Calorimetry

concept & examples

European School of Instrumentation in Particle & Astroparticle Physics ESIPAP 2016

Lecture 1

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PROGRAMME

Lesson 1

Why build calorimeters ?

Lesson 1

Why build calorimeters ?

Electromagnetic showers

Calorimeter energy resolution

Lesson 2

Hadronic showers & calorimeters

Jets

Missing Transverse Energy

CMS & ATLAS calorimeters

Lesson 3

Other calorimeters

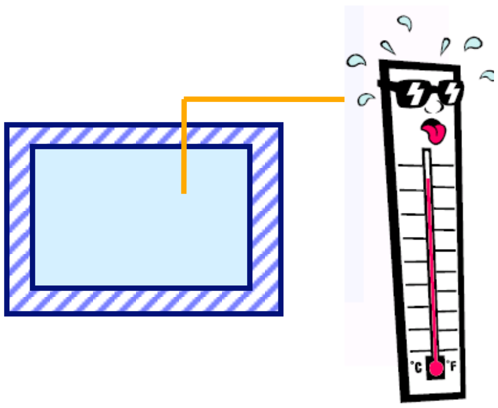
Calorimeter R&Ds for future colliders

Tutorial

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 degree

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.

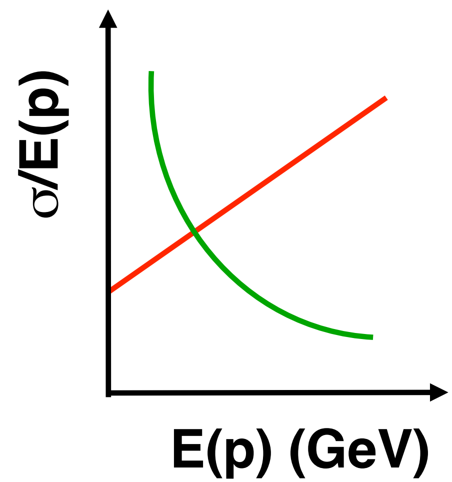
Until then, only the momentum of charged particles was measured using magnetic analysis.

The measurement with a calorimeter is destructive e.g.

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

Magnetic analysis

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

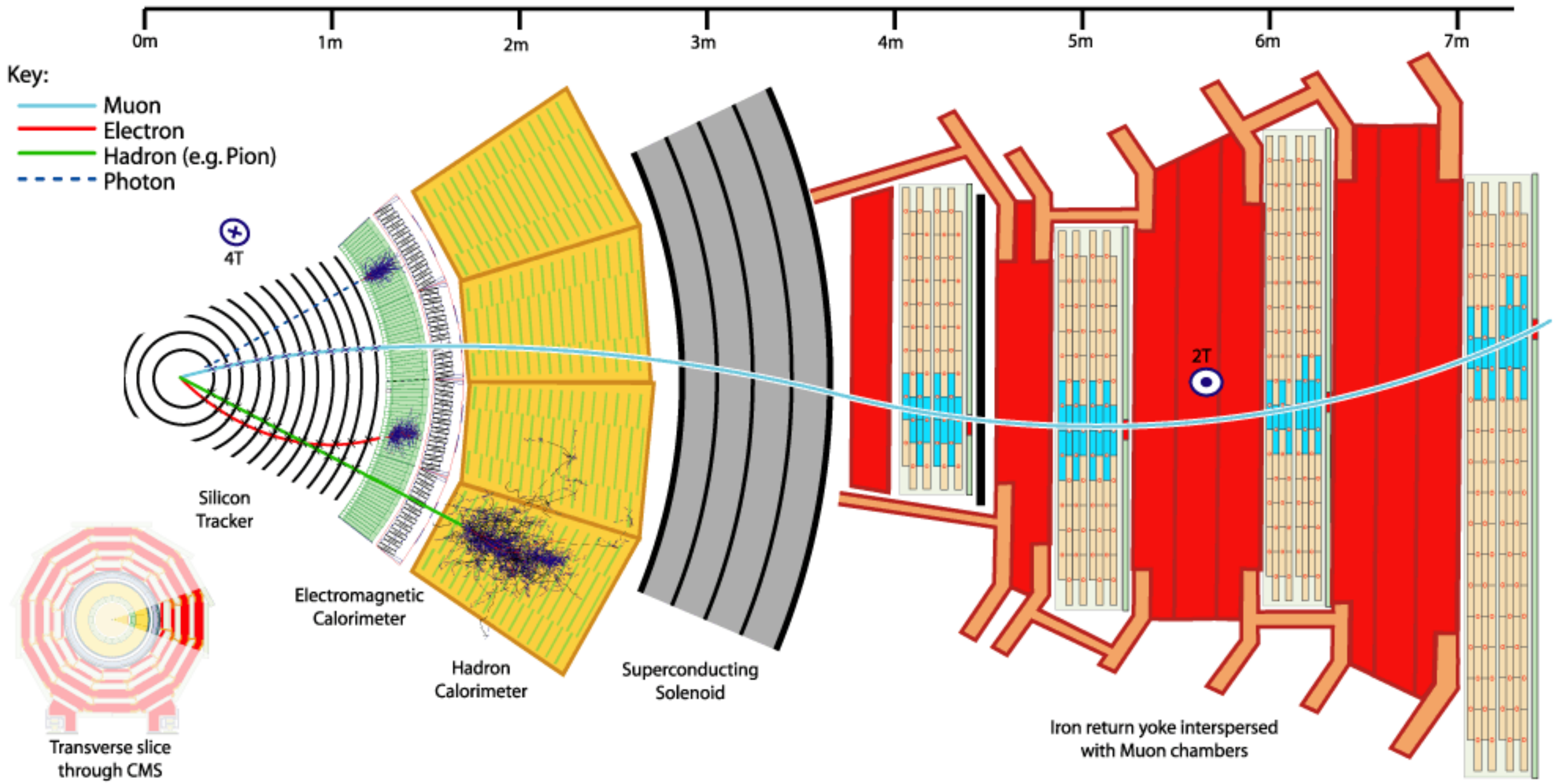


$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

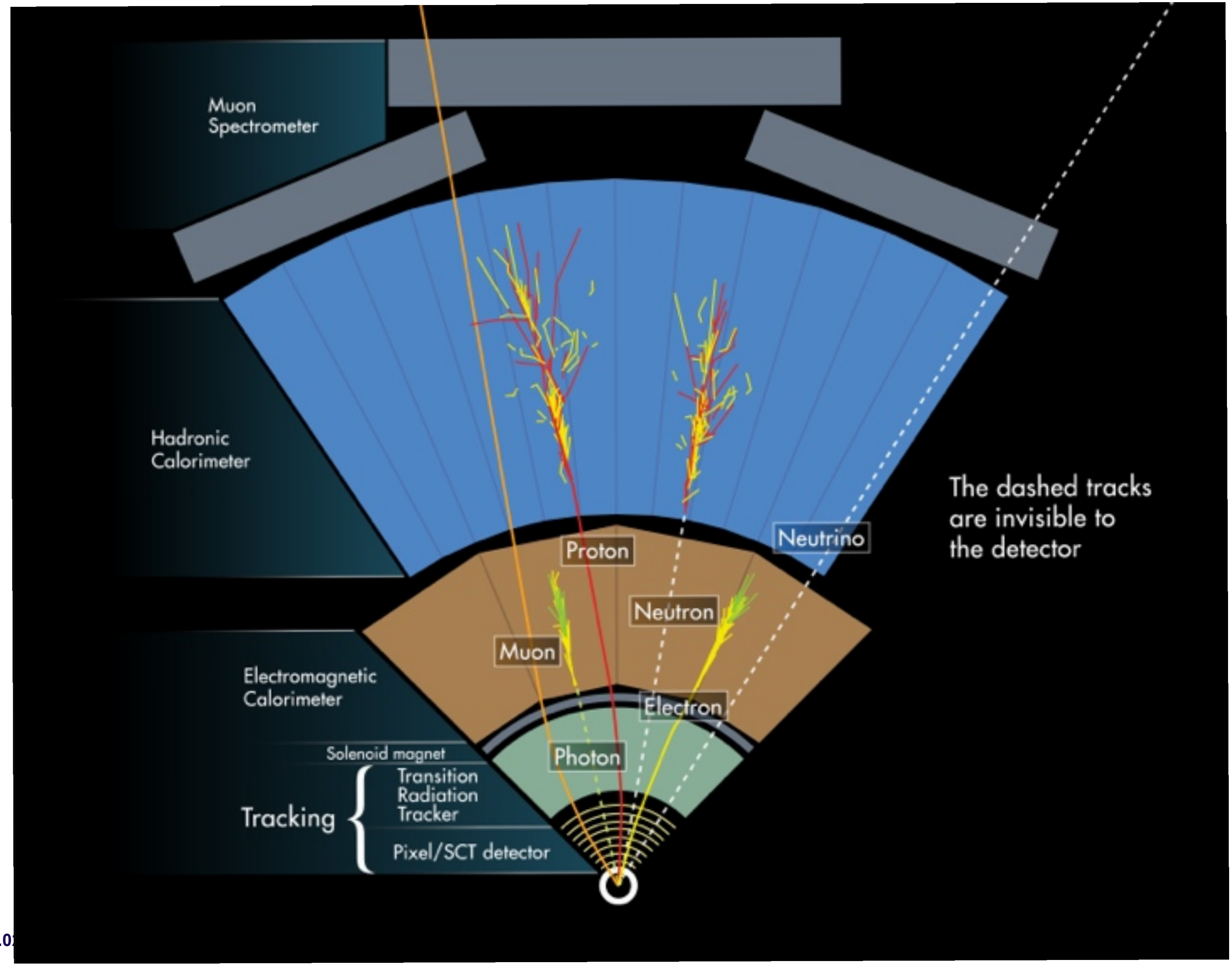
Calorimetry

Particles do not come out alive of a calorimeter

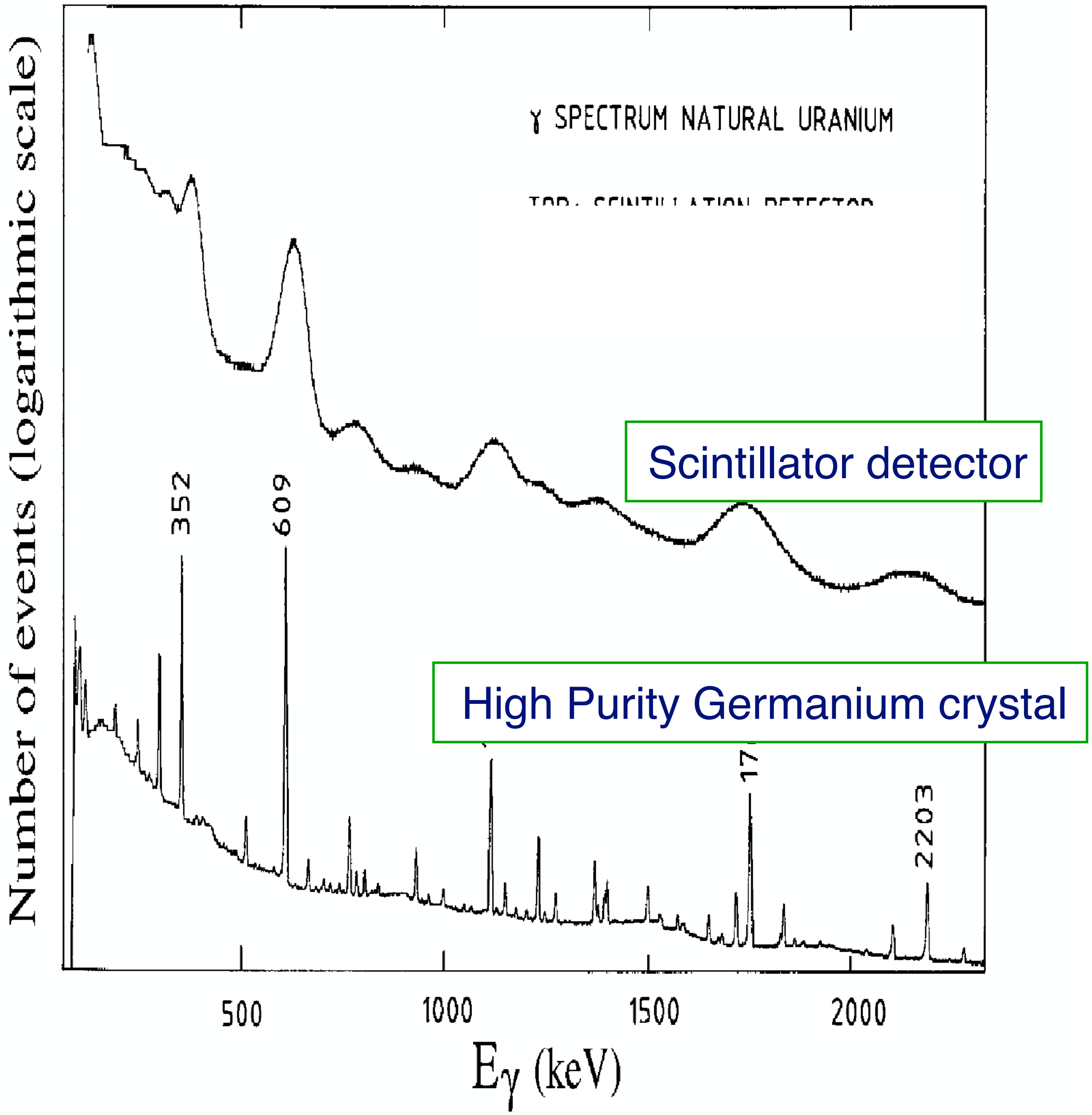
GENERAL STRUCTURE of a DETECTOR



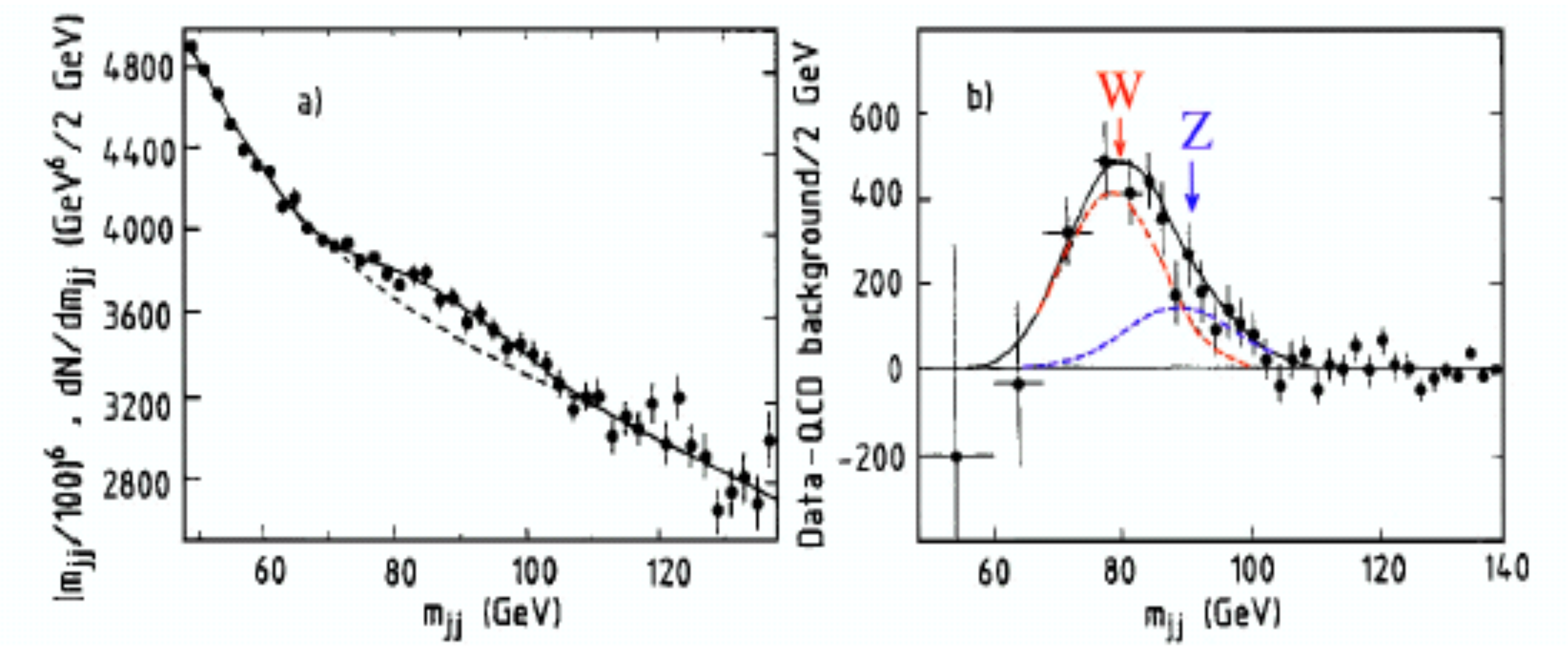
GENERAL STRUCTURE of a DETECTOR



ENERGY RESOLUTION



ENERGY RESOLUTION

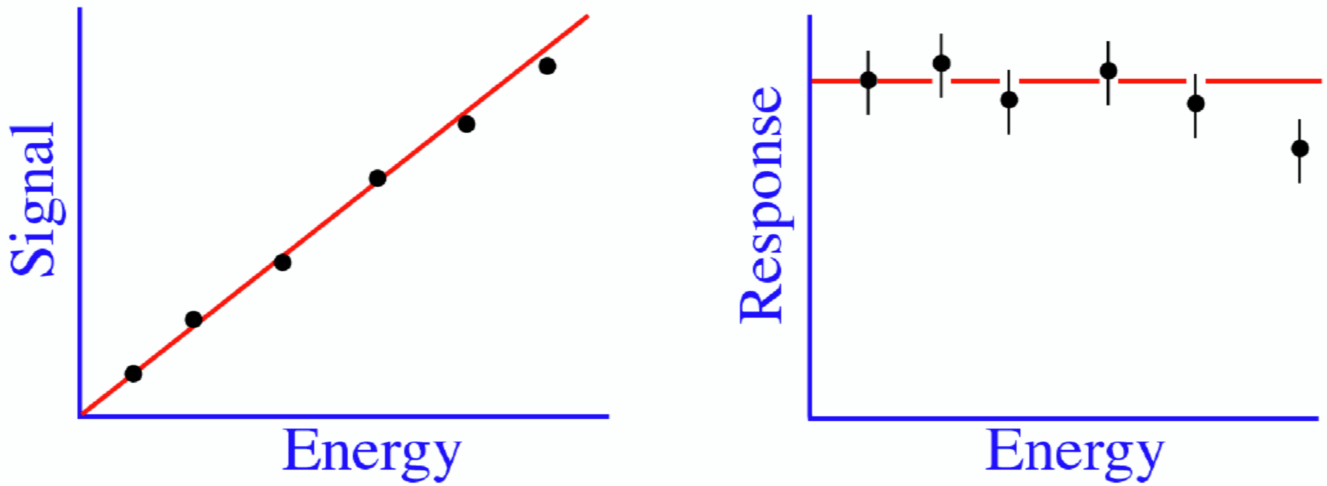


Mass Reconstruction of W & Z^0 in UA2
(years 80-90)

