Lectures on calorimetry

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Lecture 1

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Plan of lectures

Lecture 1

Why/what calorimeters ?

Physics of EM showers

Calorimeter Energy Resolution

Lecture 2

Physics of hadronic showers

ATLAS & CMS calorimeters

Calorimeter Objects

Lecture 3

Example of calorimeters (suite)

Future of calorimetry

Lecture 4

Tutorial
Exercises

Disclaimer

Calorimetry is a vast topic.

This series of lectures only scratch the surface…

No way to cover all technologies, detectors, features.

This is thus a **selective**, **personal** and (surely) **biased** presentation of calorimetry.

Also, it is likely some (unavoidable) redundancy is there wrt the previous lectures.

References

These lectures were built upon numerous (excellent) lectures, books or papers:

➢ Lectures:

- V. Boudry, *"La Calorimétrie"*, Ecole du détecteur à la mesure, mai 2013 (Fréjus)
- D. Cockerill, *"Introduction to Calorimeters"*, Southampton Lecture May 2016
- M. Diemoz, *"Calorimetry"*, EDIT 2011 (CERN)
- D. Fournier, *"Calorimetry"*, EDIT 2011 (CERN)
- E. Garutti, *The art of calorimetry*
- F. Sefkow, *Particle Flow: A Calorimeter Reconstruction Exercise",* EDIT 2010 (CERN)
- J. Stark, *"Counting Calories at DØ"*, University of DØ 2010, Fermilab
- J. Virdee, "Experimental Techniques, European School of HEP 1998 (St Andrews)
- I. Wingerter-Seez, *"Calorimetry: Concepts and Examples"*, ESIPAP 2016 (Archamps)
- A. Zabi, *"Instrumentation for High Energy Physics"*, TES-HEP 2016 (Yaremche)

➢ Book:

- R. Wigmans,*"Calorimetry, Energy Measurements in Particle Physics"*, Oxford science publications,
- Particle Data Group

➢ Talks, proceedings, articles:

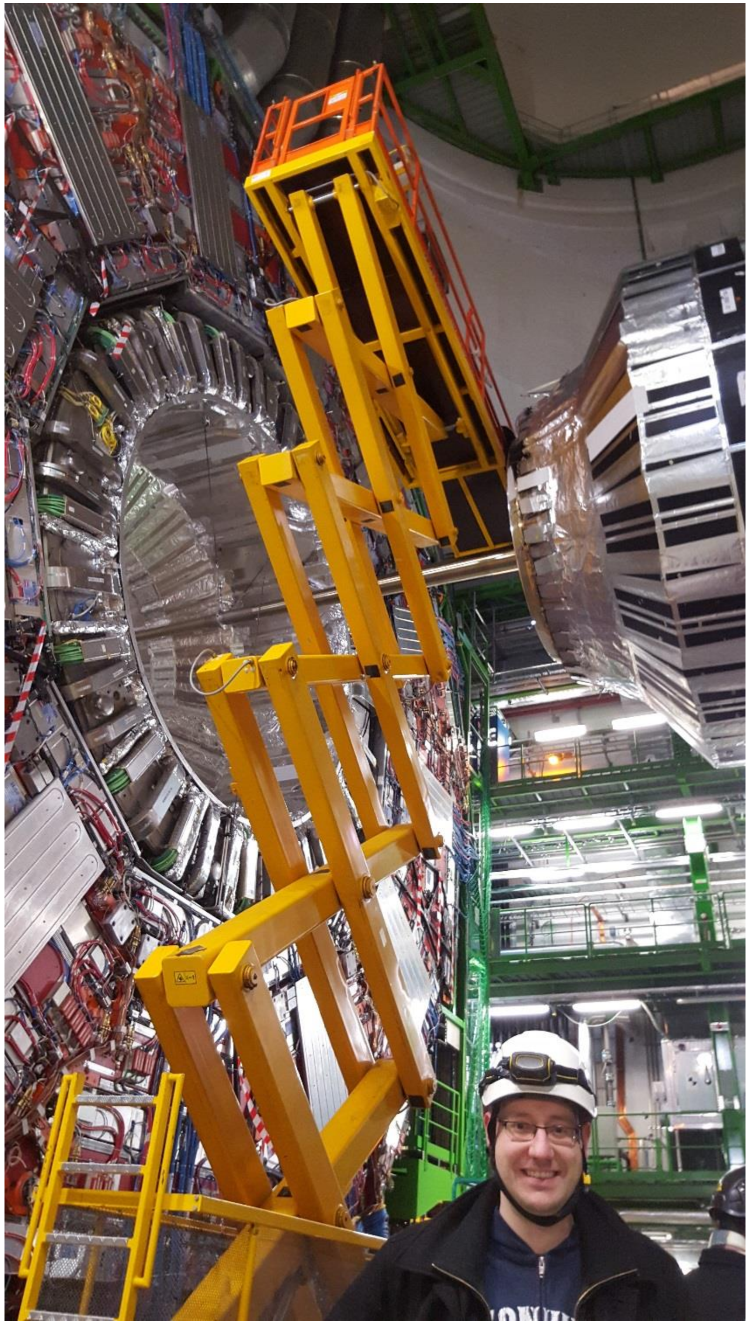
- J-C. Brient, Improving the Jet Reconstruction with the Particle Flow Methodd; An Introduction
- F. Beaudette, *Performance of the Particle Flow Algorithm in CMS*, ICHEP 2010 (Paris)
- F. Beaudette, *The CMS Particle Flow Algorithm*, CHEF 2013 (Paris)
- C. Bernet, Particle Flow and τ, LHC France 2013 (Annecy)
- L. Gray, *Challenges of Single Particle Reconstruction in Hadronic Environment*s, Rencontres du Vietnam: Physics at LHC and Beyond 2014 (Qui-Nhon)
- J.S. Marshall, *Pandora Particle Flow Algorithm*, CHEF 2013 (Paris)
- H. Videau, *Energy Flow or Particle Flow The technique of energy flow for pedestrians.*

A few words about myself

- **Thesis at DØ (at Tevatron ppbar collider)**
  - **Jet Calibration**,
  - **Jet+Missing E_T** Trigger,
  - Search for Higgs boson

- **Post-doc ATLAS (at LHC pp collider)**
  - **Jet** Triggers
  - Z+jets cross section

- **In CMS (LHC) since 2009**.
  - Search and discovery of Higgs boson
    - $H \rightarrow ZZ^* \rightarrow 4$ lepton channels
  - **Electron Identification**
  - Since 2014, convener of Engineering of the **High Granularity CALorimeter** upgrade project

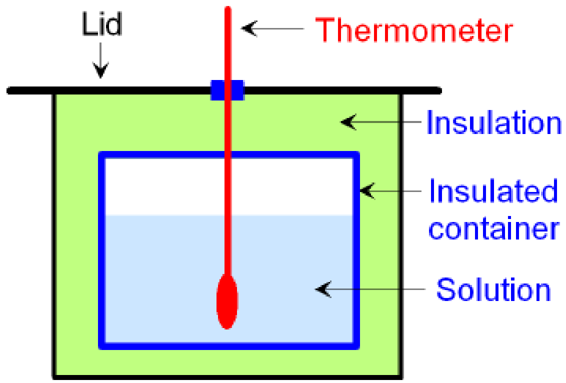


What is a calorimeter ?

Concept comes from thermodynamics.

- *Calor*: latin for “heat”
- **Calorimeter:** thermally isolated box containing a substance to study (e.g., measure its temperature)

  Ex: Calorimeter of Curie-Laborde (1903) to measure heat produced by radium radioactivity (~100 cal / g / h).



- 1 calorie (4,185 J) is the necessary energy to increase the T° of 1g of water at 15°C by 1 degree
- At hadron colliders, we measure GeV particles (0.1 – 1000)

  1 GeV = 10^9 eV ~ 10^9 x 10^{-19} J = $2.4.10^{-9}$ cal !

  <=> 1 GeV particle will heat up 1L water (20°C) by… ~10^{-14} K !

The increase of heat in a material by the passage of particle is negligible !
More sophisticated methods have to be used to detect stable particles…

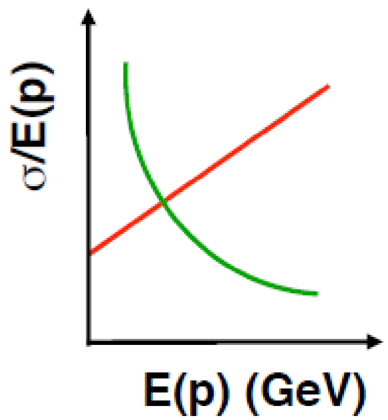
What is a calorimeter… in high energy physics ?

Calorimeters in HEP: detection & measurement of properties of particles through their absorption in a block of (dense) matter.

- **Up to 1970',** mostly tracking system (with magnetic field) were used:
  - Measure charged particles… (curvature => momentum, charge, dE/dX: information on mass)
  - … and neutrals, through interaction with matter (e.g. $\pi^0 \rightarrow \gamma\gamma$ with conversion: $\gamma \rightarrow$e+e-)
- **But:**
  - Very poor efficiency and/or resolution on π^0
  - Necessity to measure particles of higher and higher mass (W/Z, top quark, Higgs, W/Z', SUSY…)

=> Calorimeter became more and more crucial in HEP

- Measure charged AND neutrals
- Resolution:



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

Magnetic analysis

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

Resolution improves with E with **Calorimeter**

The measurement in process with calorimeters is **destructive** !

Note: in the absorption, almost all particle's energy is eventually converted to heat, hence the term "calorimeter"

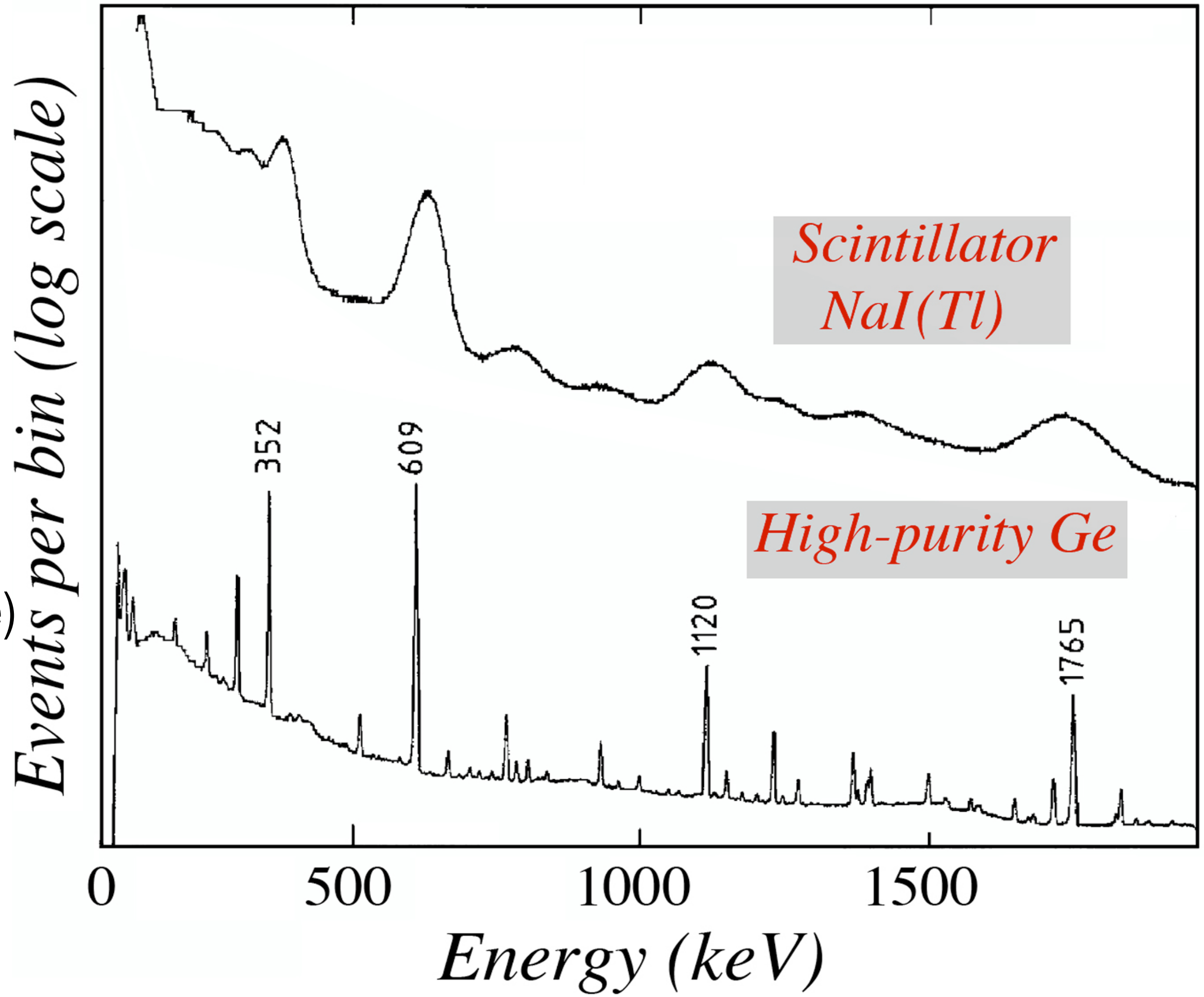
Some (historical) examples… (1)

A wide variety of calorimeters… for a wide physics program !

1940's: calorimeters used for detection of α, β, γ from nuclear decays
Scintillating crystals
+ PhotoMultiplier Tubes (PMT)

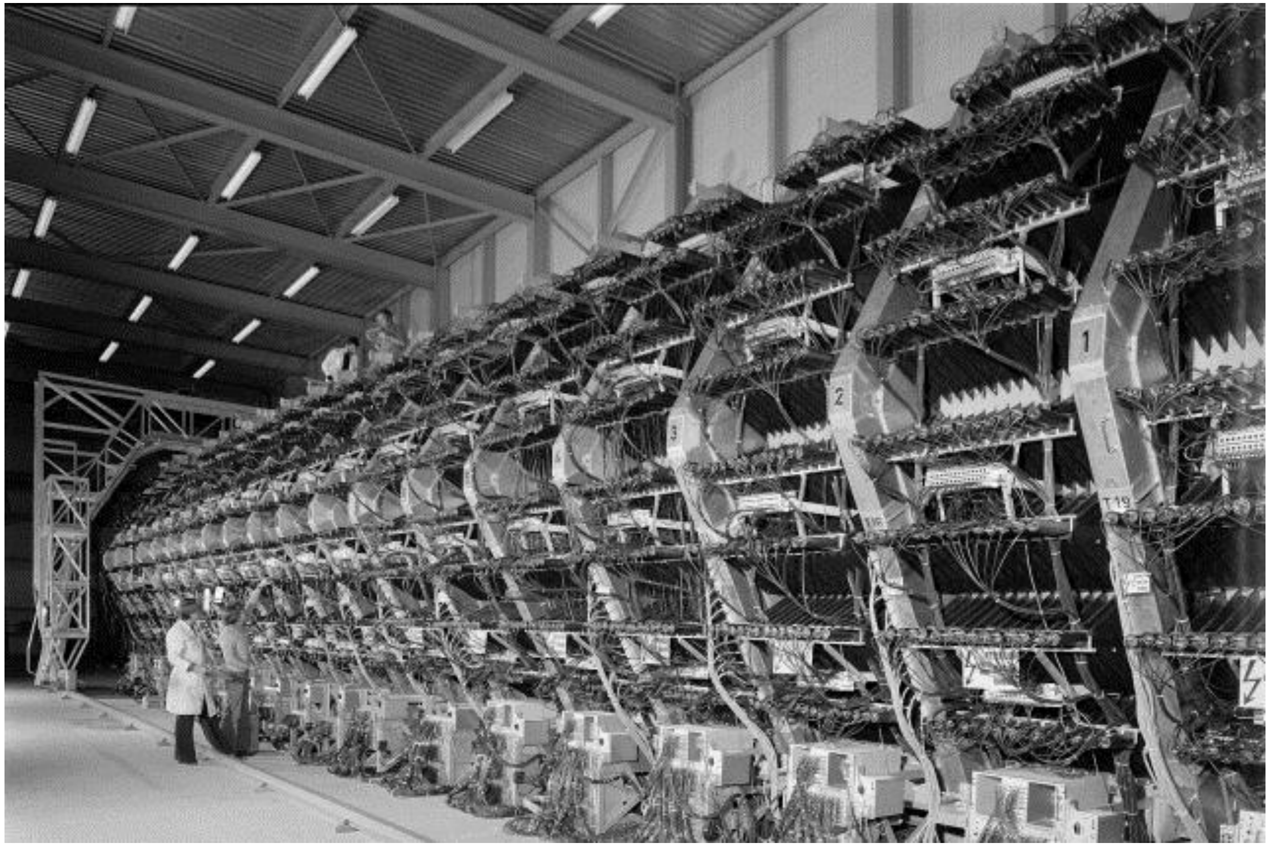
1960's: first **semi-conductor detectors** (Si, Ge)

Impressive improvement in resolution !



Some (historical) examples… (2)

A wide variety of calorimeters… for a wide physics program !



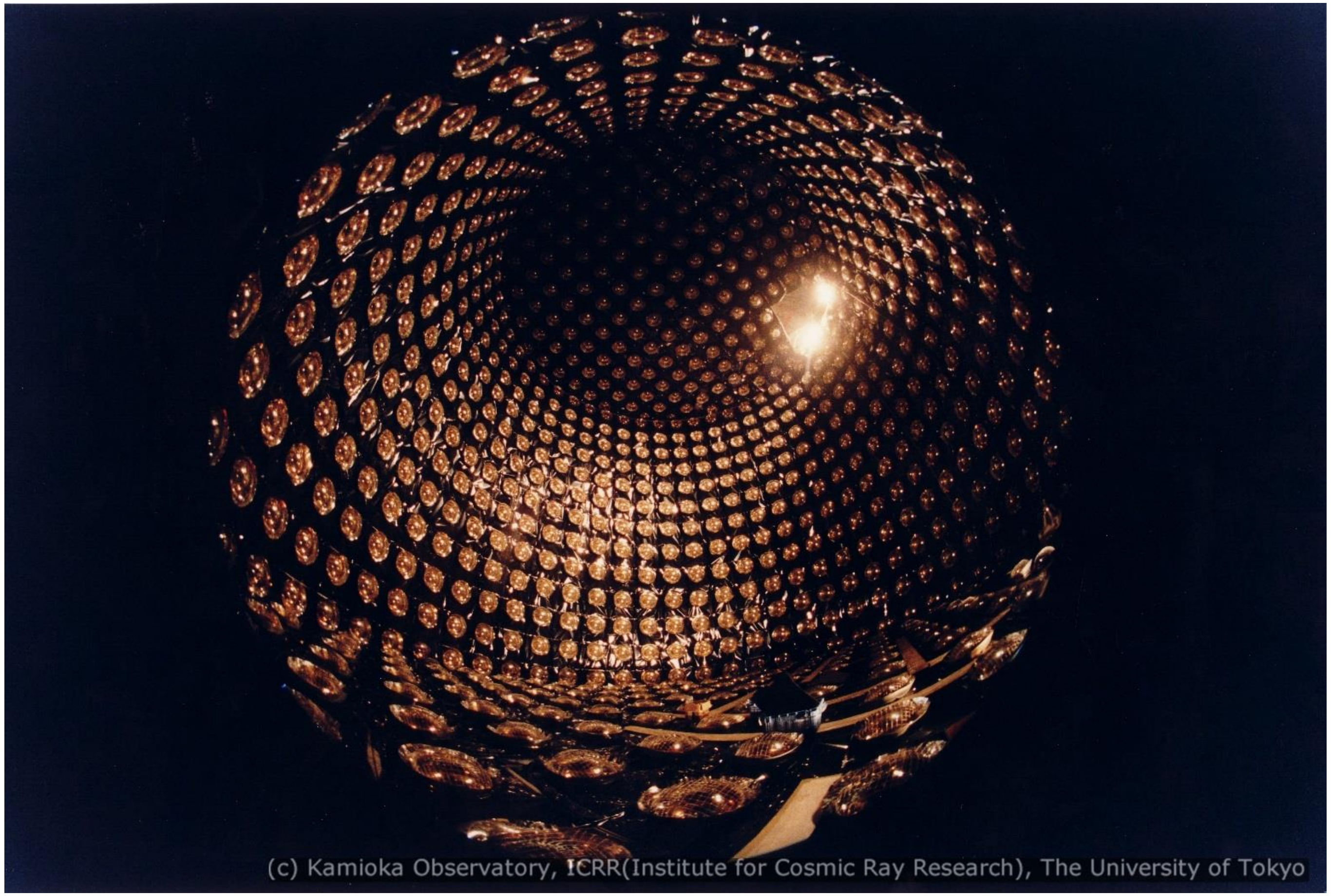
WA1 Experiment (1976 - 1984)

- First neutrino experiment at SPS (CERN)
- Looking at deep inelastic neutrinos interactions.

