Calorimeters at Hadron Colliders

Showers & Detectors

Signal Treatment & Calibration

Simulation & Reconstruction

Thanks to L. Serin, W. Riegler, N. Hadley, all speakers of CALOR 2008

“Calorimetry for particle physics” C. Fabjan, F. Gianotti - 2003

What is a calorimeter ?

Calorimeter – Wikipedia, the free encyclopedia

http://en.wikipedia.org/wiki/Calorimeter

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Calorimeter

From Wikipedia, the free encyclopedia

A **calorimeter** is a device used for calorimetry, the science of measuring the heat of chemical reactions or physical changes as well as heat capacity. The word *calorimeter* is derived from the Latin word *calor*, meaning heat. Differential scanning calorimeters, isothermal microcalorimeters, titration calorimeters and accelerated rate calorimeters are among the most common types. A simple calorimeter just consists of a thermometer attached to an insulated container.

To find the enthalpy change per mole of a substance X in a reaction between two liquids X and Y, the liquids are added to a calorimeter and the initial and final (after the reaction has finished) temperatures are noted. Multiplying the temperature change by the mass and specific heat capacities of the liquids gives a value for the energy given off during the reaction (assuming the reaction was exothermic.). Dividing the energy change by how many moles of X were present gives its enthalpy change of reaction. This method is used primarily in academic teaching as it describes the theory of calorimetry. It doesn't however account for the heat loss through the container or the heat capacity of the thermometer and container itself. In addition, the object placed inside the calorimeter show that the objects transferred their heat to the calorimeter and into the liquid, and the heat absorbed by the calorimeter and the liquid is equal to the heat given off by the metals.

Contents [hide]

1 Types
- 1.1 Reaction calorimeters
  - 1.1.1 Bomb calorimeters
- 1.2 Constant-pressure calorimeter
- 1.3 Differential scanning calorimeter
- 1.4 Isothermal titration calorimeter
- 1.5 X-ray microcalorimeter
- 1.6 Heat-loss calorimeter
- 1.7 High-energy particle calorimeter

2 See also

Calorimeter



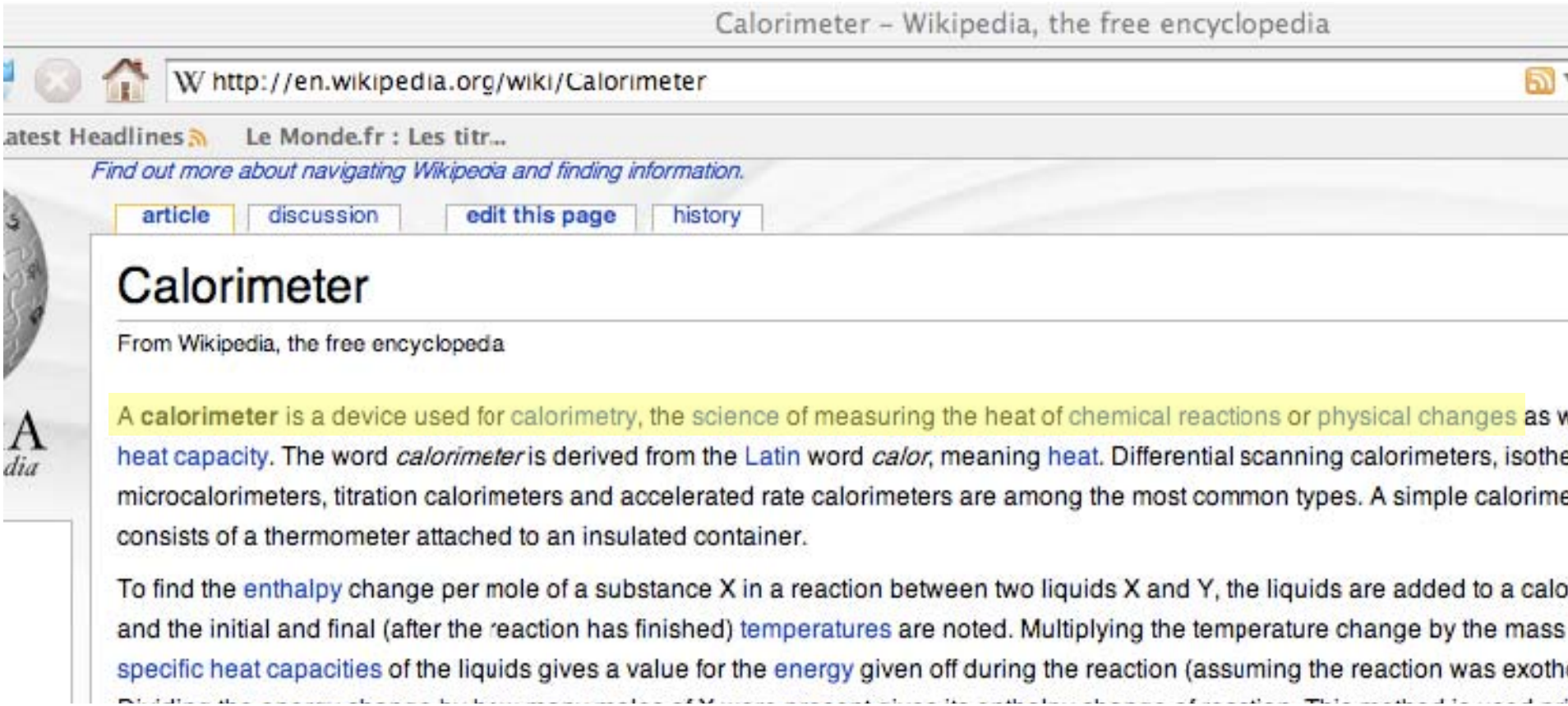
An example of a reaction calorimeter

Uses	Measuring the heat of reaction
Related items	Reaction calorimeter

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Types [edit]

What is a calorimeter ?



What is a calorimeter ?

Calorimeter (particle physics) – Wikipedia, the free encyclopedia

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Calorimeter (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, a **calorimeter** is an experimental apparatus that measures the energy of particles. Most particles enter the calorimeter and initiate a particle shower and the particles' energy is deposited in the calorimeter, collected, and measured. The energy may be measured in its entirety, requiring total containment of the particle shower, or it may be sampled. Typically, calorimeters are segmented transversely to provide information about the direction of the particle or particles, as well as the energy deposited, and longitudinal segmentation can provide information about the identity of the particle based on the shape of the shower as it develops. Calorimetry design is an active area of research in particle physics.

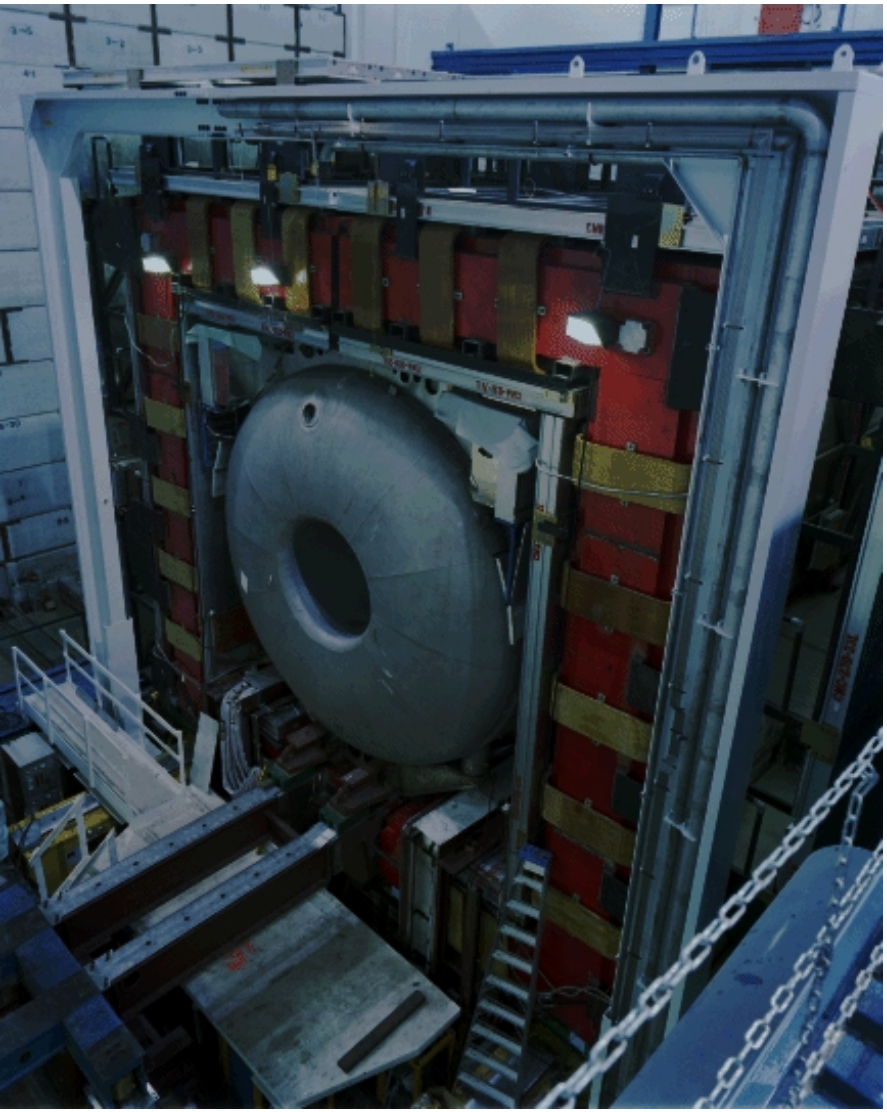
See also

- Calorimeter (for other uses of the term)

This particle physics-related article is a stub. You can help Wikipedia by expanding it.

Categories: Particle physics | Particle detectors | Particle physics stubs

The calorimeter I know best



D0 liquid Argon calorimeter:

- Conception started in 1983
- Uranium/Liquid Argon em calorimeter
- Copper/Stainless Steal had calormeter

➔"compensating" e/$\pi \sim 1$ (with 3.4μs integration time)

- 55 000 read-out cells
  - ➔**4 em layers (2, 2, 7, 10 X_0),**
  - ➔**shower-max (EM3): 0.05 x 0.05**
  - ➔**4-5 hadronic layers (FH + CH)**
  - ➔**$\lambda_{int} > 7.2$ (total)**
- 5000 semi-projective trigger towers

➔**$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$**

- Hermetic :

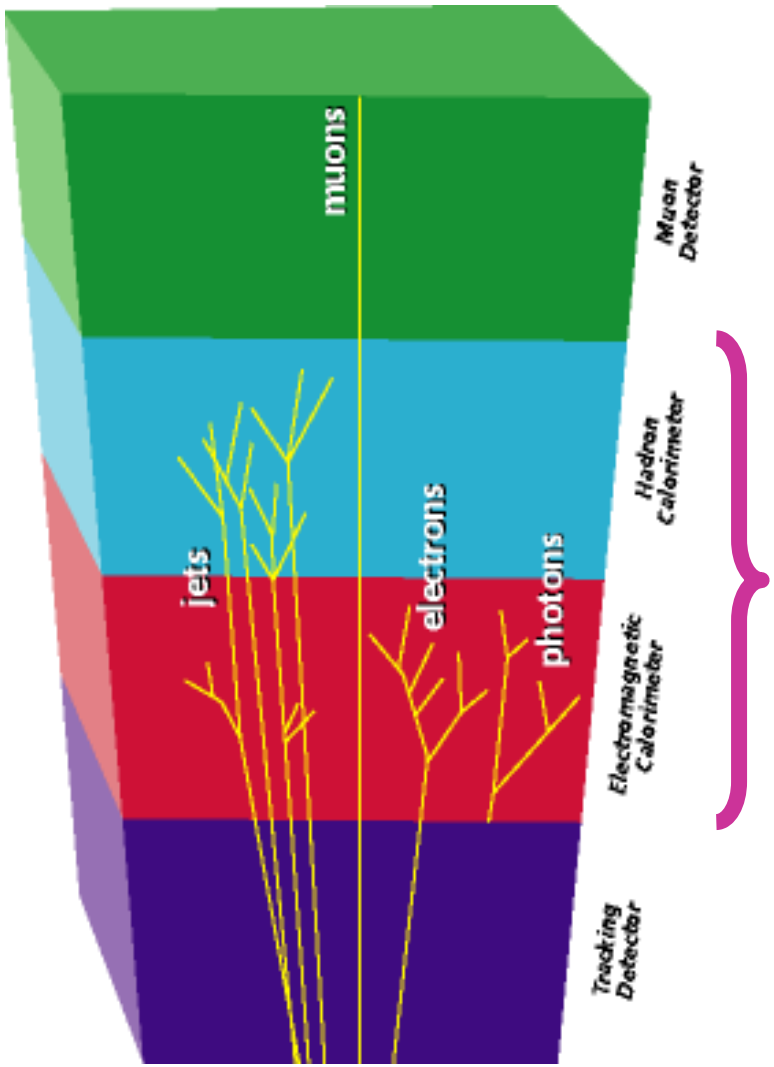
➔**$|\eta| < 4.2$ ($\theta \approx 2^o$),**

- single particle resolution from test beam

e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$

π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$

Calorimeters in HEP detectors



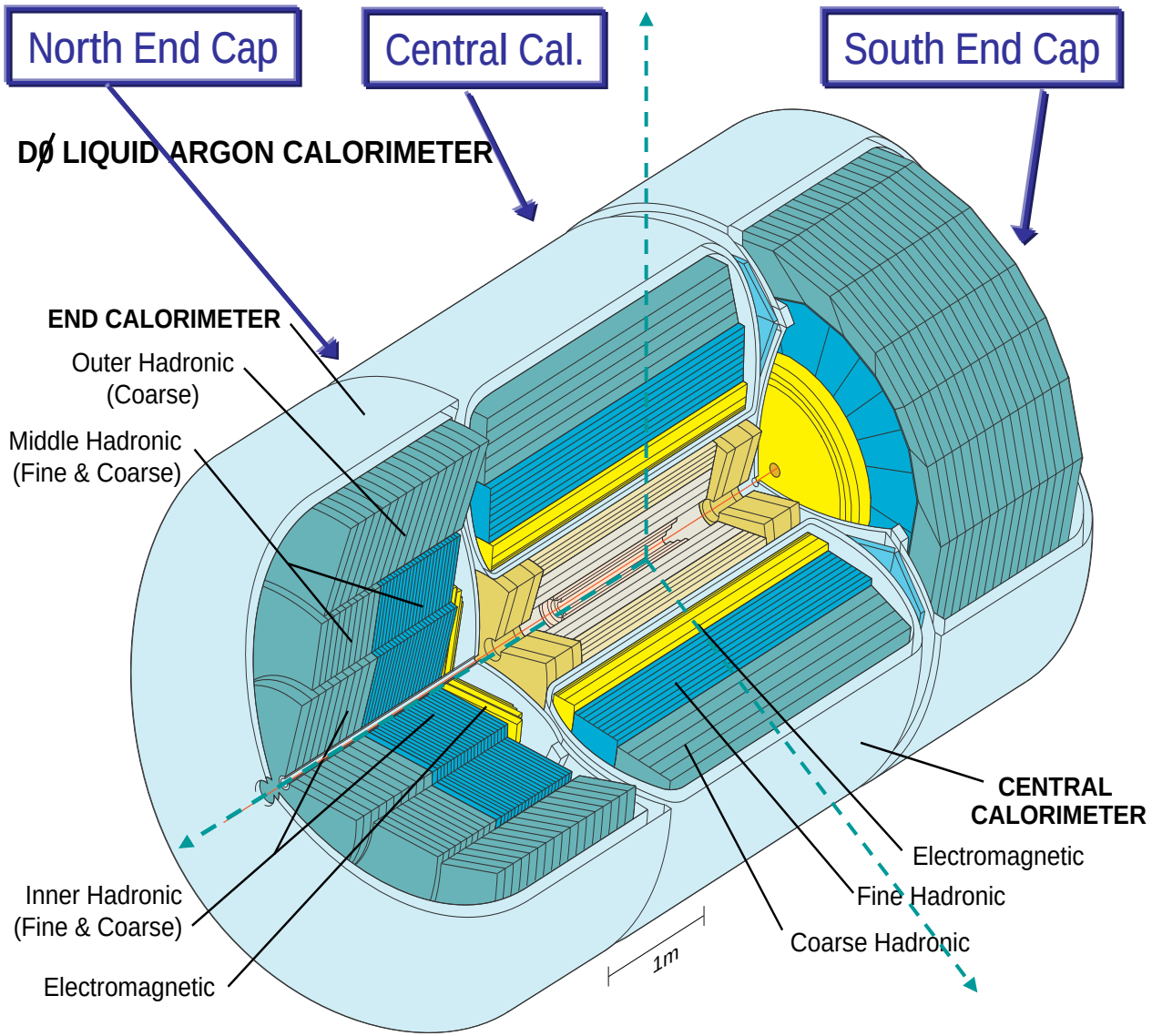
Aim: measure the energy of charged and neutral particles

For most particles, the energy is deposited by particle showers which are resulting from radiation and ionization process until the complete absorption of the incident energy in the calorimeter.

