Calorimetry

Mika Vesterinen
University of Warwick

Warwick week 2024

WARWICK
erc
UKRI
Science and Technology Facilities Council

1. Short overview
2. EM showers
3. EM calorimeters
4. Hadronic showers/calorimeters

Calorimetry

- Wide usage in particle physics, e.g.

  4π (or LHCb-like) collider experiments

  Instrumented targets

  Shower counters

- Various detection mechanisms

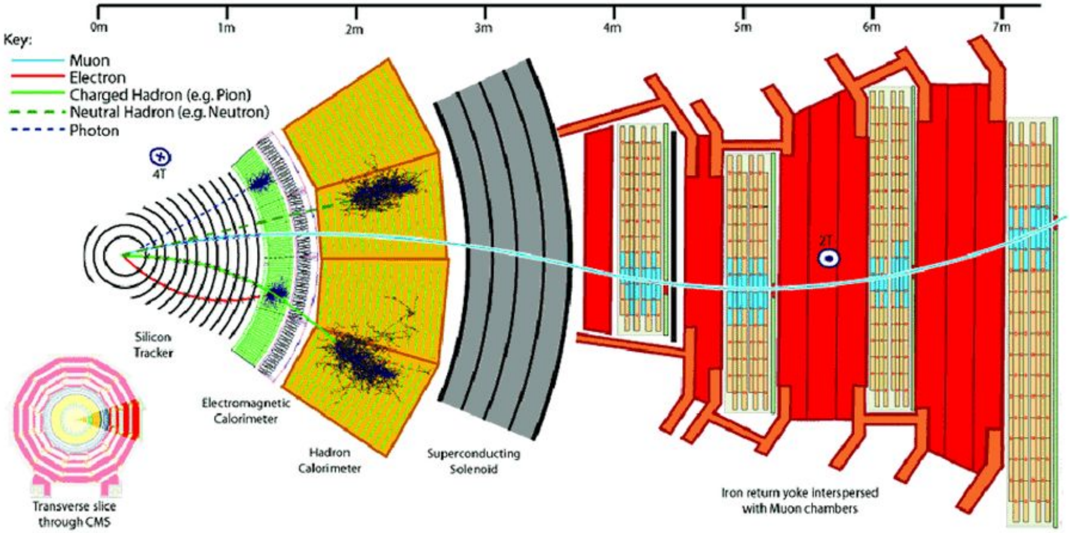
  Scintillation

  Ionisation

  Cerenkov

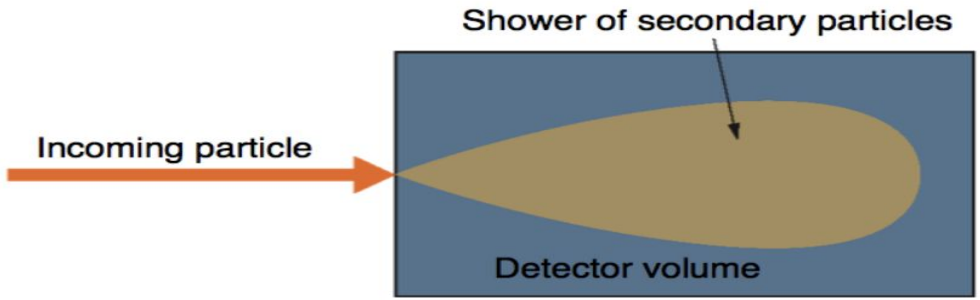
  Cryogenics

Typical collider detector schematic



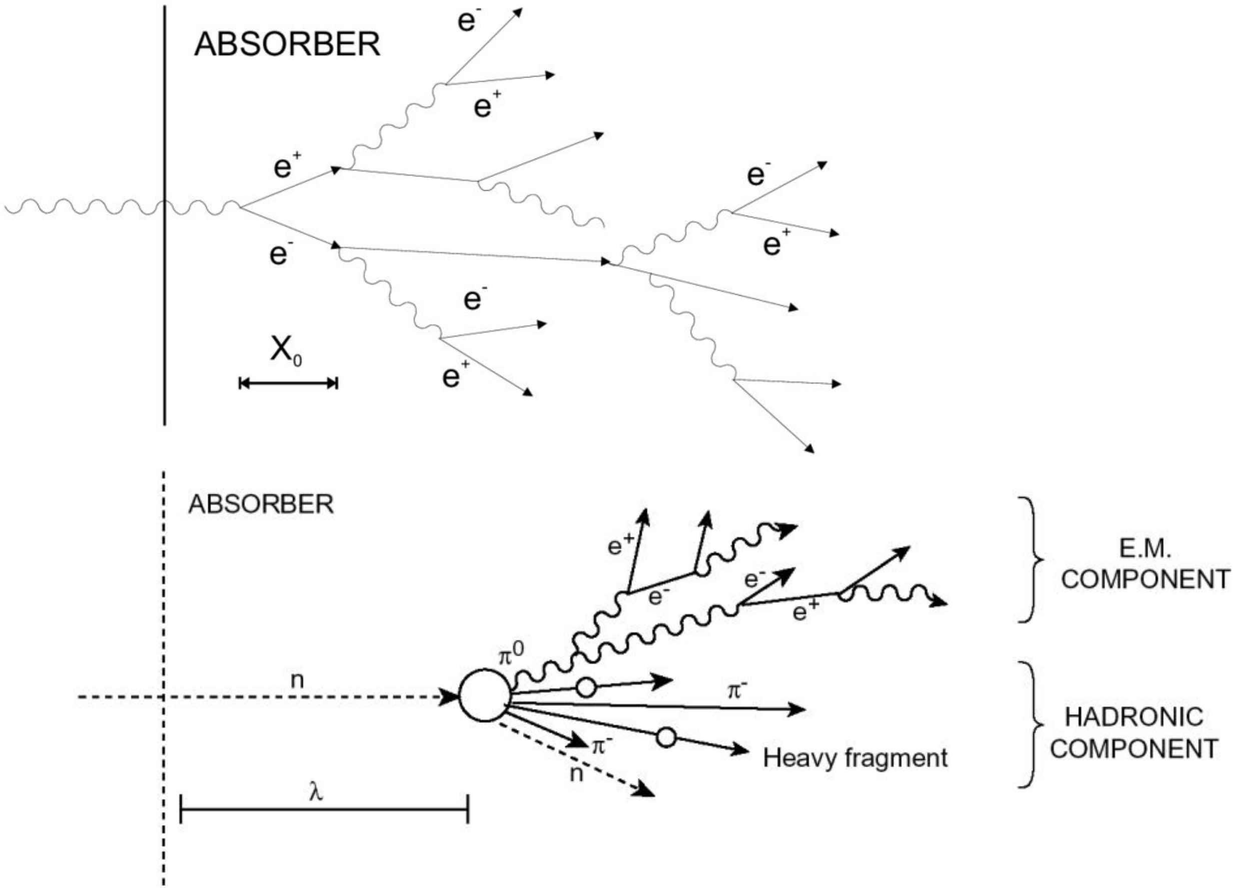
- Tracking system is ideally massless
- Calorimeter is *massive* and should totally absorb the energy of a particle [or jet] in 1 GeV to 1 TeV range.
- Electromagnetic and hadronic calorimeters.

The basic idea



- Stop/contain particle/jet by **shower** and absorption processes.
- Convert energy to signal with ionisation, scintillation etc..
- **Linearity** and good **resolution** desirable.
- Direction measurement for neutral particles.
- Missing transverse energy in ~4π detectors.
- Intrinsically fast → triggering.

Electromagnetic and hadronic shower processes



Interplay with stable visible particles

- Charged hadrons (π, K, p)

  Hadronic showers

- Electrons and photons

  Electromagnetic showers

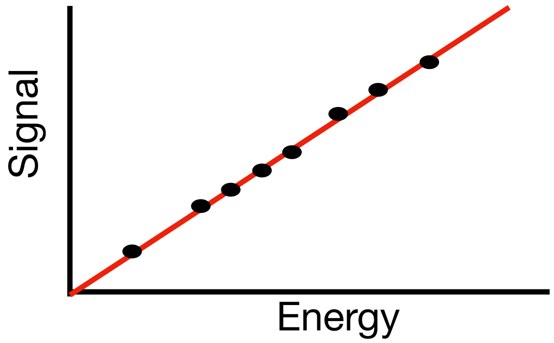
- Neutral hadrons (n, K_L)

  Hadronic showers

- Muons

  Minimum ionising (track in calorimeter)

Linearity

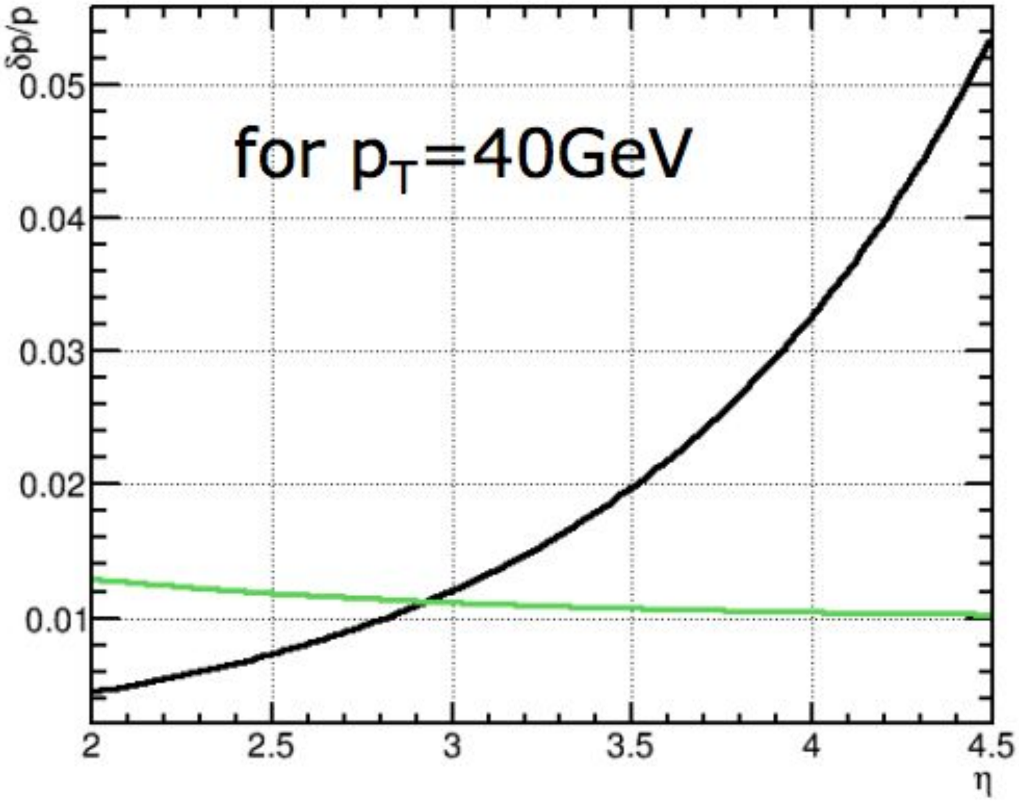


- Readily achieved in EM calorimeters

Non-linearity can still be caused by, e.g., shower leakage, variation of response with depth, saturation of electronics etc…

