Apparati Sperimentali

Lezione 5

Calorimetri e identificazione di particelle

Calorimetri

- Misura dell’energia tramite assorbimento totale di particelle cariche o neutre
- Una frazione dell’energia e’ trasformata in quantita’ misurabili:
  - Scintillazione : (Na I/Tl, BGO, …)
  - Ionizzazione : (L-Ar, MWPC, Si …)
  - Radiazione Cherenkov (Vetri a Pb)

Processi di assorbimento

- Sciami elettromagnetici
  - Elettroni (positroni) e fotoni
  - Bremsstrahlung e produzione di coppie
  - Lunghezza di radiazione X_0

$$X_0 = \frac{716\,\mathrm{g\,cm^{-2}}\,A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Sciami adronici
  - Processi inelastici di adroni (sia carichi che neutri)
  - Eccitazione e rottura del nucleo
  - Per energie >1 GeV poca dipendenza dal tipo di particella incidente (π, p, K…)
  - Lunghezza di interazione λ_I

$$\lambda_I = \frac{A}{N_A \sigma_{tot}} \sim 35\,\mathrm{g\,cm^{-2}}\,A^{1/3}$$

Risoluzione energetica

- Limite intrinseco

$$N_{tot} \propto \frac{E_0}{E_C} \quad \text{numero totale di segmenti di traccia}$$

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} \propto \frac{\sigma(\mathrm{N})}{\mathrm{N}} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E}}$$

  - Risoluzione energetica (anche quella spaziale) migliora con E

- Realta`

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

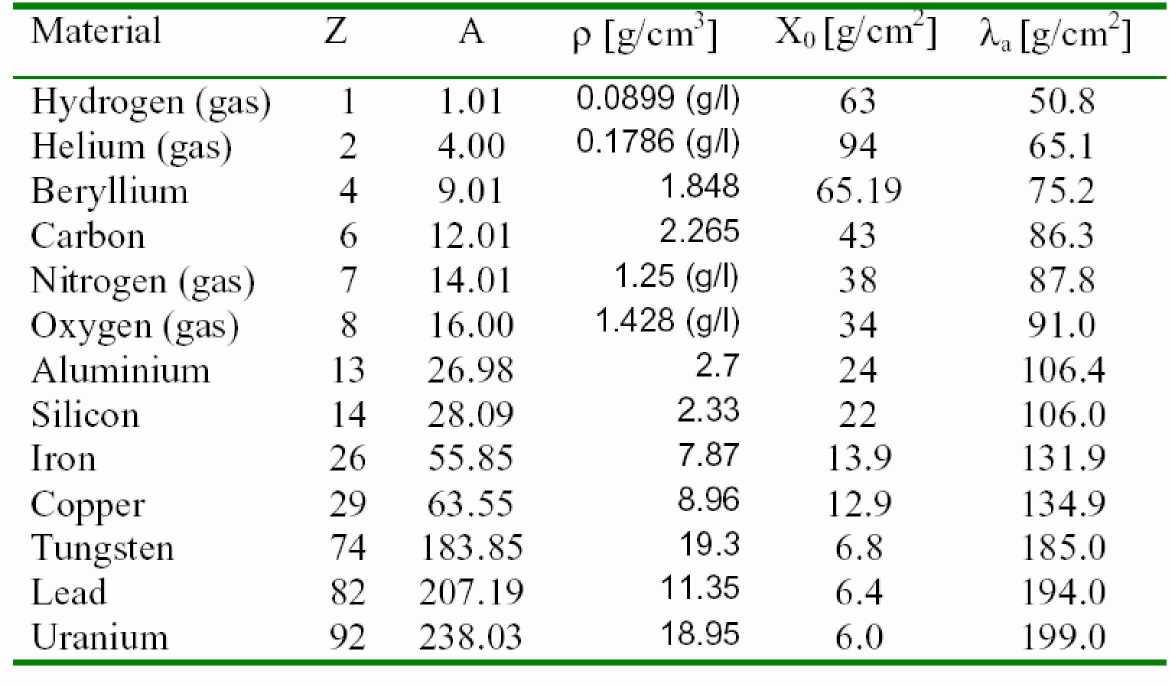
  - a = termine stocastico
  - b = Rumore elettronico, radioattivita’, pileup
  - c = inomogenita’, non linearita’, calibrazioni intermodulo

Processi di assorbimento

- Lunghezze tipiche dei calorimetri
  ECAL ~ 21 X_0
  HCAL ~ 6 λ_I

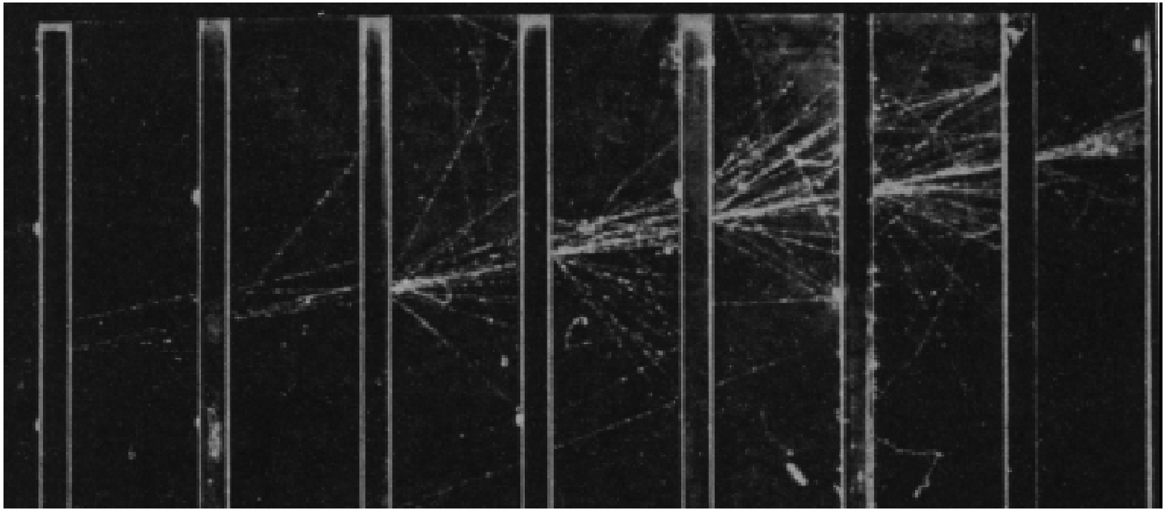
6 λ_I» 21 X_0

HCAL » ECAL



Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_a [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Sciami elettromagnetici



Sciame in una camera a nebbia con intervallati strati di piombo

Sviluppo longitudinale dello sciame

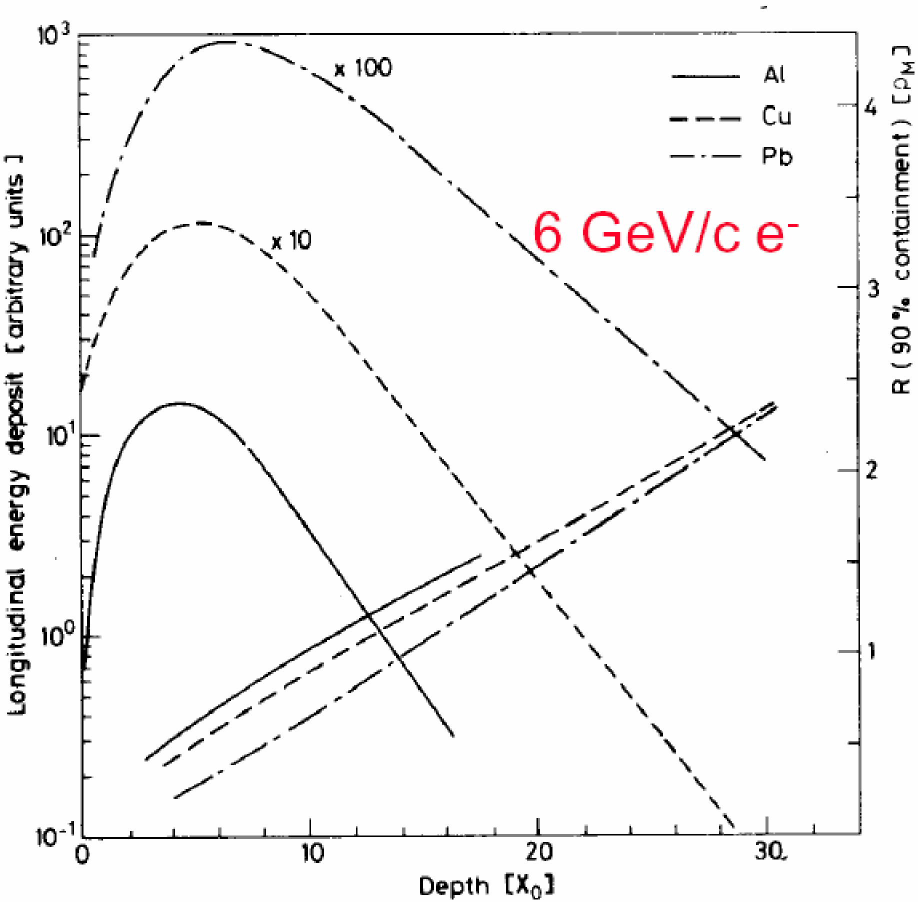
Massimo numero delle particelle $t_{max} \sim \ln(E_0/E_c)/\ln 2$

Contenimento al 95% $t_{95\%} \sim t_{max} + 0.08Z + 9.6$

Sviluppo trasversale dello sciame

Contenimento al 9% in un cilindro di raggio $\sim 2\ R_M$

$R_M = 21\ \text{MeV}\ X_0\ /E_c$

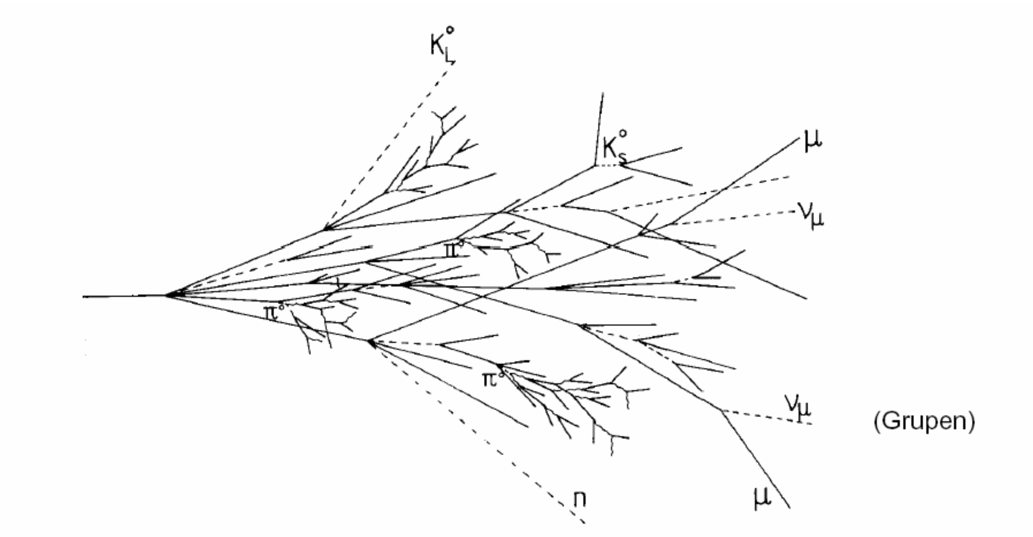


$6\ \mathrm{GeV}/c\ e^-$

Longitudinal and transverse development scale with X_0, R_M

(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Sciami adronici



(Grupen)

Componente adronica + elettromagnetica

Pioni carichi, protoni, k …

(energia di legame)

Neutroni, neutrini, fotoni soffici

Muoni … → energia invisibile

pioni neutri$\rightarrow\gamma\gamma\rightarrow$ Rottura di nuclei

sciame e.m.

