Particle Detectors

Lecture 21
20/05/16

a.a. 2015-2016

Emanuele Fiandrini

Energy Measurement (Calorimetry)

A calorimeter is used to measure the energy of a charged and/or neutral particle

The calorimeter should absorb all of the energy of an incident particle

Energy measurement by a calorimeter is a DESTRUCTIVE process.

Original particle no longer exists after the measurement.

Calorimeter usually located behind charged particle tracking chambers

MWPCs, drift chambers, silicon trackers are non-destructive measuring devices

The energy resolution of a calorimeter is determined by many factors:

Actual energy deposited in calorimeter (sampling fluctuations)

Leakage of energy out of the calorimeter

Noise (e.g. from electronics or pickup)

Ion or light collection efficiency

Usually, the dominant term in the energy resolution is due to sampling fluctuations which are Poisson in nature. Thus this term in the energy resolution varies like:

$$\sigma_E / E = A / \sqrt{E} \quad A \text{ is a constant}$$

A more complete description of the energy resolution is:

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + C^2 + (D \ln E)^2$$

Since C and D are usually small energy resolution **improves** as E increases. This is different than momentum resolution which gets worse as momentum increases.

B=contribution due to electronics (e.g. ADC resolution)

C=contribution due to calibration errors and other systematic effects

D=contribution due to energy leakage

Calorimetria

Le caratteristiche (vantaggi) principali di un calorimetro sono:

- ☺ La precisione della misura aumenta al crescere di E

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

rumore

termine costante

termine stocastico

- ☺ Le dimensioni di un calorimetro necessarie a contenere lo sciame scala logaritmicamente con l'energia (*)➔riduzione del prezzo e dimensioni.
- ☺ Se segmentato finemente è in grado di produrre misure di posizione ed angolo di incidenza.
- ☺ Specialmente ai Collider i calorimetri sono in grado di misurare proprietà globali dell'evento (e.g. energia dei jet)

(*) Ricorda: $L_{max} \approx \ln(E_0)$

Calorimetria

I calorimetri si suddividono ulteriormente in:

- Calorimetri omogenei:
  - ⇨ Rivelatore = assorbitore
  - ⇨ Buona risoluzione in energia
  - ⇨ Risoluzione spaziale limitata nella direzione longitudinale
  - ⇨ Usati solo per calorimetria e.m.
- Calorimetri a campionamento:
  - ⇨ Rivelatore ed assorbitore separati → solo parte dell'energia viene misurata
  - ⇨ Risoluzione in energia limitata
  - ⇨ Buona risoluzione spaziale nella direzione longitudinale
  - ⇨ Usati sia per calorimetria adronica che e.m.

Calorimetry

Calorimeter information can also be used to:

- identify particles (e.g. γ's, e's)
- measure space coordinates of particles (no B-field necessary)
- form a "trigger" to signal an interesting event
- eliminate background events (e.g. cosmic rays, beam spill)
- can be optimized to measure electromagnetic or hadronic energy

Calorimeter usually divided into active and passive parts:

- Active: responsible for generation of signal (e.g. ionization, light)
- Passive: responsible for creating the "shower"

Many choices for the "active" material in a calorimeter:

- inorganic crystals (CsI used by CLEO, BELLE, BABAR)
- organic crystals (ancthracene) {mainly used a reference for light output}
- plastic scintillator (ZEUS, CDF)
- liquid scintillator (used by miniBoone)
- Noble liquids (liquid argon used by D0, ATLAS)
- gas (similar gases as used by wire proportional chambers)
- glass (leaded or doped with scintillator)
- water (SuperK)
- silicon (Fermi)

Many choices for the "passive" material in a calorimeter:

- high density stuff: marble, iron, steel, lead, depleted uranium
- lower(er) density stuff: sand, ice, water

Calorimetri omogenei

Calorimetri omogenei

Sono costituiti da un blocco di materiale sensibile alle particelle cariche dello sciame. Usati solamente per calorimetri e.m.

Il materiale usato può essere scintillatore o radiatore Cerenkov.

La lettura del segnale è normalmente ottenuta con fotomoltiplicatori o diodi/triodi.

Se il numero di fotoelettroni è piccolo il contributo delle fluttuazioni statistiche:

$$\left(\frac{\sigma(E)}{E}\right)_{p.e.} = \sqrt{\frac{\left(1+g^{-1}\right)}{\left\langle n_{p.e.}\right\rangle}}$$

g = guadagno del PM → fluttuazioni al dinodo

può contribuire parecchio alla risoluzione in energia.

Notiamo che per PM con guadagni $g \sim 10^5$ possiamo trascurare il termine g^{-1}, ma per diodi e/o triodi con $g=1 \div 10$ ➔ questo termine contribuisce al degrado della risoluzione in energia.

Calorimetri

Radiatori Cerenkov

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)

Calorimetri omogenei

♦ Radiatori Cerenkov

Il vetro-piombo (lead glass) è il materiale più usato sia per la buona risoluzione che per il prezzo abbordabile.

Ricordiamo:

$$\boxed{\frac{dN_\gamma}{dx} = 2\pi^2\left(1-\frac{1}{\beta^2 n^2}\right)\cdot\frac{d\lambda}{\lambda^2}}$$

La dipendenza λ^{-2} significa che l'emissione è concentrata a piccole lunghezze d'onda ➔ poca luce perché il vetro-piombo assorbe a piccole lunghezze d'onda (λ=350 nm è la soglia di assorbimento).

Regge poca radiazione (~10 Gy) (diventa giallo → si degrada a basse lunghezze d'onda). Se si droga con Cs ➔ regge 10^4 Gy però meno luce alle λ corte.

Calorimetri omogenei

Accorgimenti per l'uso del vetro-piombo:

1) Non usare guide di luce. Infatti n(vetro-piombo)~1.7, mentre le colle e le guide hanno n + basso ➔ si perde luce.

   Soluzioni: usare il vetro piombo stesso come guida oppure usare una guida costituita da tanti strati sottili che degradano fino a raggiungere l'indice di rifrazione della finestra del PM, o anche incollare direttamente il PM sul vetro-piombo con una colla ad alto n.

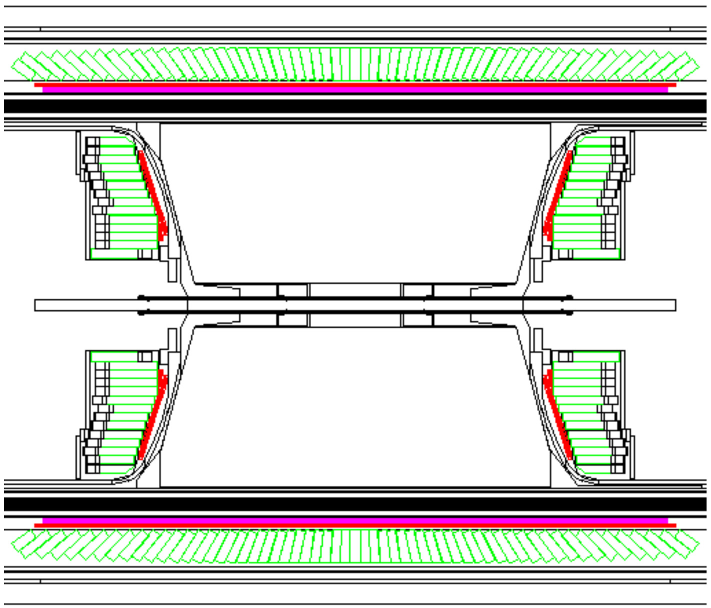
2) Tenere la luce nel vetro-piombo → ricoprire il vetro piombo con un materiale diffondente (e.g. Tyvek) → n(glass):n(air)=1.7:1 ➔ tutta la luce con angoli d'incidenza > 36° viene riflessa totalmente.

3) L'assorbimento del vetro-piombo dipende dalla lunghezza d'onda ➔ siamo sensibili alle fluttuazioni longitudinali dello sciame. Sciami che si formano prima danno meno luce di sciami che si formano dopo ➔ compromesso sulla lunghezza del rivelatore (18÷20 X_0)

Calorimetri omogenei

Esempio : OPAL Barrel +end-cap: vetro-piombo + pre-sampler

(OPAL collab. NIM A 305 (1991) 275)



≈10500 blocks (10 x 10 x 37 cm^3, 24.6 X_0), PM (barrel) or PT (end-cap) readout.

$$\sigma(E)/E = 0.06/\sqrt{E} \oplus 0.002$$

Spatial resolution (intrinsic) ≈ 11 mm at 6 GeV

Calorimetri omogenei

♦ **Scintillatori in calorimetri**

Nei calorimetri omogenei sono quasi sempre usati scintillatori inorganici (cristalli e gas nobili liquidi) per i seguenti motivi:

a. Inorganici
   - ☺ buona emissione di luce
   - ☺ linearità con l’energia
   - ☹ sono lenti (non è del tutto vero)
   - ☹ meno luce di quelli organici

b. Organici
   - ☹ minore linearità (Birk)
   - ☺ sono veloci (almeno una componente)

Calorimetri omogenei

- **Scintillatori (cristalli inorganici)**

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	$\geq$10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005	565	$\geq$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	$\approx$100	10 10	$\approx$440 $\approx$530	10^4	light yield =f(T)

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

Calorimetri omogenei

Promettente il $PbWO_4$ (CMS, Alice)

Parametro	valore
densità [g/cm^3]	8.28
lunghezza di radiazione [cm]	0.89
raggio di Moliere [cm]	2.0
punto di liquefazione [°C]	1123
conduttività [Moh]	4
indice di rifrazione (λ=632 nm) (birifrangente)	2.16
igroscopicità	nulla
attività chimica	inerte

Drogato con Nb è resistente alla radiazione.

Emette poca luce alla temperatura ambiente, ma rapida

Grosso indice di rifrazione → difficile il contatto ottico.

