Calorimetry

for Hadron Colliders

(mainly LHC)

Isabelle Wingerter-Seez (LAPP-Annecy)

A few points

Why build calorimeters ?

- Calorimeters important properties

Electromagnetic processes involved

EM shower developments

Experimental techniques

- Homogeneous calorimeters
- Sampling calorimeters

Hadronic Showers

Tevatron and LHC calorimeters

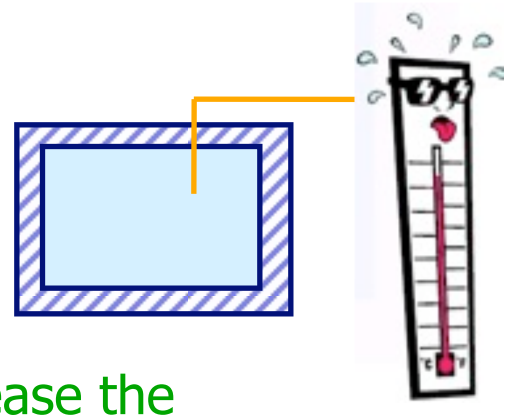
- CDF, D0, CMS, LHCb, ALICE, ATLAS
  - Structure
  - Performance

Calorimeters for Linear Colliders

What is a calorimeter?

Concept comes from thermo-dynamics:

A leak-proof closed box containing a substance which temperature is to be measured.



Temperature scale:

1 calorie (4.185J) is the necessary energy to increase the temperature of 1 g of water at 15°C by one degre

At hadron colliders we measure GeV (0.1 - 1000)

1 GeV = 10^9 eV ≈ $10^9 * 10^{-19}$J = 10^{-10} J = 2.4 10^{-9} cal

1 TeV = 1000 GeV : kinetic energy of a flying mosquito

Required sensitivity for our calorimeters is
~ a thousand million time larger than
to measure the increase of temperature by 1°C of 1 g of water

Why calorimeters ?

First calorimeters appeared in the 70's:

need to measure the energy of all particles, charged and neutral.

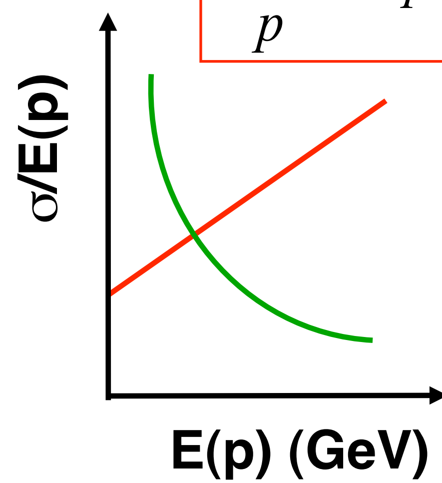
Until then, only the momentum of charged particles was measured using magnetic analysis.

The measurement with a calorimeter is destructive e.g.

$$\pi^- + p \rightarrow \pi^0 + n$$
$$\pi^0 \rightarrow \gamma\,\gamma$$

Magentic analysis

$$\frac{\sigma(p)}{p} = ap \oplus b$$

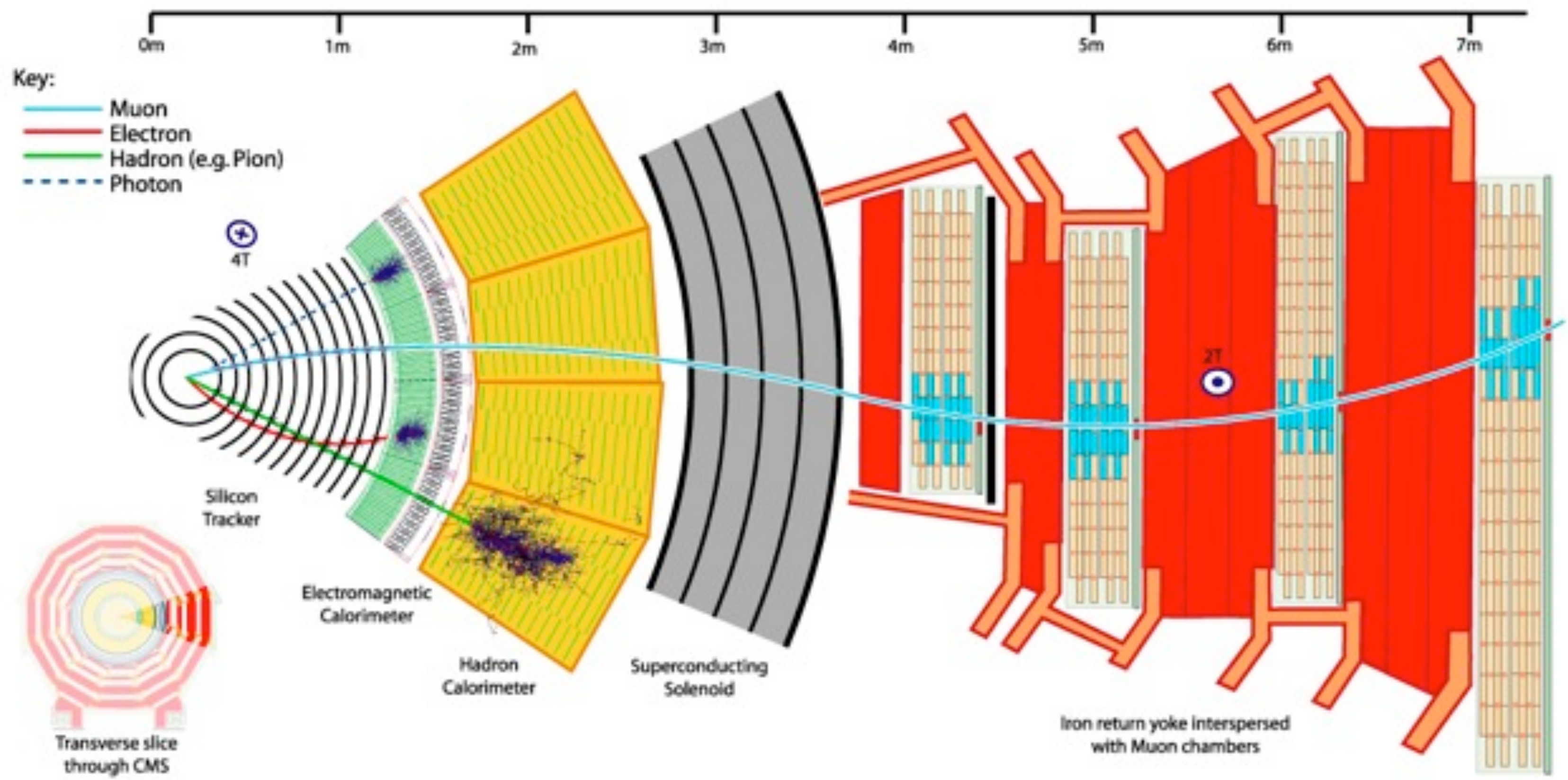


$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

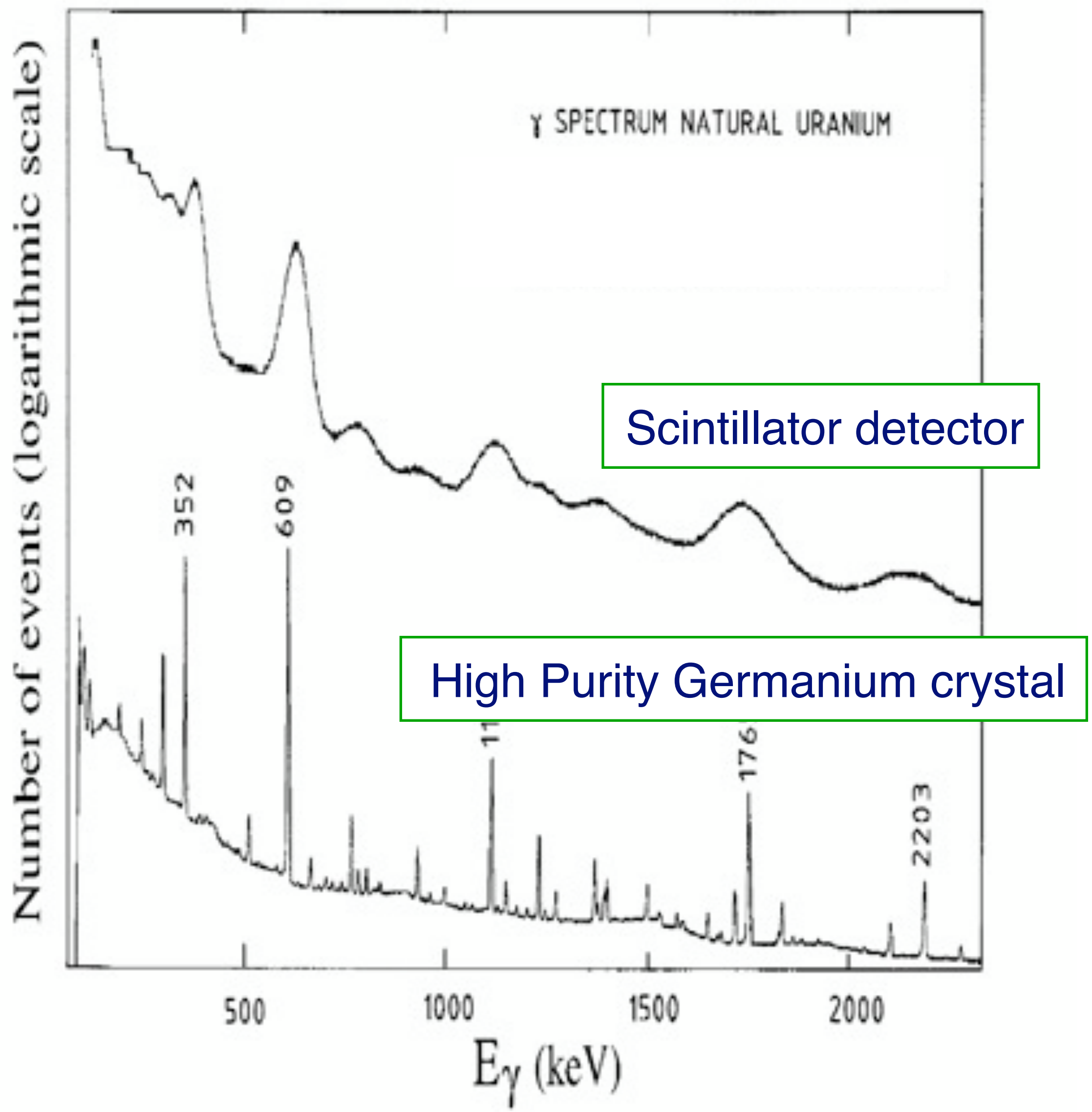
Calorimetry

Particles do not come out alive of a calorimeter

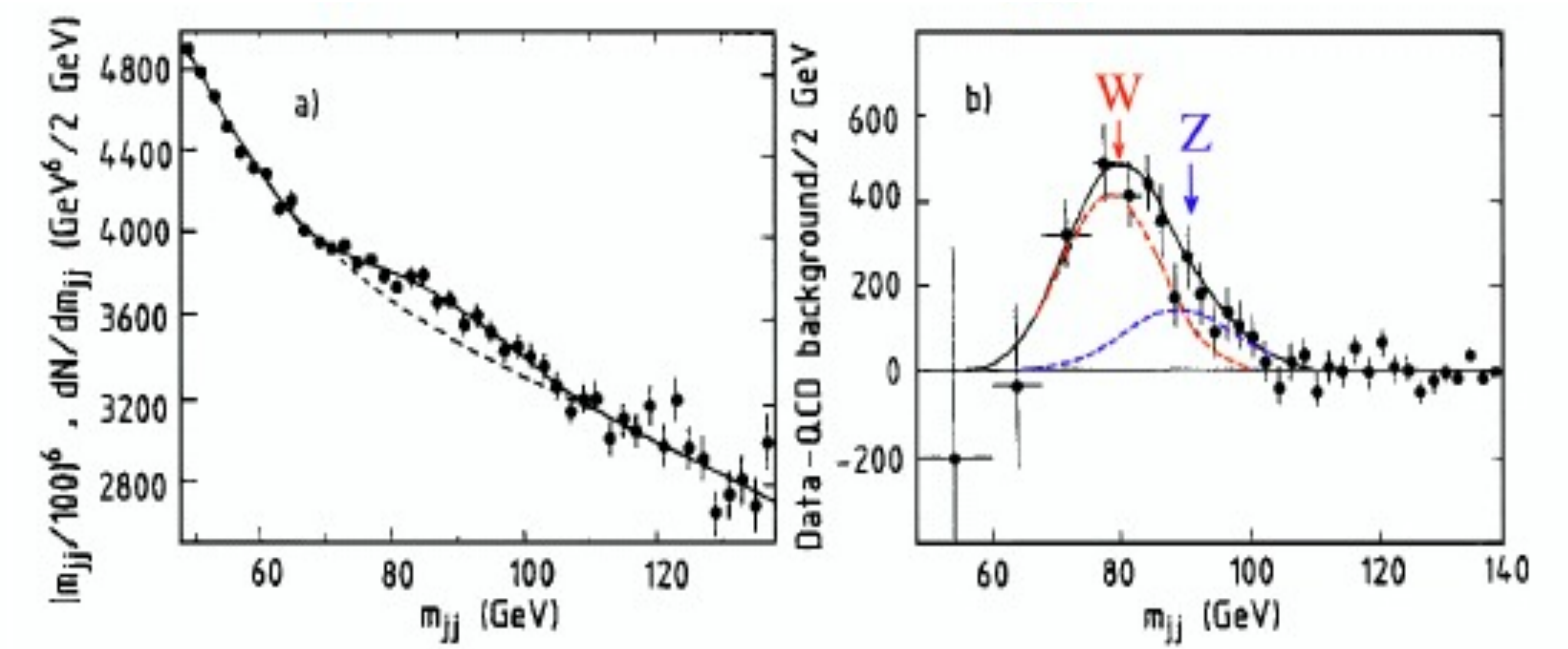
General structure of a calorimeter in particle physics



Important characteristic: Energy Resolution



Important characteristic: Energy Resolution

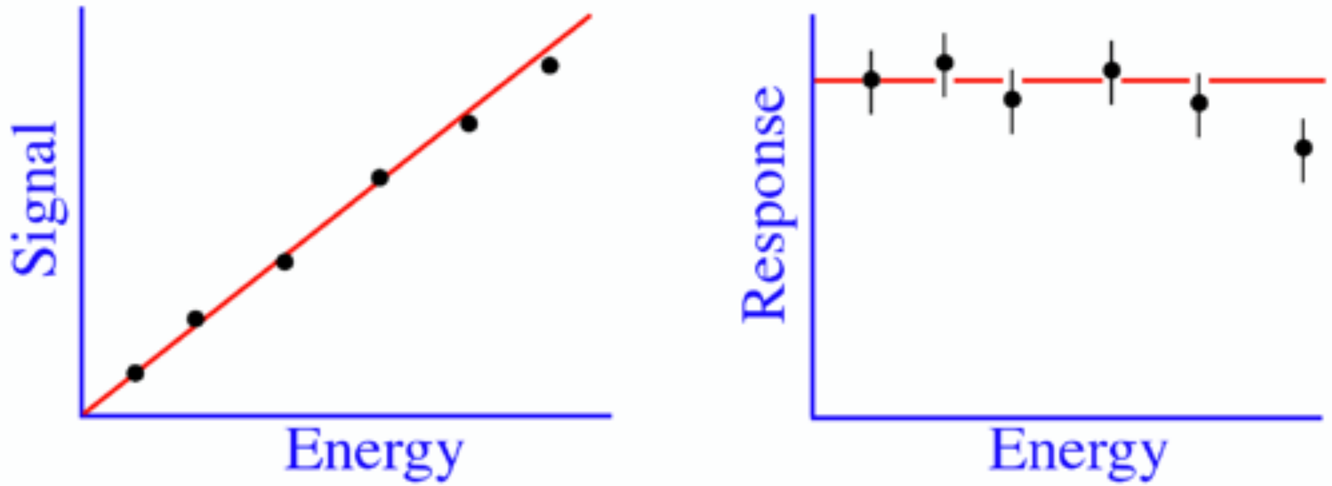


Mass Reconstruction of W & Z^0 in UA2
(years 80-90)

Important characteristic: Linearity

Response: mean signal per unit of deposited energy
e.g. # of photons electrons/GeV, pC/MeV, μA/GeV

➔ A linear calorimeter has a constant response



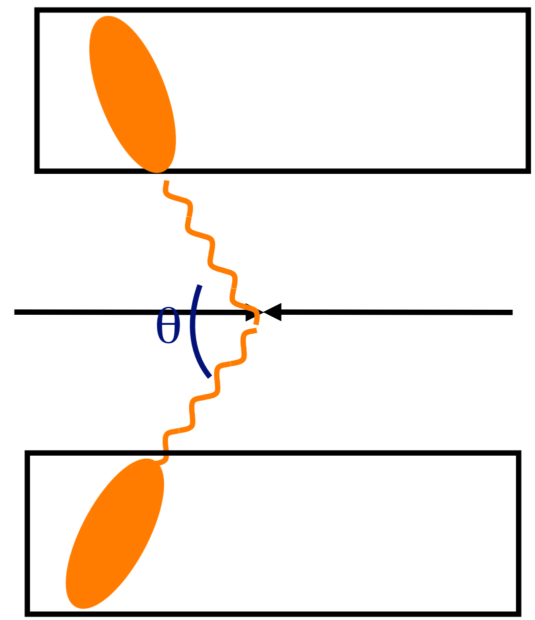
Electromagnetic calorimeters are in general linear.
All energies are deposited via ionisation/excitation of the absorber.