- Hadronic calorimeters are intrinsically non-linear…

Complementarity with tracking



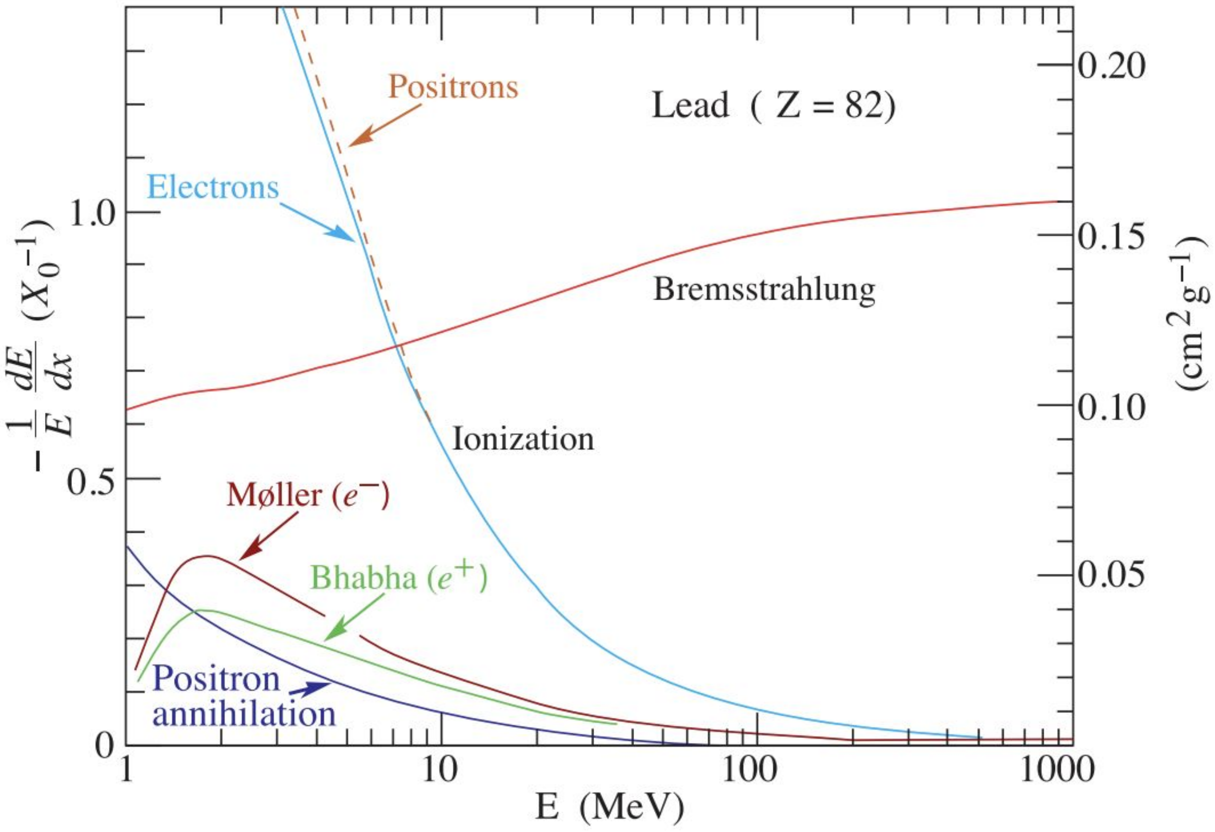
$$\frac{\sigma_p}{p} \sim p$$

$$\frac{\sigma_E}{E} \sim 1/\sqrt{E}$$

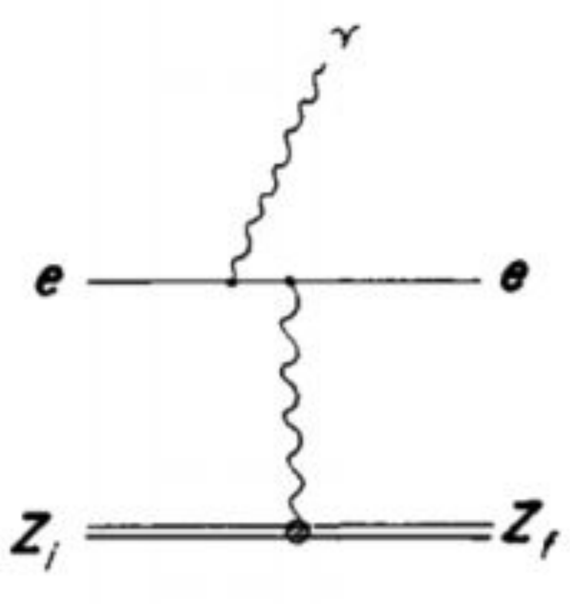
1. Short overview
2. EM showers
3. EM calorimeters
4. Hadronic showers/calorimeters

Electron interactions with matter

rpp2022-rev-passage-particles-matter



Bremsstrahlung: dominant for electrons at high energy



$$\sigma \sim \frac{1}{m^4}$$

$$\frac{dE}{dx} \propto E$$

Radiation length (X_0)

$$\frac{1}{E}\left(\frac{dE}{\rho dx}\right) = -\frac{1}{X_0} \qquad E = E_0 e^{-x/X_0}$$

~Density of scattering centres

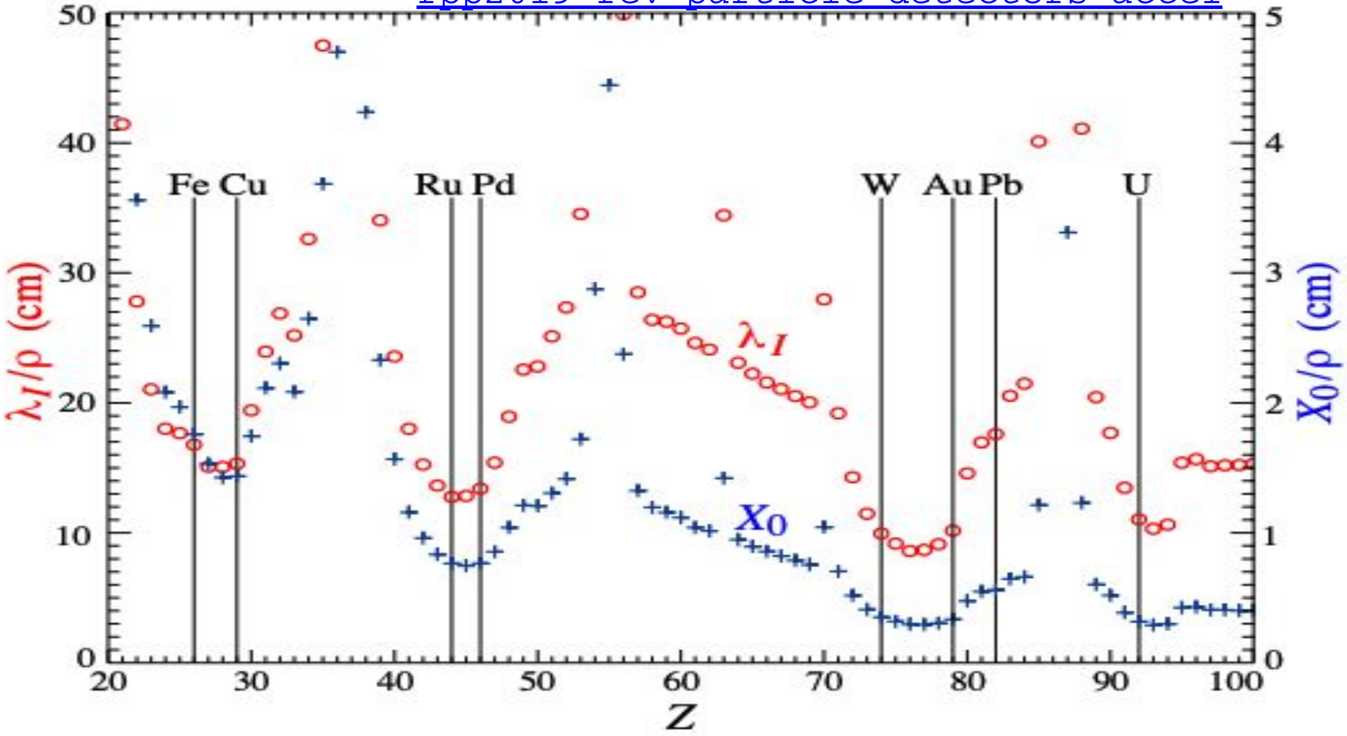
Approximation:

$$X_0 \sim \left[180\frac{\text{g}}{\text{cm}^2}\right]\frac{A}{Z^2} \qquad \sigma_{\text{brem}} \propto Z^2$$

👍if we express material thickness in X_0 then the radiation loss is independent of material.

Material dependence

rpp2019-rev-particle-detectors-accel



👍 X_0/ρ is a convenient quantity [with length units].

The critical energy (E_C),

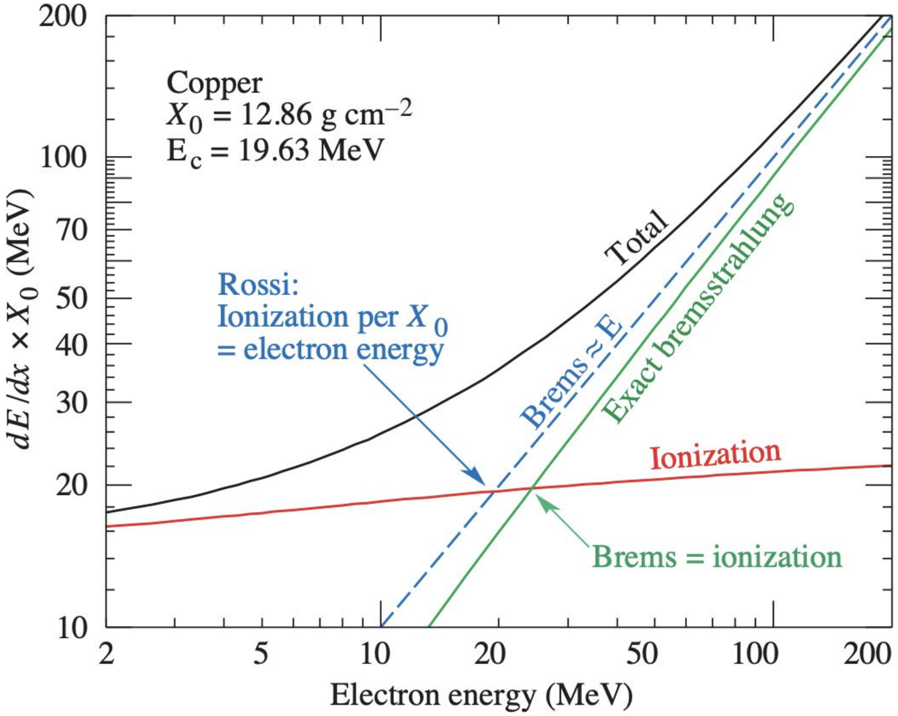
at which Brem. and ionisation losses are equal.

Ionisation $\sim \dfrac{Z}{A}\beta^{-2}$

Brem $\sim Z^2$

$$E_c \approx \frac{600\ \text{MeV}}{Z}$$

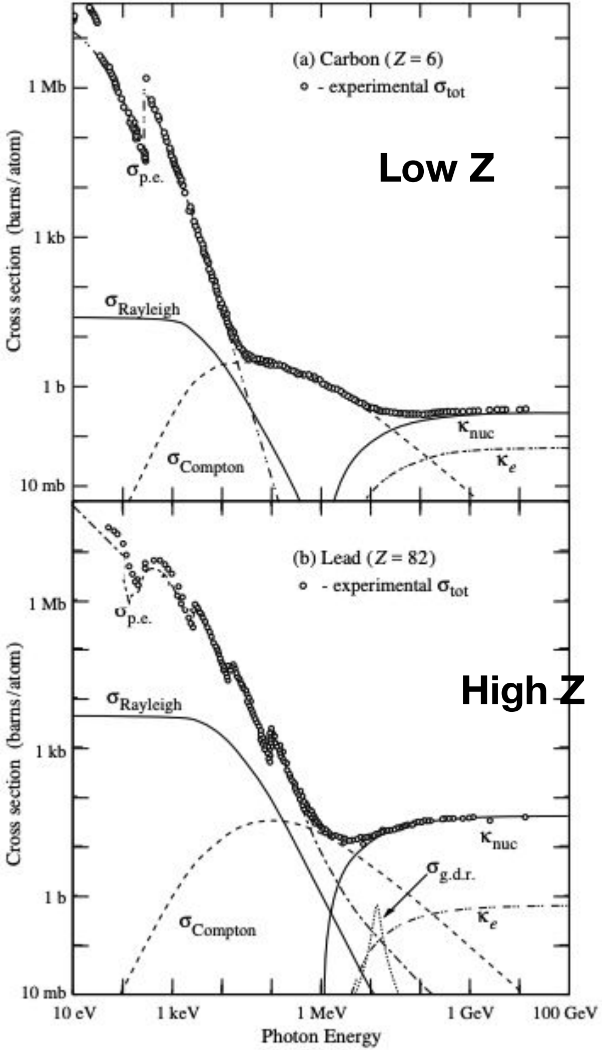
rpp2022-rev-passage-particles-matter



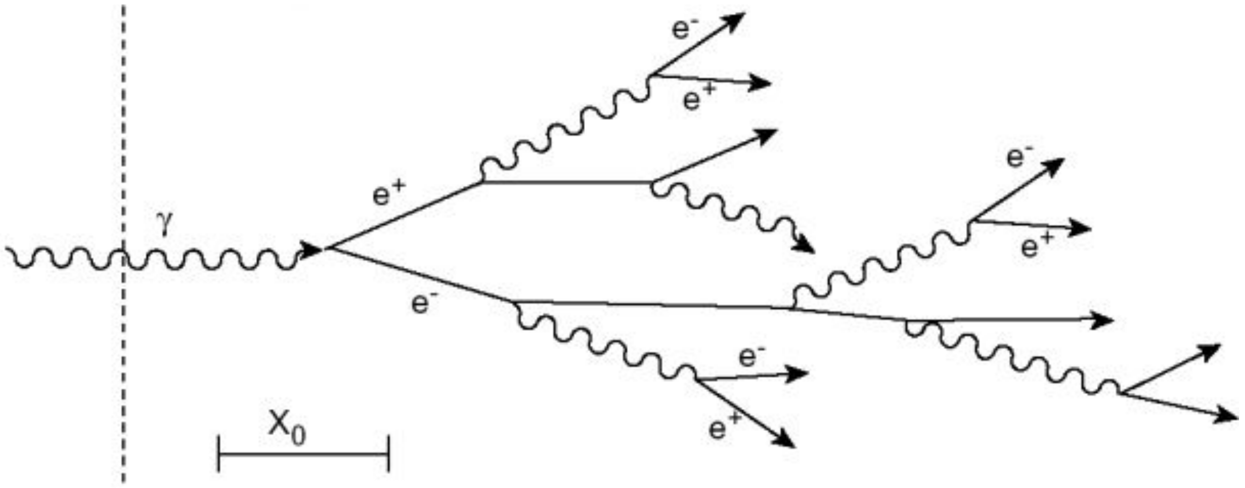
Photon interactions

1. Pair production at high energy
2. Compton scattering at lower energy
3. PE effect at even lower energy

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



Electromagnetic shower



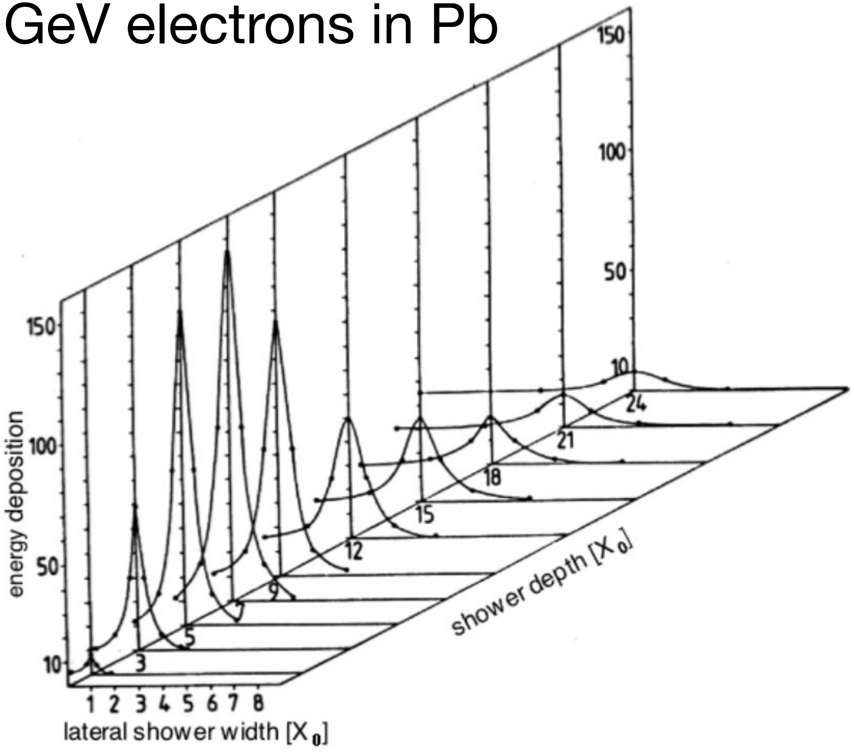
- Secondary electrons/photons from pair production and bremsstrahlung.