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



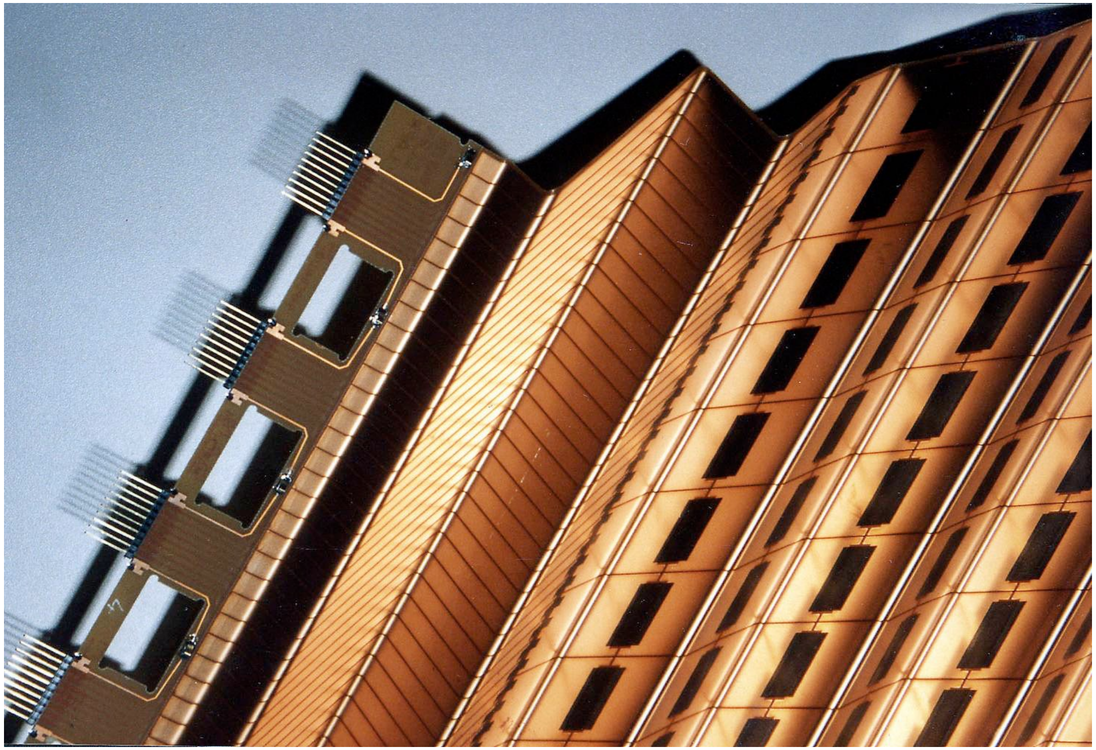
Electromagnetic calorimeters are in general linear.
All energies are deposited via ionisation/excitation of the absorber.

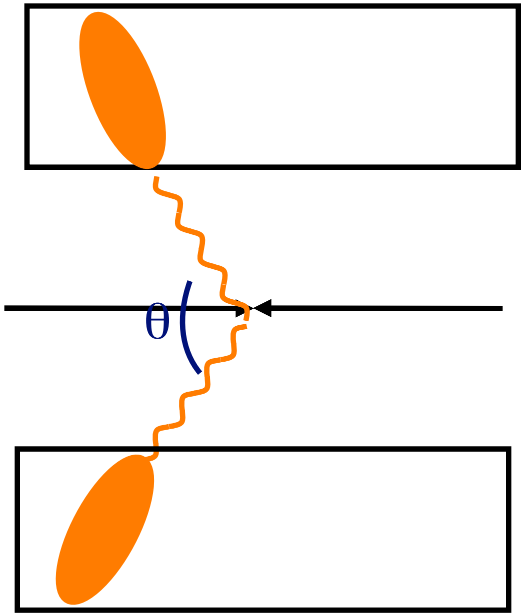
POSITION RESOLUTION

Higgs Boson in ATLAS

For $M_H \sim 120$ GeV, in the channel $H \rightarrow \gamma\gamma$

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





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

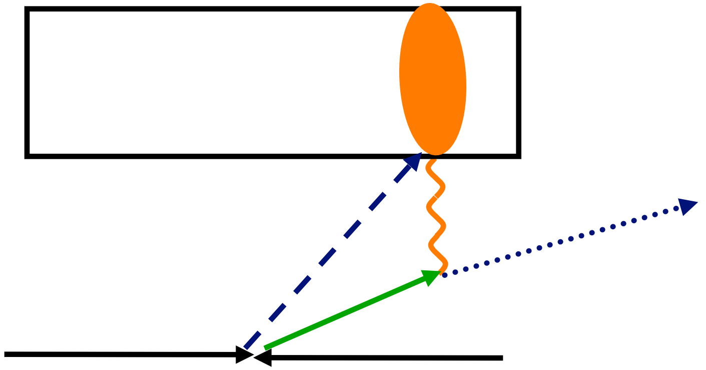
TIME RESOLUTION

At LHC, pp collisions will have a frequency of 25ns and ~40 interactions/bunch crossing when $L=10^{34}cm^{-2}s^{-1}$

Some theoretical models predict existence of long lived particles

Time measurement

- Validate the synchronisation 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)

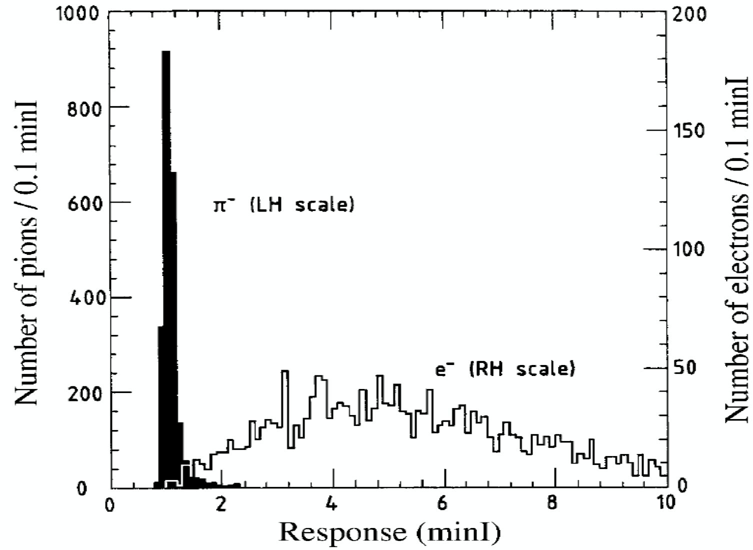


PARTICLE IDENTIFICATION

Particle Identification is particularly crucial at Hadron Colliders:

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

e±/π± rejection



Means

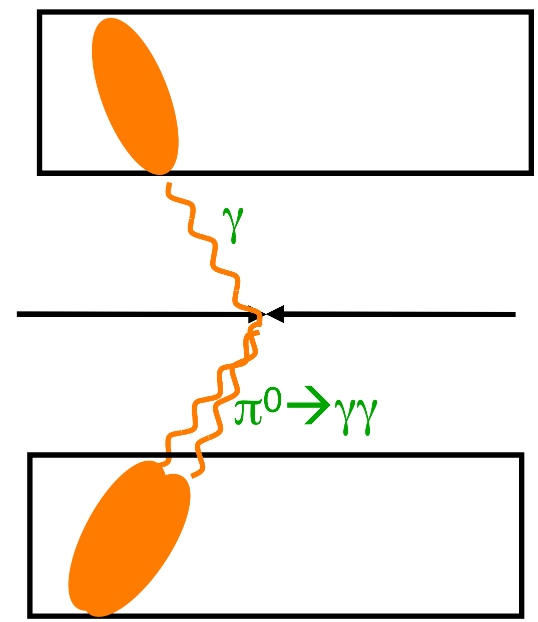
- Shower shapes (lateral & longitudinal segmentations)
- Track association with energy deposit in calorimeter
- Signal time

PARTICLE IDENTIFICATION

Higgs boson in ATLAS

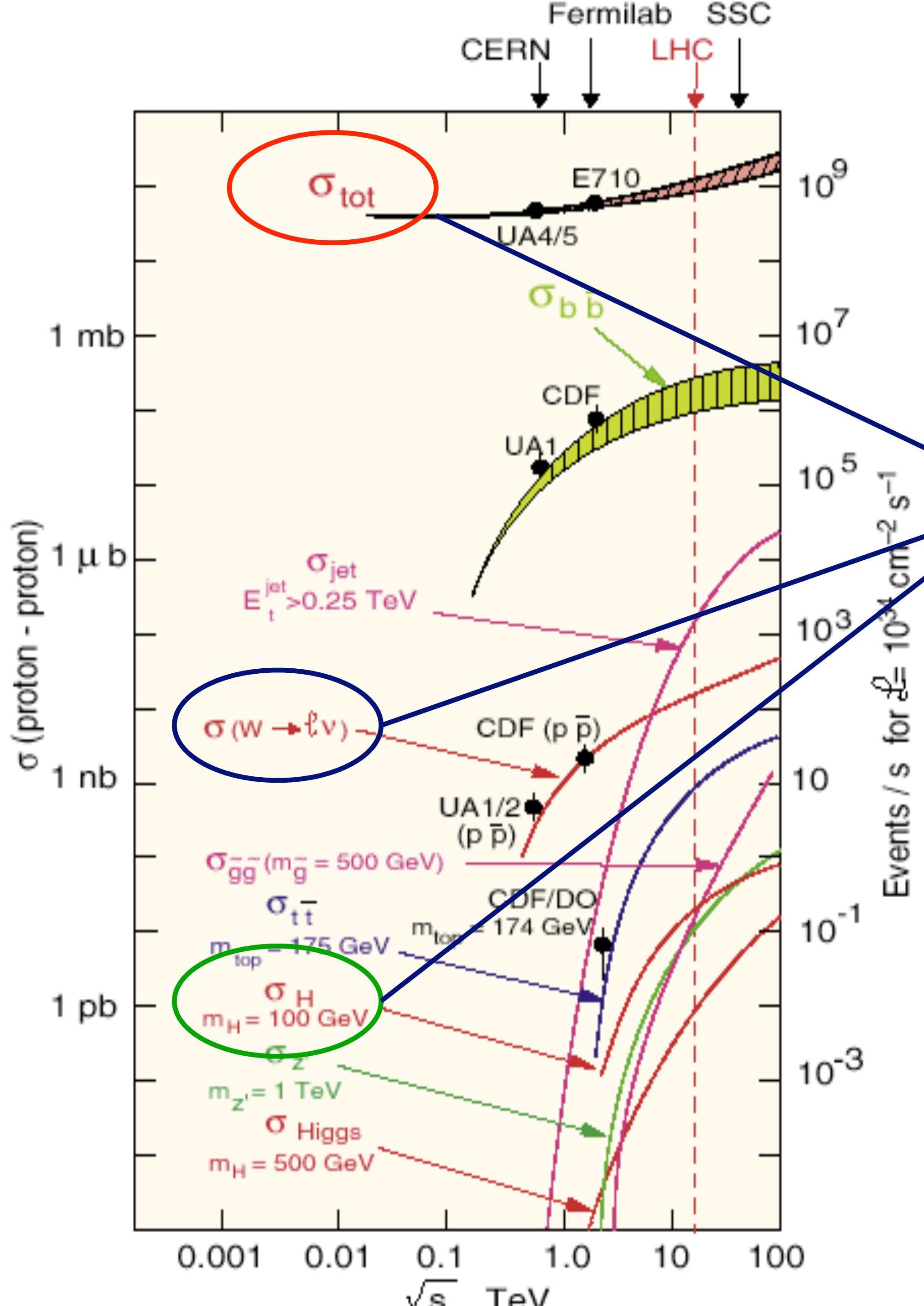
With $M_H \sim 125$ GeV in the channel $H \rightarrow \gamma\gamma$

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 and 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.

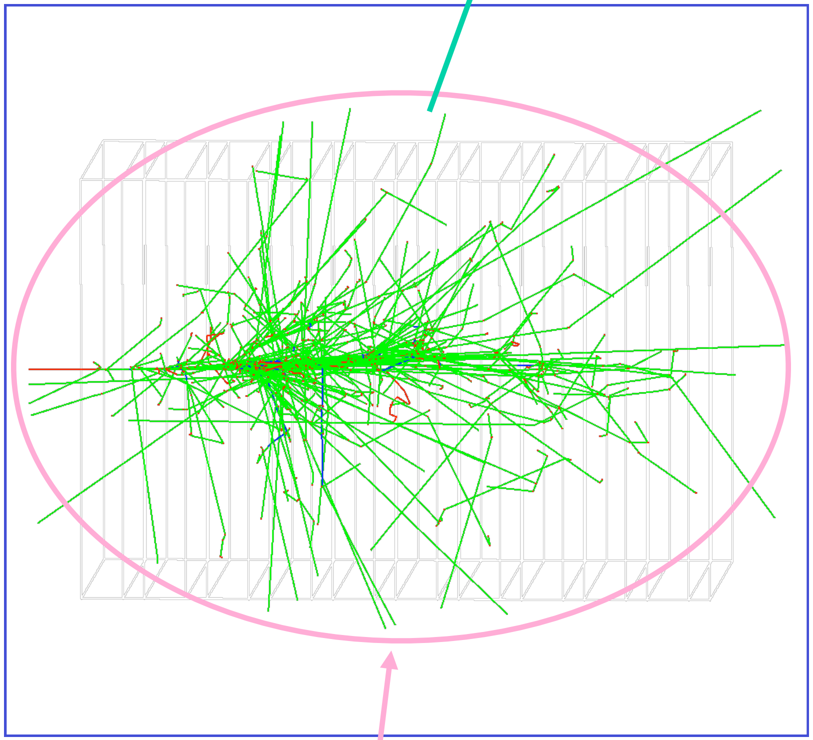
This was (and is still) one of the challenge when designing the calorimeters for LHC

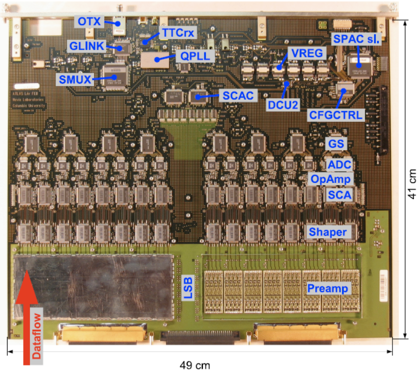
- Detailed maps produced by simulation to assess expected level
- Dedicated tests in very high intensity beam lines

Experiments have installed monitoring detectors which now allow to confront the models with measurements.