Important characteristic: Position Resolution

Higgs Boson search in ATLAS

if MH ~ 120 GeV search in channel $H \rightarrow \gamma\gamma$

$\sigma(M_H) / M_H = ½ [\sigma(E_{\gamma 1})/E_{\gamma 1} \oplus \sigma(E_{\gamma 2})/E_{\gamma 2} \oplus \cot(\theta/2)\, \sigma(\theta)]$



$pp \rightarrow H + x \rightarrow \gamma\gamma + x$

Important property: Time Resolution

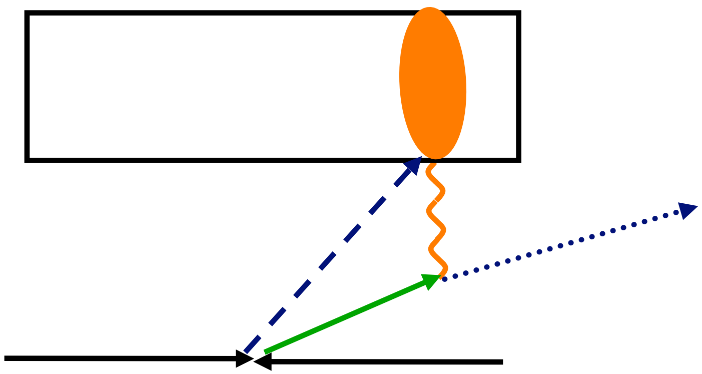
pp collisions will have a frequency of 25ns (now 50ns)

~20 interactions/bunch crossing when $L=10^{34}cm^{-2}s^{-1}$

Some theoretical models predict existence of long lived particles

Time measurement

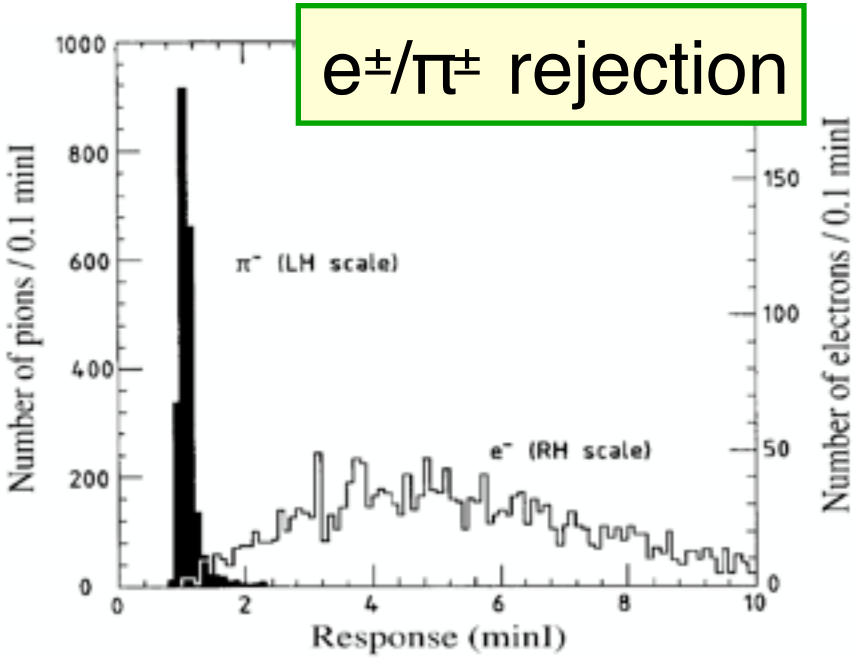
- Validate the synchronization between sub-detectors (~1ns)
  - Reject non-collisions background (beam, cosmic muons,..)
  - Identify particles which reach the detector with a non nominal time of flight (~5ns measured with ~100ps precision)



Important characteristic: Particle Identification

Particle Identification is particularly crucial at Hadron Colliders:

- Large hadron background
- Need to separate
  - Electrons, photons, muons from
  - Jets, hadrons



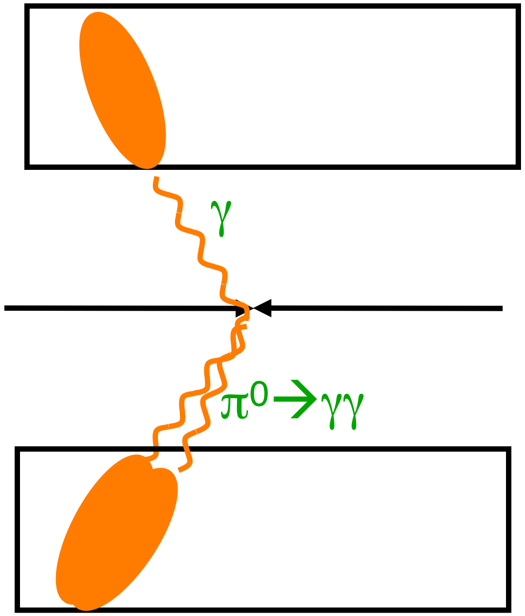
Means

- Shower shapes (lateral & longitudinal segmentations)
- Track association with energy deposit in calorimeter
- Signal time

Important property: Particle Identification

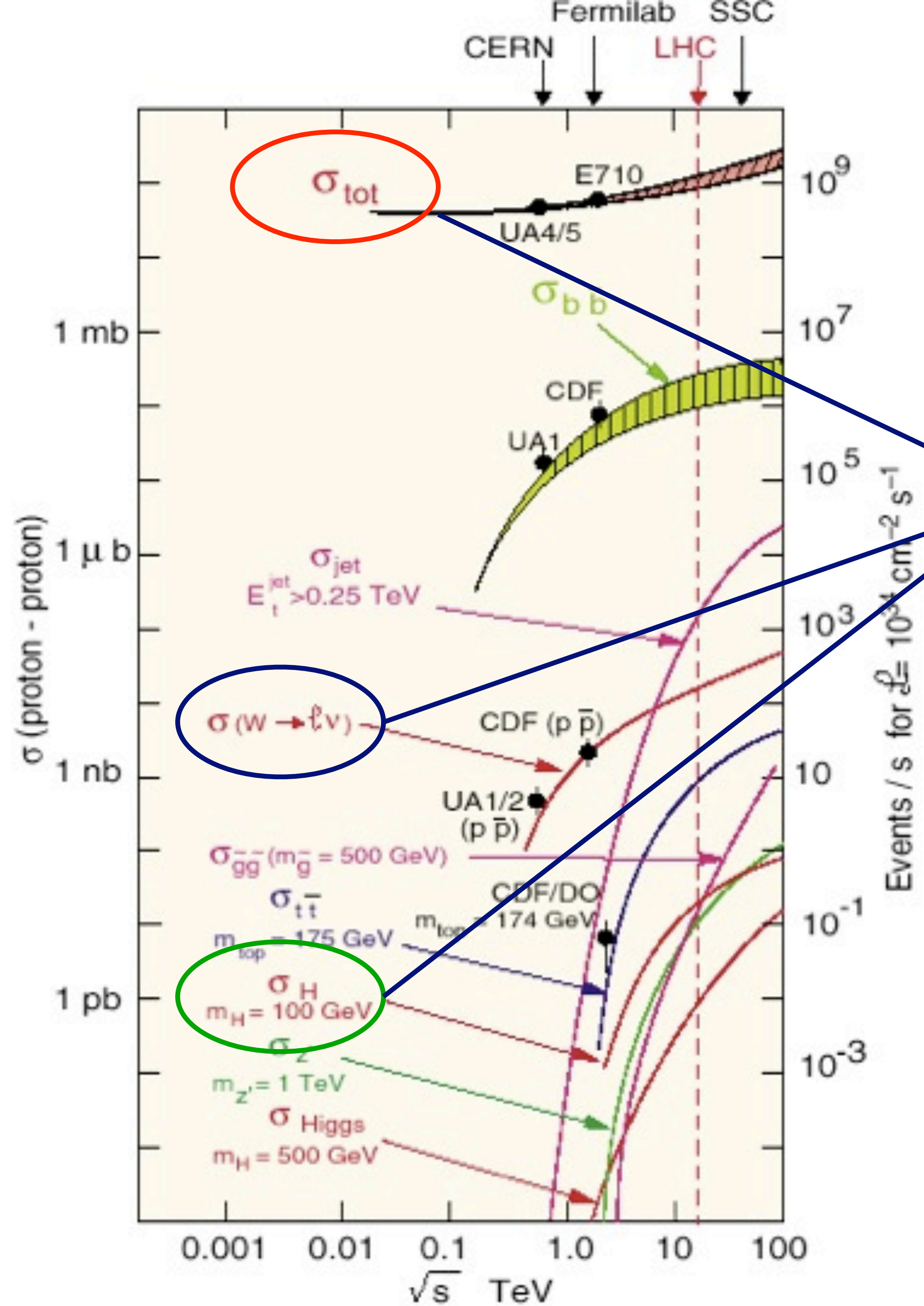
Higgs boson search in ATLAS

- if $M_H \sim 120$ GeV search in channel $H \rightarrow \gamma\gamma$
- Background: π^0 looking like a γ



$pp \rightarrow \gamma\text{-jet} \rightarrow \gamma + \pi^0 + x$

Triggering



One has to select the good events

Radiation Hardness & Activation

At LHC, detectors, and in particular calorimeters, have to be radiation hard

- Material (active material), glues, support structure, cables,…
- Electronics installed on the detector

Dominant source of particles (for the calorimeter) is coming from particles produced by the pp collisions

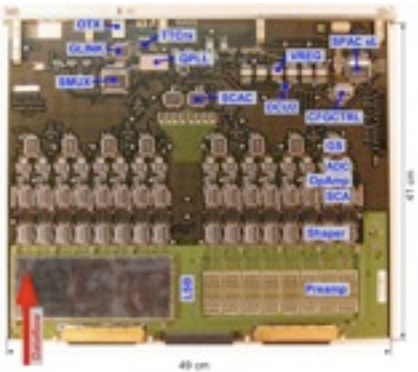
This was (and is still) one of the challenge when designing the calorimeters for LHC

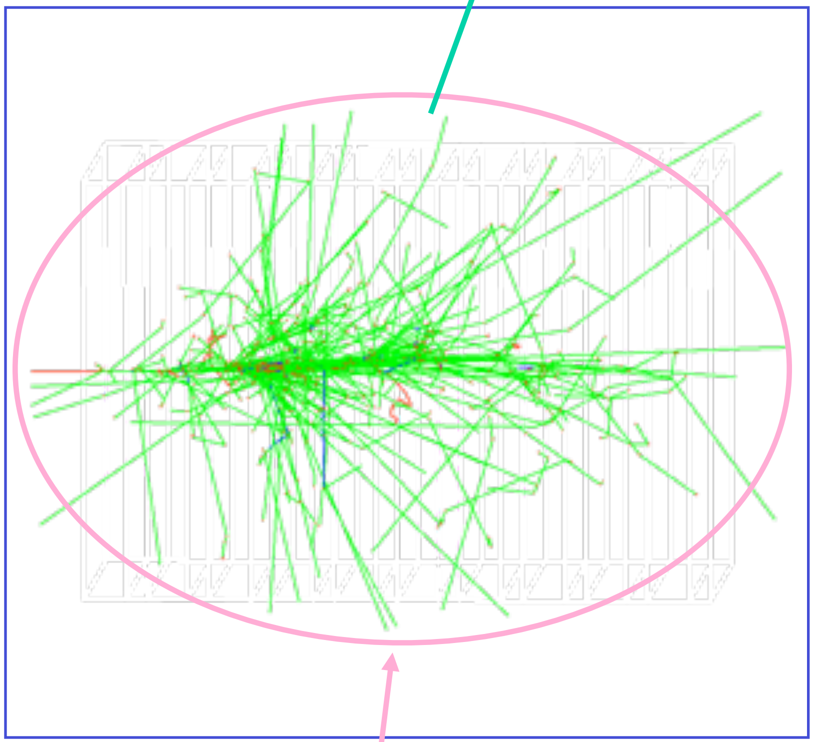
- Detailed maps produced by MC to assess expected level
- Dedicated tests in very high intensity beam lines

Experiments have installed monitoring detectors which will allow (in the near future) to confront the models with measurements.

Electronics
(conversion, amplification,
signal transmission)

Signal detection (light, electric charge)
Homogenous or sampling calorimeters



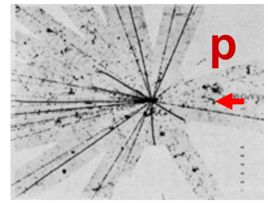


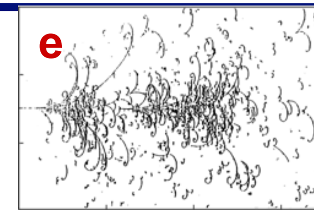
Calorimeters

Interaction with matter

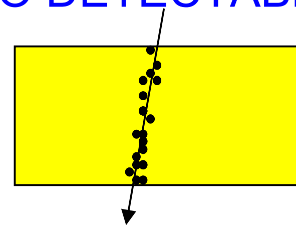
Four steps

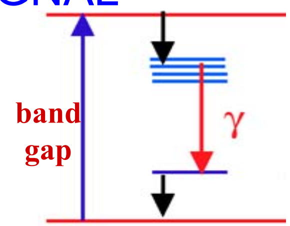
PARTICLE INTERACTION IN MATTER (depends on the impinging particle and on the kind of material)

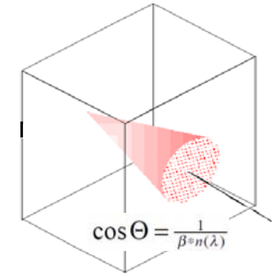




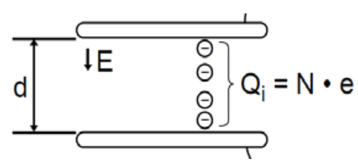
ENERGY LOSS TRANSFER TO DETECTABLE SIGNAL (depends on the material)

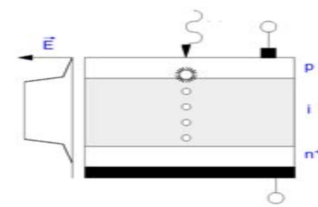




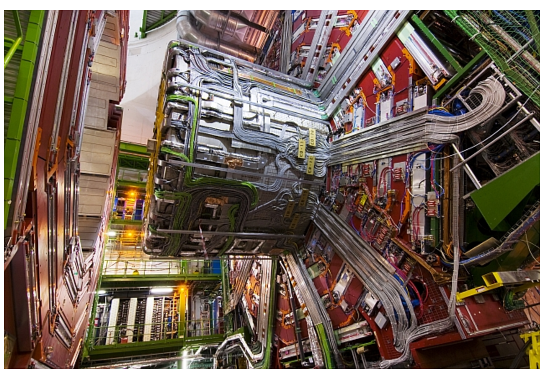


SIGNAL COLLECTION (depends on signal, many techniques of collection)





BUILD A SYSTEM



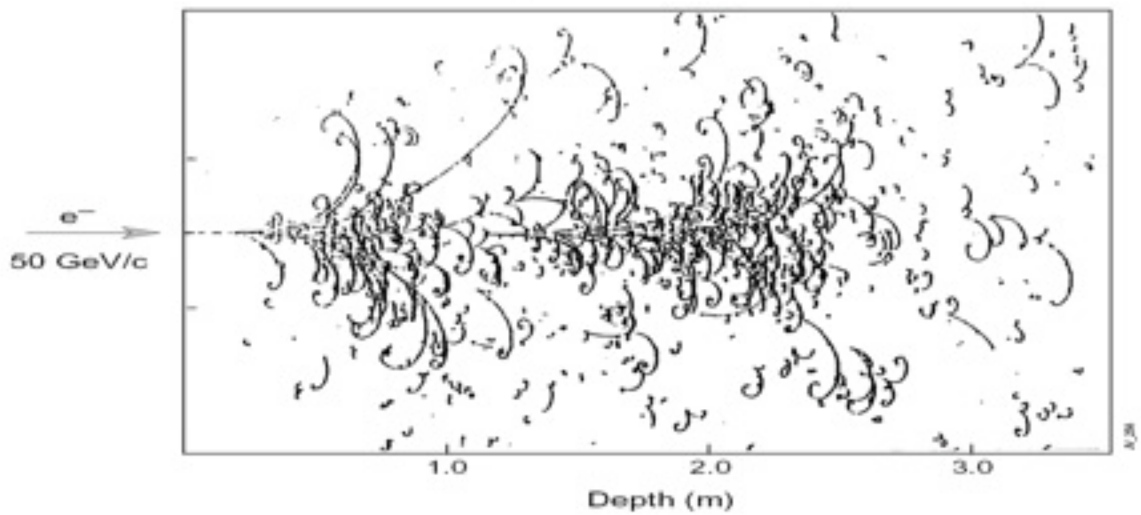
c.f. M. Diemoz at EDIT2011

General charatericties

Calorimeters have the following properties:

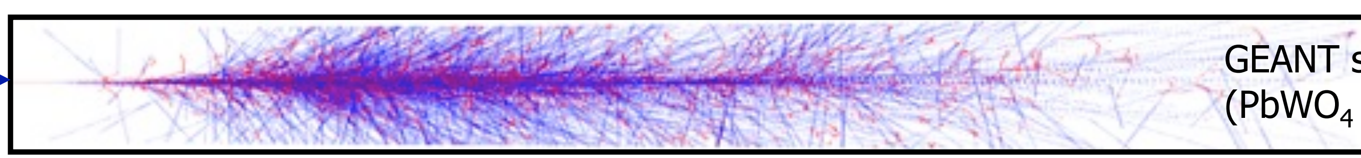
- Sensitive to charged and neutral particles
- Precision improves with Energy (opposite to magnetic measurements)
- No need of magnetic field
- Containment varies as ln(E): compact
- Segmentation: position measurement and identification
- Fast response
- Triggering capabilities

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 showers

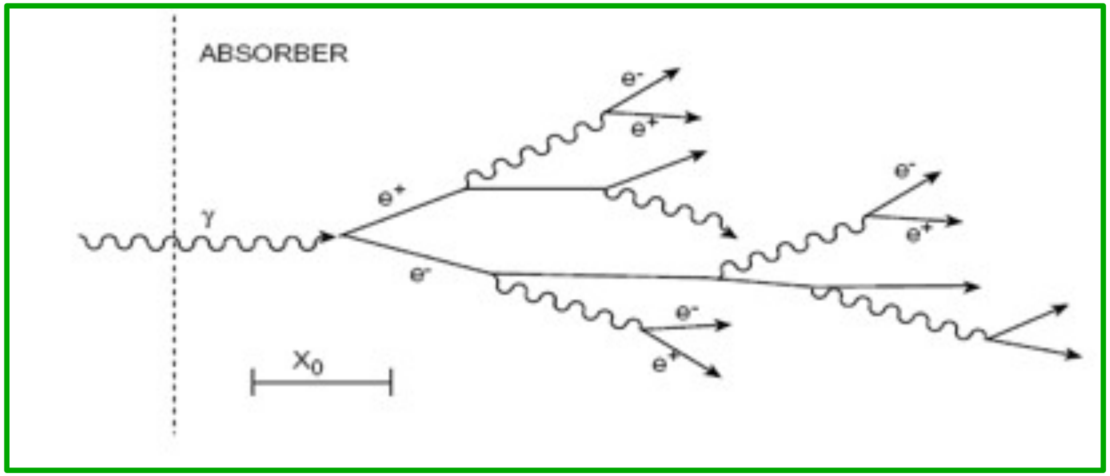
e



GEANT shower ($PbWO_4$ crystal)

