XIX Seminar on Software for Nuclear, Subnuclear and Applied Physics

Calorimetry for HEP

L. Carminati

Università degli Studi e INFN di Milano

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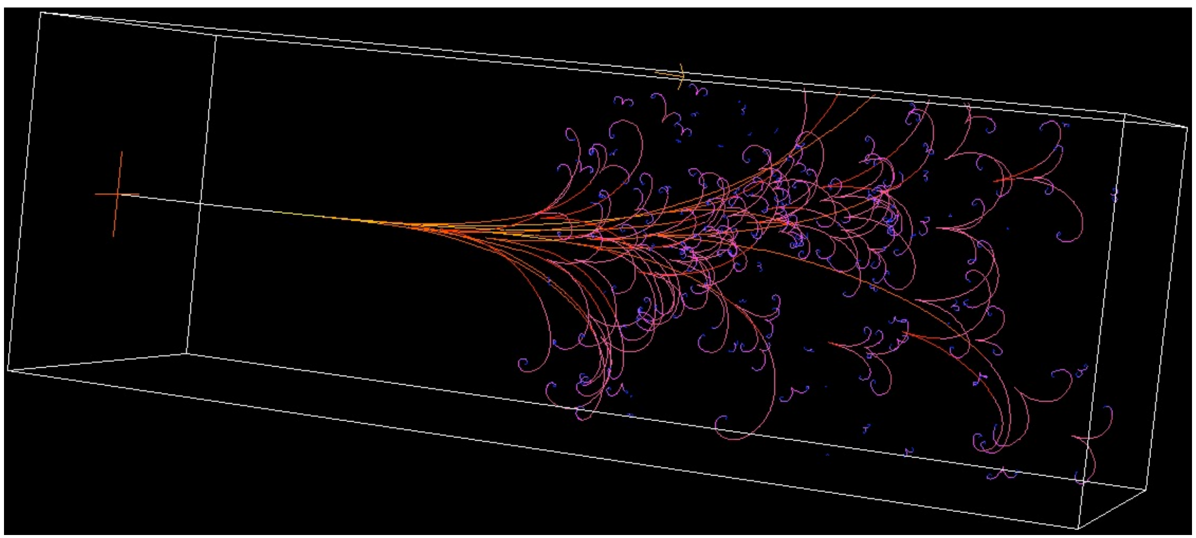
What's a calorimeter?

"Calorimeters are blocks of instrumented material in which particles to be measured are fully absorbed and their energy transformed into a measurable quantity. The interaction of the incident particle with the detector (through electromagnetic or strong processes) produces a shower of secondary particles with progressively degraded energy. The energy deposited by the charged particles of the shower in the active part of the calorimeter, which can be detected in the form of charge or light, serves as a measurement of the energy of the incident particle."

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003



Facts about calorimetry

- The purpose of a calorimeter is to measure the energy E (well, not only) of electrons, photons and (jets of) hadrons (for this seminar focus on the GeV-TeV range)

- The particle energy E is measured by (ideally) fully absorbing the particle in the calorimeter material. it's a «destructive measurement» !

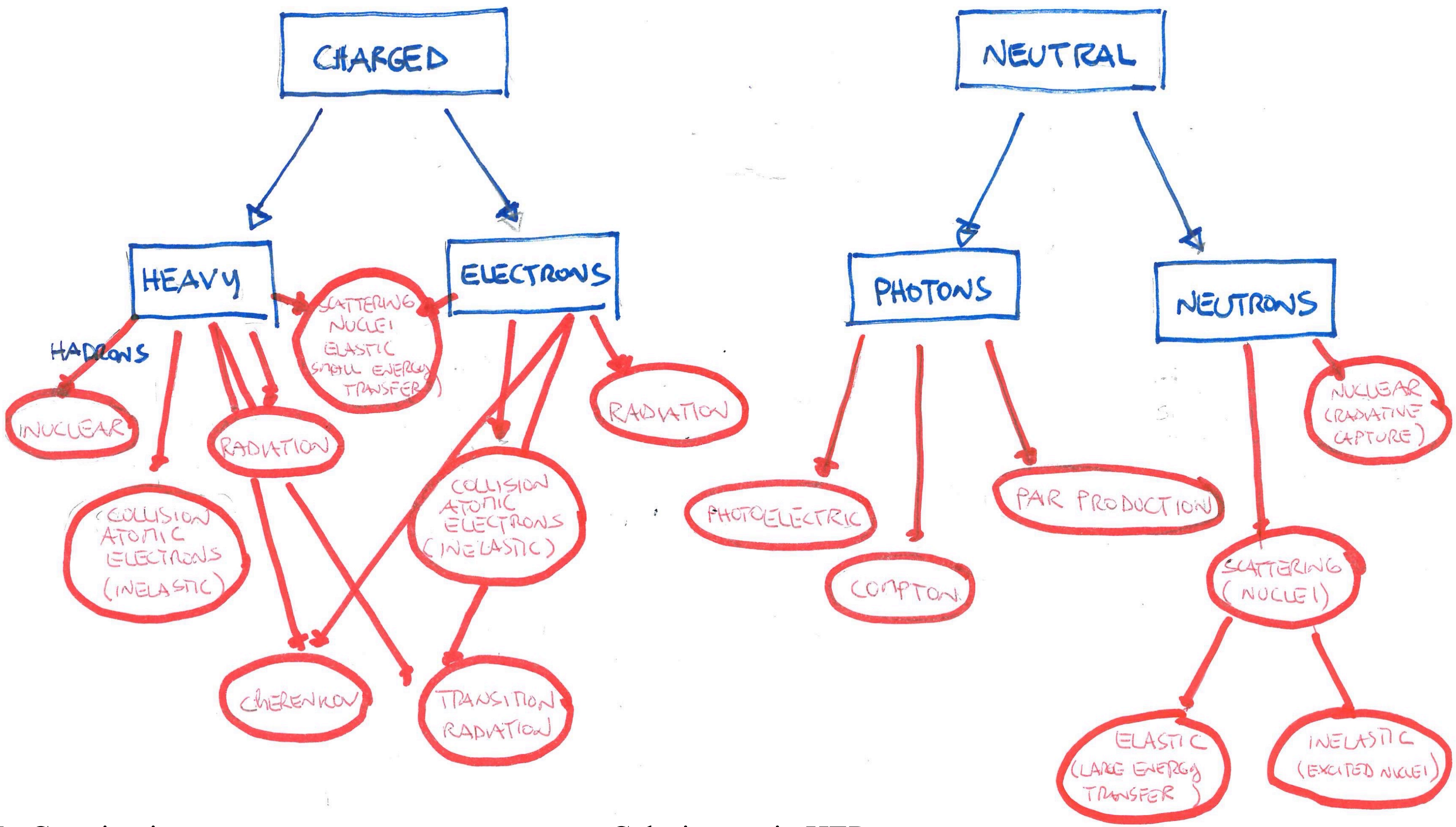
- The particle deposits an energy E_{dep} which is (desireded to be) proportional to the original energy E

- E_{dep} in the calorimeters is converted to a response signal (S) in the active parts of the detector. S is in turn (desired to be) proportional to the deposited energy

- Calorimeters can exploit various detection mechanisms to reveal the energy lost by the original particle in the material: scintillation, Cherenkov radiation, ionization…

The particles-matter interactions zoo :

The intrinsic nature of the calorimetry requires a good recollection of the main features of particles-to-matter interactions processes



Energy loss by electrons

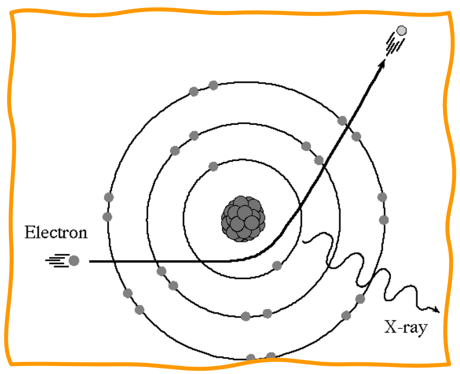
- Energy loss by 'collision' with atomic electrons: basically, immediately in the relativistic regime of the Bethe-Block

$$\left(\frac{dE}{dX}\right)_{coll} \approx -\ln(E_e)$$

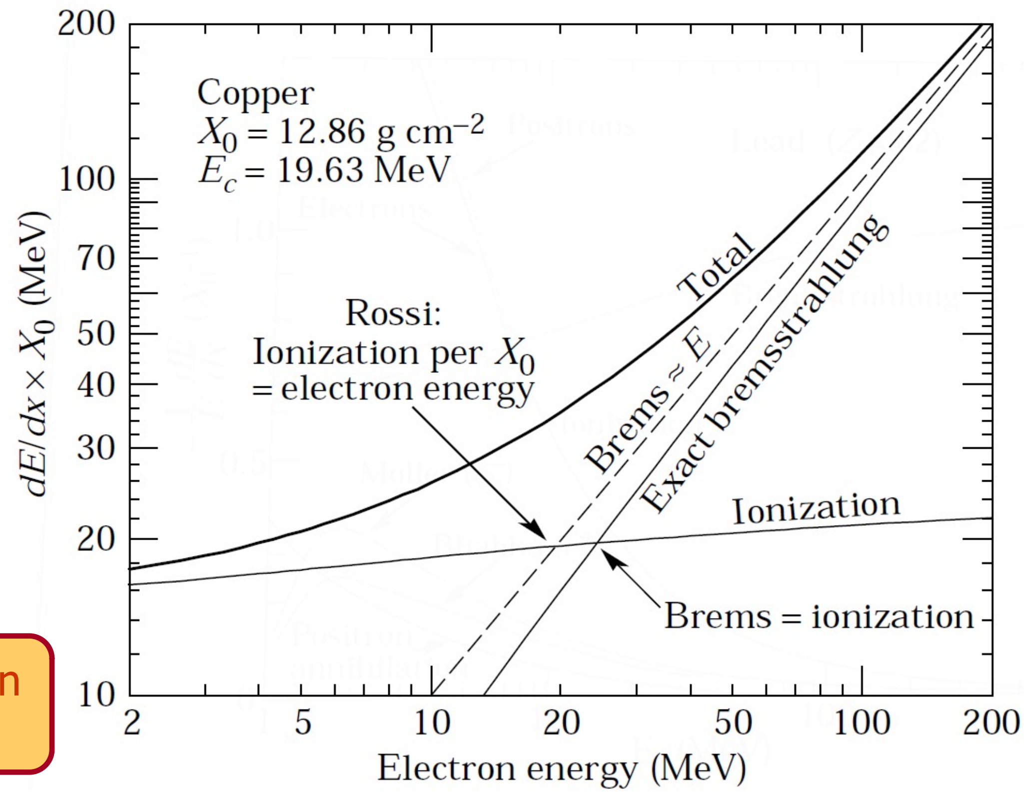
- Energy loss by bremsstrahlung (interaction of electrons with the electric field of the nuclei)

$$\left(\frac{dE}{dX}\right)_{brem} \approx \frac{E_e}{X_0}$$

Radiation length



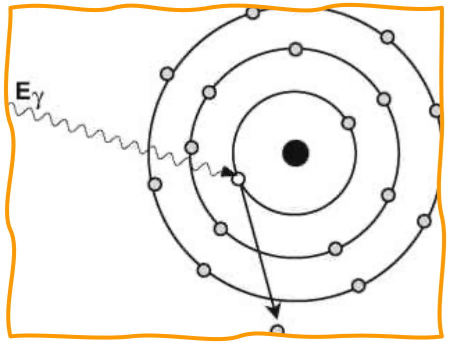
$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

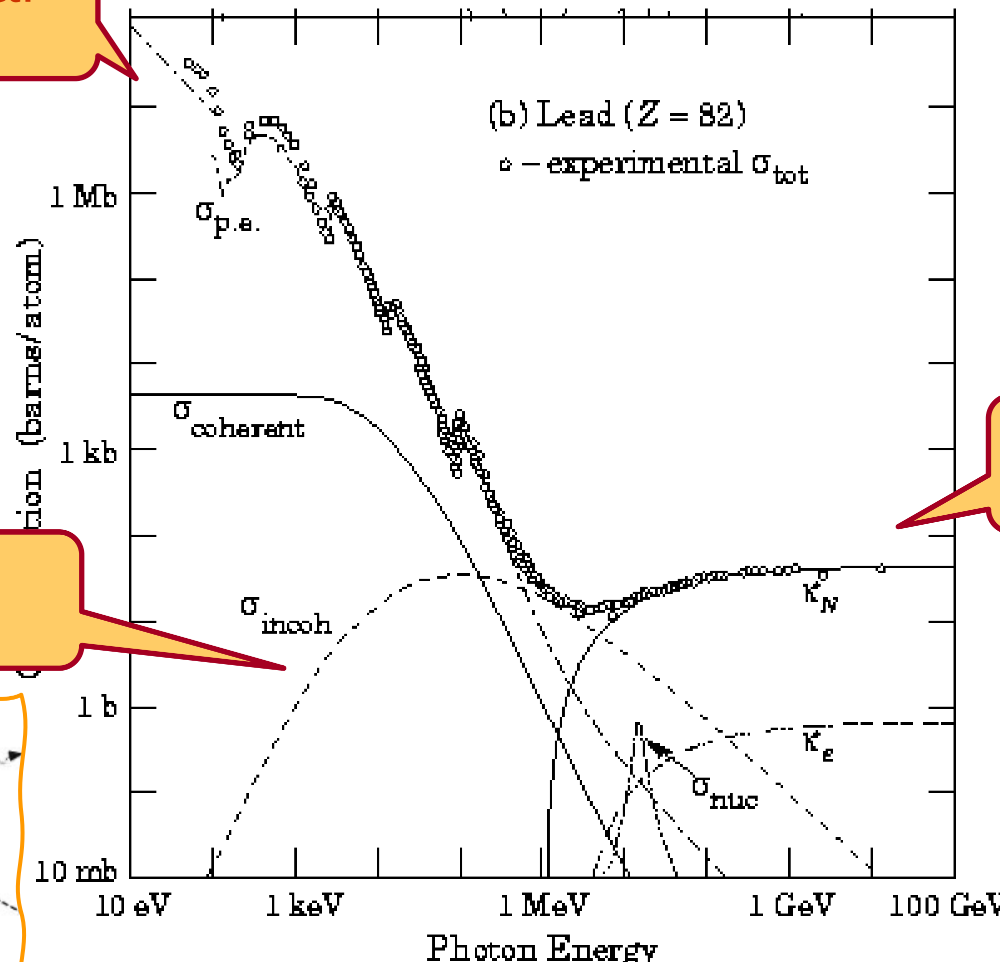


Critical energy E_c: energy at which the losses due to ionization and exact radiation are equal

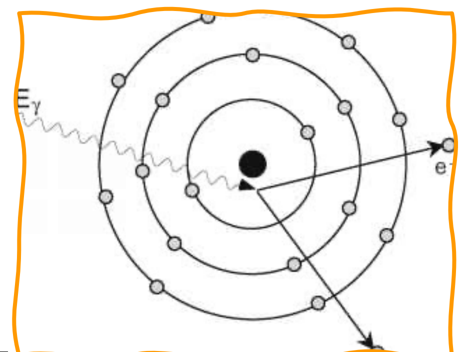
Photons interactions with matter

Phot-electric effect:
$\sigma_{ph}(E_\gamma,Z) \sim Z^5/E^3_\gamma$

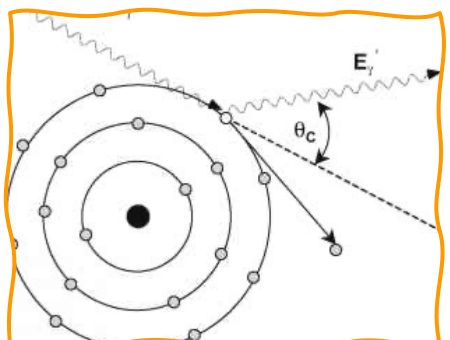




Pair-production:
$\sigma_{pa}(E_\gamma,Z) \sim Z^2\,(1/X_0)$



Compton scattering:
$\sigma_C(E_\gamma,Z) \sim Z \ln E_\gamma / E_\gamma$



The concept of shower: let's start with the EM cascade case

What happens to a (GeV-TeV) electron or photon hitting a block of matter ?

- Above 1 GeV the dominant process is bremsstrahlung for electrons and positron while pair production for γ

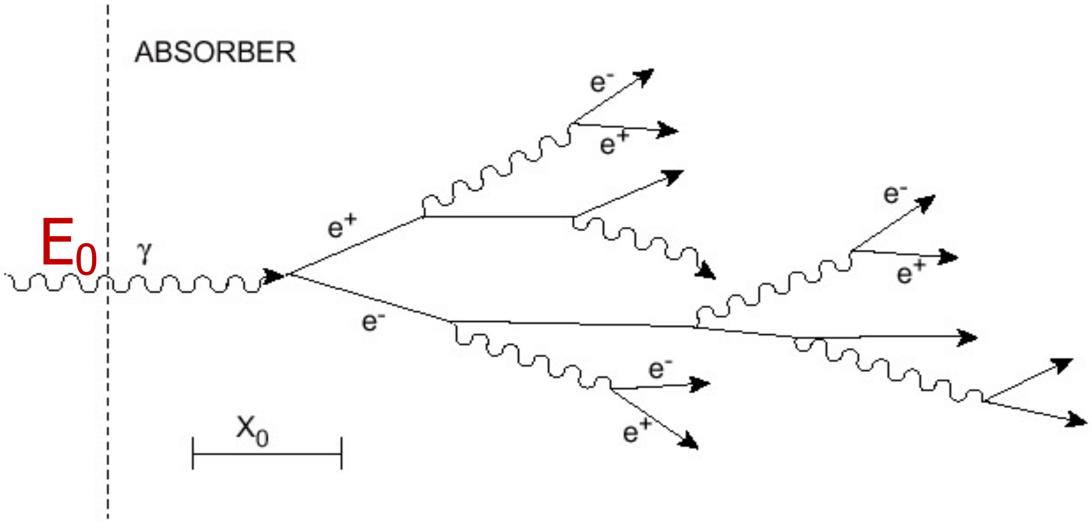
- Electrons and positron also loose energy quasi-continuously by collision

- In contrast photon interactions are localized. In passing through a medium, photons will traverse a certain distance unaffected, until they interact by on of the 3 possible processes

- The concepts of showers : through a succession of these energy losses an e.m. cascade is propagated until the energy of charged secondaries has been degraded to the regime dominated by ionization loss or photon absorbtion (~ below E_c)

- Below E_c a slow decrease in number of particles occurs as electrons are stopped and photons absorbed (photo-electric effect)

A simple model for EM showers



Assumptions to build a simplified model of the electromagnetic cascade:

- in 1 X_0 an electron radiates one photon with half of its energy
- in 1 X_0 a photon creates an electron-positron pair with equal energy

The model is extremely naïve, but some interesting considerations can be made on the shower development features

Assume that the shower is initiated by a photon

Step	Electrons	Photons	Tot	Energy
After 1 X_0	2		2	$E_M=E_0/2$
After 2 X_0	2	2	4	$E_M=E_0/4$
After 3 X_0	6	2	8	$E_M=E_0/8$
…	…	…	…	…

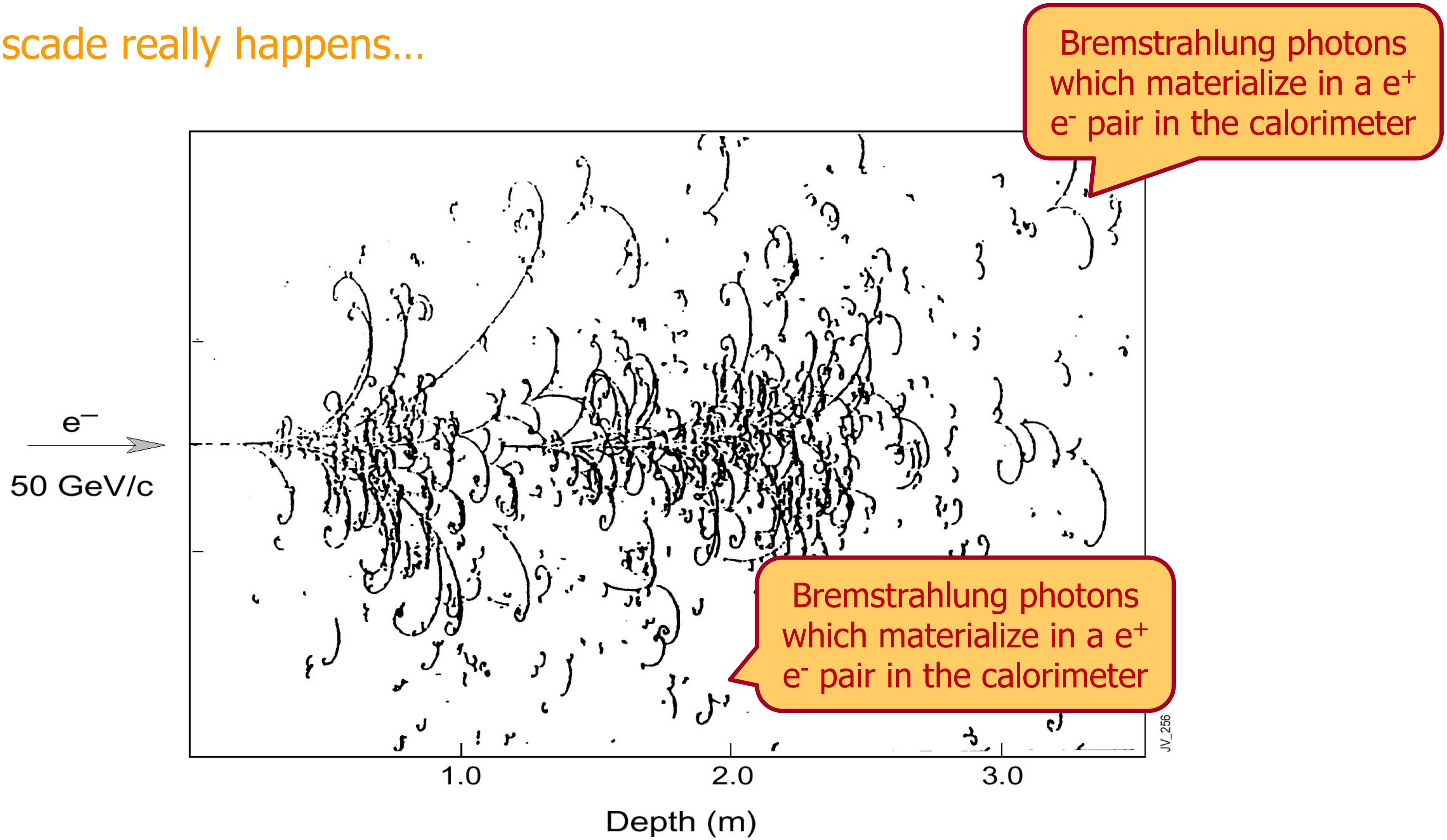
$\Delta x = tX_0$ $N(t) = 2^t$ $E(t) = E_0 / 2^t$

Assume that the process ends up when $E_M=E_C$ (energy loss by ionization dominates, no multiplication)

$E(t_{max}) = E_c$ $E_0 / 2^{t_{max}} = E_c$

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

EM cascade really happens…

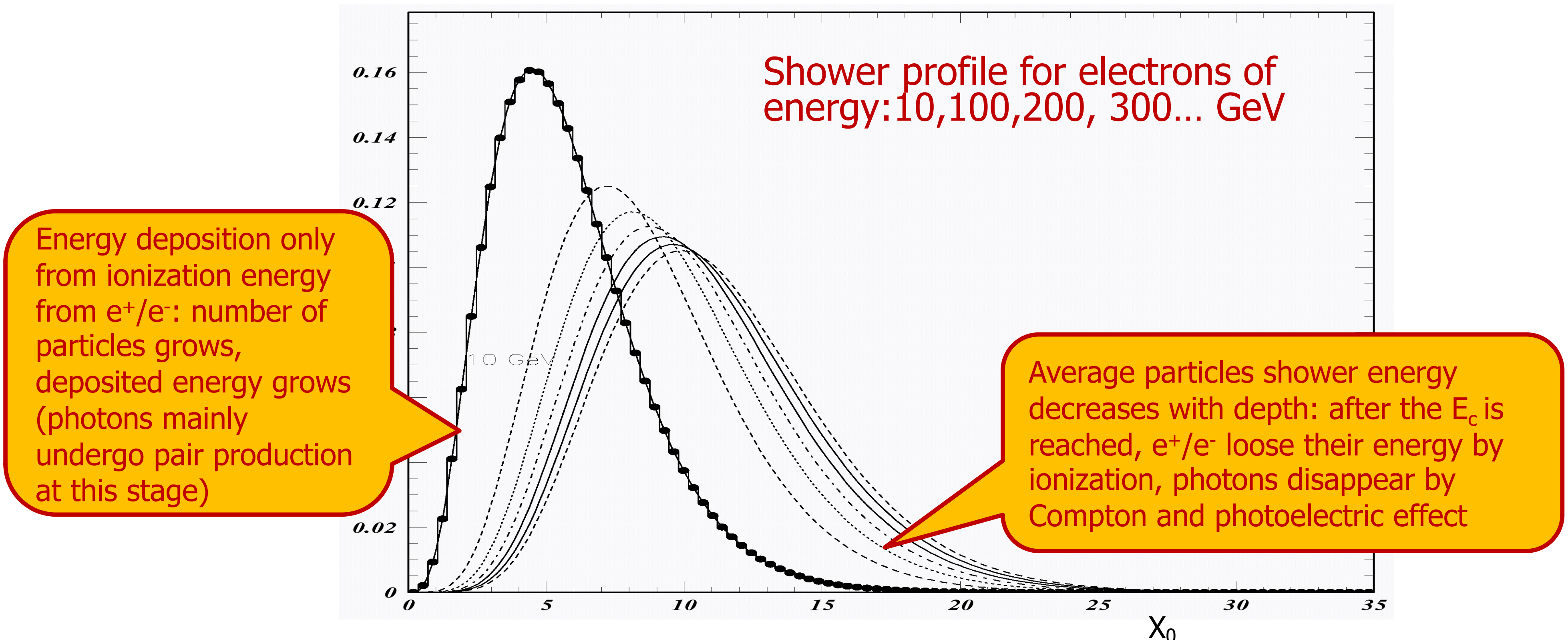


Big European Bubble Chamber filled with Ne:H2 (70%:30%), 3T field, L=3.5m, X_0=34 cm, 50 GeV incident electron

EM showers : longitudinal profile

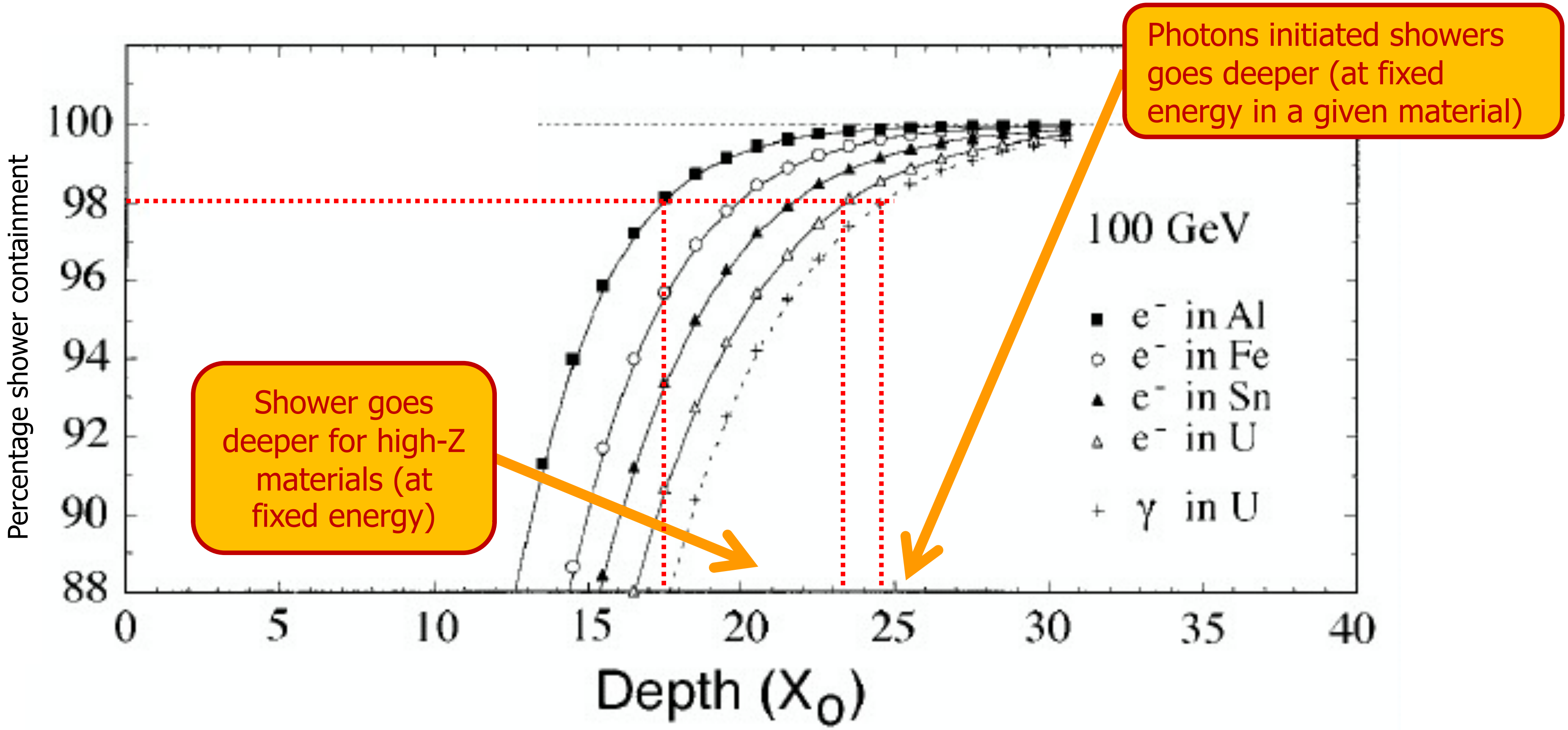
Understanding the shower development (=fraction of the total energy deposited in a slice) in the detectors is crucial for HEP: tons of data/simulation comparisons

