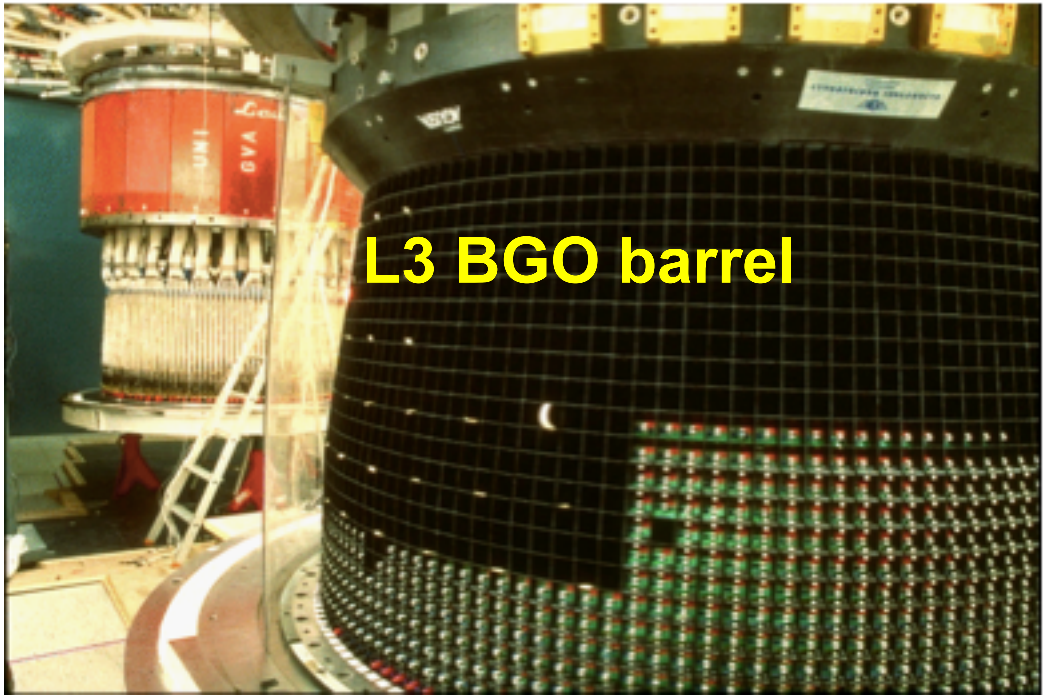
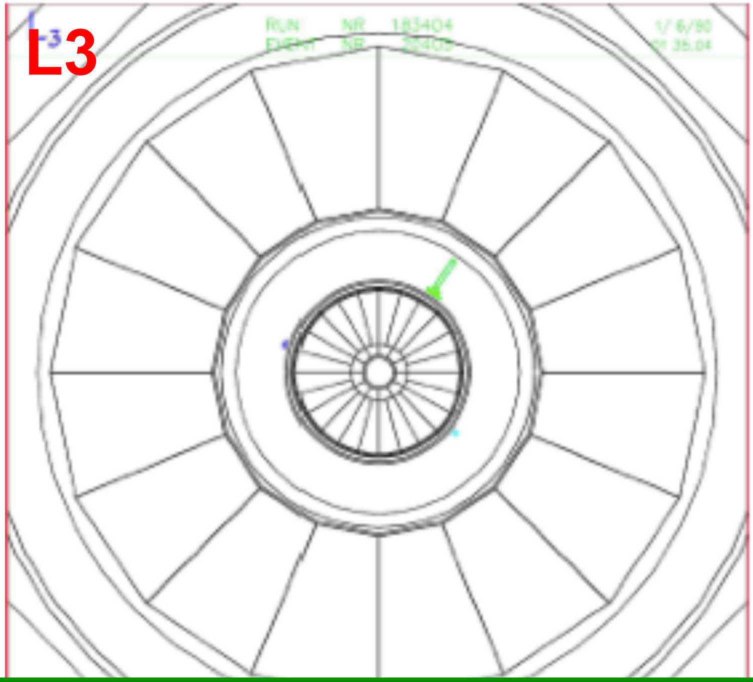
Capitolo 16
Calorimetria nella Fisica delle alte energie



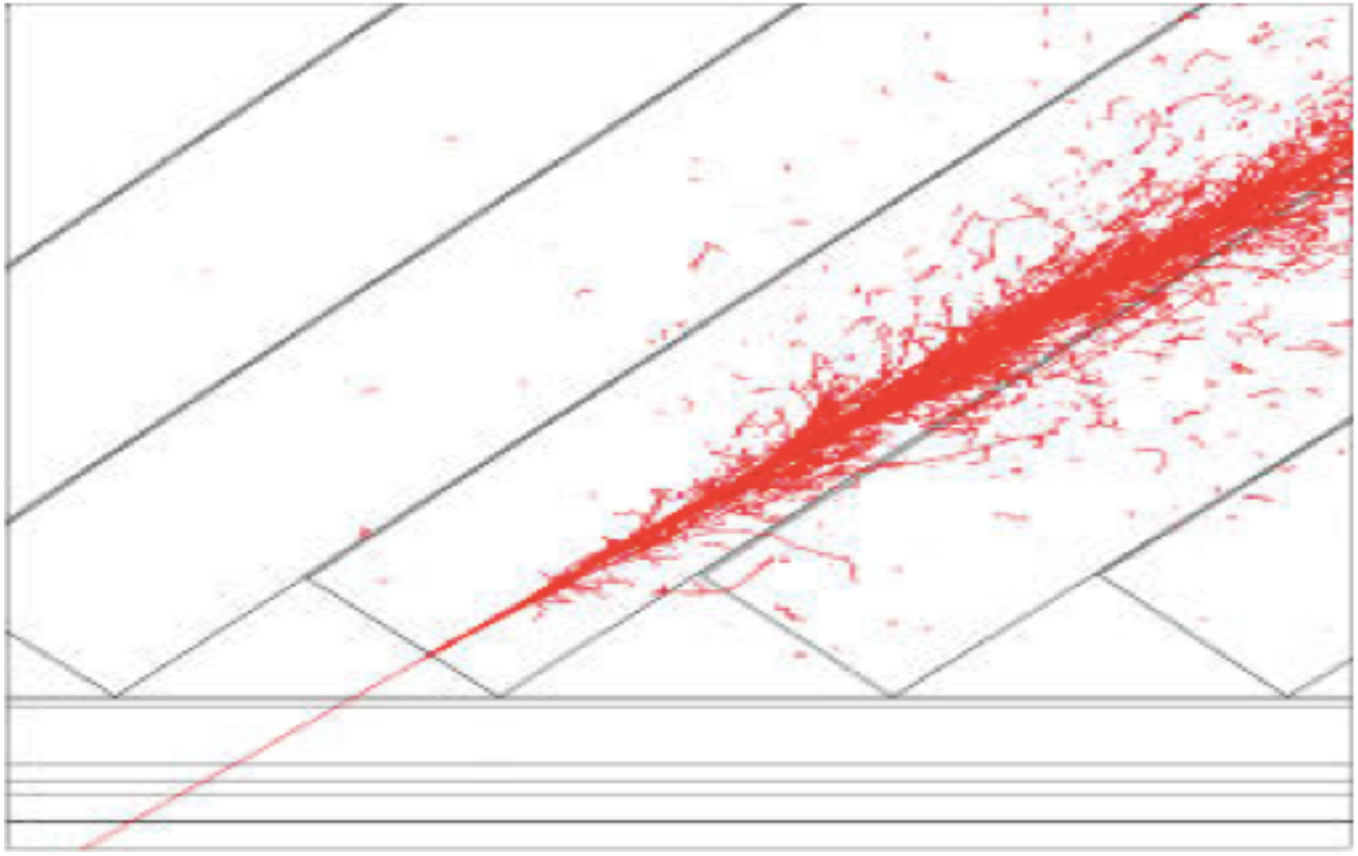


Evento con fotone singolo

Carlo Dionisi,
A.A. 2012-2013, Corso FNSN II

CALORIMETRO: e' **un blocco di materia instrumentato** dove elettroni, fotoni e adroni incidenti, sono completamente assorbiti e la loro energia viene trasformata in una quantita' misurabile.

- L'interazione della particella incidente (attraverso processi elettromagnetici o forti) produce **sciami di particelle secondarie** di energie progressivamente piu' piccole.
- Il segnale, totale o in parte, puo' essere raccolto in forma di carica elettrica o di luce
- Il segnale raccolto e' proporzionale alla energia della particella incidente.



I Calorimetri hanno un ruolo sempre piu' importante nella fisica delle alte energie

❖ **La risoluzione in energia migliora al crescere di E:**

$$\frac{\sigma}{E} \approx \frac{1}{\sqrt{E}}$$ calorimetro

$$\frac{\sigma}{p} \approx p$$ Spettrometro Magnetico

→ **Si accorda molto bene con le esigenze della fisica delle alte energie**

- sensibile ~ a tutte le particelle (cariche e neutre):
  - -- electrons, photons, hadrons
  - -- muons
  - -- neutrinos (attraverso la misura delle energia mancante)

- **sono rivelatori molto versatili:**
  -- energy measurement :
    original task
  -- position/angular measurement:
    can be segmented longitudinally and laterally
  -- particle identification:
    different response to electrons/photons, single hadrons, taus, jets, muons
  -- time measurement
  -- trigger: provide fast signals (up to ~ 40 ns) easy to process and interpret

- cost/space effective: thickness to contain a shower : ~ log E
  Note: size of magnetic spectrometer ~ √p for given momentum resolution

→ Ben adatti ai requisiti molto impegnativi degli esperimenti di alte energie moderni.

Classificazione dei Calorimetri

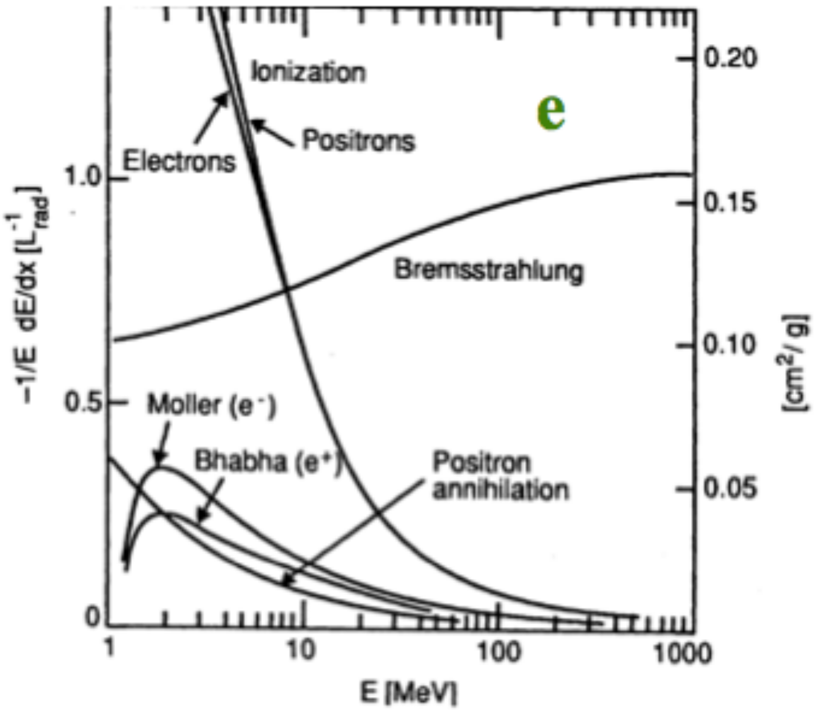
- **per la fisica:** **electromagnetic calorimeters:** detect (mainly) electrons and photons through electromagnetic interactions
  (γ Bremsstrahlung, e^+e^- production, etc.)

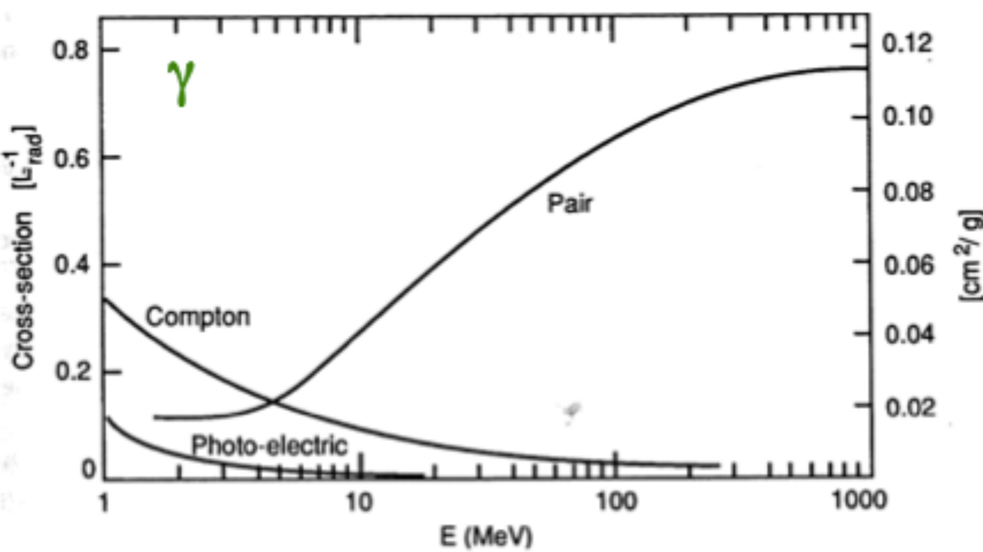
  hadronic calorimeters: detect (mainly) hadrons through electromagnetic and strong interactions

- **per la tecnica:** **sampling calorimeters:** alternating layers of two materials: absorber (high Z) produces the shower cascade and active medium used for signal collection. Functions of energy measurement and energy degradation are separated.

  homogeneous calorimeters: one type of material (used as absorber and active medium)

La fisica degli sciami Elettromagnetici





Interazioni di elettroni e fotoni nel piombo

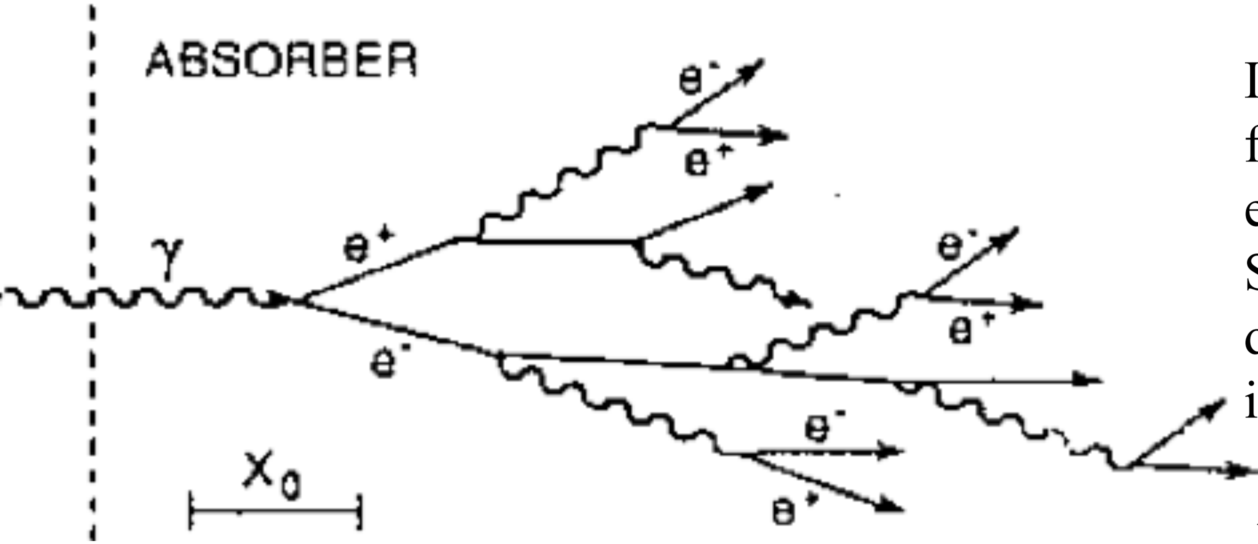
~ E-independent sopra 1 GeV

Energia Critica ε :
ionisation loss = radiation loss per elettroni.

$$\varepsilon \approx \frac{800\,\mathrm{MeV}}{Z}$$

e.g. $\varepsilon \approx 10$ MeV in Pb

in un materiale e/γ , con E ≥ 1 GeV , danno luogo a fotoni secondari da **Bremsstrahlung**, o a elettroni secondari da **produzione di coppia**
→ **cascade** of particles



Il numero di particelle aumenta fino a quando la loro energia e' > ε.
Sotto ε , l'energia viene dissipata principalmente per ionizzazione e eccitazione di atomi/molecole e NON da produzione di nuove particelle.

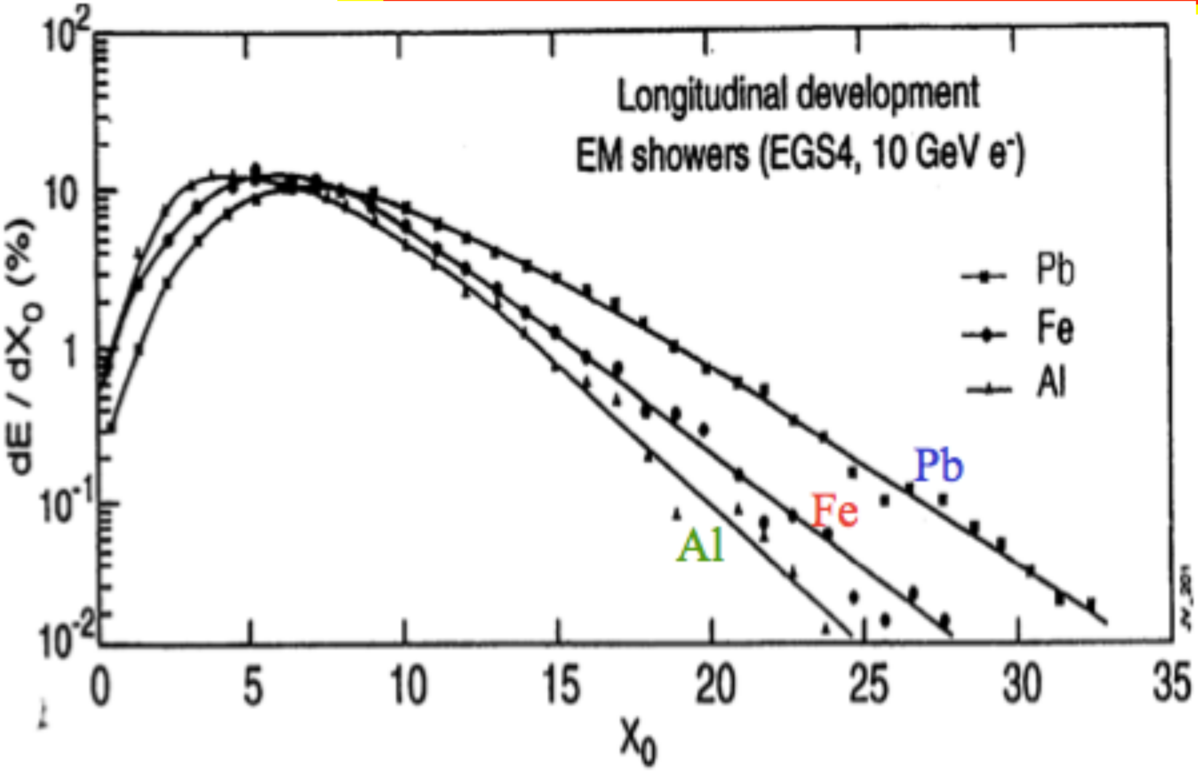
Lunghezza di Radiazione : $$X_0 \approx \frac{(716\,\mathrm{g\,cm^{-2}})\,A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

$e^\pm$ E-loss by Bremsstrahlung: $$< E(x) > = E_0\, e^{-\frac{x}{X_0}}$$

γ absorption through e^+e^- production: $$< I(x) > = I_0\, e^{-\frac{7}{9}\frac{x}{X_0}}$$

Per e / γ abbiamo stesse scale fisiche → le cascate EM possono essere descritte in modo universale con funzioni semplici di X_0

Profilo longitudinale delle cascate EM



Energy lost in $1\ X_0$:

$$\frac{dE}{dx} X_0 \sim Z \frac{1}{Z^2} \sim \frac{1}{Z}$$

e.g. : ~ 39 MeV (Al) Z = 13
~ 7 MeV (Pb) Z = 82
→ shower starts /ends earlier in Al than in Pb

Il massimo della cascata si ha a: $t_{max}(X_0) \sim \ln \frac{E_0}{\varepsilon} \pm 0.5$ (γ / $e^{\pm}$)

→ La lunghezza della cascata aumenta con il log della energia incidente

Il 95% della cascata e' contenuta in $t_{95\%}(X_0) \sim t_{max} + 0.08\,Z + 9.6$

→ Tipicamente l'energia della cascata e' contenuta in 25 X_0 fino a cascate di alcune centinaia di GeV

→ Perfino a LHC (E ~TeV) le cascate EM sono contenute in rivelatori piu' corti di mezzo metro:

ATLAS EM calorimeter (Pb-LAr) : ~ 50 cm thick

CMS EM calorimeter ($PbW0_4$ crystals) : ~23 cm thick

Profilo laterale delle cascate EM

Le particelle "soffici" alla fine della cascata EM subiscono scattering coulombiano multiplo nell'assorbitore:

→ viaggiano quindi ad angoli grandi rispetto all'asse della cascata EM.

Piu' piccola e' l'energia della particella piu' grande e' la sua deflessione:

→ verso la fine lo sciame diventa piu' largo.

Transverse size: 95% of shower contained in

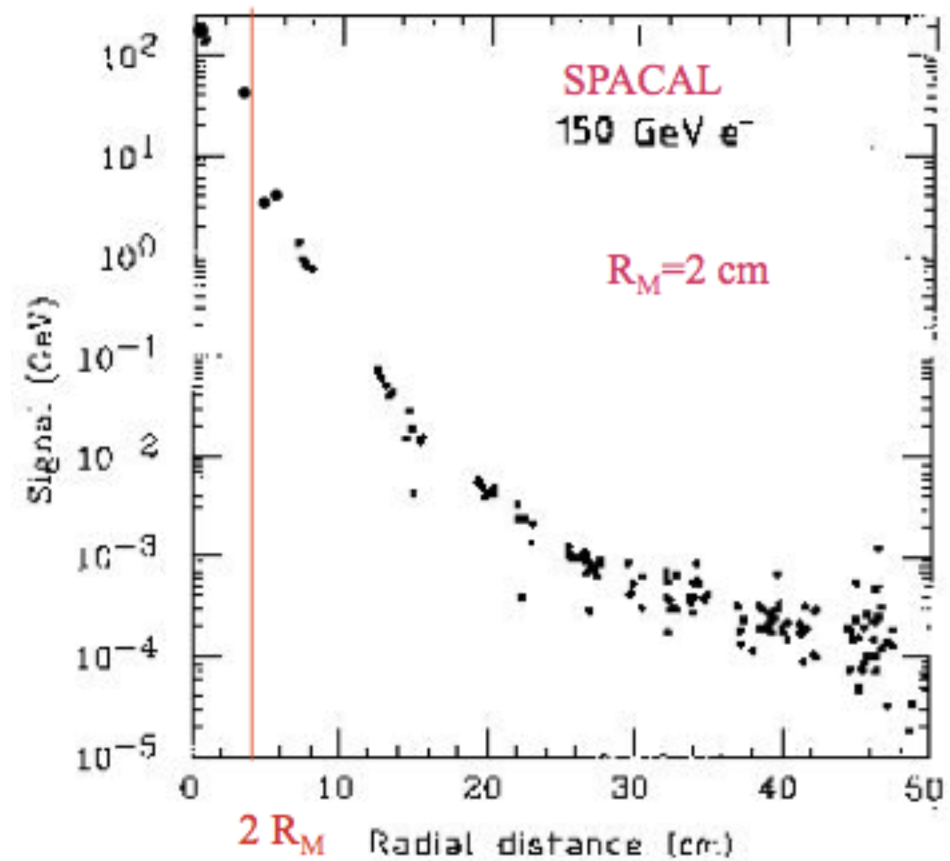
~ 2 Molière radii (R_M):

$$R_M\ (g/cm^2) \sim 21\ \text{MeV}\ \frac{X_0}{\varepsilon}$$

Most calorimeters : $R_M \sim$ cm

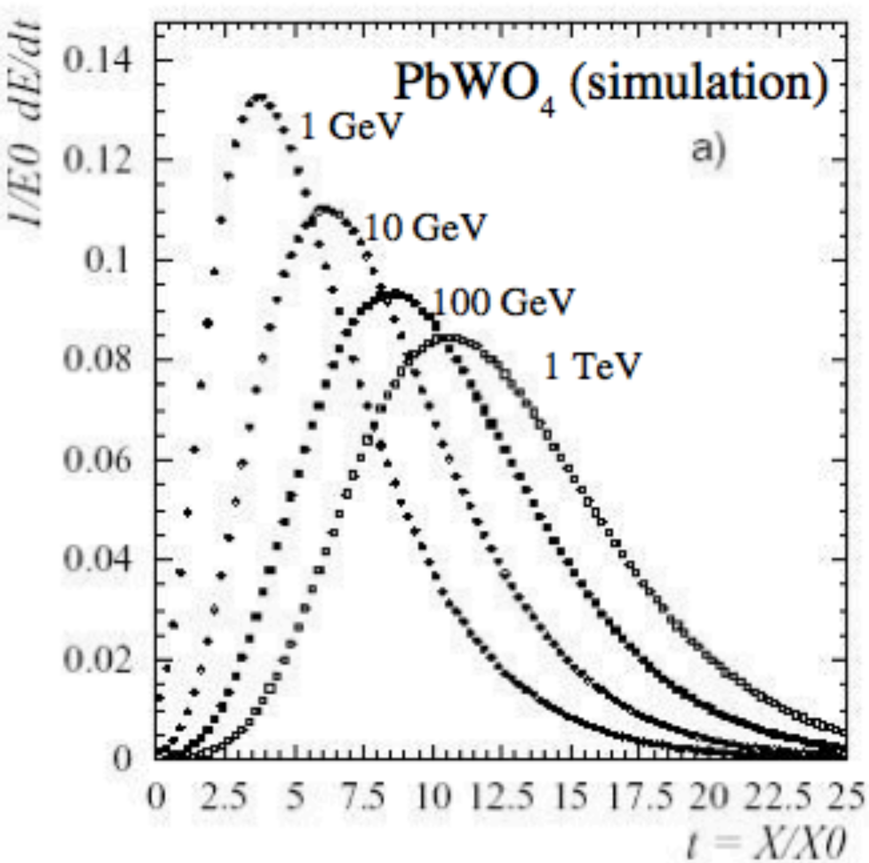
→ shower is narrow

Note: cell size of calorimeter should be ≤ 1 R_M to measure Shower lateral position

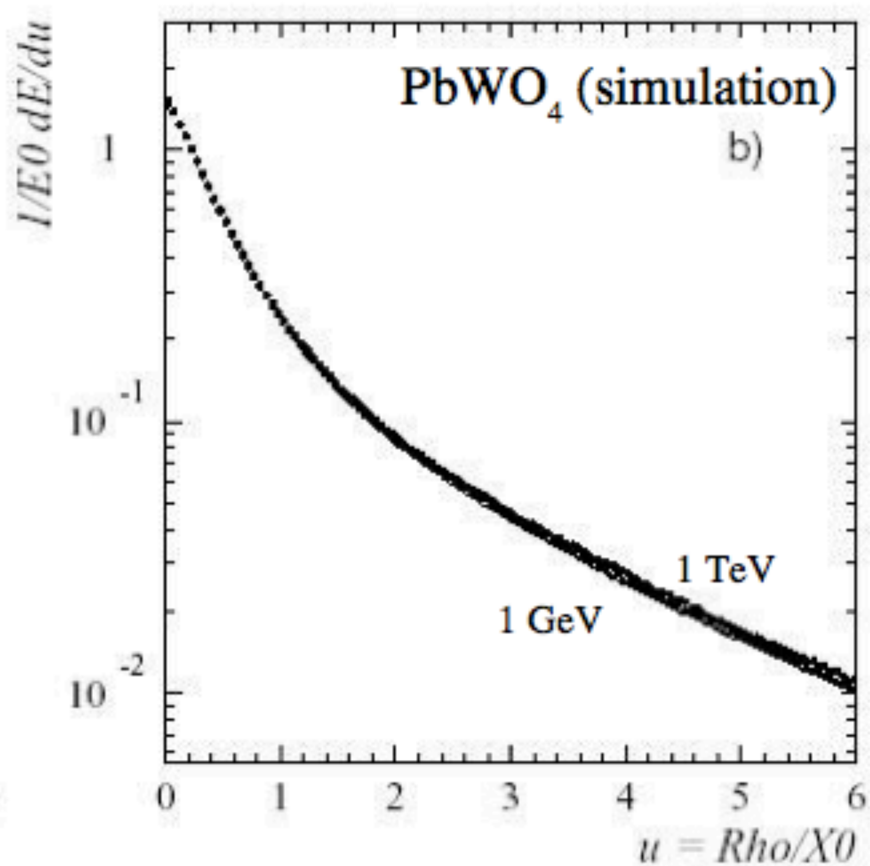


Dimensioni dello sciame per varie E del fascio

Dimensioni longitudinali



Dimensioni trasversali



Risoluzione per calorimetri e.m.
Termine stocastico

- L'energia rivelabile (rilasciata sotto forma di ionizzazione, eccitazione etc...) dalle particelle cariche dello sciame è proporzionale all'energia della particella incidente E.
- Per uno sciame formato da N particelle cariche la cui energia media è ε, **in un calorimetro ideale**:

Le fluttuazioni in energia saranno dunque proporzionali alle fluttuazioni nel numero di particelle, che seguono la statistica poissoniana:

$$\sigma_{stochastic}(E) \propto \sqrt{N} \propto \sqrt{E}$$

dunque:

$$\boxed{\frac{\sigma_{stochastic}(E)}{E} \propto \frac{1}{\sqrt{E}}}$$

Termine stocastico

Fattore di Fano

Nei calorimetri omogenei le fluttuazioni intrinseche sono piccole perchè l'energia depositata nel materiale attivo dalle particelle di un fascio monocromatico non fluttua evento per evento.
In termini statistici ciò significa che i valori di energia delle singole particelle dello sciame non sono delle variabili indipendenti.
Si può mostrare che:

$$\sigma = F\,J$$

J: ionizzazione media

F: fattore di Fano.
F è difficilmente calcolabile
F~1 per scintillatori
F<1 per rivelatori a semiconduttore e a ionizzazione in elementi nobili liquidi

Nei **calorimetri a campionamento** l'energia depositata nel mezzo attivo fluttua evento per evento a causa della presenza del materiale passivo (fluttuazioni di campionamento). **Vedi dopo**

Il numero N_{ch} di particelle cariche che attraversano il materiale attivo è inversamente proporzionale allo spessore t del materiale passivo (espresso in lunghezze di radiazione)

$$N_{ch} \propto \frac{E_0}{t} \qquad \frac{\sigma_{stochastic}}{E} \propto \sqrt{\frac{t}{E_0}}$$

Diminuendo lo spessore di assorbitore la risoluzione migliora

Per avere prestazioni simili a quelle dei calorimetri omogenei, si dovrebbe avere t dell'ordine di qualche % di X_0 (non fattibile)

Tipicamente

$$\frac{\sigma_{stochastic}}{E} = \frac{5-20\%}{\sqrt{E}}$$

Un altro parametro caratteristico è la **frazione di campionamento**

$$f_s = \frac{E_{mip}(active)}{E_{mip}(active) + E_{mip}(absorber)}$$

Energia misurata e Risoluzione

- **Riassumendo**, l'energia rilasciata in un mezzo dalle particelle cariche dello sciame, attraverso la ionizzazione e' proporzionale alla energia della particella incidente.

