Calorimetry

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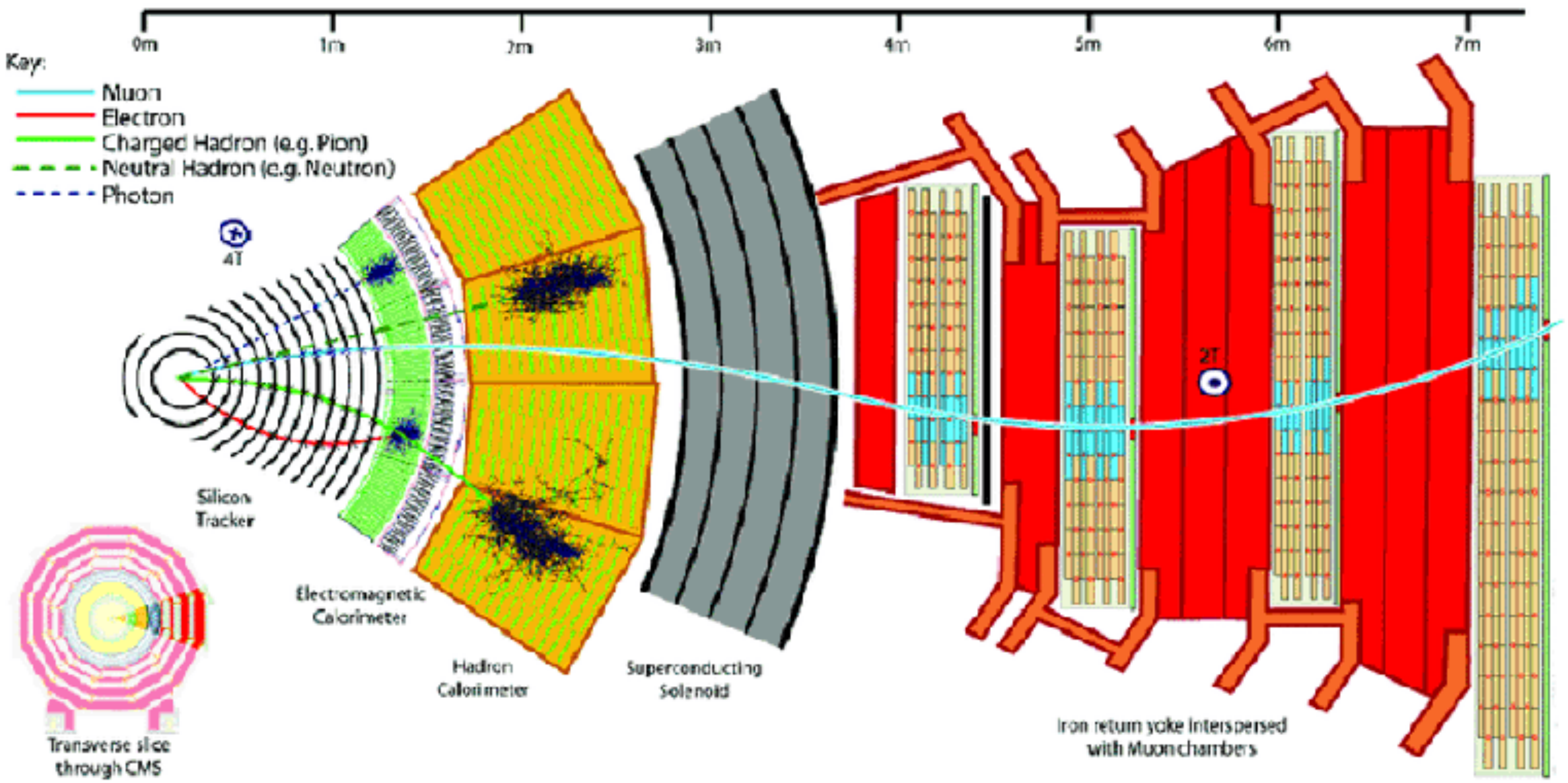
Virtual Warwick week 2020

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

Calorimetry

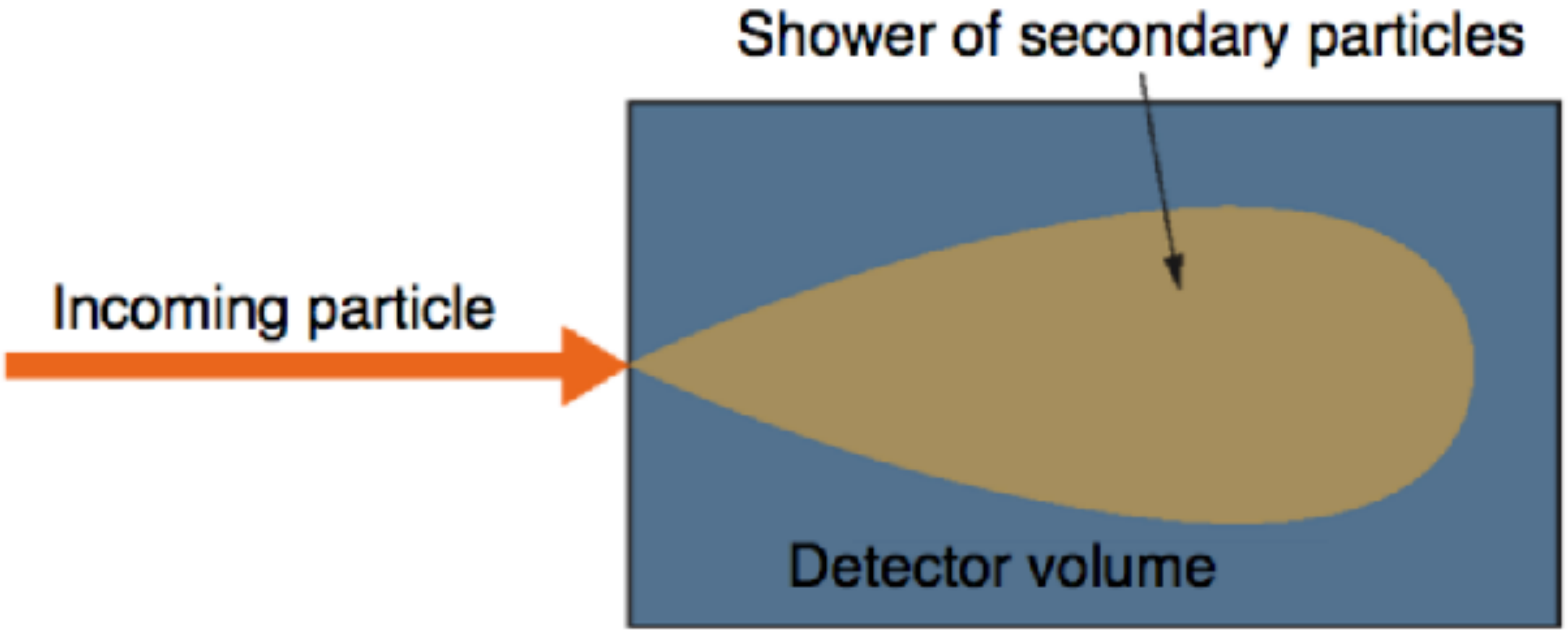
- Wide usage in particle physics, e.g.
    - 4π (or LHCb-like) collider experiments
    - Instrumented targets
    - Shower counters
- Various detection mechanisms
    - Scintillation
    - Ionisation
    - Cerenkov
    - Cryogenics

Typical collider detector schematic



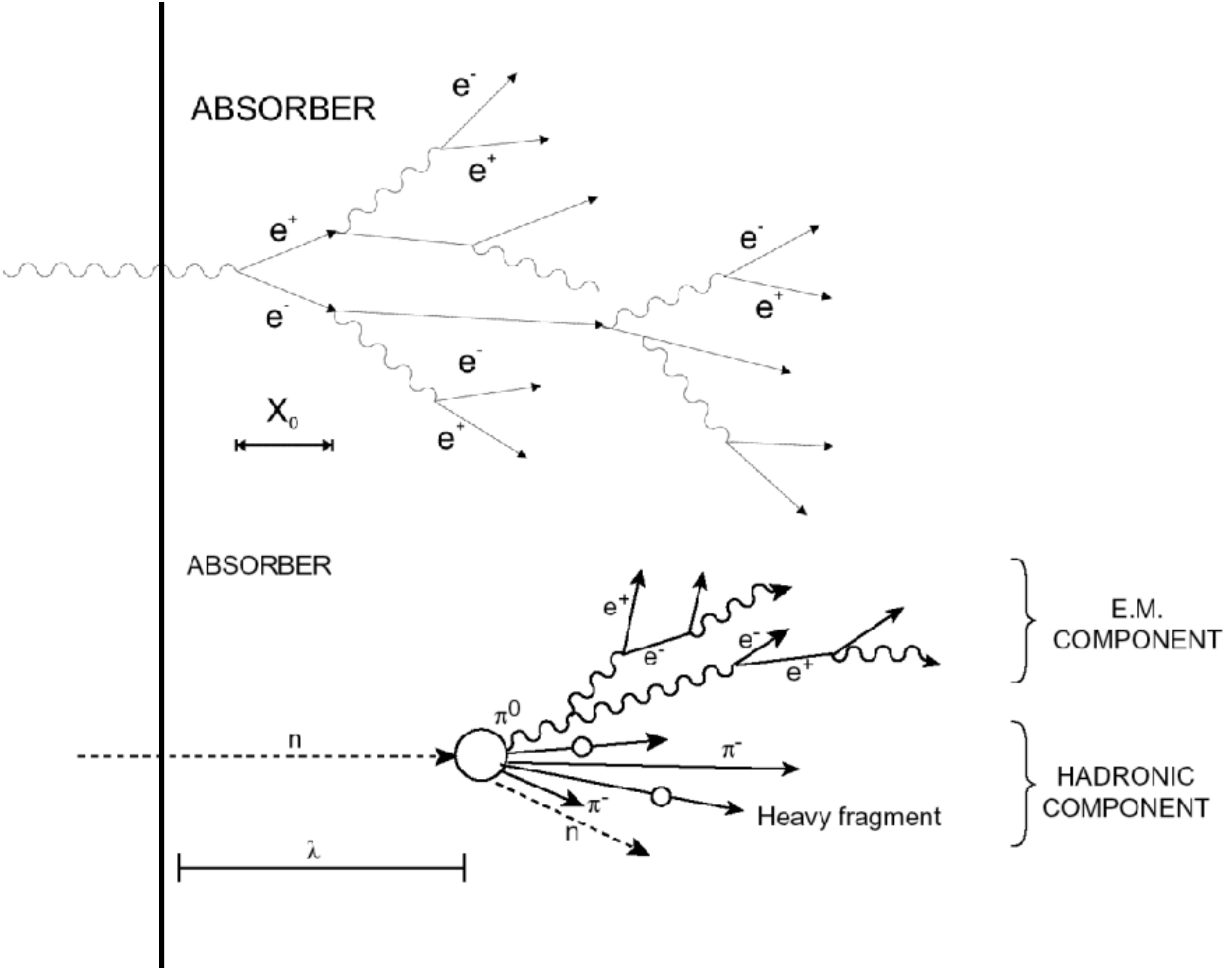
- Tracking system is ideally massless
- Calorimeter is *massive* and should totally absorb the energy of a particle [or jet] in 1 GeV to 1 TeV range.
- Electromagnetic and hadronic calorimeters.