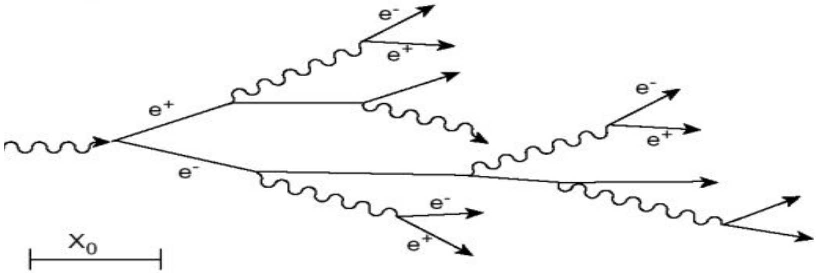
- Number *increases* but mean energy *decreases*.

- Ionisation and excitation take over when mean energy falls below E_C.

Shower development

6 GeV electrons in Pb

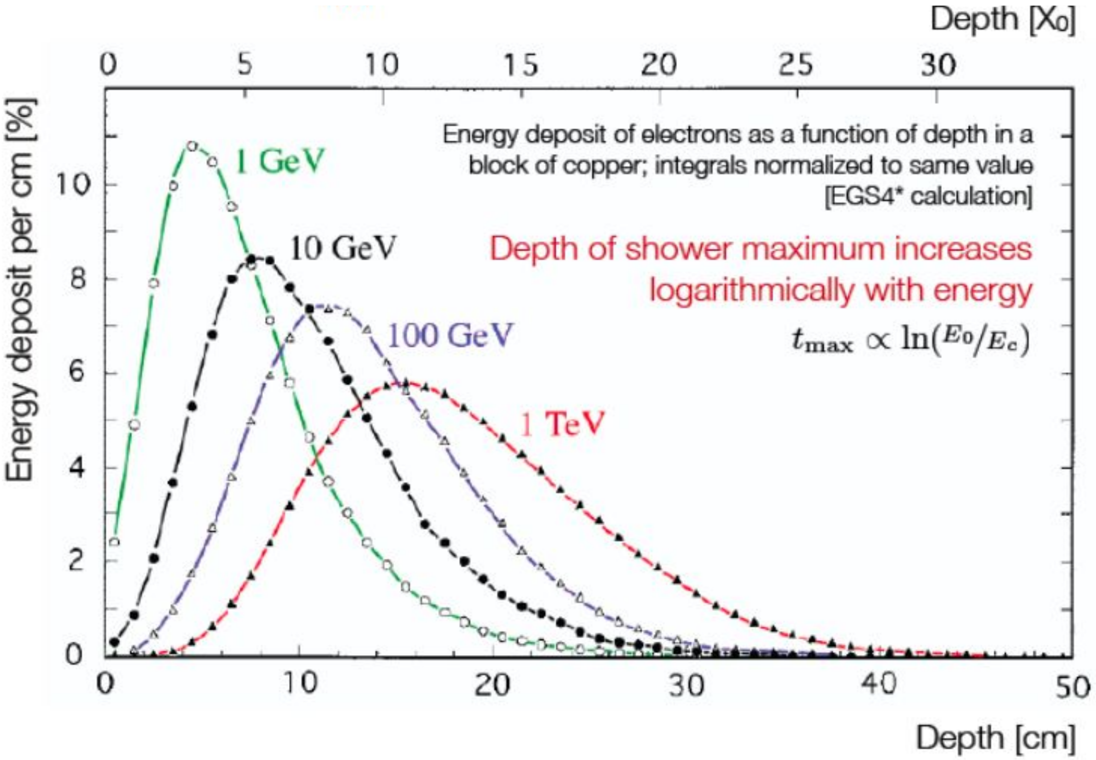




Key characteristics:

- Depth of shower max (t).
- Moliere radius (R_M).

Depth of shower max

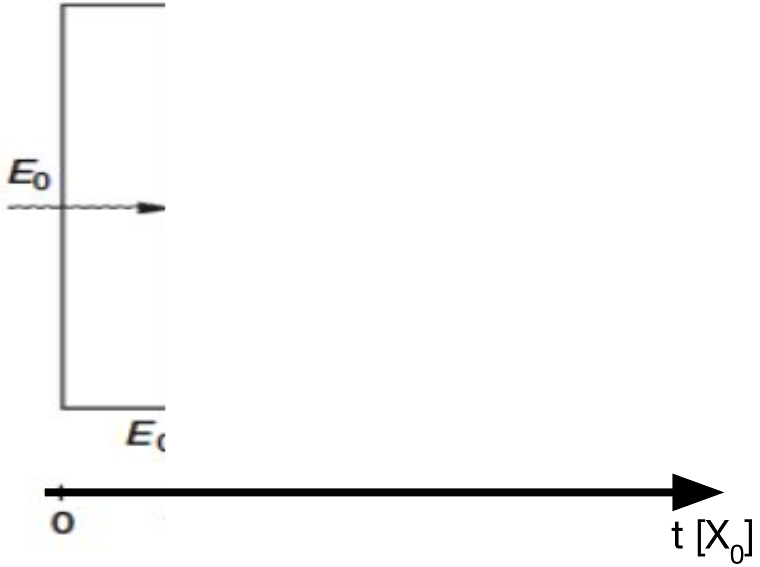


Depth only has log(E) scaling → can build compact calorimeters!

Simple shower model

After t [X_0] we have 2^t particles with energy $E/2^t$

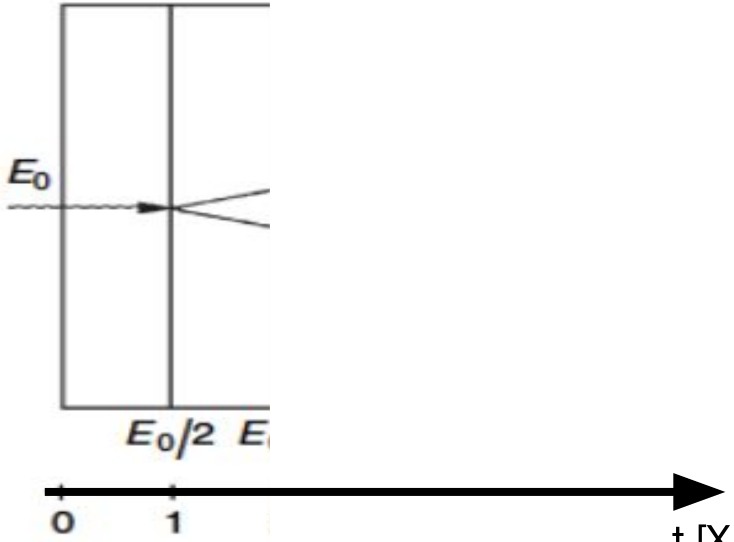
Shower stops when $E < E_c$



Simple shower model

After t [X_0] we have 2^t particles with energy $E/2^t$

Shower stops when $E < E_c$

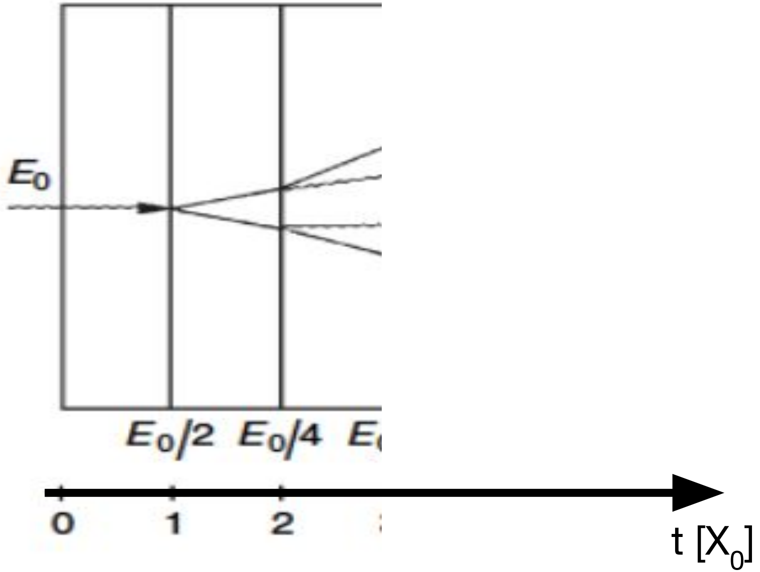


t [X_0]

Simple shower model

After t [X_0] we have 2^t particles with energy $E/2^t$

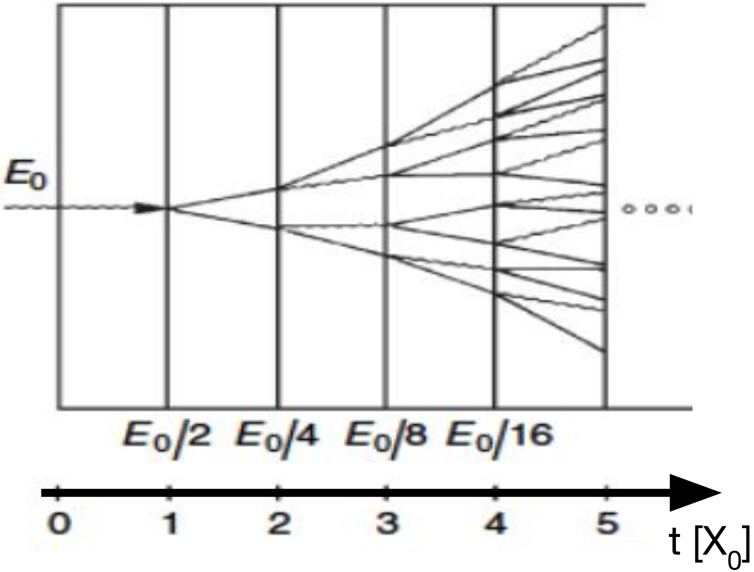
Shower stops when $E < E_c$



Simple shower model

After t [X_0] we have 2^t particles with energy $E/2^t$

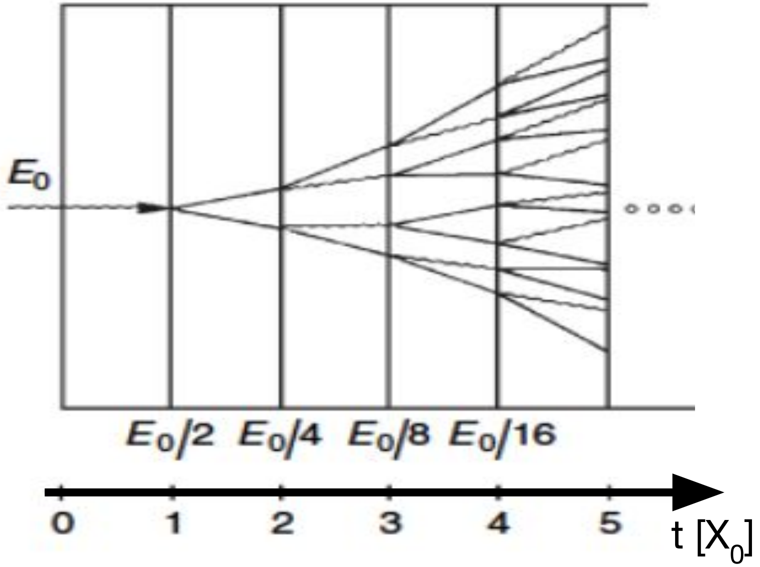
Shower stops when $E < E_c$



Simple shower model

After t [X_0] we have 2^t particles with energy $E/2^t$

Shower stops when $E < E_c$



$N = 2E/E_c$ particles

Shower max at $t_{max} \sim \ln(E_0/E_c)$

Lateral shower development

- Bremsstrahlung and pair production at small angles because m_e is small. $\langle \theta^2 \rangle \sim (m/E)^2$