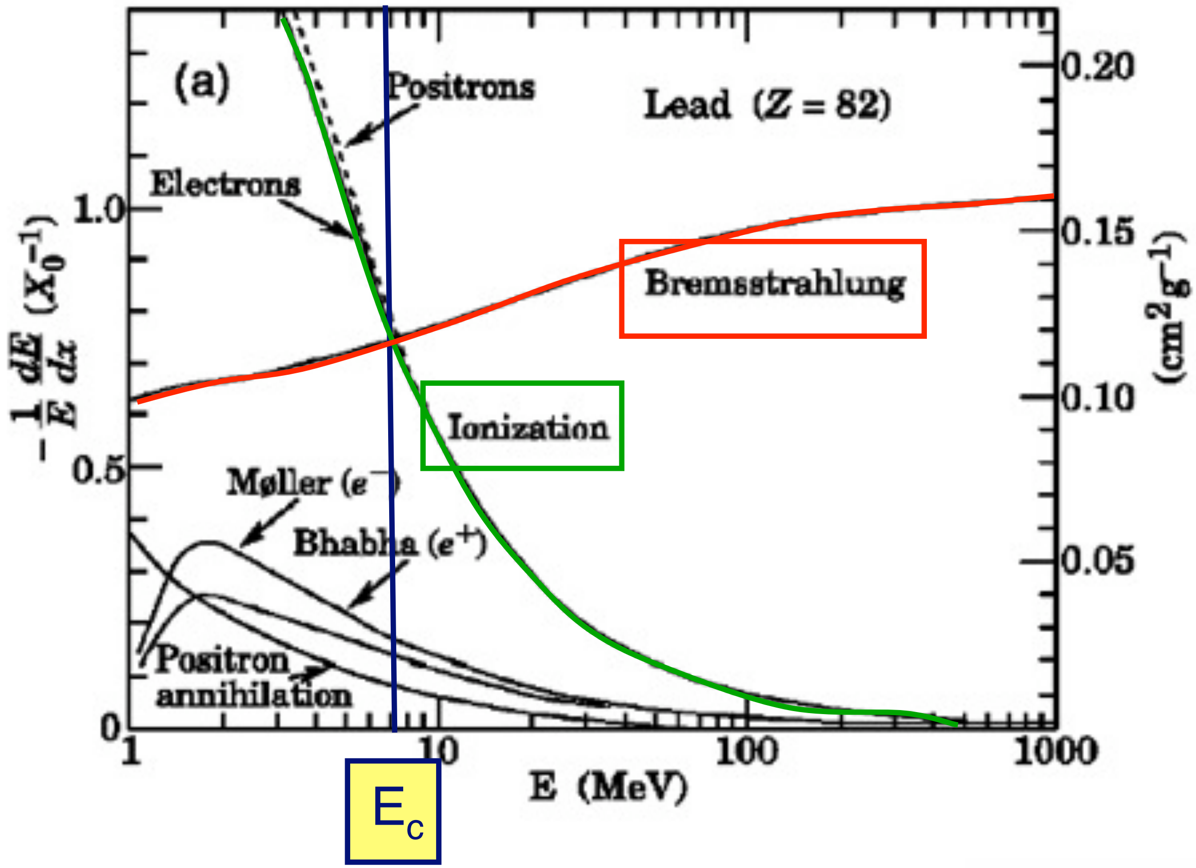
Electromagnetic showers

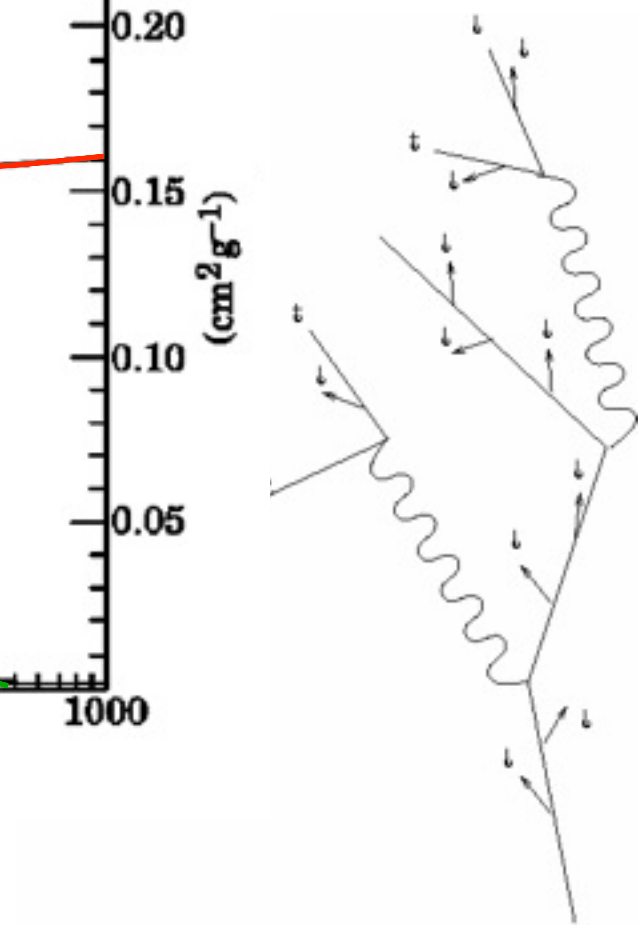
Electromagnetic showers result from electrons and photons undergoing bremsstrahlung and pair creation



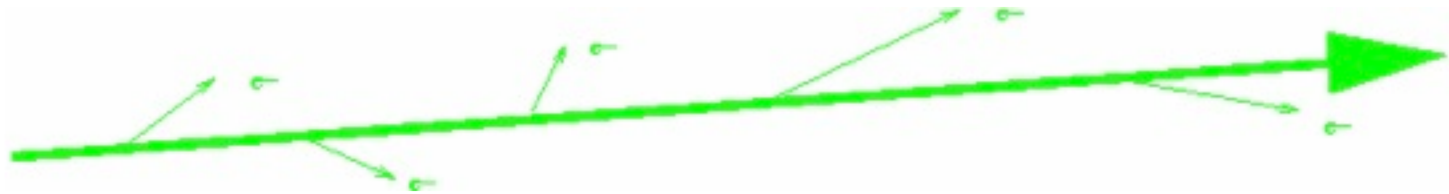
For high energy (GeV scale) electrons bremsstrahlung is the dominant energy loss mechanism
For high energy photons pair creation is the dominant absorption mechanism
Shower development is governed by these processes

Which processes contributes for electrons ?





Ionization



Interaction of charged particles with the atomic electronic cloud

Dominant process at low energy $E<E_c$

The whole incident energy is ultimately lost in the form of ionization and excitation of the medium

$$-\frac{dE}{dx}\bigg|_{ion} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

$\sigma \prec Z$

Ionization: detectable

Critical Energy E_c

$$\frac{dE}{dx}(E_c)\Big|_{Brem} = \frac{dE}{dx}(E_c)\Big|_{ioniz} \Rightarrow E_c$$

Solide

$$E_c = \frac{610 MeV}{Z + 1.24}$$

Liquide

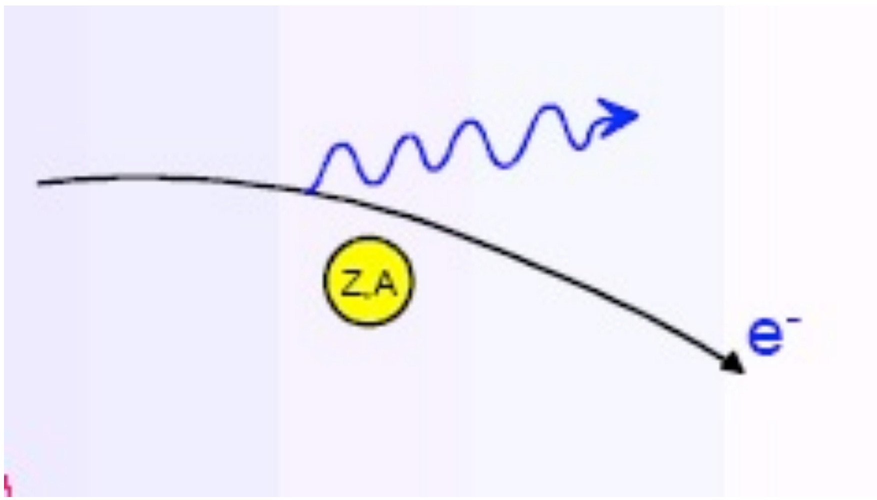
$$E_c = \frac{710 MeV}{Z + 0.92}$$

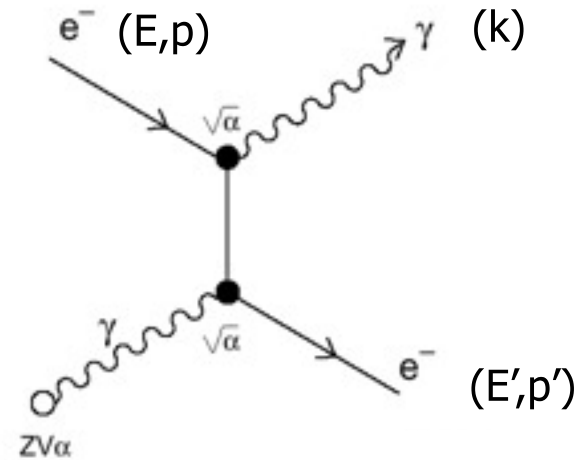
Materials	Z	Ec (MeV)	X_0 (cm)
Liquid Argon	18	37	14
Fe	26	22	1.8
Lead	82	7.4	0.56
Uranium	92	6.2	0.32

There are more ionizing particles ($E<E_C$) in a dense medium

Bremsstrahlung

Real photon emission in the electromagnetic field of the atomic nucleus





$$-\frac{dE}{dx}\bigg|_{Brem} = \frac{E}{X_0}$$

$$-\frac{dE}{dx}\bigg|_{rad} = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right]E$$

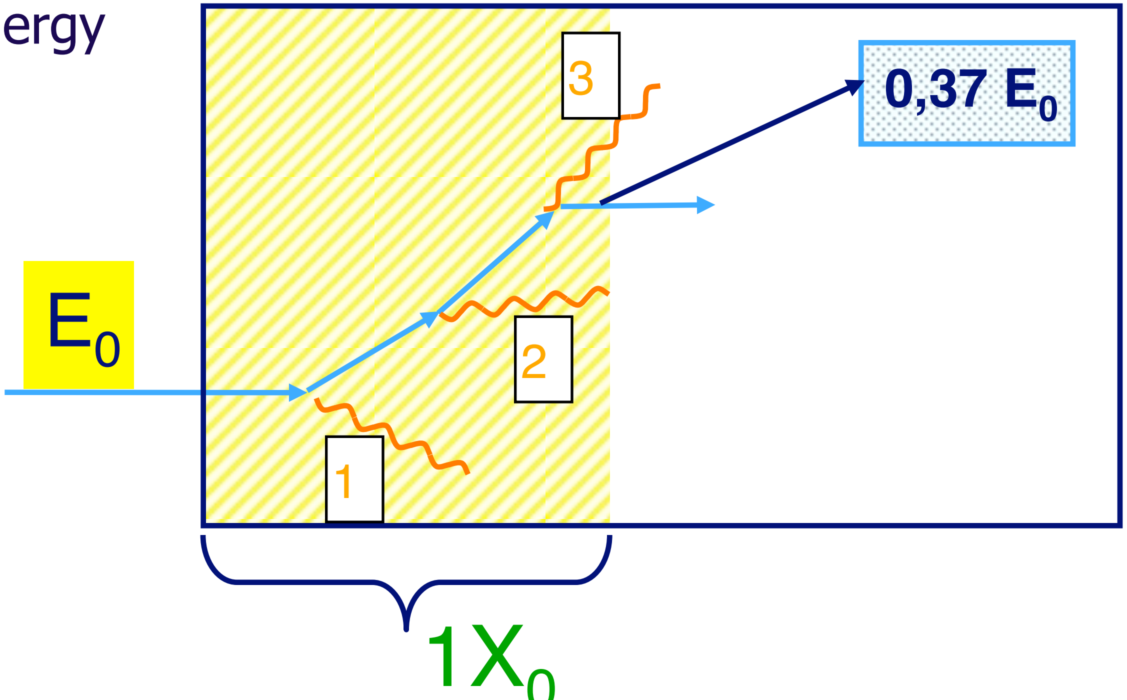
$\sigma \propto Z(Z+1)$

$\sigma \propto A/X_0$ $E>1$ GeV

Radiation Length

The radiation length is a "universal" distance, very useful to describe electromagnetic showers (electrons & photons)

X_0 is the distance after which the incident electron has radiated (1-1/e) 63% of its incident energy



	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

Radiation Length

Approximation

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

Energy loss by radiation

$$\langle E(x) \rangle = E_0\, e^{-\frac{x}{X_0}}$$

γ Absorption ($e^+ e^-$ pair creation)

$$\langle I(x) \rangle = I_0\, e^{-\frac{7}{9}\frac{x}{X_0}}$$

For compound material

$$1/X_0 = \Sigma\, w_j / X_j$$

Energy loss in matter: photons

Pair Production

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

Probability of conversion in 1 X_0 is $e^{-7/9}$

Can define mean free path:

$$\lambda_{pair} \approx \frac{9}{7} X_0$$

Compton scattering

$$\sigma_C \approx \frac{\ln E_\gamma}{E_\gamma}$$

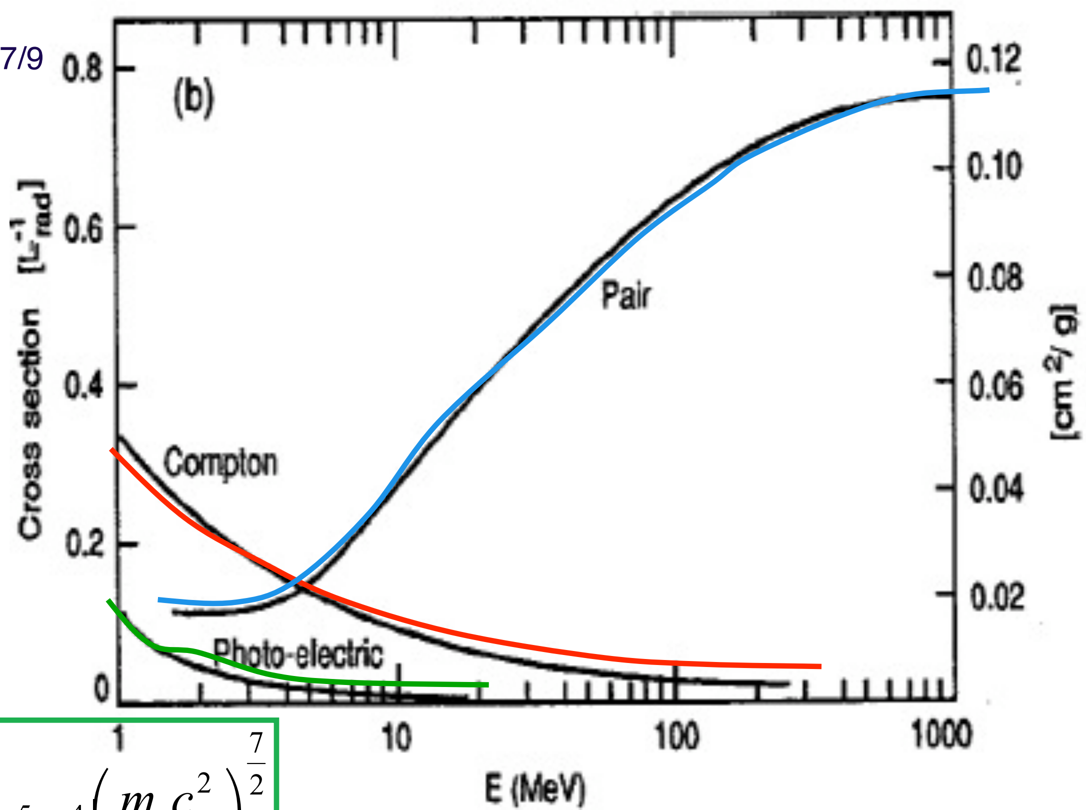


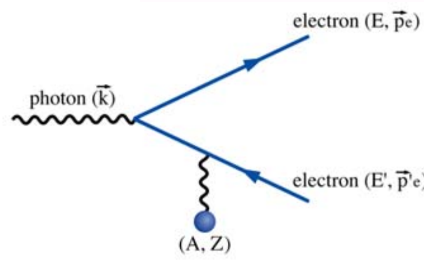
Photo-electric effect

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$

Pair production

Photon interaction with nucleus electric field or electrons if $E_\gamma > 2.m_e.c^2$.

$$\sigma_{pair} \sim 7/9 \ . \ A/N_A \ . \ 1/X_0 \ \propto Z(Z+1)$$



Cross-section is independent of E_γ (E_γ>1 GeV)