- Se indichiamo con T_0 la somma di tutti i segmenti di traccia delle particelle cariche che emergono dallo sciame , avremo: (Track length $T_0 \equiv$ sum)

$$T_0 \approx X_0 \frac{E_0}{\varepsilon}$$ $\approx$ mean free path times number of particles in the shower

- Ionization energy collected in form of: -- **light** (e.g. scintillator, Cerenkov)
  -- **electric signal** (e.g. liquid, gas)

As already said, Intrinsic resolution of an ideal calorimeter with infinite size and no instrumental losses (cracks, readout, etc.) is due to fluctuations in T_0. T_0 proportional to number of tracks in shower and cascade process is random in nature

$$\sigma(E) \sim \sqrt{T_0} \quad \Longrightarrow \quad \frac{\sigma(E)}{E} \sim \frac{1}{\sqrt{T_0}} \sim \frac{a}{\sqrt{E}}$$

These intrinsic fluctuations are large in sampling calorimeters and small in homogeneous calorimeters.

Risoluzione in Energia : calorimetro reale

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

L'importanza relativa dei tre termini varia con l'energia

→ La scelta del calorimetro dipende dal range di energia rilevante per un dato esperimento

a : termine stocastico

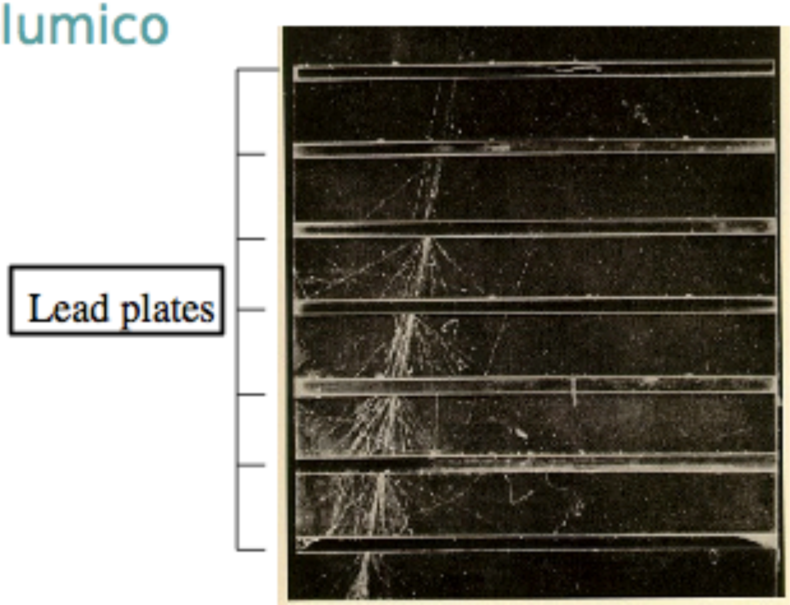
La fluttuazione intrinseca e' legata allo sviluppo fisico dello sciame.

- **Calorimetri Omogenei**: le fluttuazioni intrinseche sono piccole poiche' l'energia depositata nel mezzo attivo NON fluttua da evento a evento.
  Le fluttuazioni residue sono dovute per esempio a ratio of charged/neutral particles, efficiency of ionization → signal conversion
  → la risoluzione di energia intrinseca puo' essere migliore, come visto nel caso del fattore di Fano, della aspettazione statistica.
  → le risoluzioni tipiche valgono :

$$\frac{\text{few \%}}{\sqrt{E\,(\text{GeV})}}$$

Calorimetri a campionamento

- Un'alternativa è fornita dai **calorimetri a campionamento** in cui piani di materiale sensibile si alternano a piani di assorbitore metallico denso (struttura a sandwich)
  - Vantaggi: economici, possono raggiungere grandi dimensioni facilmente segmentabili, migliore risoluzione spaziale
  - Svantaggi: risoluzione in energia peggiore
    Ma la risoluzione può essere adattata alla misura fisica scegliendo opportunamente il rapporto tra il volume di materiale attivo e di assorbitore (rapporto volumico)
  - Il numero di particelle che danno segnale dipende dal rapporto volumico



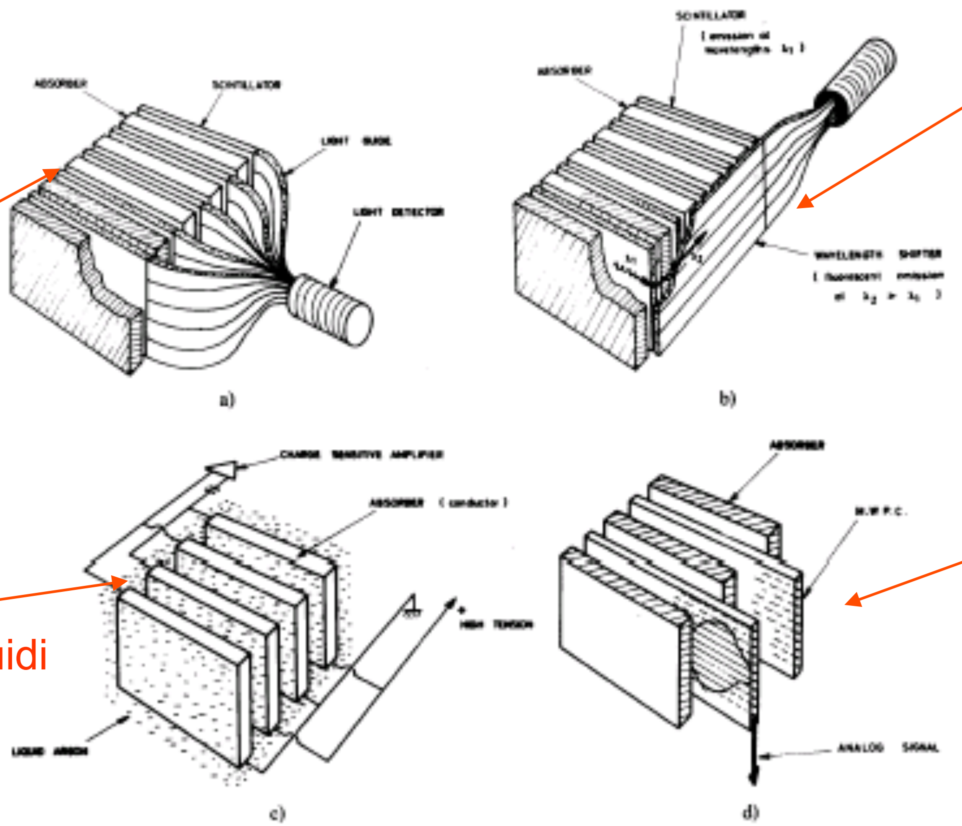
Cloud chamber photo of an electromagnetic shower. A high energy electron initiates the shower. The electron radiates photons via bremsstrahlung when it goes through the first lead plate. The photons are converted to electrons and positrons by the lead and they in turn create new photons. This process continues until the photons are no longer energetic enough to undergo pair production.

Calorimetri a Campionamento

Rivelatori

wave length shifter

Scintillatori



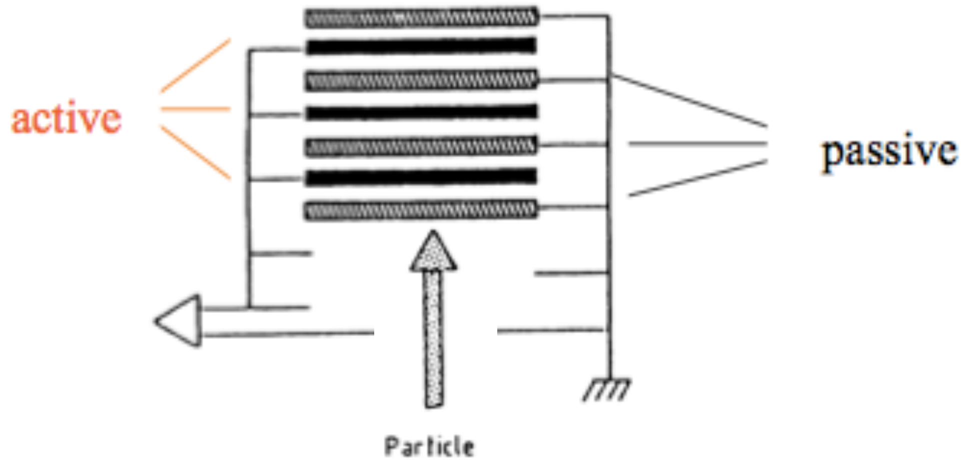
TMP,TMS

Gas nobili Liquidi

MWPC, tubi streamer

- **Sampling calorimeters:**

  Energy deposited in active medium fluctuates from event to event (sampling fluctuations)



Fluctuations related to number of charged particles crossing active layers.
Assuming statistically independent crossings from layers to layers (i.e. absorber not too thin):

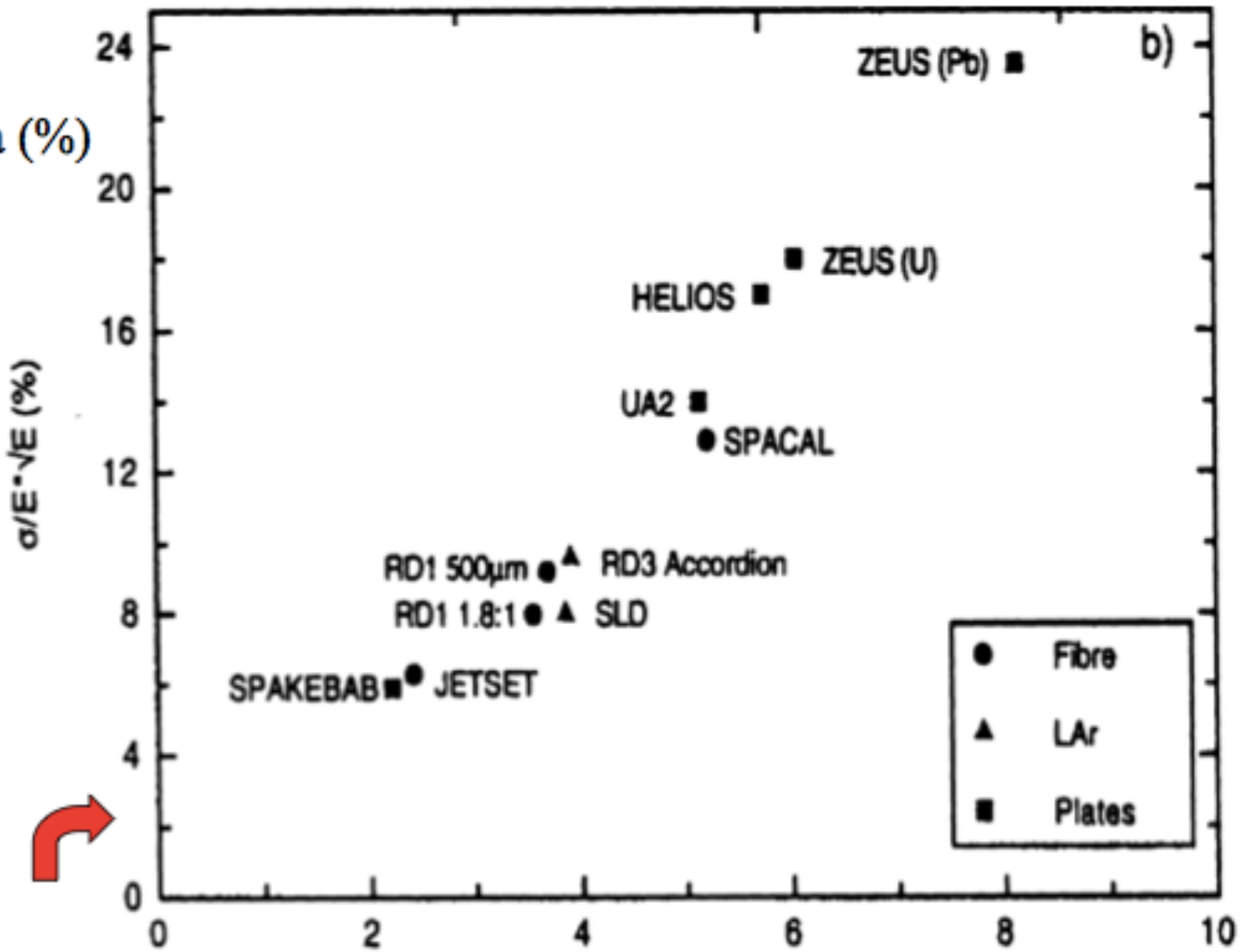
$$N_{ch} \sim \frac{T_0}{t}$$

t = thickness of absorber layer in X_0. For a given calo thickness, the smaller t the larger the number of time the shower is sampled and therefore the number of detected particles.

$$\Rightarrow \quad \frac{\sigma}{E} \sim \frac{1}{\sqrt{N_{ch}}} \sim \sqrt{\frac{t}{E\,(\mathrm{GeV})}}$$

→ **E resolution of sampling calorimeters** improved by reducing absorber thickness (i.e. increasing sampling frequency)

a (%)



√t (arbitrary units)

However: to reach resolutions of homogeneous calorimeters one needs t ~ few % X_0 → not feasible

Sampling fraction

Sampling fraction ≡ F_{mip} ≡ fraction of energy deposited by a minimum ionising particle in the active layers of a sampling calorimeter

$$F_{mip} = \frac{E_{mip}(vis)}{E_{mip}(vis) + E_{mip}(inv)}$$

$F_e < F_{mip}$: low-E photons at the end of cascade absorbed by passive material by photoelectric effect ($\sim Z^5$)

In other words : $\frac{e}{\mu} < 1$

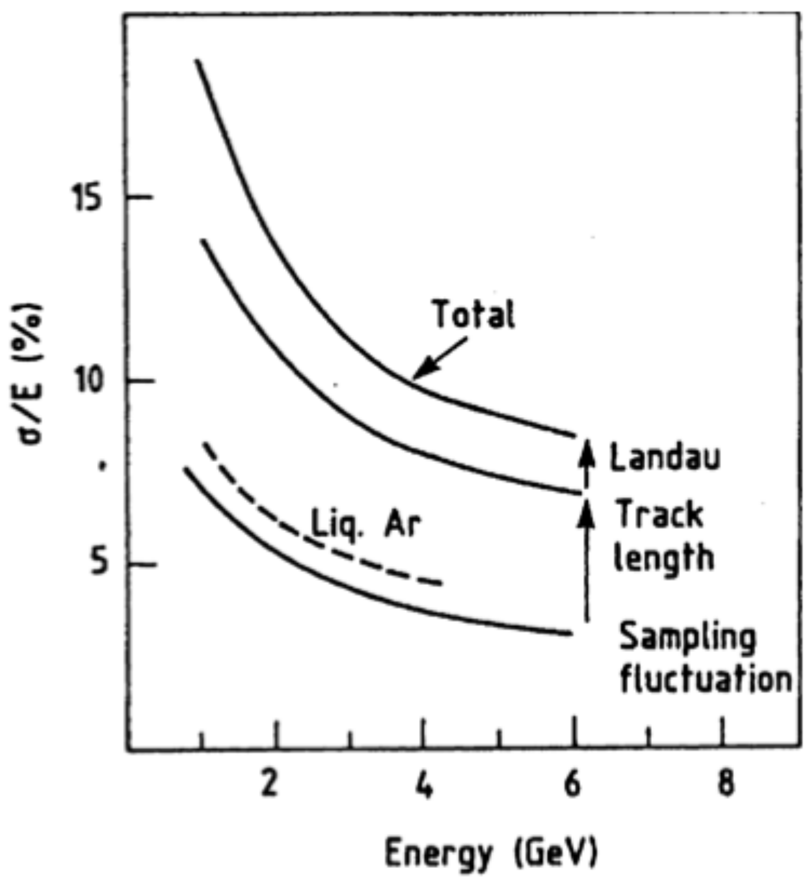
ratio between the energy deposited in the active layers by an electron and a muon of the same energy. Decreases with increasing Z of the absorber: ~ 0.7 Pb, ~ 0.9 Fe

Note: a muon is a mip only for $200 < E_\mu < 500$ MeV, but relativistic rise at higher energy is < 30%

Two more fluctuation sources in **gaseous sampling calorimeter:**

-- **Landau fluctuations**: δ-rays in high-E tails of energy loss distribution occasionally lose all energy in an active layer.

-- **path-length fluctuations**: low-E electrons ~ orthogonal to shower axis → large signal in active layers.



Monte Carlo (Fischer)

Reduced in high-Z gas (e.g. Xe)

b : noise term

- from thermal noise of the readout chain
- depends on detector technique and details of signal collections
  (detector capacitance, cables, electronic chain)
- **small if signal ≡ light** : first step of electronic chain is photosensitive device
  (e.g. phototube) with high-gain multiplication of signal and no noise
  larger if signal ≡ charge: first element of readout chain is preamplifier
  (brings noise) → sophisticated techniques (shaping, optimal filtering)
  used to improve signal/noise.
- noise term smaller for larger sampling fractions (larger signal in active medium)

High-E machines: noise term is usually small since E is large

Typical requirement : << 100 MeV per cell (equivalent rms energy of noise)

c : constant term

- includes contributions independent of particle E
- any instrumental effect which produces response variations vs position in the detector
- examples : detector geometry, imperfections in the mechanics or readout, temperature gradients, non-uniform aging,, radiation damage → varying charge/light collection with the position inside the detector → additional smearing of energy reconstructed in large systems

Some can be corrected: e.g. response non-uniformity from readout chain (calibration), geometrical effects with regular pattern.
Others (e.g. mechanical defects) are randomly distributed.

High-E machines: constant term often dominates (especially in homogeneous calorimeters) → tight construction tolerances (e.g. LHC calorimeters)

Typical requirement : $c \leq 1\%$

Other contributions to the energy resolution

Some come from calorimeter integration inside an experiment. E.g. :

- longitudinal leakage:
  space/cost constraints → limited thickness of calorimeters.
  Leakage varies event by event → fluctuations
  Important at high energy (> 100 GeV). Can be in part corrected by software (weighting last compartment).

- upstream E losses:
  due to material in front of calorimeters (tracking detectors, solenoid coil, calorimeter support structure, cryostats, cables, etc.) → additional fluctuations
  Can be recovered with dedicated devices (presampler, massless gaps)

- inactive regions:
  cracks between e.g. mechanical independent modules, or barrrel/end-cap transition. → resolution deteriorated, low-E tails

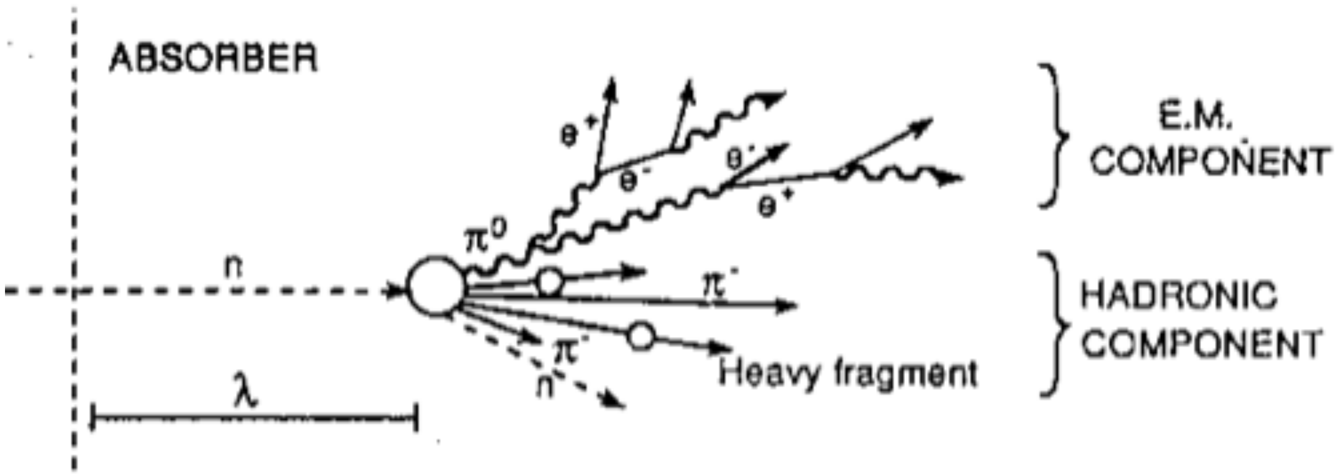
Physics of hadronic showers

Incident hadron produces cascade of secondary particles (pions, n, p, etc.) through electromagnetic and strong interactions.

Hadronic showers more complicated than EM showers:

-- EM component (π^0): ~1/3 at 10 GeV (increases with E). Prompt and short range

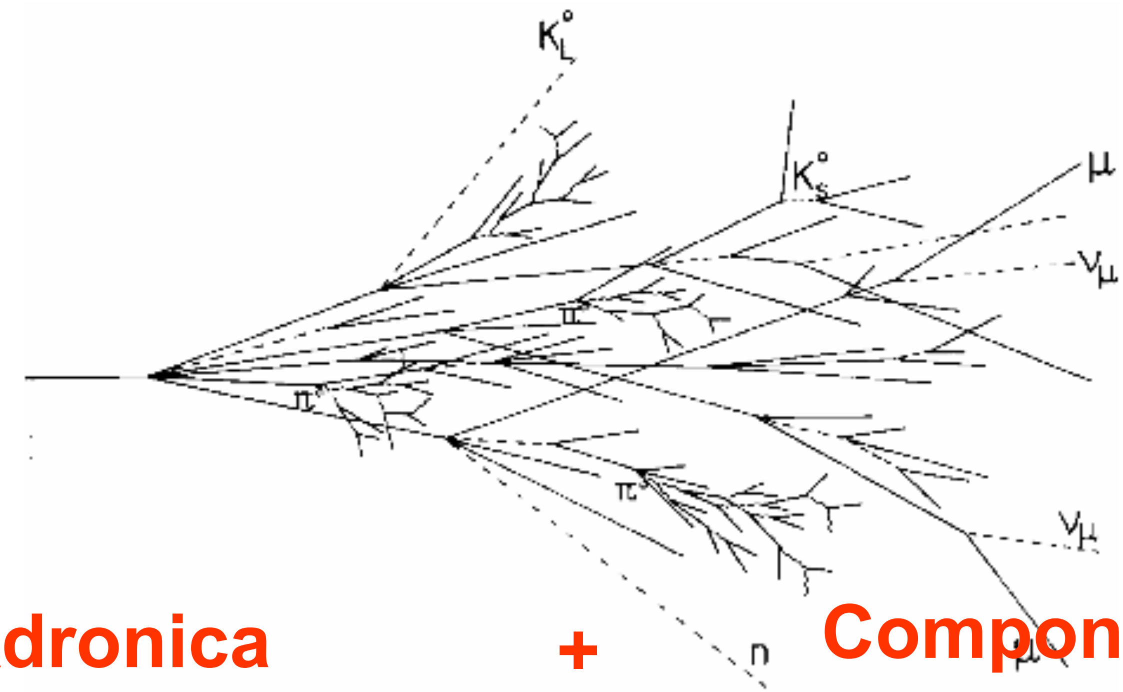
-- HAD component: large variety of complicated processes (e.g. nuclear excitation, fission). Slower and longer range.