In CMS si leggerà con APD

Calorimetri omogenei

Spettro di emissione

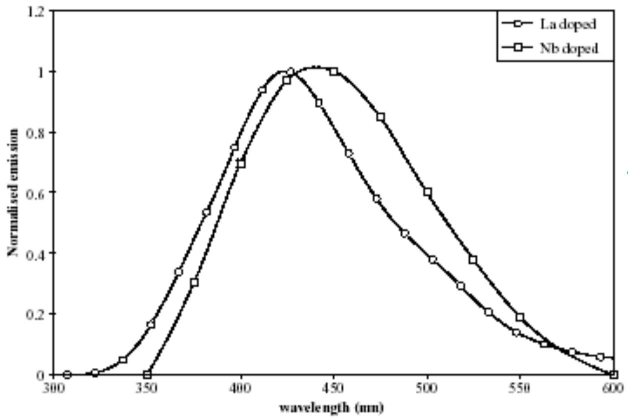


Fig. 2.1: Scintillation light spectrum of niobium- and lanthanum-doped $PbWO_4$.

Dipendenza dalla temperatura

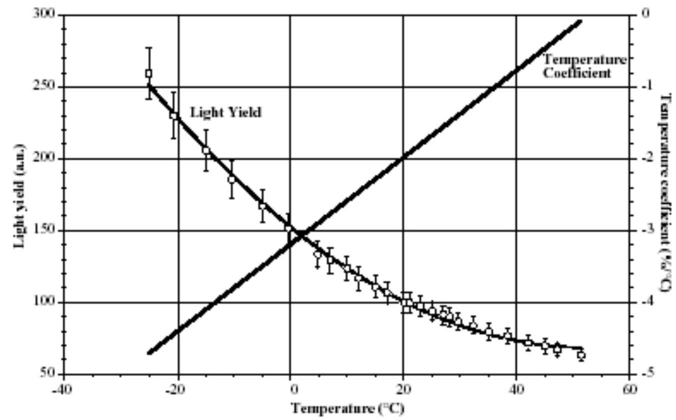


Fig. 2.4: Temperature dependence of $PbWO_4$ light yield (Ref. [2.4]).

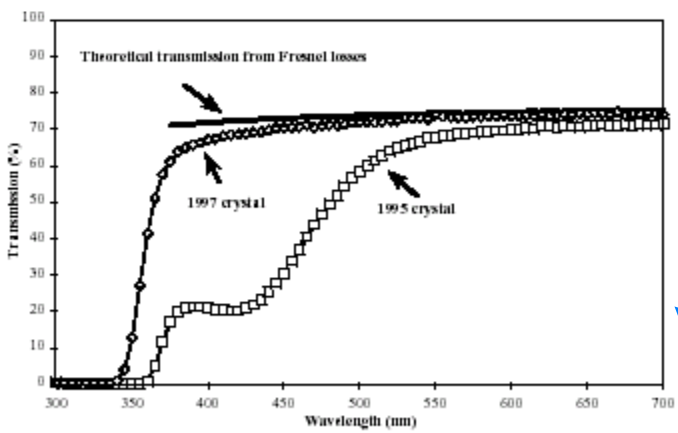


Fig. 2.2: Typical longitudinal transmissions for 23-cm-long $PbWO_4$ crystals produced in 1995 and 1997, compared to the maximum achievable transmission taking into account Fresnel losses and assuming infinite absorption length.

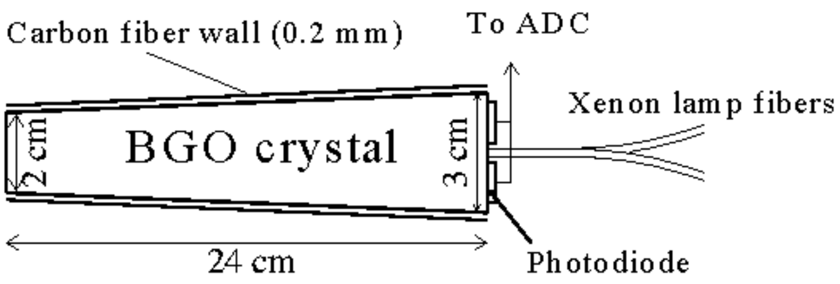
Spettro di assorbimento

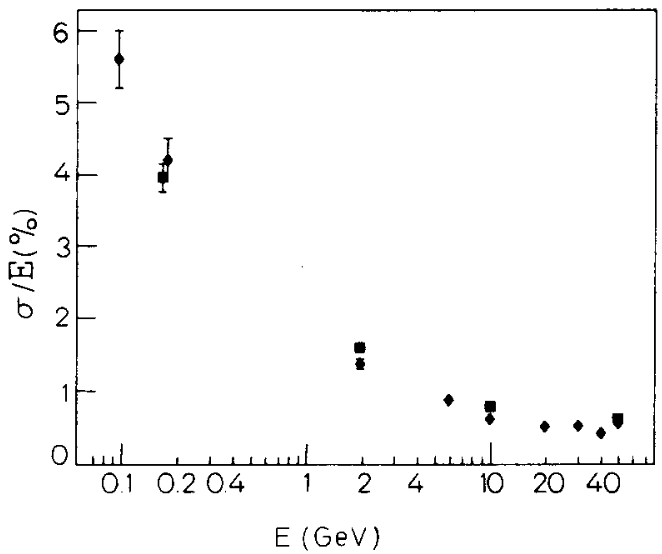
Calorimetri omogenei

Esempio: Calorimetro e.m. a BGO di L3

(L3 collab. NIM A 289 (1991) 53)

11000 crystals, 21.4 X_0,
temperature monitoring + control system
light output -1.55% / °C





σ_E/E < 1% for E > 1 GeV
spatial resolution < 2 mm
(E >2 GeV)

Partly test beam results !

Calorimetri a campionamento

Calorimetri a sampling (campionamento)

Sono i più usati sia come e.m. che adronici.

Costituiti da assorbitore + rivelatore

- Assorbitore: in generale Pb (e.m) Fe, Uranio (Adronici)
- Rivelatore: MWPC, tubi streamer, Scintillatori, fibre scintillanti, rivelatori al silicio, liquidi caldi (TMP, TMS), Liquidi nobili (LAr,LKr,LXe)

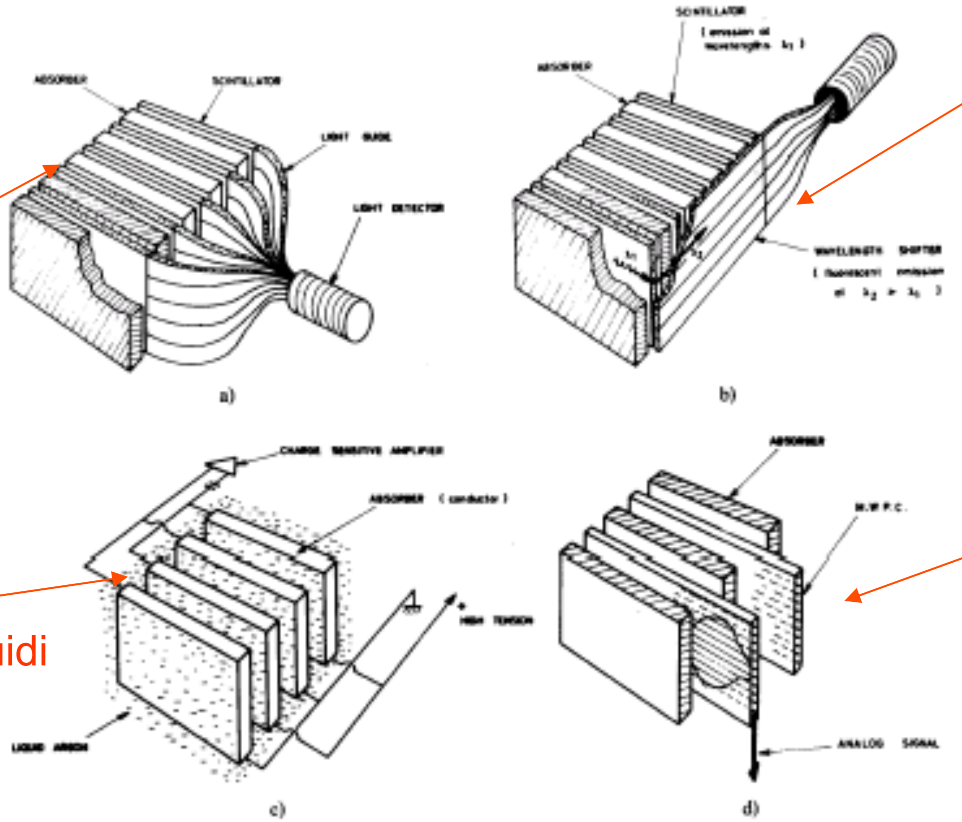
Assorbitore e rivelatore separati → ulteriori fluttuazioni (fluttuazione di campionamento)

Calorimetri a campionamento

Rivelatori

wave length shifter

Scintillatori



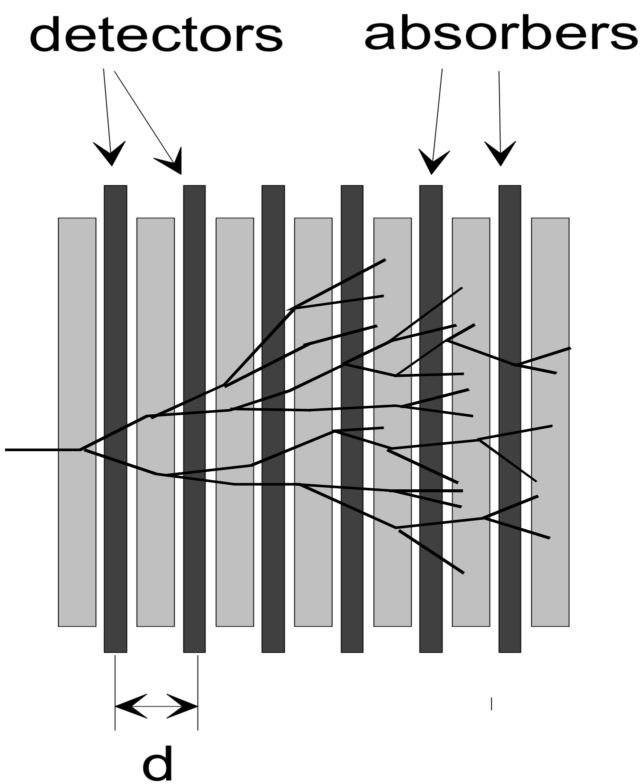
MWPC, tubi streamer

TMP,TMS

Gas nobili Liquidi

Calorimetri a campionamento

Fluttuazioni di sampling



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

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

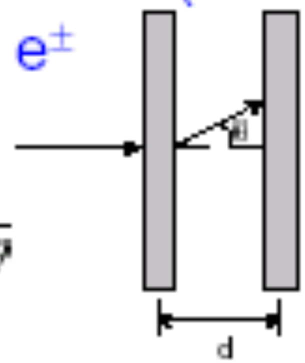
$$\frac{\sigma(E)}{E} \propto \frac{\sqrt{N}}{N} \propto \sqrt{\frac{1}{E}} \cdot \sqrt{\frac{d}{X_0}}$$