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

Electronics
(conversion, amplification,
signal transmission)



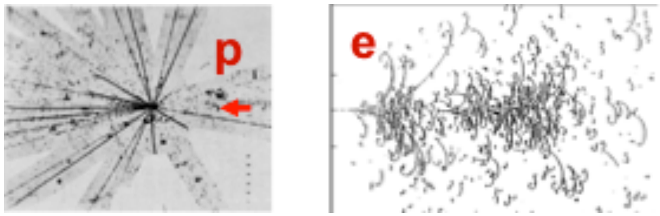


Interaction with matter

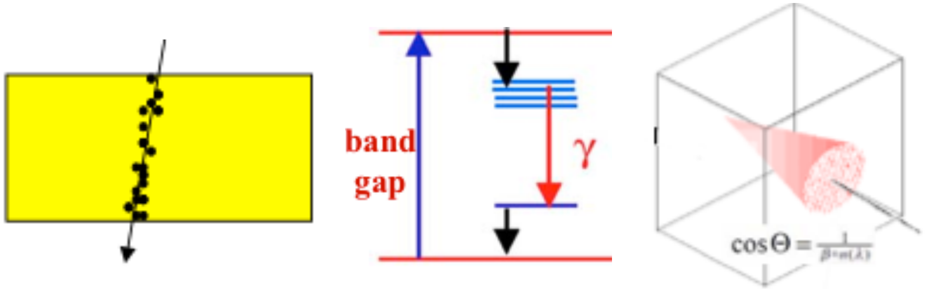
Calorimeters

FOUR STEPS

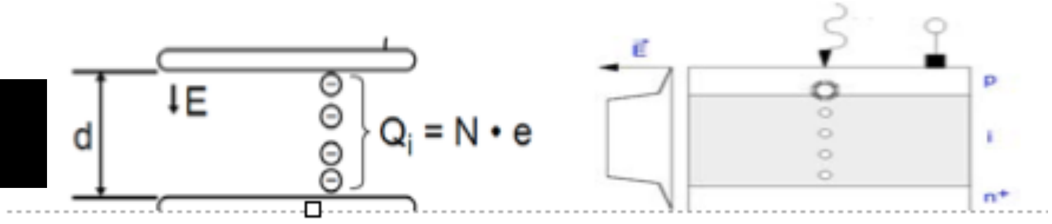
1. Particles interact with matter
   depends on particle and material



2. Energy loss transfer to detectable signal
   depends on the material



3. Signal collection
   depends on signal and type of detection



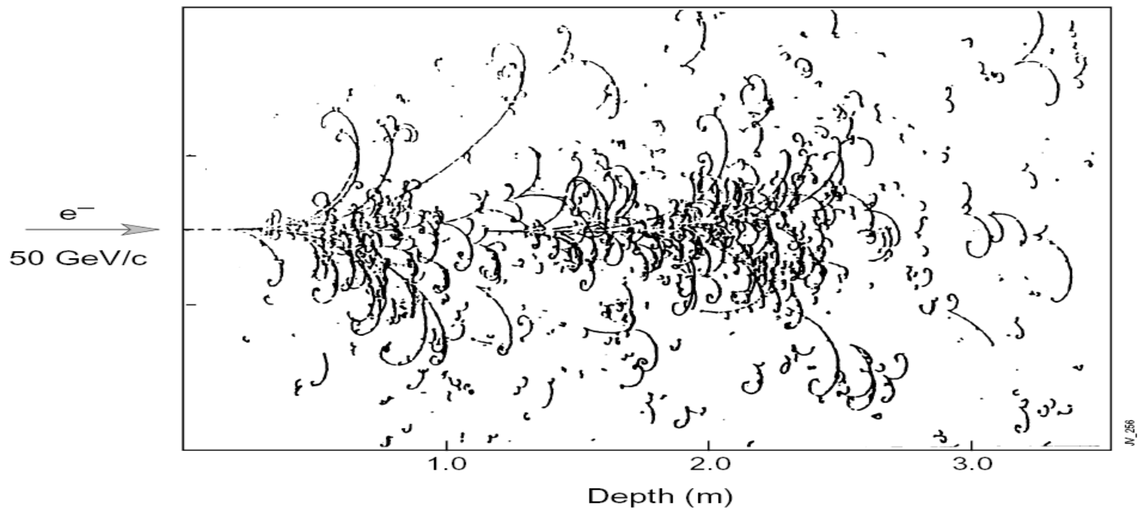
4. BUILD a SYSTEM
   depends on physics, experimental conditions,….

GENERAL CHARACTERISTICS

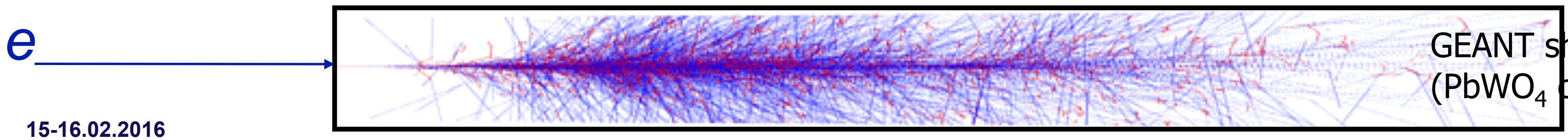
Calorimeters have the following properties:

- 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, $X_0 \approx 34$ cm, 50 GeV incident electron



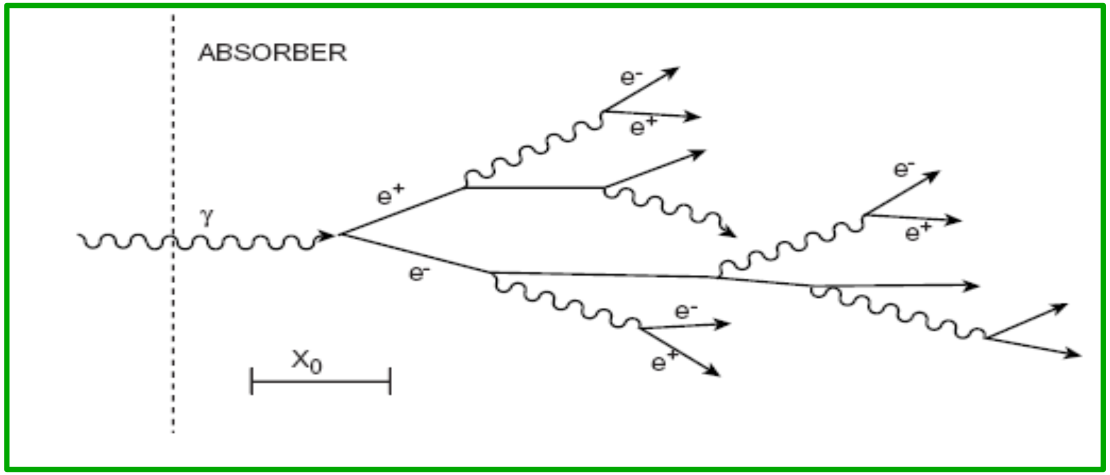
Electromagnetic showers



GEANT shower
($PbWO_4$ crystal)

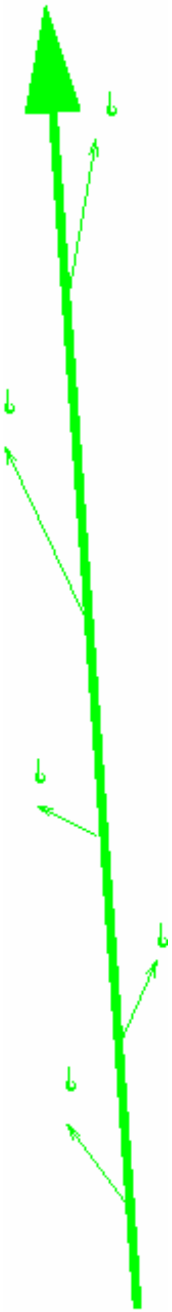
ELECTROMAGNETIC SHOWERS

At high energies, electromagnetic showers result from electrons and photons undergoing mainly bremsstrahlung and pair creation.

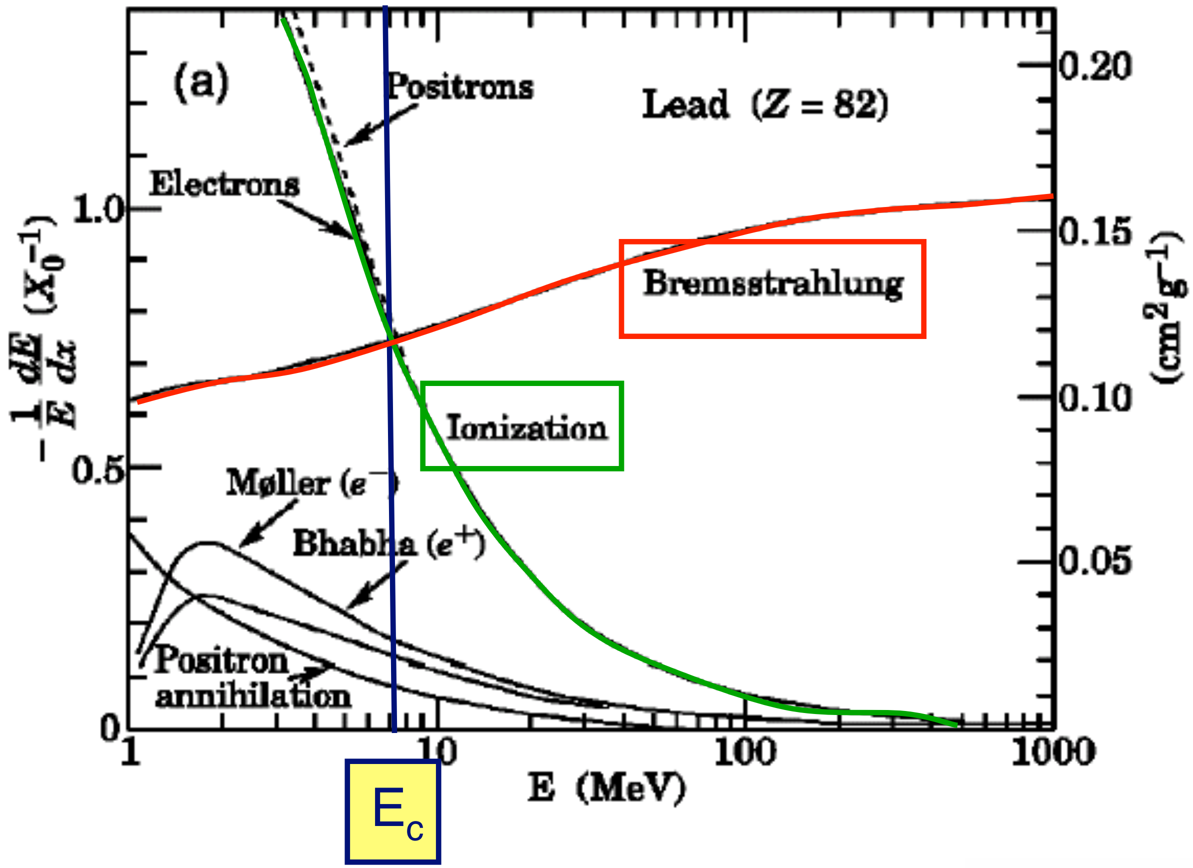


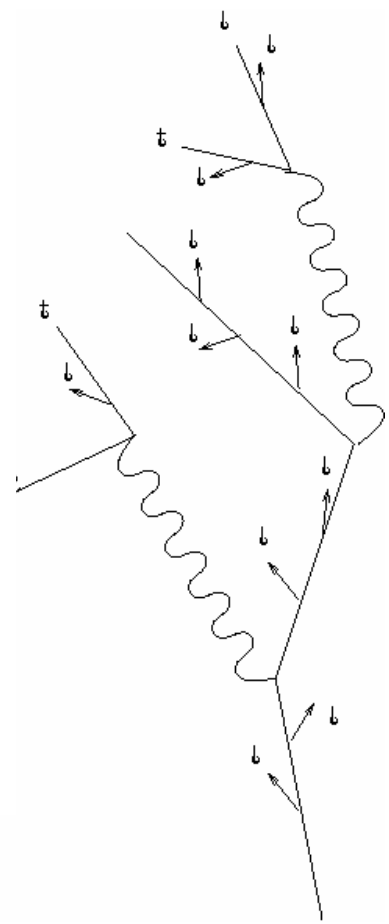
For high energy (GeV scale) electrons bremsstrahlung is the dominant energy loss mechanism.
For high energy photons pair creation is the dominant absorption mechanism.
Shower development is governed by these processes.

WHICH PROCESSES CONTRIBUTE for ELECTRONS

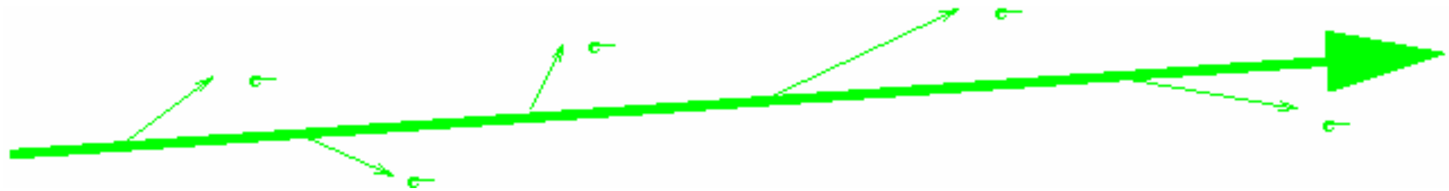


Electrons mainly loose their energy via ionization & Bremsstralung





IONISATION



Interaction of charged particles with the atomic electronic cloud.

Dominant process at low energy $E<E_{c.}$ (defined in a moment)

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

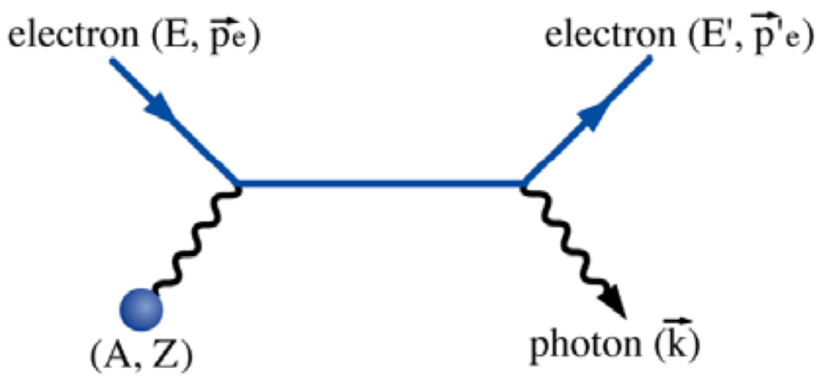
$\boxed{\sigma \propto Z}$

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

where E is the kinetic energy of the incident particle with velocity β and charge Z_i, I (≈ 10×Z eV) is the mean ionization potential in a medium with atomic number Z.

BREMSSTRAHLUNG

Real photon emission in the electromagnetic field of the atomic nucleus



Electric field of the nucleus + of the electrons Z(Z+1)

At large radius, electrons screen the nucleus $\ln(183Z^{-1/3})$

$$\boxed{d\sigma/dk = 4\,\alpha\,Z(Z+1)r_e^2 \ln(183Z^{-1/3})(4/3-4/3y+y^2)/k}$$ [D.F.]

where y=k/E and $r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2} = 2.818\ 10^{-15}$ m classical radius of the electron.

→ For a given E, the average energy lost by radiation, dE, is obtained by integrating over y.

