

Calorimetry

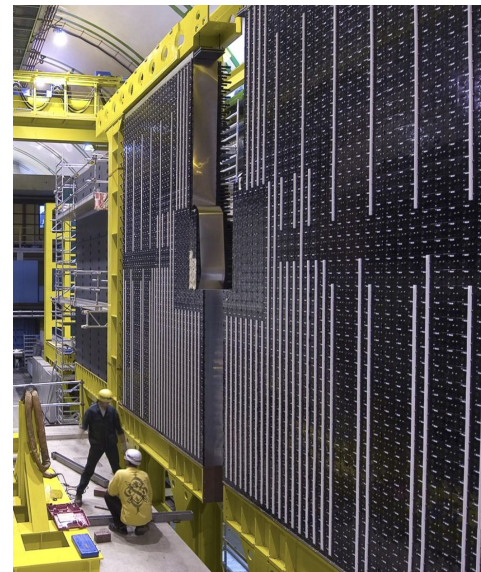
Mika Vesterinen
University of Warwick

Warwick week 2026

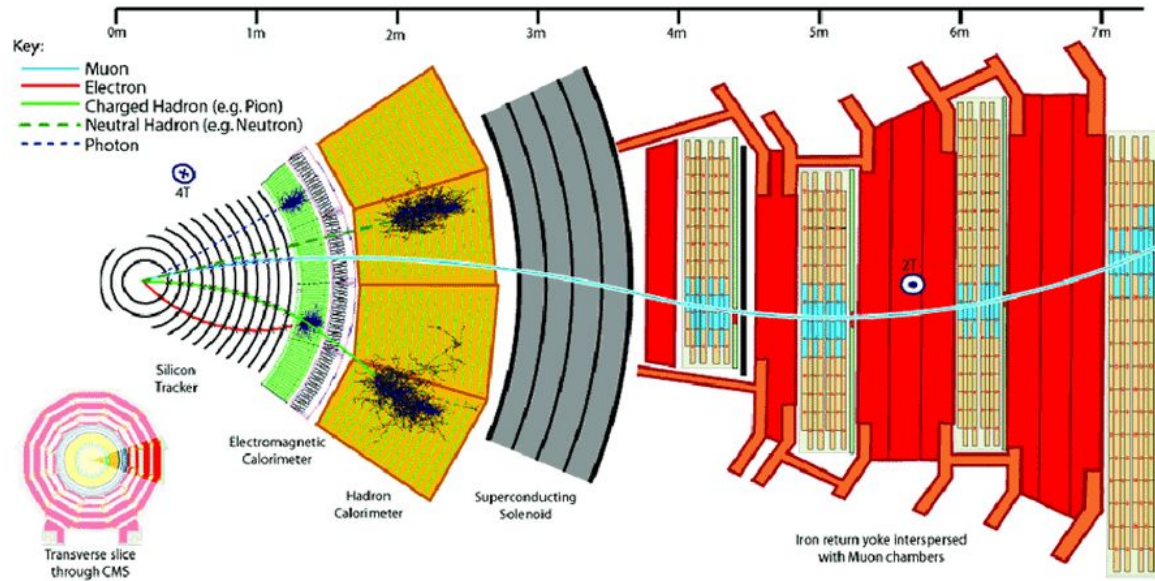
1. Short overview
2. EM showers
3. EM calorimeters
4. Hadronic showers/calorimeters

Calorimetry

- Wide usage in particle physics, e.g.
 - 4 π (or LHCb-like) collider experiments
 - Instrumented targets
 - Shower counters
- Various detection mechanisms
 - Scintillation
 - Ionisation
 - Cerenkov
 - Cryogenics

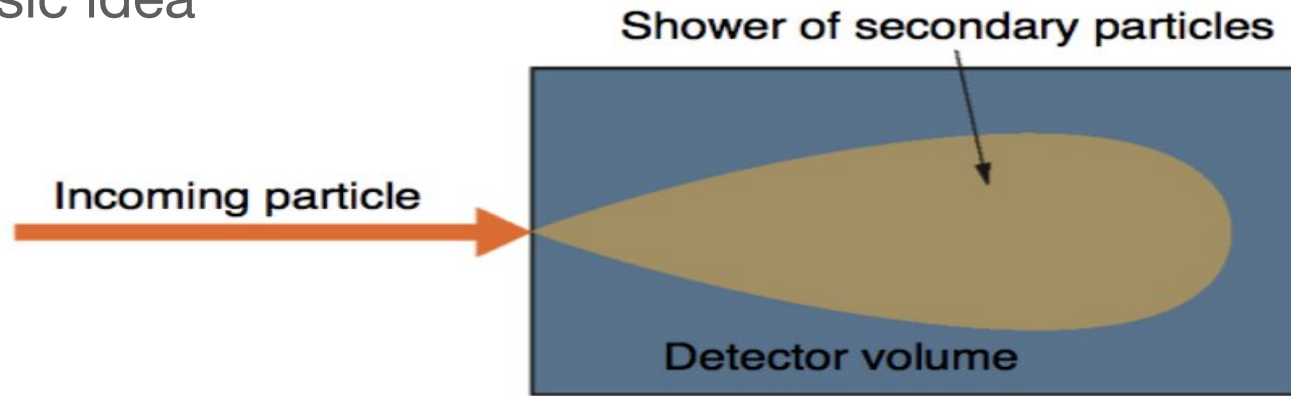


Typical collider detector schematic



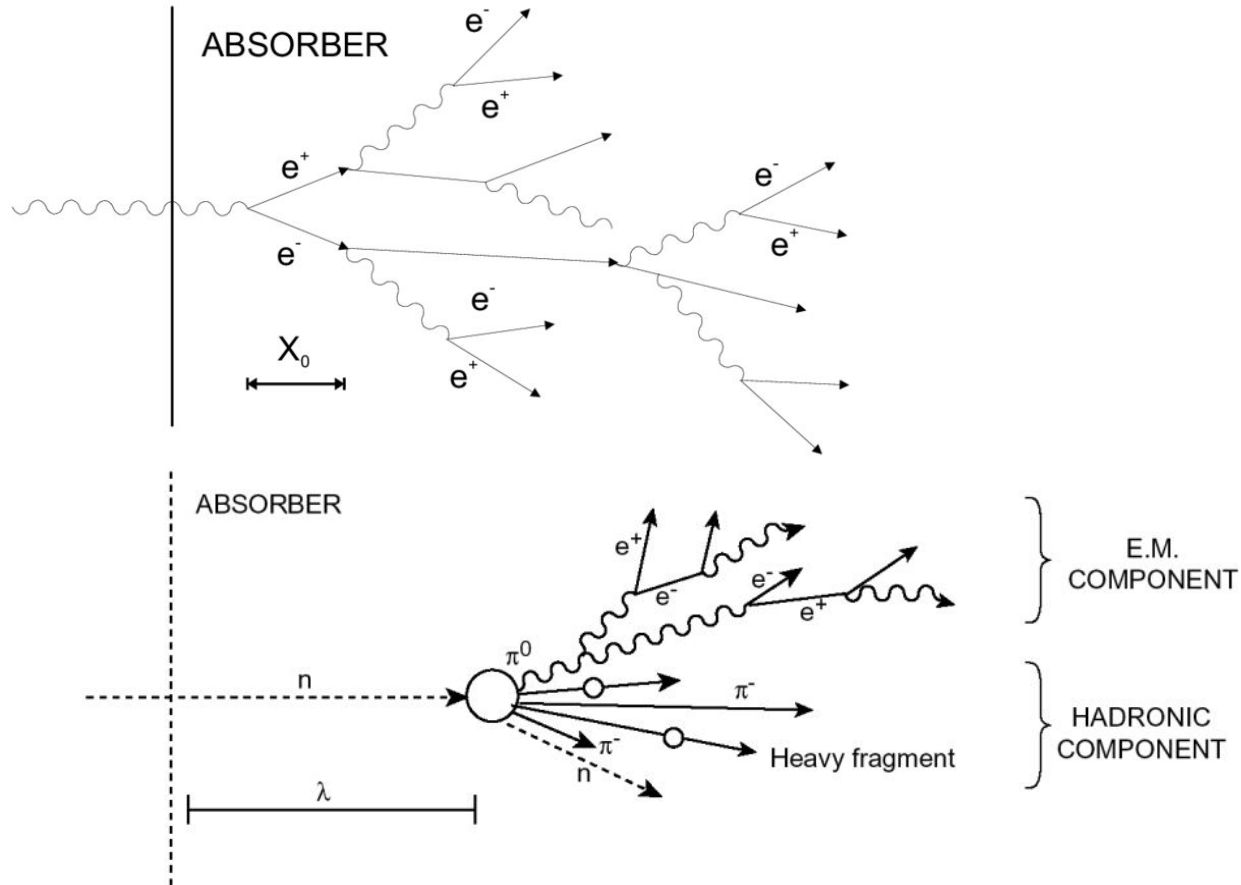
- Tracking system is ideally massless
- Calorimeter is massive and should totally absorb the energy of a particle [or jet] in 1 GeV to 1 TeV range.
- Electromagnetic and hadronic calorimeters.

The basic idea

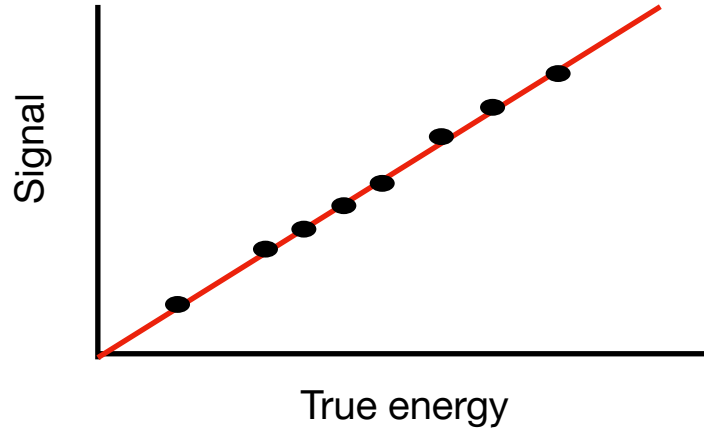


- Stop/contain particle/jet by shower and absorption processes.
- Convert energy to signal with ionisation, scintillation etc..
- Also provides:
 - Direction measurement for neutral particles, and missing transverse energy in “ 4π ” detectors.
 - Intrinsically fast signal → triggering.
- Aim for good energy resolution and *linearity*...

Electromagnetic and hadronic shower processes



Linearity



- Readily achieved in EM calorimeters

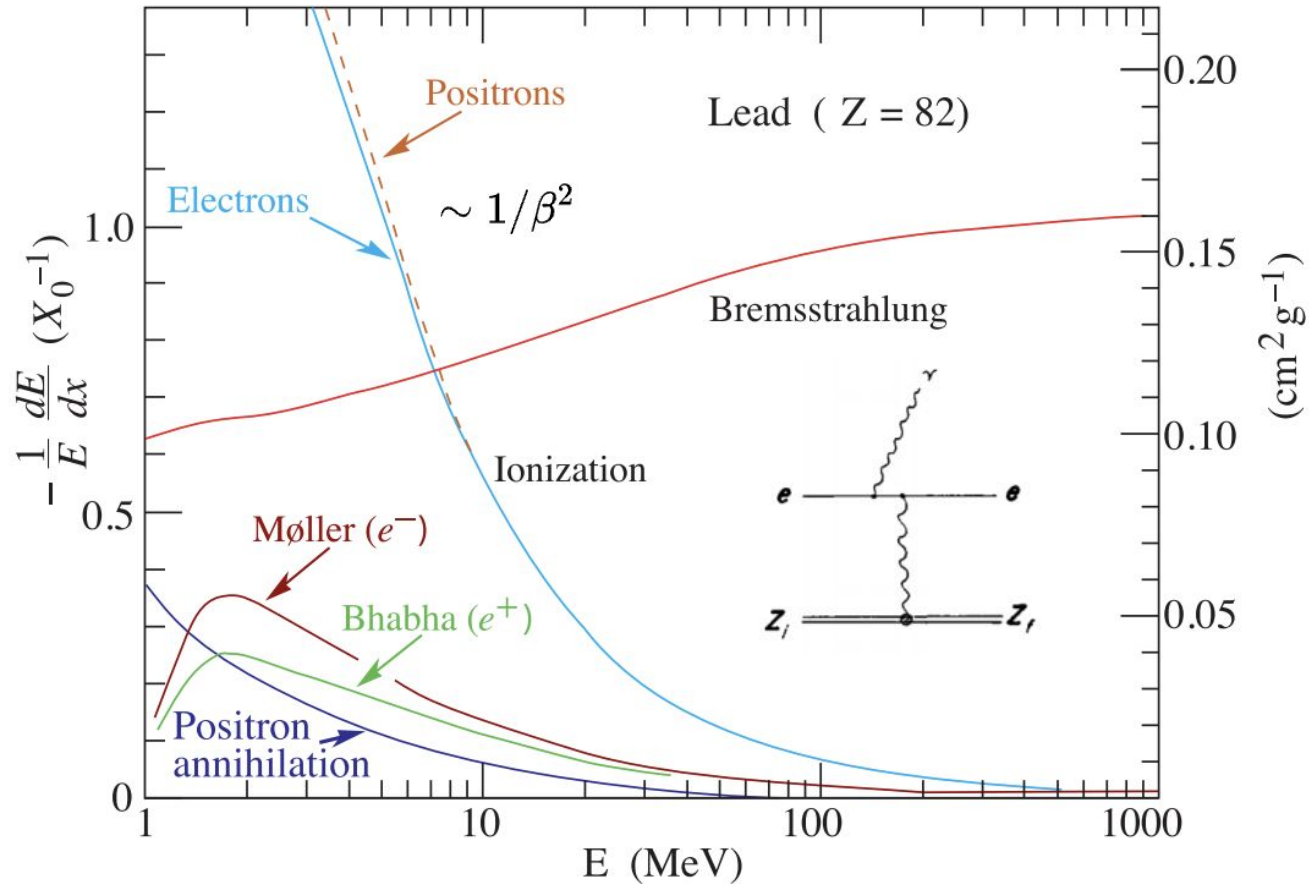
Non-linearity can still be caused by, e.g., shower leakage, variation of response with depth, saturation of electronics etc...