Conversion length $\lambda_{conv} = 9/7 \ X_0$

e^+e^- pair is emitted in the photon direction

$\theta \sim m_e/E_\gamma$

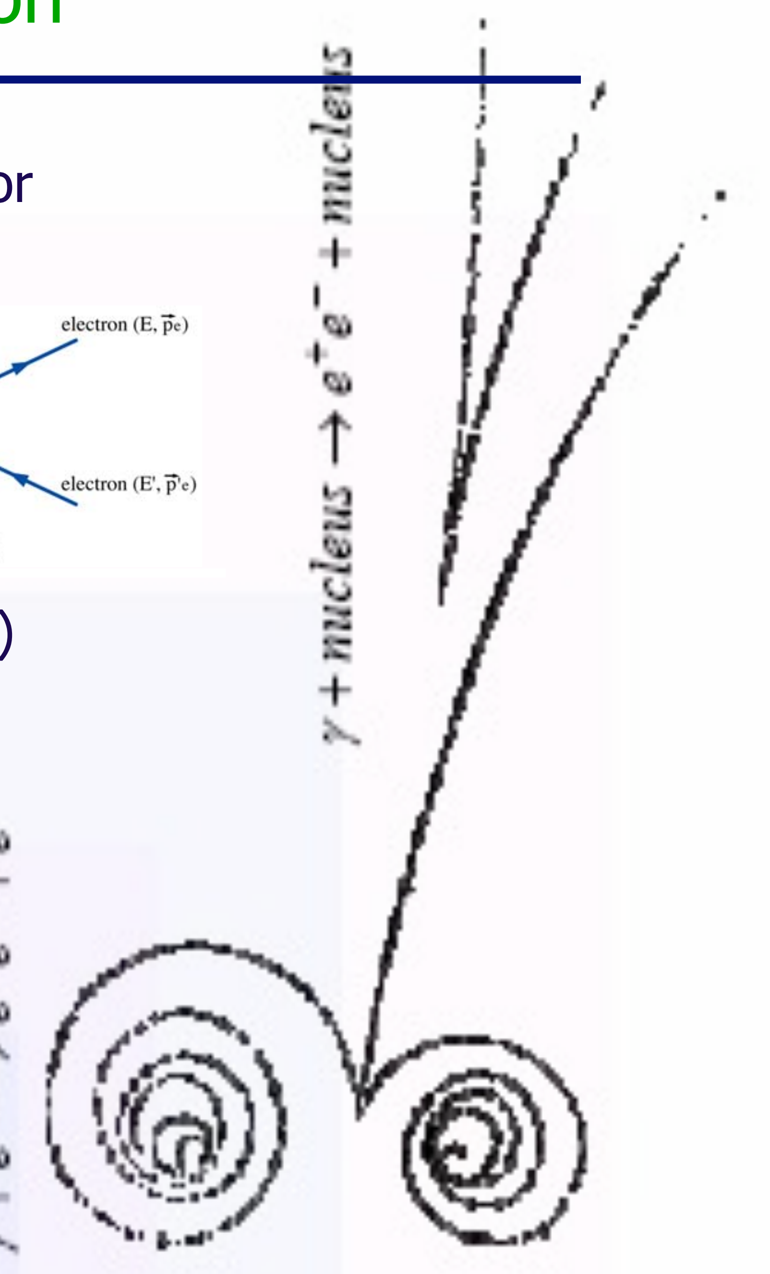


Photo-electric effect

Photon extracts an electron from the atom

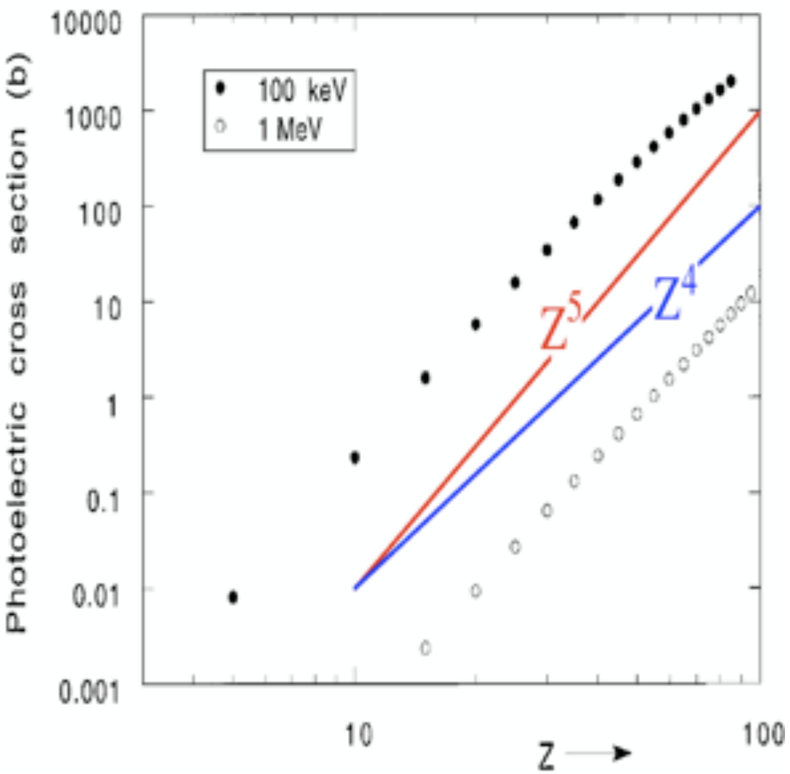
$\gamma + \text{atom} \rightarrow e^- + \text{atom}^*$

Cross-section

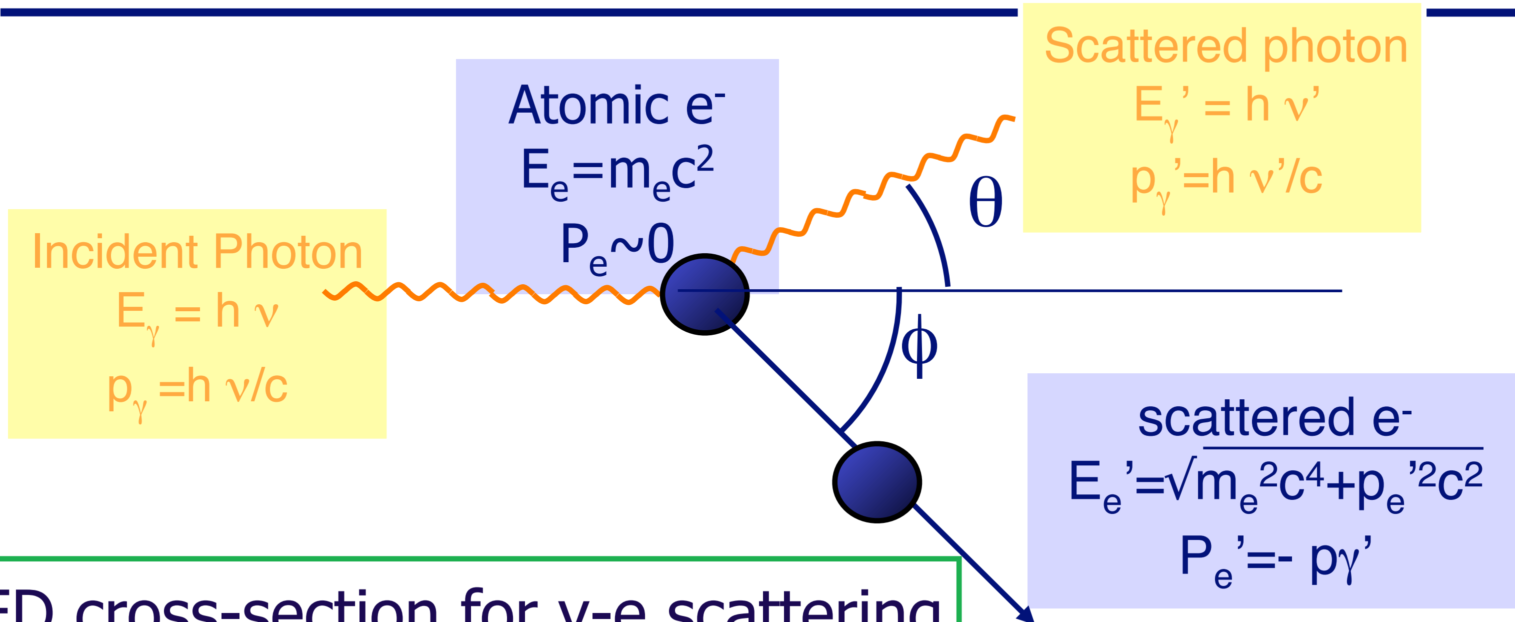
- strong function of the number of electrons
- Dominant at very low energy

$$\sigma \propto \frac{Z^5}{E^3}$$

Electrons are emitted isotropically



Compton scattering

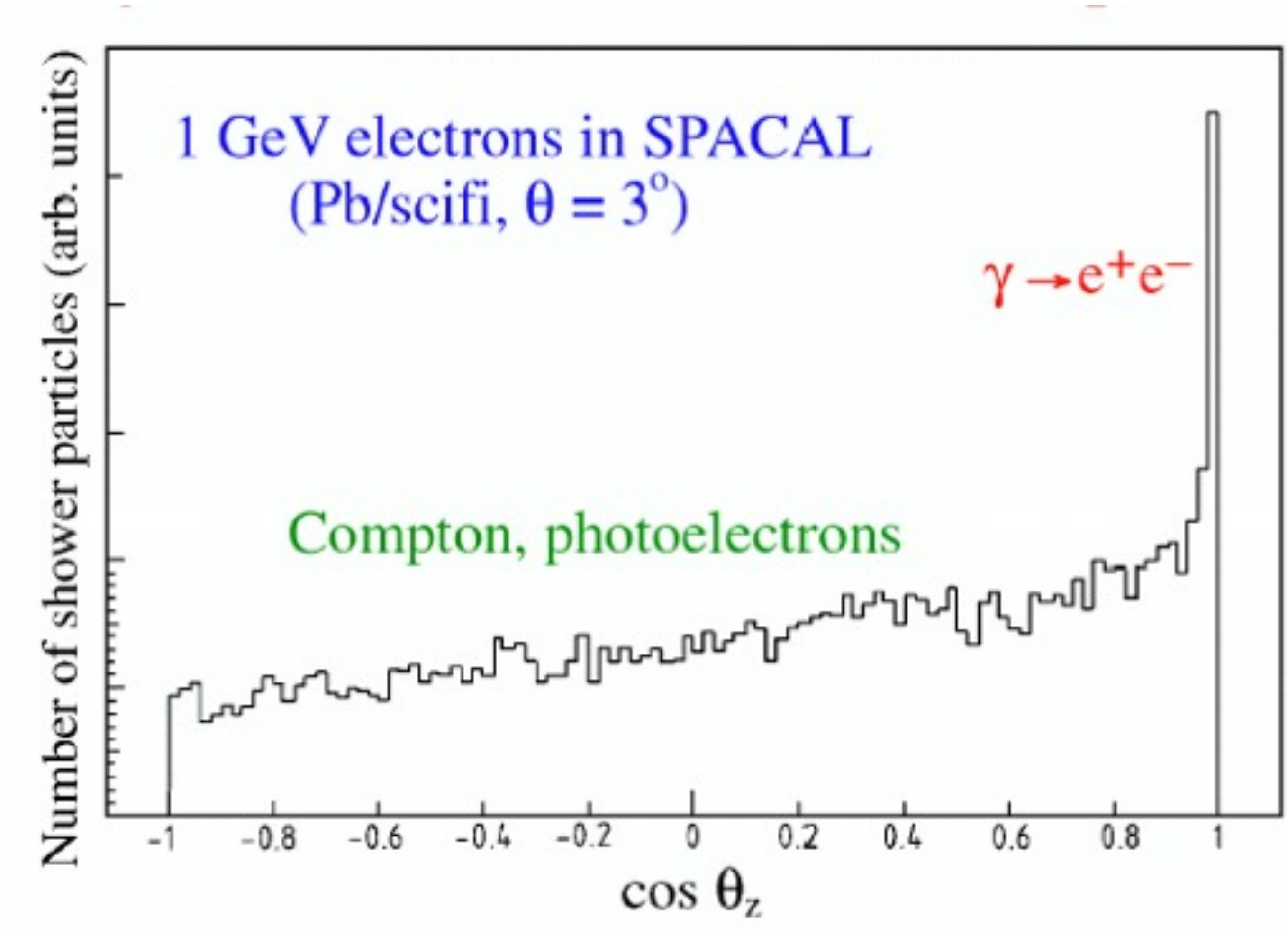


QED cross-section for γ-e scattering

$$\sigma_{compton} \sim Z \,.\, \ln(E_\gamma)/E_\gamma$$

Process dominant at $E\gamma \simeq$ 100 keV - 5 GeV

Angular distribution: γ



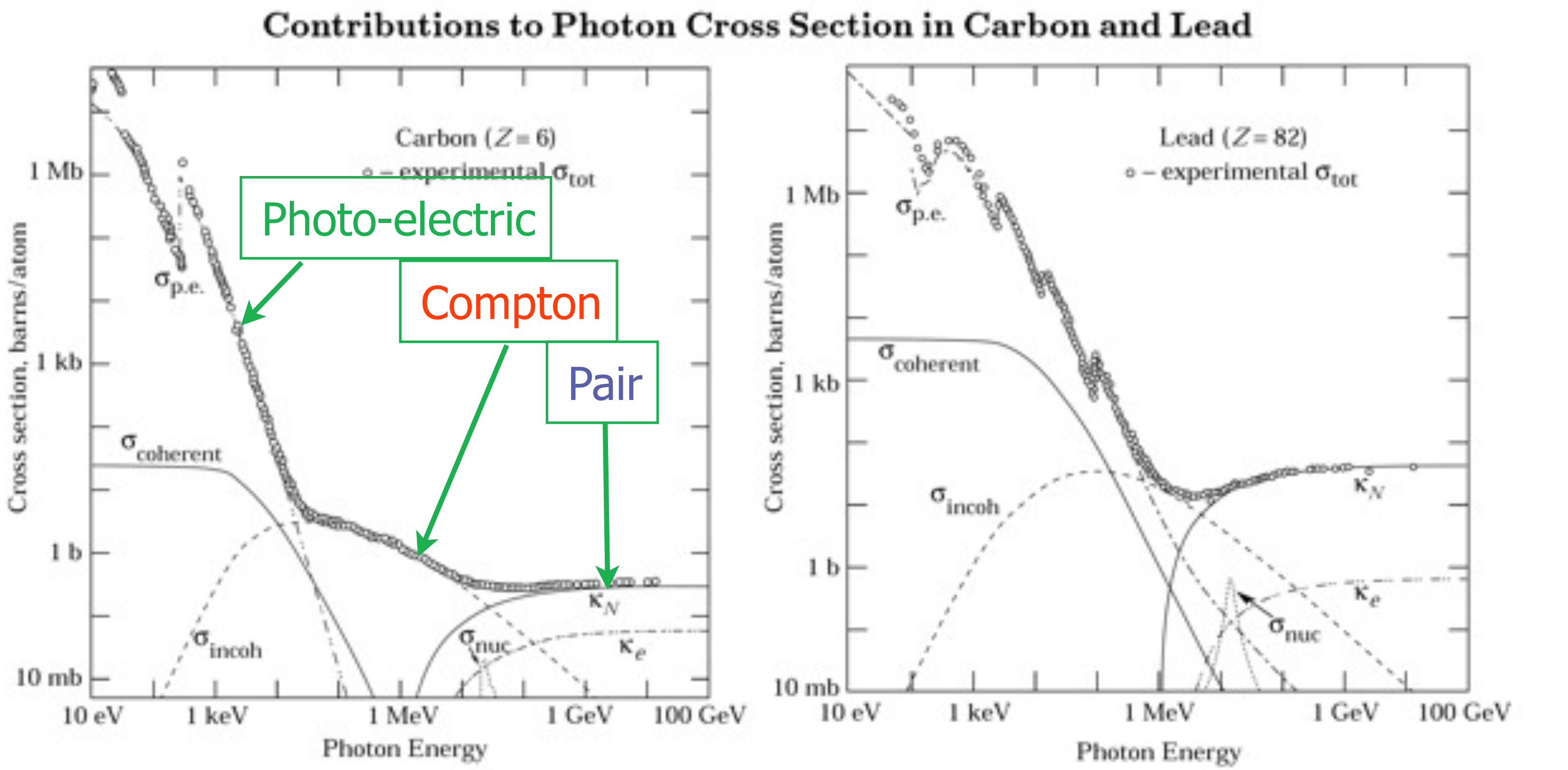


Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

$\sigma_{\rm p.e.}$ = Atomic photo-effect (electron ejection, photon absorption)

$\sigma_{\rm coherent}$ = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)

$\sigma_{\rm incoherent}$ = Incoherent scattering (Compton scattering off an electron)