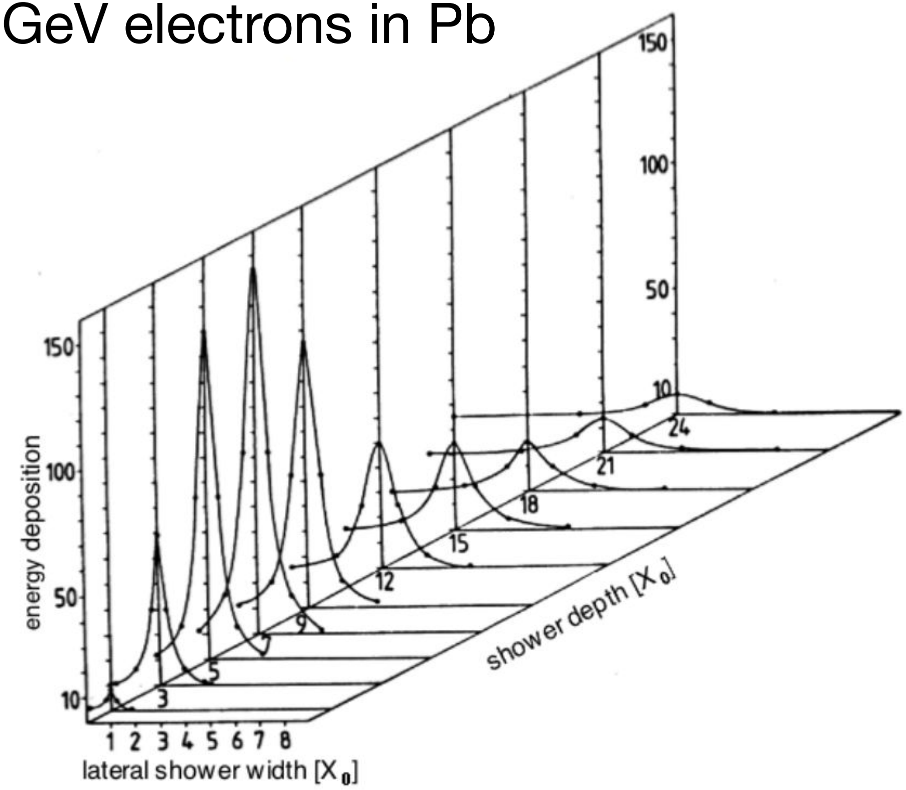
- Multiple coulomb scattering [Mollier theory] of low energy electrons dominates lateral spread.

- Characteristic Mollier radius

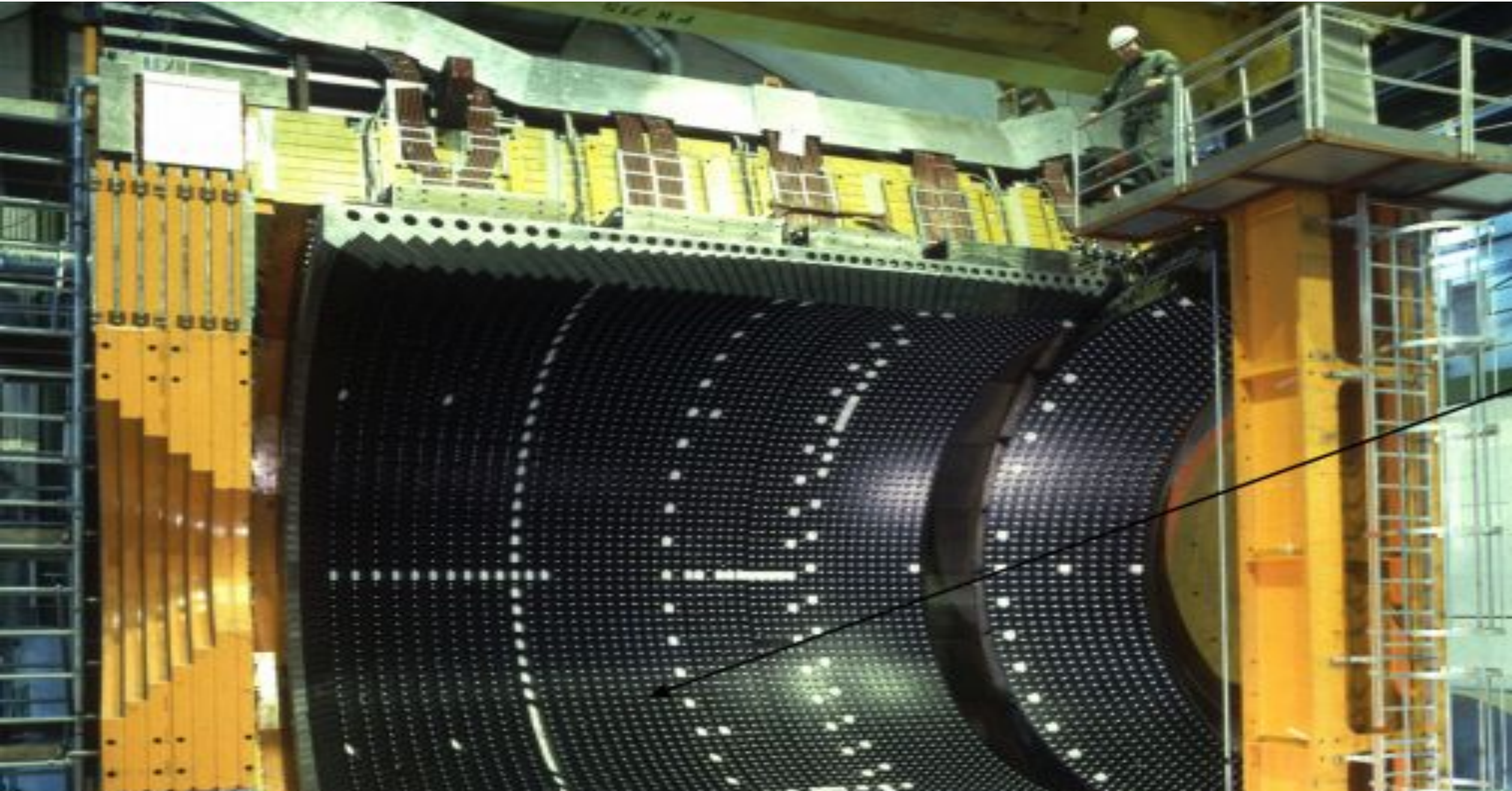
$$R_M \approx \left[7 \frac{\mathrm{g}}{\mathrm{cm}^2} \right] \frac{A}{Z}$$

R_M is a crucial consideration when specifying the segmentation (calorimeter cell size).

6 GeV electrons in Pb

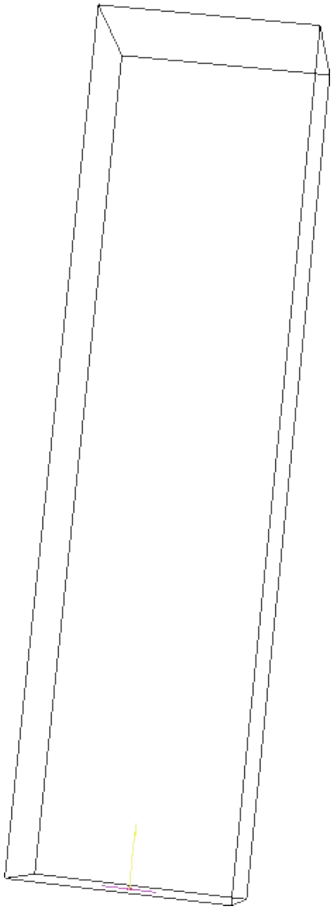


OPAL experiment lead glass



OPAL experiment lead glass

https://www.mpp.mpg.de/~menke/elss/



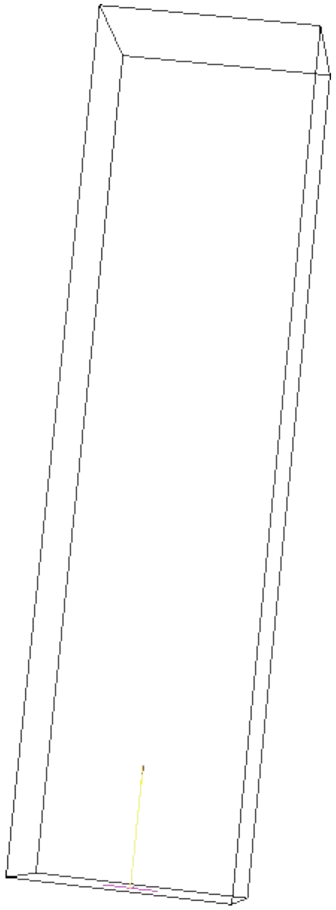
1 GeV e^-

37 x 10 x 10 cm

OPAL experiment lead glass

https://www.mpp.mpg.de/~menke/elss/

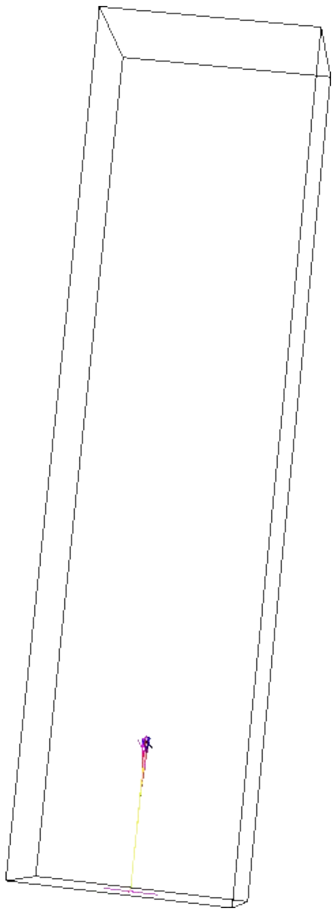
10 GeV e^-



37 x 10 x 10 cm

OPAL experiment lead glass

https://www.mpp.mpg.de/~menke/elss/



80 GeV e^-

37 x 10 x 10 cm

Back of the envelope EM shower characteristics

Radiation length $$X_0 \sim \left[180 \frac{\mathrm{g}}{\mathrm{cm}^2}\right] \frac{A}{Z^2}$$

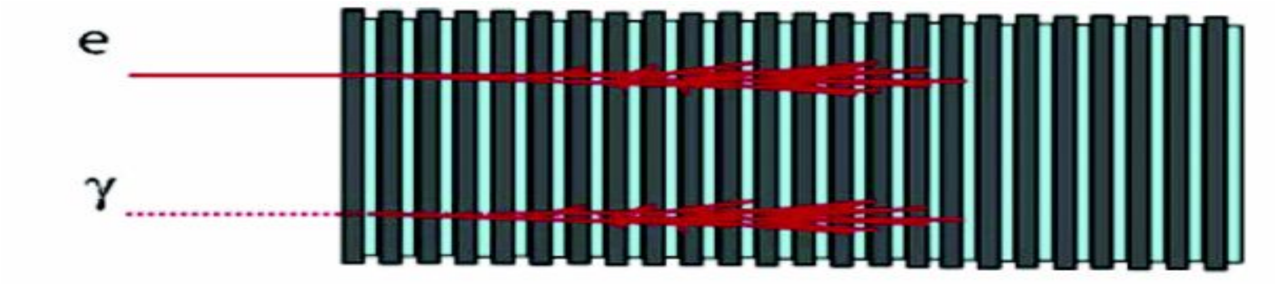
Critical energy $$E_c \approx \frac{600\ \mathrm{MeV}}{Z}$$

Shower max $$t_{\mathrm{max}} \approx \ln \frac{E}{E_c}$$

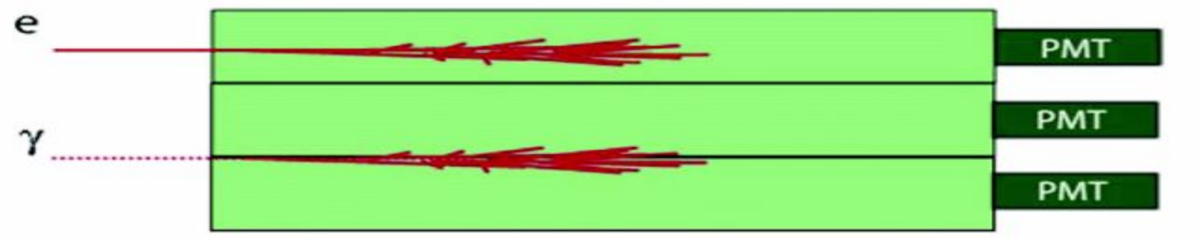
Moliere radius $$R_M \approx \left[7 \frac{\mathrm{g}}{\mathrm{cm}^2}\right] \frac{A}{Z}$$

inite cylinder of radius R_M contains 90% of the energy.