- Hadronic calorimeters are intrinsically non-linear...

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

Electrons: fractional energy loss per radiation length

[rpp2025-rev-passage-particles-matter](#)



Radiation length (X_0)

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

- On average an electron has $1/e$ of original energy after one X_0
- Approximate material dependence:

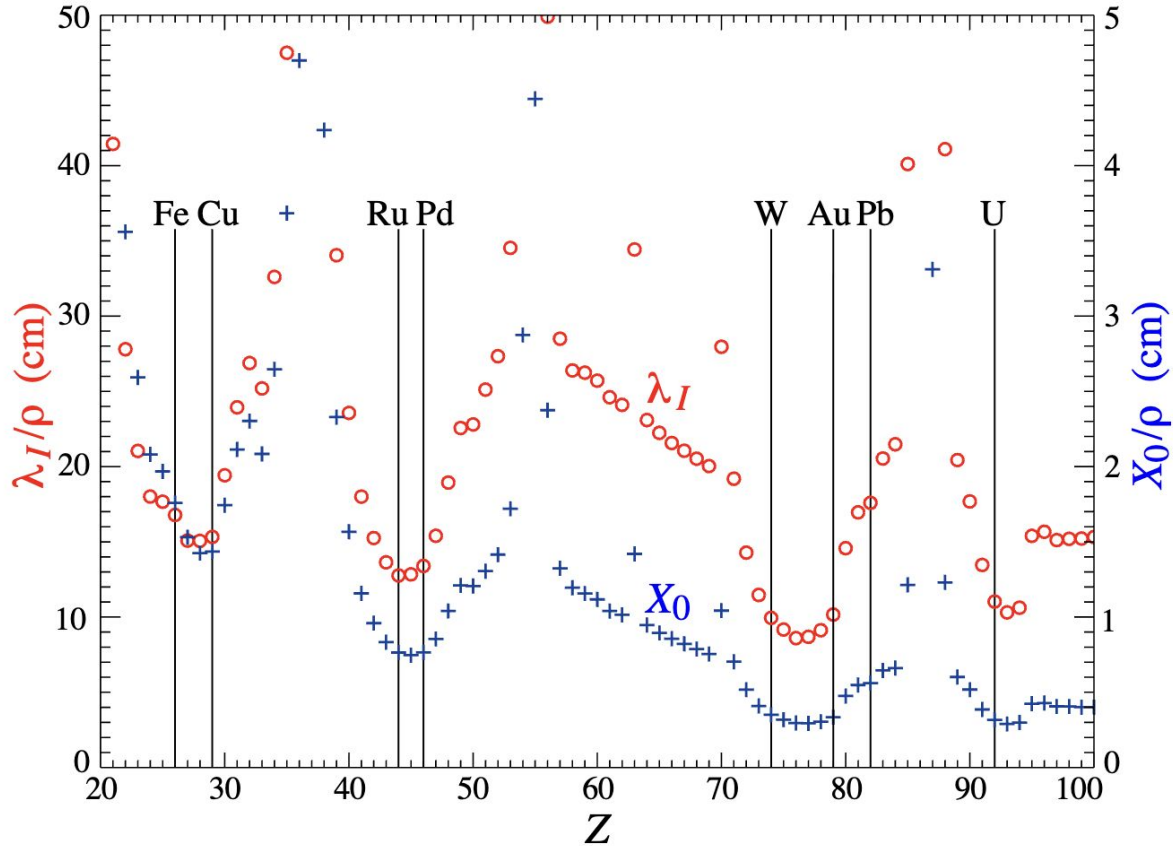
$$X_0 \approx C \frac{A}{Z^2} \quad C = 180 \text{ g/cm}^2$$

- If we express material thickness in X_0 then the radiation loss is independent of material.
- What material should we use for calorimeters?

A is the mass number (of nucleons) and Z is the atomic number (of protons).

Material dependence of X_0/ρ

[rpp2025-rev-particle-detectors-accel](#)



✓ Note the convenient units

The critical energy (E_c),

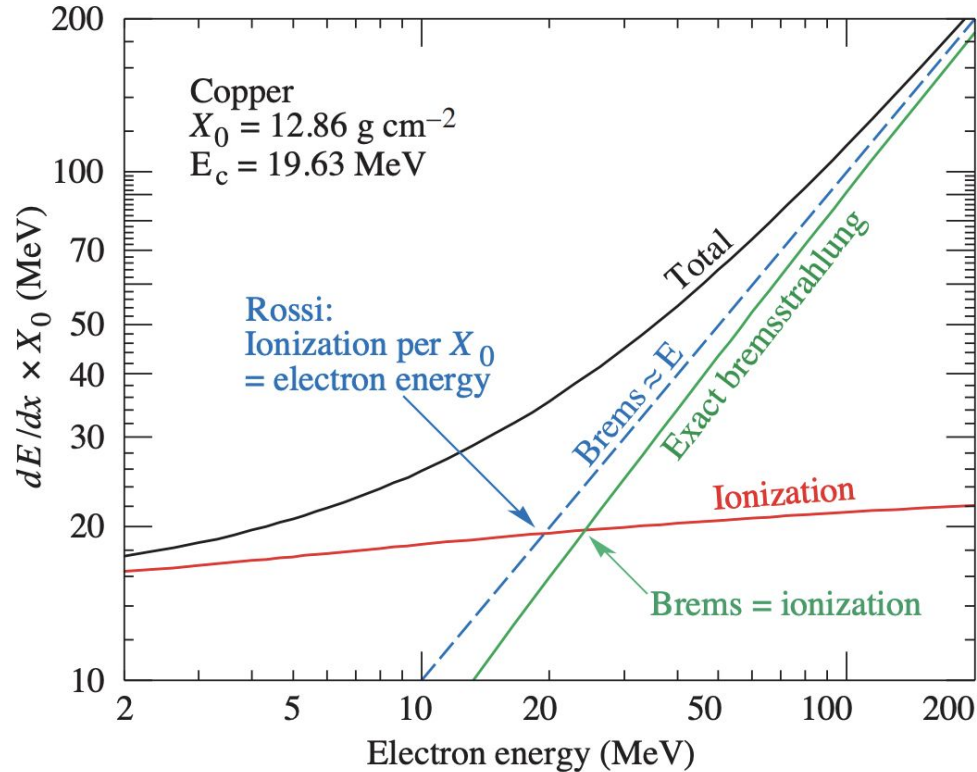
at which Brem. and ionisation losses are equal.

[rpp2025-rev-passage-particles-matter](#)

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

$$\text{Brem} \sim Z^2$$

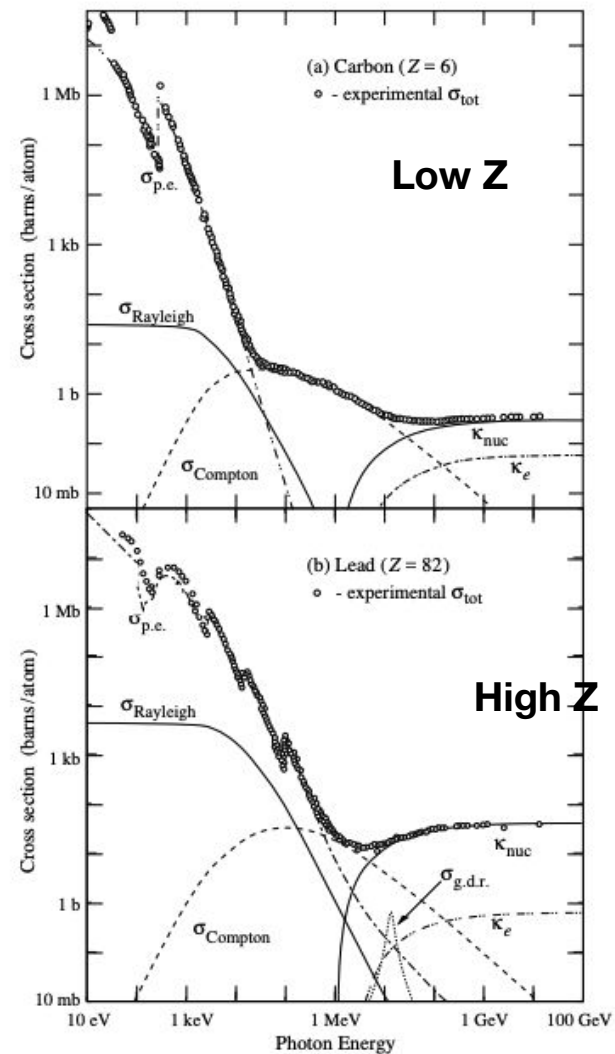
$$E_c \approx \frac{600 \text{ MeV}}{Z}$$



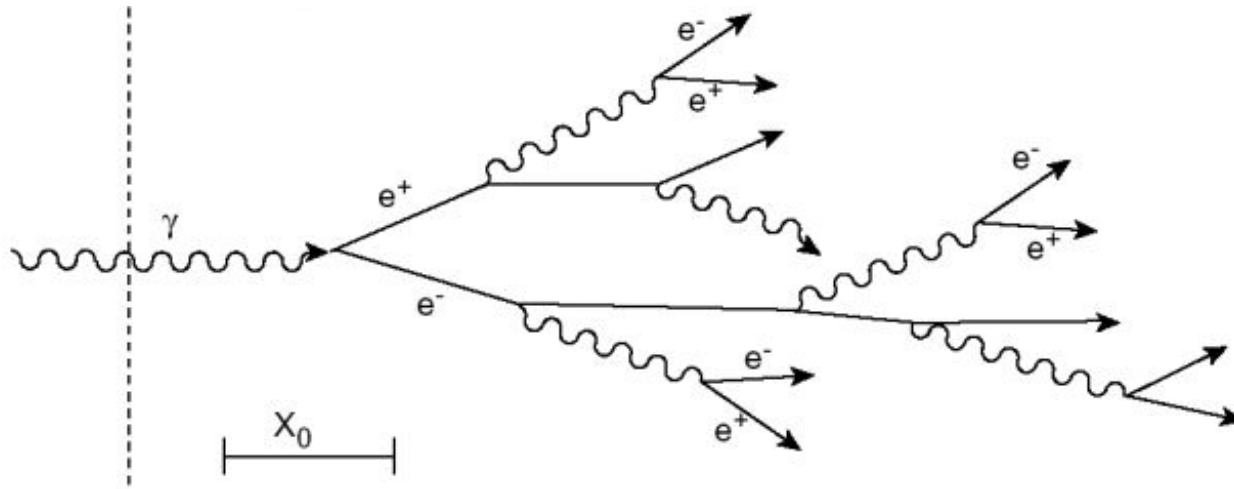
Photon interactions

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

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



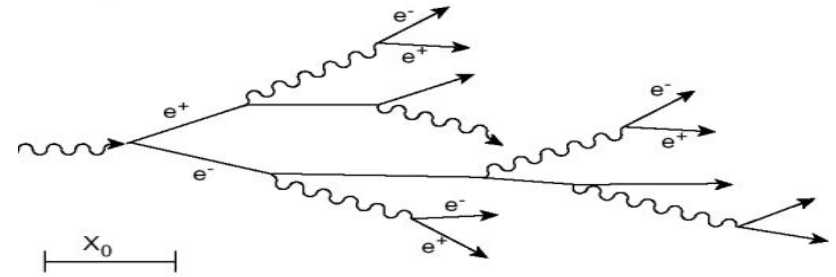
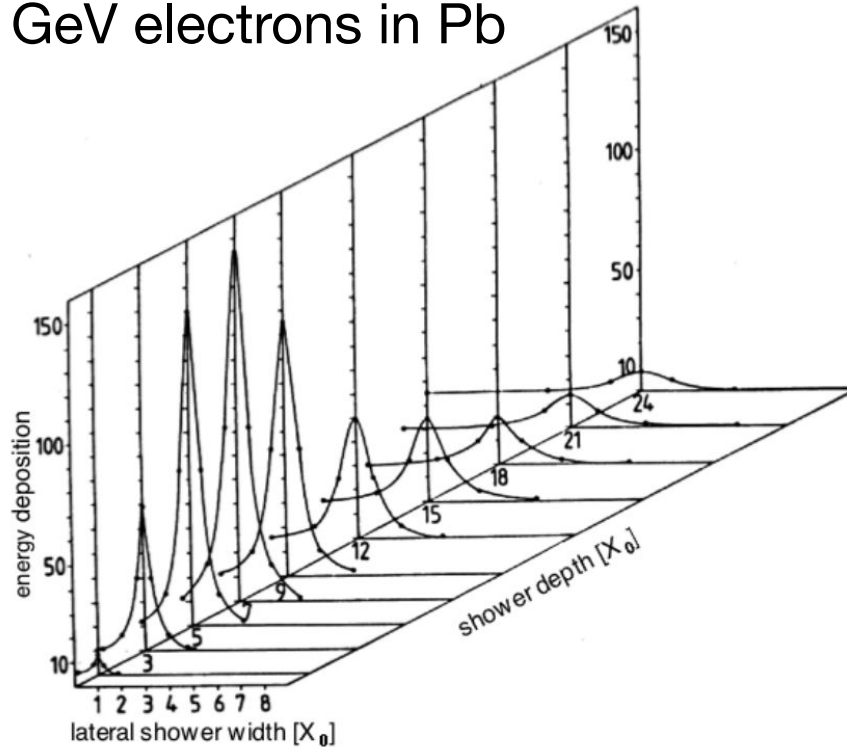
Electromagnetic shower



