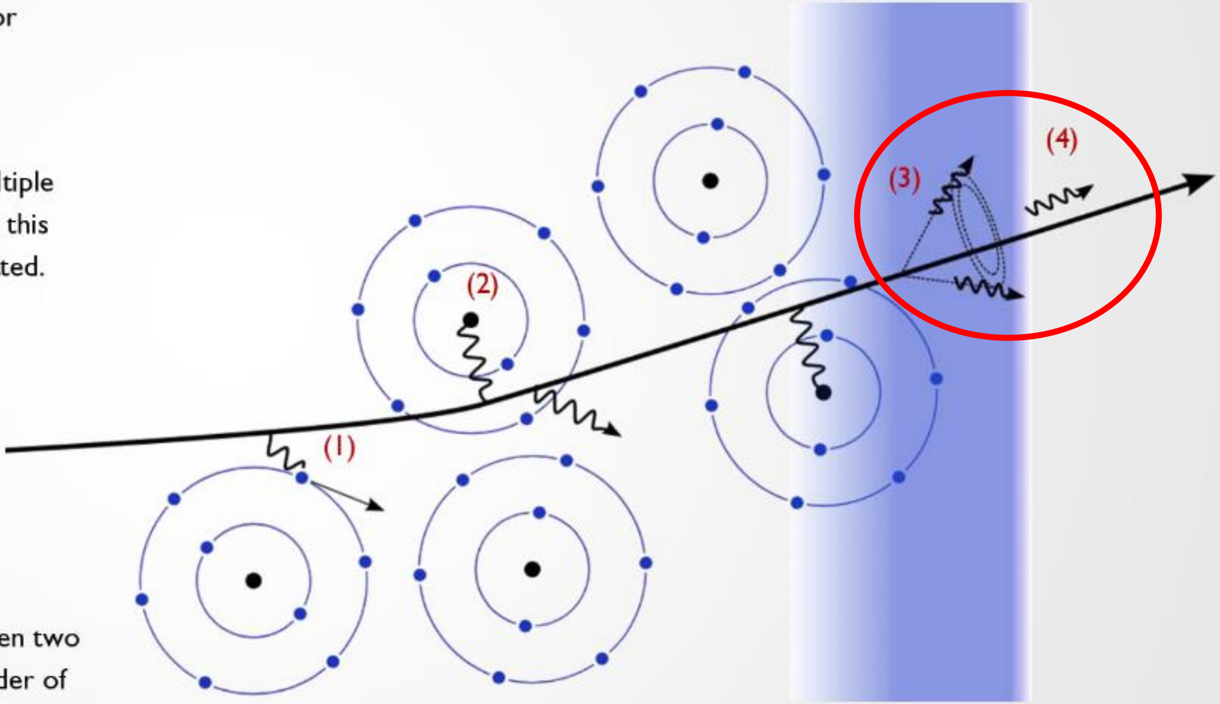
HE386: MID-TERM PRESENTATION

CHERENKOV DETECTORS AND TRANSITION RADIATION

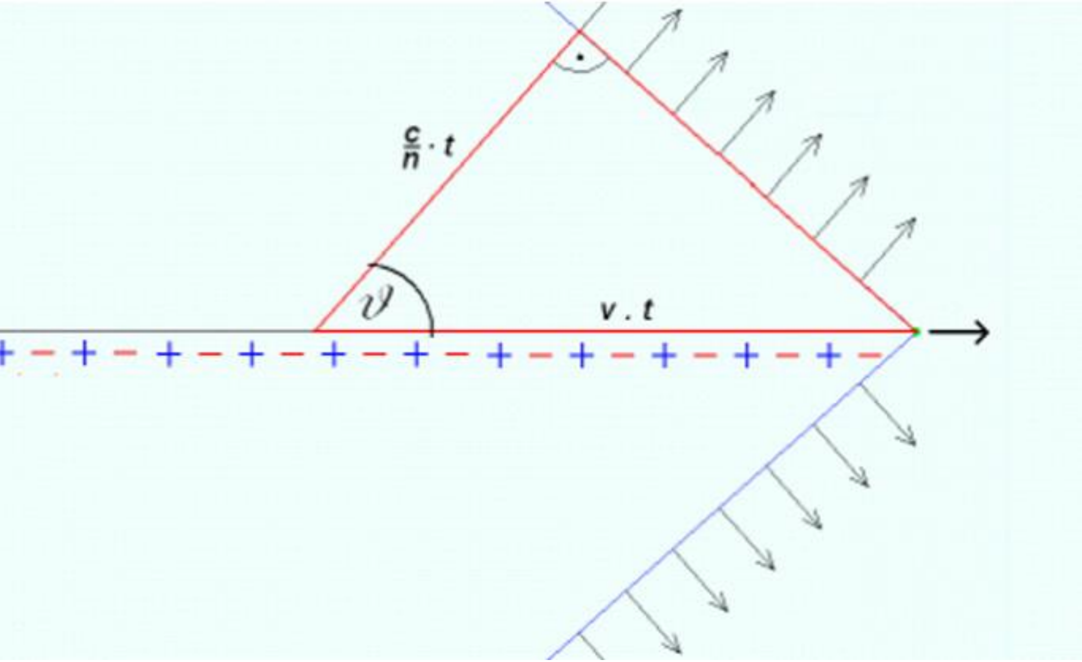
Aman Sahoo, UG 3rd Year

Types of Particle-Matter Interactions

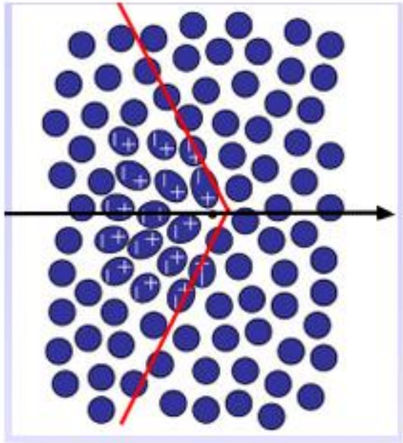
1. Ionization (or excitation) of detector material
   - The incoming particle loses energy by ionizing or exciting the atoms
2. Interaction with the nucleus
   - The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a bremsstrahlung photon can be emitted.
3. Emission of Cherenkov light
   - In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation.
4. Emission of transition radiation
   - When the particle crosses the boundary between two refractive media, there is a probability of the order of ≈1% to produced and X ray photon, called Transition radiation.



Cherenkov Radiation



- Applicable to charged and massive particles only
- Speed of light in dielectric medium: $c_n = \frac{c}{n}; where\ n > 1$
- For $v_p < c_n$, wavefronts do not interact.
- Excitation radiation like normal
- For $v_p > c_n$, wavefronts cross each other and produce interference
- Constructive interference causes Cherenkov radiation

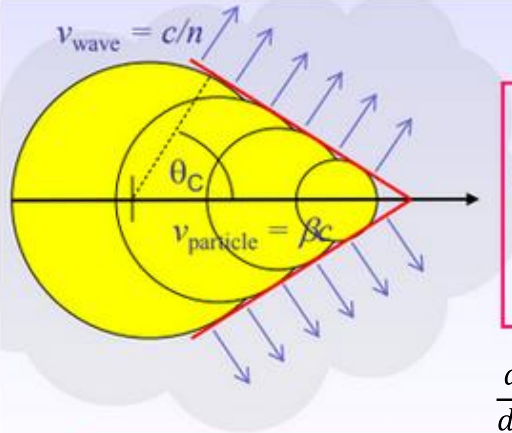


The dielectric medium is polarized by the passing particle.

Jackson, John David (1999). Classical electrodynamics (3rd ed.)

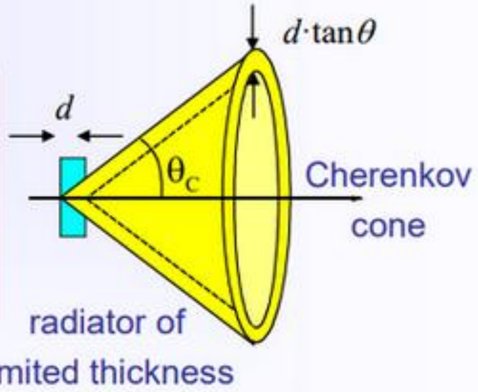
$$v_{\text{particle}} \geq c_{\text{medium}} = \frac{c}{n}$$

$$\beta_{\text{particle}} \geq \frac{1}{n} \qquad (n = \text{refr. index})$$



$$\cos\theta_C = \frac{v_{\text{wave}}}{v_{\text{particle}}} = \frac{1}{n\beta}$$

with $n = n(\lambda) \geq 1$



$$\frac{d^2N}{dx d\lambda} = \frac{4\pi^2 z^2 e^2}{hc\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

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

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

Components of a Cherenkov Detector

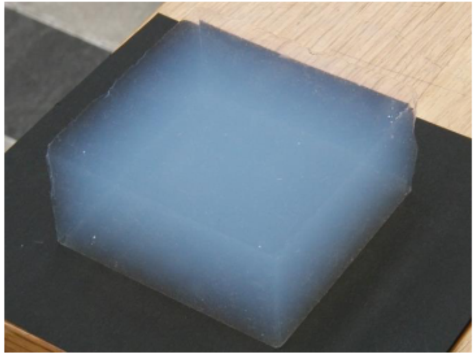
- Main Components:
  - Radiator : To produce photons
  - Mirror/lens/quartz bar etc. : To help with the transport of photons
  - Photon detector : To detect the photons

- Radiator: Any medium with a Refractive Index.