- Integrated Target (target, calorimeter, tracker):
  - Slabs of (magnetized) Iron, interleaved with scintillators
  - + wire chamber to track muons

Some (historical) examples… (2)

A wide variety of calorimeters… for a wide physics program !

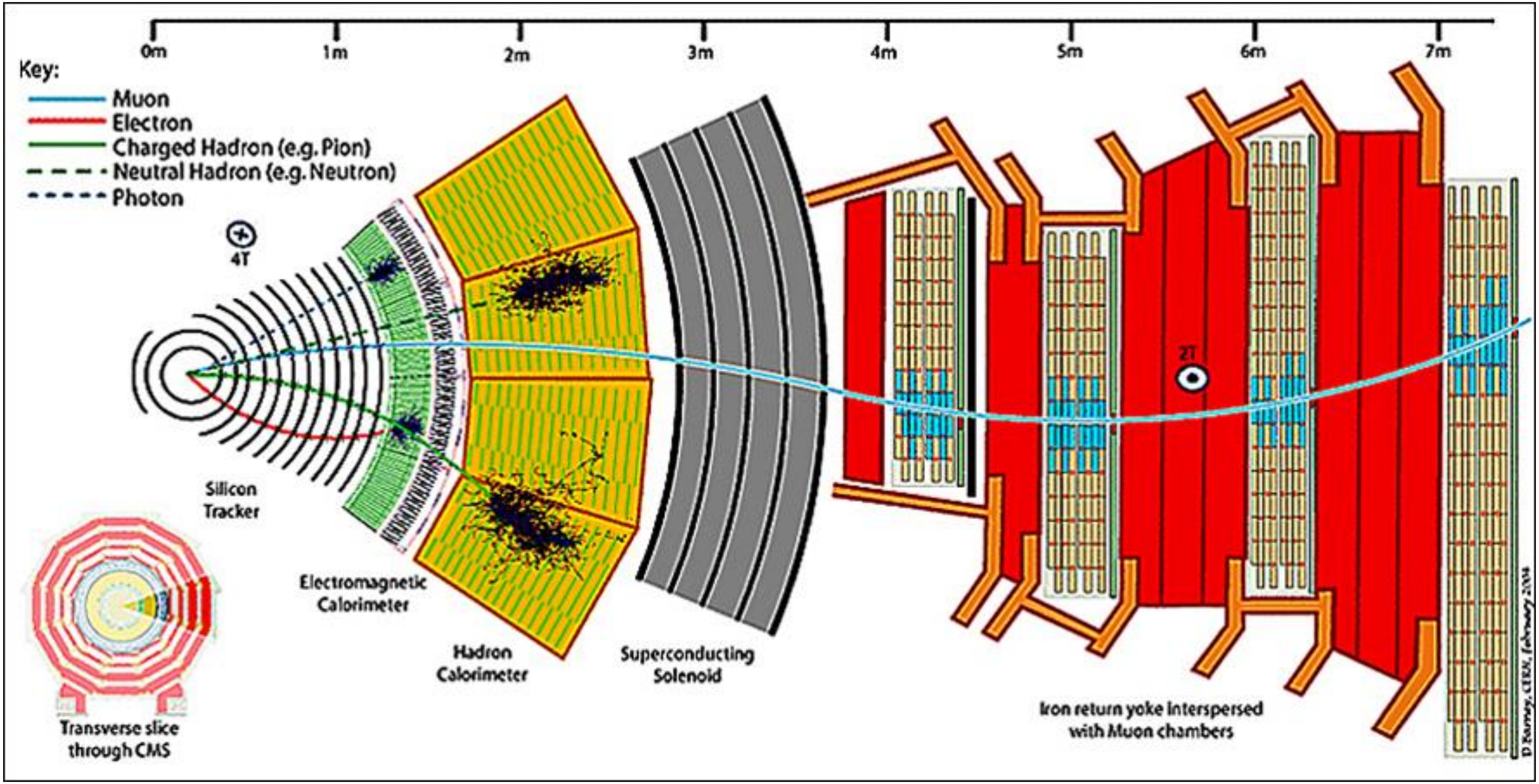


Kamiokande

- Water tank placed in an underground mine
- >2140 t of water
- Surrounded by 1k of large phototubes
- Detect Cerenkov light emitted by the scattering of neutrinos with electron or nuclei of water

Measurement of solar neutrinos flux deficit (together with “Homestake” experiment) in 1990’s
Nobel Prize in 2002

General Structure of modern HEP colliders detectors



Onion-like structure

- Magnet (or not) to generated B-field for tracking (& muon system)
- Calorimeters (Electromagnetic and Hadronic parts): inside or outside the coil….

Some (historical) examples… (3)

A wide variety of calorimeters… for a wide physics program !

UA1 detector

- Modern particle physics detectors at SppS (CERN, $\sqrt{s}$=540 GeV)
- Calorimeters: Lead or Fe + Scintillator

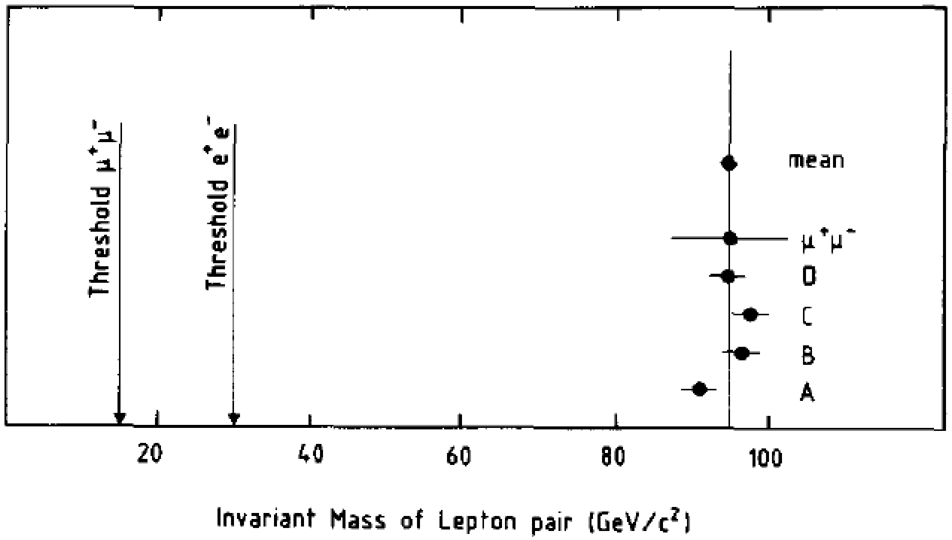
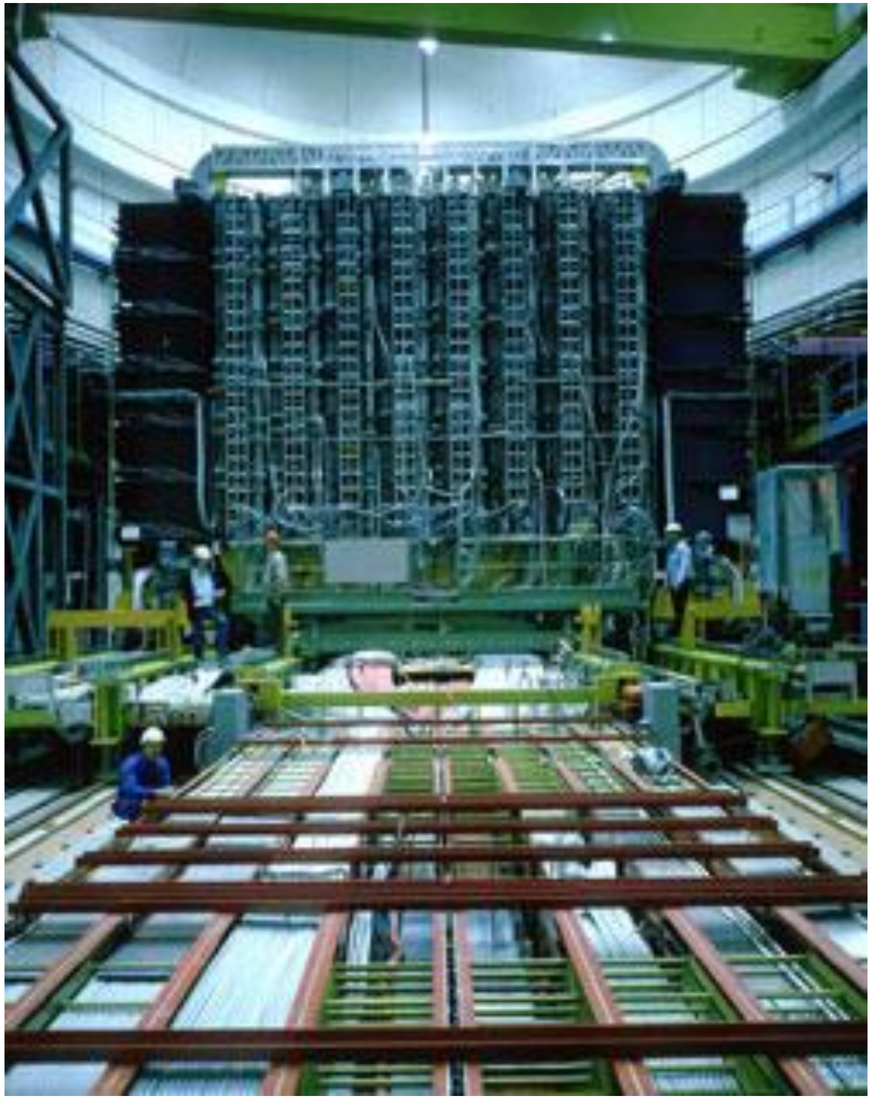


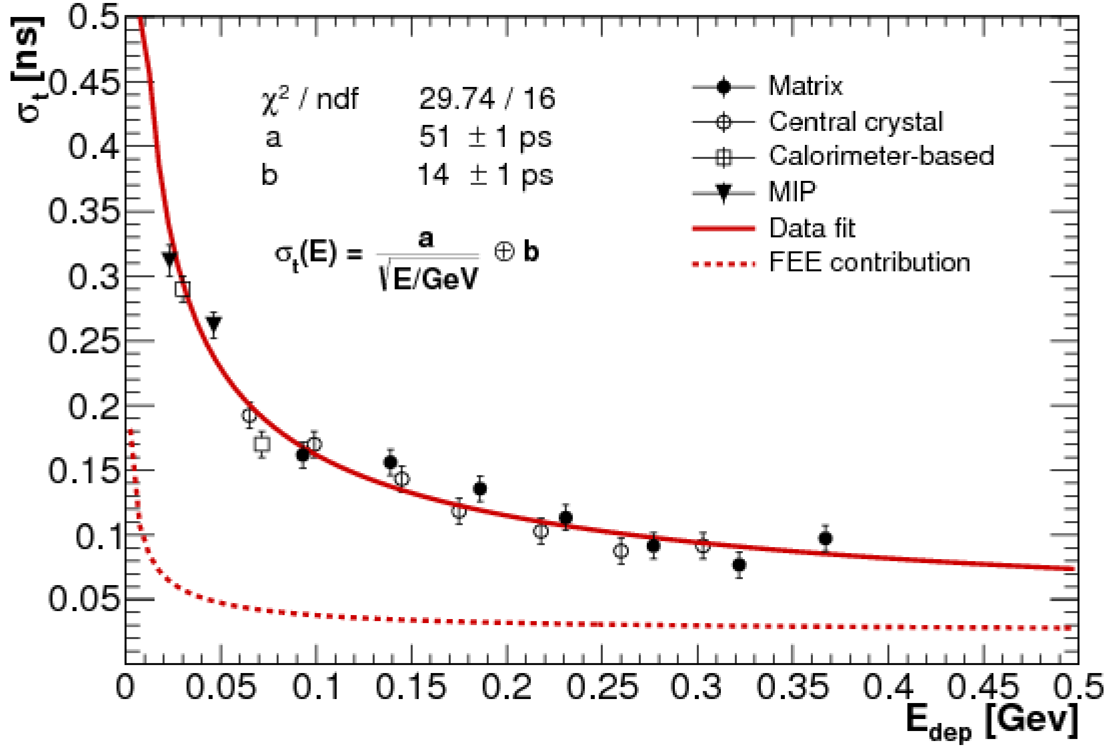
Fig. 8. Invariant masses of lepton pairs.



Discovery of W's and Z bosons (1983)
Nobel Prize in 1984

Calorimeter Features

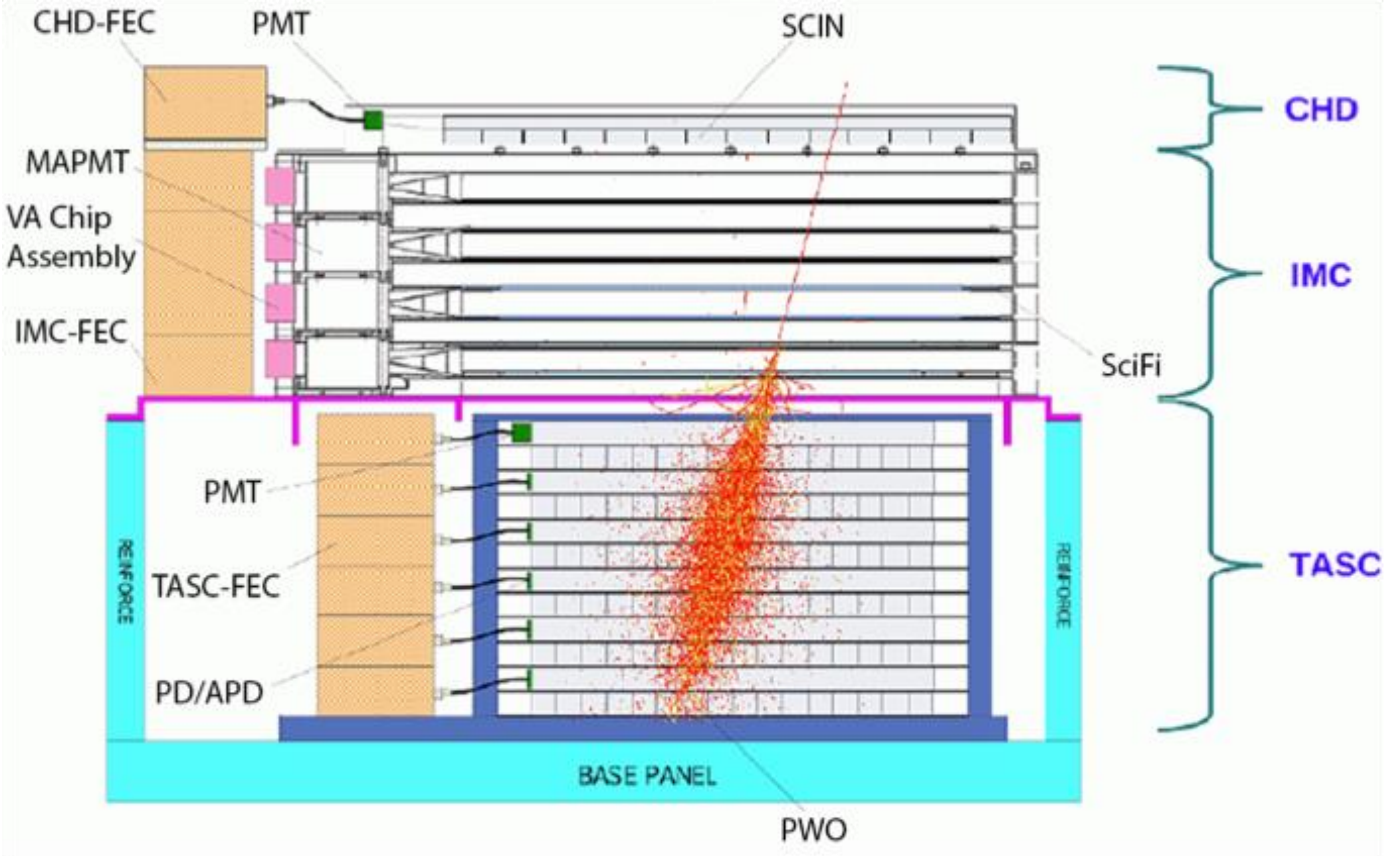
- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- Particle ID
- Timing
- Triggering



Mu2e LYSO crystal calorimeter

Calorimeter Features

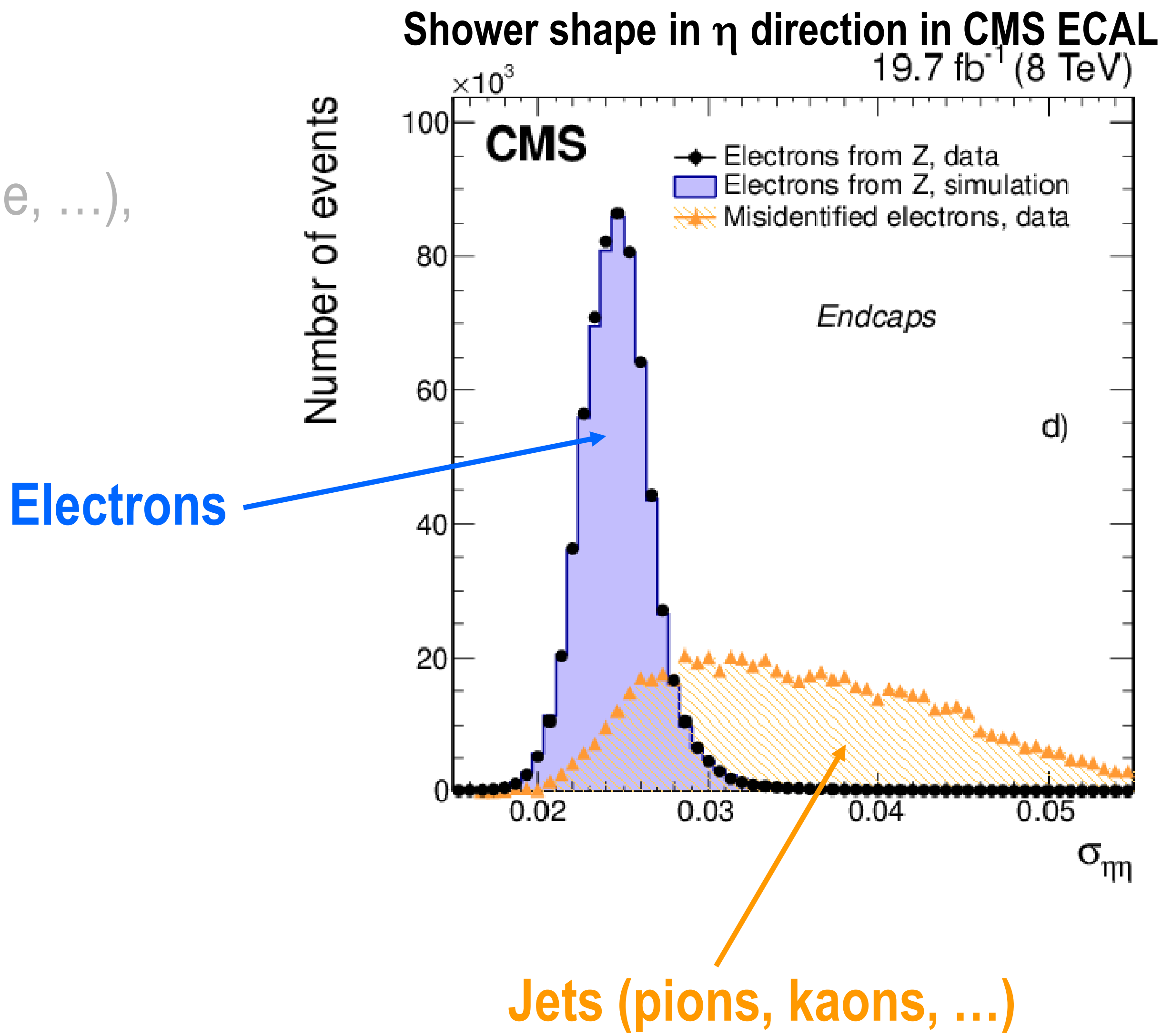
- ➢ Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- ➢ Precision improves with energy
- ➢ **Position Measurement**
- ➢ Particle ID
- ➢ Timing
- ➢ Triggering