- 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

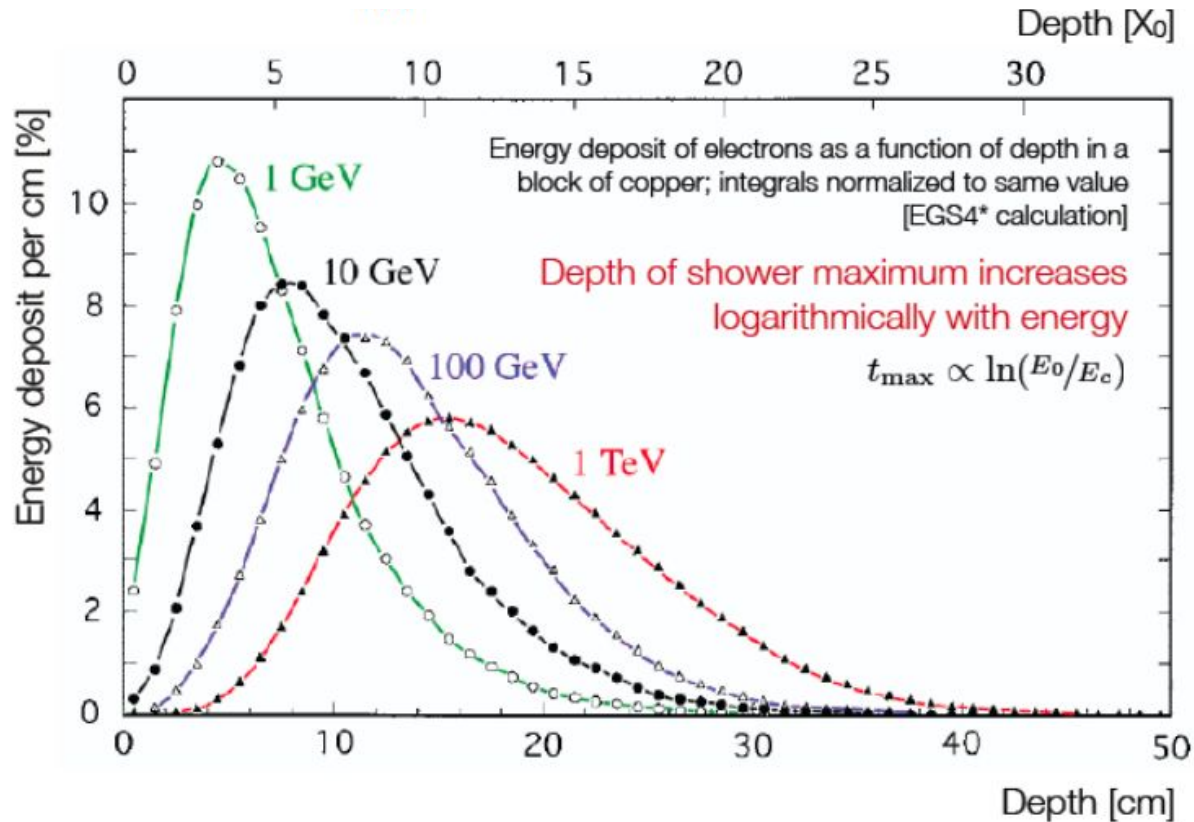
6 GeV electrons in Pb



Key characteristics:

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

Depth of shower max

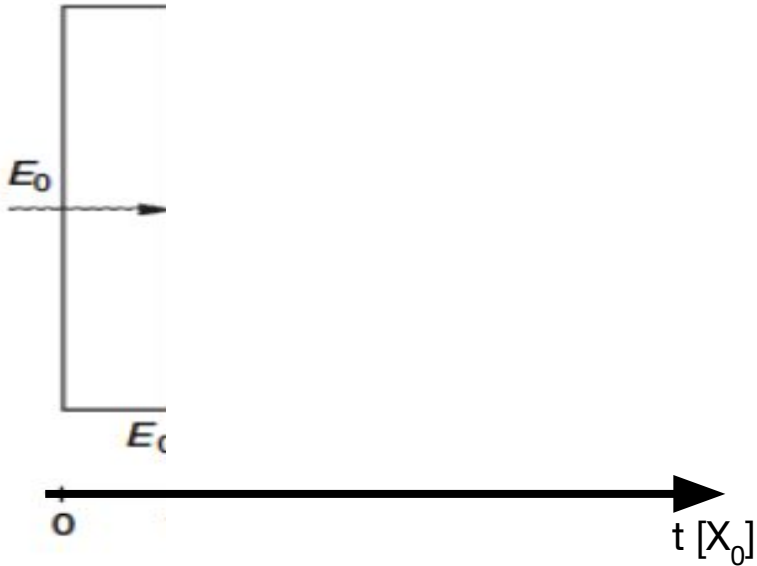


Depth only has $\log(E)$ scaling \rightarrow can build compact calorimeters!

Simple shower model

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

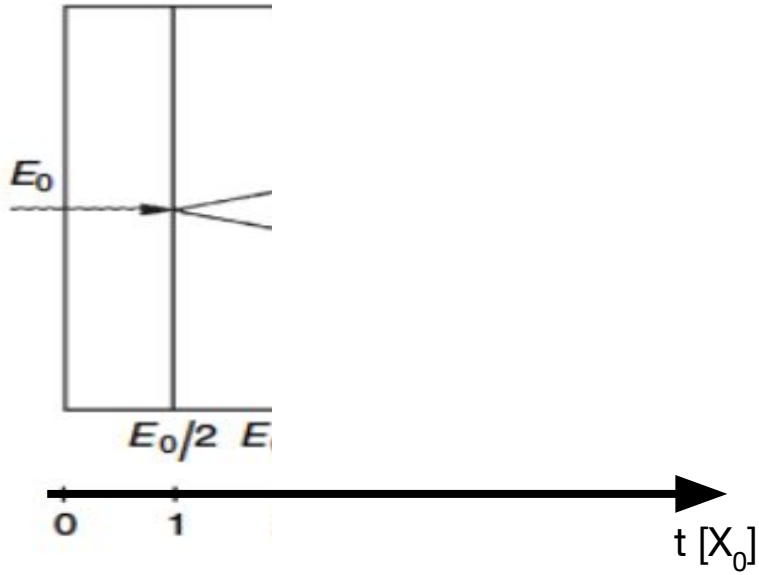
Shower stops when $E < E_c$



Simple shower model

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

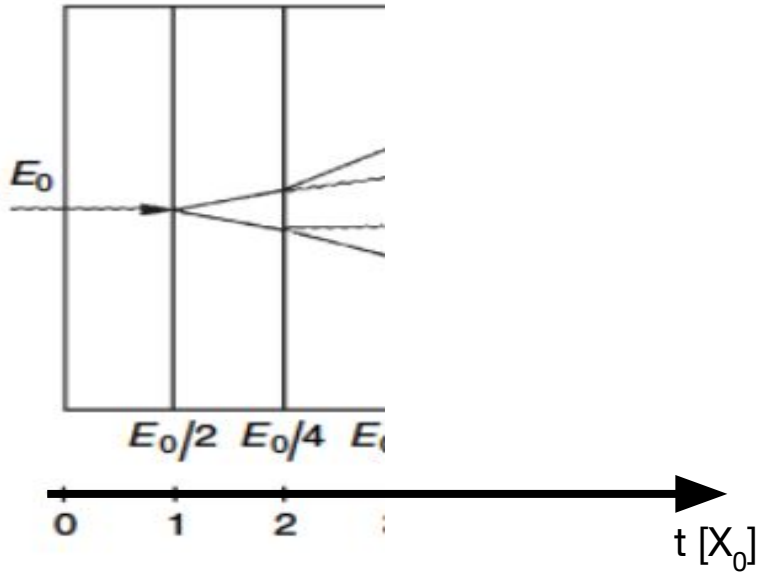
Shower stops when $E < E_c$



Simple shower model

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

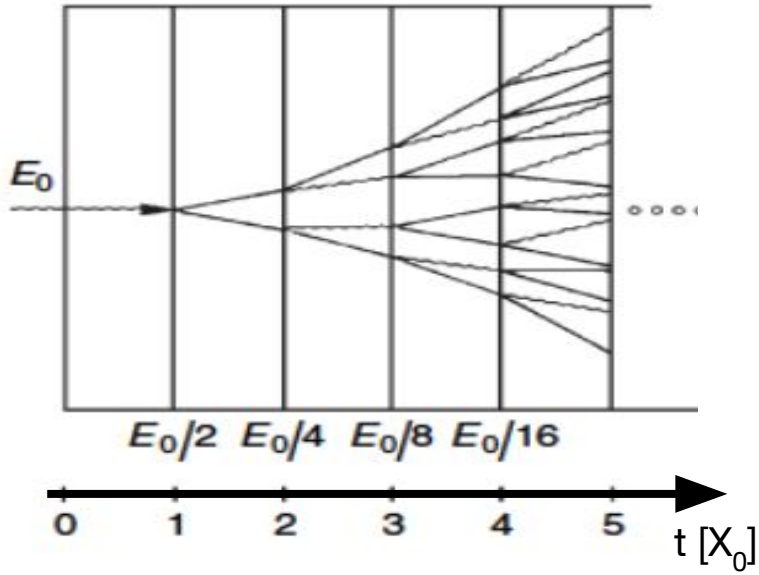
Shower stops when $E < E_c$



Simple shower model

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

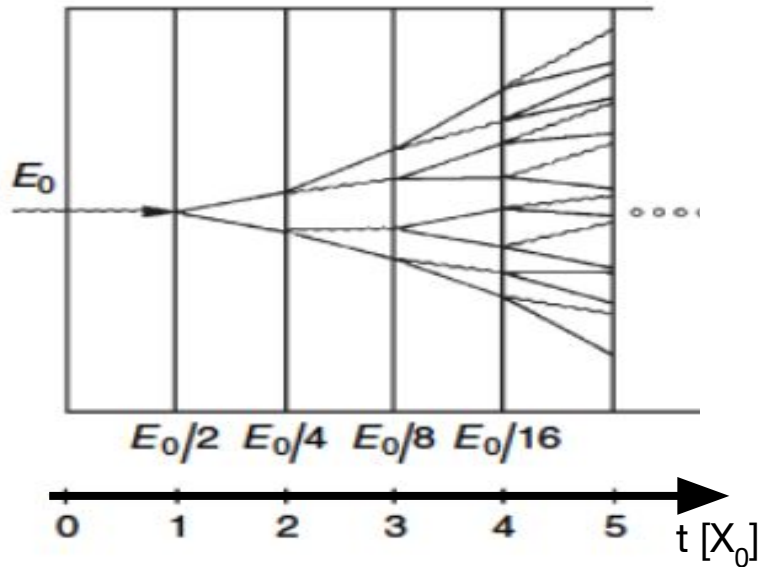
Shower stops when $E < E_c$



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.

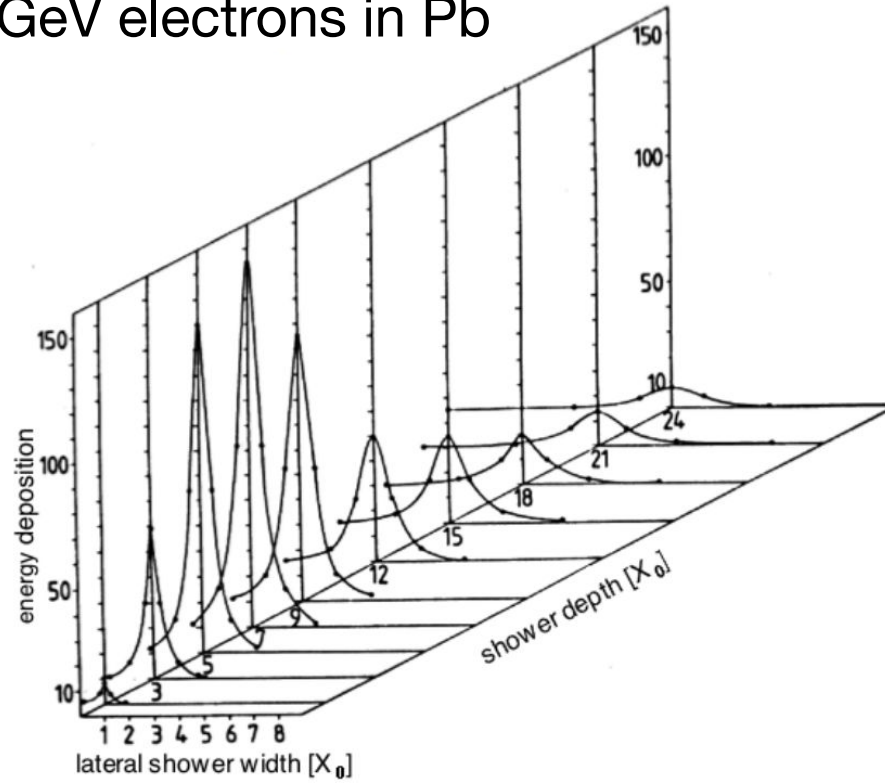
$$\langle \theta^2 \rangle \sim (m/E)^2$$