Example of radiators

Medium	n-1	γ_{th}	Photons/m
He (STP)	$3.5\ 10^{-5}$	120	3
CO_2 (STP)	$4.1\ 10^{-4}$	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

Aerogel: network of SiO_2 nano-crystals



$$\gamma = 1/\sqrt{1-\beta^2}$$

Cherenkov detectors

Cherenkov detectors can exploit …

1 $N_{ph}(\beta)$ → Threshold detector. Do not measure θ_C

2 $\theta(\beta)$ → Ring Imaging Cherenkov detectors "RICH"

→ Detection of Internally reflected Cherenkov light "DIRC".

Measure θ_C

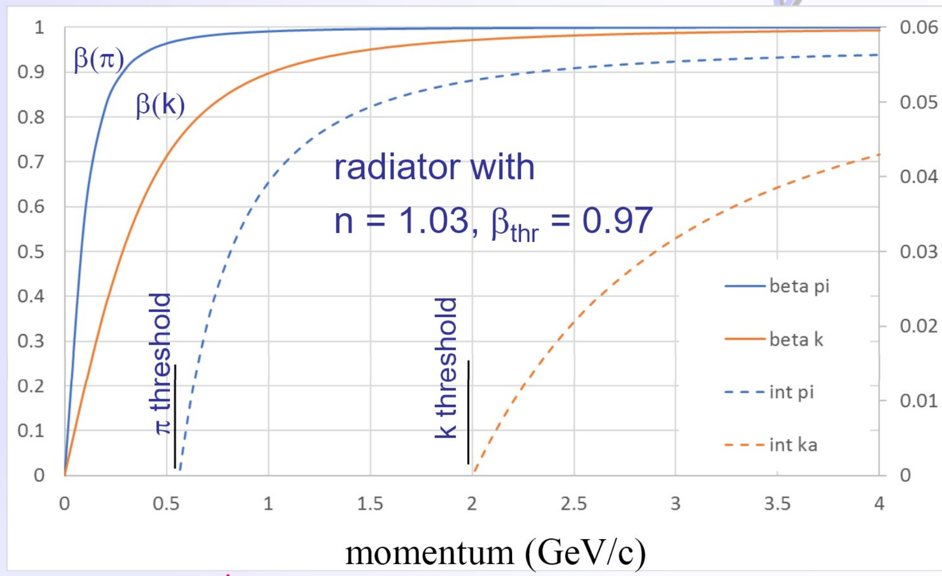
Knowing both the speed $\beta = v/c$ and the momentum p of the particle allows to derive the mass of the particle and hence identify it (e.g. π, K, p, d,…).

Particle ID.

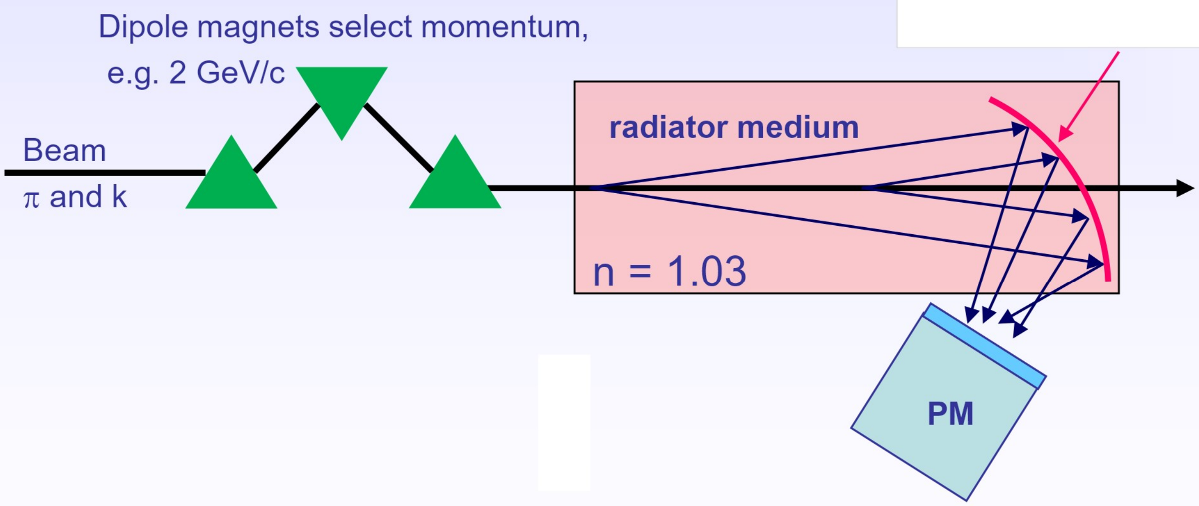
3 Prompt emission of Cherenkov light (different from scintillation) plus angular information → very fast timing detectors. TOP, TORCH

Threshold Cherenkov detectors

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



Often used in secondary beamlines (e.g. CERN PS, SPS) to tagg particle type



Principle of a simple in-beam threshold Cherenkov counter

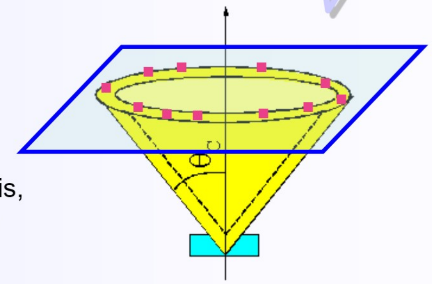
Ring Imaging Cherenkov detectors (RICH)

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

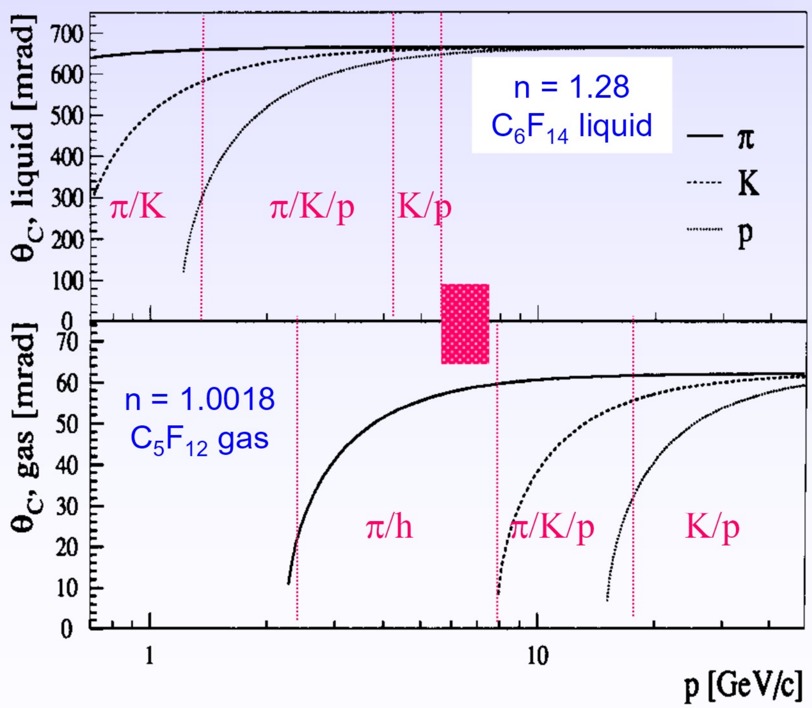
→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