BREMSSTRAHLUNG

In this formulae $Z(Z+1) \sim Z^2$

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

where n is the number of nucleus/unit volume.

dE/dx is conveniently described by introducing the radiation length X_0

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

$$X_0 = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right]^{-1} \text{g/cm}^2$$

Approximation $\quad X_0 \approx \frac{180A}{Z^2}\ g.cm^{-2}$

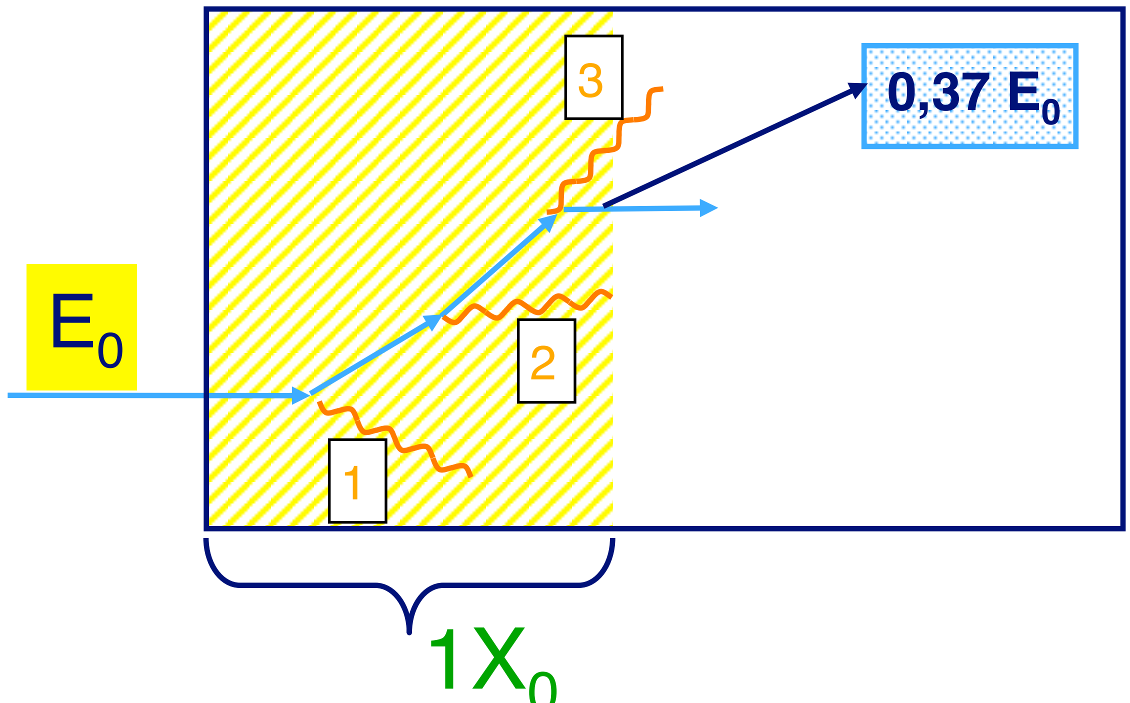
X_0 is most of the time expressed in [length] $X_0[g.cm^{-2}]/\rho$

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

$$dE/dx=E/X_0$$
$$dE/E=dx/X_0$$
$$E=E_0e^{-x/X0}$$



	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

$$X_0 \approx \frac{180A}{Z^2} \quad g.cm^{-2}$$

Energy loss by radiation

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

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

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

For compound material

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

IONISATION: 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 ionising particles ($E<E_c$) in a dense medium

ENERGY LOSS in MATTER for PHOTONS

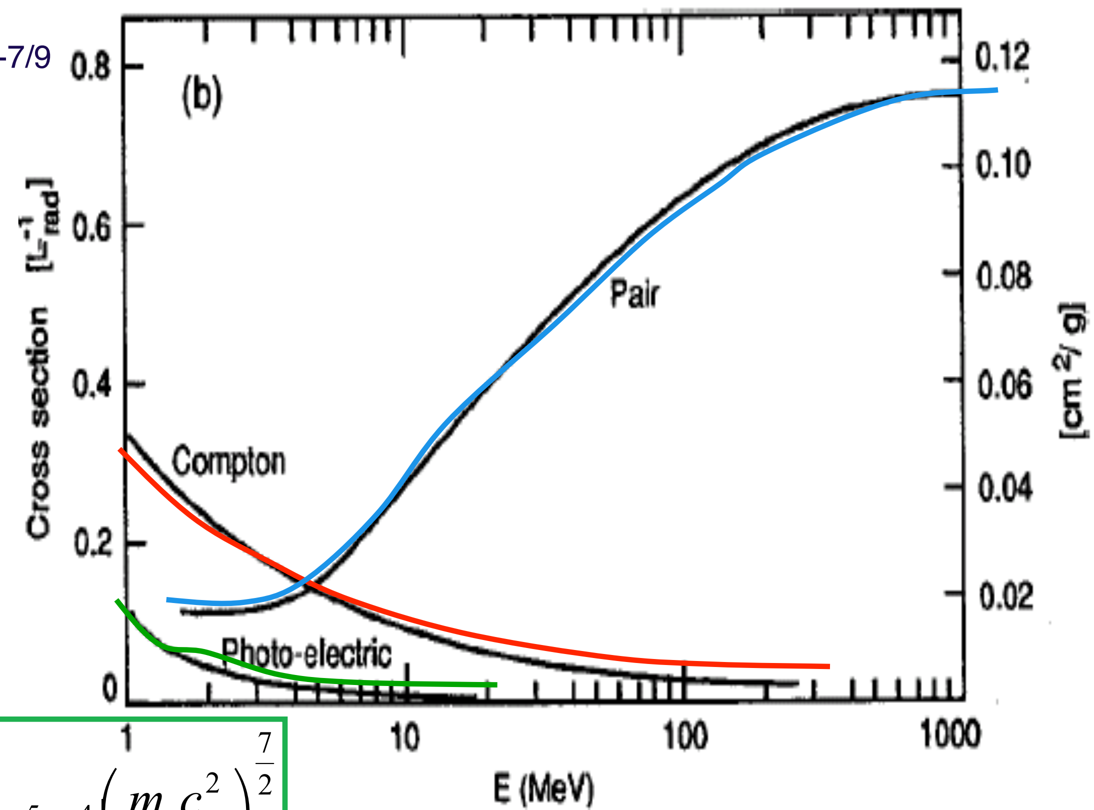
Pair Production

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

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

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

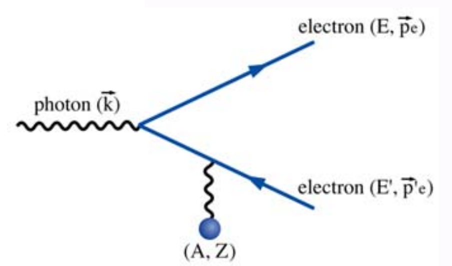
Photo-electric effect

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

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

$\theta \sim m_e/E_\gamma$

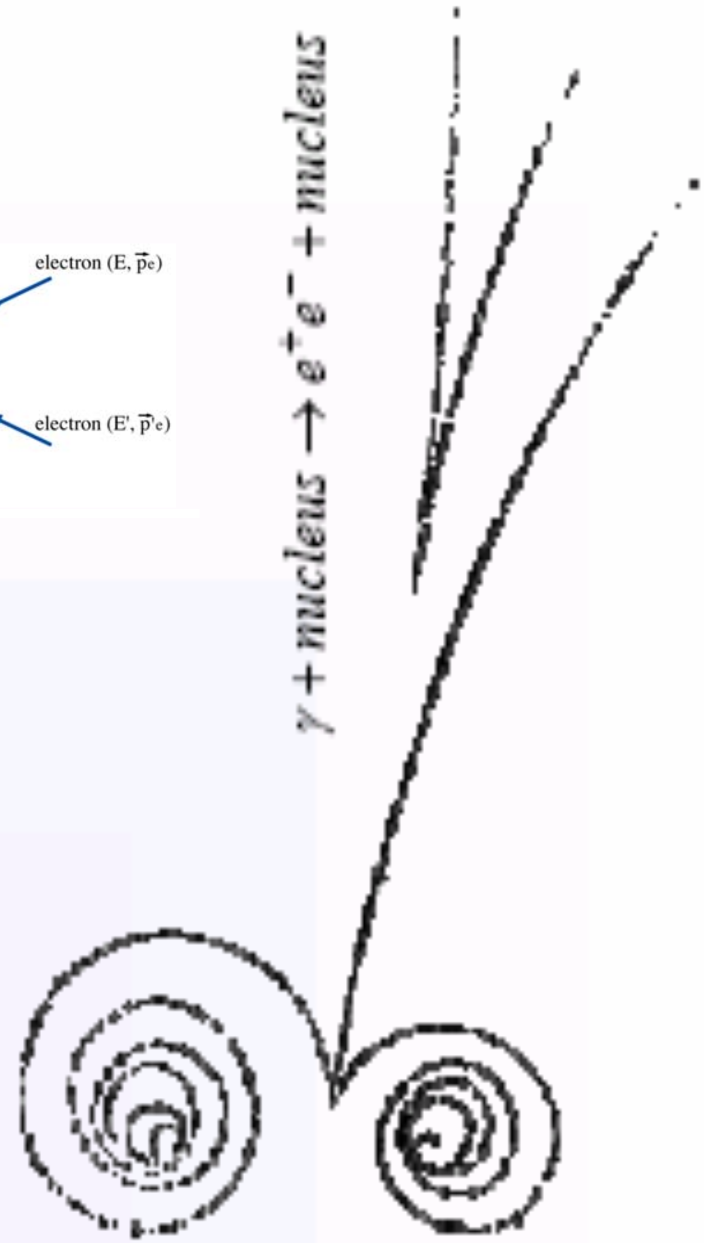


PHOTO-ELECTRIC EFFECT

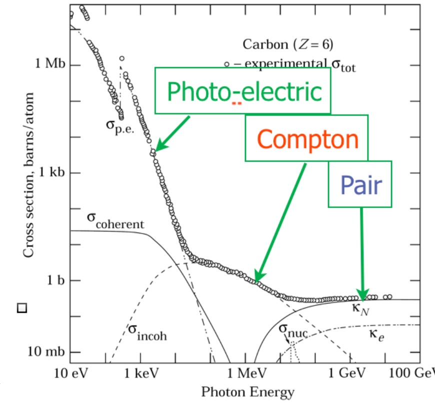
Photon extracts an electron from the atom