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

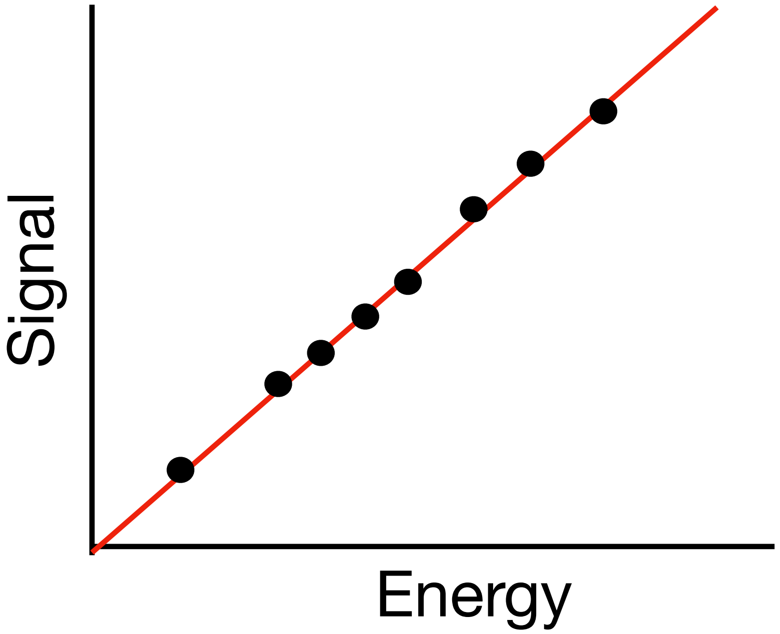
- Neutral hadrons (n, K_L)

  Hadronic showers

- Muons

  Minimum ionising (track in calorimeter)

Linearity

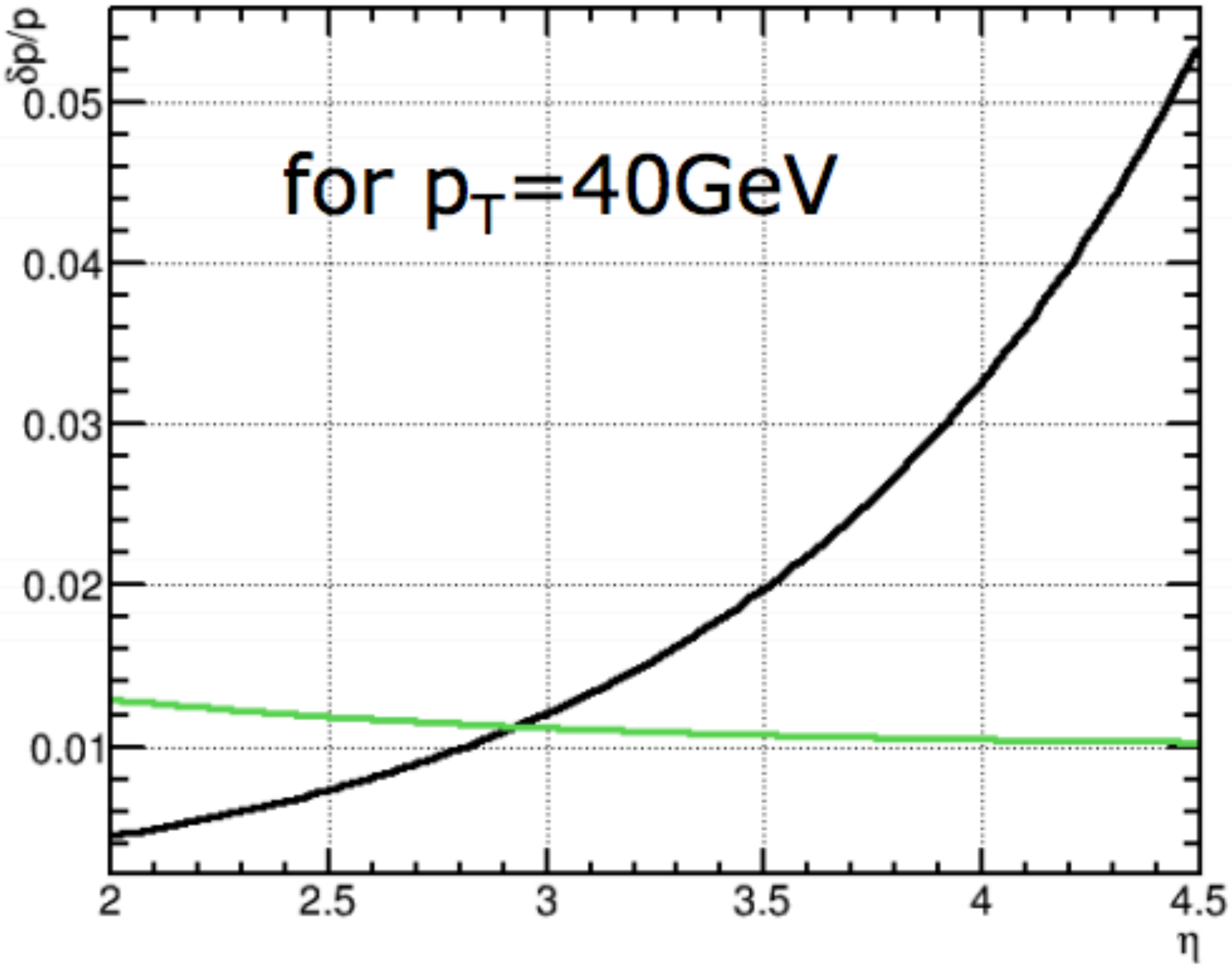


- Readily achieved in EM calorimeters

  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



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

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

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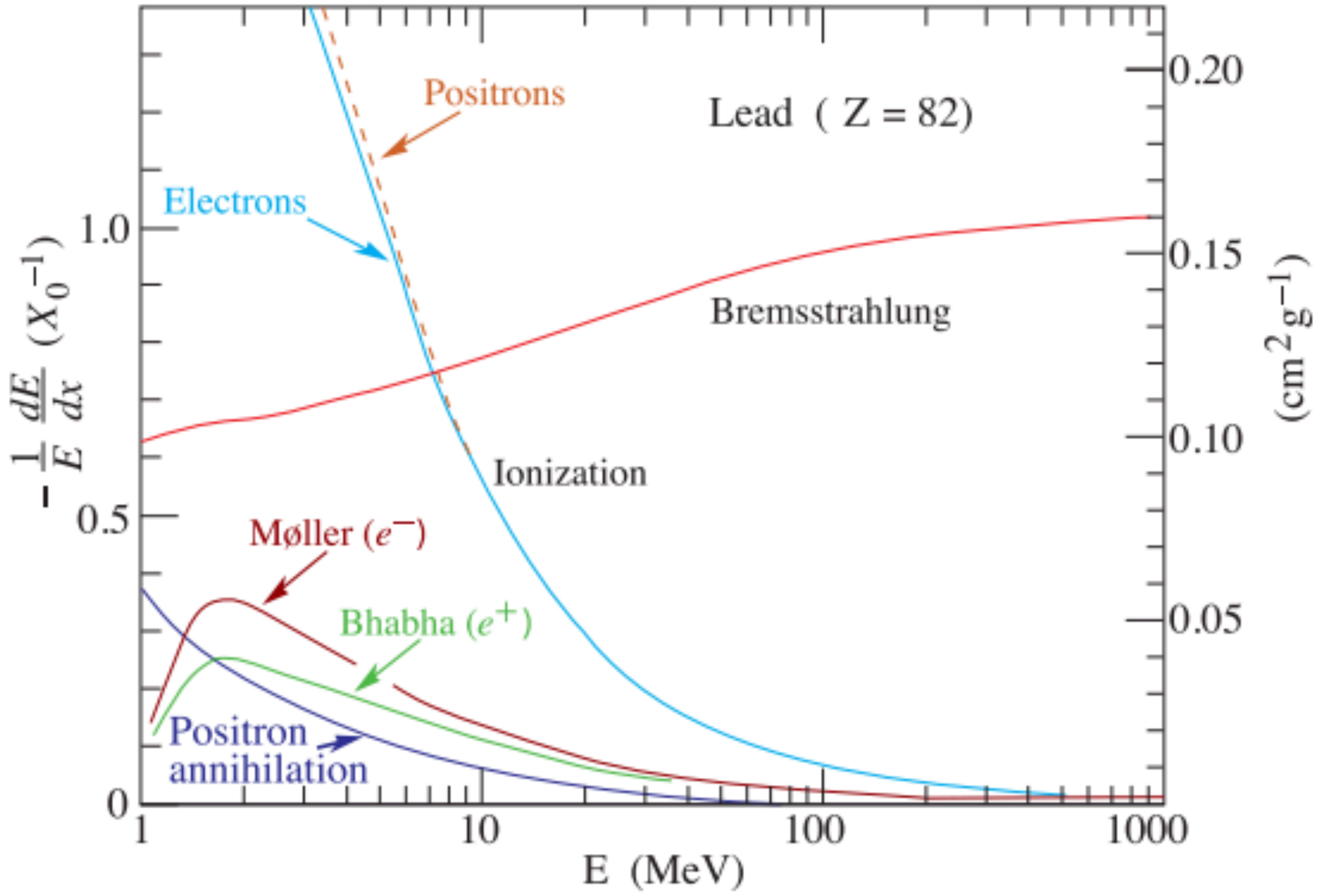
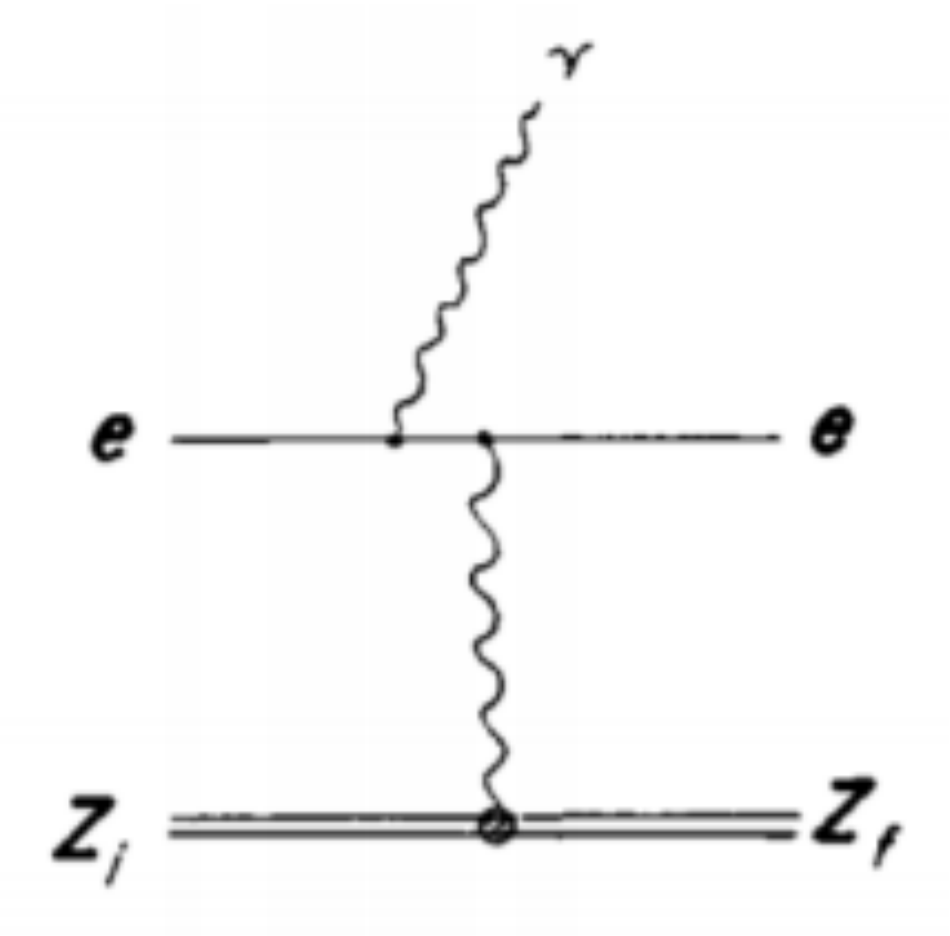
2. **EM showers**
3. EM calorimeters
4. Hadronic showers/calorimeters

