Particle Detection Techniques in HEP

Lecture 5: Particle Identification

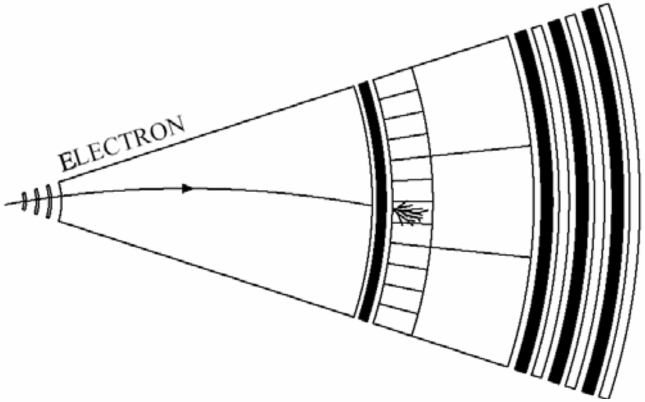
Post-graduate lecture series

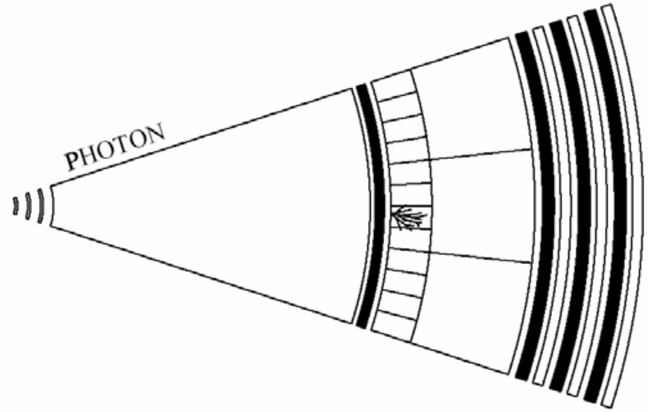
Joost Vossebeld

Lecture 5 “Particle identification techniques”

- Particle identification by global signatures
- Muon detection
- **d*E*/dx**
- Time-of-Flight detectors
- Cherenkov detectors
- Transition radiation detectors

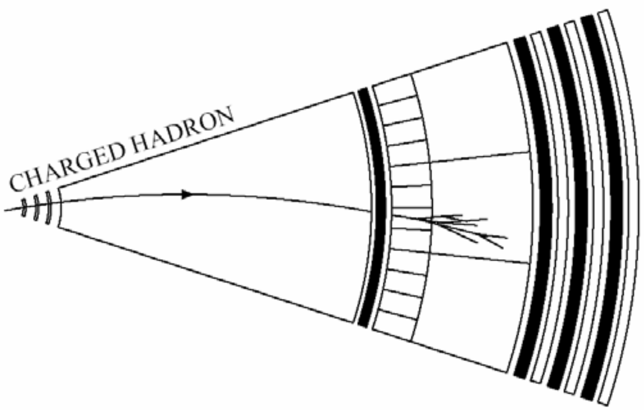
Particle identification from global signatures (recap.)

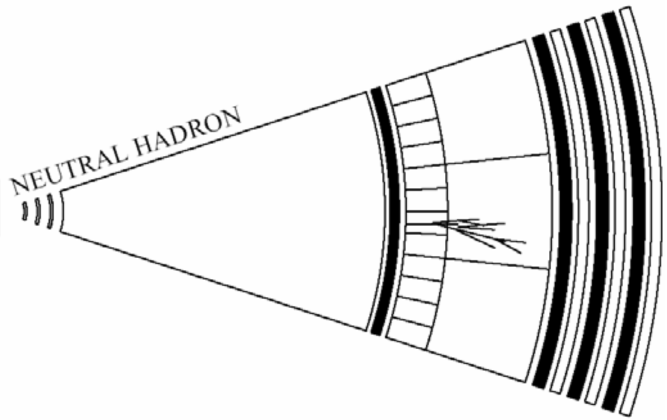




Electrons & photons:

- track if electron
- shallow E.M.-shower

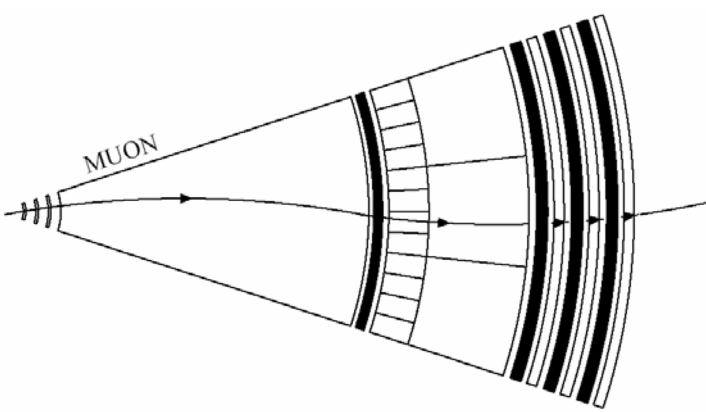




Charged/neutral hadrons:

- track if charged track
- deep hadronic shower

At low ***E*** similar to **e**/γ!



Muons:

- track in inner tracking detectors
- not stopped in calorimeter

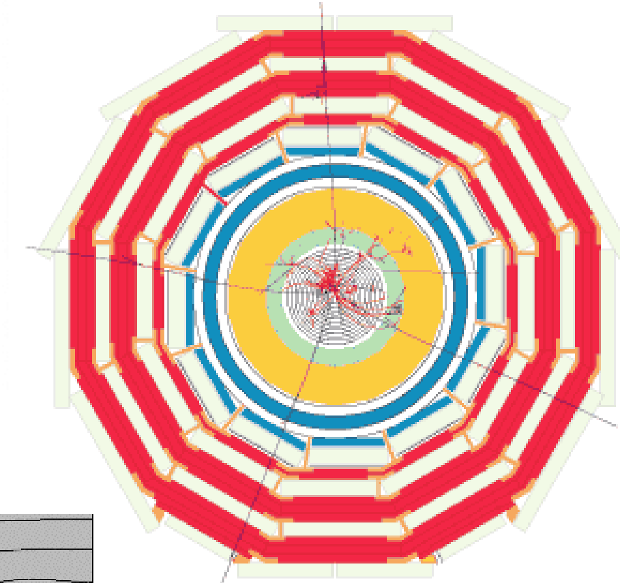
  (only energy deposition from ionisation)
- track in muon detectors

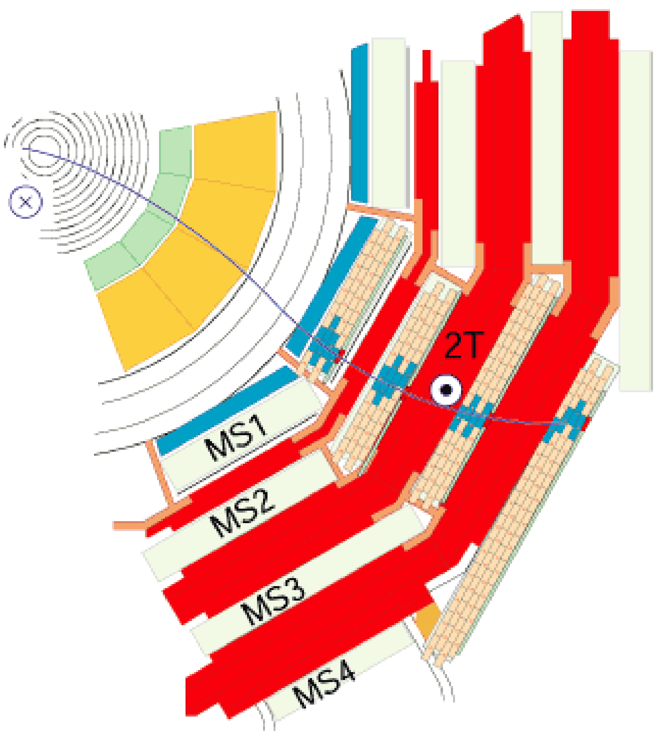
Muon detection: example CMS μ-chambers:

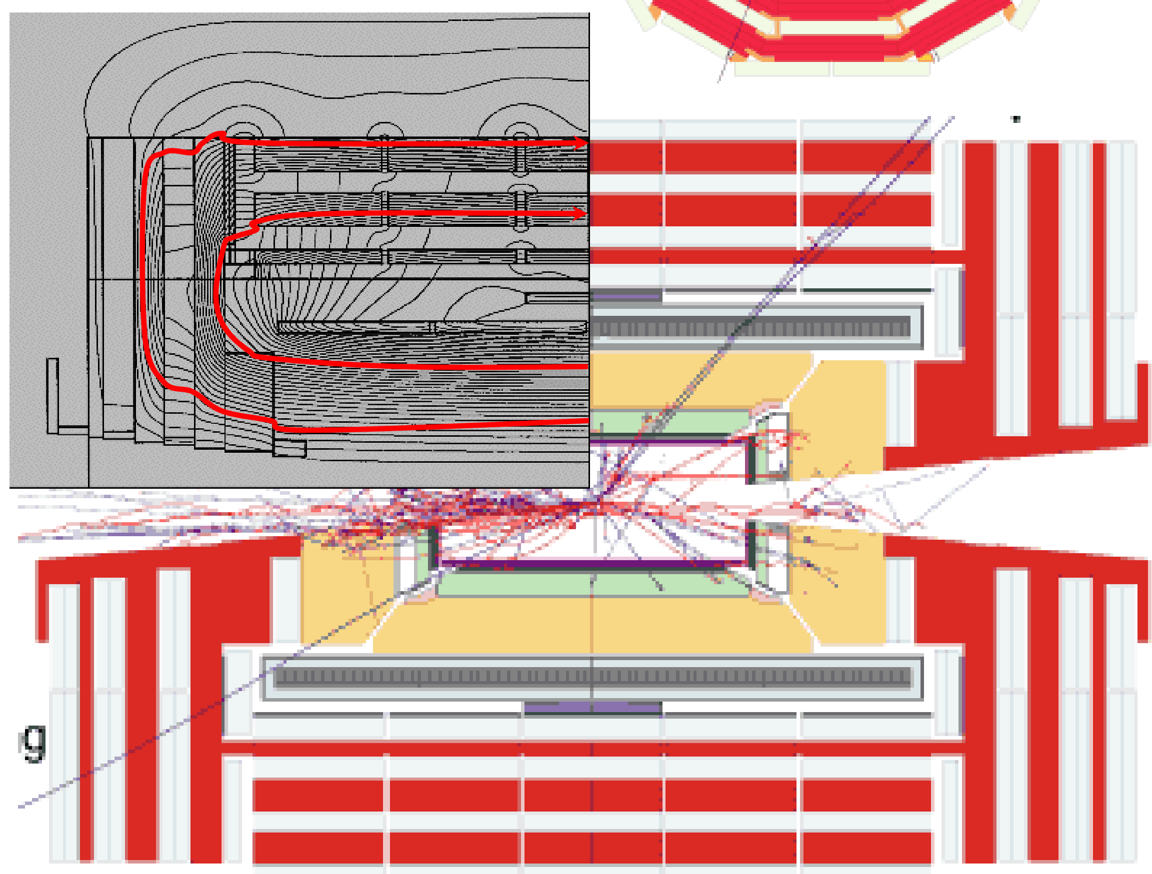
Sandwich of iron and detectors: drift-tubes / resistive parallel plate chambers / cathode strip chambers

Iron cylinders (barrel) and disks (endcap) act as return yoke for the ***B***-field. (Tracks are bent twice!)

This helps the measurement of the momenta of muons.







Particle ID based on the detectors discussed so far:

Global signatures: electrons, photons, hadrons and muons (if ***p*** > few GeV/c!)

Using tracking (and calorimetry) information:

- identify the charge of particles (from bending direction in the ***B***-field)
- identify some unstable hadrons by:
  - Mass reconstruction from the decay products
    e.g. $\pi^0/\eta \to \gamma\gamma, \quad K_s^0 \to \pi^+\pi^-, \quad ....$
  - observation of the displaced decay vertex (e.g. B-hadron decays)

What we would like to do in addition:

- Identify more charged hadron species (**p/pbar**, $\pi^{\pm}$, **K**$^{\pm}$,..)
- Identify neutral hadron species (we can't)
- Distinguish electrons from hadrons at low energies

Two basic approaches:

1. Measure the mass! (identification of charged hadrons species and electrons)
   - Ionisation energy loss (**d*E*/dx**)
   - Cherenkov radiation
   - Time-of-flight measurements
2. Exploit special energy loss properties of electrons
   - Improved longitudinal segmentation of e.m.-calorimeter (not discussed here)
   - Transition radiation

Particle identification from **d*E*/dx**

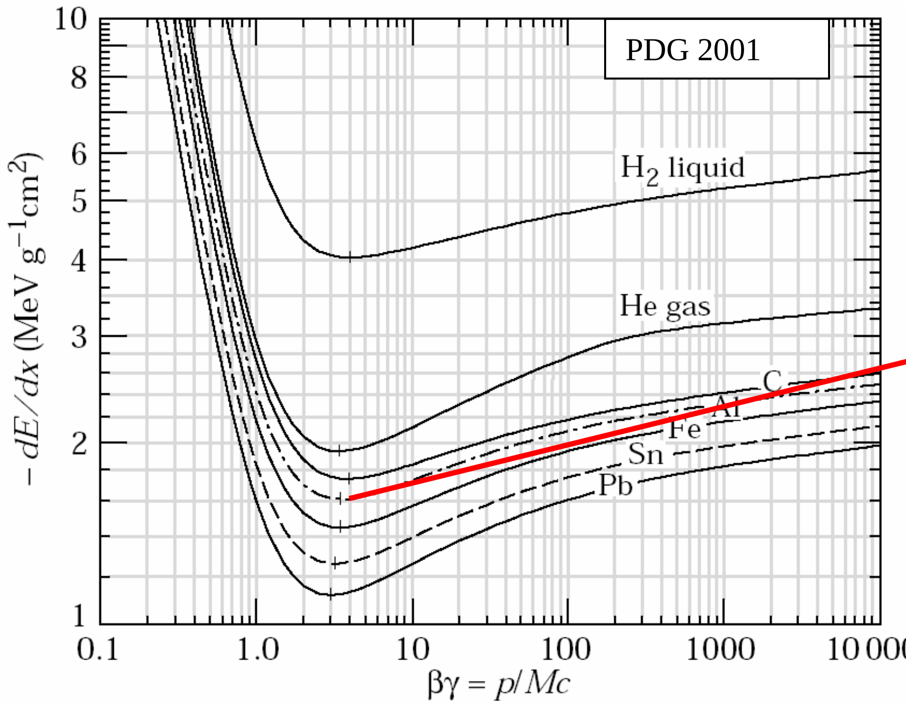
Maccabee & Papworth 1969

In tracking detectors we can measure the ionisation energy loss **d*E*/dx** by ionisation.

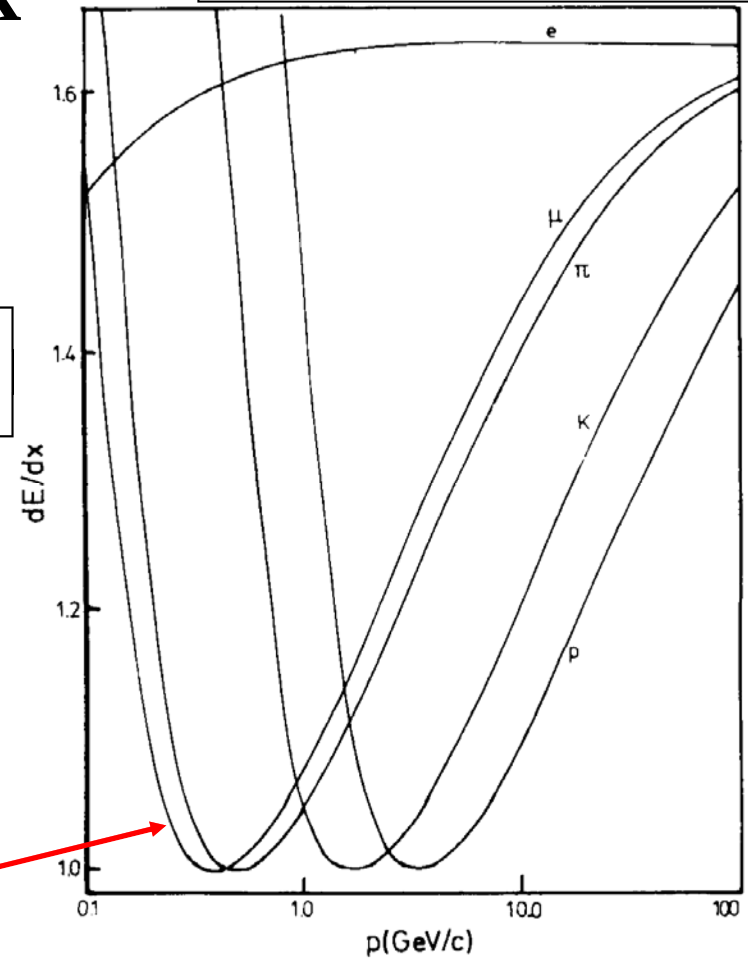
Bethe-Bloch equation:

$$-\frac{dE}{dx} = N_A \frac{2\pi\,\alpha^2(\hbar c)^2}{m_e c^2} z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2\gamma^2\beta^2 m_e c^2}{I_0}\right) - \beta^2 - \frac{\delta(\beta)}{2}\right]$$

Energy loss spectrum depends on βγ:



$p=m\beta\gamma$

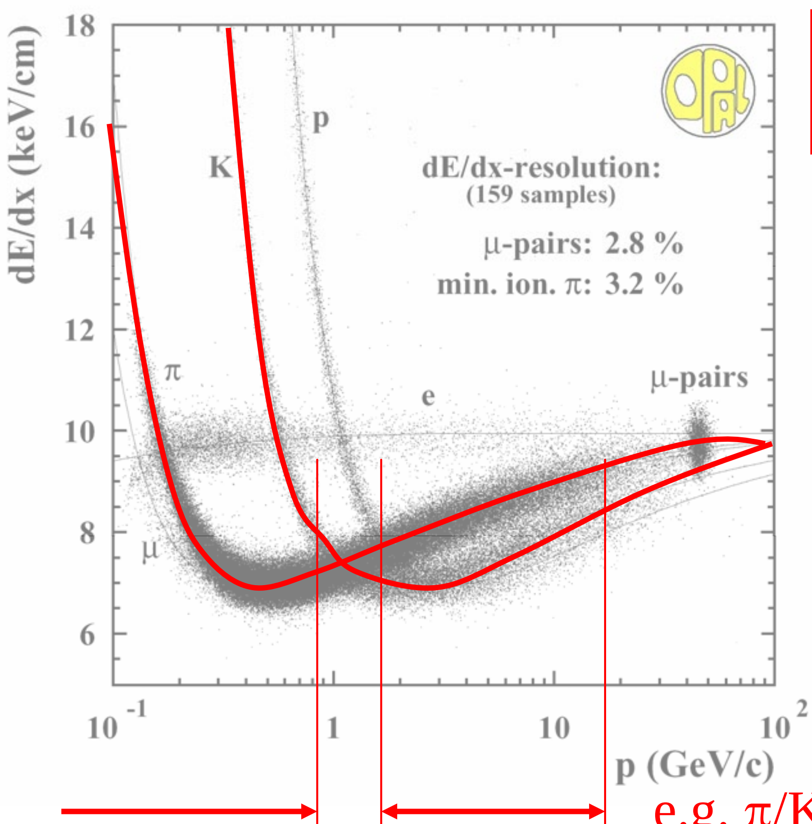


For different particle masses the spectra are shifted along ***p***.

Exception: Electrons have Bremsstrahlung.

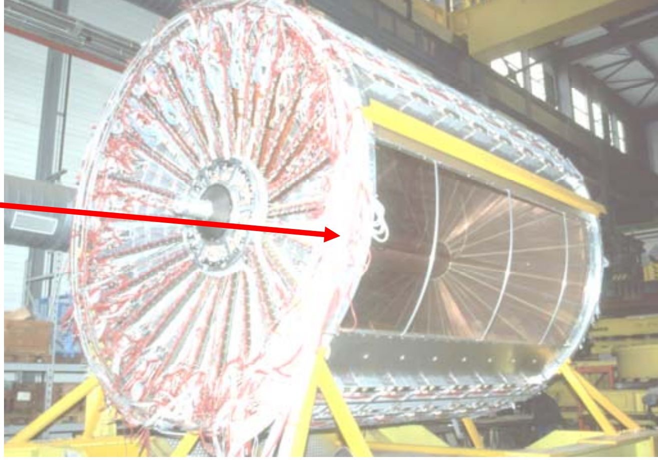
Thus a simultaneous measurement of **d*E*/dx** and ***p*** provides information on the mass!

Example: **d*E*/dx** OPAL central drift-chamber.



e.g. π/K separation >2σ

24 radial sectors with 159 wires each



Different particle types form “bands” in the plane of **d*E*/dx** and ***p***.

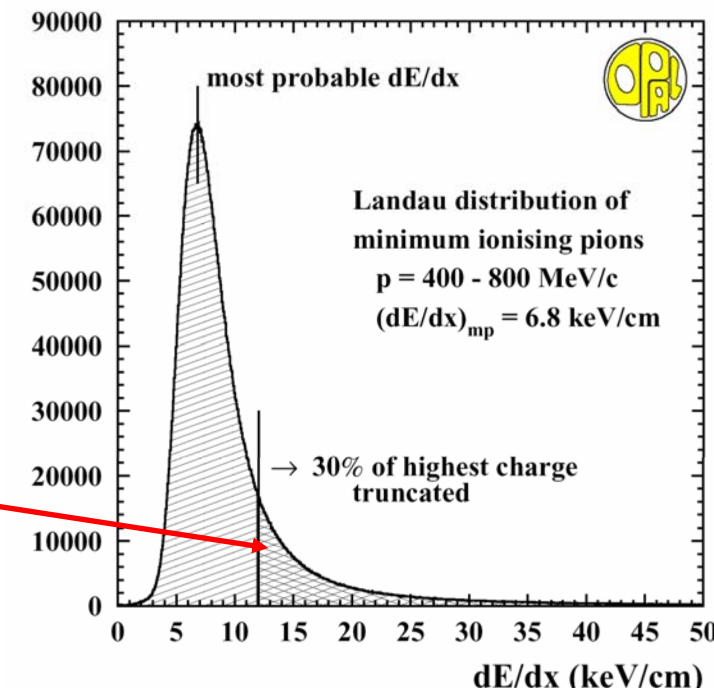
Thus we can identify particle species (except where the bands overlap!)

For best separation we need good resolution in **d*E*/d*x***.

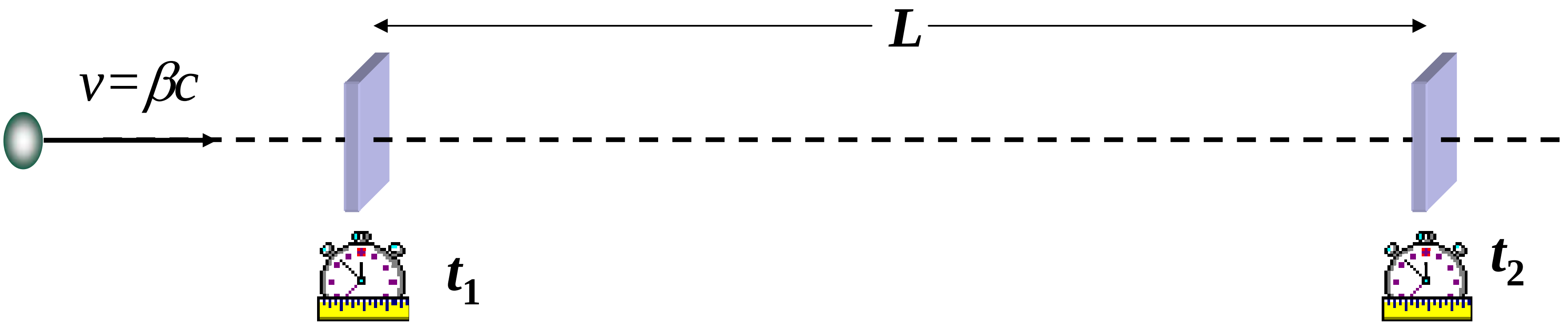
- take many samples (here: 159 wires hit per particle)

d*E*/d*x* distribution is not Gaussian (Landau tail)

- reject highest signal hits



Time-of-Flight (TOF)



$$t_2 - t_1 = \Delta t = \frac{L}{\beta c} = \frac{L}{c}\sqrt{1+\frac{m^2c^4}{p^2c^2}}$$

Combined measurement of $\Delta \boldsymbol{t}$ and $\boldsymbol{p}$ provides information on the mass!

- Only works in non-relativistic regime, $\beta<1$! (up to a few GeV/c)

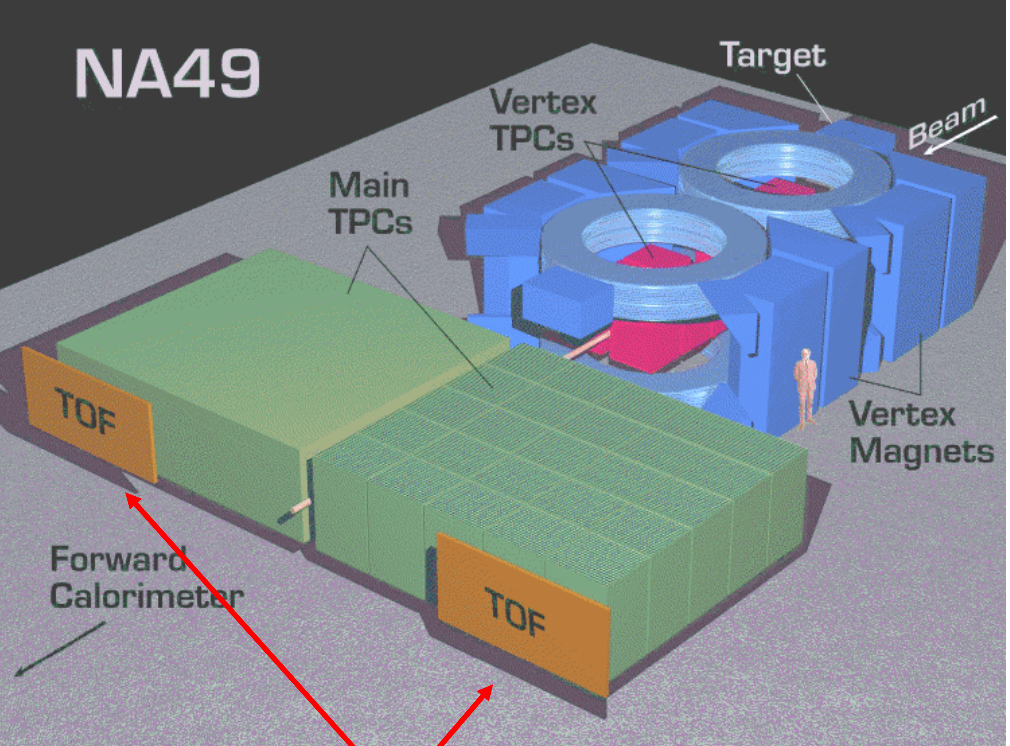
For best mass determination we need:

- good time resolution (e.g. using scintillator detectors)
- long path length ***L***

$\boldsymbol{t_1}$: usually taken to be the collision time (from combined timing measurements)

$\boldsymbol{t_2}$: detector typically installed after tracking detectors and before calorimeters. (longest possible ***L***)

NA49 Time-of-flight detector



NA-49: fixed target experiment for heavy ion collisions

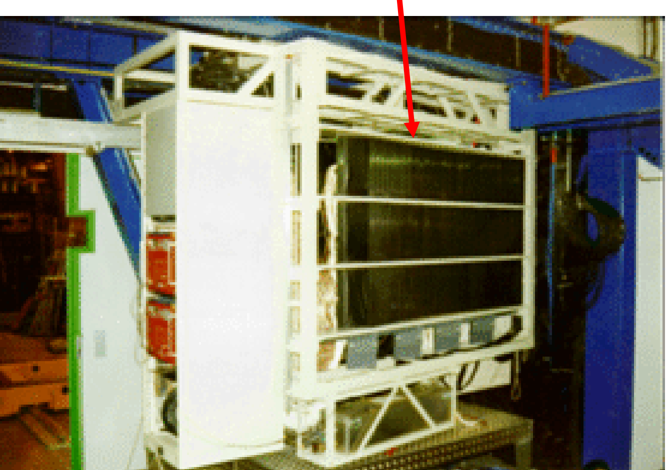
This allows for long path length:

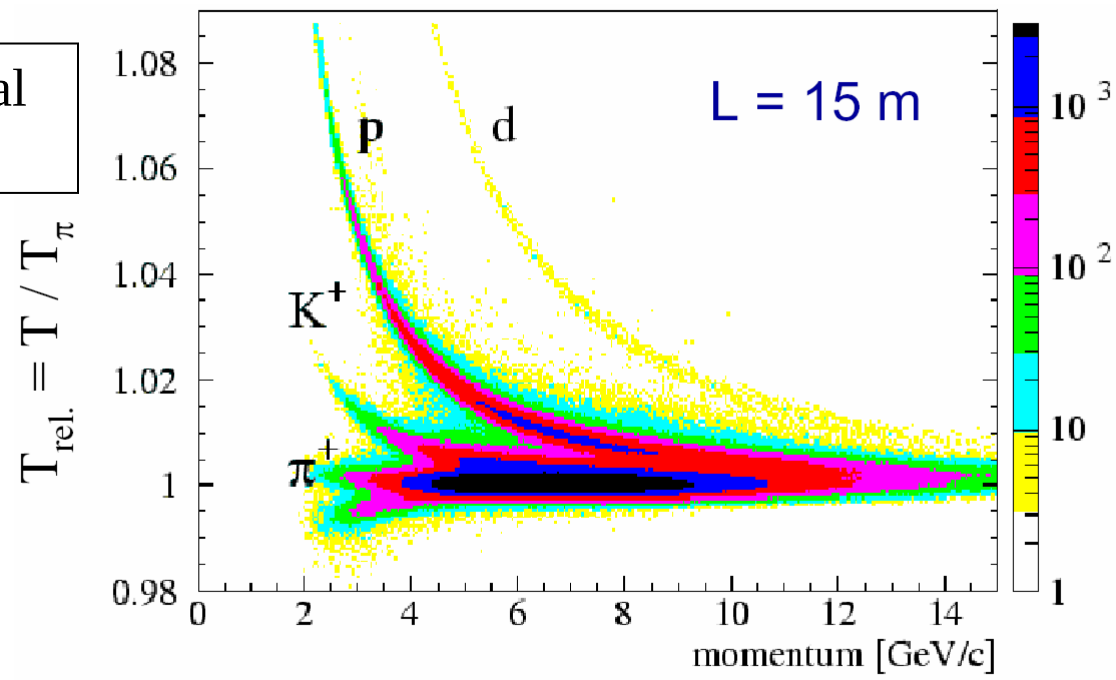
$$L \approx 15\text{m!}$$

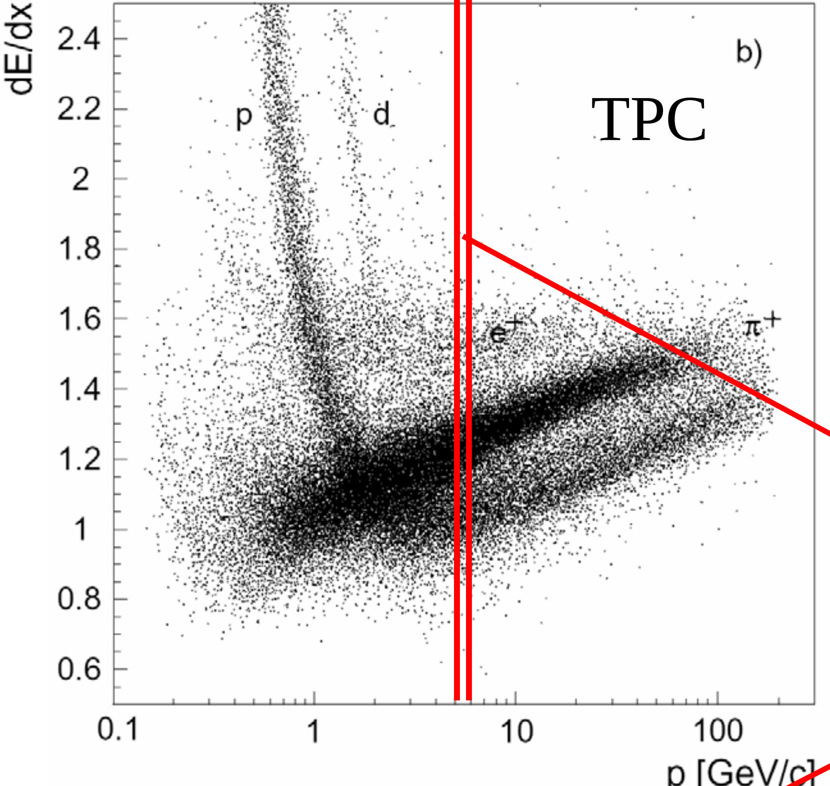
In addition big scintillator rods have excellent time resolution:

$$\sigma(\Delta t) \approx 60 \text{ ps!}$$

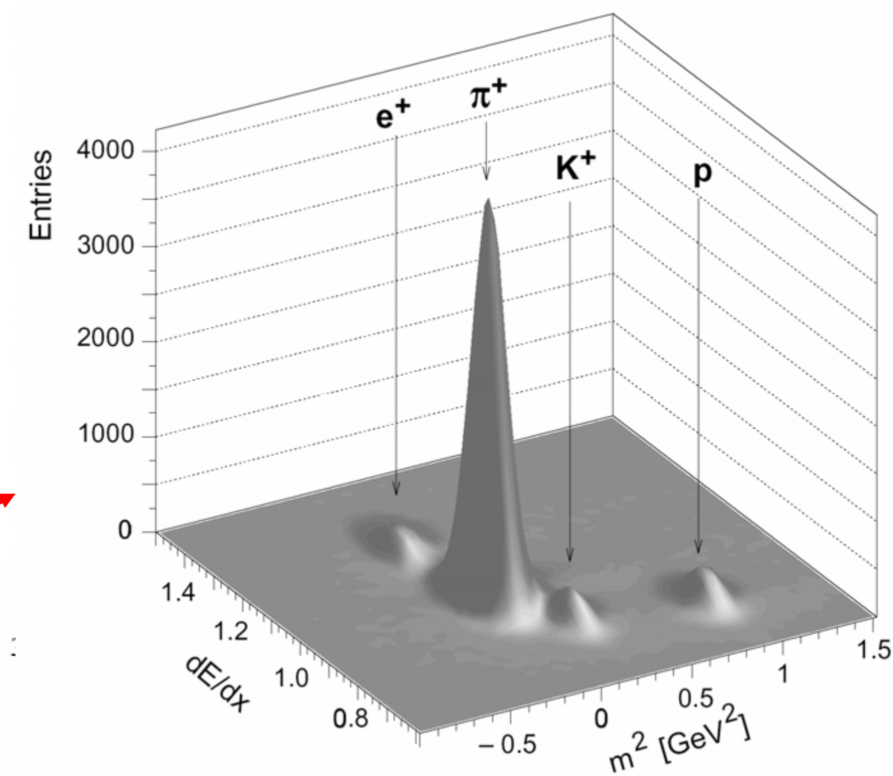
TOF chambers: layers of horizontal and vertical scintillator rods