(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 $N_{p.e.}$

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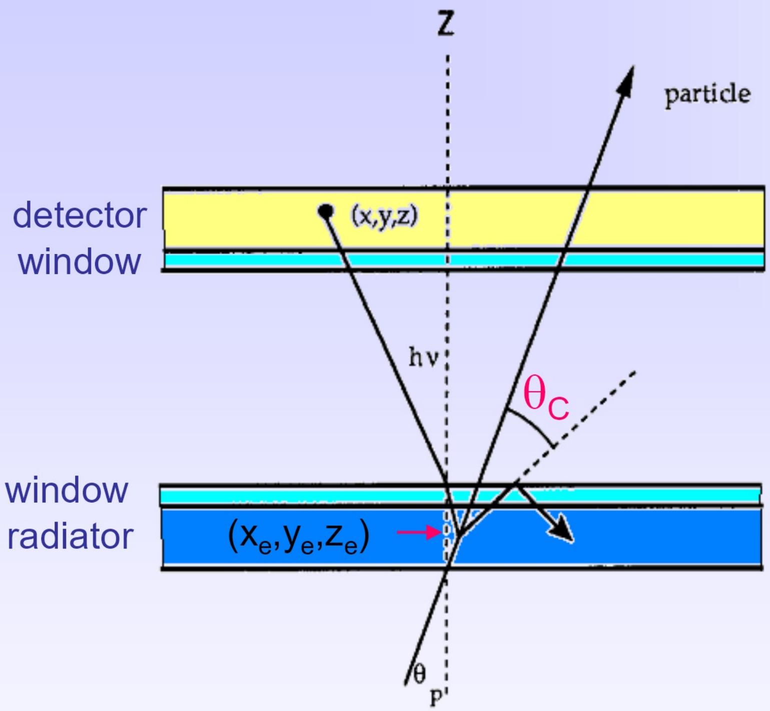
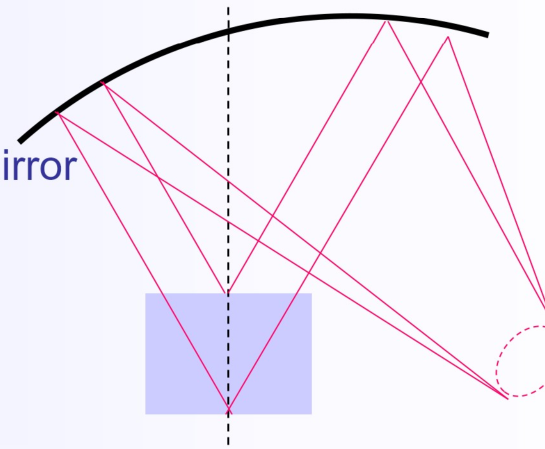
Reconstruction and resolution of Cherenkov angle

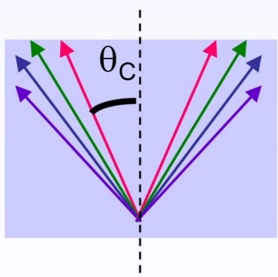


Determination of θ_C requires:

- space point of the detected photon (x,y,z)
  - photodetector granularity (σ_x, σ_y), depth of interaction (σ_z)
- emission point (x_e,y_e,z_e)
  - keep radiator thin or use focusing mirror
- particle direction θ_p, ϕ_p
  - RICH requires good tracker



- the chromatic error - an 'irreducible' error



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

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

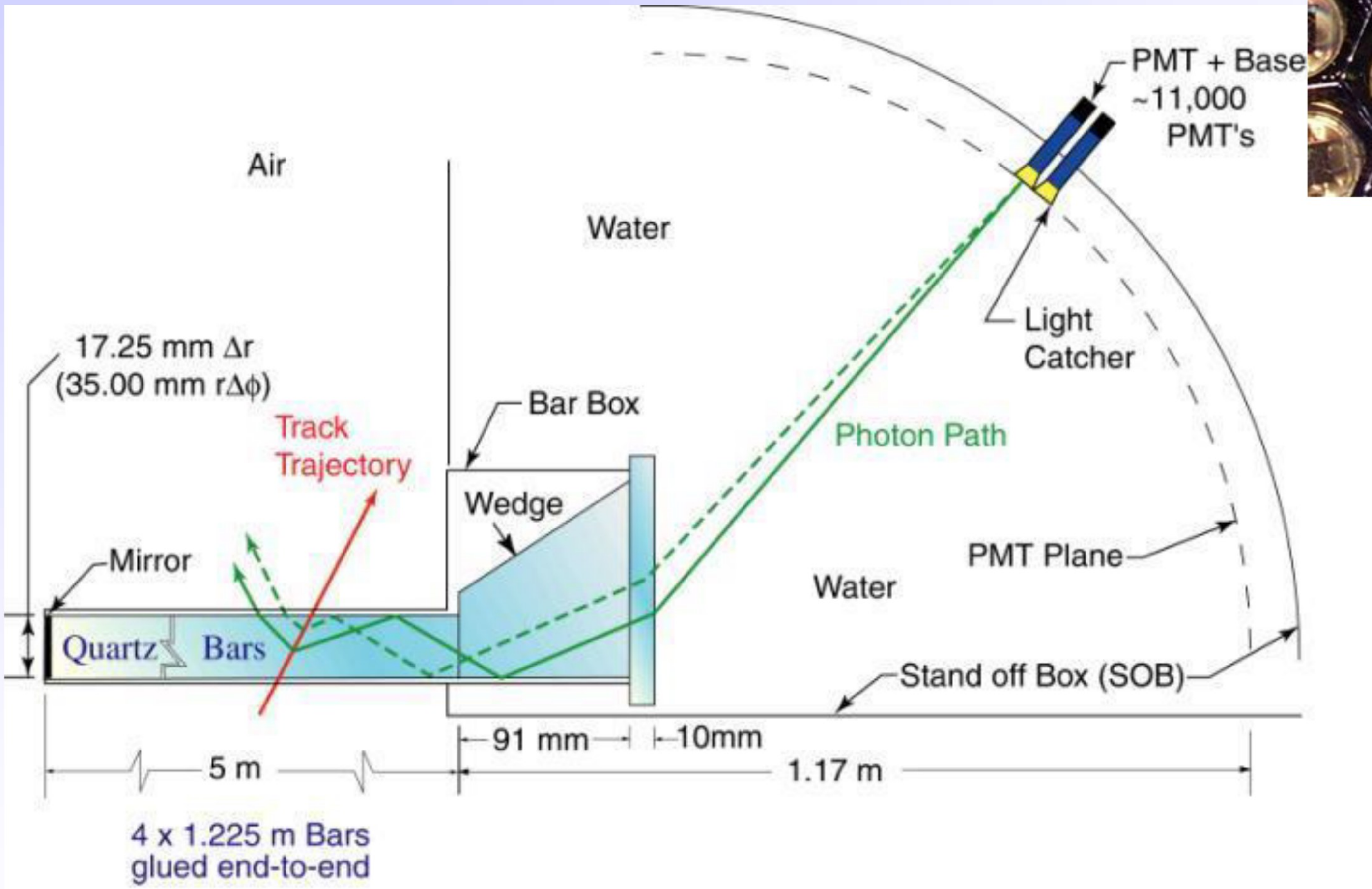
σ_E is related to the sensitivity range of the photodetector ΔE

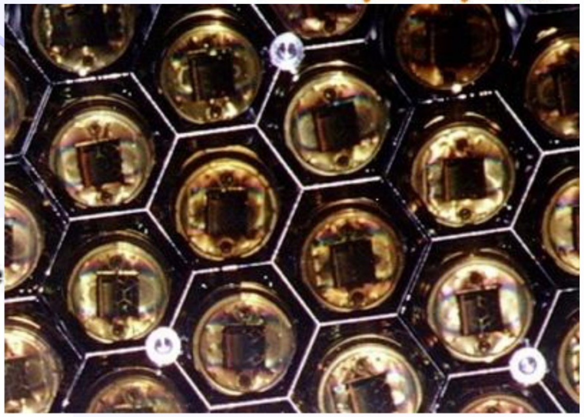
$\Delta E \uparrow \rightarrow N_{pe} \uparrow$ good $\quad \sigma_E \uparrow$ bad

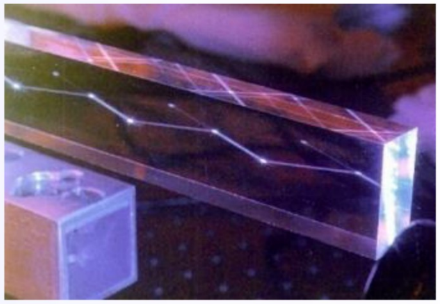
$\Delta E \downarrow \rightarrow N_{pe} \downarrow$ bad $\quad \sigma_E \downarrow$ good

DIRC @BaBar: Detection of Internally Reflected Cherenkov light

Use the internally reflected C-light, which would normally be lost!