- Detailed showers simulations: reproduce the shower development by a sequence of elementary interactions randomly sampled according to the cross sections (e.g., Geant4, Fluka …)
- Effective parameterizations of showers development :



EM showers longitudinal profile : material and particle dependence

Understanding the shower development is crucial for real detector design :

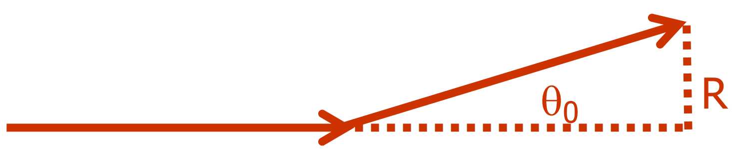


- Take away message: usually full longitudinal containment (~98%) achieved in 25 X_0 (225 cm of Al, 14 cm of Lead) loosely dependent on the incoming particle energy

EM showers : transverse profile

- High energy (early) part of the shower is dominated by pair production (photons) and radiation (electrons)
    - Negligible opening angles, typically goes like 1/γ of the particle

- Shower trasverse size again driven by the low energy part of the shower
    - Driven by multiple scattering of low energy electrons.
    - Let's consider the multiple scattering for e^-/e^+ just after the shower maximum at energies ~ E_c : assuming these electrons will survive ~ $1X_0$ we can get an estimate of the transverse size (Moliere Radius R_M)



$$R(x,E) \approx x\,\theta_0^{space}$$

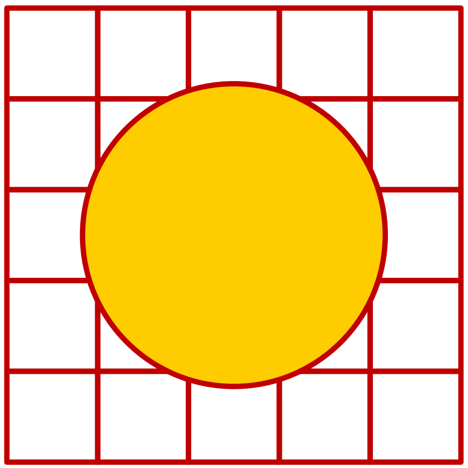
$$R_{shower} = R(x = X_0, E = E_c)$$

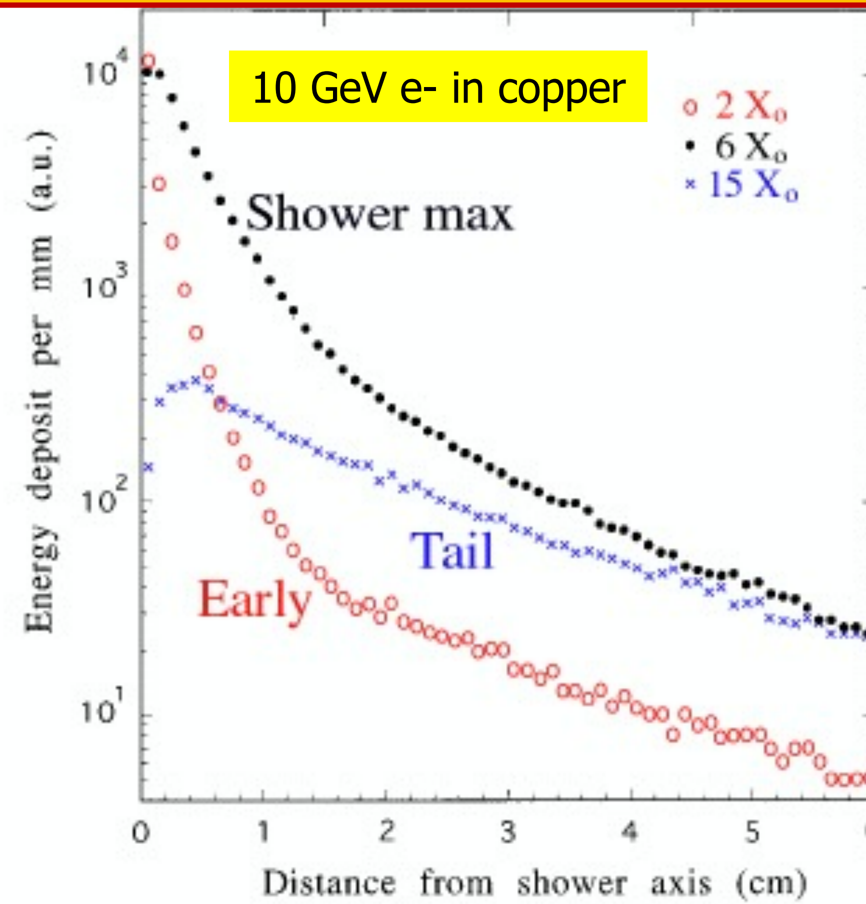
$$\theta_0^{space}(x,E) = \sqrt{2}\,\theta_0 \approx \sqrt{2}\,\frac{13.6MeV}{E}\sqrt{\frac{x}{X_0}} \Rightarrow R_M = \frac{21MeV}{E_c}X_0$$

- Low energy photons cloud finally define the real size of the shower : compton and photon-electric effects spread the shower further

EM showers : transverse profile

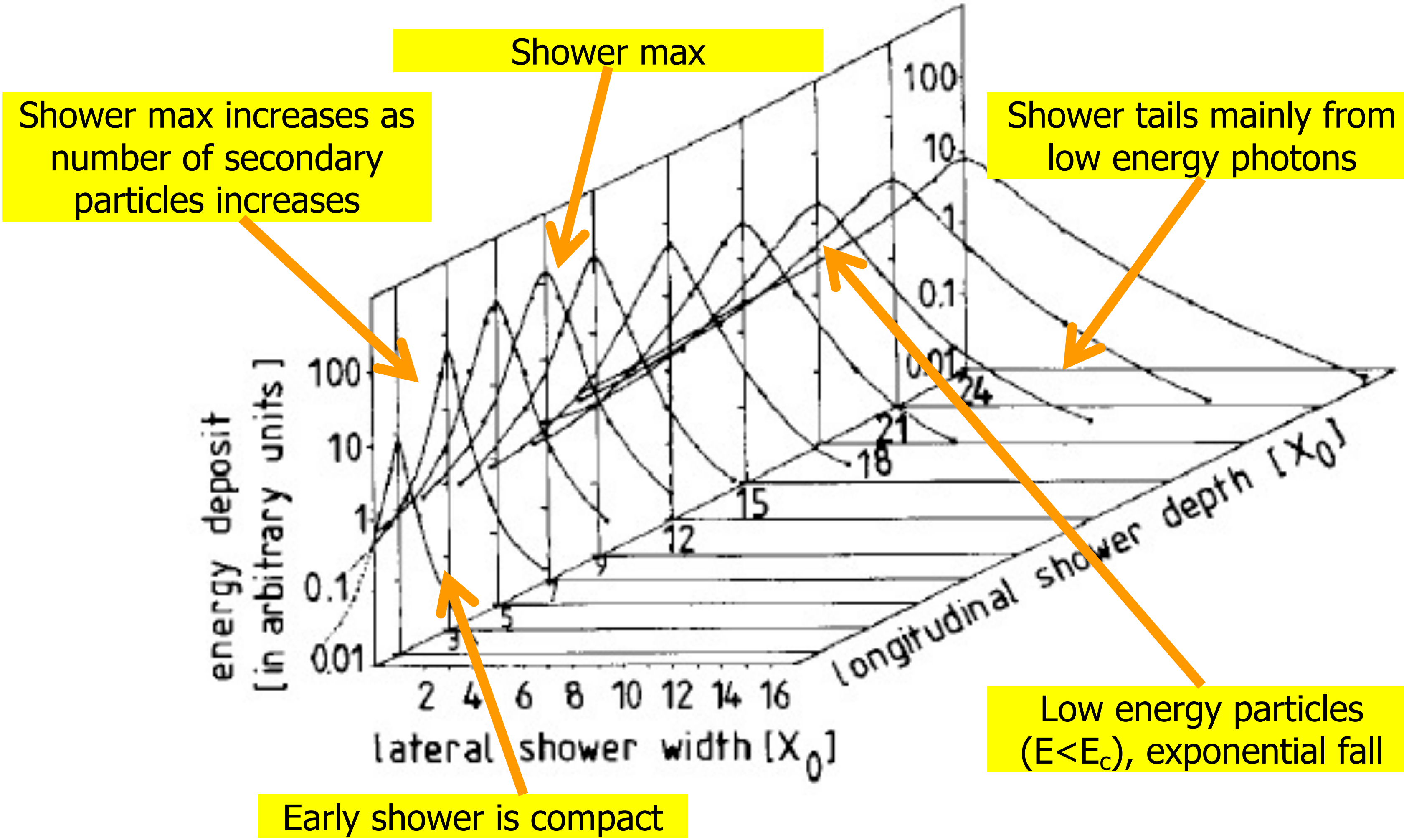
- The Moliere radius R_M : ~90% (87% to be precise) E_0 within $1R_M$, 95% within $2R_M$
- R_M is used to define the trasverse size of the calorimeter cells: typically an e/γ reconstructed in a 3x3 cluster of cells





Material	Z	X_0/cm	Ec/MeV	R_M/cm
LAr	18	14	37	8
Lead	82	0.56	7.4	1.6

Putting everything together : how an electromagnetic shower looks like



Energy loss by charged hadrons (strong force)

- In the 1 GeV – 1 TeV range the inelastic cross section dominates, approximately 40 mb, (4×10^{-26} cm^2) ~ constant with energy of the incident hadron
  - Can be interpreted naively considering the cross section as the apparent size of a nucleon. A proton or a neutron have an apparent size of slightly more than 10^{-13} cm, and the cross section for the collision on another proton or neutron is $\approx 4\times10^{-26}$ cm^2 , 40 mb.
- A hadron hitting a block of matter will interact with the atomic nuclei. A nucleus with atomic mass number *A* has a diameter that is $(A)^{1/3}$ times the proton diameter and a geometrical cross section that is $(A)^{2/3}$ times that of a proton. The cross section for the interaction of a proton on a nucleus of atomic number *A* is therefore expected to be

$$\sigma \approx 4\cdot10^{-26} A^{2/3} cm^2$$

- Therefore, the mean free path for a proton/neutron to undergo a nuclear interaction

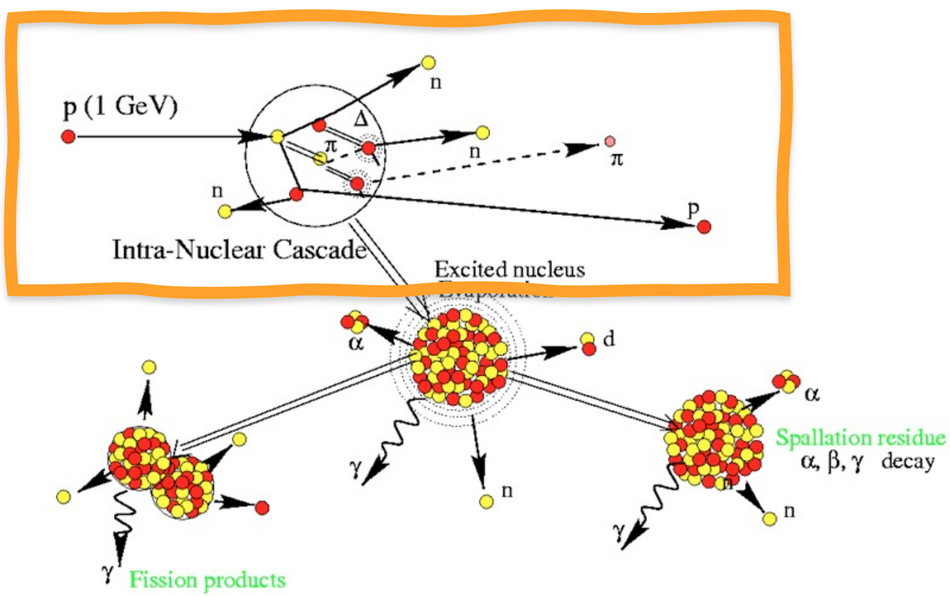
$$\lambda(cm) = \frac{1}{\sigma N} \approx \frac{A^{1/3}}{\rho}\frac{1}{N_A 4\cdot10^{-26}} \approx 35(g/cm^2)\frac{A^{1/3}}{\rho} \qquad \left(N = \rho\frac{N_A}{A}\right)$$

$$\lambda(g/cm^2) = \lambda(cm)\rho = 35\,(g/cm^2)A^{1/3}$$

- In Lead λ ~ 17 cm (199 g/cm^2) while X_0 ~ 0.56 cm (6.37 g/cm^2).

Energy loss by charged hadrons (strong force)

- Typical values of the mean free path (hadronic interaction length) 10-100 cm in solids
  - Hadrons in the GeV range typically loose a few MeV per cm by collision. The range is larger than λ: likely to have strong interactions before loosing all its energy by collision.
  - A hadron will undergo a nuclear interaction before it has lost all its energy by collision.
- In such collision with a nucleus (for incoming hadrons in the GeV range) a nuclear spallation reaction will most likely take place. Can be modeled as a 2-step process:



(I)-Fast intra-nuclear cascade : the incoming hadron makes quasi-free collisions with nucleons inside the struck nucleus.

- The affected nucleons start traveling themselves through the nucleus and collide with other nucleons (a cascade of fast nucleons).
- In this stage, pions (π^+, π^- and π^0) may be created if the transferred energy is sufficiently high.
- Some of the particles taking part in this cascade reach the nuclear boundary and escape.
- Others get absorbed resulting in the production of an excited nucleus.

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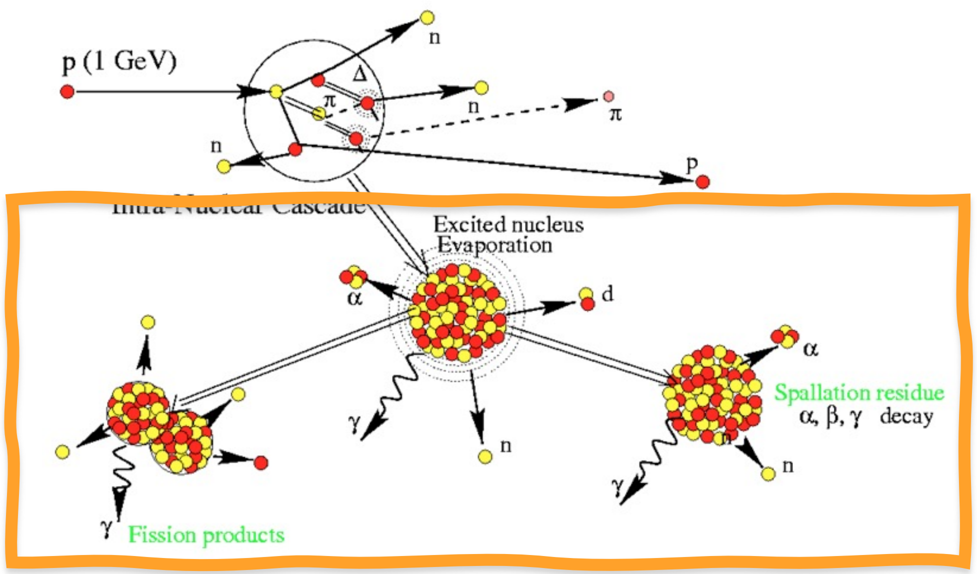
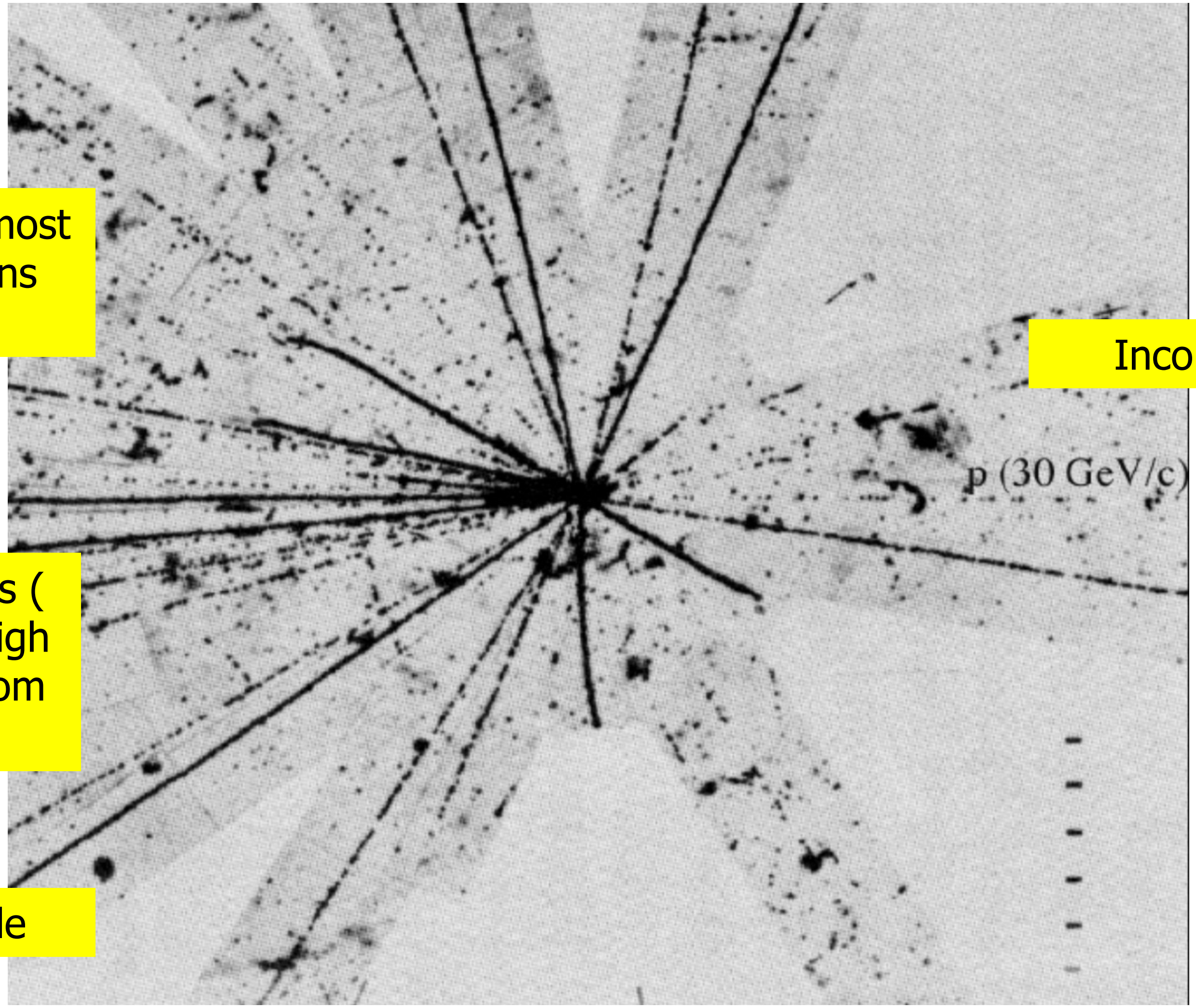


(II)-De-excitation of the excited nucleus. This is achieved by evaporating a certain number of particles, predominantly free nucleons, but sometimes also α's or even heavier nucleon aggregates, until the excitation energy is less than the binding energy of a single nucleon. The remaining energy, typically a few MeV, is released in the form of γ rays. In very heavy nuclei, e.g., uranium, the excited nucleus may also undergo a fission.

Energy loss by charged hadrons (strong force)

Spallation reaction by a 30 GeV proton (nuclear emulsion)



Dense ionisation tracks,most likely low energy protons (from evaporation)

Incoming proton

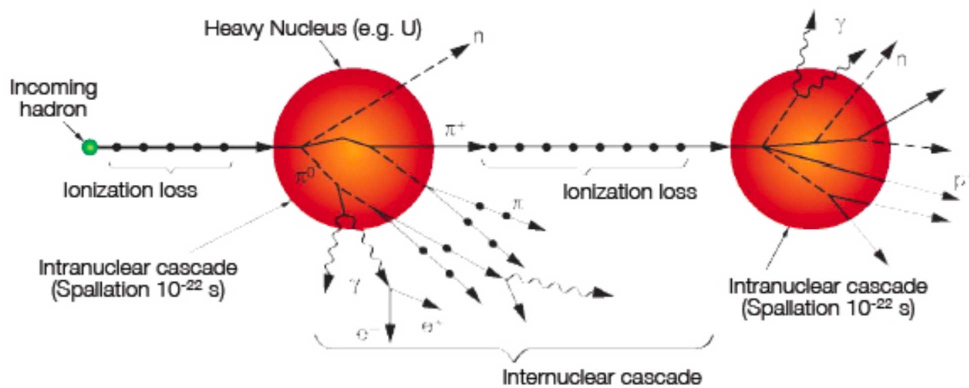
Less dense ionising tracks (more collimated) from high energy protons/pions (from intranuclear cscade)

Neutrons are not visible

Hadrons interactions in matter : hadronic showers

Strong interactions makes modelling of hadrons behaviour in matter more difficult:

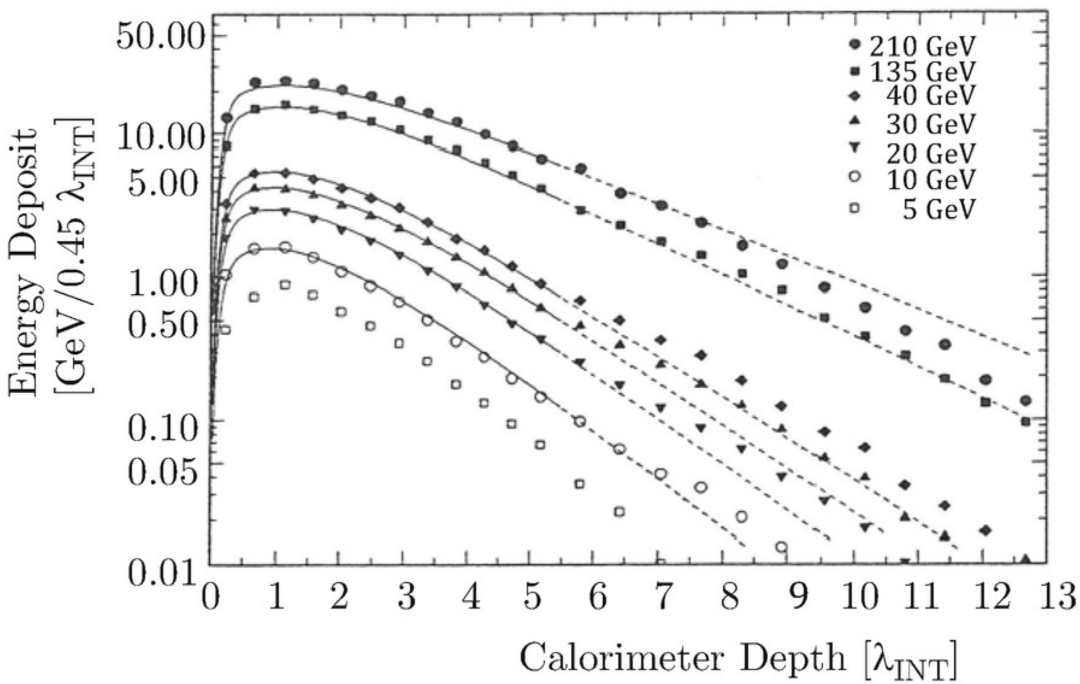
A. Strong interaction leads to production of secondary hadrons (hadronic showers !)
   - Secondary hadrons can in turn loose their energy ionizing the material or again via nuclear interactions until they fall below pion production threshold and loose their energy by ionization or they are absorbed by nuclei



Hadronic showers longitudinal profile

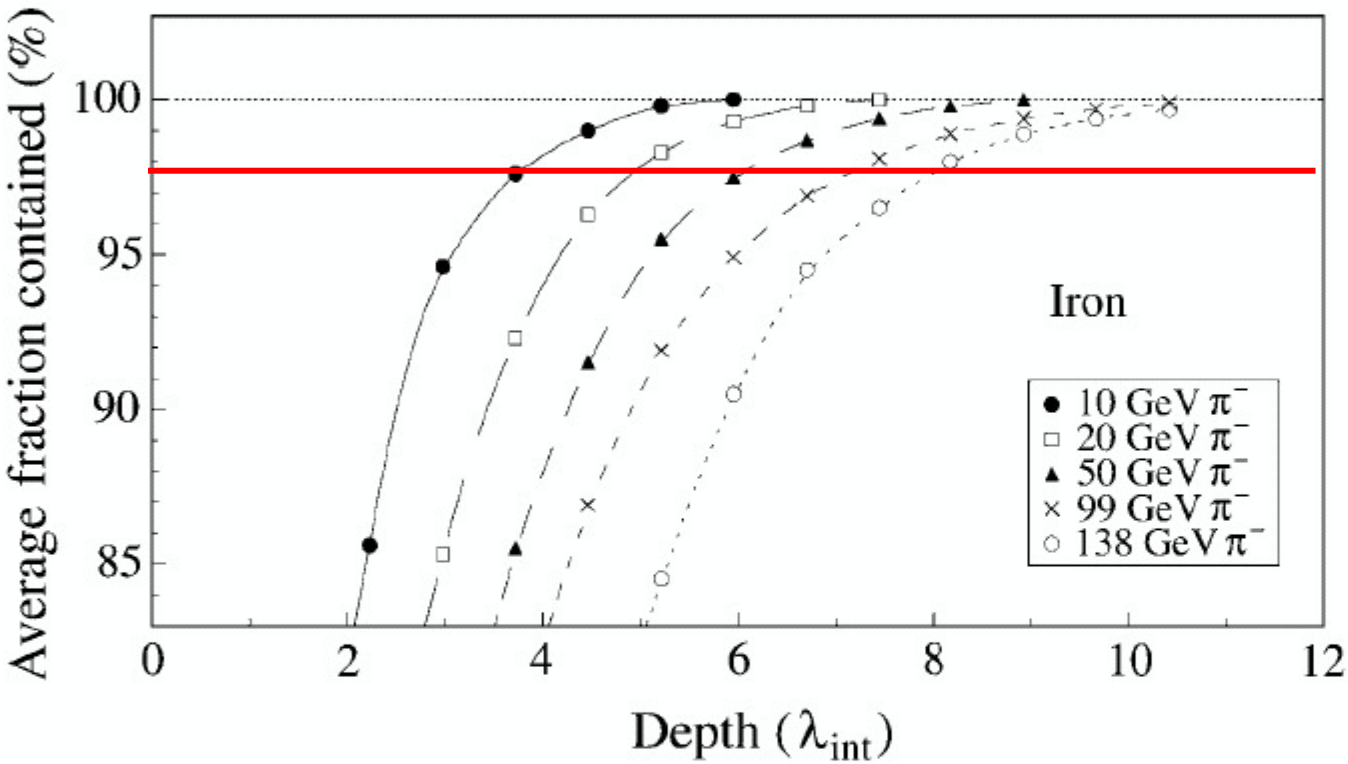
As in the EM shower models the hadronic showers exhibit a scaling with the interaction length parameter λ

- ❑ Same logaritmic scaling of the shower max position with the energy of the incoming hadron as for EM sshowers
- ❑ Hadonic showers are on average broader and longer than em showers :
  - ❑ Uranium calorimeter : 95% containment of 300 GeV p (8l) 85 cm For 300 GeV electrons 10 cm



Material	Z	λ_I/cm	X_0/cm
Fe	26	16.8	1.8
Cu	29	15.1	1.4

Hadronic showers longitudinal profile



- Take away message: for 98% containment of multi-hundreds GeV jets at the LHC use 10 λ (mild dependence with energy)

Hadrons interactions in matter : hadronic showers

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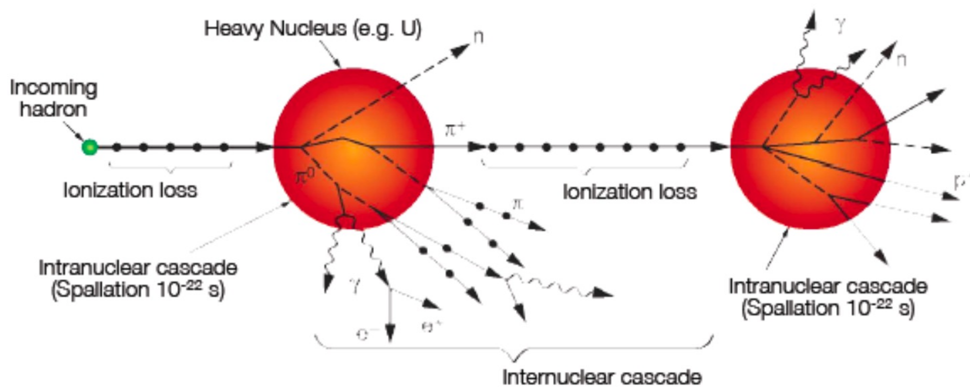

B. In these processes, neutrons and protons are released from atomic nuclei. The nuclear binding energy of these nucleons must be provided. Therefore, the fraction of the shower energy needed for this purpose does not contribute to the calorimeter signals.
   - This is the so-called invisible-energy phenomenon.