- ◆EM showers well understood → reliable MC (e.g. EGS)
- ❖**Phenomenology of HAD showers not fully mastered**

  → various MC (e.g. GEISHA, GCALOR, FLUKA) with different physics and often very different predictions

Sciami adronici



Adronica + **Componente e.m.**

↓

charged pions, protons, kaons ….
Breaking up of nuclei
(binding energy),
neutrons, neutrinos, soft g's
muons …. → invisible energy

↓

neutral pions → 2g →
electromagnetic cascade

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

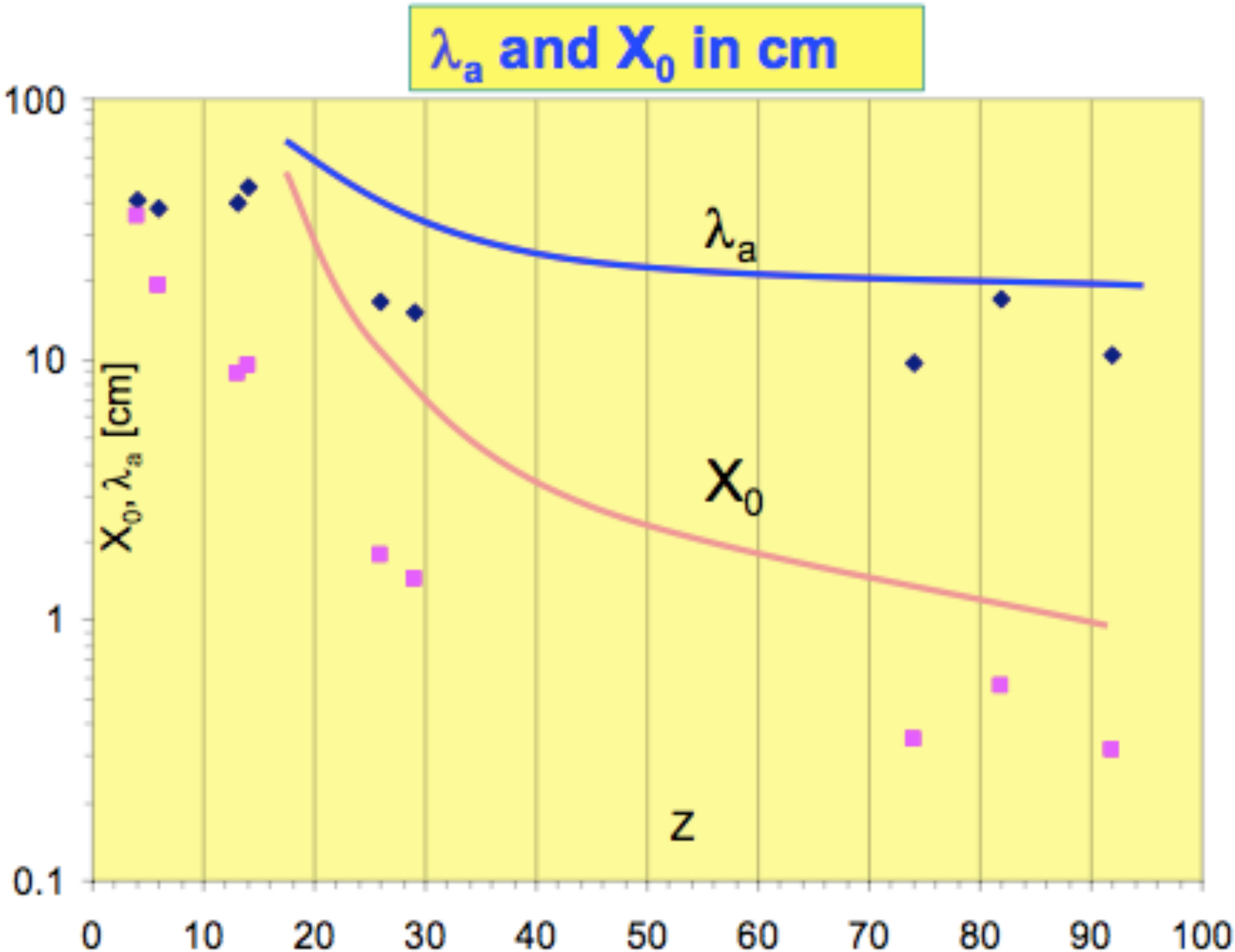
example 100 GeV: n(π^0)≈18

Grandi fluttuazioni di energia ➡ risoluzione in energia limitata

Interazioni di particelle cariche

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

For $Z > 6$: $\lambda_a > X_0$



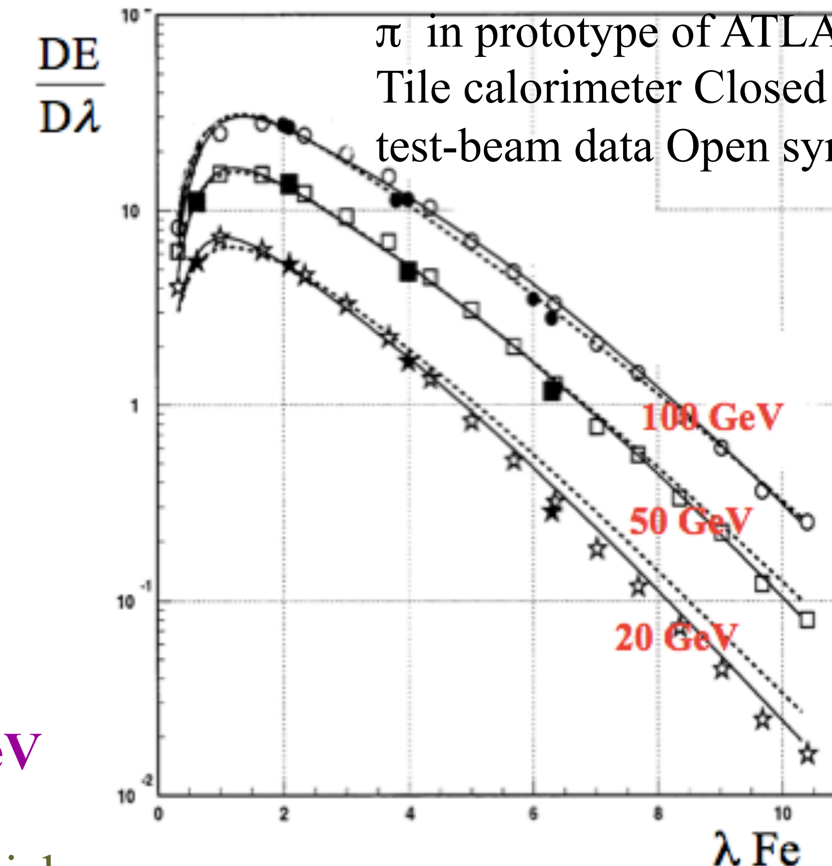
λa and X0 in cm
100
10
1
0.1
X0, λa [cm]
λa
X0
Z
0
10
20
30
40
50
60
70
80
90
100

Phenomenological parametrisations

- $\lambda \equiv$ interaction length $\equiv$ mean free path between two inelastic nuclear interactions
  $\lambda \approx 35\ g\ cm^{-2}\ A^{1/3}$ e.g. λ = 17 cm (Fe) , 10 cm (U)

- **longitudinal shower profile**: ➔

π in prototype of ATLAS Fe-Sci Tile calorimeter Closed symbols: test-beam data Open symbols: MC



Shower maximum:

$t_{max}(\lambda) \approx 0.2 \ln E(GeV) + 0.7$

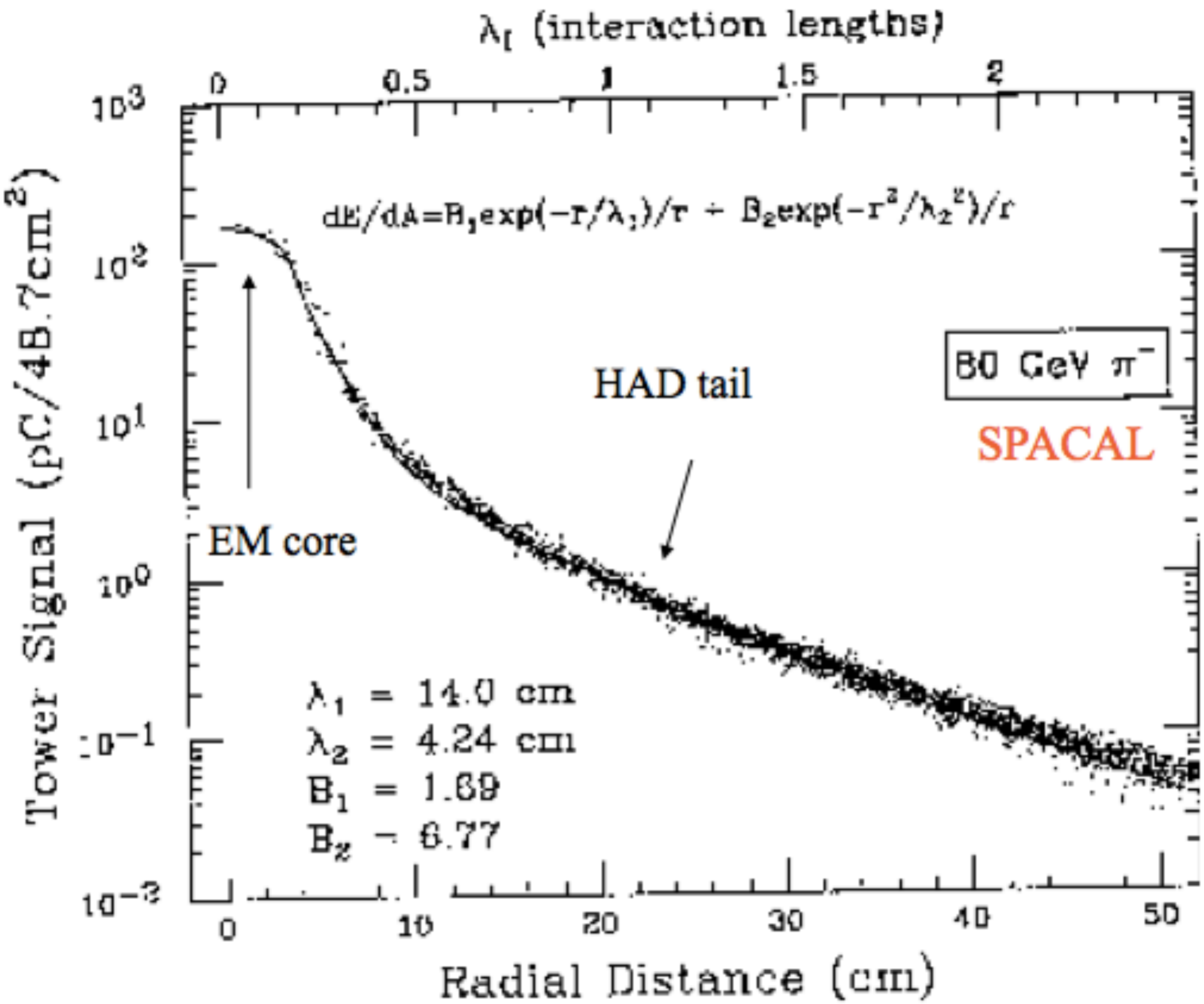
→ max occurs at 1-2 λ

Single hadrons and jets up to ~ TeV contained in 10–11 λ

→ hadronic calorimeters : ~ 1-2 m thick

→ sampling technique is only practical solution

- **lateral shower profile: 95% contained in 1 λ**



→ fine cell granularity not needed in hadronic calo
(→ several cm cell size)

Energy resolution of hadronic showers

In addition to sources contributing also to resolutionfor EM showers (e.g. noise term, constant term, sampling fluctuations, etc.) there are other (dominant !) contributions for hadronic showers:

- **muons and neutrinos**
- **strong interactions**
- **saturation effects**
- **non -compensation**

❶ Muons and neutrinos:

e.g. from pion decays. **Escape detection.**
Muon energy can be measured from muon spectrometer behind. Soft neutrinos inside jets can not be measured.
~1% of incident hadron energy at 40 GeV.

❷ Strong interactions:

❷ E.g. nuclear excitation and break-up, fission (energy range ~ MeV)

They produce:

-- ionising particles (p, α, nuclear fragments) → detected

-- neutrons → often invisible: can travel ~ 1 μs before to be moderated and captured → out of time/space window for measurement.

-- invisible energy (binding energy to break up nuclei): few percent of incident energy

⇓

only fraction of energy detected (undetected energy up to 40% of HAD component) with large fluctuations

→ even if EM component absent, energy resolution for hadronic showers >> $30/\sqrt{E}$. Non-linear response.

If active medium rich in protons: n → p scattering → p ionise → part of neutron energy recovered

E.g. : plastic scintillators (rich in hydrogen): ~100% of n → p energy transfer (only ~10% in argon)

❸ Saturation effects:

Nuclear fragments (heavily ionising) can saturate response of active medium through molecule damage (e.g. in scintillators), recombination (e.g. in liquid argon), etc.

In a scintillator, light emitted per unit path:

$$\frac{dL}{dx} = S\frac{dE}{dx}$$

S ≡ scintillation efficiency

If high ionization density along the track, density of damaged molecules proportional to dE/dx. A fraction k of these lead to **quenching**:

$$\frac{dL}{dx} = \frac{S\,dE/dx}{1 + kB\,dE/dx}$$

Birk's law

k ≡ fraction of quenching molecules
B ≡ proportionality factor

e.g. kB ~ 0.01-0.02 g/cm^{-2} MeV^{-1} scintillator
kB ~ 0.005 g/cm^{-2} MeV^{-1} liquid argon

→ **response suppressed**

non-compensation

The response to muons

Because of the similarity between the energy deposit mechanisms, the responses of a homogeneous calorimeter to muons and to em showers are equal. This means that the average signal for a muon that traverses such a calorimeter and loses, for example, 573 MeV in that process is equal to the average signal generated by a 573 MeV electron or photon that is absorbed by shower development in the calorimeter. One may also say:

$$e/mip = 1$$

In practice, this means that if a calorimeter of this type is calibrated with em showers, *i.e. if the relation between the deposited energy and the resulting calorimeter signal* (the "calibration constant") has been established with electrons of known energy, then the signals produced by muons traversing the calorimeter may be converted into the energy lost by these muons in the calorimeter, using the same calibration constant.

Although this may seem rather trivial, we will see in the following that this conversion is in general *not valid for other types of calorimeters, and in particular for sampling* calorimeters using high-*Z absorber material.*

The response to hadrons and jets

The calibration constant derived in the way described above is most certainly not valid for hadrons and jets. Because of the invisible energy phenomenon, only a fraction of the energy carried by these (collections of) particles is used to excite the atoms or molecules of the detector medium. Another fraction is used to dissociate the atomic nuclei and does not contribute to the calorimeter signals.Therefore, if the calibration constant derived from the detection of electrons is applied to the signals generated by pion showers, the energy value comes out too low.

In other words, the pion response is smaller than the em one, or

$$\pi/e < 1$$

Pions of a given energy generate signals that are, on average, smaller than those generated by electrons of the same energy. And since e/mip = 1, one may also say: π/mip < 1. Pions generate signals that are, on average, smaller than the signals from muons that deposit the same energy.

The response to hadron-induced showers is not only smaller than the electromagnetic one, it is also energy dependent. Homogeneous calorimeters are ***intrinsically non- linear*** for the detection of hadrons and jets. The reason for this is the energy-dependent em fraction in hadronic showers. The response to this em component, caused by π^0s produced in the hadronic shower development, equals the response to em showers initiated by high-energy electrons or photons.
The response to the non- em shower component is smaller than the em response, because of the invisible energy. Since the average em fraction of hadron-induced showers increases with energy, so does the calorimeter response to such showers. Therefore***, the π/e ratio increases with energy***.

On the other hand the calorimeter response to the non-em component of hadronic showers may be considered constant. We will call this ***non-em calorimeter response h***. Because of invisible energy, h is smaller than the electromagnetic response:

$$e/h > 1$$

A calorimeter for which this relation holds is said to be ***non-compensating***. All homogeneous calorimeters are non-compensating. The precise value of e/h indicates the degree of non-compensation.

In homogeneous calorimeters, it is only determined by the average fraction of the non-em energy that escapes detection. The e/π ratio is *not* a measure for the degree of non-compensation, since part of the pion-induced showers is of an electromagnetic nature. As the energy increases, so does this em fraction. At very high energies, the e/π ratio will be close to 1, even in extremely non-compensating calorimeters.

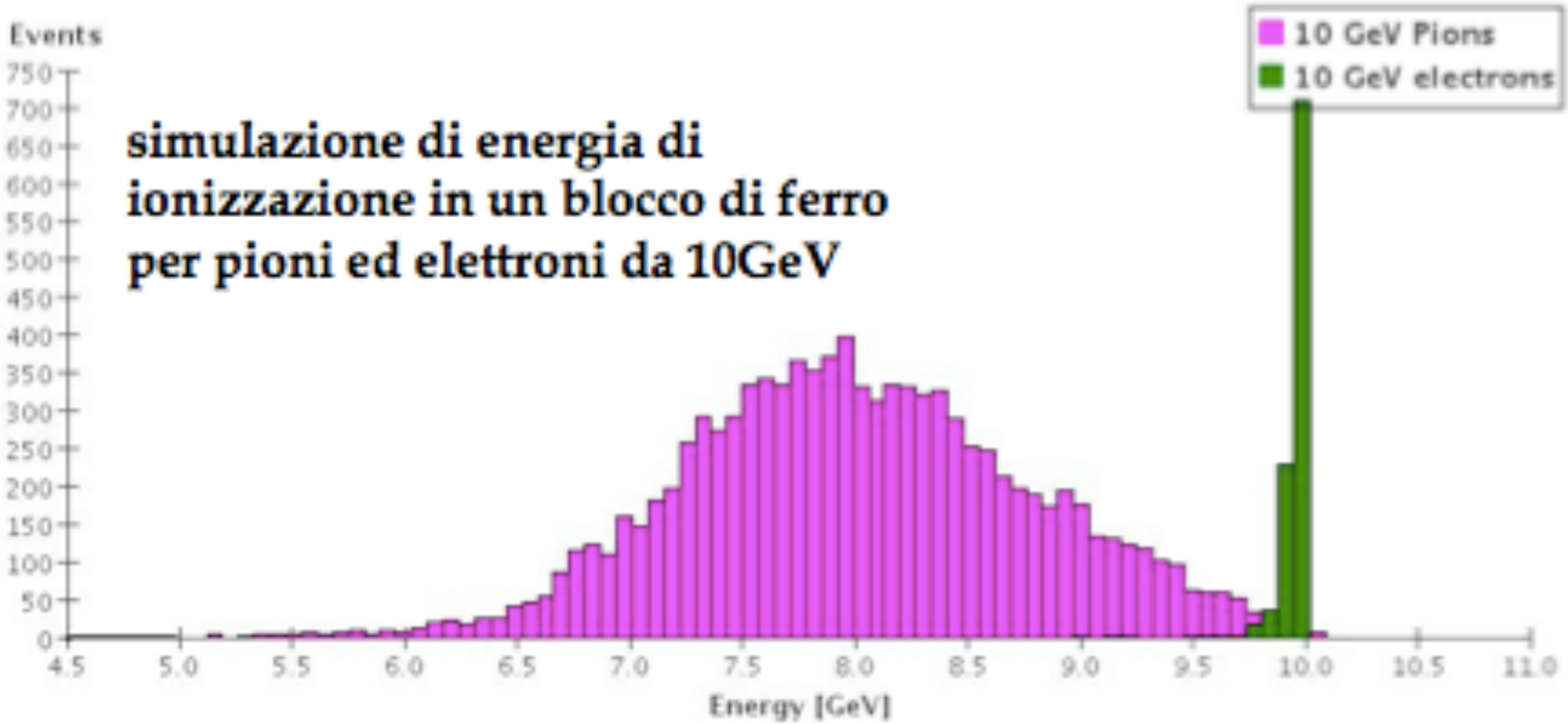
Experimentally, the e/h ratio cannot be directly measured. It may be derived from measurements of the e/π signal ratios at a series of energies, preferably spanning as large an energy range as possible. One needs to know the average em fraction, fem, for this purpose. If e and h denote the calorimeter response to the em and non-em shower fractions, then the response to pions can be written as

$$\pi = f_{em} \cdot e + (1 - f_{em}) \cdot h \longrightarrow \pi/e = f_{em} + [1 - f_{em}] \cdot h/e$$

$$e/\pi = \frac{e/h}{1 - f_{em}[1 - e/h]}$$

And since fem is a function of the energy of the showering hadron, so is the e/π ratio.

- frazione f_{em} è importante per la risoluzione dei calorimetri



  - risposta di adroni ed elettroni molto diversa

SAMPLING CALORIMETERS

The response to electrons and photons

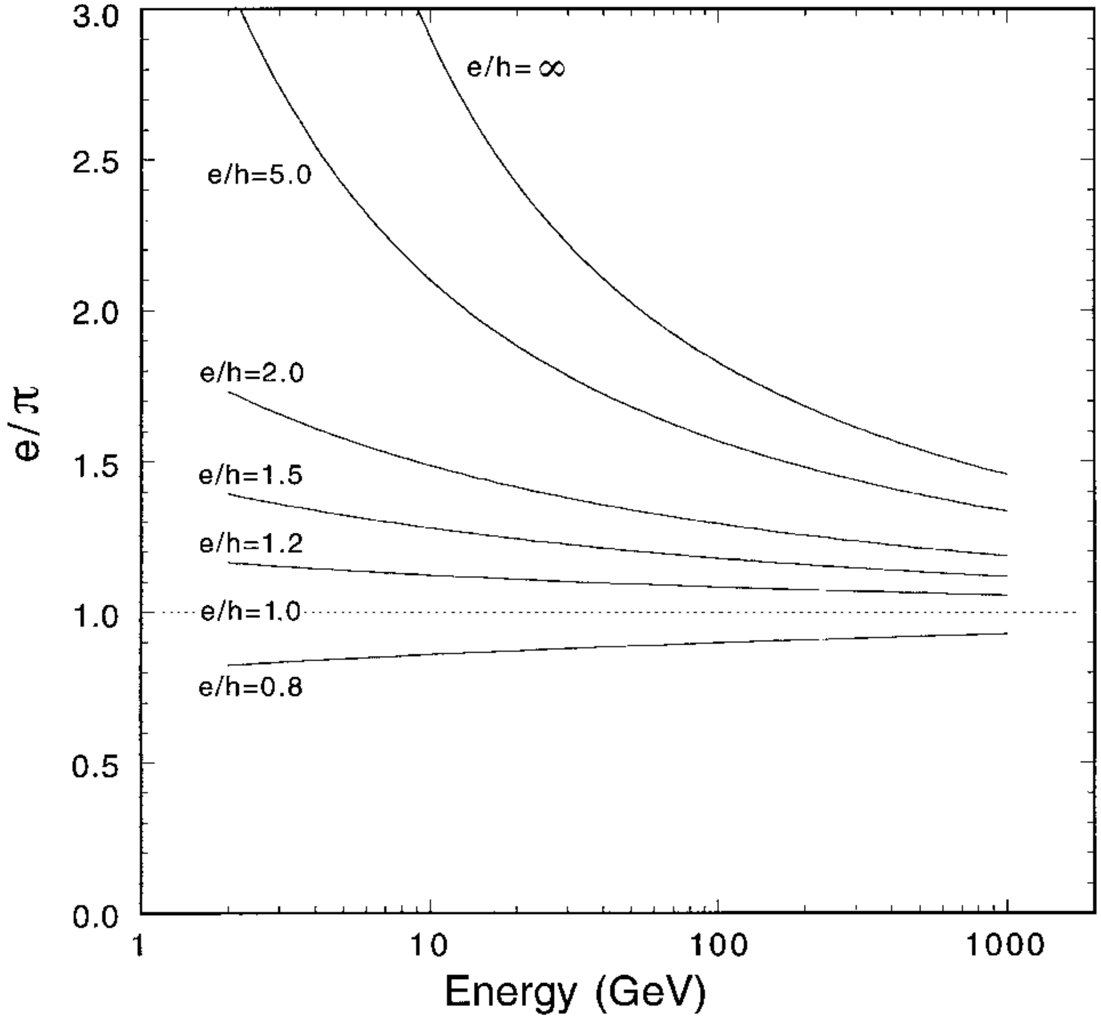
We have seen that the response of homogeneous calorimeters is the same for all particles that lose their energy exclusively through electromagnetic interactions with the absorber material (hence e/mip = 1). This is not the case for sampling calorimeters.

In sampling calorimeters of which the Z value of the absorber material is larger than the (average) Z value of the active medium, the response to em showers is smaller than the response to minimum ionizing particles (e/mip < 1). The larger this difference in Z, the smaller the value of e/mip becomes. We are not dealing with a small effect here. In calorimeters using high-Z absorber materials, such as lead or depleted uranium, e/mip values as low as 0.6 have been measured.

The response to hadrons

We have found that the hadronic response of homogeneous calorimeters is always smaller than the em response and that, as a result, the hadronic signals from such calorimeters are non-linear: the hadronic response is not constant as a function of energy.

The latter conclusion also applies to sampling calorimeters.



The relation between the calorimeter response ratio to em and non-em energy deposition, e/h, and the measured e/π signal ratios.

❹ Non compensation:

Calorimeter response to EM component of shower larger than response to hadronic component (see above):

$$R_h = \varepsilon_e E_e + \varepsilon_h E_h$$

- R_h: response to hadron
- ε_e: fraction of detected EM energy
- E_e: EM energy of shower
- ε_h: fraction of detected HAD energy
- E_h: HAD energy of shower (i.e. non-EM)

$$\frac{e}{h} = \frac{\varepsilon_e}{\varepsilon_h}$$

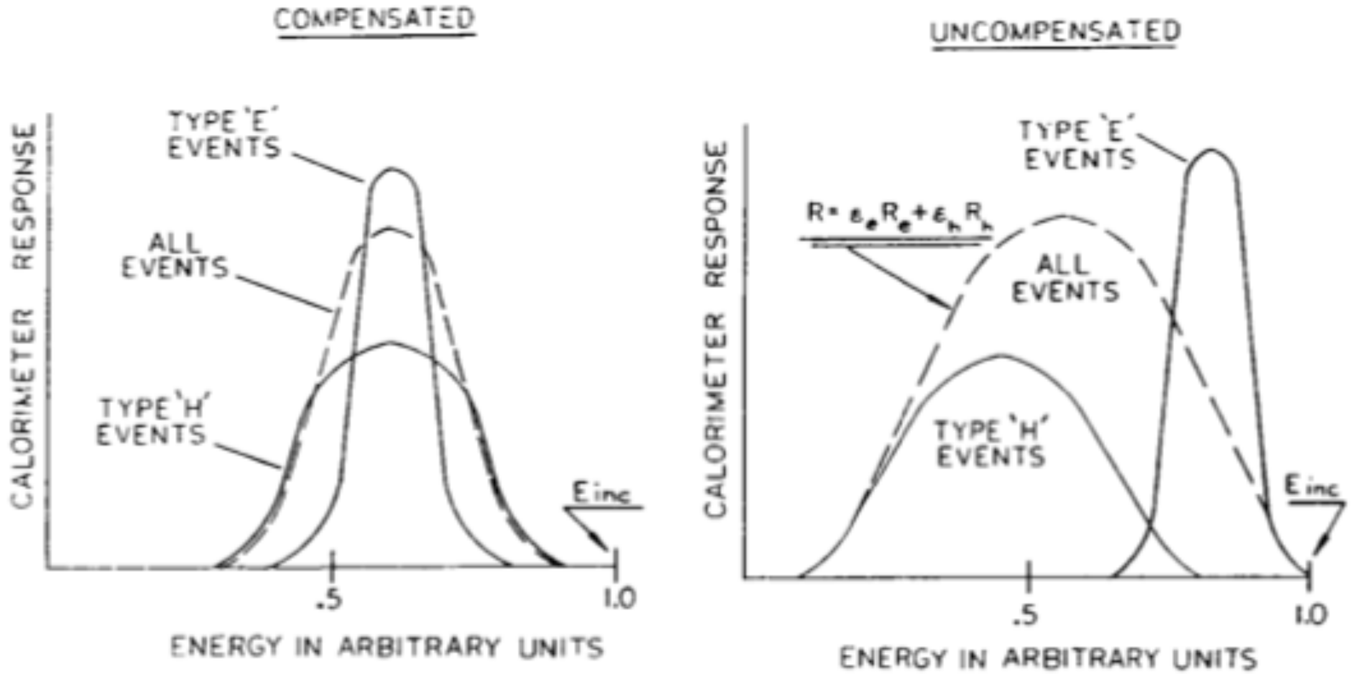
- ≈ 1 : compensated calorimeter
- > 1 : uncompensated calorimeter (i.e. small efficiency for h is not compensated for)

Most calorimeters are uncompensated

Note : e/h is roughly E-independent (not exactly true ..) and so is intrinsic feature of a calorimeter

If **e/h > 1**, since EM fraction in shower fluctuates from event to event

→ **energy resolution deteriorated**



➔The further distant e/h from one, the worse the resolution

In addition, EM fraction increases with E : F (π^0) ~ 0.11 ln E

30% incident $\pi^{\pm}$ E ~ 10 GeV ; 60% incident $\pi^{\pm}$ E ~ 150 GeV

→ **if e/ h > 1, then calorimeter responses increases with E**

- a non -compensated calorimeter is highly non-linear

- E-resolution does not scale as 1/√E

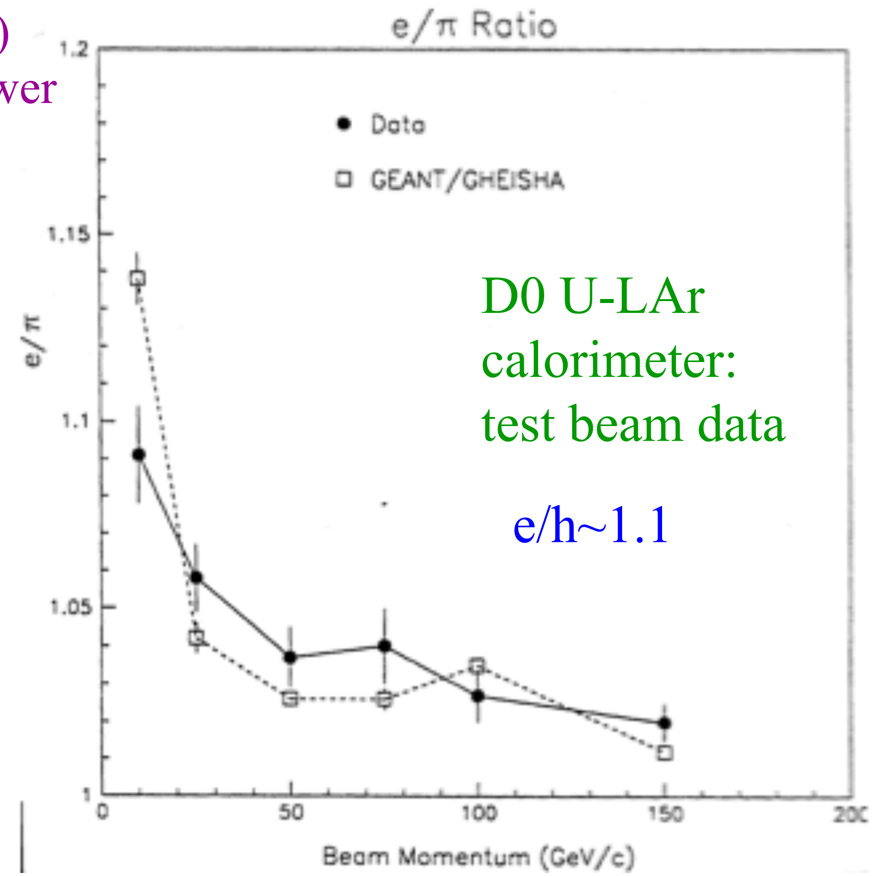
$\frac{e}{\pi} \equiv$ average calorimeter response to $e^{\pm}$ and $\pi^{\pm}$ of same E

Unlike e/h :

-- directly measurable quantity (e.g. test beam)

-- E-dependent, since EM component in π shower increases with E

$$\frac{e}{\pi} = \frac{e/h}{1 + (e/h - 1)\, F(\pi^0)}$$



Note : e / h > e / π > e / jet > 1

How to "compensate" a calorimeter ?