According to the particle nature, different type of interactions can be observed: em-particles, hadrons, mip (muons) and the calorimeter type

In (nearly) 4π detectors:
measure of the total (transverse) energy
➔ (transverse) energy of weakly- or non-interacting particles (ν, LSP…)

Calorimeter characterizations



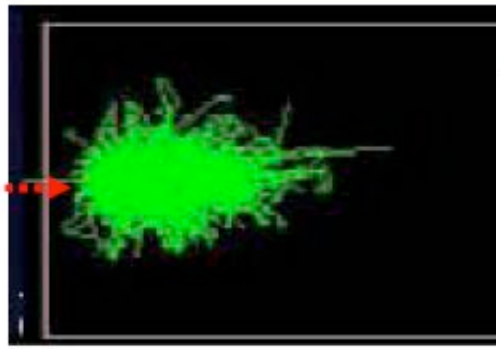
- Many Calorimeters in HEP have an **electromagnetic** section and an **hadronic** section
- They are either **homogenous** or **sampling** calorimeters
- Calorimeters are characterized by:

- energy resolution
- timing resolution
- position resolution
- e/π ratio

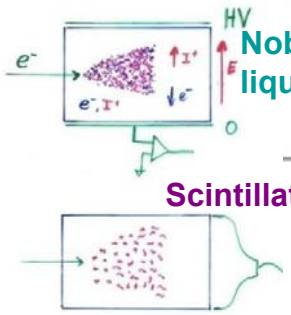
Calorimeters in a nutshell

E

incident particle

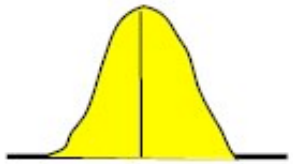


shower development



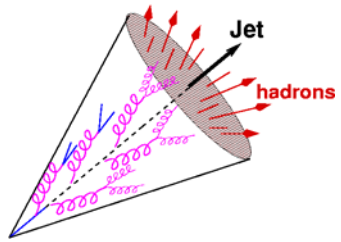
detection

amplification, shaping and digitization



conversion from digital signals to energies

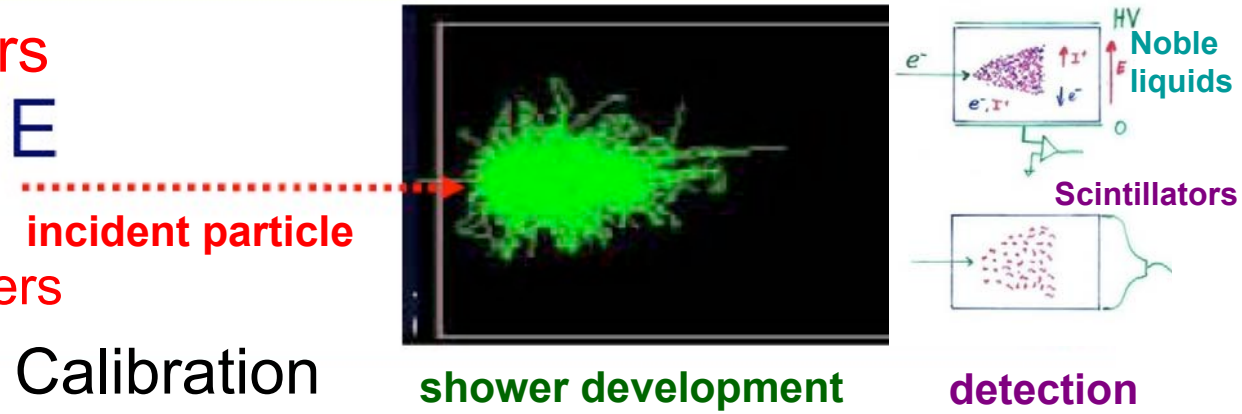
- Formation of electromagnetic or hadronic showers, total absorption of incident particle energy with signal production $\propto E$
- The signals measured are either electrons from an ionized material or photons emitted after atomic desexcitation
- Provide position/angular measurements (for γ) and contributes to particle identification when segmented laterally and longitudinally
- Can be fast : trigger and out of time events



Object reconstruction

Overview

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Calibration
  - Signal treatment
  - Test Beams
  - Electronics Calibration
  - Cell level calibration
- Simulation & Reconstruction
  - Electrons/photons
  - Jets
  - Missing E_T
  - E-flow



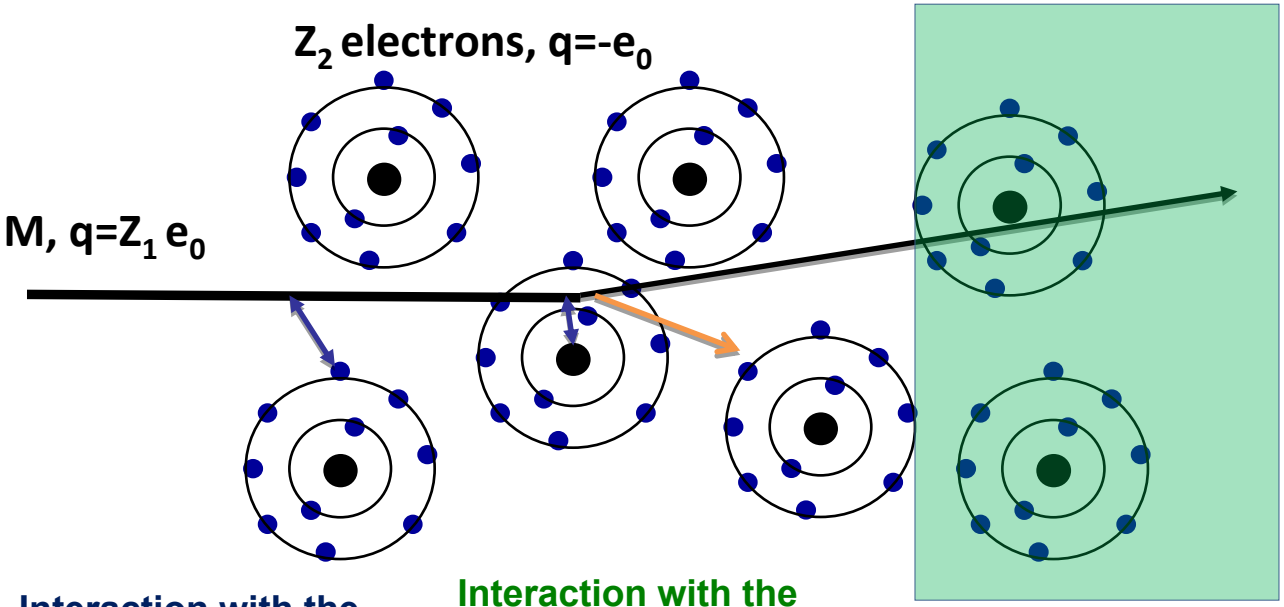
How to built a calorimeter?

- **What do you want to measure?**
  - Looking for wimps with bolometers or jets at the LHC?
- **What energy resolution do you want to achieve?**
  - 3% for excellent resolution on H→γγ or the energy of a cosmic ray?
- **What spatial resolution do you need?**
  - Need to measure photon position or the direction of a μin the Sea ?
- **What object overlap is acceptable?**
  - Do you need to distinguish particles in a jet or the missing E_T?
- **What is the event rate?**
  - Do you μs to form your signal or ns?
- **What is the environment your calorimeter will work in?**
  - High luminosity hadron collider or a mine shaft 1000m below surface?
- **What size should your calorimeter be?**
  - Some cm or 10m or kilometers?
- **How much money to you have?**
  - Actually never enough…

If you want to measure something…

it has to interact!

em-interaction of a charged particle

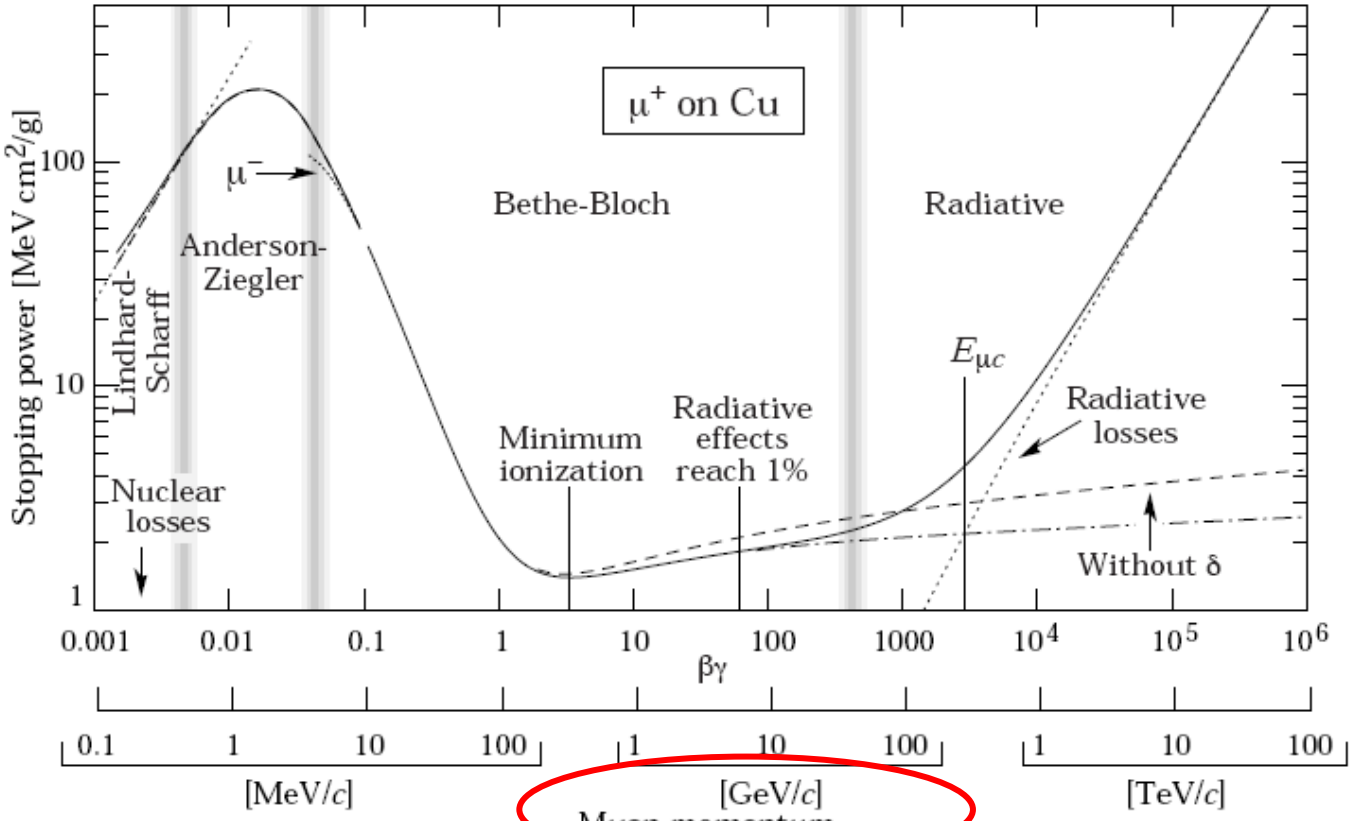


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized ➔process used to produce measureable signals

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted ➔ shower production

If the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation ➔ used to measure the energy of atmospheric showers by "Astrophysics Calorimeter"