Hadrons interactions in matter : hadronic showers

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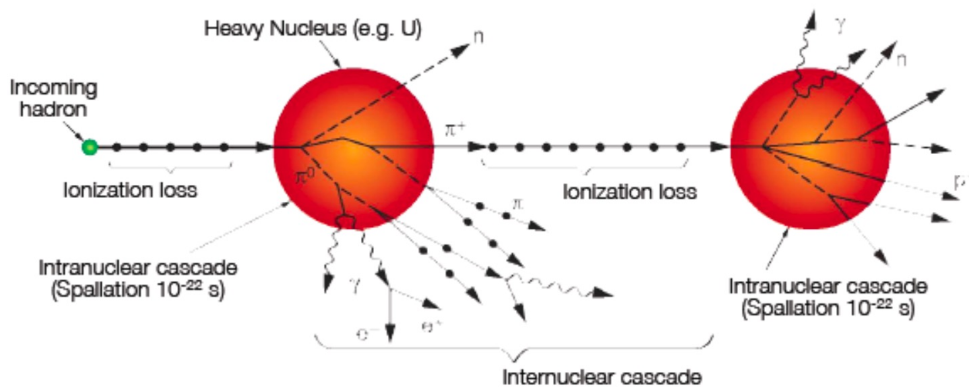

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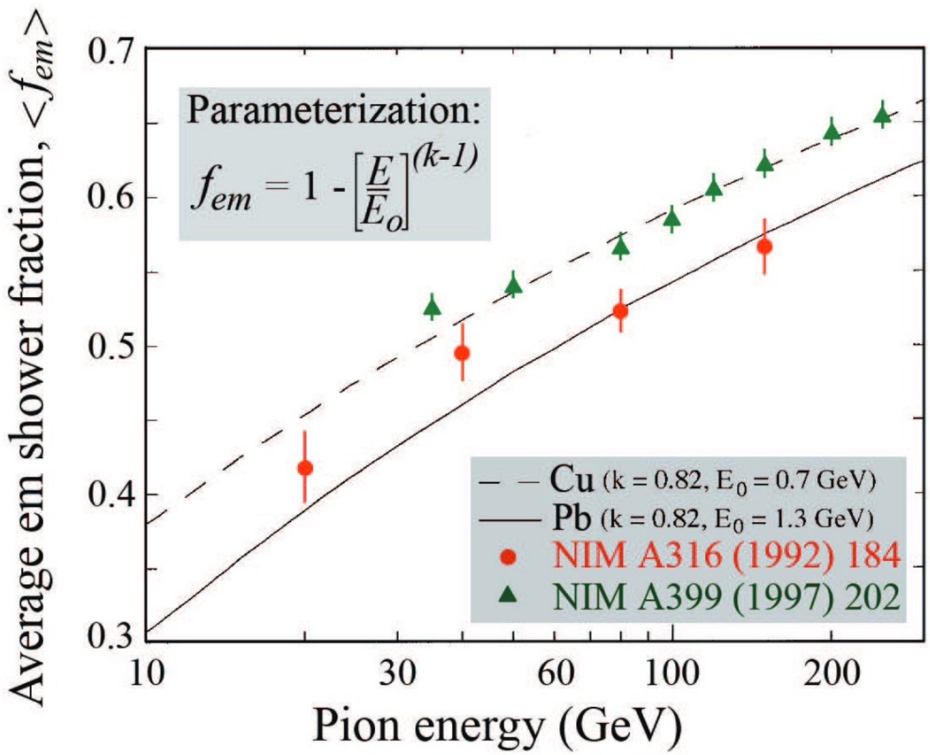
C. The neutral pions decay into 2 photons which develop EM showers.
   - ❑ One of more electromagnetic showers inside a hadronic shower !

The electromagnetic component in hadronic showers

- The electromagnetic fraction of the hadron showers increases with energy of the incoming hadron



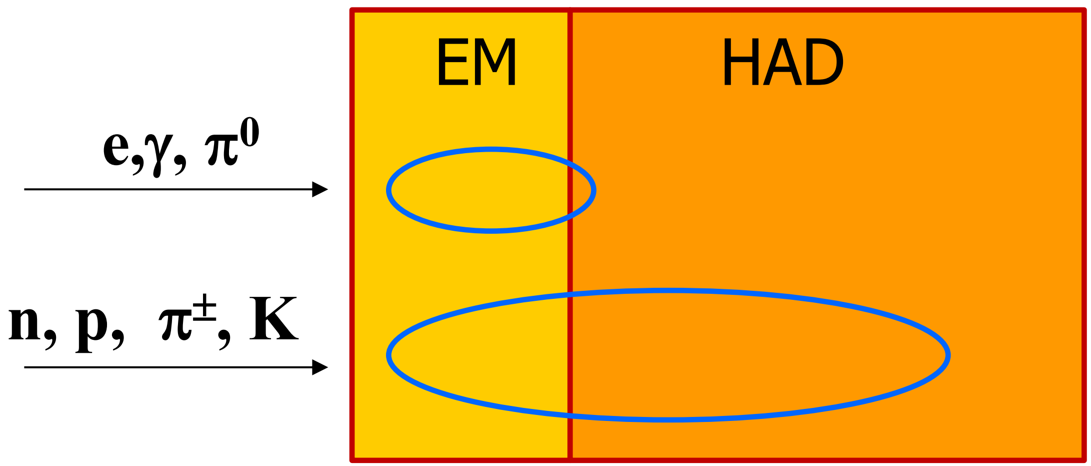
- Simplified model : assume only pions are produced
- Pions are iso-triplet so $\pi^{+/-}$ and π^0 are produced democratically in each nuclear interaction
- $\pi^0 \rightarrow \gamma\gamma$ is a one way process: generate an electromagnetic component
  - f_{EM} = 0.33 after the first interaction
  - f_{EM} = 0.33 x 2/3 + 0.33 = 0.55 after the second interaction
  - $f_{EM} = 1 - (1-0.33)^b$ after b iterations
- the process stops when the available energy drops below the pion production threshold (300MeV) and b depends on the average multiplicity of mesons produced per interaction

- f_{em} increases with increasing incoming hadron energy: more refined parameterisations (facing the rough assumptions in our model)

Calorimeter types

Calorimeters can be classified according to the following criteria:

- Type of particles you want to be sensitive to:
  - electromagnetic/hadronic calorimeters are optimized to measure the energy (well not only energy…) of electron and photons / hadrons or jets of hadrons.
  - Typically differ by material choices and size

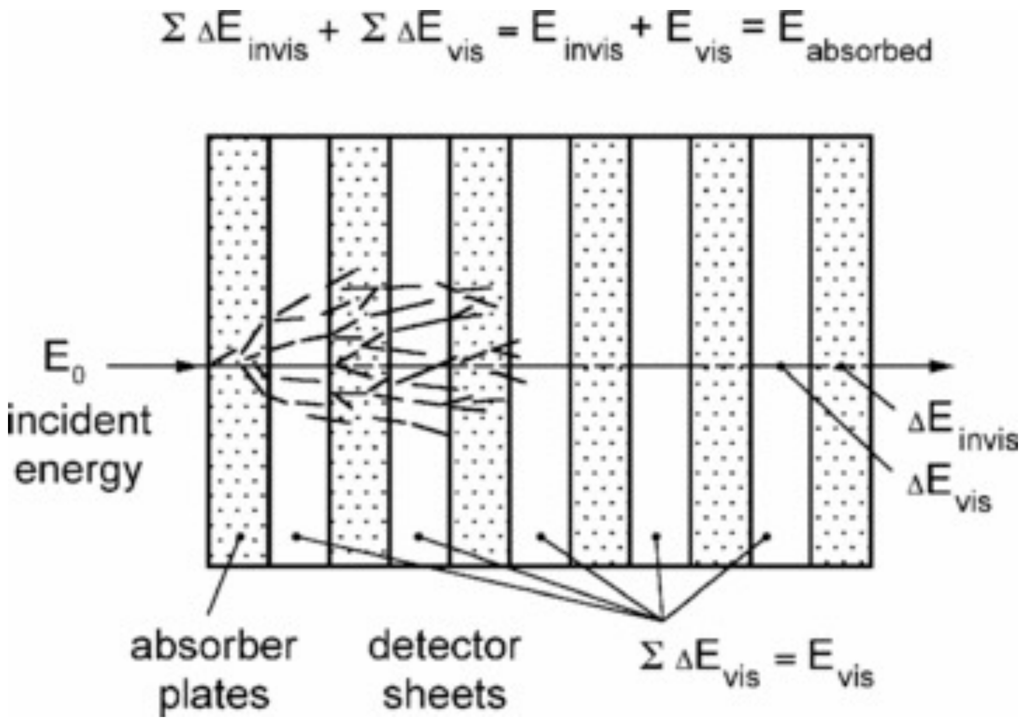


- The dimensions of HAD calorimeters are usually larger than EM calorimeters.
- In HEP detectors HAD calos follow EM calo in the radial directions: one can consider the sum of EM+HAD as hadronic calorimeter

Calorimeter types

Calorimeters can be classified according to the following criteria:

- Construction technique:
  - Homogeneous calorimeters : the calorimeter is made of one single material which absorb the energy of the incoming particle and provide a signal
  - Sampling calorimeters : the active material (= the one which can provide a signal) is interleaved by layers of inactive material (= absorb the energy without giving signal)

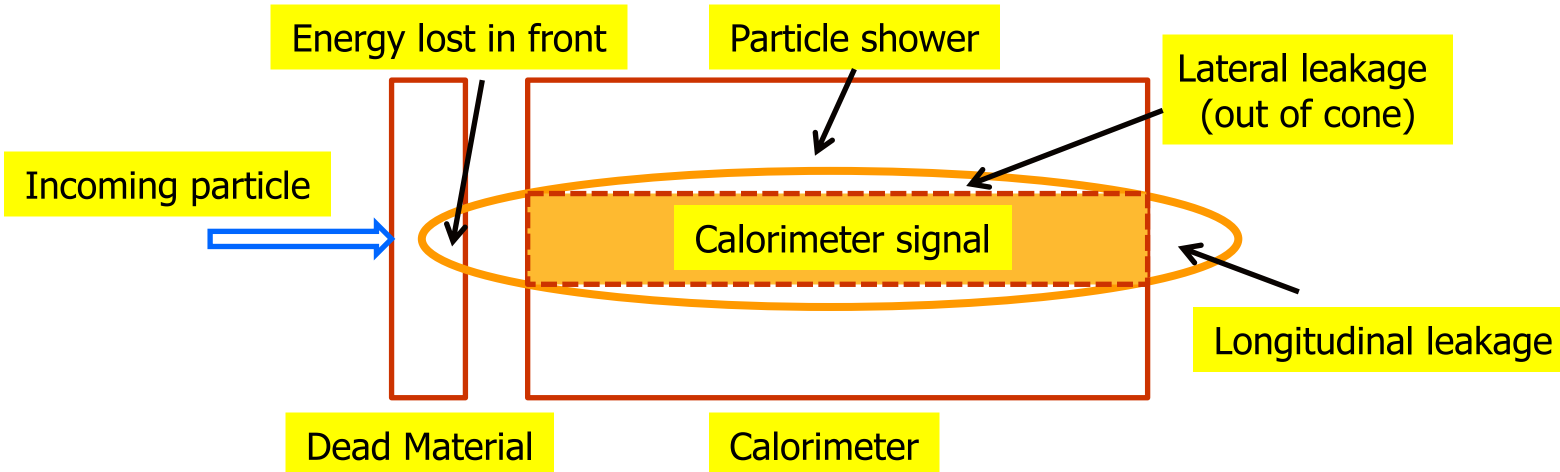


Sampling fraction

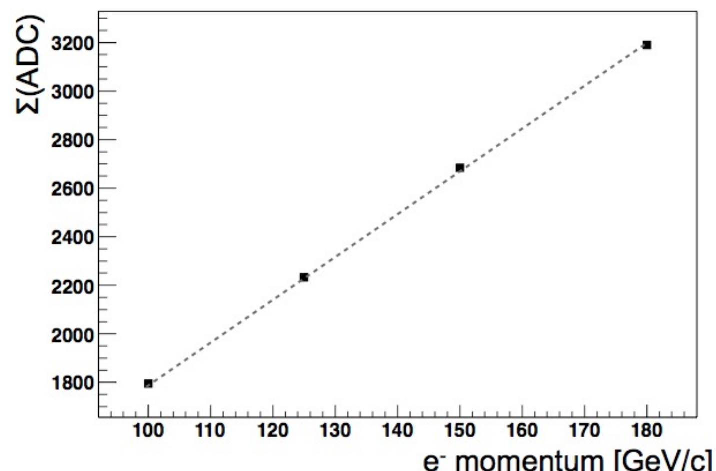
$$f_{samp} = \frac{E_{mip}(active)}{E_{mip}(active) + E_{mip}(absorber)}$$

Calorimeters response : linearity

Final goal: infer our best estimation of the energy of a particle hitting in the calorimeter

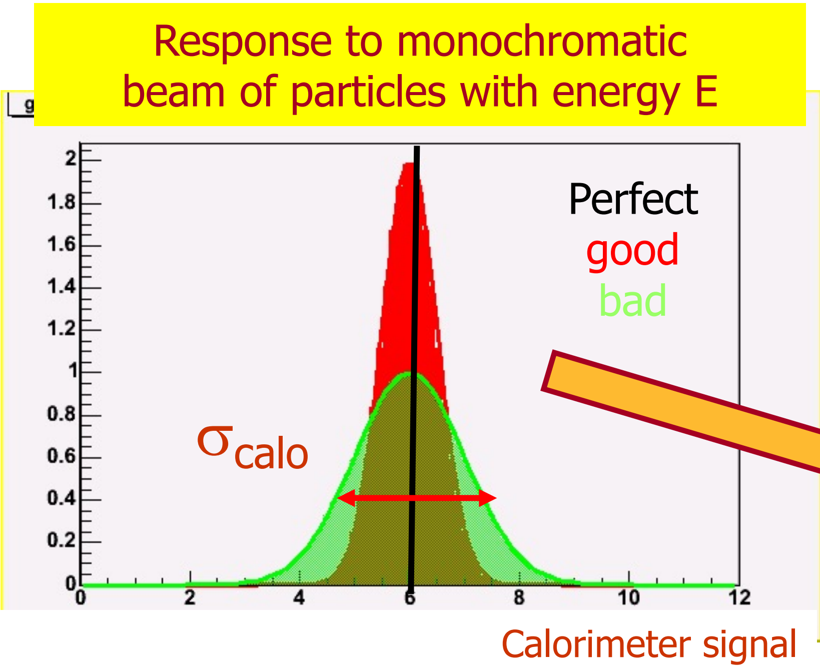


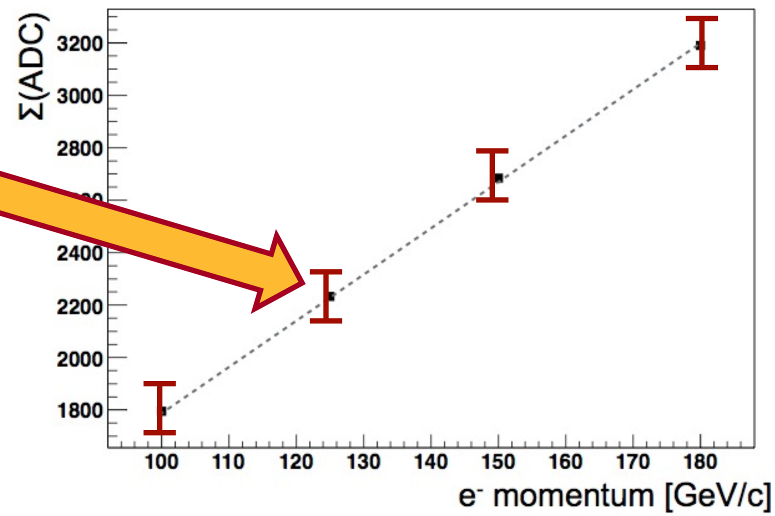
- ❑ Measure the calorimeter signal (i.e., energy deposited in the calorimeter): linearity of the calorimeter signal vs the deposited energy (understand all limiting effects, i.e., saturation of the response from electronic)
- ❑ Calculate the particle energy : correct of longitudinal leakage, energy loss upstream, compensation (for hadronic showers)



Calorimeters response: resolution

- Resolution: precision with which the unknown energy can be measured
  - Fluctuations: event to event variations of the signal





σ_{calo} defines the energy resolution

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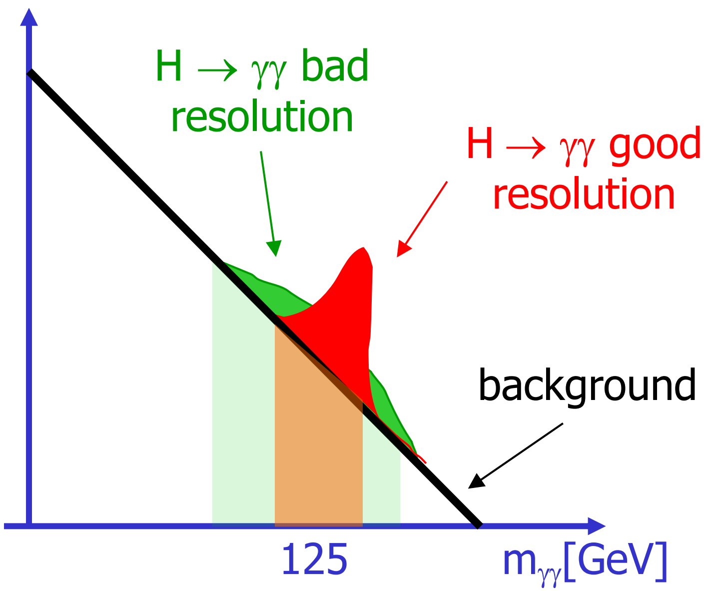
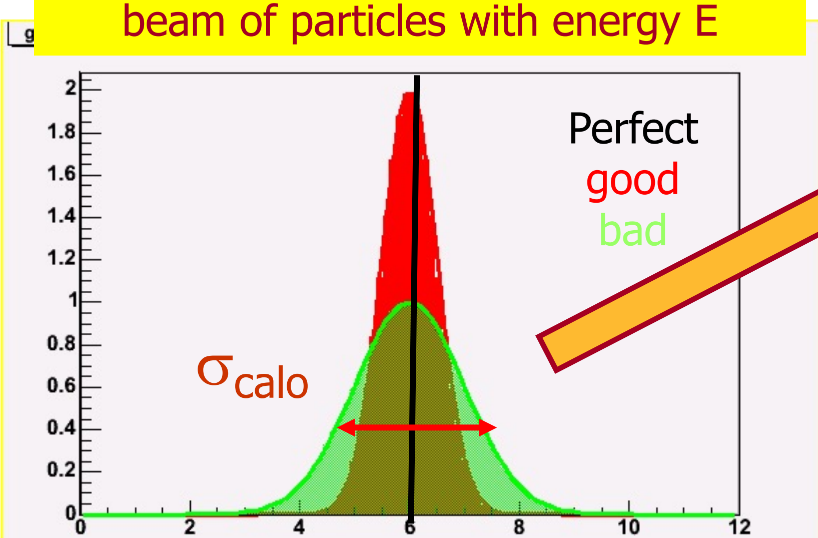


Why is the resolution a crucial parameter in calorimeters design? Suppose you are looking for a tiny signal over a huge background (consider the two photons channel)

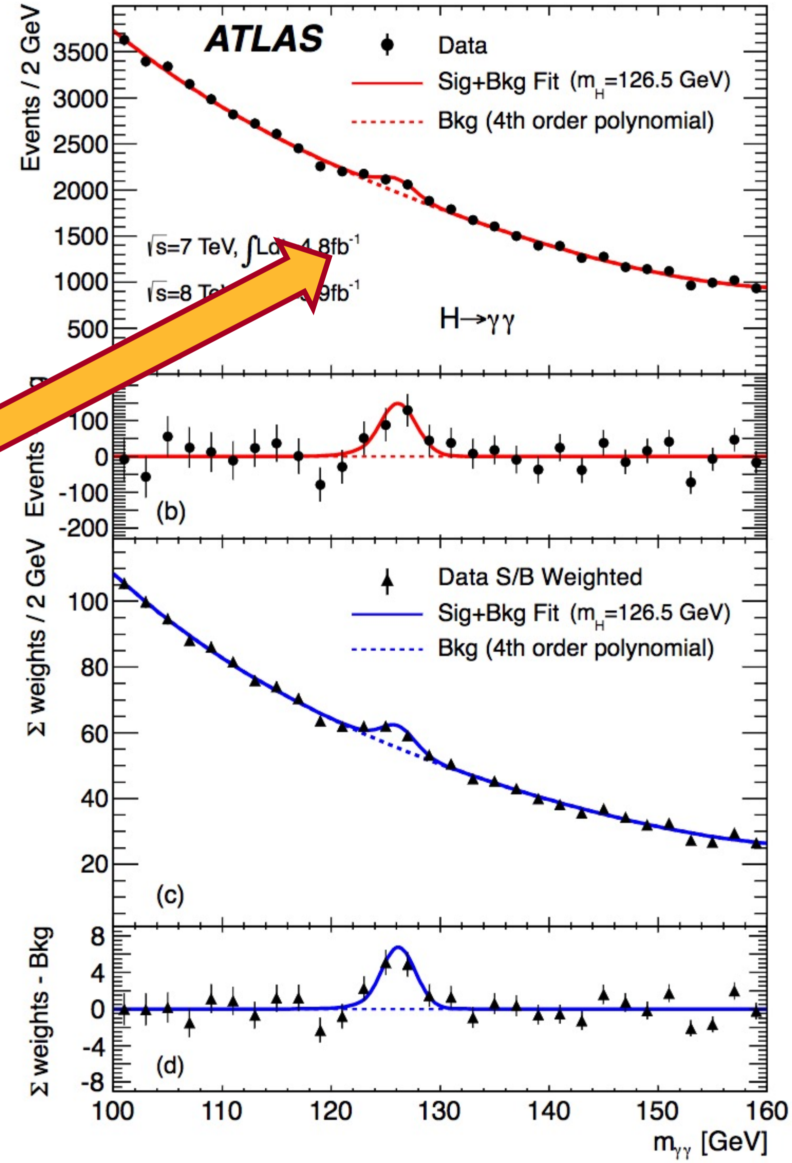
- The new boson (signal) has a negligible intrinsic width and its mass resolution $\sigma_{\gamma\gamma}$ is fully experimental
- Look for an excess of events at a given invariant mass (125 GeV) in a mass window of a few $\sigma_{\gamma\gamma}$
- Estimate the number of background events B in the window
- If assume B is flat in $m_{\gamma\gamma}$ then $B \propto \sigma_{\gamma\gamma}$
- S = constant (signal is fully contained in the window)
- Significance of an excess: compare the measured signal S with the background fluctuation ($\sqrt{B}$ assuming Poisson statistic)
- $S/\sqrt{B} \propto 1/\sqrt{\sigma_{\gamma\gamma}}$ [but $\sigma_{\gamma\gamma} = f(\sigma_{calo})$]
- The better the calorimeter resolution, the higher is the probability to catch a small signal of new physics!

Calorimeters respose : resolution

Response to monochromatic
beam of particles with energy E



Calorimeter signal



σ_{calo} defines the energy resolution

Energy resolution of real calorimeters

Parameterization of a calorimeter resolution as a function of the incoming particle energy

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

a: stochastic term

Intrinsic fluctuations from signal quanta generation. Fluctuations on active/passive energy deposition. (+shower containment) For hadronic calorimeters, the fluctuations in the invisible energy and em-fraction degrades the stochastic term

b: Noise term

It is the term introduced by the read-out chain electronics (preamps, shapers etc): clearly relevant for low particle energies

c: Constant term

Includes any instrumental effect which produces response variations in the detector: detector geometry, imperfections in the mechanics or readout, temperature gradients, non-uniform aging, radiation damage. It dominates at high energy and defines the "construction quality of the calorimeter".

More on the stochastic term in energy resolution

- Simple model: according to what we have learnt a particle of energy E_p will produce N signal quanta:

$$N \propto E_p/E_S \qquad E_p = k\,N$$

- Taking into account that the signal quanta generation process is statistical, fluctuations on deposited energy are $\sigma(E_M) \sim \sqrt{N}$

$$\frac{\sigma(E_p)}{E_p} = \frac{k\sqrt{N}}{kN} = \frac{1}{\sqrt{N}} = \frac{\sqrt{k}}{\sqrt{E}} = \frac{a}{\sqrt{E}}$$

- The intrinsic limit to the energy resolution is given by the maximum detectable signal quanta which depends on the signal threshold energy (E_S)
  - in the case of calorimeters based on scintillation and Cherenkov light the limiting factor is normally the fluctuation in the generation of photo-electron from the light readout

Stocastic term in energy resolution for sampling calorimeters

❑ In sampling calorimeters there's an additional contribution to the energy resolution due to the presence of the passive material: less carriers and fluctuations in the number of carriers crossing the sensitive layers.

❑ This number depends on the incident particle energy and is found to be inversely proportional to the thickness of the passive layer

$$N_{ch} \propto \frac{E}{E_S d}$$

N_{ch} : charged particles reaching active layer

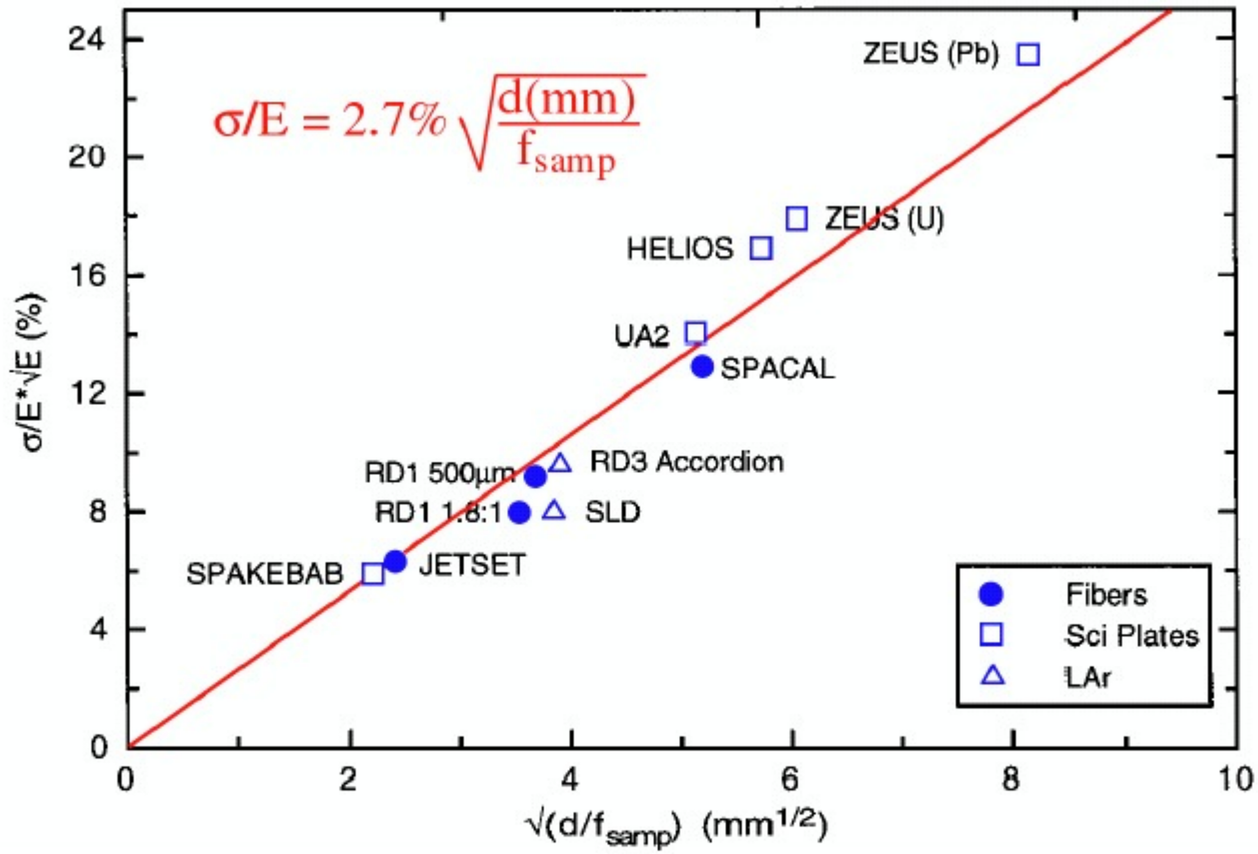
d : absorber thickness in X_0

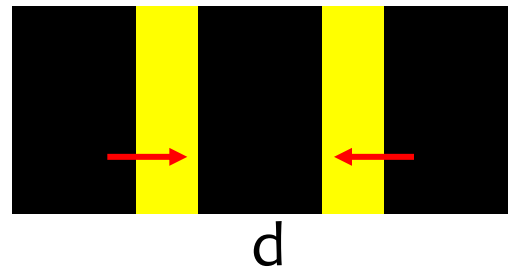
$$\Rightarrow \quad \frac{\sigma_E}{E} \propto \frac{\sigma_{N_{ch}}}{N_{ch}} \propto \sqrt{\frac{E_S d}{E}}$$

❑ Reasoning: energy deposition is dominated by low energy particles (electrons, pions), the probability that such particles generated in the passive material reach the active layer and are not absorbed in the passive material increases for thinner passive layers

Stocastic term in energy resolution for sampling calorimeters

- *Sampling fraction* and *sampling frequency* contribute to the energy resolution of the sampling calorimeters





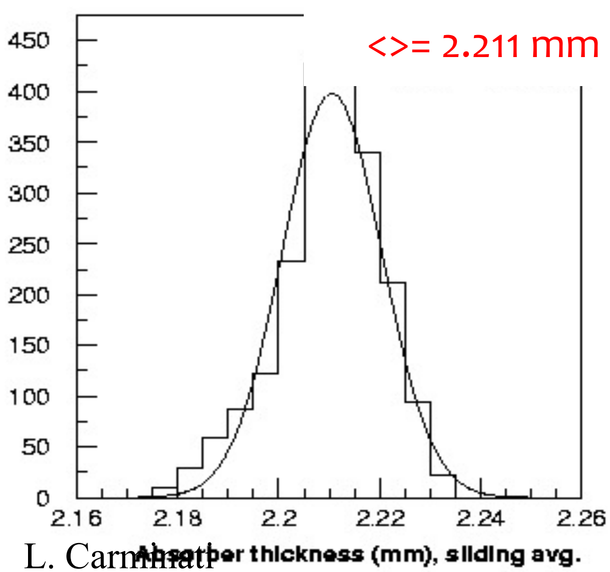
Take away message :

- Large sampling fraction is beneficial
- Large sampling frequency is beneficial

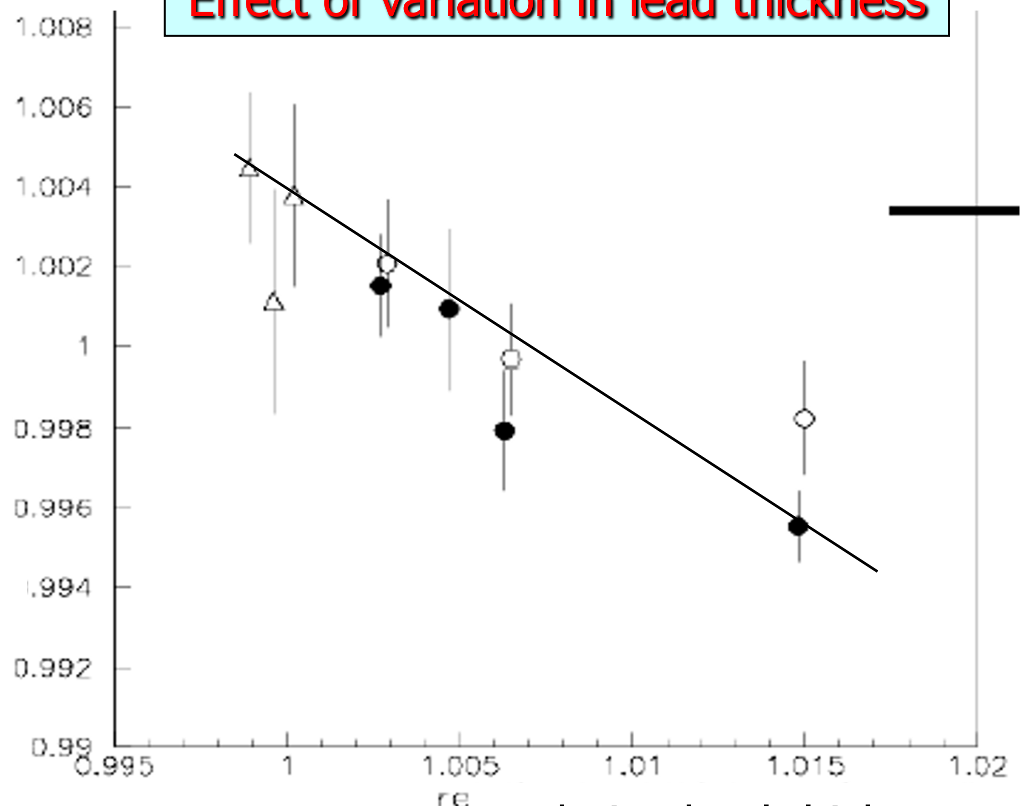
Constant term in the energy resolution: ATLAS EM Calo absorber thickness

Efforts during construction, calorimeter modules as reproducible as possible : few corrections, as small as possible

Absorber thickness



Effect of variation in lead thickness



1% Pb variation → 0.6% drop in response

Measured dispersion σ = 9 μm (calo)

Translates to < 2 ‰ effect on constant term

Why are calorimeter attractive? A bit of advertising...