$n(\pi^0) \sim \ln(E/GeV) - 4.6$

100 GeV $n(\pi^0) \sim 18$

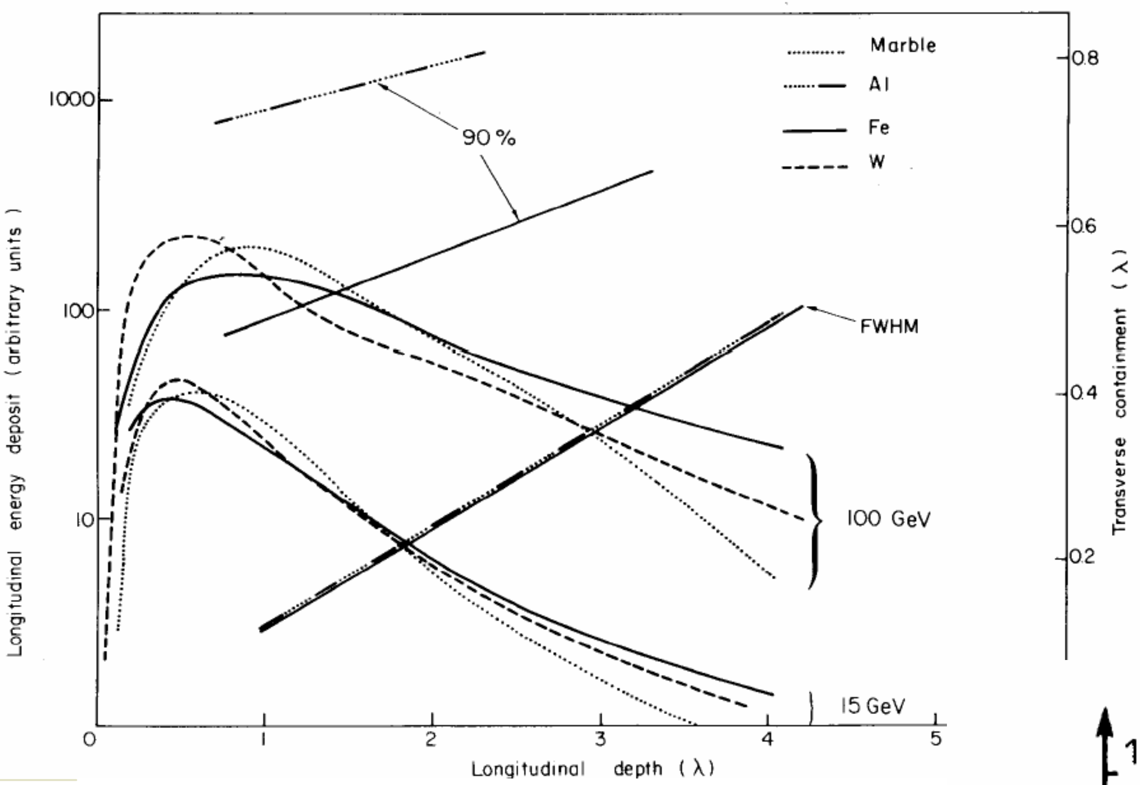
Maggiori fluttuazioni e quindi peggiore risoluzione energetica

ongitudinal shower development

$$t_{\max}(\lambda_I) \approx 0.2 \ln E[GeV] + 0.7$$

$$t_{95\%} \approx a \ln E + b$$

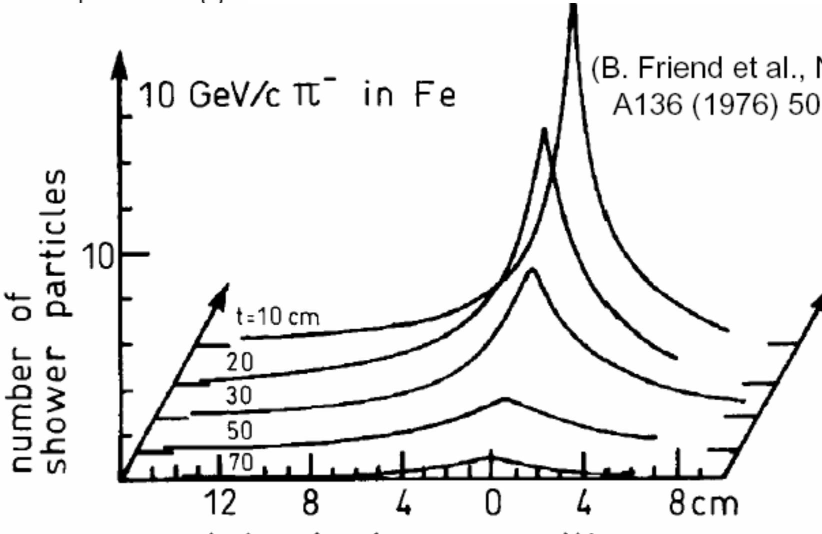
For Iron: a = 9.4, b=39
E =100 GeV
→ $t_{95\%} \approx$ 80 cm



C. Fabjan, T. Ludlam, CERN-EP/82-37)

Lateralmente 2 componenti

Contenimento al 95% entro 1 λ_I
λ_I^{Fe}=16.7 cm



(B. Friend et al., N
A136 (1976) 50

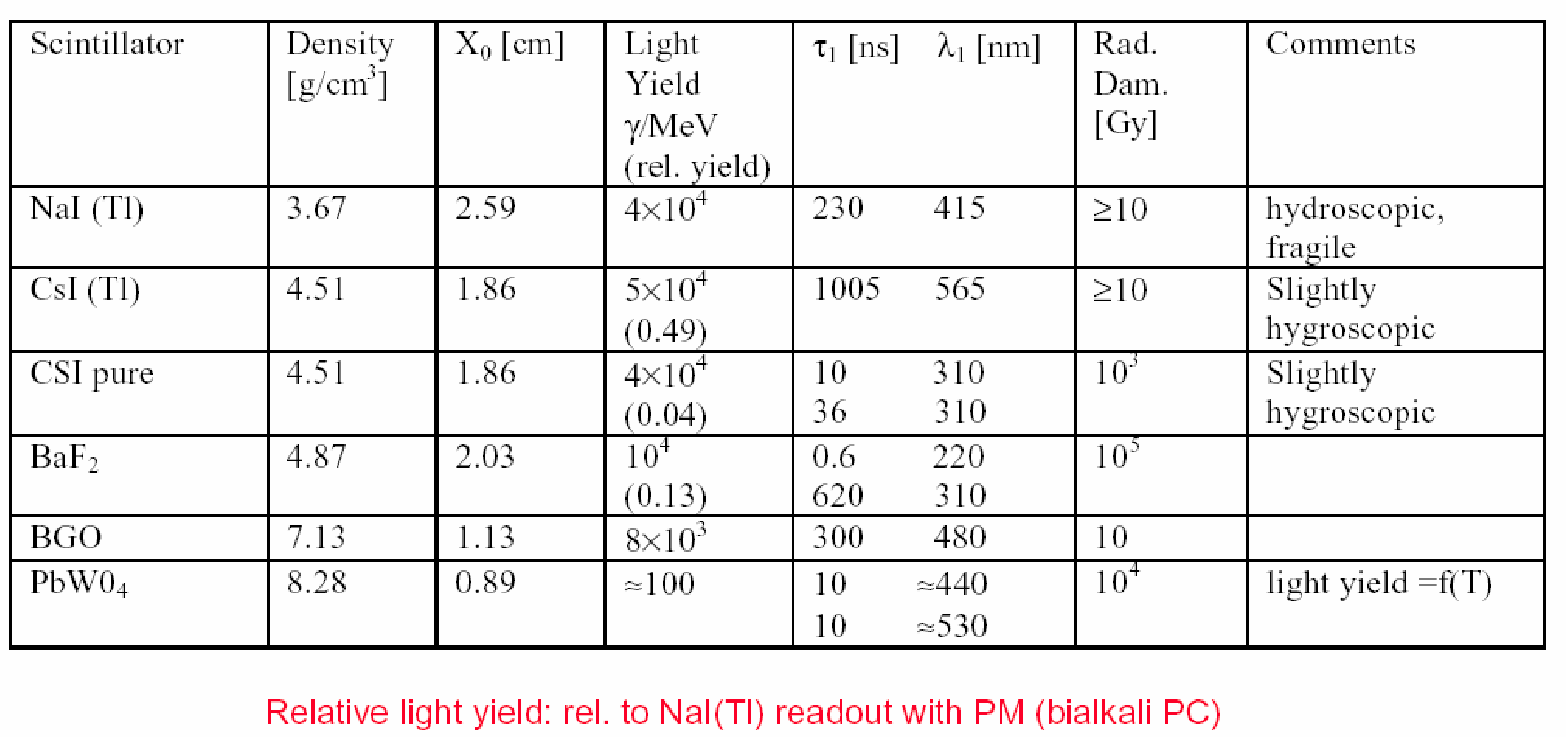
Tipi di calorimetri

- Omogenei
    - Rivelatore = assorbitore
    - Buona risoluzione energetica
    - Risoluzione spaziale peggiore (soprattutto in profondita’)
    - Usati solo per ECAL

- A campionamento
    - Rivelatore e assorbitore separati (campionamento parziale)
    - Peggiore risoluzione energetica
    - Buona risoluzione spaziale peggiore
    - Usati sia per ECAL che per HCAL

Calorimetri omogenei

- A scintillatori

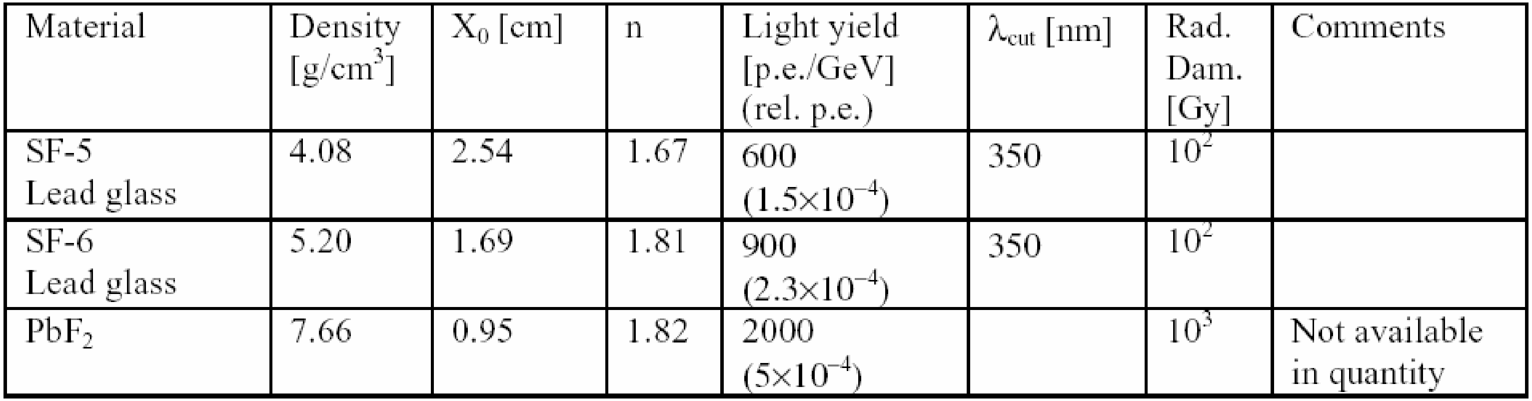


Scintillator	Density [g/cm^3]	X_0 [cm]	Light Yield γ/MeV (rel. yield)	τ_1 [ns]	λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230	415	≥10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005	565	≥10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 36	310 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 620	220 310	10^5	
BGO	7.13	1.13	8×10^3	300	480	10	
$PbW0_4$	8.28	0.89	≈100	10 10	≈440 ≈530	10^4	light yield =f(T)

Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

Calorimetri omogenei

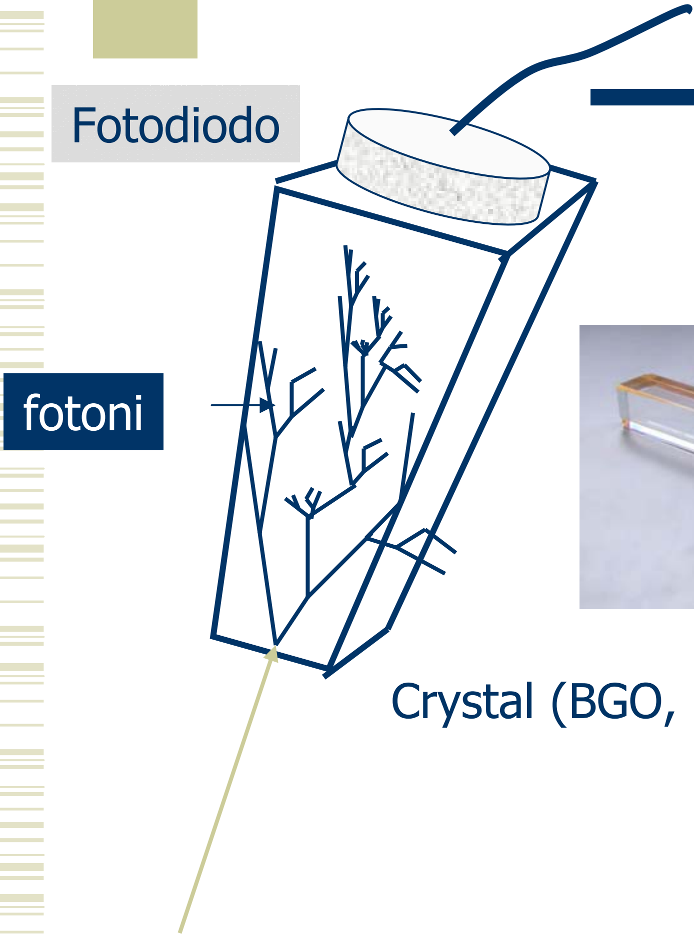
- Ad effetto Cherenkov



Material	Density [g/cm^3]	X_0 [cm]	n	Light yield [p.e./GeV] (rel. p.e.)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

Principio di lettura

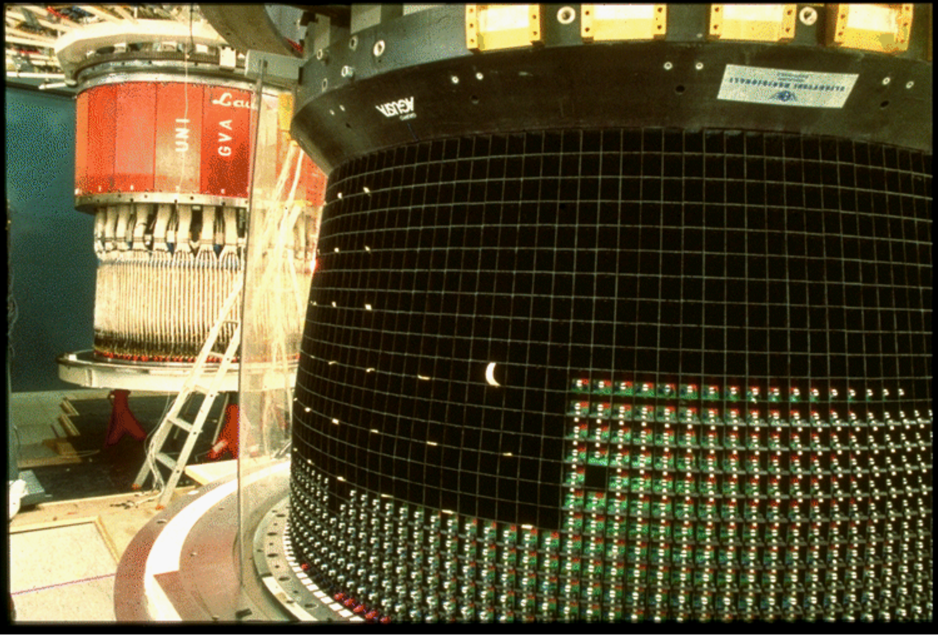


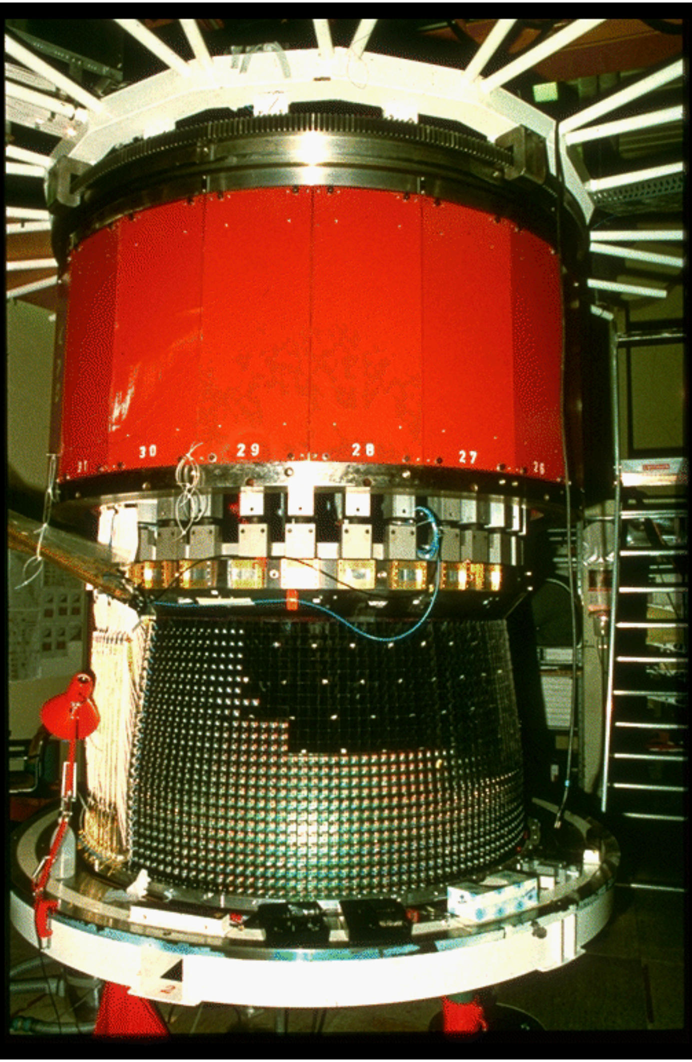
Fotodiodo

fotoni

Crystal (BGO, $PbWO_4$,…)

L3





BGO:

density $\rho=7.13\ \mathrm{g/cm^3}$

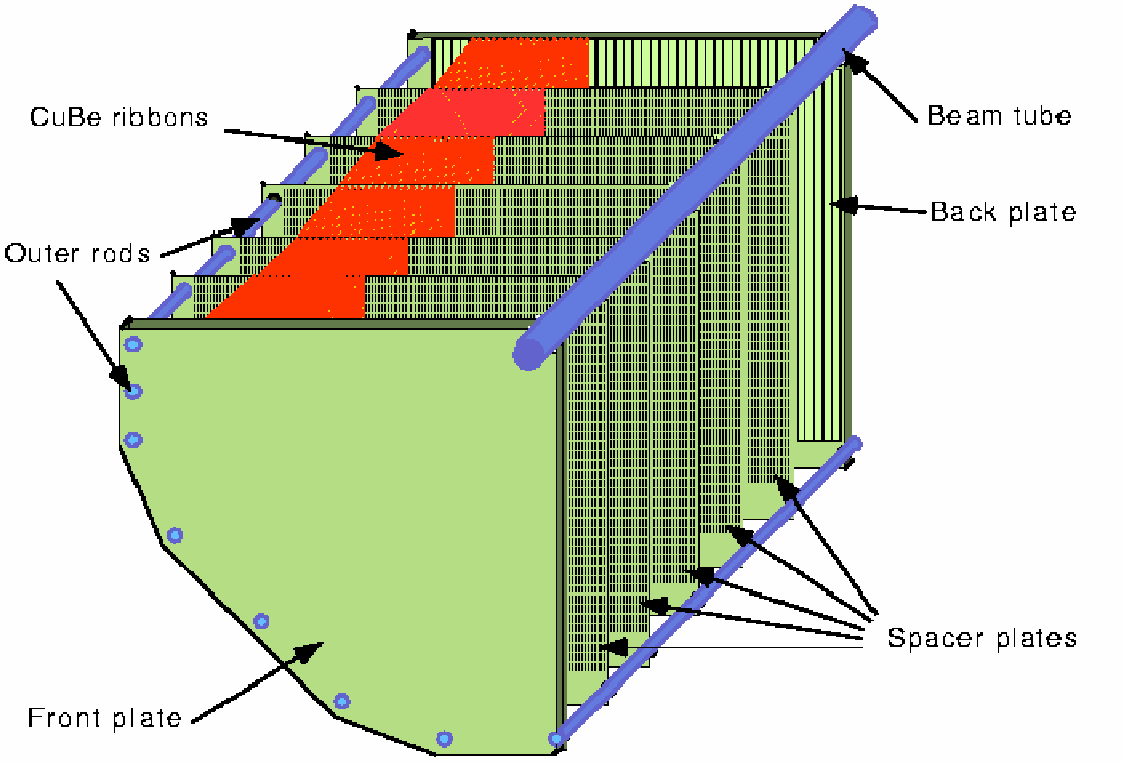
$X_0=1.12$ cm

$\rho_M=2.33$ cm

all light collected in 300 ns (+short component of 60 ns)

$\sigma_E/E=2\%/\sqrt{E} \oplus 0.8\%$

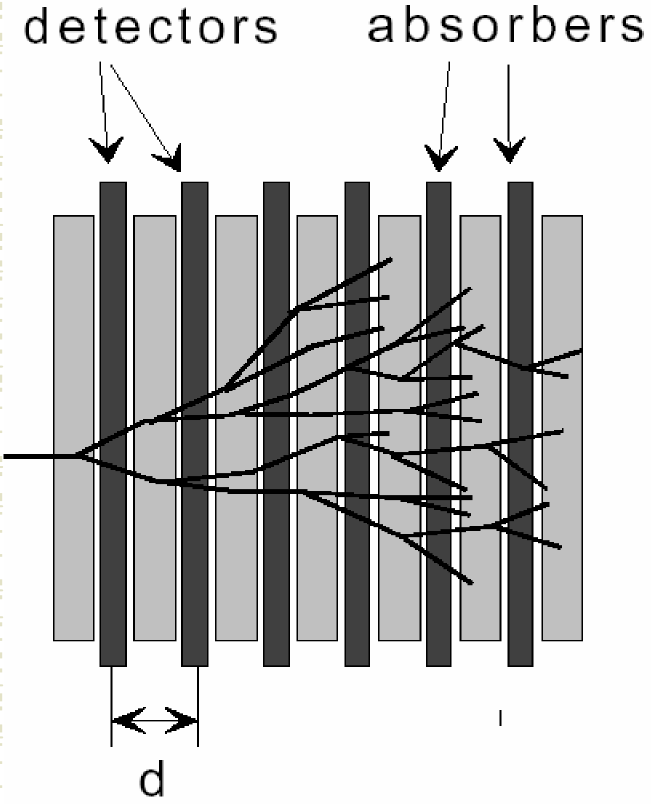
NA48: LKr Ionisation chamber (T = 120 K)
no metal absorbers → quasi homogenous !