- Software weights (H1 calorimeter) :
  if EM and HAD calorimeters longitudinally and laterally segmented:
  weight energy deposited in the various compartments and cells, i.e.
  suppress energy in the EM calo, and in core cells.
- Increase ε_h using hydrogenated materials
- Decrease ε_{em} using high-Z material in EM calo
  $\rightarrow$low-E γ and electrons do not reach active layers
- Use ^{238}Uranium (fissionable for ~MeV neutrons) as absorber (e.g. D0, ZEUS):
  many neutrons produced (~10 n per incident GeV) which induce chain reaction.
  Better if coupled to a hydrogenated material.
- Use long shaping times (to collect slow n interactions)

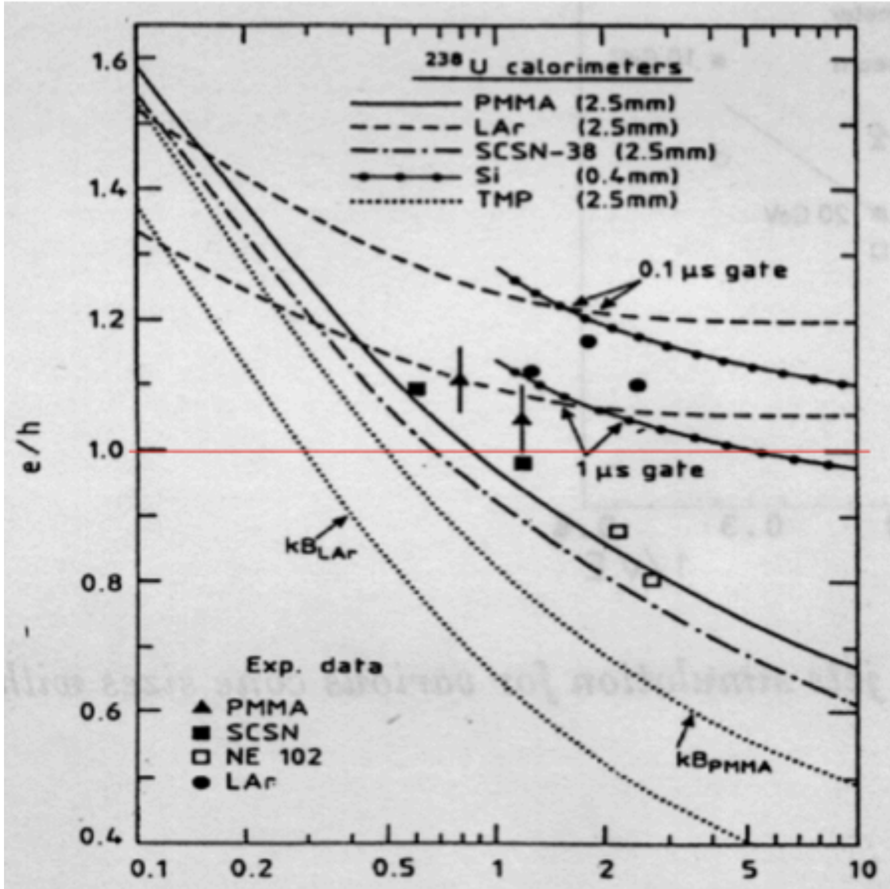
Note:

-- compensation easier in a sampling calorimeter (can play with two media)

-- radiation damage favours compensation:
EM calo damaged first $\rightarrow$ EM response drops

-- energy resolution better for jets than for single hadrons: e / jet closer to 1 than e/π since jets have large EM component
$\rightarrow$ e/h ~ 1.2 is enough for good jet resolution (dominated by other effects)

e/h for a ^{238}U sampling calorimeter with different active media

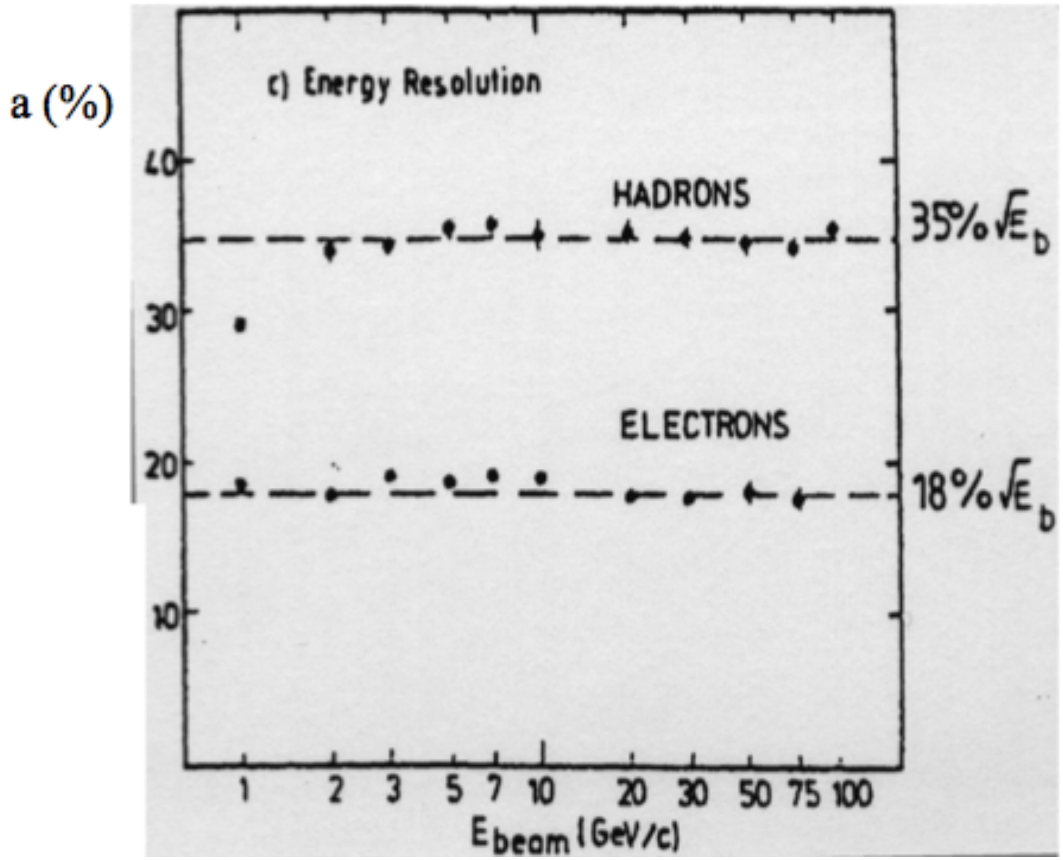


$$\frac{t\ \text{absorber}}{t\ \text{active}}$$

-- **LAr and Si** : e/h ~ 1 not achievable for reasonable U thickness

-- **scintillators (PMMA, SCSN) and warm liquid (TMP)**:
e/h ~ 1 can be achieved (rich in hydrogen)

Example: the ZEUS Uranium-scintillator calorimeter



Hadron resolution: excellent !

EM resolution: modest because of low sampling frequency to achieve compensation.
U plates : 3.3 mm   Scintillator plates : 2.6 mm

Note: first compensated calorimeter:
U-scintillator calorimeter of Axial Field Spectrometer (AFS) at CERN ISR.

Calorimeter performance requirements

- Have become more and more rich and stringent with time:
  from E-measurement to space / angle / time measurement, particle identification, etc.
  Many “technical” requirements as well: speed, noise, coherent noise, cross-talk, etc.

- Stringent constraints also from integration with the rest of experiment
  (e.g. space, magnetic field, size) and from environment (e.g. radiation hardness).

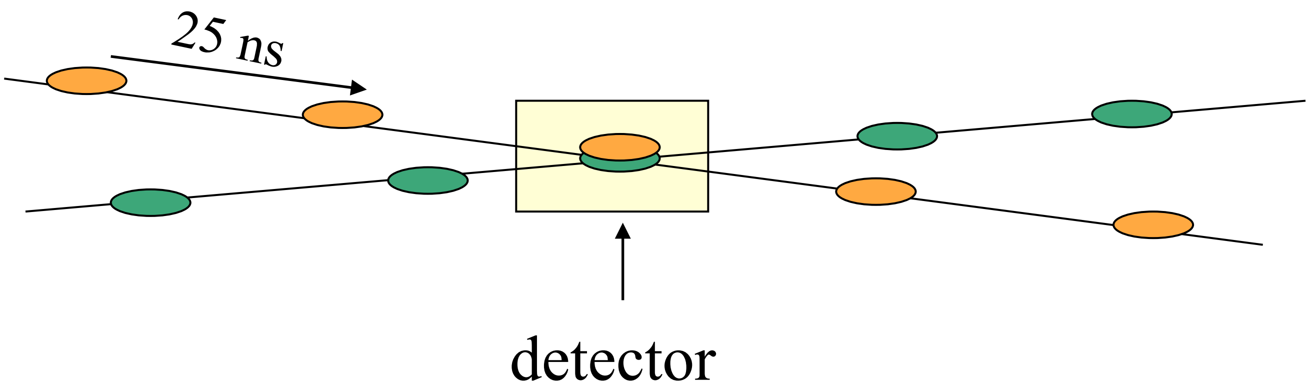
- Requirements and therefore detector choice can be very different according to applications (e.g. neutrino physics vs B-factory). Often more than one solution possible for a given application.

- Here as an example: ATLAS and CMS calorimeter requirements
  (LHC very demanding in terms of physics and environment).

Main calorimeter requirements at LHC (ATLAS and CMS)

- Fast response:

Interaction rate at LHC : $R = L\sigma\,(pp) = 10^{34}\ cm^{-2}\ s^{-1} \times 70\ mb = 10^{9}$ int. / second
Protons are grouped in bunches (of $\approx 10^{11}$ protons)
colliding at interaction points every 25 ns



$\Rightarrow$ At each interaction on average $\approx$ 25 soft (low-p_T) interactions are produced.
From time to time an interesting (high-p_T) event is also produced
(e.g. $pp \rightarrow W$, $\sigma \sim 150$ nb)
Soft interactions overlap with interesting high p_T event, giving rise to so-called
pile-up noise

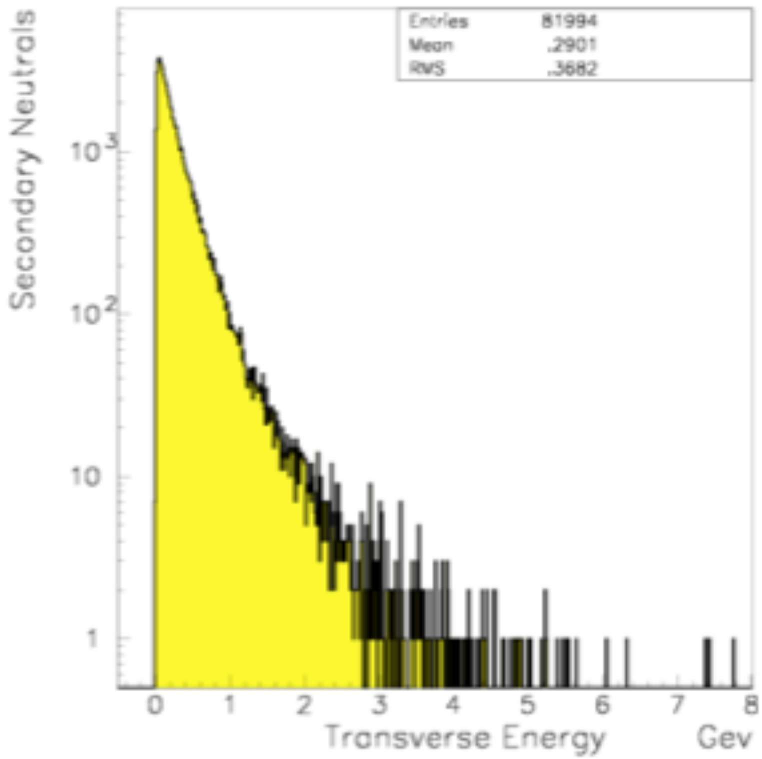
Pile-up:

~1000 charged particles and 500 neutral produced over $|\eta| < 2.5$ at each crossing

$< p_T > \approx 500$ MeV

(soft interactions)

→ applying p_T cut allows extraction of interesting particles

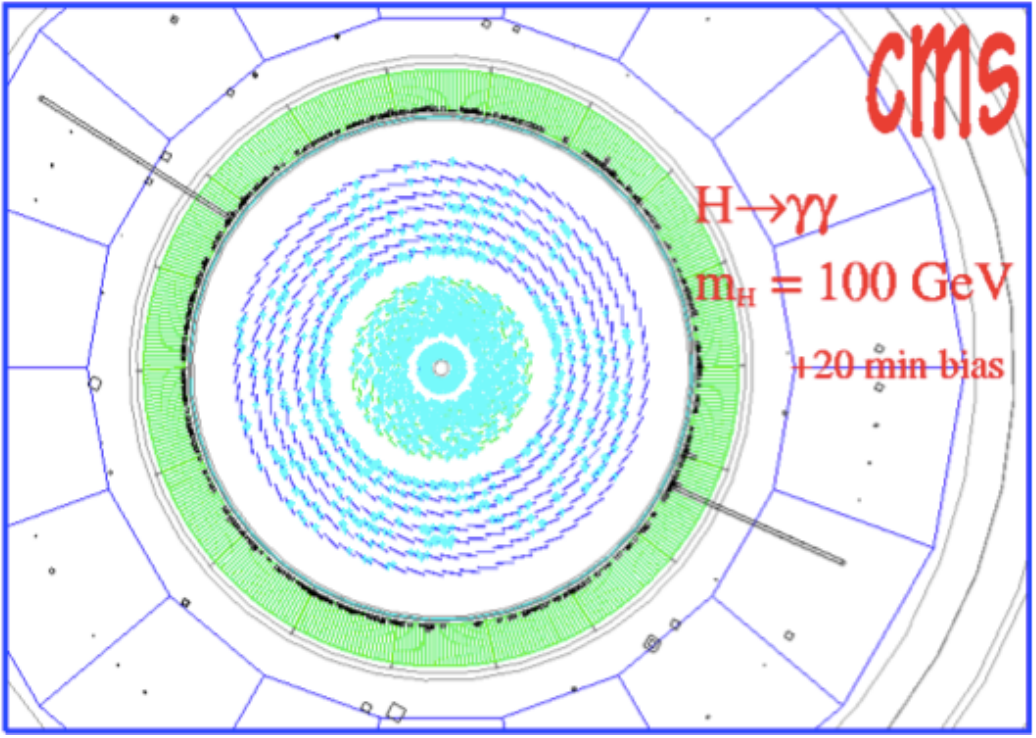


However: **pile-up** produces **"noise"** in the calo cells therefore contributes to energy resolution with term:

$$\frac{\sigma}{E} \sim \frac{\text{rms (pile-up)}}{E}$$

→ need **fast calorimeter response ≤ 50 ns** not to integrate over many bunch crossing (challenging electronics !)

→ need **fine granularity** to minimise probability that pile-up particles be in the same cell as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)



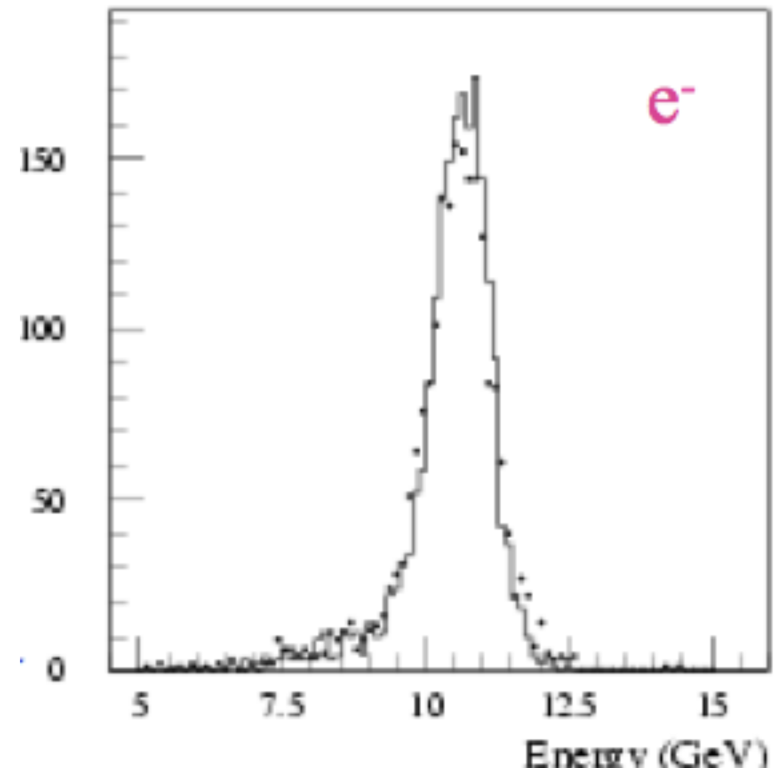
Simulation of electrons in ATLAS EM calorimeter

——— w/o pile-up

. . . . . with pile-up

Response time ~ 40 ns

Pile-up noise contribution to an EM shower:
rms (pile-up) $E_T \approx 250$ MeV



• Radiation resistance:

High flux of particles from pp collisions → high radiation environment

	Neutrons per cm^2	Dose (Gy)
EM barrel	10^{14}	10^3
HAD barrel	10^{13}	10^2
Forward calo $\|\eta\| > 3$	10^{17}	10^7

1 Gy = unit of absorbed energy = 1 Joule/Kg

n fluxes and doses integrated over 10 years of LHC operation

Radiation damage :

-- decreases like d^2 from the beam → detectors nearest to beam pipe are more affected
-- more important in the forward region (higher particle energies)
-- need also radiation hard electronics (military-type technology)
-- need quality control for every piece of material
-- detector + electronics must survive 10 years of operation

Rapidity coverage | η | < 5:

For reliable measurement of event missing transverse energy → neutrino detection (challenging for forward calorimeter)

Unlike at e^+e^- machines, at pp or $p\bar{p}$ collider centre-of-mass energy of interacting partons not known → cannot detect neutrinos from measurement of missing energy.

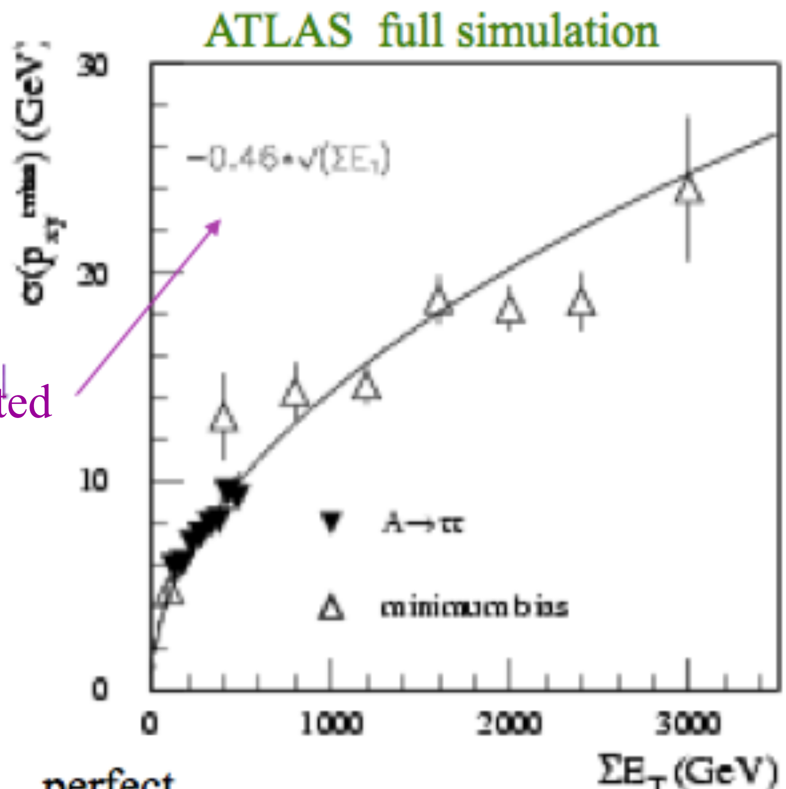
However p_T (initial state) ≈ 0 → a non zero missing **transverse** energy indicate presence of neutrinos:

$$|\vec{P}_{T\nu}| = E_T^{miss}$$

E_T^{miss} resolution dominated by hadronic calorimeter

Needed to observe
A/H → ττ, SUSY, etc.

A → ττ events with m_A = 150 GeV:



Calorimeter coverage | η |< 5 : σ (p_x, p_y) ~ 2 GeV
Calorimeter coverage | η |< 3 : σ (p_x, p_y) ~ 8 GeV

} perfect detector

Coverage for precision physics (full granularity, best E resolution, tracker in front):
| η | < 2.5 (~10^0 from beam axis)

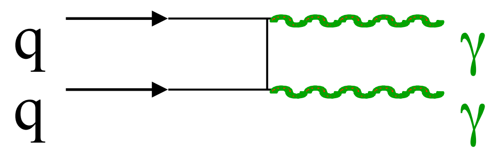
- <u>Excellent EM energy resolution:</u>

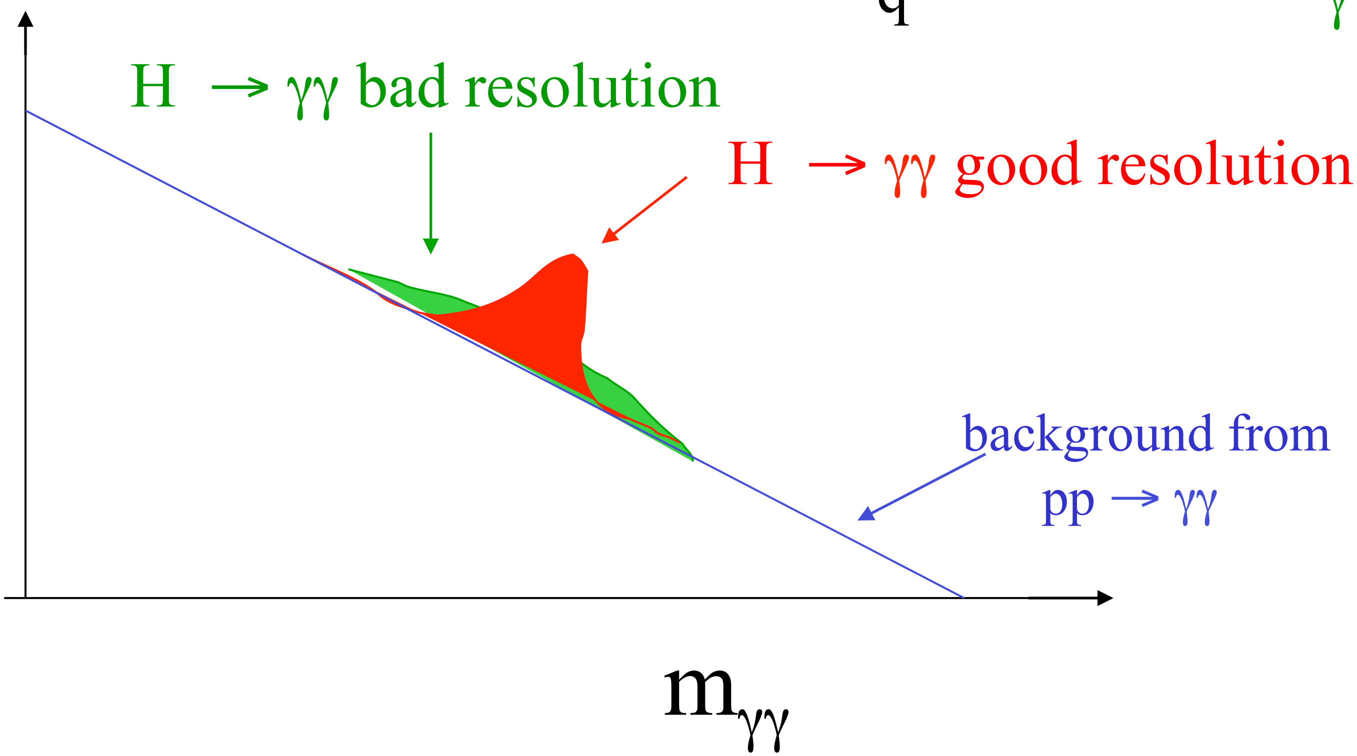
e.g. to extract a $H \to \gamma\gamma$ signal over the background

$\sigma\,(H \to \gamma\gamma) \approx 50$ fb

$\sigma\,(pp \to \gamma\gamma) \approx 2$ pb

$m_H \approx 100$ GeV





Mass resolution of ~ 1 % needed for m ≈ 100 GeV

In particular : constant term < 1%

• Good jet energy resolution:

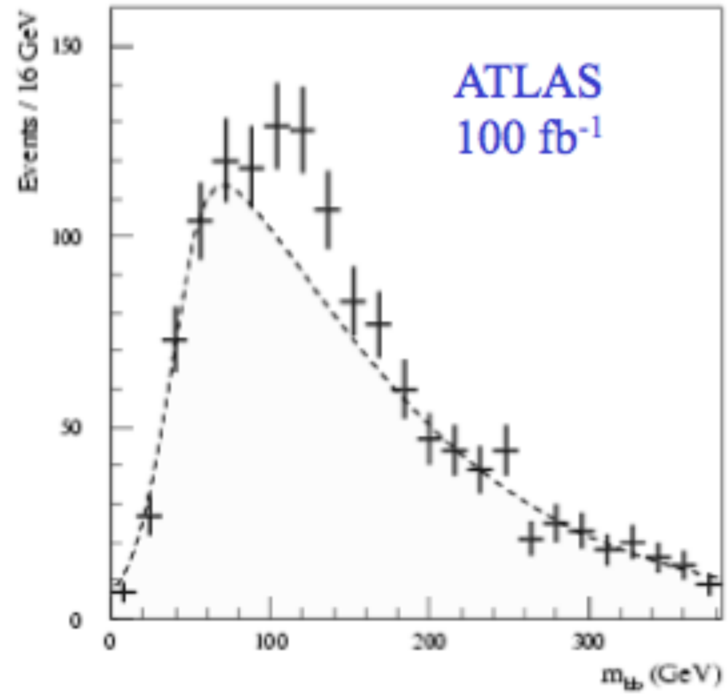
$$\frac{\sigma}{E} \approx \frac{50\%}{\sqrt{E}} \oplus 3\%$$

Mainly requirement for hadronic calorimeter.

For jet mass spectroscopy : $W \to jj$ and top $\to bW \to bjj$ decays, search for $H \to bb$, SUSY $\to$ multijets, etc.

$pp \to t\bar{t}H$ with $H \to b\bar{b}$

important decay mode to observe Higgs at LHC and measure Yukawa coupling both in SM and MSSM for masses 100-130 GeV.
Need to reconstruct both top (kinematic fit) efficiently to reject background.



Small constant term :

-- to extract high-mass resonances over background:
e.g. $Z' \to jj$ for m ~ 1 TeV
-- not to fake compositeness (see later)

Related requirements: longitudinal and lateral segmentation (software compensation, good jet-jet separation, etc.)

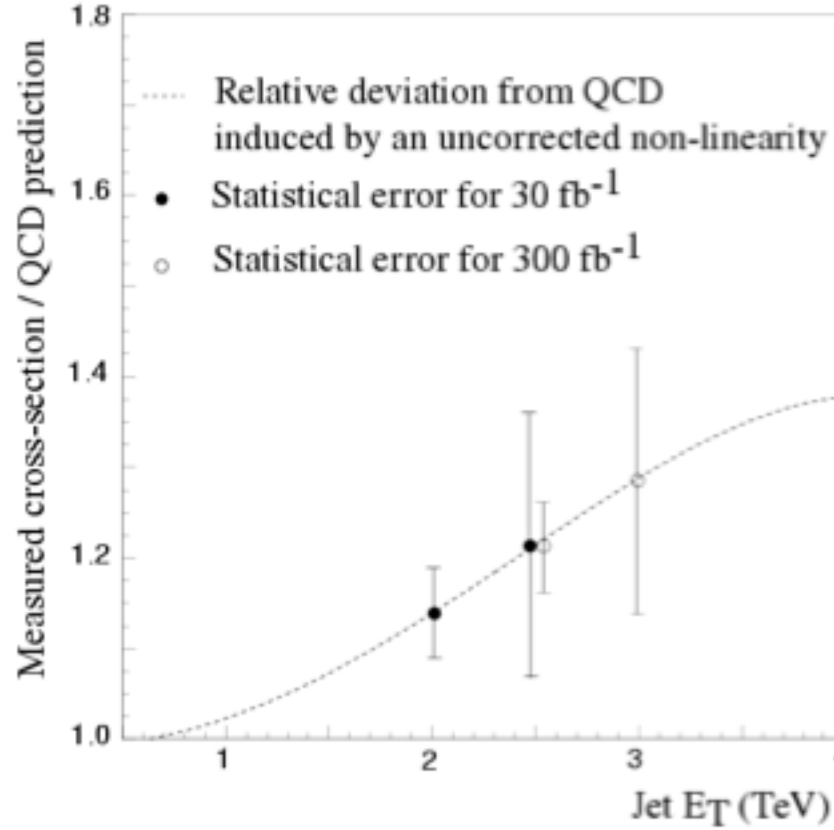
• Response linearity:

- EM : better than 0.5 % up to ~ 300 GeV not to spoil resolution, fake new physics, etc.
- HAD : better than 2% up to ~ 4 TeV (challenging).

Uncorrected non linearity can produce enhancement of the (steeply falling) QCD jet cross-section at high p_T → fake quark compositeness

ATLAS :
assuming uncorrected non-linearity of 2% → fake $\Lambda_c \sim 30$ TeV

Non-linearity of 5% would fake $\Lambda_c \sim 20$ TeV



Note : *jet energy scale is calibrated in situ* with Z+ jet events (see later) up to ~ 500 GeV. Then extrapolate to higher energy using data and MC (need to know e/h to ~ 0.2).