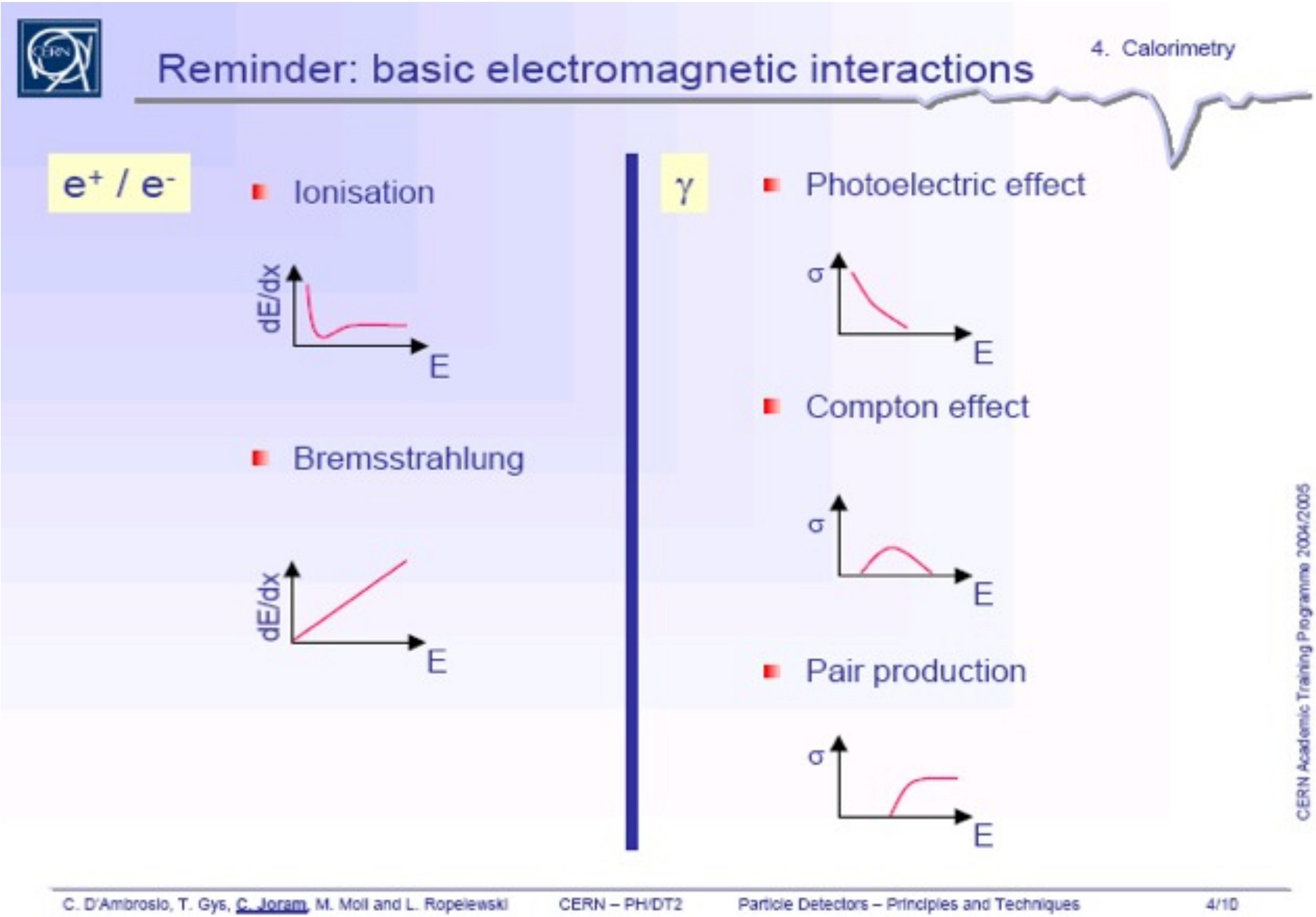
κ_n = Pair production, nuclear field

κ_e = Pair production, electron field

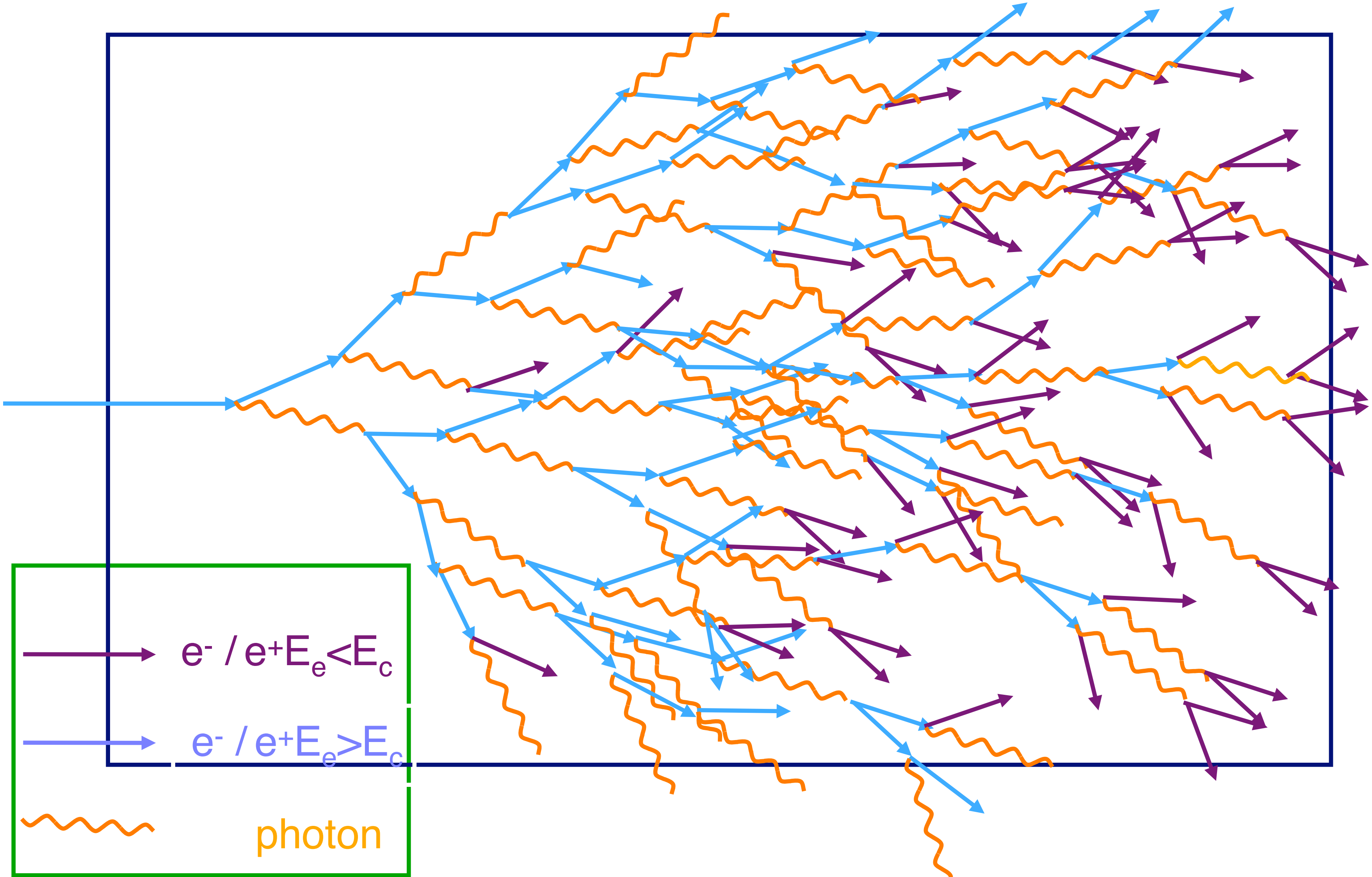
$\sigma_{\rm nuc}$ = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from `http://physics.nist.gov/PhysRefData`. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell (NIST).

Summary: electrons vs photon



Schematic shower development



Summary: development of EM showers

The shower develops as a cascade by energy transfer from the incident particle to a multitude of particles ($e^{\pm}$ and γ).

The number of cascade particles is proportional to the energy deposited by the incident particle

The role of the calorimeter is to count these cascade particles

The relative occurrence of the various processes briefly described is a function of the material (Z)

The radiation length (X_0) allows to universally describe the shower development

EM shower description: simple model

The multiplication of the shower continues until the energies fall below the critical energy, E_c

A simple model of the shower uses variables scaled to X_0 and E_c

$$t = \frac{x}{X_0}, y = \frac{E}{E_c}$$

Electrons loose about 2/3 of their energy in $1X_0$, and the photons have a probability of 7/9 for conversion: X_0 ~ generation length

After distance t:

number of particles, $n(t) = 2^t$

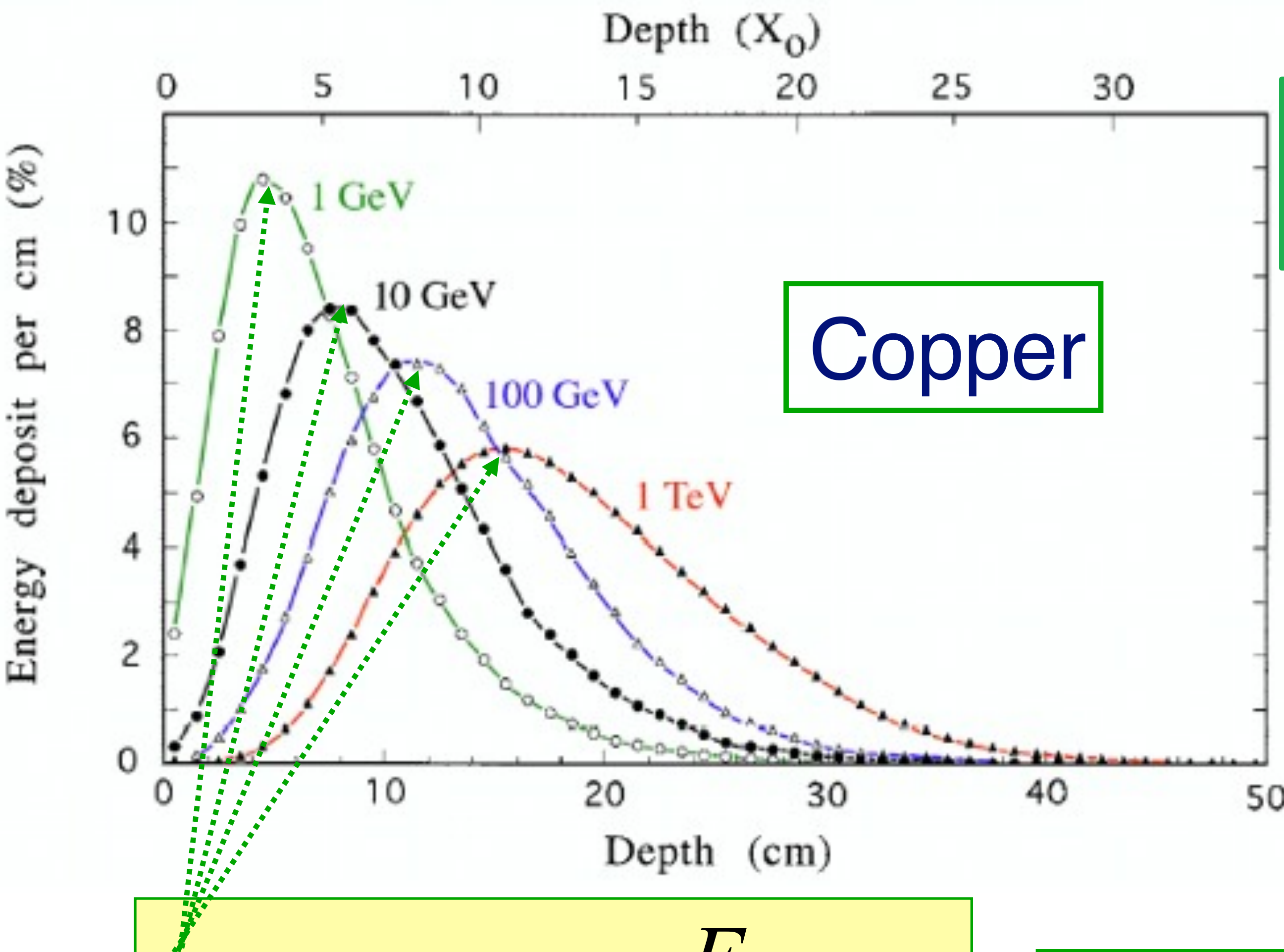
energy of particles, $E(t) \approx \frac{E}{2^t}$

When E~ E_c shower maximum:

$$n(t_{\max}) \approx \frac{E}{E_c} = y$$

$$t_{\max} \approx \ln\left(\frac{E}{E_c}\right) = \ln y$$

EM showers longitudinal development



$$\frac{dE}{dt} \propto E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Shower energy development parametrization

b: material

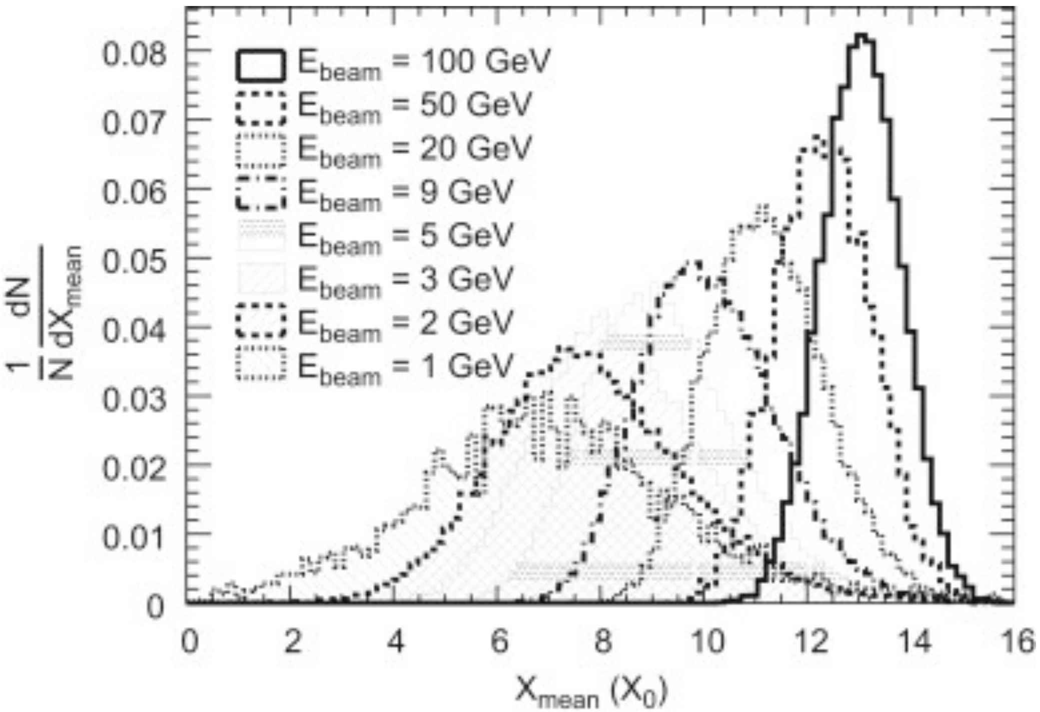
E.Longo & I.Sestili

(NIM128 (1975))

$$X_{max} = X_0 \ln\left(\frac{E}{E_c} + t_0\right)$$

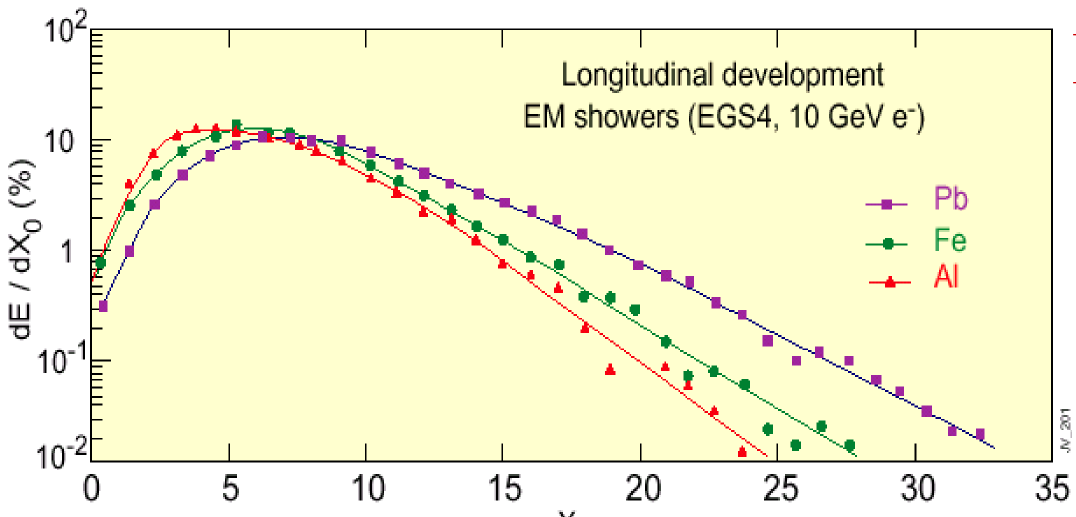
t_0= -0.5 electrons
+0.5 photons

EM showers longitudinal development



ATLAS combined testbeam 2004 setup

Electrons shower mean depth in X_0 (MC)
1,2,3,5,9,20,50, 100 GeV



$E_c \propto 1/Z$
→ Shower maximum
→ Shower tails
$t_{95\%} = t_{max} + 0.08Z + 9.6$

SEARCH FOR DECAYS OF THE Z^0 INTO A PHOTON AND A PSEUDOSCALAR MESON

- ALEPH Collaboration

D. DECAMP, B. DESCHIZEAUX, C. GOY, J.-P. LEES, M.-N. MINARD
Laboratoire de Physique des Particules (LAPP), IN2P3–CNRS, F-74019 Annecy-le-Vieux Cedex, France

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Measurement made by ALEPH

$e^+e^- \rightarrow e^+e^-$

$e^+e^- \rightarrow \gamma\gamma$

Electron/Photon longitudinal development: different

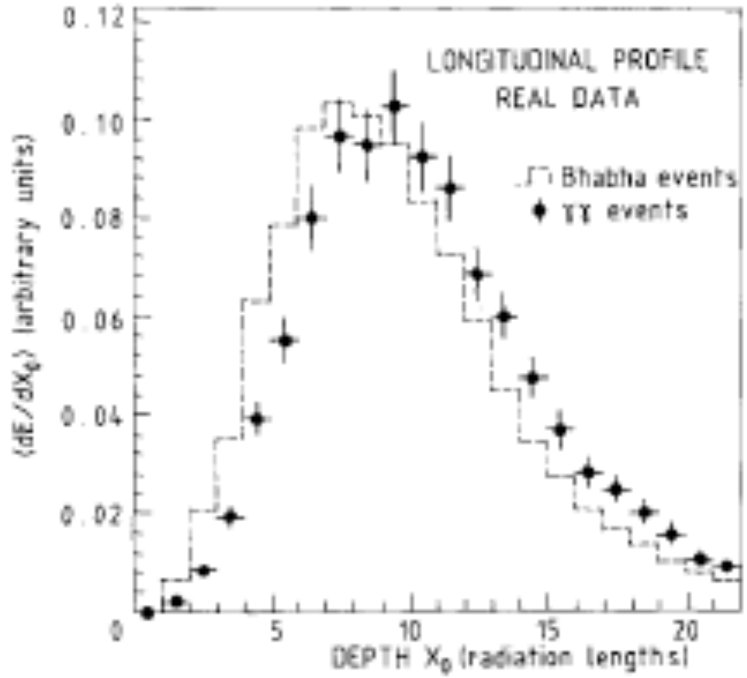


Fig. 1. Longitudinal profile of electromagnetic showers, both for electrons from $e^+e^- \rightarrow e^+e^-$ and for the $\gamma\gamma$ candidates. Both samples are real data. There is a clear shift by about 1 radiation length of the photon showers with respect to electron showers, as expected.