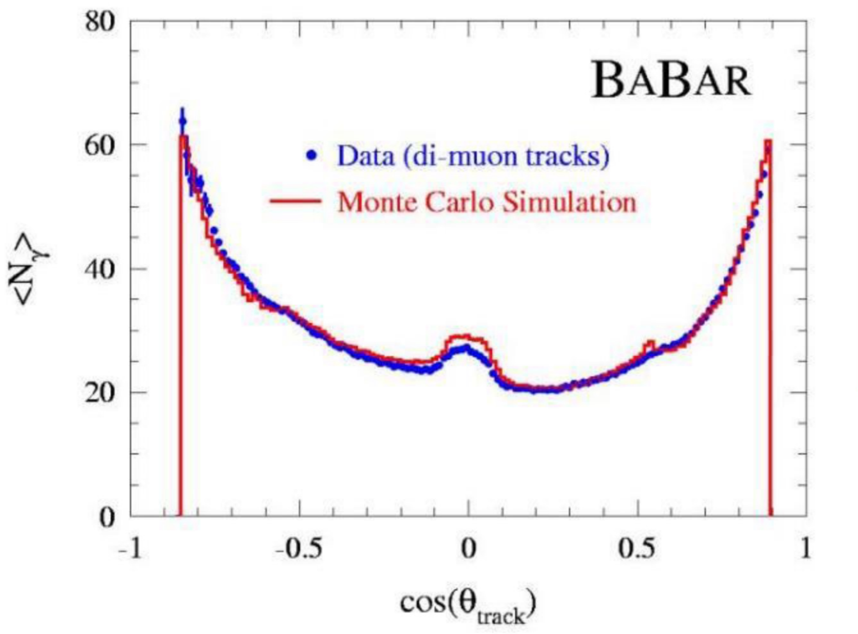




During propagation: angle of Cherenkov light is conserved, except of left/right and up/down ambiguities

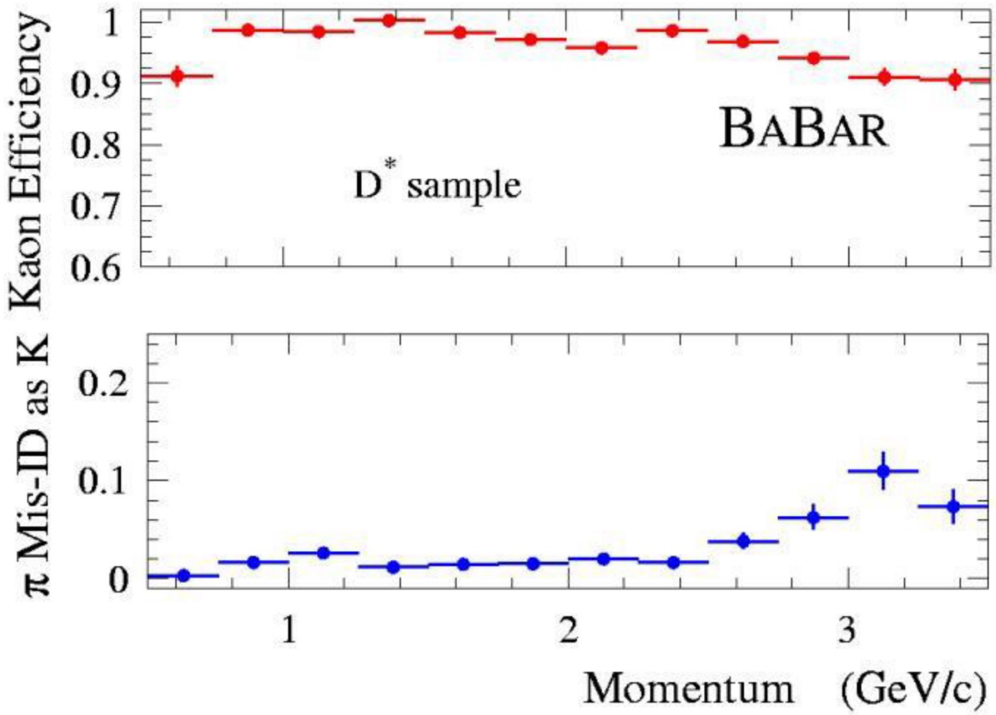
I. Adam, et al.
Nucl. Instr. and Meth. A, 433 (1999), p. 121

DIRC performance



← Lots of photons!

Excellent π/K separation



NIM A553 (2005) 317

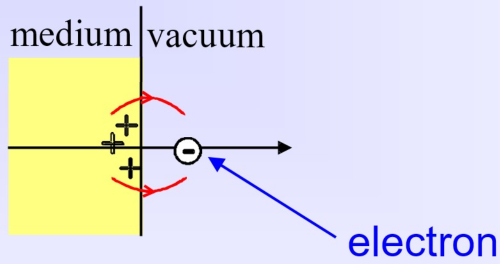
Particle ID by Transition radiation

(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.

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

Lorentz boost

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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

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Particle ID by Transition radiation

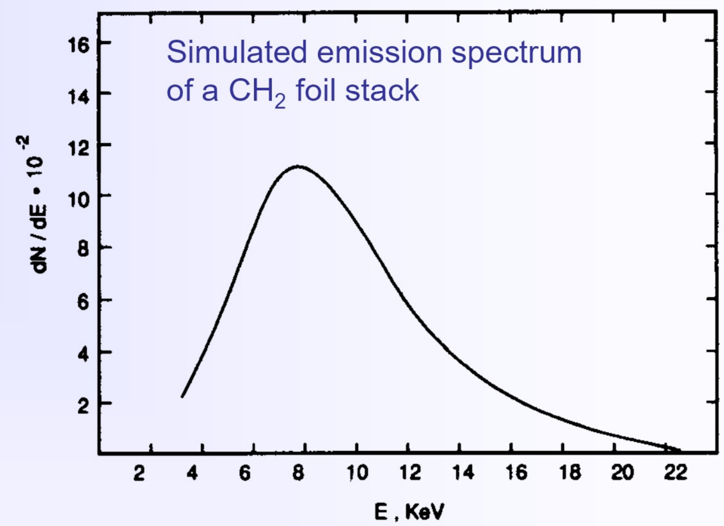
- Number of emitted photons / boundary is small $N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$

  → 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 (ω_p), TR frequency (ω) and on γ.

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

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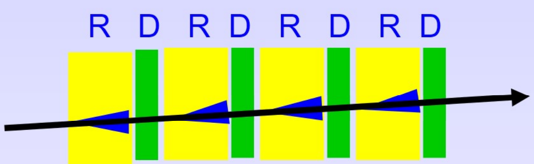
Particle ID by Transition radiation

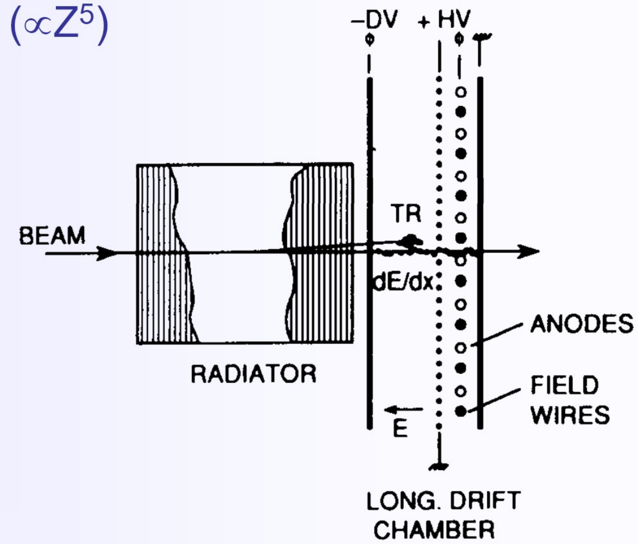
TR Radiators:

- 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



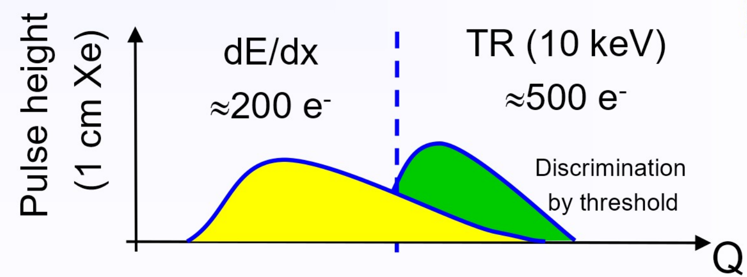
TR X-ray detectors:

- Detector should be sensitive for $3 \leq E_\gamma \leq 30$ 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