γ+atom→e$^-$+atom*

Electrons are not free → binding energy → discontinuities

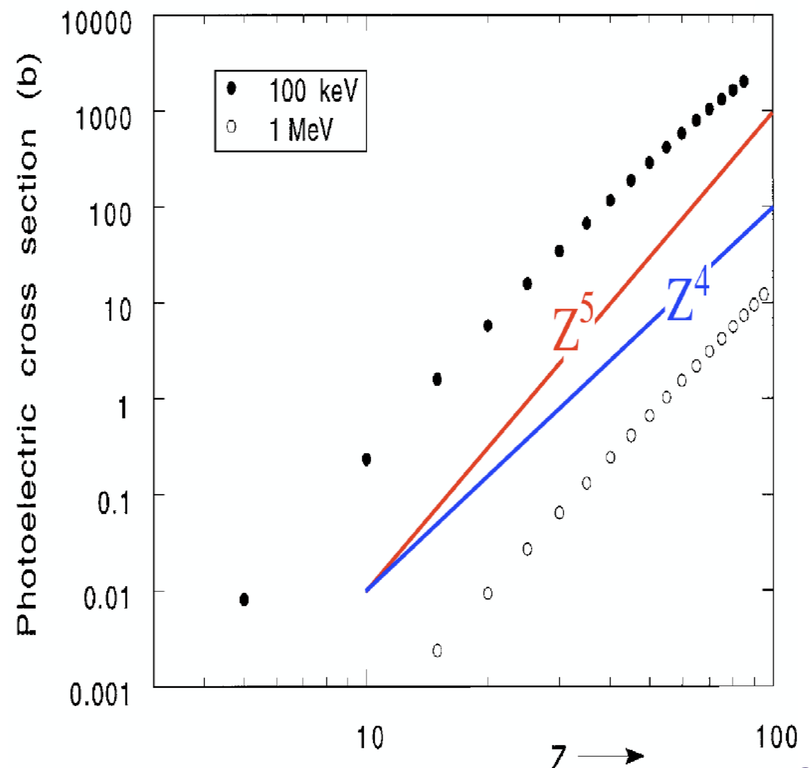
Cross-section

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

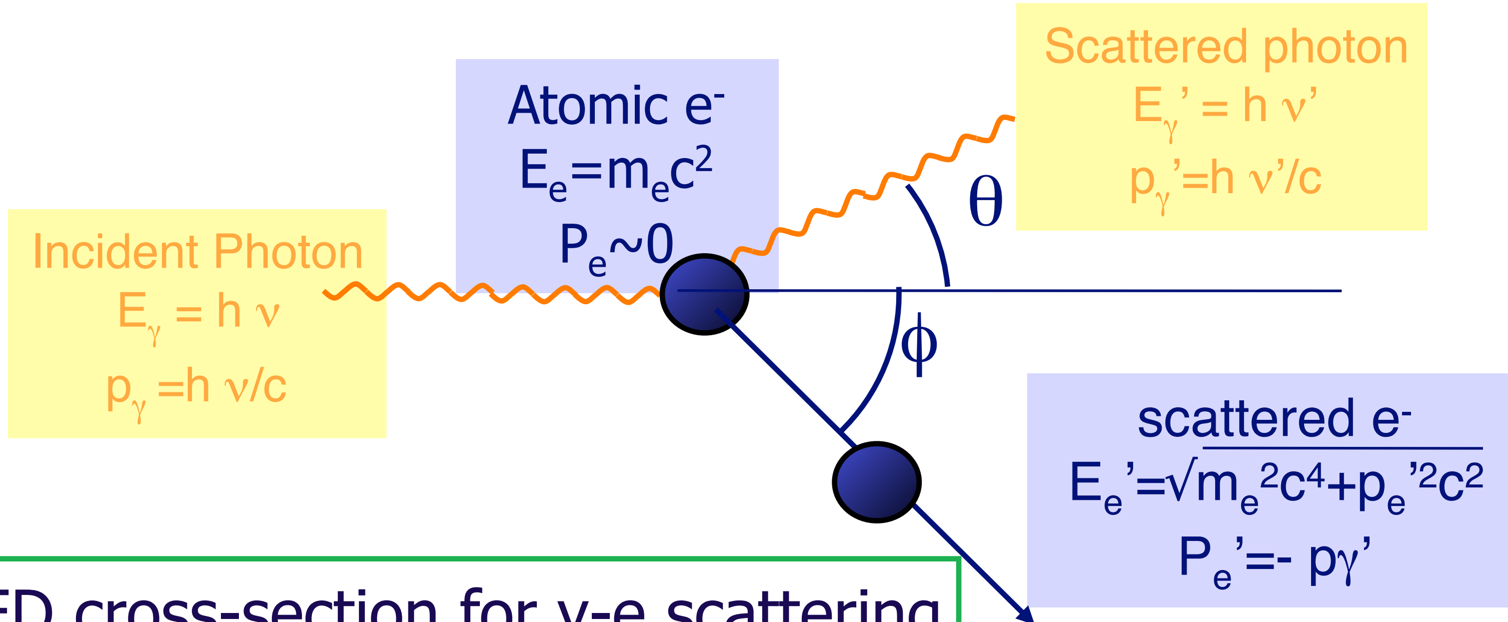


Electrons are emitted isotropically

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



COMPTON SCATTERING

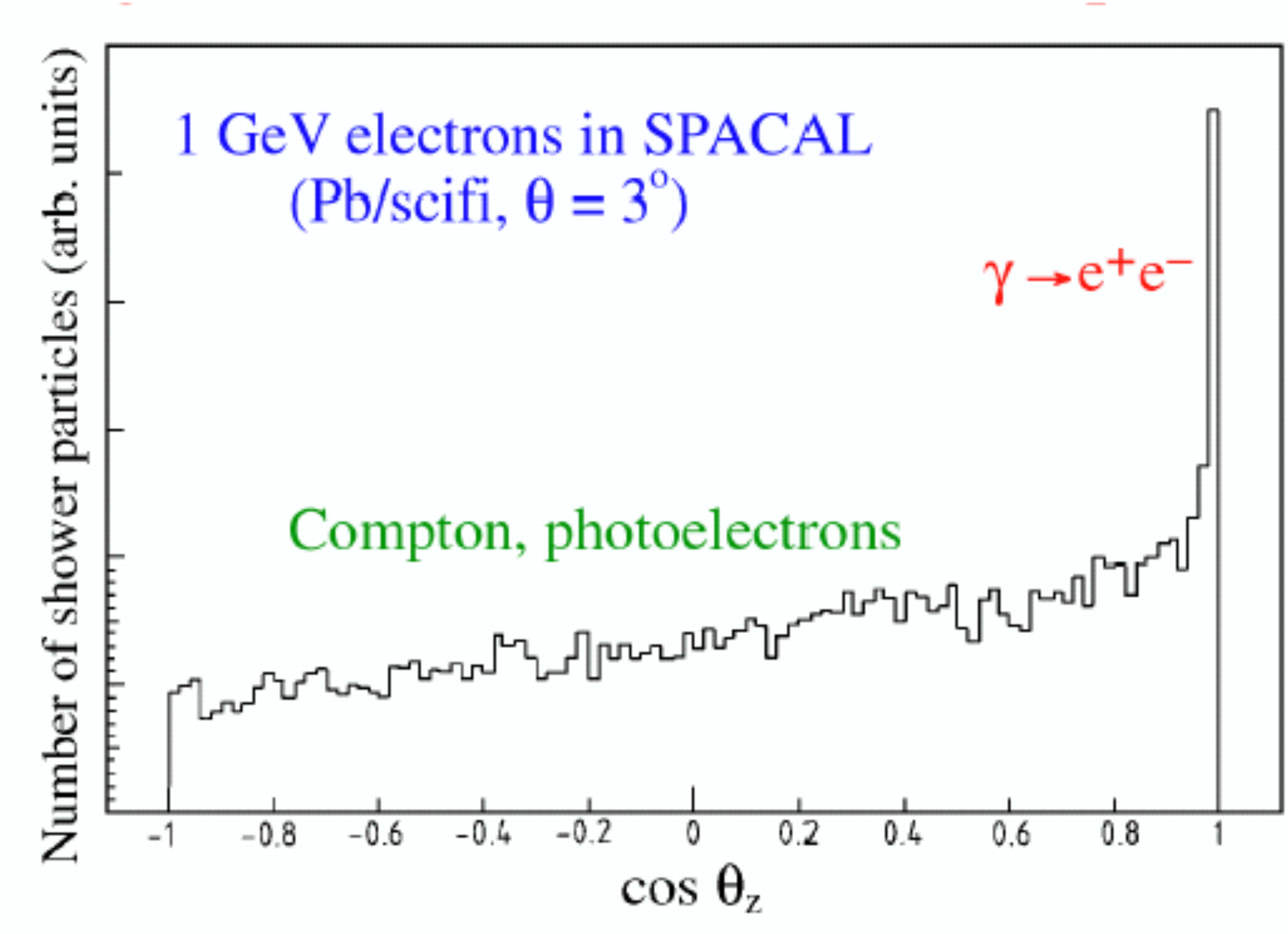


QED cross-section for γ-e scattering

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

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

PHOTON ANGULAR DISTRIBUTION



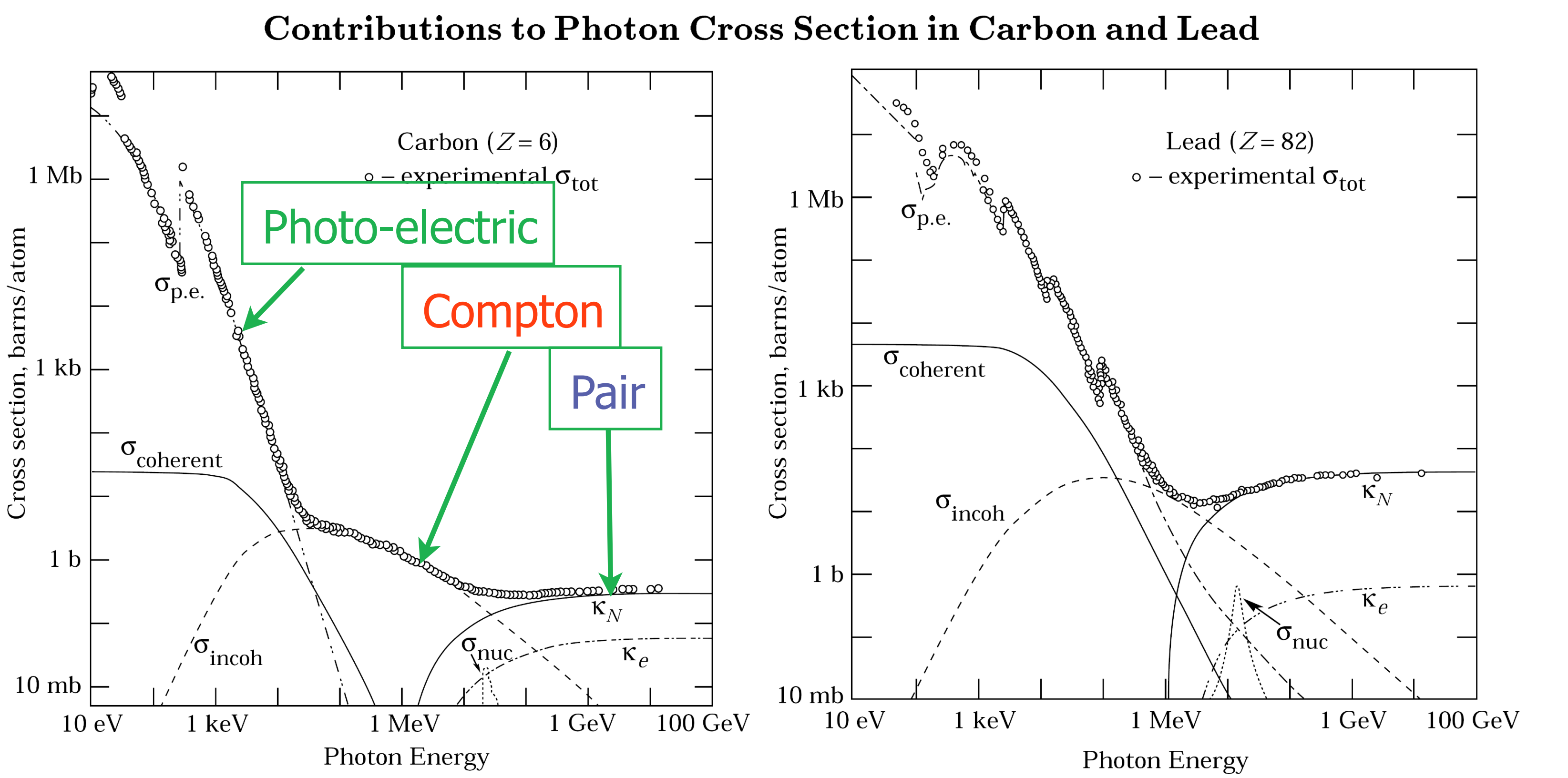


Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

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

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

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

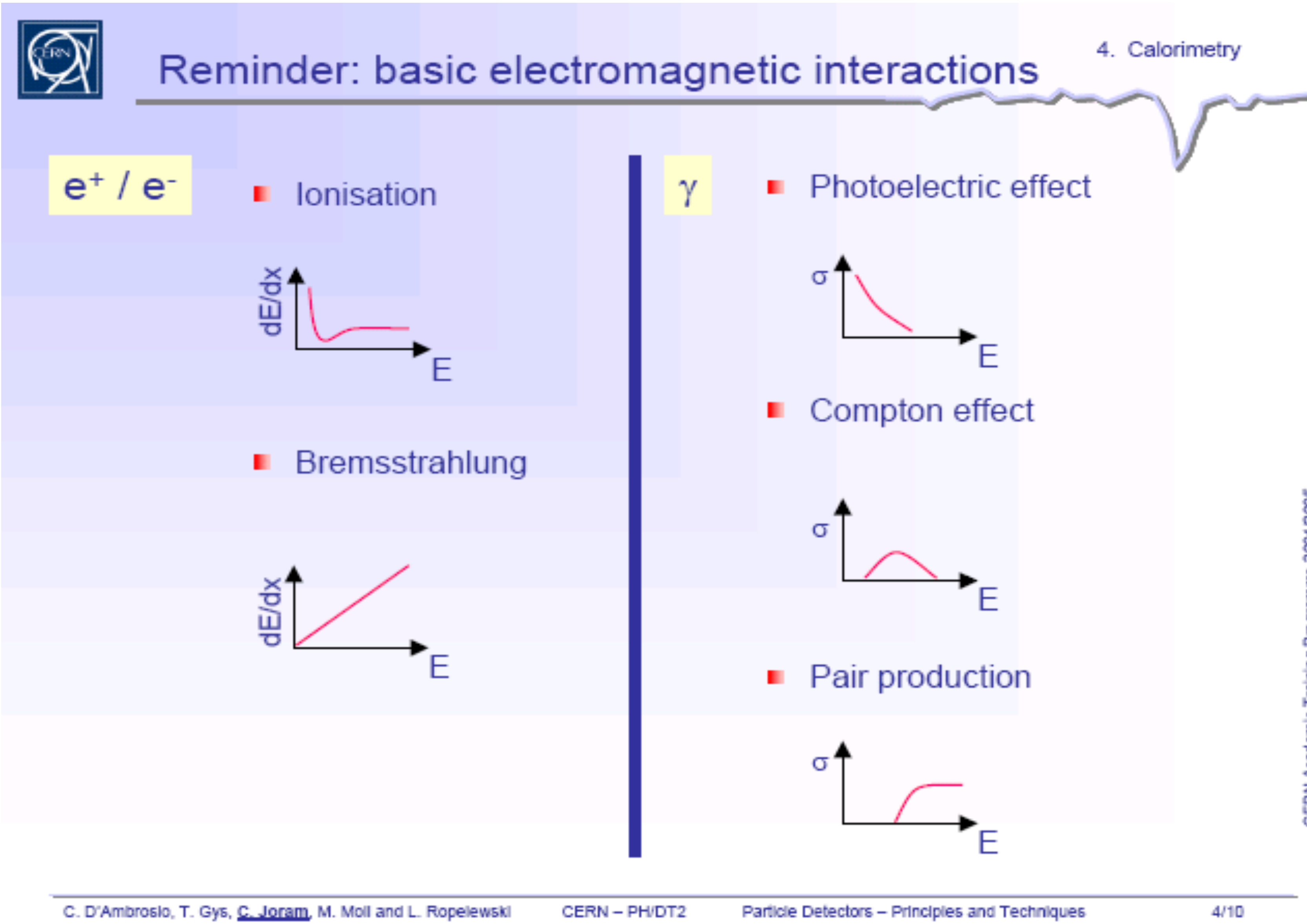
κ_n = Pair production, nuclear field

κ_e = Pair production, electron field

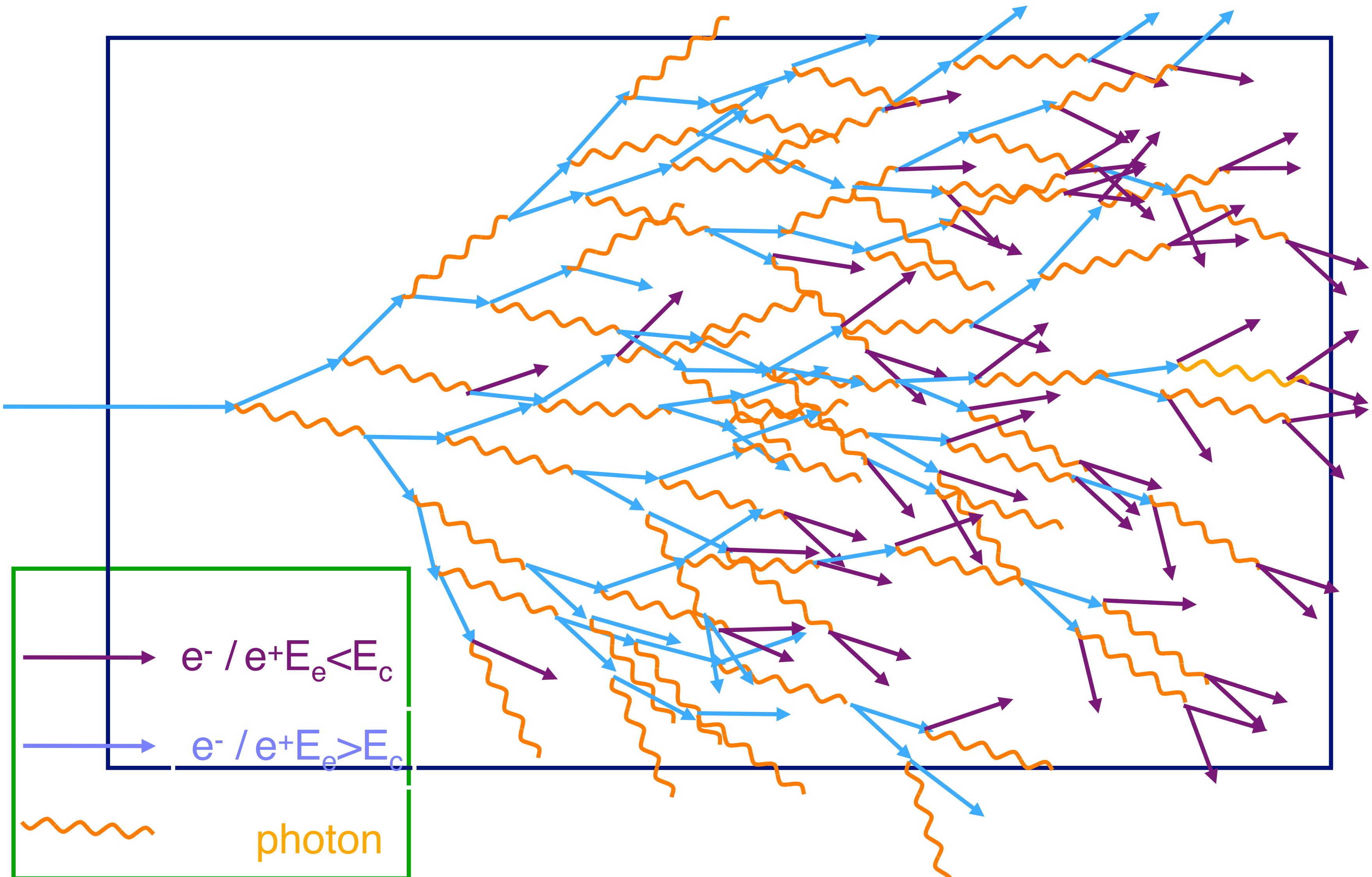
σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

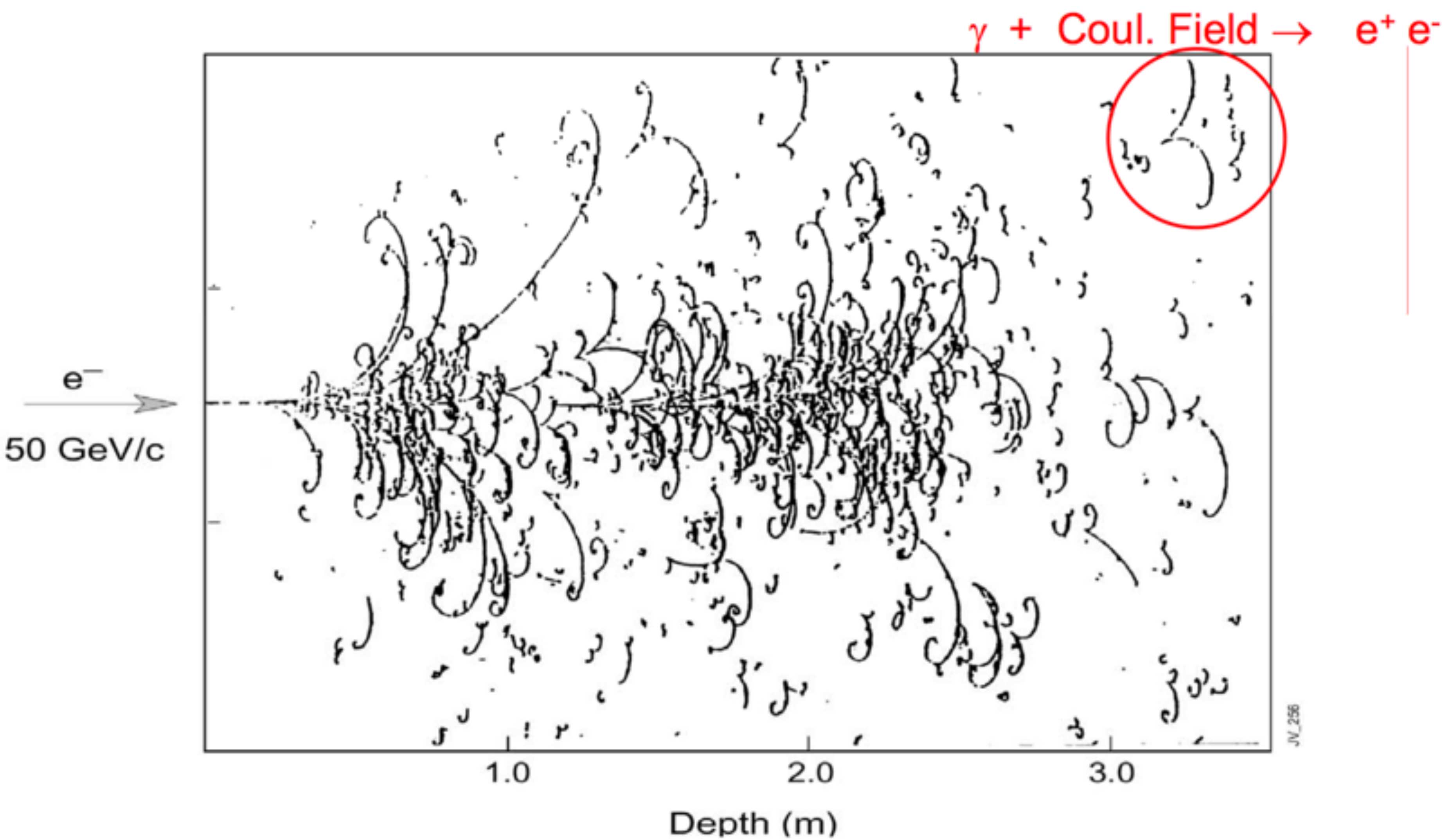
From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from `http://physics.nist.gov/PhysRefData`. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range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

SUMMARY: ELECTRONS vs PHOTONS



SCHEMATIC SHOWER DEVELOPMENT





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

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 is a function of the material (Z)

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

A SIMPLE EM SHOWER MODEL

Simple shower model:
[from Heitler]

Only two dominant interactions:
Pair production and Bremsstrahlung ...

γ + Nucleus ➛ Nucleus + e^+ + e^-
[Photons absorbed via pair production]

e + Nucleus ➛ Nucleus + e + γ
[Energy loss of electrons via Bremsstrahlung]

Shower development governed by X_0 ...