Cu-Be ribbon electrode

Sampling calorimeters

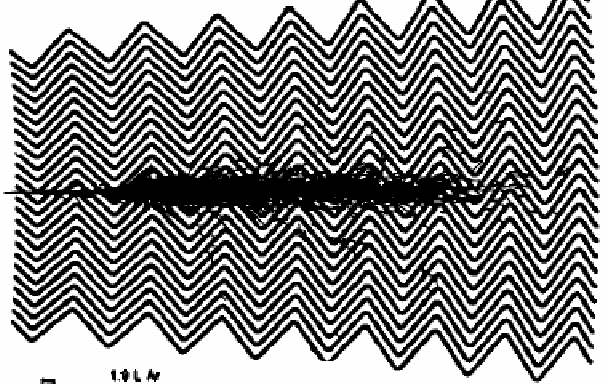
Absorber + detector separated → additional sampling fluctuations

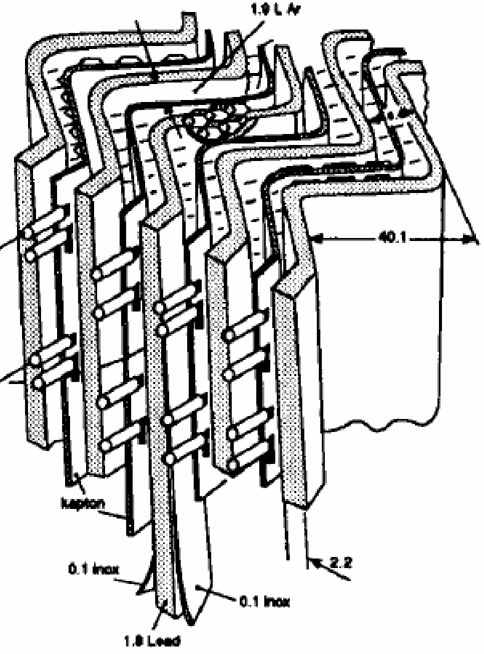


$$N = \frac{T_{\det}}{d}$$ Detectable track segments

$$= F(\xi)\frac{E}{E_c}X_0\frac{1}{d}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sqrt{N}}{N} \propto \sqrt{\frac{1}{E}} \cdot \sqrt{\frac{d}{X_0}}$$





Liquid Argon (90K)

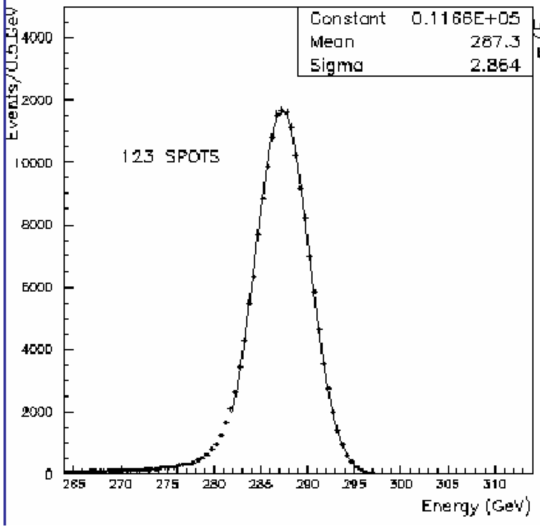
+ lead-steal absorbers (1-2 mm)

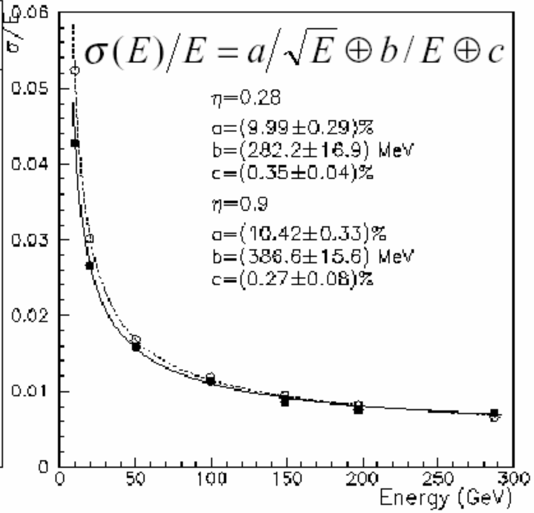
+ multilayer copper-polyimide readout boards

→ Ionization chamber.

1 GeV E-deposit → 5 x10^6 e^-

Test beam results, e^- 300 GeV (ATLAS TDR)





$$\sigma(E)/E = a/\sqrt{E} \oplus b/E \oplus c$$

$\eta=0.28$
$a=(9.99\pm0.29)\%$
$b=(282.2\pm16.9)$ MeV
$c=(0.35\pm0.04)\%$

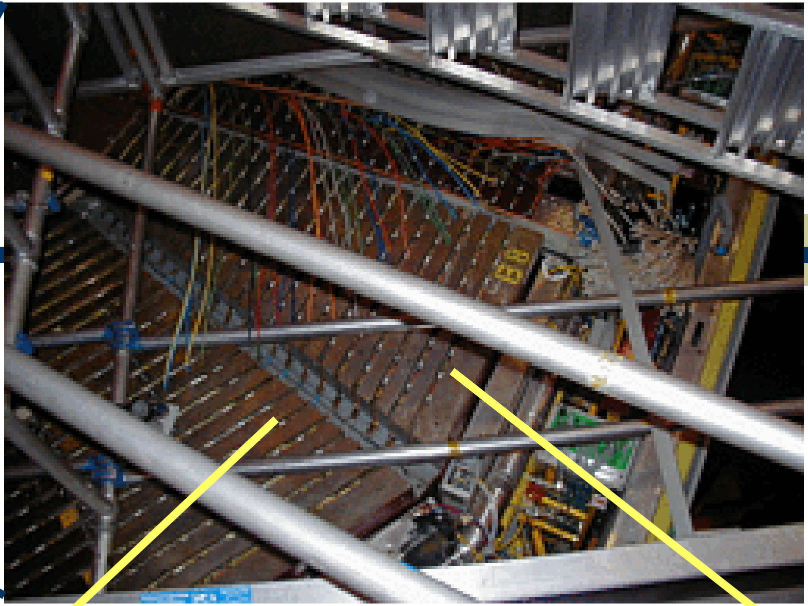
$\eta=0.9$
$a=(10.42\pm0.33)\%$
$b=(386.6\pm15.6)$ MeV
$c=(0.27\pm0.08)\%$

Spatial and angular uniformity ≈0.5%

Spatial resolution ≈ 5mm / $E^{1/2}$

ALEPH ℵ

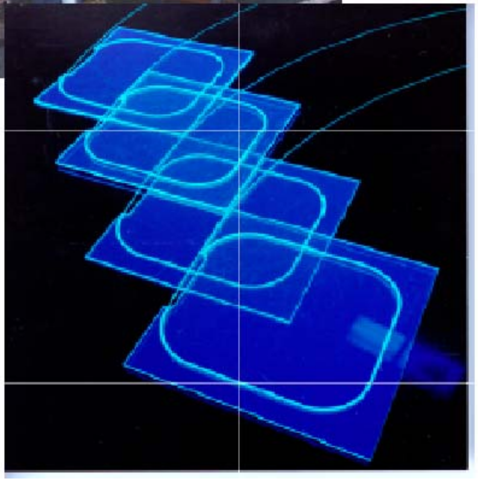
$_E/E=80\%/\sqrt{E}$, $\lambda_I(\mathrm{Fe}) \sim 17\mathrm{cm}$