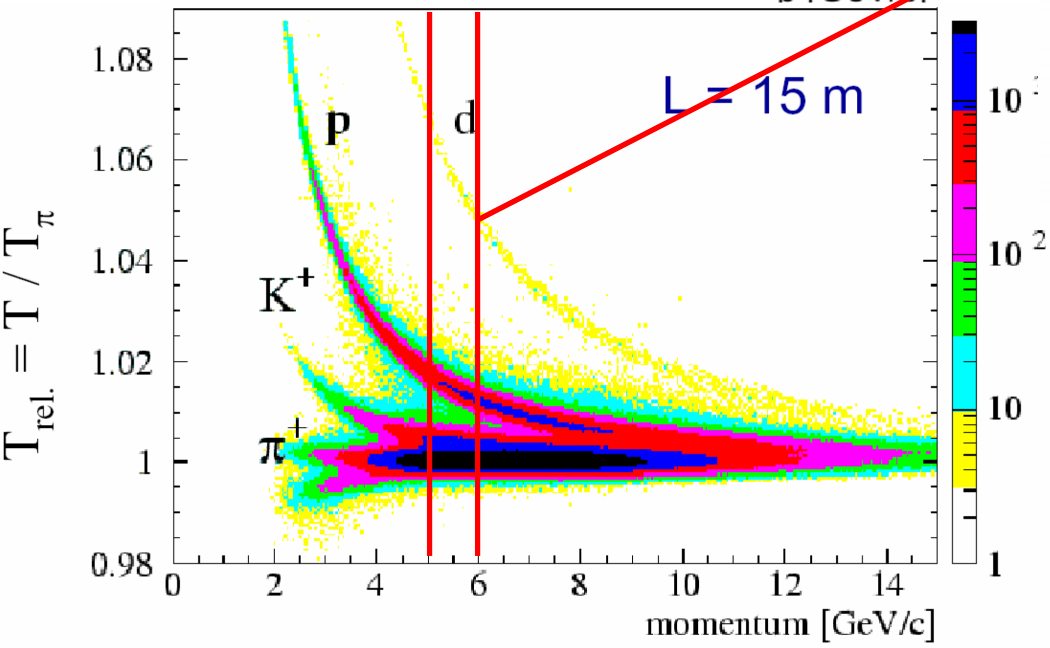






Best particle identification when different techniques are combined:





Example:

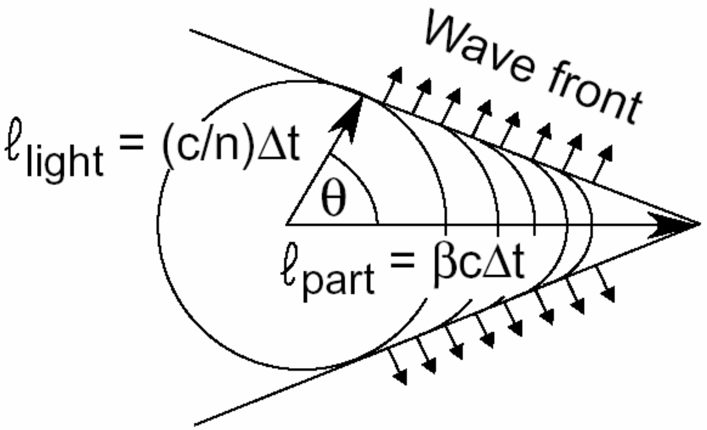
NA49: **d*E*/d*x*** versus m_{TOF}

for p = 5..6 GeV

Cherenkov radiation:

Photo emission by a charged particle travelling in a dielectric medium with a velocity greater than the velocity of light in that medium:

$$v_{\text{particle}} > \frac{c}{n} \quad \left(\beta_{\text{thr}} = \frac{1}{n}\right)$$



Huygens wavelets emitted all along the particles trajectory form a single wave front under an angle θ_c w.r.t. the particle direction:

$$\cos\theta_c = \frac{(c/n)\Delta t}{\beta c \Delta t} = \frac{1}{\beta n}$$

Photon yield:

$$\frac{d^2 N}{dx d\lambda} = 2\pi z \alpha \frac{1}{\lambda^2} \sin^2\theta_c$$

$\propto$ **$\sin^2(\theta_c) = 1-(1/\beta n)^2$** $\Rightarrow$ small when $n \approx 1$!

$\propto$ **$1/\lambda^2$** $\Rightarrow$ mostly blue light!

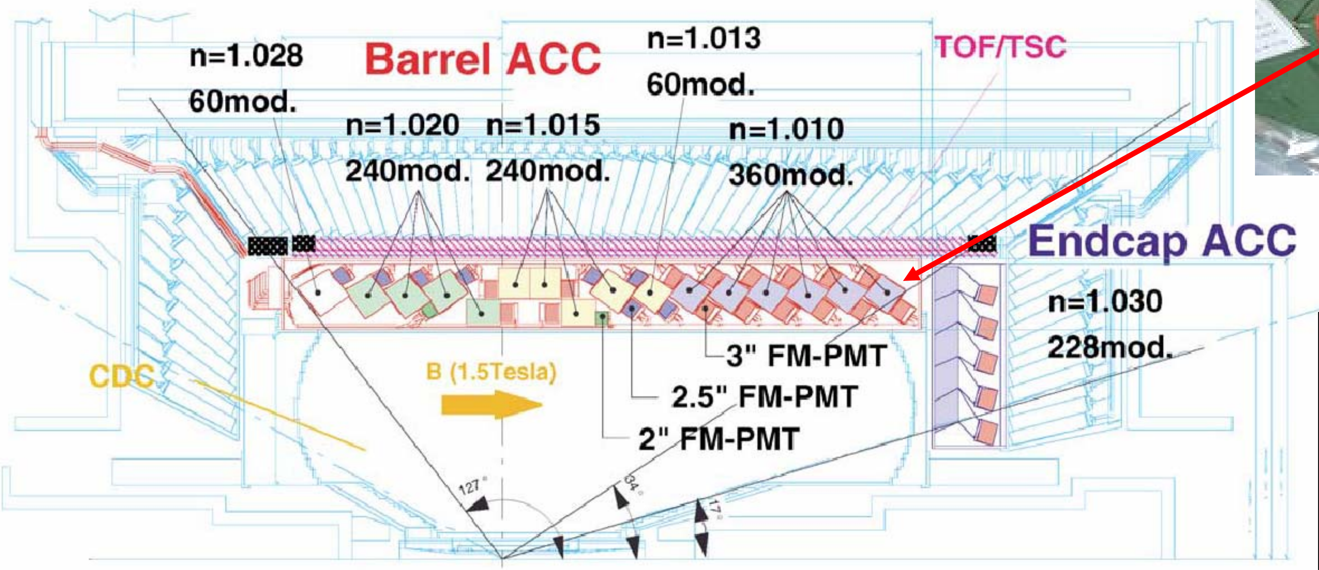
Medium	n-1	θ_{max}	$\pi_{thr}(p)$ GeV/c	N_γ ($eV^{-1}cm^{-1}$)
Air	1.000283	1.36°	5.9	0.21
Isobutane	1.00217	3.77°	2.12	0.94
Aerogel	1.0065	6,51°	1.23	4.7
Aerogel	1.055	18.6°	0.42	37.1
Water	1.33	41.2°	0.16	160.8
Quartz	1.46	46.7°	0.13	196.4

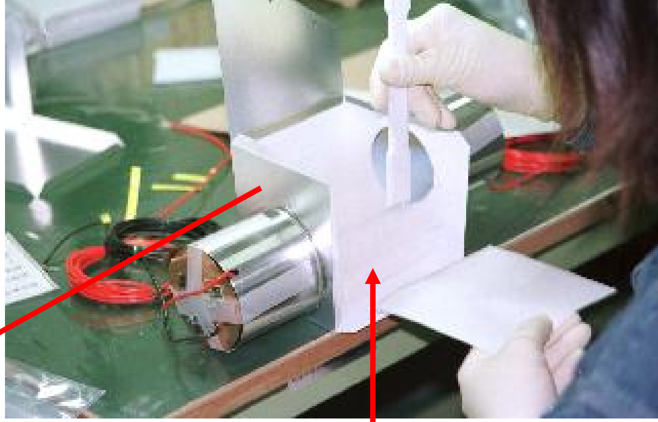
Both β_{thr} and θ_c (combined with ***p***) can be used for particle ID.

n values can be chosen to get particle ID in a particular range of momenta!