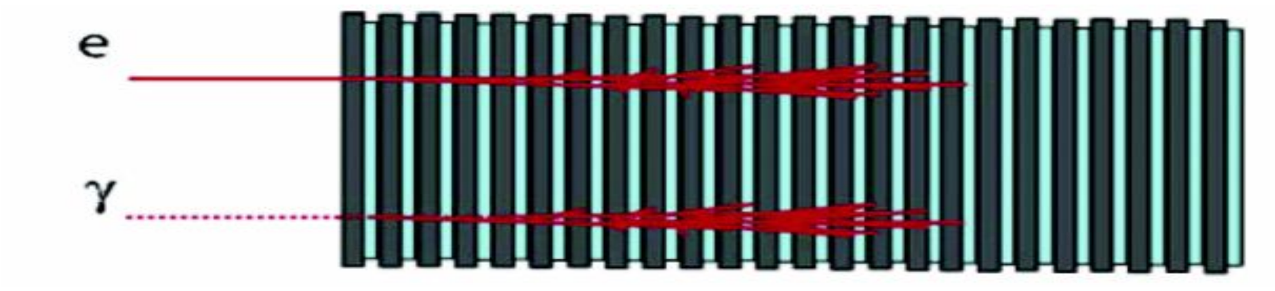
Sampling



Homogenous



Sampling



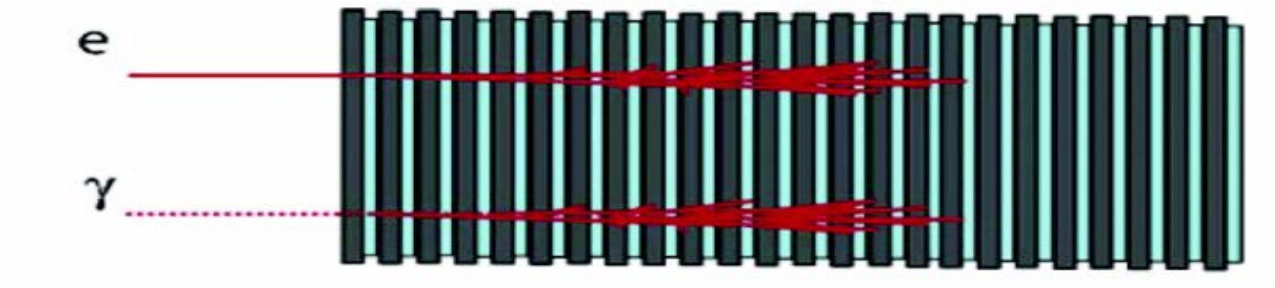
👍Freedom to independently choose optimal absorber and active detector material

👍Dense absorber → compact calorimeters

👍Can be cost effective (cheap absorber)

👎Not all particles seen in active layers.

Sampling

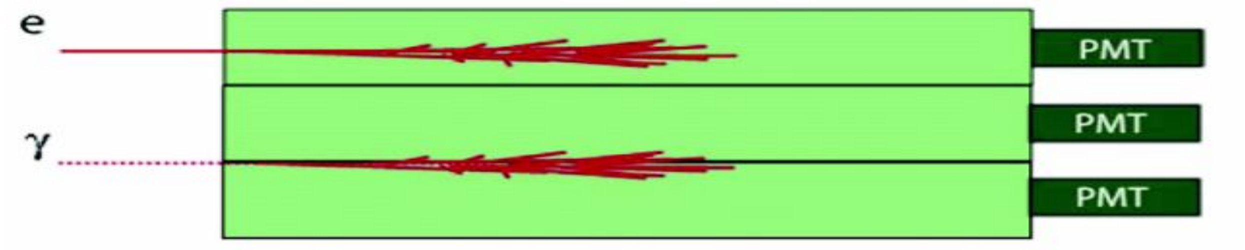


Sampling fraction *d*

$$\frac{\sigma}{E} \propto \frac{\sqrt{d}}{\sqrt{E}}$$

Smaller d means better resolution but more active material, lower density and higher cost.

Homogenous



👍Good resolution because all shower particles seen

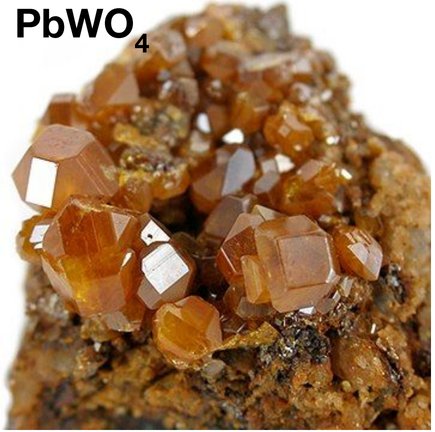
👍Uniform response → linearity

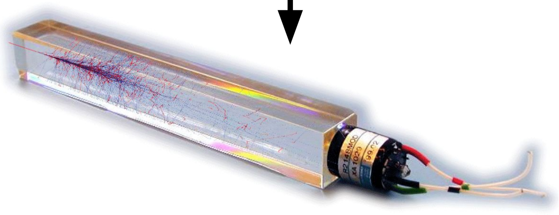
👎Expensive and limited segmentation

Special use cases e.g.

1. “medium energy” ECAL-only B-factory experiments,
2. CMS and ultimate H→ɣɣ mass resolution

Active material





- Charged based

  Semiconductors

  Liquid Nobel gases

- Light based

  Cerenkov

  Inorganic scintillator

  Organic scintillator (plastic, liquid, or crystal)

EM energy resolution

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

S: sampling or stochastic term

Fluctuations in the signal generating process

The ideal calorimeter has E ~ N, $\sigma \sim \sqrt{N} \sim \sqrt{E}$

N: noise term

E.g., readout electronics

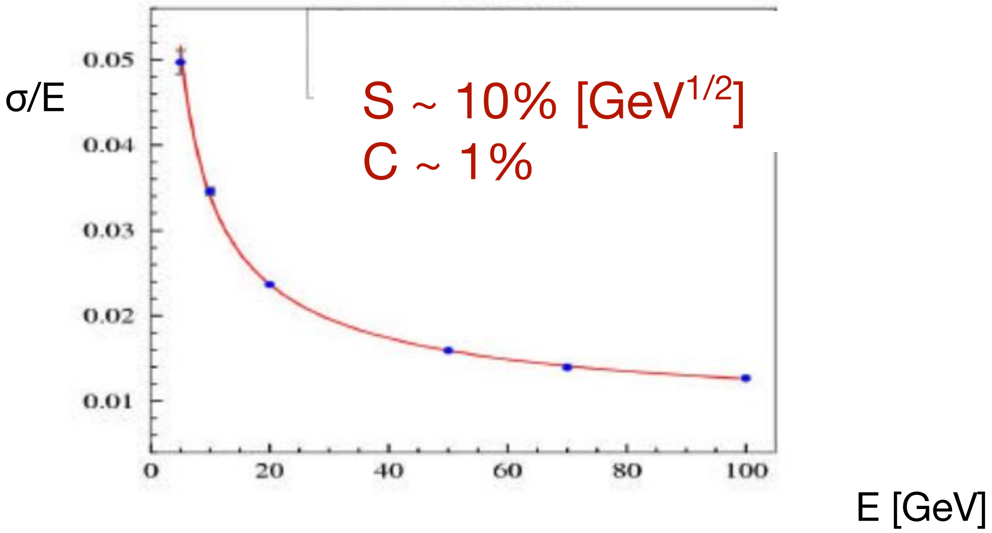
C: constant term

E.g., Non uniformity, calibration etc…

EM energy resolution

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

E.g., LHCb ECAL



Examples

rpp2019-rev-particle-detectors-accel

Table 34.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

~ [Few %]/√E

Homogeneous

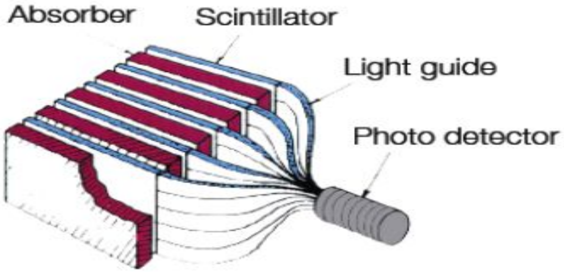
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Sampling

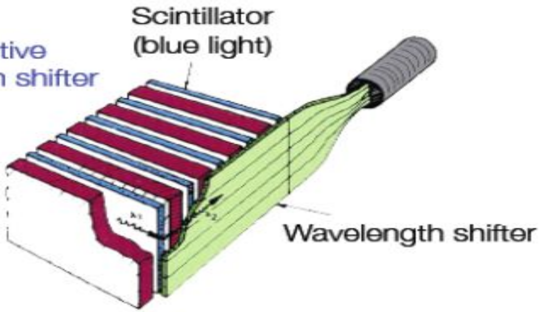
~ [10 %]/√E

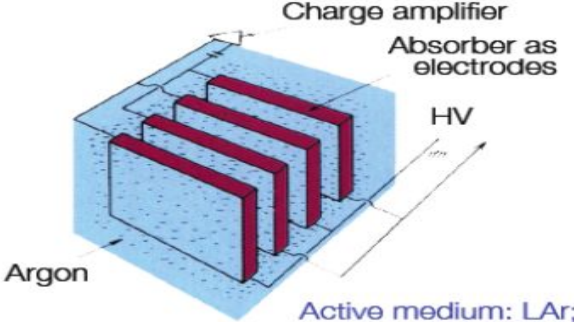
Sampling calorimeter designs

Scintillators as active layer;
signal readout via photo multipliers



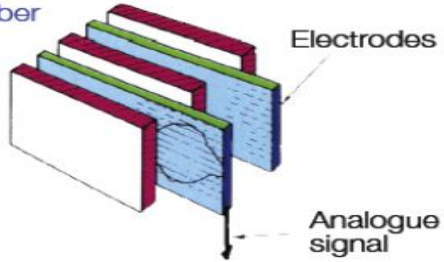
Scintillators as active layer; wave length shifter to convert light





Active medium: LAr; absorber embedded in liquid serve as electrods

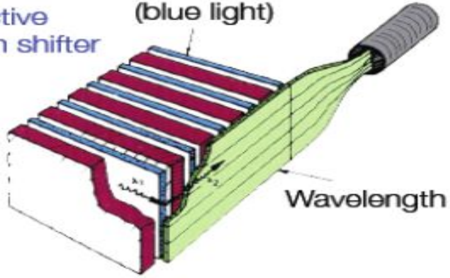
Ionization chambers between absorber plates



Sampling calorimeter designs

Scintillators as active layer;
signal readout via photo multipliers

Scintillators as active
layer; wave length shifter
to convert light



Active medium: LAr; absorber
embedded in liquid serve as electrods

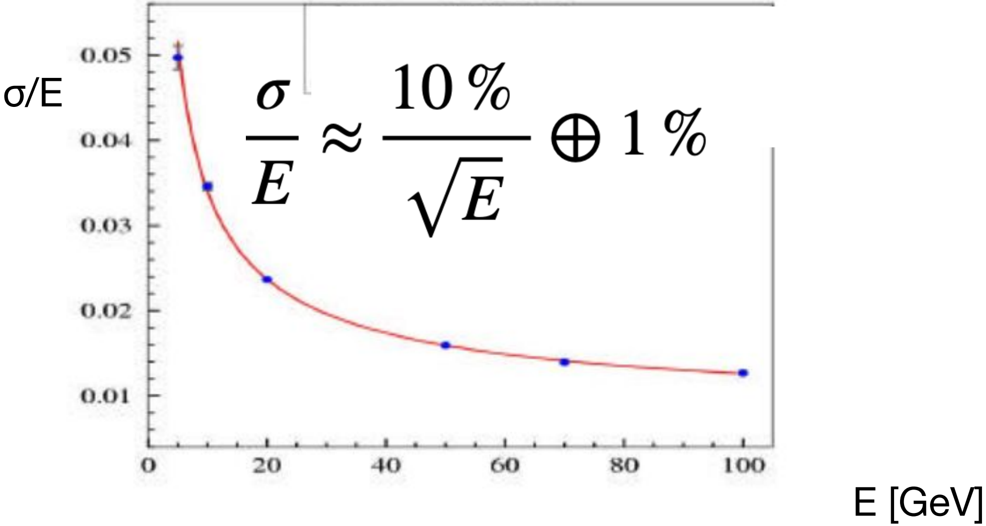
Ionization chambers
between absorber
plates

LHCb ECAL

“Shashlik” design alternating Pb absorber and scintillator

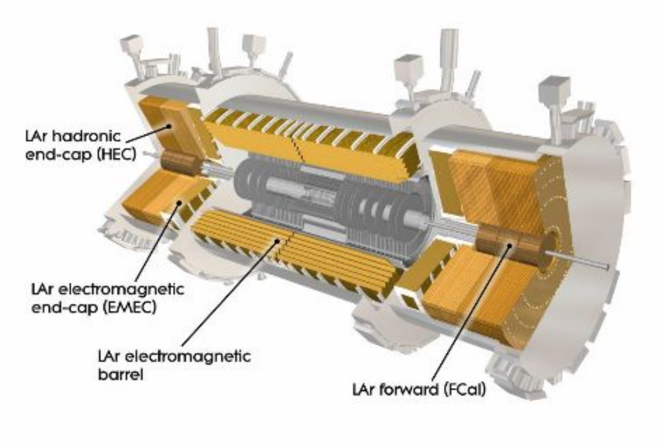
👍 Fast response

👍 Cost effective solution

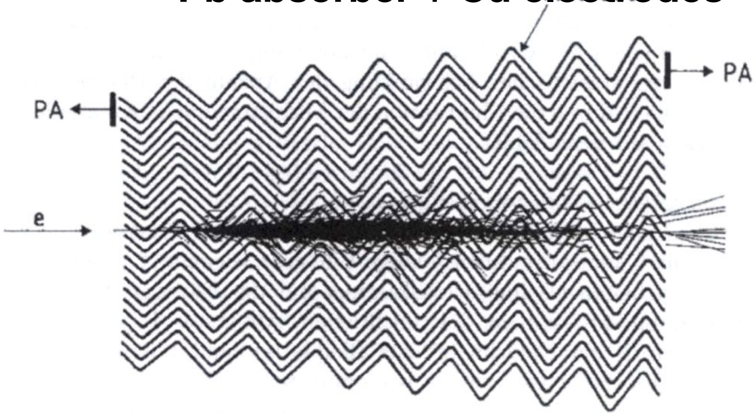


$$\frac{\sigma}{E} \approx \frac{10\,\%}{\sqrt{E}} \oplus 1\,\%$$

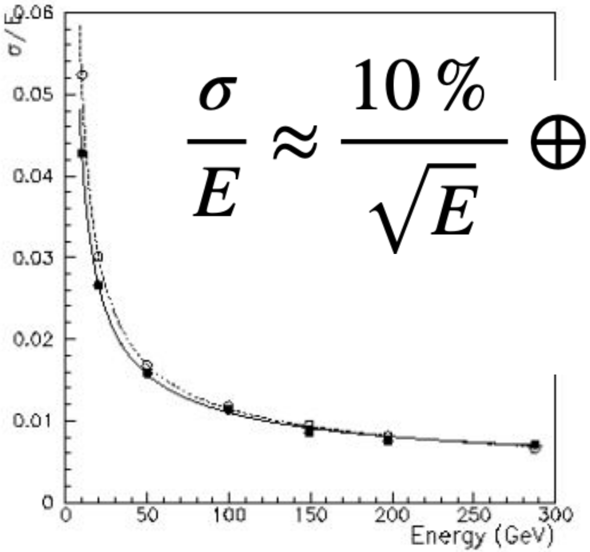
ATLAS Liquid Argon calorimeter



Pb absorber + Cu electrodes



- 👍Accordian shape →ϕ symmetry without cracks
- 👍Stability and radiation hardness
- 👎Slower response than e.g. scintillator approaches