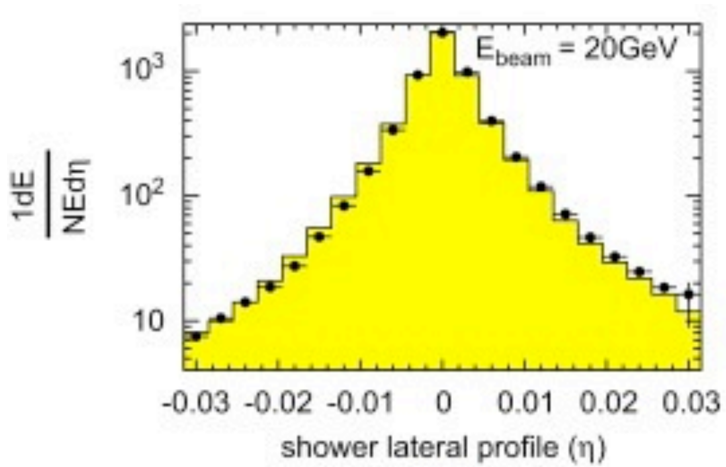
EM showers lateral development

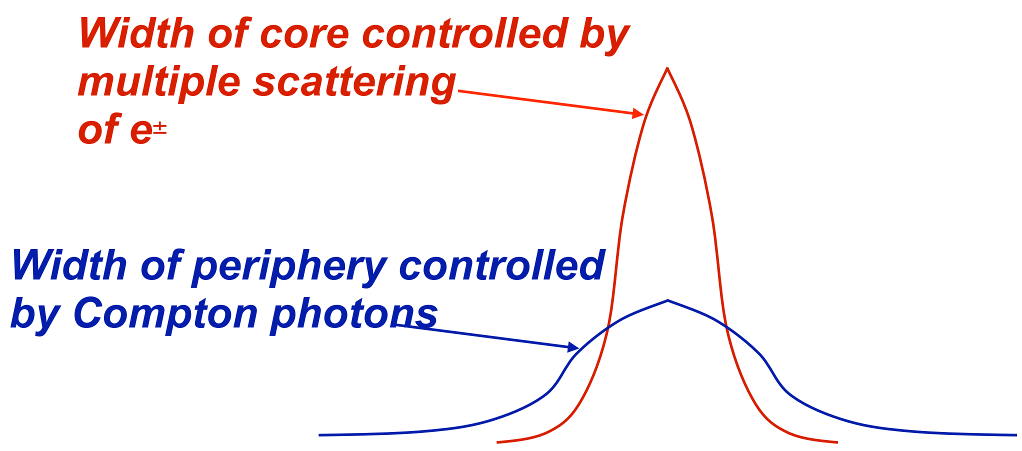
Molière radius, R_m, scaling factor for lateral extent, defined by:

$$R_M = \frac{21 MeV \times X_0}{E_c} \approx \frac{7A}{Z} g \times cm^{-2}$$

Gives the average lateral deflection of electrons of critical energy after $1X_0$

- 90% of shower energy contained in a cylinder of $1R_m$
- 95% of shower energy contained in a cylinder of $2R_m$
- 99% of shower energy contained in a cylinder of $3.5R_m$

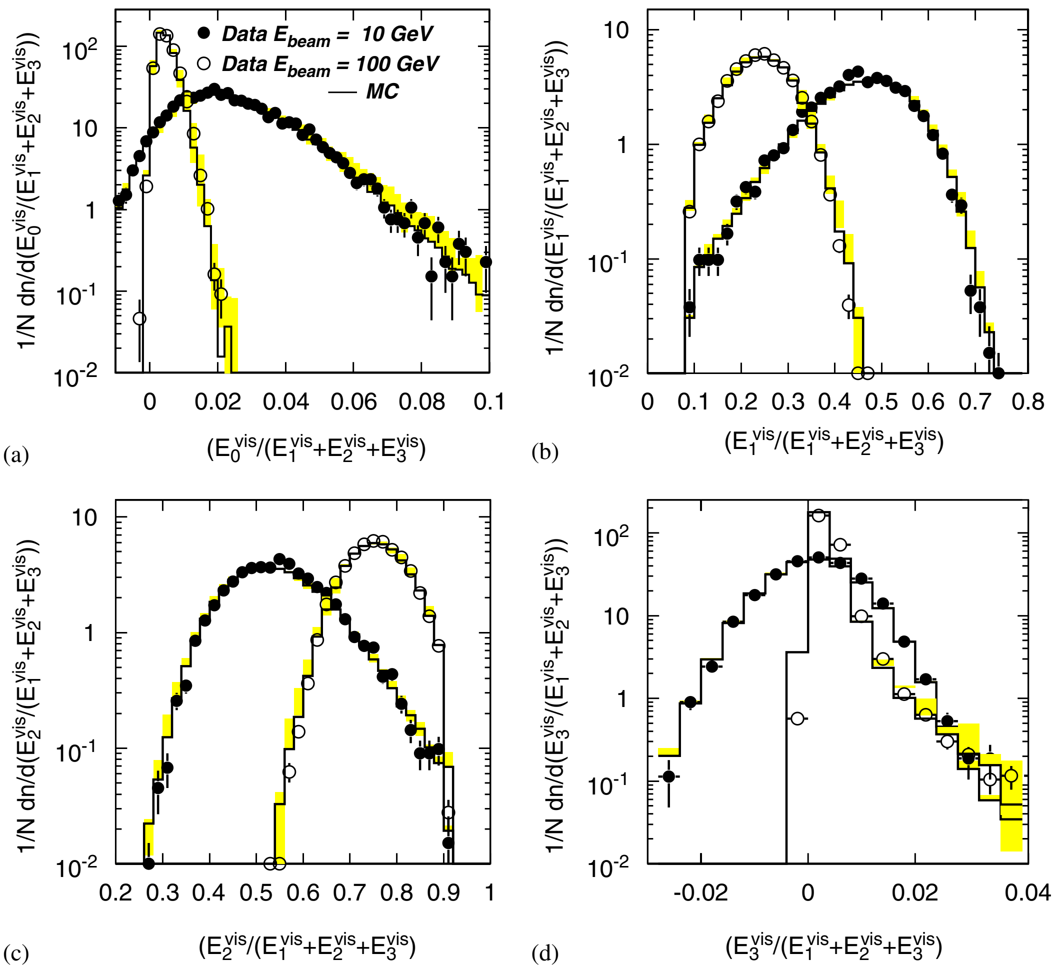




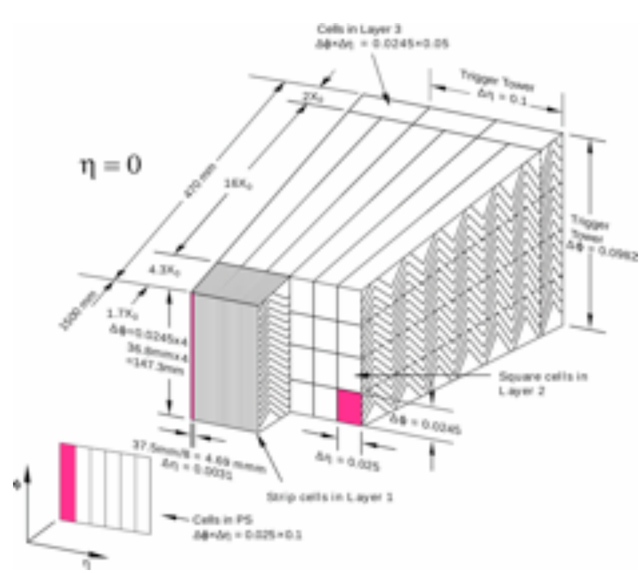
EM showers simulations

Electromagnetic processes are well understood and can be very well reproduced by MC simulation:

A key element in understanding detector performance



ATLAS EM calorimeter testbeam



Properties for electromagnetic calorimeters

Material	Z	Density [g cm^{-3}]	E_c [MeV]	X_0 [mm]	ρ_M [mm]	λ_{int} [mm]	$(dE/dx)_{mip}$ [MeV cm^{-1}]
C	6	2.27	83	188	48	381	3.95
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

Towards Electromagnetic Calorimeters

Detectable signal is proportional to the number of potentially detectable particles in the shower $N_{tot} \propto E_0/E_c$

Total track length $T_0 = N_{tot} \cdot X_0 \sim E_0/E_c \cdot X_0$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{T_0}} \propto \frac{1}{\sqrt{E}}$$

Detectable track length $T_r = f_s \cdot T_0$ where f_s is the fraction of N_{tot} which can be detected by the involved detection process (Cerenkov light, scintillation light, ionization) $E_{kin} > E_{th}$

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

Converting back to materials ($X_0 \propto A/Z^2$, $E_c \propto 1/Z$) and fixing E

- Maximize detection f_s
- Minimize Z/A

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{Z}{A}}$$

Exemple

Take a Lead Glass crystal

E_c = 15 MeV

produces Cerenkov light

Cerenkov radiation is produced par $e^{\pm}$ with $\beta > 1/n$, i.e $E > 0.7$MeV

Take a 1 GeV electron

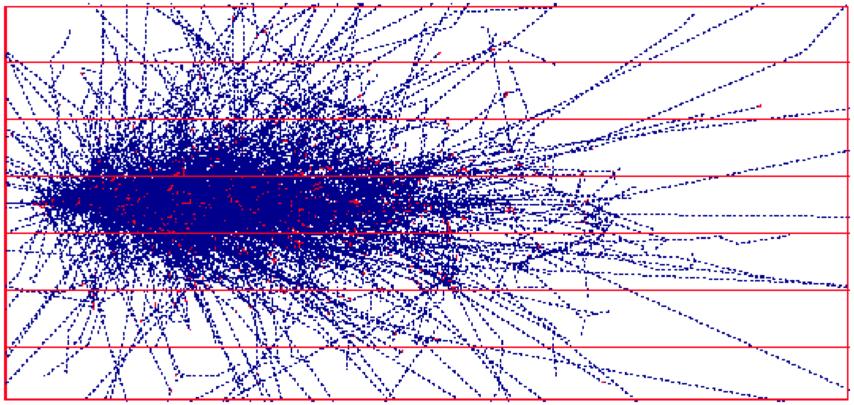
At maximum 1000 MeV/0.7 MeV $e^{\pm}$ will produce light

Fluctuation $1/\sqrt{1400} = 3\%$

One then has to take into account the photon detection efficiency which is typically 1000 photo-electrons/GeV: $1/\sqrt{1000} \sim 3\%$

Final resolution $\sigma/E \sim 5\%/\sqrt{E}$

Homogeneous calorimeters

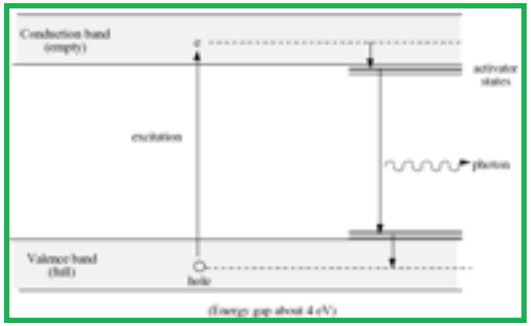


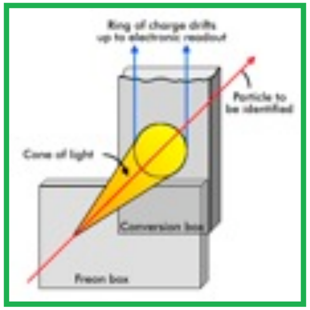
All the energy is deposited in the active medium

- Excellent energy resolution
- No longitudinal segmentation

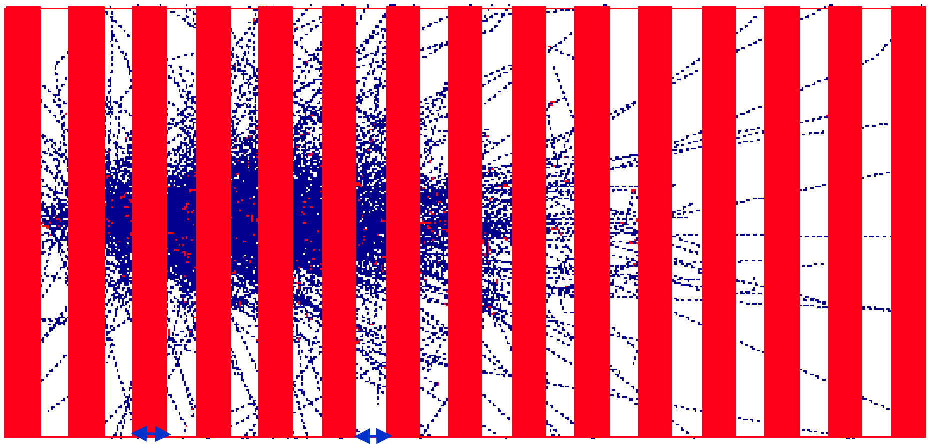
All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals	Cerenkov radiatros
$E_{th} \approx \beta . E_{gap} \sim$ eV	$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV
$\rightarrow 10^2 \div 10^4$ γ/MeV	$\rightarrow 10 \div 30$ γ/MeV
$\sigma/E \sim (1 \div 3)\% / \sqrt{E}$ (GeV)	$\sigma/E \sim (5 \div 10)\% / \sqrt{E}$ (GeV)





Sampling calorimeters



Shower is sampled by layers of an active medium and dense radiator

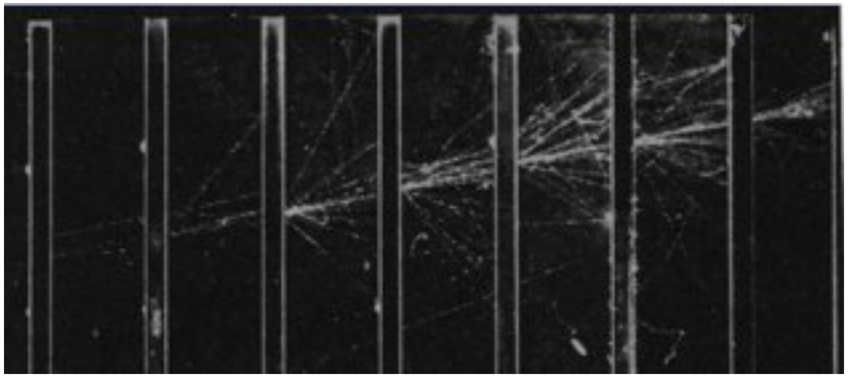
- Limited energy resolution
- Longitudinal segmentation

Only $e^{\pm}$ with $E_{kin} > E_{th}$ of the active layer produce a signal

Absorber (high Z): typically Lead, Uranium

Active medium (low Z): typically Scintillators, Liquid Argon, Wire chamber

Energy resolution of sampling calorimeter dominated by fluctuations in energy deposited in the active layers



$$\sigma(E)/E \sim (10 \div 20)\%/\sqrt{E}\ (\mathrm{GeV})$$

Sampling fluctuations

Most of detectable particles are produced in the absorber layers

Need to enter the active material to be counted/measured

Using the model of the track length

$T_r = f_s T_0 \sim f_s \,.\, E/E_c^{abs} \,.\, X_0^{abs}$

f_s: sampling fraction

Number of detectable particles in active layer

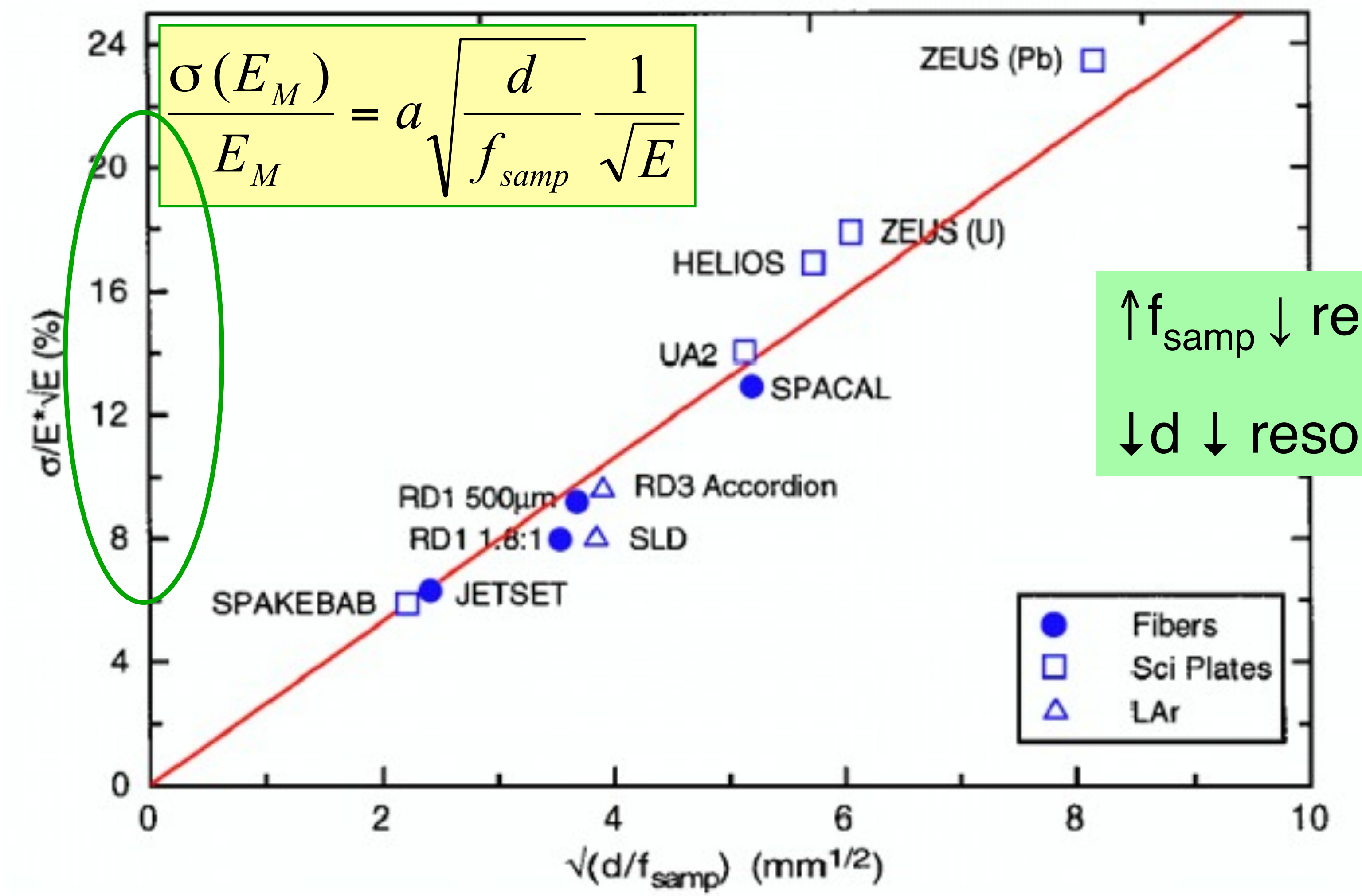
$N_r = T_r/d = f_s \,.\, E/E_c^{abs} \,.\, X_0^{abs}/d$