- Segmented calorimeters allows precise position / angle measurement
  - Ex: ATLAS EM: 60 mr / √E

Calorimeter Features

- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- **Particle ID**
- Timing
- Triggering



- Difference in shower patterns: **Identification is possible**
  - Lateral and longitudinal shower profile
  - Can also **match with tracking**

Calorimeter Features

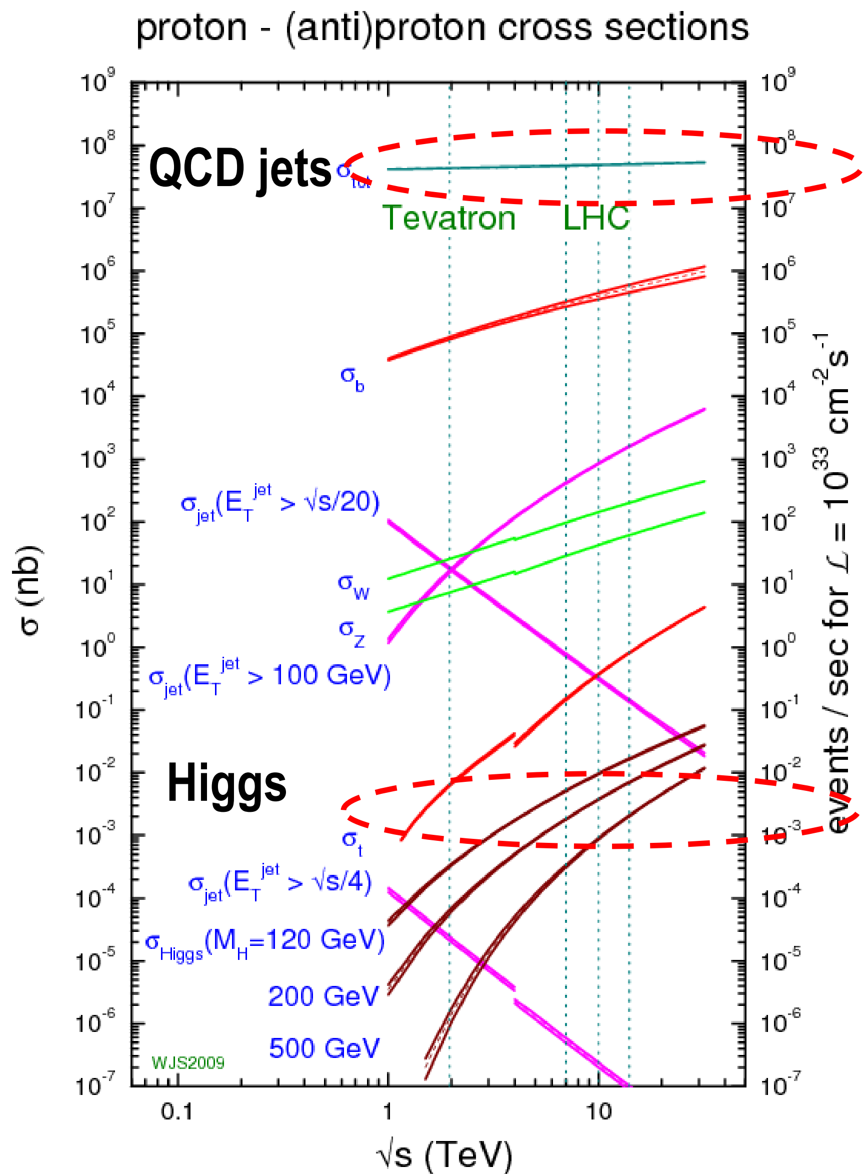
- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- Particle ID
- **Timing**
- Triggering

- Calorimeters can have “fast” signal response with good resolution (100 ps achievable)

- Helps mitigating “out of time” Pile-up (PU) at hadron colliders
  - ex: at LHC, collisions every 25ns. Signal from other bunch crossing can pile up…
- May help with **Particle ID** (time structure of showers)
- May allow mitigation of “in time” PU
  - If resolution better than 100ps, can constraint vertex of neutral particles
- **Allows efficient triggering** (see next slide)

Calorimeter Features

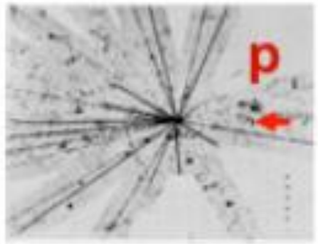
- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
- Particle ID
- Timing
- **Triggering**

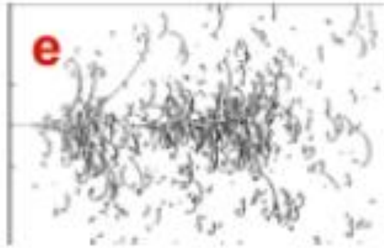


- Enormous rejection factor needed at hadron colliders to select "interesting" events (Higgs, SUSY,…)
- **Calorimeters**, thanks to their fast response and particle ID capabilities play a **leading role in triggering aspects** at hadron colliders !

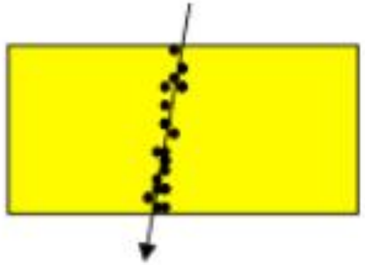
FOUR STEPS

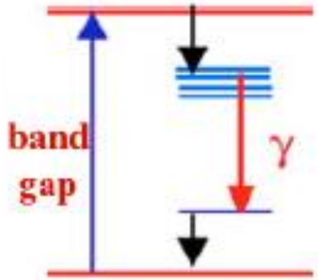
1. Particles interact with matter
depends on particle and material

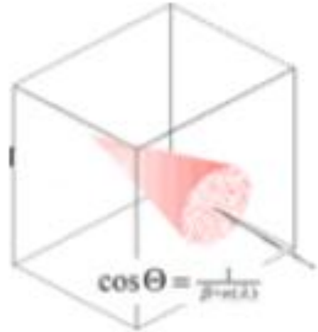




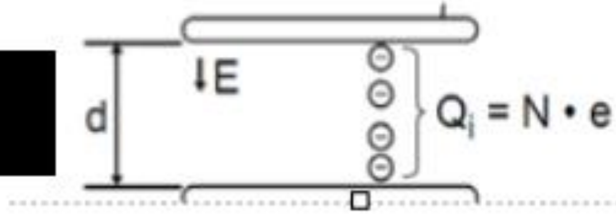
2. Energy loss transfer to detectable signal
depends on the material

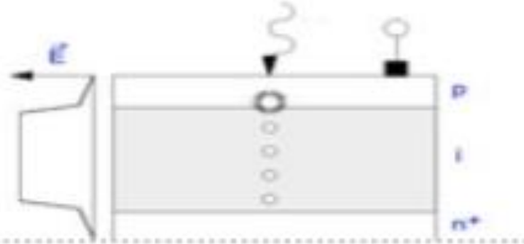






3. Signal collection
depends on signal and type of detection





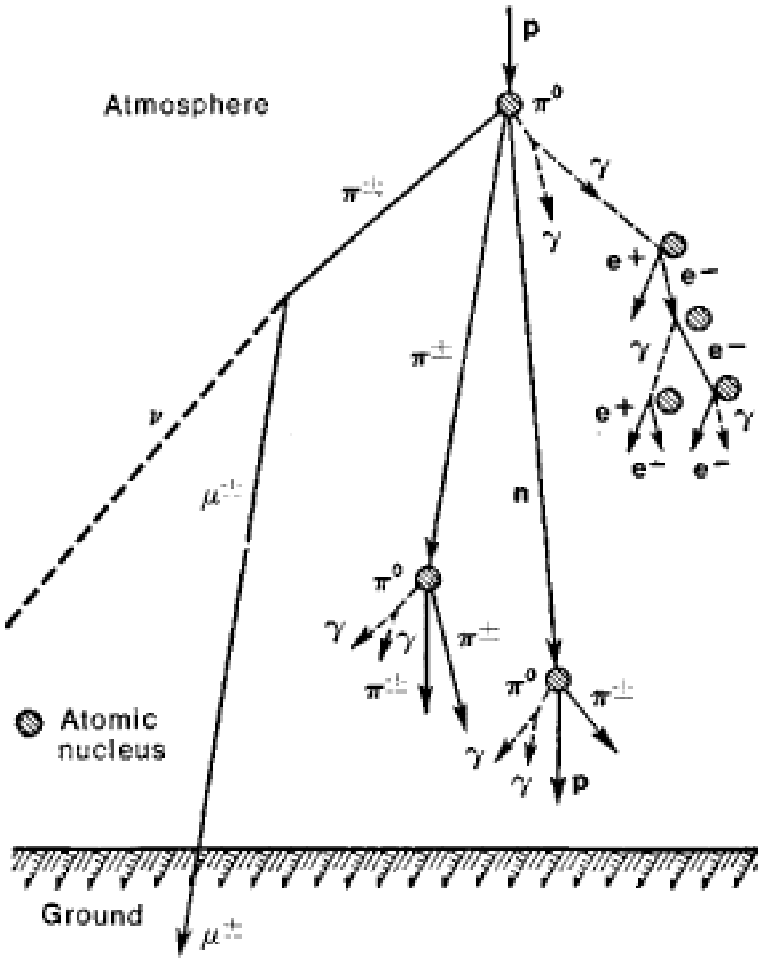
4. BUILD a SYSTEM
depends on physics, experimental conditions,….

Calorimeter measurement: how ? (1)

1. Particles interact with matter
depends on particle and material

- Particles interact with matter (ie, “absorption” of the initial particle by dense material)
  - Only charged particles ultimately leave signal…
  - Neutrals have to convert ($\gamma \rightarrow e+e-$, …)
- Creates cascade of N secondary particles

$$\boxed{E_{deposited} \propto N \text{ secondary particles}}$$

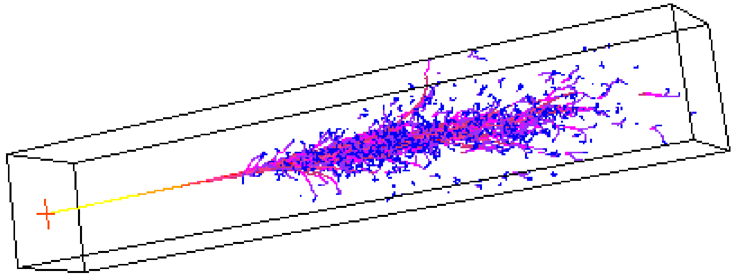


- Need to provide:
  - Dense material to initiate secondary particles: **Absorber**
  - Sensible medium to “measure” secondary particles: **Active medium**

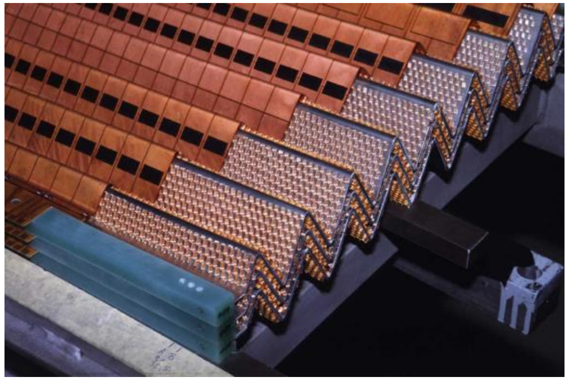
Calorimeter measurement: how ? (2)

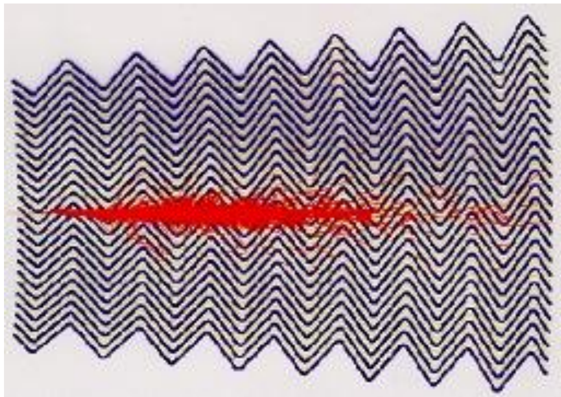
1. Particles interact with matter
depends on particle and material

- Two types of calorimeters:
  - **Homogenous:**
    - Absorber == active medium
    - Material **dense** enough to contain shower, **scintillating** and **transparent** (for light transportation) or non-scintillating **Cerenkov**
      - Ex: CMS (PbWO4 scintillating crystals), L3 (BGO scintillating crystals), Lead Glass (Cerenkov), …



  - **Sampling**
    - Sandwich of **high-Z absorber** (Pb, W, Ur,…) and **low-Z active media** (liquid, gaz, …)
      - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), …



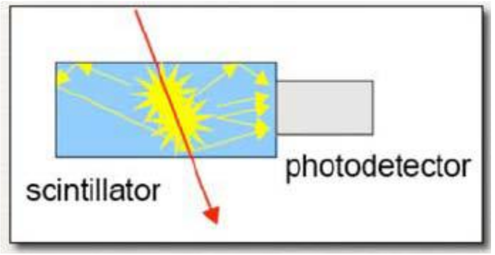


How do we "see" a signal ?

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

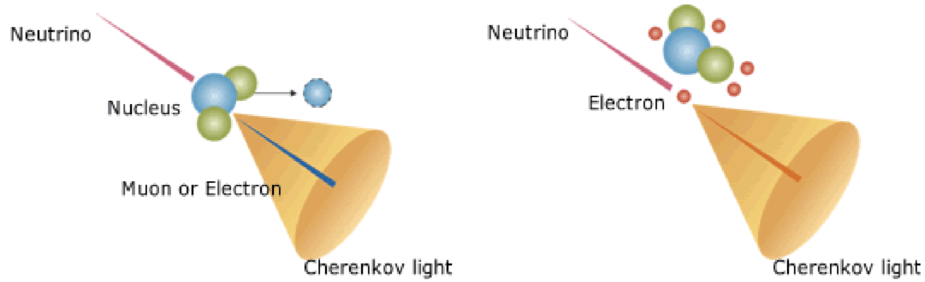
In practice, calorimeters used one of the **3 following effects for signal detection**:

- **Scintillation:**
  - Charged particles in shower excites atoms in detector, atoms de-excite => emission of light. Light collected by photo-detectors (PMT, APD, SiPM…)
  - Rather slow ($10^{-6} – 10^{-12}$ s).
  - Ex: crystal, scintillating fibers…



- **Ionization:**
  - Charged particles in shower ionize atoms in detector => free charge => "collect" free charge
  - Ex: Noble liquid (LAr, Xe, Kr…), gas (wire or drift chambers) , semi-conductor (Si…)

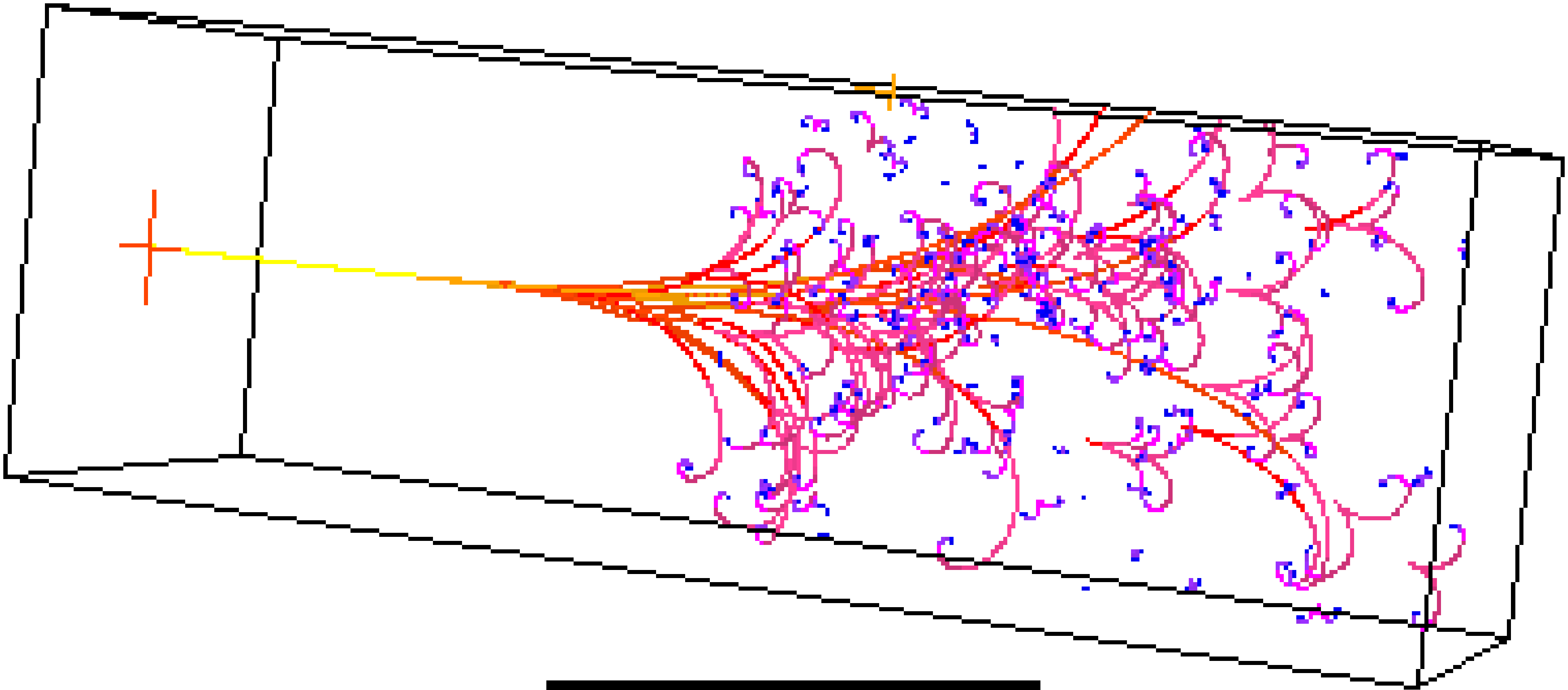
- **Cerenkov:**
  - Light emitted when charged particles goes faster than the speed of light in the media.
  - Light collected by photo-detectors.
  - Very fast
  - Ex: quartz fiber



The generated charged particle emits the Cherenkov light.