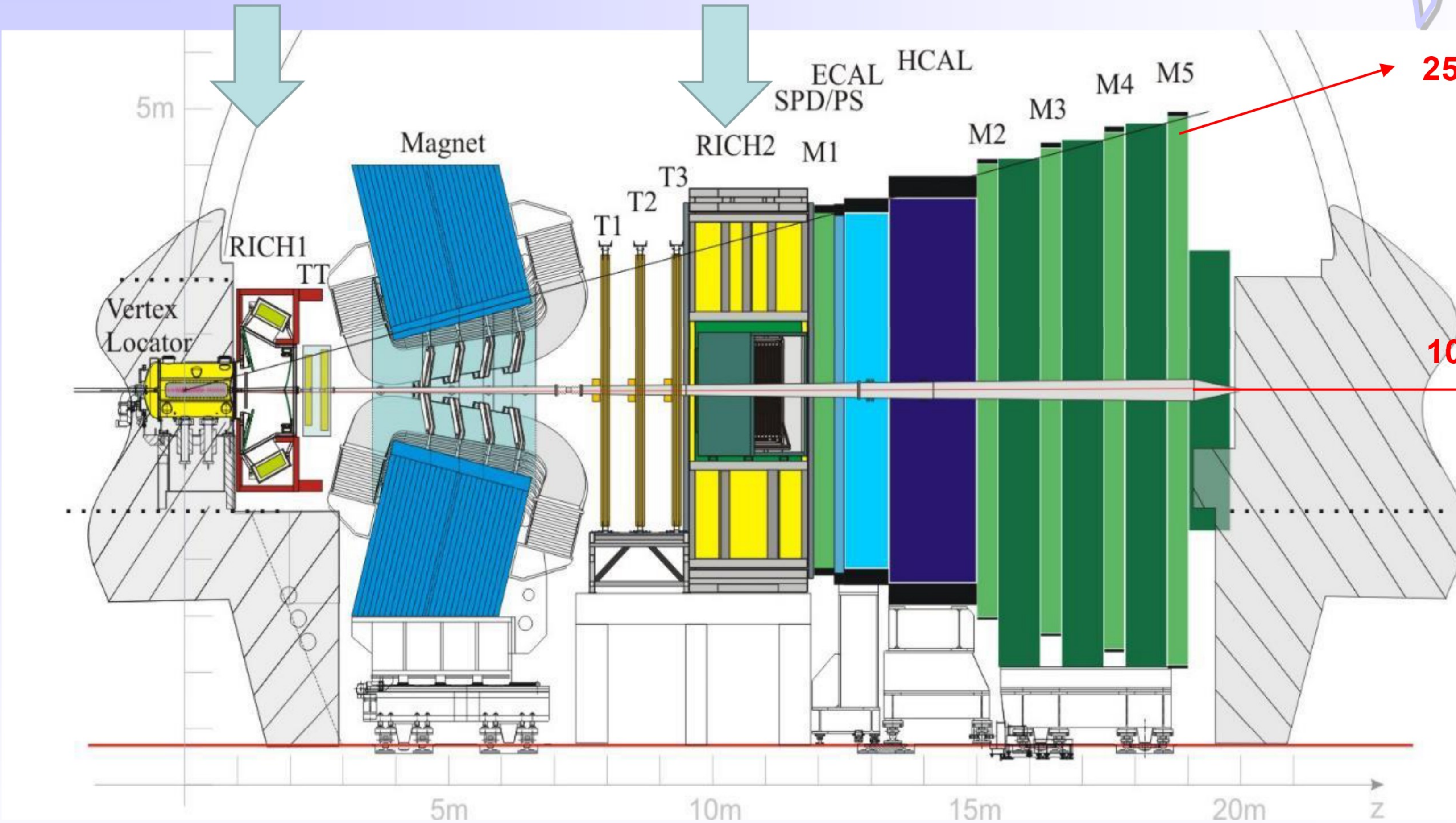
Very Schematic!



The LHCb RICH counters

Generation 2

https://doi.org/10.1140/epjc/s10052-013-2431-9



Vertex reconstruction:
VELO

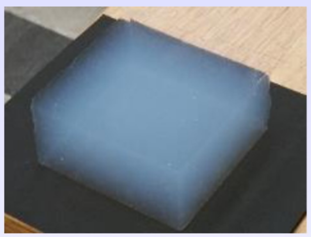
Trigger:
Muon Chambers
Calorimeters
Tracker

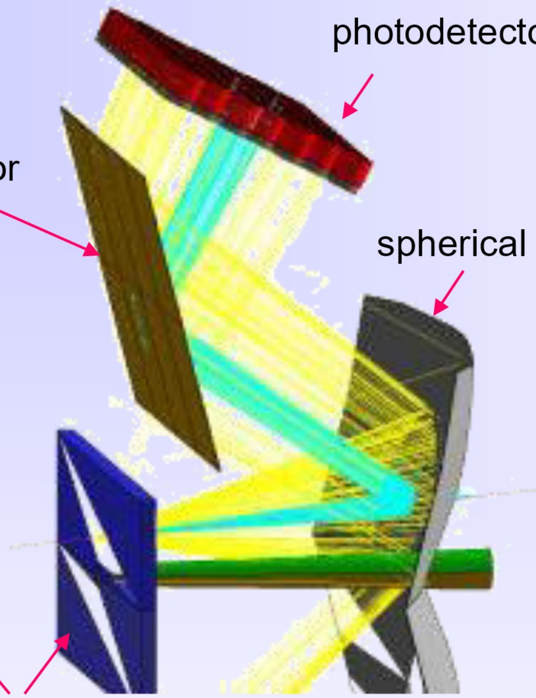
PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

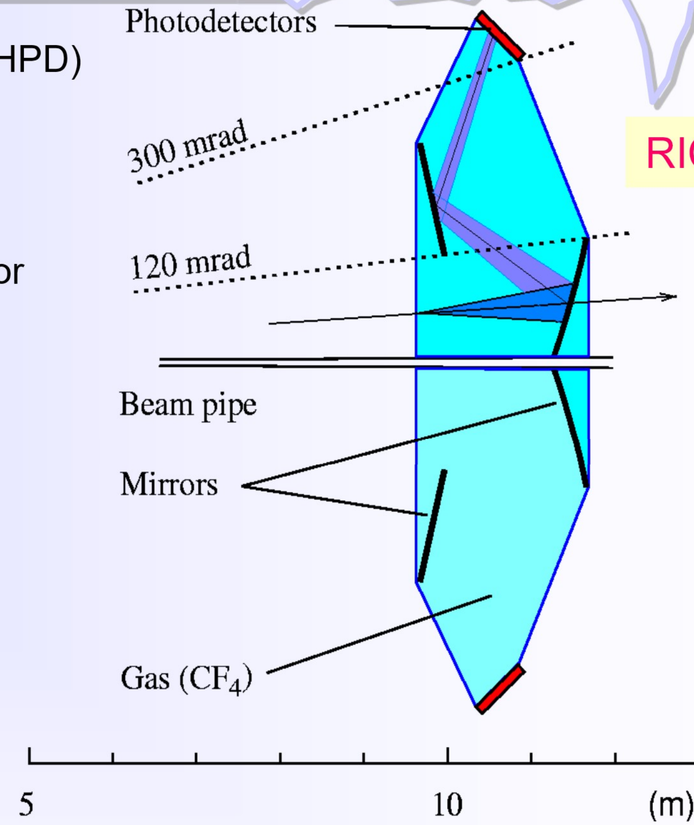
2 RICH detectors in LHCb

RICH 1





RICH 2

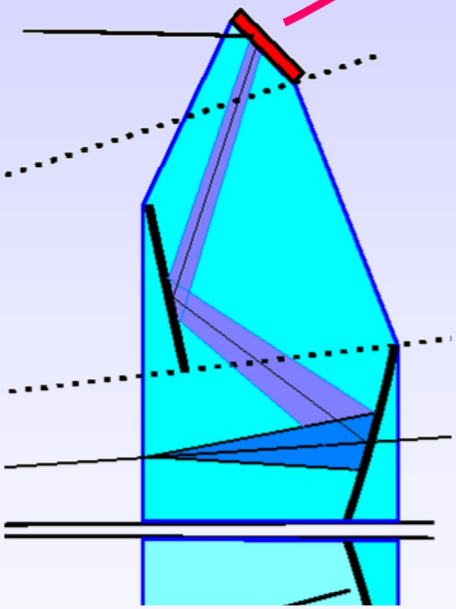


radiator	C_4F_{10}	aerogel
θ_C	3.03°	13.8°
n	1.0014	1.03
$p_{thresh}(\pi)$	2.6	0.6 GeV/c
$N_{p.e.}$	31	6.8
σ_θ	1.29	2.19 mrad
$p\ (3\sigma)$	56	13.5 GeV/c