Electron interactions with matter

`rpp2019-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

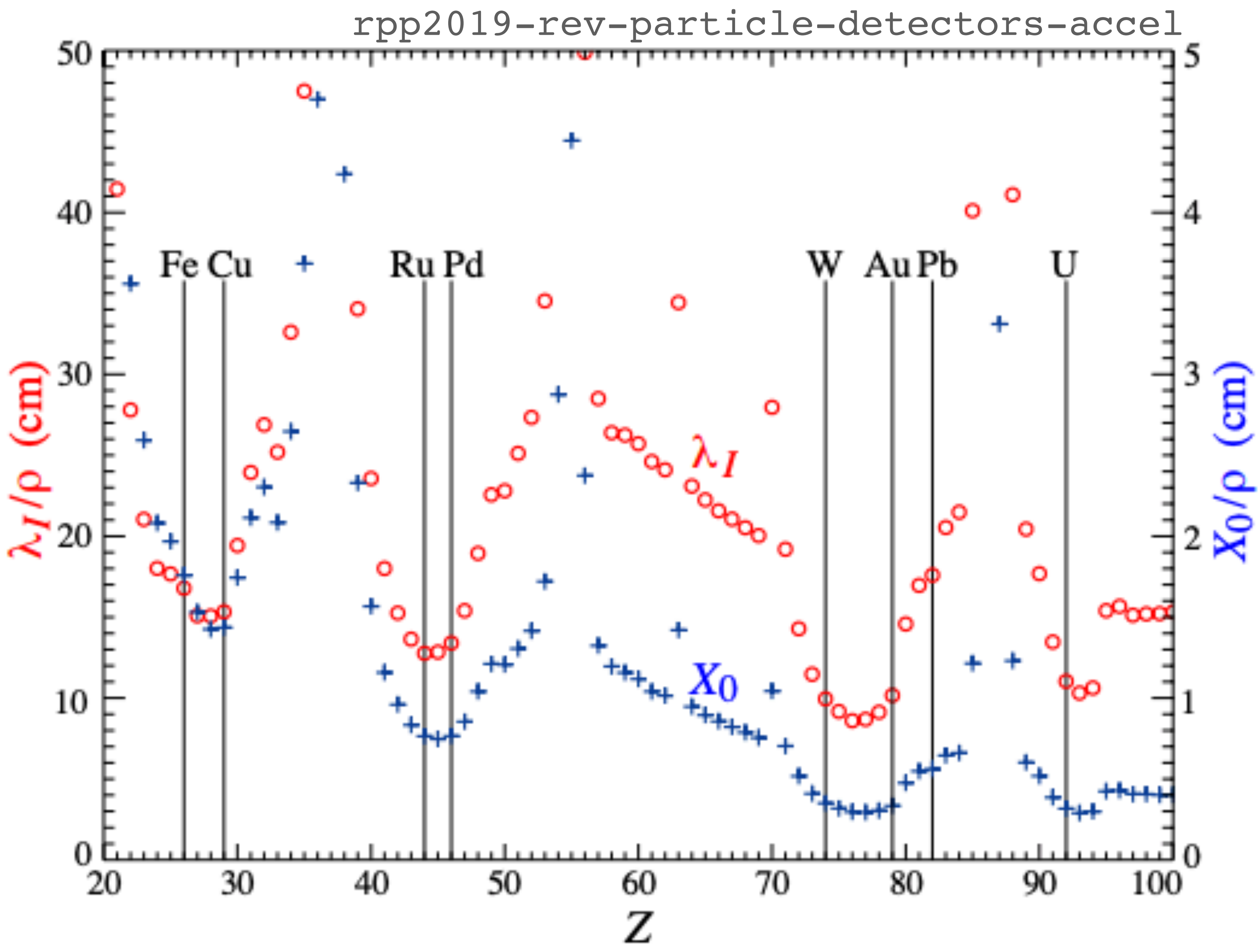
Approximation:

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

$$\sigma_{\text{brem}} \propto Z^2$$

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

Material dependence



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

The critical energy (E_c),

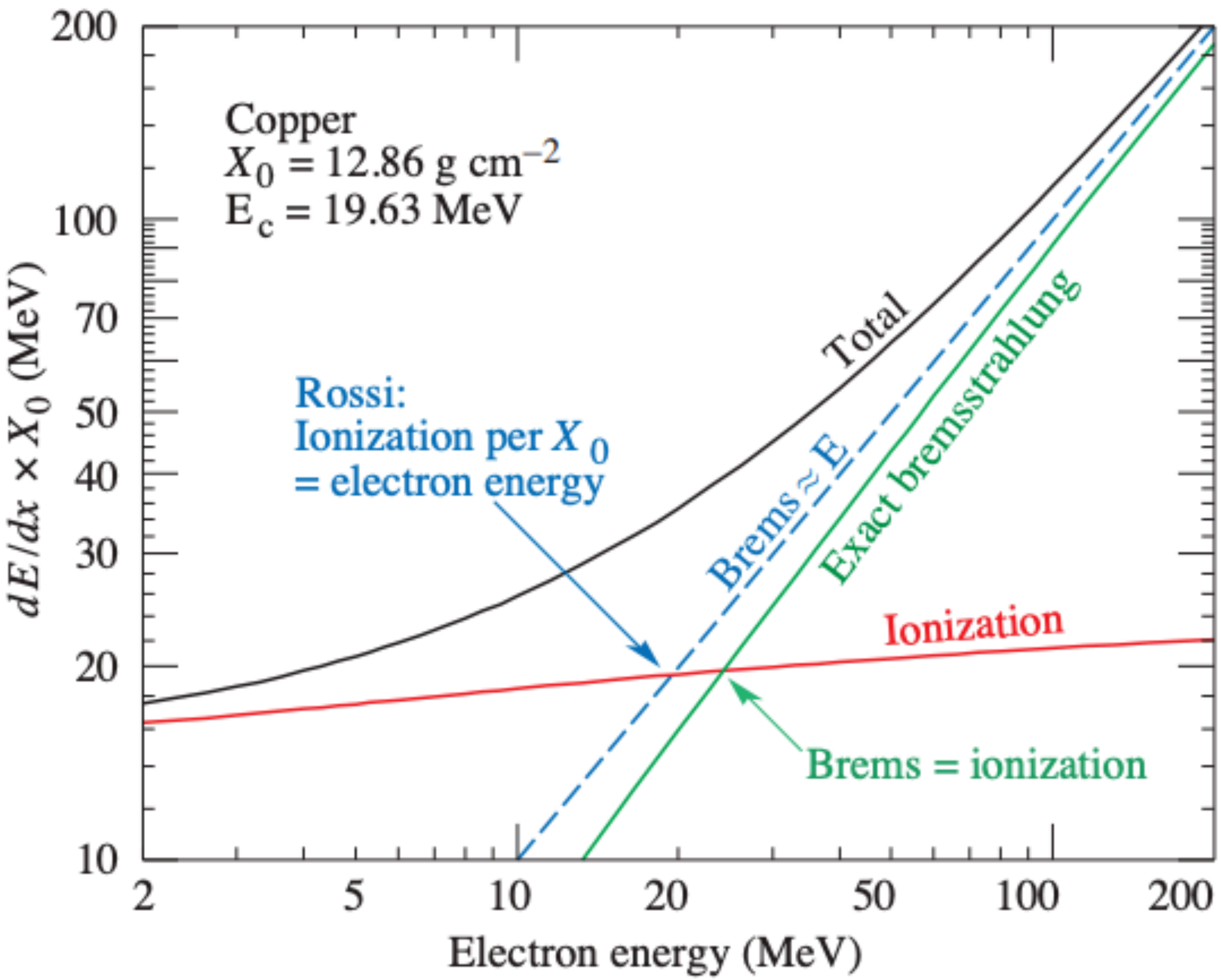
at which Brem. and ionisation losses are equal.