Energy loss of particles in matter



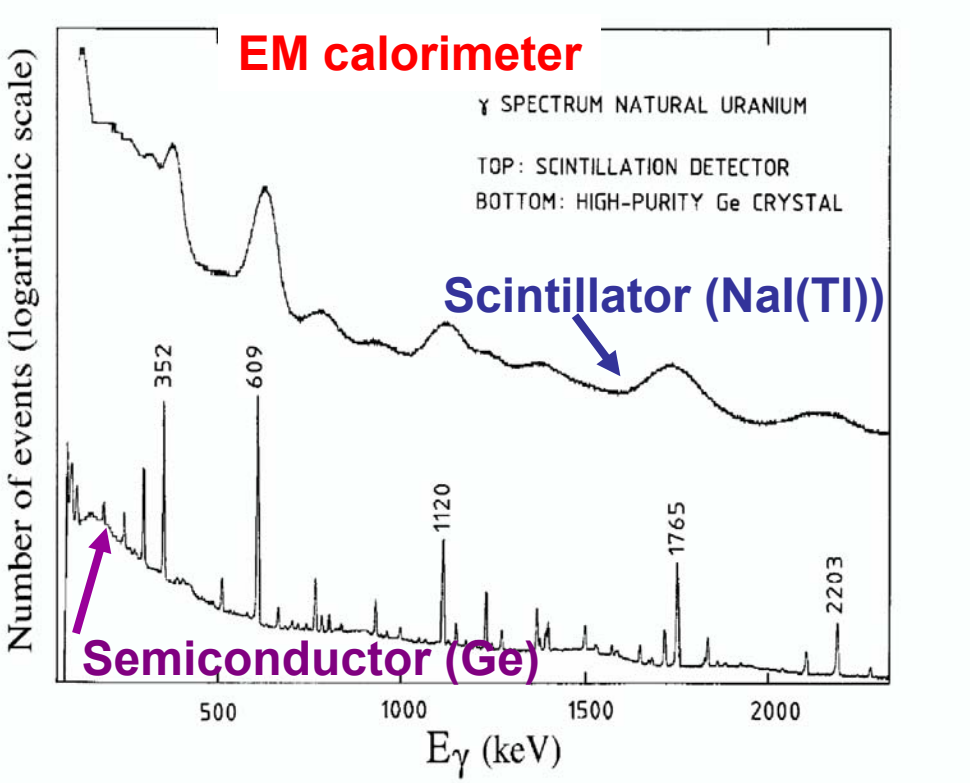
5 50 500
[MeV/c]
Electron Momentum

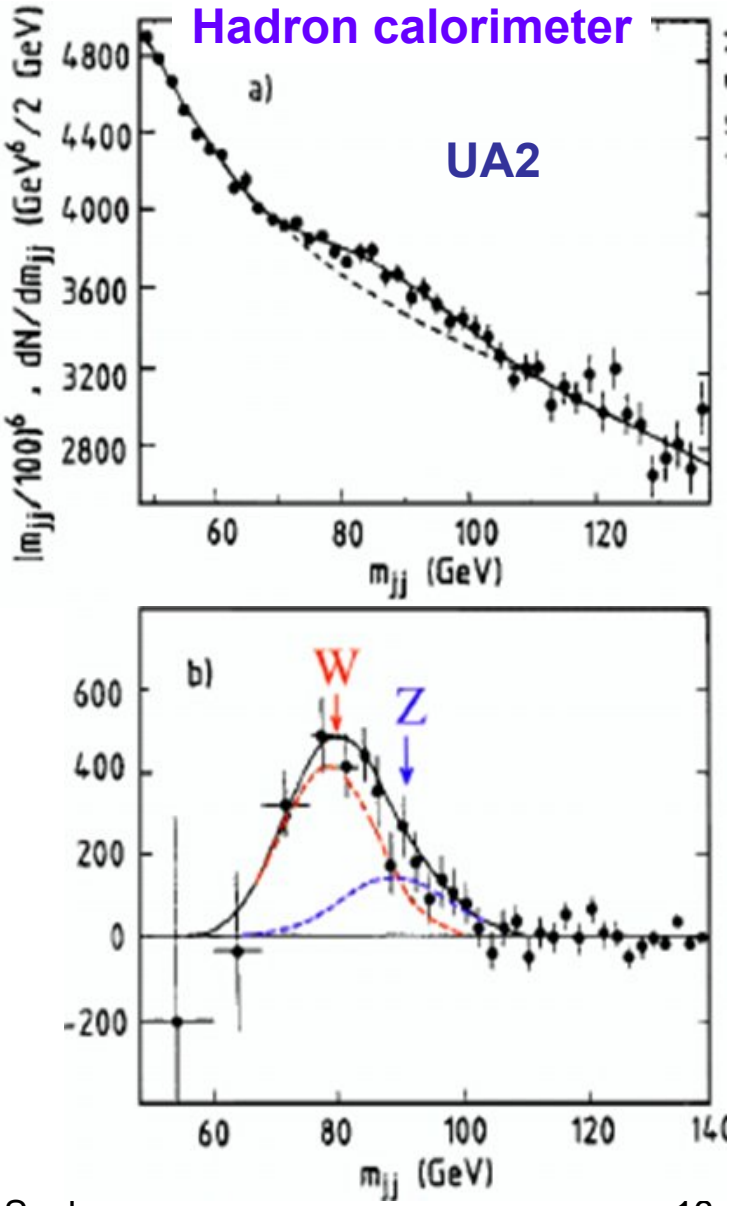
➔ radiation process lead to shower developments,

➔ ionization and atomic excitation lead to measurable signals (light or charge)

μ are essentially considered as mip, but radiative effects have to be taken into account, in particular at LHC!

What resolution?



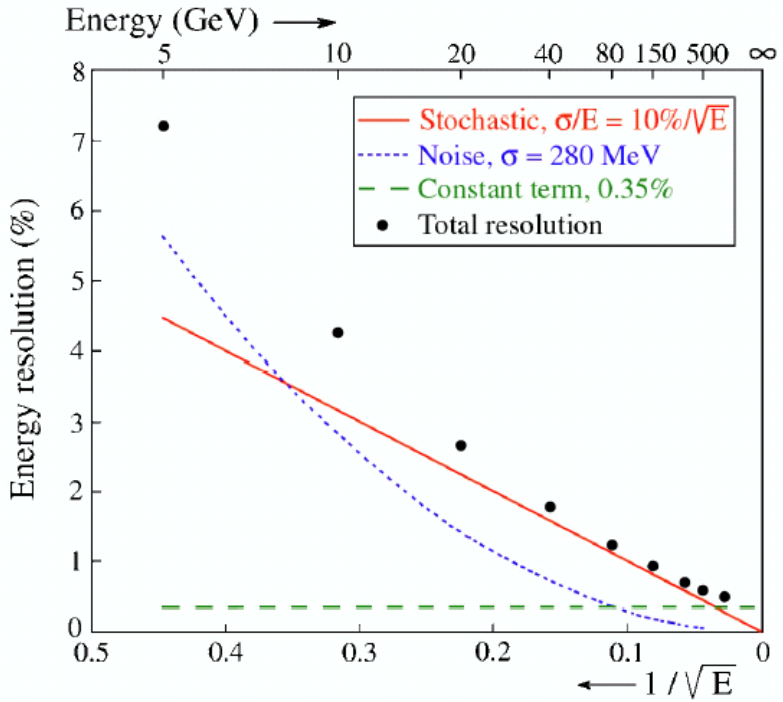


- Energy resolution depends on the material used, the calorimeter type, the read-out electronics, but also on the nature of the particles measured

Energy resolution

Usually parameterized by :

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



a : intrinsic resolution or stochastic term
→ given by technology choice

b : contribution of noise:
material, electronics, pile up, radioactivity
→ give by the electronics design

c : constant term: contains all the imperfection
response variation versus position (uniformity), time (stability), temperature….
→ Constraints on all aspects : mechanics, electronics….

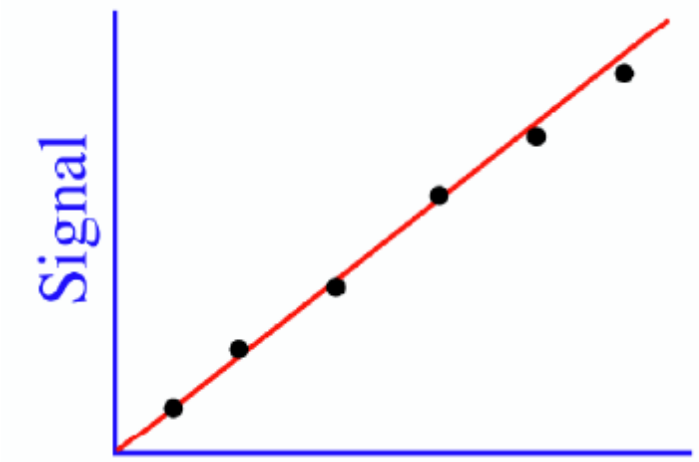
Homogenous calorimeters: noise and constant term dominate
Sampling calorimeters: stochastic term dominates

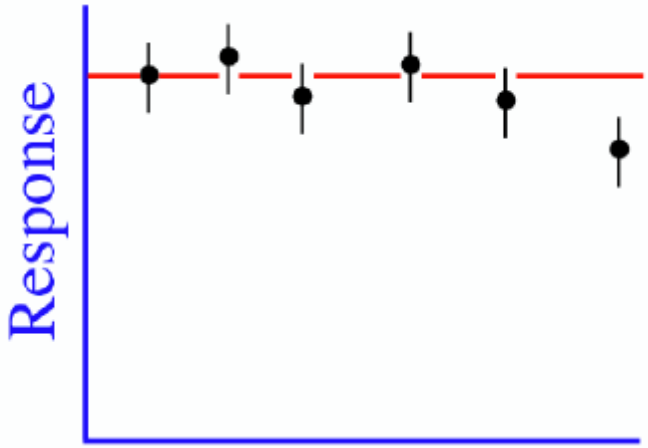
➔ Energy resolution improves with energy compared to tracking detectors, where the momentum measurement degrades at high momentum ($dp/p \propto p$)

Calibration and linearity

Signal is measured in pC and digitized (adc counts), not in GeV!
Calorimeter response should be linear

Measured energy can be non-linear:
- Leakage
- upstream material
- non linearity in electronics





Measured signal → Cell energy (GeV) → cluster → particle energy

- relative calibration equalizes the response between the channels
- absolute calibration provides the conversion factor fro, ADC-counts to energy

→ techniques: test-beam, electronics calibration, in-situ calibration, simulation

EM Calorimeters

- Showers & Detectors
  - Generalities
  - EM Calorimeters
    - Interactions of electrons/γ with matter
    - EM shower characterizations
    - Calorimeter principle
  - Hadron Calorimeters
    - Hadron Showers
    - Compensation
- Calibration
  - Test Beams
  - Electronics Calibration
  - Cell level calibration
- Calorimeter Reconstruction
  - Electron/photon reconstruction
  - Jet reconstruction
  - E_T^{miss} reconstruction
  - E-flow

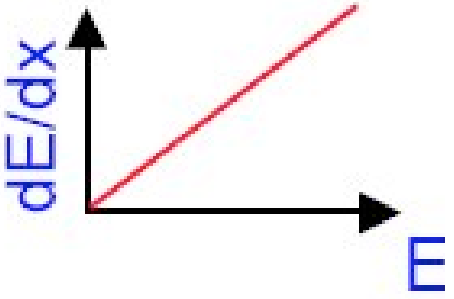
em interactions with matter

Process taking place during EM Shower development

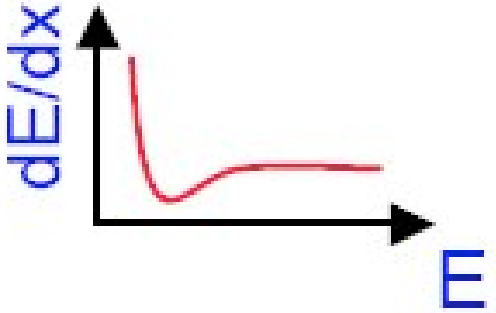
Electrons:

- **High energy: Bremsstrahlung**
  - photon radiation close to an atom
- **Low energy: ionization**
  - energy dissipation by creating free electrons

Bremsstrahlung

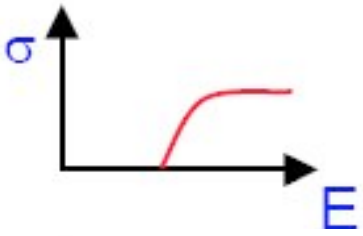


Ionization

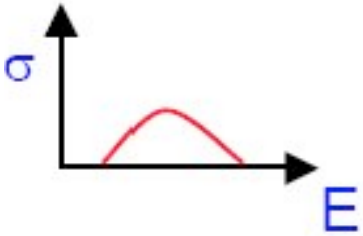


Photons:

- **High energy : e^+/e^- pair production**
  - materialization of photons
- **Medium energy: Compton effect**
  - photon diffusion liberating an electron from the atomic cortex
- **Low energy: photoelectric effect**
  - photon absorption liberating an electron from the atomic cortex



Pair production



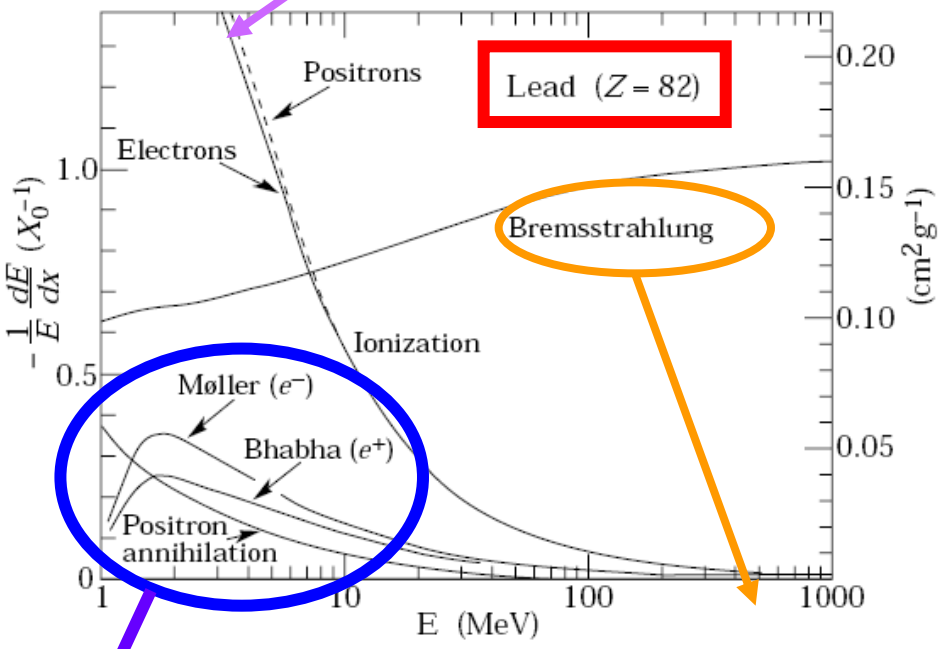
Compton effect



Photoelectric effect

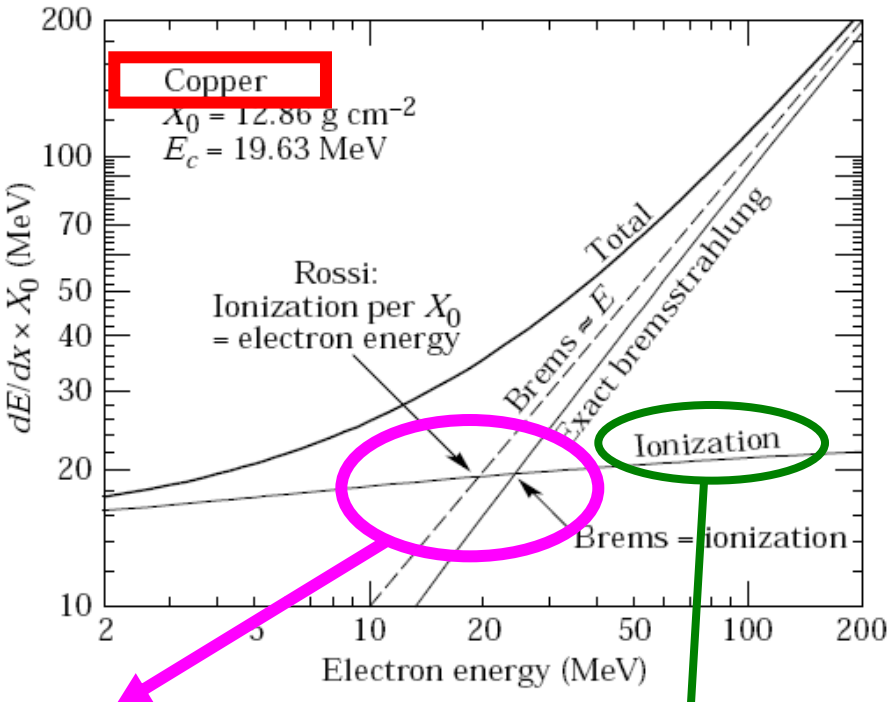
Energy loss for electrons

e^+/e^- difference



Can be mostly neglected!