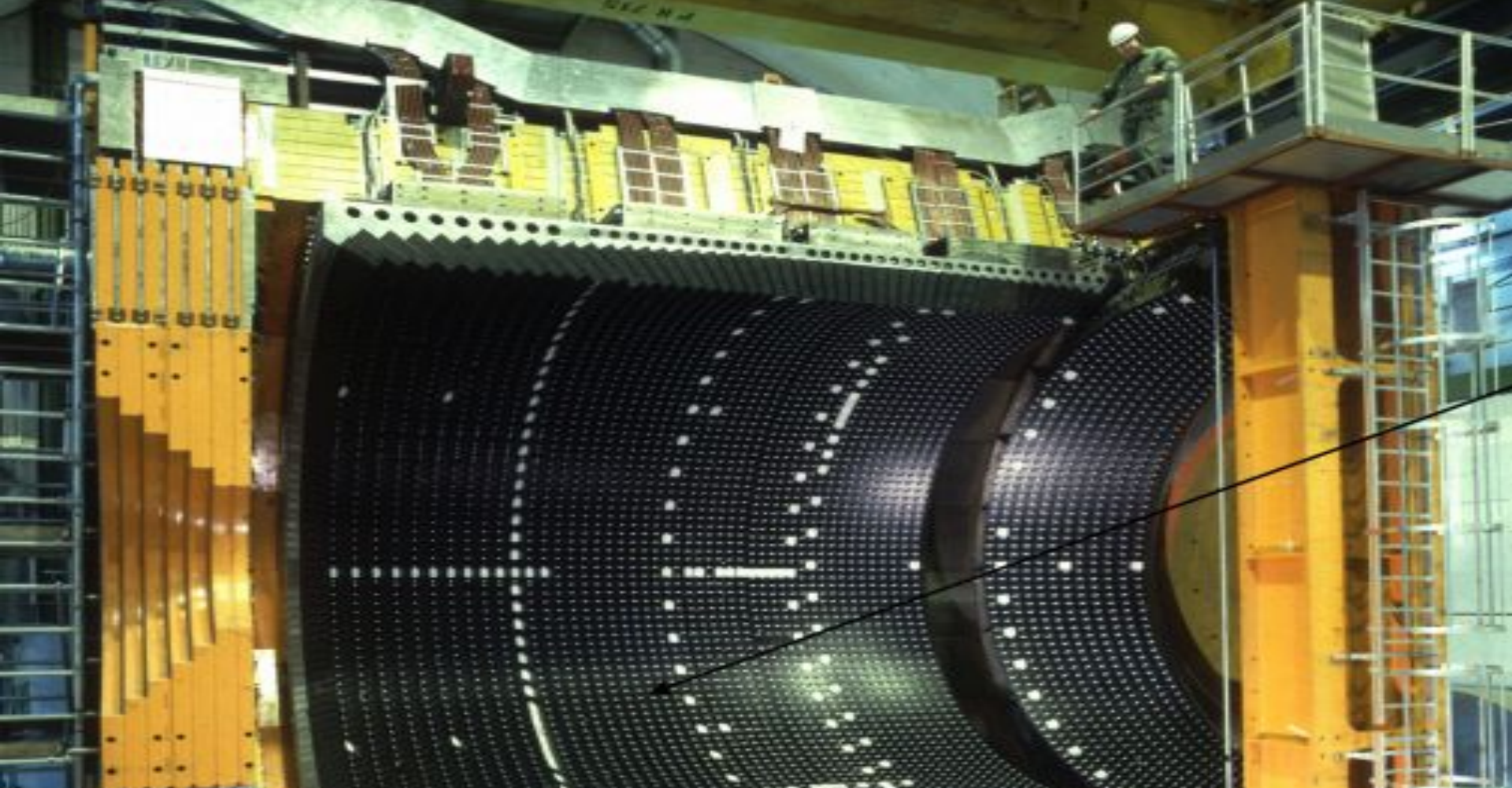
- Multiple coulomb scattering [Mollier theory] of low energy electrons dominates lateral spread.
- Characteristic Mollier radius

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

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

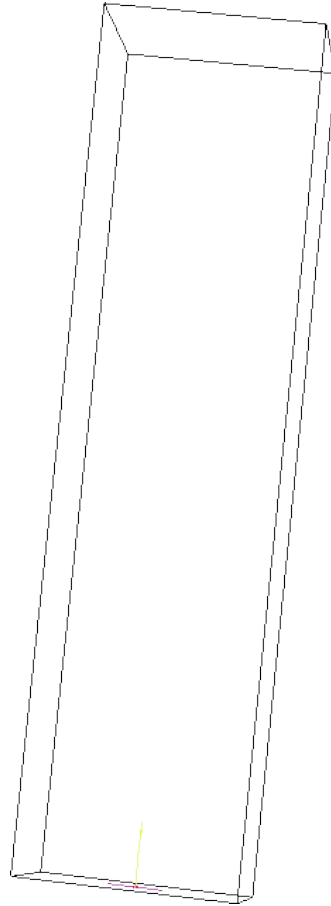
6 GeV electrons in Pb





OPAL experiment lead glass

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

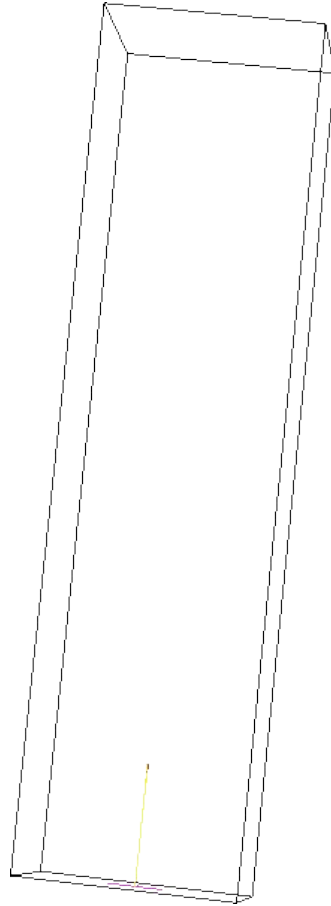


1 GeV e^-

37 x 10 x 10 cm

OPAL experiment lead glass

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

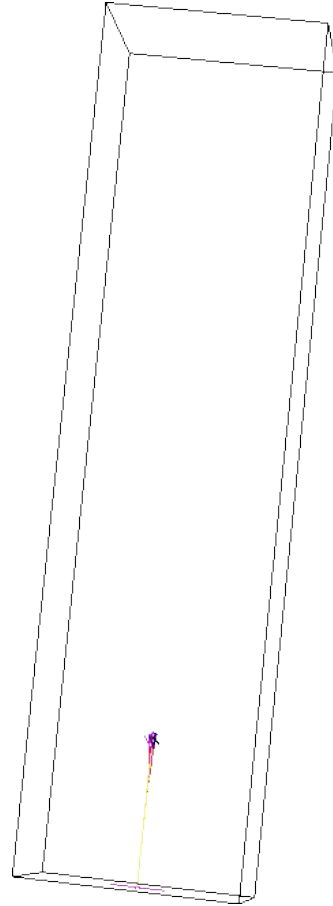


10 GeV e^-

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

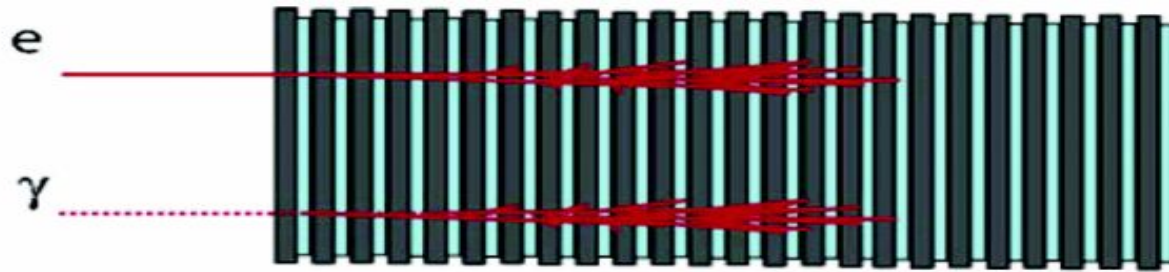
Critical energy $E_c \approx \frac{600 \text{ MeV}}{Z}$

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

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

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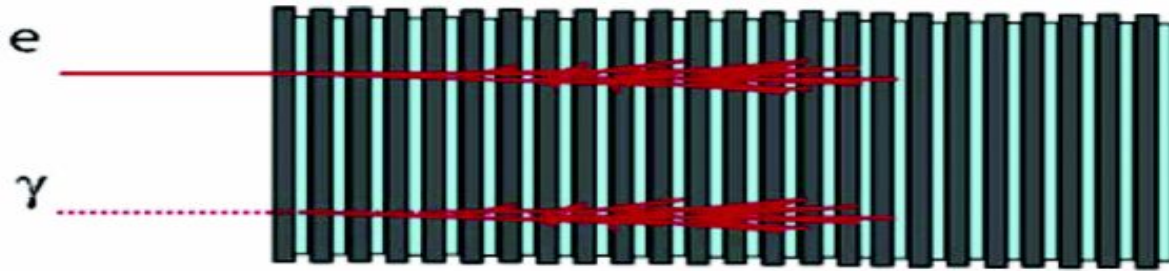
Sampling



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.

Homogenous



- 👍 Good resolution because all shower particles seen
- 👍 Uniform response \rightarrow linearity
- 👎 Expensive and limited segmentation

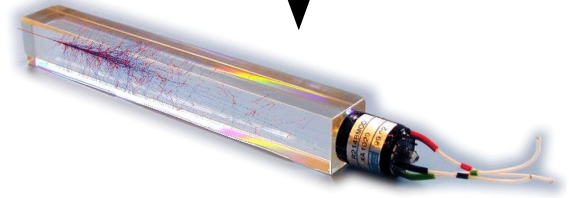
Special use cases e.g.

1. “medium energy” ECAL-only B-factory experiments,
2. CMS and ultimate $H \rightarrow \gamma\gamma$ mass resolution

Active material

- Charged based
 - Semiconductors
 - Liquid Nobel gases
- Light based
 - Cerenkov
 - Inorganic scintillator
 - Organic scintillator (plastic, liquid, or crystal)

PbWO_4



EM energy resolution

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

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 $E \sim N$, $\sigma \sim \sqrt{N} \sim \sqrt{E}$

N: noise term

E.g., readout electronics

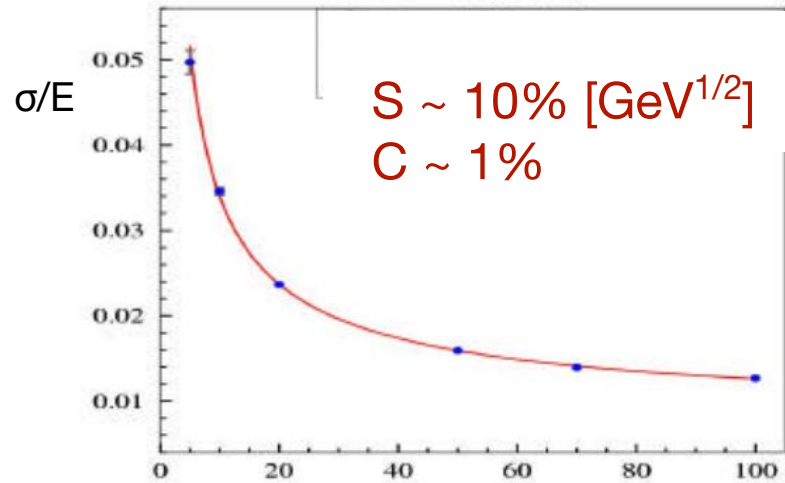
C: constant term

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



E [GeV]

Examples

[rpp2025-rev-particle-detectors-accel](#)

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

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (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)	$16\text{--}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	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)	$20\text{--}30X_0$	$18\%/\sqrt{E}$	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)	$20\text{--}30X_0$	$12\%/\sqrt{E} \oplus 1\%$	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

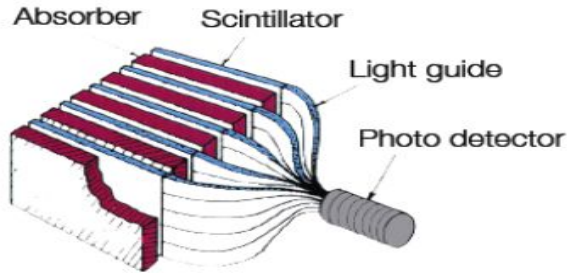
Homogeneous
Sampling

$\sim [\text{Few \%}]/\sqrt{E}$

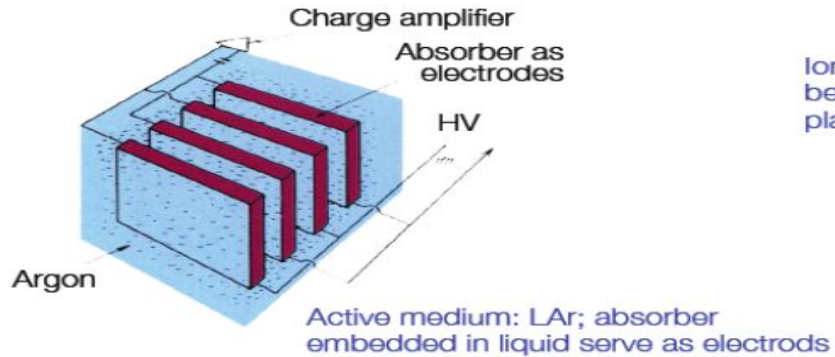
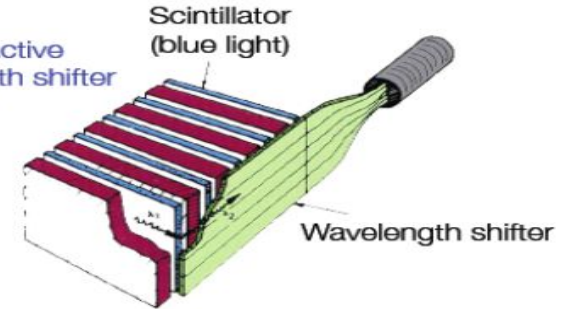
$\sim [10 \%]/\sqrt{E}$