- **Note:**
- Also,… measure temperature !
- Cryogenic detector for Dark Matter searches, neutrinos, … => bolometers ! (not covered in these lectures)

Physics of Electromagnetic Showers



1. Particles interact with matter
   depends on particle and material

Glossary

Table 27.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV/c^2
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times$ c^2	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075$ MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\; m_ec^2/\alpha)$	$\sqrt{\rho\langle Z/A\rangle} \times 28.816$ eV (ρ in g cm^{-3})
N_e	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408$ g cm$^{-2})^{-1}$ for $A = 1$ g mol^{-1}
X_0	Radiation length	g cm^{-2}
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\; m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

Electromagnetic Showers

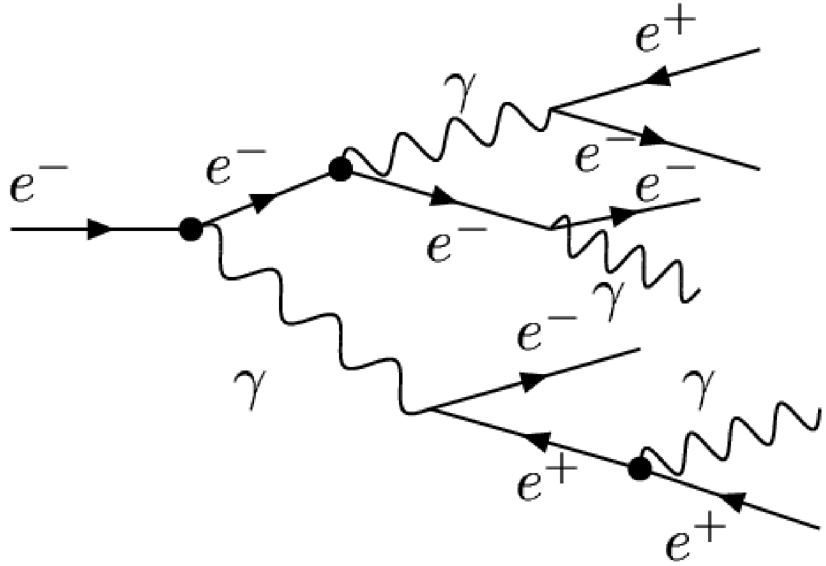
An ElectroMagnetic (EM) shower is a cascade of secondary electrons/positrons and photons initiated by the interaction with matter (ie, energy loss) of an incoming of electron/positron or photon.

- The main energy loss mechanism are:
  - Ionization
  - Bremsstrahlung

  } for e+/e-

  - Compton scattering
  - Pair creation
  - Photo-electric effect

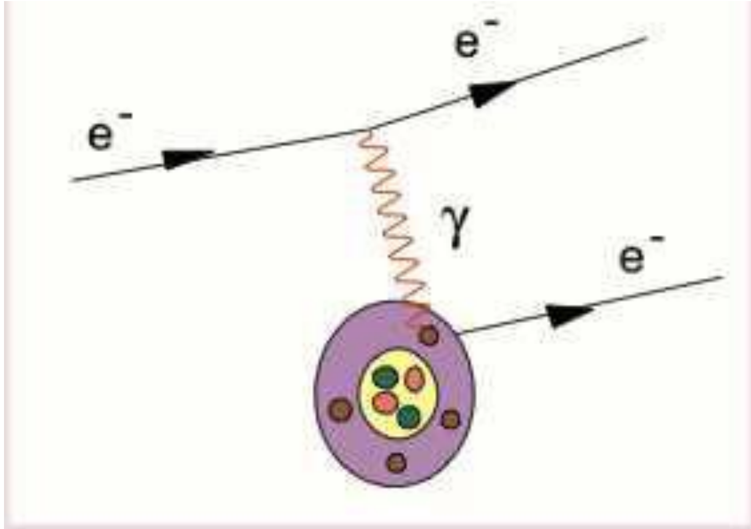
  } for γ



Ionization

- Interaction of charged particles with electron cloud of atoms (loss of electrons, atoms -> ions)

- **Dominant process at low energy**



- **Bethe-Bloch formula** (general)

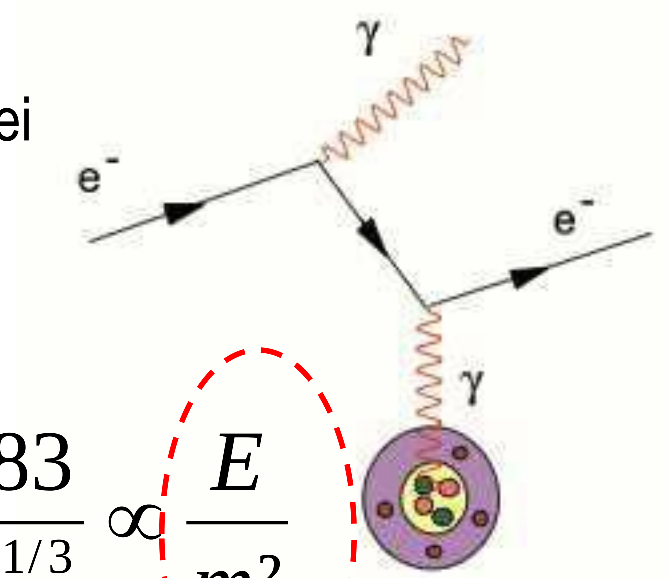
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (\mathrm{MeV.g^{-1}.cm^2})$$

Energy loss depends:

- quadratic ally on the charge and velocity of the incident particle (but not on its mass)
- Linearly on the material (through electron density)
- Logarithmically on the material (through mean ionization I)

Bremsstrahlung

- Radiation of real photons in the Coulomb field of the atomic nuclei
- **Dominant process at high energy**



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

- Important for electrons, much less for muons (apart from ultra-relativistic)

$$\left(-\frac{dE}{dx}\right)_{rad} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} \quad \text{(for electrons)}$$

- Conveniently re-written as: $\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}$

Radiation length

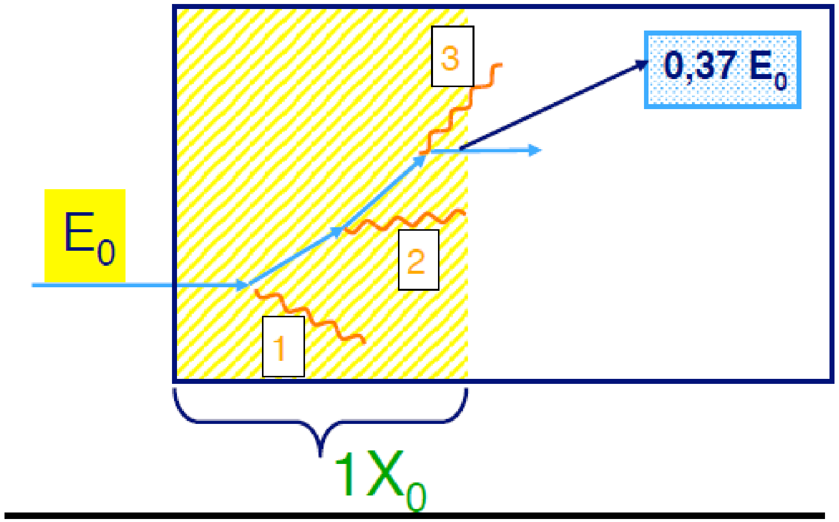
$$\boxed{X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}}$$

Radiation Length

➤ **Definition:** mean distance over which the incident electron loses all BUT 1/e ≈ 37% of its incident energy via radiation (ie, it radiated ≈63% of its incident energy)

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0} \Rightarrow \frac{dE}{E} = \frac{dx}{X_0}$$

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



➤ Useful approximation: $$\boxed{X_0 \approx \frac{180A}{Z^2}}$$ (g.cm^{-2}) Also in cm (taking into account density)

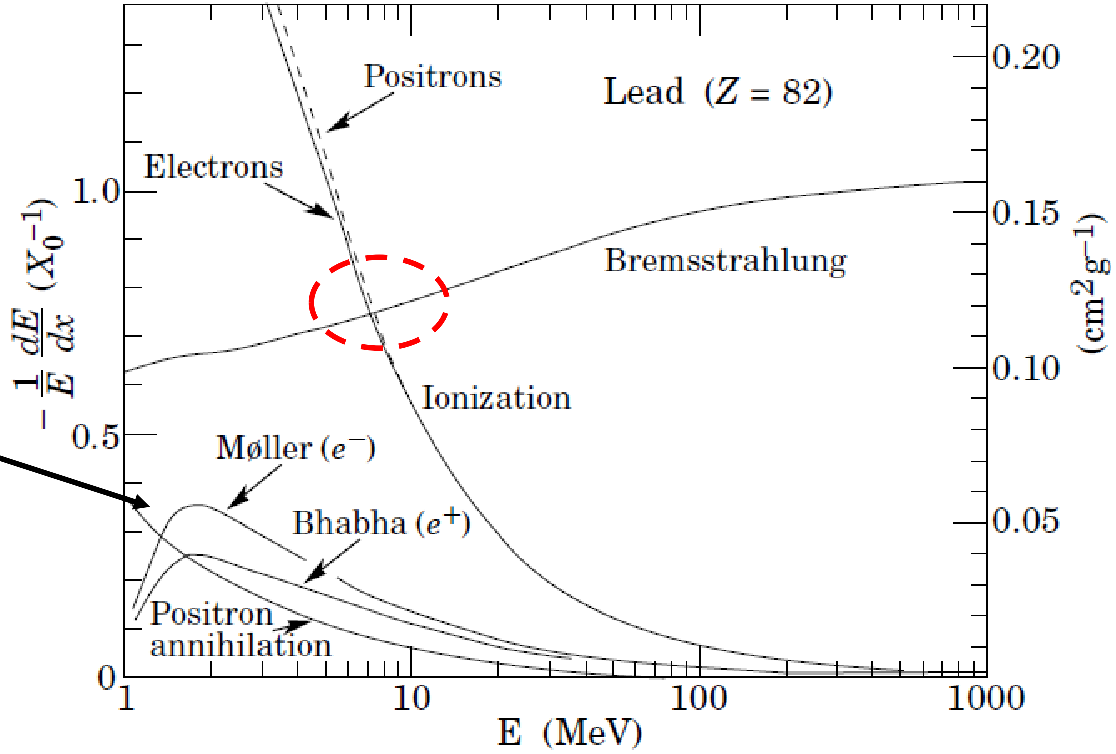
➤ Examples:

Material	W	Pb	Cu	Al	Stainless Steel	PbWO4	(dry) Air	(liquid) Water
Z	74	82	29	13	-	-	-	-
X_0 (cm)	0,35	0,56	1,4	8,9	1,76	0,89	30390	36,08

Critical Energy

Fractional energy loss for electrons/positrons in Lead

Other processes (Bhabha, meller, …) neglected in HEP (most of the time)



- Radiation (ionization) dominant at high (low) energies
- Crossing point: $\left(\frac{dE}{dx}\right)_{rad}(E_C) = \left(\frac{dE}{dx}\right)_{ioniz}(E_C)$ E_C: **critical energy**

Strongly material dependent (scales as 1/Z)

- **Examples:**

Material	W	Pb	(liquid) Ar	Cu
Z	74	82	29	13
E_C(MeV)	8,4	7,1	37	20,2

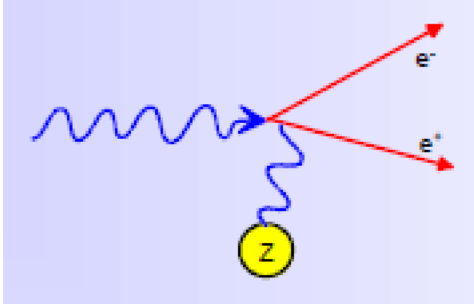
$$E_C(solid) = \frac{610\ \mathrm{MeV}}{Z + 1.24}$$

$$E_C(liquid) = \frac{710\ \mathrm{MeV}}{Z + 0.92}$$

Photons: Pair production

- Can only occurs in the Coulomb field of a nucleus (or an electron) if $E_\gamma > 2m_ec^2$

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



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

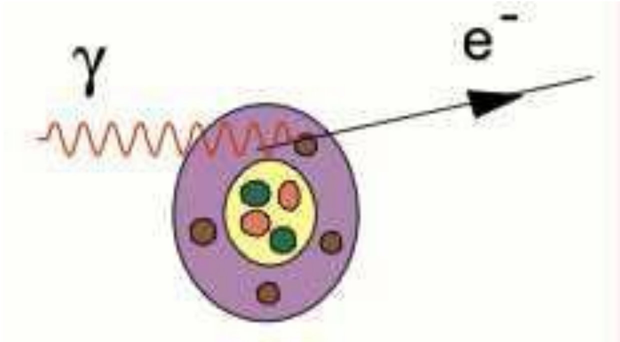
- Mean free path of photon before it creates a pair $\boxed{\lambda_{pair} \approx \frac{9}{7} X_0}$

- **Remarks:**
  - $\sigma_{pair} \propto Z(Z+1)$
  - Photons have a high penetrating power than electrons
  - Pair creation is independent of incident energy (for $E_\gamma > 1$ GeV)
  - e+e- is **emitted in photon direction**

Photons: Photo-Electric effect

- Photon extract an electron from the atom

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



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

- **Remarks:**
  - $\sigma_{pe} \propto Z^5, E^{-3.5}$
  - Electrons are emitted (more or less) **isotropically**

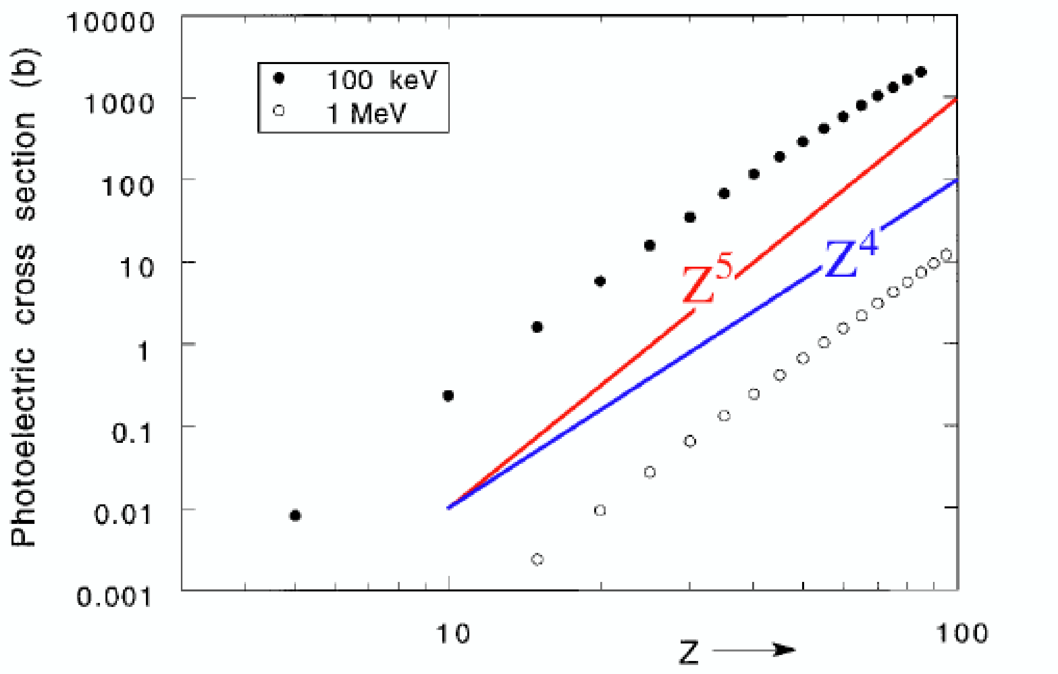
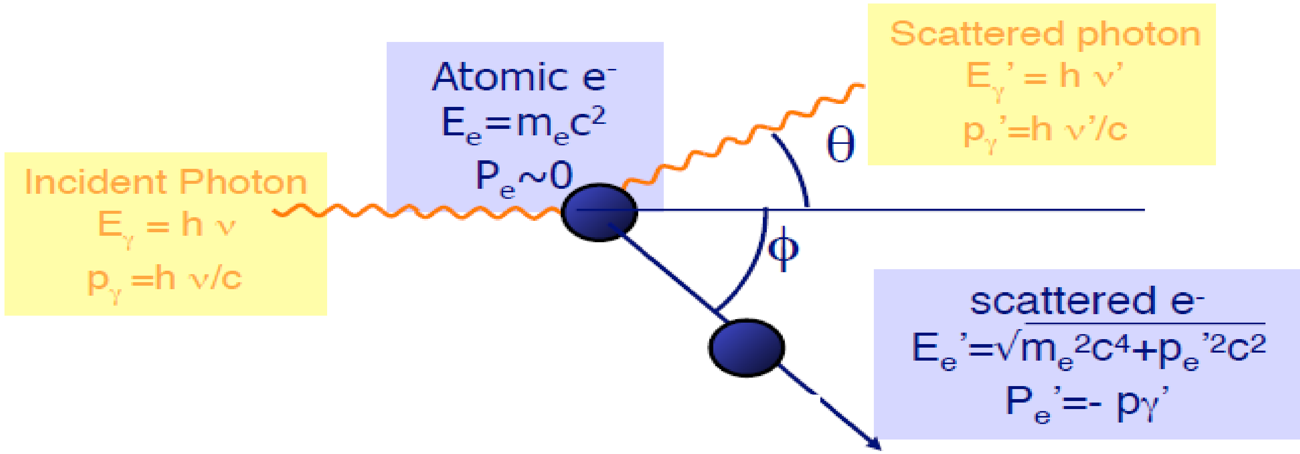


FIG. 2.3. Cross section for the photoelectric effect as a function of the Z value of the absorber. Data for 100 keV and 1 MeV γs.