Threshold Cherenkov detector

Example: Belle Aerogel Cherenkov Counter (ACC)





Silica Aerogel radiators
(***n***=1.010..1.030)
photo-multiplier tubes

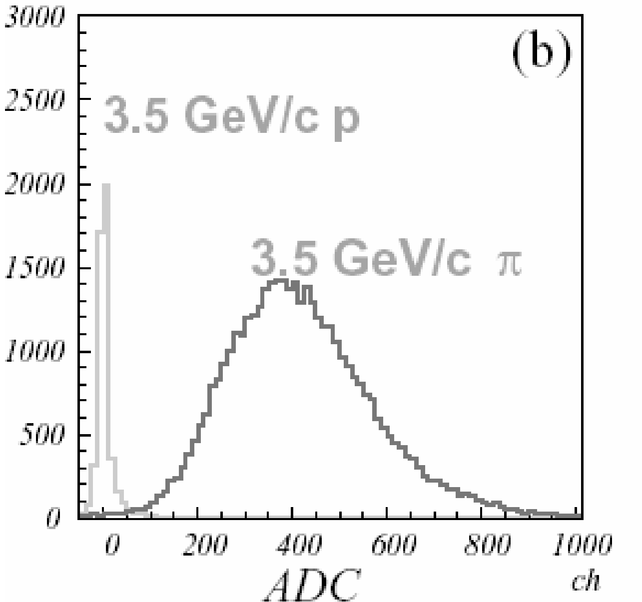
Example: ***n***=1.015

Threshold for Cherenkov radiation (β_{thr} = **1/*n*** = 0.985)

p_{thr} = 0.80 GeV/c for pions

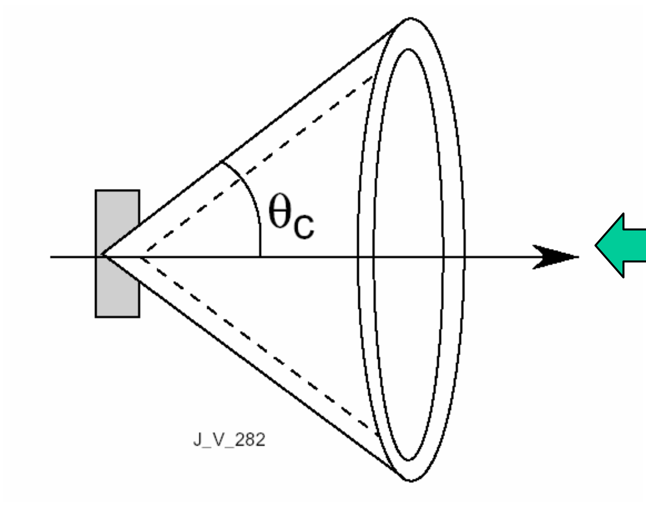
p_{thr} = 2.8 GeV/c for kaons

P_{thr} = 5.4 GeV/c for protons



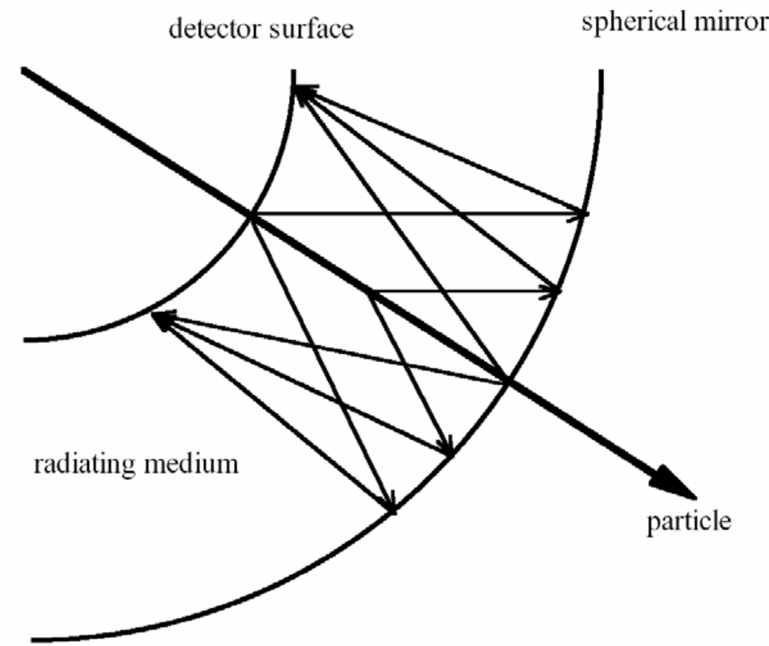
Ring Imaging Cherenkov Detectors (RICH)

θ_c can be measured from Cherenkov rings. (two ways to produce rings)



A charged particle traversing a thin layer of a radiator material will produce a ring of photons.

Suitable for high ***n*** materials (high photon yield)



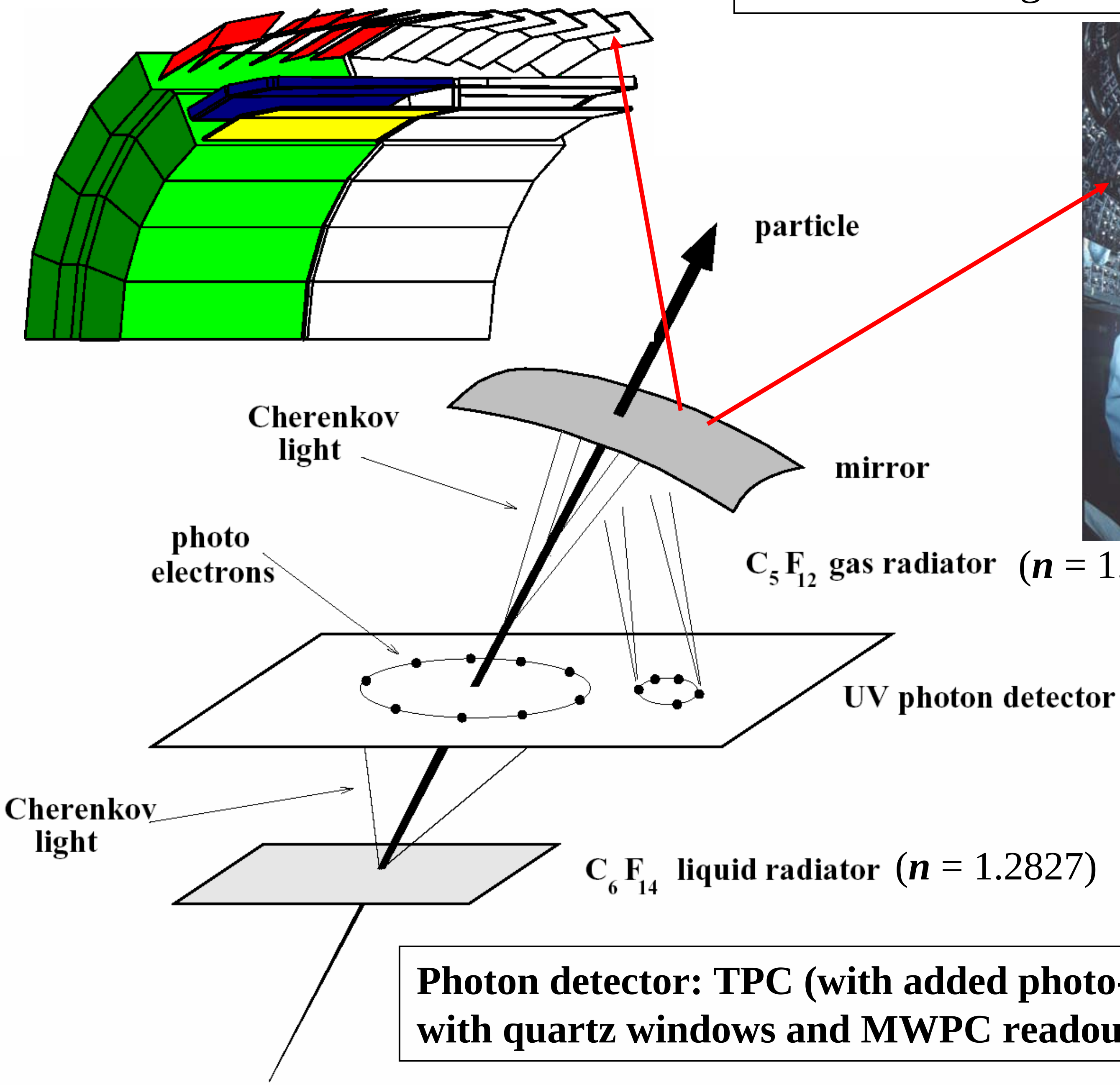
A spherical mirror will produce a ring-shaped image of the Cherenkov cone.

Suitable for low ***n*** materials (e.g. gas)

Both the <u>radius of the ring</u> and the <u>intensity</u> are related to θ_c and thus to β.