Sampling calorimeter designs

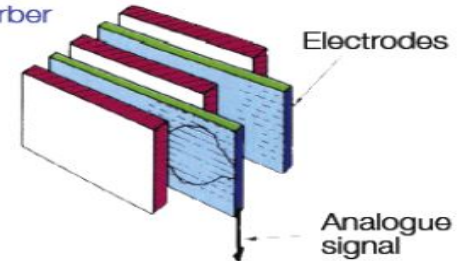
Scintillators as active layer;
signal readout via photo multipliers



Scintillators as active
layer; wave length shifter
to convert light

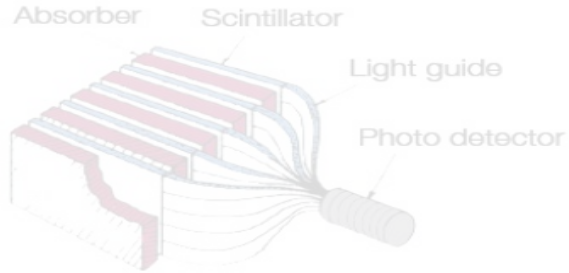


Ionization chambers
between absorber
plates

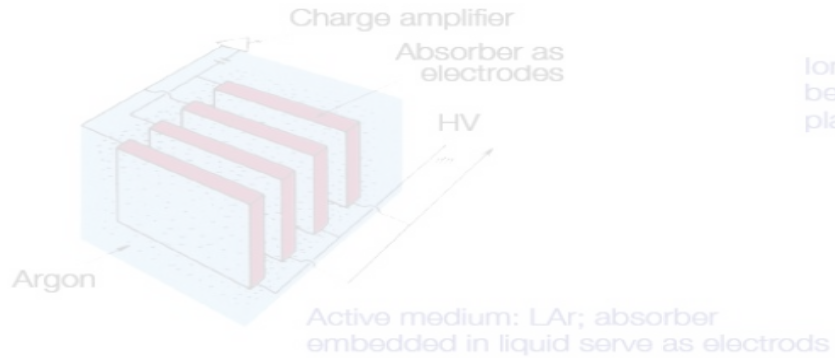
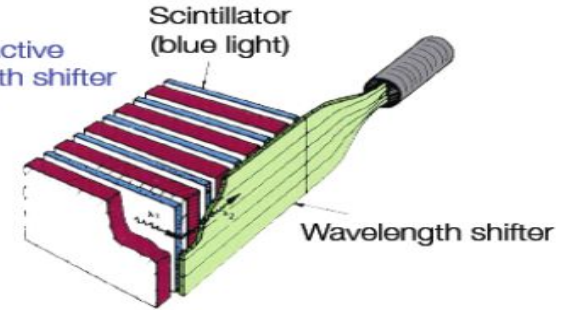


Sampling calorimeter designs

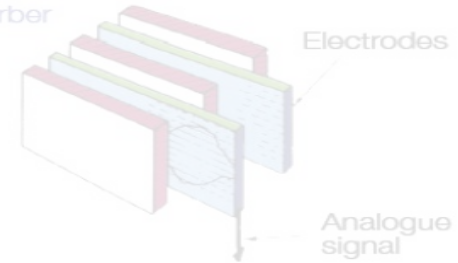
Scintillators as active layer;
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Scintillators as active
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Ionization chambers
between absorber
plates



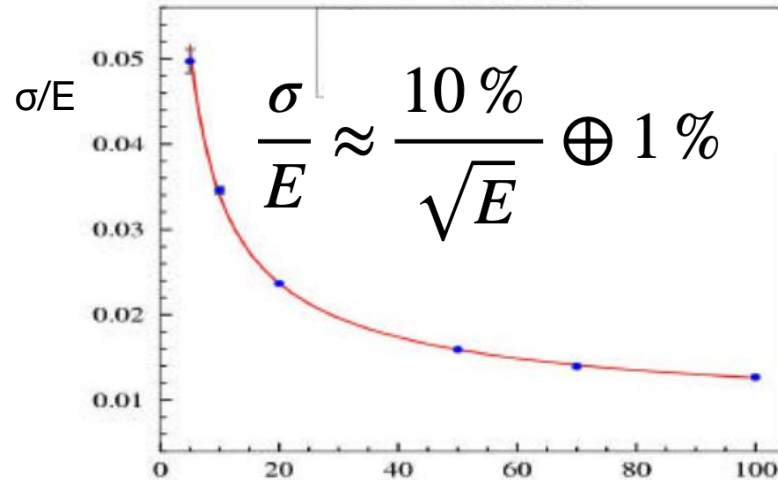
LHCb ECAL



“Shashlik” design alternating Pb absorber and scintillator

👍 Fast response

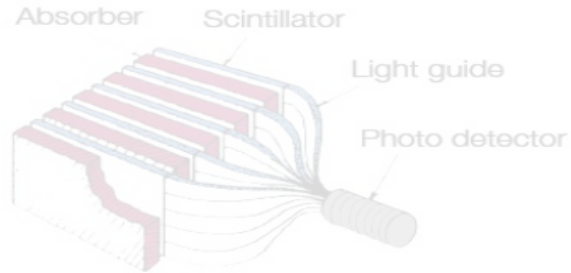
👍 Cost effective solution



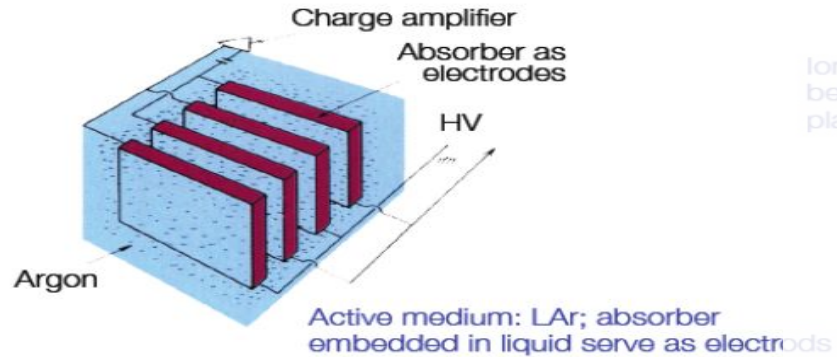
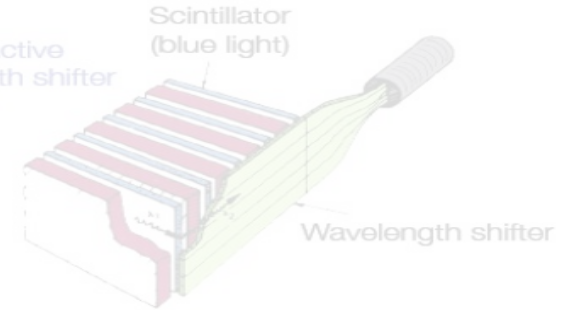
E [GeV]

Sampling calorimeter designs

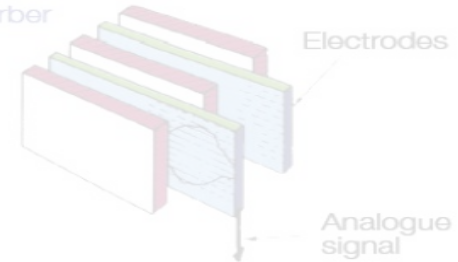
Scintillators as active layer;
signal readout via photo multipliers



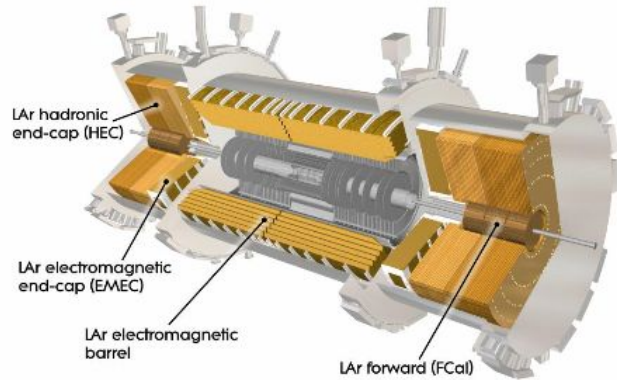
Scintillators as active layer; wavelength shifter to convert light



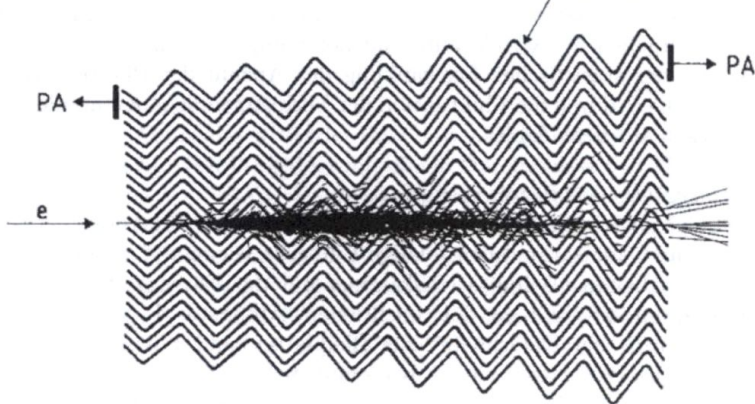
Ionization chambers between absorber plates



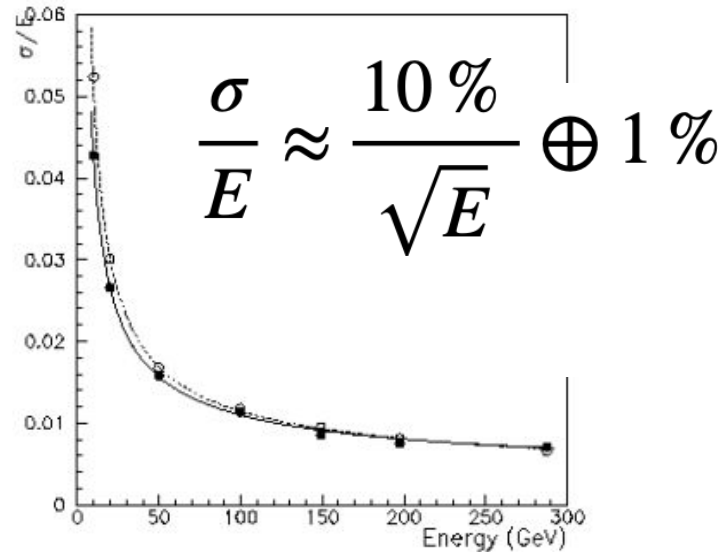
ATLAS Liquid Argon calorimeter



Pb absorber + Cu electrodes



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

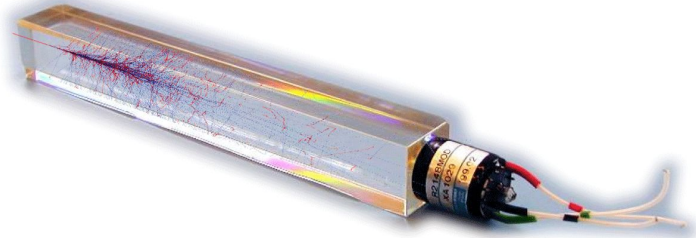
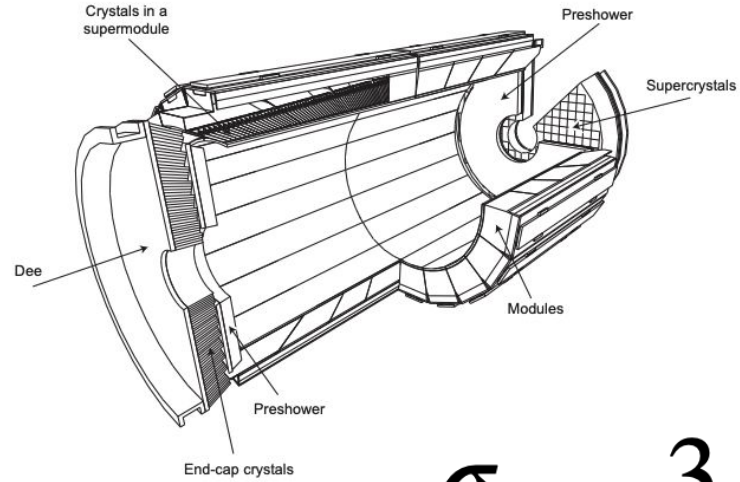
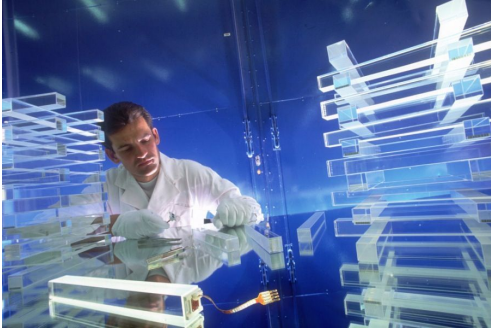


Homogenous calorimeters

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 PbWO₄ ECAL

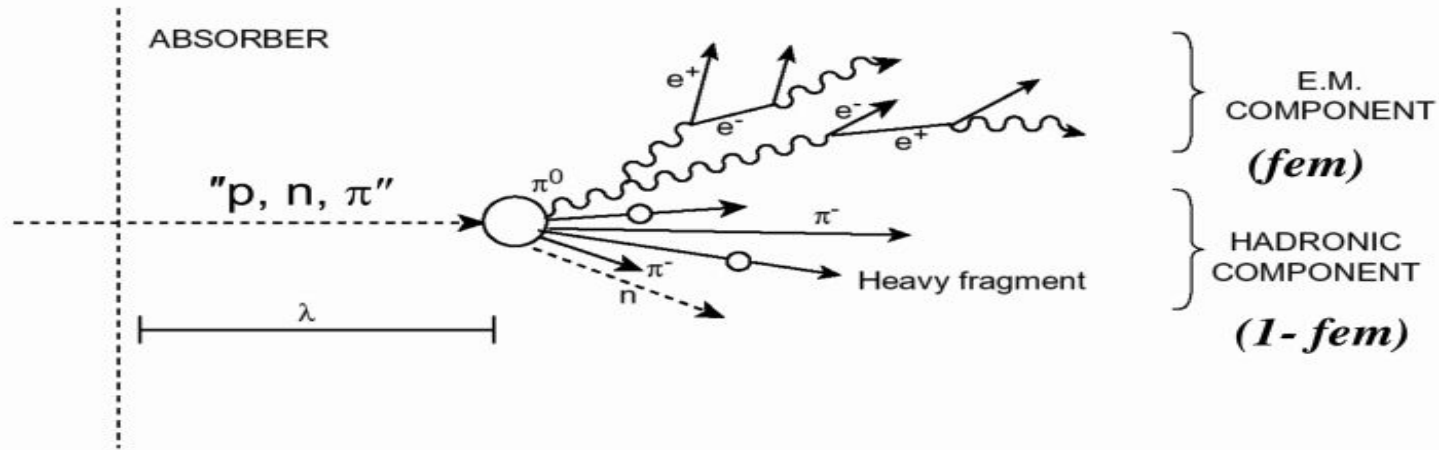


$$\frac{\sigma}{E} \approx \frac{3\%}{\sqrt{E}}$$

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Hadronic showers

- High energy hadrons interact with nuclei to produce secondary hadrons.
- Two distinct components, with very different detector response!