Calorimetri a campionamento

Fluttuazioni di percorso + fluttuazioni di Landau

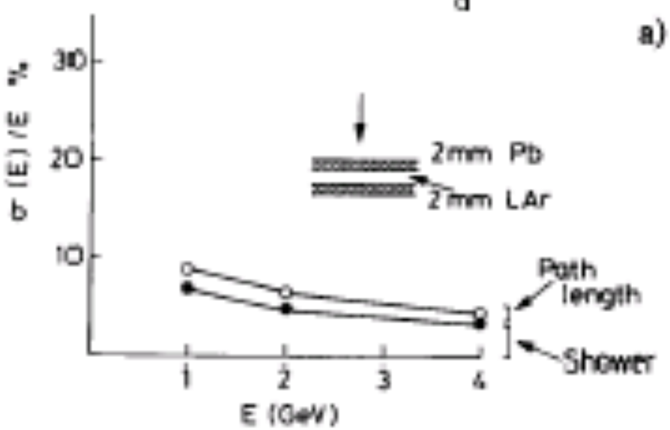
wide spread angular distribution of (low energy) $e^{\pm}$

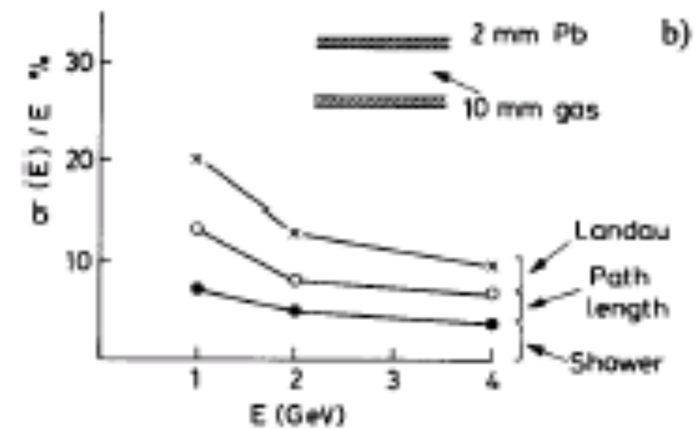
$$d_{eff} = \frac{d}{\cos\vartheta}$$



In thin gas detector layers the deposited energy shows typical Landau tails

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





Calorimetria

NOTE:

- In generale meglio scintillatore – piombo che rivelatore a gas – piombo per un calorimetro e.m.

- Fondamentale calibrare il calorimetro in assoluto e relativamente cella-cella

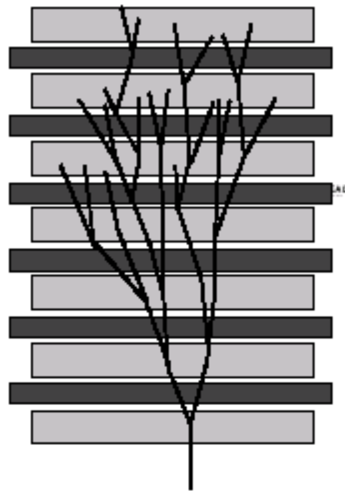
- Ordine di grandezza per la risoluzione di un calorimetro e.m. scintillatore piombo $\sigma(E)/E \sim 7\%/(E)^{1/2}$

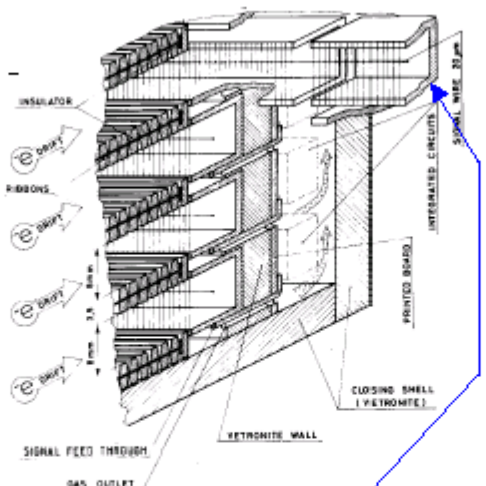
Calorimetri a campionamento

Esempi

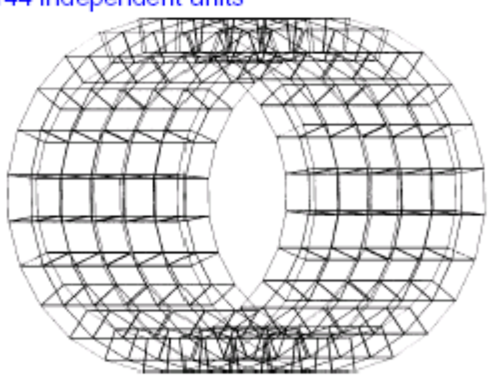
- A special sampling ECAL: DELPHI High Density Projection Chamber (HPC)

(H.G. Fischer and O. Ullaland, IEEE NS-27 (1980), 38)

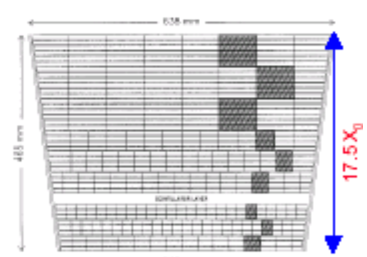




144 independent units



Segmented cathodes + drift times ('TPC') → full 3D reconstruction of shower



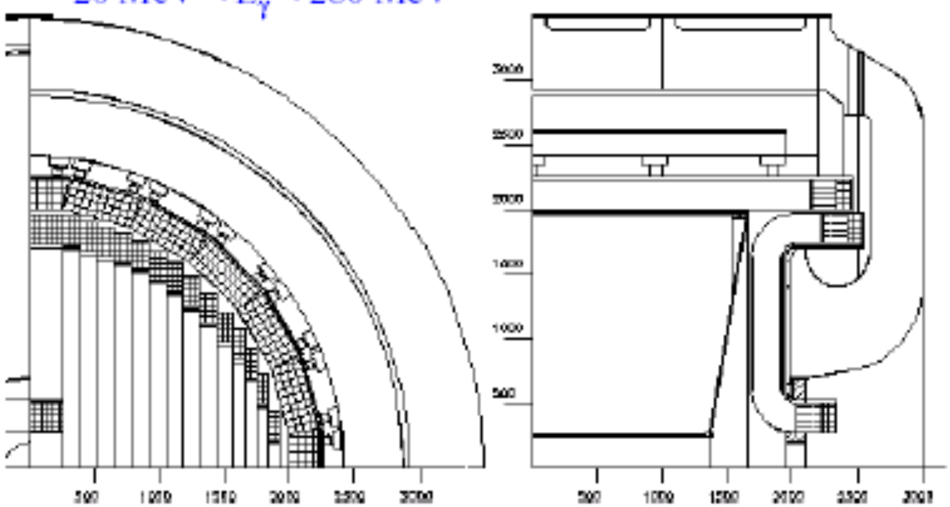
Calorimetri a campionamento

KLOE Spaghetti Calorimeter

$K_L \to \pi^0 \pi^0 \to 4\gamma$

$20\ \text{MeV} < E_\gamma < 280\ \text{MeV}$

(J. Lee-Franzini et al. NIM A 360 (1995) 201)



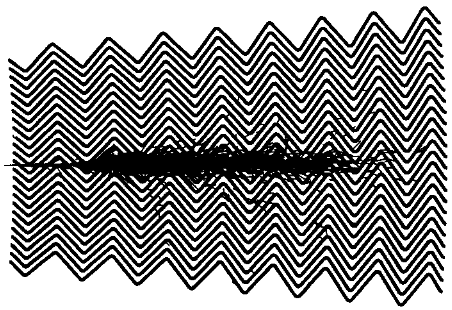
Scintillating fibers in grooved lead plates. PM (Ø5cm) readout.
(lead:fiber:glue 48:42:10 %)

$\sigma(E)/E \approx 0.05/\sqrt{E}$ $\sigma(t)/E \approx 35ps/\sqrt{E}$ $\sigma(z)/E \approx 0.6cm/\sqrt{E}$

Test beam data !

Calorimetri a campionamento

Calorimetro e.m. di ATLAS



(RD3 / ATLAS)

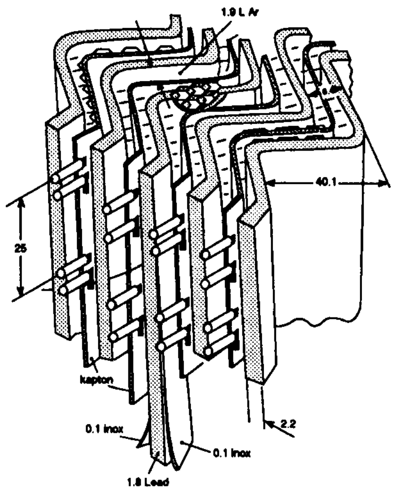
Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)

+ multilayer copper-polyimide
  readout boards

→ Ionization chamber.

