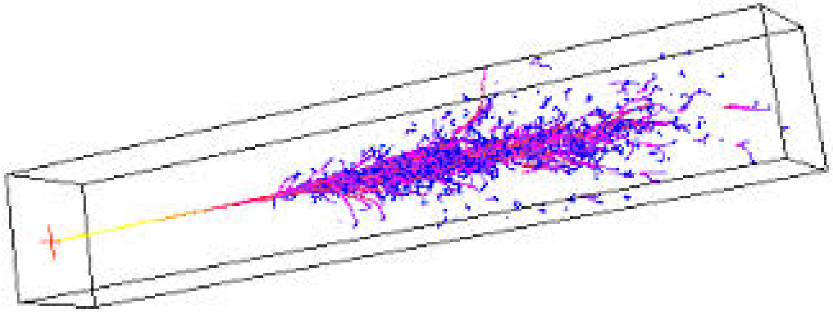
Calorimetry – part 1



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Kerkrade – 3rd September 2014

Outline of the lectures

- Part1 (today)
  - Particle interaction with matter
  - Electromagnetic and hadronic showers
  - Homogeneous and sampling calorimeters
  - Compensation
  - Energy detection mechanisms and scintillators
  - Energy resolution

Outline of the lectures

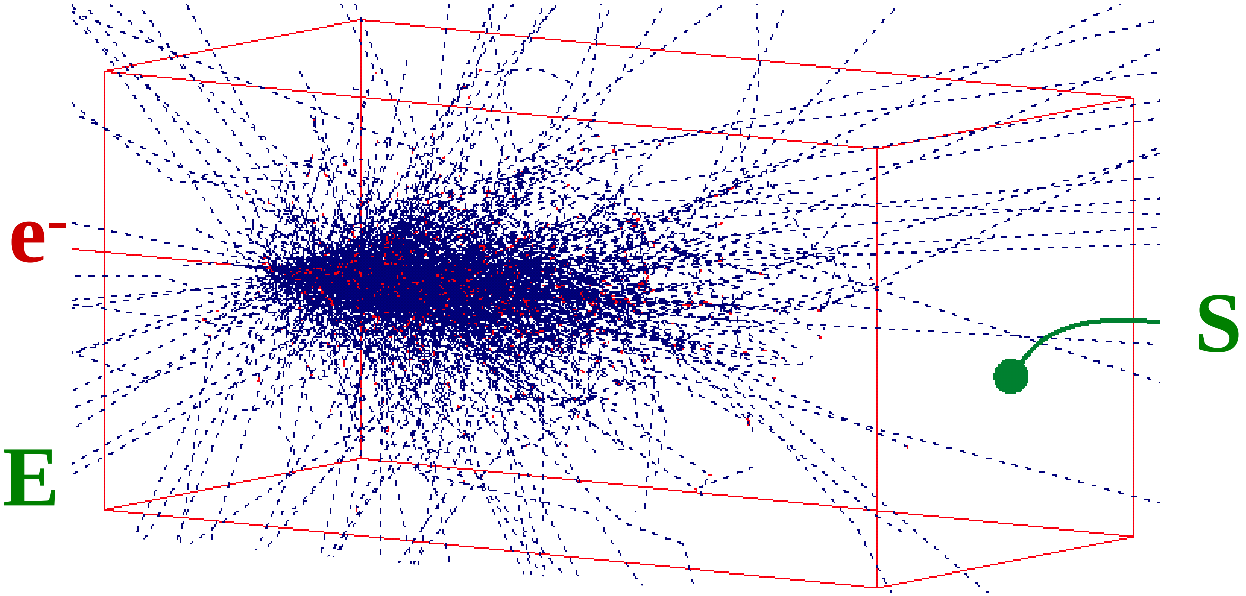
- Part2 (tomorrow morning): introduction to electromagnetic and hadron calorimeters at LHC and their performance during LHC run1

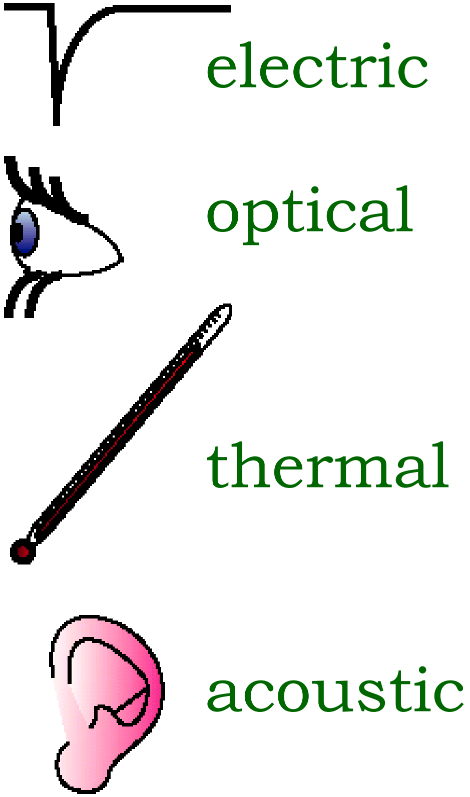
- Part3 (tomorrow afternoon): R&D for future calorimeters and upgrade for High Luminosity LHC

Suggested readings

- Part1
  - R. Wigmans, “Calorimetry - Energy Measurement in Particle Physics”, Oxford University Press, 2000
    - many plots taken from this excellent book
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
  - Particle Data Book, J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012) http://pdg.lbl.gov/pdg.html
- Part2
  - CMS Collaboration, “Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at √s = 7 TeV”, JINST 8 (2013) P09009
  - ATLAS Collaboration, “Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data”, arXiv:1407.5063v1 (submitted to EPJC)

Calorimeters: a simple concept





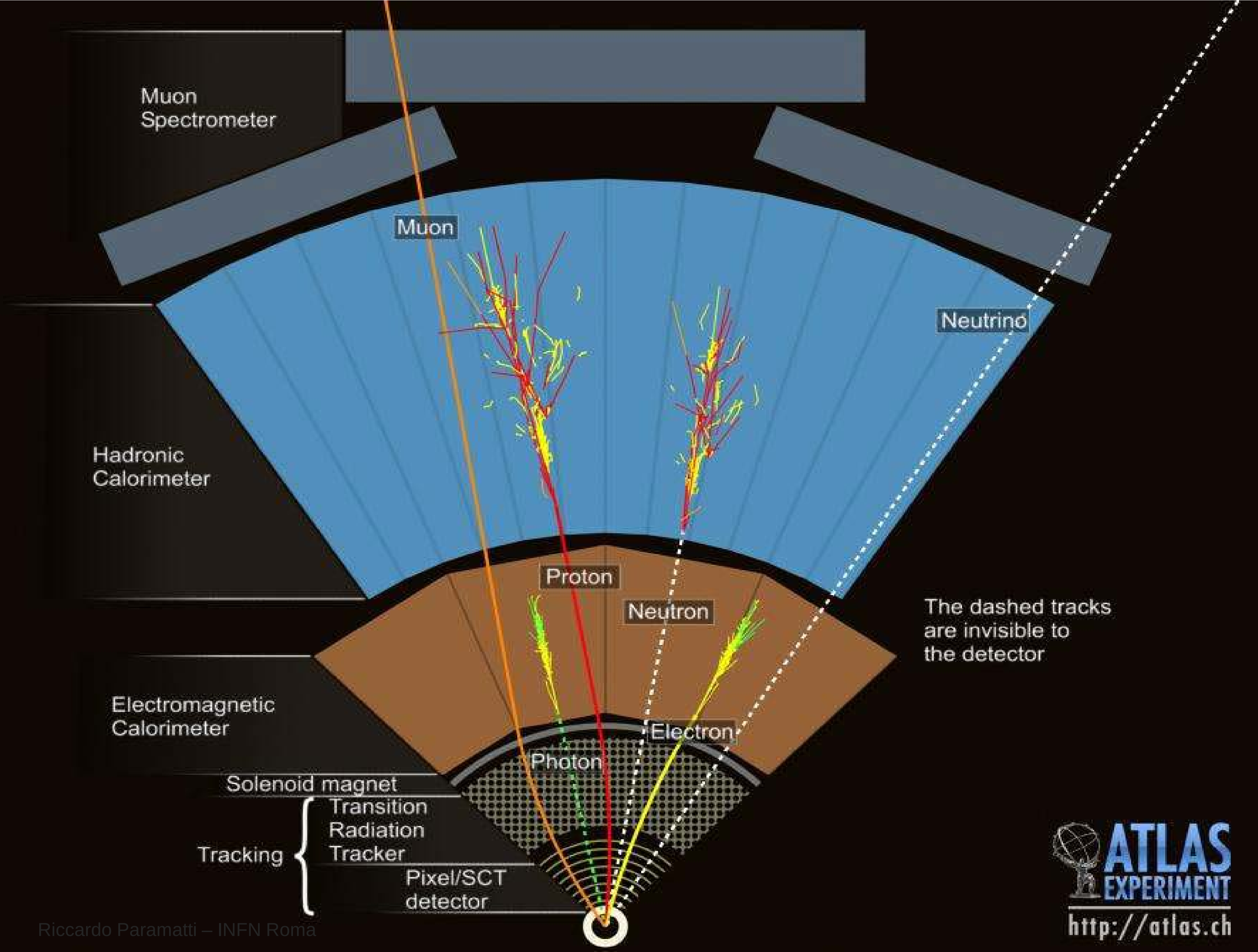
Convert energy **E** of incident particle to detector response **S**: $S \propto E$

The temperature effect of a 100 GeV particle in 1 liter of water (at 20 °C) is: $\Delta T = 3.8 \cdot 10^{-12} K$

Calorimeters: some features

- Detection of both charged and neutral particles
  only means to measure energy of neutrals
- Particle identification by «simple» topological algorithms
- Detection based on stochastic processes →
  precision increases with E
- Dimensions necessary to containment ∝ lnE →
  compactness
- Segmentation → measure of position and direction
- Fast → high rate capability, trigger

Calorimetry is a “destructive” method.
Energy and particle get absorbed !

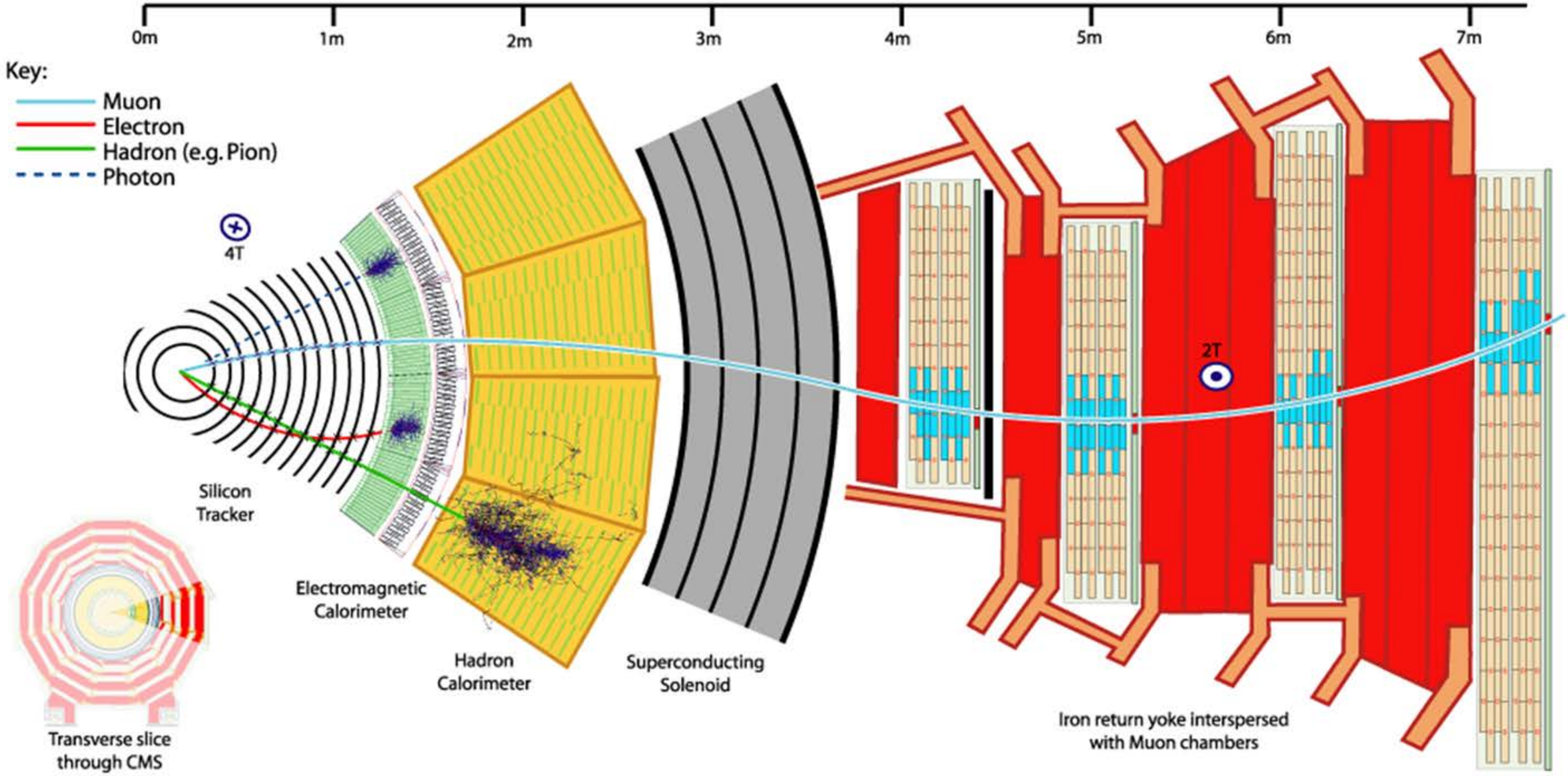


The dashed tracks are invisible to the detector

http://atlas.ch

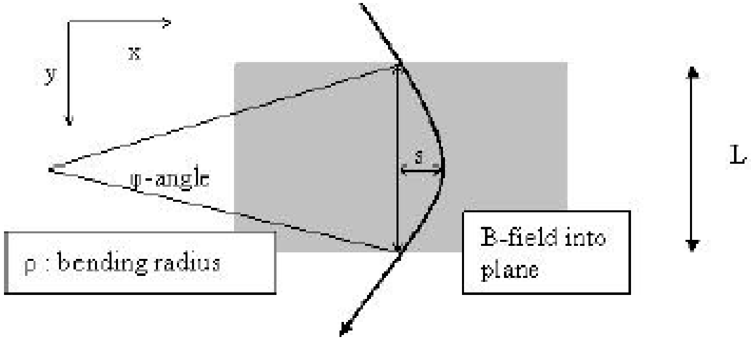
Particles in HEP detectors

CMS @ LHC



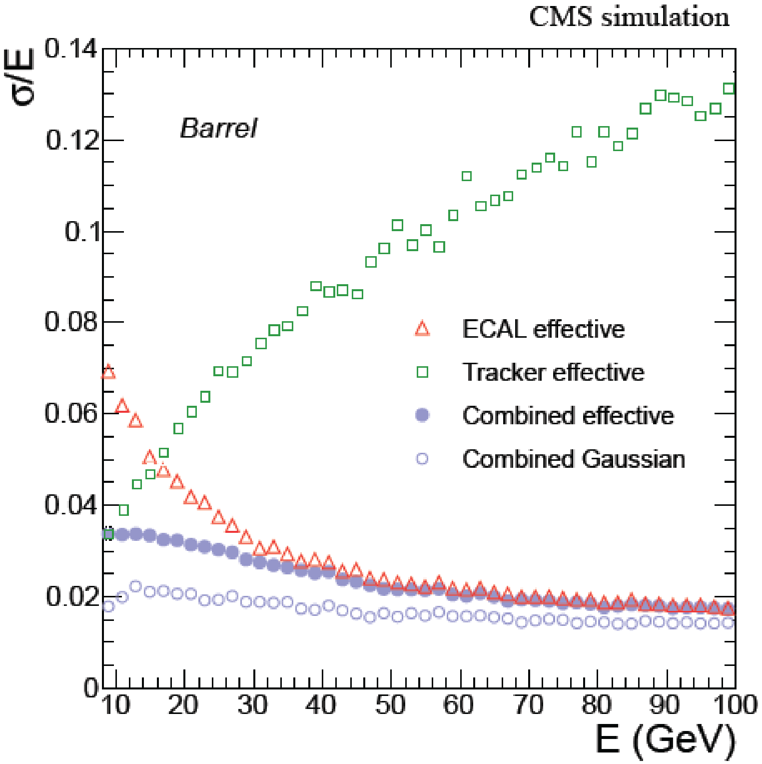
Resolution: calorimeter vs tracker

tracker momentum measurement with the sagitta method

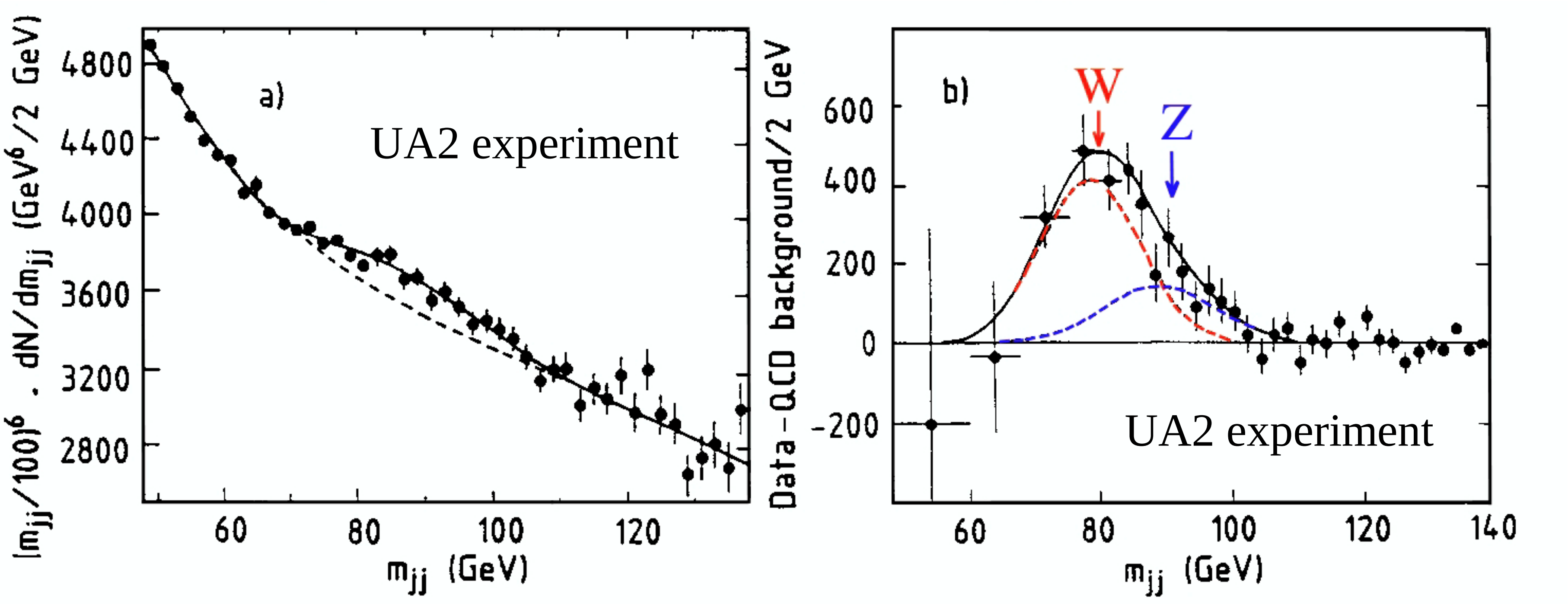


$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)\, p_T}{0.3BL^2}\sqrt{720/(N+4)}$$

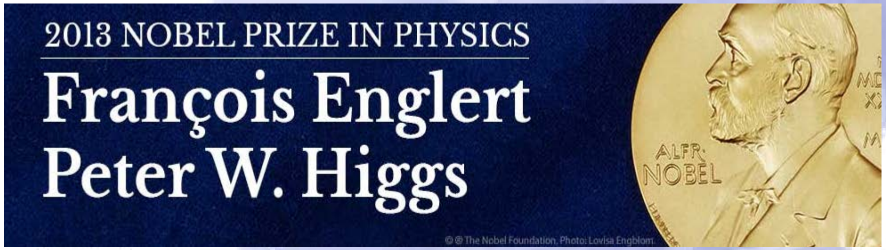
The contribution to the electron energy measurement from the tracker is relevant only at low energy (for instance below ~20 GeV in CMS).