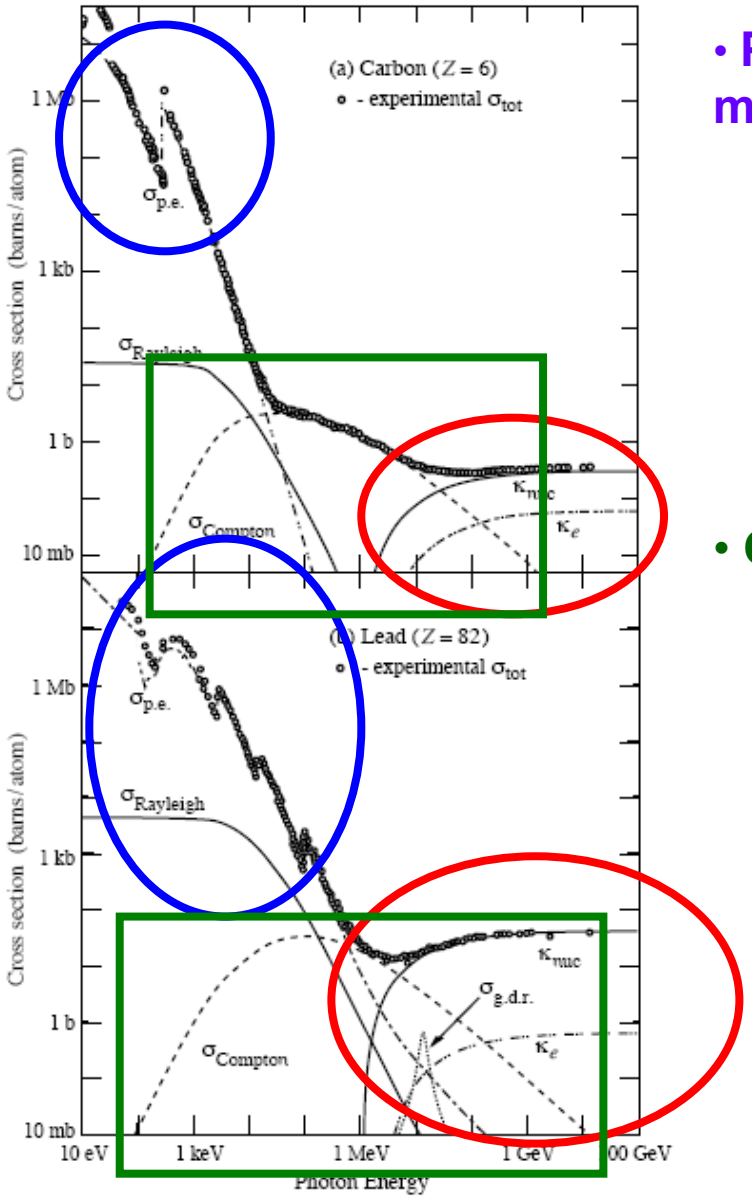
Linear contribution > 100 MeV



Critical energy: Contributions from Bremsstrahlung and Ionization are equal

Logarithmic contribution

Energy loss for photons



- **Photo electric effect depends strongly on the material, dominant at low photon energies**

$$\sigma = Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma}\right)^n$$

$$n = 7/2 \quad \text{for} \quad E << m_e c^2$$

$$n \rightarrow 1 \text{ for } E >> m_e c^2$$

- **Compton scattering**

$$\sigma_C^e \propto \frac{\ln E_\gamma}{E\gamma} \text{ and atomic compton} = Z\,\sigma_C^e$$

- **Pair production dominant for $E >> m_e c^2$ the cross-section becomes independent of the photon energy**

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}}\right) = \frac{A}{N_A} \frac{7}{9} \frac{1}{X_0}$$

Radiation length

Radiation length X_0:

- mean distance over which a high-energy electron loses 1-1/*e*≈ *63%* of its energy by Bremsstrahlung
- mean free path for pair production by a high-energy photon (9/7 X_0)

The actual depth depends on the nature of the material:

$$X_0 = \frac{716.4\,\mathrm{g\,cm^{-2}}\,A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

$1X_0 \approx$ 9 cm Al

$1X_0 \approx 0.6$ cm Pb

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

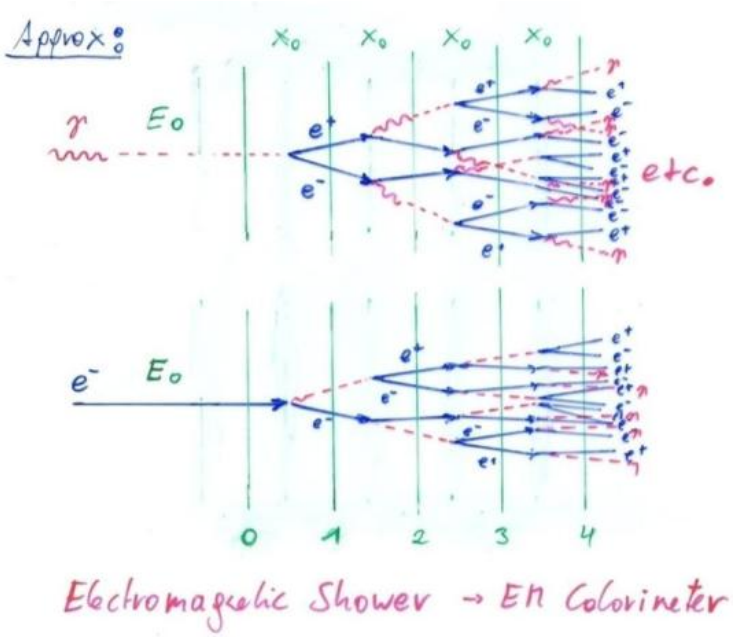
Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at http://pdg.lbl.gov/AtomicNuclearProperties.

Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\rm min}$ [b] {MeV/(g/cm^2)}	Radiation length [c] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	(0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	(2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

EM Shower Development

- e/γ with E> 1GeV are mainly interacting via production of secondary particles (Bremsstahlung, pair production)
  - **$E_i > E_C$: new e^+/e^- pairs and γ are created but at lower and lower energy**
  - **$E_i < E_C$: the energy is absorbed by ionization type of processes**

$$E_C \cong \frac{610(710)MeV}{Z + 1.24(0.92)}$$



After nX_0 the total number of e and γ is $N(n)=2^n$

With an average energy of $\langle E(n)\rangle = E_0/2^n$

➔**The shower development stops for $E(n) = E_c$**

Shower length: $n_{max}=1/\ln 2 \ln(E_0/E_c)$

➔ shower length rises with $\ln E_0$

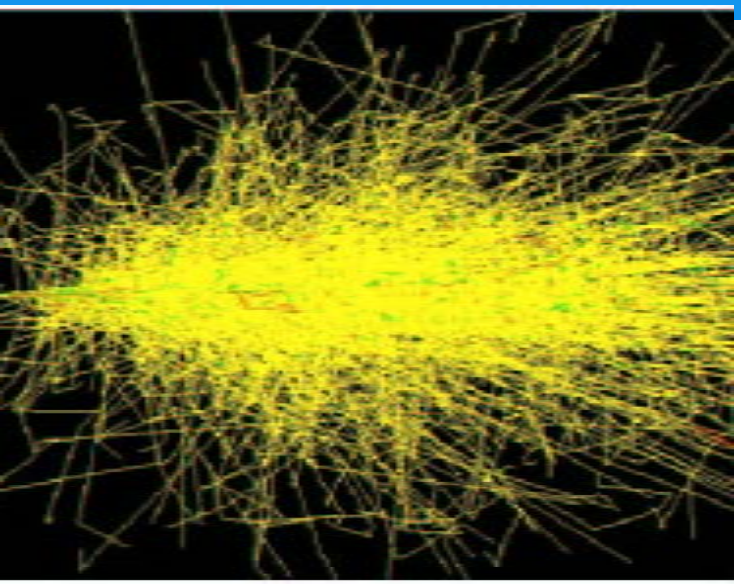
Total number of electrons produced

$N_{tot} = \sum^{nmax} 2^n X_0 = (2 E_0/E_C - 1) X_0 \sim 2E_0/E_C X_0 \propto cE_0$

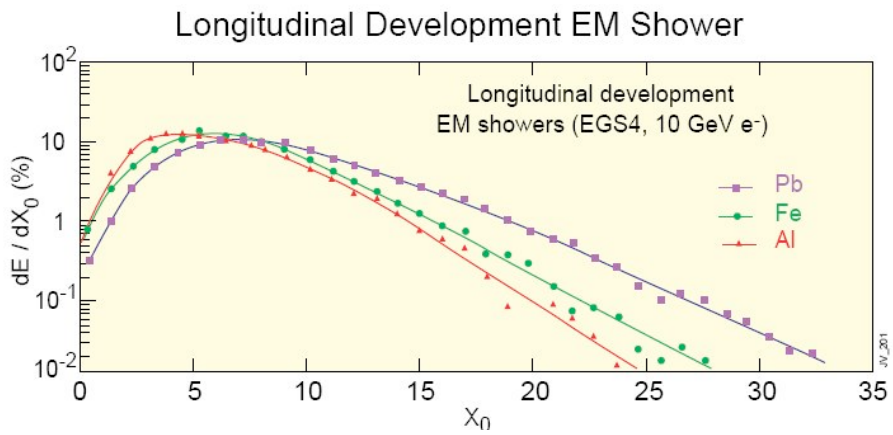
The total number of electrons produced is proportional to the incident energy

➔ Calorimeter Principle!

Longitudinal shower profiles



Simulation of 1 GeV electron in copper



- Multiplication of e/γ up to max shower depth where most particles reach E_c
- Exponential fall off of the shower afterwards
- Maximum shower development ~6 X_0
- Quasi universal behavior wrt X_0 but :

- Shower maximum deeper at high Z

- Slower decay at high Z

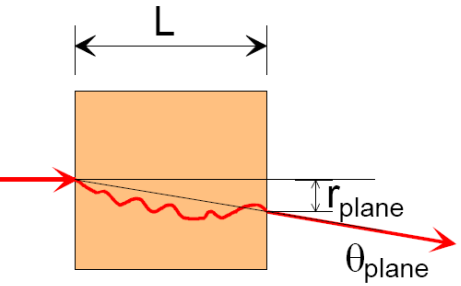
→Critical energy ∝ 1/Z

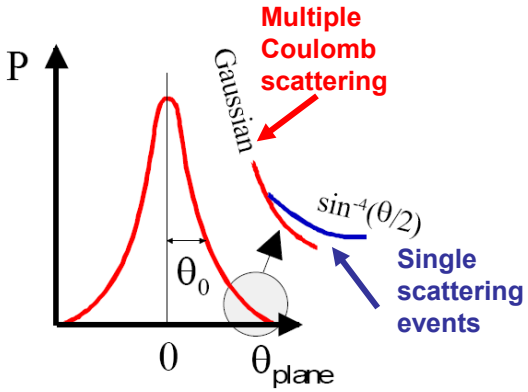
The depth of a calorimeter goes as ln(E)

After 25 X_0 only 1% leakage for E up to 300 GeV → compact detectors!

Lateral shower profiles

- Momentum transfer → change in direction (Rutherford scattering formula)
- If the material is thick enough → multiple scattering, effect on average null for many particles but seen as a fluctuation (important for position resolution)

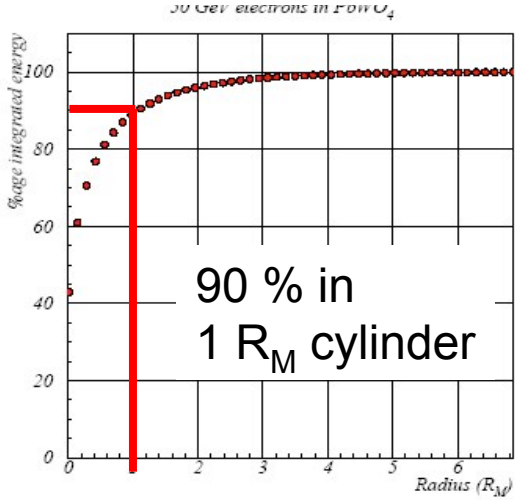




rms is given by:

$$\theta_0 = \frac{13.6\ MeV}{E} z \sqrt{\frac{L}{X_0}} \left\{1 + 0.038 \ln\left[\frac{L}{X_0}\right]\right\}$$

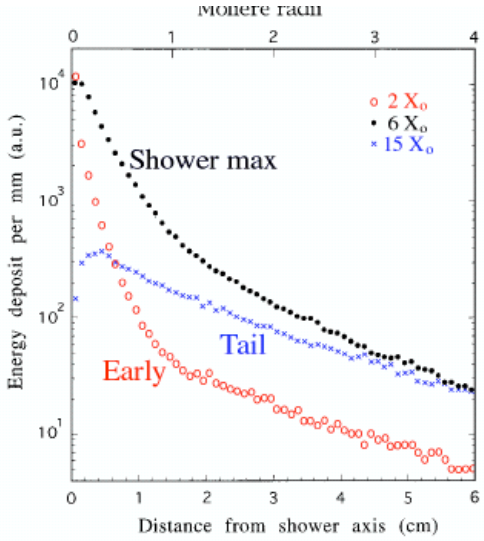
➔ **Smaller for high E, small material thickness and large X_0.**



Moliere Radius (R_M): average lateral deflection of electron with E_c after 1 X_0

$R_M = 0.0265\ X_0(Z+1.2)$

Important parameter for shower separation!



Calorimeter cell sizes should be <R_M for position measurements!

Intrinsic energy resolution

Simplified model :

Number of produced ions/e^- pairs or photons:

Detectable signal ($\rightarrow$E) is $\propto$ N (N being quite large)

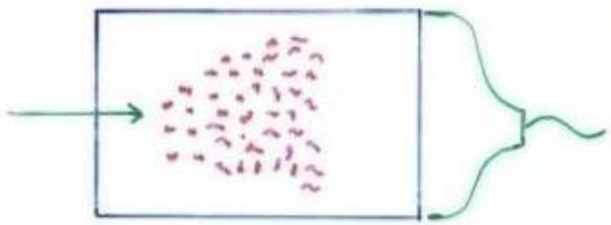
$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

- Most of the time not all the released energy is measured through ionization or light:
  - in front dead material,
  - longitudinal leakage,
  - module boundaries,
  - “out of cluster” energy – reconstruction effects
- Intrinsic resolution can go from 1-3 % for crystal or homogeneous noble liquids to 8-12% for sampling calorimeters

Homogenous crystals

In crystals the light emission is related to the crystal structure of the material. Incident charged particles create electron-hole pairs and photons are emitted when electrons return to the valence band.

The incident electron or photon is completely absorbed and the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors.



Measuring the Photons produced by the collision of the $e^{\pm}$ with Atom Electrons of the Material.