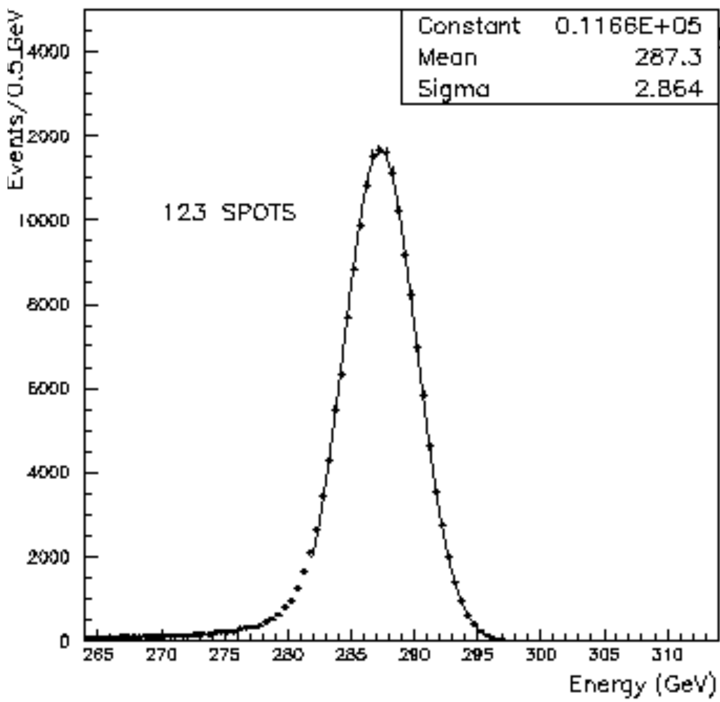
1 GeV E-deposit → 5 x10^6 e^-

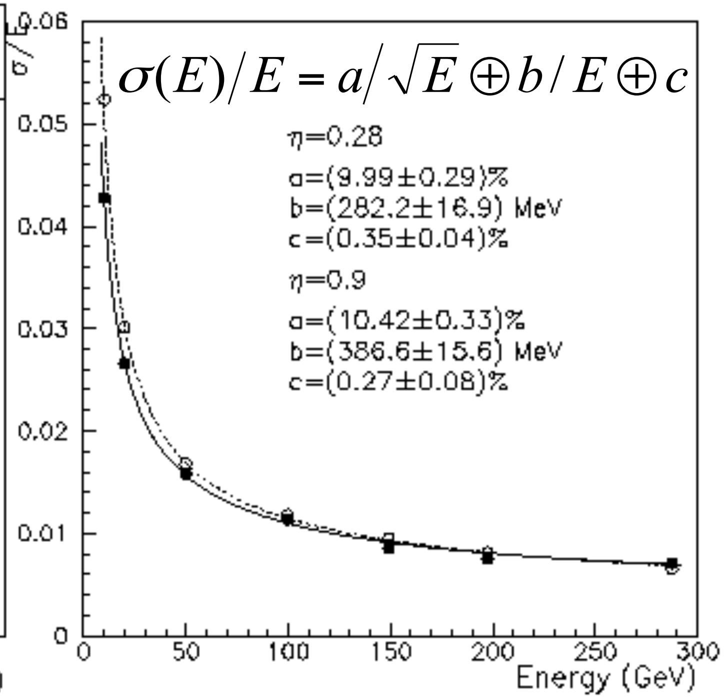


- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs

Calorimetri a campionamento

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





Spatial and angular uniformity $\approx$0.5%

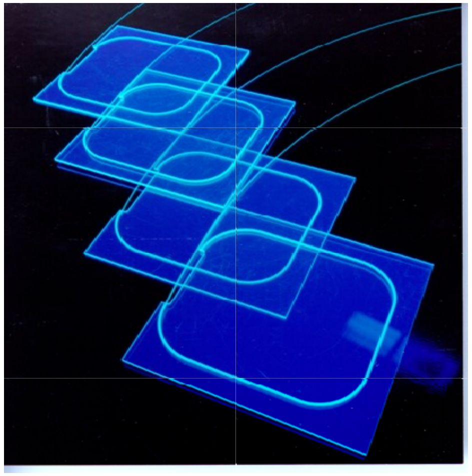
Spatial resolution $\approx$ 5mm / $E^{1/2}$

Calorimetri a campionamento

Calorimetro adronico di CMS

Assorbitore di Cu + scintillatore

1500 T di assorbitore

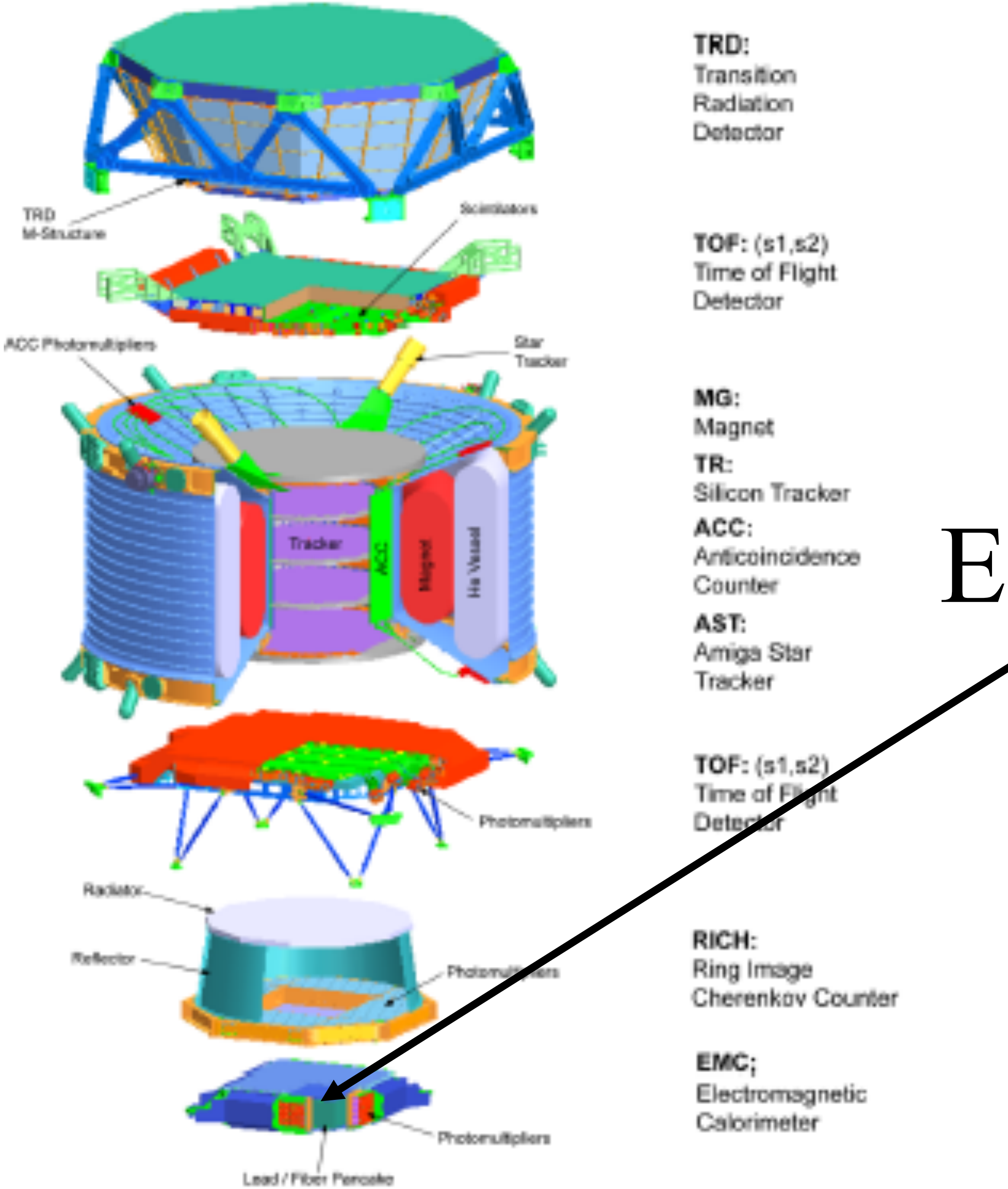


Scintillators fill slots and are read out via fibres by HPDs

Test beam resolution for single hadrons

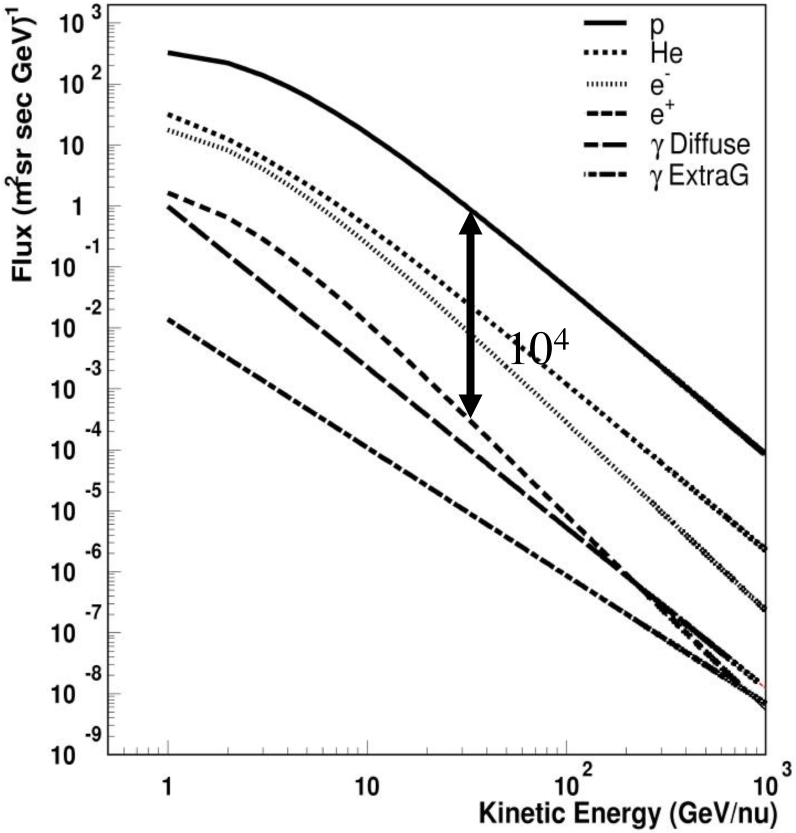
$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$