Calorimeters present a series of appealing features for High Energy Physics applications:

- Typically, energy resolution improves with energy as $1/\sqrt{E}$ (E= incident particle energy). Remember that the momentum resolution provided by magnetic spectrometers deteriorates linearly with the particle momentum.

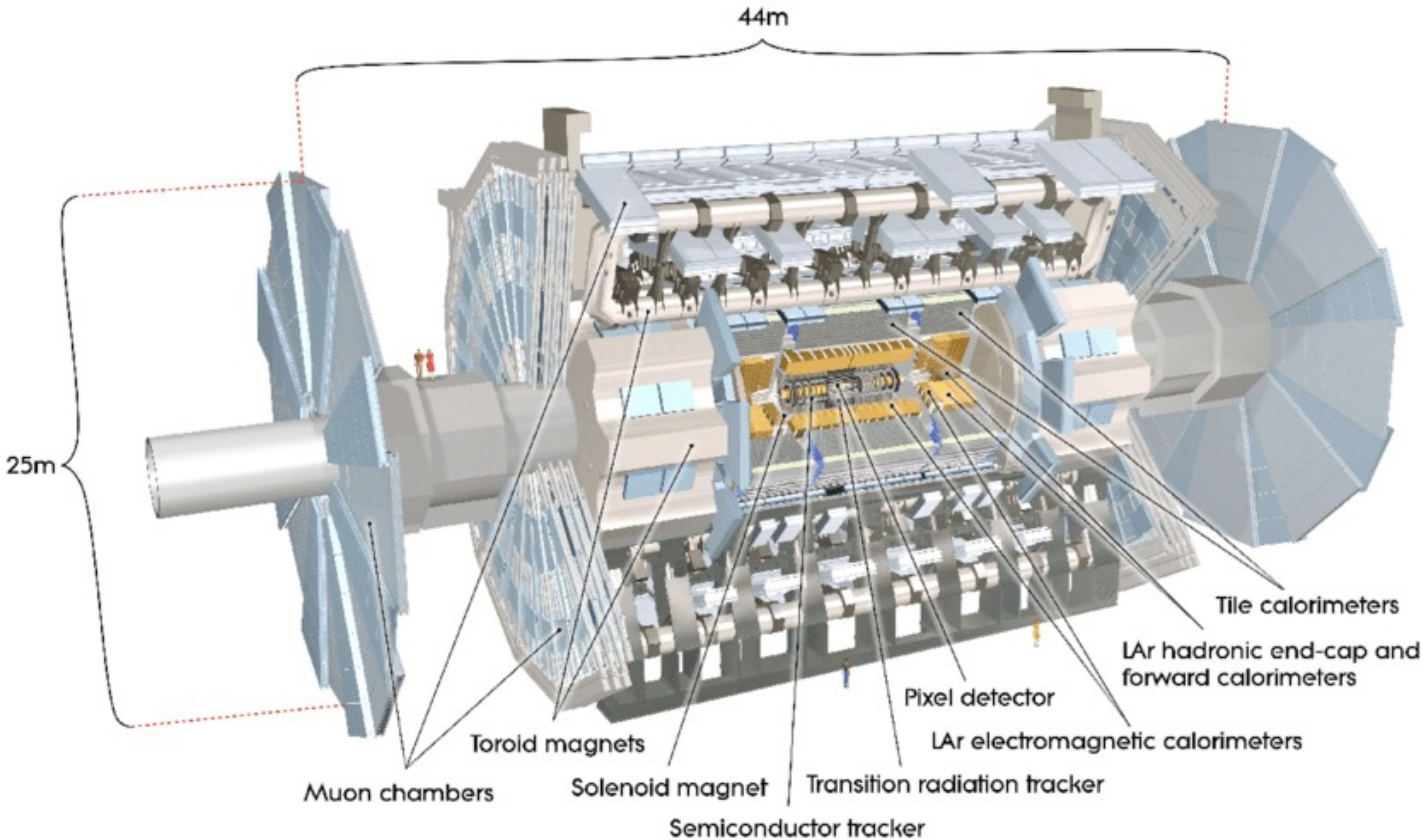
- Calorimeters are sensitive to all types of particle, both charged and neutrals (again remember that magnetic spectrometers are sensitive to charged particles only).

- Calorimeters are versatile detectors : they could be segmented and therefore in addition to energy they could provide position information, timing and particle identification information.

- Calorimeters provide generally fast signals; they are can be used for trigger purpose

- Space (and therefore cost!) is important : the shower length increases only logarithmically with the energy and so the detector thickness should increase only logarithmically the particle energy. Remember that for a magnetic spectrometer, for a fixed momentum resolution, the bending power (BL^2) must increase linearly with p

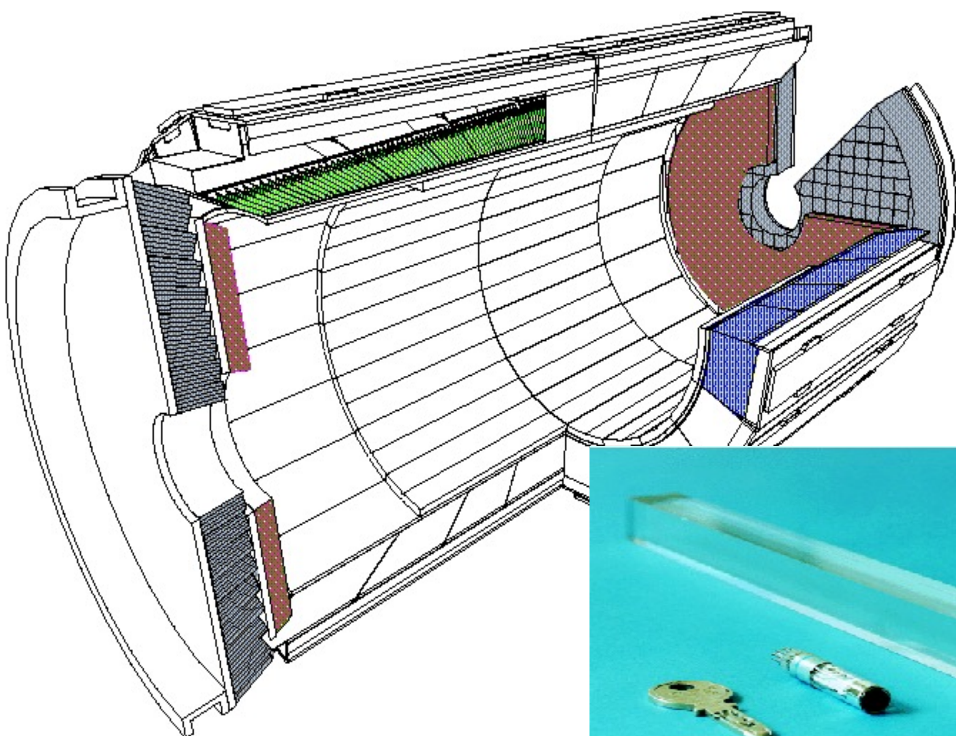
Calorimeters in HEP experiments

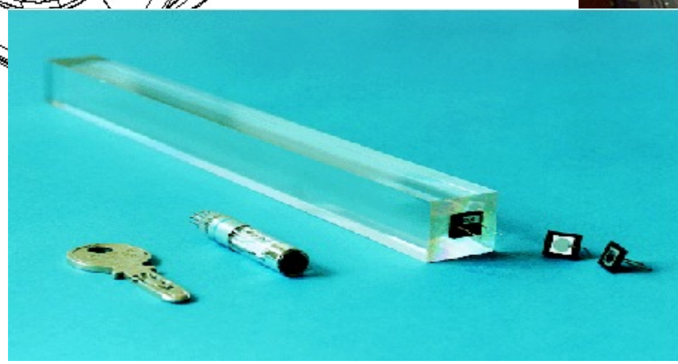


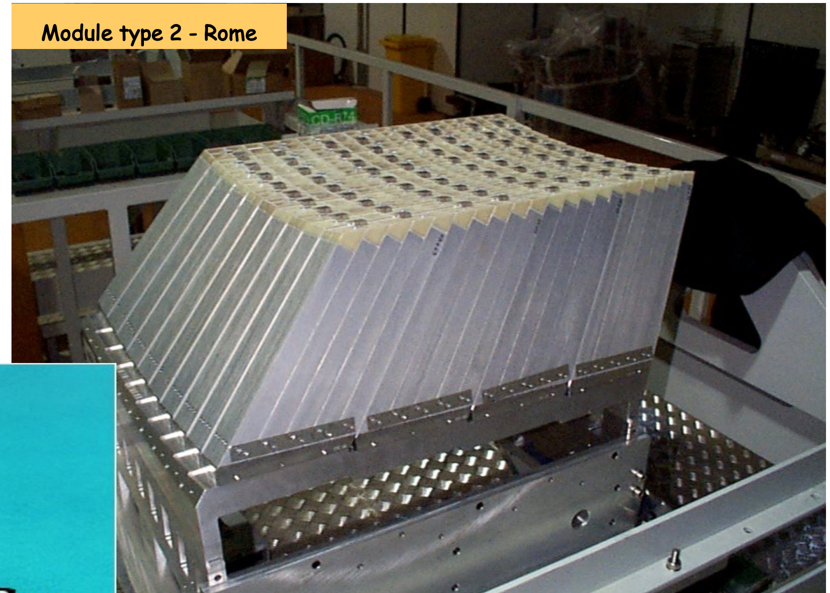
CMS choice: homogeneous crystal calorimeter

- Compact : longitudinal 25 X0 = 22.2 cm
- Transverse segmentation :1 RM = 2.2 cm. 95% of the shower contained in 2 RM

Material	X_0/cm	Ec/MeV	R_M/cm
Fe	1.8	22	1.7
Lead	0.56	7.4	1.6
$PbWO_4$	**0.89**	**8.5**	**2.2**

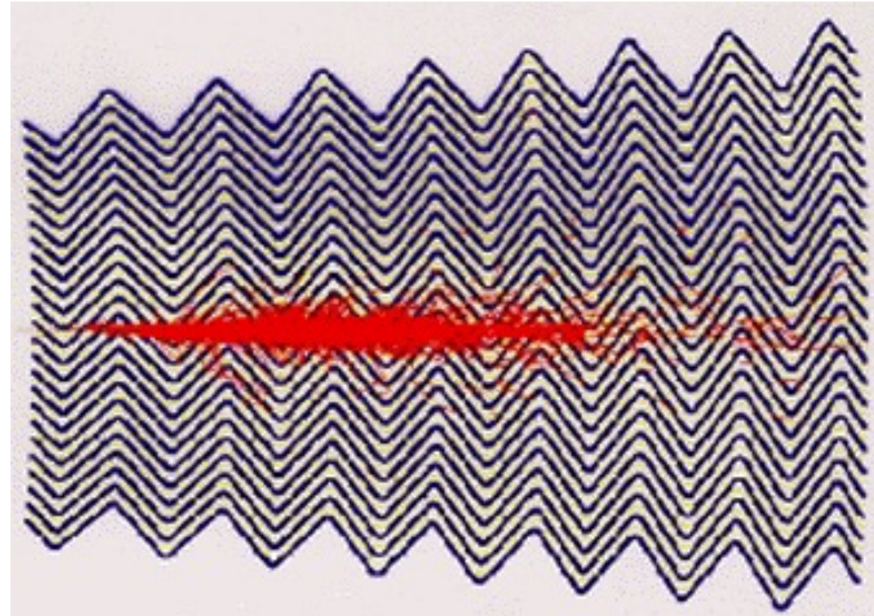


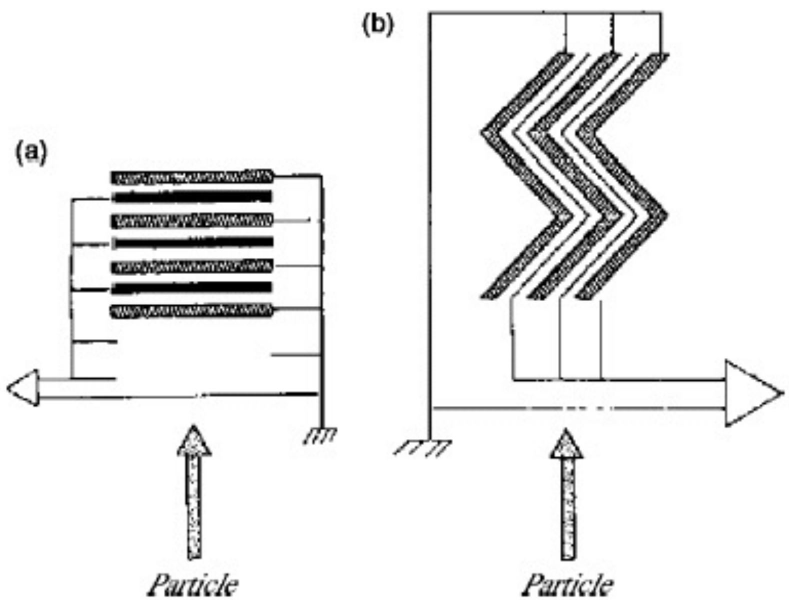


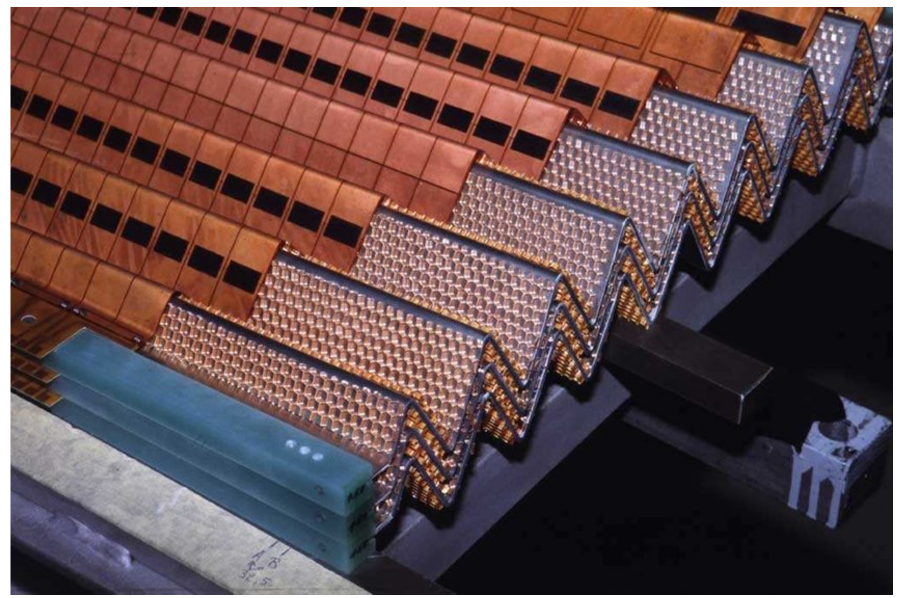


The ATLAS accordion EM calorimeter

- The ATLAS electromagnetic calorimeter is a lead–liquid Argon sampling calorimeter with an accordion geometry
- The 'accordion' geometry allows a full coverage in the azimutal angle without dead regions of cracks since it's the electrode itself that brings the signal outside.







Energy resolution for real calorimeters in HEP experiment environment

Experiment	Calorimeter	a	c	b
L3	BGO	2.0%	0.7%	
BaBar	CsI (Tl)	(*) 2.3%	1.4%	40 MeV
CMS	$PbWO_4$	3.0%	0.5%	200 MeV
OPAL	Lead glass	(**) 5% (++) 3%		
NA48	Liquid krypton	3.2%	0.4%	90 MeV
UA2	Pb /Scintillator	15%	1.0%	
ALEPH	Pb / Prop. chambers	18%	0.9%	
ZEUS	U / Scintillator	18%	1.0%	
H1	Pb / Liquid argon	12.0%	1.0%	150 MeV
D0	U / Liquid argon	16.0%	0.3%	300 MeV
ATLAS	Pb / Liquid argon	10.0%	0.4%	200 MeV

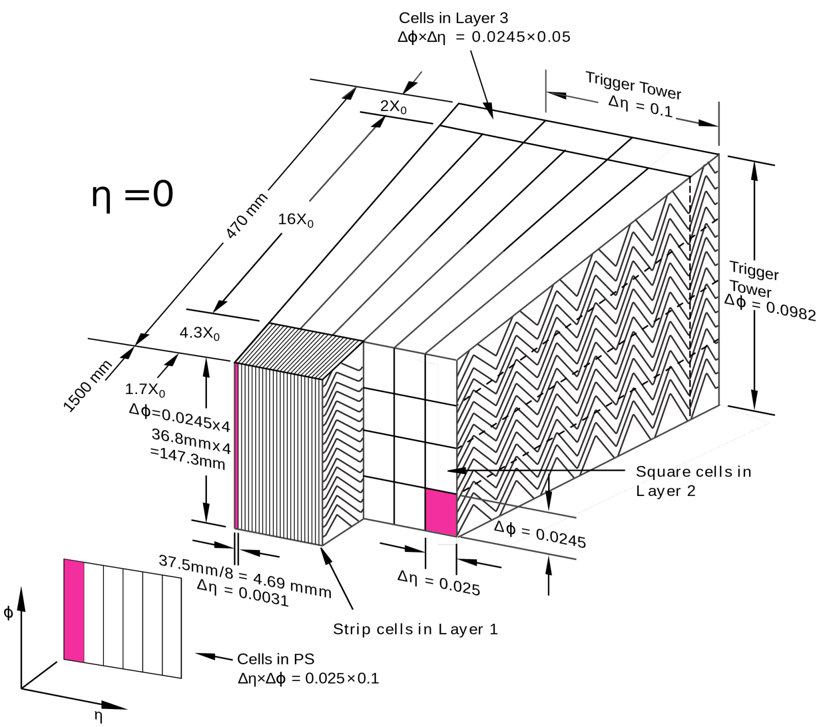
homogeneous calorimeters (L3 – NA48)

sampling calorimeters (UA2 – ATLAS)

Calorimeter segmentation: photon identification

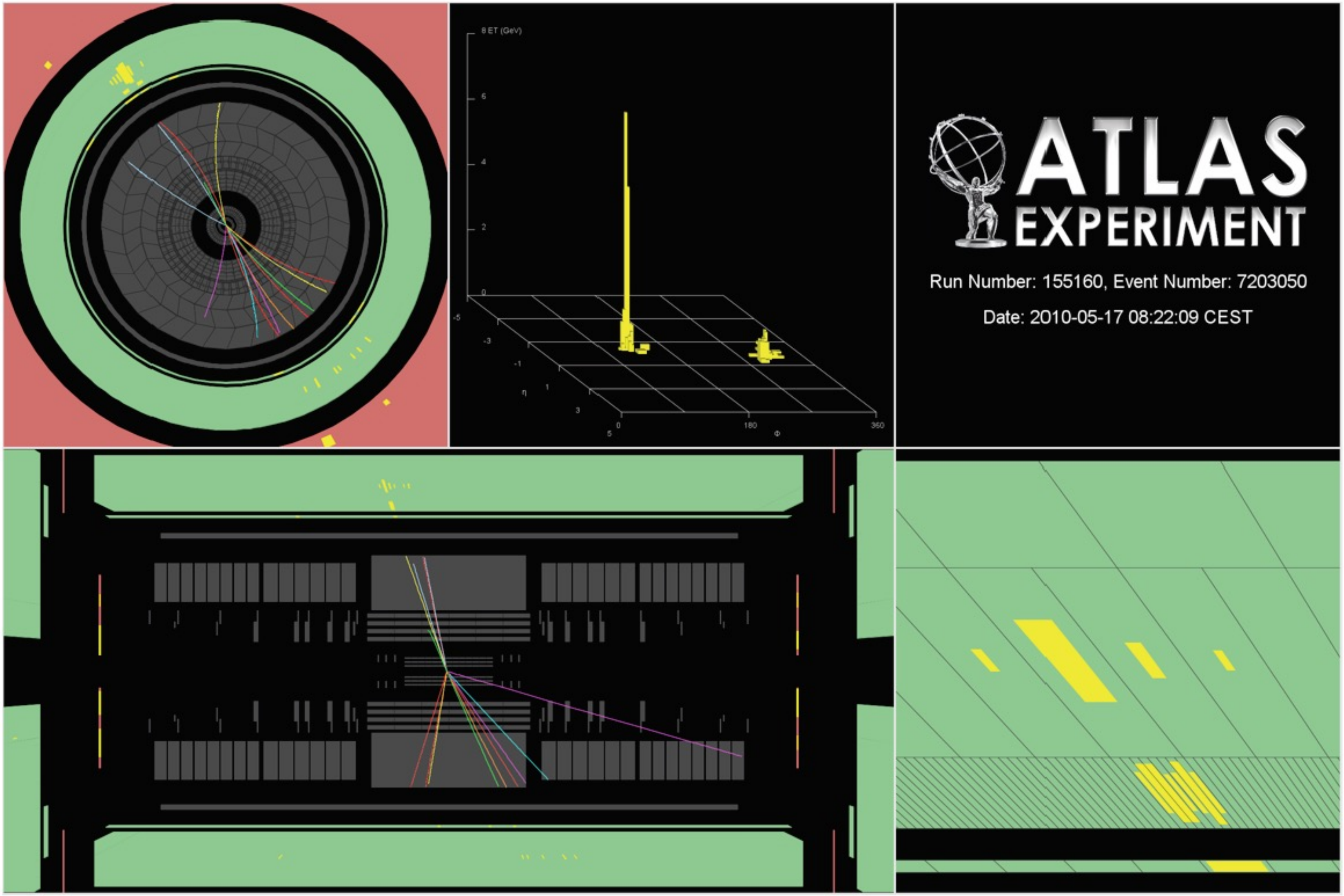
Need to reduce the probability that a different particle can be reconstructed as a photon: exploit the features of the calorimeter to reject fake photons

- Use information from calorimeter cells to discriminate candidates with a shower development compatible with the one from a photon
- Calorimeter segmentation (longitudinal and lateral) is the key item here



Category	Description	Name	Loose	Tight
Acceptance	$\|\eta\| < 2.37$, $1.37 < \|\eta\| < 1.52$ excluded	–		✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| > 0.8$ and $\|\eta\| < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio in η of cell energies in 3×7 versus 7×7 cells	R_η	✓	✓
	Lateral width of the shower	w_2	✓	✓
	Ratio in ϕ of cell energies in 3×3 and 3×7 cells	R_ϕ		✓
EM Strip layer	Shower width for three strips around maximum strip	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\text{tot}}$		✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	Difference between the energy of the strip with the second largest energy deposit and the energy of the strip with the smallest energy deposit between the two leading strips	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

A nice π^0 candidate

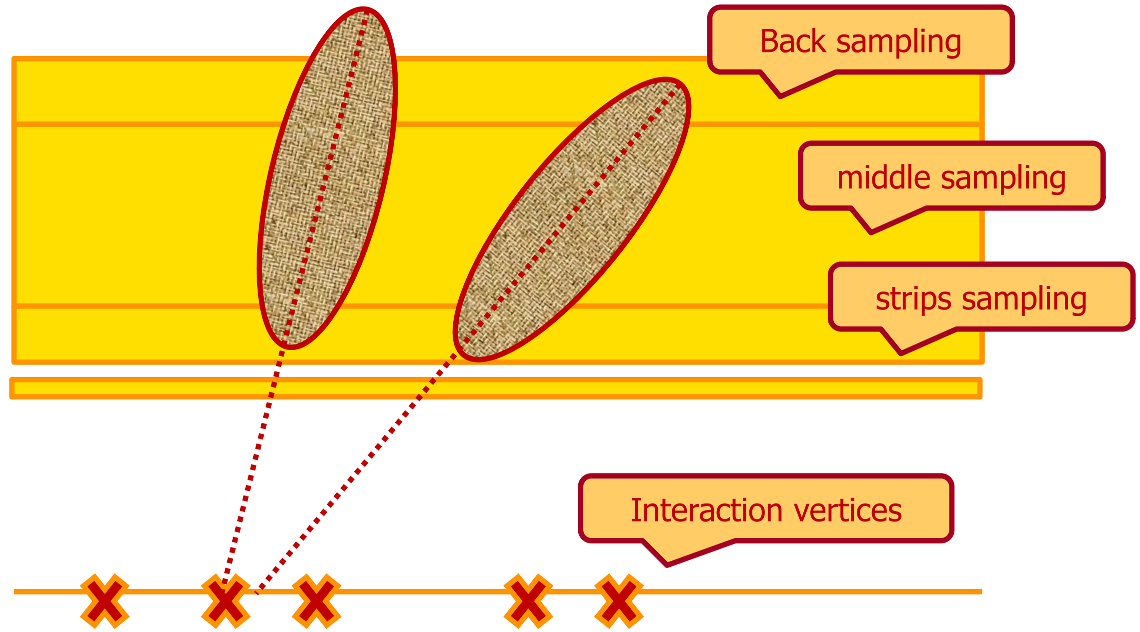


Calorimeter segmentation: primary vertex reconstruction

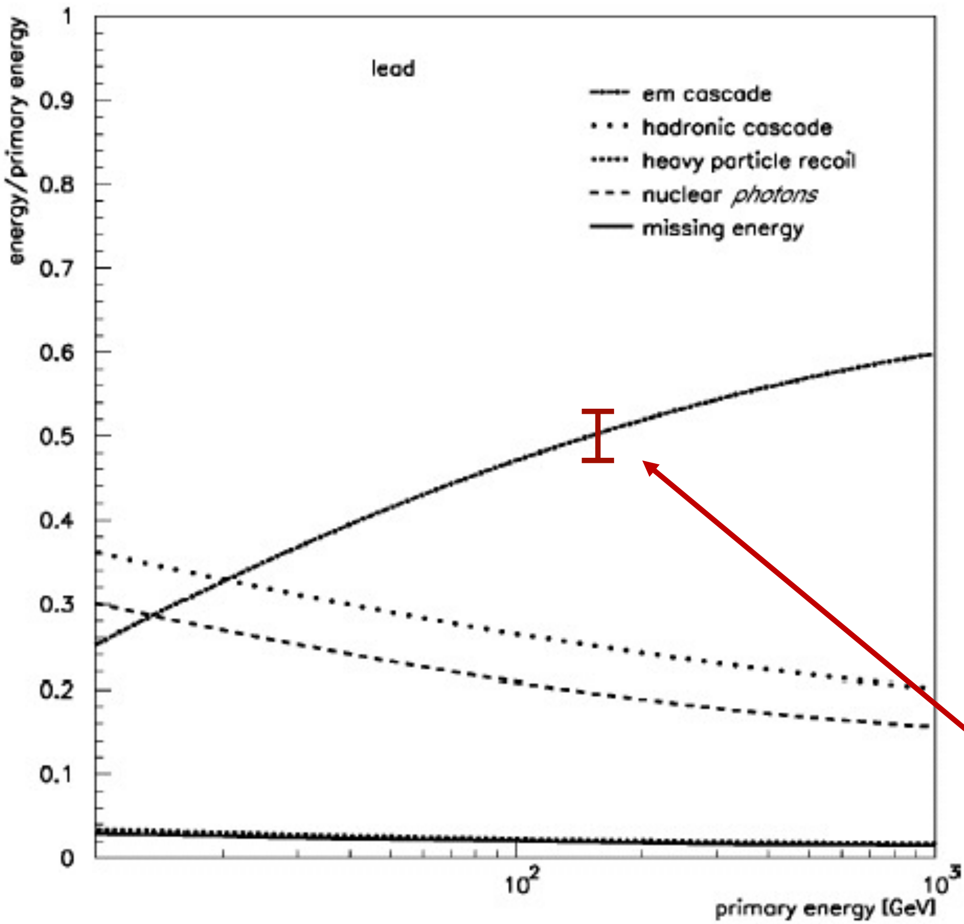
- Reconstruct the di-photon invariant mass from measured photon energies and opening angle between the two photons

$$m_{\gamma\gamma} = 2E_{\gamma_1}E_{\gamma_2}\left[1 - \cos(\theta(\gamma_1, \gamma_2))\right]$$