Ferro + tubi a streamer

CMS

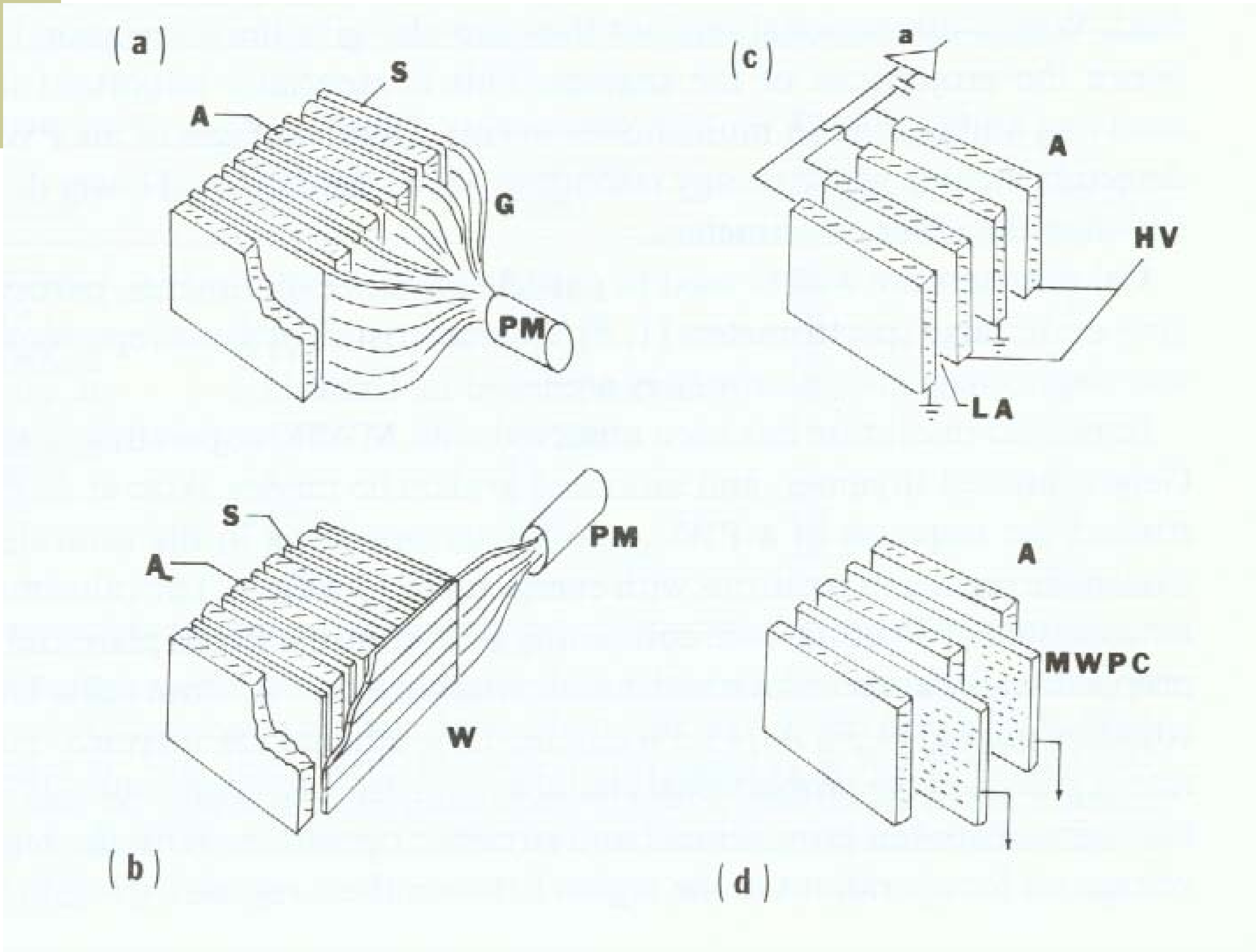
Rame + scintillatore



Scintillators fill slots and are read out via fibres by HPDs

Test beam resolution for single hadrons

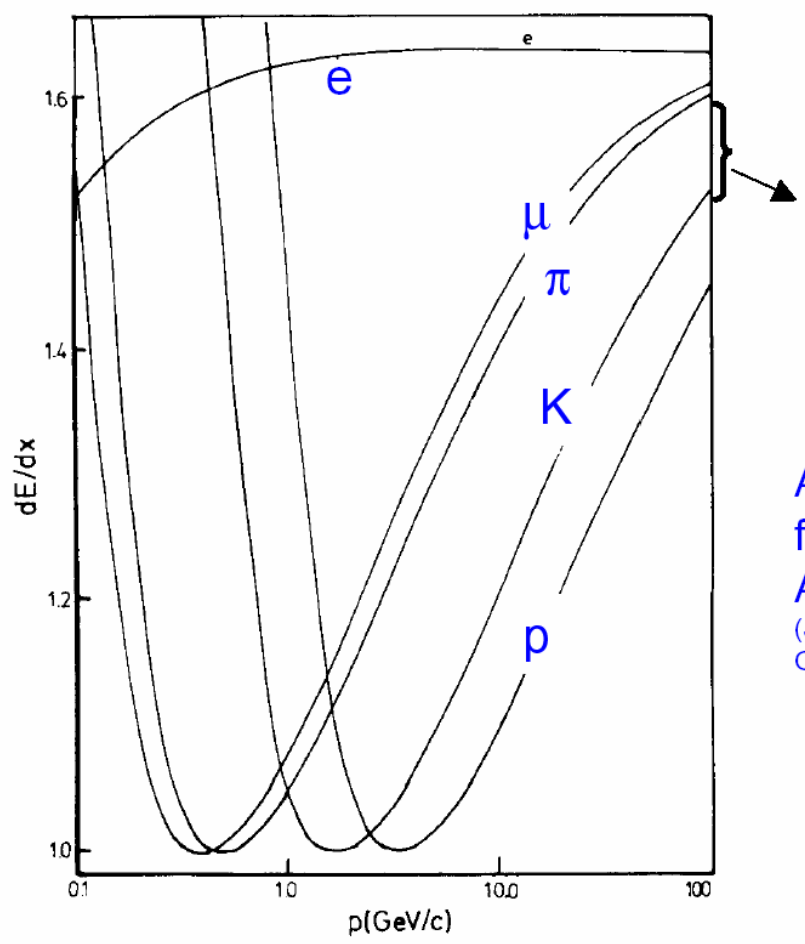
$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$


(a)
S
A
G
PM
(c)
a
A
HV
LA
S
A
PM
W
(b)
A
MWPC
(d)

Identificazione di particelle

- Principi fondamentali
  - Attraverso le interazioni diverse (cfr le trasparenze precedenti)
  - Misurando la massa dai prodotti di decadimento
  - Misurando contemporaneamente la velocita' e l'impulso
    - Le misure sensibili alla velocita' sono
      - Ionizzazione
      - Luce Cherenkov
      - Tempo di volo
      - Radiazione di transizione (TRD)

Ionizzazione

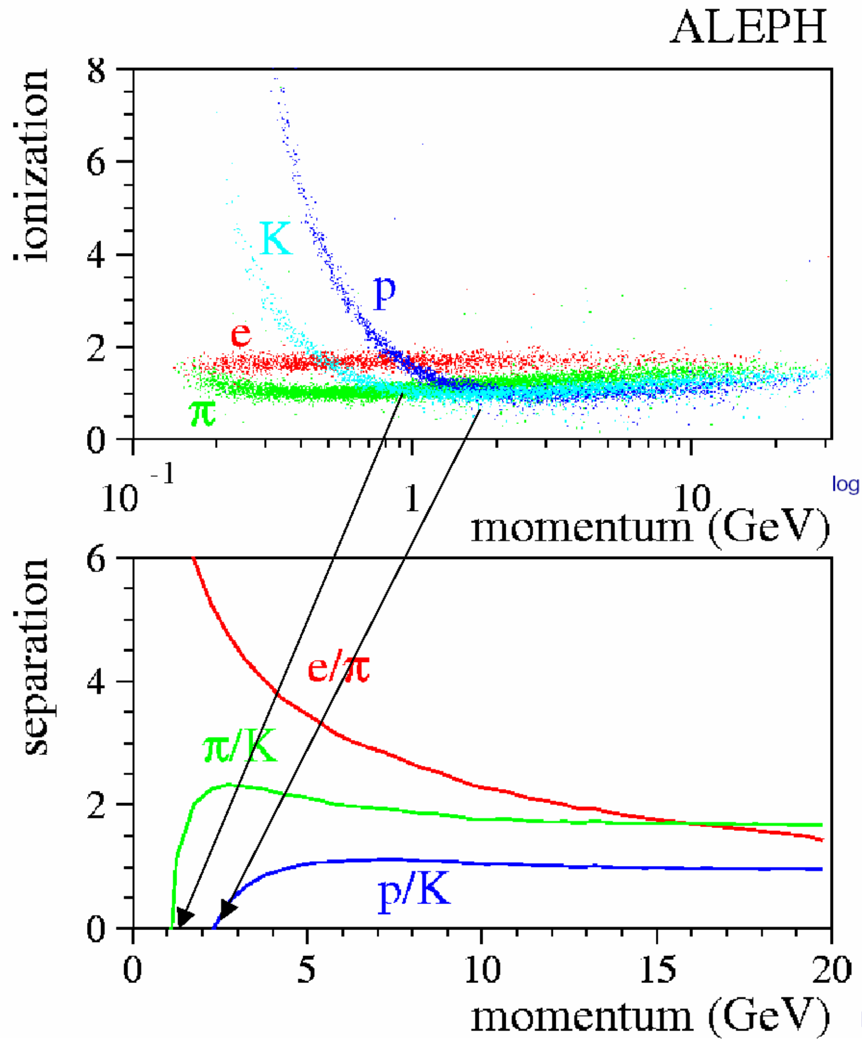


π/K separation (2σ) requires a dE/dx resolution of < 5%

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

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

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

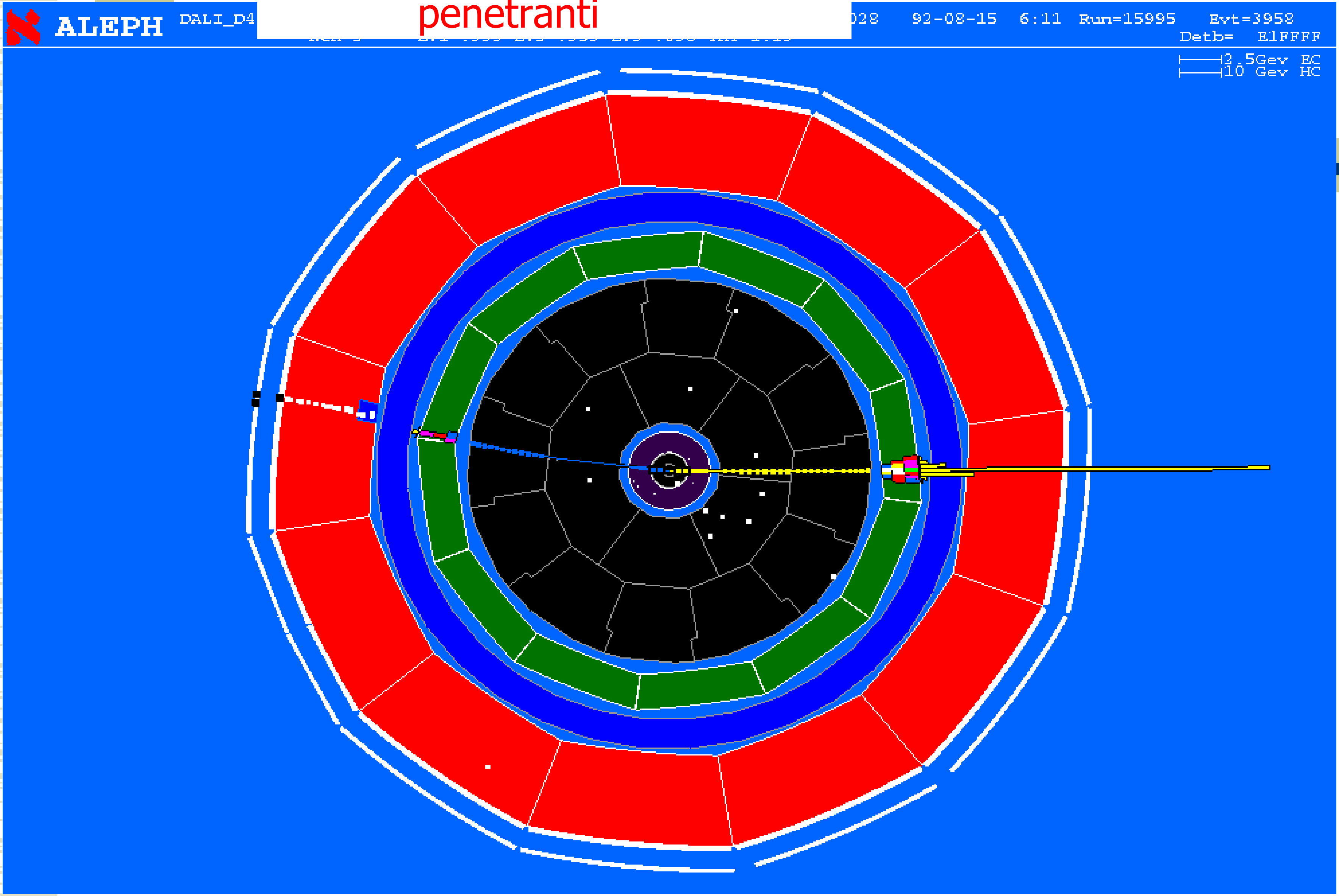


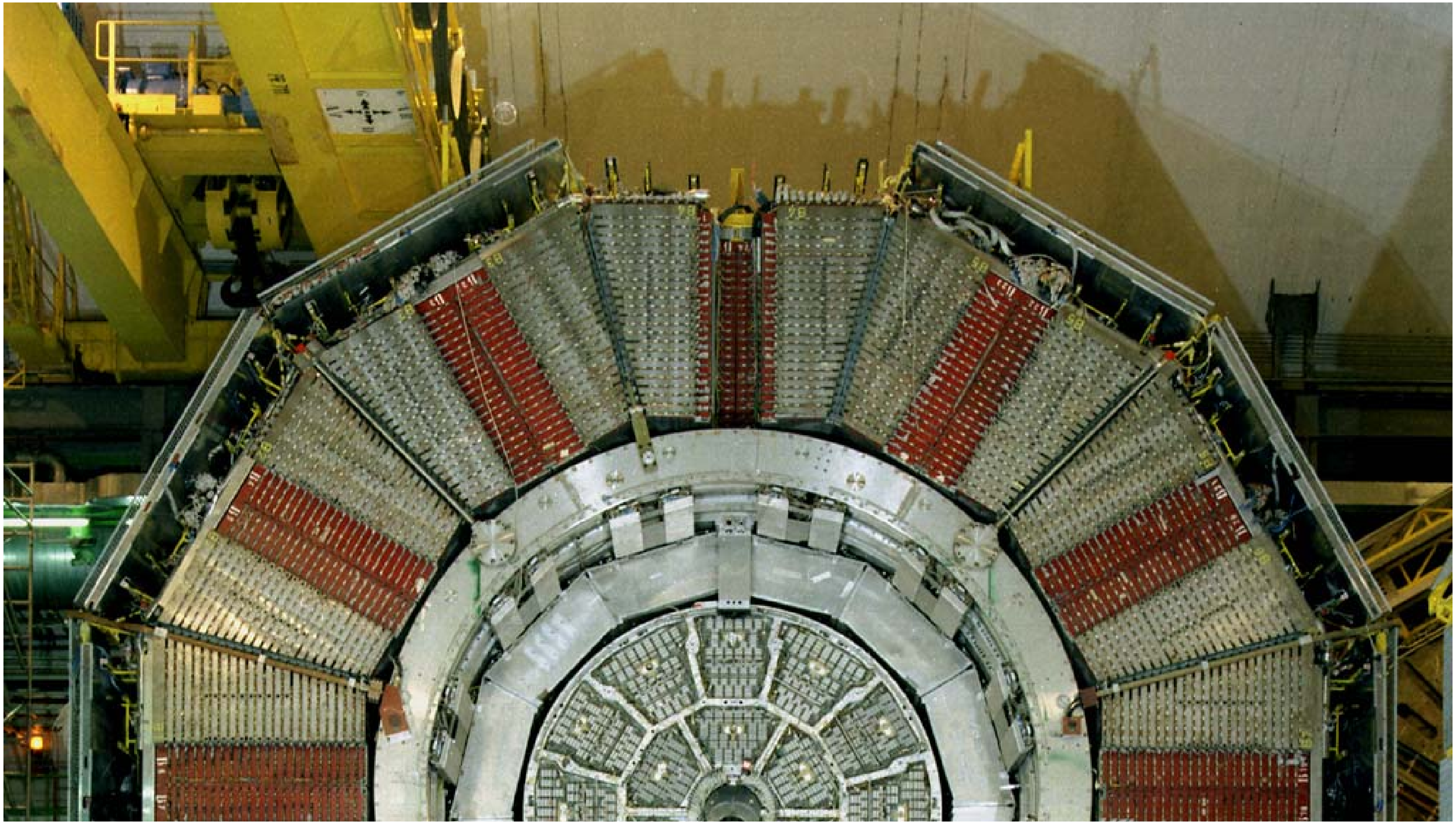
log scale !