Resolution scales like

$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}}$$

Resolution for sampling calorimeters

$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}}$$



$\uparrow f_{samp} \downarrow$ resolution

$\downarrow d \downarrow$ resolution

Energy Resolution

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

a the stochastic term accounts for Poisson-like fluctuations

naturally small for homogeneous calorimeters

takes into account sampling fluctuations for sampling calorimeters

b the noise term (hits at low energy)

mainly the energy equivalent of the electronics noise

at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

c the constant term (hits at high energy)

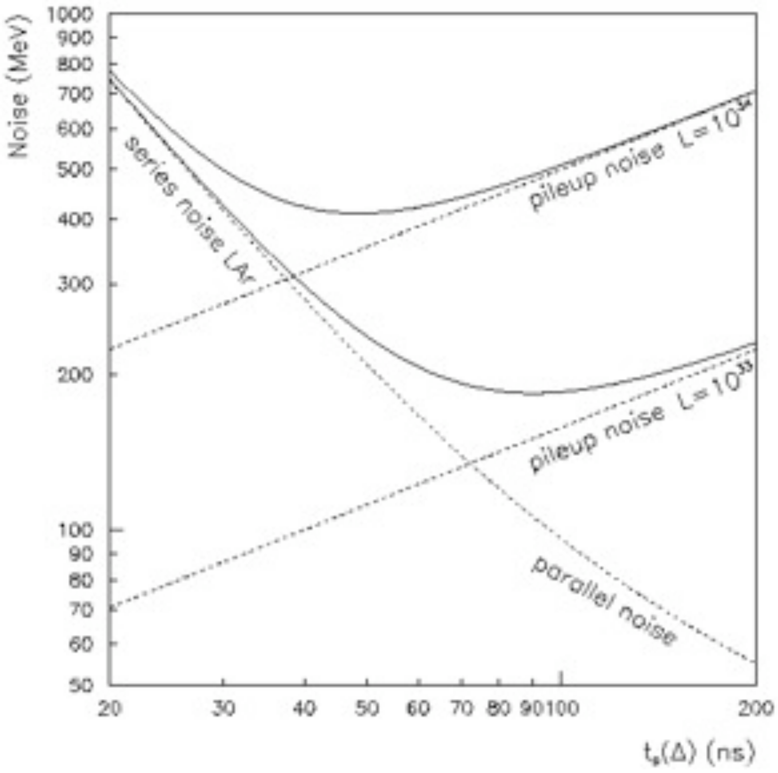
Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

Noise term at LHC: example for ATLAS EM

Electronics noise vs pile-up noise

Electronics integration time was optimized taking into account both contributions for LHC nominal luminosity if $10^{34}cm^{-2}s^{-1}$

Contribution from the noise to an electron is typically ~ 300-400 MeV at such luminosity



The constant term

The constant term describes the level of uniformity of response of the calorimeter as a function of position, time, temperature and which are not corrected for.

- Geometry non uniformity
- Non uniformity in electronics response
- Signal reconstruction
- Energy leakage

Dominant term at high energy

ATLAS LAr EMB testbeam

Correlated contributions	Impact on uniformity	
Calibration	0.23%	
Readout electronics	0.10%	
Signal reconstruction	0.25%	
Monte Carlo	0.08%	
Energy scheme	0.09%	
Overall (**data**)	0.38% (**0.34%**)	
Uncorrelated contribution	P13	P15
Lead thickness	0.09%	0.14%
Gap dispersion	0.18%	0.12%
Energy modulation	0.14%	0.10%
Time stability	0.09%	0.15%
Overall (**data**)	0.26% (**0.26%**)	0.25% (**0.23%**)

Interlude: muons

Muons interacting with matter

Muons are like electrons but behave differently when interacting with matter (at a given energy).

Bremsstralhung process is ~ $1/m^2$

m_e=0.519 MeV/c^2

m_μ=105,66 MeV/c^2

} $m\mu / m_e \sim$ **200** ➔ $(m\mu / me)^2 \sim$ **40000**

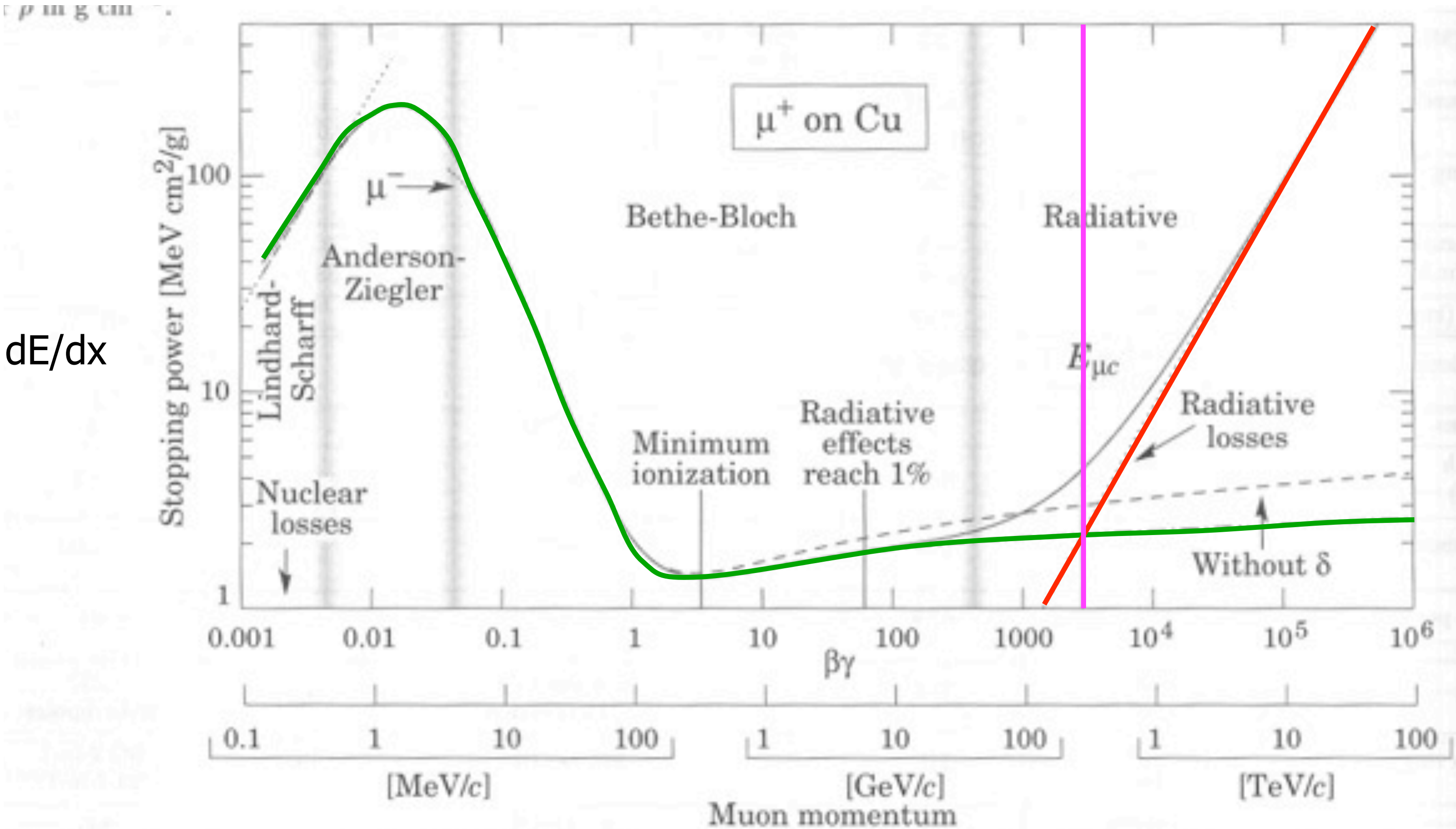
Contrary to electrons, muons (E<100GeV) loose energy mainly via ionization with

$E_c(\mu)=(m_\mu / m_e)^2 \times E_c(e)$

$E_c(\mu) \approx 200$ GeV in lead

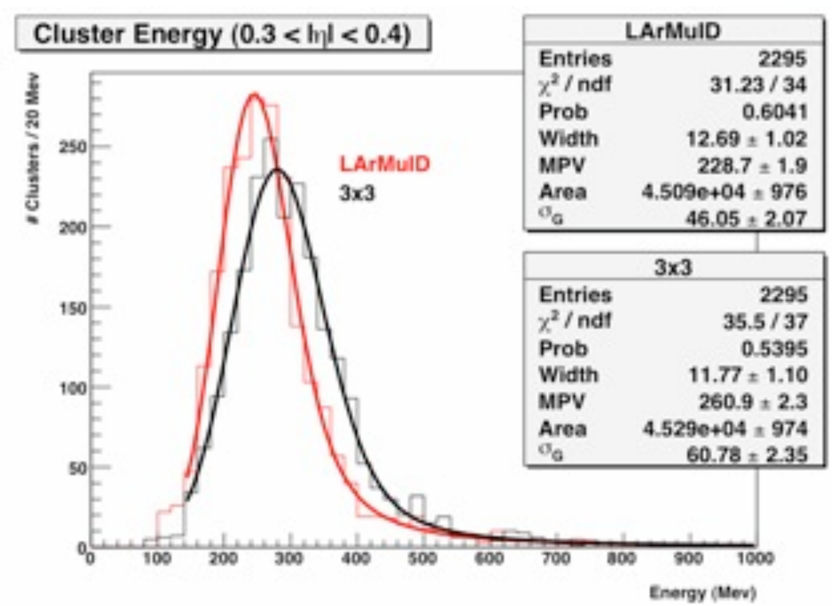
Muons in matter

dE/dx

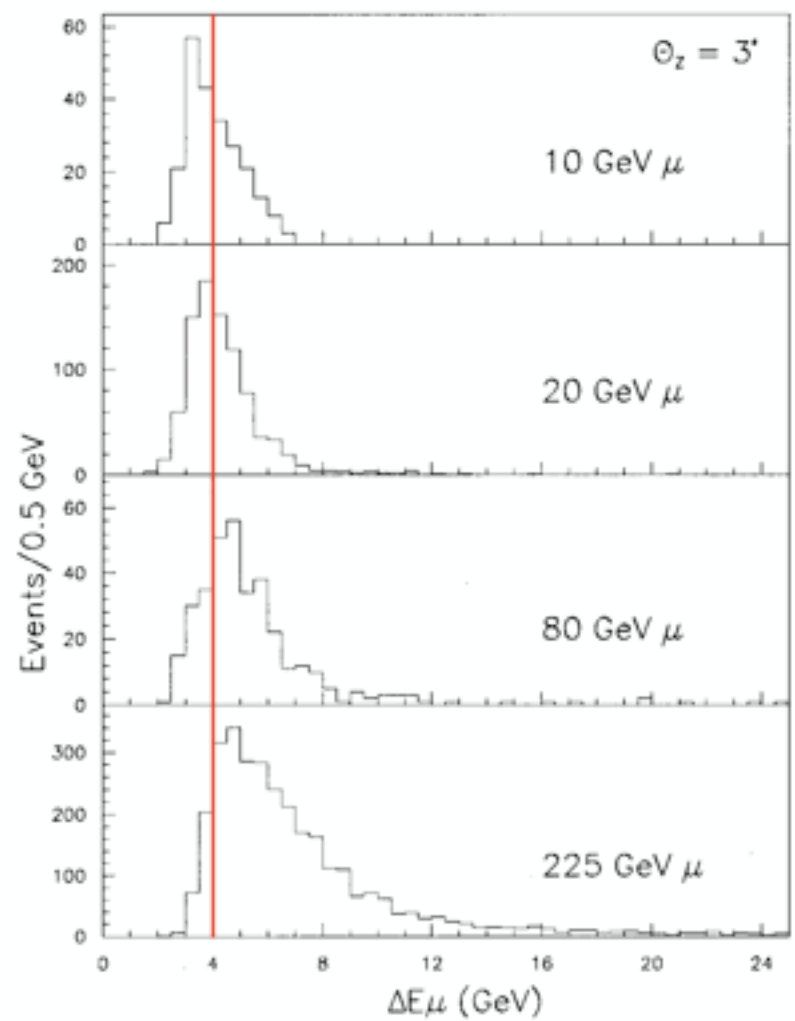


Energy deposit of muons in matter

Muons energy deposit in matter is not simply proportional to their energy.



Cosmic μ in ATLAS LAr EM barrel



Muons for calorimeters

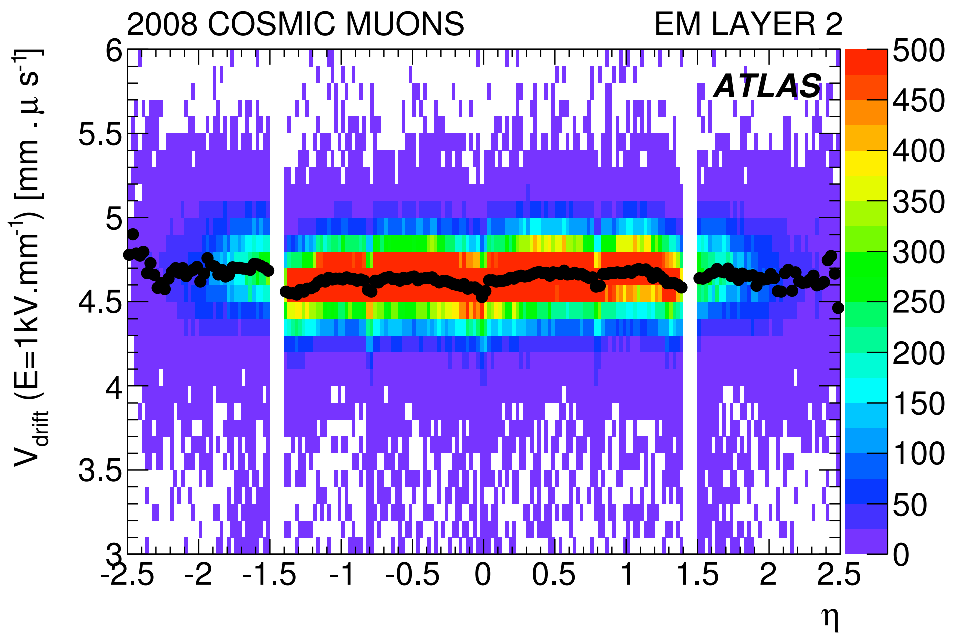
Muons deposit very little energy in calorimeter: dE/dx . x

- Except for catastrophic energy loss (γ emission)

They are nice tools to assess calorimeter response uniformity

- at low energy

They are nice clean probes to analyze the calorimeter geometry



(b) Drift velocity

End of interlude

Hadronic Showers

Hadron showers

Hadronic cascades develop in an analogous way to e.m. showers

- Strong interaction controls overall development
- High energy hadron interacts with material, leading to multi-particle production of more hadrons
- These in turn interact with further nuclei
- Nuclear breakup and spallation neutrons
- Multiplication continues down to the pion production threshold
  - $E \sim 2m_{\pi} = 0.28$ GeV/c^2
- Neutral pions result in an electromagnetic component (immediate decay: $\pi^0 \to \gamma\gamma$) (also: $\eta \to \gamma\gamma$)

Energy deposited by:

- Electromagnetic component (i.e. as for e.m. showers)
- Charged pions or protons
- Low energy neutrons
- Energy lost in breaking nuclei (nuclear binding energy)

Hadronic Showers: Where does the energy go?