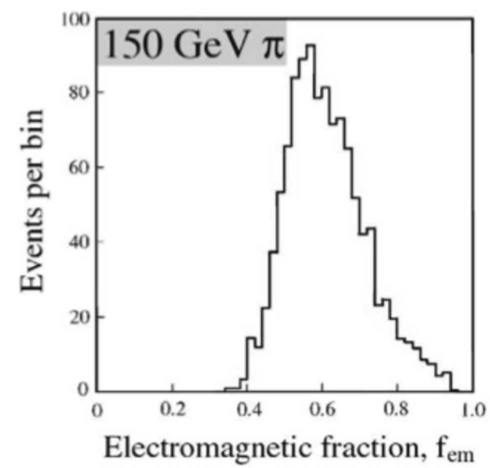
- Precise determination of the photons energy from a good calorimetric measurement
- Opening angle measurement requires the precise determination of the primary vertex
- Segmented calorimeter allows the standalone determination of the primary interaction vertex
  - from the barycenter of the shower developments in the compartments the photon direction can be extrapolated
  - opening angle resolution contribution to the mass resolution is negligible



Issues with hadronic calorimeters



- ❑ Issue #1: 20-40% of the incoming particle energy is 'invisible' (nuclear delayed photons, doesn't not contribute to the signal). Typically, the calorimeter response to hadrons is lower than the one to e/γ
- ❑ Issue #2: in a hadronic shower there's an energy-dependent fraction of em-component.
  - ❑ Potential issue for the linearity
  - ❑ Fluctuations in this component introduce a source of additional resolution increase



R. Wigmans, EDIT, CERN, 2011

Compensation for hadronic calorimeters

- In a hadron shower typically we have a hadronic and an electomagnetic component

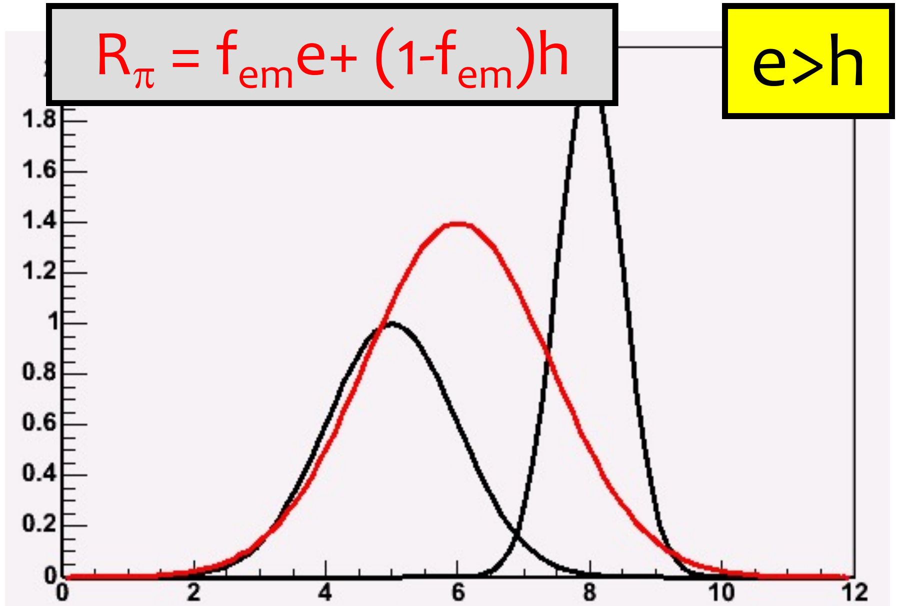
- The calorimeter response to e (EM response) is larger than h (HAD response) ('invisible' energy)

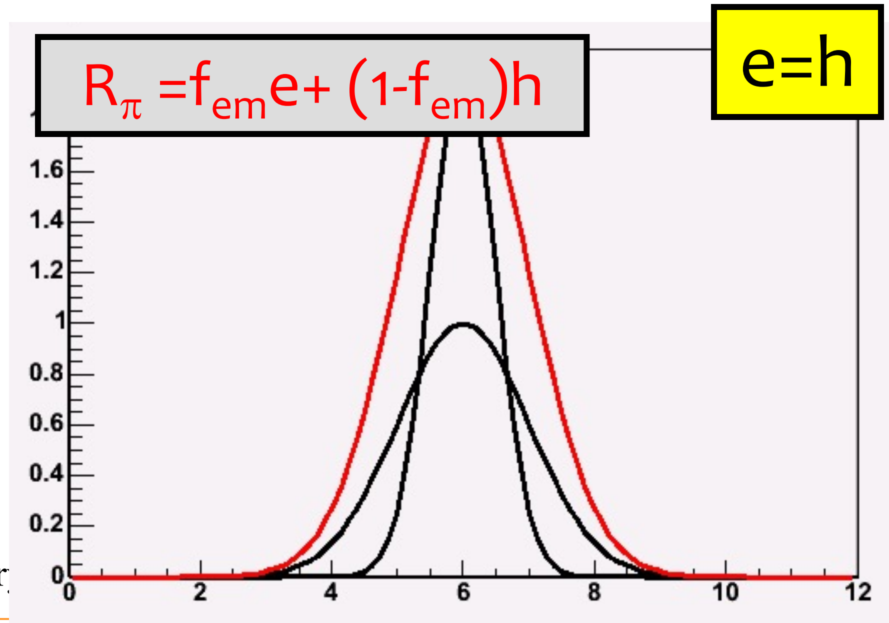
- Calorimeter response to a real pion:

$$R_\pi = (f_{em} e + (1 - f_{em})h) = f_{em}(E)(e - h) + h$$

- Linearity of pions response requires e~h (compensation!) for which the energy dependent term $f_{em}(E)$ is cancelled

- At the same time resolution also benefits from compensation: no sensitivity to fluctuation in the em fraction (the calorimeter responds in the same way !)





Compensation : linearity

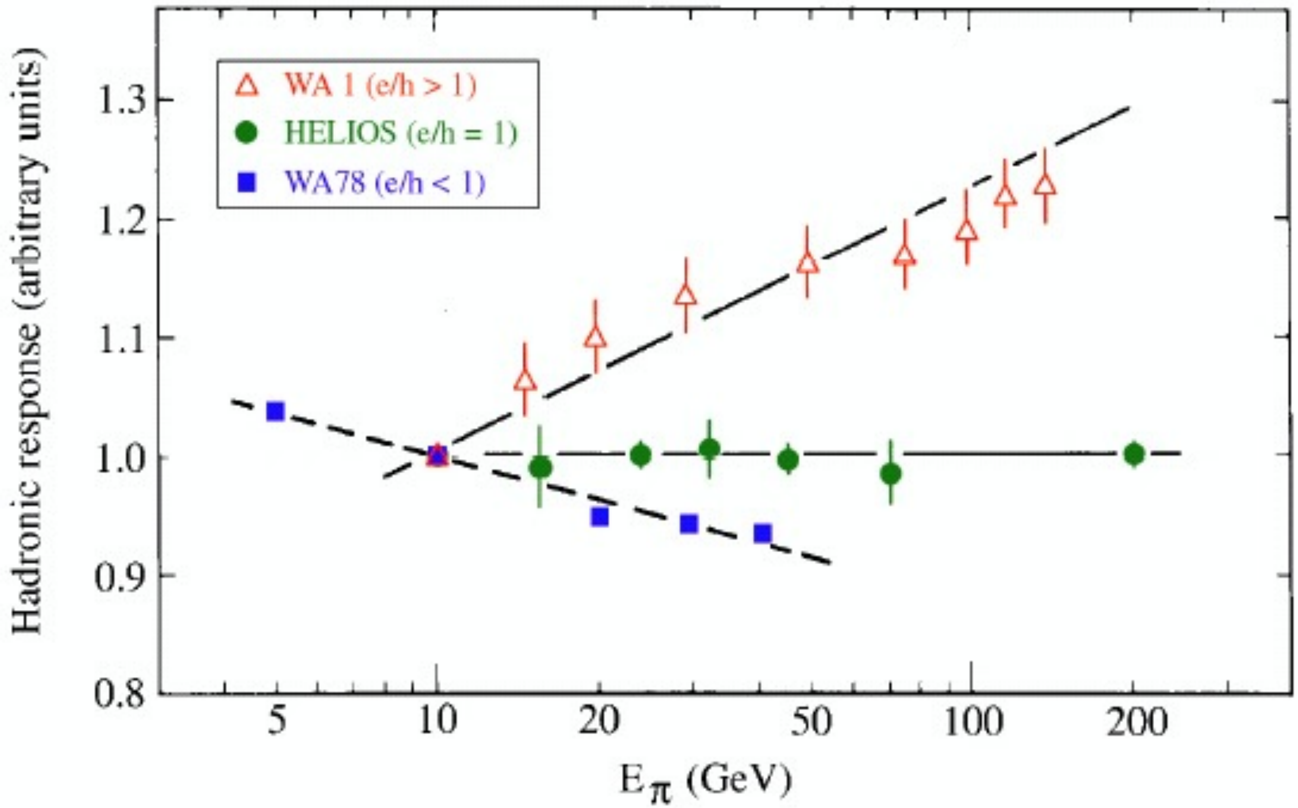


FIG. 3.14. The response to pions as a function of energy for three calorimeters with different e/h values: the WA1 calorimeter ($e/h > 1$, [Abr 81]), the HELIOS calorimeter ($e/h \approx 1$, [Ake 87]) and the WA78 calorimeter ($e/h < 1$, [Dev 86, Cat 87]). All data are normalized to the results for 10 GeV.

Energy resolution in calorimeters

The energy resolution depends on the fluctuation on the measured signal for a given incoming particle energy

- Homogeneous calorimeters :
  - Shower fluctuations (fluctuation on the generation of the signal quanta)
  - Photo-electron fluctuations (in case of scintillating detectors)
  - Shower longitudinal and lateral leakage
  - Instrumental effects (i.e.: structural non-uniformity, electronic noise, light attenuation , …)
- Sampling calorimeters (in addition):
  - Sampling fluctuations
  - Landau fluctuations and track length fluctuations (gas calorimeters)
- Hadronic calorimeters (in addition) :
  - Fluctuation in the invisible energy (ultimate limit for hadronic energy resolution)
  - Fluctuations in the electromagnetic fractions (main contribution in non-compensating calorimeters)

Energy resolution for real calorimeters in HEP experiment environment

Experiment	Detectors	Absorber material	*e/h*	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%$*
D0	liquid Ar	U	1.11	$48\%/\sqrt{E} \oplus 5\%$*
H1	liquid Ar	Pb/Cu	≤ 1.025*	$45\%/\sqrt{E} \oplus 1.6\%$
CMS	Scintillator	Brass (70% Cu / 30% Zn)	$\neq 1$	$100\%/\sqrt{E} \oplus 5\%$
ATLAS (Barrel)	Scintillator	Fe	$\neq 1$	$50\%/\sqrt{E} \oplus 3\%$**
ATLAS (Endcap)	liquid Ar	Brass	$\neq 1$	$60\%/\sqrt{E} \oplus 3\%$**

Only for curious kids

How to achive compensation:

Need to examine carefully energy deposition mechanisms relevant for the absorption of the non-EM shower energy:

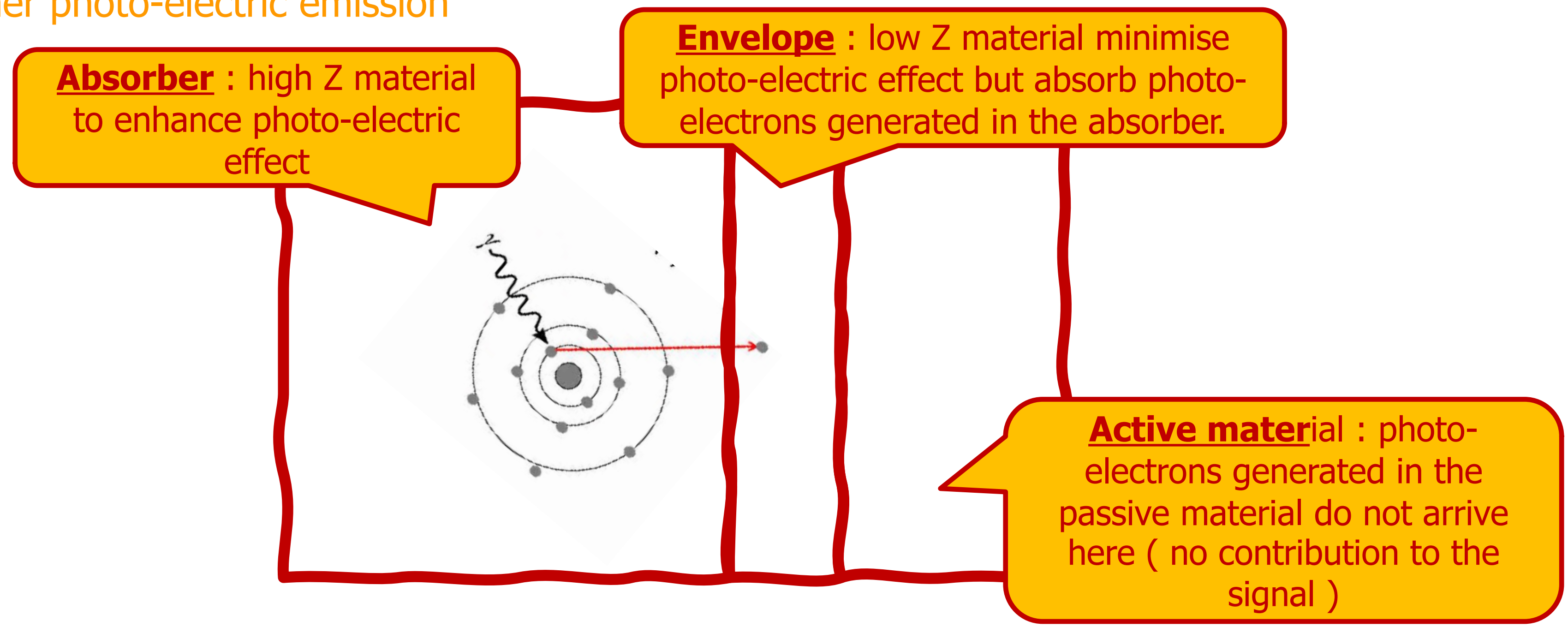
- Ionization by charged pions f_{rel} (Relativistic shower component).
- spallation protons f_p (non-relativistic shower component).
- Kinetic energy carried by evaporation neutrons f_n
- The energy used to release protons and neutrons from calorimeter nuclei, and the kinetic energy carried by recoil nuclei do not lead to a calorimeter signal. This is the invisible fraction f_{inv} of the non-em shower energy

$$\frac{e}{h} = \frac{e/mip}{f_{rel} rel/mip + f_p p/mip + f_n n/mip + f_{inv} inv/mip} =$$

Normalize to a common reference (mip), an ideal particle which only looses energy through collisions

How to achive compensation: manipulate e/mip

- Reduce the electron response:
  - use absorbers with high Z to enhance the photo-electric effect (low energy photons captured in the absorber do not contribute to the signal)
  - Increase the absorber size (reduce sampling frequency) : photo-electrons that contribute to the signal is minimized
  - Shielding the active layers with thin sheets of passive low-Z material (iron): capture photo-electrons so that they do not contribute to the signal in the active layers. Being low-Z no further photo-electric emission



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How to achive compensation: the role of neutrons

- Boost hadronic response through neutrons response manipulation (main handle!): assuming the number of neutrons (measured through their total kinetic energy) is correlated to the invisible energy one can enhance the neutron response (n/mip) to compensate.
  - active material has to contain hydrogen: loss of kinetic energy of soft neutrons through elastic scattering with the hydrogen nuclei: the neutron energy will go to active material (only a little in the passive high A material)
    - Recoil Protons are absorbed locally: direct contribution to calorimeter signal.
  - Increasing the absorber size (for a fixed active material layer) so decreasing the sampling fraction (and therefore the sampling frequency) will reduce the mip response only (neutrons will not deposit energy in the absorber anyway), effectively regulating n/mip : need a well tuned and specific (typically small) sampling fraction to achieve compensation.
  - Time structure of the collected signal: neutron energy released to protons arrives after a certain time (the time needed to a few MeV neutron) to encounter a proton.

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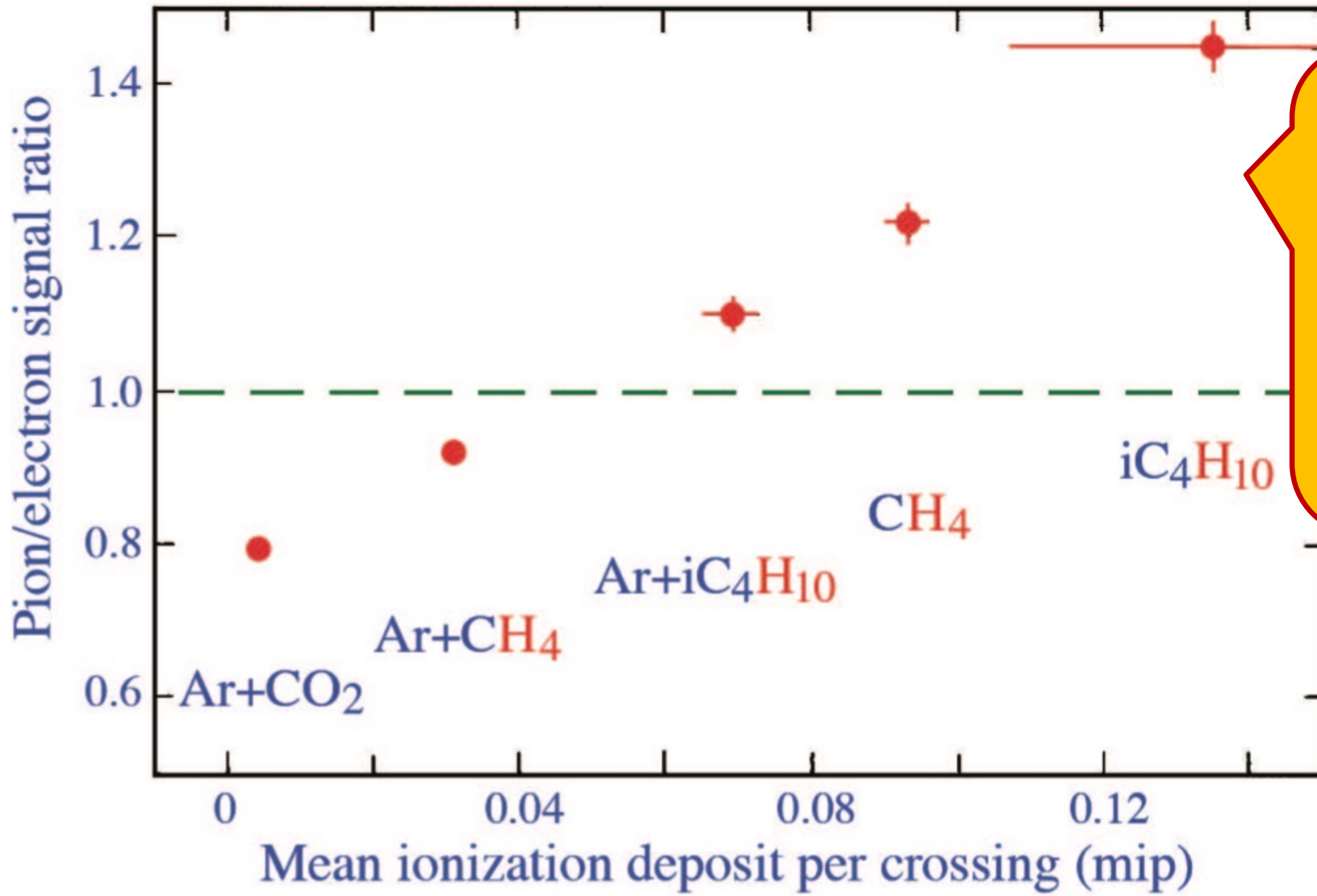
How to achive compensation: the role of neutrons



Pion/electron response ratio in the L3 uranium/gas calorimeter as a function of the hydrogen content of the gas mixture.

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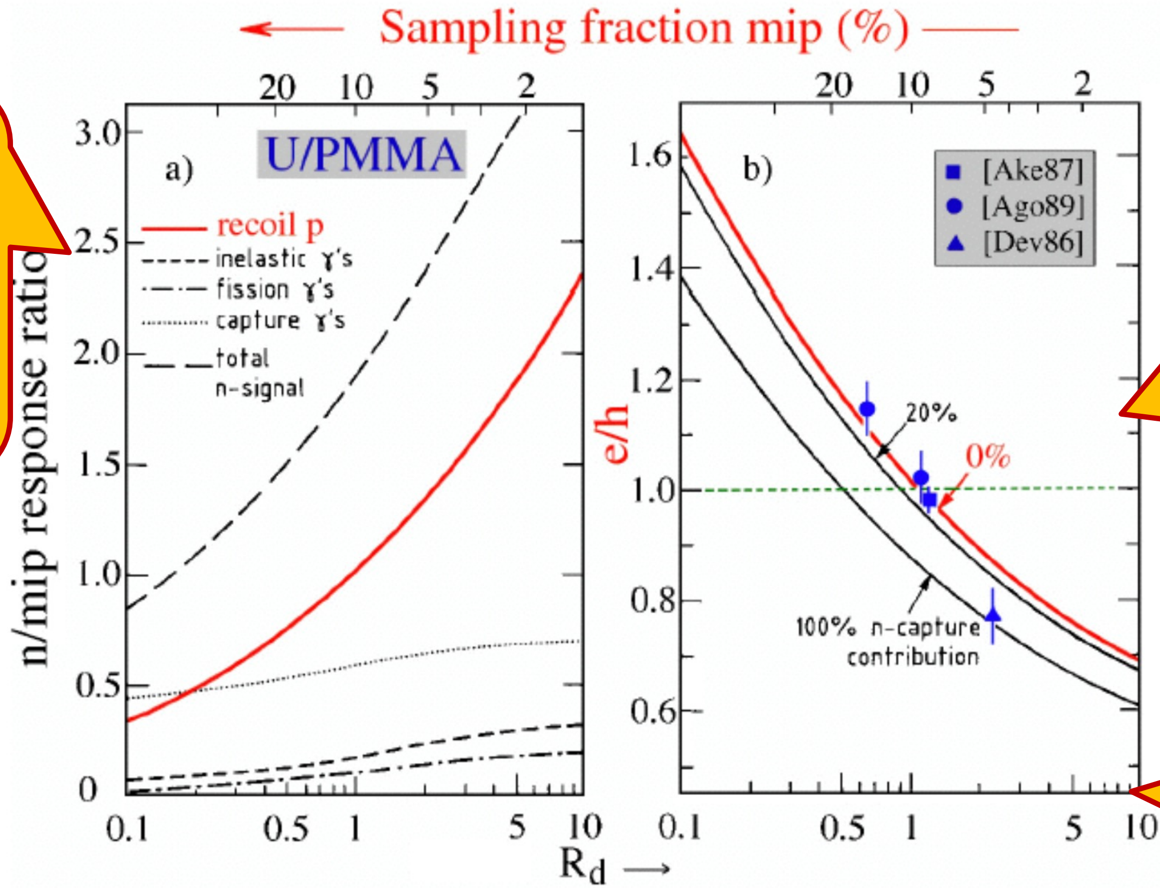
How to achive compensation: the role of neutrons

Increasing the absorber thickness reduces the mip response but has no effect on neutrons effectively amplifying n/mip



Increasing R_d (reducing sampling fraction) results in a decrease of e/h. Compensation can be achieved by tuning the sampling fraction !

R_d = ratio between passive and active material

FIG. 3.39. The n/mip response ratio, split up into its components, for ^{238}U/PMMA calorimeters, as a function of R_d, the ratio of the thicknesses of the passive and active calorimeter layers (a). The e/h ratio as a function of R_d, assuming that 0%, 20% or 100% of the γs released in thermal neutron capture contribute to the calorimeter signals (b). The top axis of both graphs indicates the sampling fraction for mips. From [Wig 88].

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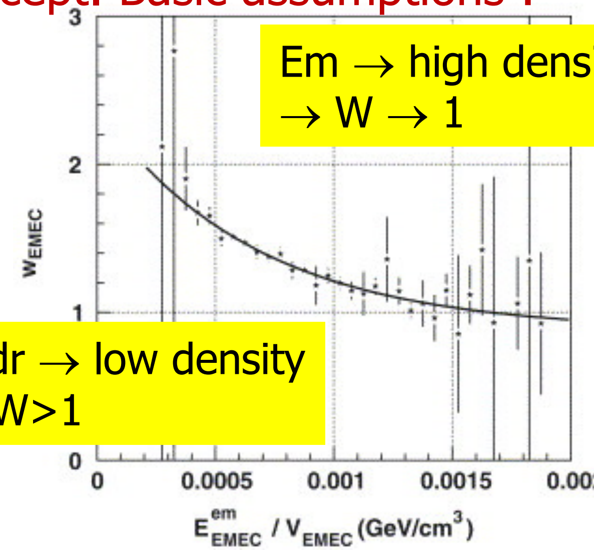
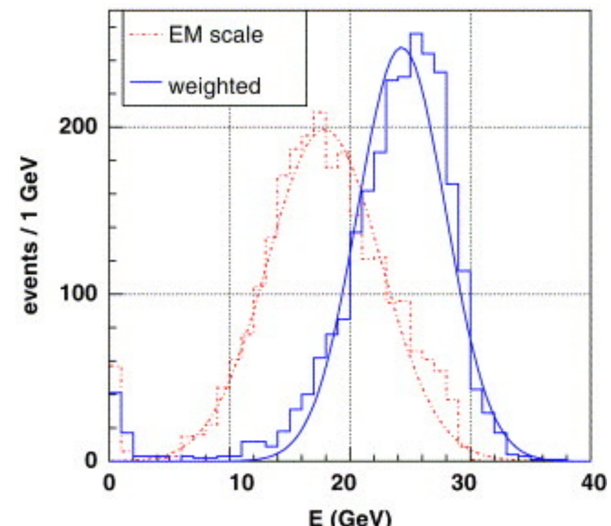
How to achive compensation: offline weighting

- Simple offline approach based on the energy density concept. Basic assumptions :
  - High energy density : EM deposit
  - Low energy density : HAD deposit
- When reconstructing an hadronic shower try to look into its insternal structure: typically a shower is reconstructed from several calorimeter cells
- Weights each cell differently to recover for eventual intrinsic non compesation of the calorimeter



$$E_{corr}\,(\text{cell}) = W(E,\ldots)\,E_{reco}(\text{cell})$$
$$W = c_1 \exp(-c_2\, E_{rec}/V) + c_3$$



- Effect on real pions resolution

$$\sigma/E = 26.2\,\% \rightarrow 15.1\%$$

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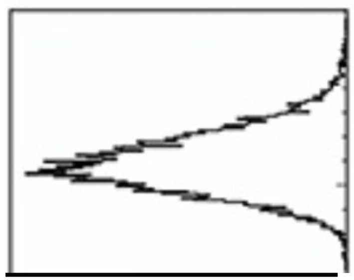
How to achieve compensation: the DREAM approach

Let's imagine a scintillator-based detector: suppose we have calibrated the response to a 200 GeV electrons beam. According to what we have studied we would expect the response of a non-compensating calorimeter to behave in this way as a function of f_{em} for a (fixed !) 200 GeV hadrons beam

$$S = E[e f_{em} + (1 - f_{em})h] = E + E\left(\frac{e}{h} - 1\right) f_{em}$$



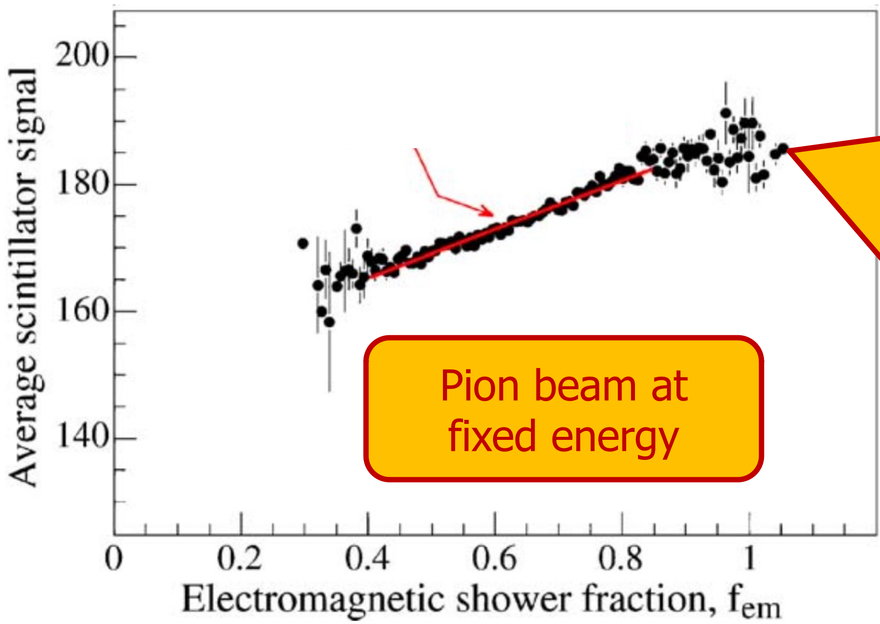


Fig. 27. The average (leakage-corrected) scintillator signal for 200 GeV jets, as a function of the em shower fraction, f_{em}.