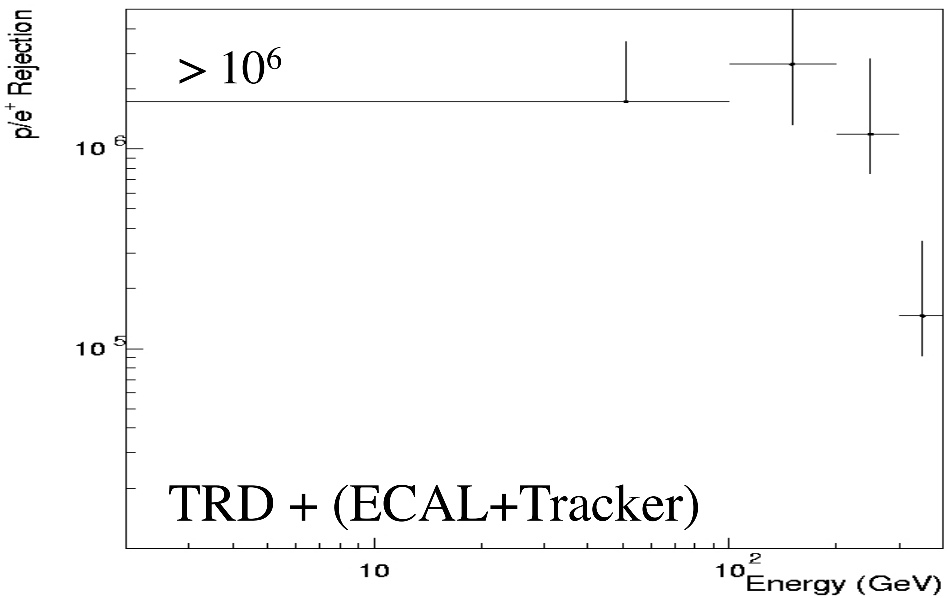
The Electromagnetic Calorimeter (ECAL)



Required ECAL performances

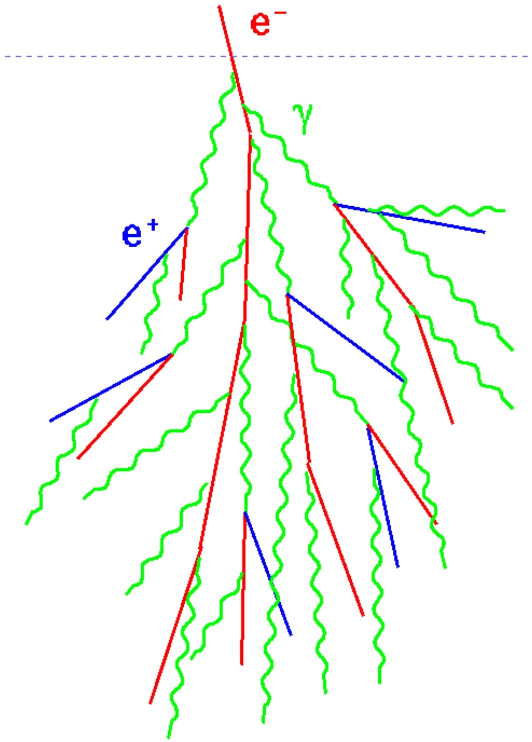
- Precise measurement of the e^-, e^+, γ energy spectrum from 1 GeV to 1 TeV :
  - $\Delta E/E < 5\%$ (from 5 GeV to 1 TeV) [Tracker: $\Delta p/p|_{hadron} < 4\%$ (<100 GV)]
- e/p discrimination from GeV to TeV :
  - $e^+/\bar{p}$ rejection ~ $O(10^3)$ (<500 GeV) [TRD: $\sim 10^3 - 10^2$ (<300 GeV)]





⇒ 3D imaging calorimeter

ECAL Operation Principle

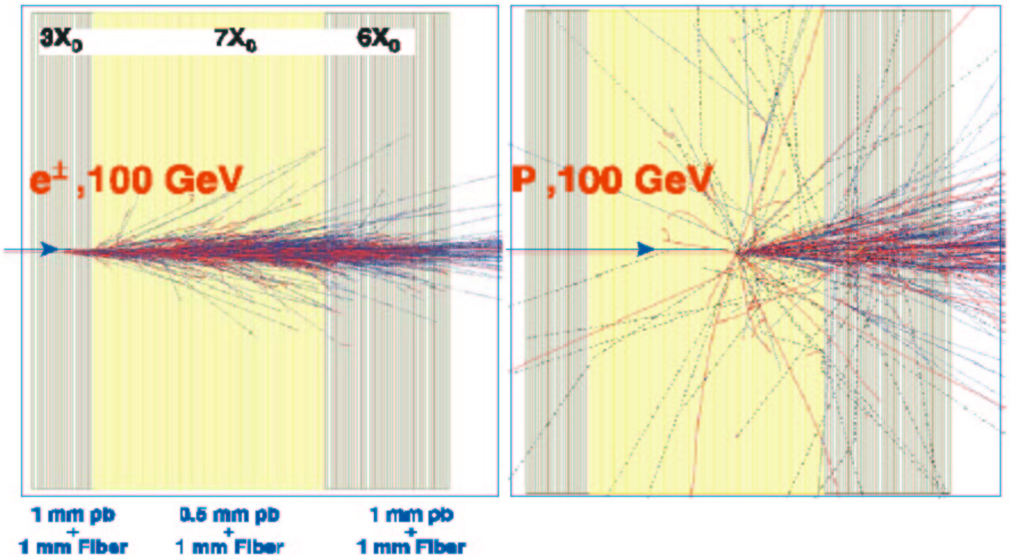


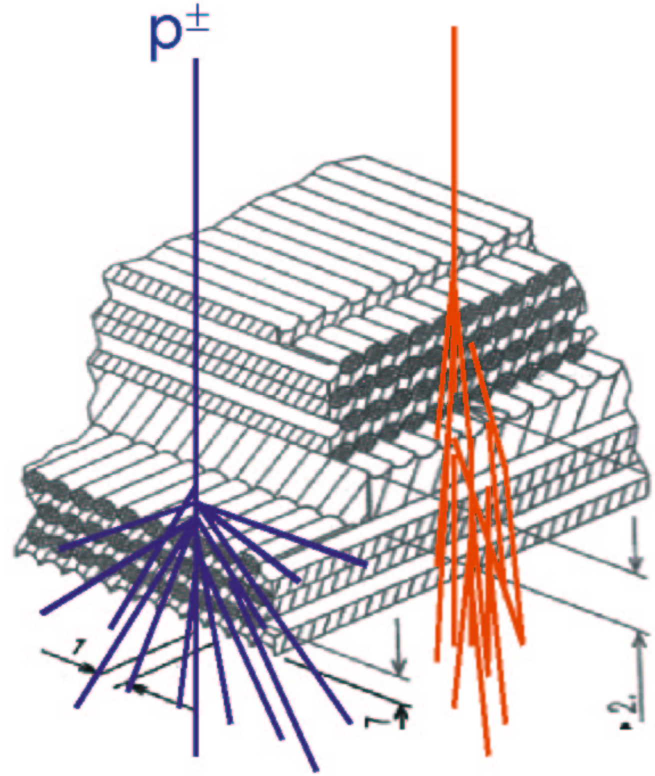
High energy electrons moving though matter lose their energies by bremsstrahlung radiation and high energy photons do by electron-positron pair production Repeated their two processes, the secondary photons and electrons multiply and expand like as a ***shower***

If a material is enough large to absorb the energies of all electrons/gamma-rays by an electromagnetic shower, it produces signals proportional to those energies. The signals are: ionization, Cerenkov light, scintillation light. For example, we read out the total scintillation light so that the incident energy can be measured

Hadrons (p) do not shower for brems but undergo to inelastic nuclear collisions that produce a spray of particles which initiate a shower

Electromagnetic Calorimeter

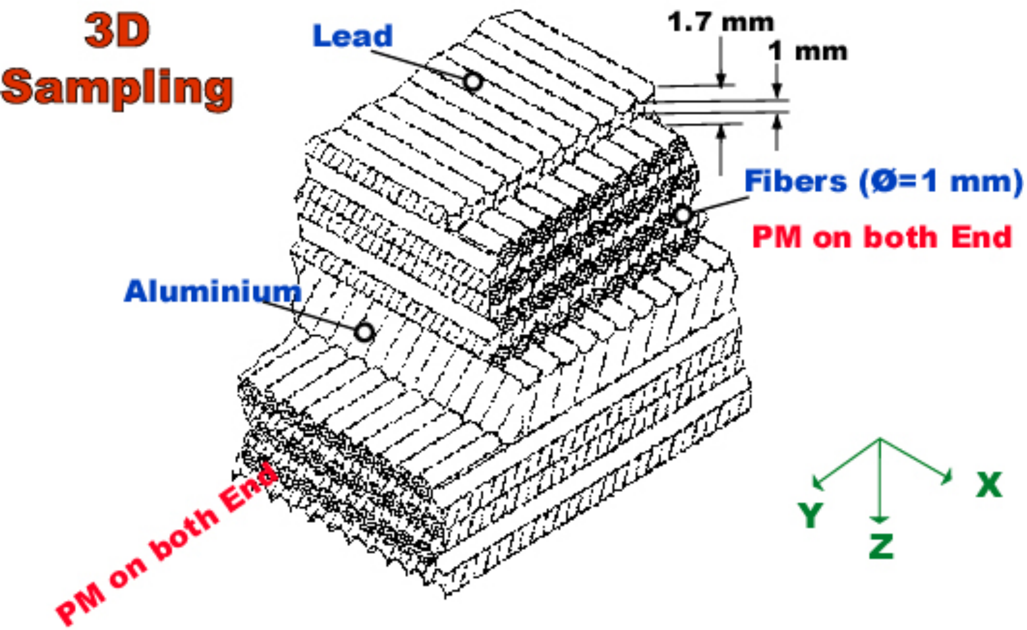


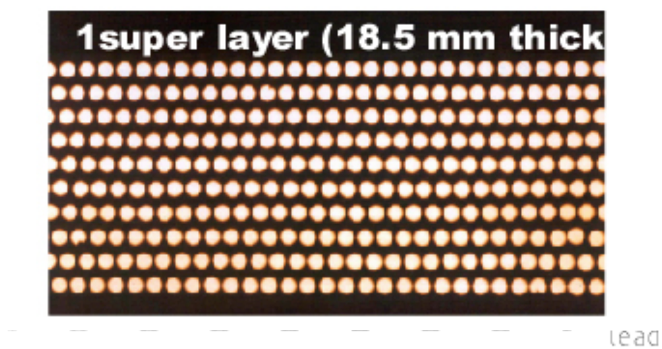


The shower shape and the starting point is different for e and hadrons→ e/p discrimination possible with high efficiency

ECAL structure (1)

The ECAL is a 3D sampling calorimeter made of Pb/scintillating fibers (Spacal Type).