Photons: Compton scattering

$$\gamma + e \rightarrow \gamma' + e'$$



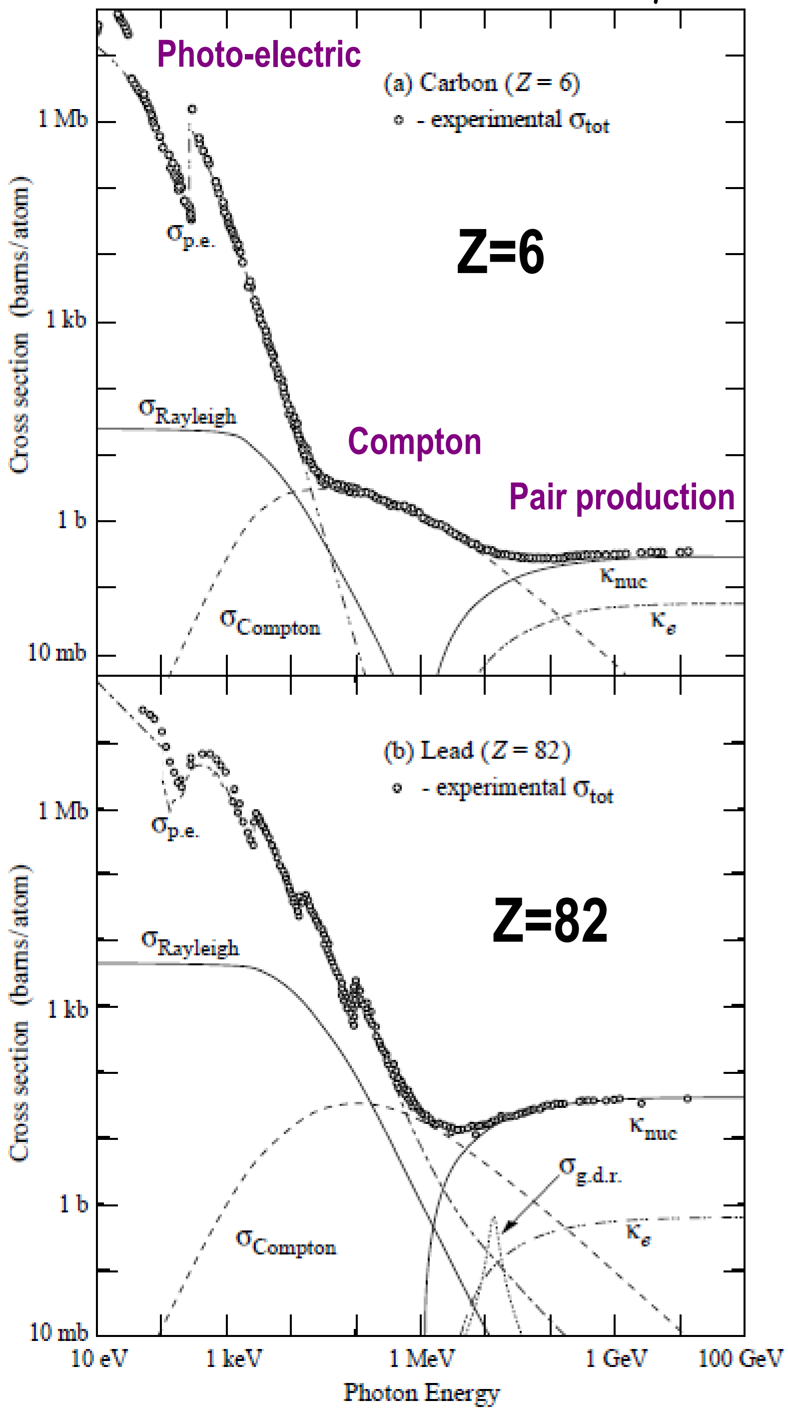
$$\boxed{\sigma_{Compton} \approx Z \frac{\ln E_\gamma}{E_\gamma}}$$

Remarks:

- $\sigma_{Compton} \propto Z, E^{-1}$
- Electrons are emitted (more or less) **isotropically**

Photons: importance of the processes

γ Total cross-section vs E_γ



- Photo-electric: dominant at very low energy
- Compton: dominant for Eγ~100 KeV – 5 GeV
- Pair Production: dominant at higher energies

Photons: Angular Distributions

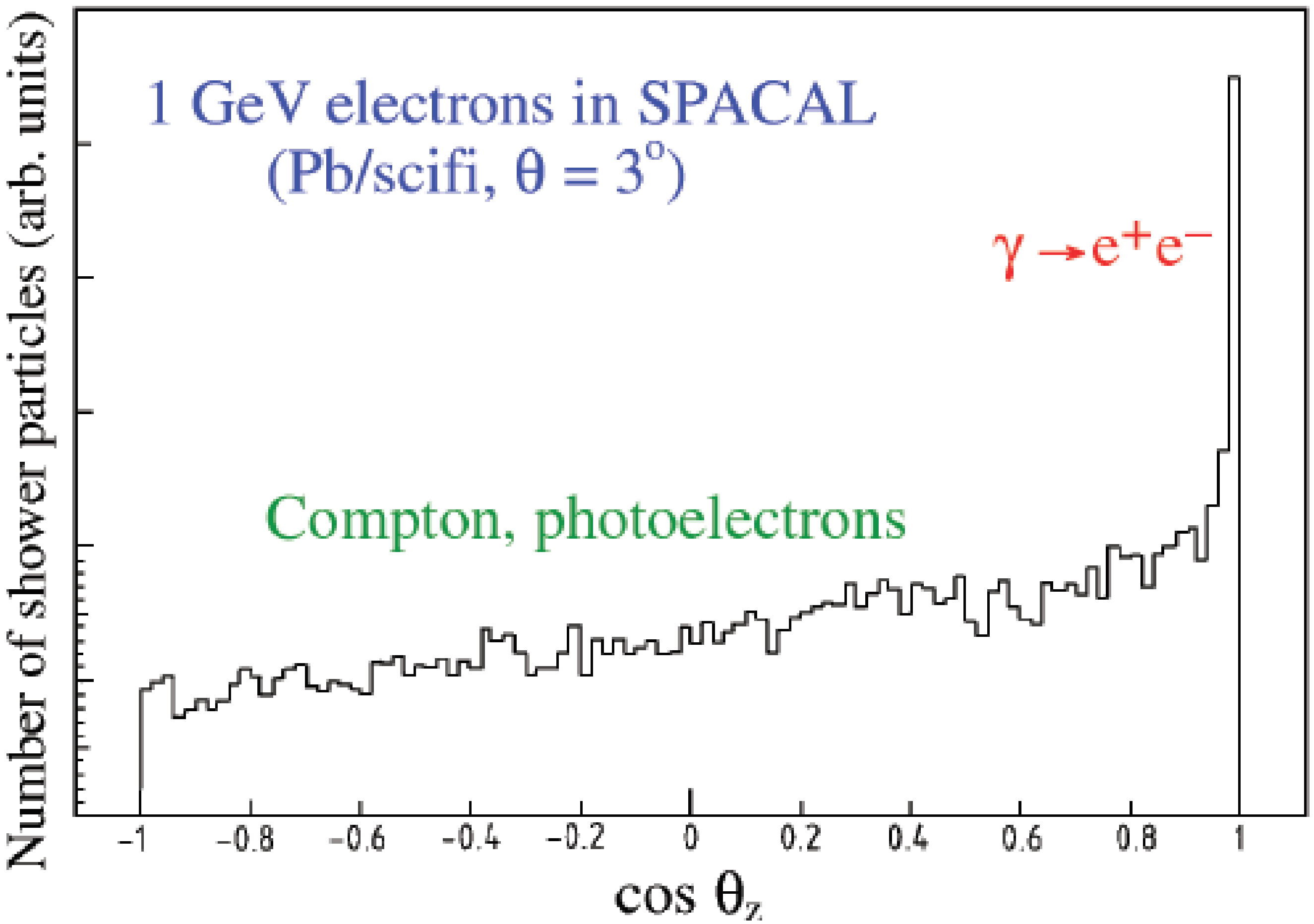


Fig. 11: Angular distribution of the shower particles (e^+, e^-) through which the energy of a 1 GeV electron is absorbed in a lead-based calorimeter [7].

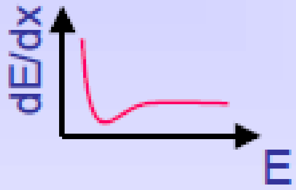
Summary for Electrons & Photons

4. Calorimetry

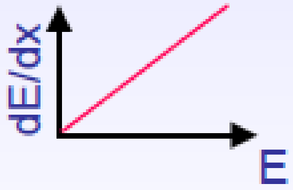
Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

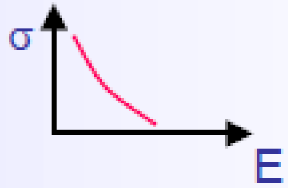


- Bremsstrahlung

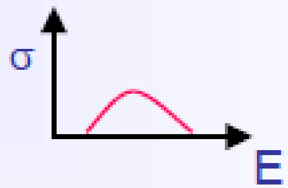


γ

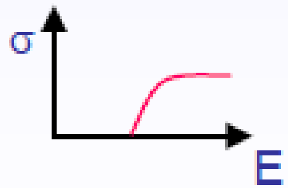
- Photoelectric effect



- Compton effect



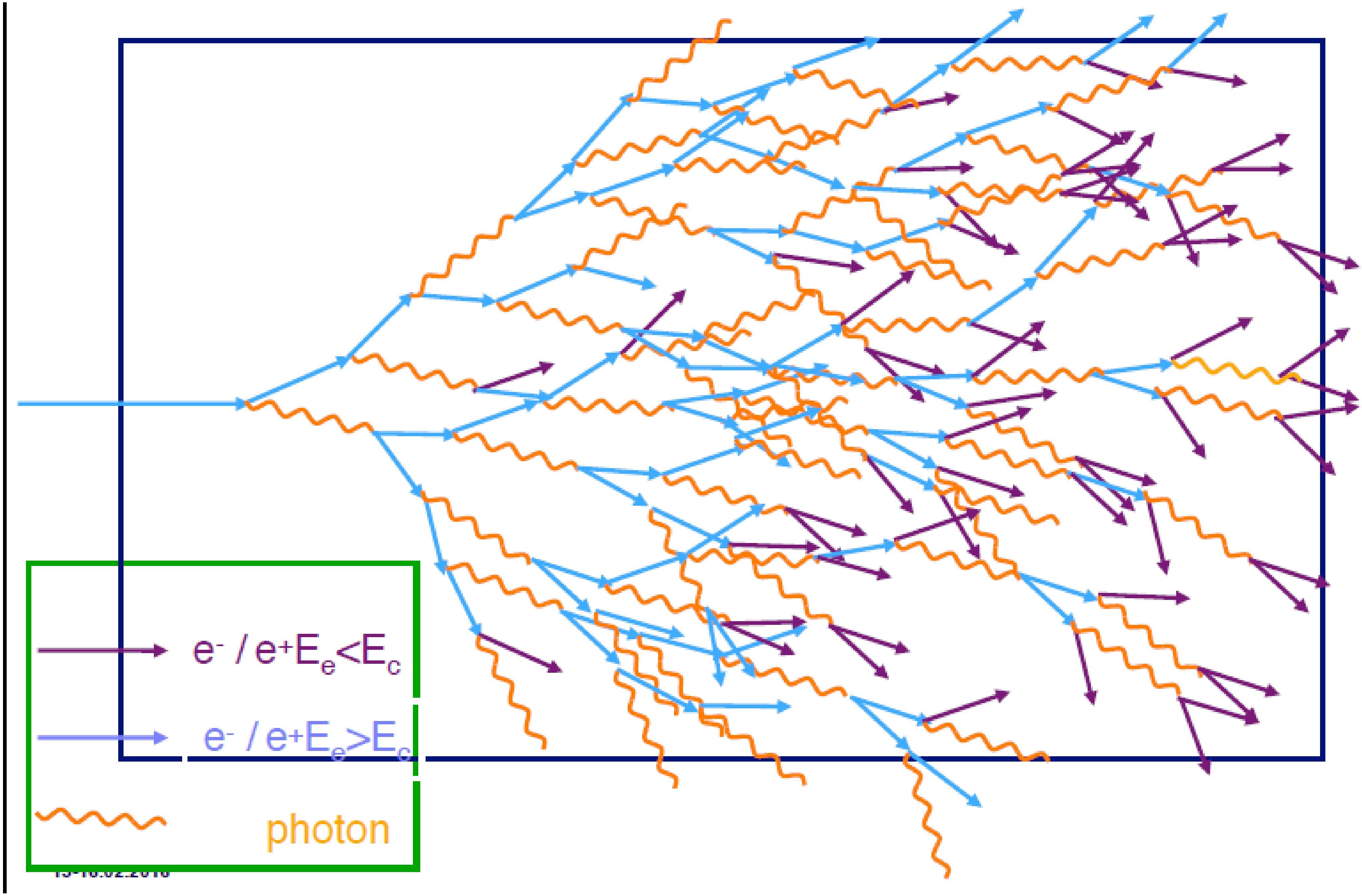
- Pair production



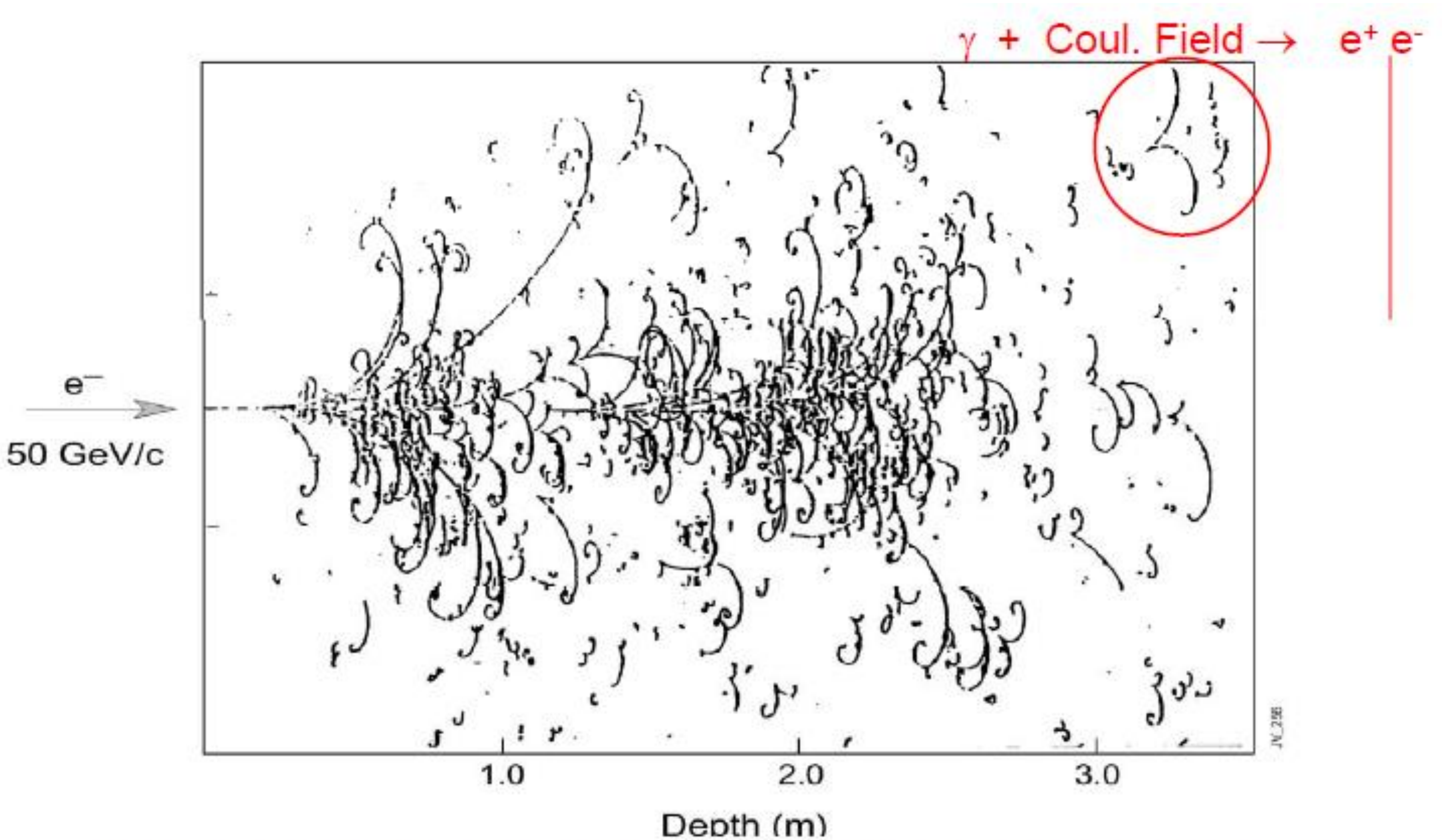
Electromagnetic shower: summary

- High-energy electrons or photons interact with dense material from calorimeter:
  cascade of secondary particles
- 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 creating the cascade particles **depends on Z.**
  - Above 1 GeV, bremsstrahlung radiation and pair production dominates
  - The shower develops like this until secondary particles reaches E_C where loss by ionization dominated
  - Below E_C, the number of secondary particles slowly decreases as electrons (photons) are stopped (absorbed)
- **The shower development is governed by the "radiation length" X_0**

Electromagnetic shower: “powerpoint” example



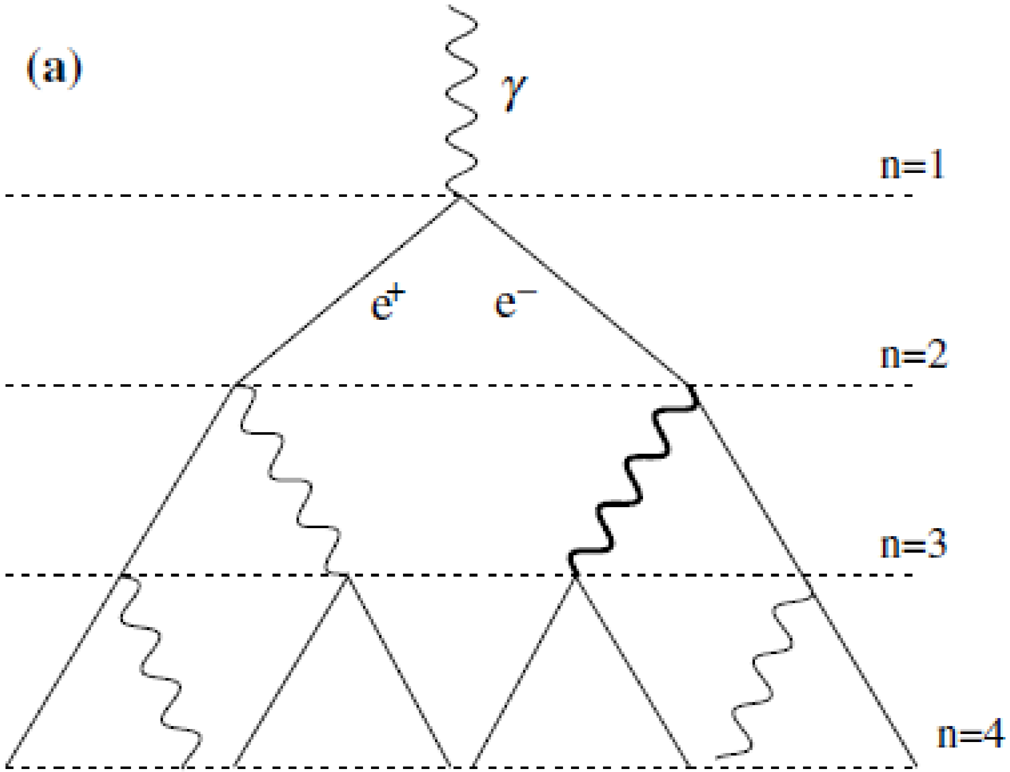
Electromagnetic Shower: real example



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

EM shower: a simple model

- “Simple” approach from **Heitler**
- **Assumptions:**
  - Only 2 dominant processes (brem, pair production) for $E>E_C$ (energy loss via ionization/excitation below)
  - Assume X_0 as a generation length
  - Energy equally shared between the production of each interaction



1 incident photon with E_0

After 1 X_0: 2 electrons with $E=E_0/2$

After 2 X_0, $e\rightarrow\gamma e'$ with $E'=E_0/4$

…

After tX0, number of particles $N(t) = 2^t$ with $E(t)=E_0/2^t$

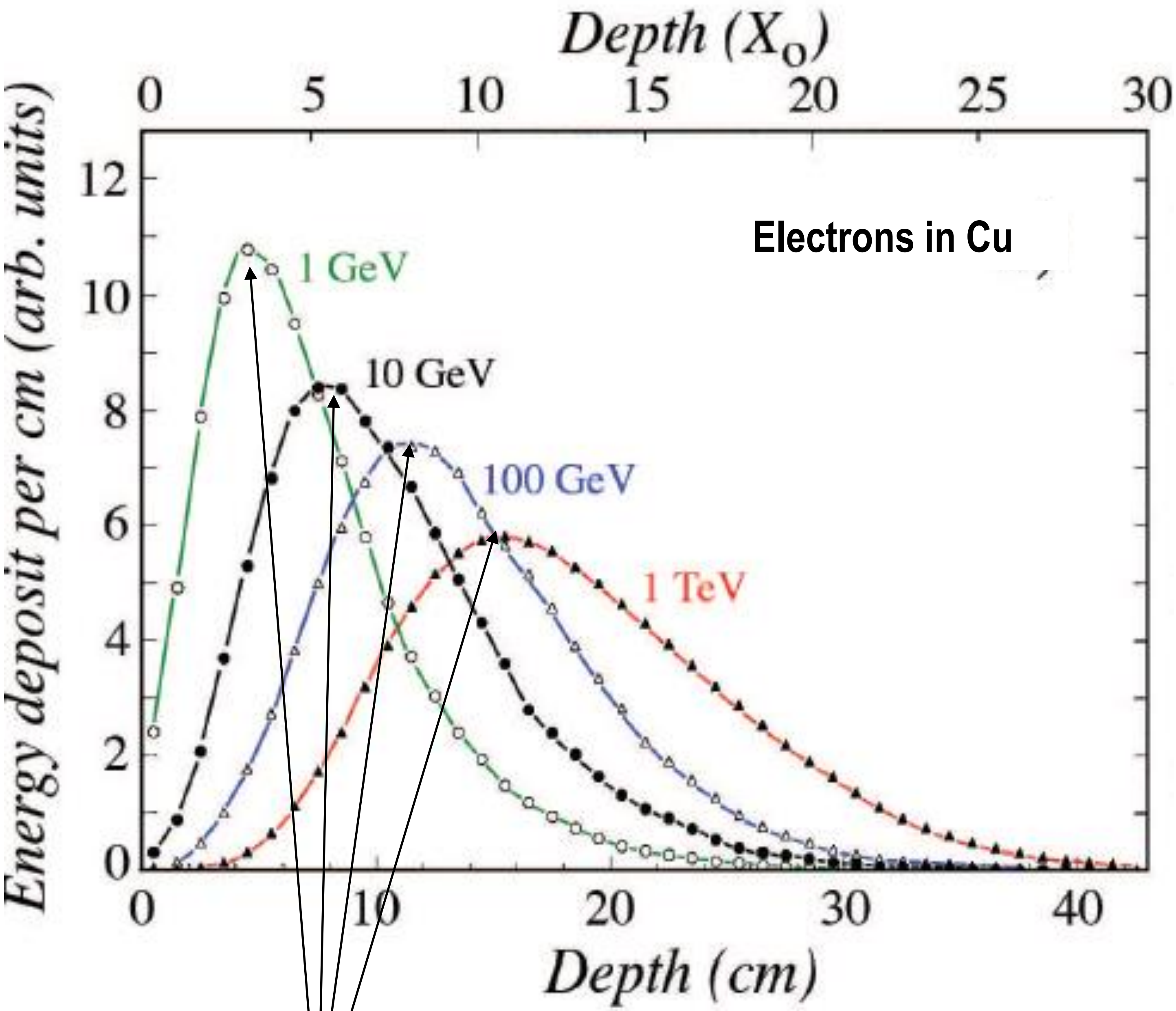
Maximum number of particles reached at $E=E_C$:

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

Shower maximum $$\boxed{t_{max} = \frac{\ln E_0 / E_C}{\ln 2}}$$

$$\boxed{N(t_{max}) \approx \frac{E_0}{E_C}}$$

EM shower: Longitudinal profile



Shower max grows with ln(E) !