If we could measure f_{em} on an event-by-event basis, we could correct the response S to:

1. Improve the resolution for a fixed energy (dump f_{em} fluctuations)
2. Improve the linearity !

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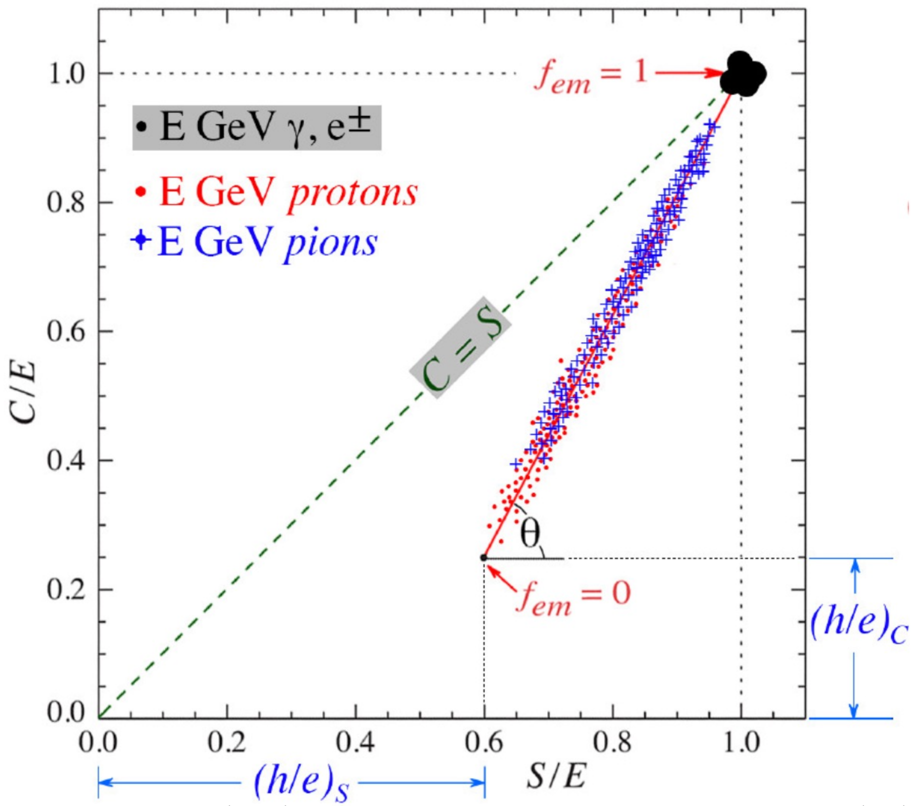
How to achieve compensation: the DREAM approach

Dual-readout calorimetry: each hadronic shower is measured in two nearly independent ways. Two independent media:

- Scintillating fibers (S) react to all charged particles of the shower
- Cherenkov fibers (C) react to the relativistic particles which are predominately the electrons and positrons from the γ-initiated showers from π^0 decay



$$S = E[f_{EM} + (1 - f_{EM})(h/e)_s]$$

$$C = E[f_{EM} + (1 - f_{EM})(h/e)_c]$$

$(h/e)_s = s$, $(h/e)_c = c$

$$f_{EM} = \frac{c - s\,(C/S)}{(C/S)(1-s) - (1-c)}$$

$$E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1-s}{1-c} = cotg(\theta)$$

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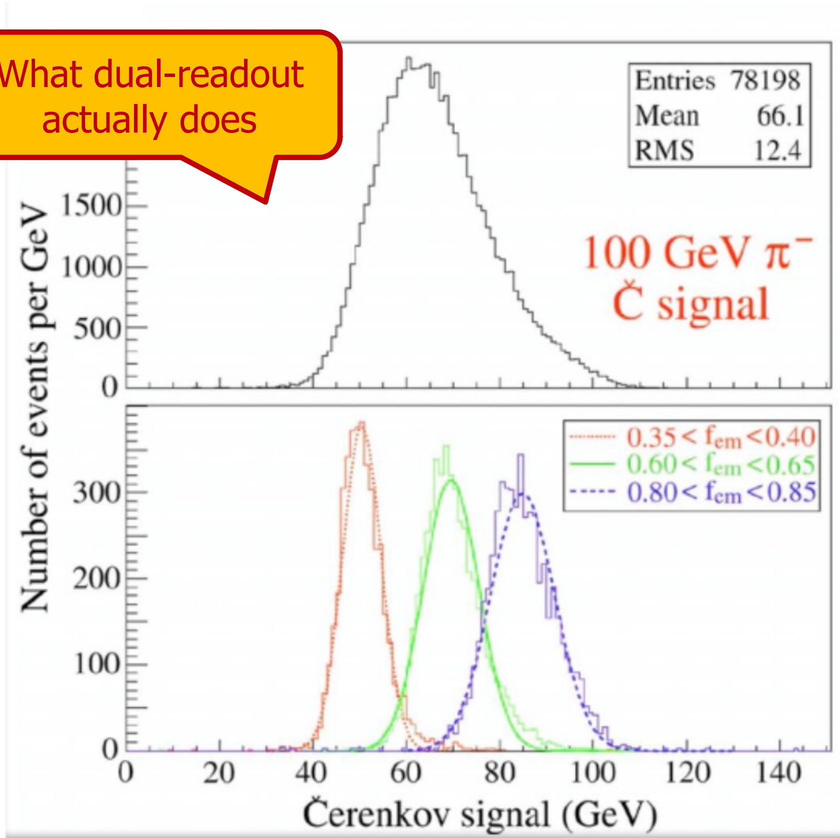
How to achieve compensation: the DREAM approach

Dual-readout calorimetry : each hadronic shower is measured in two nearly independent ways. Two independent media:

- From the two measurements one can extract (event-by-event) the value of f_{em} and correct the response to reduce the fluctuations on f_{em}

What dual-readout actually does



- Calibrate the response of S and C on electrons
- Measure $(h/e)_{S/C}$ from signal (S and C) correlation with f_{EM} with fixed energy hadron beams
- Solve the system of equations above and write E and f_{EM} as a function of S and C : the hadron energy E is effectively corrected event by event for f_{EM} !

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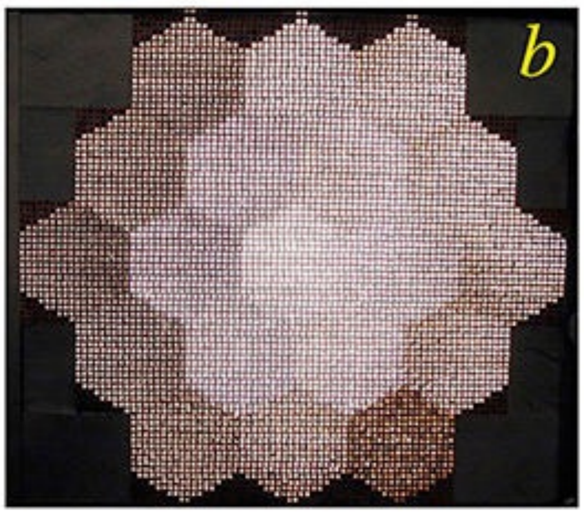
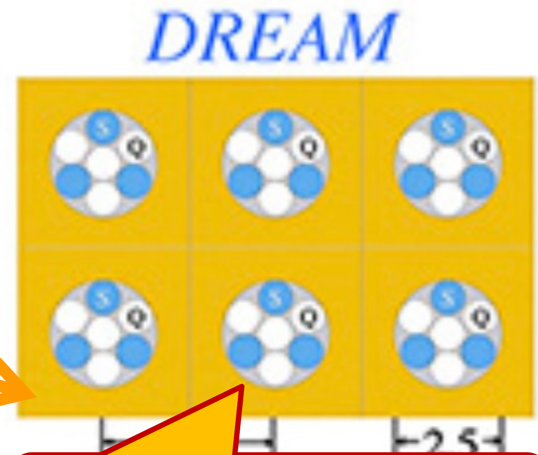
How to achieve compensation: the DREAM and RD52 prototypes

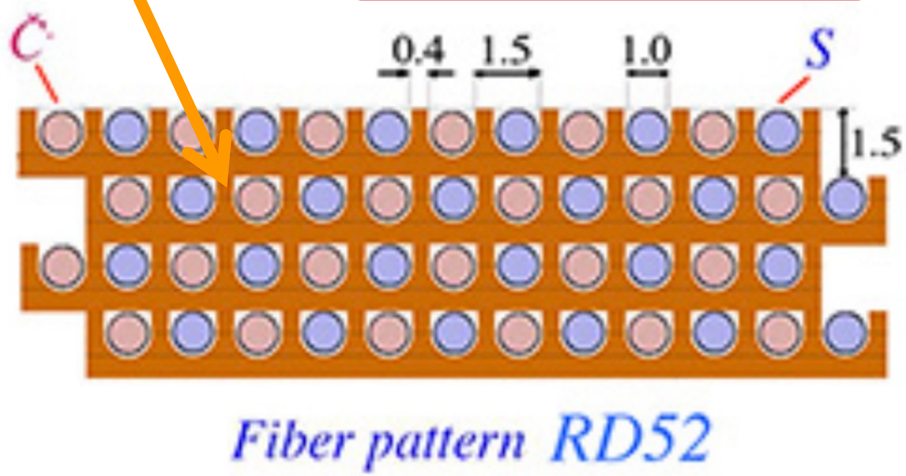
DREAM calorimeter



Copper is used as absorber in both cases

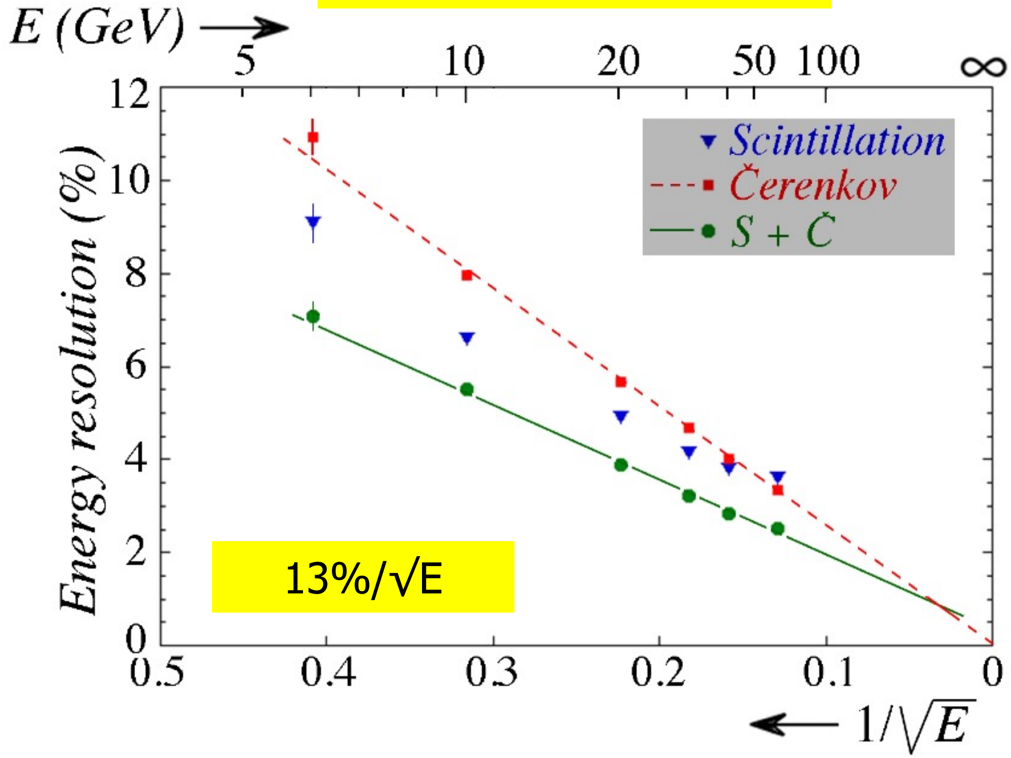


Scintillating and quarz (Cherenkov) fibers

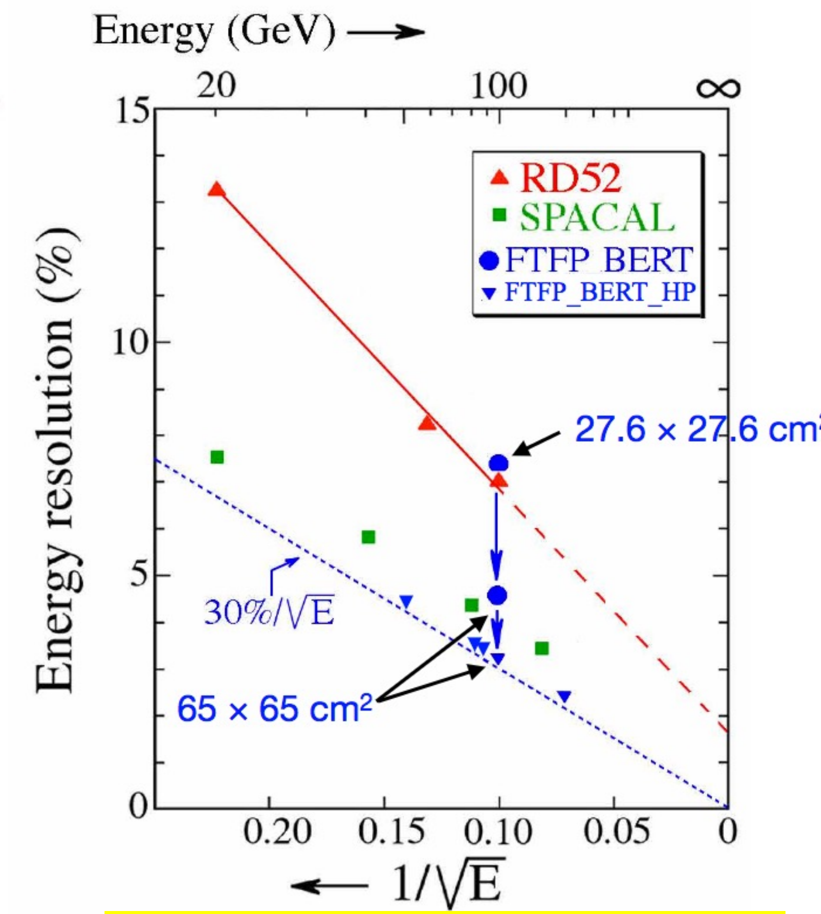


How to achieve compensation: the DREAM and RD52 prototypes

Response to electrons



Response to hadrons



Linearity within 1% for both EM and Had response

70%/√E : could achieve 30%/√E with a larger size calorimeter

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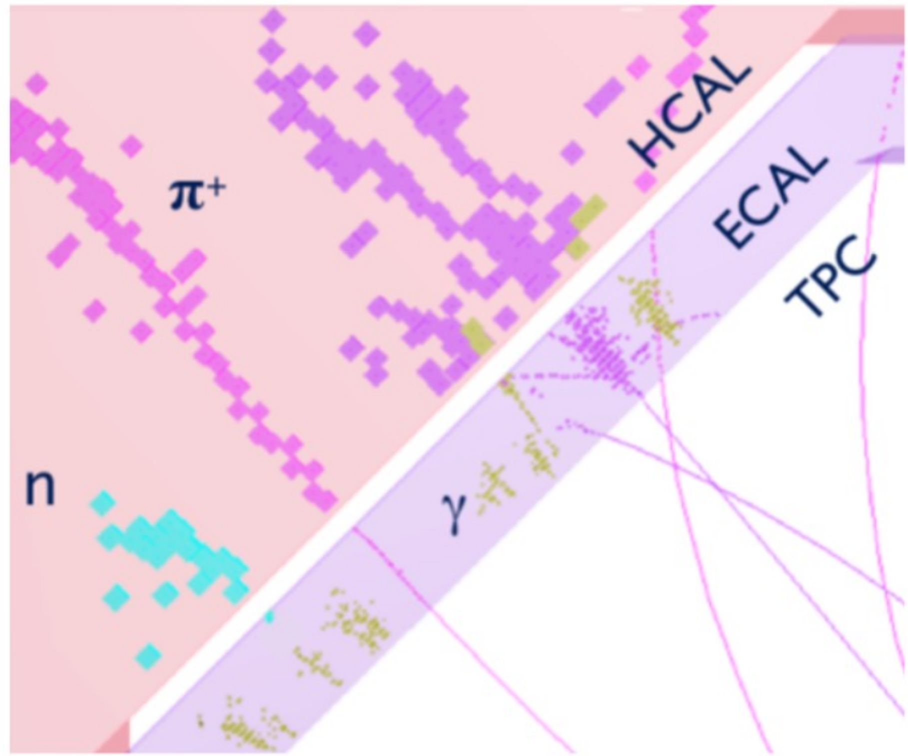
Improving energy resolution: particle flow and the High Granularity Paradigm

- At hadron colliders typically one measures jets (group of hadrons) instead of single hadrons
- To improve the jet reconstruction, measure every single particle combining the information from tracking, electromagnetic and hadron calorimeters

Typical jet of hadrons composition

- Charged hadrons (70%) : use the tracker ($\sigma(p_T)/p_T \sim 1\%$)!
- Photons (20%) use the EM calorimeter ($\sigma(E)/E \sim 10\%/\sqrt{E}$)
- Neutral hadrons (10%) use the hadron calorimeter ($\sigma(E)/E \sim 60\%/\sqrt{E}$ but only for 10% of the jet composition)
- Main challenge is the correct resolution of different showers in the jet and the association with tracks (granularity !)

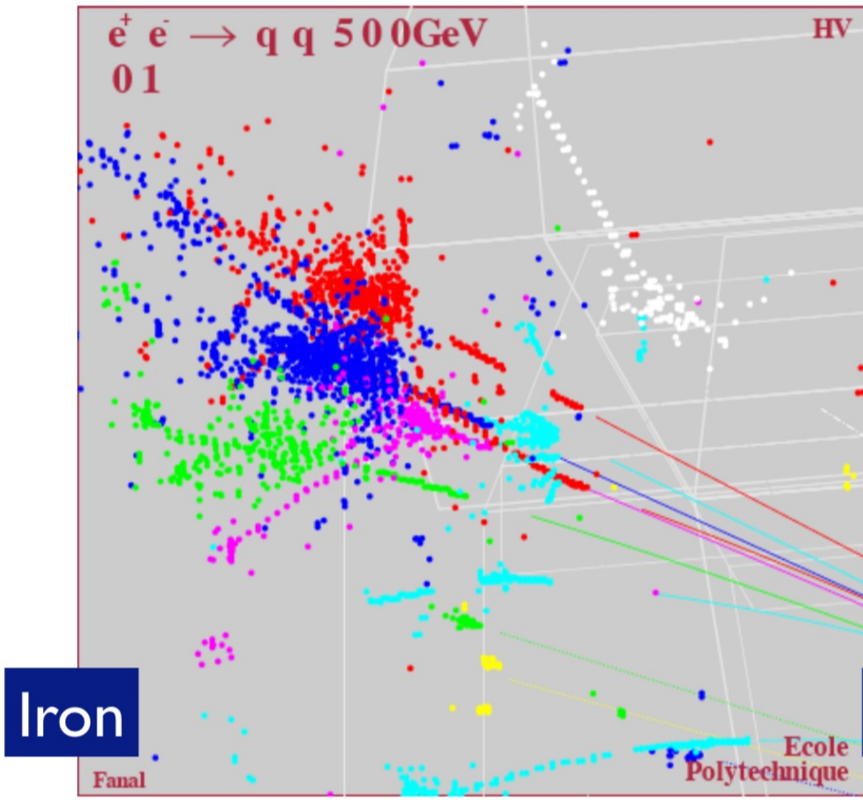


Only for curious kids

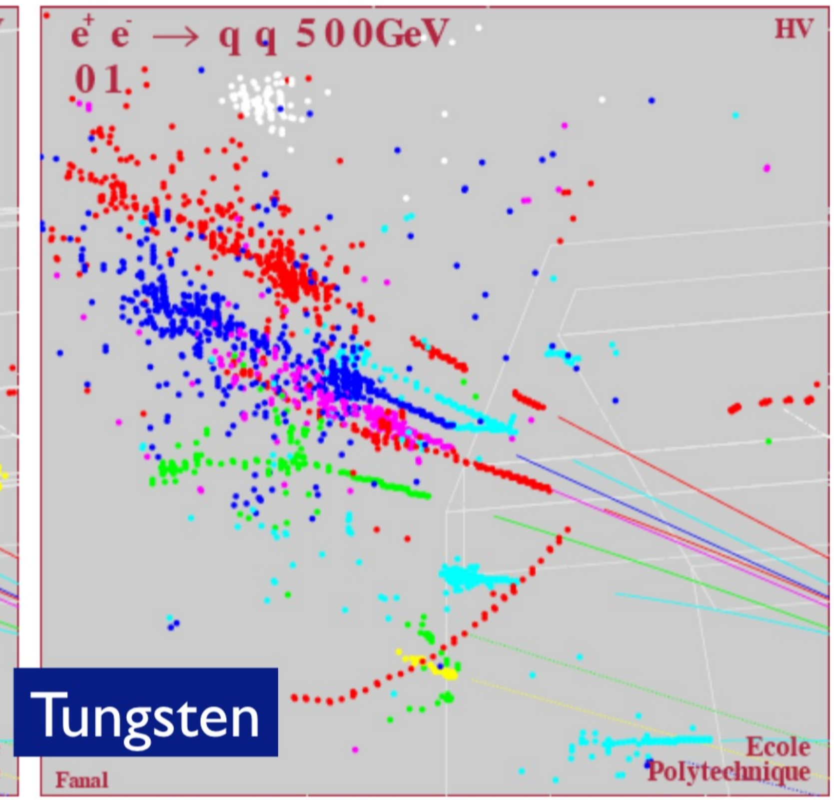
How to achieve compensation: particle flow and the High Granularity Paradigm

- R&D for future accelerators calorimeters : make shower narrower and increase the granularity (CALICE). Granularity more important than energy resolution ?
  - Digital calorimeters concept: 1cm^2 pads, 40 layers, 0.5 M readout channel per m^3 of active volume

X_0 = 1.8 cm, λ_I=17 cm



X_0 = 0.35 cm, λ_I=9.6 cm



A tentative summary

- Calorimeters have peculiar features that make them very attractive for particle physics experiments
  - Resolution improves with energy, shower max growth logarithmically with the energy…
- Homogeneous calorimeters: one block of material serves as absorber and active medium at the same time scintillating crystals with high density and high Z
  - Advantages:
    - Makes use of all energy deposits => best statistical precision
  - Disadvantages
    - cost and limited segmentation, radiation hardness
- Sampling calorimeter: use different media, a high-density absorber interleaved with active readout devices.
  - Advantages:
    - Relatively low cost, transverse and longitudinal segmentation, radiation hardness
  - Disadvantages:
    - Only part of shower seen, less precise, more fluctuations
- Sampling calorimeters are used for (jets of) hadrons energy measurements :
  - Compensation is the key element, intensive R&D program. Role of granularity ?

Short biblio

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- R.Wigmans: “Calorimetry, Energy Measurement in Particle Physics”, Oxford University press
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- Particle Data book
- ATLAS & CMS Technical Design Reports

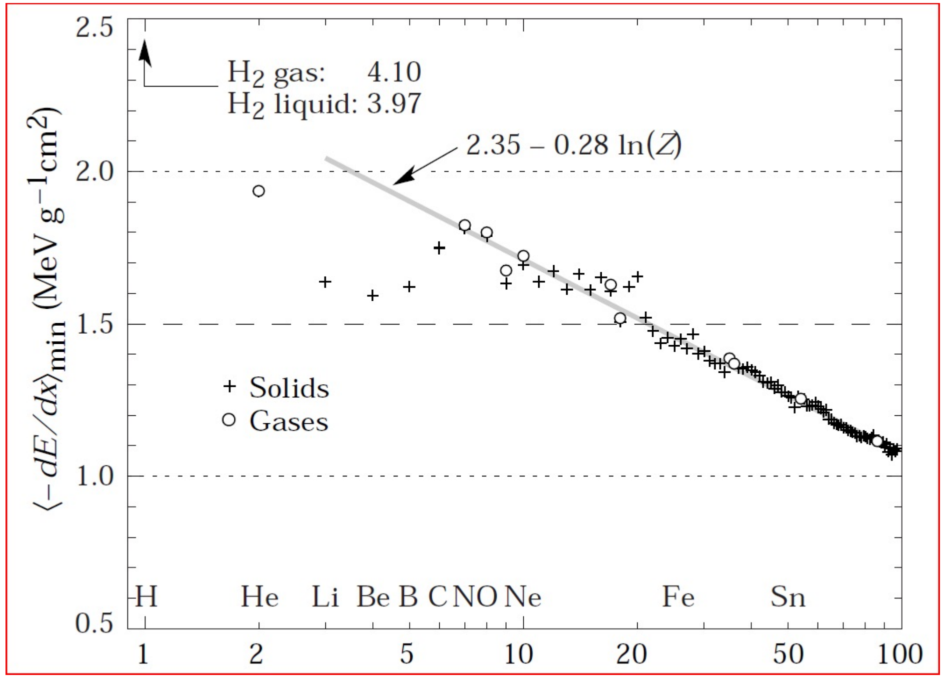
BACKUP

Bethe-Block formula : minimum ionization loss

- particles of the same velocity have similar rates of energy loss in different materials; there is a slow decrease in the rate of energy loss with increasing *Z*

- In all practical cases, most relativistic particles (*e.g.*, cosmic-ray muons) have mean energy loss rates close to the minimum, and are said to be minimum ionizing particles, or mip's

- For a mip, the velocity doesn't change significantly passing through the material and so the average energy loss is roughly dE/dx ~ 1-2 MeV/(g/cm^2).