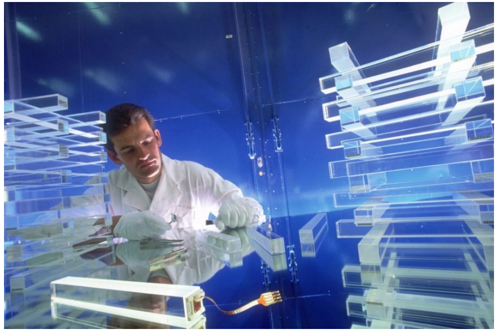
$$\frac{\sigma}{E} \approx \frac{10\,\%}{\sqrt{E}} \oplus 1\,\%$$

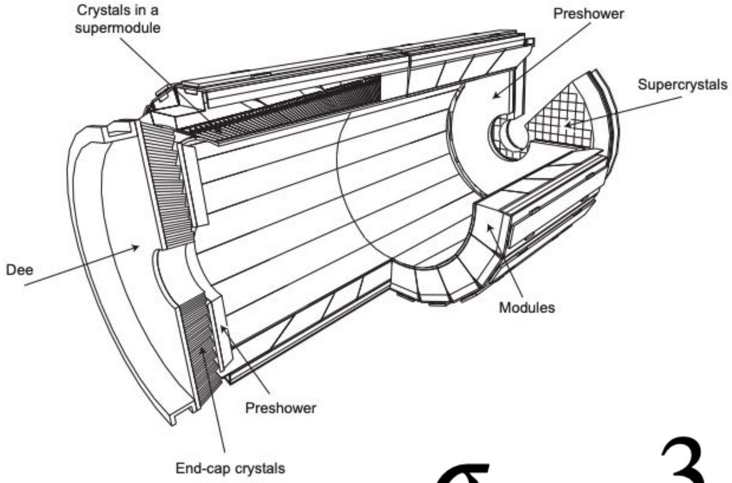
Homogenous calorimeters

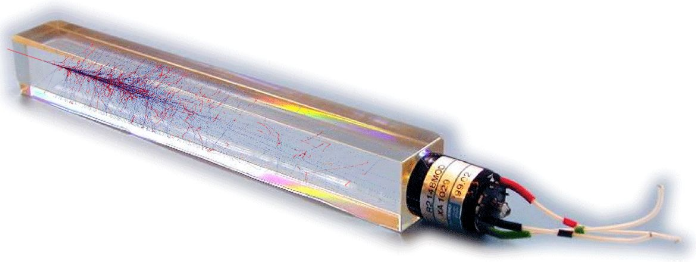
Scintillating crystals (sodium iodide NaI, bismuth germanate BGO, caesium iodide CsI, lead tungstate $PbWO_4$, etc.)

	NaI(Tl)	BGO	CsI(Tl)	$PbWO_4$
density (g/cm^3)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_M (cm)	4.5	2.4	3.8	2.2
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$	$2.5\%/\sqrt{E}$

CMS $PbWO_4$ ECAL

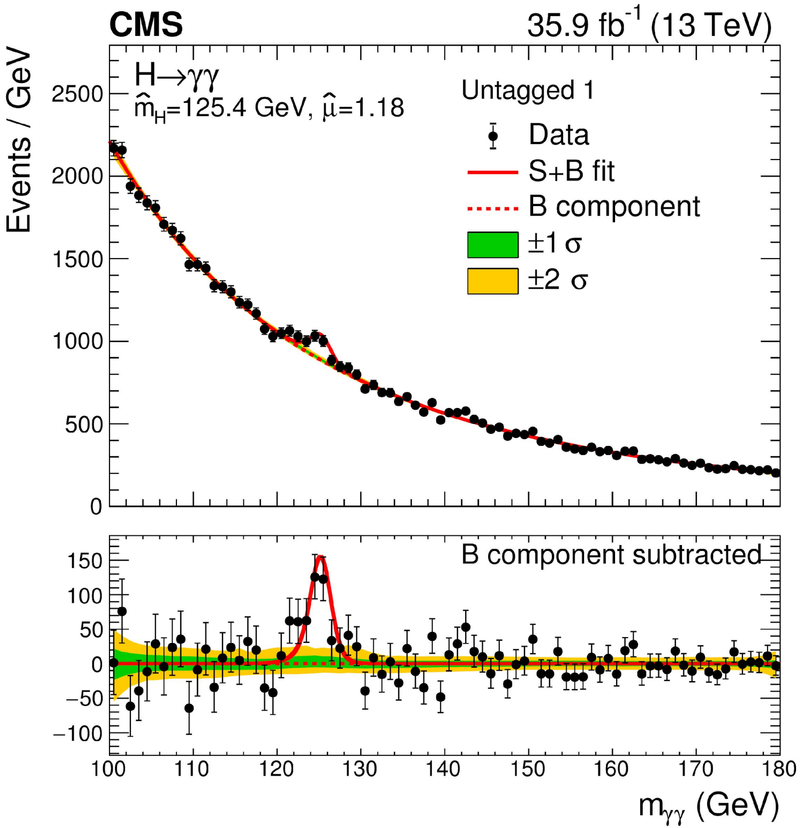


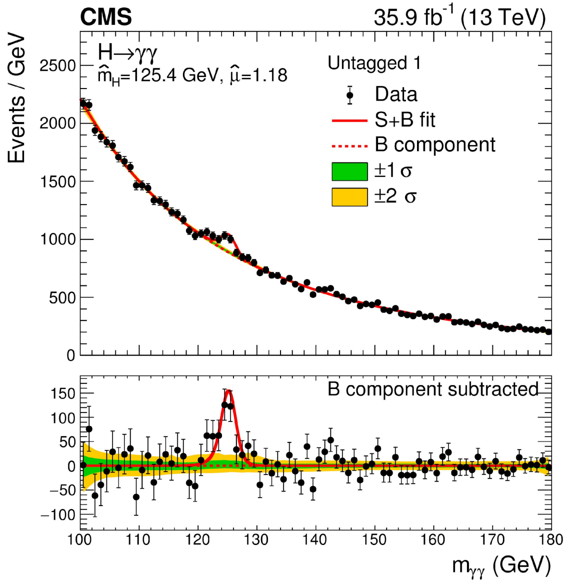


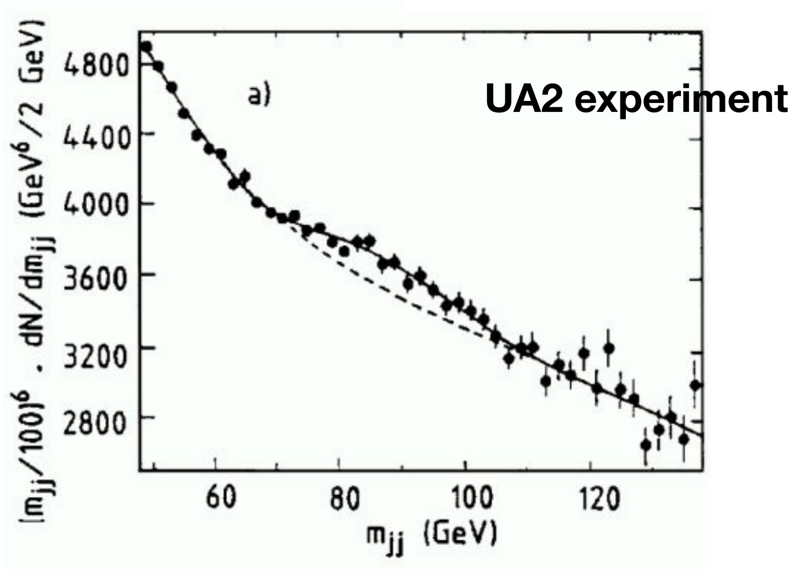


$$\frac{\sigma}{E} \approx \frac{3\,\%}{\sqrt{E}}$$

5 minute break question:
What would be the width of the H →ɣɣ peak in data?

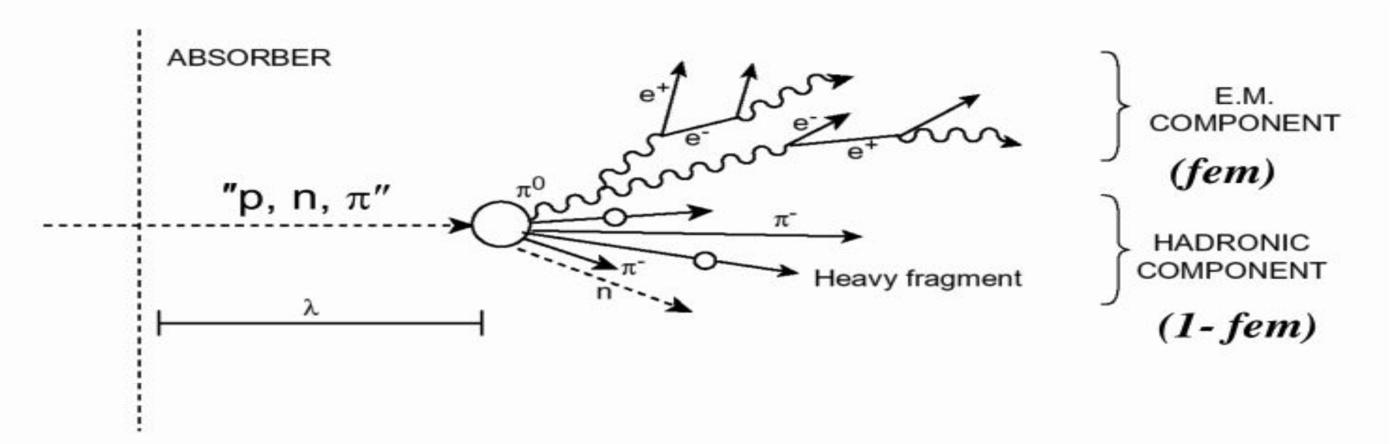

CMS
35.9 fb^{-1} (13 TeV)
H→γγ
$\hat{m}_H$=125.4 GeV, $\hat{\mu}$=1.18
Untagged 1
Data
S+B fit
B component
±1 σ
±2 σ
Events / GeV
B component subtracted
$m_{\gamma\gamma}$ (GeV)
0
500
1000
1500
2000
2500
150
100
50
0
−50
−100
100
110
120
130
140
150
160
170
180


CMS
35.9 fb^{-1} (13 TeV)
H→γγ
$\hat{m}_H$=125.4 GeV, $\hat{\mu}$=1.18
Untagged 1
Data
S+B fit
B component
±1 σ
±2 σ
B component subtracted
Events / GeV
$m_{\gamma\gamma}$ (GeV)


a)
UA2 experiment
$[m_{jj}/100]^6 \cdot dN/dm_{jj}$ (GeV^6/2 GeV)
m_{jj} (GeV)

Hadronic showers

- High energy hadrons interact with nuclei to produce secondary hadrons.
- Number of secondary hadrons ~ ln(E).
- Characteristic interaction length λ_I.
- Multiplication until <E> below [few x m_π].
- Two distinct components



Detector response to EM and had components is different

Hadronic showers

EM component from π^0,η^0

Hadronic component

~20% Charged hadrons

~25% Nuclear fragments

~15% neutrons + soft photons

~40% nuclear breakup (invisible)

Nuclear interaction length and containment

- Nuclear integration length

$$\lambda_i \approx \frac{1}{\sigma_{\text{tot}}}\frac{A}{N_A} \sim \left[35\frac{\text{g}}{\text{cm}^2}\right] A^{1/3}$$