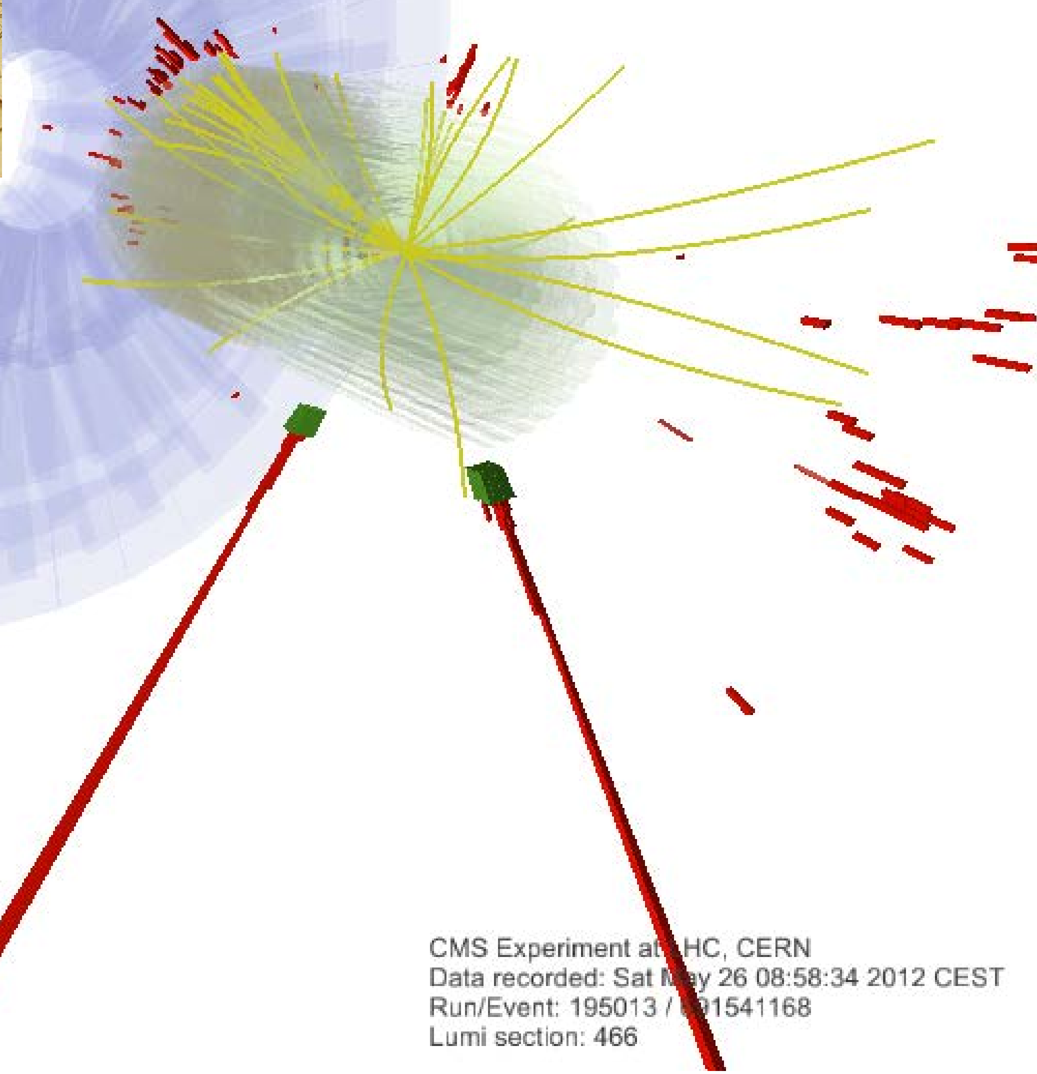
Calorimeters and discoveries: a long relationship (J/Ψ, W & Z…)



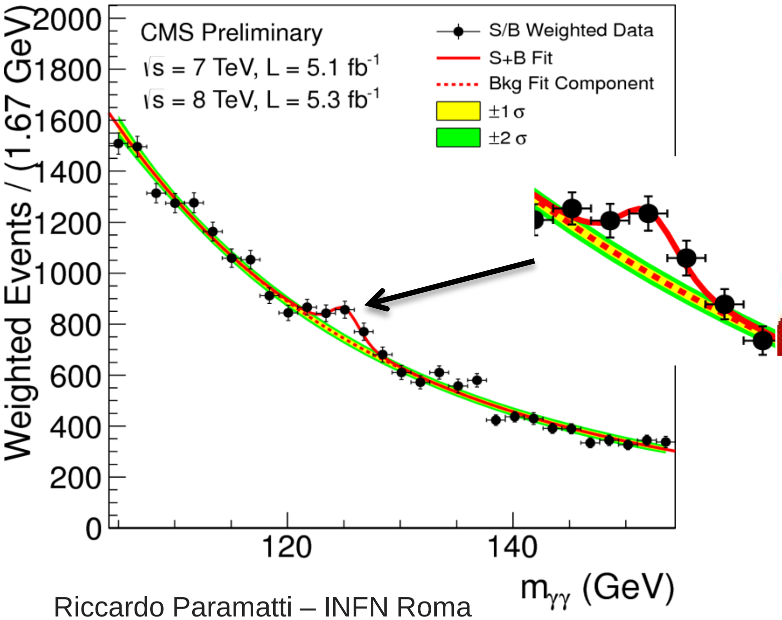
Final states with electrons, photons and jets also fundamental in new physics.



Calorimeters and discoveries: a long relationship



Plot from the CMS 4th July 2012 Higgs search presentation



Particle interaction with matter and electromagnetic shower

Electron and photon energy loss in matter

- In matter electrons and photons loose energy interacting with nuclei and atomic electrons
- Electrons and positrons
  - ionization (atomic electrons)
  - bremsstrahlung (interaction with nuclei)
- Photons
  - photoelectric effect (atomic electrons)
  - compton scattering (atomic electrons)
  - pair production (interaction with nuclei)

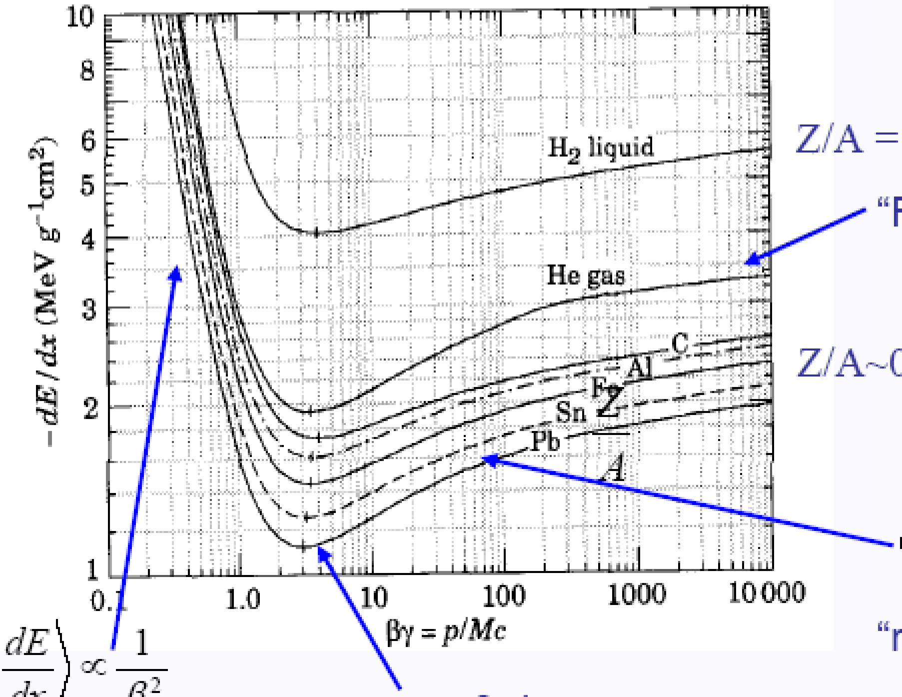
Energy loss: ionization

- Charged particles: continuous energy loss due to excitation and ionization of the medium atoms

βγ dependence

Proportional to the square of the particle charge (z=1 in the figure)

MIP (minimum ionizing particle) energy loss is 1-2 MeV/(g/cm^2)



Z/A = 1

“Fermi plateau”

Z/A~0.5

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$$

“relativistic rise”

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

“kinematical term”

βγ ≈ 3-4

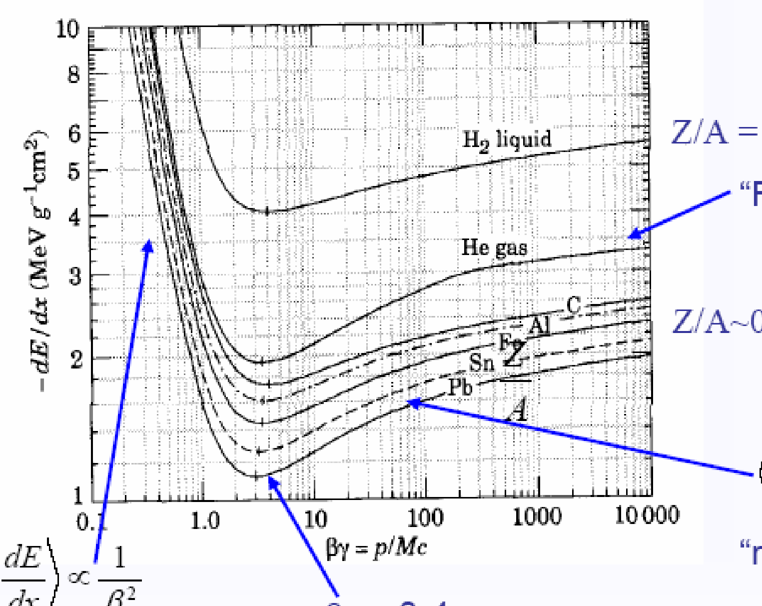
minimum ionizing particles, MIPs

Energy loss: ionization (2)

- Average energy loss: Bethe-Block

$$-\frac{dE}{dx} = 4\pi N_A \cdot r_e \cdot m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

Electrons require some corrections due to their small mass and Pauli principle.



Z/A = 1

"Fermi plateau"

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$$\left\langle\frac{dE}{dx}\right\rangle \propto \ln\beta^2\gamma^2$$

"relativistic rise"

$$\left\langle\frac{dE}{dx}\right\rangle \propto \frac{1}{\beta^2}$$

"kinematical term"

$\beta\gamma \approx$ 3-4

minimum ionizing particles, MIPs

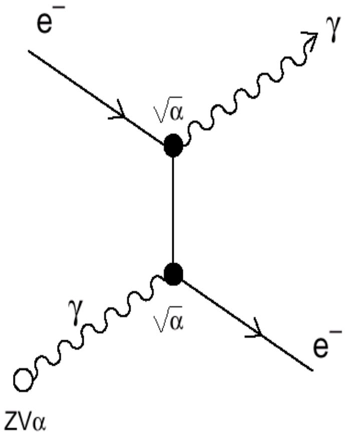
Energy loss: Bremsstrahlung

- Electromagnetic interaction of the charged particle with the nucleus: continuous emission of photons.

$$-\frac{dE}{dx} = 4\alpha N_A \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 z^2 \frac{Z^2}{A} E \cdot \ln \frac{183}{Z^{1/3}}$$

Important for light particles

$$-\left.\frac{dE}{dx}\right|_{\mu} \approx \frac{1}{40000} \left.\frac{dE}{dx}\right|_{e}$$



Dominant at high energies

Photon energy spectrum ∝ 1/E

Emission angle $\langle \Theta \rangle = \frac{1}{\gamma_e}$

Radiation length X_0

- For high energy electrons: $$-\left.\frac{dE}{dx}\right|_{Brem} = \frac{E}{X_0}$$

$$E = E_0 \cdot e^{-x/X_0}$$

- Radiation length:
  thickness of material that reduces the mean energy of a (high energy) electron to 1/e of initial energy.

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}\left[\frac{g}{cm^2}\right]$$

air: 300 m
plastic scintillator: 40 cm
aluminium: 18.8 cm
iron: 1.76 cm
lead: 0.56 cm

Critical energy

Critical energy E_c:
same energy loss due to ionization and Bremsstrahlung

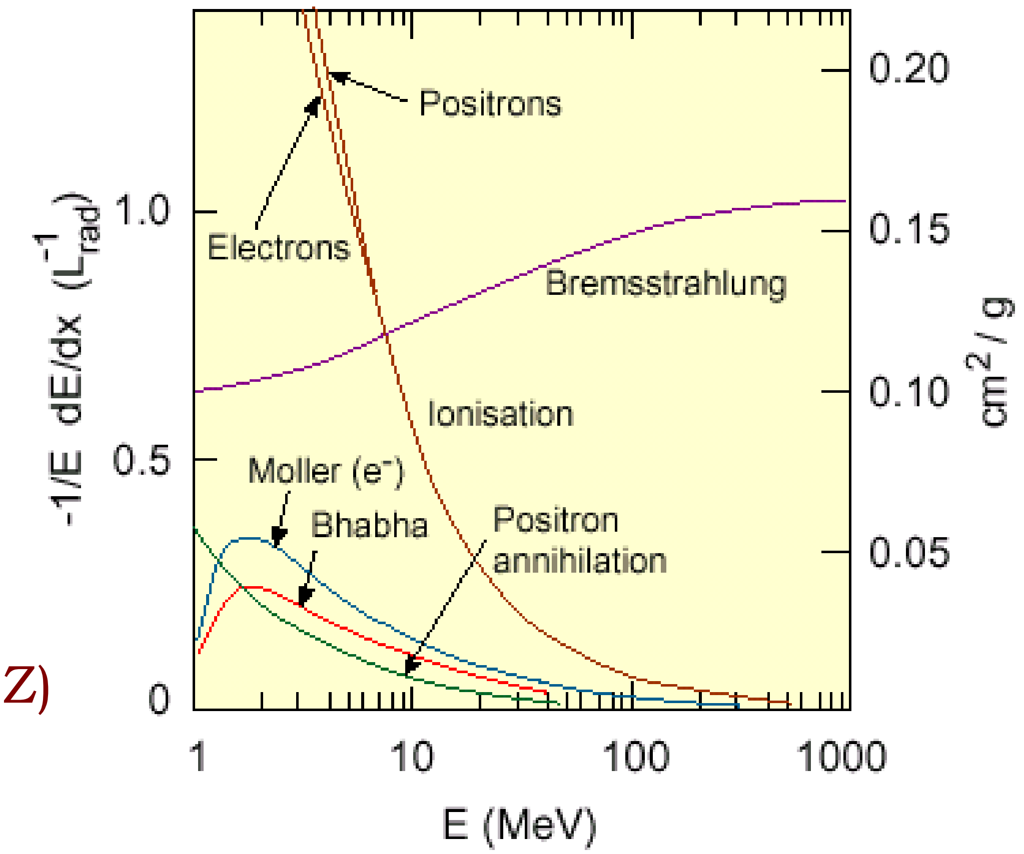
$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = 1$$

$$E_c \approx \frac{610\text{MeV}}{Z+1.24}$$

(solids, liquids)

Strongly material dependent (1/Z)
(eg. 7 MeV for lead, 20 MeV for copper, 95 MeV for carbon;
1 TeV for muons in copper !)