+ very compact calorimeter
+ good energy resolution
+ can be rad hard

- Crystals are not uniform by construction
- Stability: transparency, temperature sensitivity
- No longitudinal segmentation, and limited laterally
- “expensive”

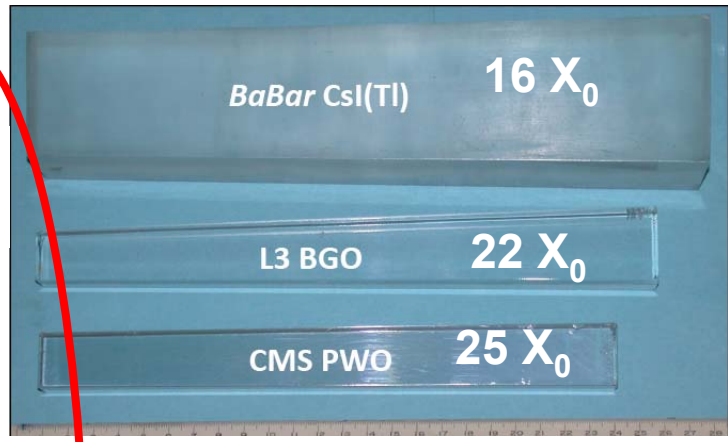
Crystals used for em calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	CeF_3	$PbWO_4$
Density $g.cm^{-2}$	3.67	4.51	4.51	4.89	7.13	6.16	8.28
Rad. length cm	2.59	1.85	1.85	2.06	1.12	1.68	0.89
Moliére radius cm	4.5	3.8	3.8	3.4	2.4	2.6	2.2
Int. length cm	41.4	36.5	36.5	29.9	22.0	25.9	22.4
Decay Time ns	250	1000	35 6	630 0.9	300	10-50	<20>
Peak emission nm	410	565	420 310	300 220	480	310- 340	425
Rel. Light Yield %	100	45	5.6 2.3	21 2.7	9	10	0.7
d(LY)/dT %/°C	≈ 0	0.3	- 0.6	- 2 ≈ 0	- 1.6	0.1	-1.9
Refractive Index	1.85	1.80	1.80	1.56	2.20	1.68	2.16

Belle/ Babar

L3

CMS/ Alice



Need to match crystal with photo-detector

10ms interaction rate, good light yield, good S/N

25μs bunch crossing, low radiation dose

25ns bunch crossing, high radiation dose

Shower profiles in $PbWO_4$

Simulation of longitudinal shower profile **Simulation of transverse shower profile**

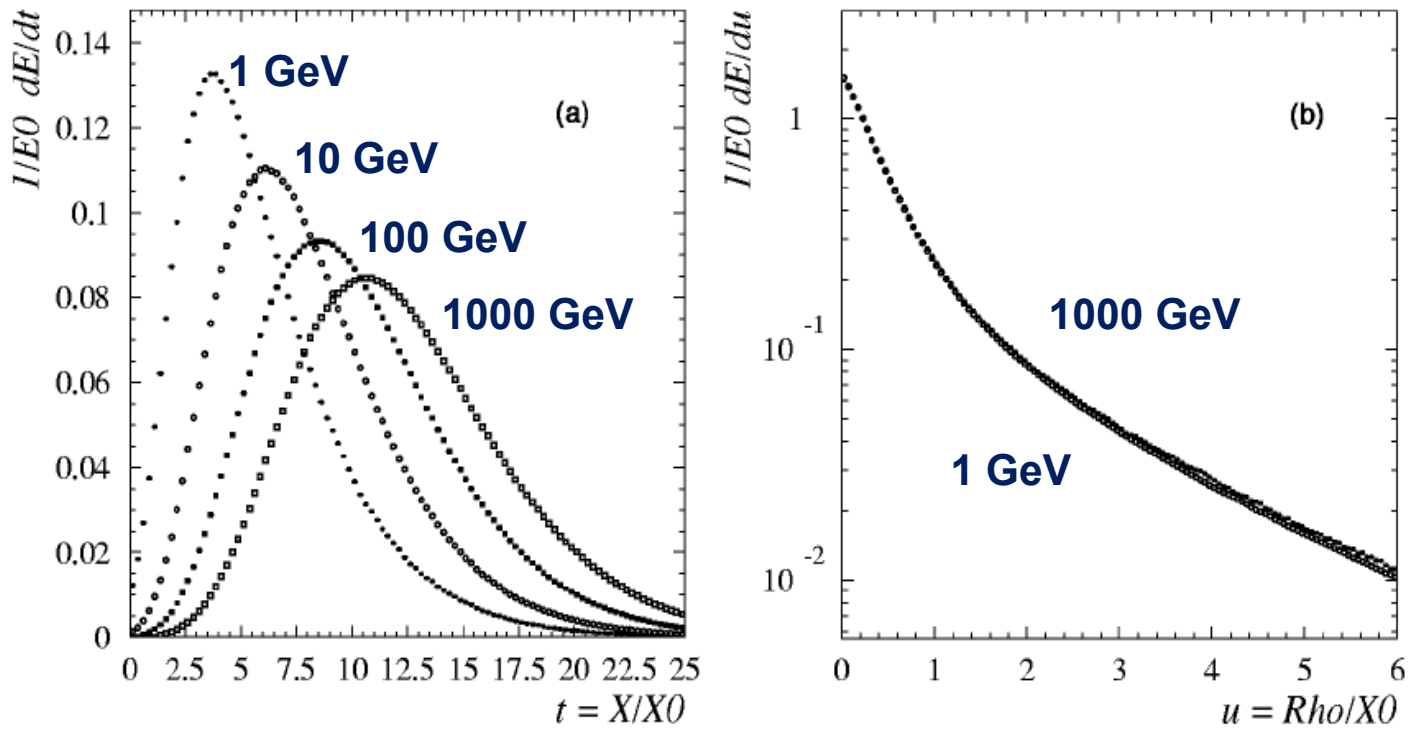


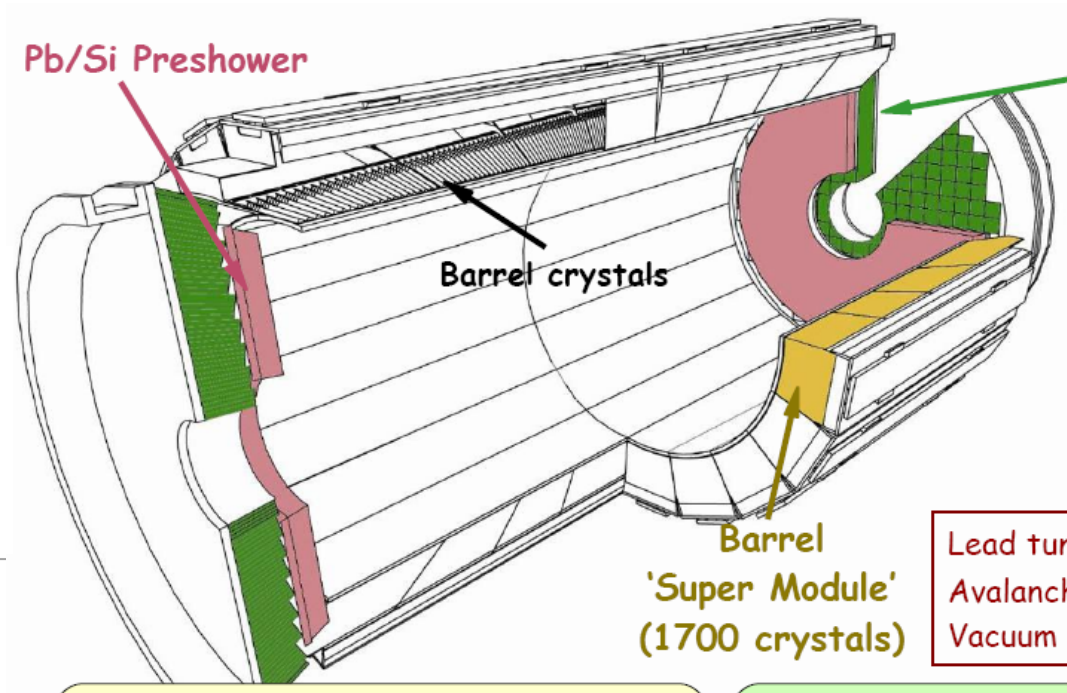
FIG. 2. (a) Simulated shower longitudinal profiles in $PbWO_4$, as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b) Simulated radial shower profiles in $PbWO_4$, as a function of the radial distance from the shower axis (expressed in radiation lengths), for 1 GeV (closed circles) and 1 TeV (open circles) incident electrons. From Maire (2001).

CMS crystal em calorimeter

Excellent stochastic term

Challenge: uniformity/stability

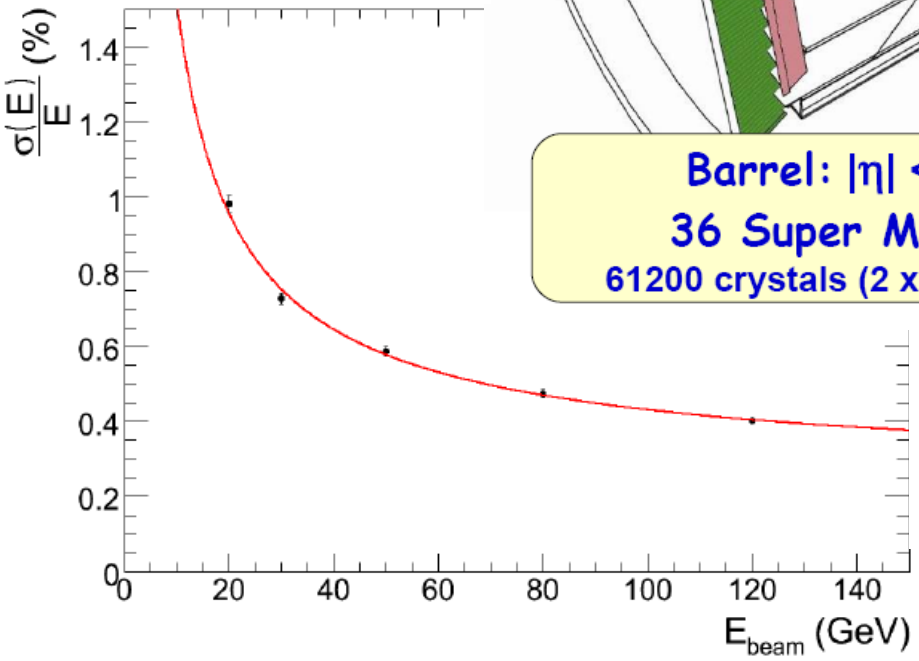
➔constant term



Lead tungstate crystals $PbWO_4$
Avalanche photodiodes (Barrel)
Vacuum phototriodes (Endcaps)

Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2 x 2 x 23 cm^3)

Endcaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3 x 3 x 22 cm^3)



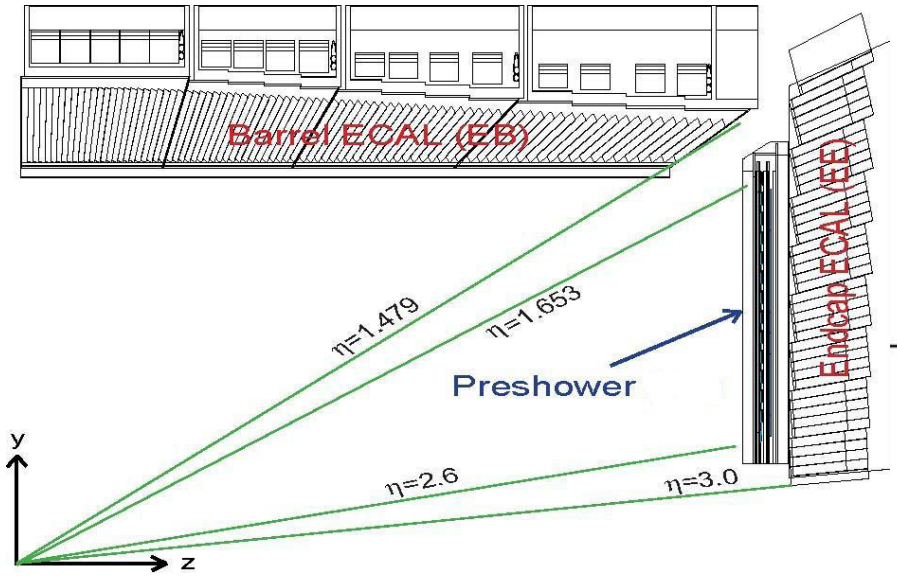
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + (0.25\%)^2$$

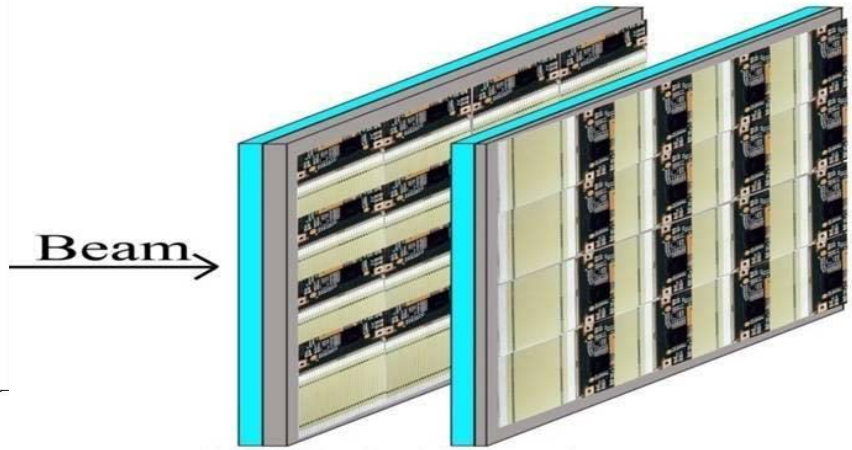
Stochastic Noise Constant

inside a crystal

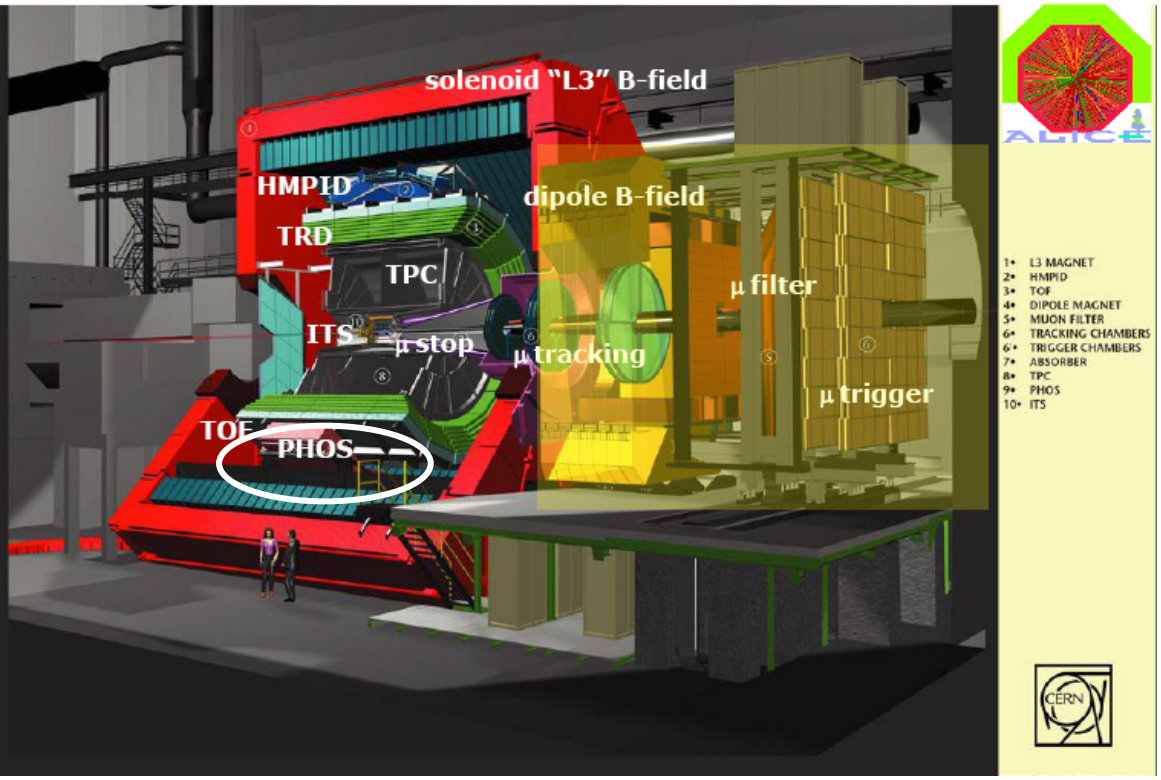
CMS Preshower

- Purpose of the Preshower: identify two closely spaced photons from π^0 decays (main background of $H \rightarrow \gamma\gamma$) in order to separate these photons from single photons, much finer granularity!
- may also contribute to energy measurement
- placed in front of the end-cap ECAL, consists of two absorbers (lead,3X0) and two orthogonal planes of silicon strip sensors