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

Brem $\sim Z^2$

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

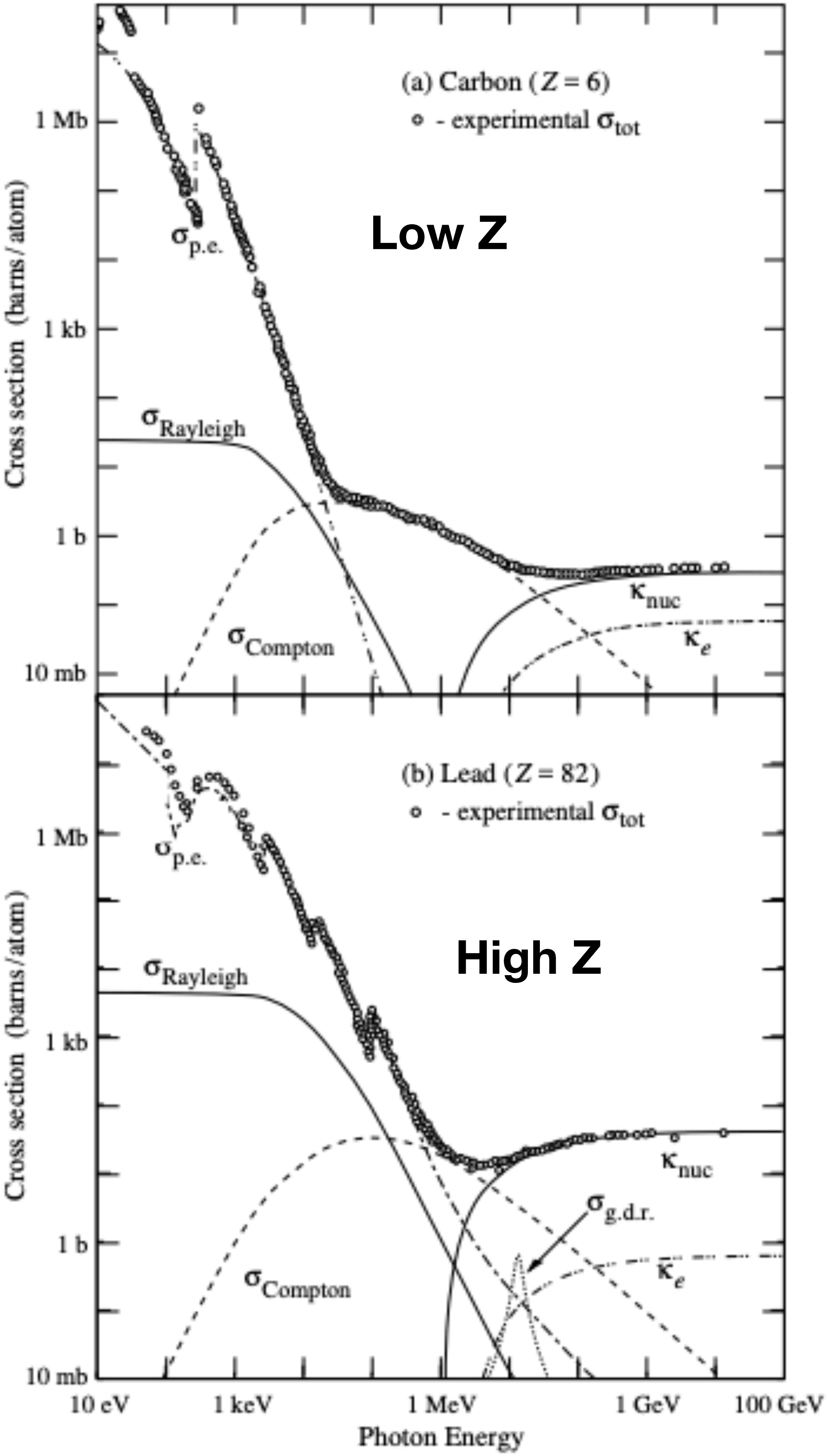
rpp2019-rev-passage-particles-matter



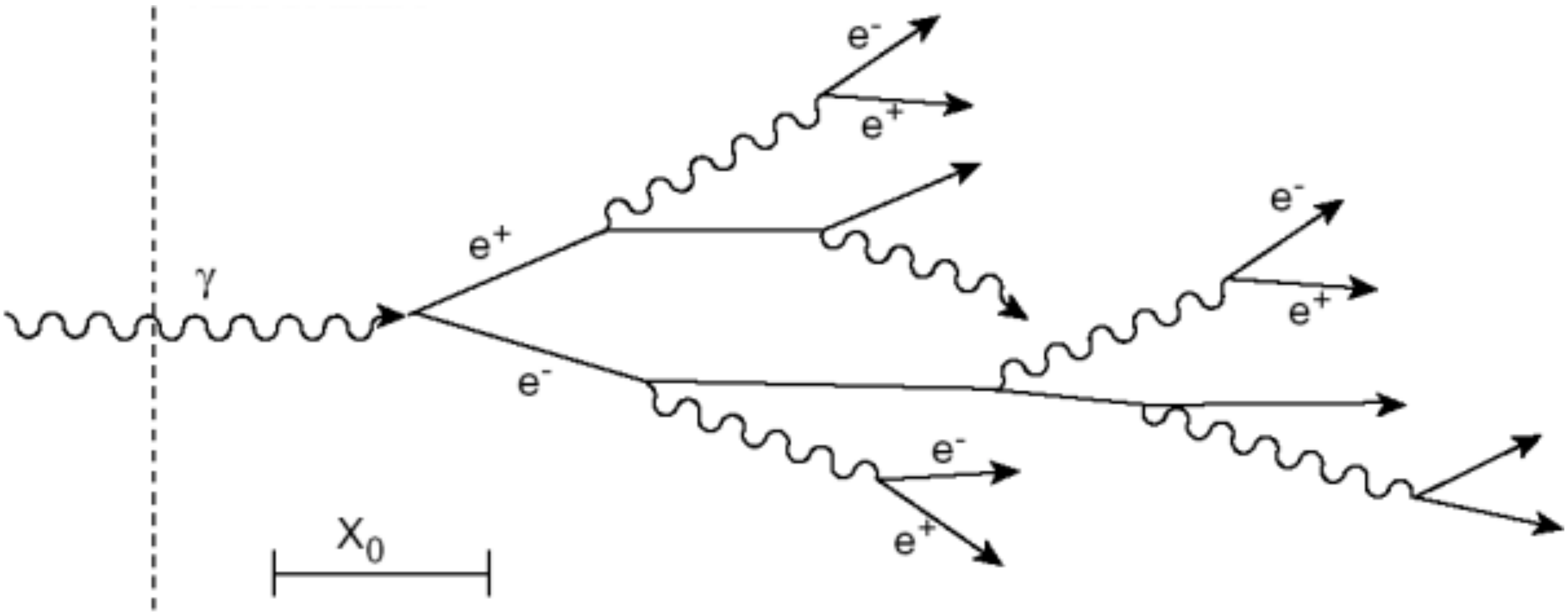
Photon interactions

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

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

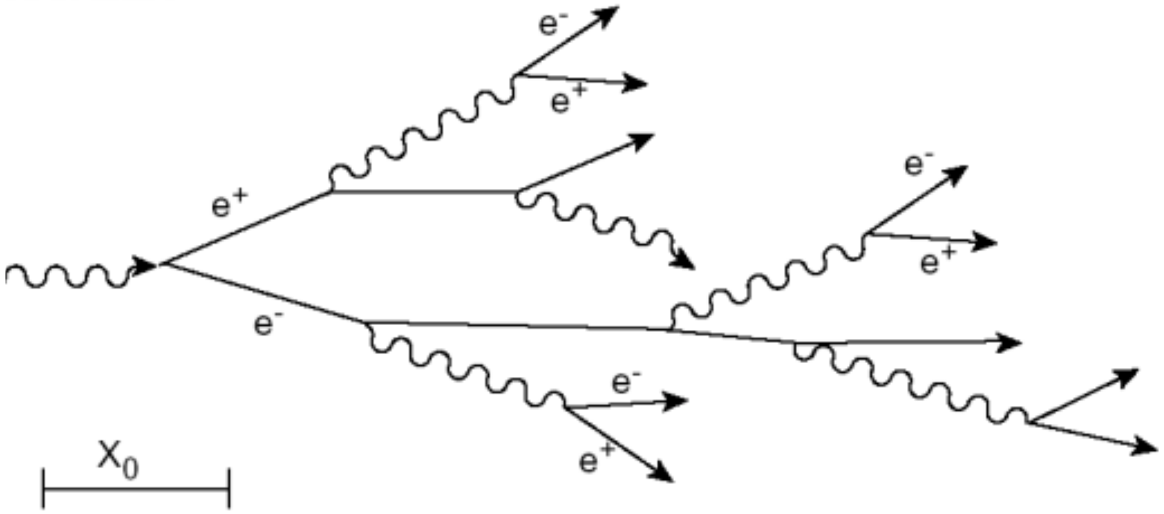


Electromagnetic shower

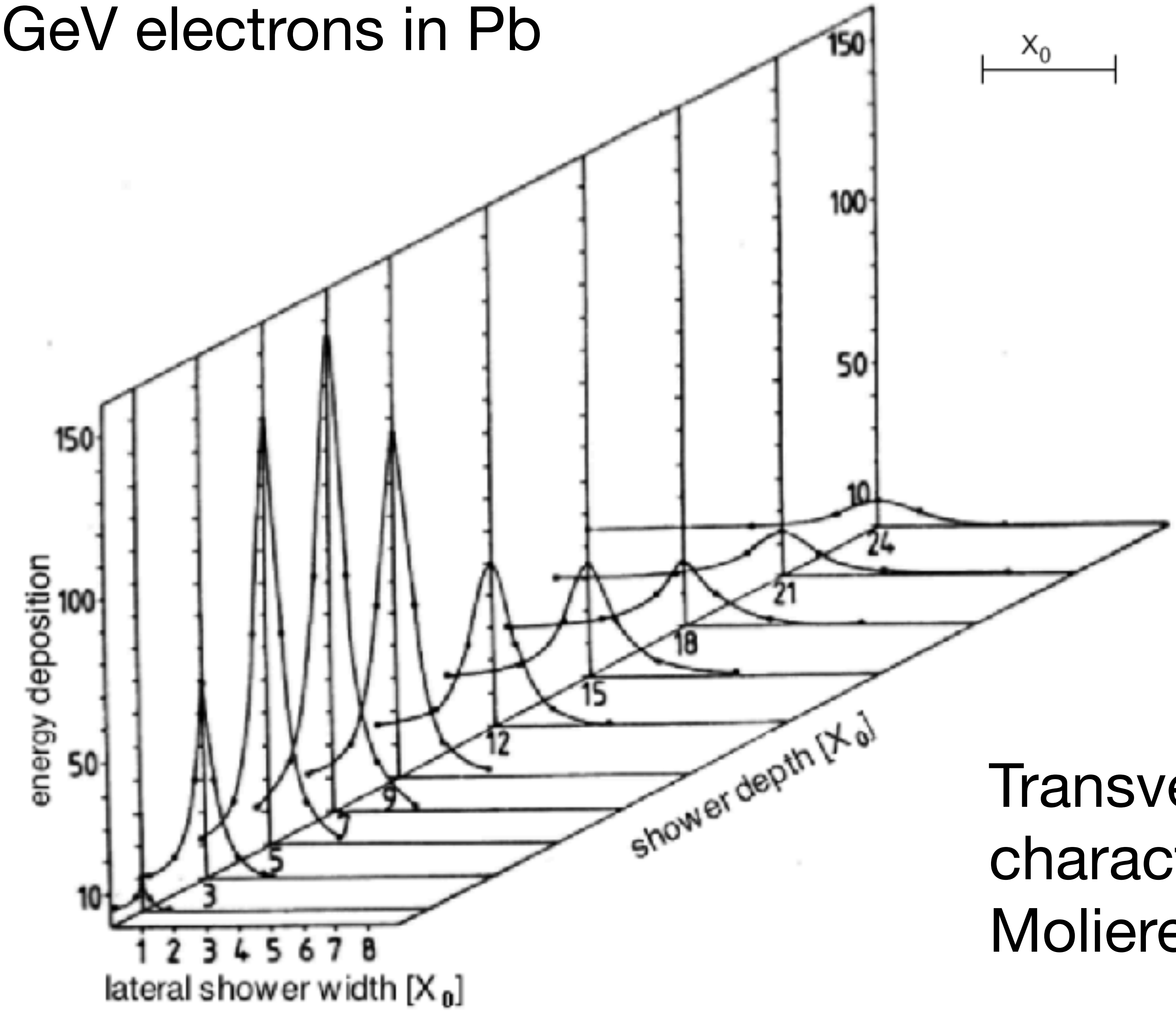


- Secondary electrons/photons from pair production and bremsstrahlung.
- Number *increases* but mean energy *decreases*.
- Ionisation and excitation take over when mean energy falls below E_C.

Shower development

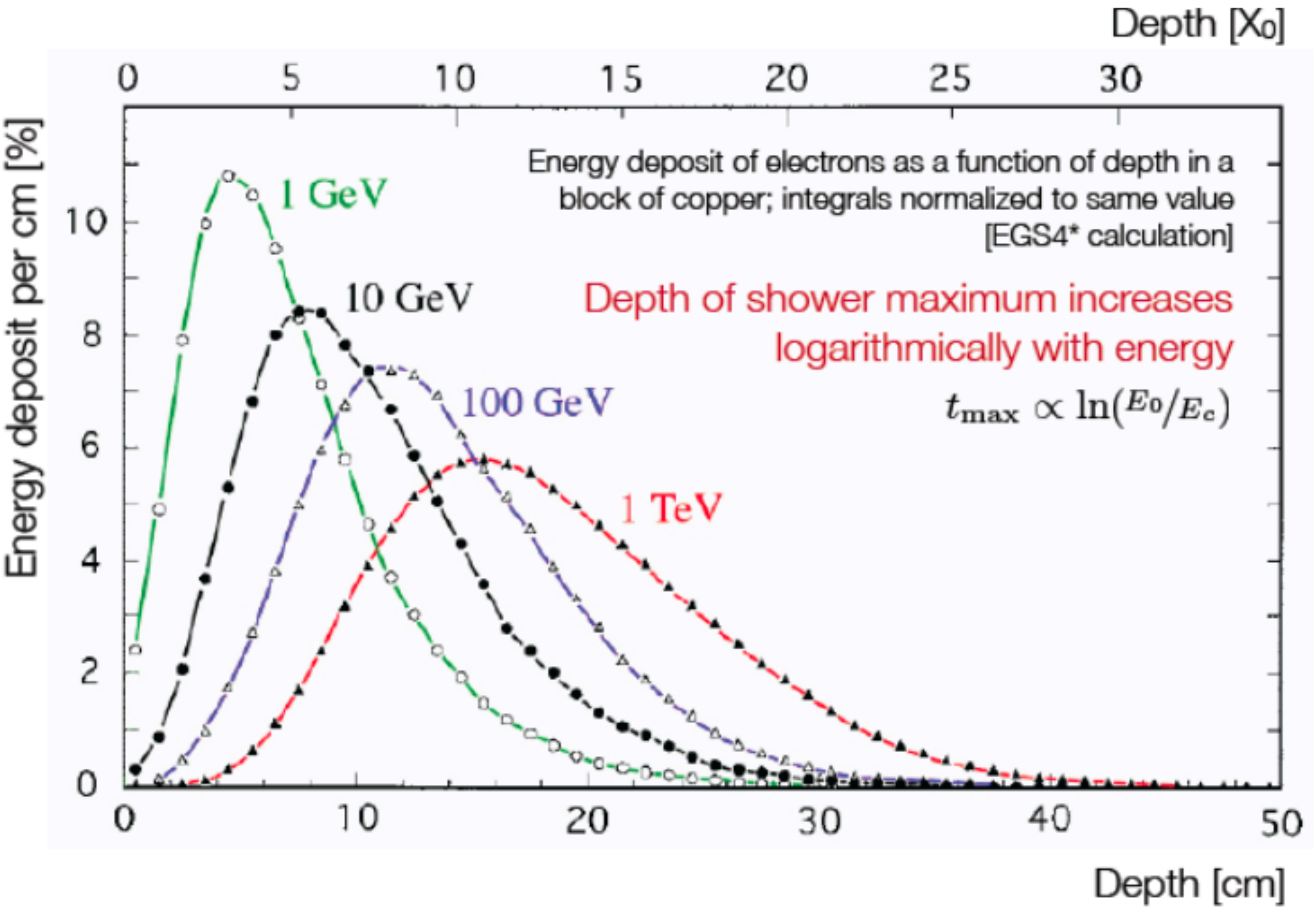


6 GeV electrons in Pb



Transverse shower extent characterised by the Moliere radius (R_M).