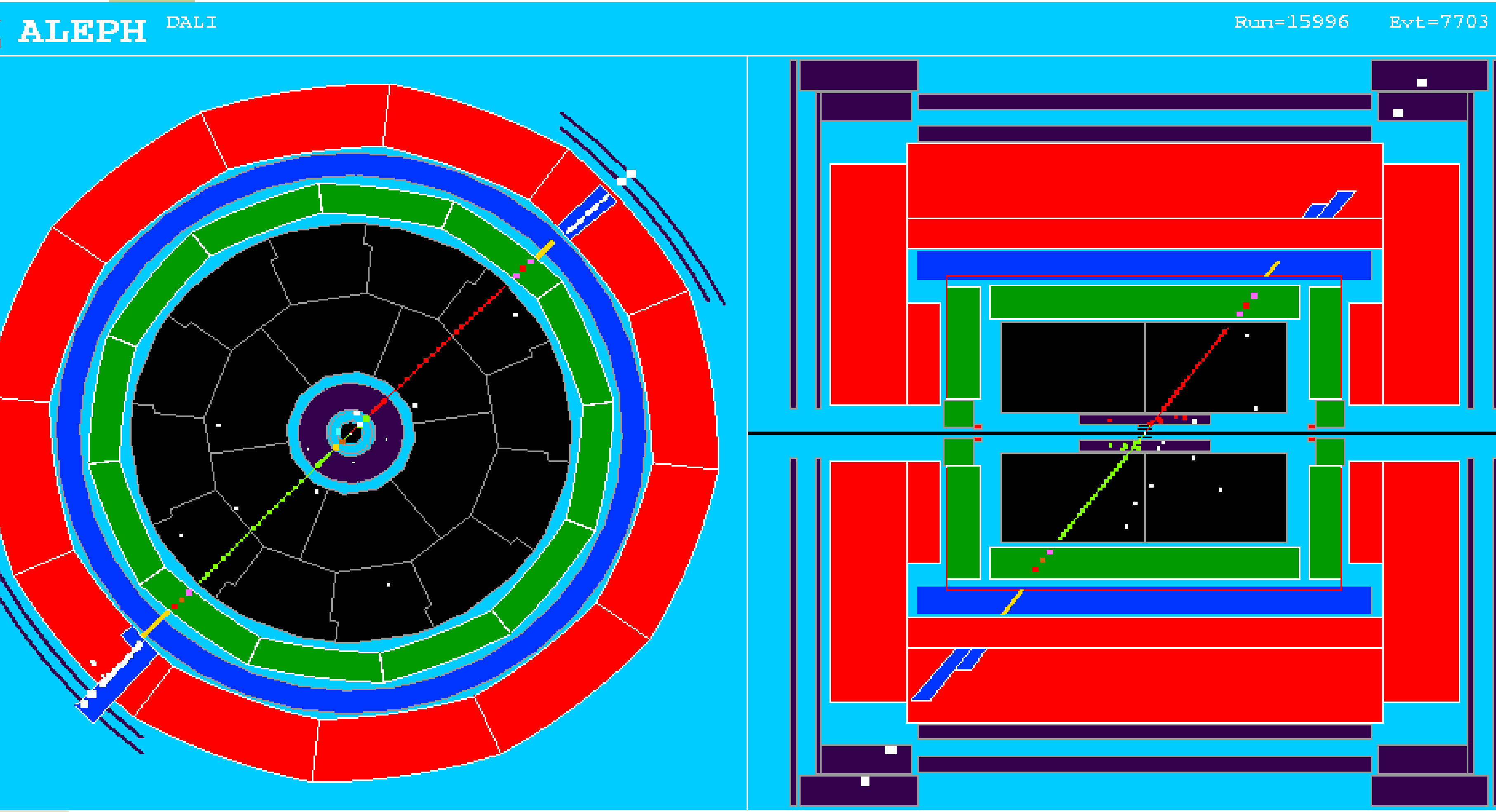
linear scale !

Muoni

poco rilascio energetico
penetranti



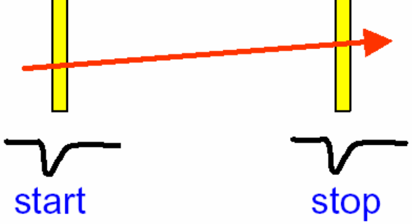




ALEPH
DALI
Run=15996
Evt=7703

Tempo di volo

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



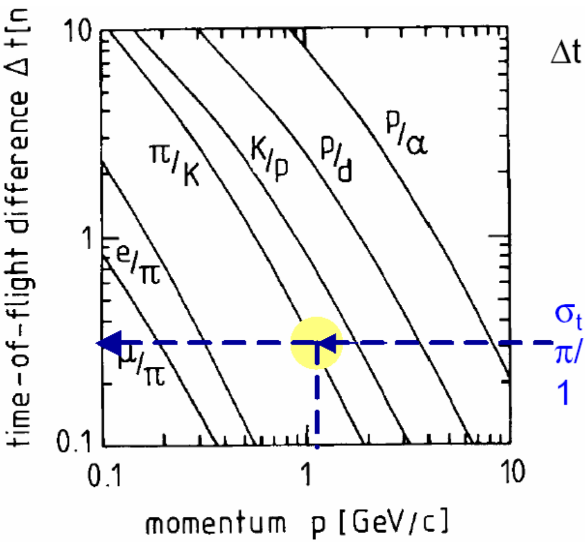
Combine TOF with momentum measurement $(p = m_0 \beta\gamma)$

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

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

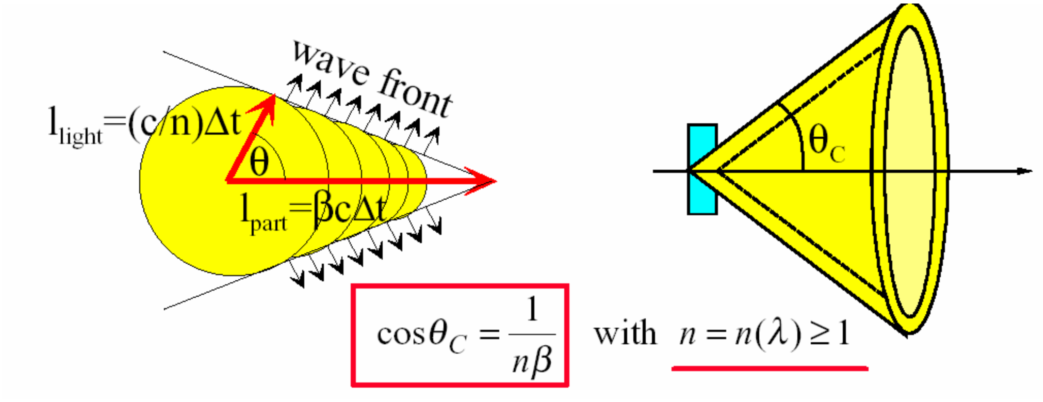
$$= \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1+m_1^2c^2/p^2} - \sqrt{1+m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$



Δt for L = 1 m path lengt

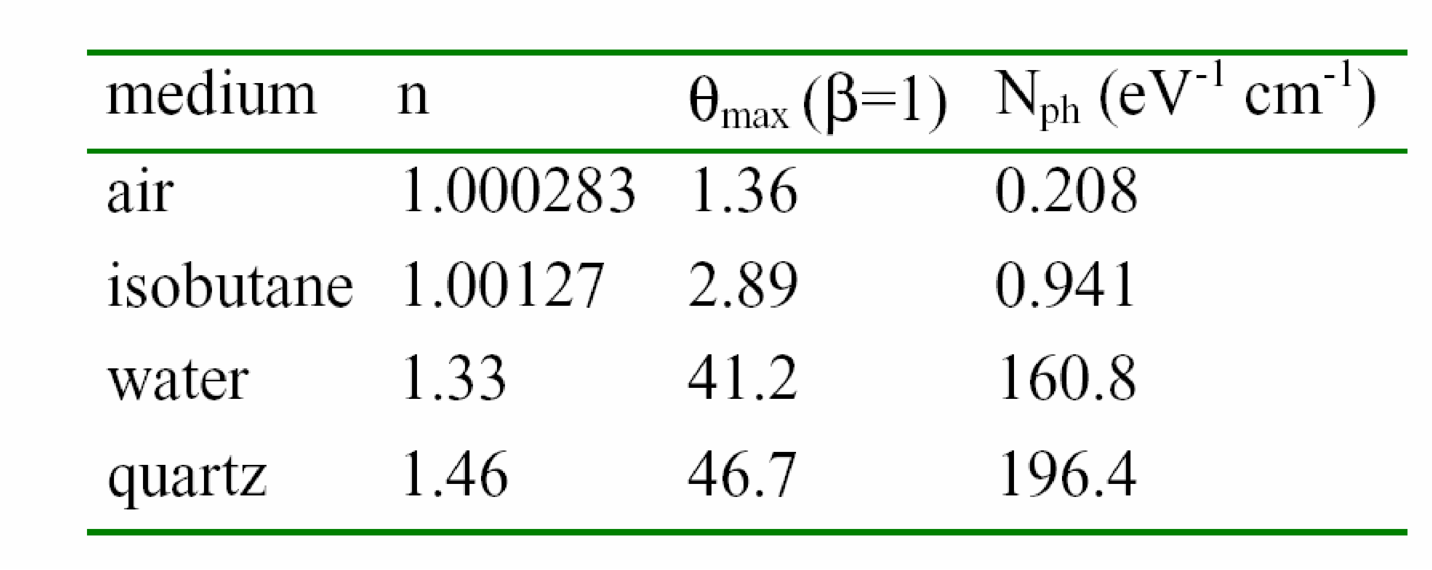
σ_t = 300 ps
π/K separation up to
1 GeV/c

Luce Cherenkov



- Due tipi di rivelatori
  - Numero di fotoni emessi
  - Misura dell'angolo θ_C
  - Ring Imaging CHerenkov (RICH)
  - DIRC