• Large dynamic range:

E.g. Excellent electron energy measurement
over $p_T \approx$ GeV $\rightarrow$ 3 TeV (b $\rightarrow \ell$ X, W', Z')

Electronic dynamic range:
~ 50 MeV $\rightarrow$ ~ 3 TeV

typical noise per cell

~ max E in one calo cell from electrons from W'/Z' with m ~ 5 TeV

Dynamic range of 16-bit needed (usually realized in a multi-gain chain).
Note: smaller range would increase noise

• Photon angular measurement :

$$m_{\gamma\gamma}^{\,2} = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = 2E_1E_2(1-\cos\theta_{12})$$

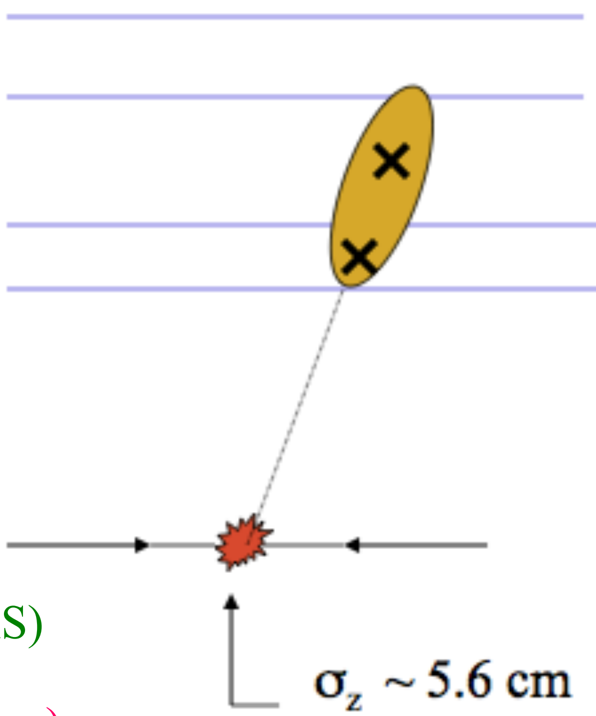
$$\frac{\sigma(m)}{m} = \frac{1}{\sqrt{2}}\left(\frac{\sigma(E_1)}{E_1} \oplus \frac{\sigma(E_2)}{E_2} \oplus \frac{\sigma(\vartheta)}{tg\vartheta/2}\right)$$

energy resolution of EM calorimeter

resolution of the measurement of the γ angle θ

At LHC : vertex spread along beam axis ~ 5.3 cm
→ >> 1% contribution to σ (m) if calorimeter gives only position measurement in z

However: longitudinal segmentation of EM calorimeter in ≥ 2 compartments allows measurement of γ direction (ATLAS)

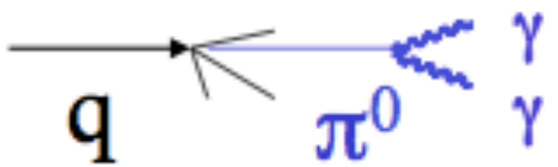


CMS: vertex from tracks from underlying event (spectator partons)
→ difficult at high L (~25 vertices) → often pick-up wrong vertex

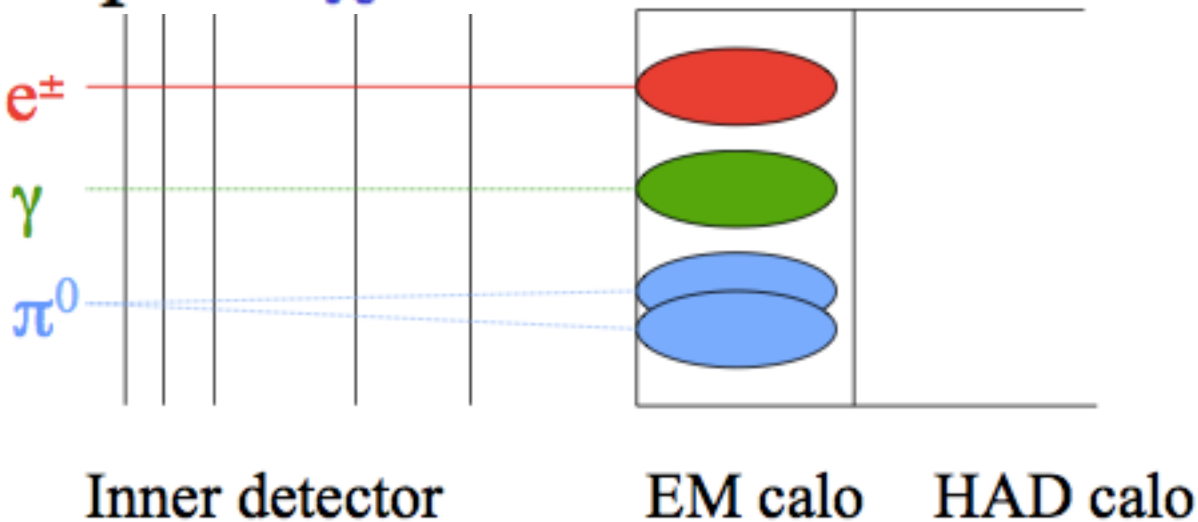
- **Excellent particle identification capability:**

e.g. e/jet , γ/jet separation

number and p_T of hadrons in a jet have large fluctuations



in some cases: one high-p_T π^0;
all other particles too soft to be detected



d (γγ) ≤ 10 mm in EM calorimeter → QCD jets can mimic photons.

Rare cases, however:

$$\text{For } m_{\gamma\gamma} \sim 100 \text{ GeV}: \quad \frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8$$

EM calo with fine granularity (~ 1 cm or better) needed to separate single γ from π^0

Homogeneous calorimeters

- Excellent energy resolution (no sampling fluctuations)

- However:
  -- less easy to segment longitudinally and laterally than sampling calorimeters
  -- compensation more difficult → ~ not used as hadronic calorimeters
- Quite common in neutrino and astroparticle physics: large volumes needed
  → air or water homogeneous calorimeters (inexpensive)

Four types :

- **Semiconductors** (e.g. Si and Ge): ionization tracks produce electron-hole pairs. Best intrinsic resolution.
- **Cerenkov** (e.g. lead -glass): high refractive index → relativistic tracks from shower produce Cerenkov light.
- **Scintillators** (e.g. BGO, CsI): ionization tracks converted into light (fluorescence).
- **Noble liquid** (e.g. liquid Kr, Xe): noble gas at cryogenic temperature. Ionization produces charge and light

Light yield

Cerenkov and scintillators:

photons from active volume converted into electrons ("photoelectrons") by photosensitive device (e.g. photomultipliers, photodiodes).

→ additional contribution to energy resolution from fluctuations in $N_{pe} \rightarrow 1/\sqrt{N_{pe}}$

Often N_{pe} small:

-- tiny signal from active medium (e.g. Cerenkov)

-- losses in light collection

-- efficiency of photons → electrons conversion (quantum efficiency of photocathode): ~ 20 %

-- small amplification of electric signal in case of photodiodes (gain 1-10). Photomultipliers (gain ~ 10^6) cannot operate in high magnetic field.

⇩

Maximisation of light yield is crucial issue for homogenous calorimeters

calorimetri EM omogenei

	NaI(Tl)	BaF_2	CsI(Tl)	CsI	CeF_3	BGO	PWO	
ρ	3.67	4.88	4.53	4.53	6.16	7.13	8.26	g/cm^3
X0	2.59	2.05	1.85	1.85	1.68	1.12	0.89	cm
RM	4.5	3.4	3.8	3.8	2.6	2.4	2.2	cm
τ	250	0.8/620	1000	20	30	300	15	ns
λp	410	220/310	565	310	310/340	480	420	nm
n (λp)	1.85	1.56	1.80	1.80	1.68	2.15	2.29	
LY	100%	15%	85%	7%	5%	10%	0.2%	%NaI

tipicamente $40\times10^3\ \gamma\,/\mathrm{MeV}$

Semiconductors

- Expensive, **not convenient for large systems**
- Excellent intrinsic resolution well suited to low energies
  → used as photon detector in nuclear physics (spectroscopy)

Number of electron-hole pairs: $N = \frac{E_0}{W}$ ← 2.9 eV Ge

Energy deposited in active medium (E_0) does not fluctuate
→ N is not statistically independent from event to event

⇒ $$\frac{\sigma(E)}{E} \sim \frac{\sqrt{F}}{\sqrt{N}}$$

F < 1 is Fano factor
F=0.13 in Ge

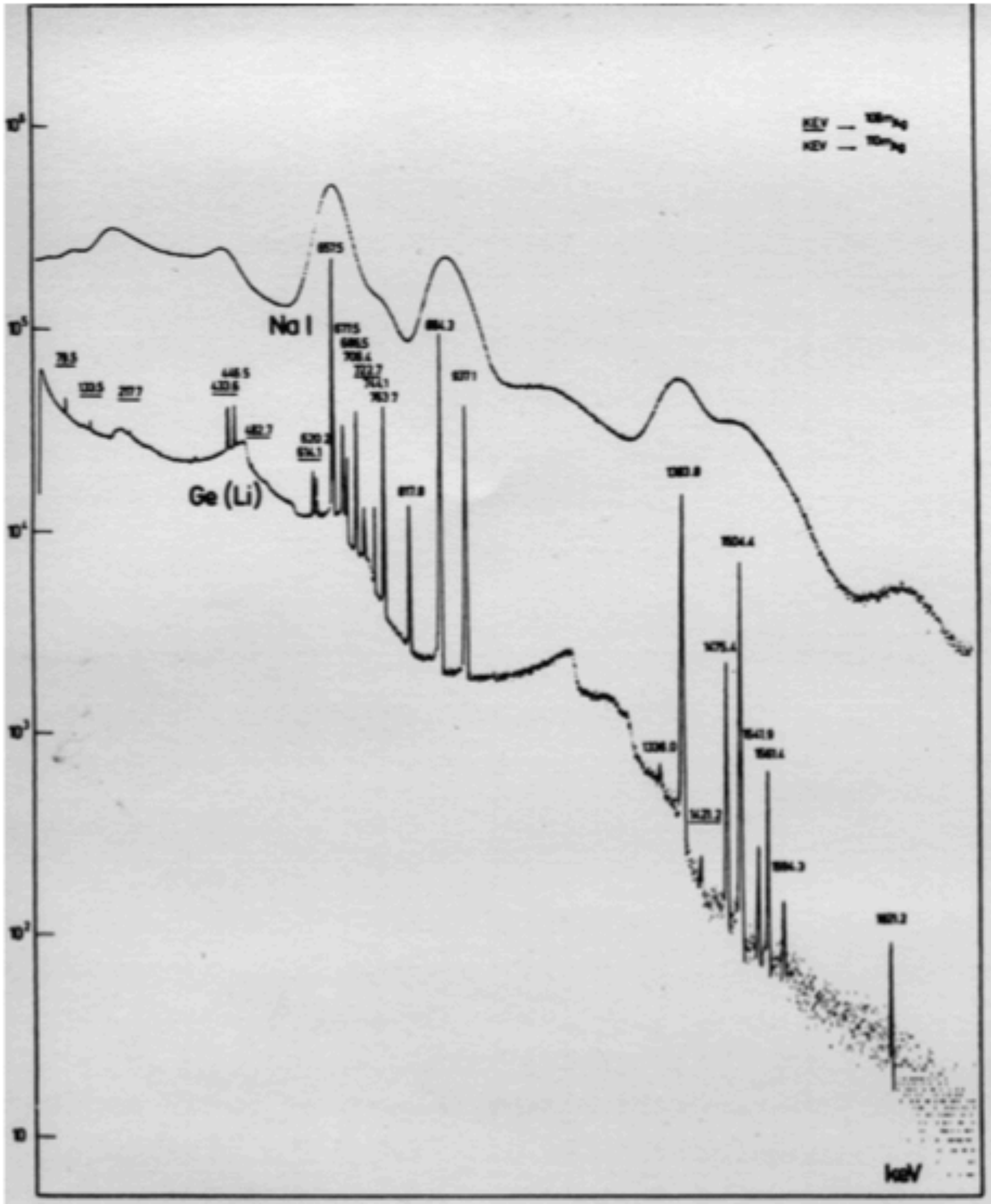
Example : γ $E_0 = 1$ MeV → $N = 3.3 \times 10^5$

$1/\sqrt{N} \approx 1.7$ KeV

$\sqrt{F}/\sqrt{N} \approx 630$ eV

measured : ≈ 550 eV

Response of NaI scintillator and Ge detector to γ source.



Cerenkov calorimeters

- Cerenkov light produced if $v > \frac{c}{n}$ → dielectric materials with high refractive index n > 1 used
- **Cerenkov light produced in a cone:**

  $\cos\theta \sim c/\,vn$

Number of emitted photons:

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

- Cerenkov detectors used for

  -- particle identification (for given p, v depends on m)

  -- calorimeters : collect light from relativistic $e^{\pm}$
- Example: lead glass (Pb O):

  -- cheap (<1 $ / cc), easy to handle

  -- poor radiation resistance (~100 Gy) → not used at LHC

  -- non-compensating (insensitive to slow nuclear fragments)

  -- worst energy resolution of all homogeneous calorimeters

  ↑ Light yield $\sim 10^4$ smaller than scintillators :

  -- Cerenkov threshold

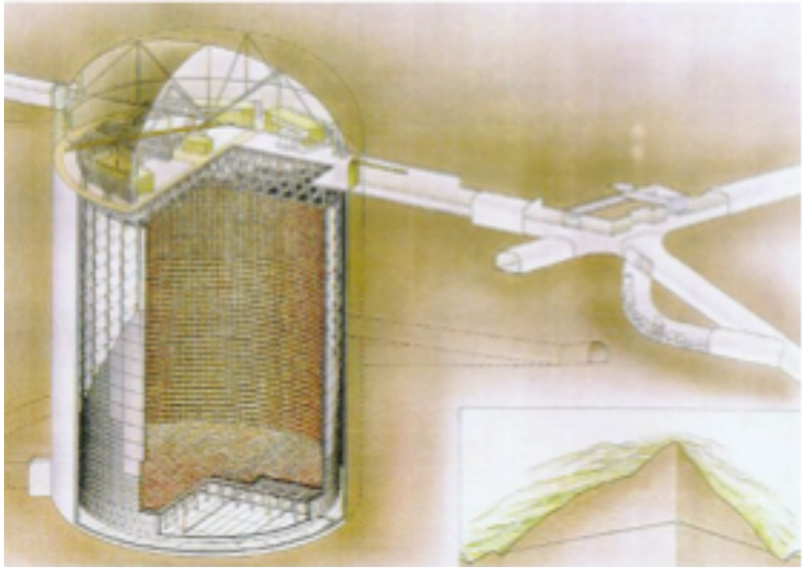
  -- max intensity for $\lambda < 300$-350 nm, most photocathodes sensitive to 300-600 nm.

Pb O : ~ 1000 photoelectrons / GeV → $\sigma/E > 3.2\%/\sqrt{E}$

Furthermore: blue part of spectrum absorbed by PbO → different energy output for showers developing early or late (→ filters)

OPAL Pb O end -cap : $\sigma / E \sim 5\%/\sqrt{E}$

Super-Kamiokande water Cerenkov

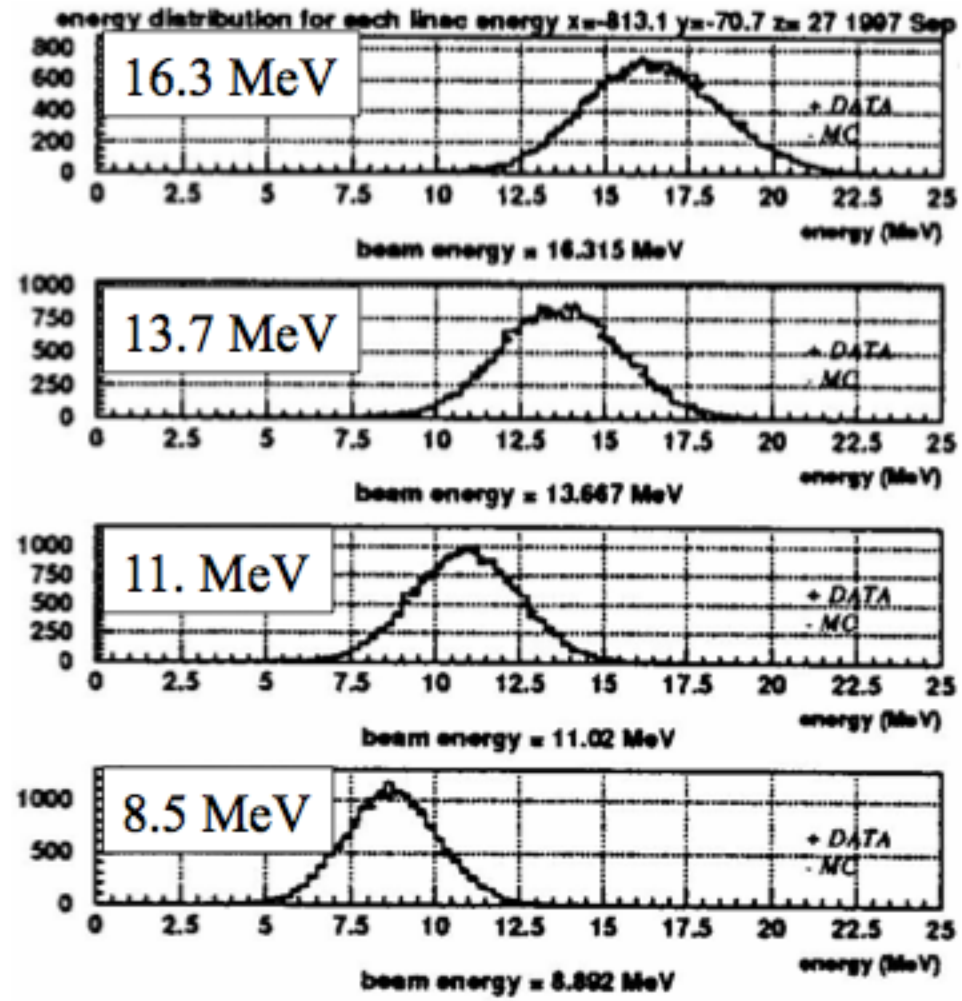


50 kton pure water read out by
~ 12 000 phototubes

One of goals : measure ^{8}B solar neutrinos by detecting electrons with 5 MeV < E < 20 MeV

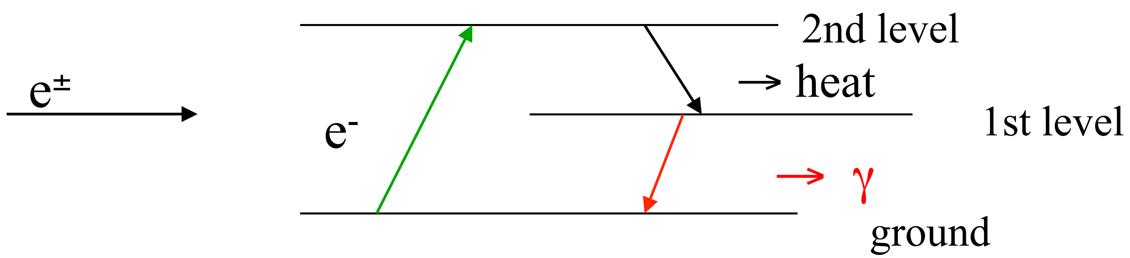
Uniformity and stability of response vs position and timeto ± 0.5 % to avoid distortions in measured spectrum.

LINAC: injects electrons of 7 different energies at 6 different positions



Scintillator calorimeters

❶ Organic scintillators



-- light emission from excited molecules

-- absorption and emission spectra well separated in λ
→ long light attenuation length

-- binary systems: organic solvent (e.g. mineral oil) + <1% of scintillating solute. Solvent molecules excited by incident particle → transfer excitation to solute (e.g. through dipole-dipole interactions) → solute scintillates
→ absorption and emission spectra even more separated

-- fast excitation/emission process → fast response

-- but: small light output because of small solute concentration

-- not much used for homogeneous calorimeters but as active medium of sampling calorimeters

❷ Inorganic crystals

-- ionization tracks produce electron-hole pairs in conduction -valence band
→ photons produced by electron returns to valence band

-- λ of emitted radiation and response time depend on lattice structure
(e.g. gap valence-conduction band, electron migration in crystal, etc.)

-- usually doped with tiny amounts of impurities (e.g. Tl): create additional activation sites in the gap between conduction-valence band, which can be excited and de-excited → increase light yield and speed of response, change frequency to match with photocathode sensitivity

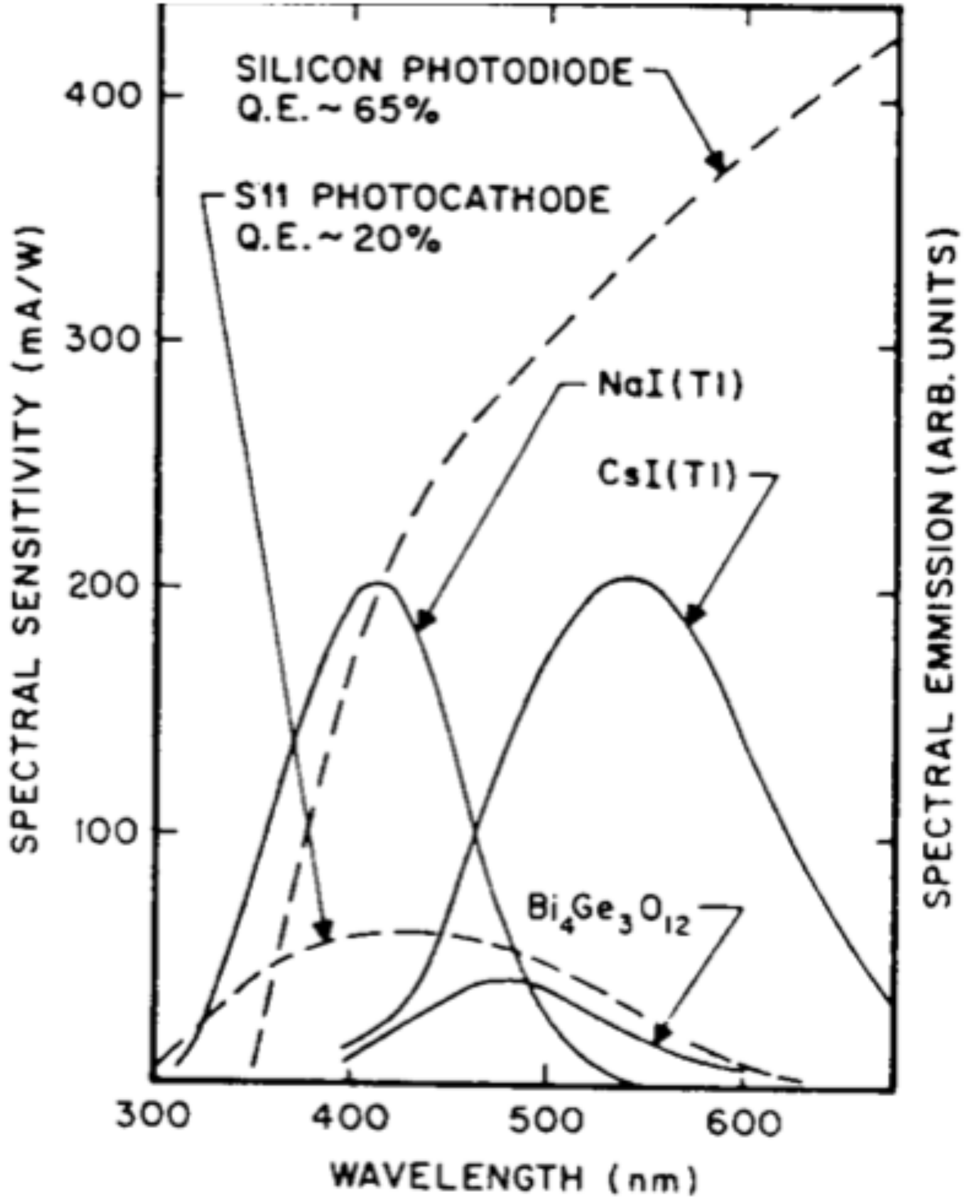
Excellent energy resolution : light yield much larger than in Cerenkov (lower cut-off energy):

$$\frac{\sigma}{E} \sim \sqrt{\frac{FW}{E}}$$

W ≡ energy needed to create electron-hole pair

Inefficiencies in light collection (γ absorption, reflections, bad matching between optical elements) must be minimised

Emission spectra of CsI (Tl), NaI (Tl), BGO and sensitivity of photodiodes and photocathodes



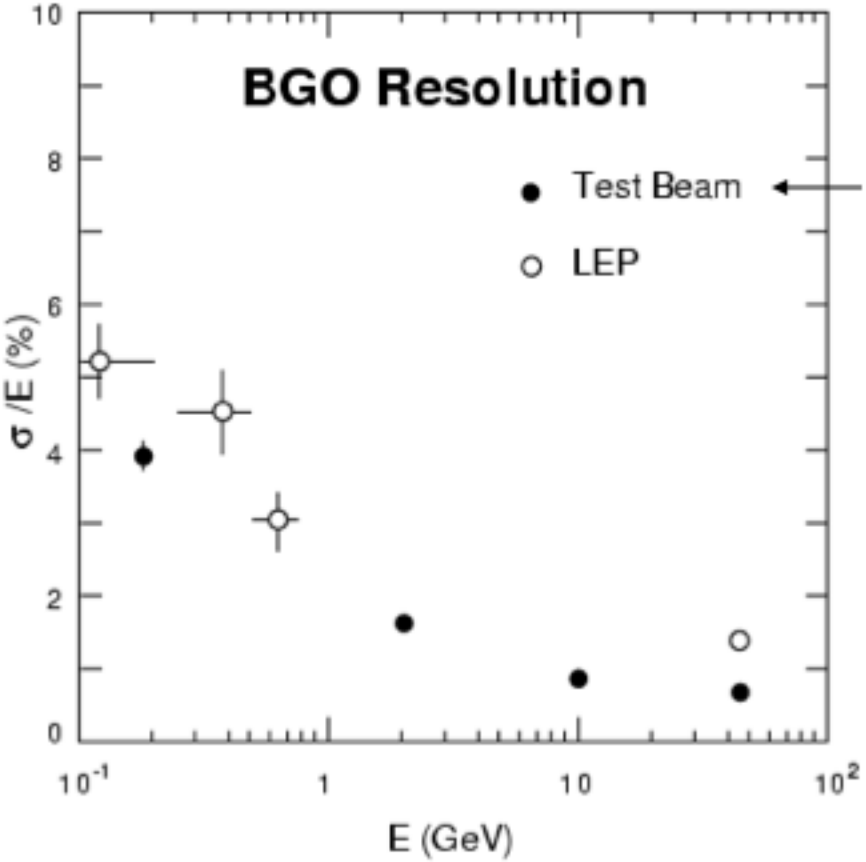
	NaI (Tl)	CsI (Tl)	CsI	BGO	$PBW0_4$
Density (g/cm³)	3.67	4.51	4.51	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.8	3.5	3.5	2.33	2.2
Emission peak (nm)	410	560	420 310	480	440
Decay time (ns) fast and slow	230	940	6 35	60 300	5 15
Light yield γ / MeV	$4\ 10^4$	$5\ 10^4$	$4\ 10^4$	$8\ 10^3$	$1.5\ 10^2$
Yield in pe (relative to NaI)	100	45	5.6 2.3	9	1.3
Rad. hardness (Gy)	1	10	10^3	1	10^5

Some crystals : complex emission Spectra with several components of different λ and decay time
→ optical filters allow suppression of slow components

- NaI widely used in the past (cheap, large light yield, λ well matched to photocathodes)
  However: low density and hygroscopic → not suited to big experiment
- CsI : Belle, BaBar, KTeV, etc. Large light output, dense. Pure CsI has fast component (→ KTeV). CsI (Tl): slow but more light (→ BaBar)
- $PbWO_4$: short X_0 , fast, rad hard → CMS

L3 BGO calorimeter

BGO ≡ bismuth germanate $Bi_4Ge_3O_{12}$

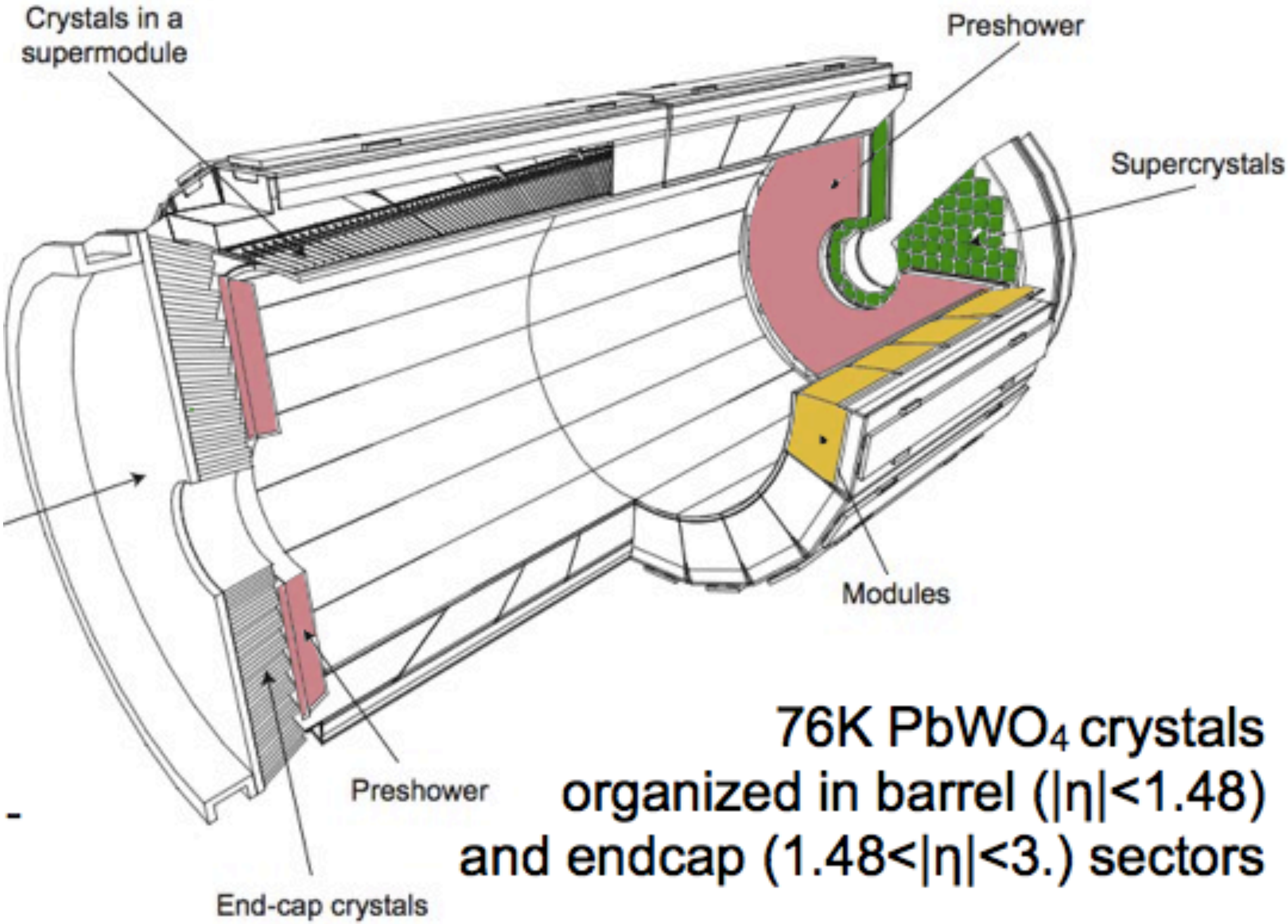


$$\frac{\sigma}{E} \cong \frac{1.5\%}{\sqrt{E}} \oplus 0.4\%$$

Biggest crystal calorimeter in operation before CMS:
~10 000 crystals, transverse cell size 2x2 cm^2