Fractional Energy Loss by Electrons



Photon energy loss

- photo-electric effect

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}} \qquad \sigma \propto \; Z^5 \;, \; E^{-3.5}$$

- compton scattering

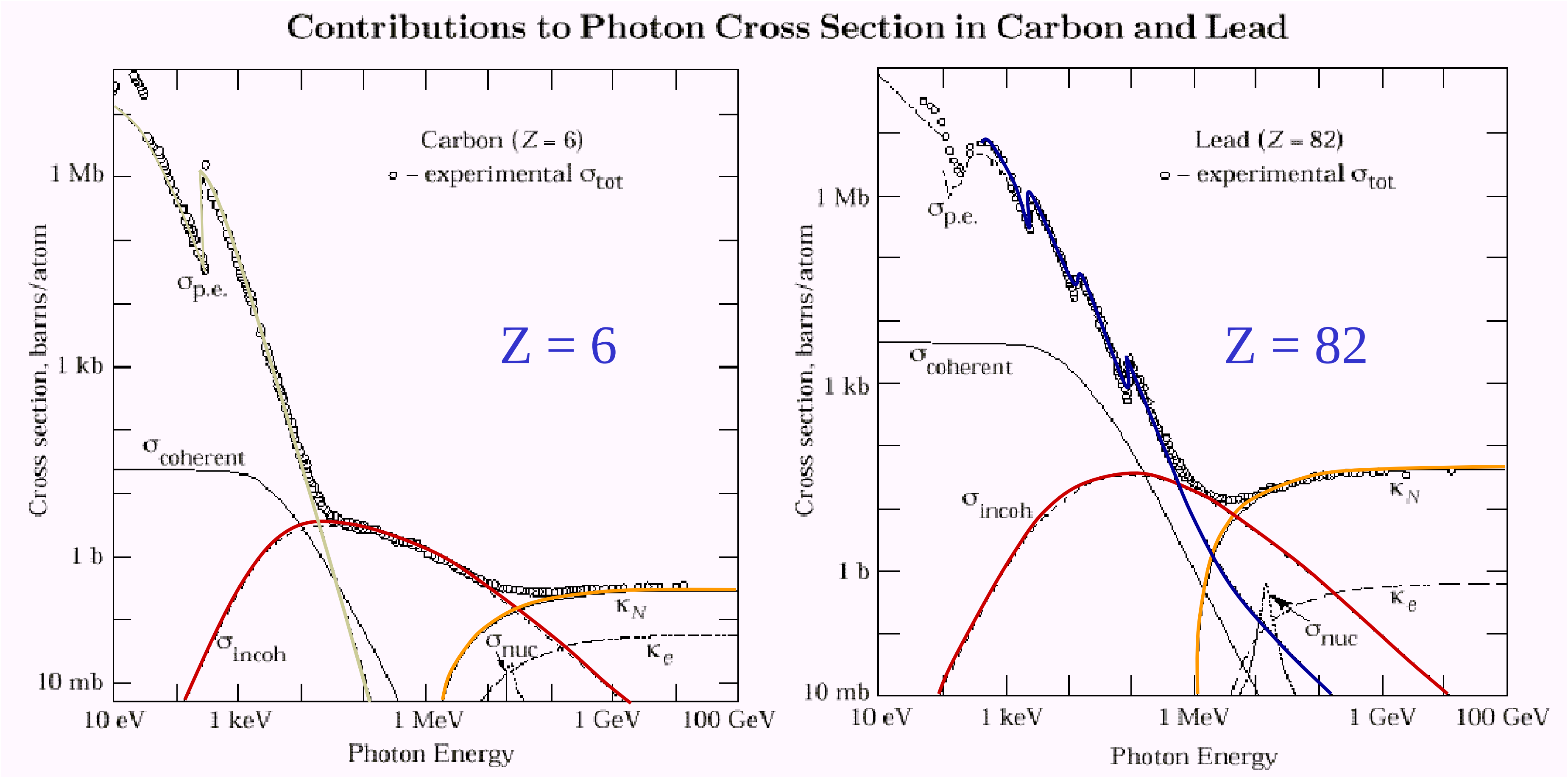
$$\sigma_c \approx Z \frac{\ln E_\gamma}{E_\gamma} \qquad \sigma \propto \; Z \;, \; E^{-1}$$

- pair production only occurs if $E_\gamma \; > 2m_ec^2$

$$\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

- $\sigma \propto \; Z\,(Z+1)$; $\propto \ln E/m_e$ for E < 1GeV <u>independent of energy above 1 GeV</u>
- intensity of the beam: $I(x)=I_0 \exp(-x/L_{pair})$
- Mean free path $L_{pair} = 9/7\, X_0$ (γ disappears)

Photon energy loss (2)

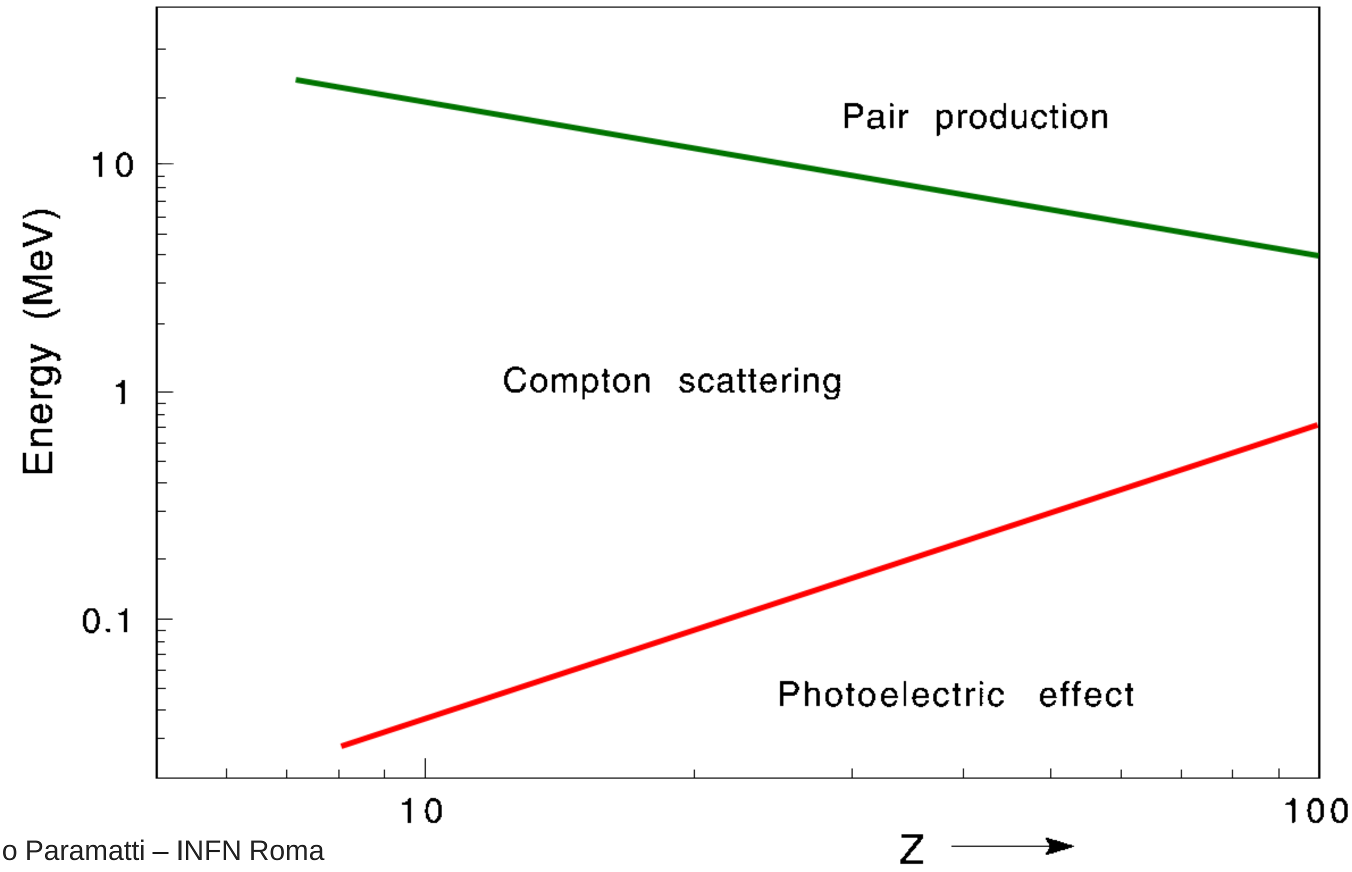


Contributions to Photon Cross Section in Carbon and Lead

Cross section in right plot: more lead is needed to absorbe a photon with 3 MeV energy than a 20 MeV photon !

Photon energy loss (3)

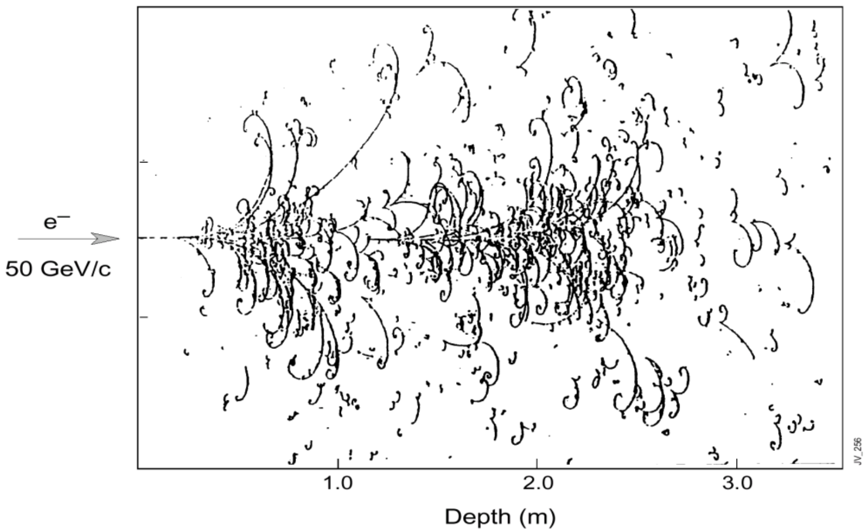
Main contribution to cross section vs photon energy and Z of the medium



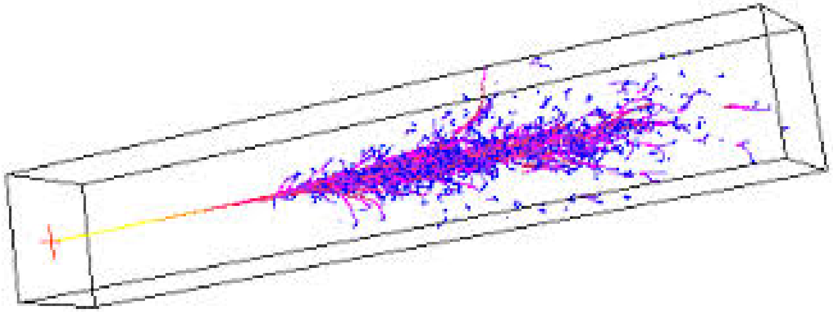
Electromagnetic shower

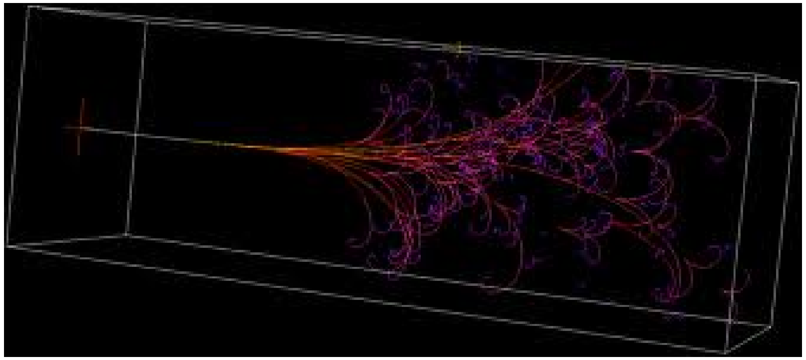
- Above 1 GeV the dominant processes, bremsstrahlung for e^+ and e^- and pair production for photons, become energy independent.
- Trough a succession of these energy loss mechanisms an electromagnetic cascade is propagated until the energy of charged secondaries has been degraded to the regime dominated by ionization loss (below E_c)
- Below E_c a slow decrease in number of particles occurs as electrons are stopped and photons absorbed.

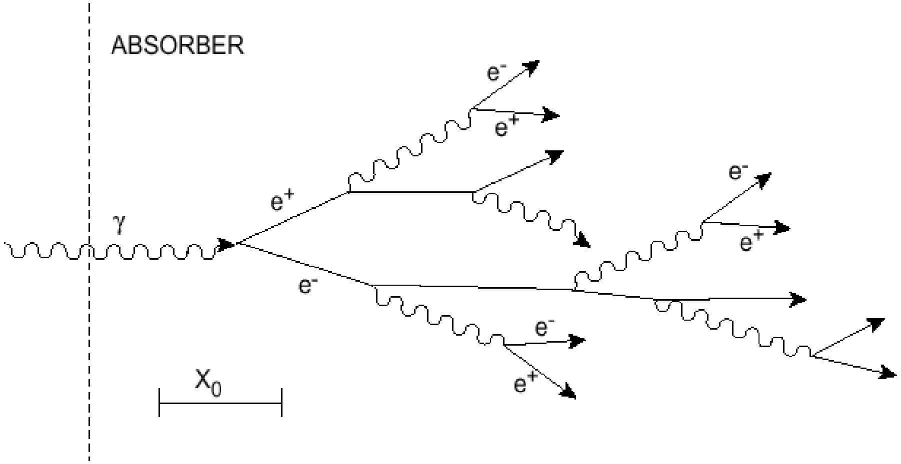
Electromagnetic shower (2)



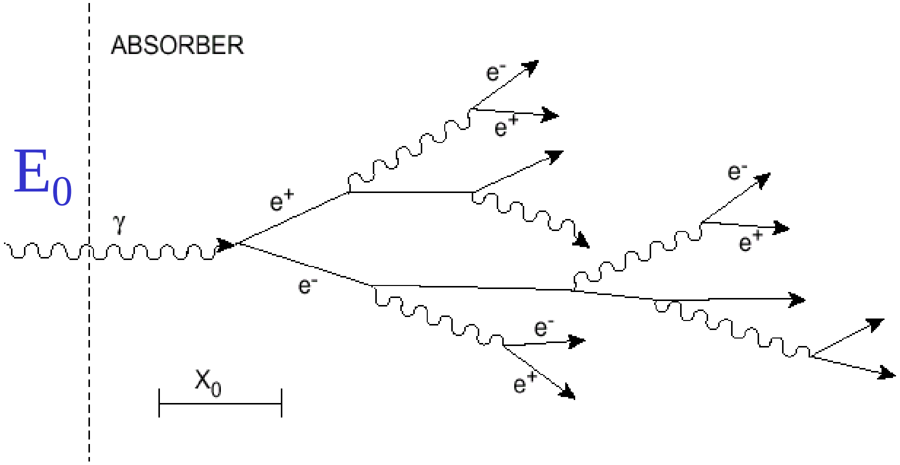
Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron







Electromagnetic shower (3)



Above the critical energy, in $1X_0$:

- an electron loses ~65% of its energy via Bremsstrahlung
- a photon has a probability of ~55% of pair conversion.

Simple model: assume X_0 as a generation length:

in each generation the number of particle increases by a factor 2

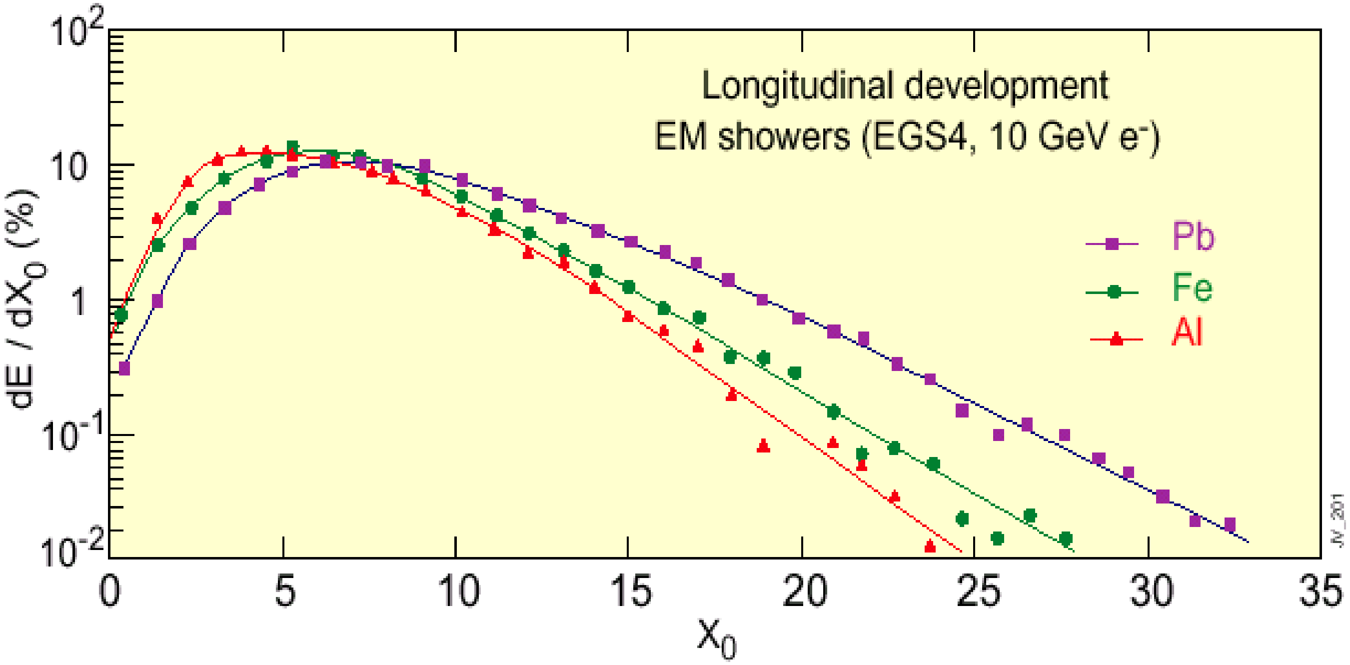
at $\Delta x = tX_0$ $\quad N(t) = 2^t \quad E(t) = E_0 / 2^t$

at $\Delta x = t_{max}X_0$ (shower max) $\quad E(t_{max}) = E_0 / 2^{t_{max}} = E_c$

$t_{max} = \ln(E_0/E_c)/\ln(2) \propto \ln(E_0) \quad N(t_{max}) \sim E_0/E_c$

Longitudinal profile of electromagnetic shower

$E_c \propto 1/Z$ → shower max shifted for high Z
shower tail extended for high Z

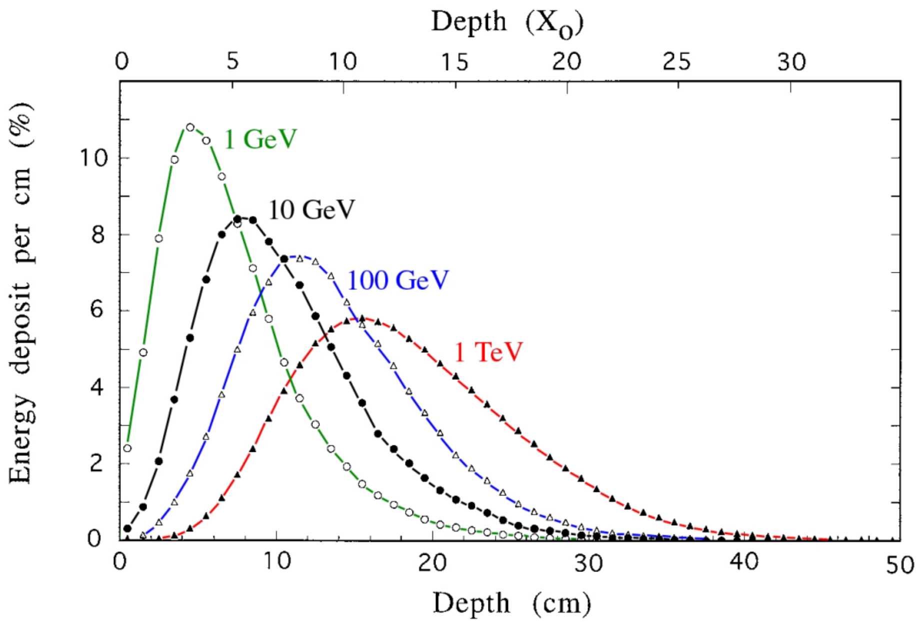


$$\boxed{\frac{dE}{dt} \propto t^{\alpha} e^{-\beta t}}$$

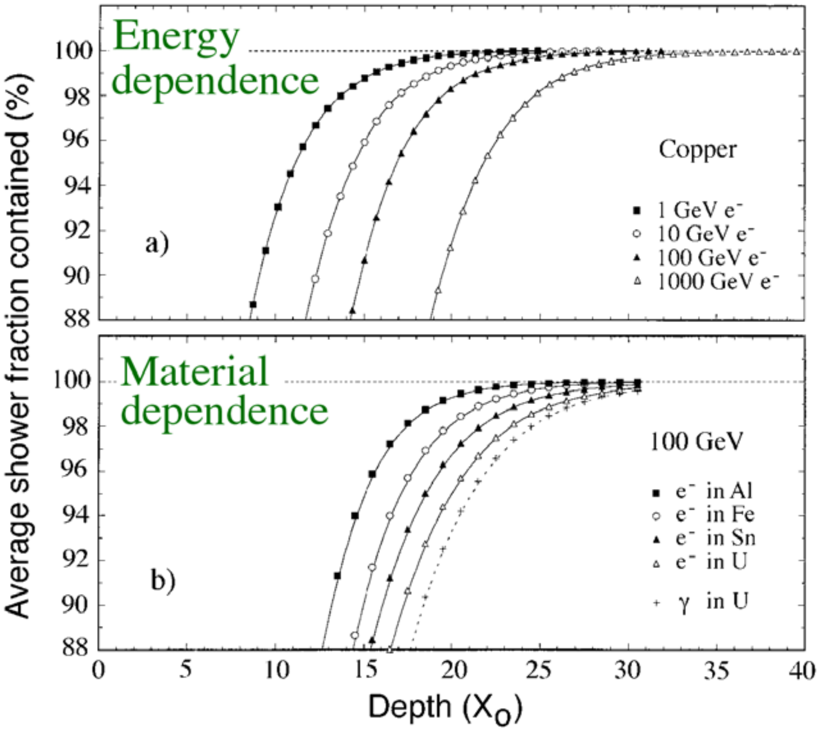
Energy is deposited by electrons and positrons of the shower. Electrons are largely dominant in population but positrons are in average more energetic.