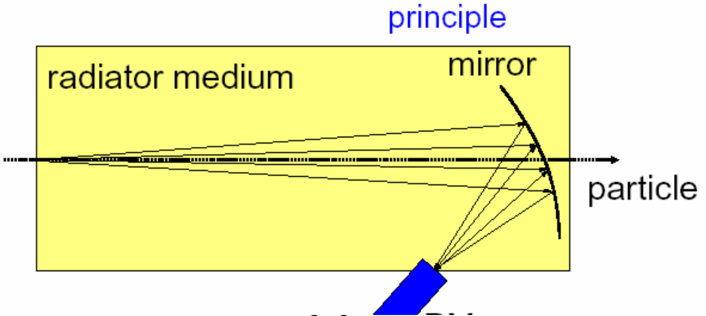
Luce Cherenkov



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

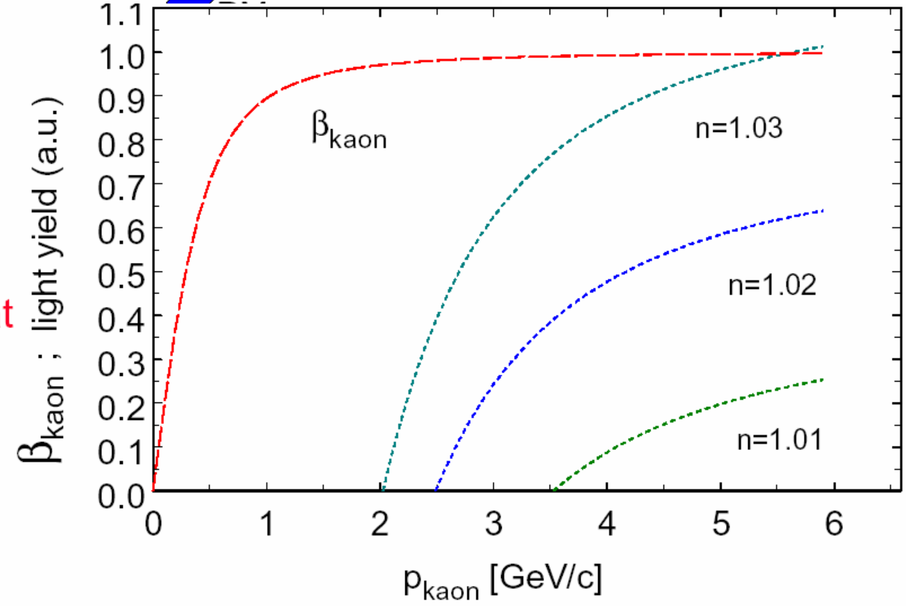
Detector a soglia

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



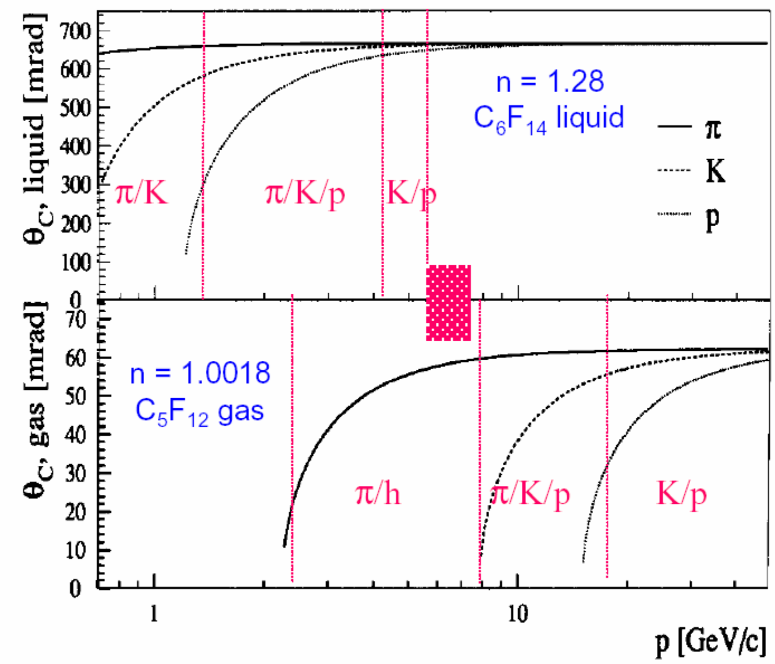
Example:
study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

Goal: π/K separation

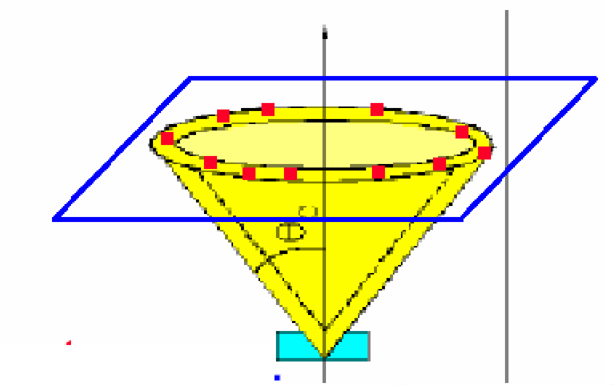


RICH

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



DELPHI



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

p [GeV/c]

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

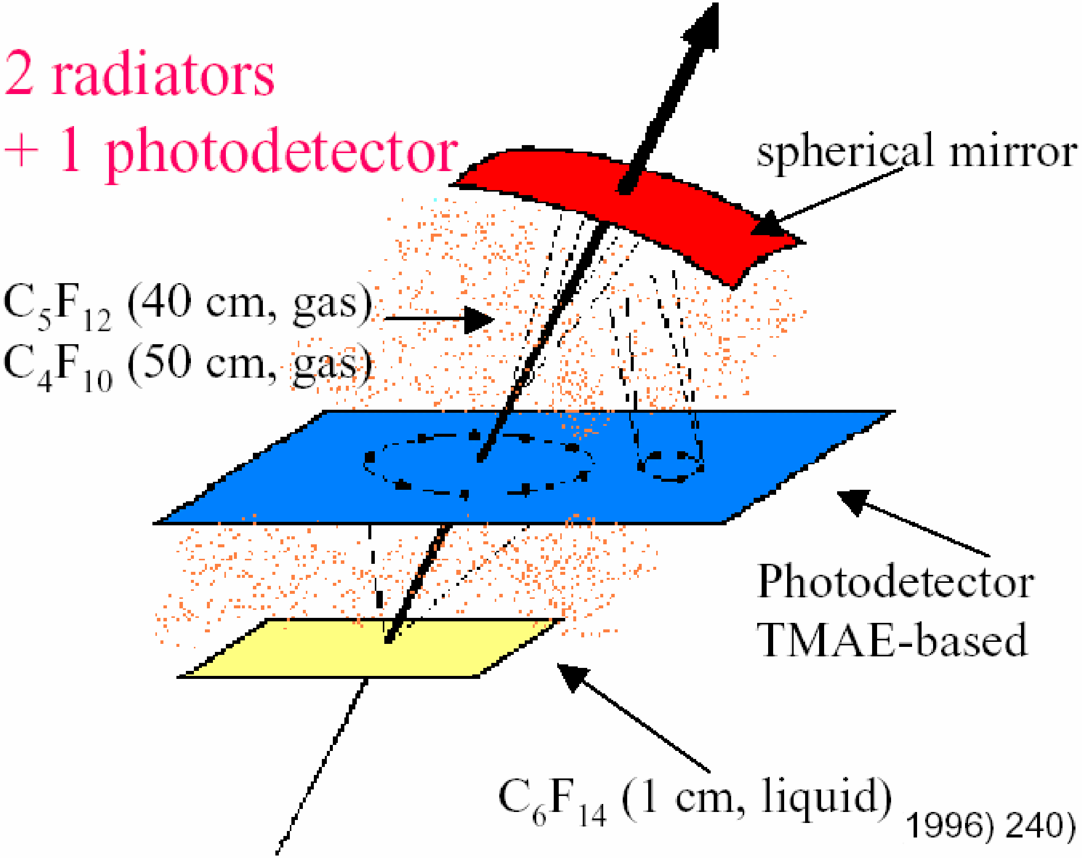
Detect N photons (p.e.) → $\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$