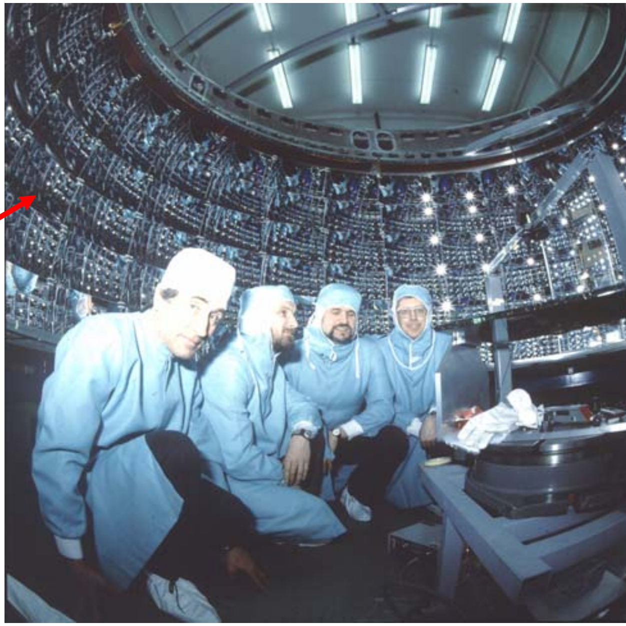
Example: Delphi RICH

RICH detector using two radiators of different refractive strength



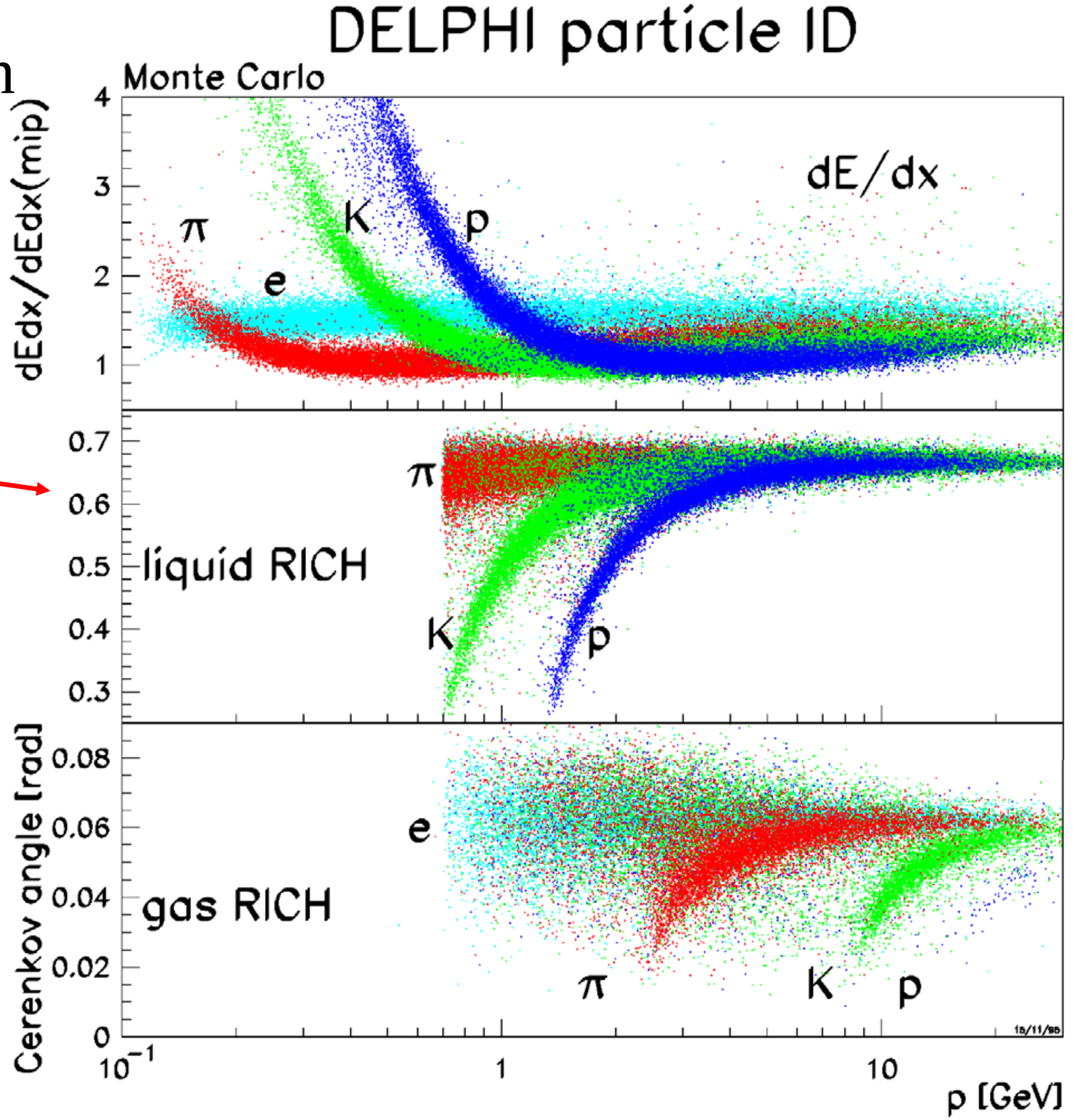
$(n = 1.00172)$

$(n = 1.2827)$



Photon detector: TPC (with added photo-ionisation vapour, TMAE) with quartz windows and MWPC readout.

Particle identification with the DELPHI RICH



<u>Liquid radiator</u> (***n*** = 1.2827)

Separation at intermediate momenta

<u>Gas radiator</u> (***n*** = 1.00172)

Separation at high momenta

Combining, **d*E*/dx** and RICH information a wide range of momenta is covered.

Transition radiation:

A particle passing the boundary between two media with different dielectric constants, will radiate photons. (predicted by Ginzburg & Frank 1946)

The energy radiated at one boundary: $E = \frac{1}{3}\alpha\,\gamma\,\hbar\omega_p$ $\left(\hbar\omega_p \approx 20\,\text{eV for a plastic foil}\right)$

$\boldsymbol{E} \propto \gamma$: potential for electron identification at high momenta! (for electrons: $\gamma > 1000$)

The photon emission angle peaks at: $\theta \propto {}^{1}\!/_{\gamma}$ (very forward)

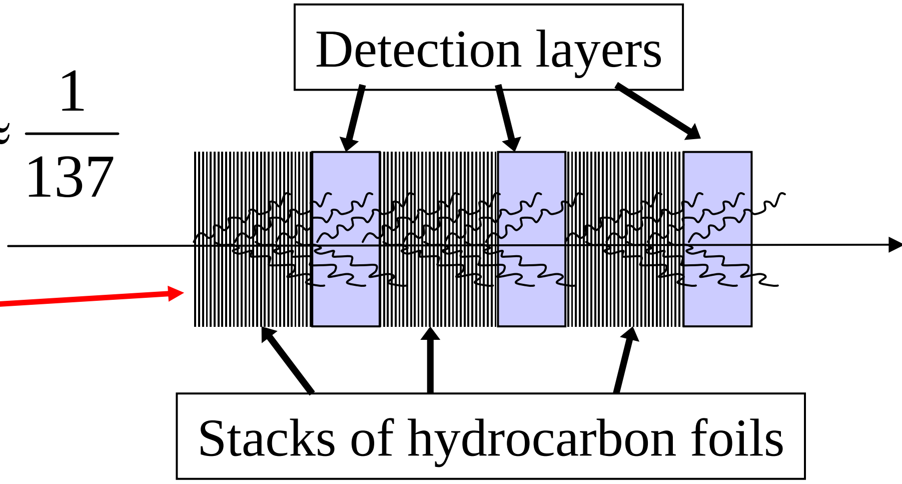
Typical photon energy: $E_\gamma \approx \frac{1}{4}\gamma\,\hbar\omega_p$

i.e. several keV for electrons. (detectable in proportional chamber with high Z gas!)