Longitudinal profile of electromagnetic shower (2)

$$t_{max} = 1.45 \ln(E_0/E_c)$$



Electron shower in a block of copper


Energy dependence

Material dependence

1 GeV electron in copper:
95% in 11 X_0 and 99% in 16 X_0

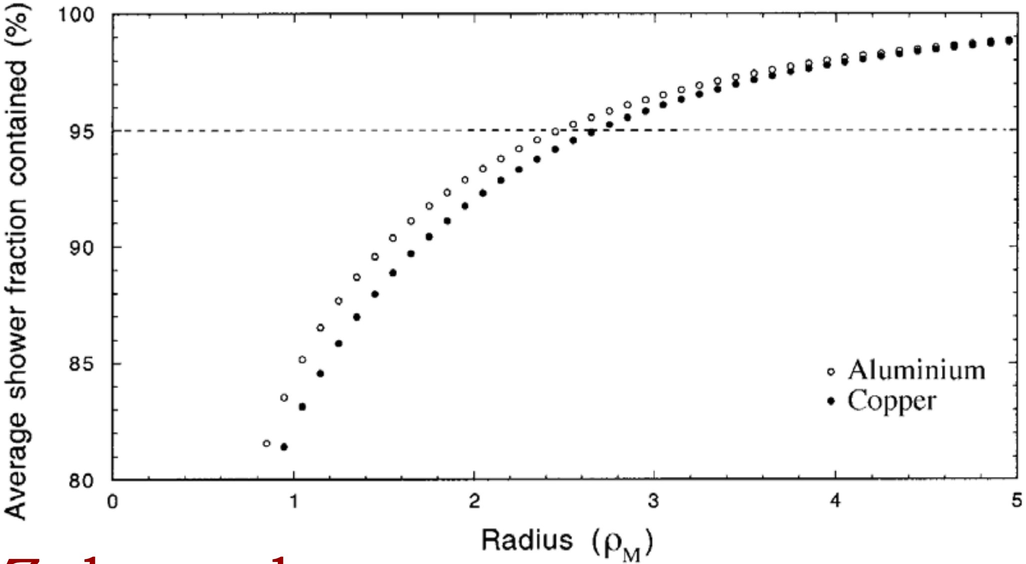
1 TeV electron in copper:
95% in 22 X_0 and 99% in 27 X_0

Transversal profile of electromagnetic shower

- Angle emission and multiple scattering make photons and electrons travelling away from shower axis.
- Molière radius (R_M) sets transverse shower size; on average 90% of the shower is contained within cylinder of radius R_M around the shower axis.

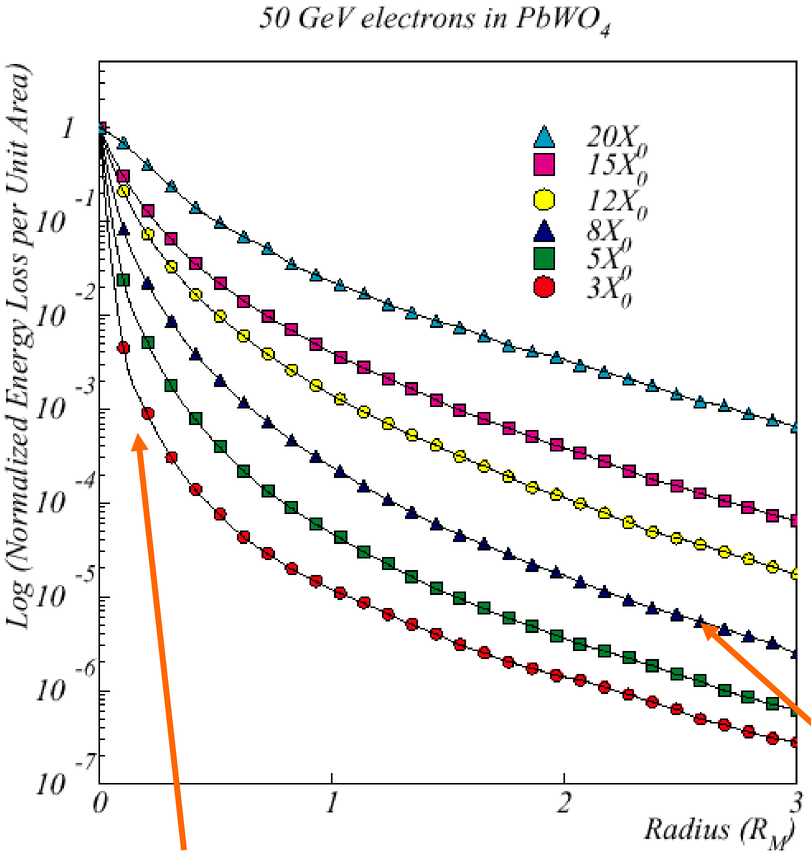
$$R_M = \frac{21\,MeV}{E_C} X_0$$

$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} (Z >> 1)$$



R_M: very small Z dependence

Transversal profile of electromagnetic shower (2)



- The energy carried by particles falls exponentially with respect to the shower axis.
- The width depends on the shower depth.

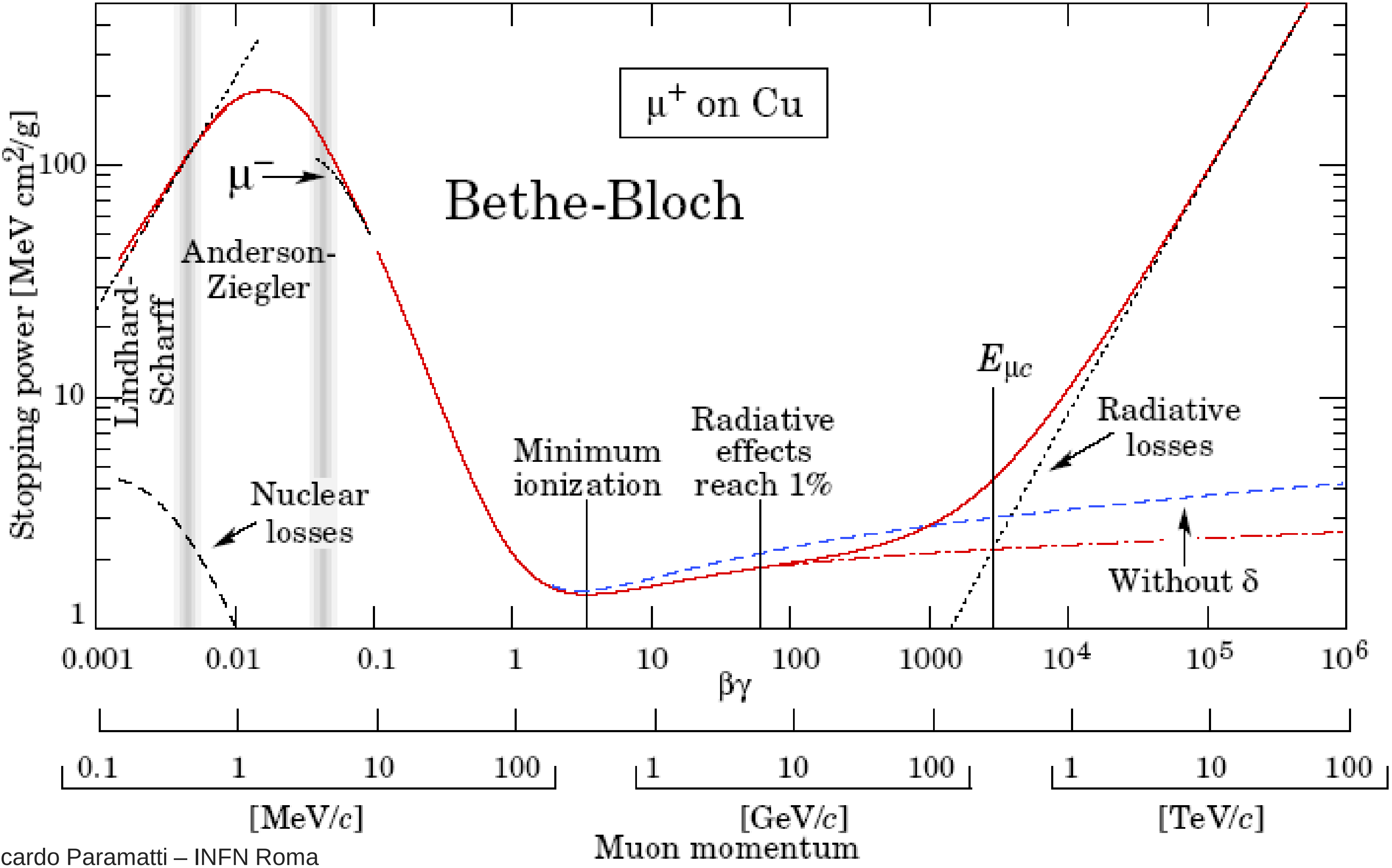
Central core: multiple scattering

Peripheral halo:
propagation of less attenuated photons,
widens with depth of the shower

Muon energy loss

- Energy loss of up to 100 GeV muons is entirely due to ionization.
- In modern accelerators final state muons are close to minimal ionizing (mip). Energy loss is about 1 GeV/m in iron or lead → need for underground laboratory (e.g. Gran Sasso) for mitigation of cosmic ray background
- Muon energy is not measureable in calorimeters with limited size → need for muon spectrometer
- At very high energies Bremsstrahlung get important. Critical energy > 100 GeV.

Muon energy loss (2)



Muon energy loss (3)

Measurement of the Muon Stopping Power in Lead Tungstate during CMS commissioning with cosmic rays.

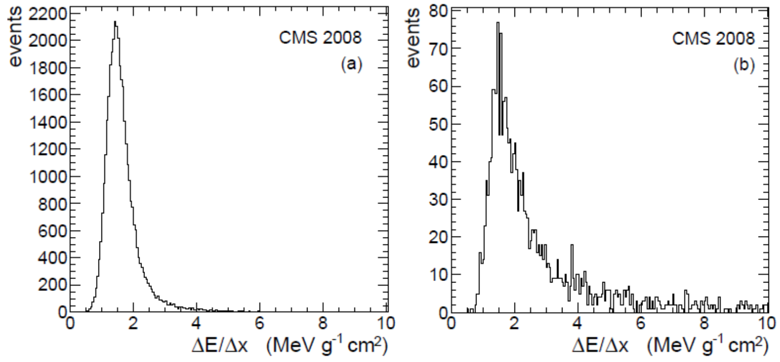
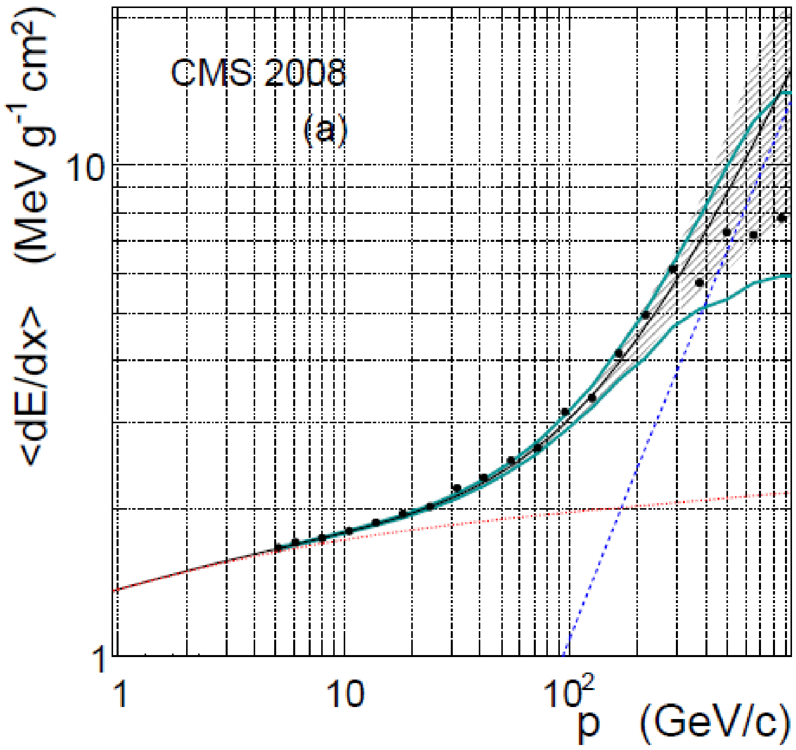


Figure 3. Measured distributions of $\Delta E/\Delta x$ in ECAL; (a) for muon momenta below 10 GeV/c; (b) for muon momenta above 300 GeV/c; the fraction of events with $\Delta E/\Delta x > 10\,\mathrm{MeV\,g^{-1}\,cm^2}$ is 1.3×10^{-3} and 8×10^{-2} in (a) and (b) respectively.



- $E_C = 160^{+5}_{-6}\,(\mathrm{stat.}) \pm 8\,(\mathrm{syst.})\,\mathrm{GeV}$

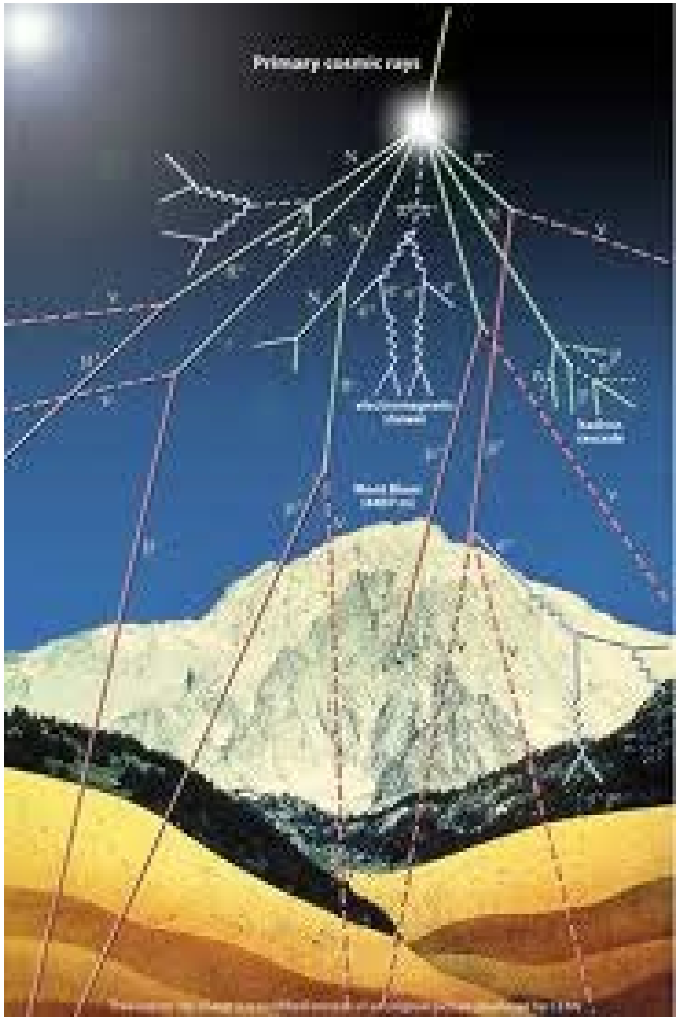
Hadronic shower, sampling calorimeters and compensation

Nuclear interactions

- Charged hadrons loose energy continuously due to ionization/excitation of atoms.
- The interaction of energetic hadrons (charged or neutral) with matter is mainly determined by inelastic nuclear processes.
- Excitation and finally break-up of nucleus → nucleus fragments + production of secondary particles.
- For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K…).

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\, mb$$

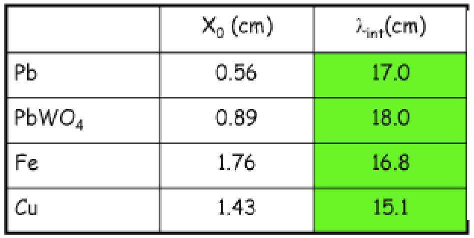
Hadronic Showers



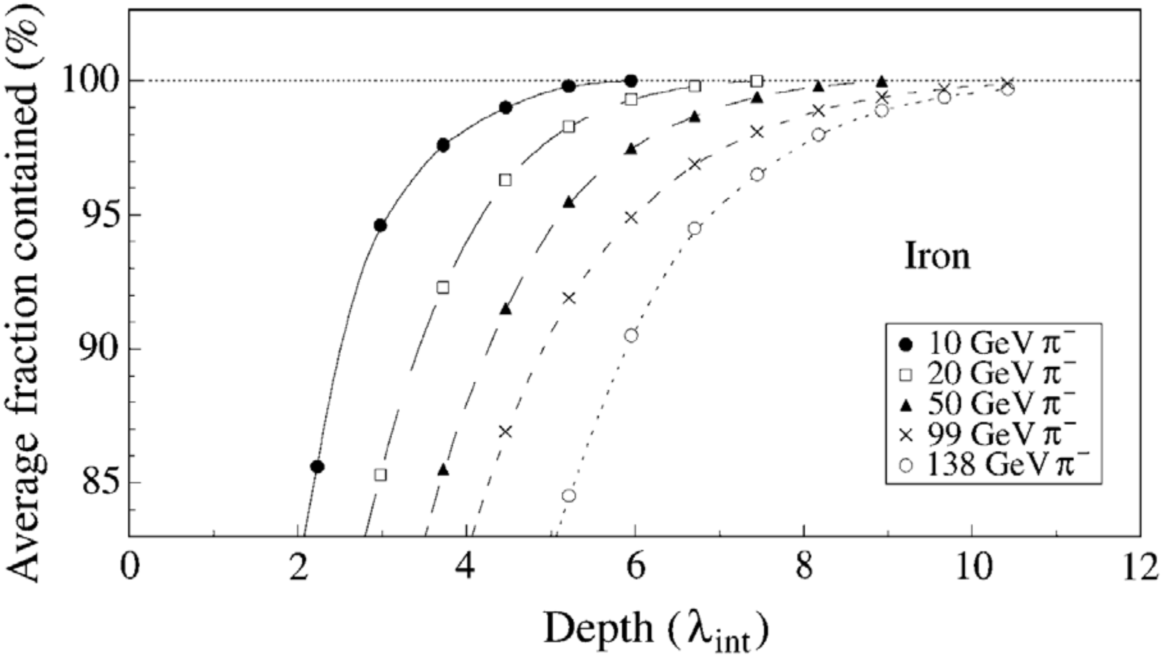
- A very common hadronic shower.