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

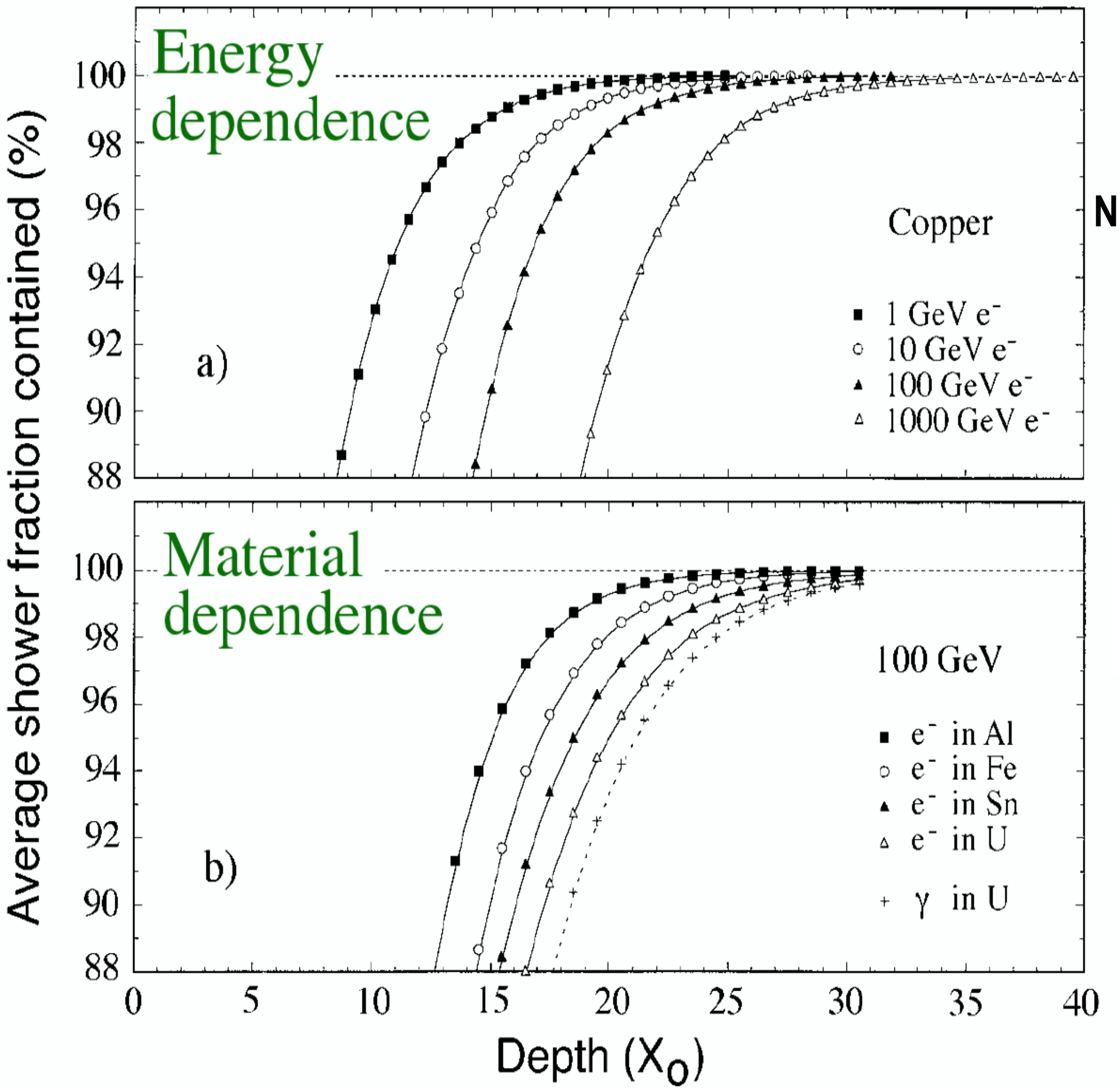
Shower energy development parametrisation

b: material

E.Longo & I.Sestili

(NIM128 (1975))

EM shower: longitudinal containment



Need about 25-30 X_0 to contain shower
(depending on the energy of interest, material)

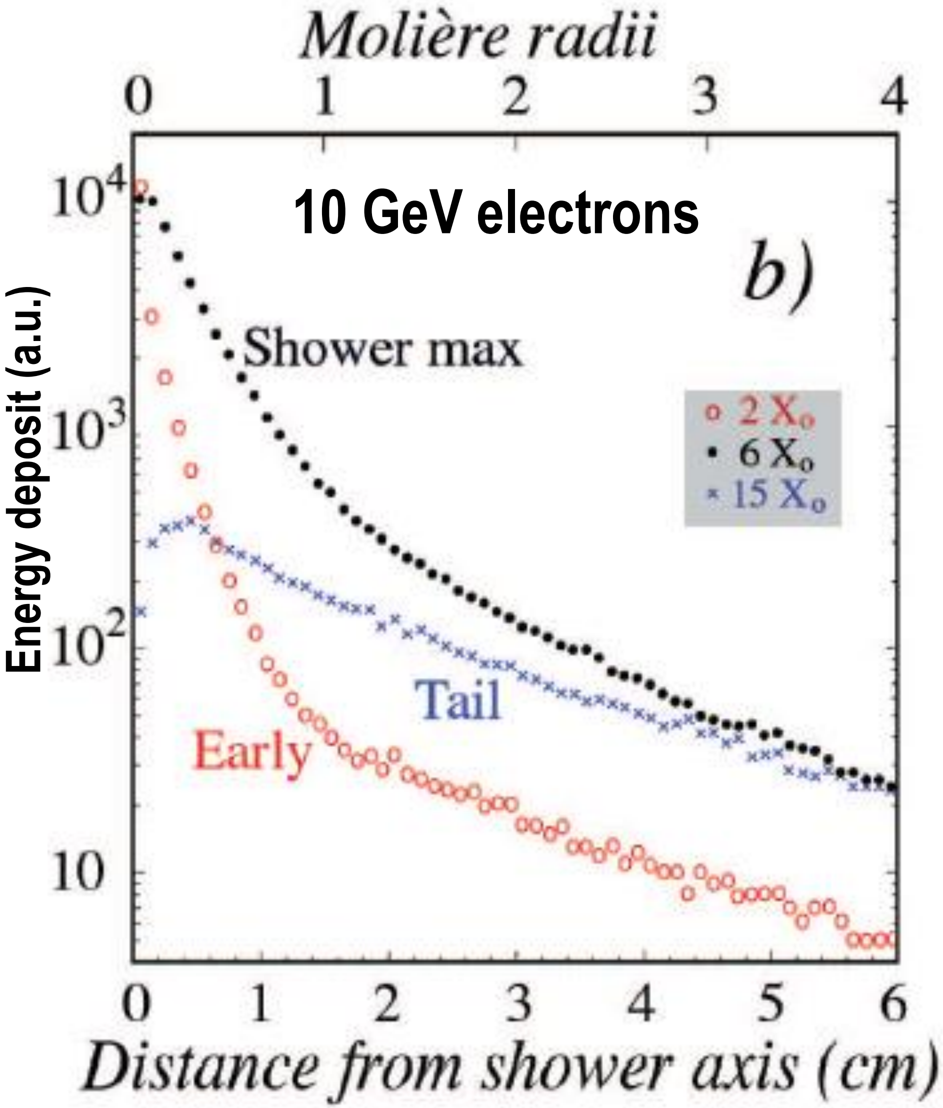
Longitudinal containment:

$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

Calorimeter can be compact !

EM shower: lateral profile

- Lateral shower width determined by:
  - Multiple scattering of e+/e- (early, up to shower max) => “core”
  - Compton γ away from axis (beyond shower max) => “halo”



Radial distributions of EM showers in Cu at various depth

The EM shower gets **wider with increasing depth…**

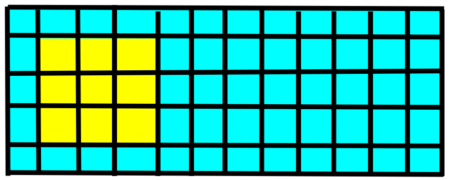
Lateral profile **independent of energy.**

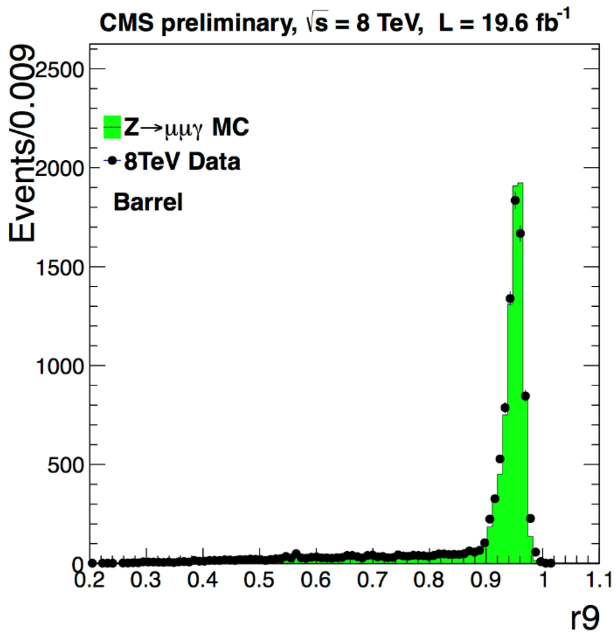
EM Shower Simulations

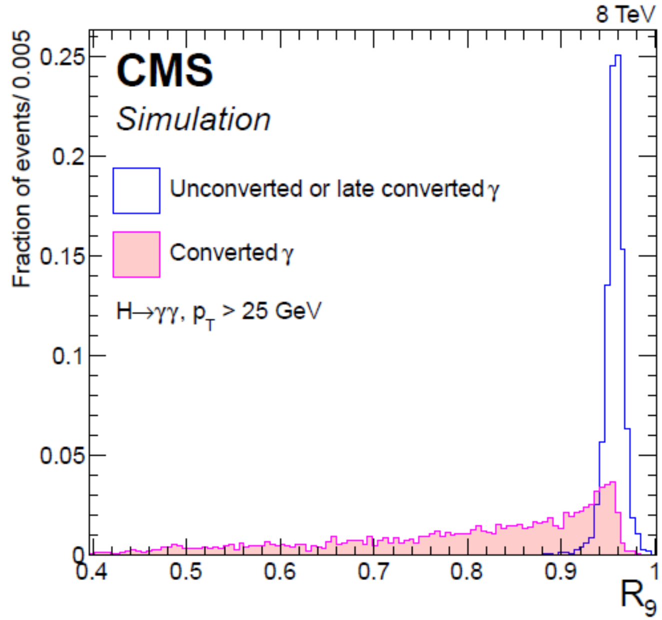
- Electromagnetic processes are well understood and can be very well reproduced by MC simulation:
  - A key element in understanding detector performance and particle ID

- **CMS in situ measurement**

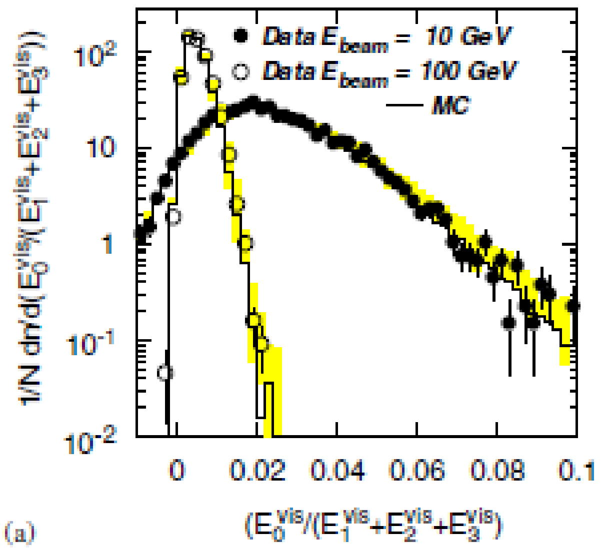
$$R_9 = E_{3\times3}/E_{SC}$$

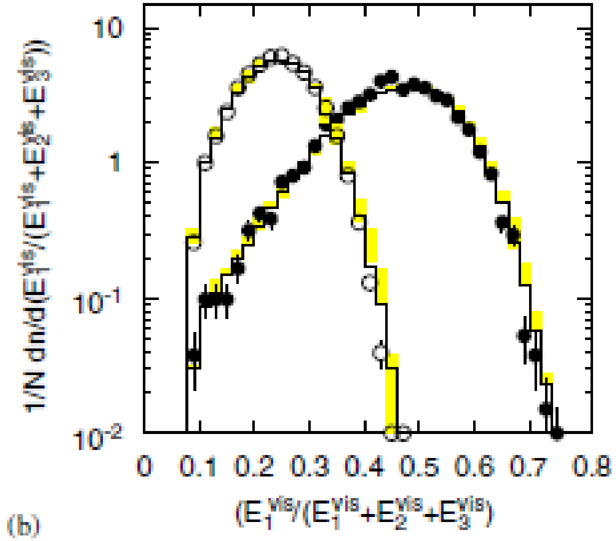


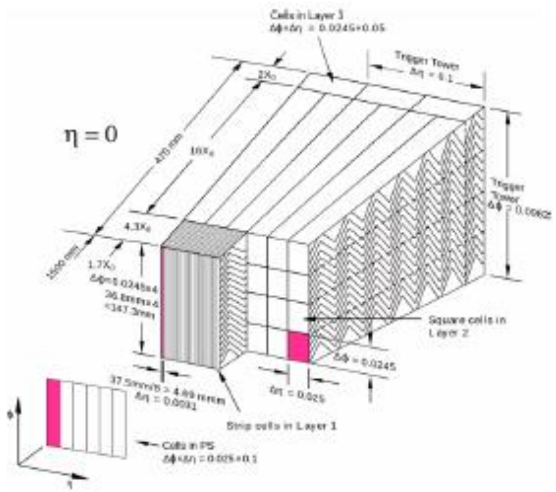




- **ATLAS test beam**







EM shower: Moliere Radius

➢ **Moliere radius:** characteristic of a material giving the scale of the transverse dimension of an EM shower

$$R_M = \frac{21 MeV}{E_C} X_0 \qquad (g.cm^{-2})$$

Scales as A/Z, while X0 scales as A/Z². much less dependent on material than X_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 $3.5R_m$

Calorimeter properties of some material

Material	Z	Density [g cm^{-3}]	E_c [MeV]	X_0 [mm]	R_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

EM shower: Energy Resolution

Calorimeter's resolution is determined by fluctuations.

- Ideally, if all N secondary particles are detected: $E \propto N \Rightarrow \sigma_E/E \propto \sigma(N)/N$

Fluctuation in N follow Poissonian distribution
$\Rightarrow \sigma(N)/N \propto \sqrt{N} / N \propto 1/\sqrt{N}$

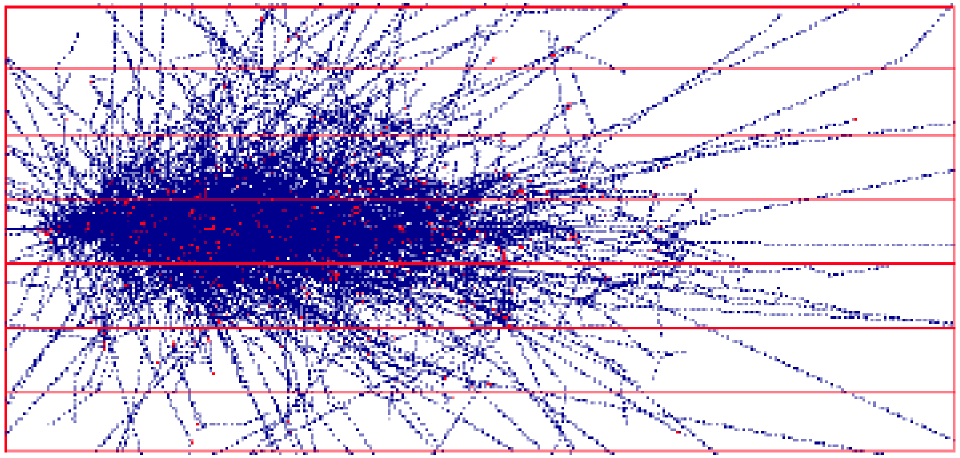
- **Intrinsic limit / ultimate resolution: determined by fluctuations of number of shower particles.**

- In reality, only a fraction f_S of secondary particles can be detected (via ionization, Cherenkov, scintillation …)
- $N_{max} = N_{tot} / E_{th}$,
  where E_{th} is the threshold energy of the detector, ie, the minimal energy to produce a detectable signal (100 eV for plastic scintillators, ~3 eV for semi-conductors…)

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

- Other type of fluctuations may impact resolution, eg:
  - Signal **quantum** fluctuations (photoelectron statistics,….)
  - Shower **leakage**,
  - **Instrumental** effects (electronic noise, light attenuation, structural non-uniformity)
  - **Sampling** fluctuations (in sampling calorimeters)

Homogenous Calorimeter



All the energy is deposited in the active medium
- Excellent energy resolution
- No longitudinal segmentation

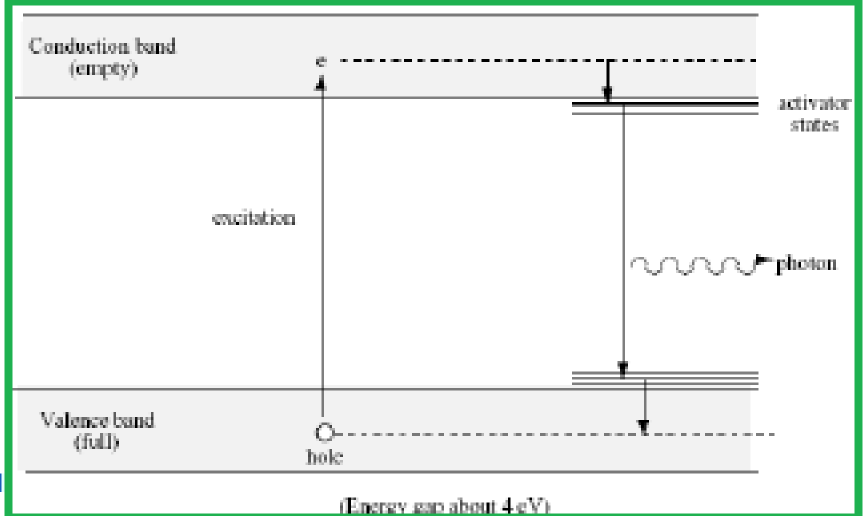
All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals

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

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

$\sigma/E \sim (1\div3)\%/\sqrt{E}$ (GeV)

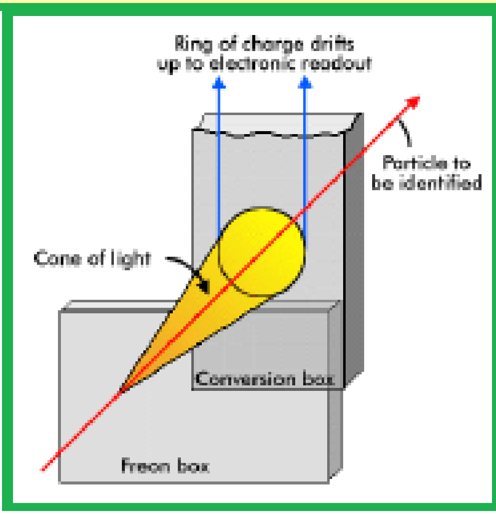


Cerenkov radiators

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

$\rightarrow 10\div30\ \gamma$/MeV

$\sigma/E \sim (5\div10)\%/\sqrt{E}$ (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

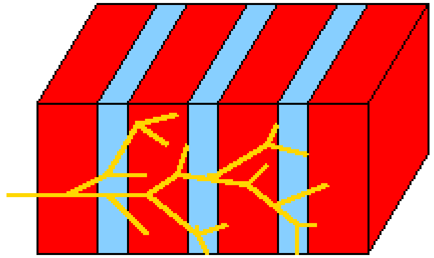
Fluctuation $1/\sqrt{1400} = 3\%$

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

- **Sampling Calorimeters:**
  - Sandwich of **high-Z absorber** (Pb, W, Ur,…) and **low-Z active media** (liquid, gaz, …)
    - Ex: ATLAS (Pb/LAr), DØ (Ur/LAr), …



- **Longitudinal segmentation**
- Energy resolution limited by fluctuations in energy deposited in the active layers (ie, the number n_{ch} of charged particles crossing the active layers)

- n_{ch} increases linearly with incident energy and fineness of the sampling: $n_{ch} \propto E / t$, where t=thickness of each absorber layer

For independent sampling:

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{n_{ch}}} \propto \sqrt{\frac{t}{E}}$$ (stochastic contribution only)

For fixed active layers thickness, the resolution should improves as absorber thickness decreases.

