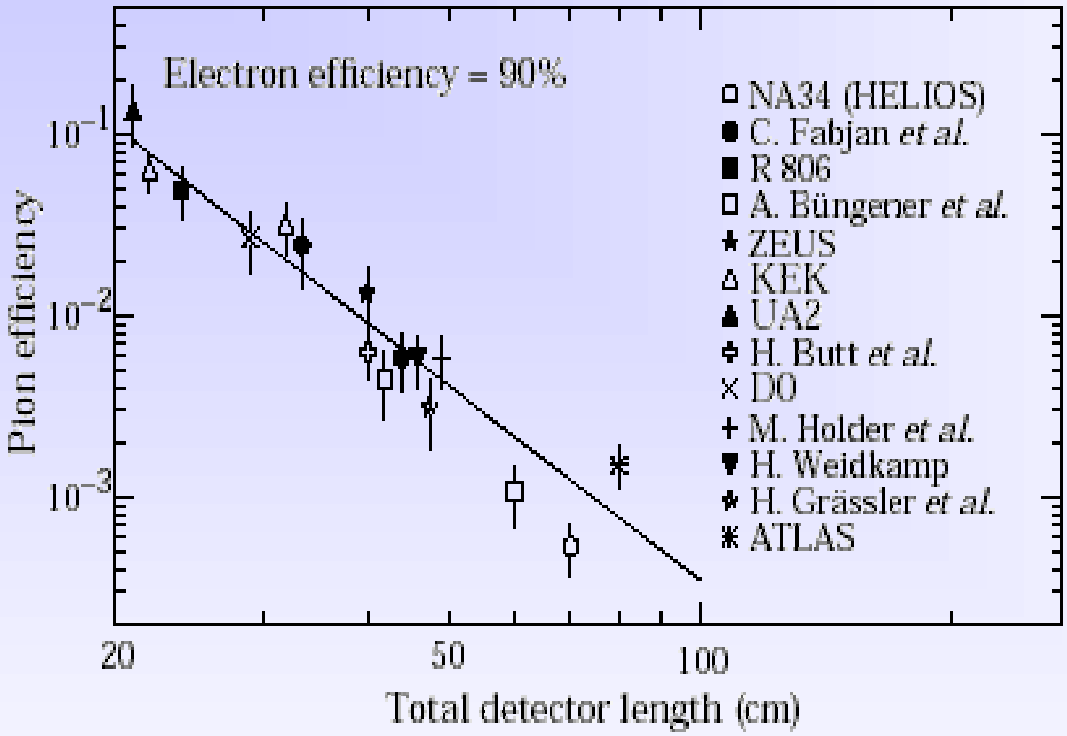
drift region 30 mm

# ALICE TRD performance



# Particle ID by Transition radiation




Rejection Power : $R_{\pi/e} = \varepsilon_{\pi}/\varepsilon_{e}\,(90\%)$

one order of magnitude in Rejection Power is gained when the TRD length is increased by ~ 20 cm

# Particle Identification

## 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 ....