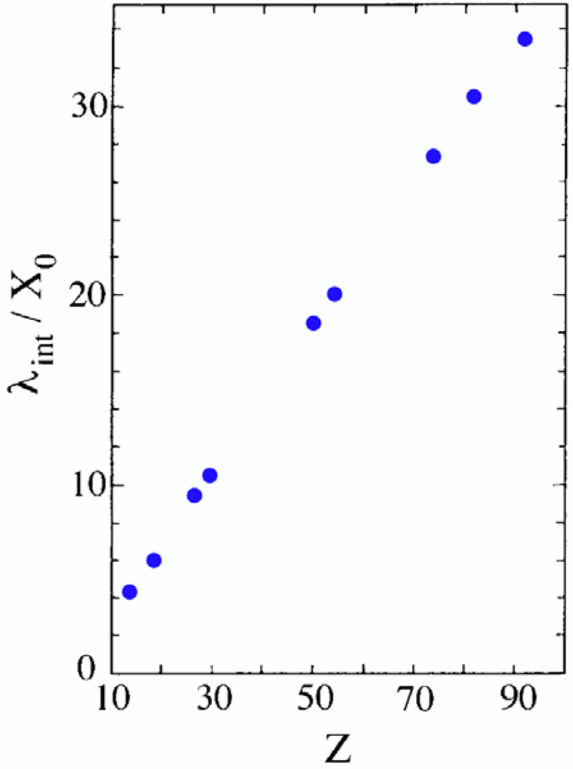
Hadronic Showers

- Typical scale is the interaction length λ
- Good containment in ~10 λ but $\lambda > X_0$ (or $\lambda >> X_0$)
- Larger size of the calorimeters drives the choice of sampling HCAL



	X_0 (cm)	λ_{int}(cm)
Pb	0.56	17.0
$PbWO_4$	0.89	18.0
Fe	1.76	16.8
Cu	1.43	15.1





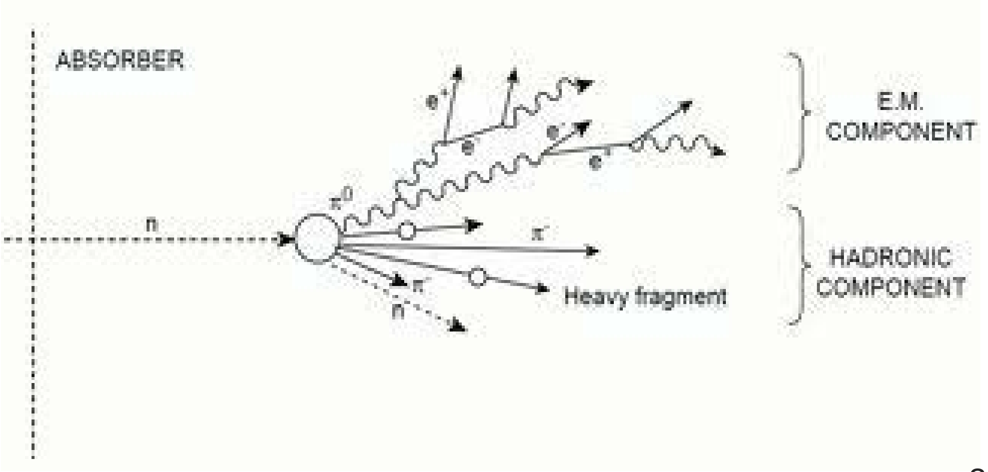
- Lateral containment: ~95% of the shower contained in a cylinder of radius λ_{int}.

Hadronic Showers

- More complicated that em shower due to the presence of strong interaction.
- Pions (charged and neutral) are by far the most important contribution in the hadronic shower composition but lot of energy is deposited through protons and neutrons.

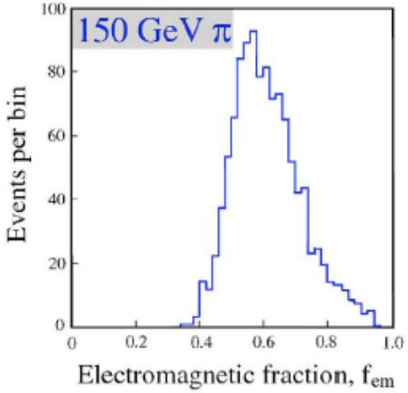
Neutral pions decay in photons before to interact

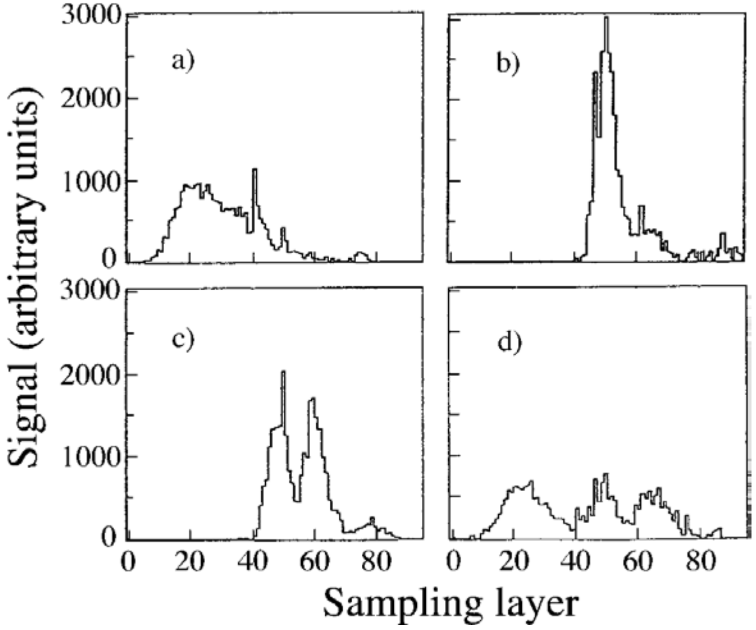
→ electromagnetic component in the hadronic shower



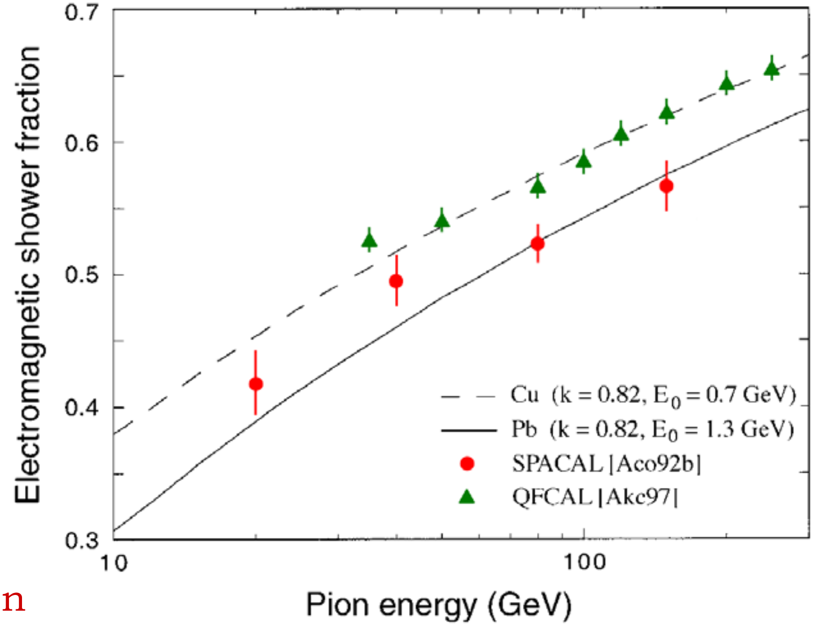
Hadronic Showers

- Big fluctuation in the hadronic shower profile (bottom left plot) and in the electromagnetic shower fraction (top right plot).
- Energy dependence of electromagnetic component (bottom right plot)





longitudinal measured profiles induced by 270 GeV pion



Hadronic Showers

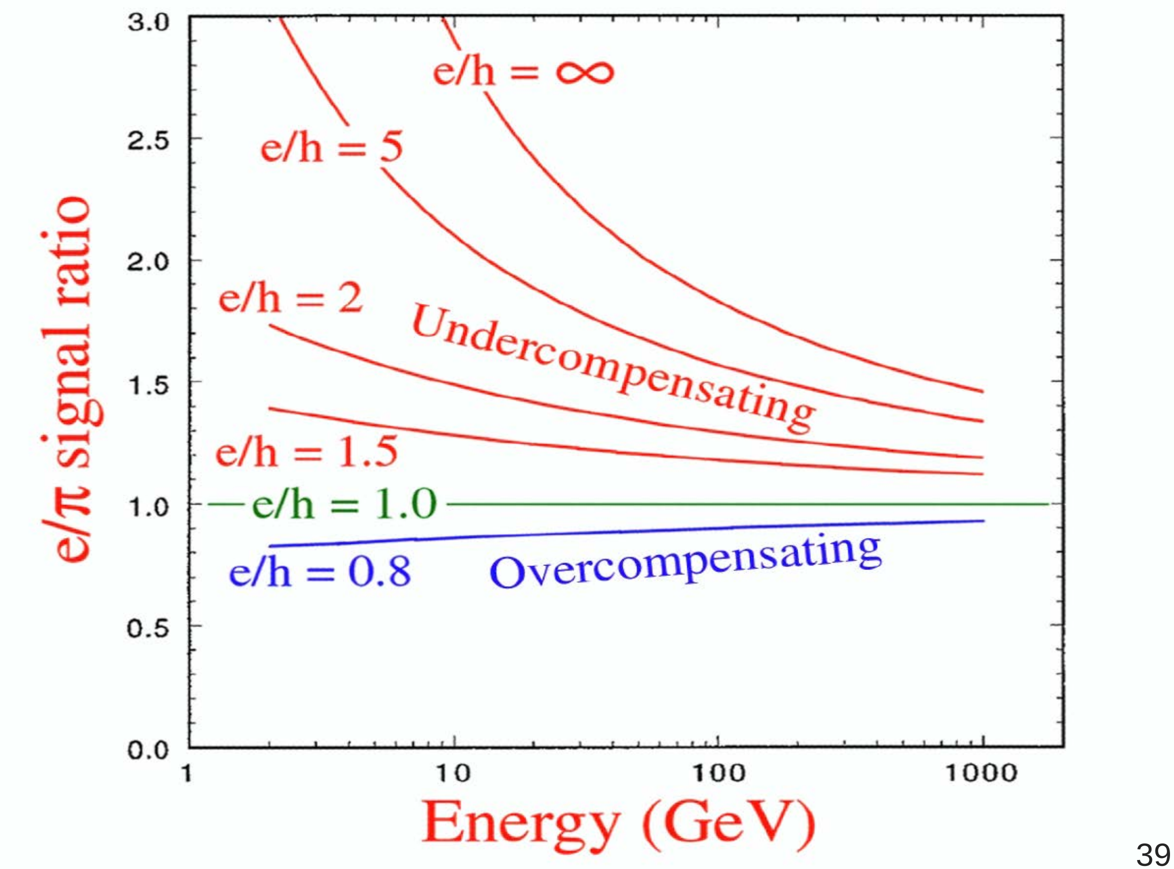
- A not negligible fraction of hadronic energy does not contribute to the calorimeter signal (e/h >1):
    - energy to release nucleons from nuclei (binding energy)
    - muons and neutrinos from pi/K decays
- The calorimeter response to hadrons is generally smaller than to electrons of the same energy (**$\pi/e < 1$**).
- Degradation in energy resolution (the energy sharing between em and non-em components varies from one event to another) and linearity (the em fraction of hadron-induced showers increases with energy, so π/e does).

Non-linear response

Calorimeter response→ $\boxed{\pi(E) = e \cdot f_{em}(E) + h \cdot \left(1 - f_{em}(E)\right)}$

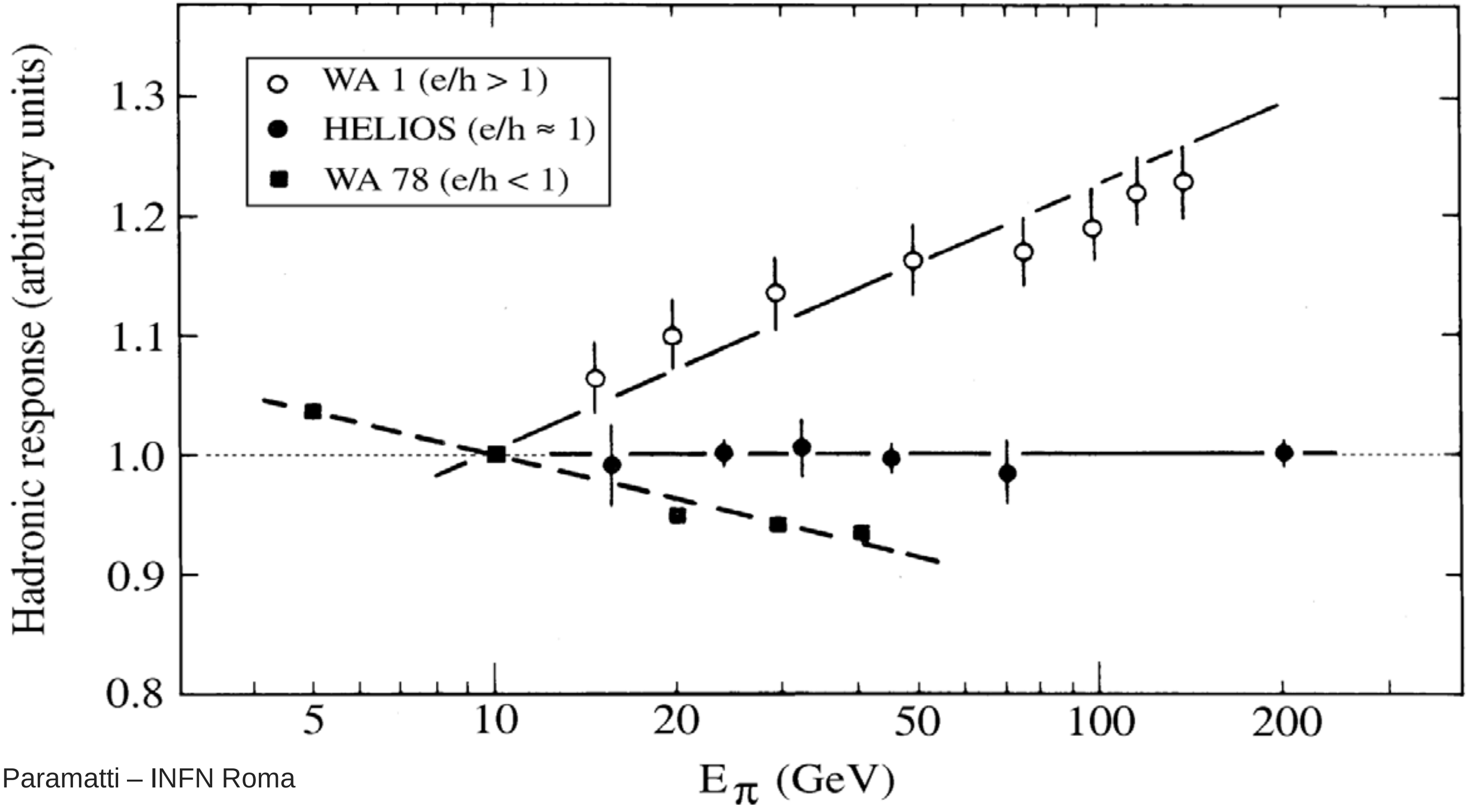
$$\frac{e}{\pi} = \frac{e/h}{1 - f_{em}(1 - e/h)}$$

Compensation: <u>equalization of the response to the electromagnetic and non-em shower components</u> (e/h = 1).