After a distance X_0 electrons remain with only $(1/e)^{th}$ of their primary energy ...

Photon produces e^+e^--pair after $9/7X_0 \approx X_0$ ...

Assume:

$E > E_c$: no energy loss by ionization/excitation

$E < E_c$: energy loss only via ionization/excitation

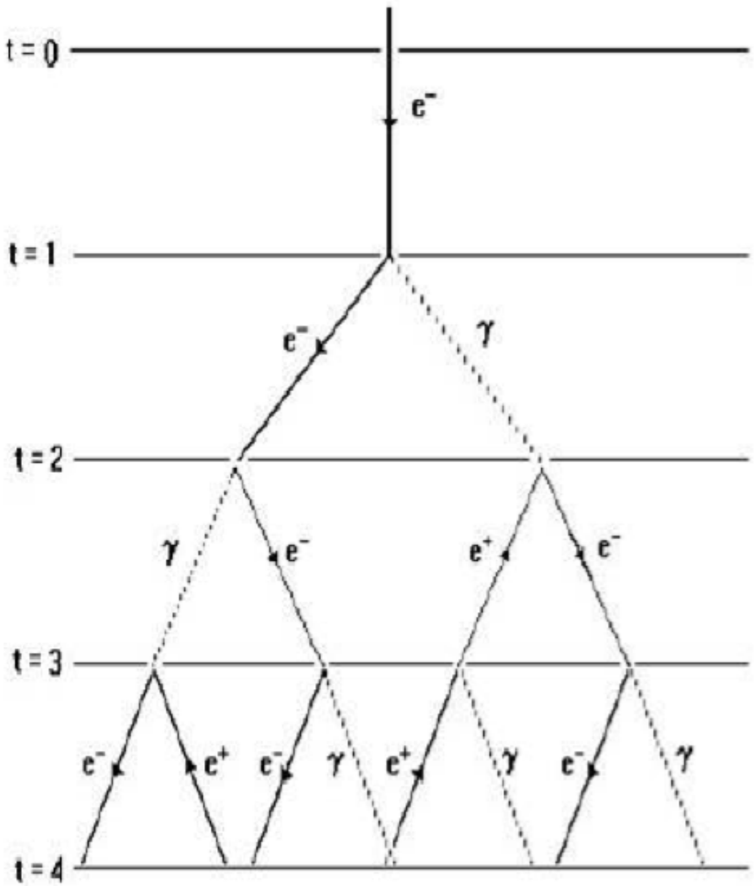
Use
Simplification:

$E_\gamma = E_e \approx E_0/2$
[E_e looses half the energy]

$E_e \approx E_0/2$
[Energy shared by e^+/e^-]

... with initial particle energy E_0

DEVELOPMENT of EM SHOWERS



For one electron of incident energy E_0

On average, for each X_0, one multiplication occurs: $e^- \rightarrow e^- \gamma$ ou $\gamma \rightarrow e^+ e^-$

The energy of the secondary particles decreases at each cascade until $E \sim E_c$

The number of detectable particles ($E<E_c$) reaches a maximum $N \sim E_0/E_c$, called shower maximum.

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, $n(t) = 2^t$

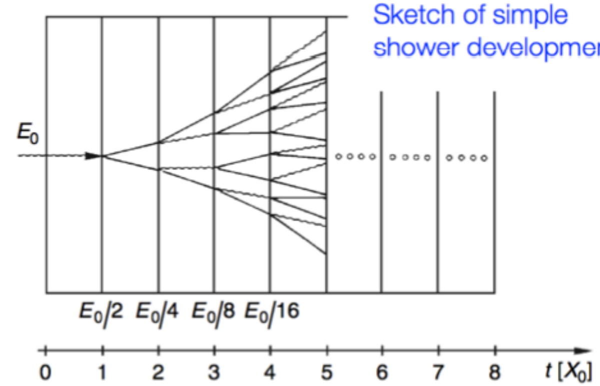
energy of particles, $E(t) \approx \frac{E}{2^t}$

Shower maximum: t_{max}

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

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

A SIMPLE EM SHOWER MODEL



Sketch of simple shower development

Simple shower model:
[continued]

Shower characterized by:

Number of particles in shower
Location of shower maximum
Longitudinal shower distribution
Transverse shower distribution

Longitudinal components;
measured in radiation length ...

... use: $t = \dfrac{x}{X_0}$

Number of shower particles
after depth t:

$$N(t) = 2^t$$

Energy per particle
after depth t:

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow \quad t = \log_2(E_0/E)$$

Total number of shower particles
with energy E_1:

$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles
at shower maximum:

$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c} \propto E_0$$

Shower maximum at:

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

A SIMPLE EM SHOWER MODEL

Simple shower model:
[continued]

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle ...

Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV → $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$
$E_0 = 100$ GeV → $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$

$$t_{\mathrm{max}}[X_0] \sim \ln \frac{E_0}{E_c}$$

EM LONGITUDINAL DEVELOPMENT

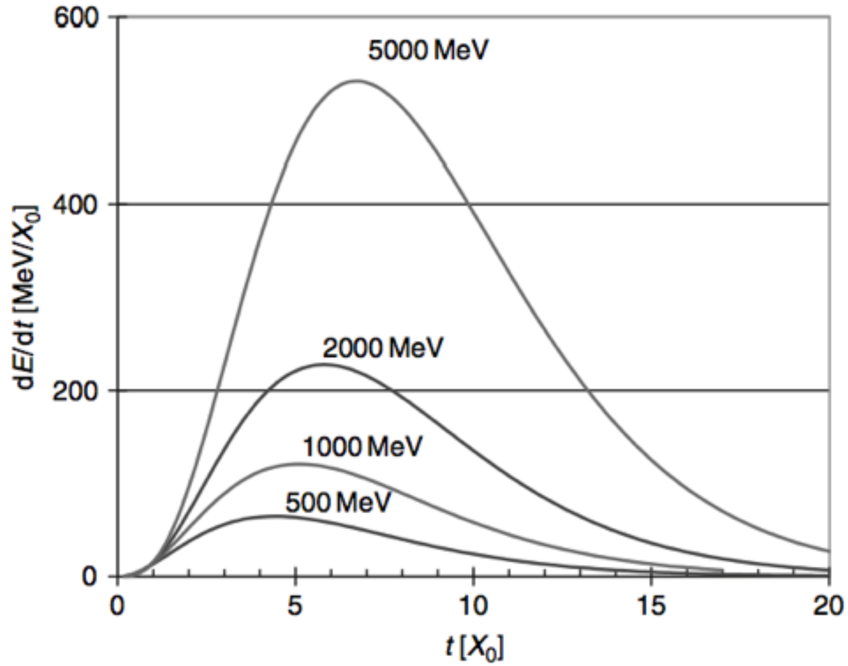
Longitudinal profile

Parametrization:
[Longo 1975]

$$\frac{dE}{dt} = E_0\, t^\alpha e^{-\beta t}$$

α,β : free parameters
t^α : at small depth number of secondaries increases ...
$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$



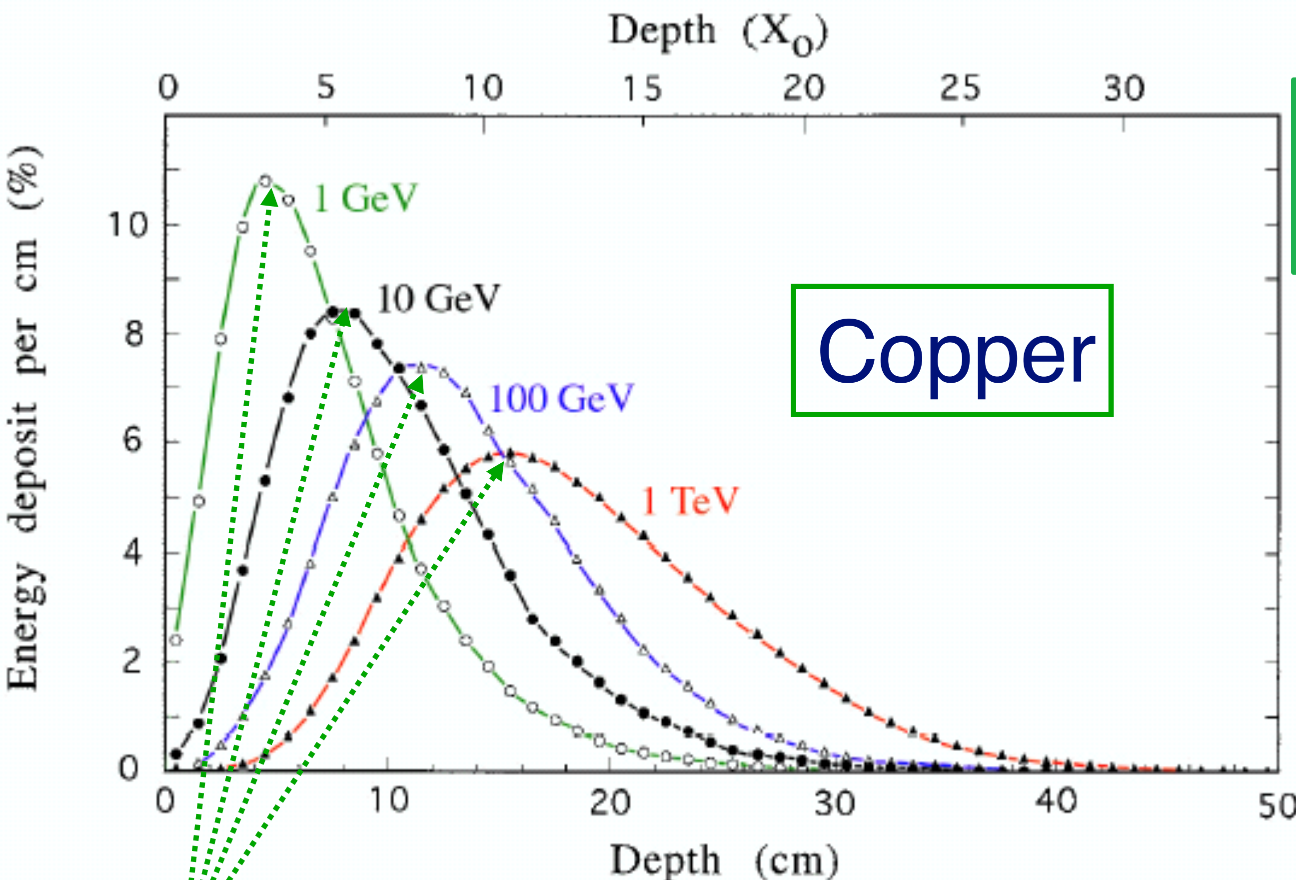
More exact
[Longo 1985]

$$\frac{dE}{dt} = E_0 \cdot \beta \cdot \frac{(\beta t)^{\alpha-1} e^{-\beta t}}{\Gamma(\alpha)} \quad \rightarrow \quad t_{\max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

[Γ: Gamma function]

with:
$C_{e\gamma} = -0.5$ [γ-induced]
$C_{e\gamma} = -1.0$ [e-induced]

EM SHOWER LONGITUDINAL DEVELOPMENT



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

Copper

Shower energy development parametrisation

b: material

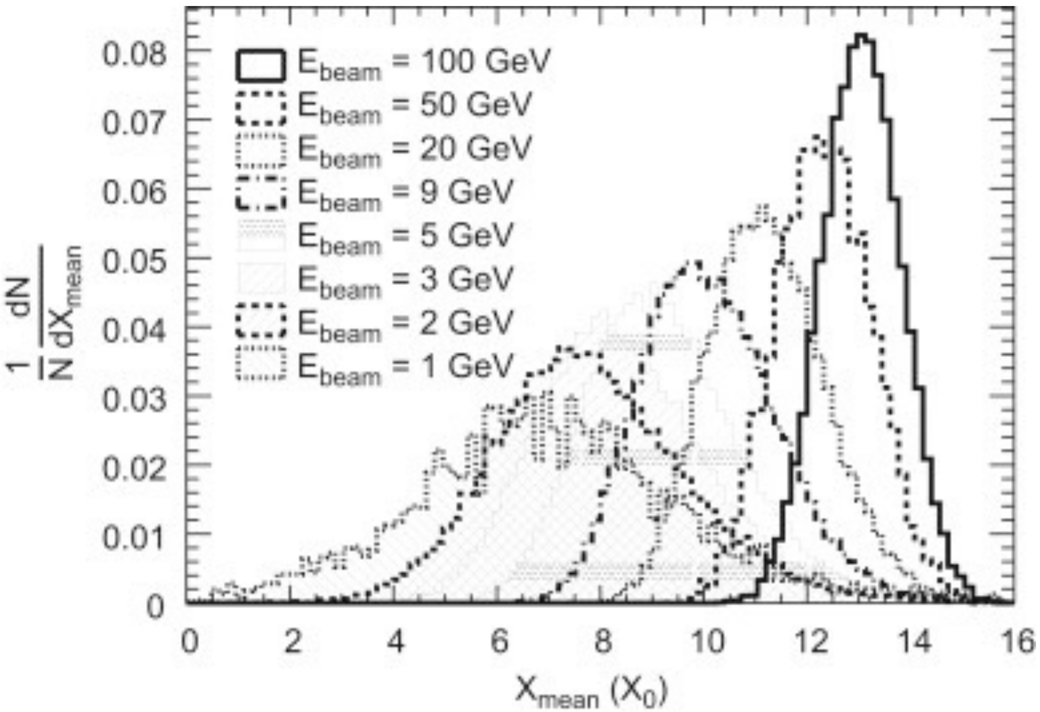
E.Longo & I.Sestili

(NIM128 (1975))

$$t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & \text{e}^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

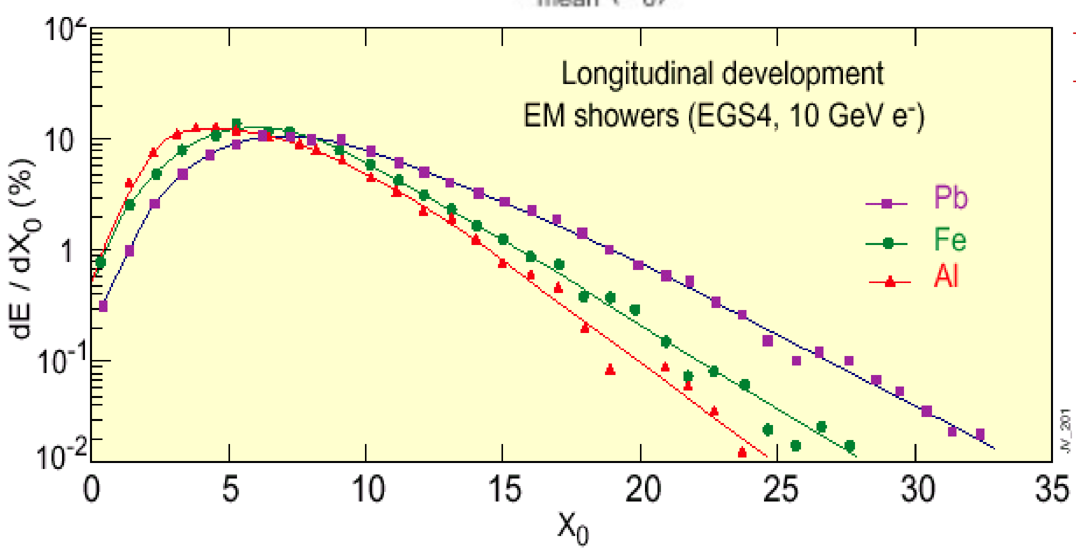
$[X_0]$

EM SHOWER 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 ∢ 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

....

Measurement made by ALEPH

Electron/Photon longitudinal development: different

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

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

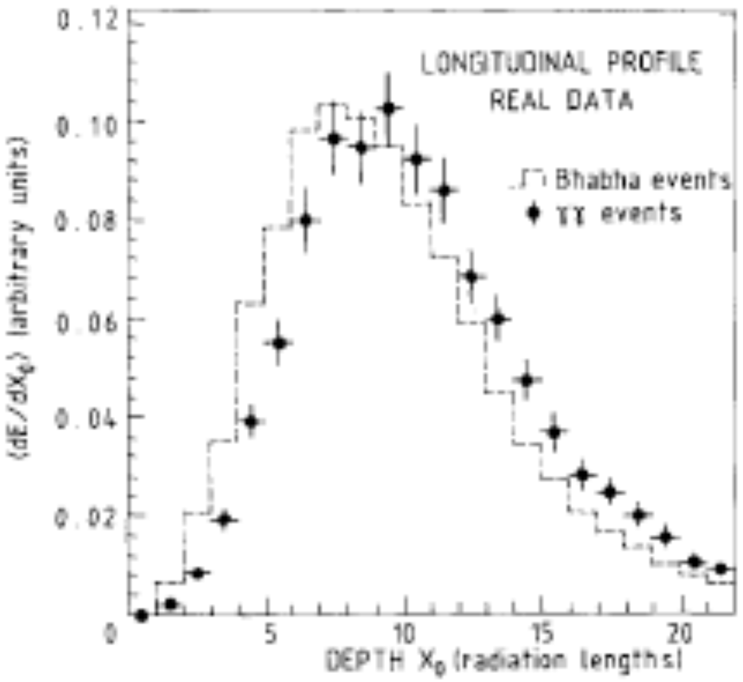


Fig. 1. Longitudinal profile of electromagnetic showers, both for electrons from $e^+e^- \rightarrow e^+e^-$ and for the $\gamma\gamma$ candidates. Both samples are real data. There is a clear shift by about 1 radiation length of the photon showers with respect to electron showers, as expected.