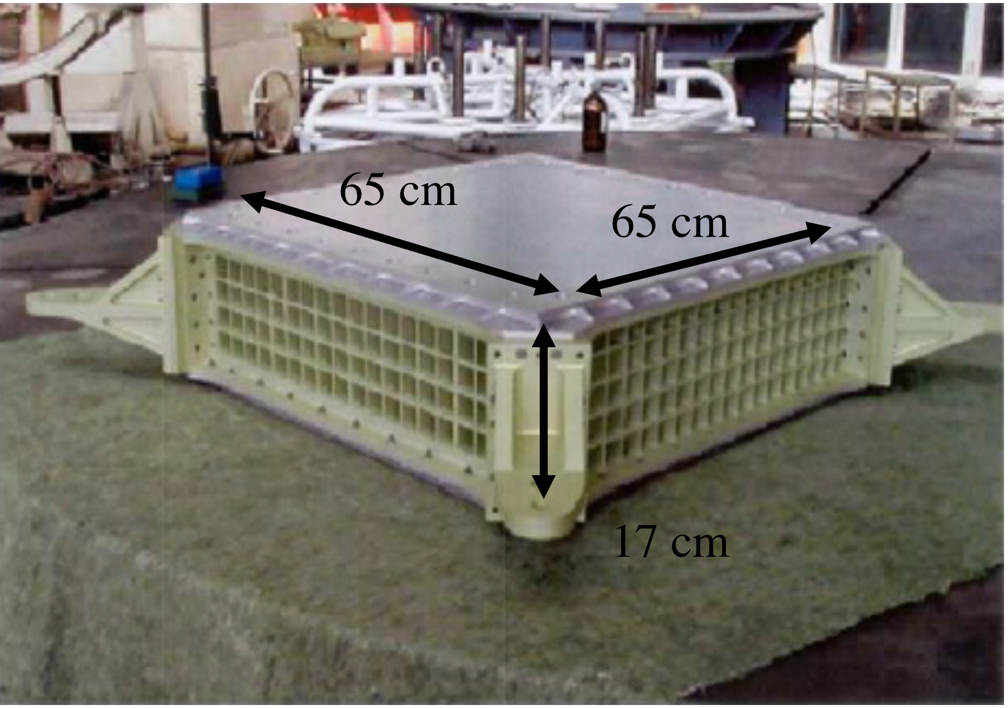


- 9 superlayers alternatively oriented along X or Y axis

- 1 SuperLayer:
  11 grooved Pb foils (1mm thick) interleaved with 10 layers of scintillator fibers (∅=1mm) glued by an epoxy resin

- Active detector
  - 9 superlayers alternatively in Y & X direction
  - <u>16 radiation lengths</u> (X_0)

ECAL structure (2)



- Each fiber is read on one side only by multi-anodes PMTs

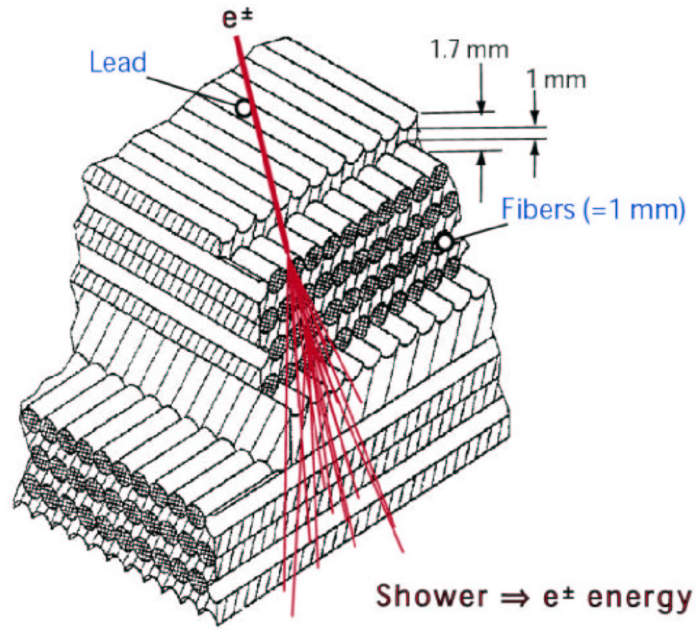
⇒ Read-out granularity: 9×9 mm^2

- 324 PMTs with 4 pixels
  - Hamamatsu R7600-00-M4
  → 324x4 = 1296 cells

⇒ High granularity :
  - 0.5 Mollier radius in X-Y
  - 0.9 X_0 in depth : 18 samplings

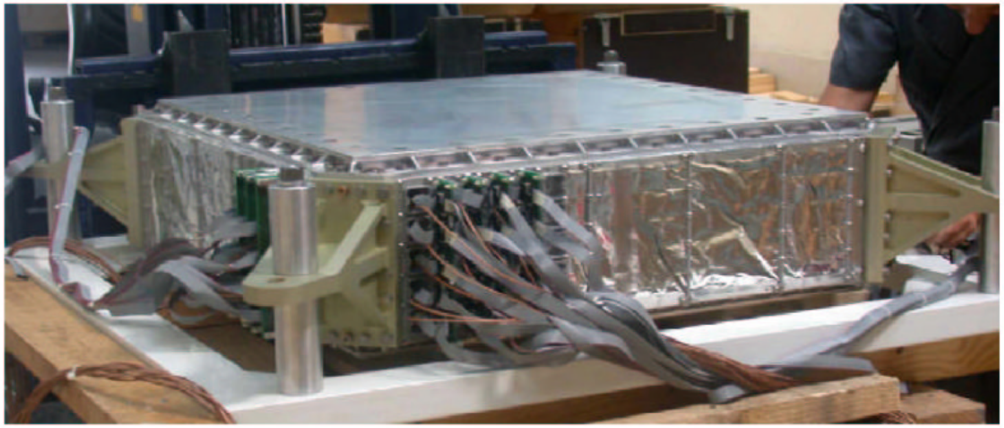
Construction

- sampling e.m. calorimeter
  $658 \times 658 \times 166\ mm^3$
- lead-scintillating fibers structure
- 9 superlayers piled up
  disposed along X and Y alternately
- $\sim 17X_0$ radiation lengths
- cell granularity $\sim 0.5\ R_M$ (35 fibers)
  18 samplings of e.m. shower
- multi-pixel (2×2) photomultiplier's
  large dynamic range

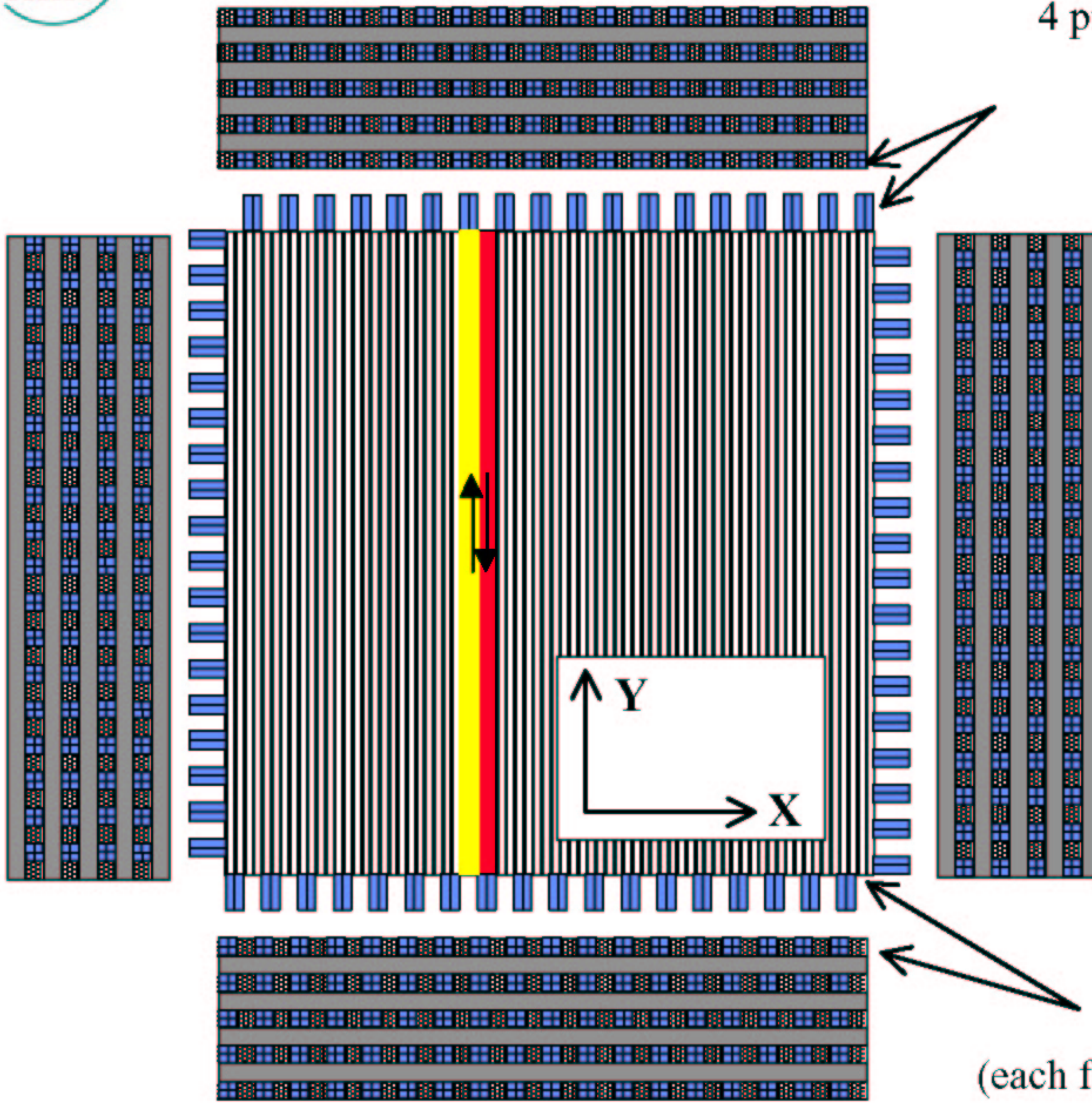


It provides

- $e^{\pm}, \gamma$ energy measurement
- particle direction
- trigger signal for photons tagging (dynode)