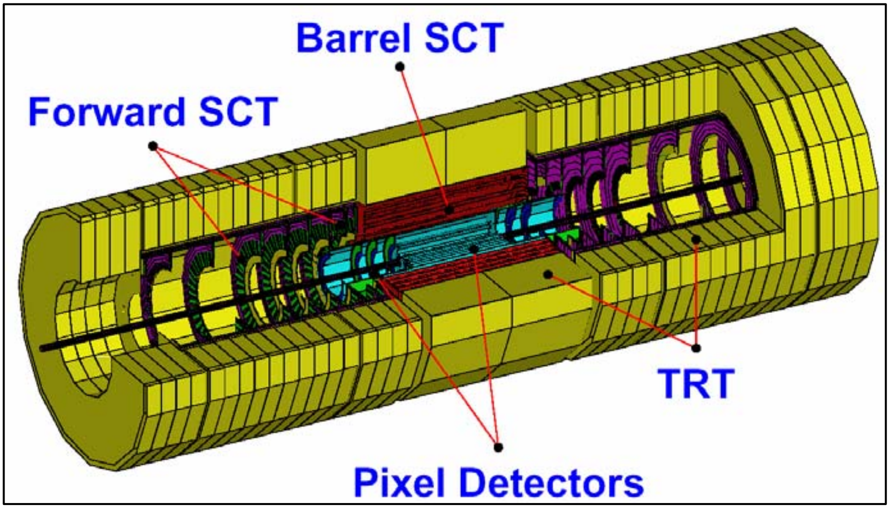
Photon yield per boundary is low: $\langle N_\gamma \rangle \approx \alpha \approx \frac{1}{137}$

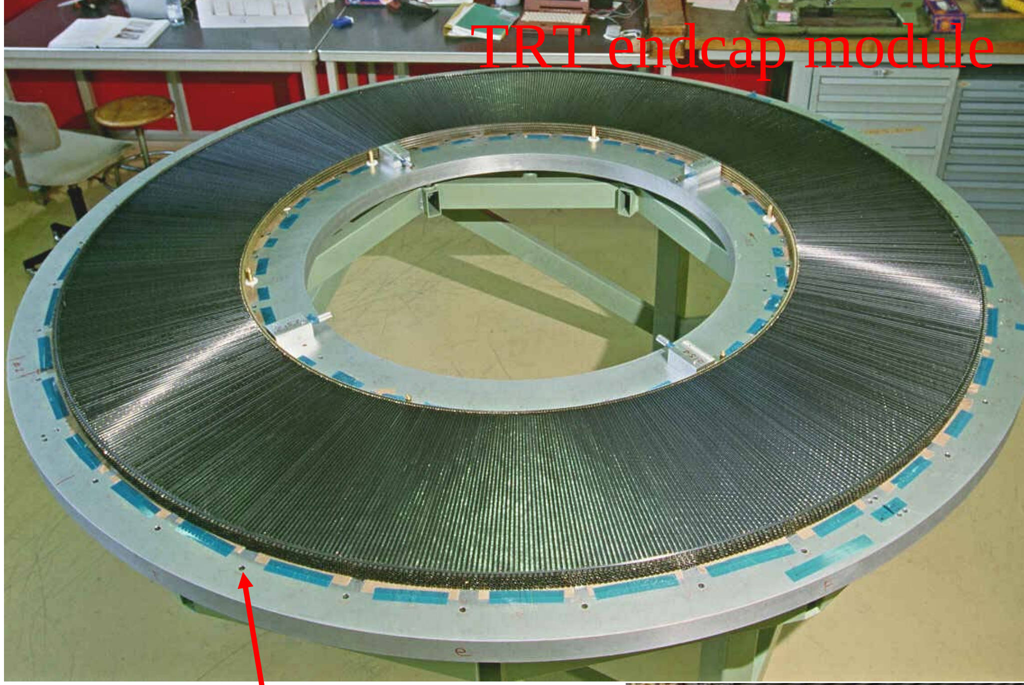
Many transitions needed!

A typical design:

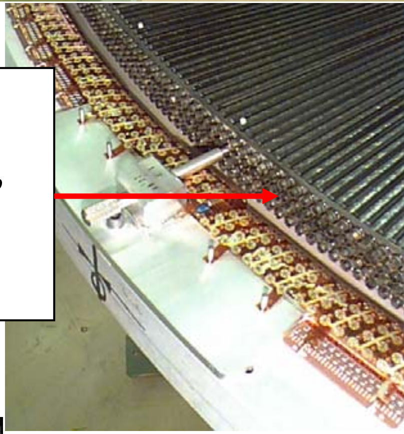


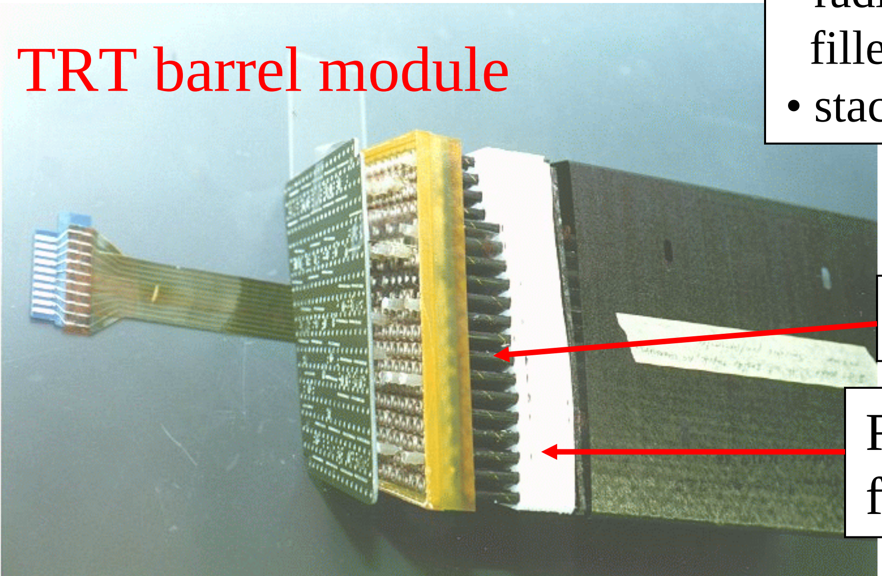
ATLAS TRT: Combined tracking & transition radiation detector





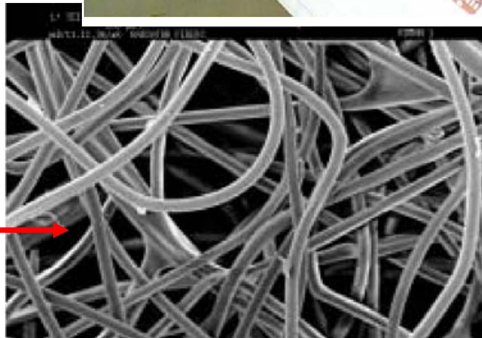
Wheels with 4 planes:
- radial straw tubes (l≈50cm,d≈4mm), filled with high Z gas
- stacks of polypropylene foils



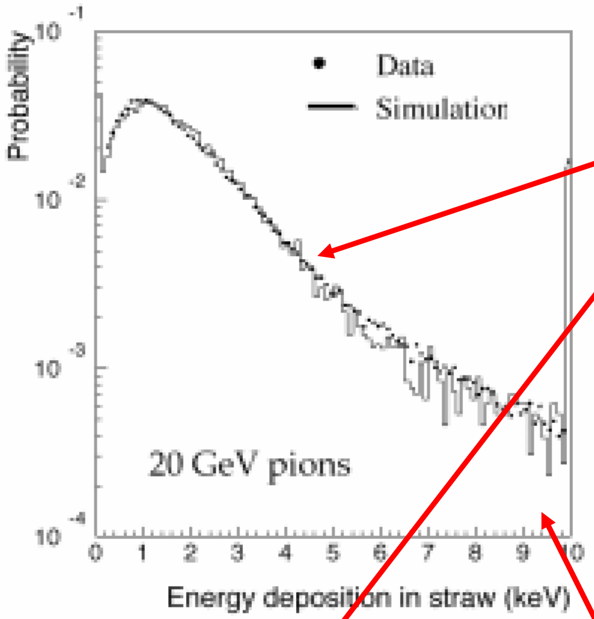


Straw-tube detectors

Radiator: polyethylene fibre mats



Electron identification with the ATLAS TRT



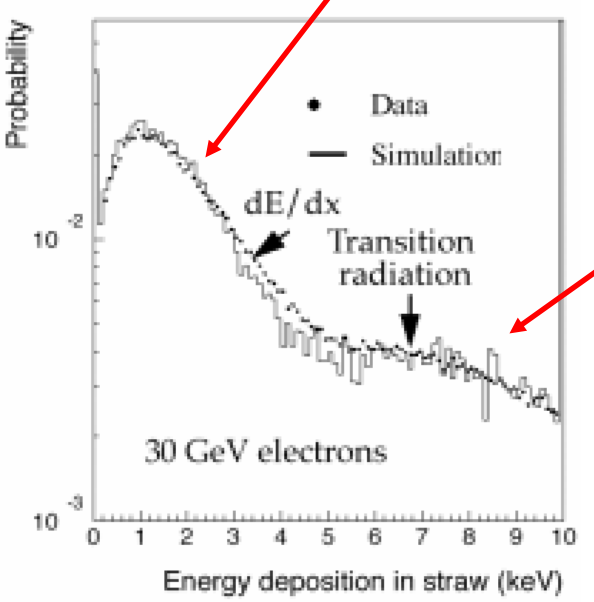
Energy deposited per straw tube:

Pions: only ionisation energy loss (**d*E*/dx**)

Electrons: **d*E*/dx** plus transition radiation photons

<u>e/π separation:</u>

Count the number of hits with deposited energy greater than some threshold value: TR-hits



Good separation between $\pi^{\pm}$ and $e^{\pm}$.

Both at high and low momenta!