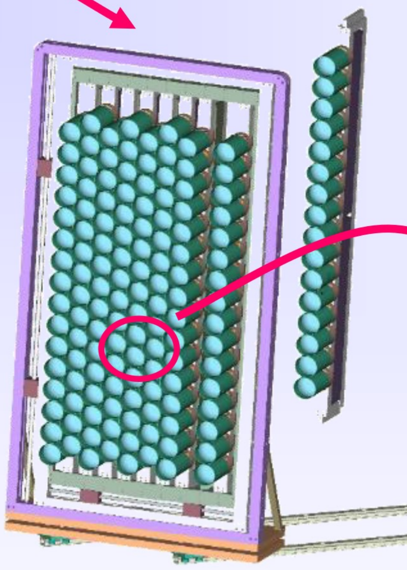
radiator	CF_4
θ_C	1.8°
n	1.0005
$p_{thresh}(\pi)$	4.4 GeV/c
$N_{p.e.}$	23
σ_θ	0.6 mrad
$p\ (3\sigma)$	98.5 GeV/c

2 RICH detectors in LHCb

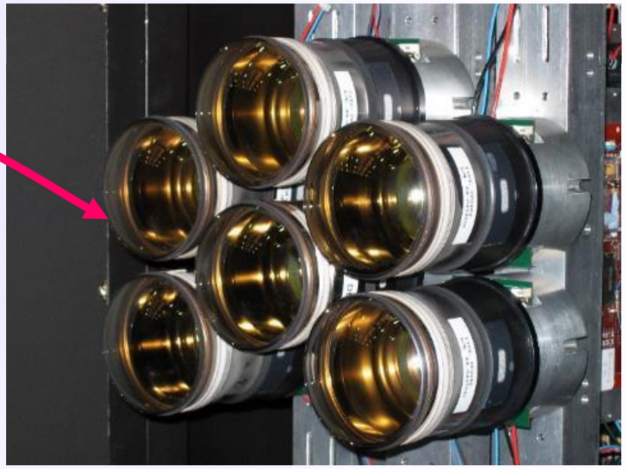
RICH 2



photodetector plane



beam test in 2004 with 6 HPDs



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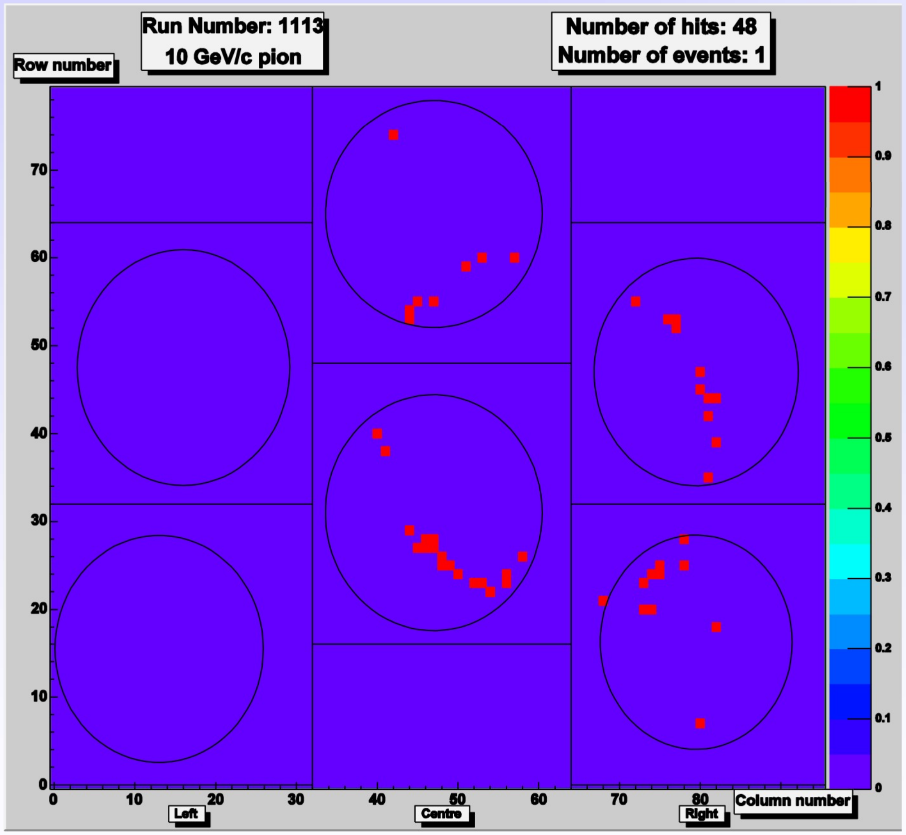
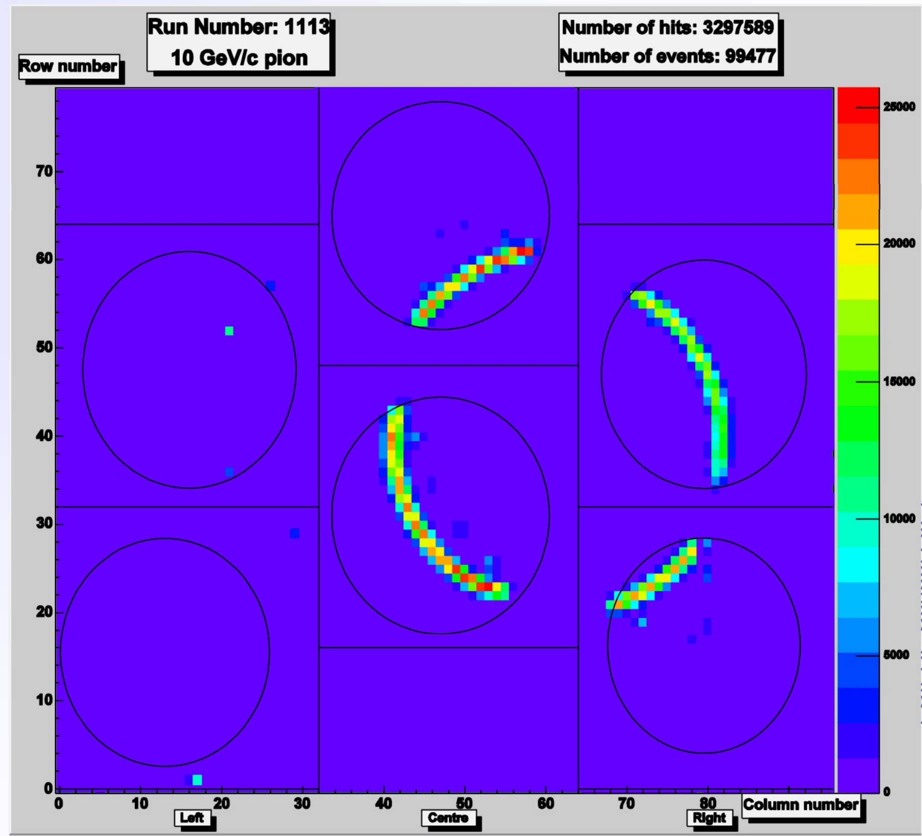
2 RICH detectors in LHCb

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

Single pion (10 GeV/c)