Resolution of sampling calorimeters

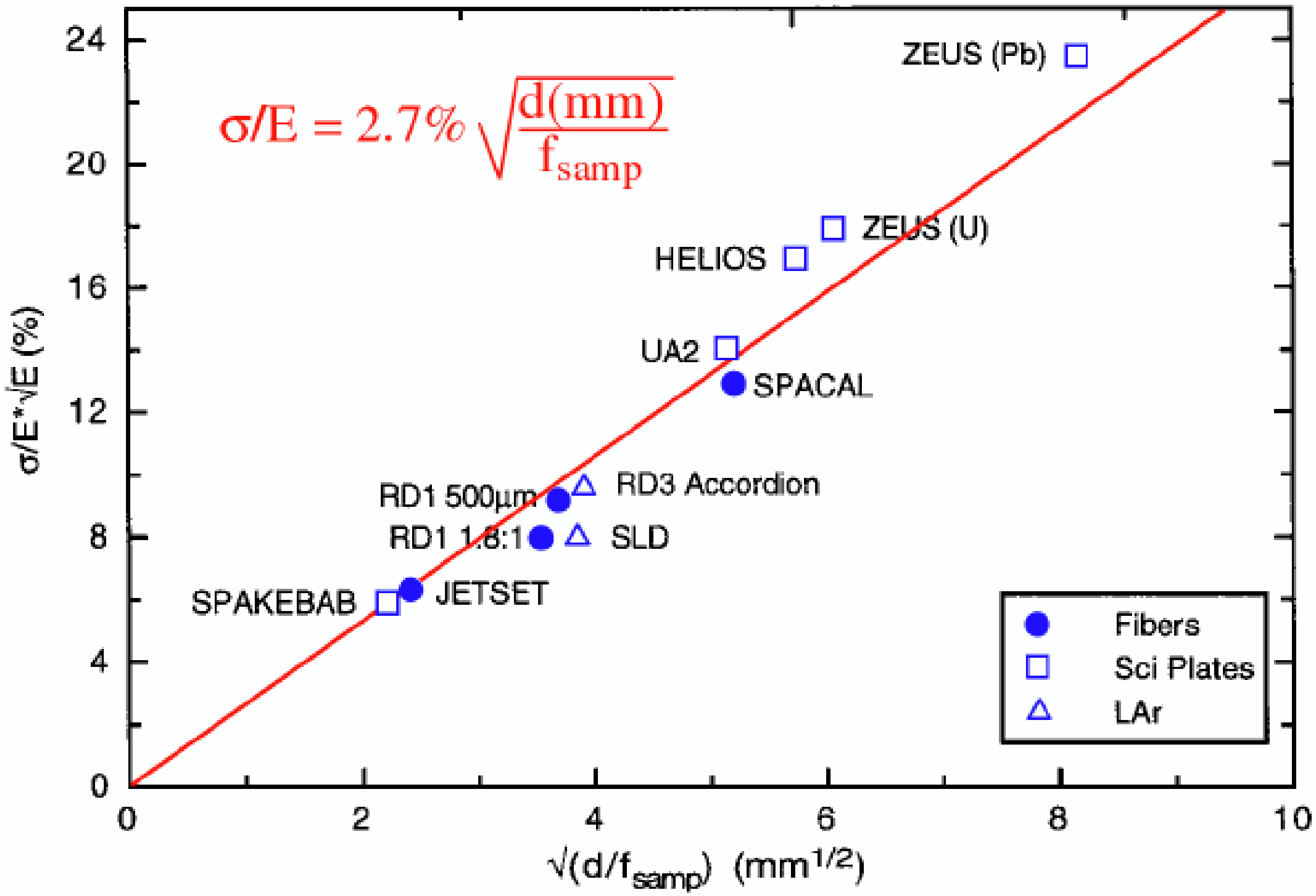


FIG. 4.8. The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\rm samp})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a scintillator plate or a liquid-argon gap), and $f_{\rm samp}$ is the sampling fraction for mips [Liv 95].

Sampling fluctuations in EM calorimeters determined by sampling **fraction** (f_{samp}) and sampling **frequency**

f_{samp}: energy deposited in active layers over total energy
d: thickness of active layer

Calorimeter: Energy Resolution

➢ Calorimeter resolution can be parameterized by the following formula:

$$\boxed{\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C}$$

$\oplus$: quadratic sum

Stochastic term (S):

- Accounts for any kind of Poisson-like fluctuations (number of secondary particles generated by processes, quantum, sampling, etc…)

Noise term (N): relevant at **low energy**

- Electronics noise from readout system
- At Hadron colliders: contributions from pile-up (from low energy particles generated by additional interactions): fluctuations of energy entering the measurement area from other source than primary particle.

Constant term (C): dominant at **high energy**

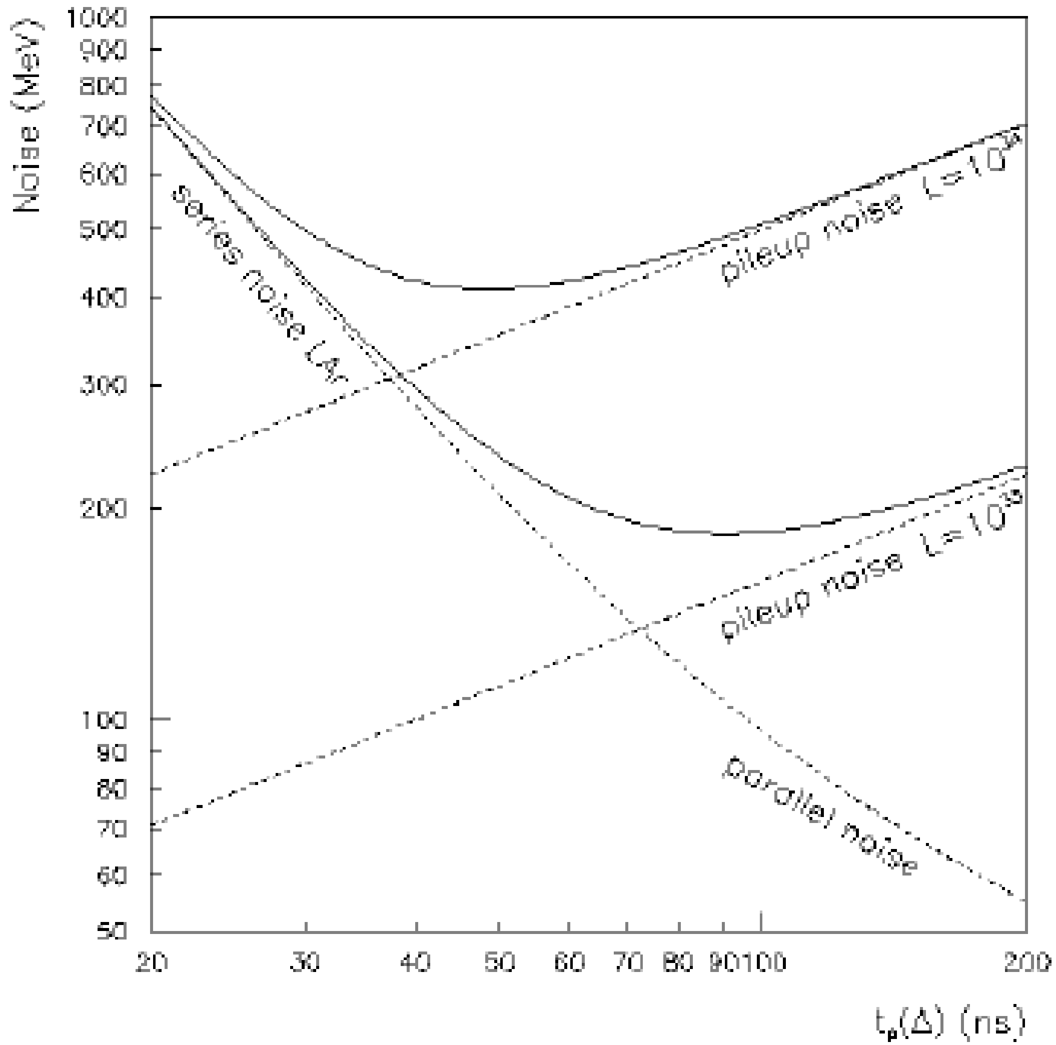
- Imperfections in construction, non-uniformity of signal collection, fluctuations in longitudinal energy containment, loss of energy in dead material, etc…

Noise Term

Electronics noise vs pile-up noise
(example from LAr ATLAS calorimeter)

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

At this luminosity, contribution from noise to an electron is typically ~300-400 MeV



Constant Term

- The constant term describes the level of uniformity of the calorimeter response vs position, time, temperature (and not corrected for)

c = (leakage)⊕(intercalibration)⊕(system instability)⊕(nonuniformity)

To have c ~ 0.5 % all contributions must stay below 0.3 %

- **Leakage:**
  - **Non-Poissonian fluctuations**
  - For a given average containment, **longitudinal fluctuations larger than lateral ones.**
  - Front face: Negligible
  - Rear face:
    - Dangerous
    - Increase as ln(E)
    - Can be removed/attenuated if sufficient X0

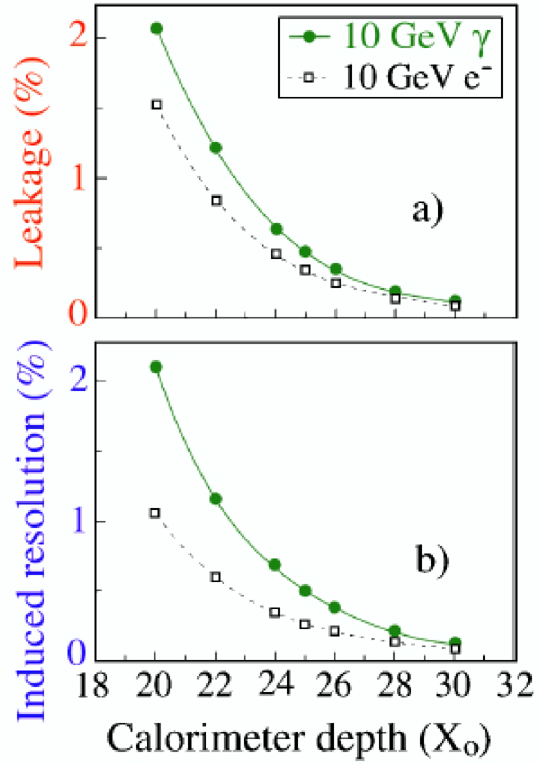
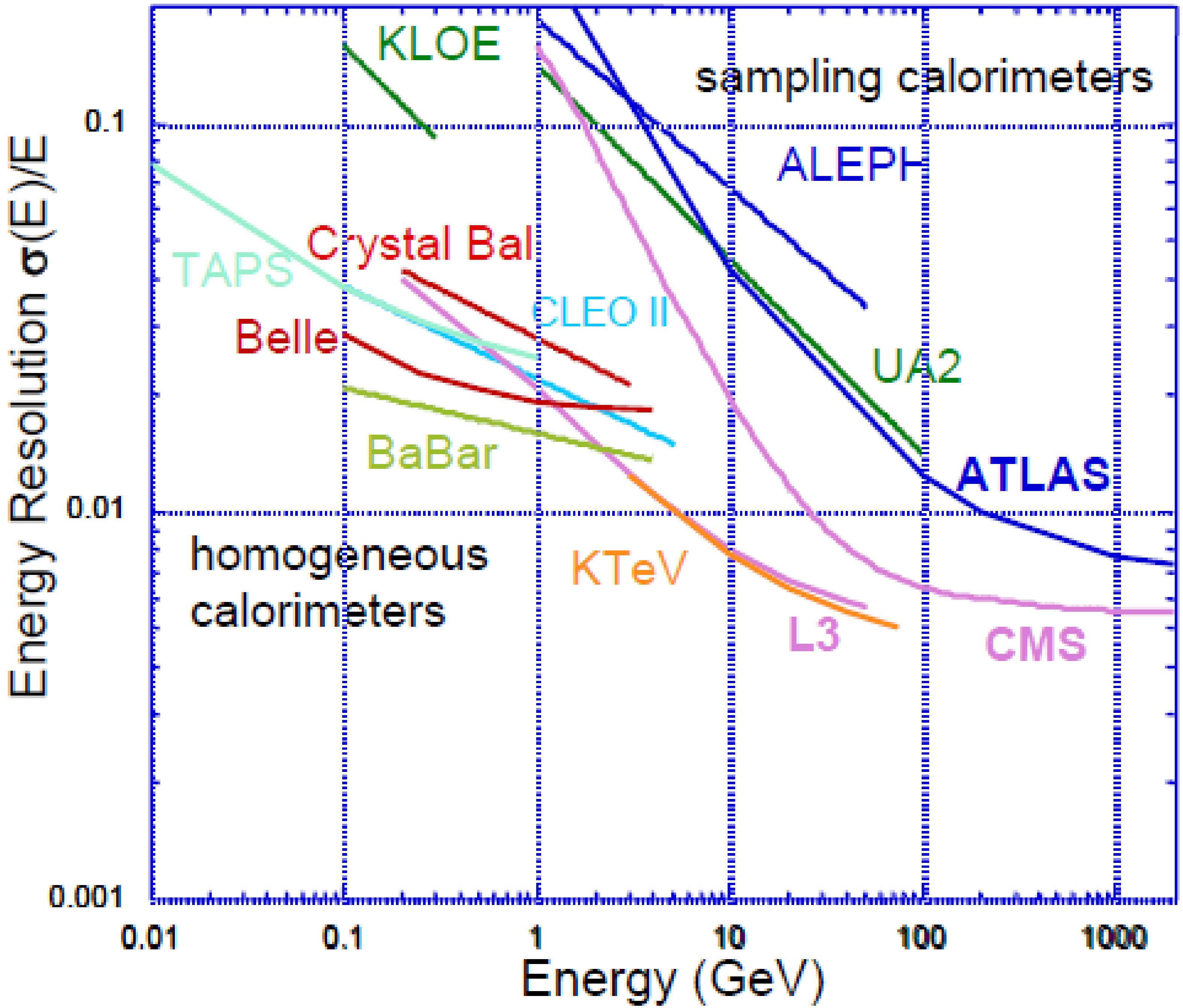


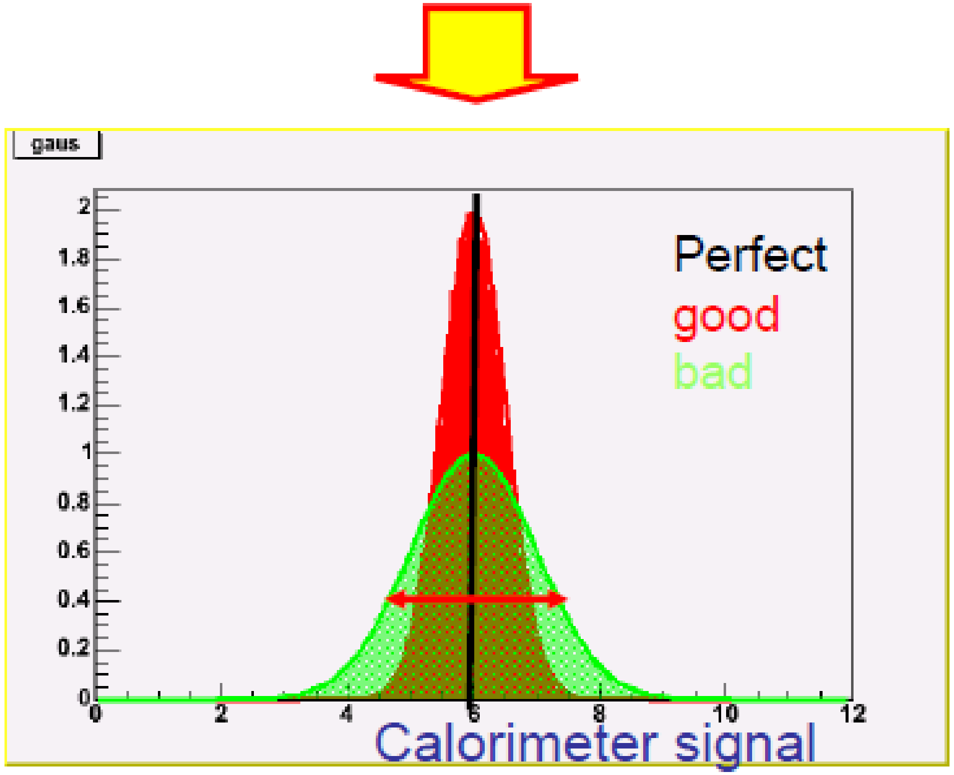
Figure 5: The average fraction of the shower energy carried by particles escaping the calorimeter through the back plane (*a*) and the relative increase in the energy resolution caused by this effect (*b*), for showers induced by 10 GeV electrons and 10 GeV γs developing in blocks of tin with different thicknesses, ranging from $20X_0$ to $30X_0$. Results from EGS4 Monte Carlo calculations.