At LEP: constant term ~ 1% (temperature map, cell-to-cell calibration, crystal boundaries)
→ difficult to operate calorimeters with excellent intrinsic resolution in large systems (good control of constant term needed)

CMS $PbWO_4$ calorimeter

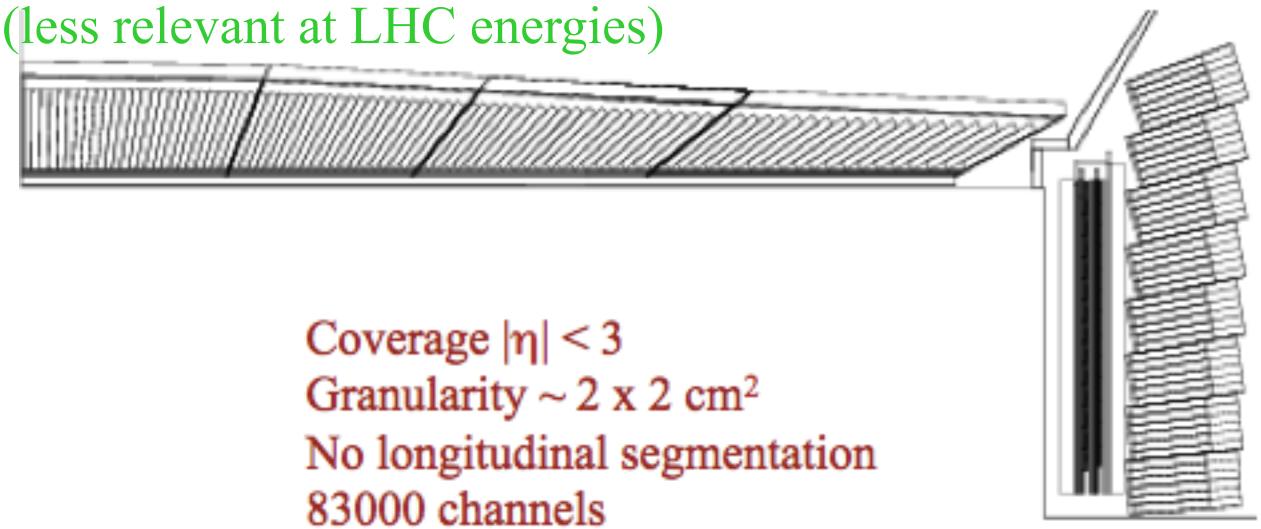


76K $PbWO_4$ crystals
organized in barrel ($|\eta|<1.48$)
and endcap ($1.48<|\eta|<3.$) sectors

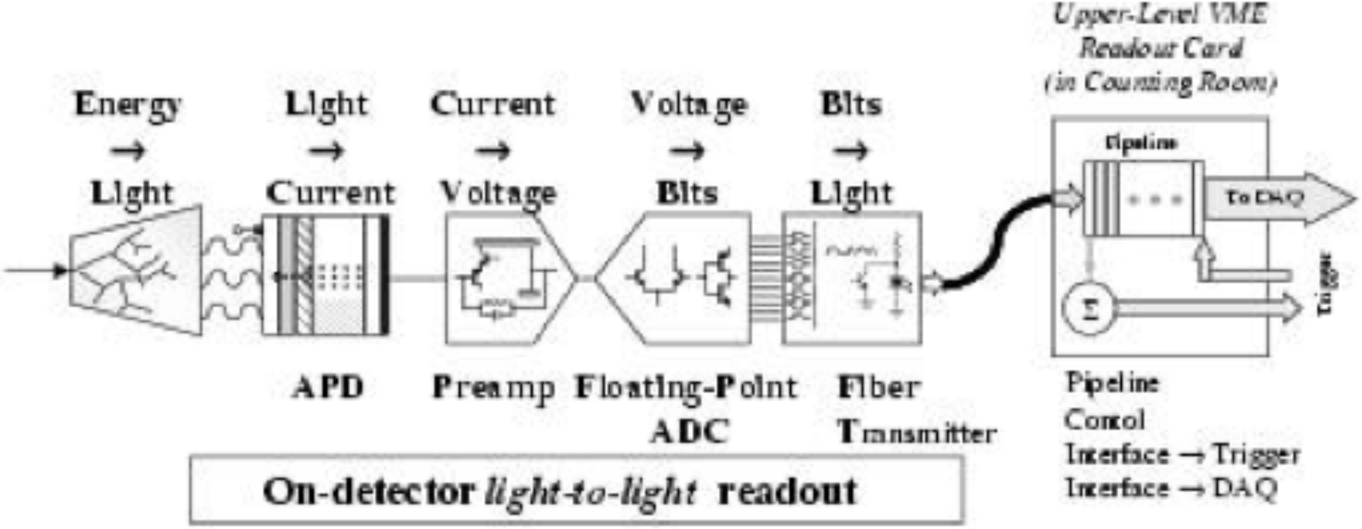
$PbWO_4$ crystals

- Motivation : excellent energy resolution (e.g. for H → γγ)
- X_0 = 0.89 cm → compact calorimeter (crystal length 23 cm = 26 X_0) fitting inside solenoid
- R_M=2.2 cm → small lateral shower size → minimise pile-up and noise contribution
- Emission peak and decay time: ~ 440 nm 80% of light in < 15 ns → fast
- Light yield : 150 γ / MeV small !! → goal 4000 pe / GeV (2000 pe/GeV achieved)
  Attenuation length : 3 m
- Radiation hardness : 10^5 Gy → ok for LHC environment

➡ denser, faster, harder than other crystals. but smaller light yield (less relevant at LHC energies)



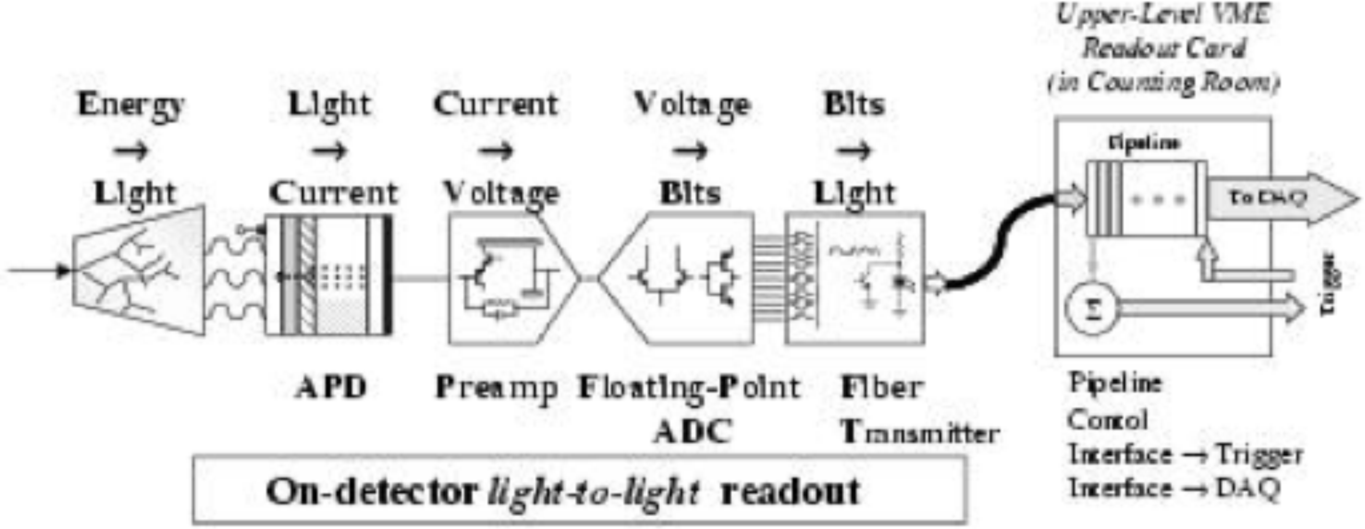
Coverage |η| < 3
Granularity ~ 2 x 2 cm²
No longitudinal segmentation
83000 channels



- Avalanche Photo Diodes (barrel): -- operate in B= 4 T -- size 50 mm^2 (1/10 of crystal surface)
  -- quantum efficiency : ~ 80% at 440 nm -- high gain devices : 50 (electrons in p-n junction undergo avalanche multiplication) needed because of $PbWO_4$ small light yield (high noise)
  -- rad hard -- but : -2% gain variation per degree → requires T regulation to < 0.1 ^{0}C
  - 2% gain variation per volt → requires bias V control to 40 mV

- 4-gain preamp + shaper (shaping time 40 ns)
- 40 MHz 12-bit ADC
- 800 Mbit/s digital optical links (one per channel)
- Digital pipeline: event stored while waiting for trigger decision (~ 2.5 μs)
- Electronic chain + temperature regulation system: ~ 25 cm

⟹ The challeng has been ~ fully digital readout chain

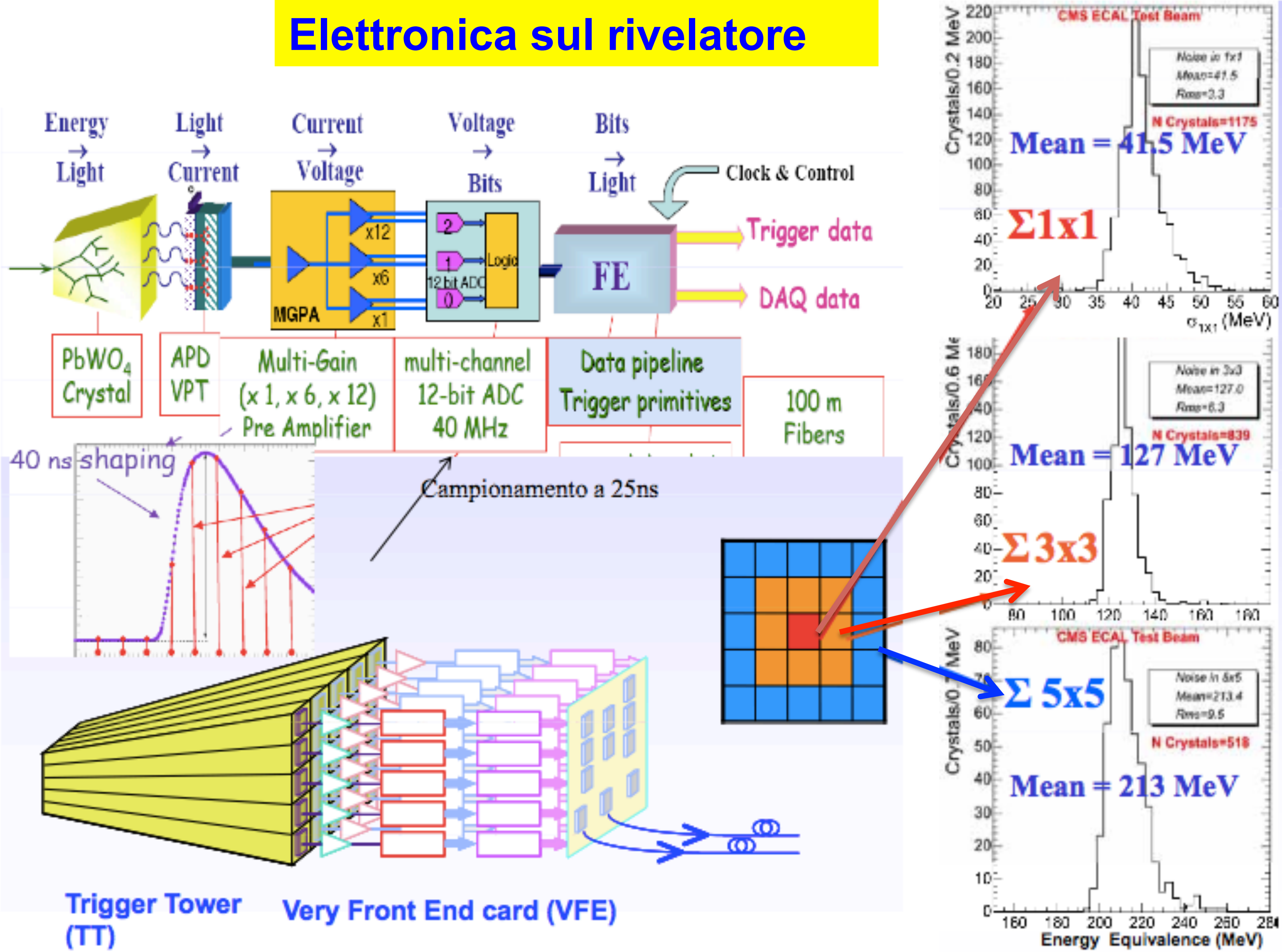


- Avalanche Photo Diodes (barrel): -- operate in B= 4 T -- size 50 mm^2 (1/10 of crystal surface)
  -- quantum efficiency : ~ 80% at 440 nm -- high gain devices : 50 (electrons in p-n junction undergo avalanche multiplication) needed because of $PbWO_4$ small light yield (high noise)
  -- rad hard -- but : -2% gain variation per degree → requires T regulation to < 0.1 ^{0}C
  - 2% gain variation per volt → requires bias V control to 40 mV

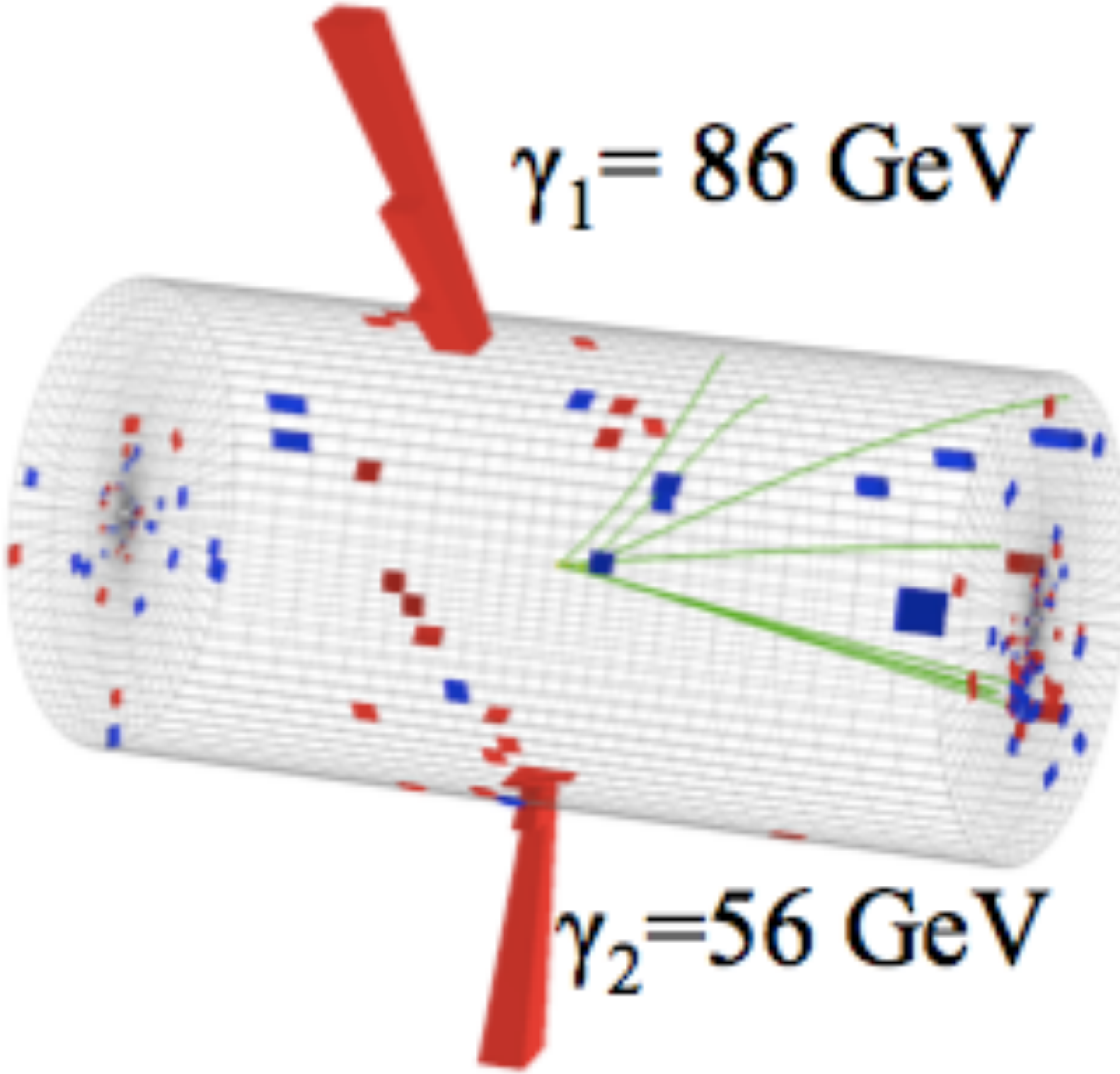
- 4-gain preamp + shaper (shaping time 40 ns)
- 40 MHz 12-bit ADC
- 800 Mbit/s digital optical links (one per channel)
- Digital pipeline: event stored while waiting for trigger decision (~ 2.5 μs)
- Electronic chain + temperature regulation system: ~ 25 cm

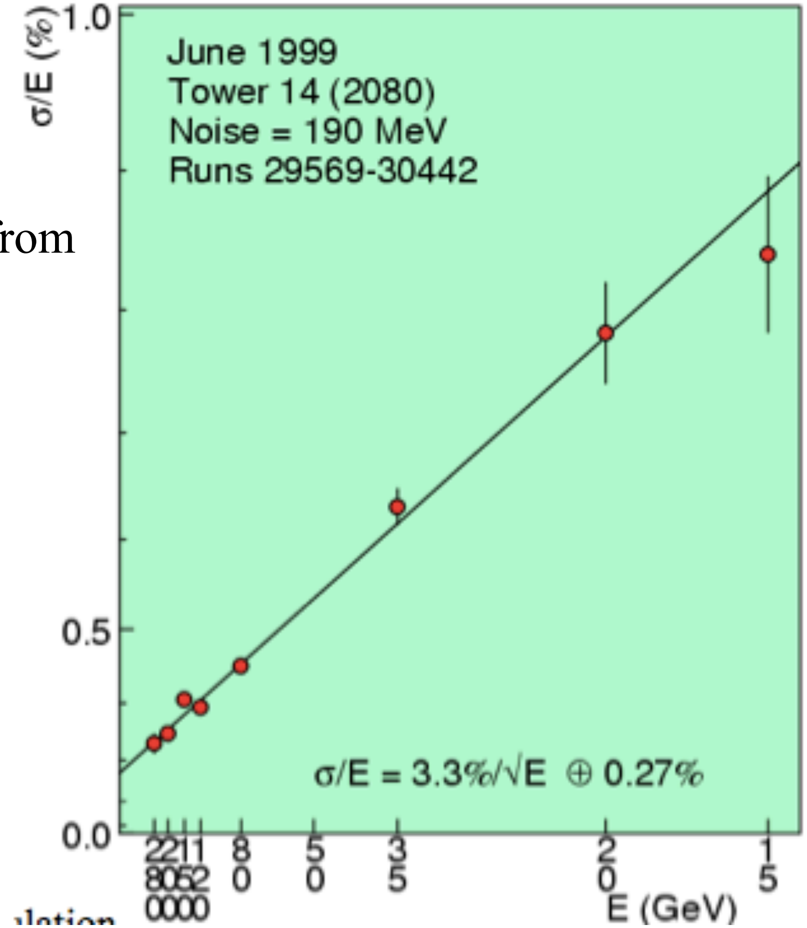
⟹ The challeng has been ~ fully digital readout chain

Elettronica sul rivelatore

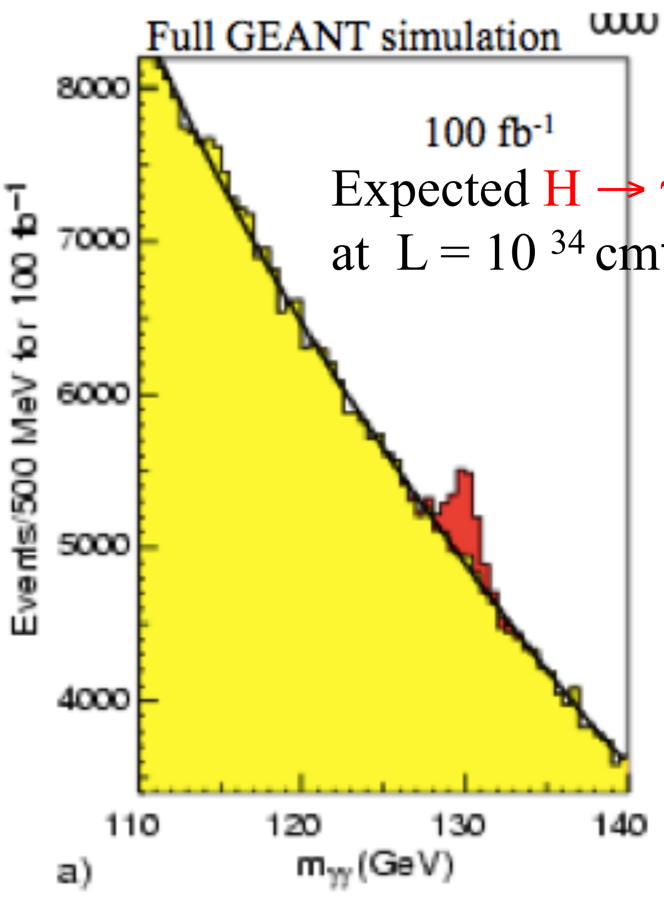


Evento di CMS con due fotoni





Electron energy resolution from test beam of prototypes



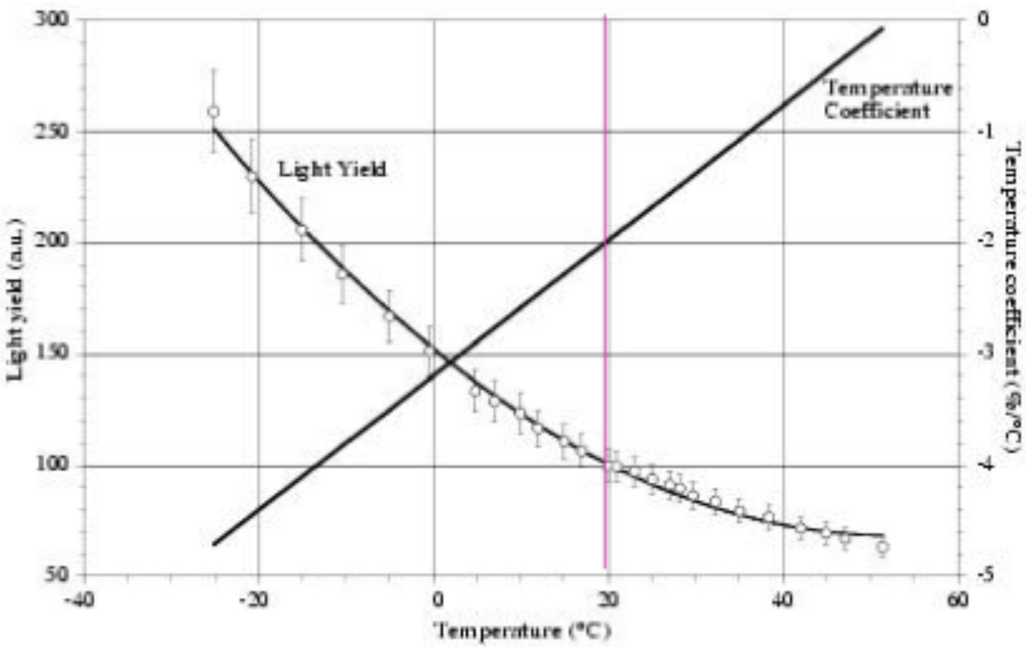
Expected H → γγ signal at $L = 10^{34}\ cm^{-2}\ s^{-1}$

Mass resolution (m_H=100 GeV):	
stochastic term	270 MeV
constant term (0.5%)	390 MeV
electronic noise	300 MeV
pile-up + angle from tracks	400 MeV
Total	~700 MeV

What is the challenge of the CMS calorimeter ?

Achieve a constant term of ~ 0.5%, i.e. minimise non-uniformitites from:

- light collection vs R, trapezoidal shape, etc.
- radiation damage: affects transparency of crystal (not light yield). Damage depends on R and shower longitudinal profile fluctuates. Short term variation: response drop > 2% over one LHC fill (recovery in between fills). Monitored with laser.
- temperature: crystal response drops by 2% per degree at room temperature (in addition to APD) → T must be monitored to < 0.1 ^{0}C



Calibration:

- each crystal calibrated on test beam
- laser system to check light transmission
- *in situ* calibration with Z → ee and E/p

Noble liquid calorimeters

Energy released by charged particles in noble liquid (Ar, Kr, Xe):

part → charge signal

part → scintillation : fast signals (~10 ns) λ=120-170 nm from recombination of electron-ion pairs

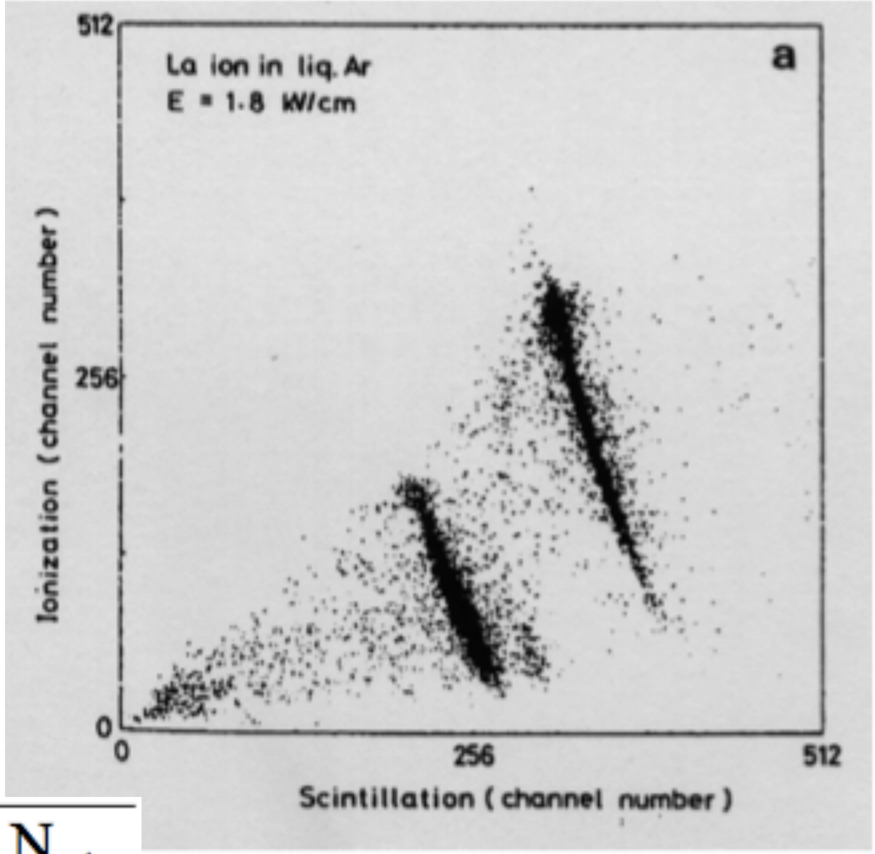
- Sampling calorimeters: only charge collected (large HV applied through gap → no recombination) . Argon most commonly used (cheap, high purity)

◆ Radiation hard

- Homogeneous calorimeters: Krypton most commonly used (short X_0 → compact detector) Note: Xe is rare → cost and procurement problems

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.77
E_C (Mev)	41.7	21.5	14.5
R_M (cm)	7.2	4.7	4.2
W (eV/pair)	23.3	20.5	15.6
v drift (mm/μs)	10	5	3

Best resolution in homogeneous calorimeters would be obtained by collecting both charge and light signals



Never realized in big systems (technically difficult), only small-scale prototypes

However: excellent performance with charge signal only (all energy is absorbed → Fano factor):

$N = N_{ion} + N_{scint}$ N does not fluctuate

→ fluctuation on N_{ion} (binomial):

$$\sigma(N_{ion}) = \sqrt{N \frac{N_{ion}}{N} \frac{N_{scint}}{N}}$$

If for instance $N_{ion} / N = 0.9$ → $\sigma(N_{ion}) \approx 0.3\sqrt{N}$

i.e. resolution factor ~ 3 better than $1/\sqrt{N}$

Note : drawback of noble liquid calorimeters : cryogenics, purity

Sampling calorimeters

Due to sampling fluctuations: energy resolution worse than homogeneous calorimeters.
E.g. 5-20% / $\sqrt{E}$ for EM calorimeters.