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

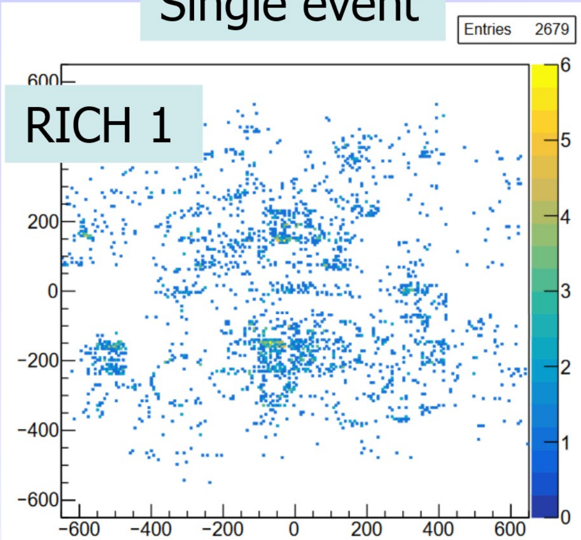


https://doi.org/10.1016/j.nima.2005.08.083

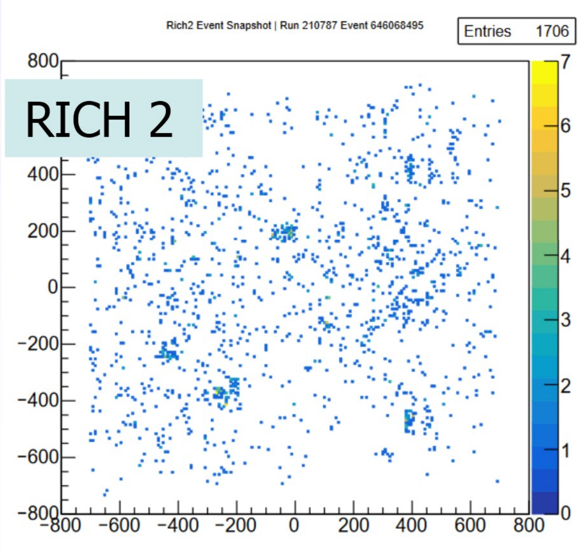
Performance of LHCb RICHes

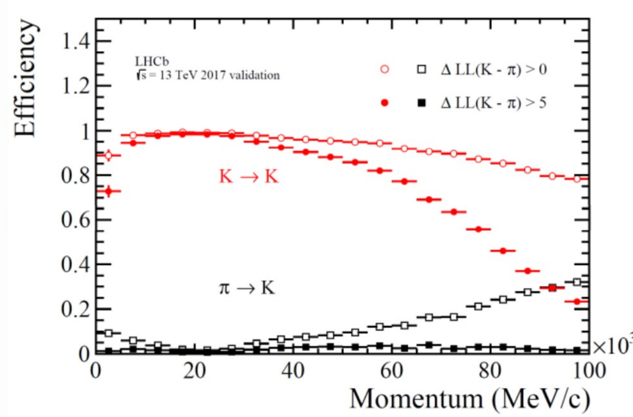
Single event

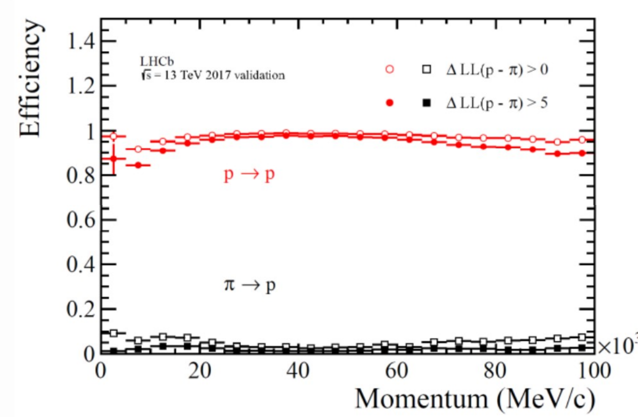
RICH 1

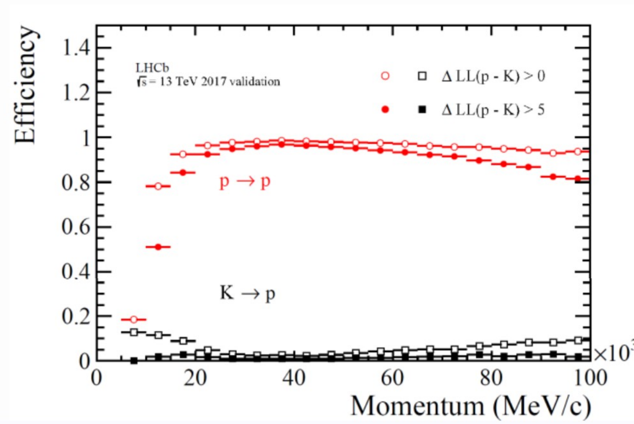


RICH 2





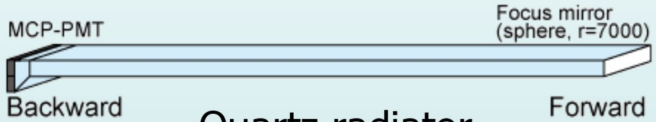




https://doi.org/10.1140/epjc/s10052-013-2431-9

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



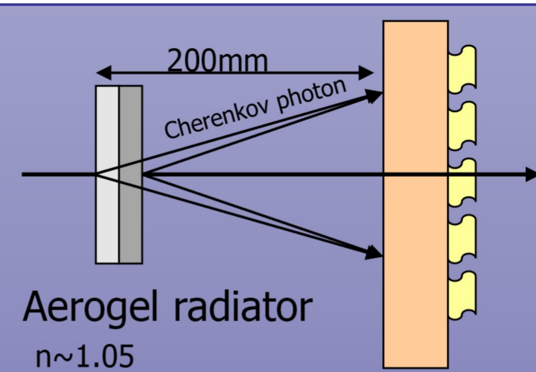
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

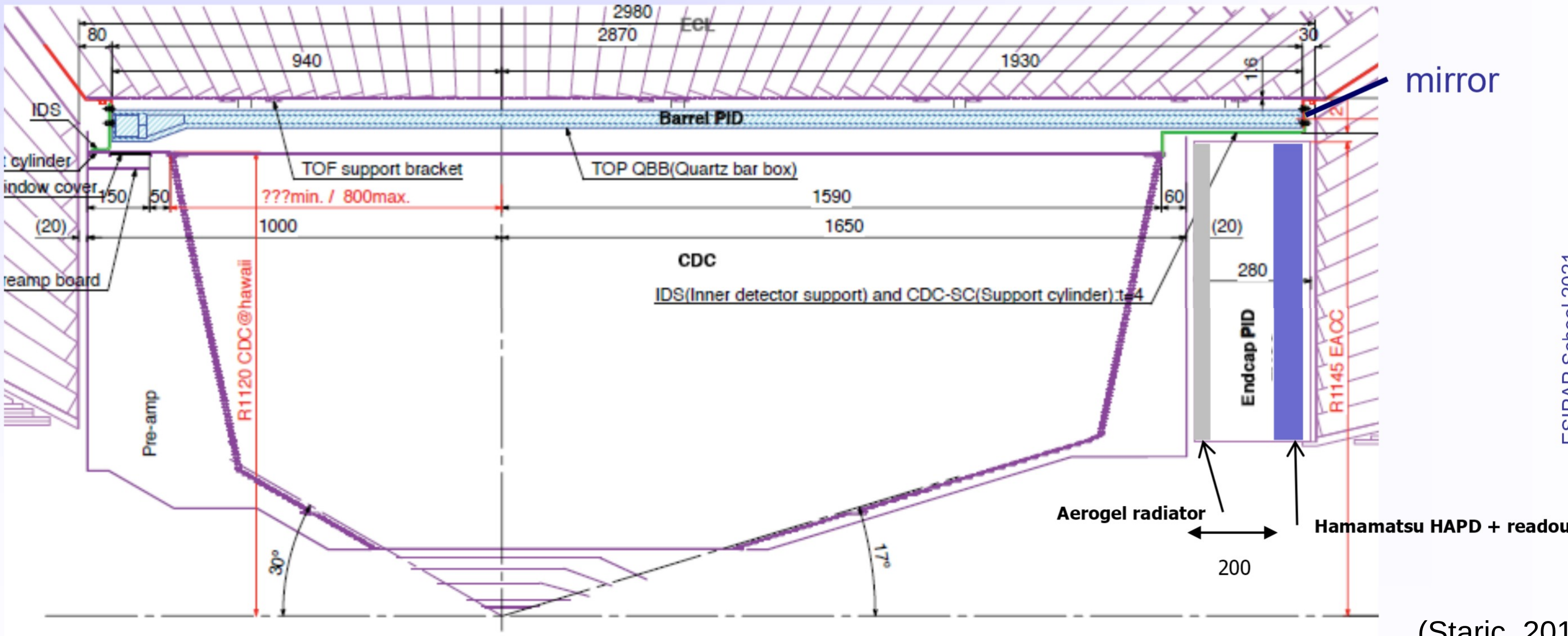
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator

n~1.05

Hamamatsu HAPD
+ new ASIC



(Staric, 2013)