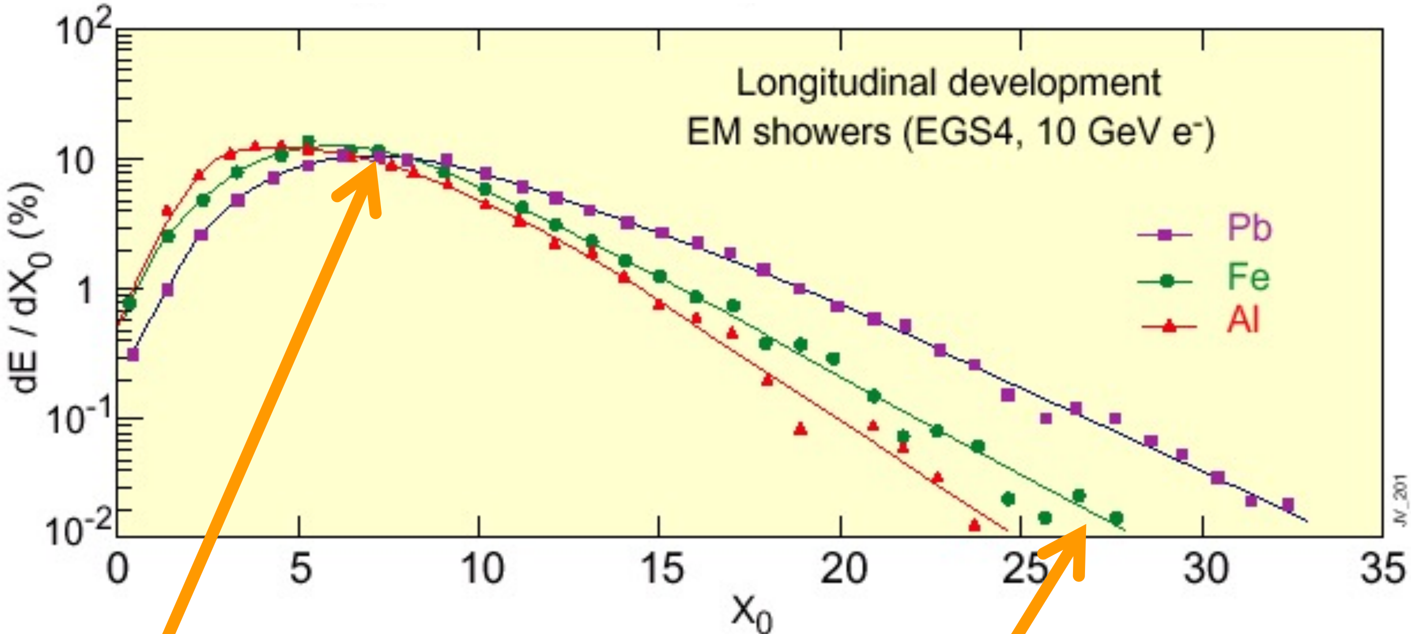
minimum ionization as a function of atomic number

- Ex: for a cosmic muon, the total average energy loss for a layer of thickness x (cm) is simply

$$<\Delta E> = 1\text{-}2 \ \frac{\text{MeV}}{\text{g/cm}^2} \ t\ (\text{g/cm}^2) \qquad t\ (\text{g/cm}^2) = x(\text{cm})\ \rho\ (\text{g/cm}^3)$$

EM showers longitudinal profile : material dependence

More on electromagnetic showers development (although you have to keep in mind that we are reasoning in terms of X_0 and not physical thickness)



1. Shower Max is deeper in Lead than in Aluminium
   - multiplication continues for longer since critical energy is lower in Lead than in Aluminum (7.4 MeV vs 43 MeV) so that the shower max $t_{max} = \ln(E_0/E_c)/\ln(2)$ is deeper in Lead
2. Shower tails much longer (in X_0) in Lead than in Aluminium (see next slide)

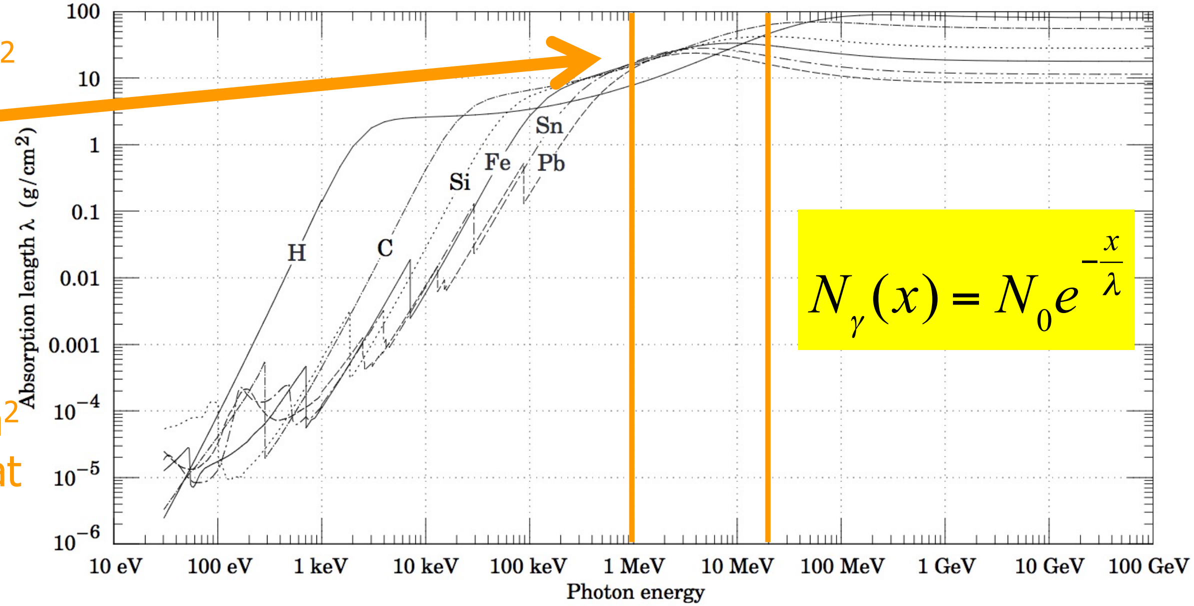
EM showers longitudinal profile : material dependence

After the shower maximum, particle production stops: electrons/positrons and photons will have energies in the ~5-20 MeV range (typical size of the critical energy)

- Electrons and positrons will stop quickly in a layer of ~$1X_0$ by ionization loss.
- Photons (~N_{max}/3) will be absorbed by phot-ele effect and/or Compton (pair prod does not occur)

- From definition of absorption length need 3 λ to absorb the 95% photons
- For 5÷20 MeV photons λ is~20 g/cm^2 (approximately material independent) so need 60 g/cm^2 after shower max
- The radiation length of Al is 24 g/cm^2 (or 9 cm). So, using Al, we need at least additional 2.5 X_0 to absorb 95% of the energy of the initial particle.
- The radiation length of Pb is 6.4 g/cm^2 (or 0.56 cm). So, using Pb, we need at least additional 9.3 X_0 to absorb 95% of the energy of the initial particle.

Absorbtion length as a function of photon energy in different materials



$$N_\gamma(x) = N_0 e^{-\frac{x}{\lambda}}$$

So, more X_0 of Pb will be needed after shower max to contain 95% of the shower energy than Al !

Energy loss by neutrons

- Neutrons are neutral particles: no Coulomb interactions as for charged particles
- Neutrons only interact with nuclei via nuclear forces : neutrons are deeply penetrating particles
- Neutrons are not directly ionizing particles : they produce secondary charged particles which are directly ionizing, neutrons are indirectly ionizing particles as photons
- Different behaviour depending on the neutron energy but in general:
  1. Scattering: modification of the E and of the trajectory of the neutron but the nucleus keeps the same number of protons and neutrons (the neutron doesn't disappear!)
  2. Absorption: Modification of the target nucleus → radiation emission

Effect of longitudinal/latera leakage

❑ Longitudinal/lateral leakage:

A shower has a long tail of soft particles and containment can't be complete

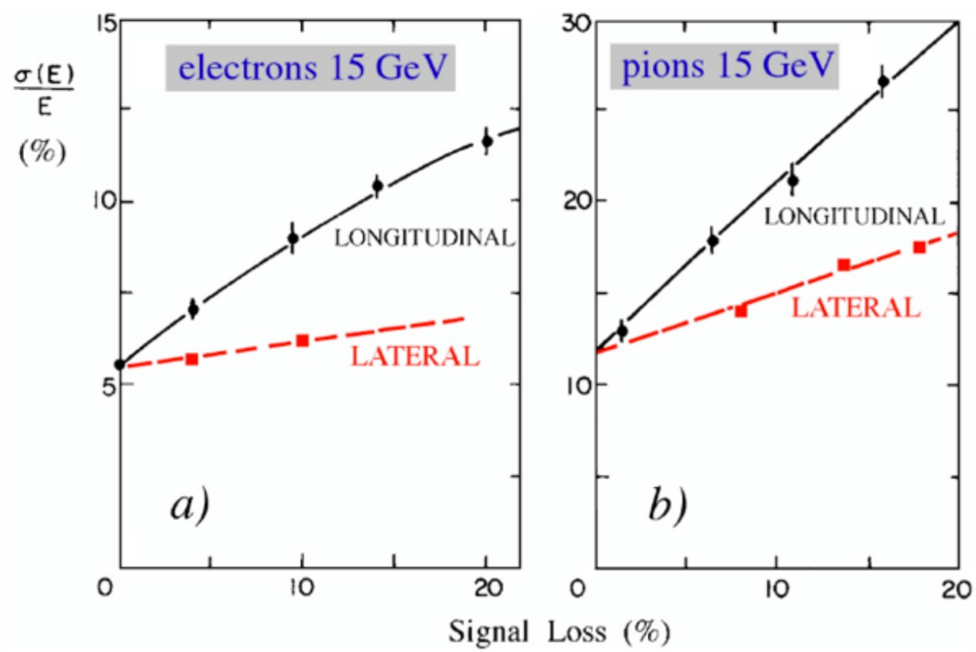


FIG. 4.33. The effects of longitudinal and lateral shower leakage on the energy resolution, as measured for 15 GeV electrons (*a*) and pions (*b*) by the CHARM Collaboration in a low-*Z* calorimeter [Did 80, Amal 81].

- ❑ Longitudinal shower fluctuations and therefore leakage are essentially driven by fluctuations in the starting point of the shower, i.e., by the behavior of one single shower particle.
- ❑ Lateral shower fluctuations generated by many particles
- ❑ Generate a quasi-sampling term which scales as $1/E^{-0.25}$

How to achive compensation : the role of neutrons (n/mip)

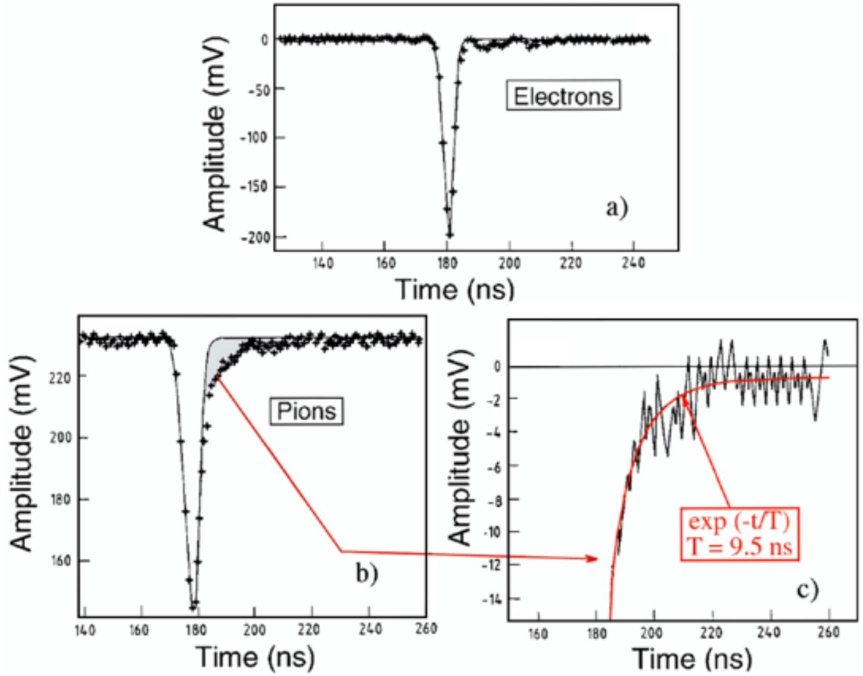


FIG. 3.22. Typical calorimeter signals for 150 GeV electrons (*a*) and pions (*b*) measured with the SPACAL calorimeter. The pion signal exhibits a clear exponential tail with a time constant of ~ 10 ns (*c*). The $t = 0$ point is arbitrary and the bin size is 1 ns. Data from [Aco 91a].

Shoulder in calorimeter signal observed on hadrons only : contribution from neutrons coming after ~ 10 ns (typical time needed to reach a proton)

For even longer integration times (~ hundreds of nanoseconds) one might catch the signal (photons) from neutron capture

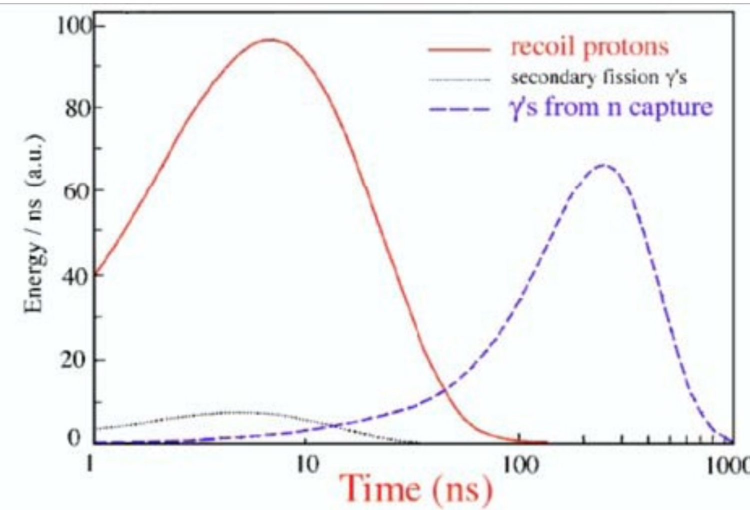


FIG. 3.22. Time structure of various contributions from neutron-induced processes to the hadronic signals of the ZEUS uranium/plastic-scintillator calorimeter [Bru 88].

Quick reminder: energy loss by collision by heavy particles

Bethe-Block formula: coulomb scattering with electrons of the material

Fundamental constants
r_e=classical radius of electron
m_e=mass of electron
N_a=Avogadro's number
c =speed of light

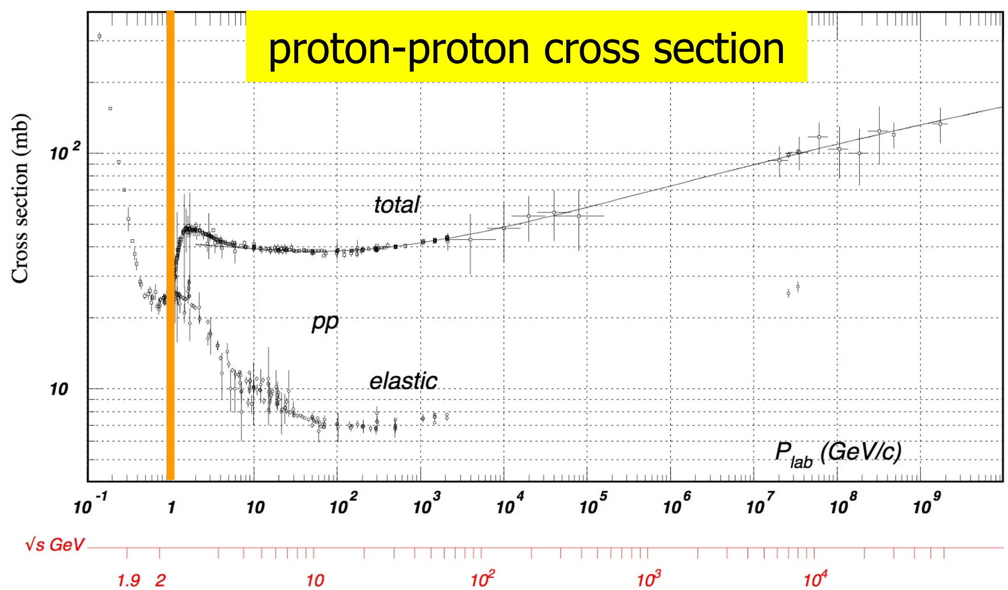
$$-\frac{dE}{dx\rho} = 4\pi r_e^2 z^2 m_e c^2 N_A \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2\gamma^2\beta^2 m_e c^2 T_{max}}{\bar{I}^2} - \beta^2 - \frac{\delta(\gamma\beta)}{2}\right]$$

Absorber medium
I = mean ionization potential
Z = atomic number of absorber
A = atomic weight of absorber
ρ = density of absorber
δ = density correction

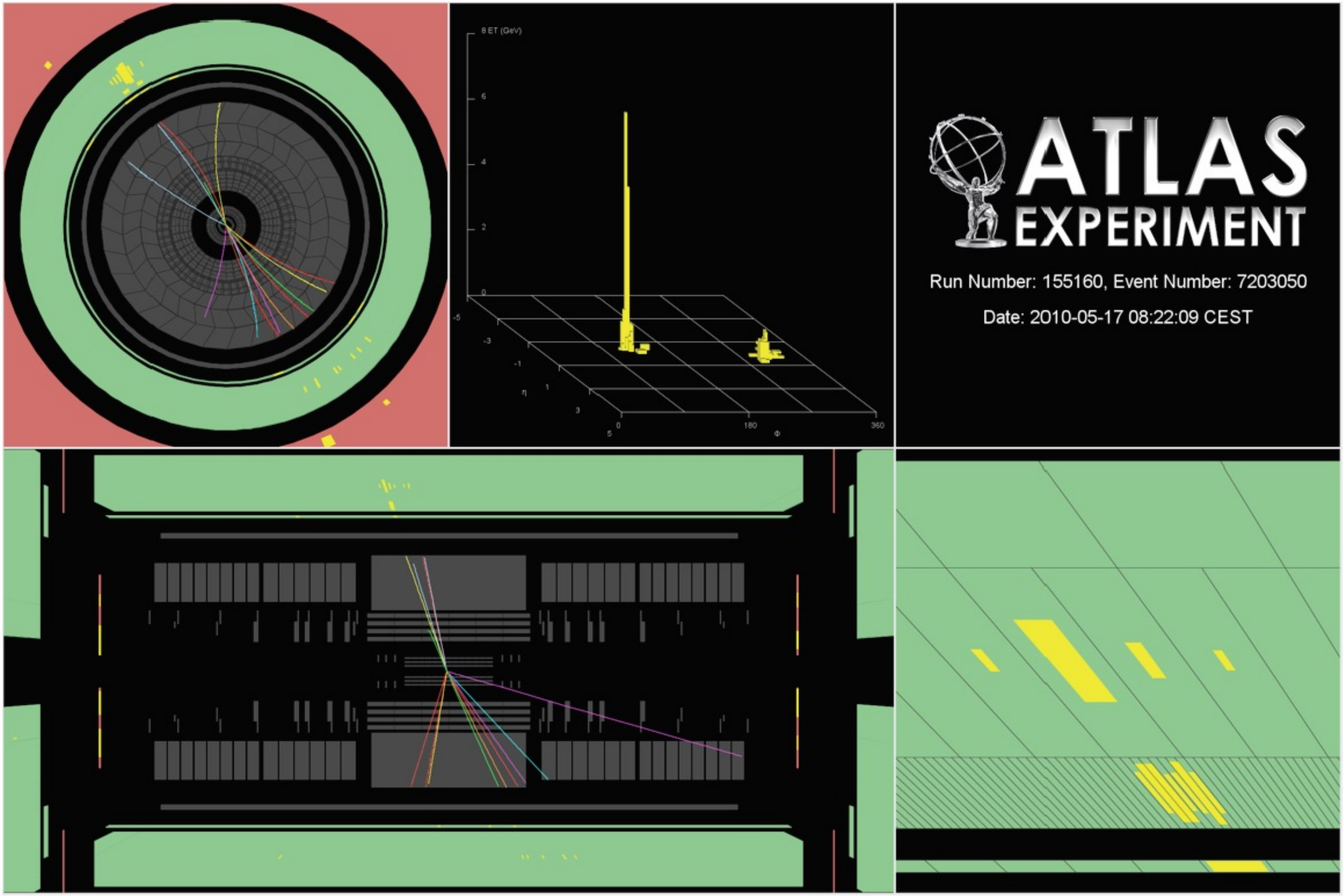
Incident particle
z = charge of incident particle
β = v/c of incident particle
$\gamma = (1-\beta^2)^{-1/2}$
W_{max}= max. energy transfer in one collision

Energy loss by charged hadrons (strong force)

- Charged hadrons in the GeV range typically loose a few MeV per cm by collision.
- Hadrons (h) will also interact with nucleons (N) of the material through strong force: both elastic (h+N->h+N) and inelastic (h+N->X)
  - In the 1 GeV – 1 TeV range the inelastic cross section dominates, approximately 40 mb, $(4 \times 10^{-26}\ \text{cm}^2)$ ~ constant with energy of the incident hadron
  - Not dramatically dependent on the hadron type, typically ~ 25 mb for pions over protons
  - Can be interpreted naively considering the cross section as the apparent size of a nucleon. A proton or a neutron have an apparent size of slightly more than 10^{-13} cm, and the cross section for the collision on another proton or neutron is $\approx 4 \times 10^{-26}\ \text{cm}^2$, 40 mb.



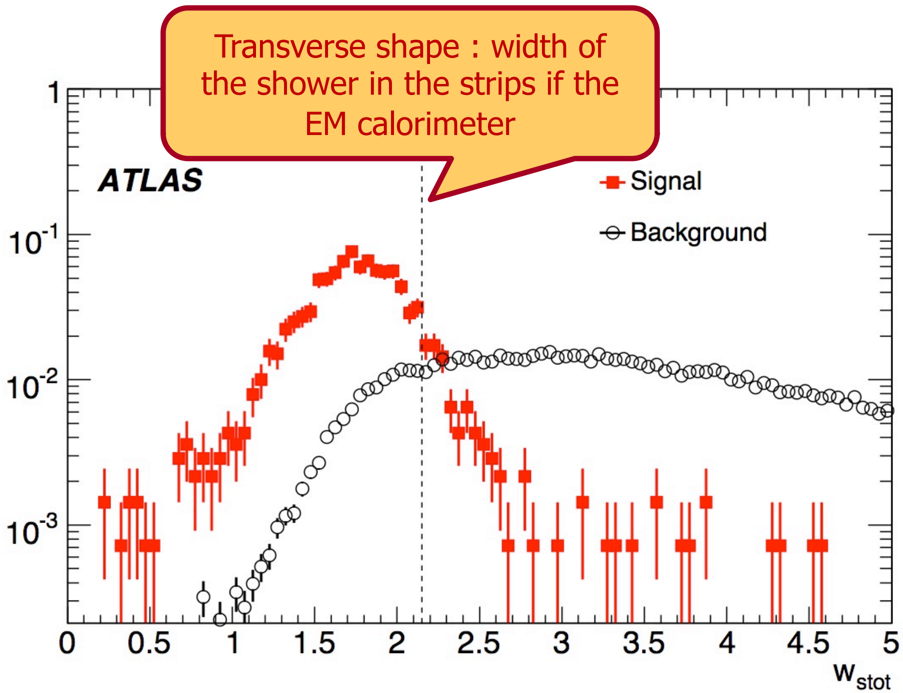
A nice π^0 candidate

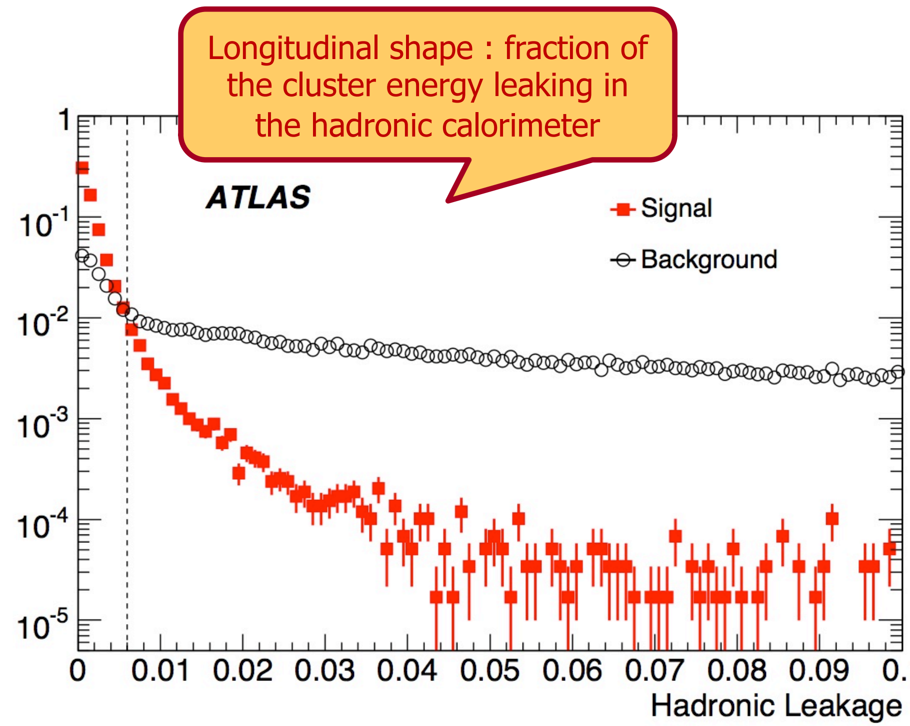


Identification efficiency and background rejection

Need to reduce the probability that a different particle can be reconstructed as a photon: exploit the features of the calorimeter to reject fake photons

- ❑ Use shower shapes in the calorimeter to discriminate candidates with a shower development compatible with the one from a photon
- ❑ Calorimeter granularity is the key item here



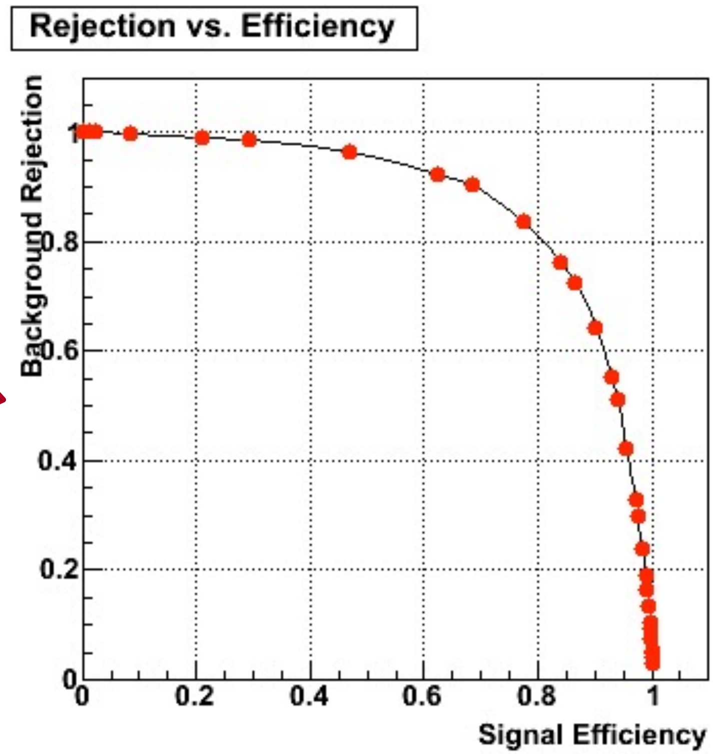


- ❑ A photon is declared if it fulfills all requirements (identification menu)

Identification efficiency and background rejection

- Efficiency : fraction of real photons my selection retains over the total true photons
- Purity : fraction of real photons in the selected sample

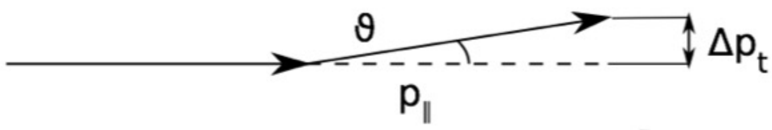
Typical classification problem: assign a label to a candidate based on a set of observables. ML techniques help : provide a score on which a decision can be taken.



Optimal working point is a trade off between efficiency and purity of the selected sample.

Multiple scattering

❑ Charged particles passing through matter not only loose their energy but can loose their direction due to coulomb scattering with material nuclei (assume small energy transfer) negligible contribution of elastic scattering on electrons



$$\theta \approx \frac{\Delta p_\perp}{p_\parallel} \approx \frac{\Delta p_\perp}{p}$$

Z protons in the nucleous

$$= \frac{Zze^2}{2\pi\varepsilon_0} \frac{1}{vbp}$$

Slide 21

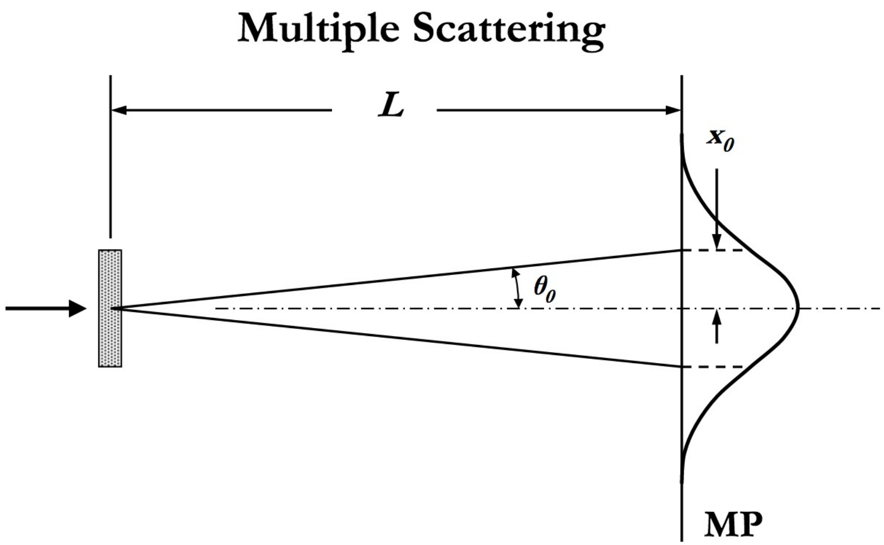
❑ In real (thick) absorbers normally many coulomb scatterings with material nuclei

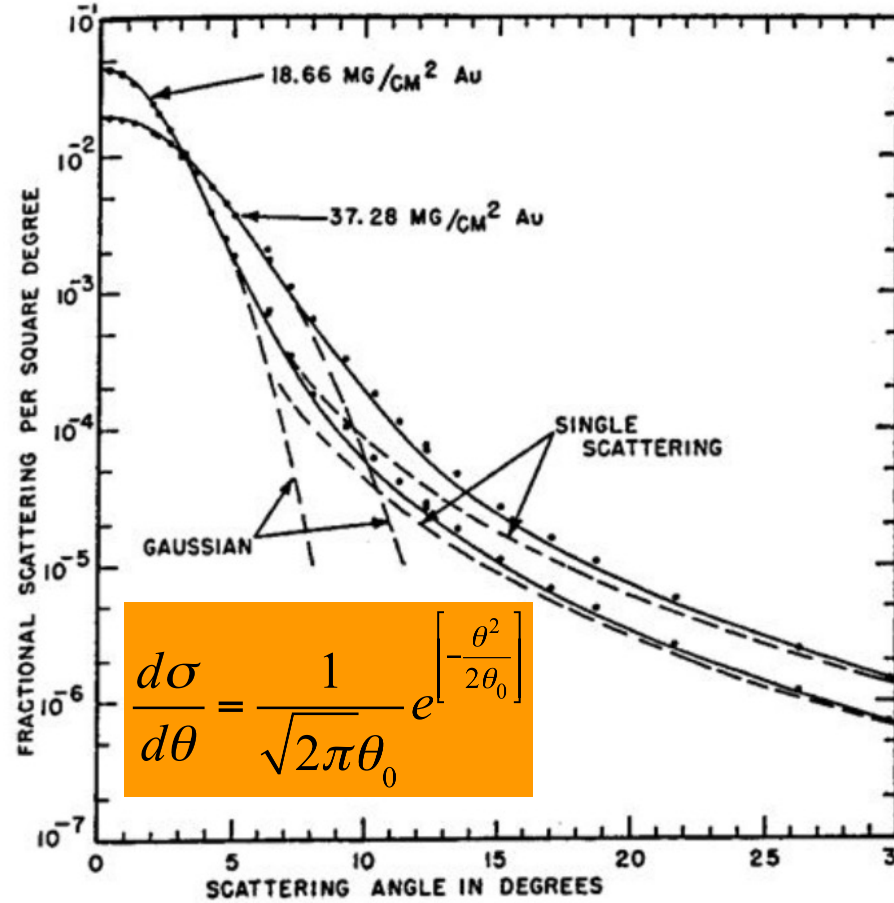
❑ Single scattering limit : if the block is very thin one can imagine a Rutherford scattering (single scattering)

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}.$$

❑ Multiple scattering limit : for thick layers -> sum of several scatterings, gaussian distribution (according to the Central Limit Theorem) + single large angle collisions (non gaussian "additional" tails) : Moliere theory

Multiple scattering





$$\frac{d\sigma}{d\theta} = \frac{1}{\sqrt{2\pi\theta_0}} e^{\left[-\frac{\theta^2}{2\theta_0}\right]}$$

FIG. 3. Angular distribution of electrons from thick and thin gold foils from 0° to 30°. The solid line represents the theory of Molière extrapolated through the region where his small and large angle approximations give different values. The dotted lines at small angles represent the continuation of the gaussians of Fig. 1. At larger angles, the dotted line represents the single scattering contribution.