BUT

- Well established technique for large systems → most widely used
- Easier to segment longitudinally and laterally than homogeneous calorimeters
  → usually better space/angular resolution and particle identification capability.

- Most popular options for hadronic calorimeters:
  -- fluctuations from strong interactions are larger than sampling fluctuations
  -- easier to compensate :
  e / h tunable using absorber and/or active medium composition and thickness
  -- offer enough λ with reasonable thickness (< 2 m)

Classification by active medium:

-- gas
-- liquid (warm, cold)
-- solid (e.g. Si)
} → charge

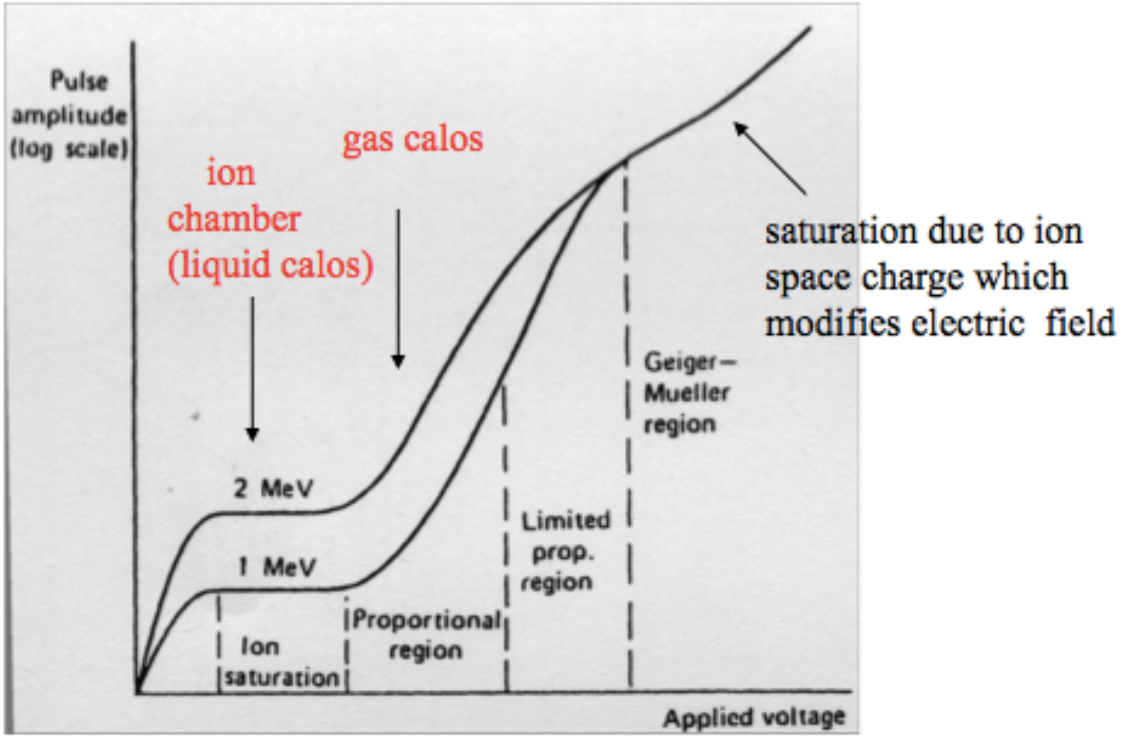
-- scintillator → light

Absorber : high Z material (e.g. Pb, Fe)

Gas calorimeters

- Low cost, flexible, easy to segment, widely used in the past (e.g. LEP).
- However: not well suited for new machines.
- Usually modest energy resolution (> 10%/√E): Landau and path length fluctuations
- Low-density of active medium (sampling fraction < 1%)

→ need to work in proportional mode to get enough signal and good S/N ratio



Proportional mode: HV~10^6 V / m gives gains of 10^3-10^5.
However: gain and therefore response very sensitive to wire diameter and position, gas P, T and purity, HV control, etc. → difficult to get response stability and uniformity to << 1% and constant term of < 1% (especially at hadron colliders)

Liquid calorimeters

Two types:

-- **cryogenic liquids** (e.g. Ar, Kr) ; -- **warm liquids** (e.g. TMP≡ tetramethylpentane)

poor radiation resistance, purity problems, no big system with this technique and some historical failure (UA1 U - TMP calo)
→ not discussed here

Advantages of sampling calorimeters with cryogenic liquids:

-- dense: 1.4 g/cm^3 (LAr), 2.5 g/cm^3 (LKr)
→ enough charge to work in ion chamber mode
→ unity gain with no electron amplification
→ uniform

-- easy to calibrate (only readout chain)

-- good energy resolution : ≤ 10% / √E

-- stable with time, robust

-- radiation hard

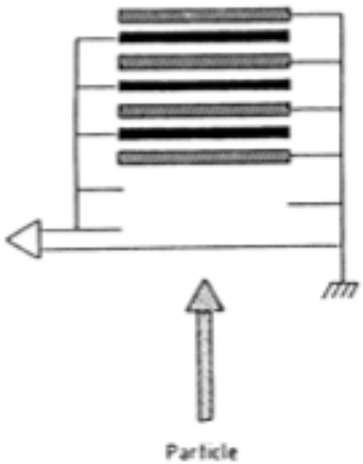
-- well established technique for big systems: →

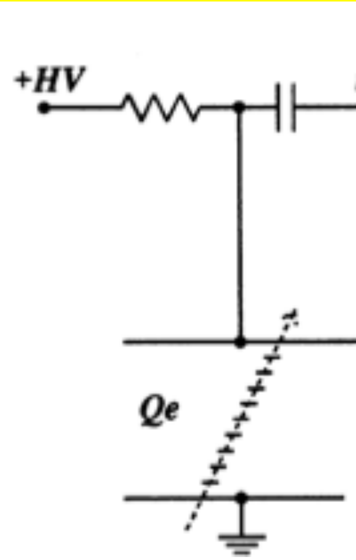
First LAr sampling calorimeter: Willis and Radeka, 1974 (R807 / ISR)
Since then: Mark II, Cello, NA31, SLD, Helios, D0, H1, etc.

Disadvantages:

-- cryogenics
-- purity
-- slow (exception : Accordion calorimter)

Principle of work of a liquid ion chamber





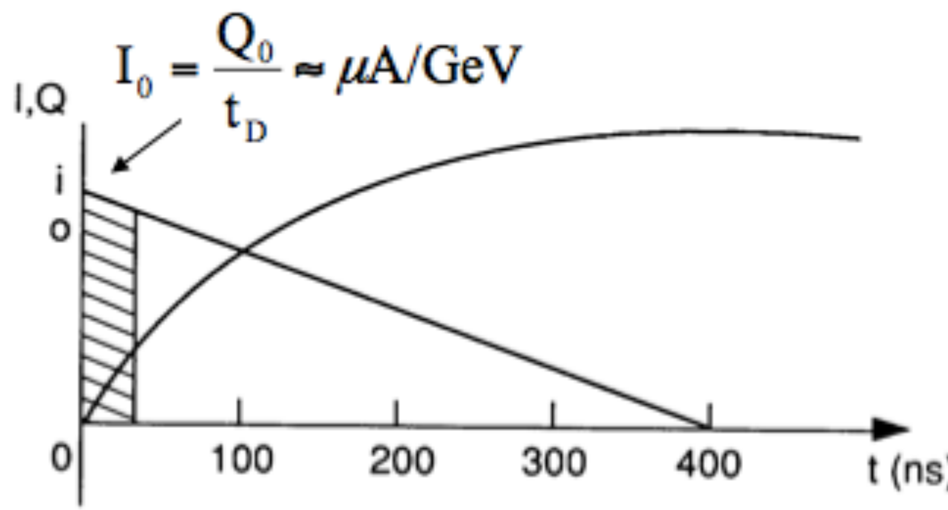
LAr gap

$t_D \approx 400$ ns
for gap = 2 mm and
HV=2kV ($v_d \approx 5$ mm/μs)

For uniform ionisation over gap:

$$I(t) = I_0\,(1 - \frac{t}{t_D})$$

$$Q(t) = Q_0\,[\frac{t}{t_D} - \frac{1}{2}(\frac{t}{t_D})^2]$$

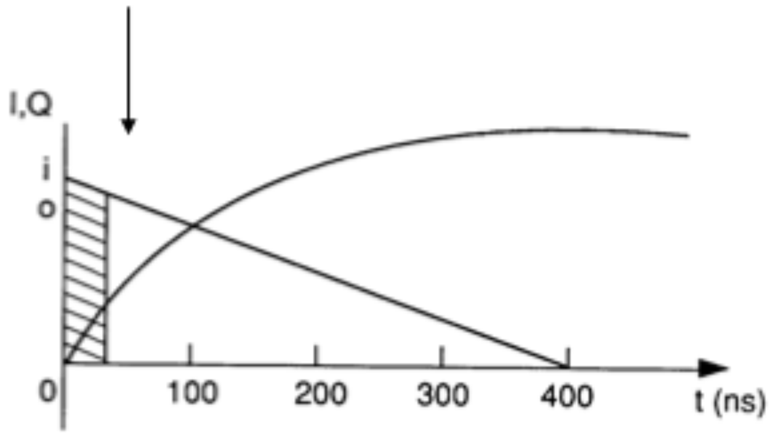


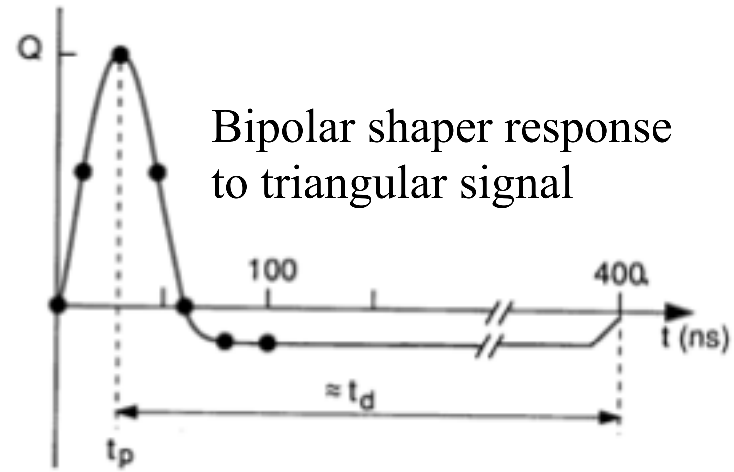
Current rise time: ~ 1 ns ≈ shower development time

However: total charge collected in 400 ns→ slow detector → can not be used at LHC (unfortunately, since all the other features are well suited !)

How to make a liquid calorimeter fast ?

Integrate the current over time $t_p << t_D$ ($t_p \sim 40$ ns)





Bipolar shaper response to triangular signal

Drawback: S / N is smaller than in the case $t_p = t_D$

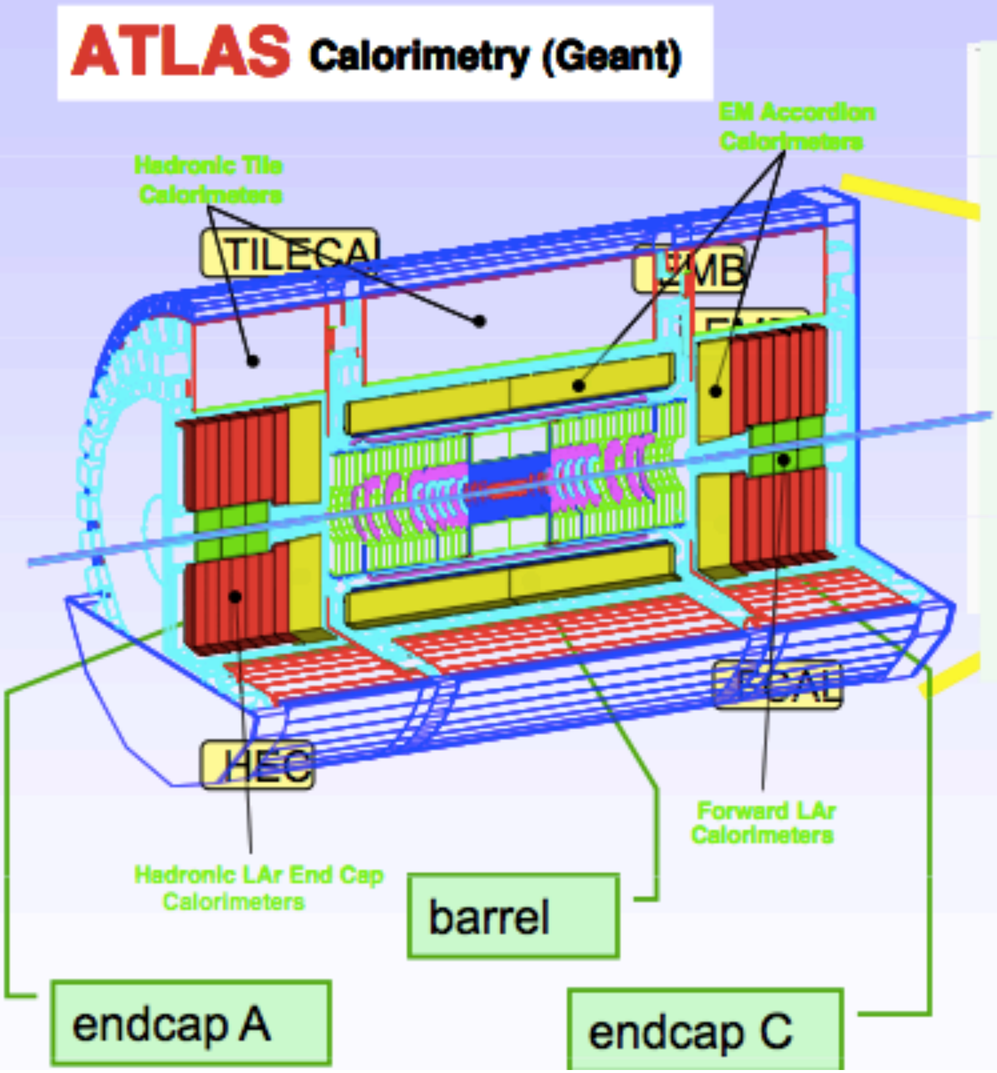
$$S \sim t_p, N \sim \frac{1}{\sqrt{t_p}} \Rightarrow \frac{S}{N} \sim t_p^{3/2}$$

→ detector response time is not t_D but t_p

~30 smaller for 40 ns than for 400 ns

→ can only work if transfer time from electrode to the preamplifier is much smaller than t_p i.e. if cables and connections (→ capacitance and inductance→ long time constant of the circuit) minimised.

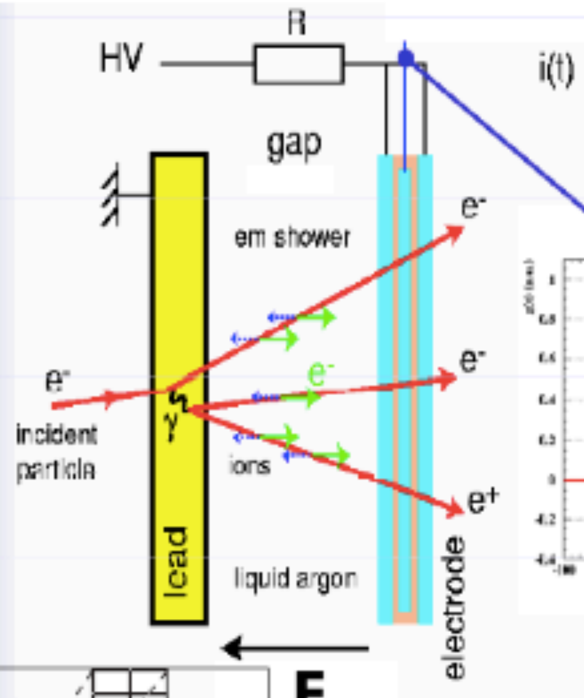
Calorimetria di ATLAS

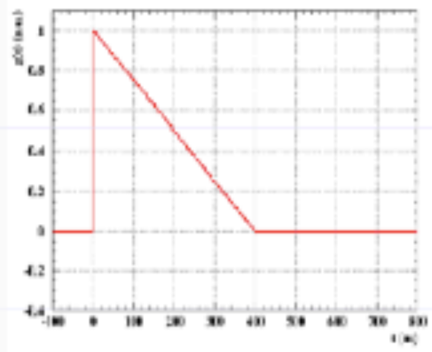


- Calorimetro a campionamento piombo-argon liquido
  - Giometria Accordion (fisarmonica)
  - Segnale da carica di ionizzazione
- Lavora a freddo (circa 90 K) fra due criostati:
- Precampionamento for $|\eta|<1.8$:
  - Layer attivo of Lar (11 mm gap nel barrel , 4 mm in endcap)
- Grande granulatita' in $2.5<|\eta|<3.2$ and no strips
- ≈190000 channels
- Il calorimetro e' fuori dal solenoide

EMB: 2 half-barrel ($|\eta|<1.4$)
EMEC: 2 end-cap ($1.4<|\eta|<3.2$)

Principio di Funzionamento di ECAL

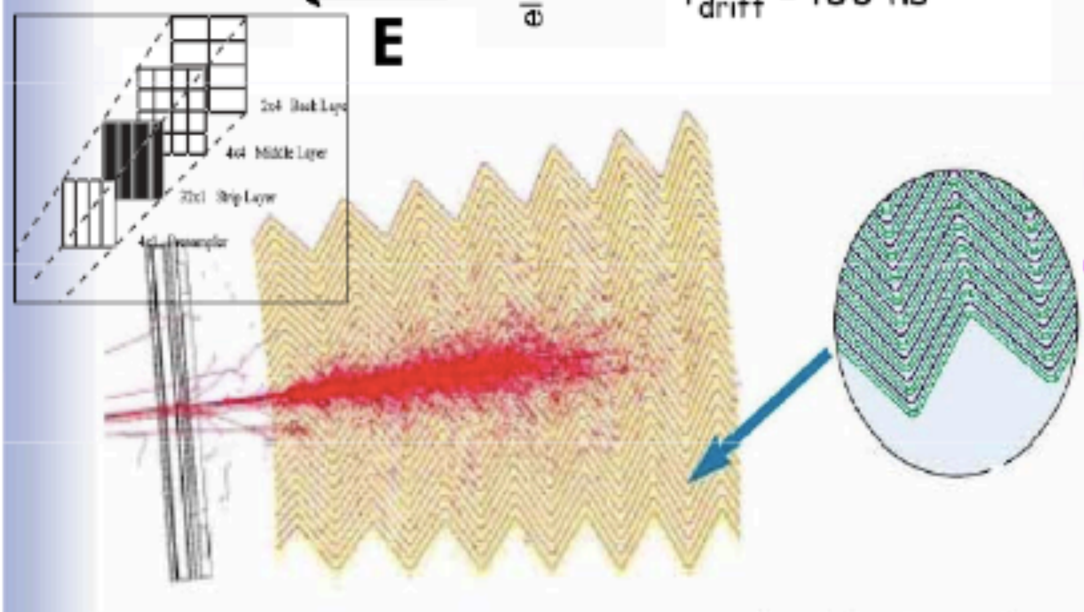


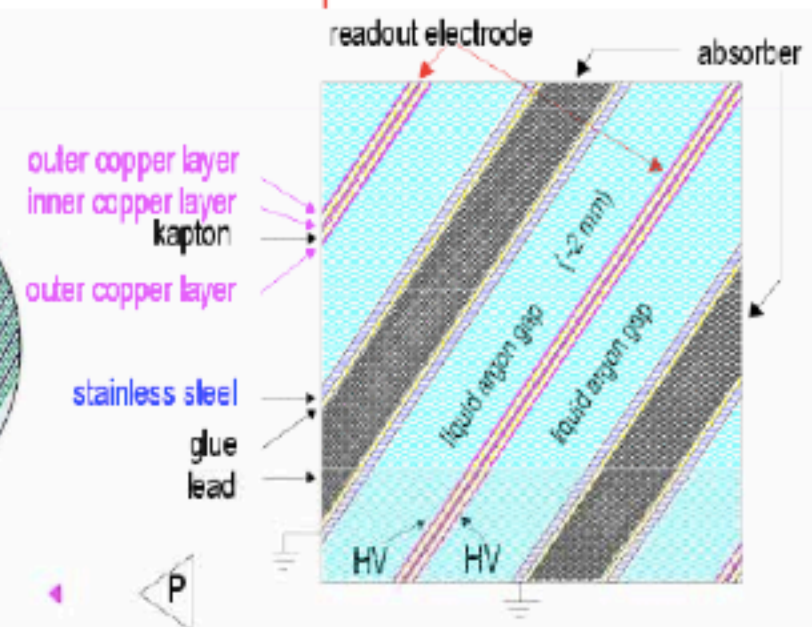


- Accordion shape in EM barrel and end cap calorimeters (>22X_0)
- 2 wheels (16 modules) in the barrel and 1 wheel (8 modules) per endcap

Main advantages

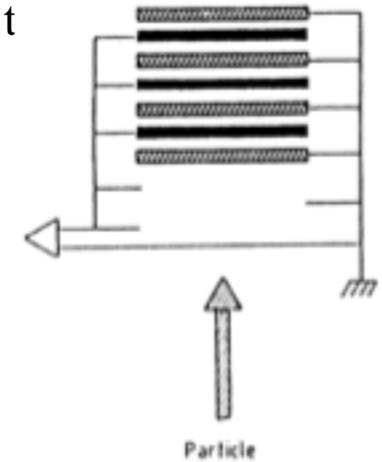
- LAr as act. material inherently linear
- Hermetic coverage (no cracks)
- Longitudinal segmentation
- High granularity (Cu etching)
- Inherently radiation hard
- Fast readout possible

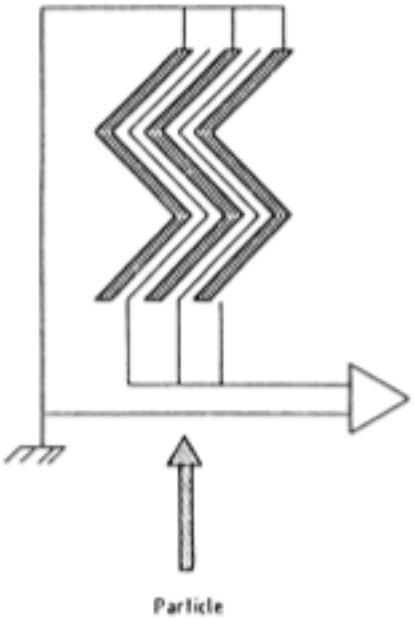




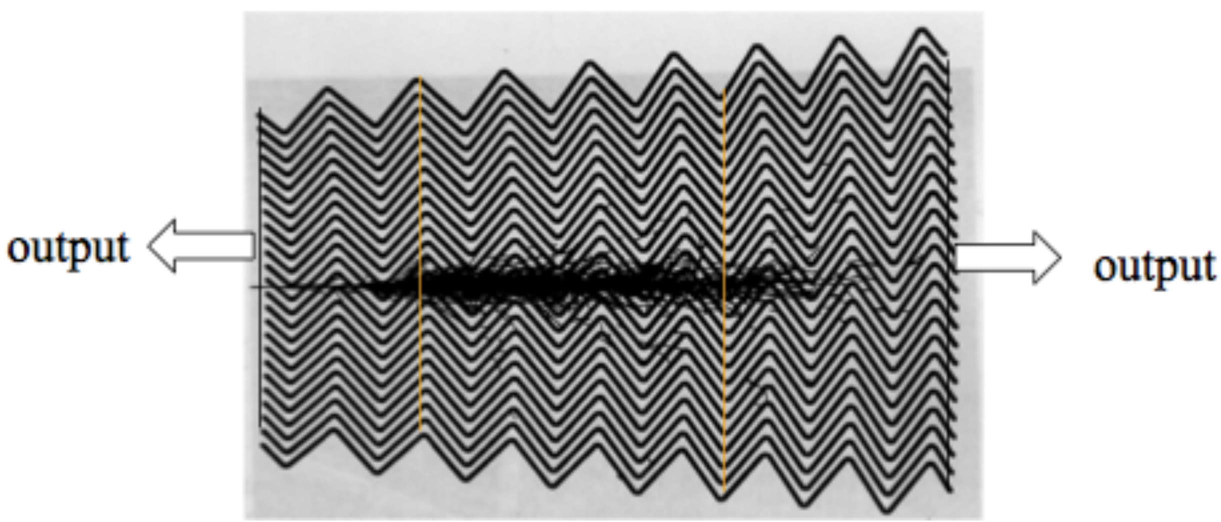
Fast liquid-argon calorimeter: Accordion EM calorimeter of ATLAS

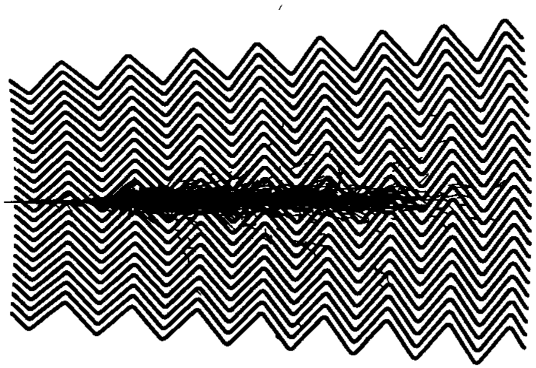
Traditional design: slow response. Electrodes perpendicular t
Long leads to gang together successive layers and to bring signal
to preamps at the end of modules → transfer time several ns.
In addition cables introduce dead space.





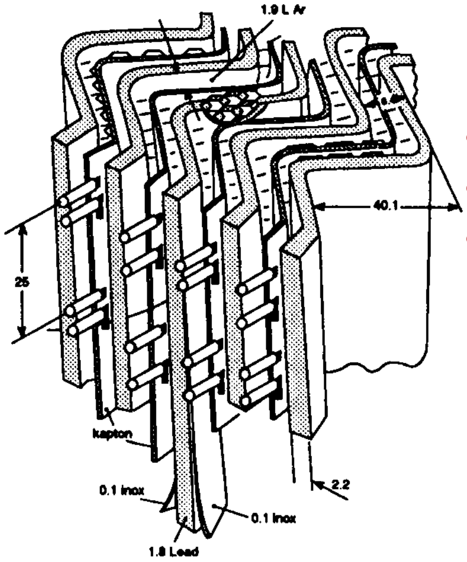
Accordion geometry : fast.
Electrodes parallel to beam.
Signal read out at calo front/back
faces → no additional connections.
Accordion shape avoids channeling.
Longitudinal segmentation obtained
by cutting electrodes longitudinally.
Dead space minimised.