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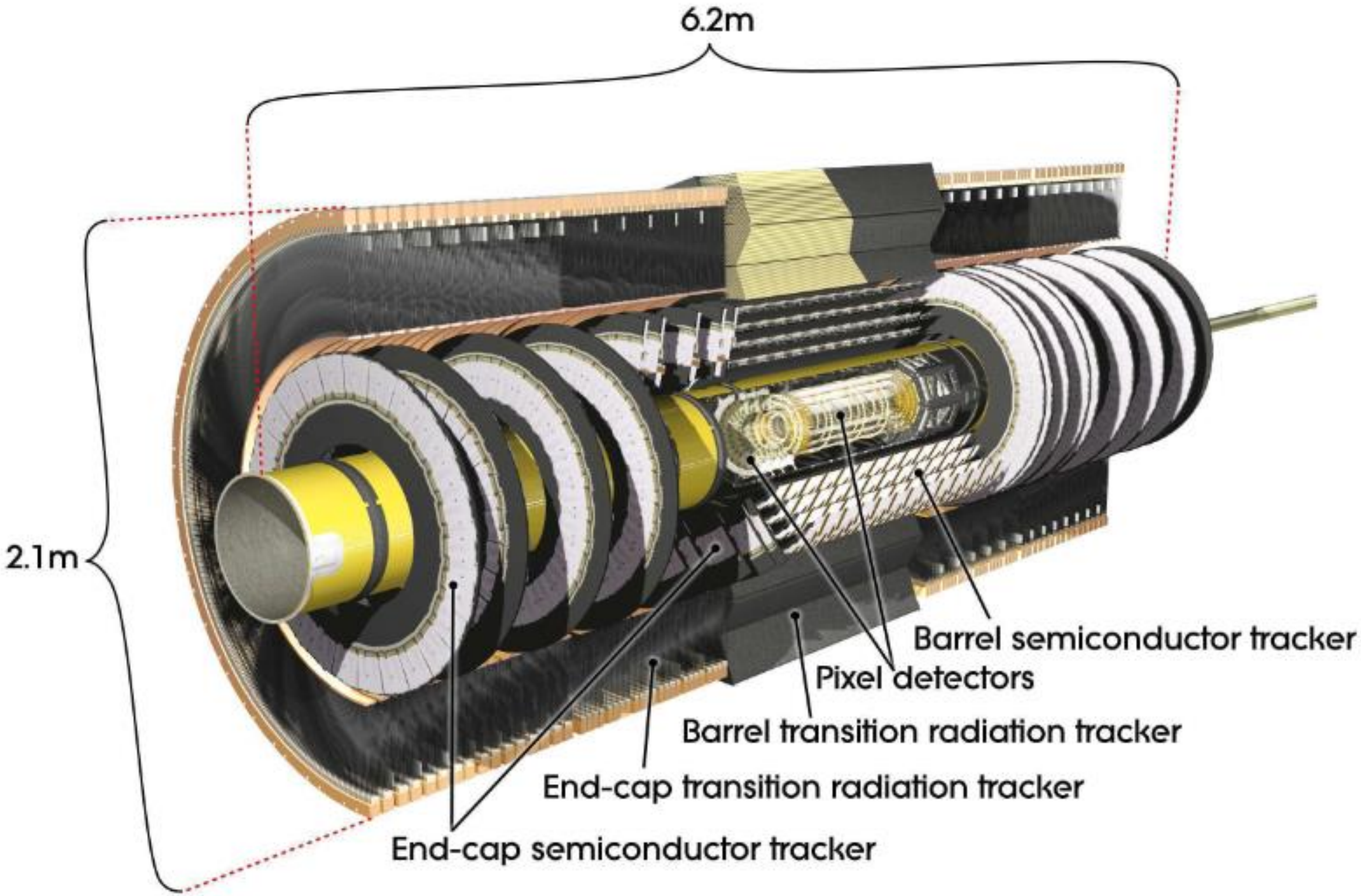
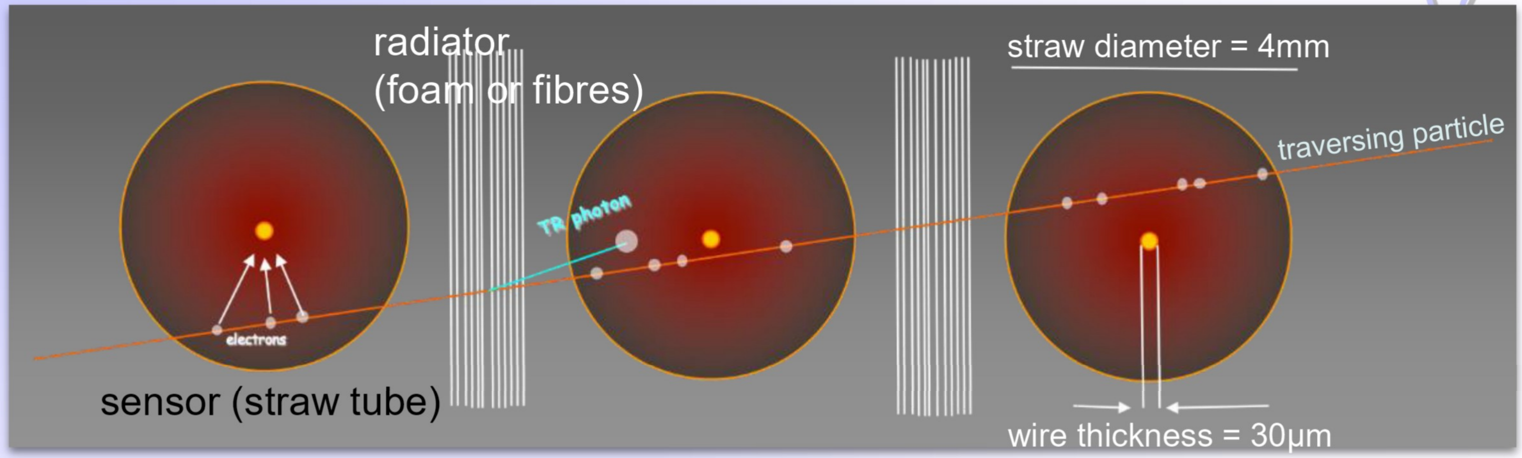


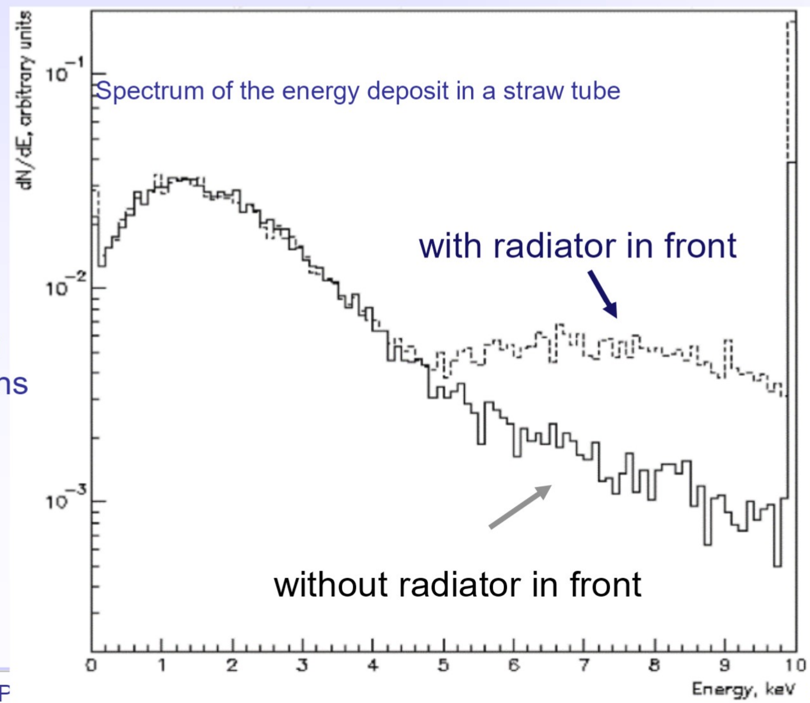
- Transition Radiation detector in ATLAS
- Based on straw like sensors and fiber-based radiators

Ahmet Bingül 2012 J. Phys.: Conf. Ser. 347 012025

Basic principle



data test beam
20GeV electrons



Signal in straw is superposition of dE/dx and TR

https://doi.org/10.1016/S0168-9002(99)00301-0

Pros and Cons of Transition and Cherenkov Detectors

Cherenkov Detectors (RICH)	Transition Detectors
Pros: 1. Highest efficiency for PID 2. Can handle large flux of particles 3. At low p, spread of ring is low	Pros: 1. Precise trajectory tracking of ultra-relativistic electrons 2. High efficiency and fast discrimination between electrons and pions with high momentum (1 GeV)
Cons: 1. High complexity and cost for building 2. At higher p or E, spread of ring is high. Leads to higher chance of mis-PID	Cons: 1. Very low intensity of transition radiation 2. Alternating layers in the detectors lead to increased complexity and cost

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

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

σ_E is related to the sensitivity range of the photodetector ΔE

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

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

THANK YOU!