X-Y, X-Z and Y-Z projections of the ECAL



4 pixels PMT : R7600-00-M4
from Hamamatsu
total of 324 PMT

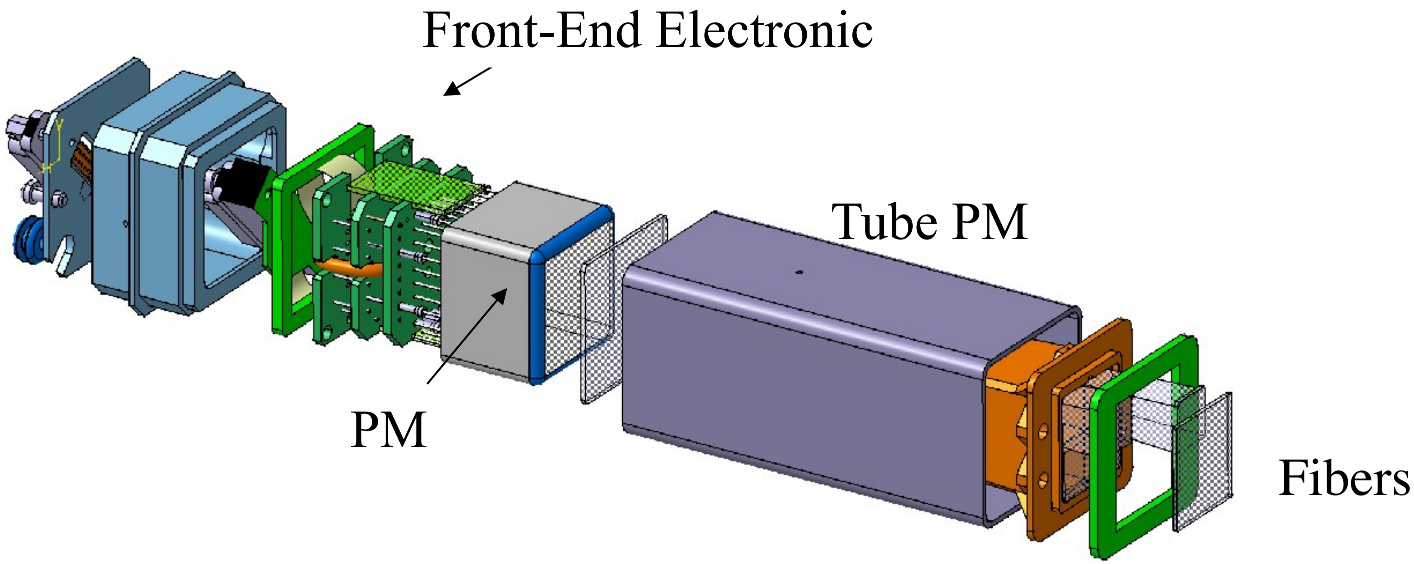
Granularity :

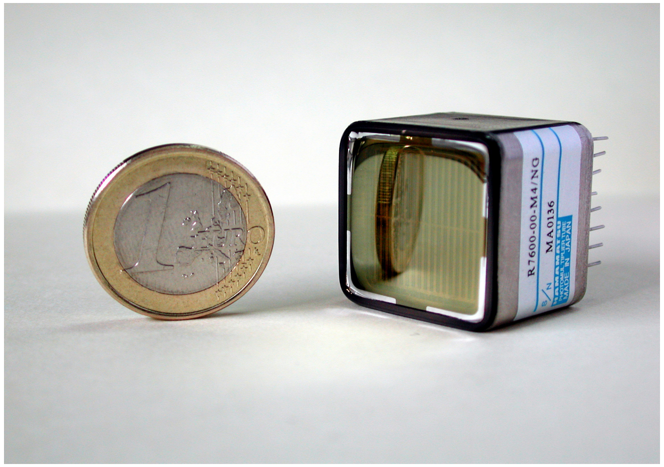
~0.5 Mollier radius in X-Y

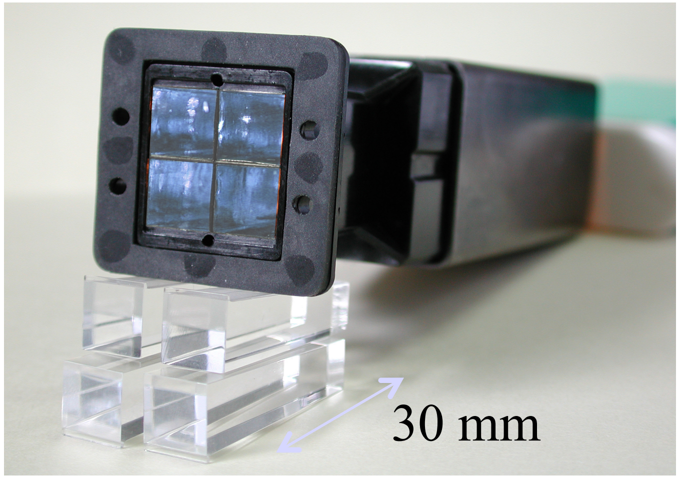
~0.9 X_0 in Z - 18 samplings

Reflecting surfaces out
of PMT windows
(each fiber is read only on one end)

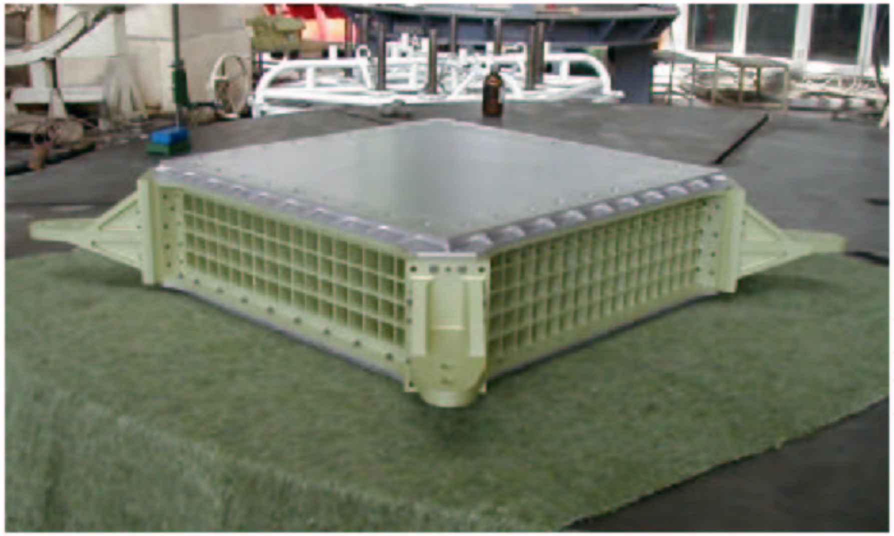
Light collection system

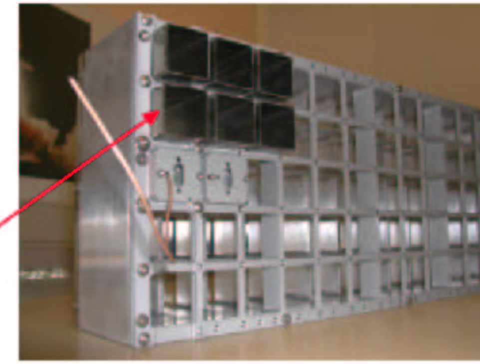






The overall optimization of the magnetic shielding and of the light collection system :

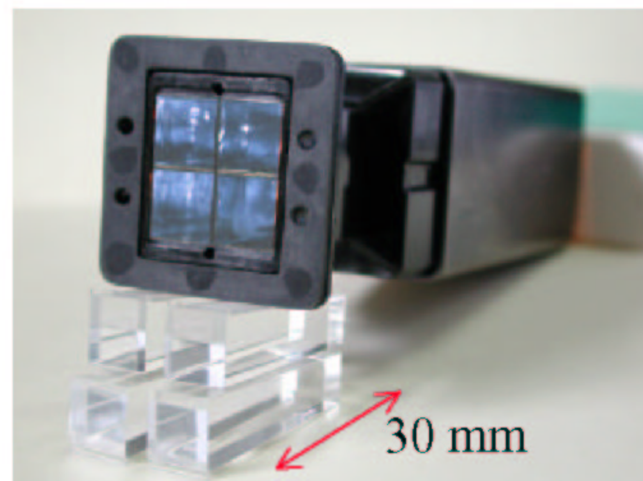




Lateral panel supporting the individual PMT shielding (square tubes made of 1mm thick soft iron)