Depth of shower max



Energy deposit of electrons as a function of depth in a block of copper; integrals normalized to same value [EGS4* calculation]

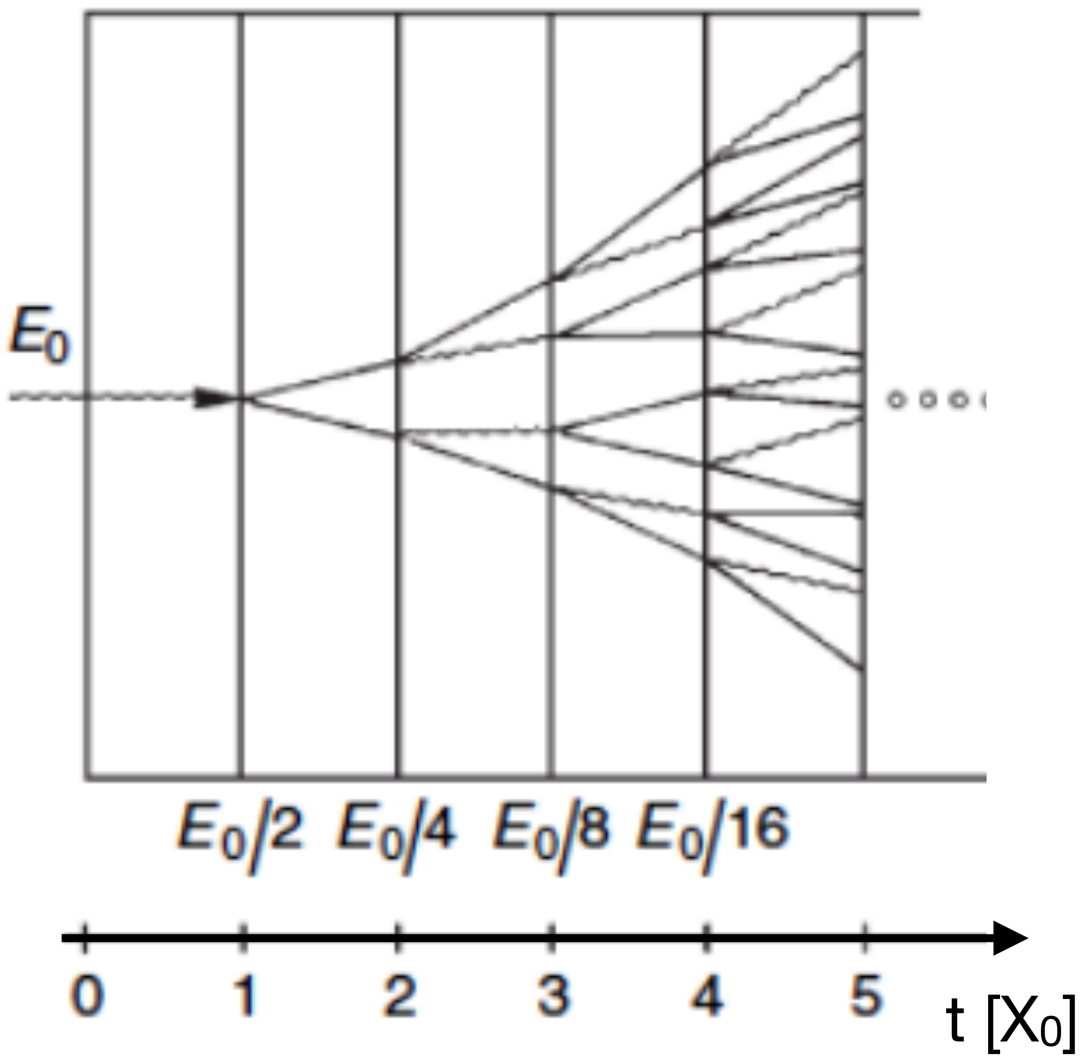
Depth of shower maximum increases logarithmically with energy

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

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

Simple shower model

1. In 1 X_0 Electron loses [1-1/e] of energy to Brem
2. Mean free path of photon is 9/7 X_0 (pair production)
3. No(only) ionisation/excitation above(below) E_C.



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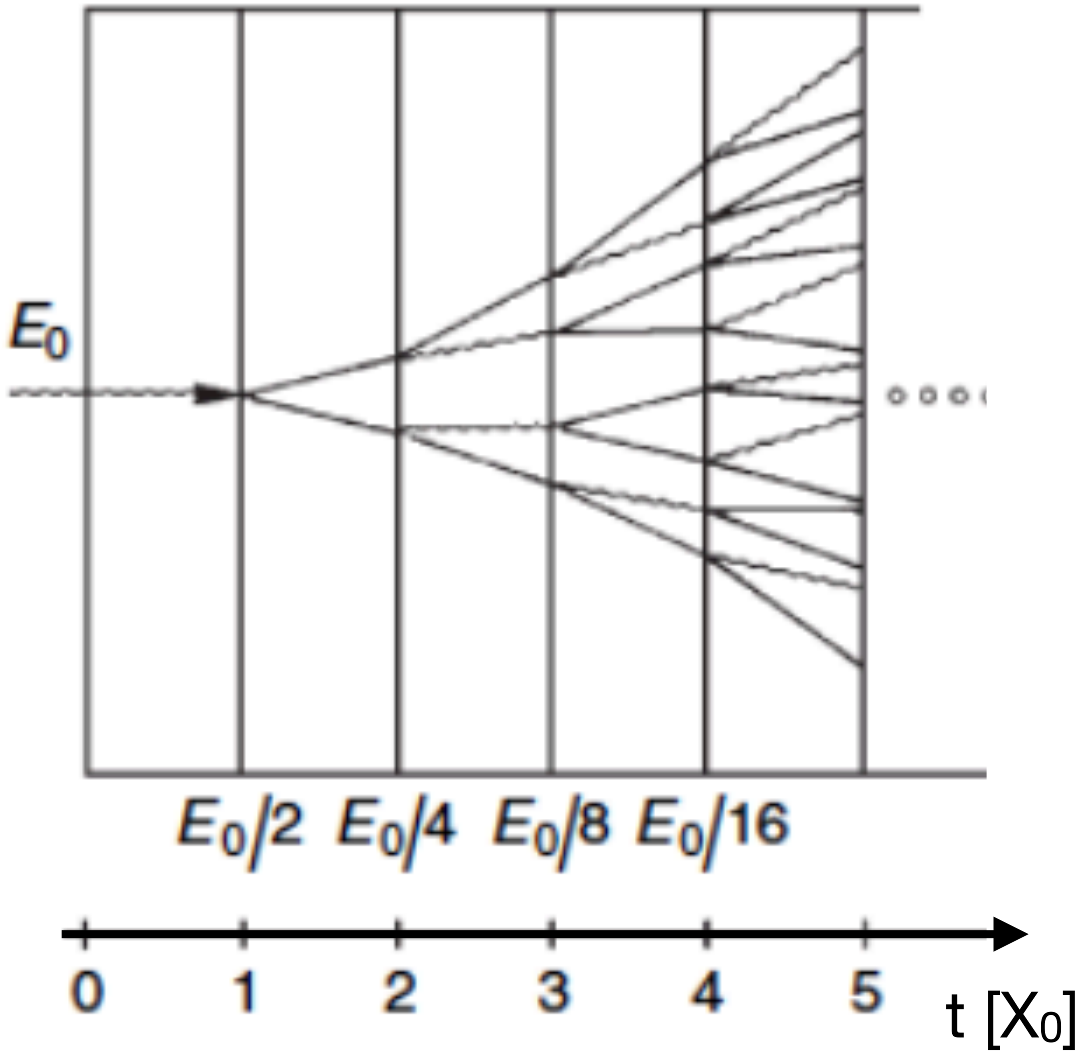


After t [X_0] we have 2^t particles with energy $E/2^t$

Shower stops when $E < E_c$, with $N=E/E_c$ 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.

$$< \theta^2 > \sim (m/E)^2$$

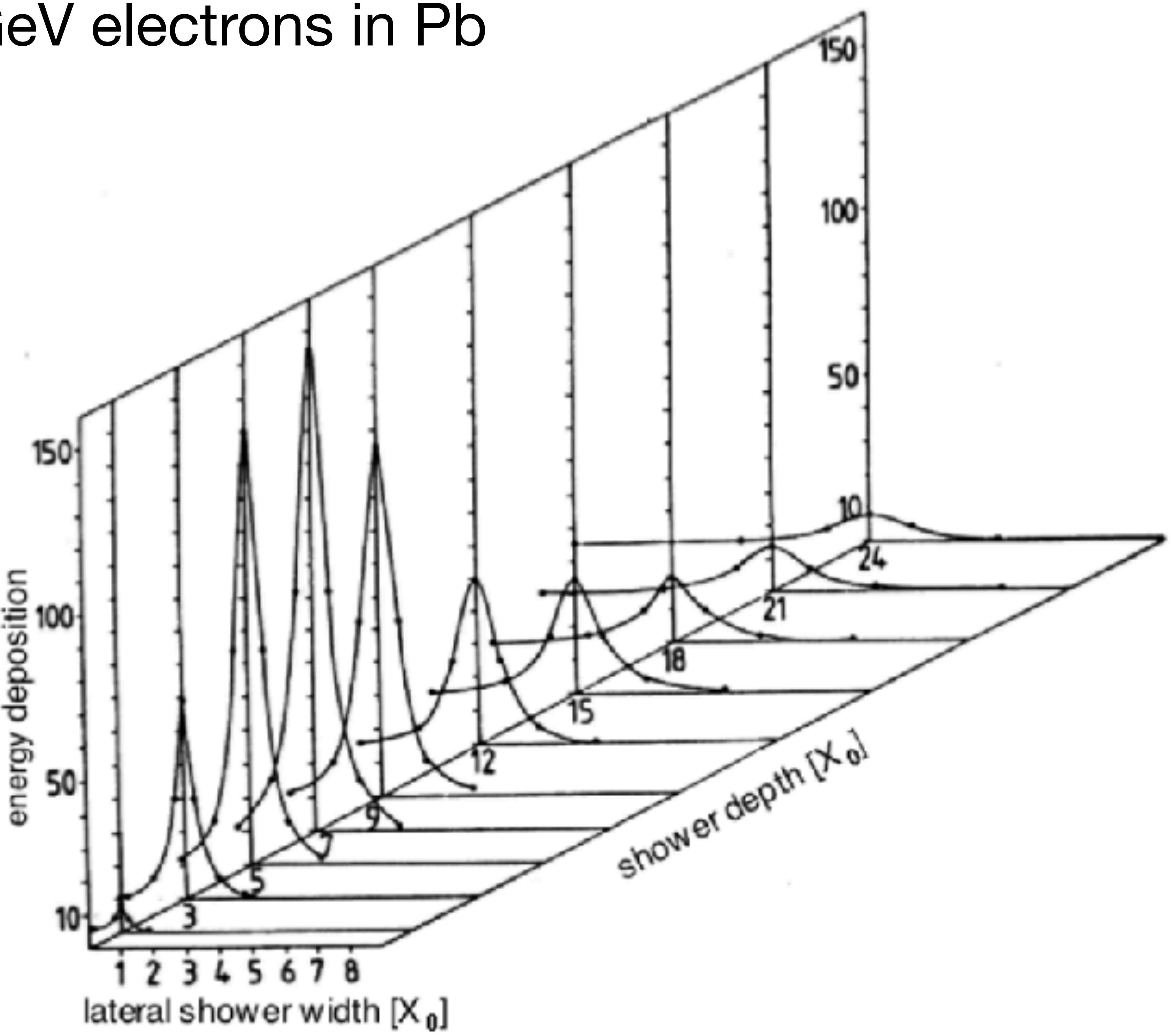
- Multiple coulomb scattering [Mollier theory] of low energy electrons dominates lateral spread.