- Typically order of magnitude larger than X_0

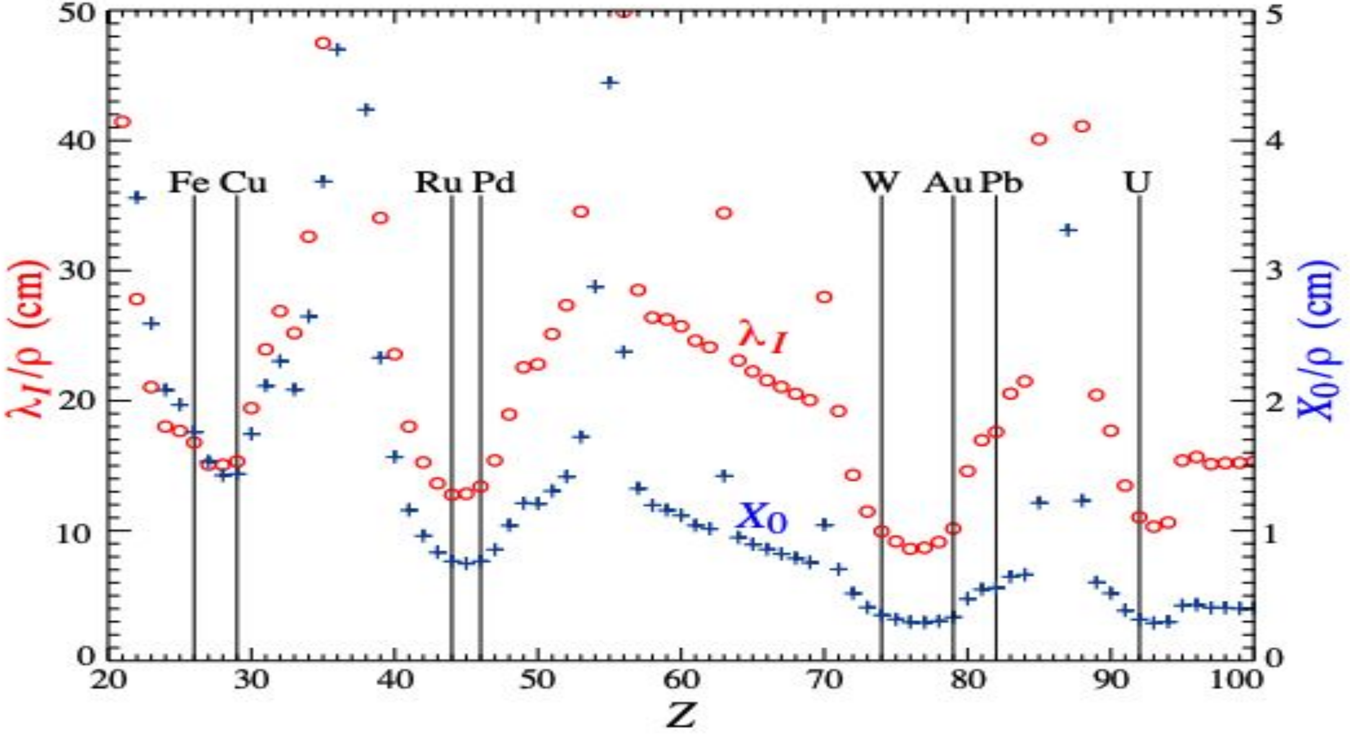
- Typically require about 10λ for containment

- Hadronic calorimeters are always of the sampling type

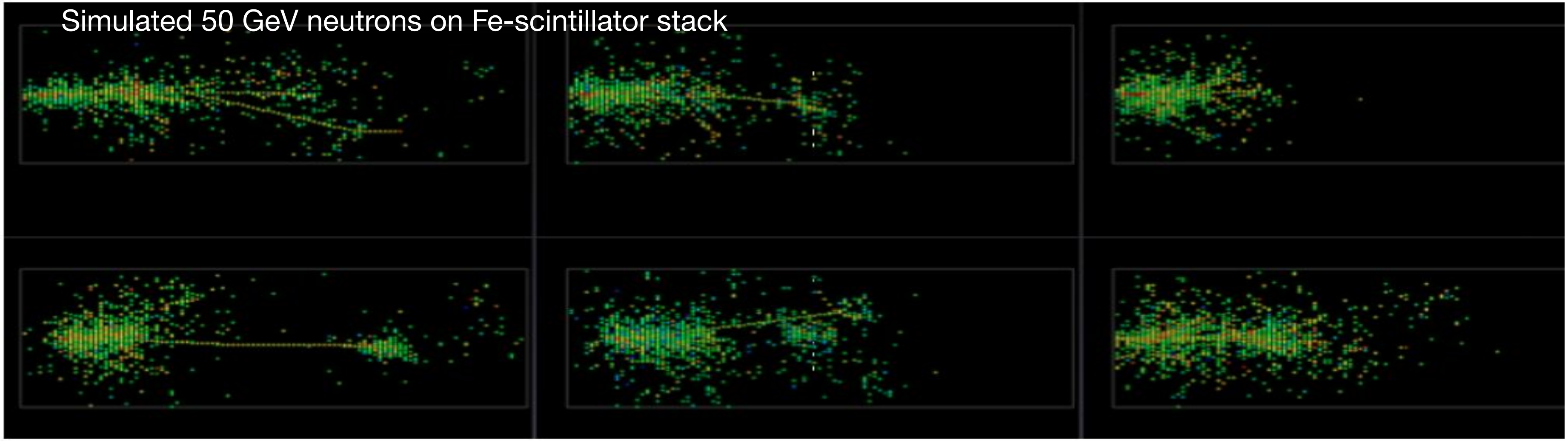
$$X_0 \sim \left[180\frac{\text{g}}{\text{cm}^2}\right] \frac{A}{Z^2}$$

Material dependence

rpp2019-rev-particle-detectors-accel



Hadron shower characteristics

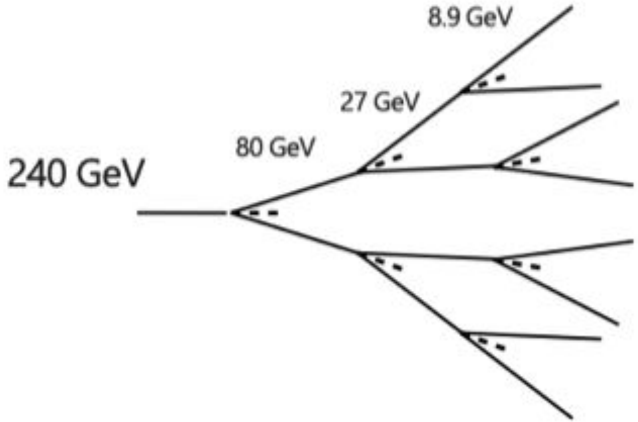


- Large fluctuations in shape/profile!
- Charge hadrons propagate shower over large scale (λ)
- Local EM showers from π^0, η^0

Simple hadronic shower model

- Shower is series of interactions producing, on average, 1/3 π^0 and 2/3 $\pi^{\pm}$
- Shower stops when $E < m_\pi$

$$f_{\mathrm{em}} = 1 - \left(\frac{2}{3}\right)^n$$

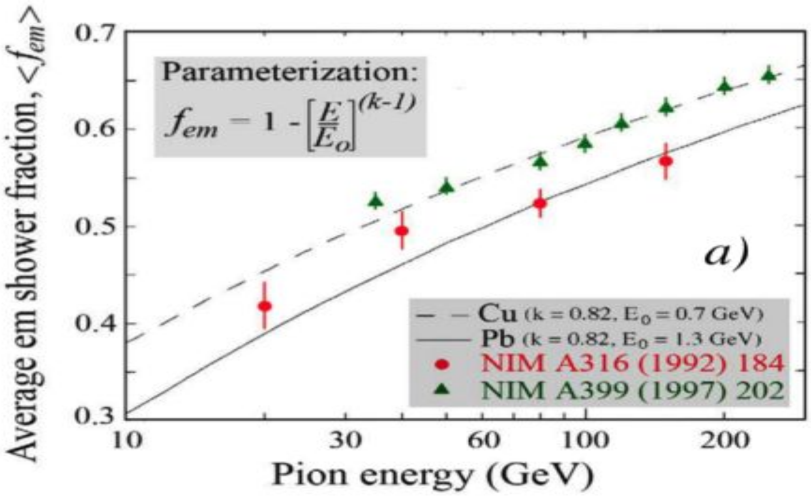


…f_{EM} increases with energy

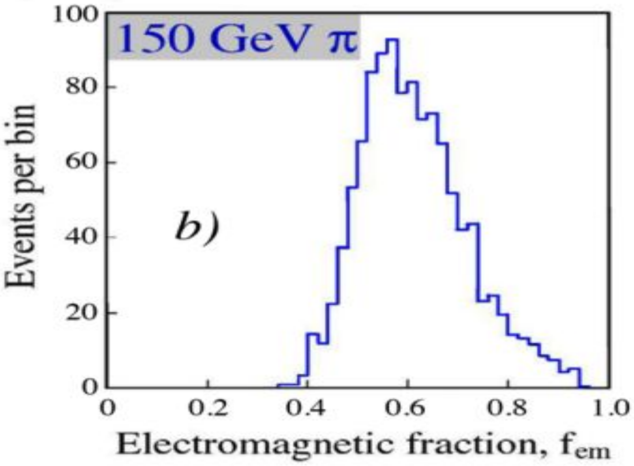
$$f_{\mathrm{em}} = 1 - \left(\frac{E}{E_{\mathrm{th}}}\right)^{k-1}$$

Challenge of hadron calorimeters

Energy dependence of f_{EM}



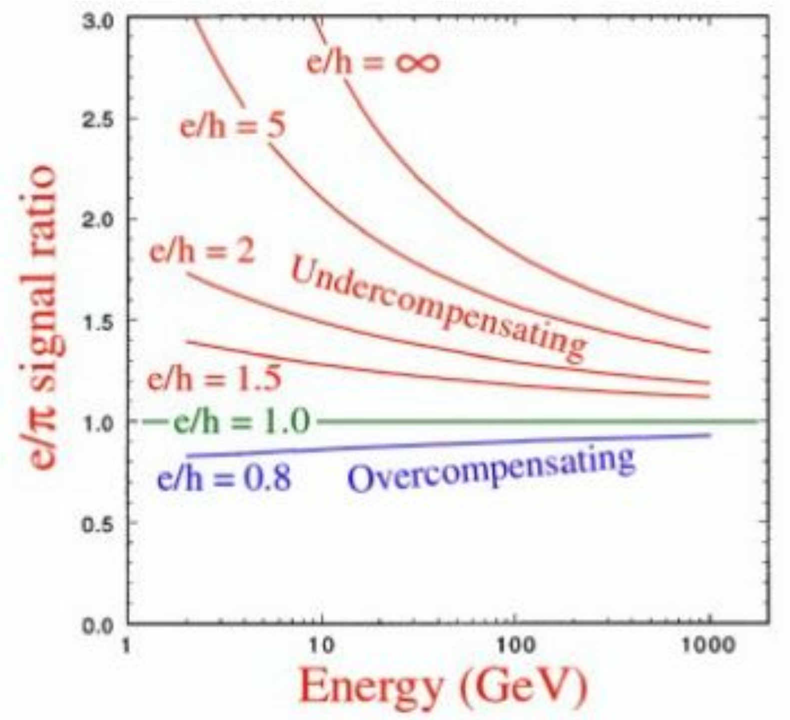
Fluctuations in f_{EM}



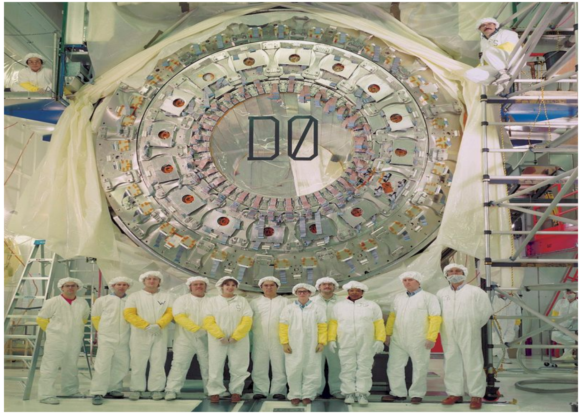
And the calorimeter response to the hadronic component tends to be smaller than to the electromagnetic component.

The response to hadrons is energy dependent and fluctuates a lot.

Challenge of hadron calorimeters



Compensation methods [for e/h ≈ 1]



D0 HCAL with U absorber

1. Software based

   Pattern recognition and reweighing.

2. Reduce EM component

   High Z material to filter out photo-electrons.

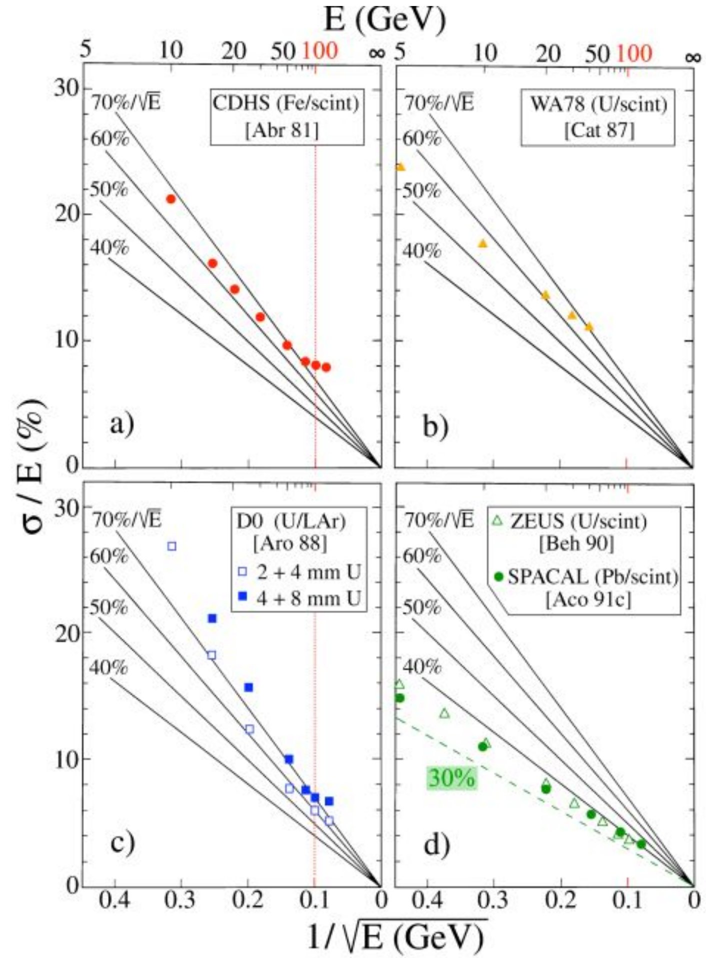
3. Boost the hadronic response

   Organic (hydrogen rich) materials with high neutron cross section.