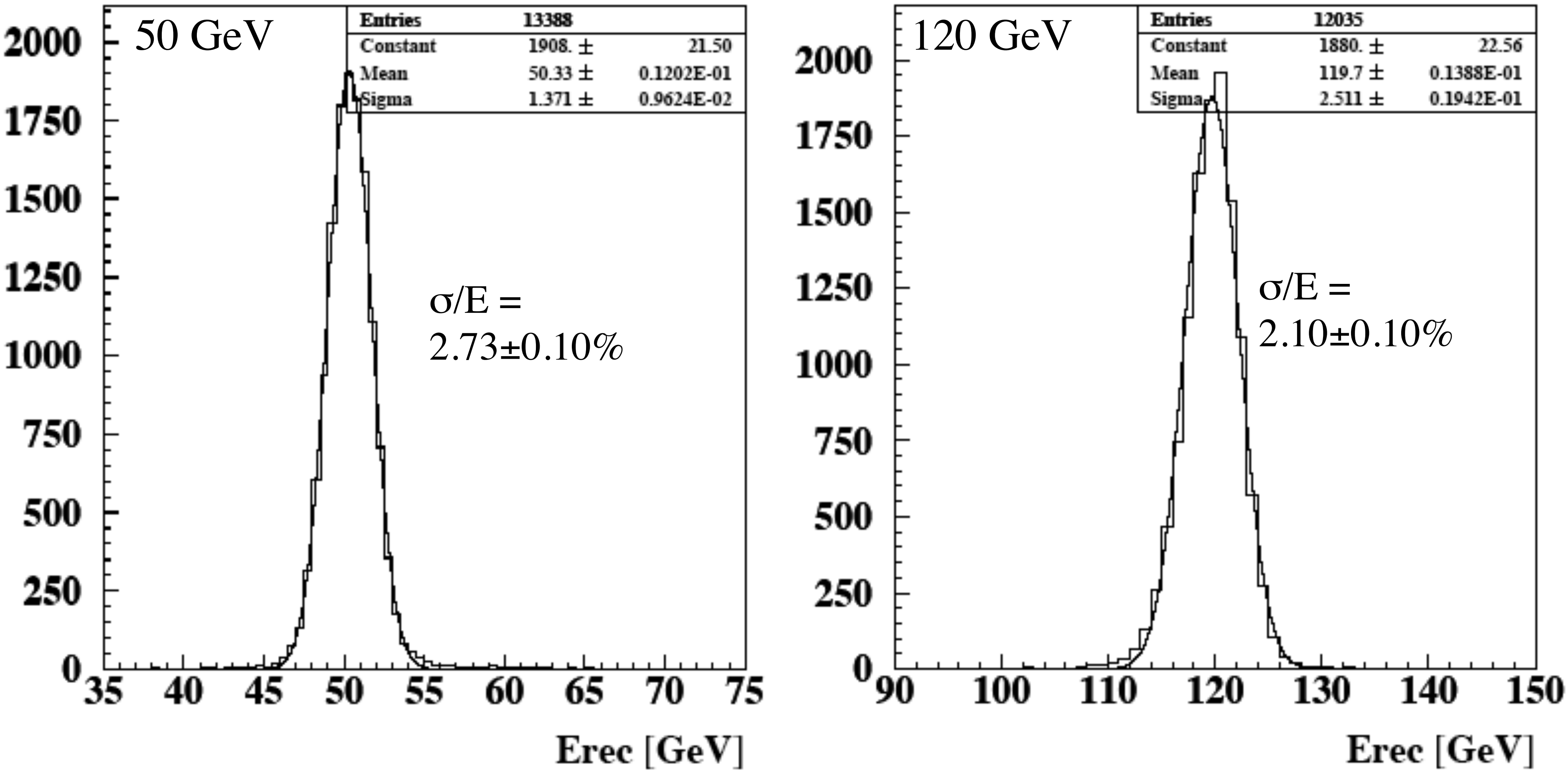
Detail of the light collection system :

- polycarbonate box logging PMT and FE electronics
- aluminum covered conical channels
- conical Plexiglas light guides
- transparent RTV joint (not shown)

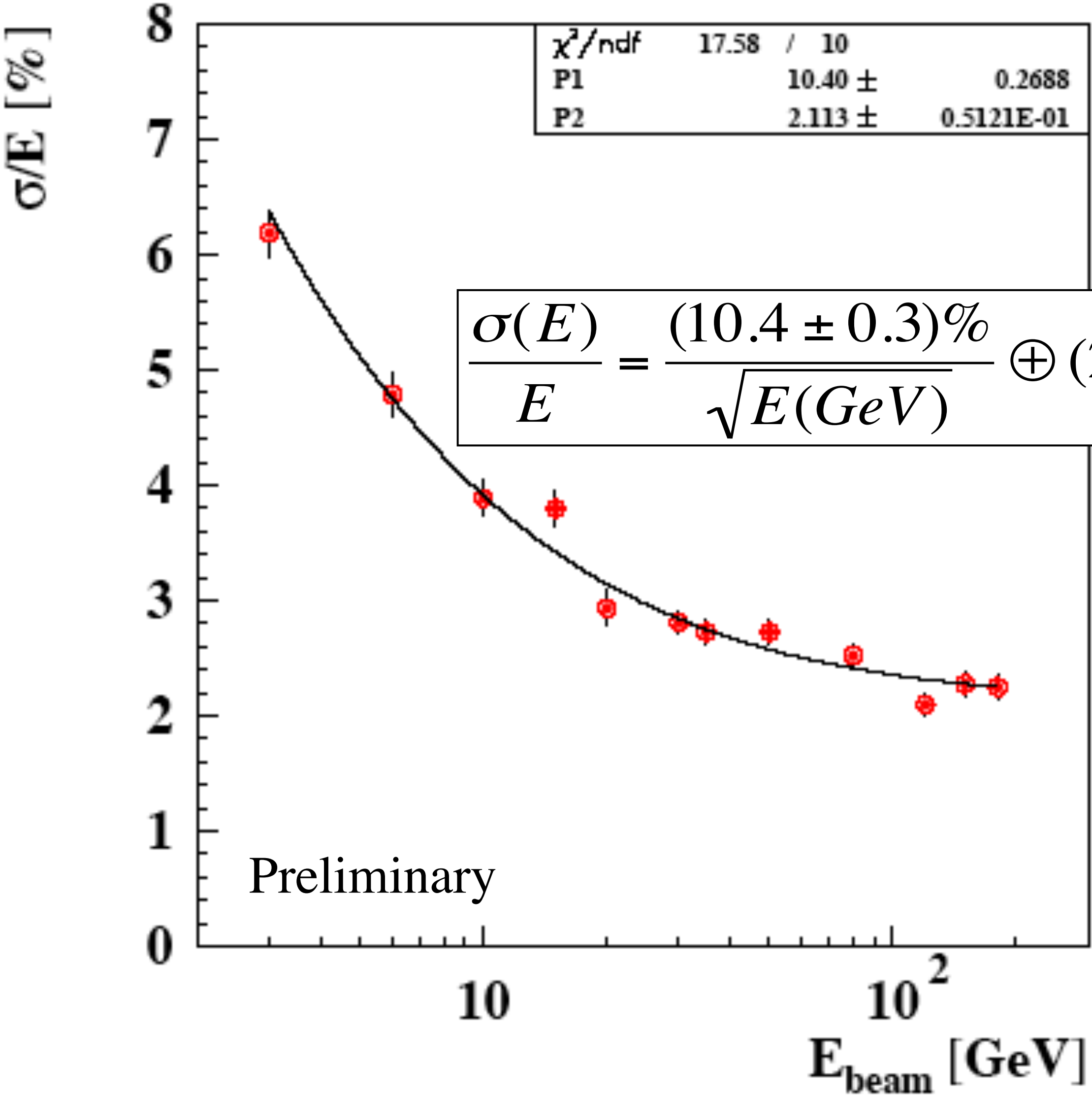


Magnetic field < 10 Gauss Light transport efficiency ~70%

Energy resolution

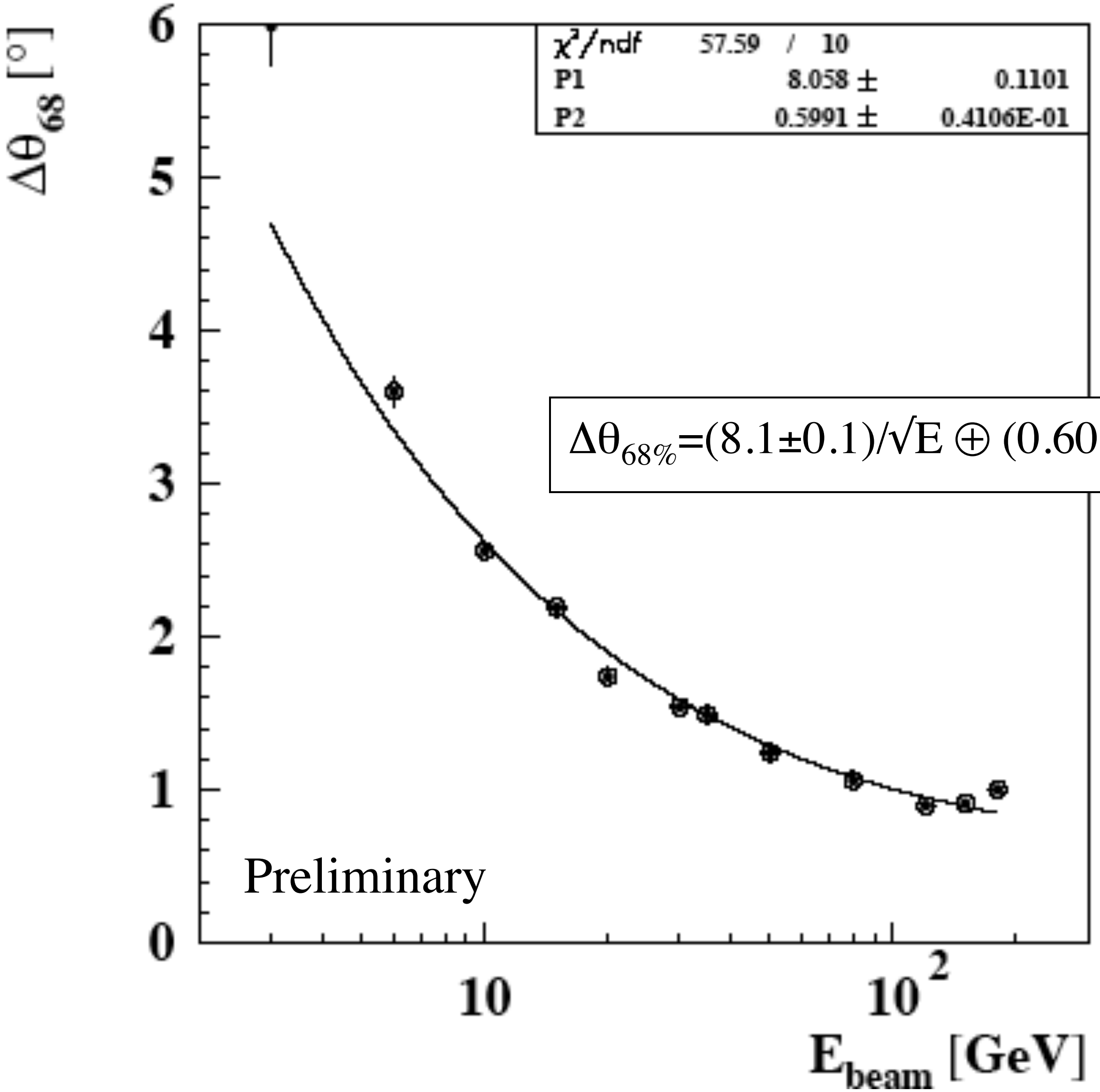


Energy resolution



$$\frac{\sigma(E)}{E} = \frac{(10.4 \pm 0.3)\%}{\sqrt{E(GeV)}} \oplus (2.11 \pm 0.05)\%$$

Angular resolution



$\Delta\theta_{68\%}=(8.1\pm0.1)/\sqrt{E} \oplus (0.60\pm0.04)°$

e/p separation (50 GeV e vs 120 GeV p)