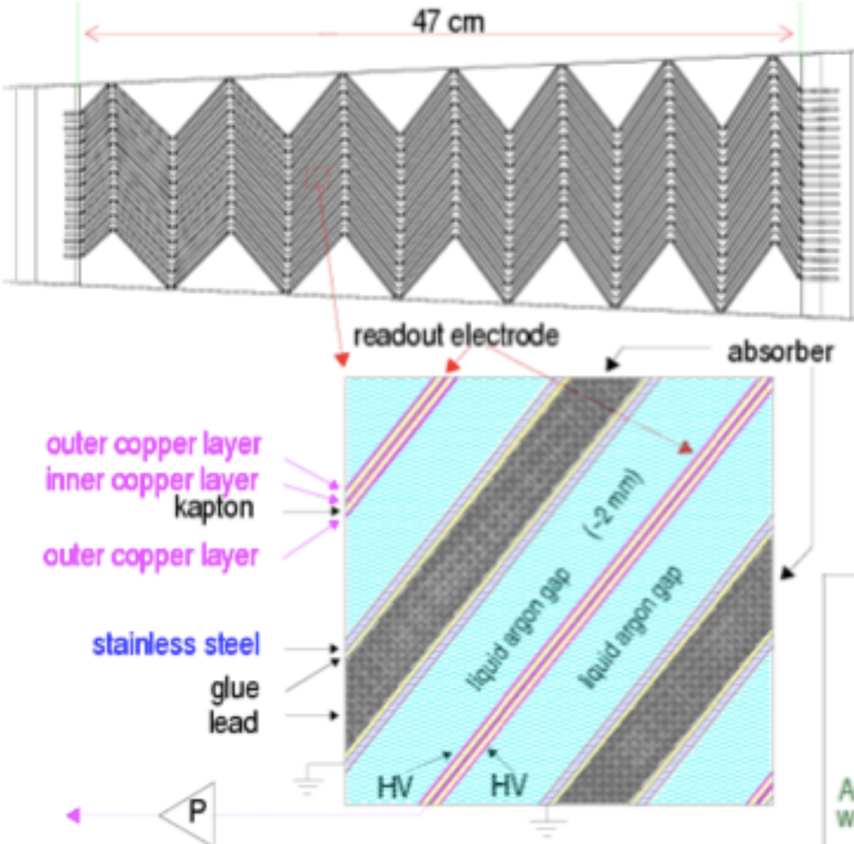


(RD3 / ATLAS)

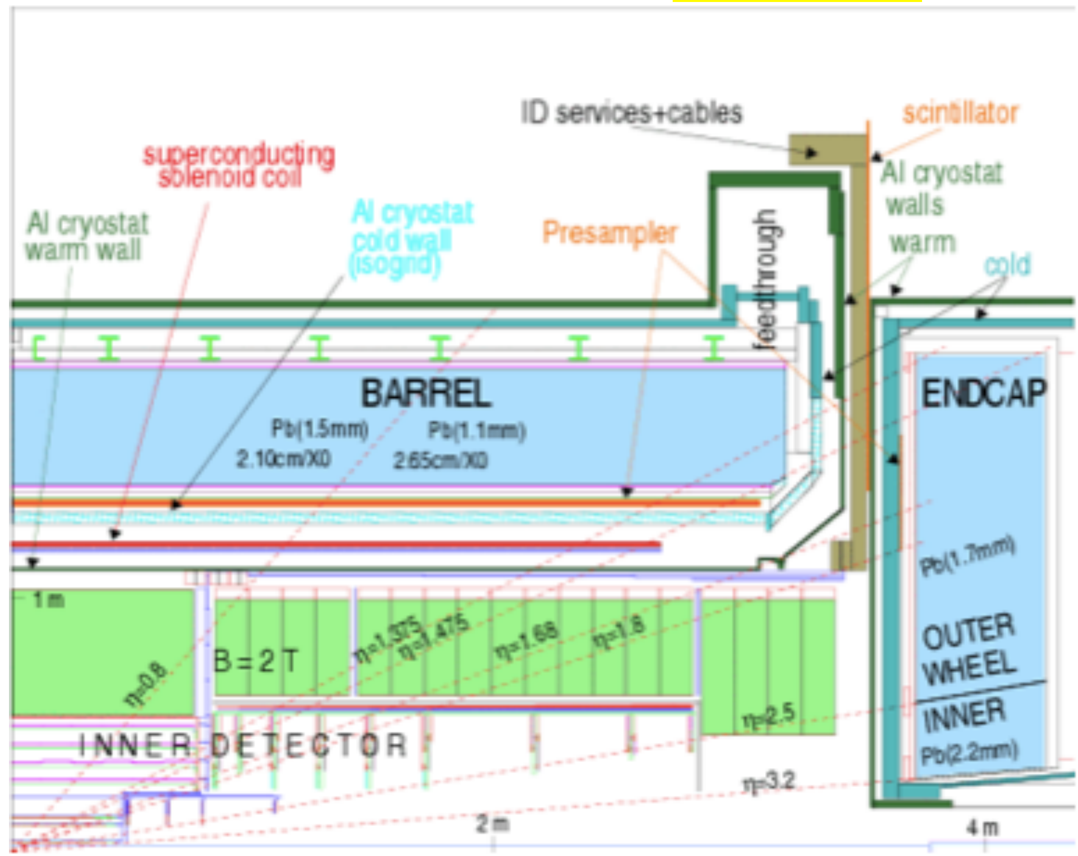
Liquid Argon (90K)
+ lead-steal absorbers (1-2 mm)
+ multilayer copper-polyimide readout boards
→ Ionization chamber.
1 GeV E-deposit → 5 x10^6 e^-



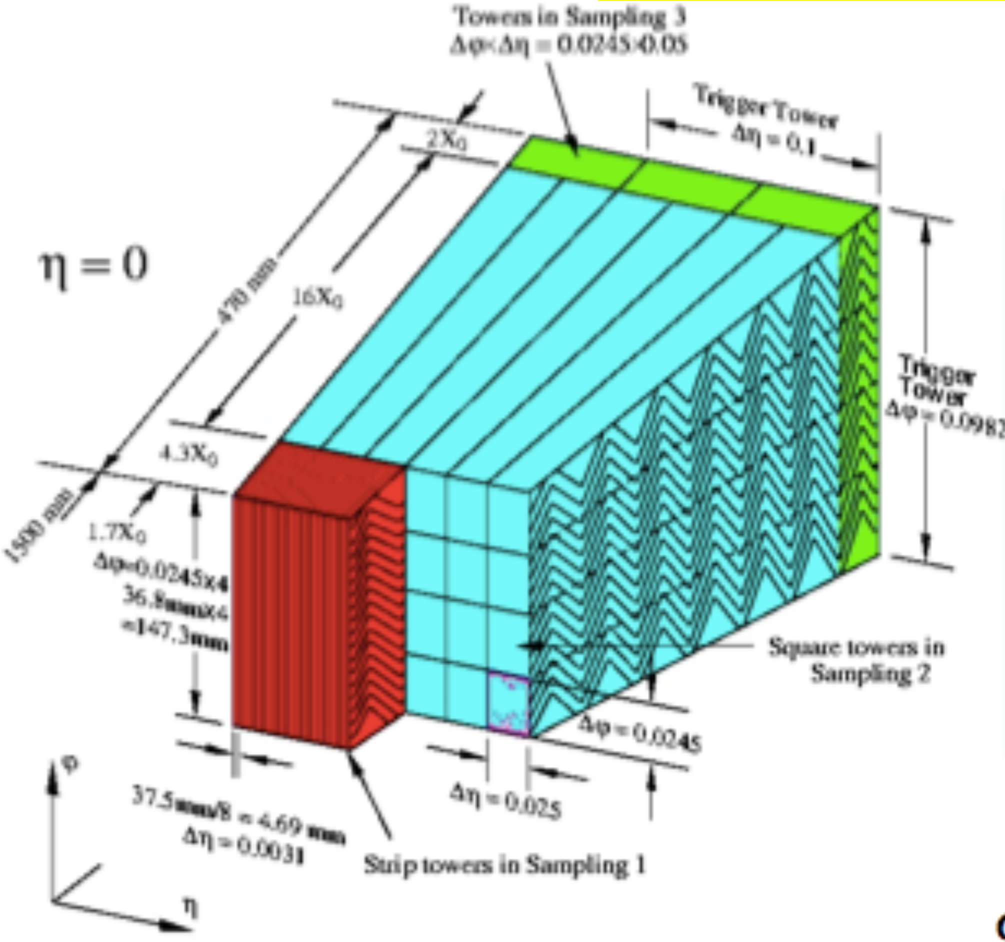
- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs


47 cm
readout electrode
absorber
outer copper layer
inner copper layer
kapton
outer copper layer
stainless steel
glue
lead
liquid argon gap
liquid argon gap
(~2 mm)
HV
HV
P

ATLAS


ID services+cables
scintillator
superconducting solenoid coil
Al cryostat walls
Al cryostat warm wall
Al cryostat cold wall (isognd)
Presampler
warm
cold
feedthrough
BARREL
Pb(1.5mm)
Pb(1.1mm)
2.10cm/X0
2.65cm/X0
ENDCAP
Pb(1.7mm)
OUTER WHEEL
INNER
Pb(2.2mm)
1 m
B = 2 T
η=0.8
η=1.375
η=1.475
η=1.68
η=1.8
η=2.5
η=3.2
INNER DETECTOR
2 m
4 m

calorimetro EM di Atlas



$$\frac{\sigma(E)}{E} = \frac{10\%\left[GeV^{1/2}\right]}{\sqrt{E}} \oplus \frac{300\,MeV}{E} \oplus 0.7\%$$

$(E \text{ in } GeV)$

– calorimetro sampling Pb/Lar

- Parte 1: misura di posizione/angolo
- Parte 2: misura di energia principale
- Parte 3: “tail catcher” identificazione degli sciami lunghi

Fine segmentation and granularity :

-- longitudinally 3 compartments

-- compartment 1 : 4 mm strips in η direction

compartment 2 : ~ 4 x 4 cm^2

compartment 3 : ~ 8 x 4 cm^2 in $\eta \times \phi$

excellent angular/position resolution and particle identification capability

Total: ~ 200 000 channels

Readout: warm preamps + 3-gain shapers (t_p ~ 40 ns) + 40 MHz analog pipeline + 12-bit ADC
Unlike CMS digitization only at the end
(less power consumption but more sensitive to pick-up, x-talk, etc.)

Purity in liquid calorimeters

Electronegative impurities (e.g. O_2, unsaturated Carbon composites)
capture e^- → reduce e^- lifetime → reduce signal

$\lambda_e \equiv$ electron mean free path $\approx 0.15 \frac{E\,(\mathrm{kV/cm})}{p\,(\mathrm{ppm})}$

Experimental parametrisation by H1

E.g. E= 10 kV/cm p =1 ppm
→ $\lambda_e \sim 1.5$ cm

- Careful about:
  -- leaks (even if small) bring oxygen
  -- any material put into the cryostat must be scrutinized: can emit electronegative impurities by out-gassing
  -- innocent materials can out-gas after irradiation
  → any single material in the cryostat must be checked under irradiation for LHC calorimeters

- Ar is best of all liquids:
  -- smallest boiling T : 87 ^{0}K (120 ^{0}K for Kr) → out-gassing reduced (materials are "frozen").
  E.g. teflon can work in LAr, kills signal in LKr
  -- commercial Ar is very pure (~ 0.5 ppm) whereas Kr needs purification
  -- even if polluted can be easily replaced (Kr and Xe are more expensive and rare)

- Purity is not big concern for ATLAS calorimeter: fast shaping reduces sensitivity to impurities by factor ~ 10.

  Drift space ~ 200 μm for t_p ~ 40 ns
  2 mm for t_p ~ 400 ns

  → + 0.5 ppm produces response drop of only 0.2%

  Purity will be monitored with α , β chambers
  + purification system (OXYSORB) available

- Has been major issue for H1 and D0 (integrate over full drift time) : sophisticated system of probes and monitors.

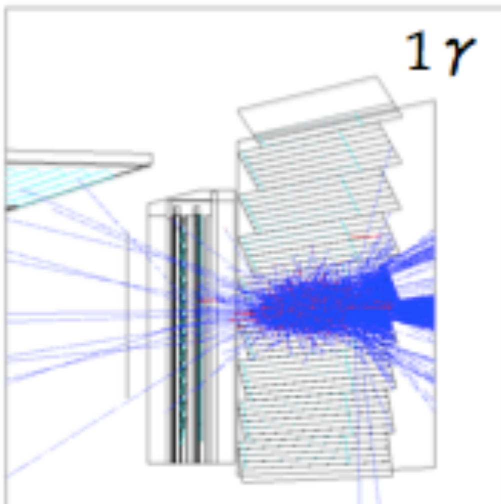
  Very good stability .
  D0 : 0.5% response drop over ~10 years operation.

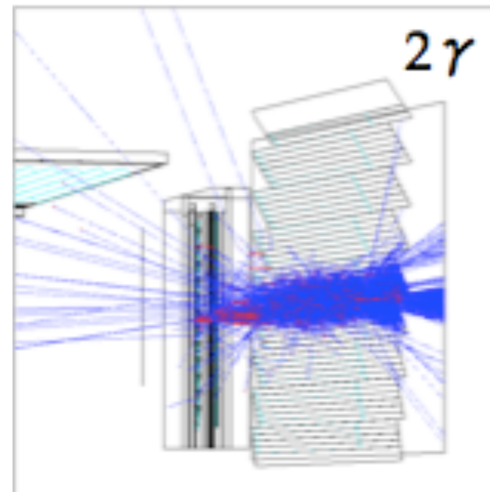
Preshower

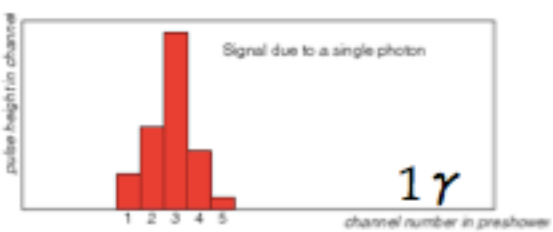
- Spesso davanti ad un calorimetro EM viene posto un rivelatore più preciso di posizione

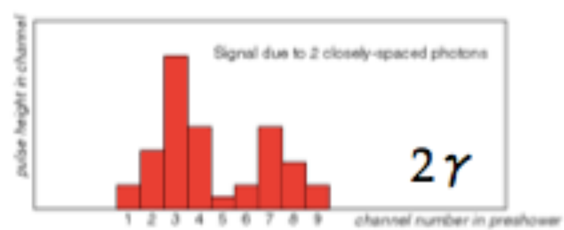
“preshower” → distinzione di γ singoli energetici da $\pi^0 \rightarrow 2\gamma$

- rivelatore ad alta granularità (silicio) posto dopo una o due X^0









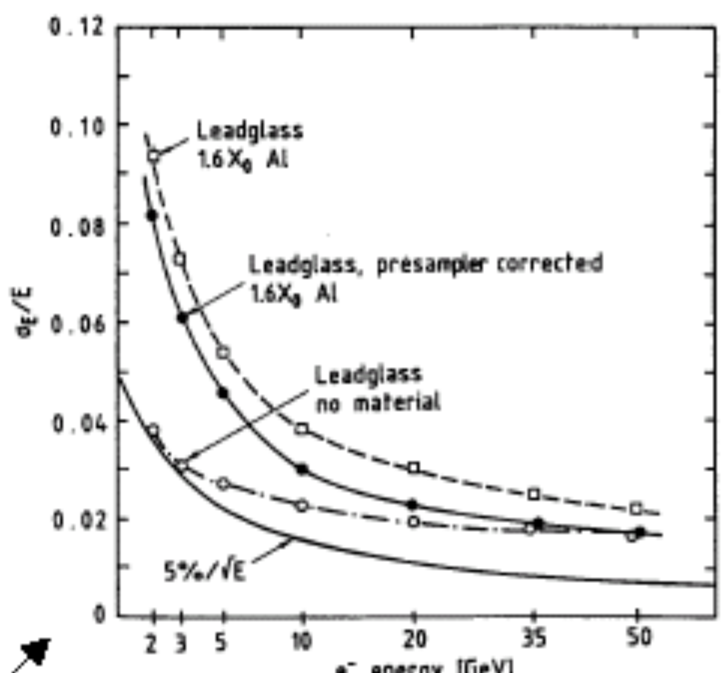
Presciamatore

Materiale davanti al calorimetro

Lo sciame e.m. può iniziare nel materiale davanti al calorimetro (altri rivelatori strutture di sostegno ecc.) ➔ installare un presciamatore altamente segmentato.

- recupera energia persa
- migliora la risoluzione in energia
- migliora la risoluzione spaziale
- migliora la risoluzione angolare

calorimetro e pre-sciamatore di OPAL



(C. Beard et al., NIM A 286 (1990) 117)

ATLAS and CMS: same physics goals and two very different EM calorimeters

	ATLAS	CMS
Technique	Sampling LAr	Homogeneos crystals
Sampling term	~10% / $\sqrt{E}$	~3 % / $\sqrt{E}$
Constant term Goal ~ 0.5 %	Uniform by construction	Less uniform
Longitudinal segmentation	Yes	No
Angular measurement	Yes	No
Particle identification	Robust	Less robust
Readout	~ fully analog	~ fully digital

Note: environment (upstream material inside B-field) more harmful for CMS calorimeter:

-- B=4 T (ATLAS: B=2 T)

-- better intrinsic resolution

→ reduces the difference between calo with excellent E-resolution and calo with good E-resolution

Calibration

- Purpose :
  - -- equalize channel-to-channel response → uniformity, small constant term
  - -- set the absolute energy scale
  - -- monitor response vs time
- With increasing energy, calibration and response uniformity become more and more important (constant term dominates)
- Challenging in large system (many channels) : calibration and monitoring more arduous.

Calibration tools:

-- electronic calibration system: inject known pulse at the input of electronic chain → channel-to-channel uniformity and stability of ~ 0.2% achieved (e.g. H1). Does not allow test of detector active element.

-- radioactive sources (scintillator calorimeters): inject known signal in detector active element → check light transmission (but usually not light emission process)

-- some calorimeter modules tested with test beams before installation → check reproducibility and uniformity over limited sample + first setting of absolute scale.

Some cases (e.g. CMS ECAL) : whole detector tested with beam.

However, in the experiment:
-- material in front of calorimeter
-- long-range non-uniformity from module to module
-- magnetic field
-- physics : e.g. jets measurements
-- response variation with time

need *in situ* calibration with physics samples

-- relatively easy at e^+e^- machines (beam constraint):
e.g. Bhabha events $e^+e^- \rightarrow e^+e^-$.
-- more difficult at hadron colliders → discussed here

EM calibration at hadron colliders:
- -- $\pi^0 \rightarrow \gamma\gamma$, $J/\Psi \rightarrow ee$, $\Upsilon \rightarrow ee$: low mass
- -- $Z \rightarrow ee$: high mass
- -- E/p measurements for isolated electrons (e.g. from W decays). Momentum scale in inner detector (p) transferred to calorimeter asking that peak of E/p distribution is 1.

HAD calibration at hadron colliders:
- -- E/p for single pions
- -- Z + 1 jet ($Z \rightarrow \ell\ell$)
- -- γ + 1 jet
- -- LHC: $W \rightarrow jj$ in top events

(Z + 1 jet and γ + 1 jet:) p_T - balance:
$p_T(\text{jet}) = p_T(\gamma/Z)$

Impact of material

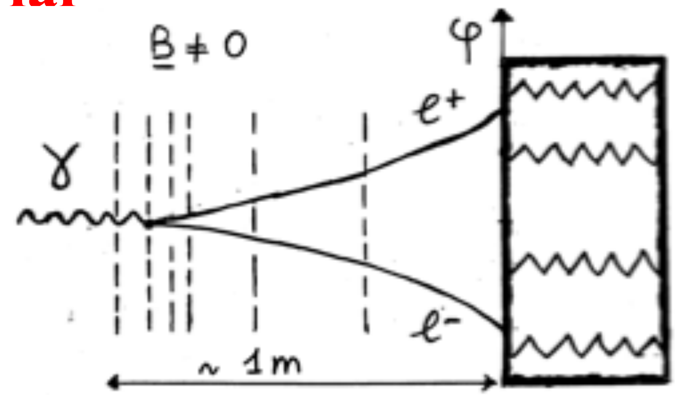
- material in the inner detector:

  -- << 0.5 X_0 in LEP/Tevatron detectors,
  up to ~ 1 X_0 in LHC detectors
  (need robust tracking)

  -- at large distance from the calorimeter

  -- usually inside B-field

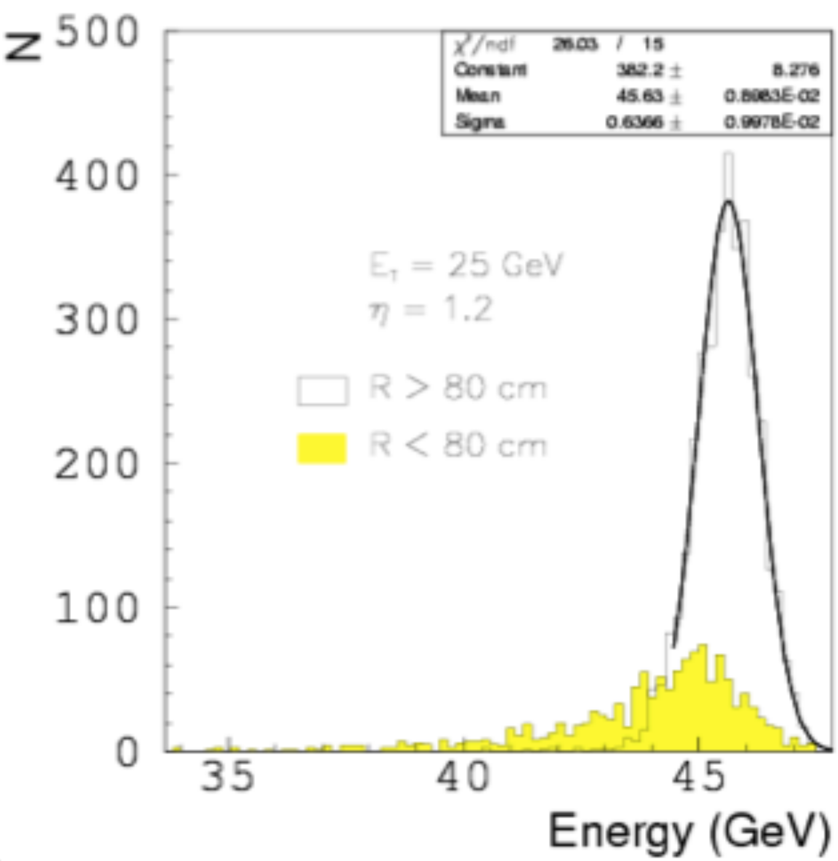
  → creates low-E tails



-- need big clusters (many cells) to collect all energy

-- however

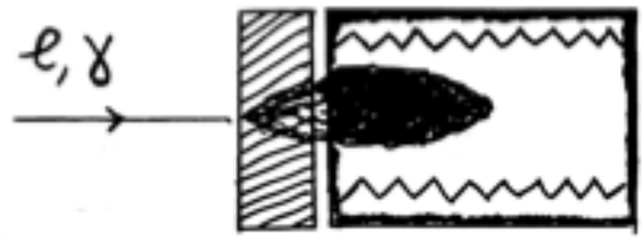
noise ⊕ pile-up ~ √area → compromise.

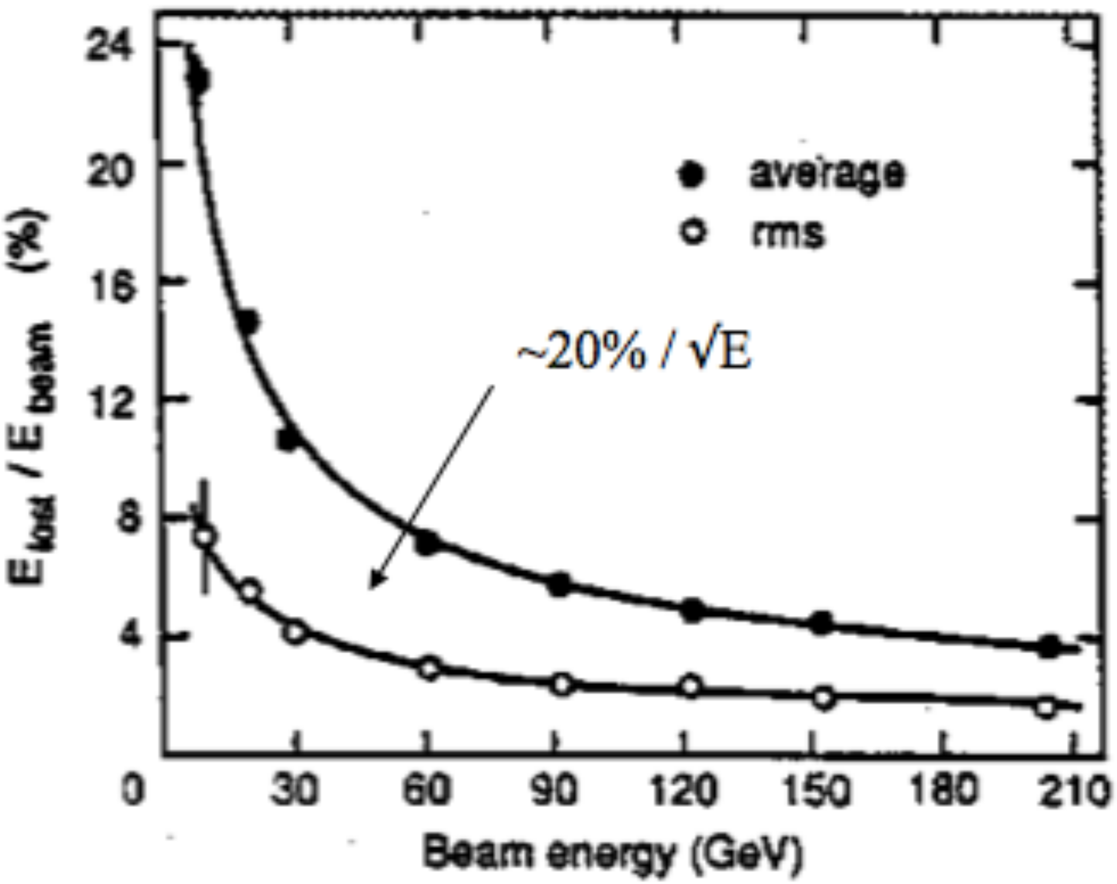


As a result :
energy leakage outside cluster for particles interacting in the tracker.

- material just in front of the calorimeter:
  -- calorimeter support, cables, sometimes solenoid, cryostats for liquid calorimeters
  -- more massive (~ 2 X_0 in front of ATLAS EM calorimeter) but closer to calorimeter

→ deteriorates sampling term, opens showers





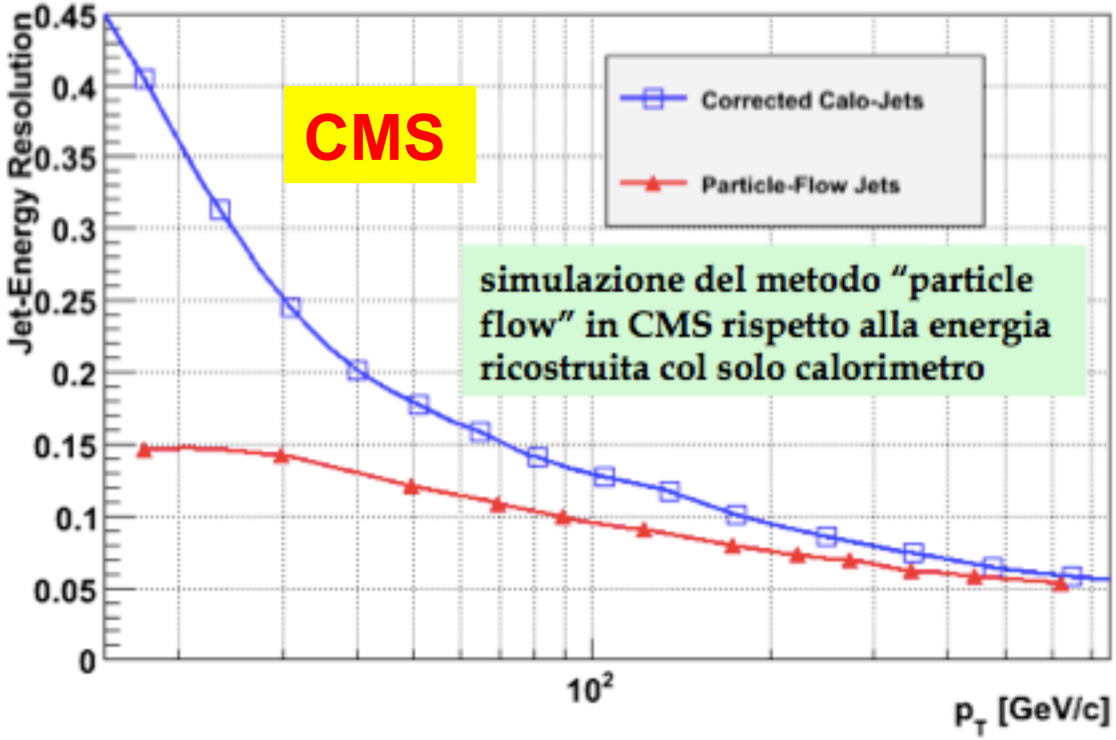
Test beam data:
~ 3.5 X0
of dead material
in front of
Accordion

- **poorly instrumented regions:**

  -- typically transition between barrel-end-cap
  (especially in liquid calorimeters)
  -- limited regions of the acceptance
  -- however: can create tails in energy measurements
  (e.g. fake large Etmiss)

Particle flow

- Particle flow
  - identificare e misurare le particelle cariche nel tracking detector
  - associare ad ogni traccia la relativa energia nel calorimetro e sottrarla
    - richiede un'ottima granularità del calorimetro
  - l'energia finale è quella delle tracce carice (misurate nel tracciatore) più quanto rimane nel calorimetro
    - fotoni, adroni neutri
  - algoritmi di ricostruzione sofisticati



Conclusions

- Calorimeters are versatile detectors: energy, position, angle, time measurement, particle identification, trigger, etc. Sensitive to ~ all particles.

- Performance (energy, position, time resolution) improves with energy
  → very well suited to high-energy experiments and machines.

- Impressive progresses over last 40 years:
  -- large variety of techniques developed with different merits and drawbacks
  -- large variety of applications
  (space, nuclear physics, accelerator and non-accelerator physics, etc.)
  -- often operated in large and complex system
  -- progresses in electronics (e.g. speed, low noise, dynamic range) allowed to exploit at the best intrinsic physics potential of the detectors.

- Today : suitable solution exists (potentially) for ~ any application. However, optimisation of calorimeter choice is a multi-dimensional problem: physics performance, cost, external constraints (e.g. available space, B-field, high-radiation environment).

Despite this, operating calorimeters at the LHC represents yet a fantastic achievement for these detectors.

Bibliografia su calorimetria

C. Fabjan- Calorimetry for particle physics (CERN-EP 2003-075)

R. Wigmans Energy loss of particles in dense matter-Calorimetry

F. Gianotti (CERN), NATO school, Virgin Islands, June 2000

C. Dionisi, Lezioni di Dottorato in Fisica 2001