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Hadronic shower development

Simple model of interaction on a disk of radius R: $\sigma_{int} = \pi R^2 \propto A^{2/3}$

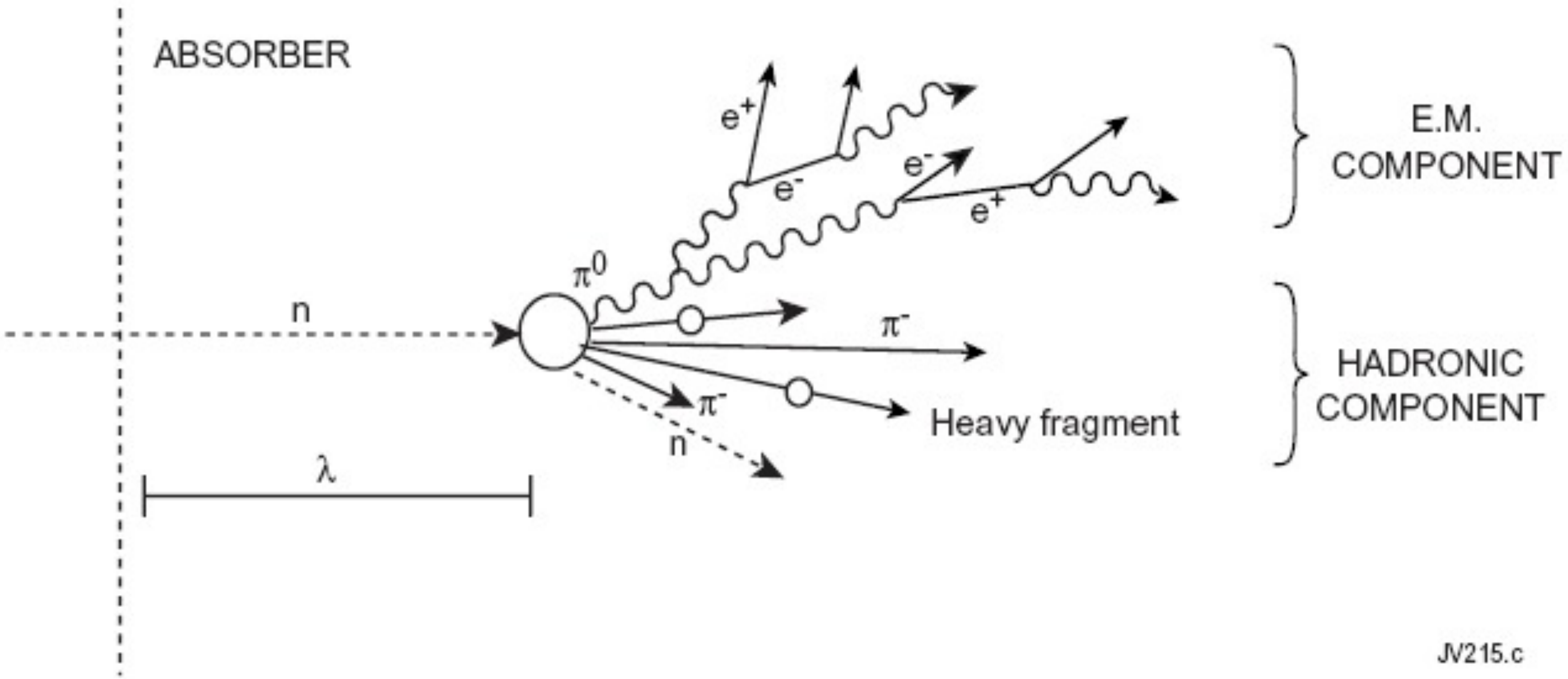
$\sigma_{inel} \approx \sigma_0 A^{0.7}$, σ_0 = 35 mb

Nuclear interaction length: mean free path before inelastic interaction

$$\lambda_{int} \approx \frac{A}{N_A \sigma_{int}} \approx 35 A^{1/3} g \times cm^{-2}$$

	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14.0	84.0
Fe	26	7.9	24	1.76	16.8
Cu	29	9.0	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19.0	6.2	0.32	10.5

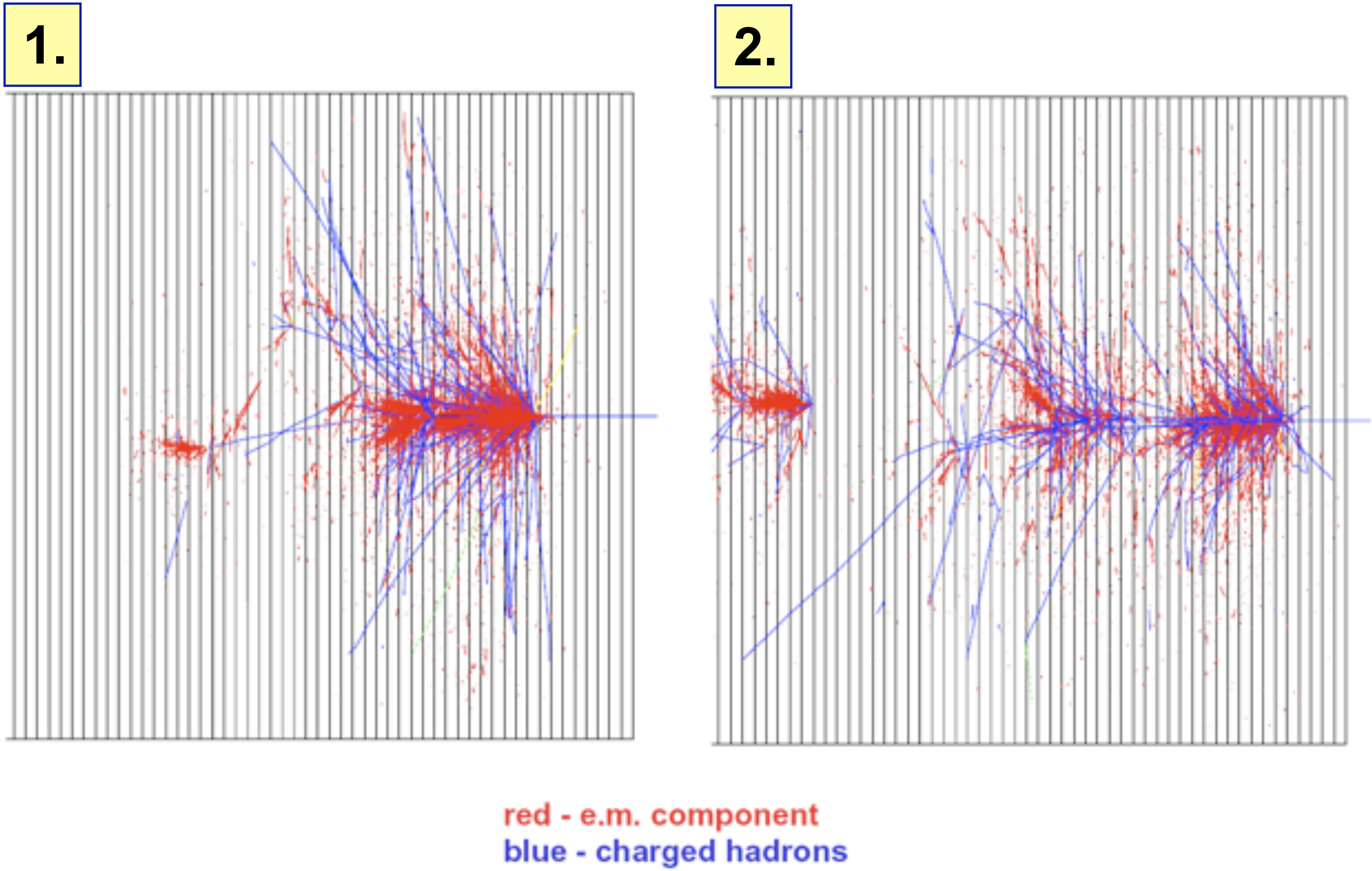
Hadronic cascade



As compared to electromagnetic showers, hadron showers are:

- Larger/more penetrating
- Subject to larger fluctuations – more erratic and varied

Hadron showers



- Individual hadron showers are quite dissimilar

Hadronic shower and non compensation

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

- R_h: Response to hadrons
- ε_e: fract. of detected EM energy
- E_e: shower EM energy
- ε_h: fract. of detected HAD energy
- E_h: shower HAD enerrgy

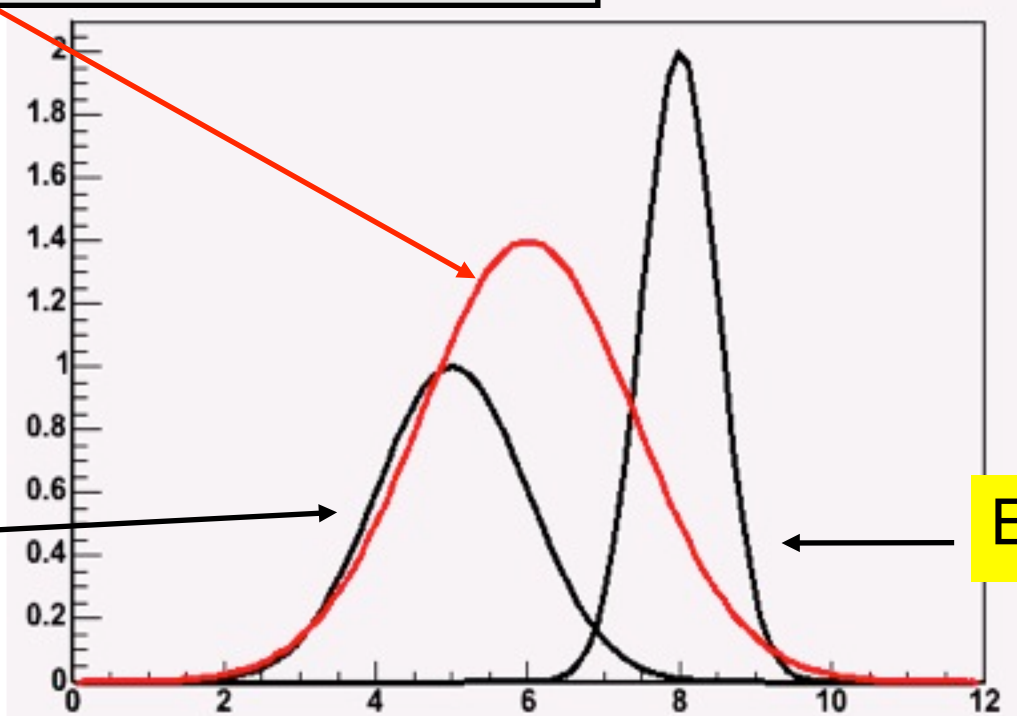
$$\frac{e}{h} = \frac{\varepsilon_e}{\varepsilon_h}$$

- ≈ 1 : compensating calorimeter
- > 1 : non compensating calorimter

Hadronic showers: non compensation

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

$\varepsilon_e > \varepsilon_h$



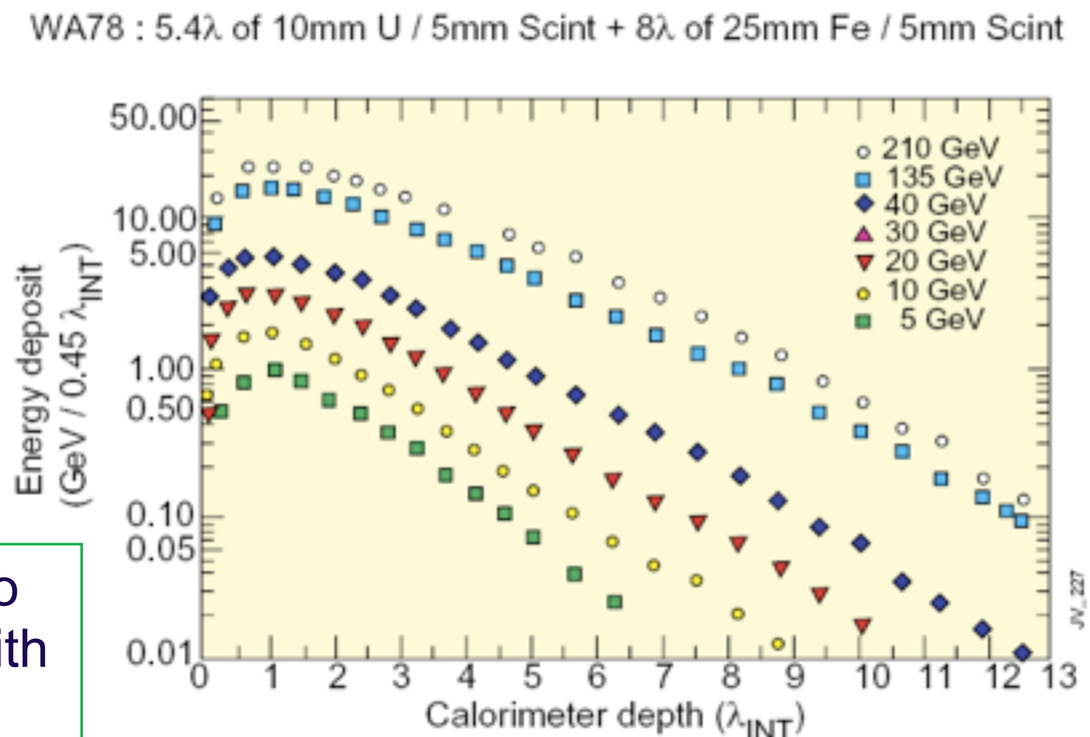
$E_e \ll E_h$

$E_e \gg E_h$

Hadron shower longitudinal profiles

Longitudinal profile

- Initial peak from π^0s produced in the first interaction
- Gradual falloff characterized by the nuclear interaction length, λ_{int}



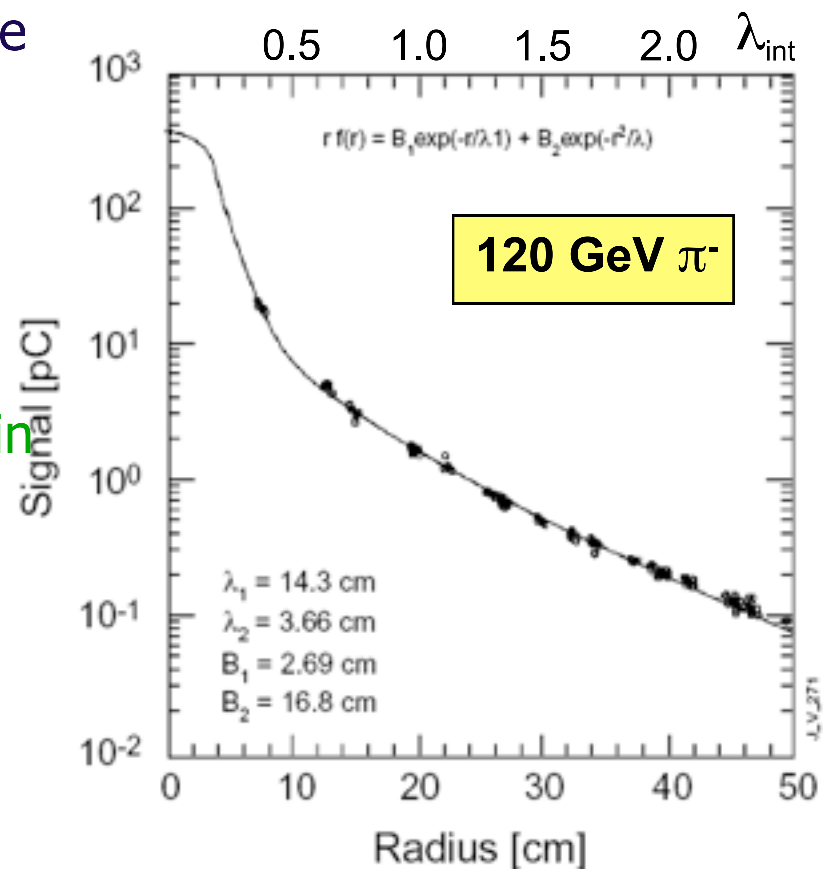
As with e.m. showers: depth to contain a shower increases with log(E)

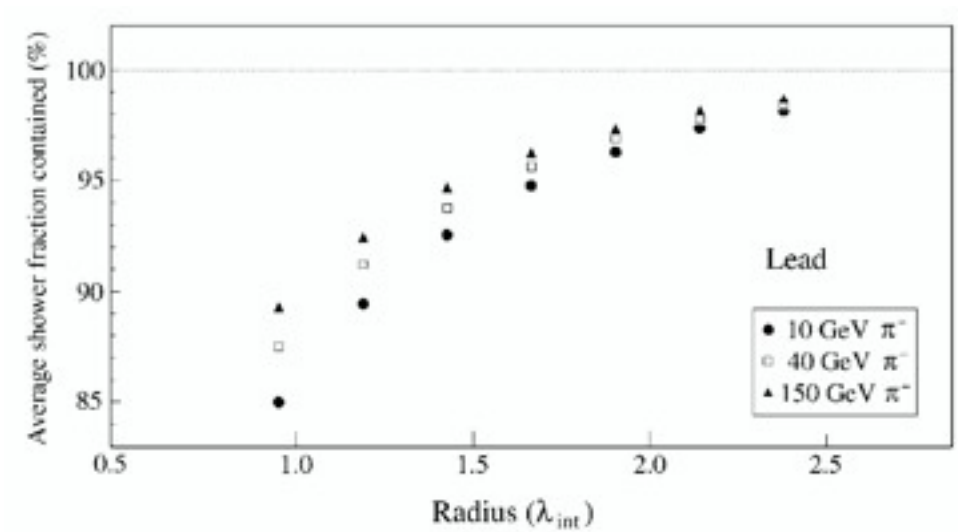
Hadron shower transverse profiles

Mean transverse momentum from interactions, $\langle p_T \rangle \sim 300$ MeV, is about the same magnitude as the energy lost traversing 1λ for many materials

So radial extent of the cascade is well characterized by λ

The π^0 component of the cascade results in an electromagnetic core





Lateral containment increases with energy

Summary

Why use calorimeters ?

EM processes involved in interactions of $e^{\pm}/\gamma$ with matter

EM showers general characteristics

EM calorimeters: homogenous vs sampling

- Stochastic term
- Energy resolution

Hadronic showers

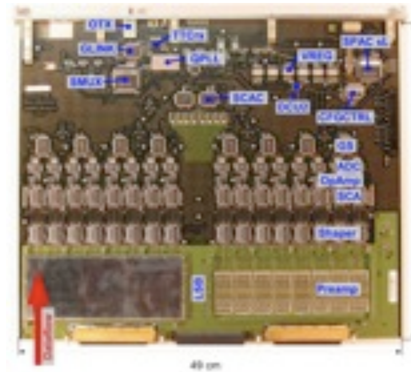
- More erratic development

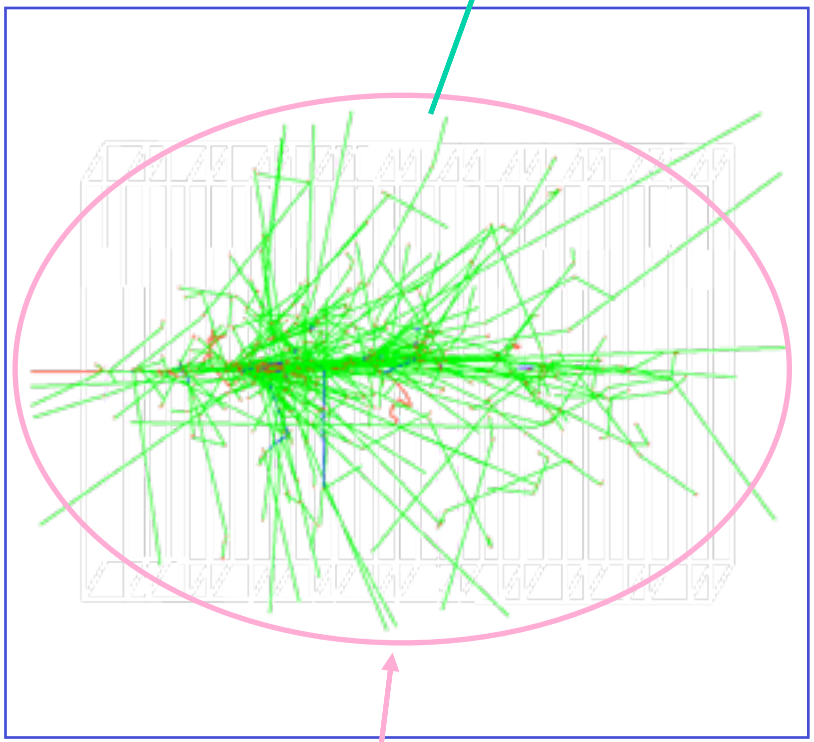
Next lecture

- Tevatron & LHC calorimeters
- Performance
- Calorimeters for ILC

Signal detection (light, electric charge)
Homogenous or sampling calorimeters

Electronics
(conversion, amplification,
signal transmission)





Interaction with matter

Calorimeters