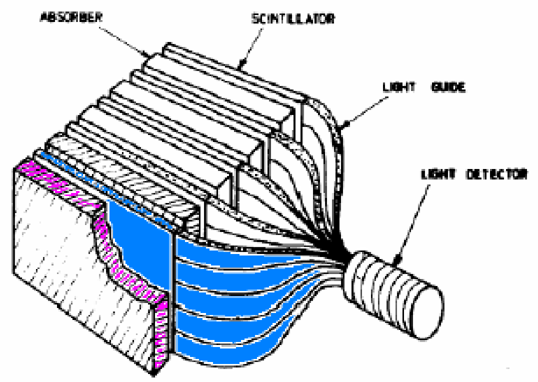
Non-linear response

$$\frac{\pi(E_1)}{\pi(E_2)} = \frac{f_{em}(E_1) + {}^{h}/_{e} \cdot \left(1 - f_{em}(E_1)\right)}{f_{em}(E_2) + {}^{h}/_{e} \cdot \left(1 - f_{em}(E_2)\right)} \neq 1$$

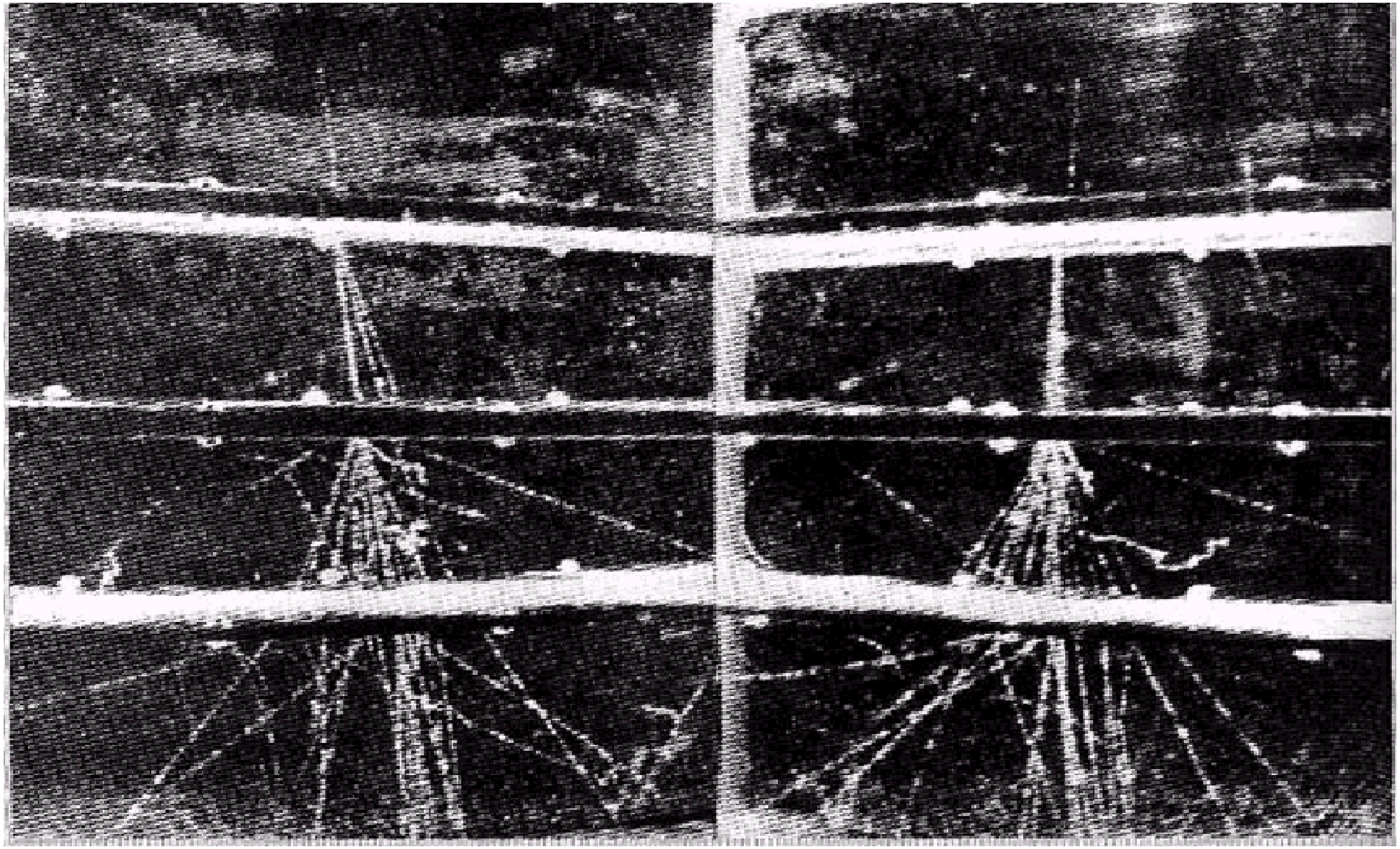


Homogeneous and sampling calorimeters

- In homogeneous calorimeters the absorber and the active medium are the same (e.g. ECAL in Opal, L3, Babar and CMS)
- In sampling calorimeters the two roles are played by two different media (e.g. ECAL in Delphi and Atlas, most of the HCAL in HEP).
  - Shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z) material.
  - Limited energy resolution
  - Detailed shower shape information
  - Reduced cost



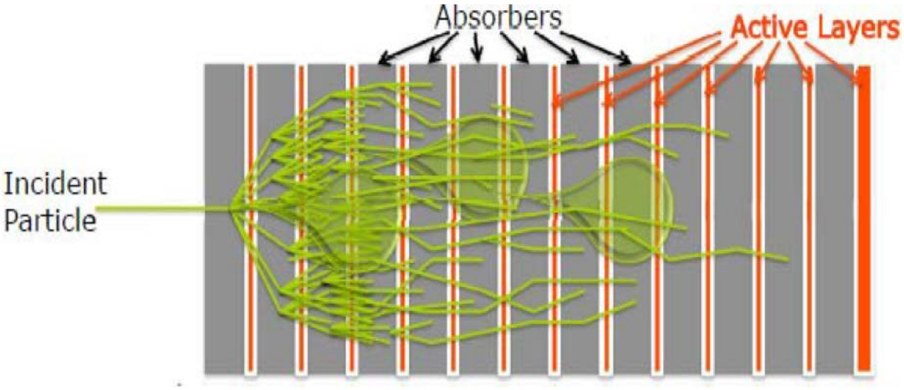
Electromagnetic shower in sampling calorimeter



Cloud chamber photograph of electromagnetic shower developing in lead plates exposed to cosmic radiation

Sampling calorimeters

- Sampling fraction = (energy deposited in the active medium)/(total deposited energy)
- The sampling fraction directly affects the energy resolution



- Active layer. Detection of ionization/excitation:
  - Gas (example L3’s Uranium/gas hcal)
  - Noble liquid (eg LAr, LKr)
  - Scintillators (fibers, tiles)
  - Cherenkov radiating fibers

The sampling fraction

- Example: a MIP in 20 layers of (5 cm of iron + 1 cm of plastic scintillator)

$$dE_{Fe} = 1.451\frac{MeV}{g/cm^2}\cdot 7.8\frac{g}{cm^3}\cdot 5cm\cdot 20 = 1131.8MeV$$

$$dE_{sci} = 1.936\frac{MeV}{g/cm^2}\cdot 1.03\frac{g}{cm^3}\cdot 1cm\cdot 20 = 39.9MeV$$

$$f_{samp} = \frac{39.9}{1131.8+39.9} = 3.4\%$$

- Only 3.4% of the MIP energy is visible (measured in the scintillator) → calibration factor for MIP = 1/0.034

Compensation (1)

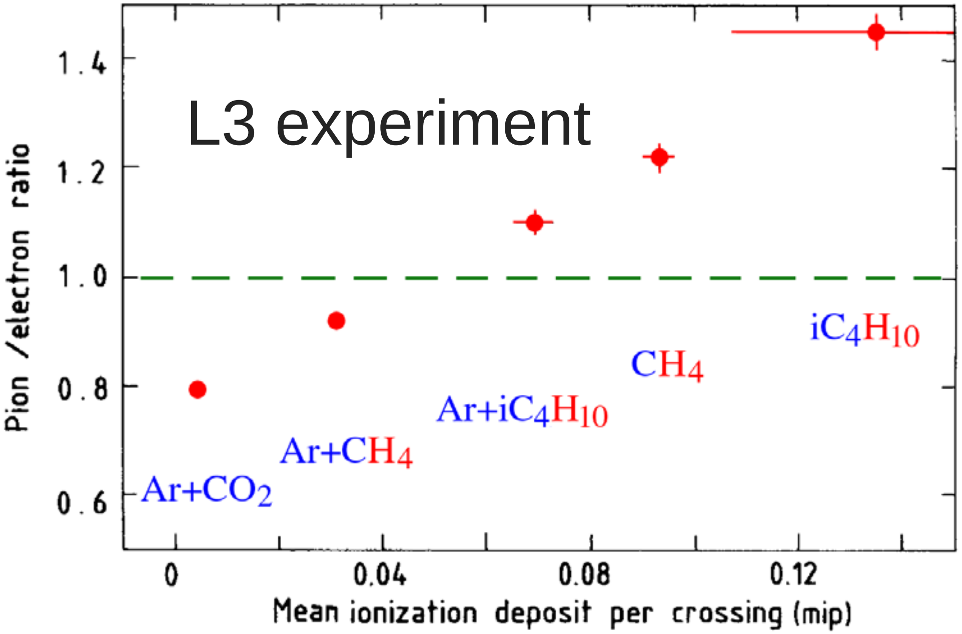
Compensation: equalization of the response to the electromagnetic and non-em shower components (e/h = 1).

Options:

- Tune (increase) the hadronic response:
  - hydrogen in the active layer
  - absorber with high neutron yield (Pb, U)
  - extend the integration time of the readout
- Tune (decrease) the electron response:
  - enlarge the thickness of absorber layer
  - higher Z material as absorber
- Software compensation
- Dual read-out

Compensation (2)

- Low energy neutrons contribute to the calorimeter signal through elastic scattering with nuclei.
- The energy transfer is strongly Z dependent and much larger in active material (low Z) than in passive material (high Z)
- Tuning the hydrogen presence in the active layer allows to tune the e/h ratio.

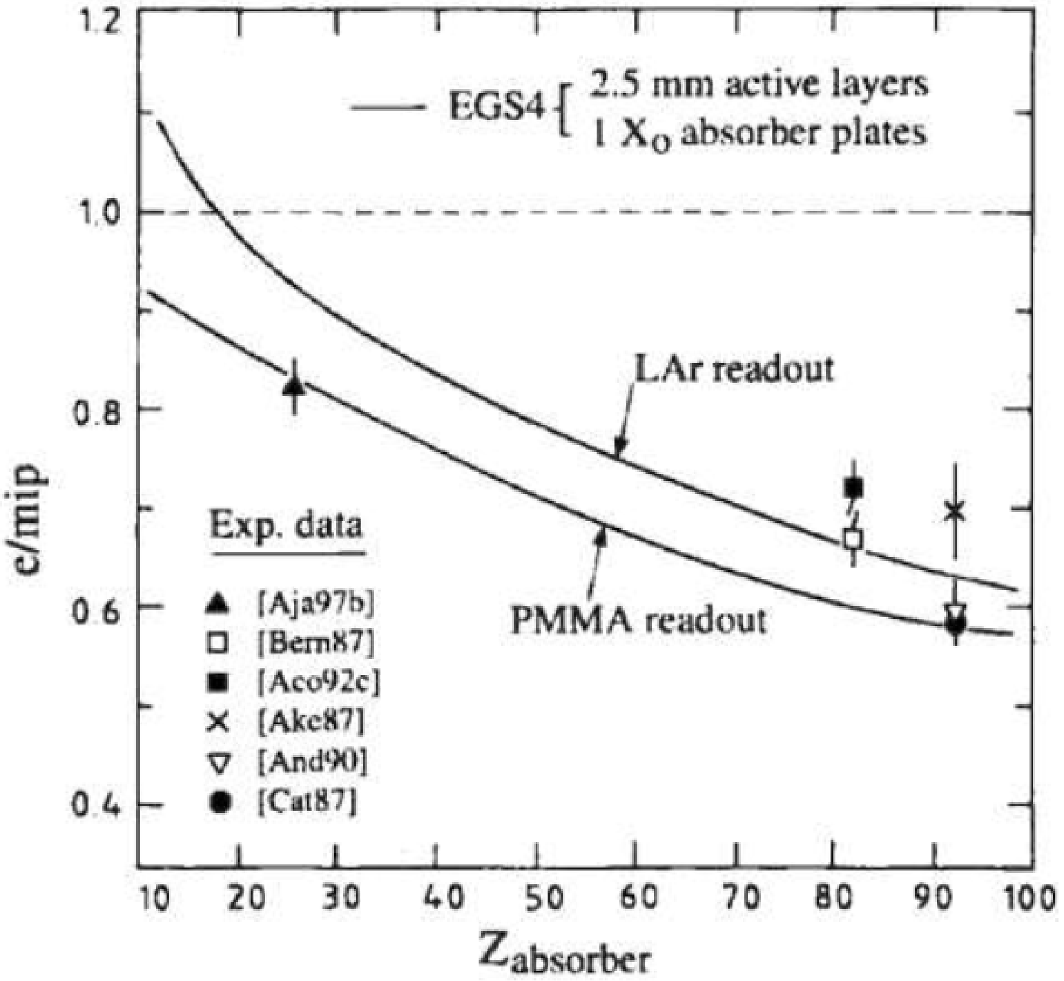

L3 experiment

- Signals from neutrons come late due to the required thermalization, capture and photon emission (~200 ns). e/h can be reduced by extending the integration time of the readout. (ZEUS calorimeters). Not possible at LHC !

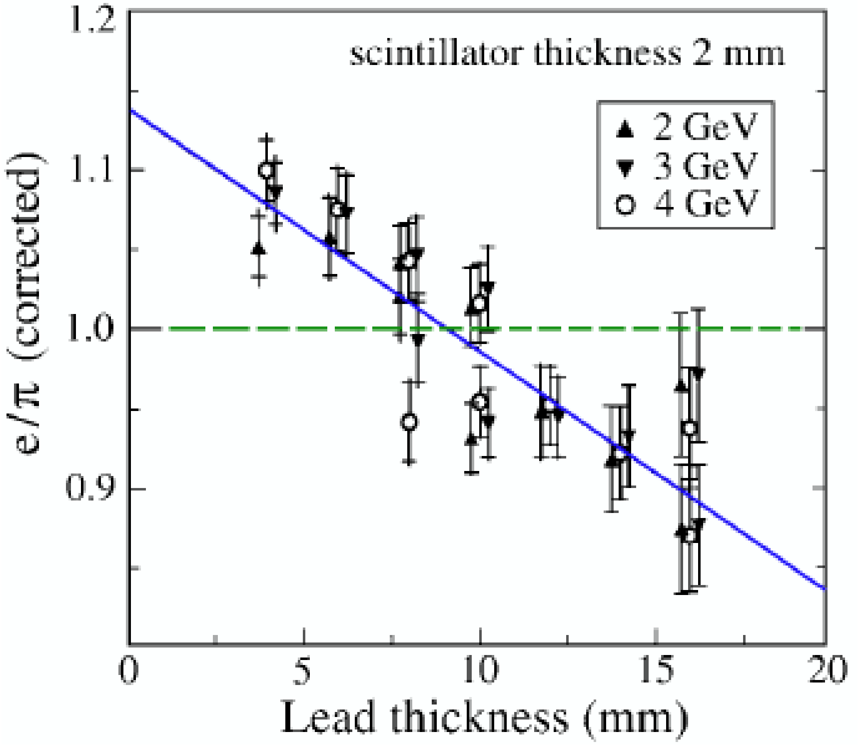
Compensation (3)

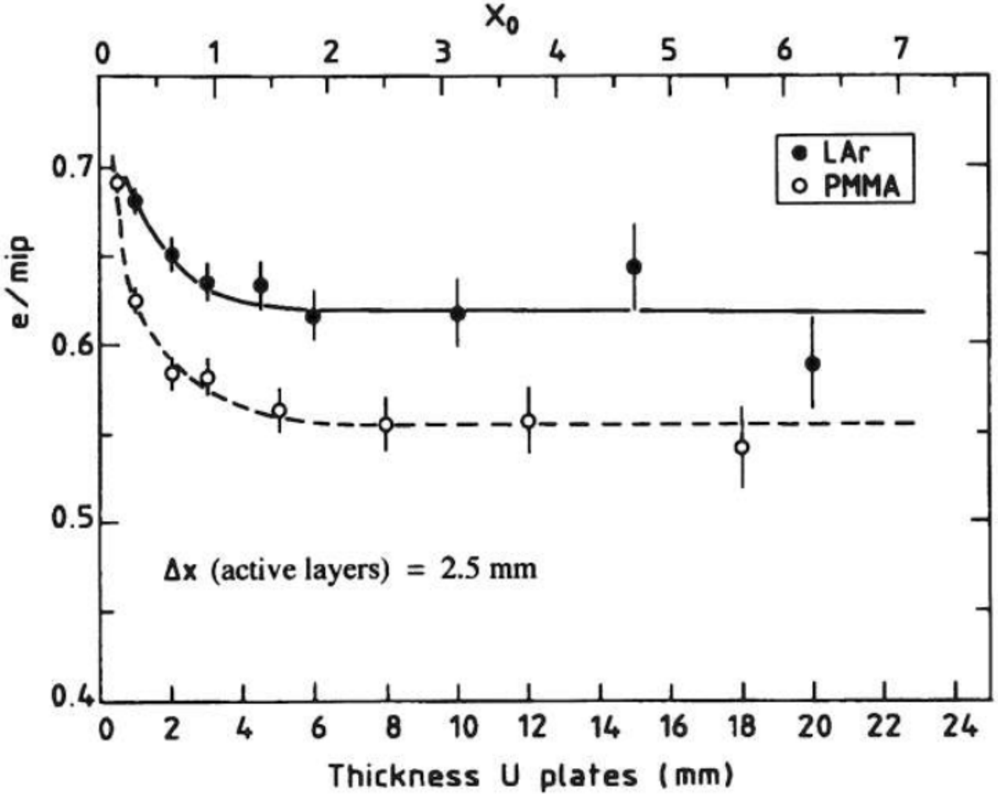
- Electromagnetic particles are mainly produced with low energy in high Z absorber (for instance photo-electric goes as Z^5).
- Range of soft particles is smaller than the thickness of the absorber layer → a fraction of e.m. particles do not reach the active layer.
- e/h ratio can be tuned with the Z and with the thickness of the absorber
- Drawback: sampling fraction is reduced; energy resolution get worse

Compensation (4)



Compensation (5)





Compensation (6)

Software compensation: high granularity calorimeter to locate the electromagnetic component of the shower

- e.m. component is very localized in the first layers (shower maximum inside $10X_0$) and in the central core ($1\ R_M$)
- Apply different weights to the cells of the calorimeters to tune e/h

Compensation with dual readout: ideally the best would be to measure the e.m. fraction event by event and correct offline.

- Production of Cherenkov light in hadron showers is mainly due to e.m. component.
- Comparing the amounts of Cherenkov light with the scintillation light allow to estimate the e.m. fraction.
- Measure the two component independently.

More on dual readout in part 3 tomorrow.

Energy detection

Energy loss detection

The energy deposited in the calorimeters is converted to active detector response

- $E_{vis} \leq E_{dep} \leq E_0$

Main conversion mechanism

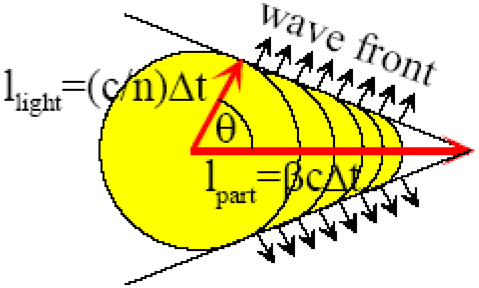
- Cerenkov radiation from $e^{\pm}$
- Scintillation light
- Ionization of the detection medium

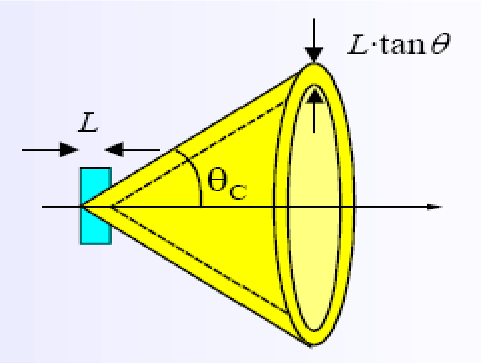
response $\propto$ total track length

Different energy threshold E_s for signal detectability

Cherenkov Light

- A charged particle traveling in matter with speed greater than c/n (the speed of the light in the same material) emits photons in the visible (mainly in the blue).