More Crystals: Alice PHOS



Phos – photon spectrometer

Aim: low energy photon measurement in central region

- covers 100° in φ, $|\eta|<0.12$

- 18000 Channel $PbWO_4$

- granularity in η x φ: 0.004x0.004

- resolution: $3.3\%/\sqrt{E}\oplus 1.1\%$

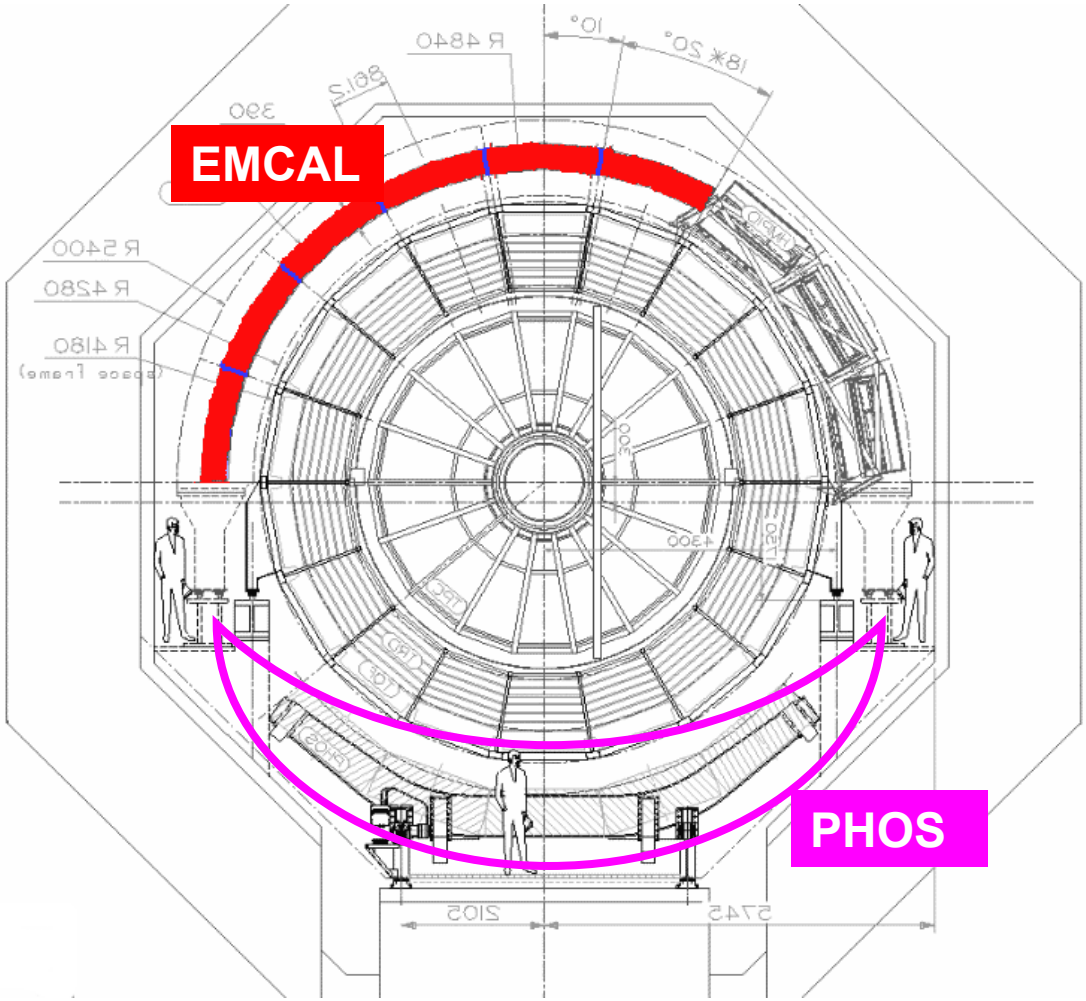
➔ Finer granularity than CMS, slightly worse resolution expected

Alice: EMcal

- Sampling calorimeter: $20X_0$

-Pb-Scint sandwich

- covers 110° in φ, $|\eta|<0.7$
-12000 Towers
- granularity in η x φ: 0.014x0.014
- resolution: ~10%
- back to back with PHOS

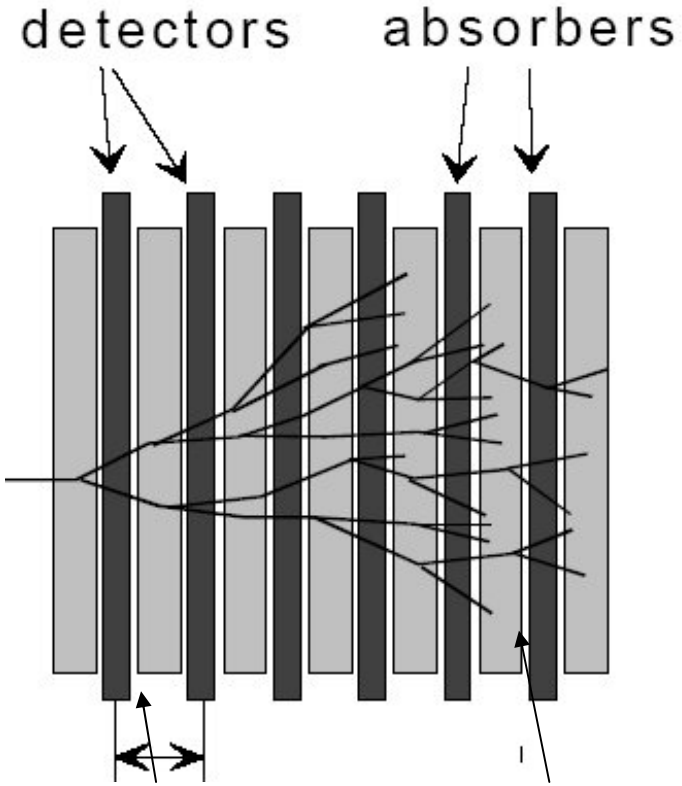


Sampling calorimeters

Use a different medium to generate the shower and to detect signal

Sampling Fraction =
Energy deposited in Active/
Energy deposited in passive material.

$$f_{samp} = \frac{E_{mip}(actif)}{E_{mip}(actif) + E_{mip}(absorbeur)}$$



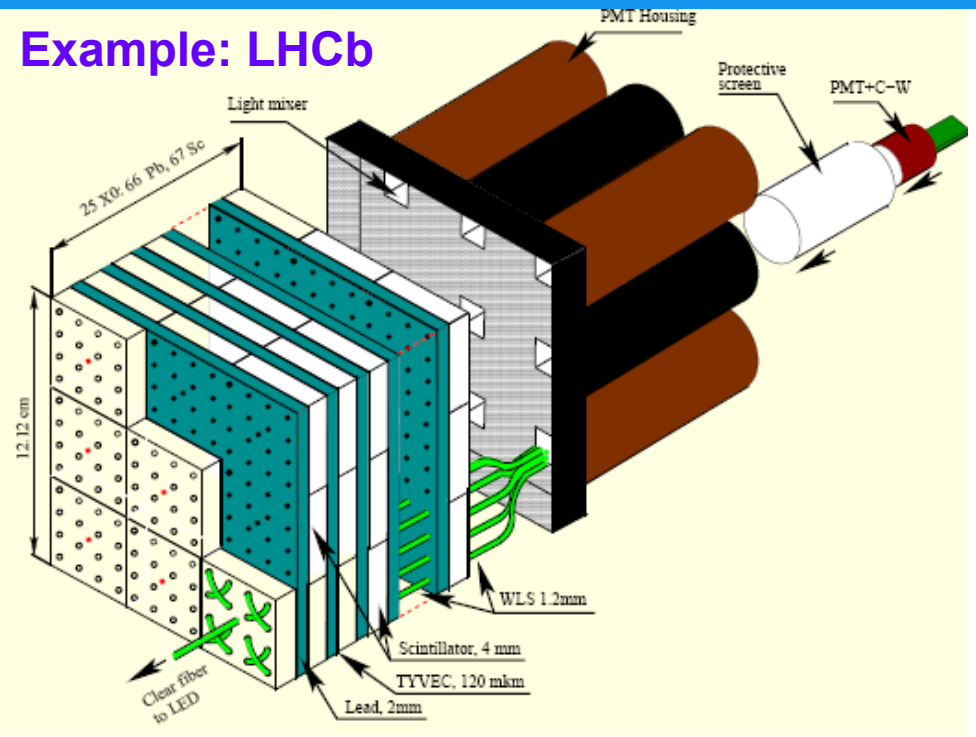
Advantage:
Optimum choice of absorber materiel (Pb, Ur, W, Fe)
Optimum choice of detector material (scintillator, noble liquid, gas or solid state detectors)
Compact and cheap construction
Easier segmentation➔ better space resolution, better particle identification

Disadvantage:
Worse resolution → larger stochastic term

$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}} \approx \frac{5-20\%}{\sqrt{E}}$$

Scintillator Sampling Calorimeters

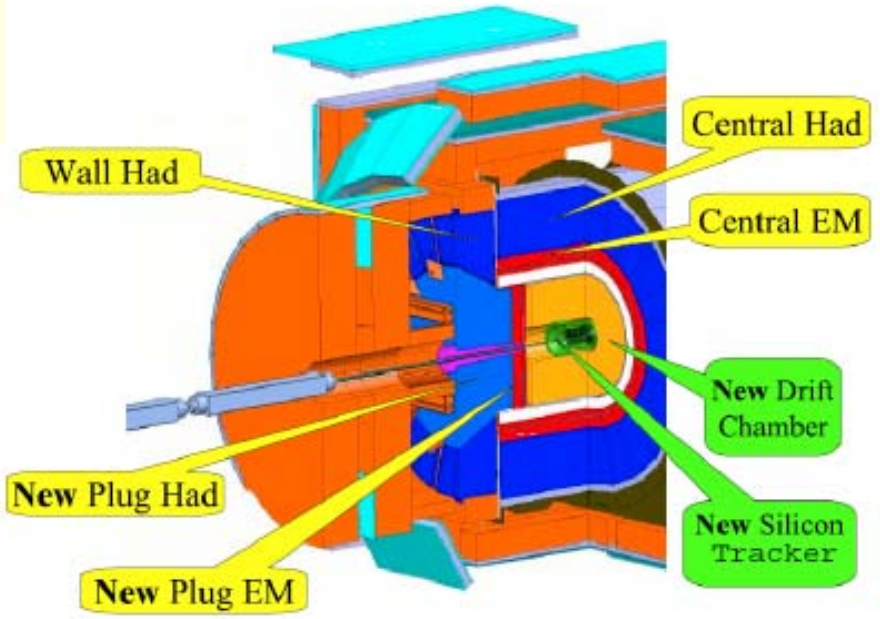
Example: LHCb



A large number of sampling calorimeters use organic scintillators arranged in fibers (SpaCal) or plates (Sandwich).

Absorber material varies: Pb, Ur,

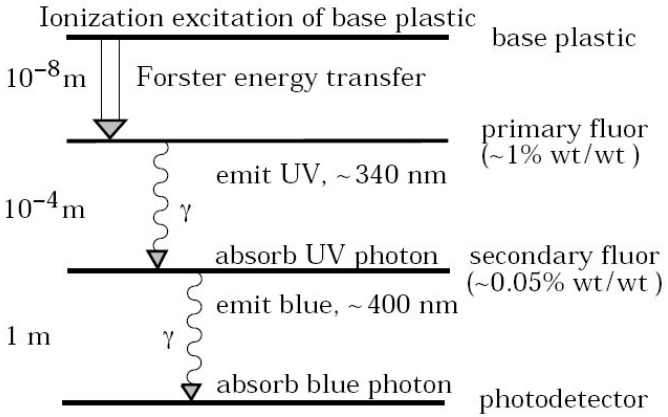
Example: CDF



Advantage: fast signals, "easy to construct" and operate, compact
Disadvantage : optical readout suffers from radiation damage and non-uniformities
➔ often source of a large constant term

Organic scintillator

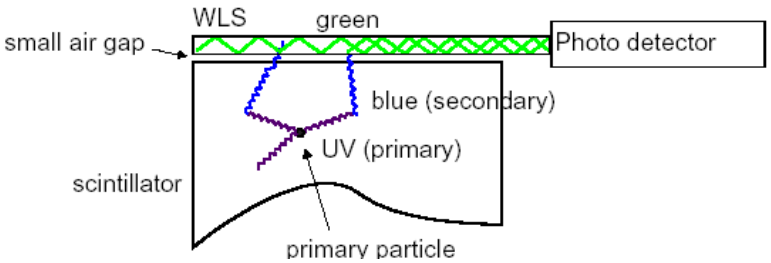
Most popular are plastic scintillators :
- would emit in UV, “slow signal” >10 ns
- Add fluor ➔longer wave length of new emitted photon and faster:
decay time 1-3 ns around 400 nm

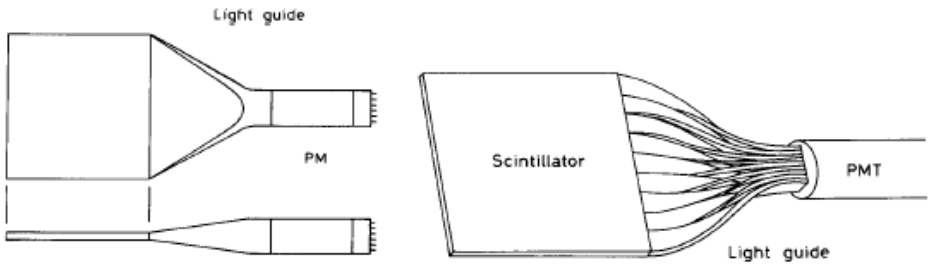


Based on same principle, external Wave Length Shifter are used to make easier the light collection

shift wave length in a material where one can get total reflection

Usually small density (low Z) ➔ used for low energy photon or as sensitive medium in calorimeter





“fish tail” adiabatic

Liquid sampling calorimeter

The active material is generally a noble liquid

➔ need for cryogenic temperatures

Warm liquids work at room temperature exists, have poor radiation resistance and suffer from purity problems

➔ operation in 'ion chamber mode', i.e. deposited charge is large and doesn't need multiplication:

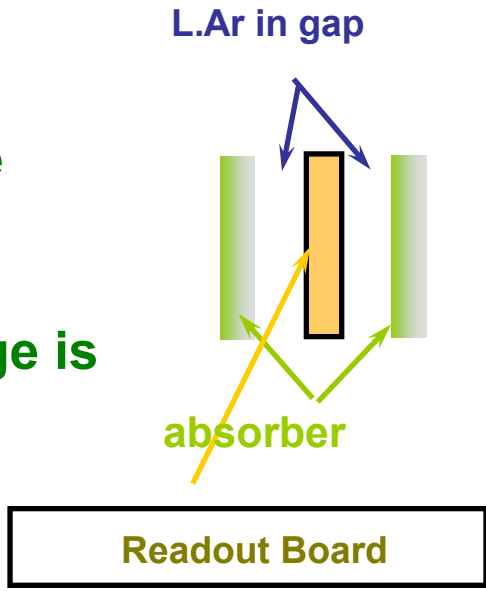
better uniformity compared to gas calorimeters that need amplification.