- 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



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

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

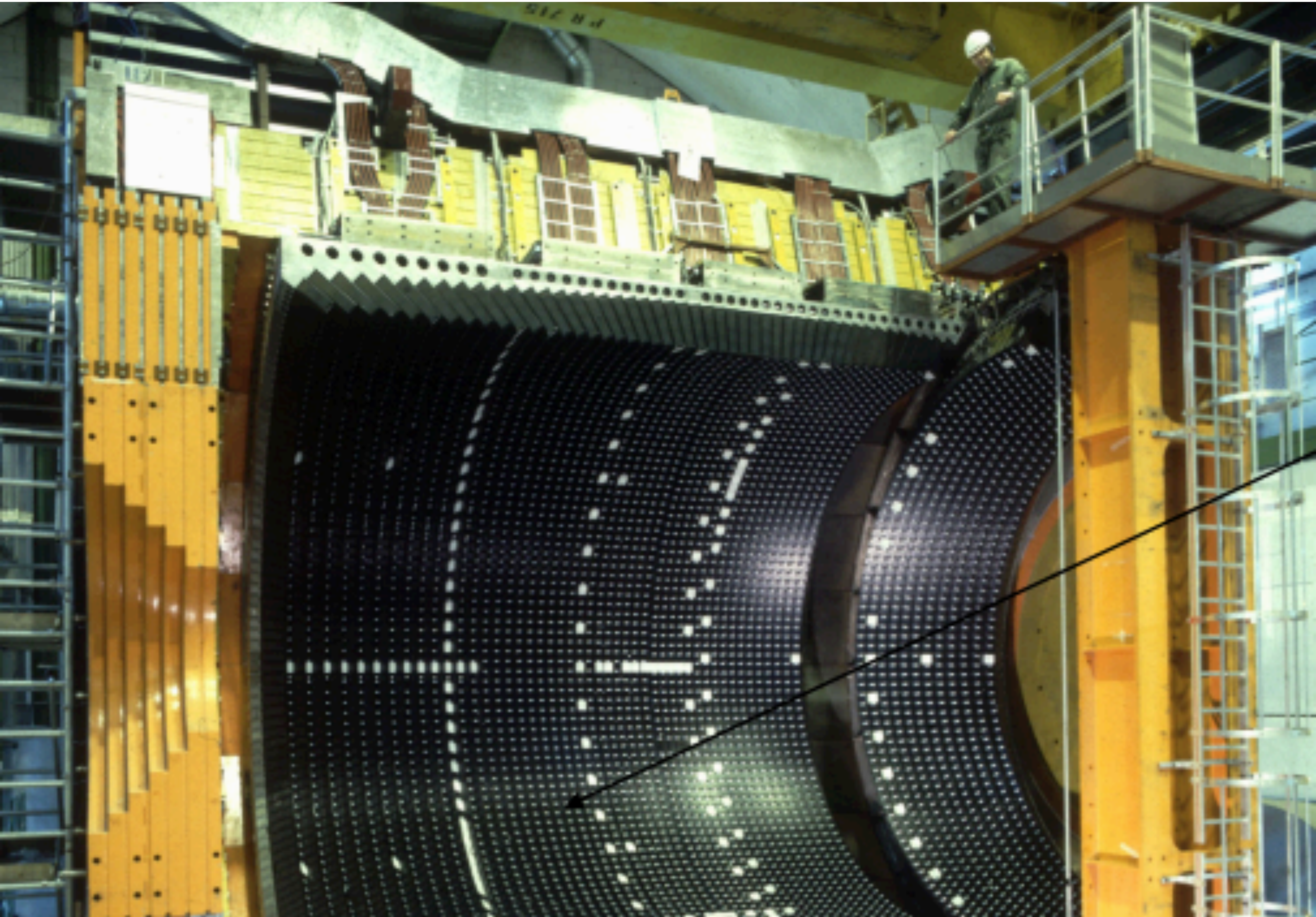
Shower max

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

Lateral

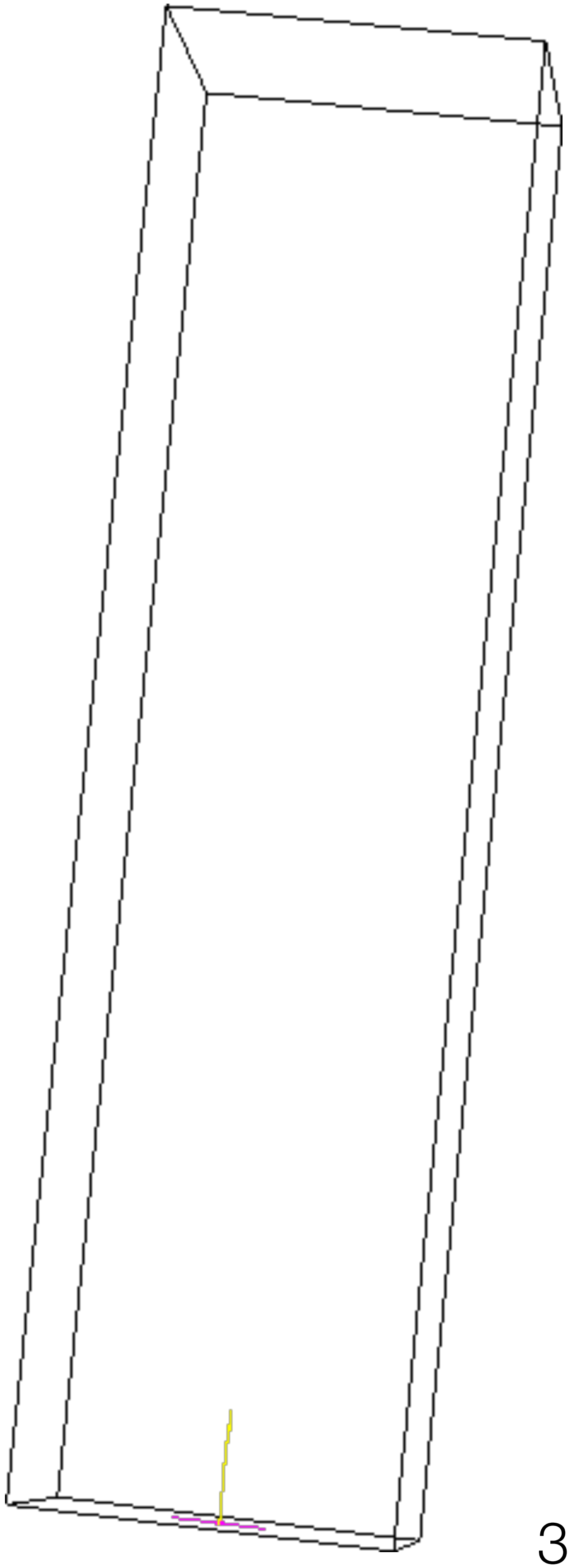
$$R_M \approx \left[7 \frac{\mathrm{g}}{\mathrm{cm}^2}\right] \frac{A}{Z}$$