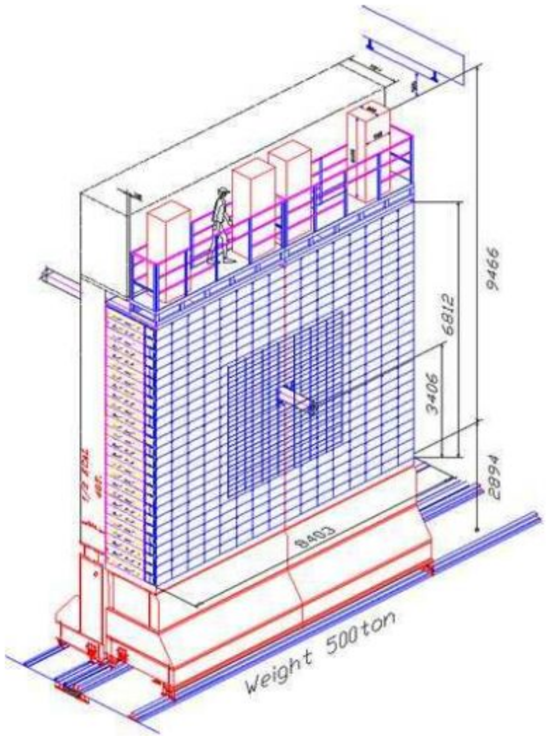
   Uranium (nuclear fission triggered by neutrons).

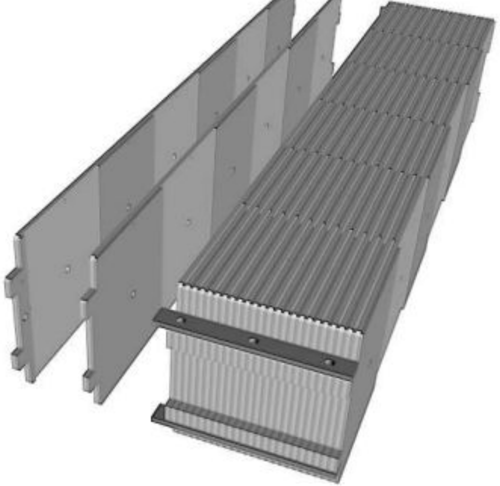
Not compatible with good EM resolution!

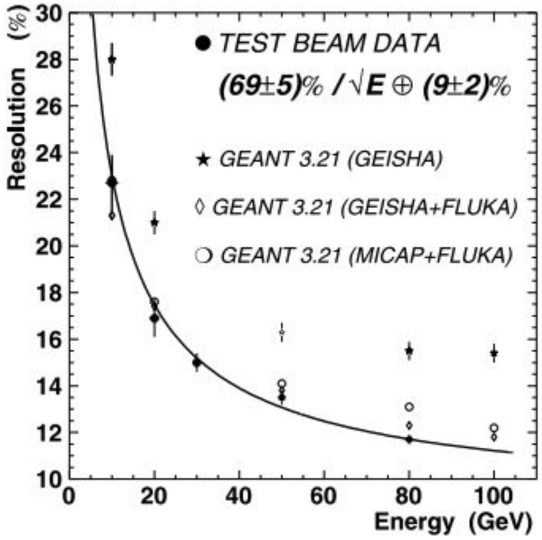
Some example performances



LHCb HCAL (Fe-scintilator)

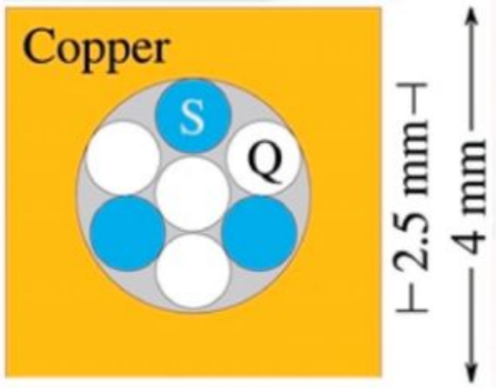


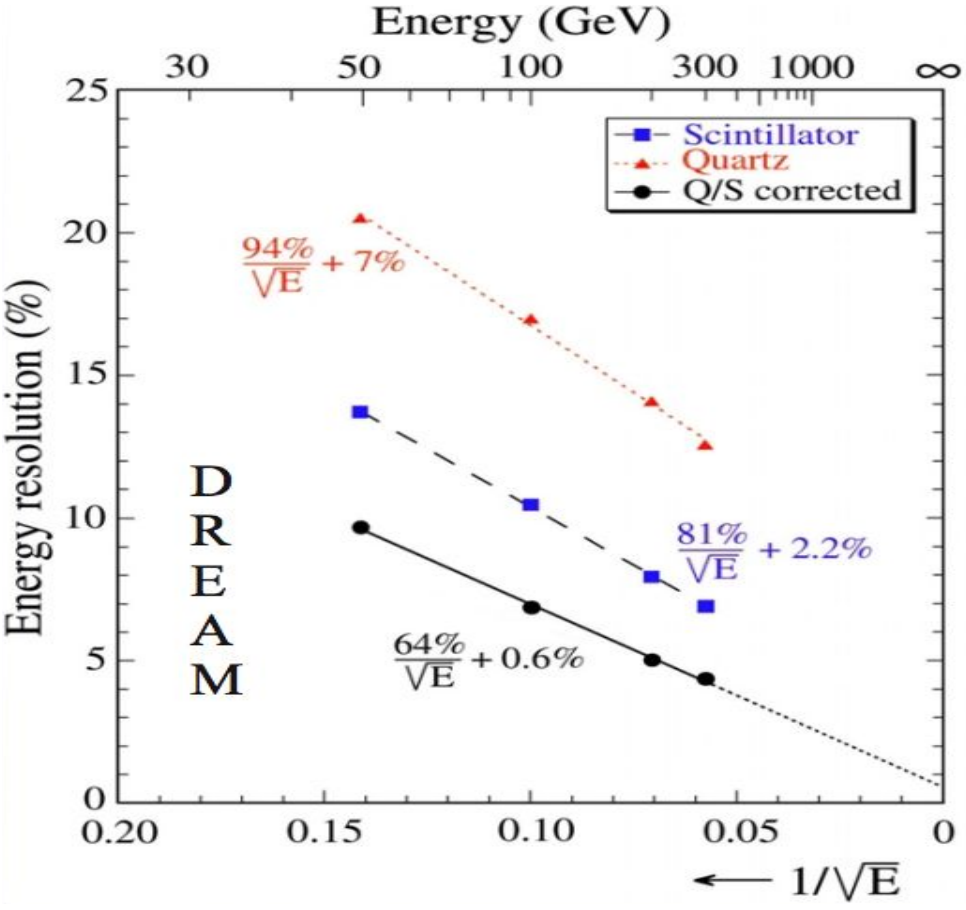




Dual readout R&D (compensation)

E.g. the original DREAM prototype with scintillating fibres and quartz fibres that have different e/h

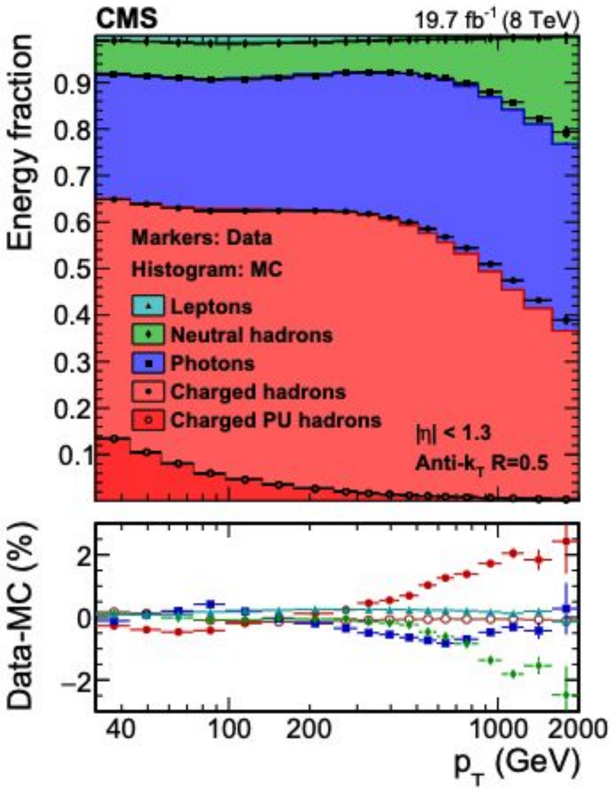


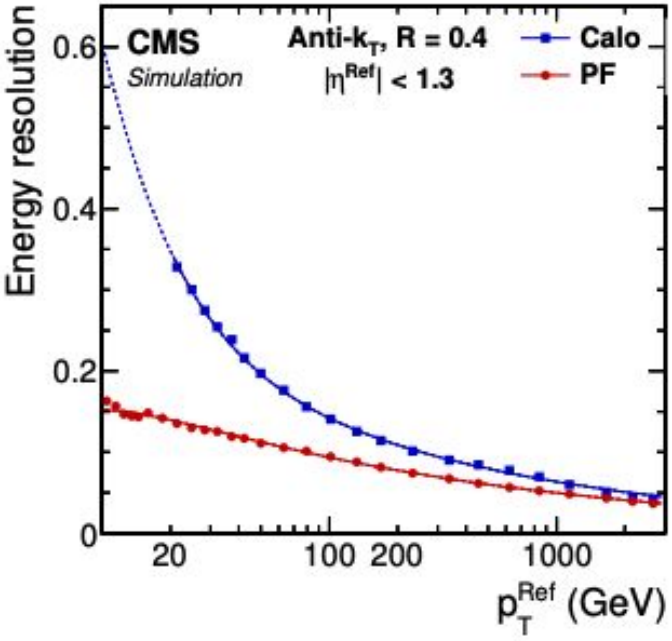


Area of ongoing R&D activity

Particle flow

JINST 12 (2017) P10003





Useful references

Book

Calorimetry: Energy Measurement in Particle Physics, Richard Wigmans

PDG reviews

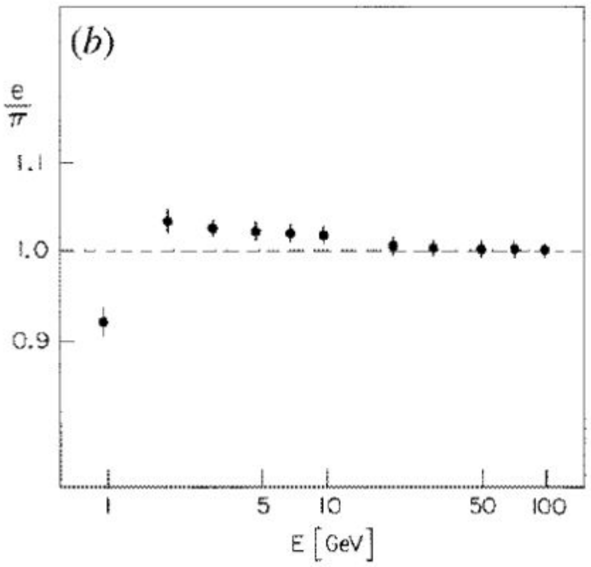
PDG review 2022: particle interactions with matter
PDG review 2022: particle detectors at accelerators

Animated gifs of shower simulations

https://www.mpp.mpg.de/~menke/elss/home.shtml

Backup slides

ZEUS HCAL



ZEUS

- U/scintillator or Pb/scintillator?
- If U, then 1:1 absorber/scintillator ratio is compensating, if Pb then a 4:1 ratio is required
- The *intrinsic* fluctuations in a Pb sampling calorimeter are smaller than those for a U calorimeter
  - Pb: 13% vs U: 20% for hadrons
  - Pb: 0.3% vs U: 2.2% for EM
- However the much poorer sampling ratio for Pb resulted in the choice of Uranium.

Moliere radius

An infinite cylinder of radius R_M contains 90% of the energy.

Back of the envelope EM shower characteristics

Radiation length

$$X_0 \sim \left[180 \frac{\mathrm{g}}{\mathrm{cm}^2}\right] \frac{A}{Z^2}$$

Critical energy

$$E_c \approx \frac{600\ \mathrm{MeV}}{Z}$$

Shower max

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

Lateral

$$R_M \approx \left[7 \frac{\mathrm{g}}{\mathrm{cm}^2}\right] \frac{A}{Z}$$

inite cylinder of radius R_M contains 90% of the energy.