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 interaction length

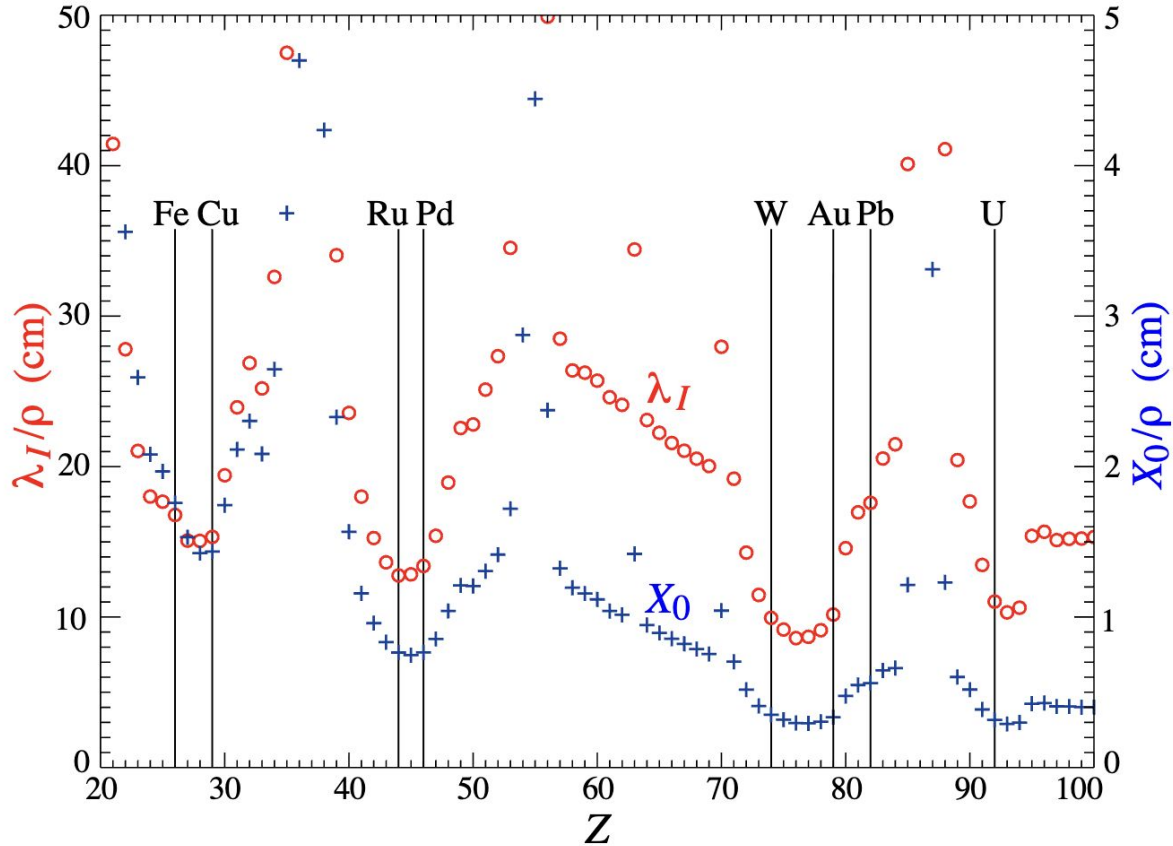
$$\lambda_i \approx \frac{1}{\sigma_{\text{tot}}} \frac{A}{N_A} \sim \left[35 \frac{\text{g}}{\text{cm}^2} \right] A^{1/3}$$

- Typically order of magnitude larger than X_0
- Typically require about 10λ for containment
- Hadronic calorimeters are always of the sampling type

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

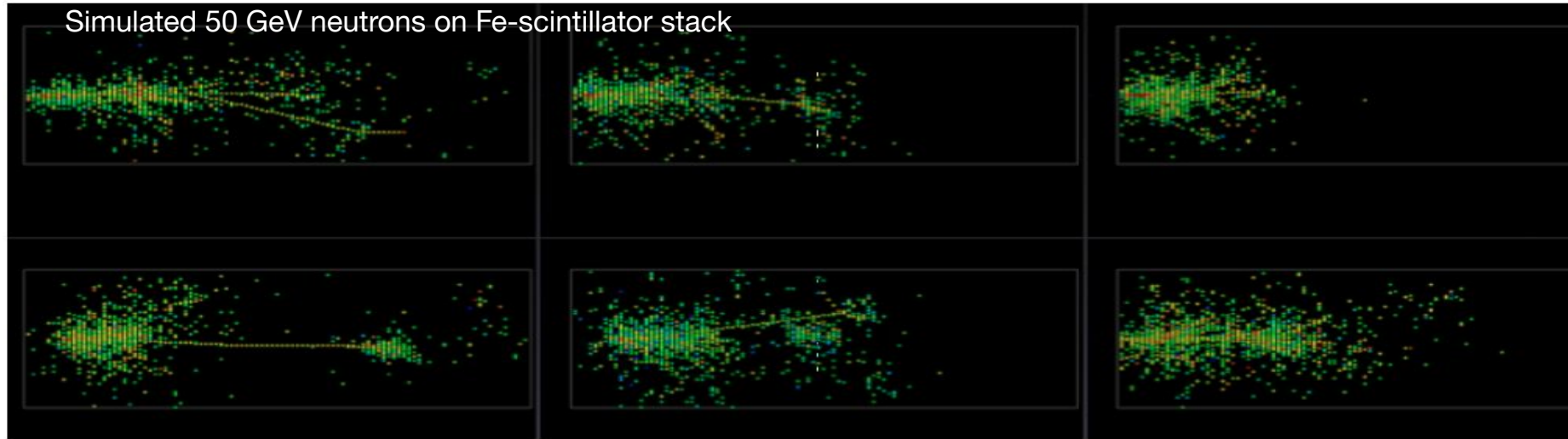
Material dependence

[rpp2025-rev-particle-detectors-accel](#)



✓ Note the convenient units

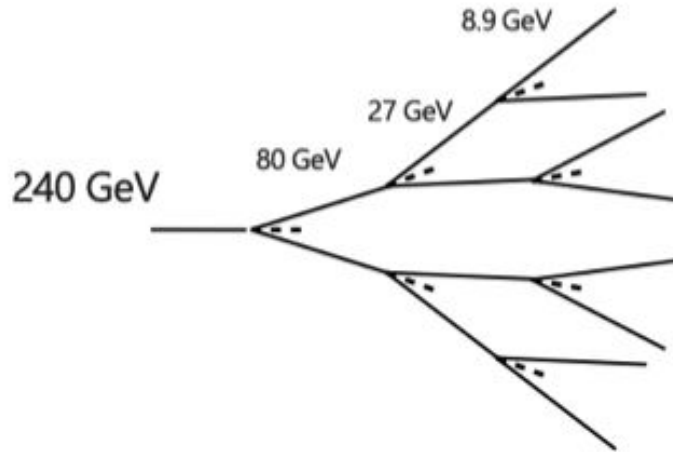
Hadron shower characteristics



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

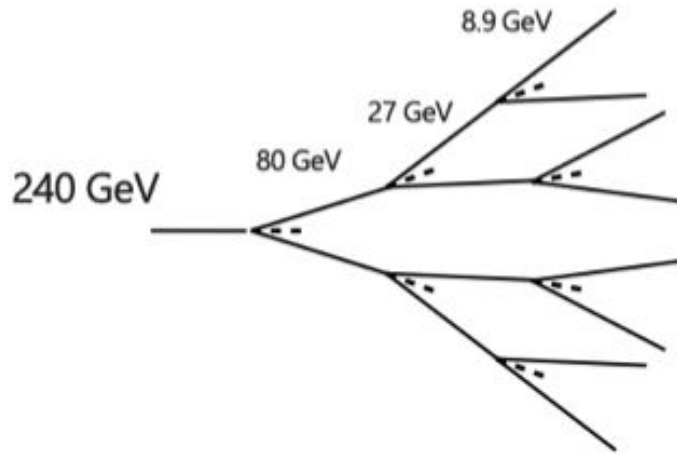
Simple hadronic shower model

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



Simple hadronic shower model

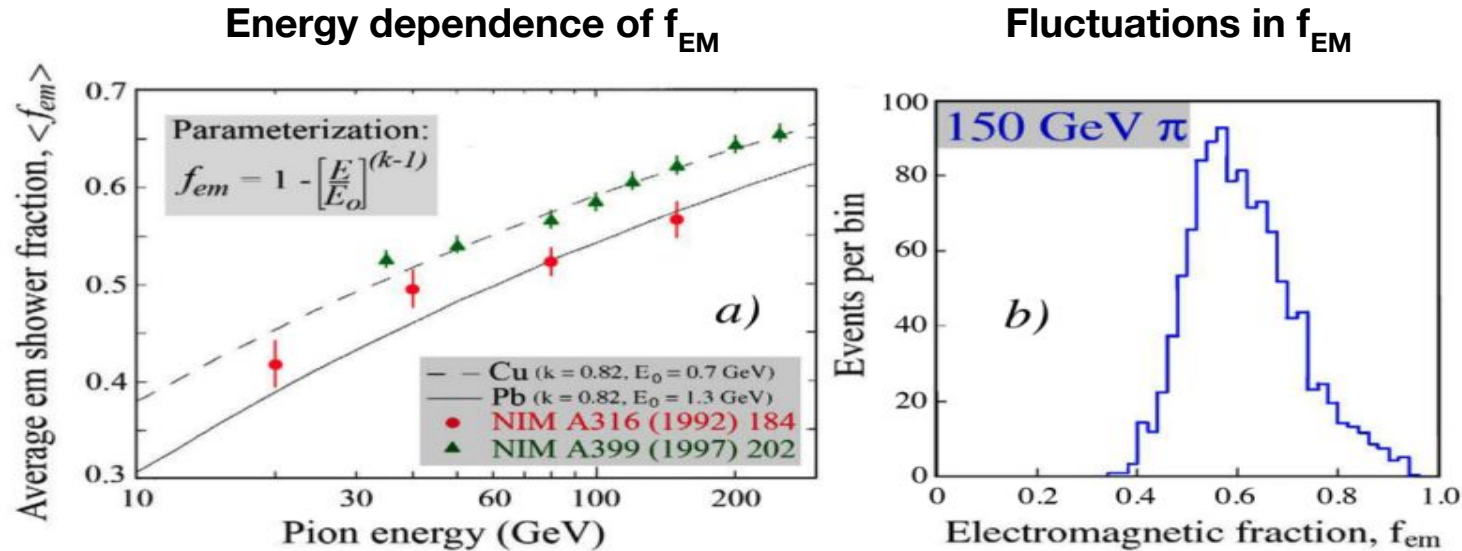
- Shower is series of interactions producing, on average, $1/3 \pi^0$ and $2/3 \pi^\pm$
- Shower stops when $E < m_\pi$



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

$$f_{\text{em}} \propto \ln(E)$$

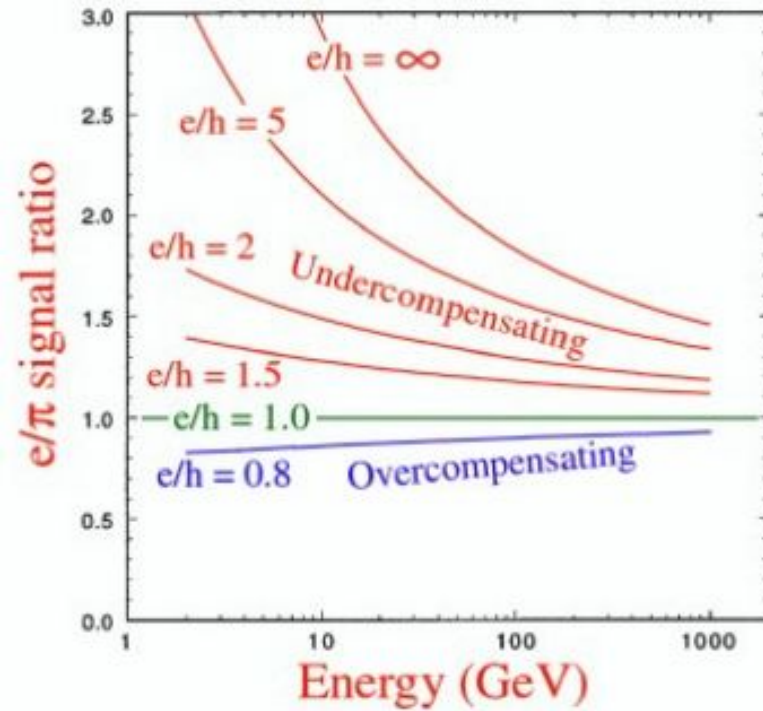
Challenge of hadron calorimeters



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 $e/h \approx 1$]

1. Software based

Pattern recognition and reweighing.