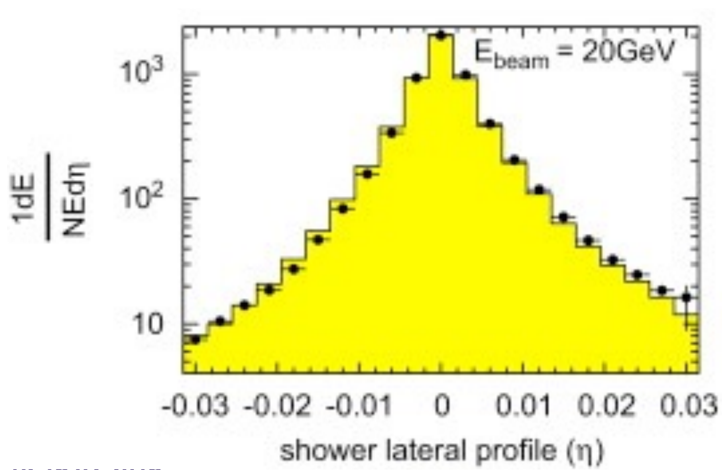
EM SHOWERS LATERAL DEVELOPMENT

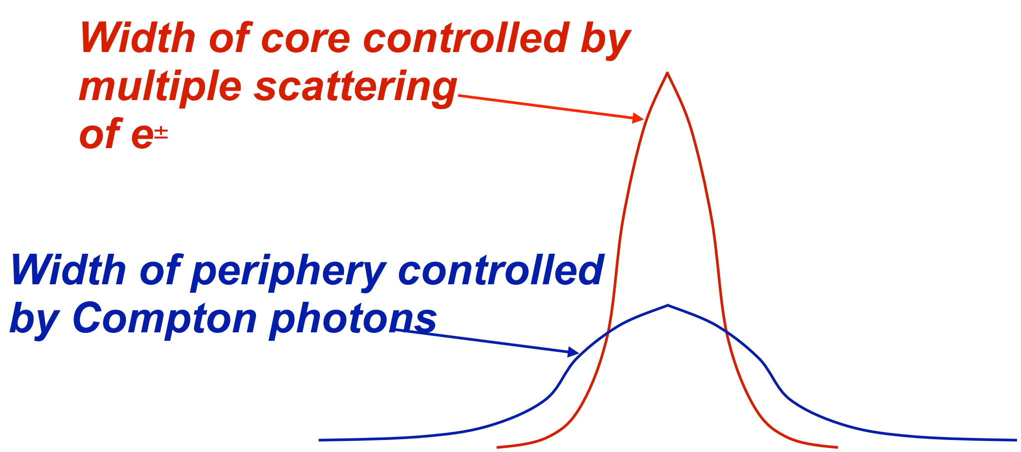
Molière radius, R_m, scaling factor for lateral extent, defined by:

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

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 $3.5R_m$

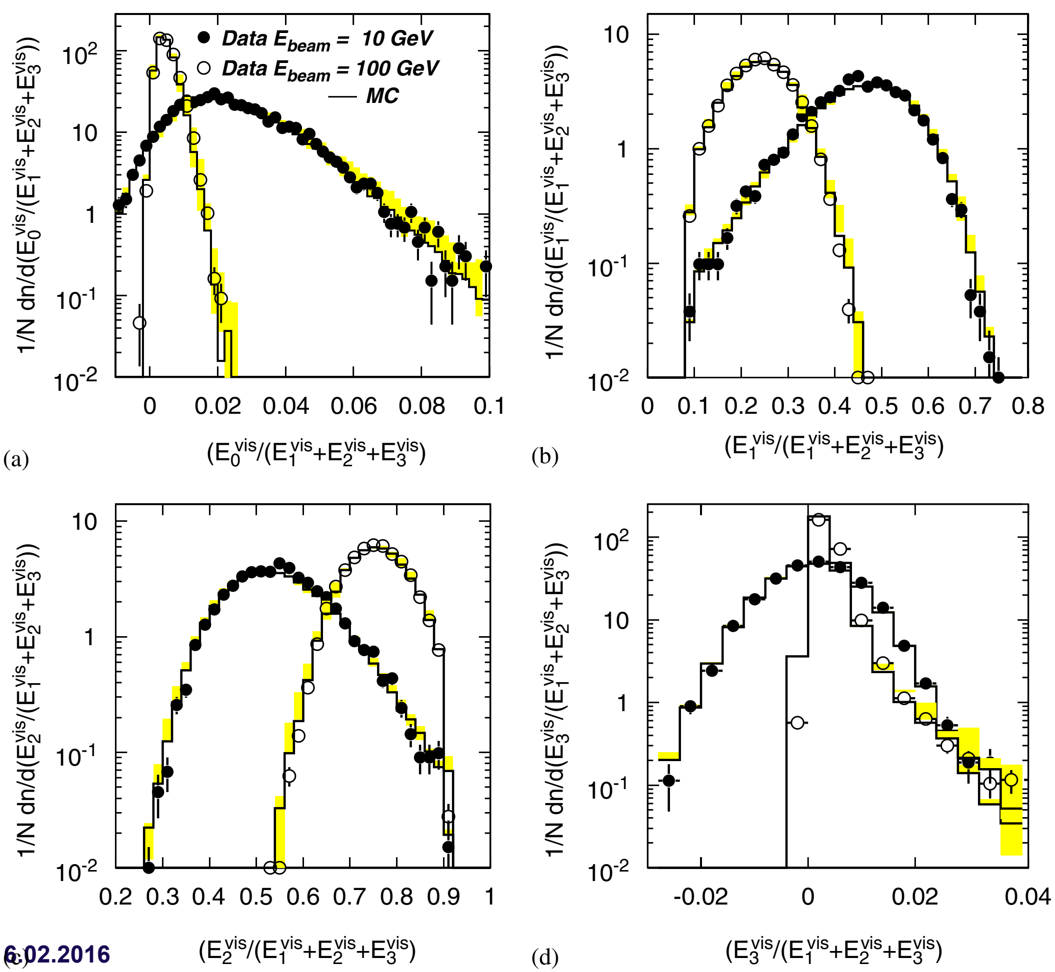




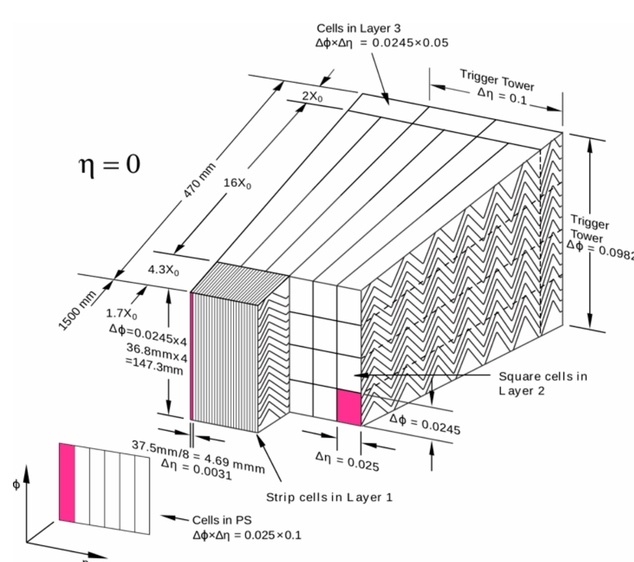
EM SHOWERS SIMULATIONS

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 of 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

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

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

Main conversion mechanism

- Cerenkov radiation from e
- Scintillation from molecules
- Ionization of the detection medium

Different energy threshold E_{th} for signal detectability

EM ENERGY RESOLUTION

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

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

The ultimate energy resolution

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

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

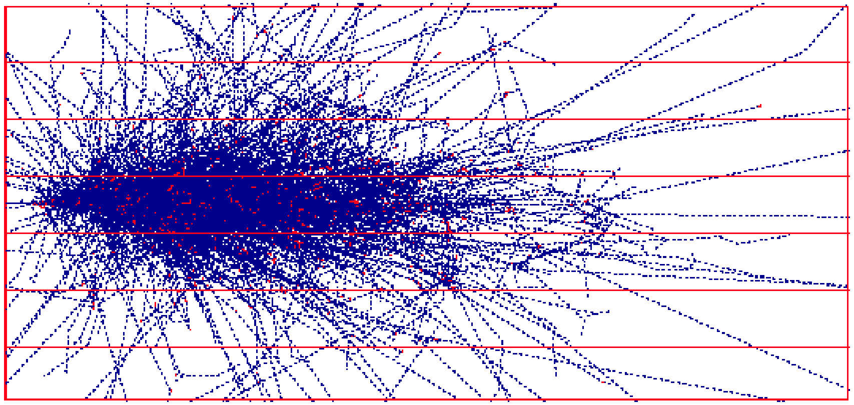
$$\frac{\sigma(E)}{E} \prec \frac{1}{\sqrt{E}} \frac{1}{\sqrt{f_S}}$$

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

- Maximise detection f_s
- Minimise Z/A

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

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

$E_{th} \approx \beta . E_{gap} \sim$ eV

$\rightarrow 10^2 \div 10^4$ γ/MeV

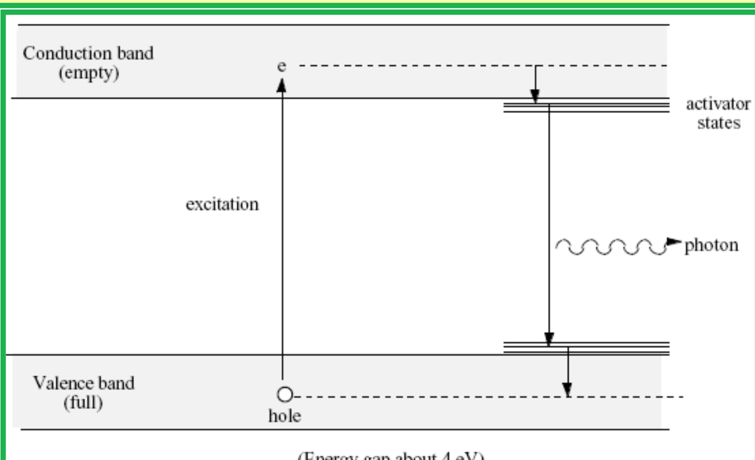
$\sigma/E \sim (1 \div 3)\%/\sqrt{E}$ (GeV)

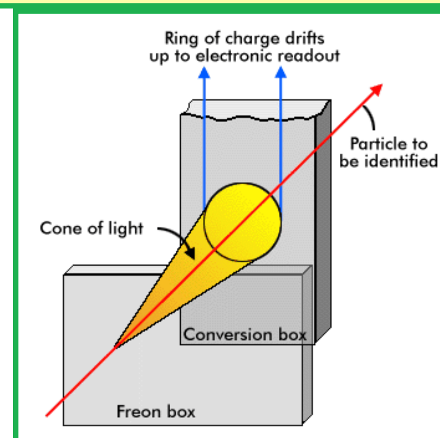
Cerenkov radiators

$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV

$\rightarrow 10 \div 30$ γ/MeV

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





EXAMPLE

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

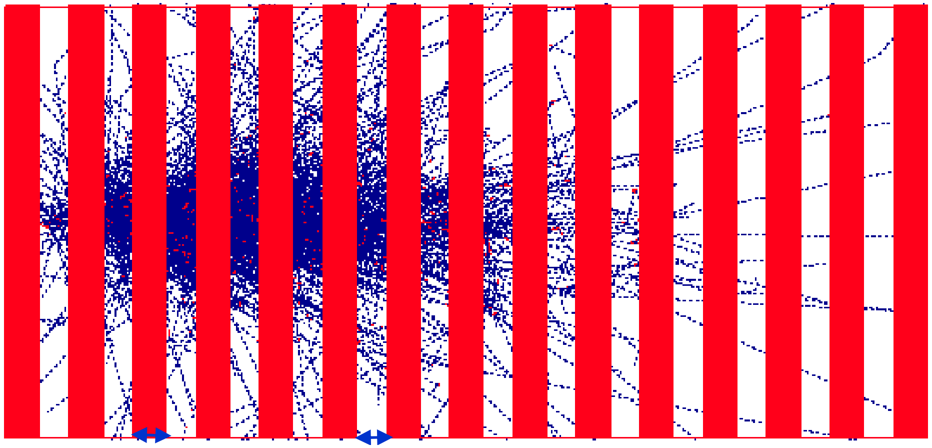
At maximum 1000 MeV/0.7 MeV $e^{\pm}$ will produce light

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

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

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

SAMPLING CALORIMETERS



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

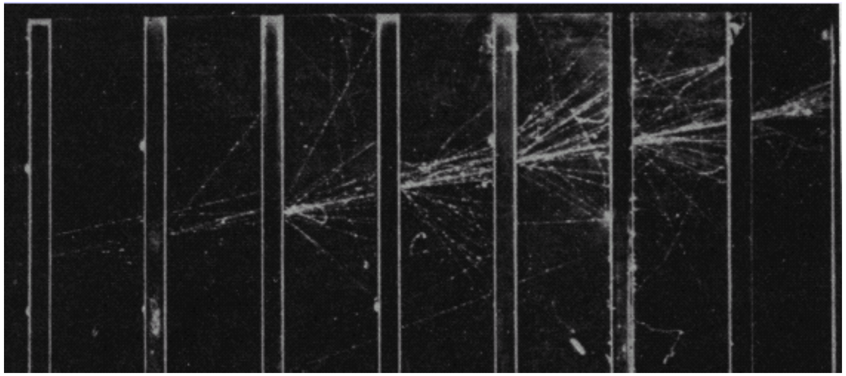
- Limited energy resolution
- Longitudinal segmentation

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

Absorber (high Z): typically Lead, Uranium

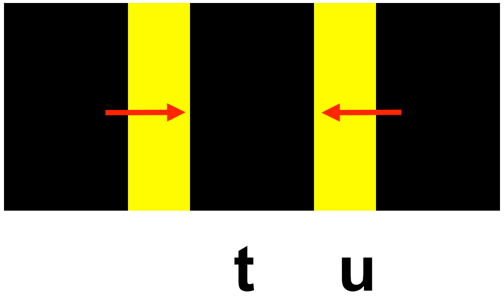
Active medium (low Z): typically Scintillators, Liquid Argon, Wire chamber

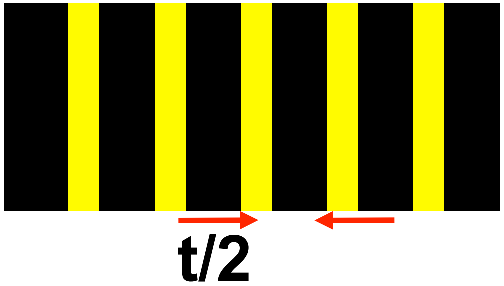
Energy resolution of sampling calorimeter dominated by fluctuations in energy deposited in the active layers



$$\sigma(E)/E \sim (10\div20)\%/\sqrt{E}\ (\mathrm{GeV})$$

SAMPLING CALORIMETERS





Sampling frequency is defined by the the thickness t (in units of X_0) of the passive layers: number of times a high energy electron or photon shower is sampled

The thinner the passive layer, the better

Sampling fraction is defined by the thickness of the active layer

$$\boxed{f_S = u.dE/dx_{active}/[u.dE/dx_{active} + t.dE/dx_{passive}] \;\; (u,t \text{ in } gcm^{-2}, dE/dx \text{ in } MeV/gcm^{-2}).}$$

for minimum ionising particles.

SAMPLING CALORIMETERS

Most of detectable particles are produced in the absorber layers

Need to enter the active material to be counted/measured

The number of crossing of a unit "cell" N_x, using the Total Track Length

N_x = TTL/(t+u) =E/E_c(t+u) = E/ΔE where ΔE is the energy lost in a unit cell t+u

Assuming the statistical independence of the crossings, the fluctuations on Nx represent the "sampling fluctuations" $\sigma(E)_{samp}$

$$\boxed{\sigma(E)_{samp}/E=\sigma(N_x)/N_x=1/\sqrt{N_x}=[\Delta E(GeV)/E(GeV)]^{1/2} = a/\sqrt{E}}$$

a is called the sampling term

SAMPLING FRACTION

The actual signal produced by the calorimeter is proportional

$$E.f_s=\sum u.dE/dx$$

If f_s is too small, the collected signal will be affected by electronics noise.