Complete multiple scattering model (Moliere) is obtained from a combination of a single scattering part (governing the high deflections regime) plus a Gaussian core which represents the sum of many small angle deflections

- 98% Gaussian around scattering angle 0
- 2 % large scattering angles

Multiple scattering

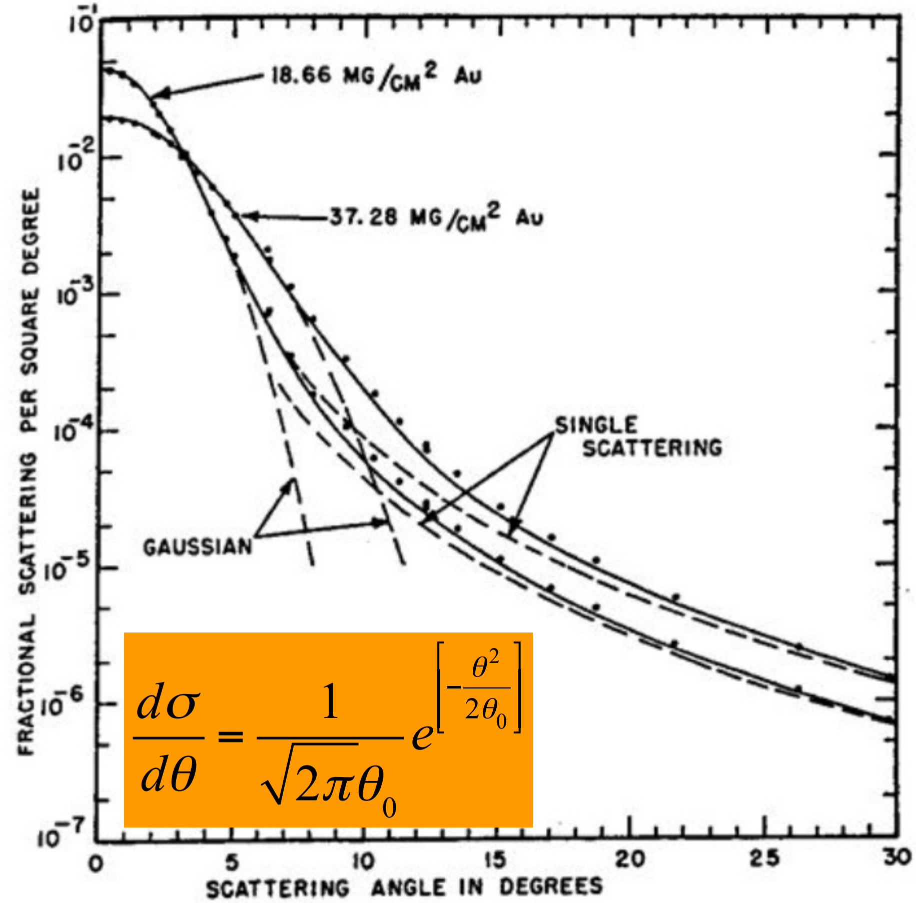
Charge of the particle

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

Particle momentum

Material thickness (in units of radiation lenghts X_0)

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



$$\frac{d\sigma}{d\theta} = \frac{1}{\sqrt{2\pi\theta_0}}\, e^{\left[-\frac{\theta^2}{2\theta_0}\right]}$$

FIG. 3. Angular distribution of electrons from thick and thin gold foils from 0° to 30°. The solid line represents the theory of Molière extrapolated through the region where his small and large angle approximations give different values. The dotted lines at small angles represent the continuation of the gaussians of Fig. 1. At larger angles, the dotted line represents the single scattering contribution.

- Strength of scattering depends on 1/p:
  - Affect the measurement of low momentum particles
- Thin detectors are better!
- Better to use light materials

Quick reminder: energy loss by collision (heavy particles)

- Bethe-Block formula: coulomb scattering with electrons of the material

0.307 MeV mol^{-1}cm^2

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

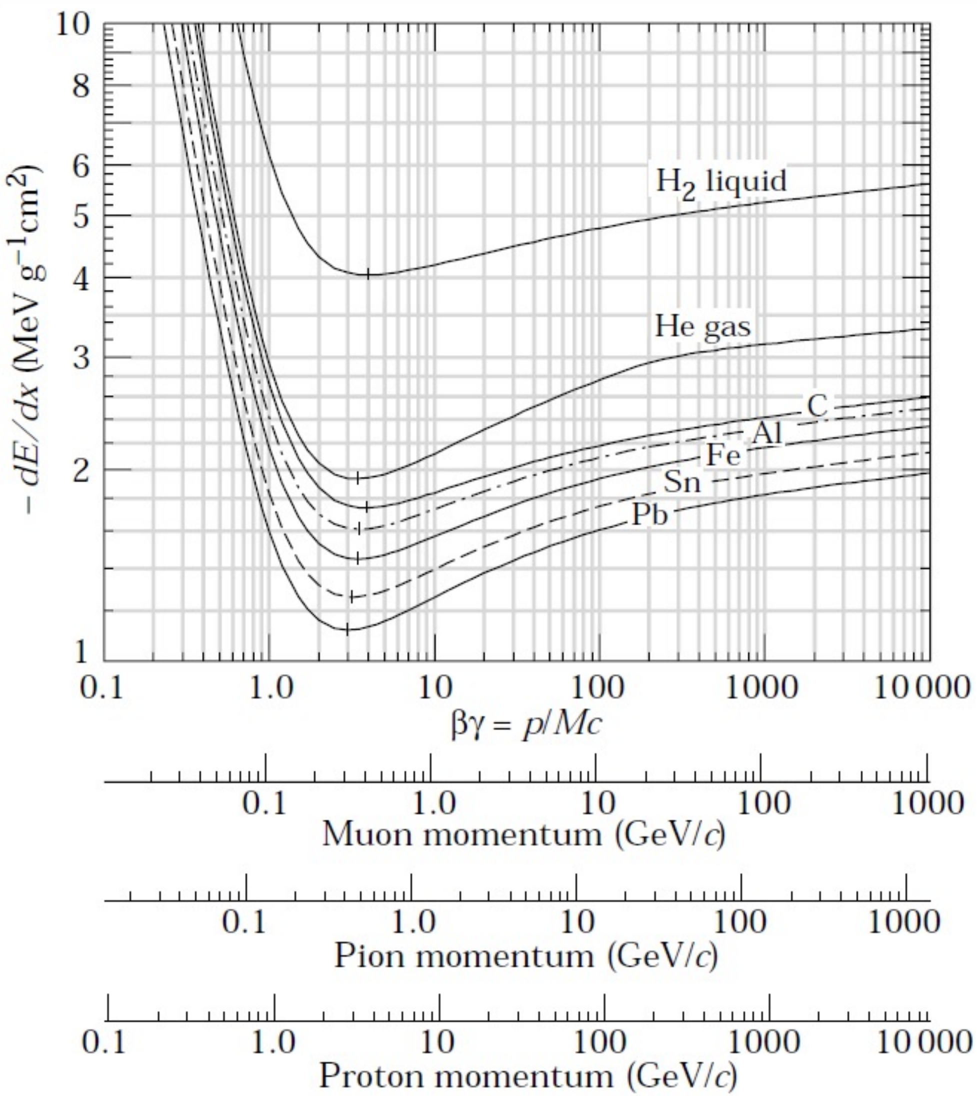
Measured in MeV/gr/cm^2

~0.5 mol g^{-1}

$I \sim I_0 Z$ (I_0=10 MeV)

1. dE/dX is a function of β and not of the mass of the particle
2. weak dependence on the material (Z/A) and through I
3. the energy loss is the sum of discrete processes (statistical !)

Quick reminder: energy loss by collision (heavy particles)



- Typically drawn as a function of $\beta\gamma$
- $\beta\gamma \ll 3$: 'Bragg fall' z^2/β^2, slower particles loose more energy
- $\beta\gamma \sim 3$: minimum in energy loss (the particle is said 'minimum ionizing particle') almost independently from the medium: dE/dx ~ 1-2 MeV/(g/cm^2).
- In the relativistic (and ultra relativistic) range ($\beta\gamma \gg 3$) need to account for :
  - Relativistic rise ($\ln(\beta^2\gamma^2)$) : transversal field increases due to Lorentz transform
  - Density effect $\delta \sim \ln(\beta\gamma)$: medium polarization effect. Shielding of electrical field far from particle path; effectively cuts of the long-range contribution

$$\frac{\delta}{2} = \ln\left(\frac{\hbar\omega}{I}\right) + \ln(\beta\gamma) - 1/2$$

Quick reminder: heavy particles vs electrons energy loss by collision

- Bethe-Bloch equation must be modified to account for:
  - Small mass of electron → deflections become more important
  - Incident and target electron have the same mass me ($T= T_{max}/2$)
  - Quantum mechanics: after the scattering, the incoming electron and the one from ionization are indistinguishable

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

- Nevertheless, same qualitative behaviour as for heavy particles: at βγ ~ 3 the differential energy loss still assumes a minimum (minimum ionizing particles), independent of absorber.
  - Dominant energy loss is rapidly the radiation !
- Energy loss for electrons and positrons is slightly different :
  - positron is not indistinguishable from electron in atom
  - Low energy positrons have larger energy loss because of annihilation
  - At same β, the difference is within 10%

Hadronic showers lateral profile

- ❑ 95% containment 80 GeV π ≈ 1.5 λ / 32 cm (Uranium)
- ❑ For electrons 95% containment of same energy 3.5 cm : factor ≈ 9 for in both directions.

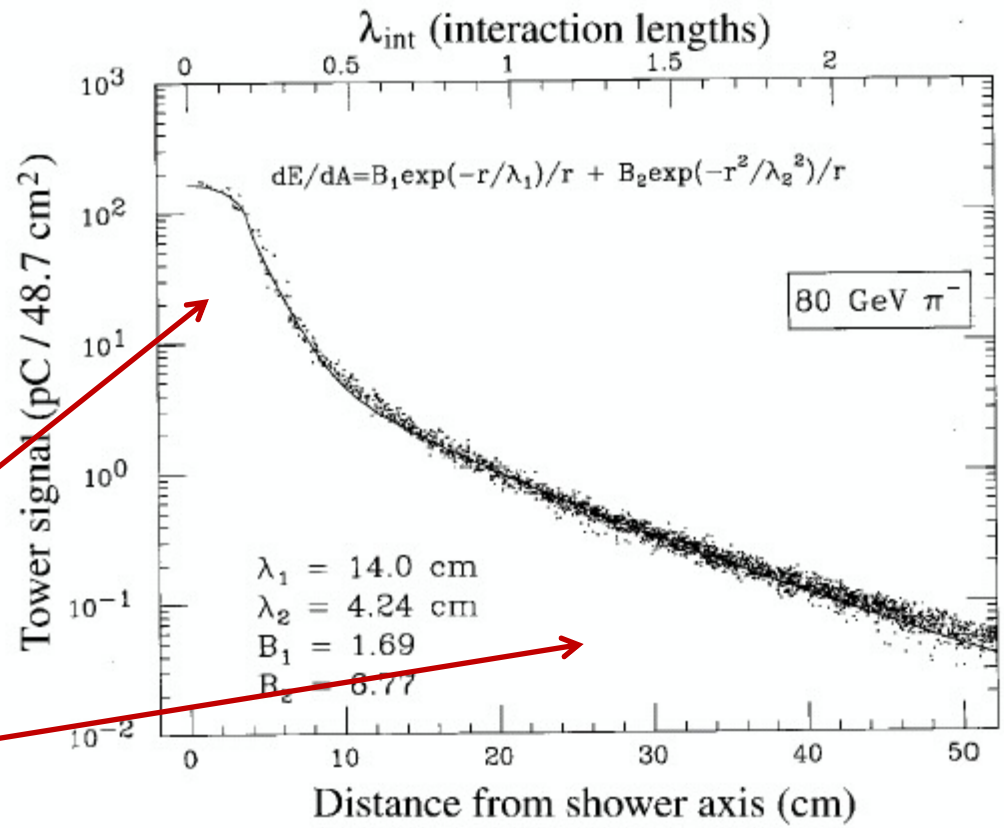


FIG. 2.32. Average lateral profile of the energy deposited by 80 GeV π^- showering in the SPACAL detector. The collected light per unit volume is plotted as a function of the radial distance to the impact point. Data from [Aco 92b].

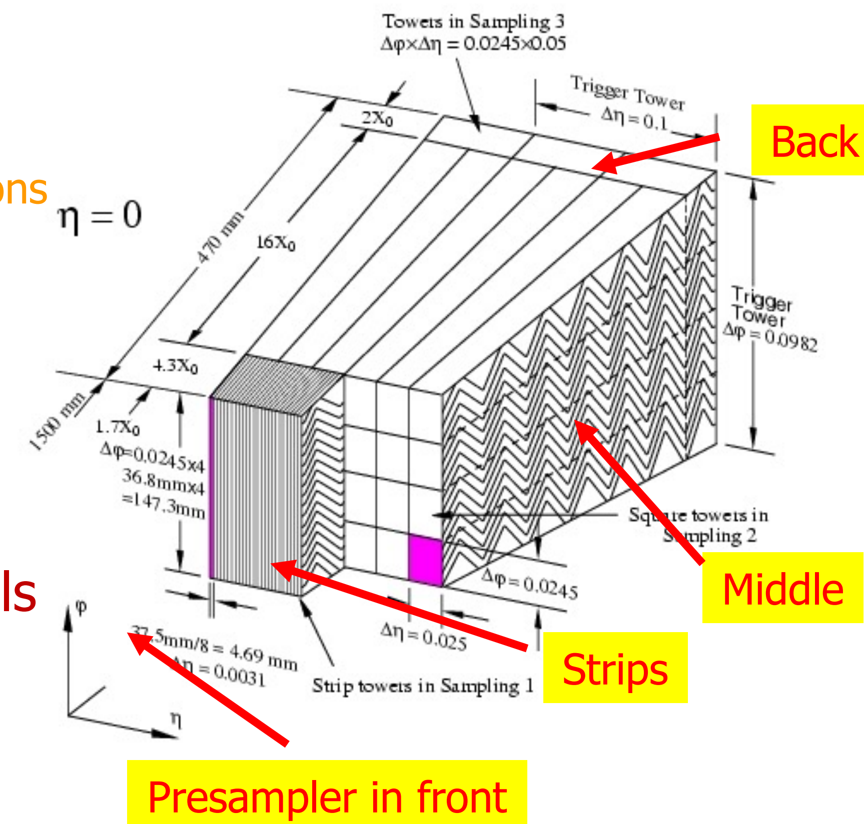
Two components are clearly visible:

- ❑ Electromagnetic core
- ❑ Hadronic halo

The ATLAS electromagnetic calorimeter design

- Sampling calorimeter: lead absorber and liquid Argon as active medium
- Accordion shape of absorbers: full azimutal coverage with no dead regions

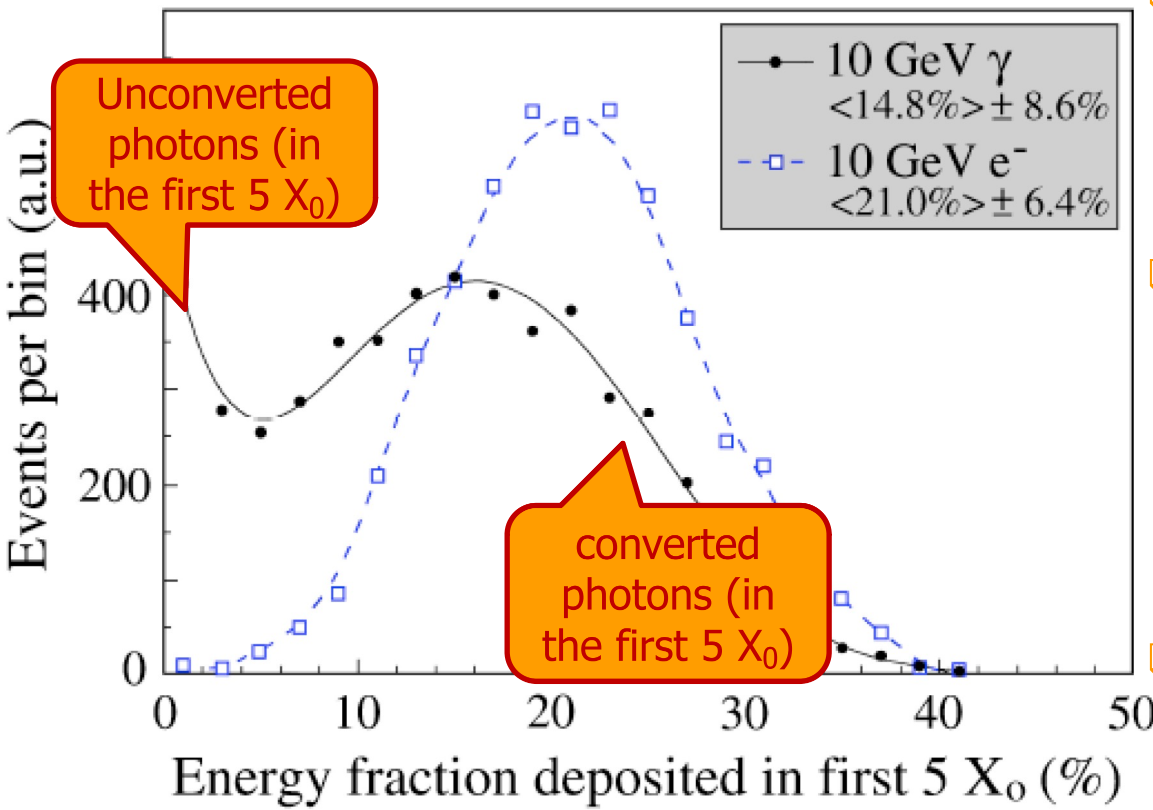
- Longitudinal dimension: 47 cm ≈ 25 X0
- Pseudorapidity coverage $0 < |\eta| < 3.2$
- Longitudinal segmentation:
  - strips (~4 X0): very fine grain in η for $\pi 0$ rejections separation of 2 photons
  - middle : 16 X0 for shower core containment
  - back : 2 X0 evaluation of late started showers



- Presampler to recover energy lost in the upstream material ≈ 2X0
- High granularity: 200000 read out channels
- Electronic calibration

EM showers longitudinal profile : electrons vs photons

- Showers initiated by high-energy electrons and by photons develop initially quite differently.



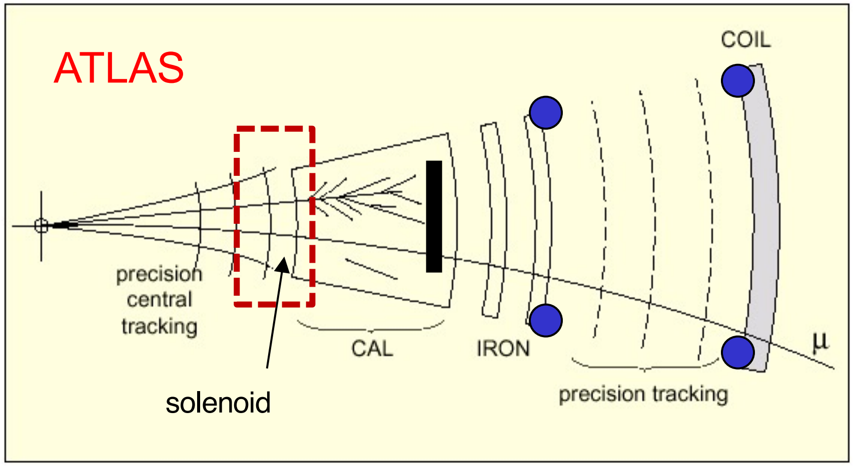
- When they encounter material, high-energy electrons start to radiate immediately. On their way through a few mm of material, they may emit thousands of bremsstrahlung photons.
- On the other hand, high-energy photons may or may not interact in the same amount of material. In the latter case, they do not loose any energy, and when they convert early on, they may lose as much as, or even more than, electrons in the same amount of material.
- In the same amount of material (in this example $5X_0$), electrons loose on average a larger fraction of their energy than photons, but the spread in the energy losses by photons is larger

More on the stochastic term in energy resolution

	eV/quantum (E_S)	quanta/GeV	a (= √k) [√GeV]
Silicon detectors	3.6	$28*10^7$	0.006%
Gas detectors	~40	$2.5*10^7$	0.02%
Scintillators (*)	~100	10^7	0.03%
(PbW04) (*)	$\sim10^4$	10^5	0.3%
Cherenkov (*)(**)	$\sim10^6$	1000	3%

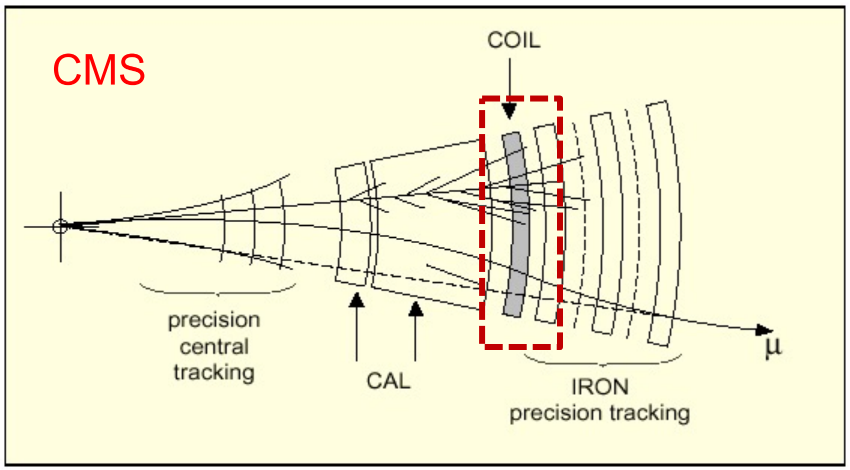
(*) Don't forget that for a realistic estimation one should account for light collection efficiency , quantum efficiency etc. For a Cherenkov detector might well reach 1 photo-electron per GeV (meaning a sampling term of 100%)
(**) Typically, only a small fraction of particles in the shower above Cherenkov radiation threshold

Considerations on detector design



ATLAS put the calos behind the solenoid (B= 2T):

- limited em energy resolution
- Uses an Air toroid μ spectrometer: optimal μ momentum resolution
- four magnets in total.



CMS uses a high field (B= 4T) solenoid placed after the calorimetry :

- Optimal em energy resolution
- The μ spectrometer uses the solenoid return flux. Only 1 (but big) magnet:
- EM calorimeter inside the B field, poor hadronic energy measurement performance

Summary for EM calorimeters:

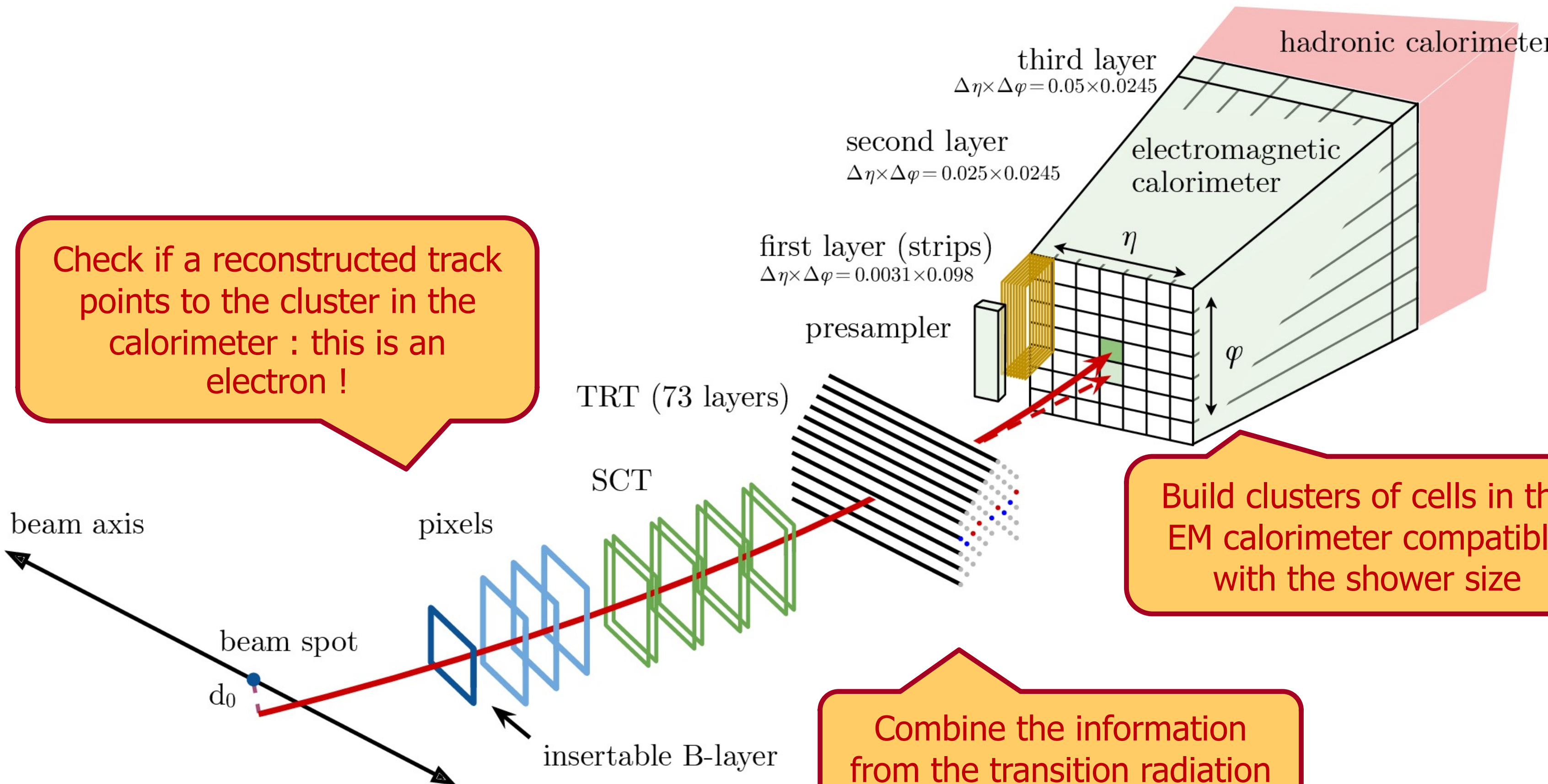
If you want to build an electromagnetic calorimeter you may want to consider the 2 following approaches from the technical point of view:

- Build a homogenous calorimeter:
  - The active material is also the absorber
  - Best energy resolution (~ 1-2% stocastic term)
  - Limited spatial resolution in the longitudinal coordinate
  - Used only for electromagnetic calorimetry
  - High cost and radiation damage should be studied carefully

- Build a sampling calorimeter:
  - The active material is interleaved with absorbers (inactive): only part of the energy is measured
  - Limited energy resolution
  - Good spatial resolution
  - Used for both electromagnetic and hadronic calorimetry

How do we ‘see’ a electrons and photons in the detector? Clusters and tracks

Check if a reconstructed track points to the cluster in the calorimeter : this is an electron !



Build clusters of cells in the EM calorimeter compatible with the shower size

Combine the information from the transition radiation

Compensation for hadronic calorimeters

- e/h ratio is not directly measurable but would give the degree of non-compensation: it is not energy independent
- e/π: ratio of response between electron-induced and pion-induced shower can be measured and is energy dependent through $f_{em}(E)$

- e/π and e/h ratio are clearly related:

$$\frac{e}{\pi} = \frac{R_e}{R_h} = \frac{e}{f_{em}e + (1 - f_{em})h} =$$

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

- e/h > 1 : undercompensating
- e/h < 1 : overcompensating