2. Reduce EM component

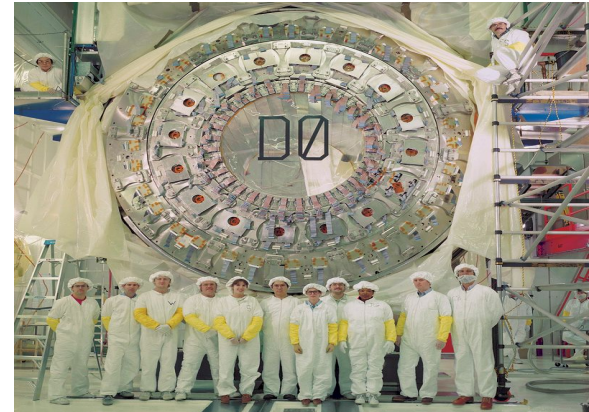
High Z material to filter out photo-electrons.

3. Boost the hadronic response

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

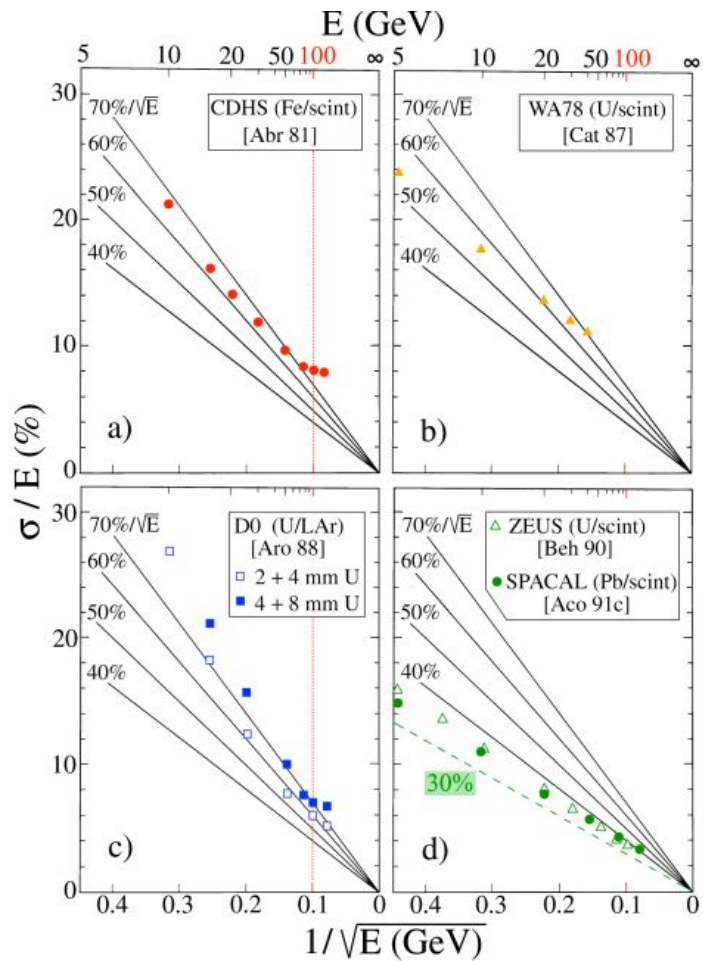
Uranium (nuclear fission triggered by neutrons).

Not compatible with good EM resolution!

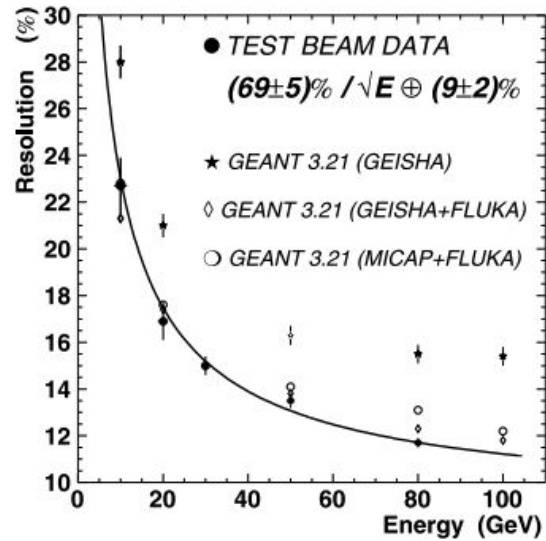
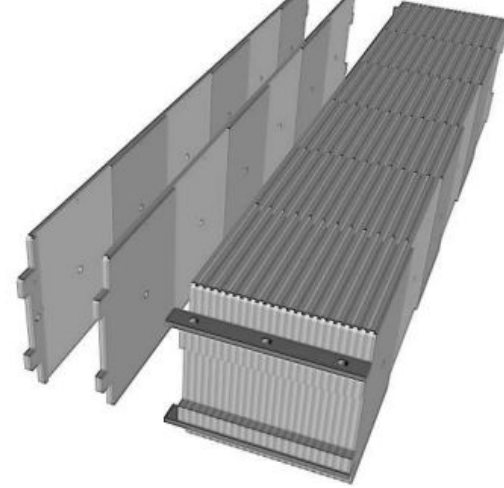
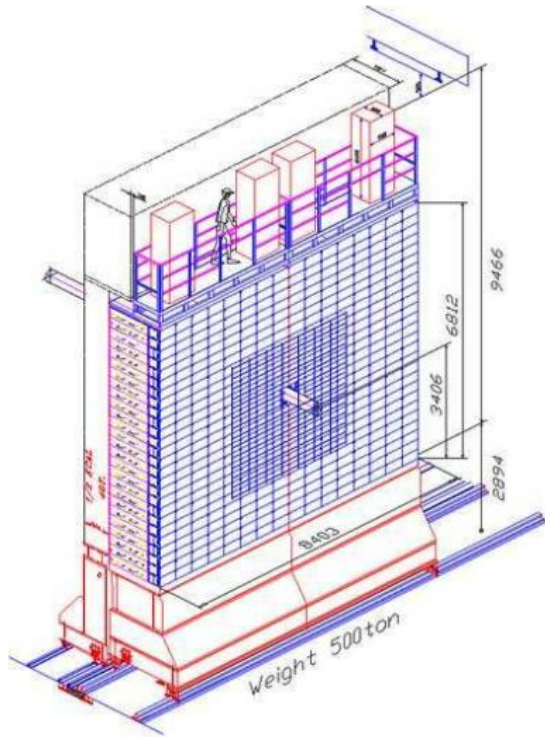


D0 HCAL with U absorber

Some example performances

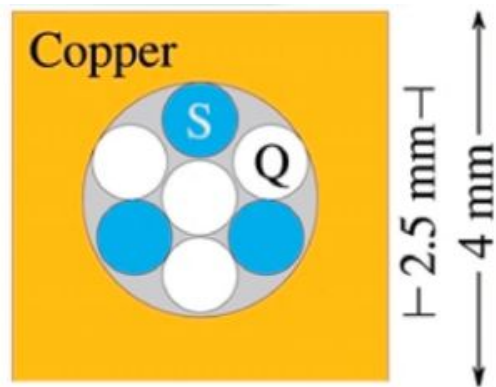


LHCb HCAL (Fe-scintillator)

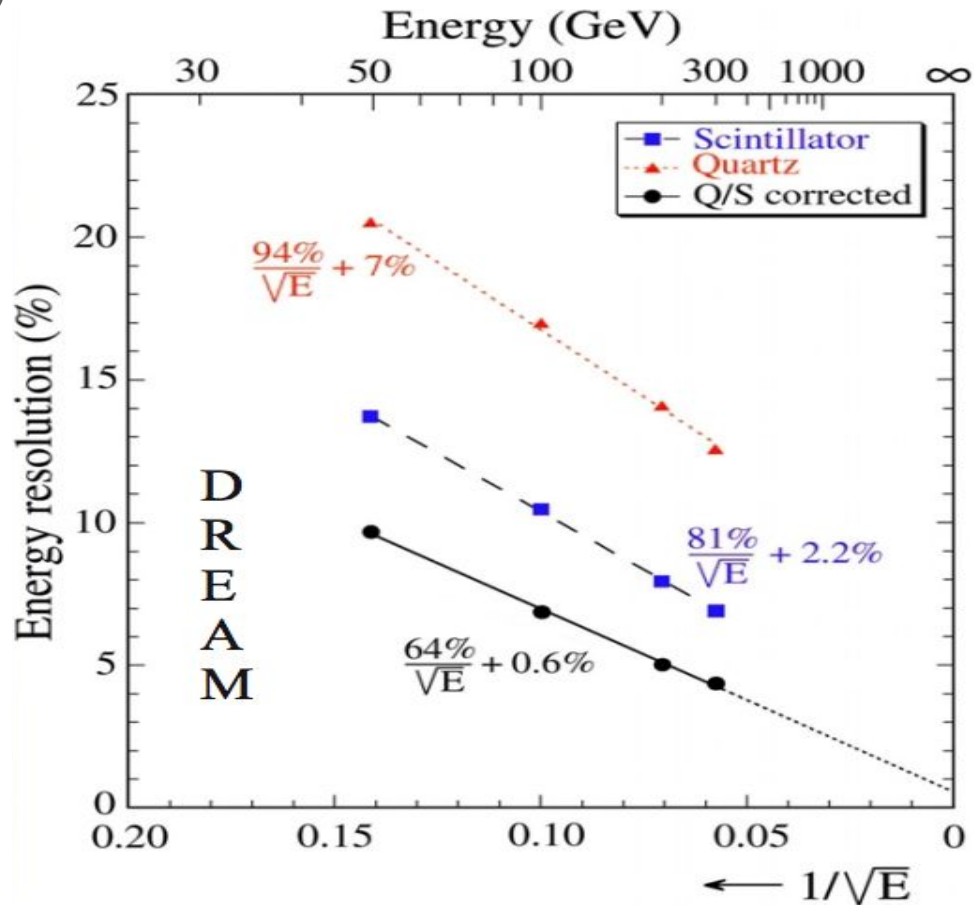


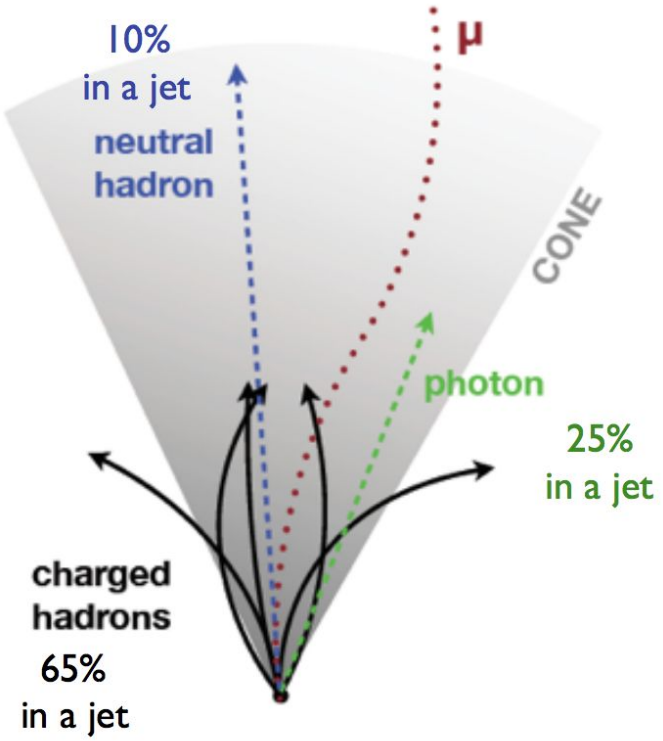
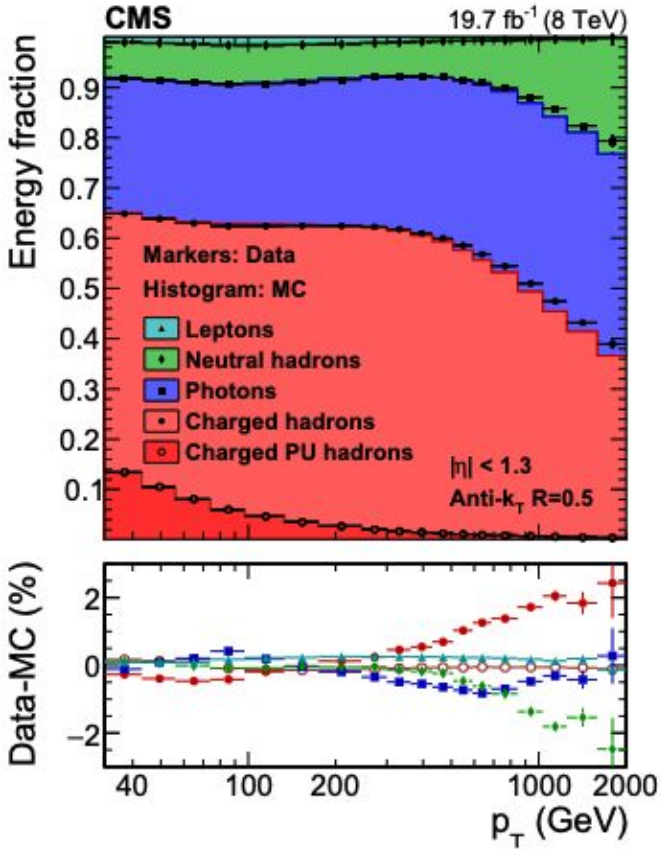
Dual readout R&D (compensation)