Calorimeters: a comparison

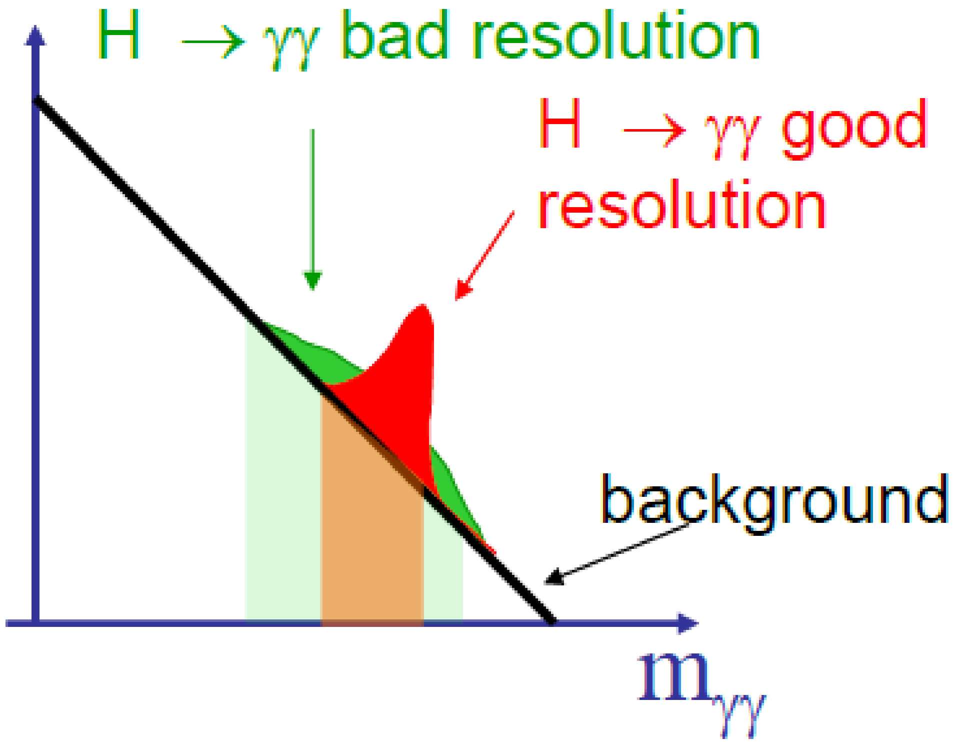


Why precision matter so much?

Response to monochromatic source of energy E



σ(calo) defines the energy resolution for energy E.



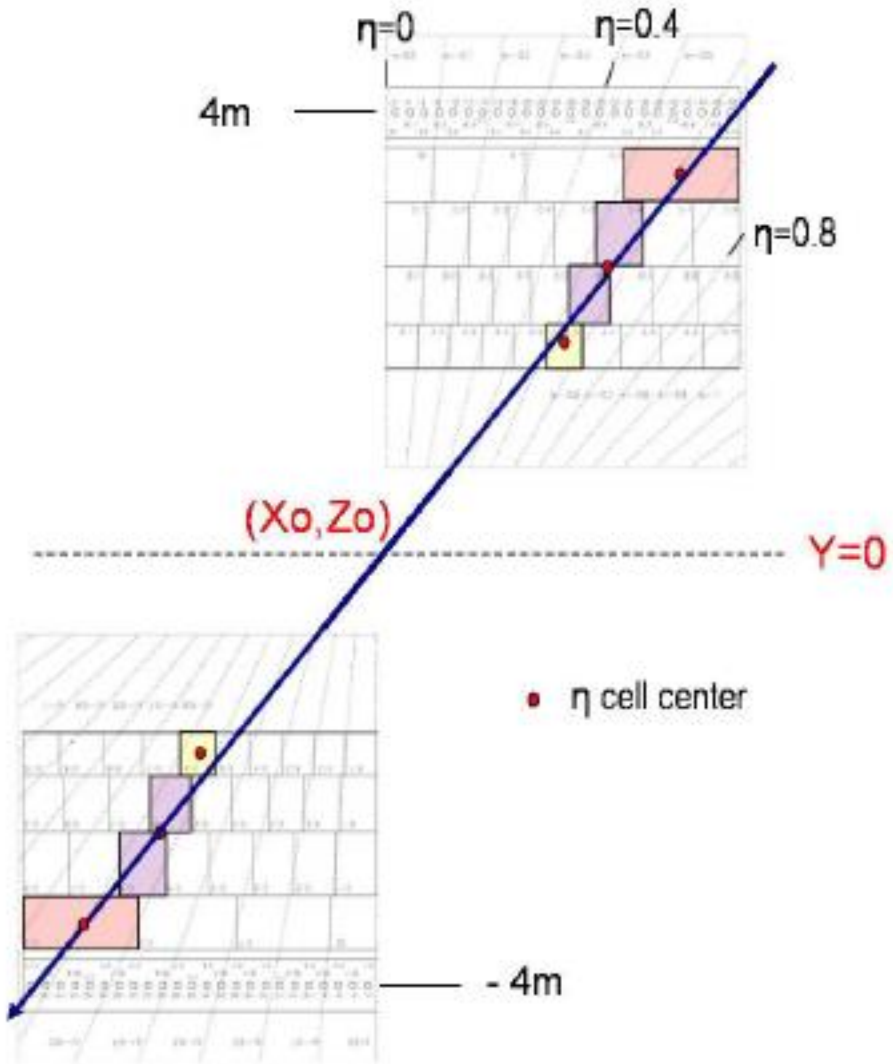
Signal = constant

integrated B $\propto \sigma_{\gamma\gamma} \rightarrow$

$S/\sqrt{B} \propto 1/\sqrt{\sigma\gamma\gamma}$

… but $\sigma_{\gamma\gamma} = f(\sigma calo)$

What about muons ?



Muons vs electrons

Muons are charged leptons, like electrons… but much heavier !

$m_{e \sim 0.511}$ MeV/c²

$m_\mu \sim 105{,}66$ MeV/c²

$\boxed{m_e/m_\mu \sim 200}$

$(m_e/m_\mu)^2 \sim 4000$

- Loss of energy via brem ?
  Remember:

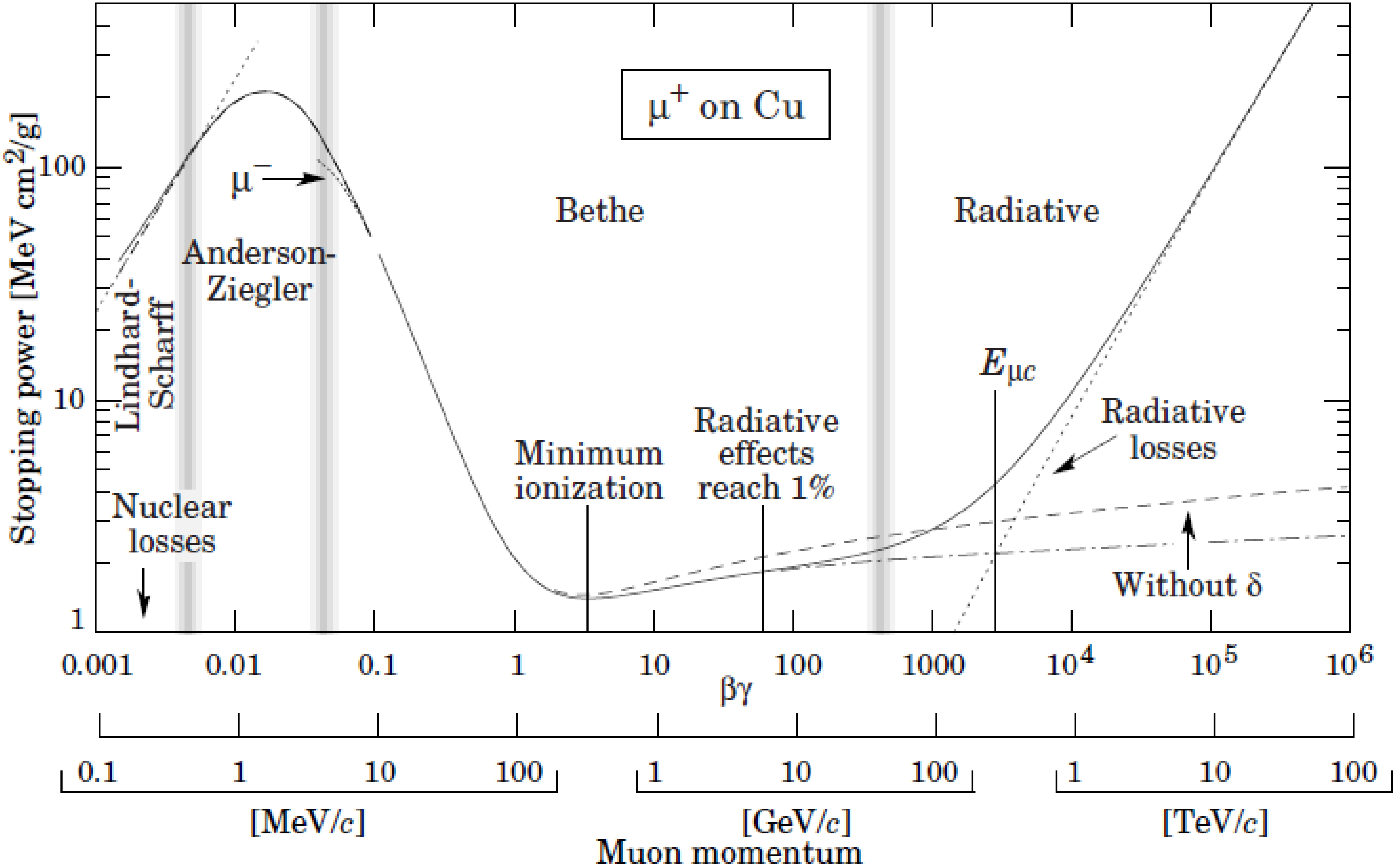
$$\left(-\frac{dE}{dx}\right)_{rad} \propto \frac{E}{m^2}$$

Much less important than for electrons…

Main mechanism for muons is ionization => no "shower" !

E_C (e-) in Cu: 20 MeV
E_C (μ) in Cu: 1 TeV…

Muon energy loss in Cu



Muons in calorimeter

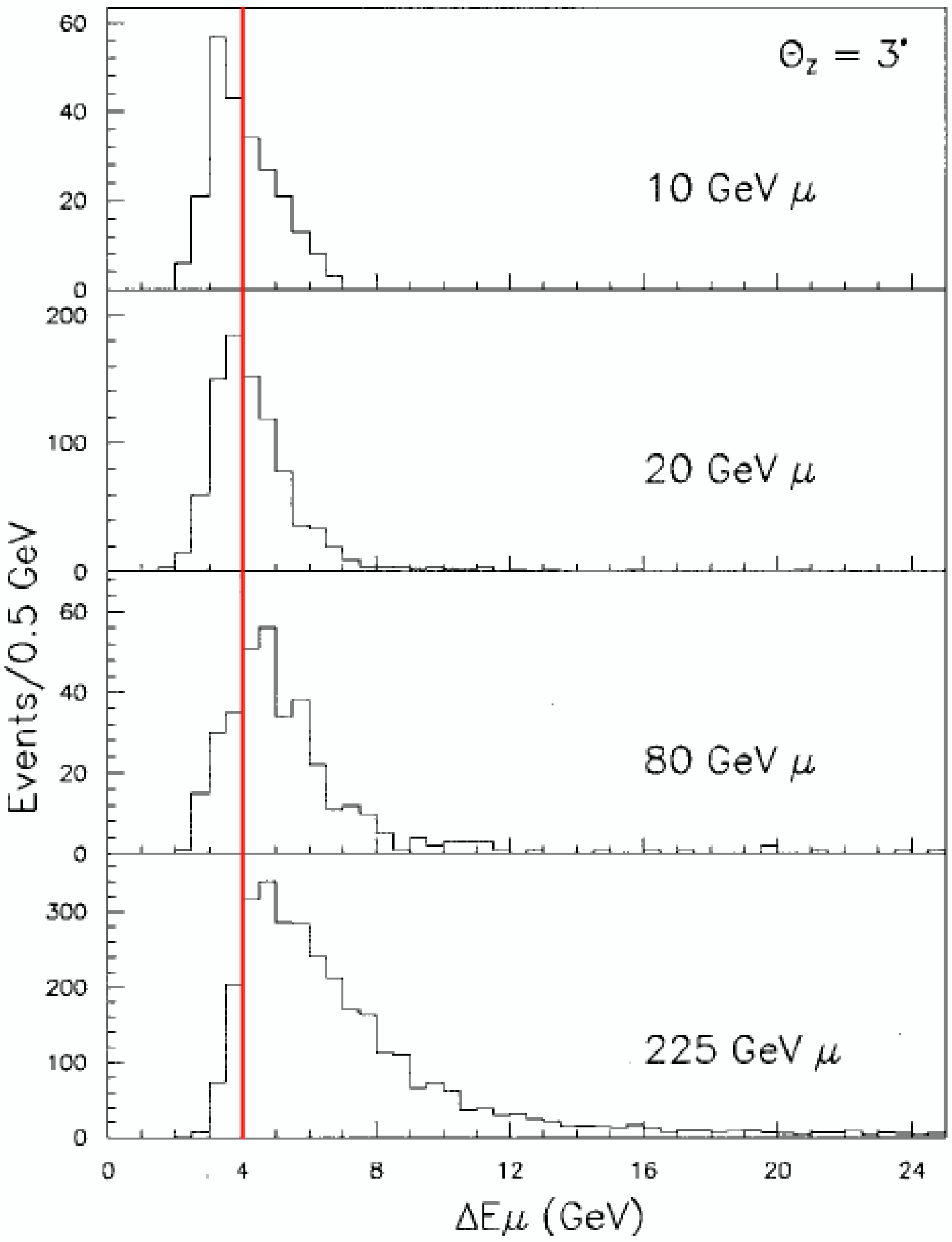


FIG. 2.19. Signal distributions for muons of 10, 20, 80 and 225 GeV traversing the $9.5\lambda_{\text{int}}$ deep SPACAL detector at $\theta_z = 3°$. From [Aco 92c].

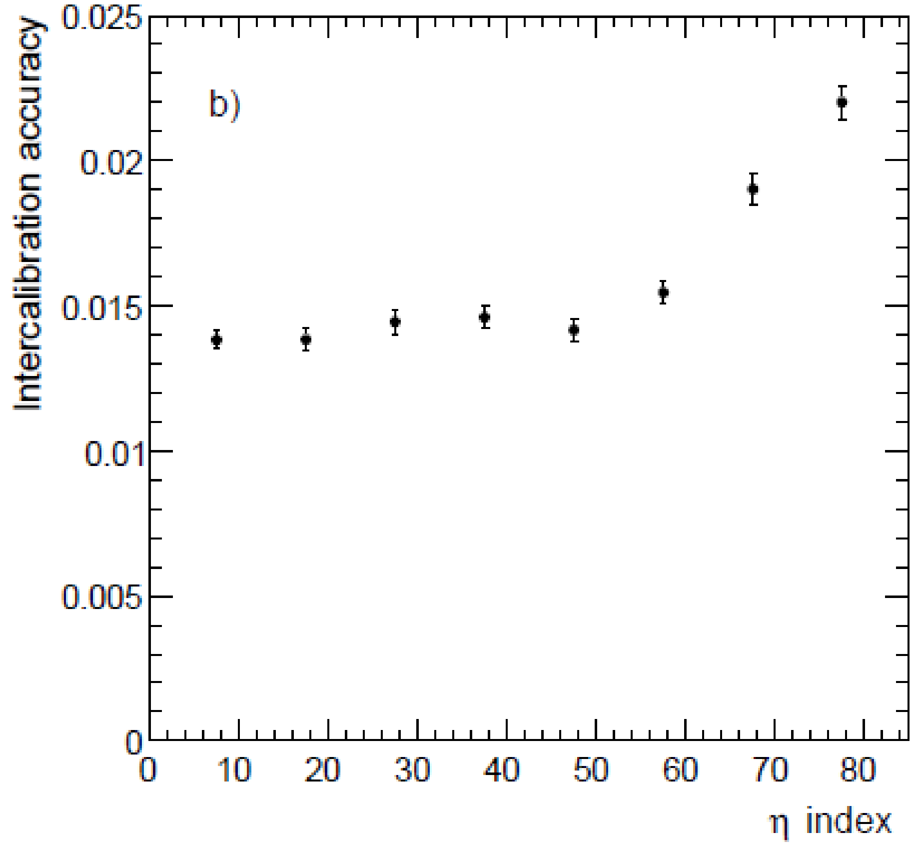
- Muons are NOT "mip" (Minimum Ionizing Particles) !
- Effect of radiation can be seen, especially at high energy and in high-Z material.
  - In Pb (Z=82), E_C (μ) =250 GeV (vs 6 MeV for e-)
- Muon energy deposit in matter NOT proportional to their energy

Muons for calorimeter

- Energy deposits from muons in calorimeter:
  - Very little (except for catastrophic loss from radiation)
  - Well known
  - Local

⇒ Muons heavily used to assess:
  - Calorimeter response uniformity (low energy), dead cells,…
  - Analyze the calorimeter geometry,

- **Cosmic muons are essential part of commissioning of calorimeters !**



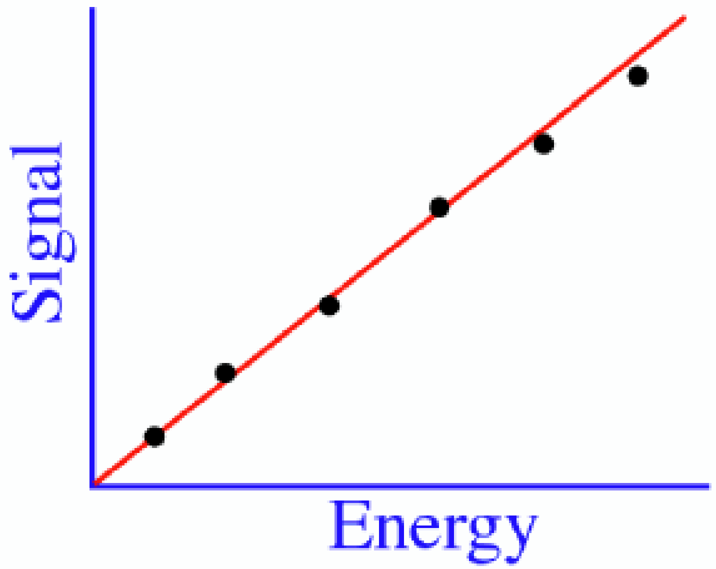
<u>Ex:</u> CMS ECAL
The intercalibration precision ranges from 1.4% in the central region to 2.2% at the high η end of the ECAL barrel **BEFORE real collisions !**

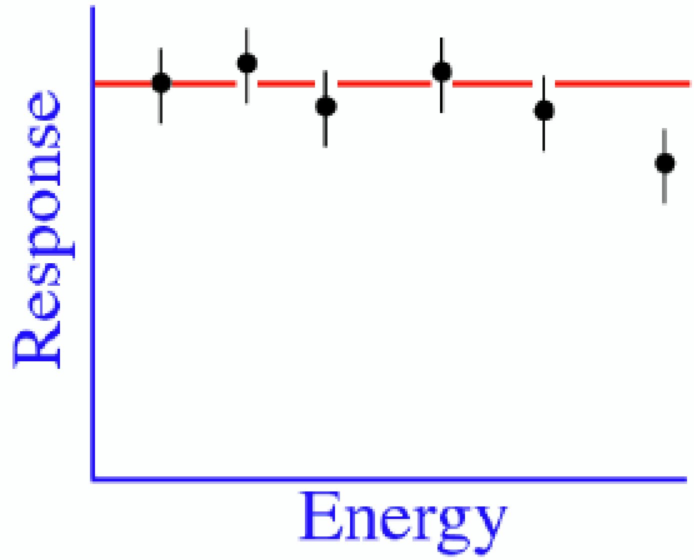
BACK UP SLIDES

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.

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

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