➔ relatively uniform and easy to calibrate because the active medium is homogeneously distributed inside the volume.

➔ good energy resolution and stable operation with time.

➔they are radiation hard.

➔ rather slow…

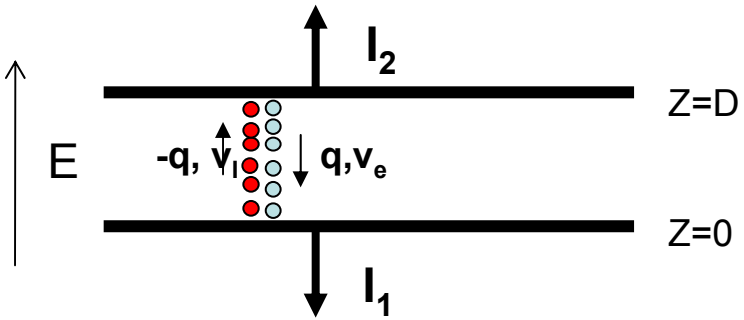


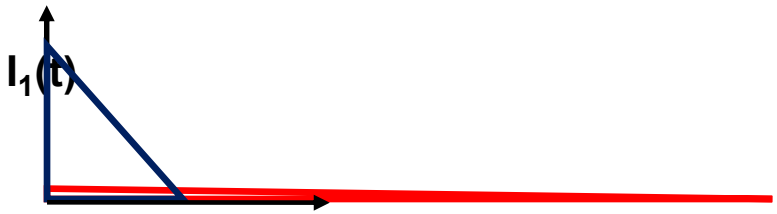
Noble liquids for em calorimeters

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

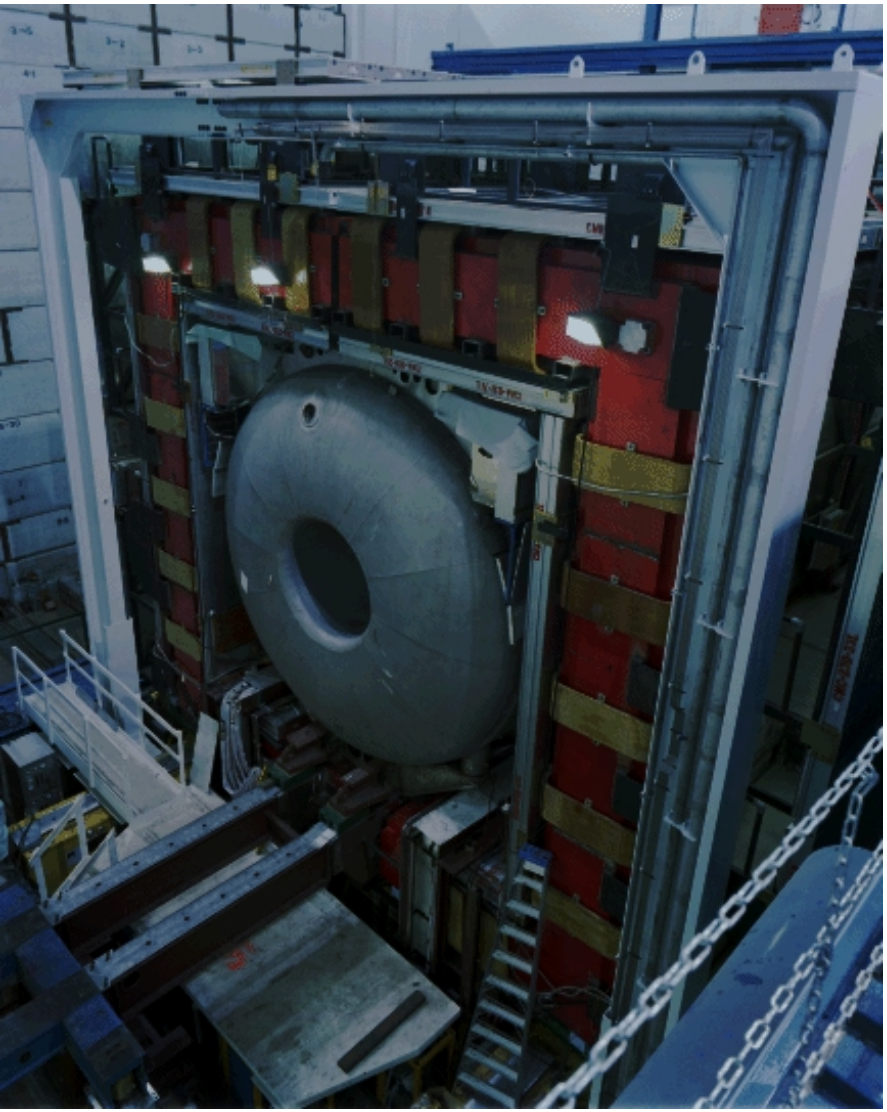
- charge particle convert about half of their lost energy into ionization and half into scintillation.
-best energy resolution if collecting both the charge and light signal!
- but rather difficult to extract light and charge in the same instrument…

Liquid Argon, 5mm/ µs at 1kV/cm, 5mm gap:
➔ 1 µs for all electrons to reach the electrode
➔ 0.1ms for ions ! → don't contribute to the signal for electronics of µs integration time.





You've already seen that!



D0 liquid Argon calorimeter:

- Conception started in 1983
- Uranium/Liquid Argon calorimeter (but also Copper/Stainless Steal)

➔"compensating" $e/\pi \sim 1$ (with 3.4μs integration time)

- 55 000 read-out cells
  - ➔**4 em layers (2, 2, 7, 10 X_0),**
  - ➔**shower-max (EM3): 0.05 x 0.05**
  - ➔**4-5 hadronic layers (FH + CH)**
  - ➔**λ_{int} > 7.2 (total)**
- 5000 semi-projective trigger towers

➔**$\Delta\eta\times\Delta\varphi$ = 0.1x0.1**

- Hermetic :
  - ➔**$|\eta| < 4.2$ ($\theta \approx 2^o$),**
- single particle resolution from test beam

e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$

π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$

Atlas liq Argon em calorimter

Standard liquid argon calorimeters: absorber and active layers are perpendicular to the direction of the incident particle.
→Long cables needed to gang together the readout electrodes
→ signal degradation, dead spaces between the calorimeter towers
➔ reduced hermeticity.



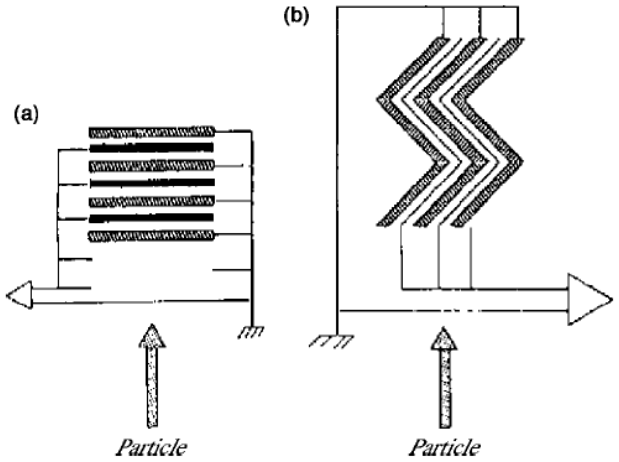
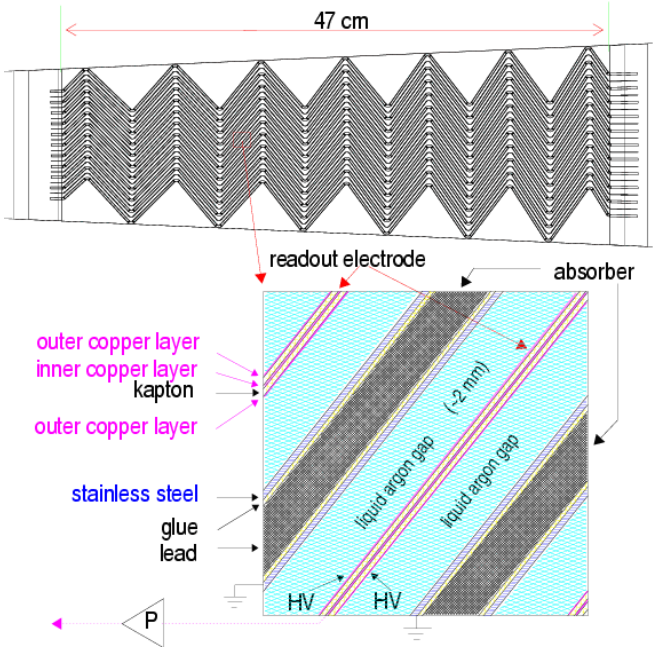


FIG. 15. Schematic view of a traditional sampling calorimeter geometry (a) and of the accordion calorimeter geometry (b).

ATLAS LAr Calorimeter: absorbers in an accordeon geometry parallel to the particle direction ➔ electrodes can easily be read out from the 'back side'.

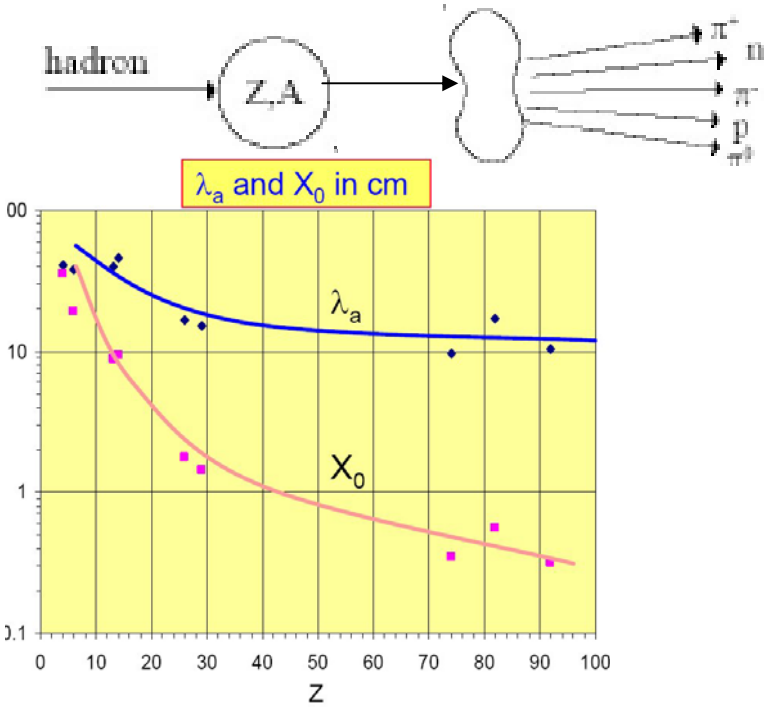


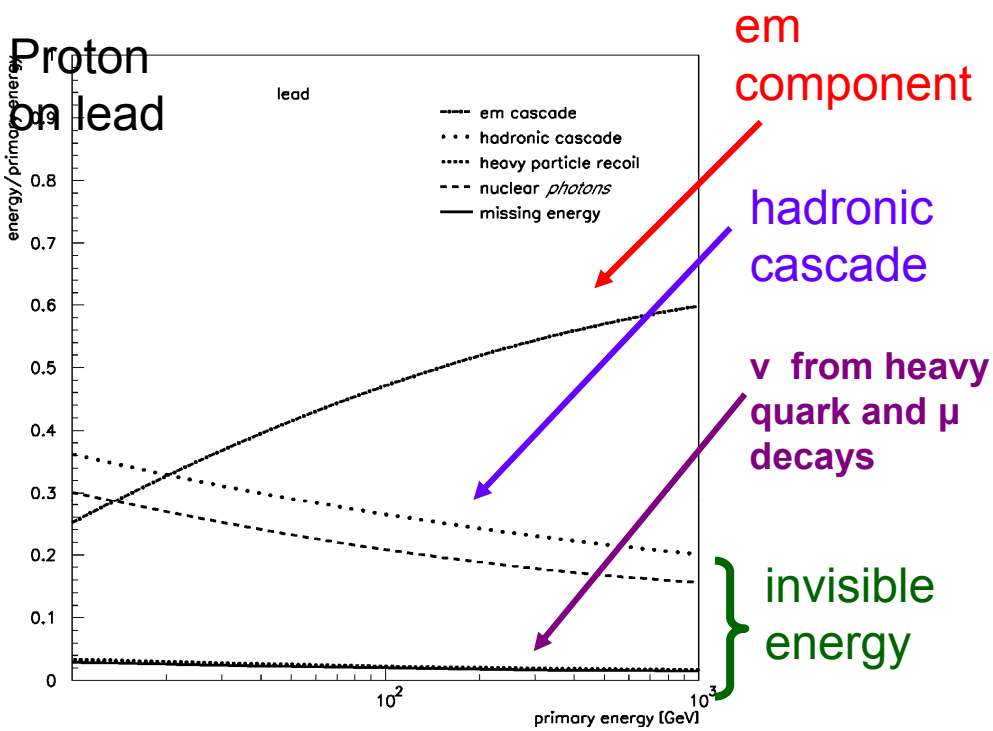
Hadron Calorimeters

- Showers & Detectors
  - Generalities
  - EM Calorimeters
    - Interactions of electrons/γ with matter
    - EM shower characterizations
    - Calorimeter principle
  - Hadron Calorimeters
    - Hadron Showers
    - Compensation
- Calibration
  - Test Beams
  - Electronics Calibration
  - Cell level calibration
- Calorimeter Reconstruction
  - Electron/photon reconstruction
  - Jet reconstruction
  - E_T^{miss} reconstruction
  - E-flow