Maximum value for the emission angle (v=c)

$$\theta_{\max} = \arccos\frac{1}{n}$$

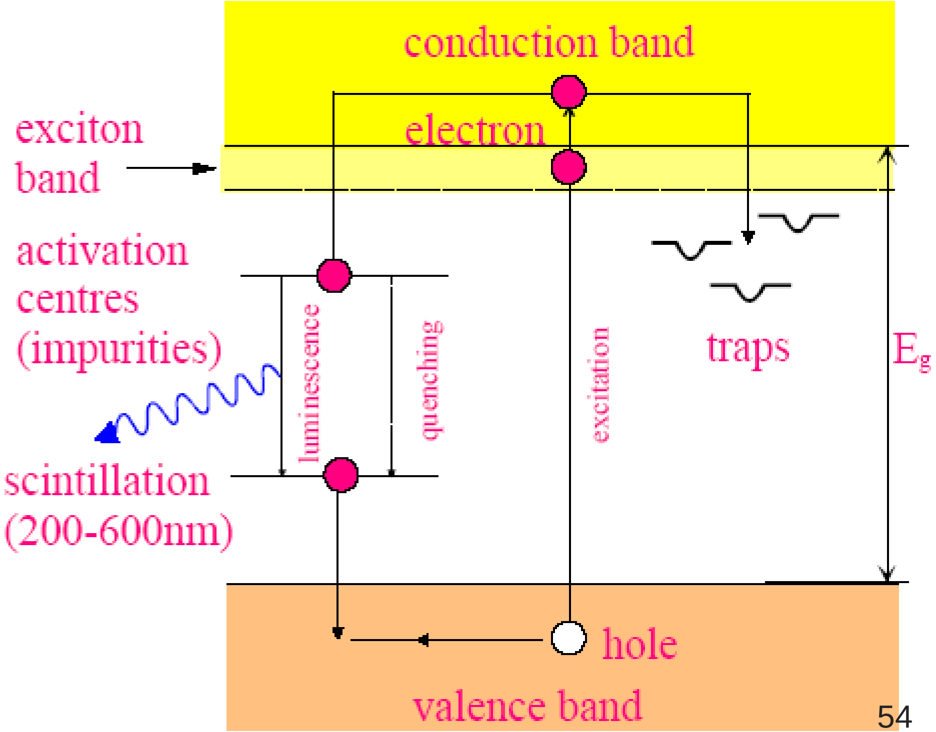
- The energy loss by Cherenkov effect is much smaller that the energy loss by ionization: high gain photodetector is needed (e.g. PMTs)

Scintillation mechanism

Luminescent materials emit light when stimulated with light and heat (photo-luminescence) and radiation (scintillation). Scintillators need impurities (dopant) in order to emit at a different wavelength and not reabsorb the light.

The centers are of three main types:

- Luminescence centers
  photon emission
- Quenching centers
  thermal dissipation of the excited energy
- Traps
  metastable levels, from where electrons may subsequently go to
    - conduction band by thermal energy
    - valence band by a radiation-less transition

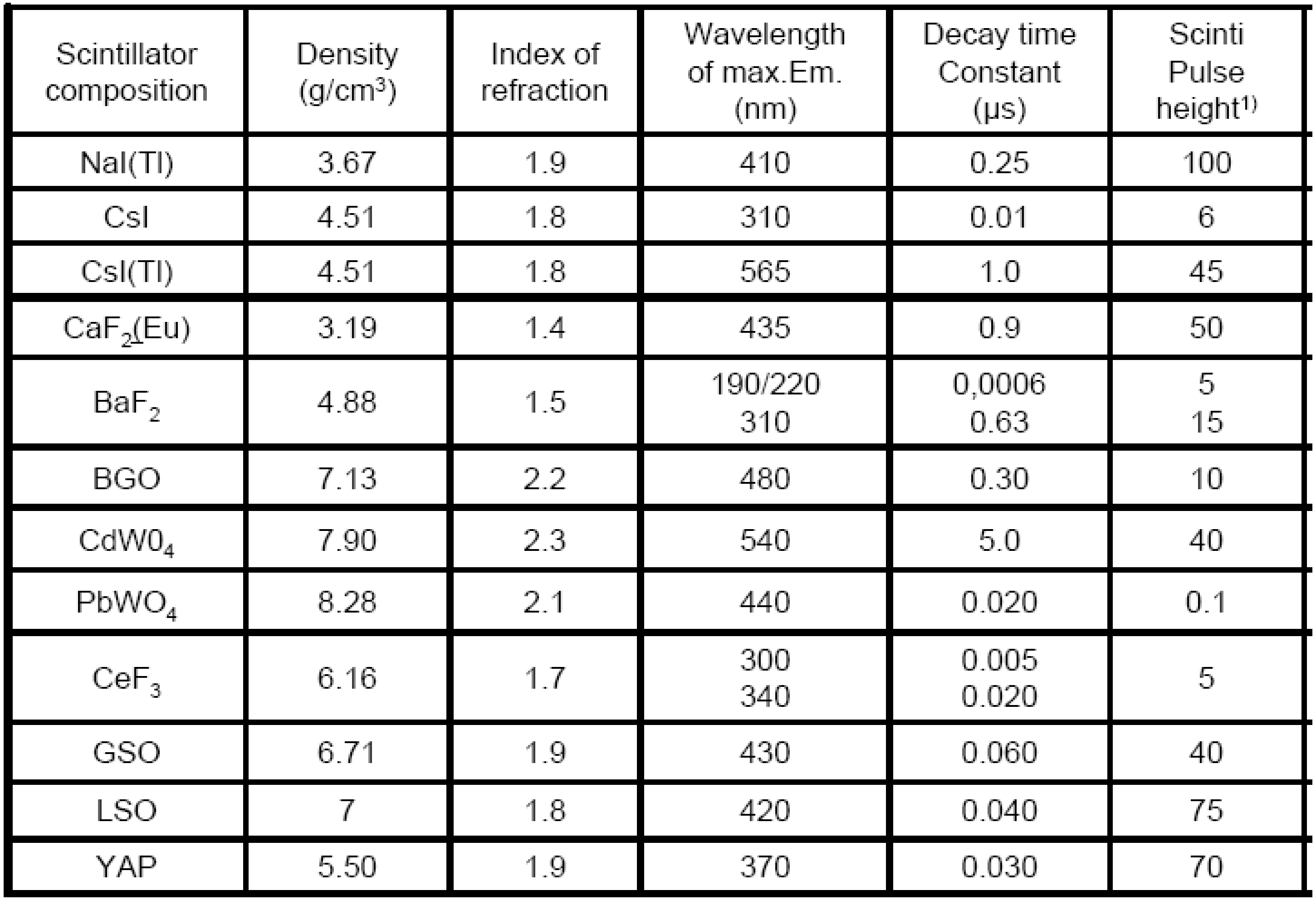


Scintillators

Two scintillator classes: organic and inorganic.

Inorganic (crystalline structure)	Organic (plastics or liquid solutions)
Up to 40000 photons per MeV	Up to 10000 photons per MeV
High Z	Low Z
Large variety of Z and ρ	$\rho \sim 1 gr/cm^3$
Undoped and doped	Doped, large choice of emission wavelength
ns to μs decay times	ns decay times
Expensive	Relatively inexpensive
E.m. calorimetry (e, γ)	Tracking, TOF, trigger, veto counters, sampling calorimeters.
Medical imaging	
Fairly Rad. Hard (100 kGy/year)	Medium Rad. Hard (10 kGy/year)

Inorganic scintillators



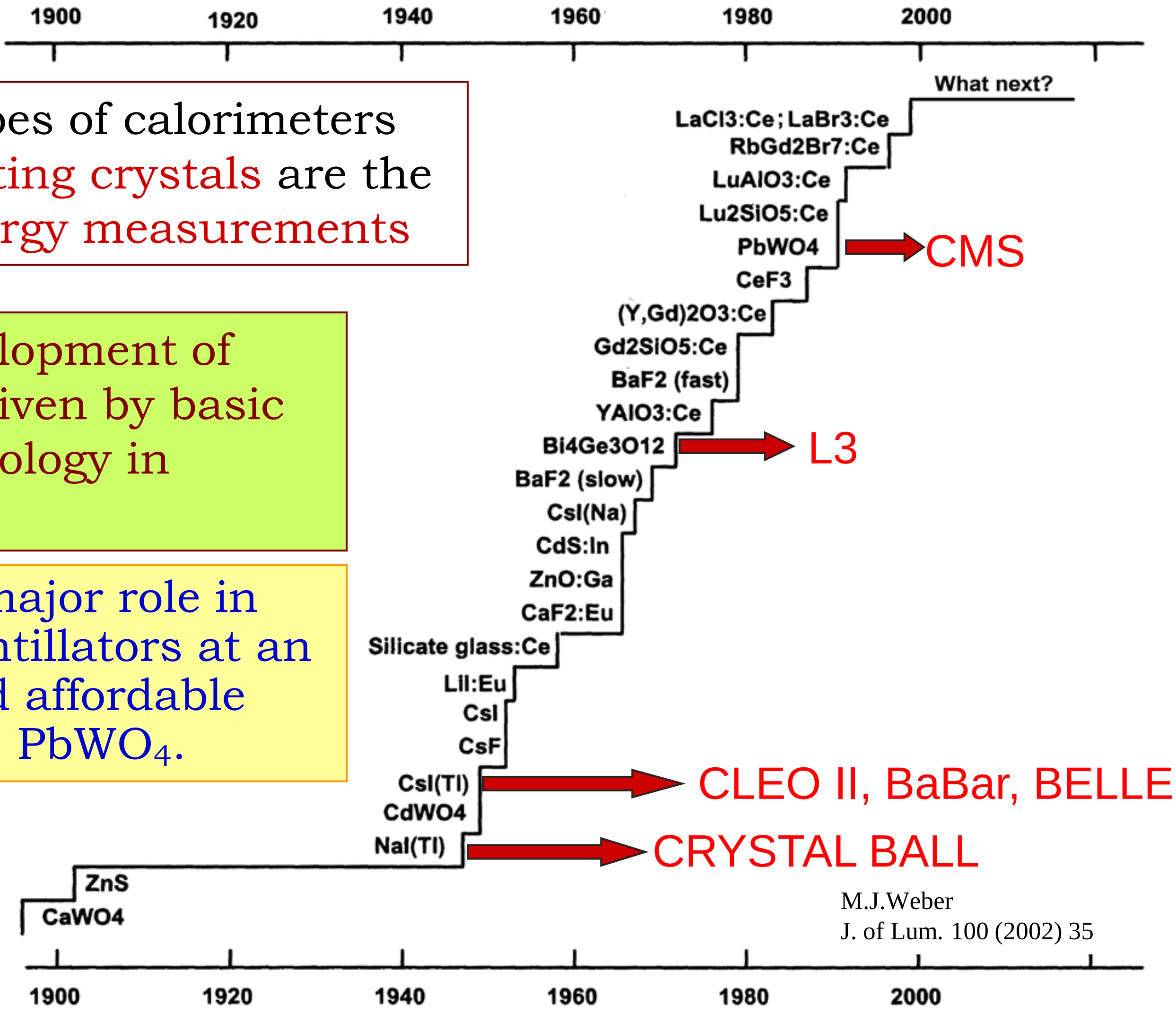
Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (μs)	Scinti Pulse height$^{1)}$
NaI(Tl)	3.67	1.9	410	0.25	100
CsI	4.51	1.8	310	0.01	6
CsI(Tl)	4.51	1.8	565	1.0	45
CaF_2(Eu)	3.19	1.4	435	0.9	50
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15
BGO	7.13	2.2	480	0.30	10
$CdW0_4$	7.90	2.3	540	5.0	40
$PbWO_4$	8.28	2.1	440	0.020	0.1
CeF_3	6.16	1.7	300 340	0.005 0.020	5
GSO	6.71	1.9	430	0.060	40
LSO	7	1.8	420	0.040	75
YAP	5.50	1.9	370	0.030	70

Scintillating Crystal History

Among different types of calorimeters those with scintillating crystals are the most precise in energy measurements

Discovery and development of new scintillators driven by basic research and technology in physics

HEP has played a major role in developing new scintillators at an industrial scale and affordable cost, e.g. BGO, CsI, $PbWO_4$.



M.J.Weber
J. of Lum. 100 (2002) 35

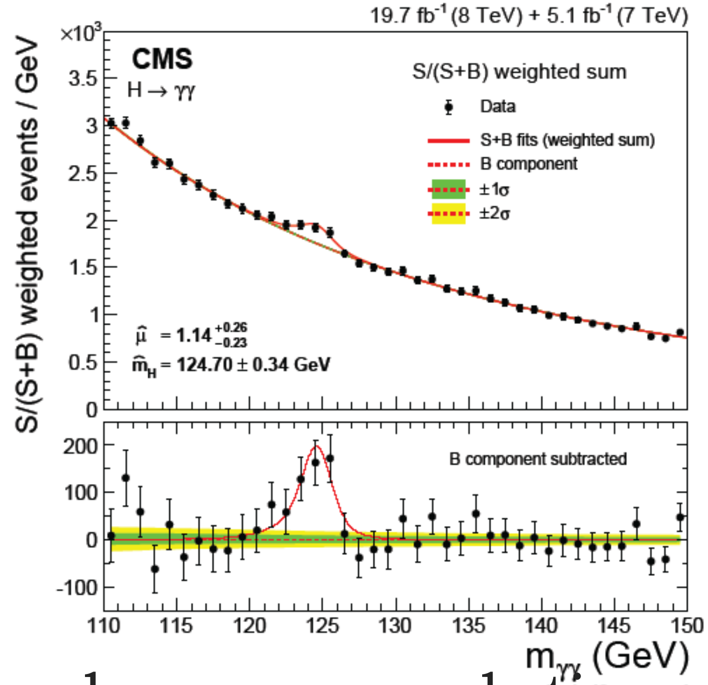
Energy resolution

Energy resolution

Γ_H (m_H ~ 100 GeV) < 100 MeV

$\Gamma_H / m_H \leq 10^{-3}$

The discovery potential of an intermediate mass Higgs boson via the two photon decay channel is strongly dependent on the energy resolution.



$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}\left(1-\cos\theta_{\gamma 1,\gamma 2}\right)}$$

$$\Downarrow$$

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan\left(\theta_{\gamma\gamma}/2\right)}\right]$$

need energy resolution:
$\Delta E/E < 1\%$
for E ~ 50 GeV

$\oplus$ represents the quadratic sum

Energy resolution (2)

- **Intrinsic fluctuations**
  - Signal in the active medium
    - photo statistics, charge fluctuations
    - saturation effects, recombination
  - Shower composition (hadrons)
  - $e/h \neq 1$ in conjunction with the fluctuation of f_{em} (hadrons)
- **Sampling calorimeters**
  - Fluctuation of the visible signal (sampling fluctuations)
- **Instrumental effects**
  - Inhomogeneities (e.g. variation of plate thickness)
  - Incorrect calibrations of different channels (intercalibration)
  - Electronic noise

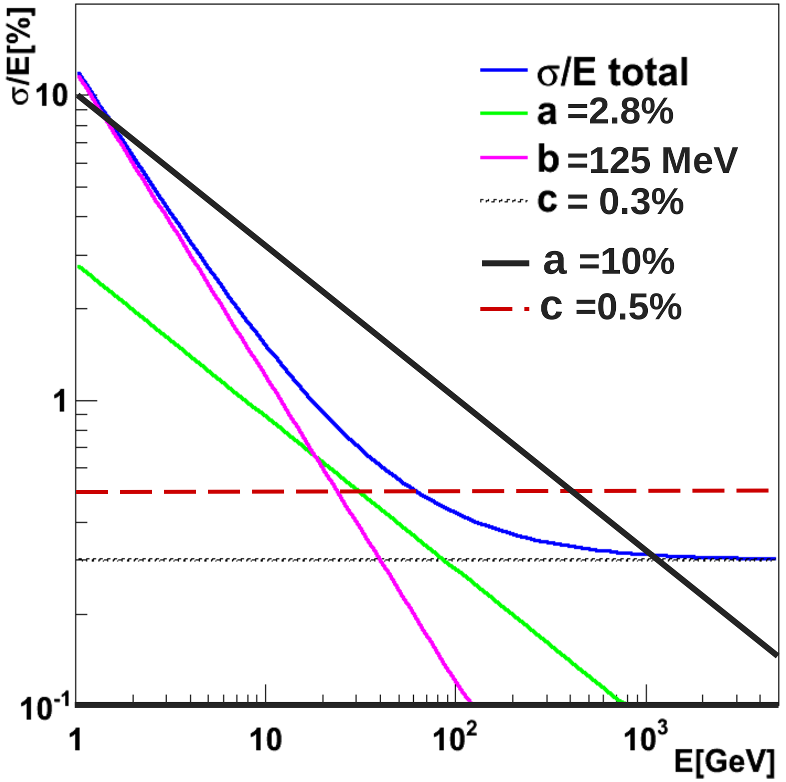
Energy resolution (3)

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

$\oplus$ represents the quadratic sum

- a: stochastic term from Poisson-like fluctuations
  - sampling contribution dominant in sampling calorimeters (f_{samp})
- b: noise term from electronic and pile-up
  - relevant at low energy
- c: constant term
  - dangerous limitation to high energy resolution
  - important contribution from inter-calibration constants

When do you have to worry about c ?