→ minimize σ_θ

→ maximize $N_{p.e.}$

DELPHI RICH

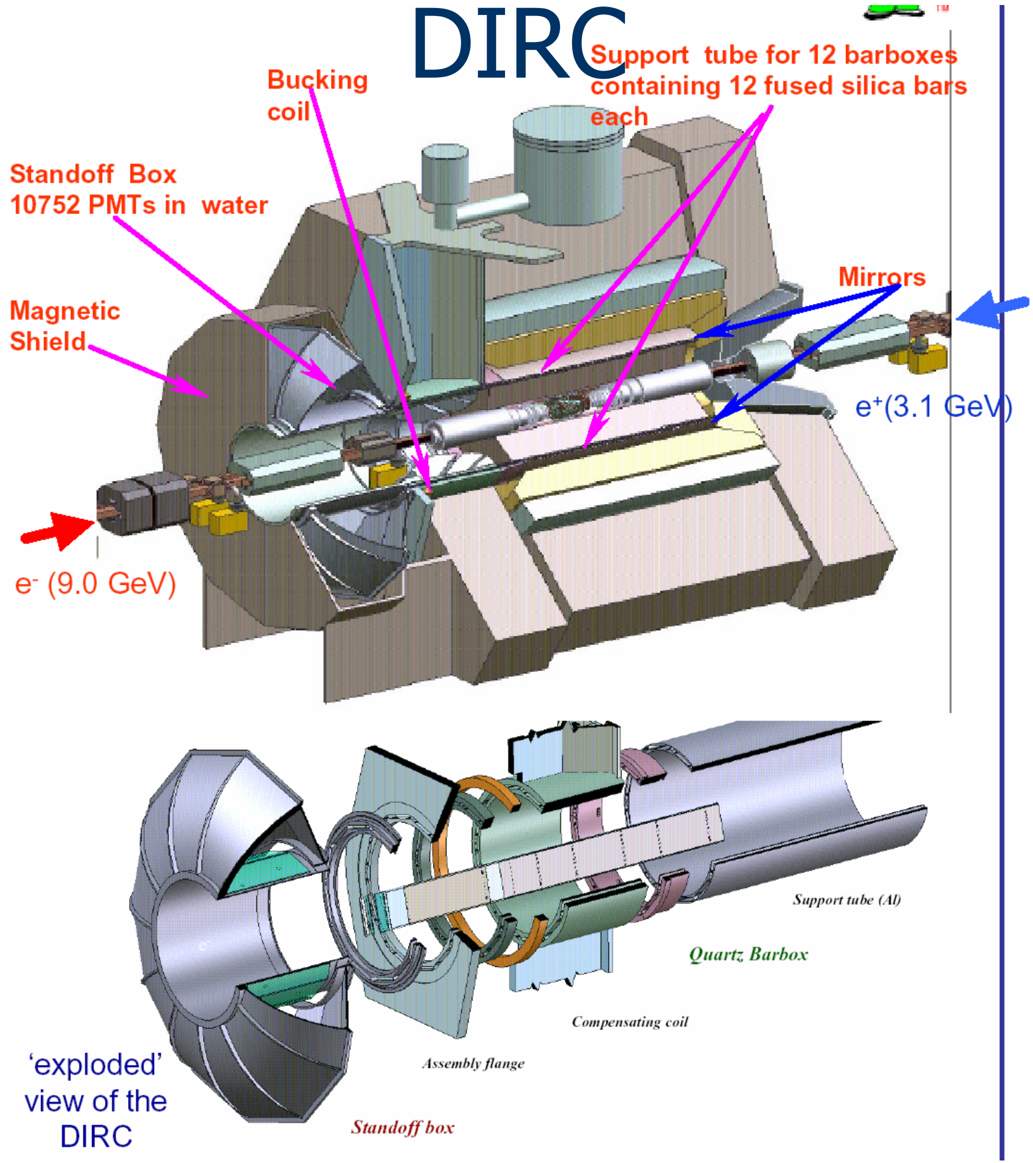
2 radiators
+ 1 photodetector



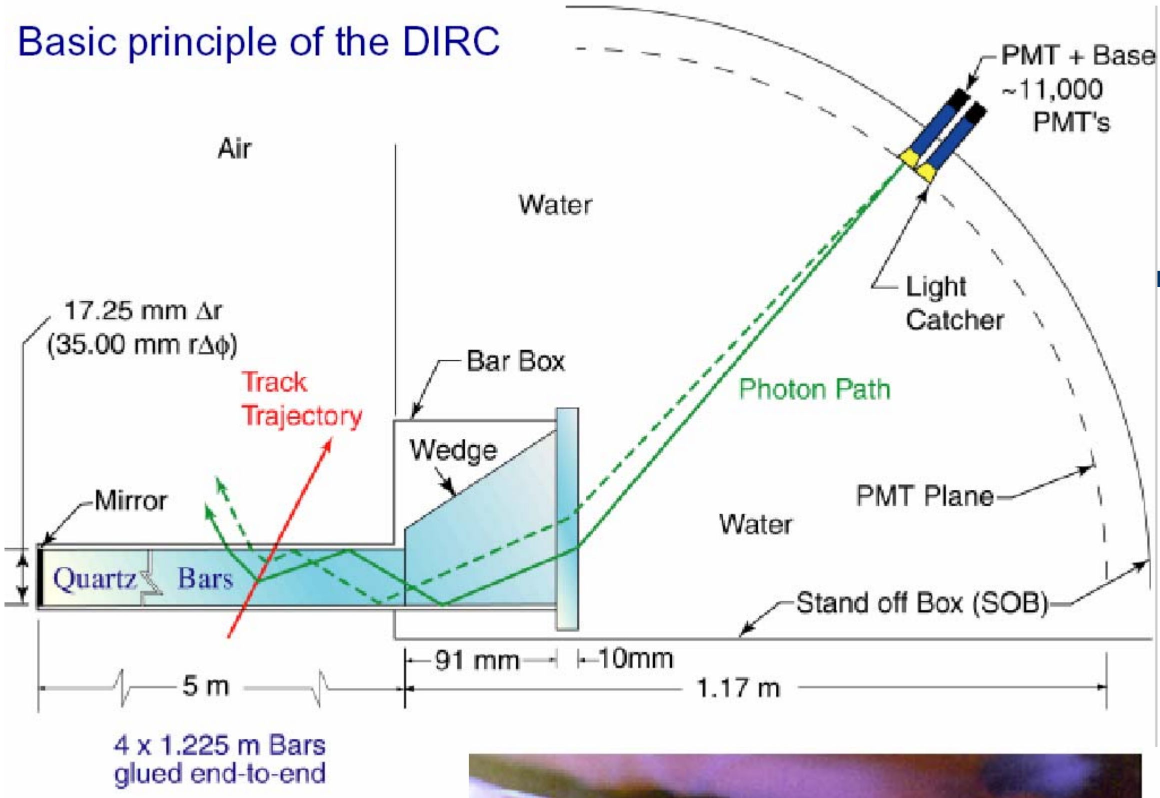
1996) 240)

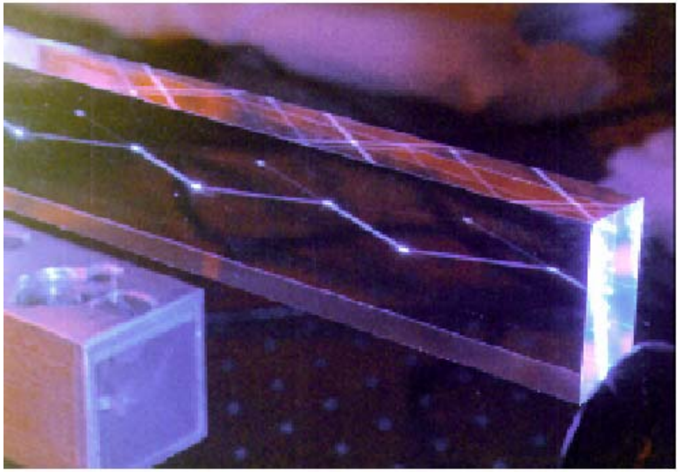
A RICH with two radiators to cover a large momentum range. π/K/p separation 0.7 - 45 GeV/c: DELPHI and SLD

DIRC


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

Basic principle of the DIRC





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

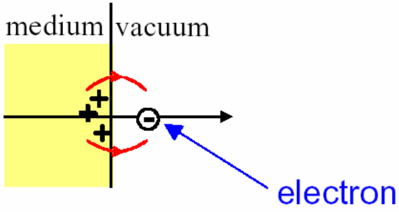
Transition radiation detectors

(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±

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

- 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

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

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

→ TR stay close to track

- Emission spectrum of TR

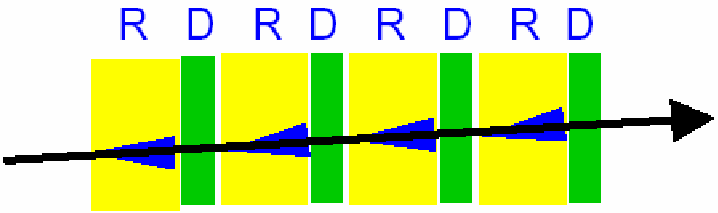
Typical energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

→ photons in the keV range

TR Radiators:

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

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



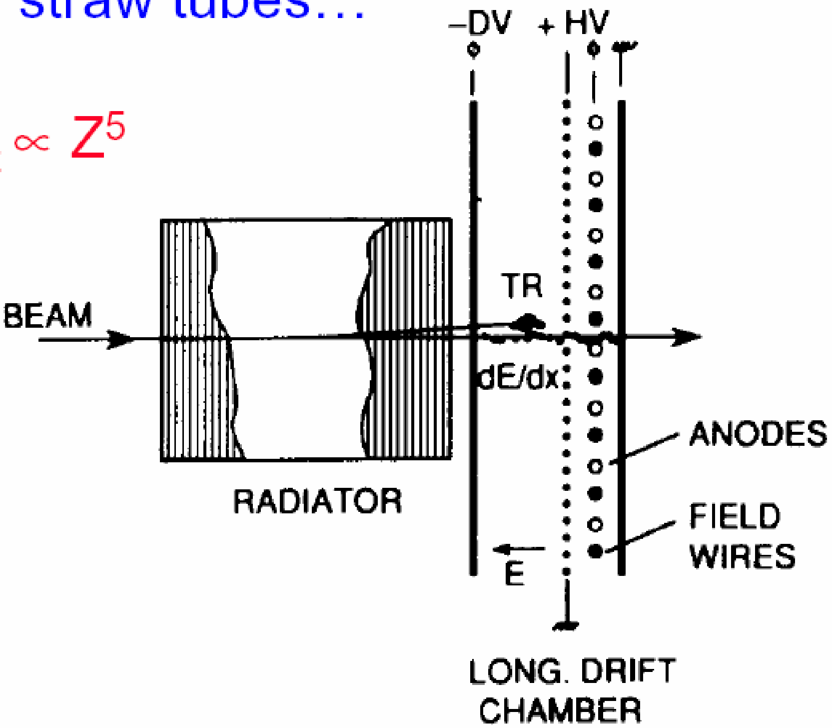
sandwich of radiator stacks and detectors

→ minimize re-absorption

TR X-ray detectors:

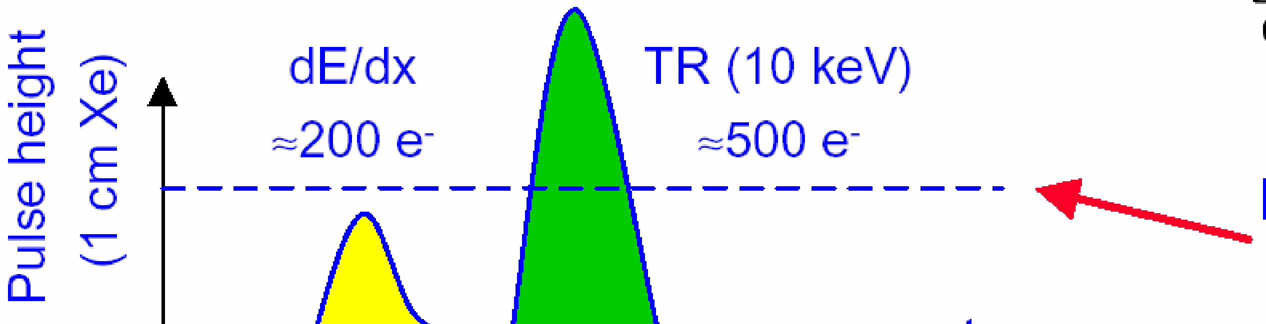
- Detector should be sensitive for $3 \leq E_{\gamma} \leq 30$ keV.
- Mainly used: Gaseous detectors: MWPC, drift chamber, straw tubes…
- Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

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



Intrinsic problem:

detector “sees” TR and dE/dx



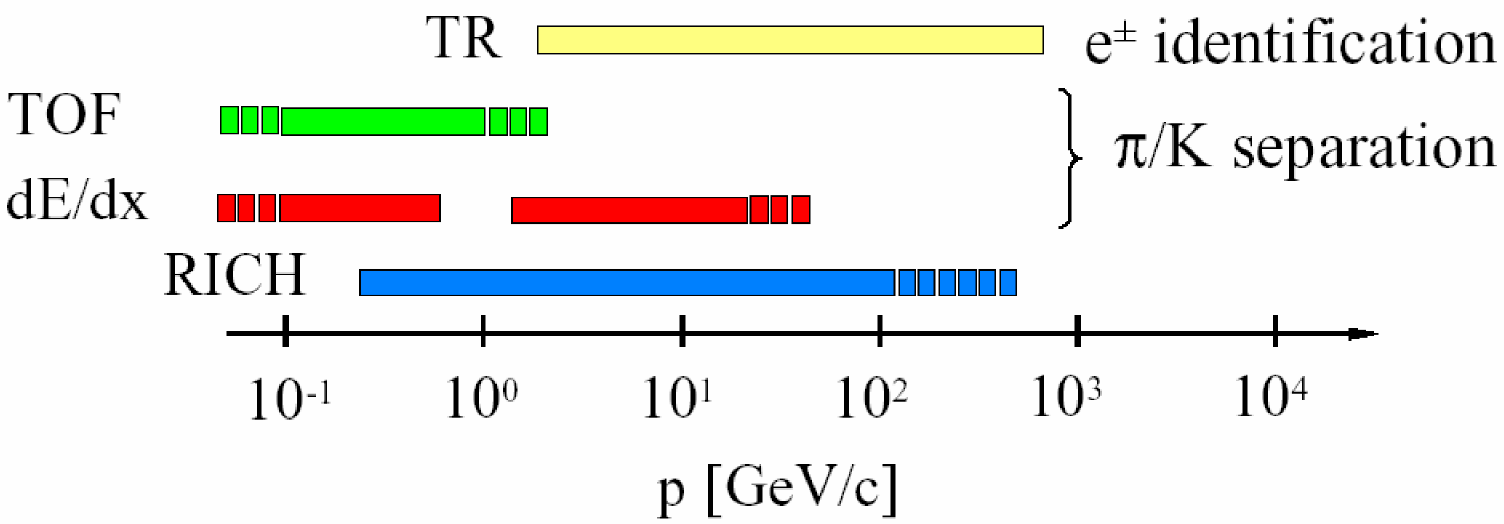
Discrimination by threshold

ATLAS **T**ransition **R**adiation **T**racker

A prototype endcap “wheel”.

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

Xe based gas


TR
e± identification
TOF
dE/dx
π/K separation
RICH
10-1
100
101
102
103
104
p [GeV/c]