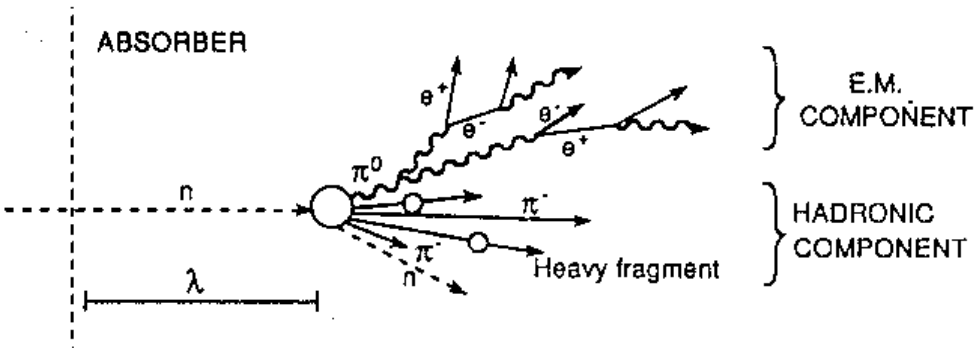
Hadron showers

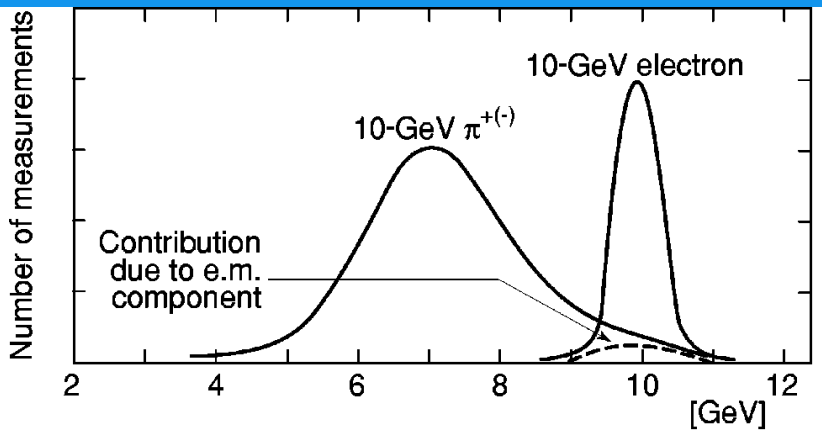
1. Production of energetic secondary hadrons
   - Number of particles produced ~ ln (E) with an "interaction length" $\lambda \approx 35\ A^{1/3}$
   - Among the particles produced: p, n, $\pi^{+/-}$,and
     π^0 ➔ 2γ ➔ electromagnetic component of the hadron shower
   - Hadron cascades thermalize, <10% energy loss through ionization
2. Nuclear interactions ➔ resulting in a few MeV photons
   - Produced slowly ~1μs ➔ mostly invisible energy



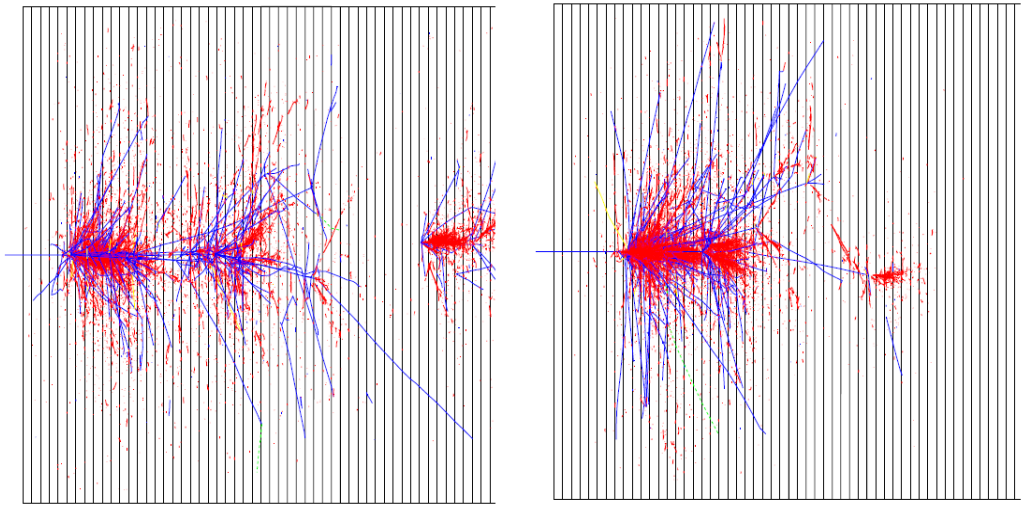


Resolution for hadron calorimeters





Signal (in energy units) obtained for a 10 GeV energy deposit



red: em component **blue: hadronic component**

- not all the incident energy is measured : e/π > 1
- very large event to event fluctuations between hadron and em component
- em component energy dependent→ non linear →resolution worse than for em showers!

Typical resolutions: $\frac{\sigma(E)}{E} \approx \frac{50-100\ \%}{\sqrt{E}} \oplus 3-5\%\ (\text{E en GeV})$

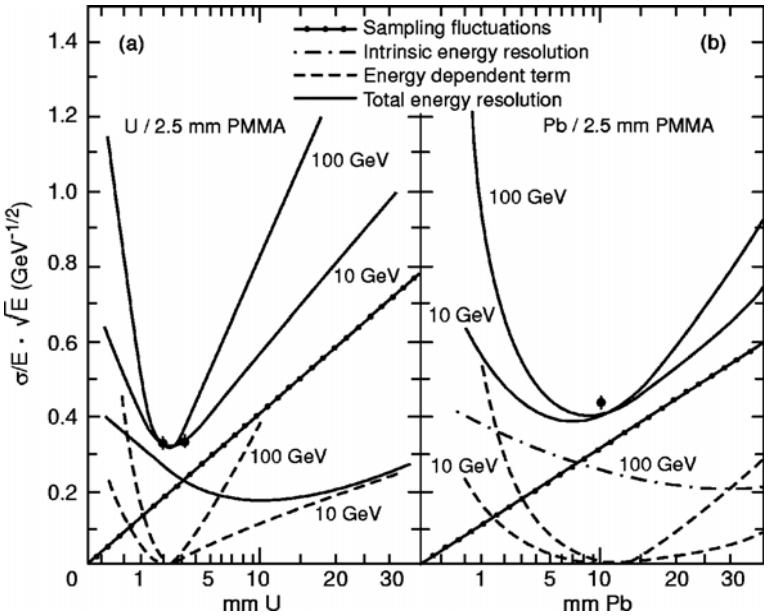
Compensation for hadron calorimeters

e/π ratio is a major component!
- if e/π ≈ 1 the calorimeter is « compensated »

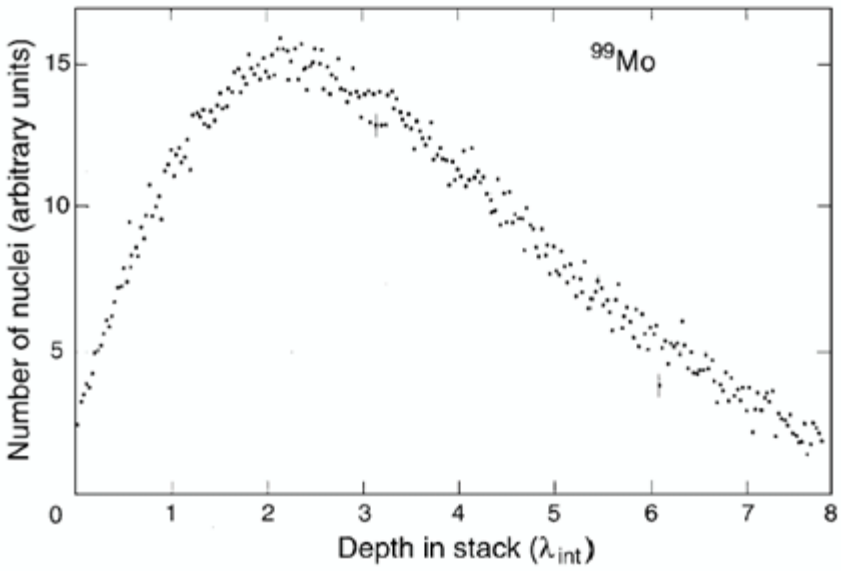
How to achieve compensation?
- Impossible to have a similar response in a homogenous calorimeter
- sampling calorimeters allow to optimize absorber and active material:
- for the hadron cascade,
- active material containing hydrogen (Scintillator) sensitive to neutrons!
- long integrations times…

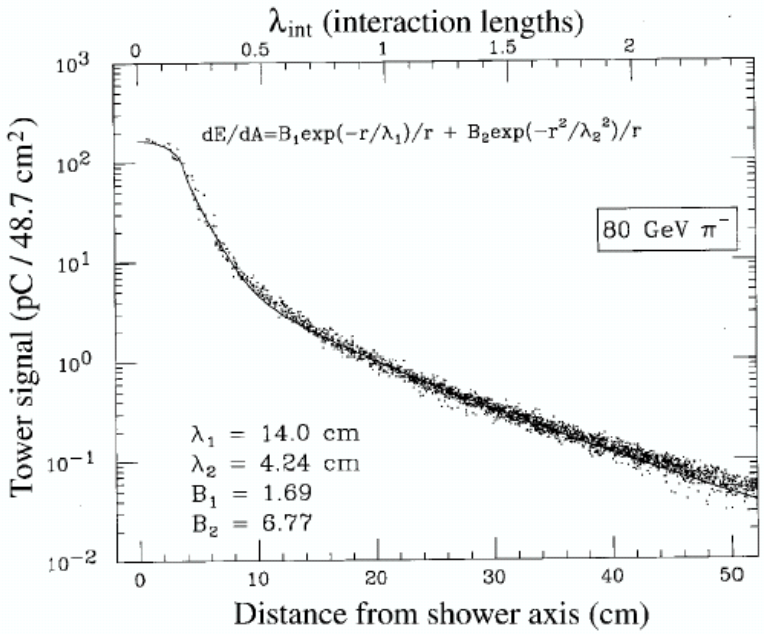
- High Z absorber material: U, Pb, but difficult due to mecanical constraints

- Tuning of the thickness between absorber and active material!



Shower profiles





300 GeV pion, 95% in 8 λ_{int} (85 cm of U)
300 GeV electron , in 30 X_0 (Pb 9cm)

80 GeV pion, 95% in 1.5 λ_{int} (32 cm)
80 GeV electron (3.5cm)

- typically factor ~10 on shower sizes
- Shower max at ~2λ

➔a large energy fraction of the hadron shower is desposited in the em sections !

HCal generalities

- All the hadronic sections of the hadron collider experiments are sampling calorimeters
  - Optimization of e/π response, yet limited resolution of hadron showers
  - Jet radius rather large: coarser granularity, fewer longitudinal segmentation
  - big devices: mechanical considerations, cost consideration
  - Energy fraction deposited decreases with depth, radius of the device increases: less performing absorber material at the outside

  ➔ use of robust and rather cheep absorber material

  ➔ active material: either liquid Argon or scintillator

Tile calorimeters

- Atlas barrel HCAL : l=5.6m r=4.2m
- iron/scintillating tiles
- 10K readout channels in 3 layers (1.4λ, 3.9λ, 1.8λ, ~2λ from em) with a η x φ segmentation of 0.1x0.1 – except last layer 0.2x0.1 (TC)
- resolution: $\sigma/E=50\%/\sqrt{E} \oplus 3\%$

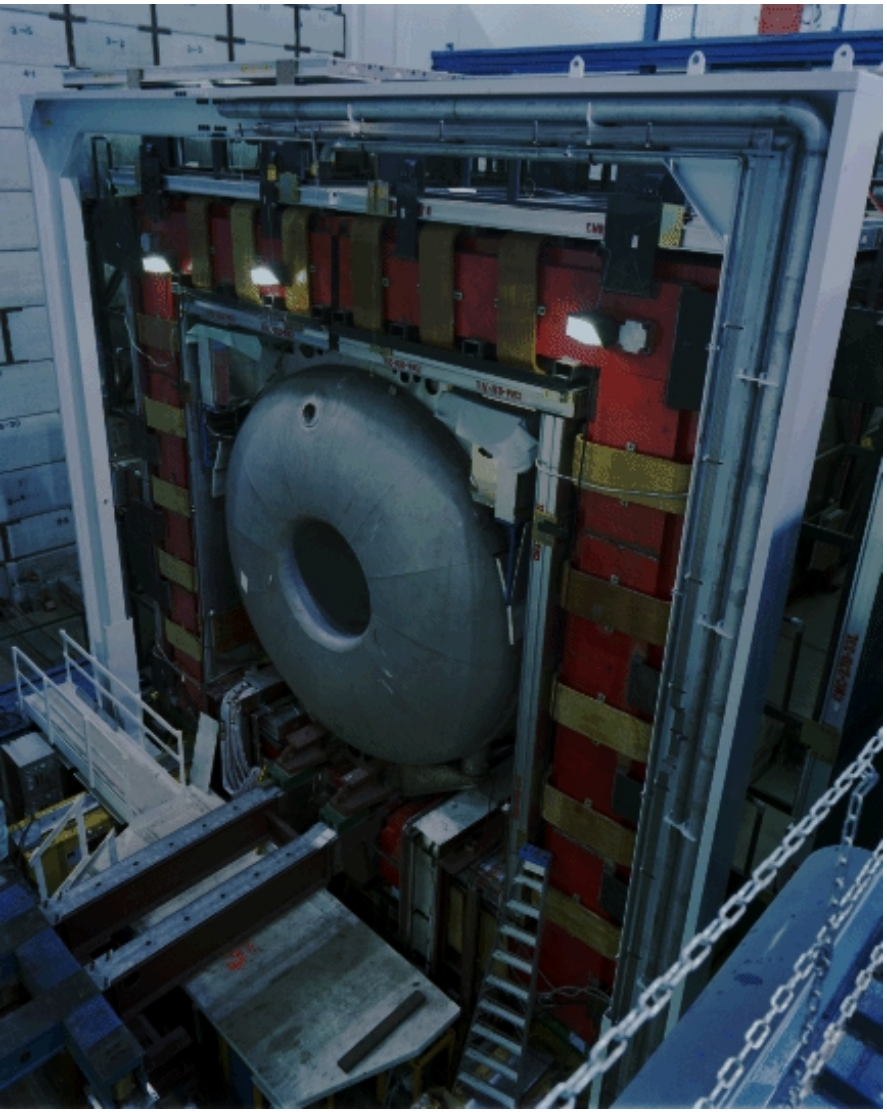




CMS: barrel HCAL: l=9m, r=6m

- brass-scintillator calorimeter
- 10k channels 5.2λ (10λ total) with a η x φ segmentation of 0.087x0.087
- HO: scintillator array in the central region outside the magnet to catch leakage energy
- resolution: $\sigma/E=100\%/\sqrt{E} \oplus 4\%$

For the last time:



D0 liquid Argon calorimeter:

- Conception started in 1983
- Uranium/Liquid Argon calorimeter (but also Copper/Stainless Steal)

➔"compensating" e/π ~ 1 (with 3.4μs integration time)

- 55 000 read-out cells
  - ➔**4 em layers (2, 2, 7, 10 X_0),**
  - ➔**shower-max (EM3): 0.05 x 0.05**
  - ➔**4-5 hadronic layers (FH + CH)**
  - ➔**λ_{int} > 7.2 (total)**
- 5000 semi-projective trigger towers

➔**$\Delta\eta\times\Delta\varphi$ = 0.1x0.1**

- Hermetic :
  - ➔**$|\eta| < 4.2$ ($\theta \approx 2^o$),**
- single particle resolution from test beam

e: $\sigma_E/E = 15\% /\sqrt{E} + 0.3\%$

π: $\sigma_E/E = 45\% /\sqrt{E} + 4\%$

Summary

- Electron, photons leave em showers in a calorimeter:
  - They are compact:
    - the shower maximum is at ~6X_0 longitudinally contained in ~25 X_0,
    - laterally contained to 90% in 1 R_M, > 99% in 3 R_M
  - Measured in homogeneous (crystal) or sampling calorimeters
    - homogenous calorimeter have an excellent intrinsic resolution, but larger non-uniformities, no longitudinal segmentation
    - Sampling calorimeters use either scintillator or liq. Argon as active material, and Pb or Ur as absorber: fine segmentation, large variety of design
    - Intrinsic resolutions 3-20%/√E
- Hadrons produce showers where 20-30% of the initial energy is lost in slow nuclear interactions, with large fluctuations
  - Intrinsic resolution: 50%-100%/√E
  - Hadronic calorimeters complete the em-sections: shower max at ~2λ
  - Sampling calorimeters which have to be solid, robust and rather cheap