Energy resolution (4)

- a: stochastic term from Poisson-like fluctuations

  (natural advantage of homogenous calorimeters; s can be ~ 2%-3%)

  - photo-statistics contribution:
    - - light yield
    - - geometrical efficiency of the photo-detector
    - - photo-cathode quantum efficiency
  - electron current multiplication in photo-detector
  - lateral containment of the shower
  - material in front of the calorimeter

$$E \propto N_{\text{p.e.}}$$

$$\sigma(N_{\text{p.e.}}) \propto \sqrt{N_{\text{p.e.}}}$$

$$\Rightarrow \quad \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

Including gain fluctuations of photo-detector (*F*) :

$$\frac{\sigma(E)}{E} = \sqrt{\frac{F}{N_{\text{p.e.}} \cdot E}}$$

$$F = 2 - 3; \quad N_{\text{p.e.}} \geq 4000/\text{GeV}$$

Energy resolution (5)

Compare processes with different energy threshold

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim \mathrm{eV}$$

$$\approx 10^2 \div 10^4 \gamma / MeV$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(GeV)}$$

Lowest possible limit

Cherenkov radiators

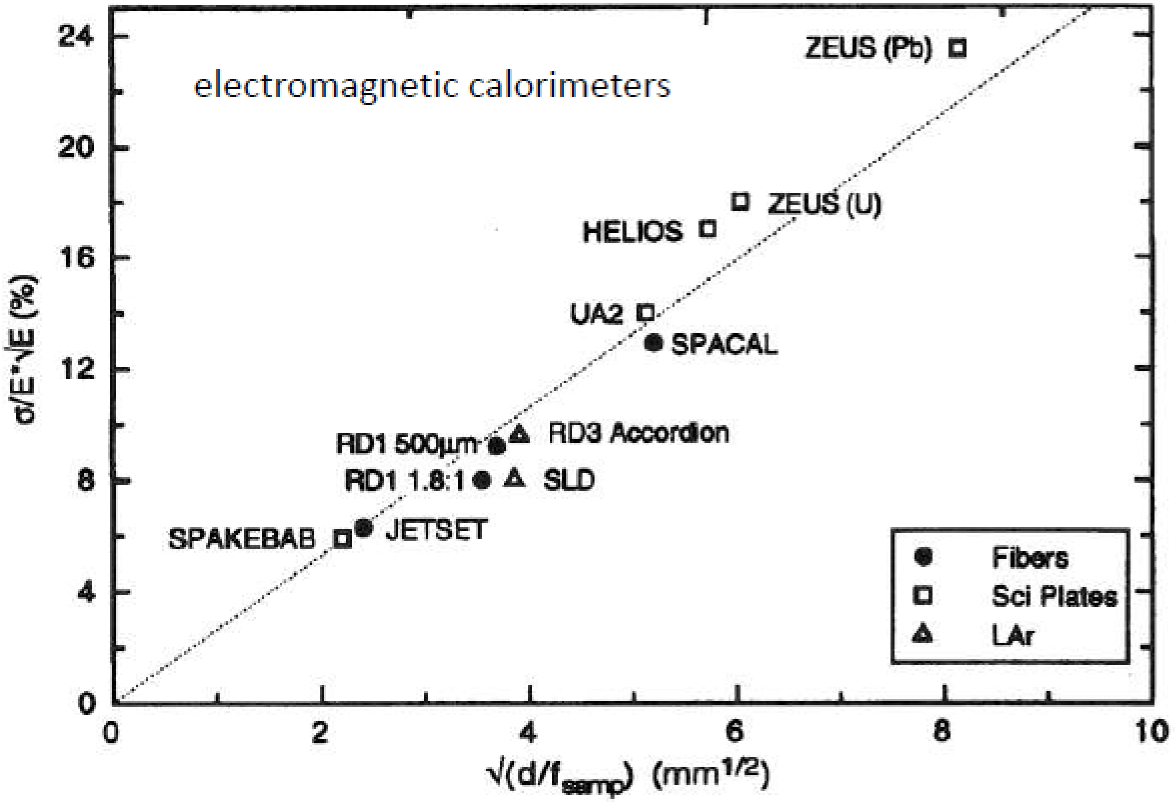
$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7\mathrm{MeV}$$

$$\approx 10 \div 30 \ \gamma / MeV$$

$$\sigma / E \sim (10 \div 5)\% / \sqrt{E(GeV)}$$

Energy resolution (6)

stochastic term in sampling calorimeters



empirical formula

$$\frac{\sigma_E}{E} = 2.7\% \frac{\sqrt{d / f_{samp}}}{\sqrt{E}} :$$

d: thickness of the active layers (in mm)

Energy resolution (7)

- Calorimeter stochastic term

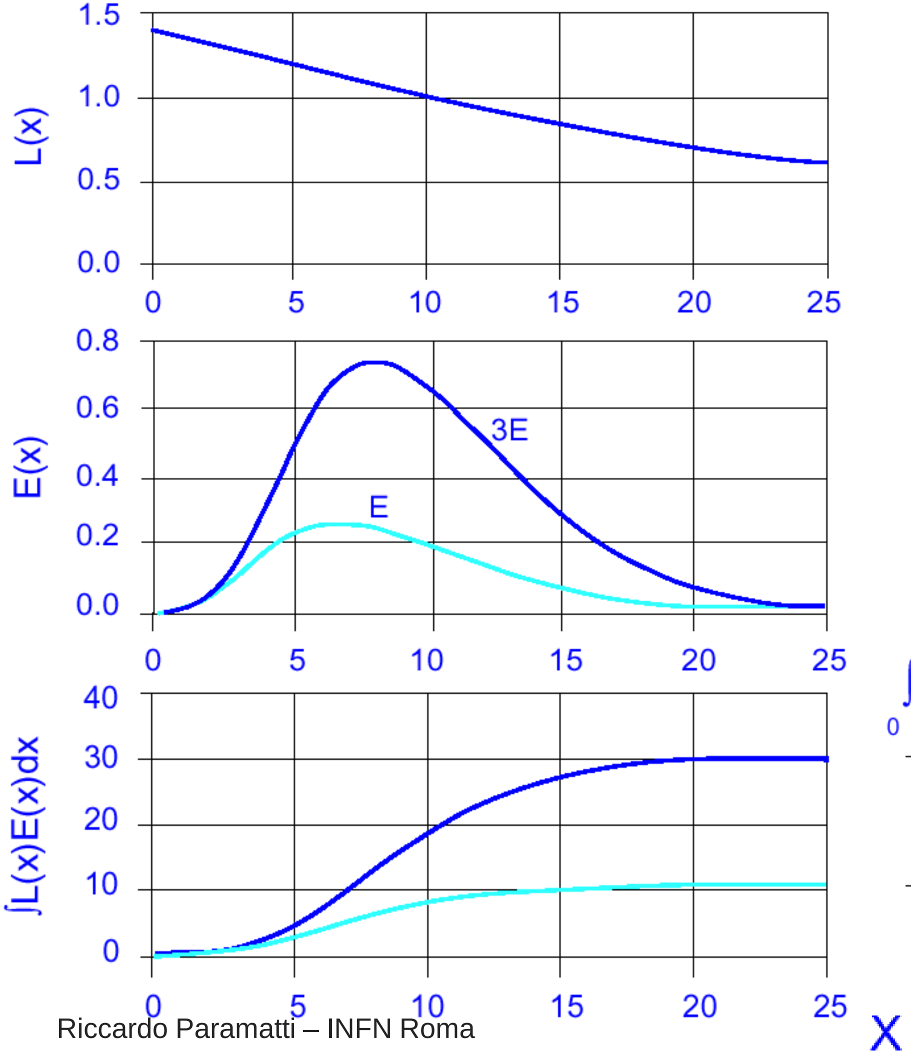
Experiment		absorber	active	resolution	type
CMS	em	$PbWO_4$	Scint.	2.8%/√E	homogeneous
CMS	had.	Fe	Scint.	77%/√E	sampling
ATLAS	em	Pb	LAr	10%/√E	sampling
ATLAS	had.	Cu	LAr	66%/√E	sampling
NA48	em	LKr	LKr	3.5%/√E	homogeneous
BaBar	em	CsI	CsI	$2.3\%/E^{1/4}$	homogeneous

Energy resolution (8)

Constant term contributions (dominant at high energy):

- temperature stability (temperature dependence of light yield in inorganic scintillator)
- photo-detector bias stability
- longitudinal uniformity
- channel inter-calibration
- leakage (front, rear, dead material)
- transparency loss due to ageing
- …

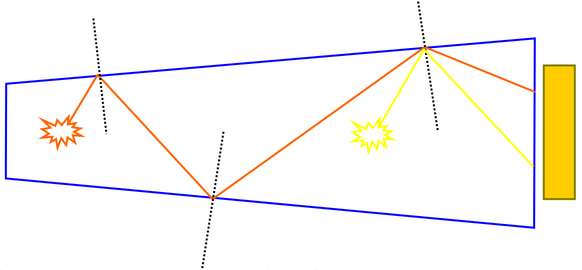
A practical example concerning the CMS ECAL construction.



$\int_0^x L(x)E(x)dx$

ratio 2.89
(instead of 3)

Light Collection Uniformity

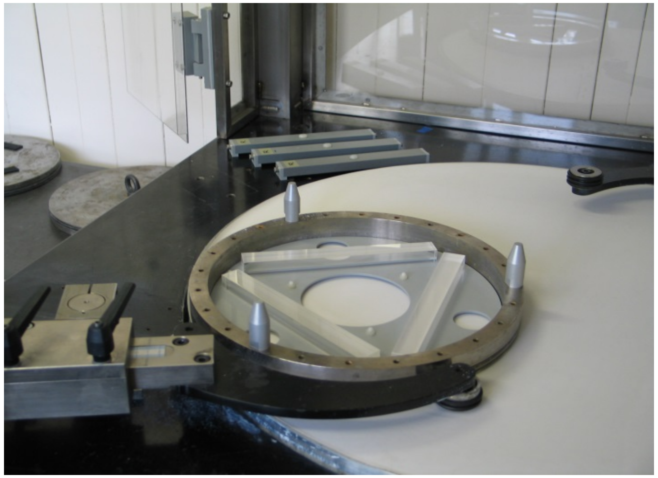


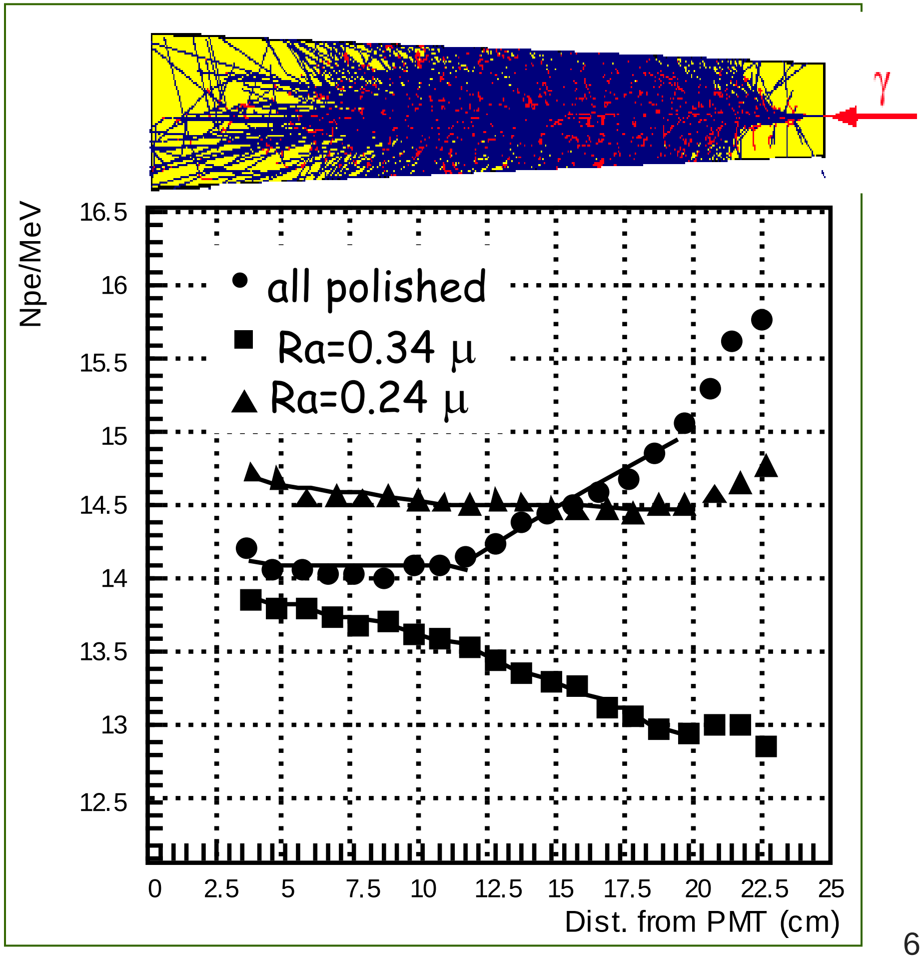
- non linearity of the response (can be corrected)
- smearing of the response at fixed energy due to shower fluctuations (can not be corrected)

A practical example concerning the CMS ECAL construction.

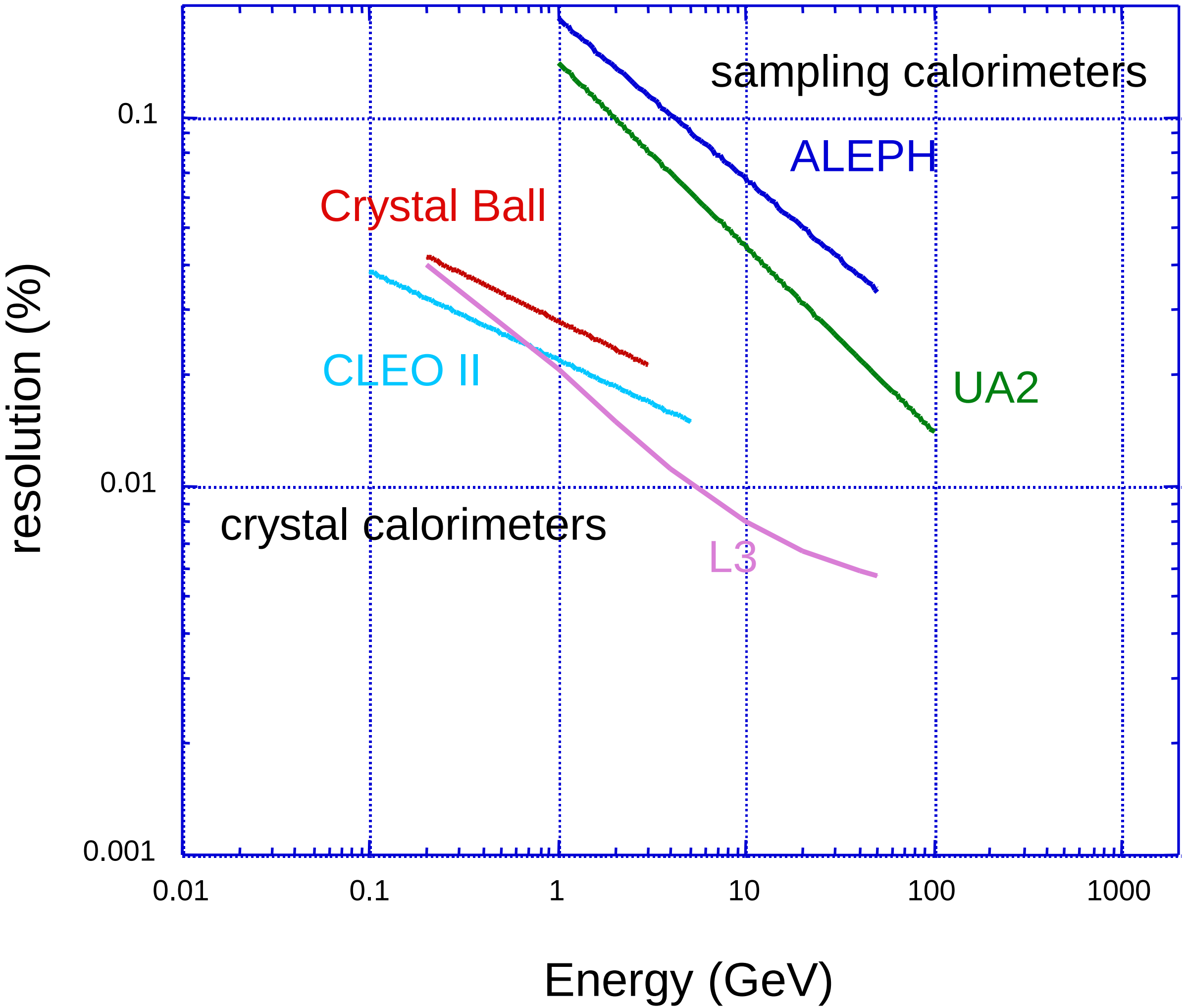
- High refractive index make light collection difficult
- Focusing effect due to tapered shape of barrel crystals
- Uniformity can be controlled by depolishing one lateral face with a given roughness

Uniformity treatment

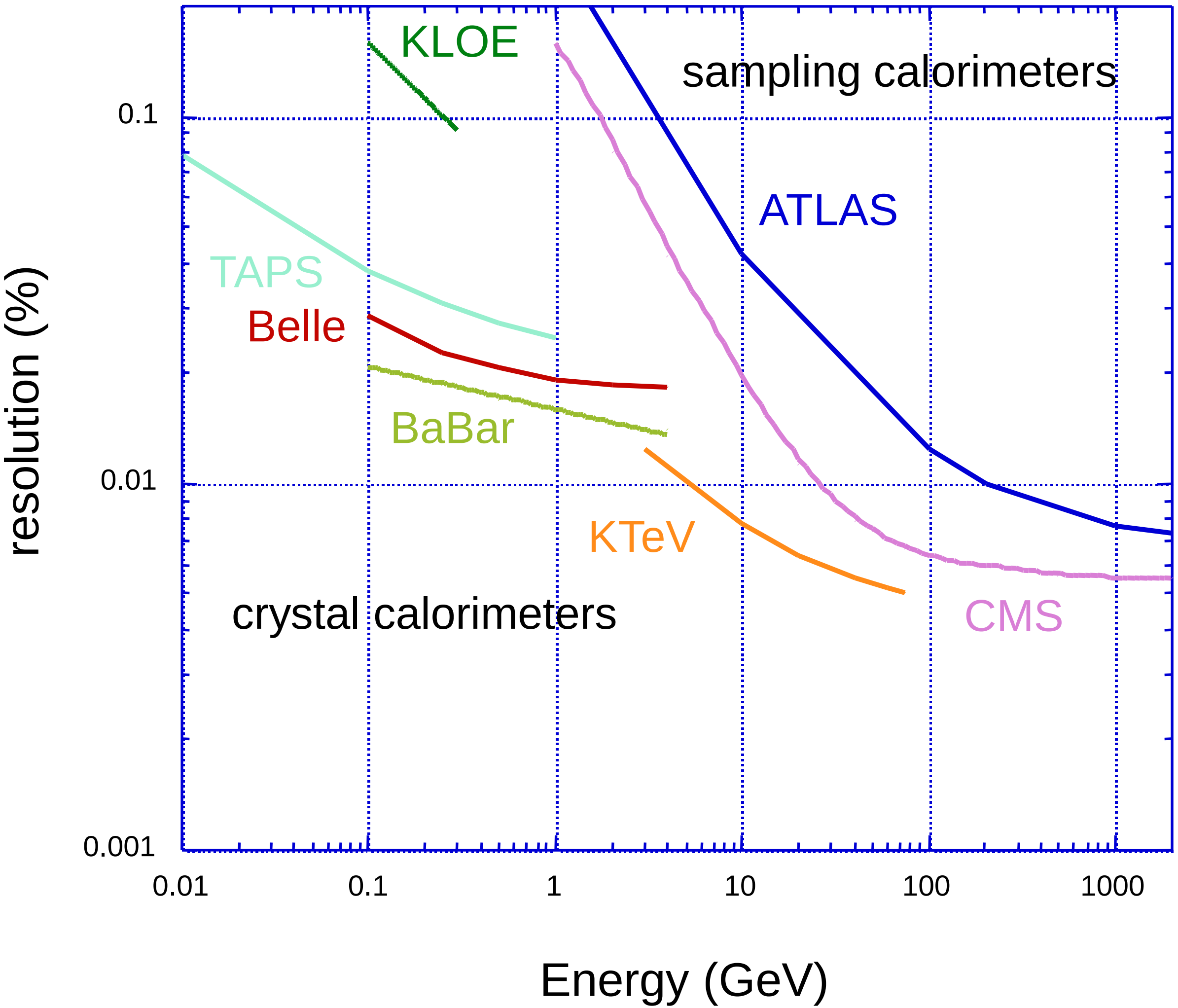




Energy resolution of past e.m. calorimeters



Energy resolution of recent e.m. calorimeters



Resolution summary

- Electromagnetic calorimetry
  - homogeneous, if well done → a ~ 3% (take care of constant term !)
  - sampling, if well done → a ~ 10%
- Hadron calorimetry
  - non compensating → a ~ 50%-100%
  - compensating → a ~ 35%
- Future calorimetry (R&D) → in part3
  - a ~ 15% is the goal for the e.m. part
  - a ~ 25%-30% is the goal for the had. part