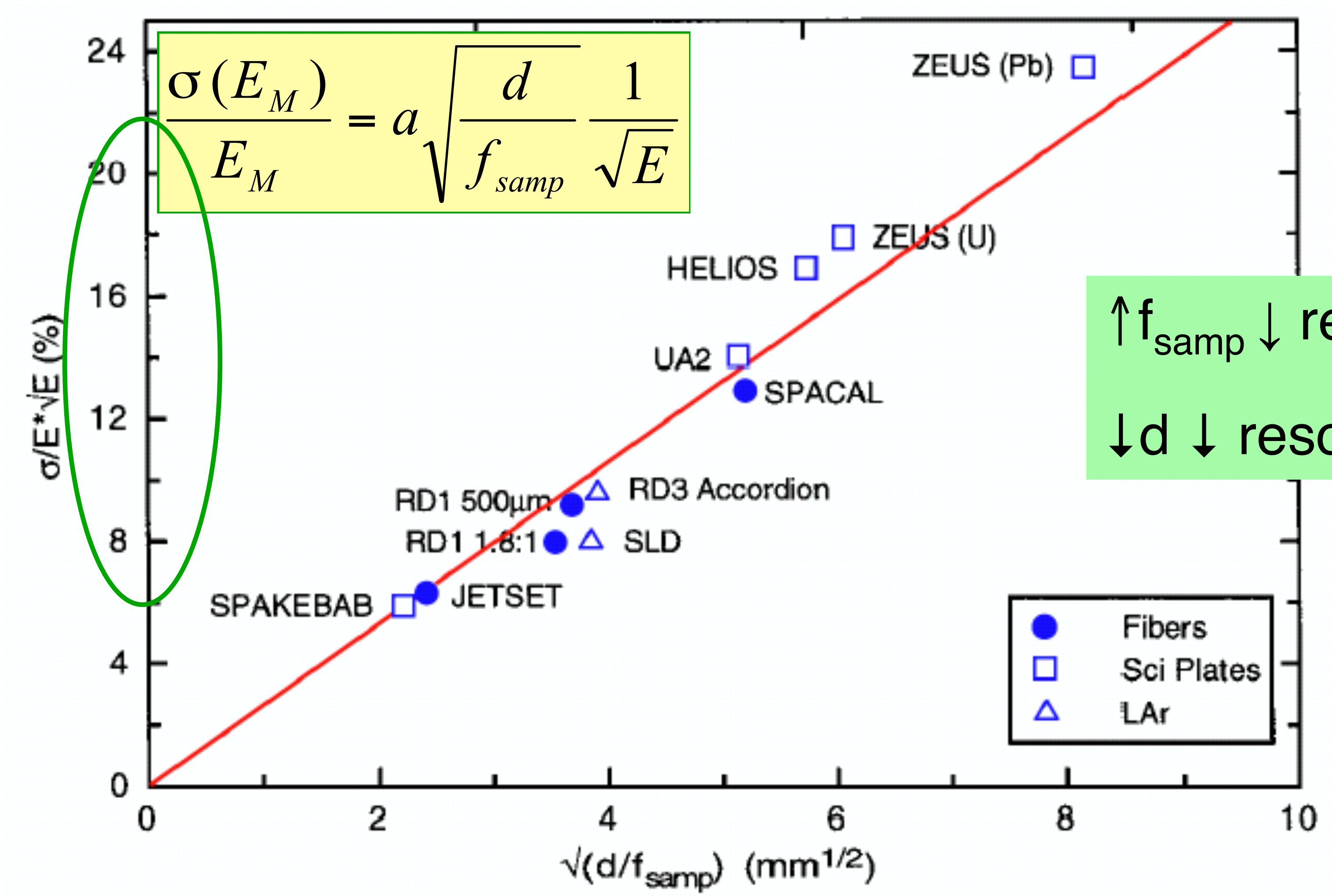
The dominant part of the calorimeter signal is not produced by minimum ionising particles (m.i.p.), but by low-energy electrons and positrons crossing the signal planes.

One defines the fractional response f_R^i of a given layer i as the ratio of energy lost in the active and of sum of active+passive layers:

$$\boxed{f_R^i=E^i_{active}/(E^i_{active} + E^i_{passive}) \text{ with } \sum^i(E^i_{active} + E^i_{passive})=E_0}$$

f_R/f_s~e/mip ~0.6 when $Z_{passive} >> Z_{active}$
due to transitions effects & low energy particles not reaching the active medium

ENERGY 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)

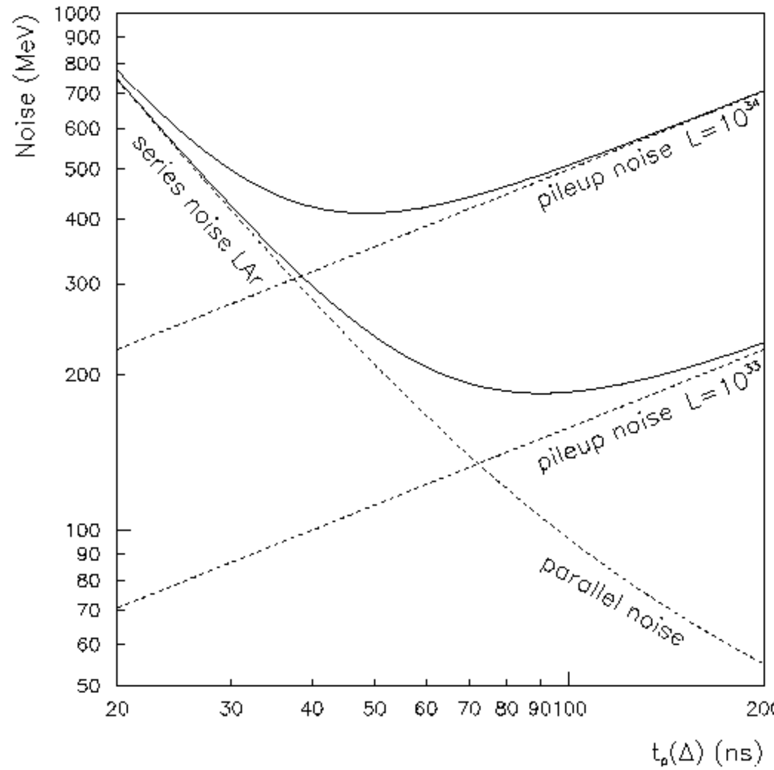
Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

NOISE TERM WITH PILE-UP

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

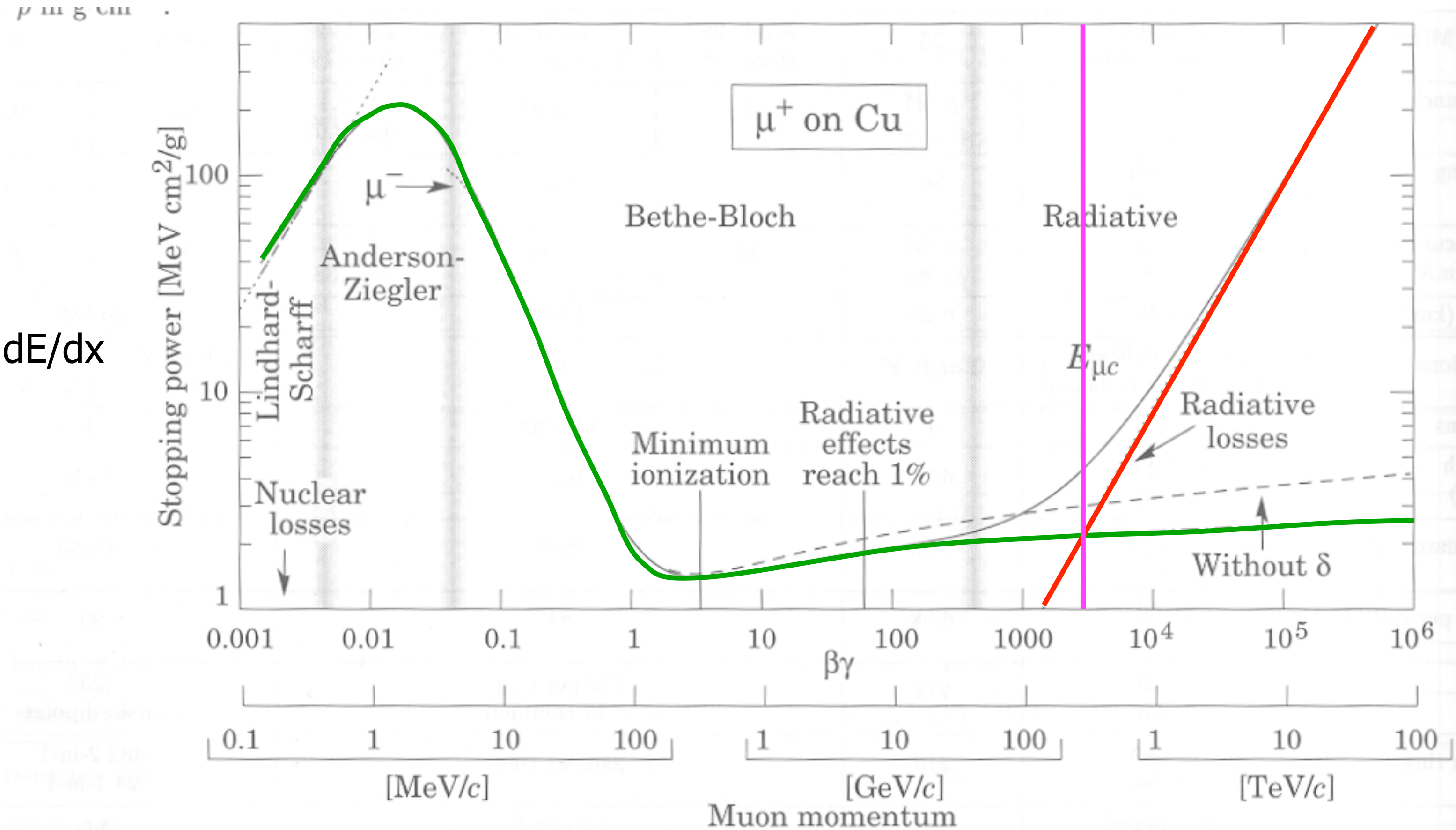
Contrary to electrons, muons (E<100GeV) loose energy mainly via ionization with

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

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

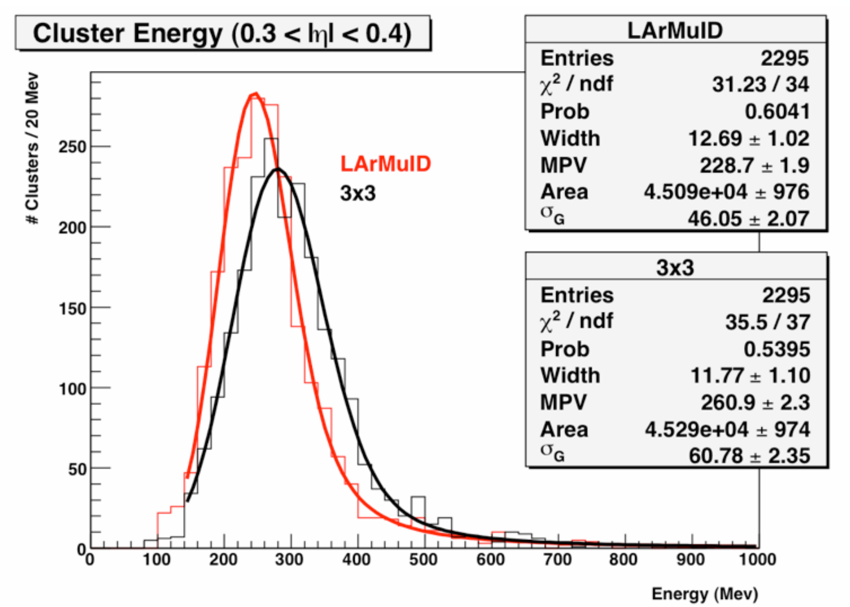
MUONS in MATTER

dE/dx

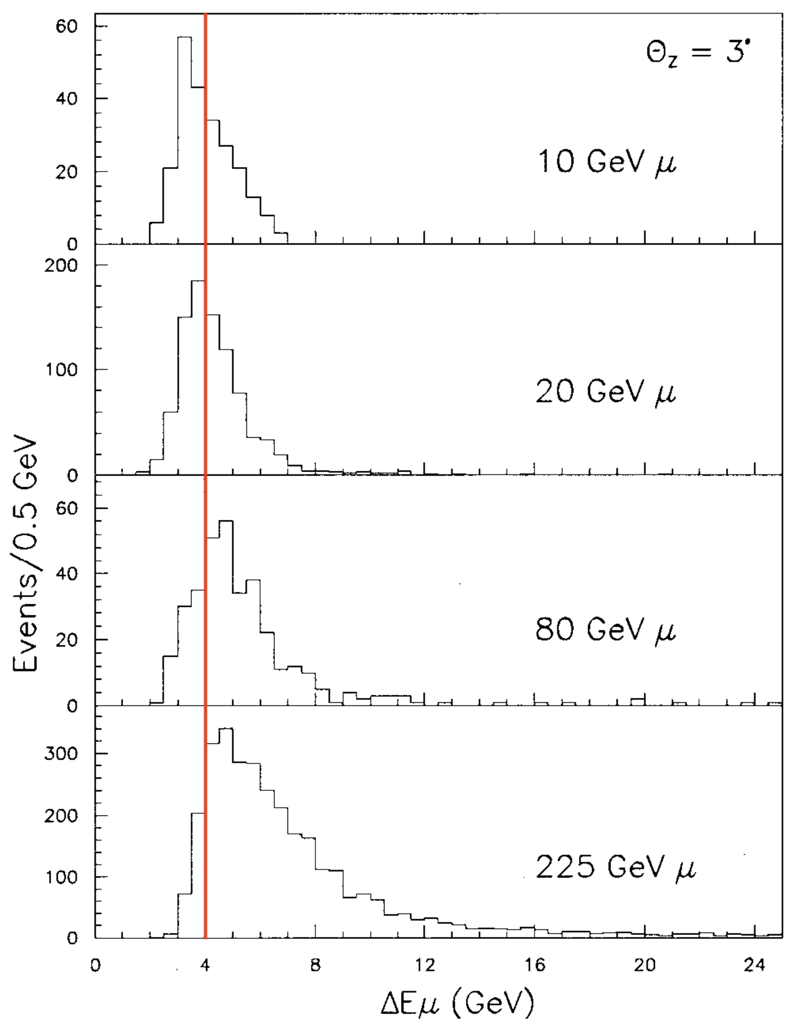


ENERGY DEPOSIT of MUONS in MATTER

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



Cosmic μ in ATLAS LAr EM barrel



MUONS for CALORIMETERS

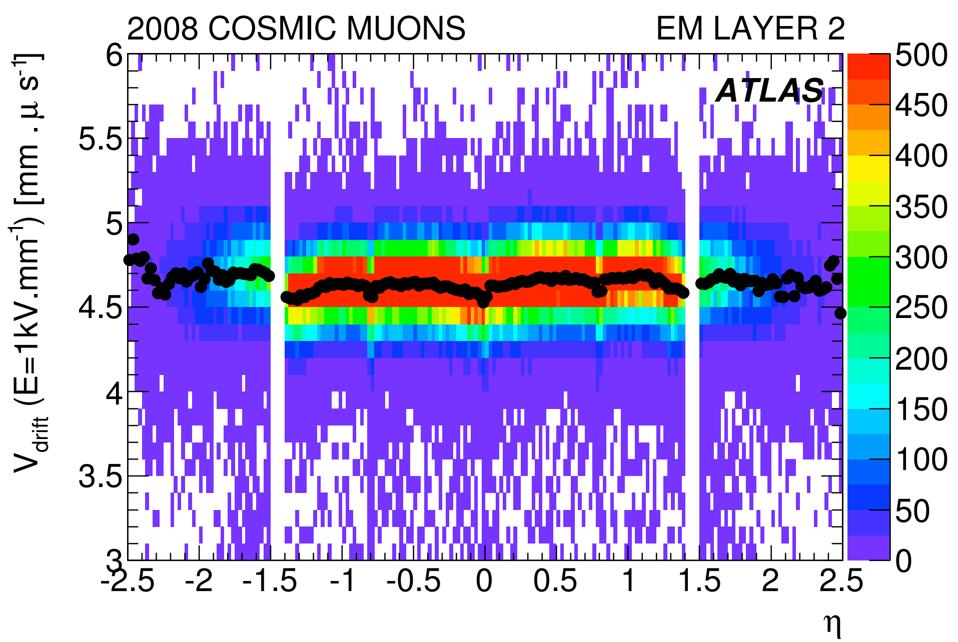
Muons deposit very little energy in calorimeter: dE/dx . x

- 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 analyse the calorimeter geometry



(b) Drift velocity

End of interlude