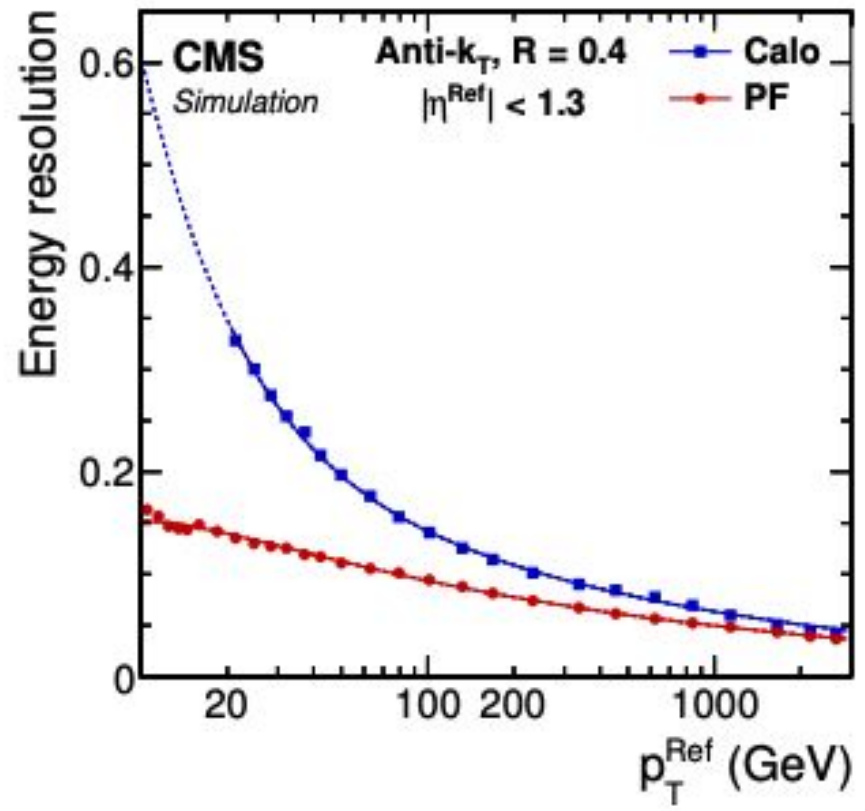
E.g. the original DREAM prototype with scintillating fibres and quartz fibres that have different e/h



Area of ongoing R&D activity







Useful references

Book

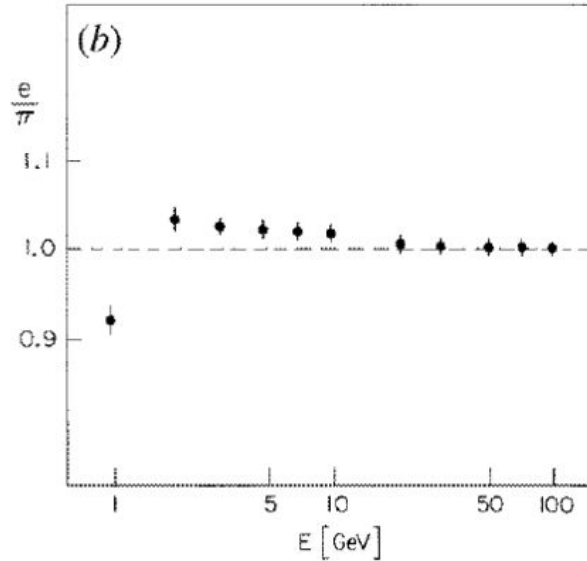
Calorimetry: Energy Measurement in Particle Physics, Richard Wigmans

PDG reviews

Experimental Methods and Colliders		
31	Accelerator physics of colliders (rev.)	PDF
32	High-energy collider parameters	PDF
33	Neutrino beam lines at High-energy proton synchrotrons (rev.)	PDF
34	Passage of particles through matter	PDF
35	Particle detectors at accelerators (rev.)	PDF
36	Particle detectors for non-accelerator physics (rev.)	PDF
37	Radioactivity and radiation protection (rev.)	PDF
38	Commonly used radioactive sources	PDF

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.

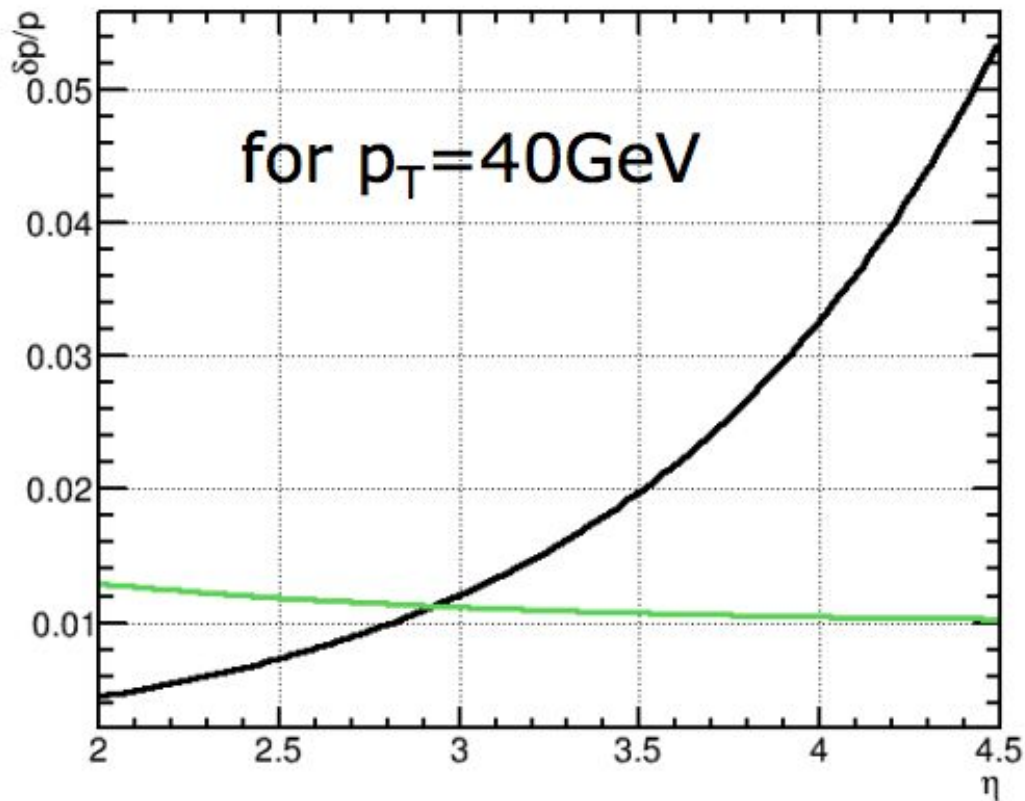
Back of the envelope EM shower characteristics

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

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

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

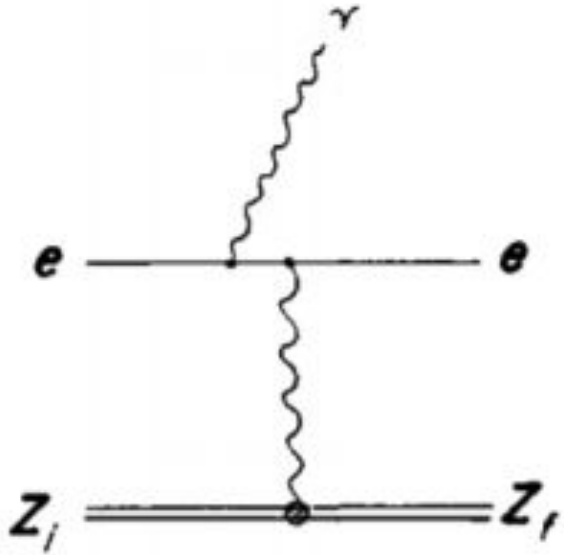
Lateral $R_M \approx \left[7 \frac{\text{g}}{\text{cm}^2} \right] \frac{A}{Z}$



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

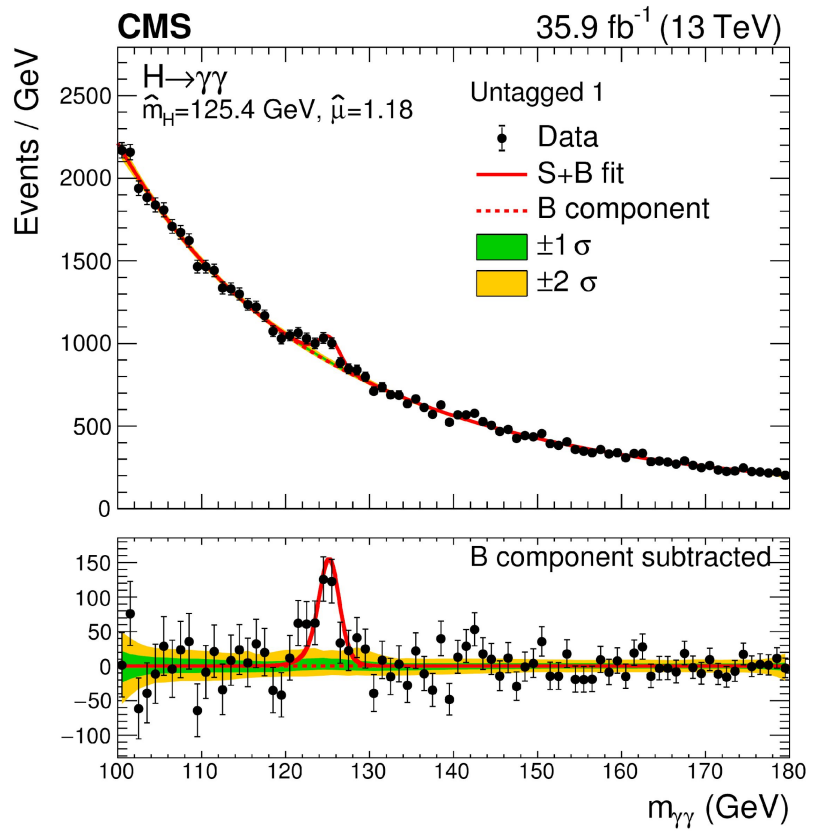
$$\frac{\sigma_E}{E} \sim 1/\sqrt{E}$$

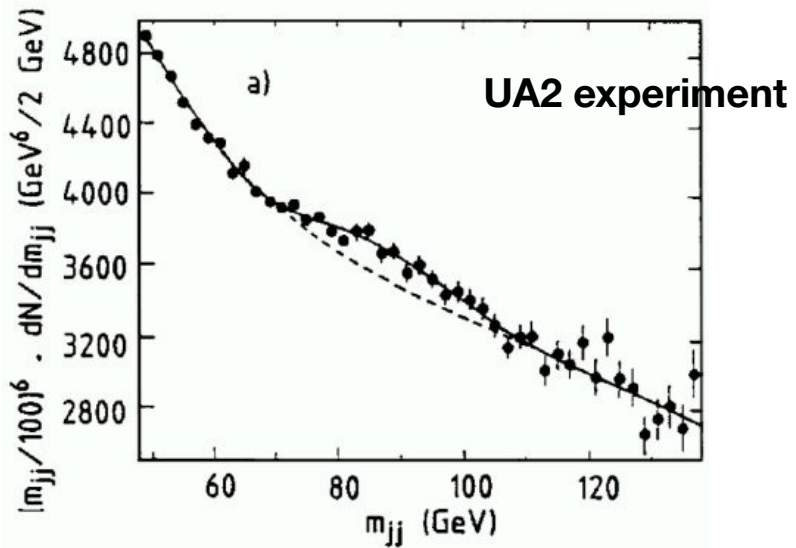
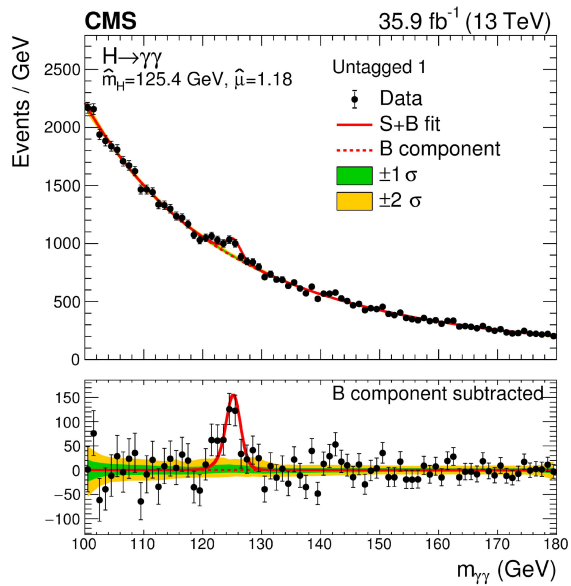
Bremsstrahlung: dominant for electrons at high energy



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

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

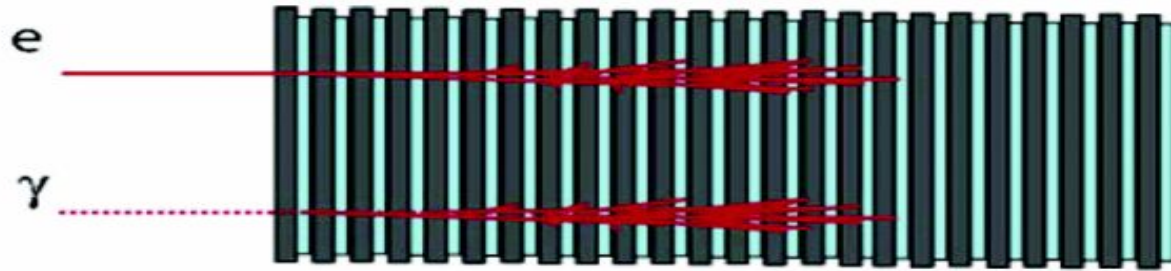




Interplay with stable visible particles

- 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)

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.