OPAL experiment lead glass



OPAL experiment lead glass

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

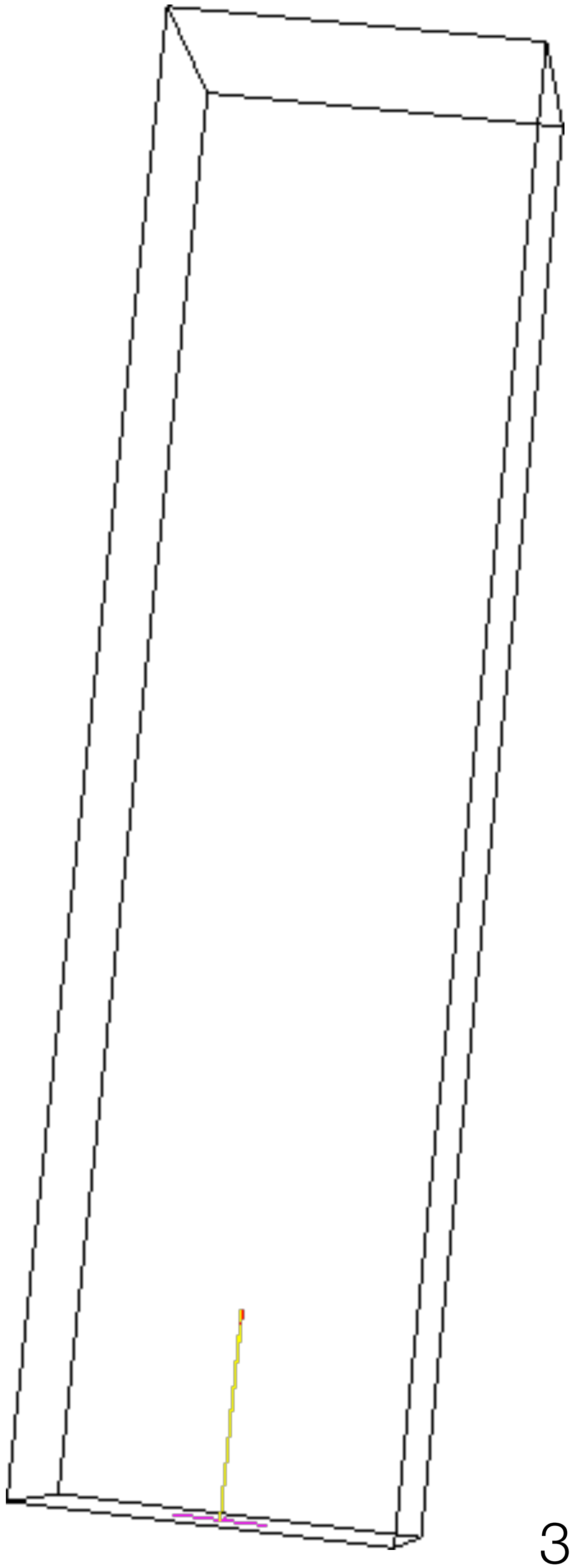


1 GeV e^-

37 x 10 x 10 cm

OPAL experiment lead glass

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

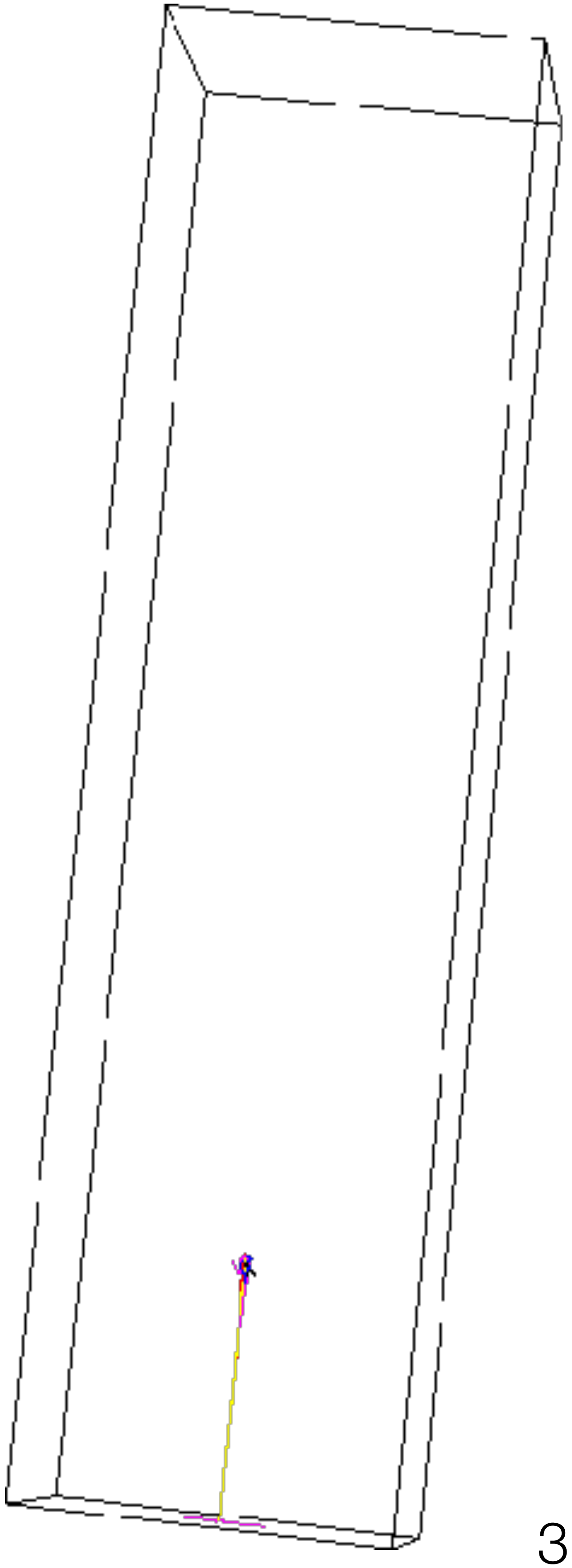


10 GeV e^-

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

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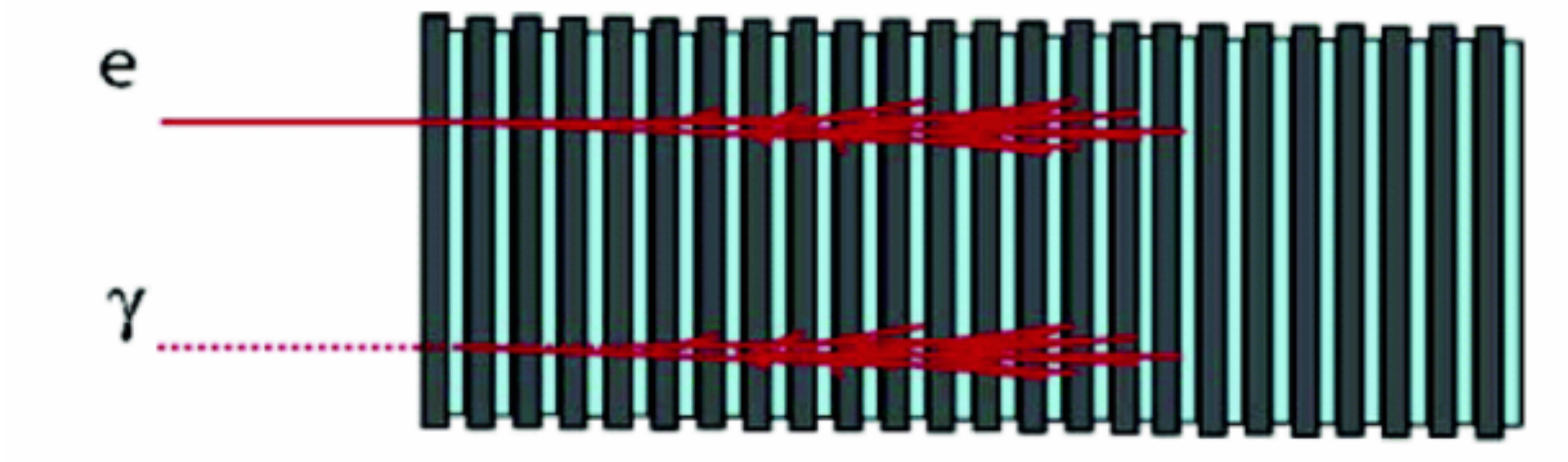
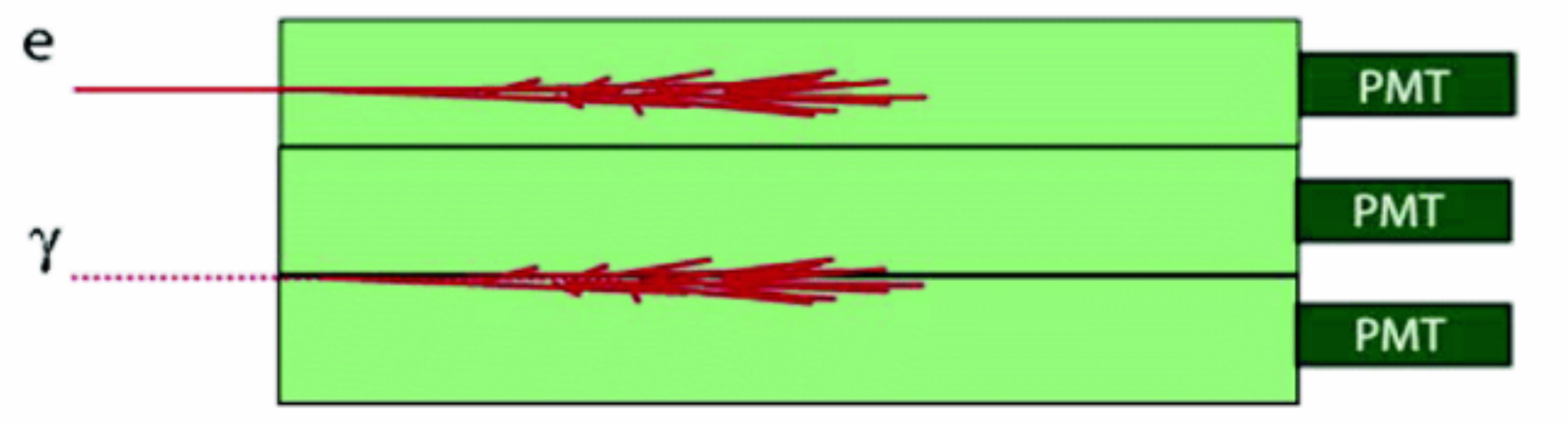
Sampling

Typically:



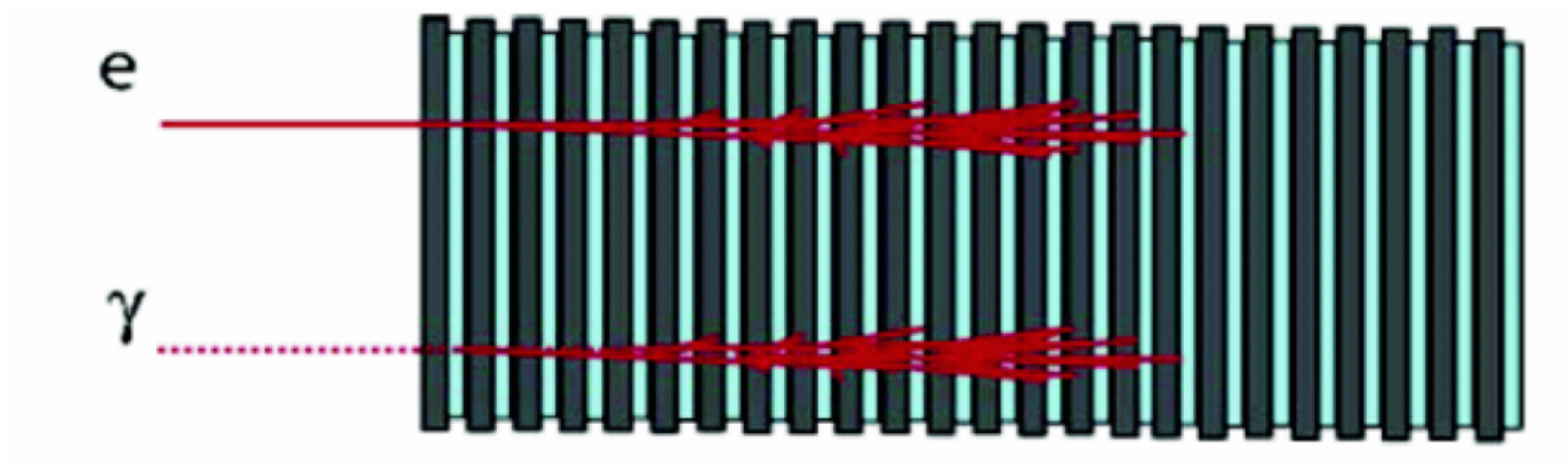
$$\sigma_E/E \sim 10\,\%/\sqrt{E}$$

Homogenous



$$\sigma_E/E \sim 1\,\%/\sqrt{E}$$

Sampling



Typically:

$$\sigma_E/E \sim 10\,\%/\sqrt{E}$$

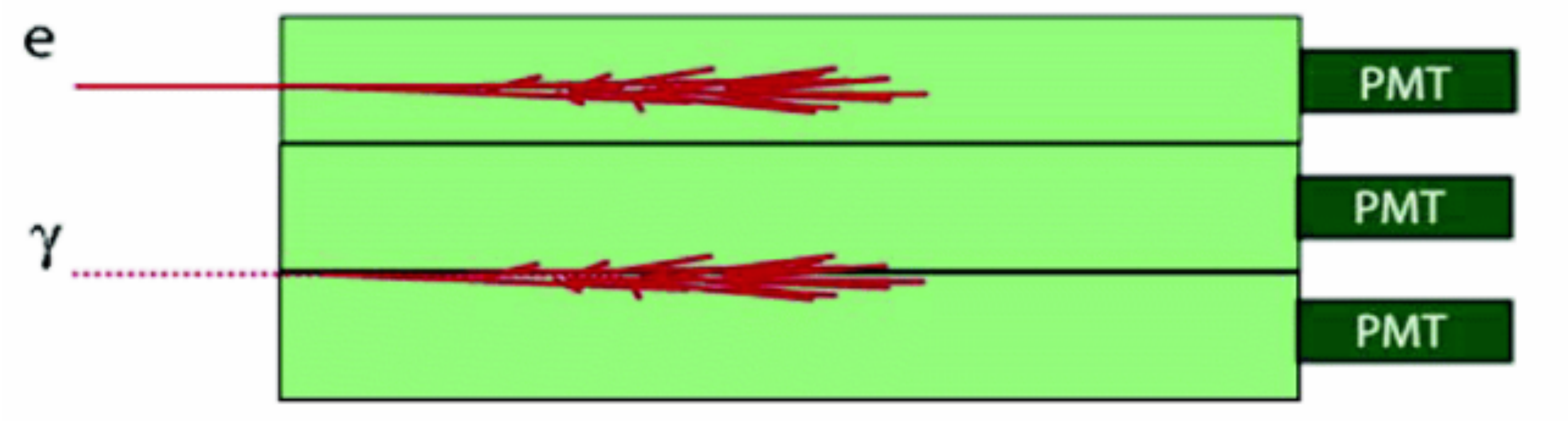
👍Freedom to independently choose optimal absorber and active detector material

👍Dense absorber → compact calorimeters

👍Can be cost effective (cheap absorber)

👎Only the sampling fraction of energy is measured → compromised resolution

Homogenous



Typically:

$$\sigma_E/E \sim 1\,\%/\sqrt{E}$$

👍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

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, σ ~ √N ~ √E

N: noise term

E.g., readout electronics

C: constant term

E.g., Non uniformity, calibration etc…

Examples `rpp2019-rev-particle-detectors-accel`

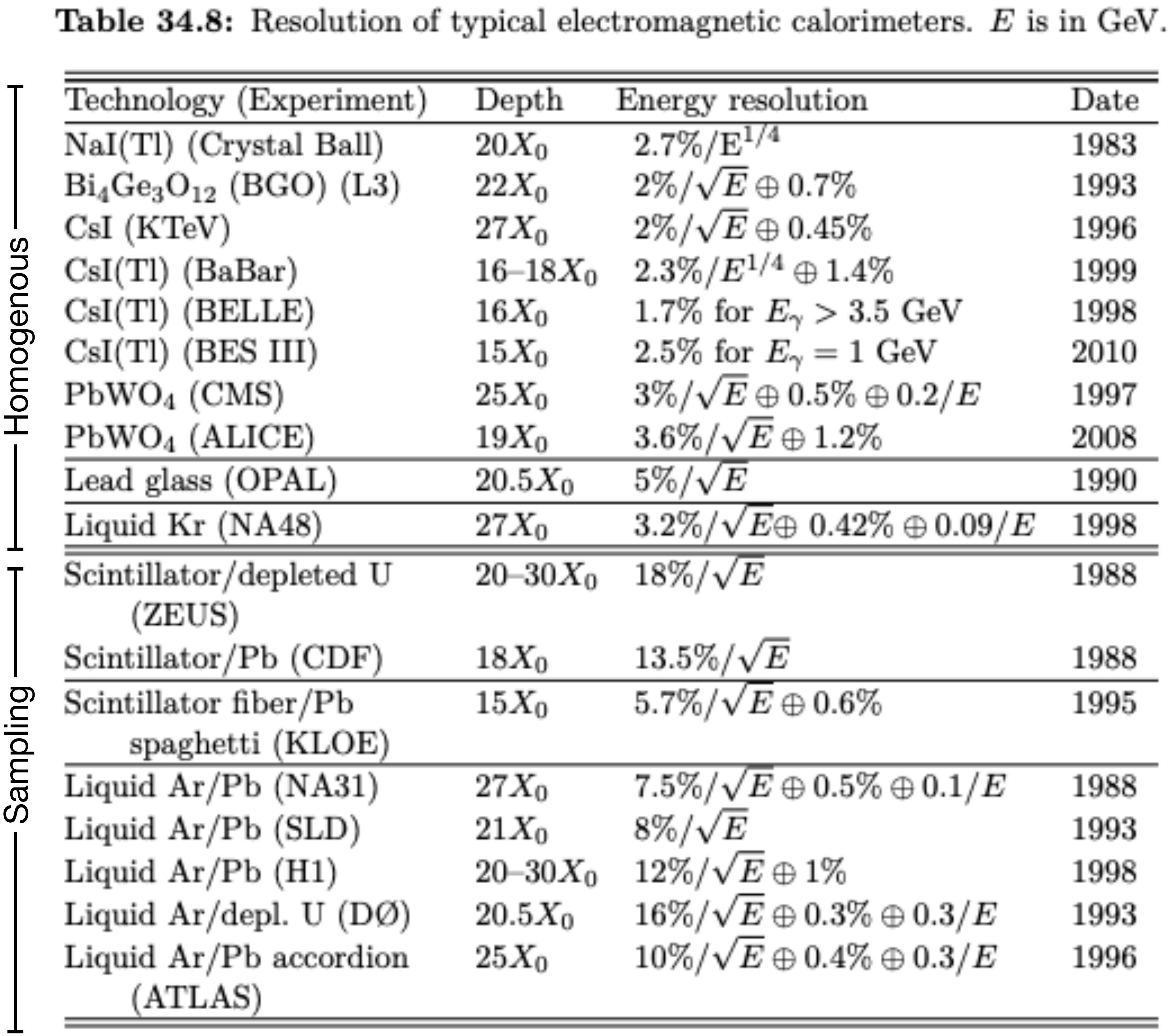
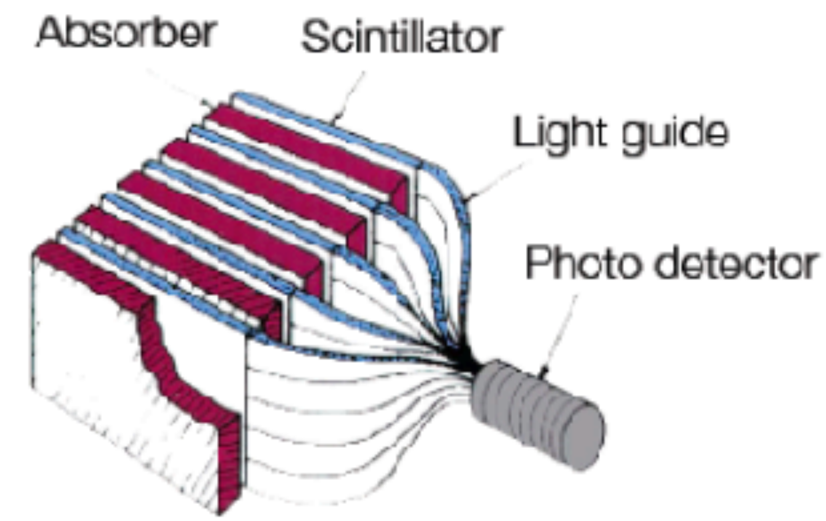


Table 34.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

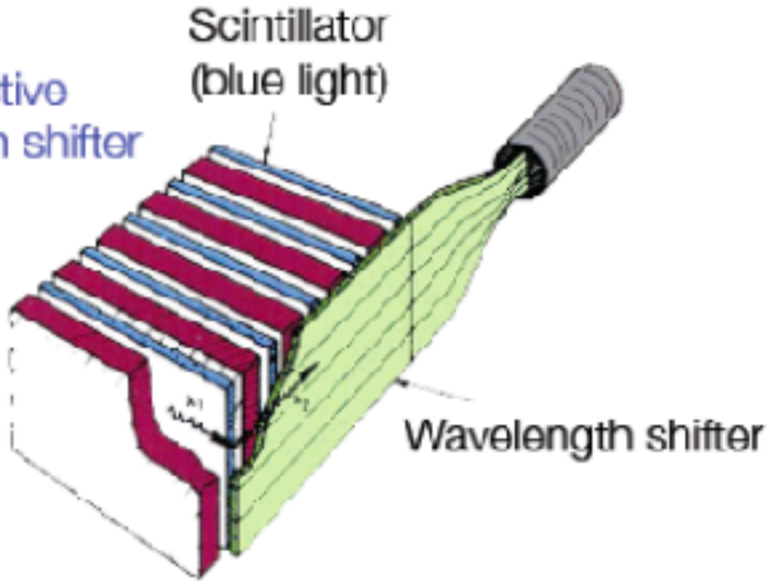
	Technology (Experiment)	Depth	Energy resolution	Date
Homogenous	NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
	$\mathrm{Bi_4Ge_3O_{12}}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
	CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
	CsI(Tl) (BaBar)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	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
	$\mathrm{PbWO_4}$ (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
	$\mathrm{PbWO_4}$ (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
Sampling	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

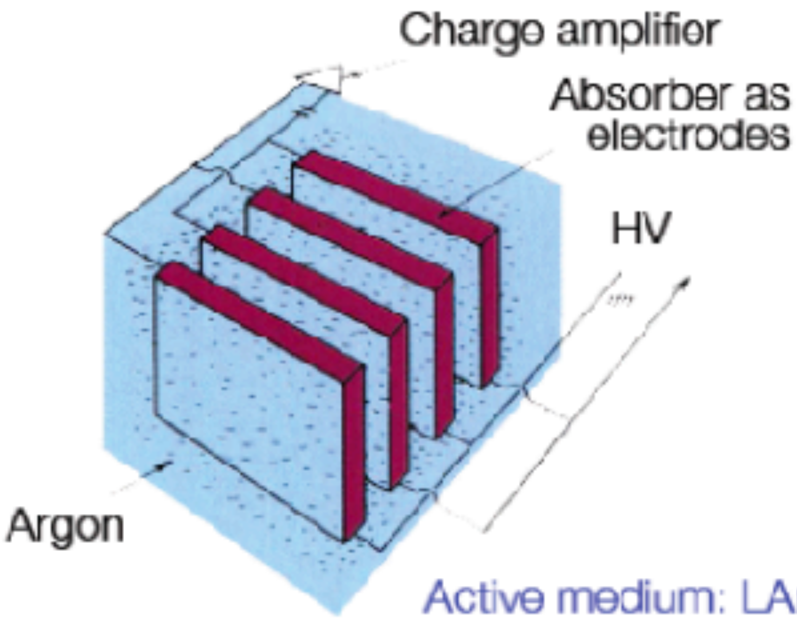
Sampling calorimeter designs

Scintillators as active layer;
signal readout via photo multipliers



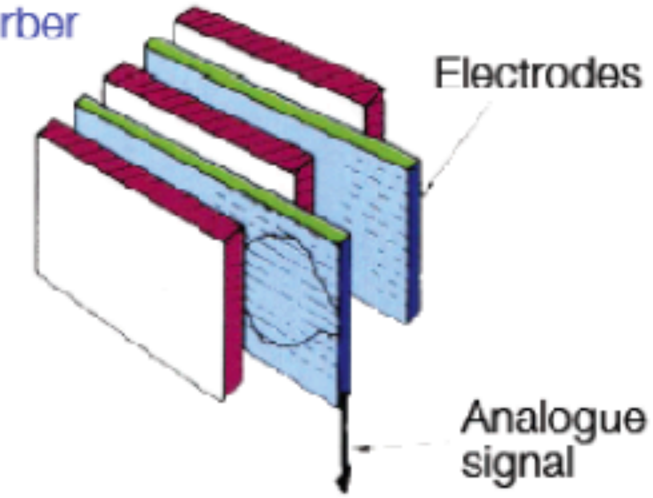
Scintillators as active
layer; wave length shifter
to convert light





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

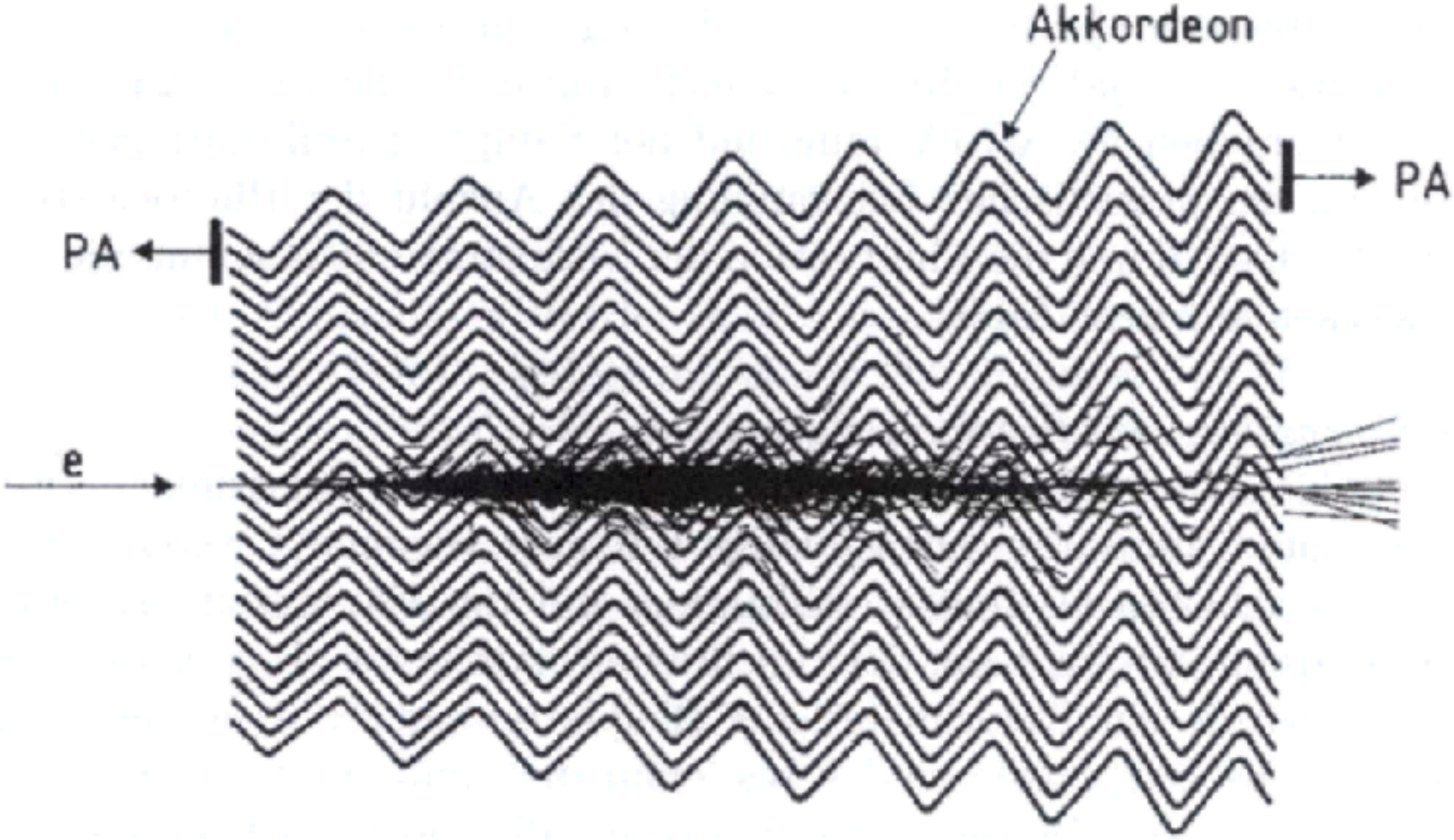
Ionization chambers
between absorber
plates



LHCb ECAL

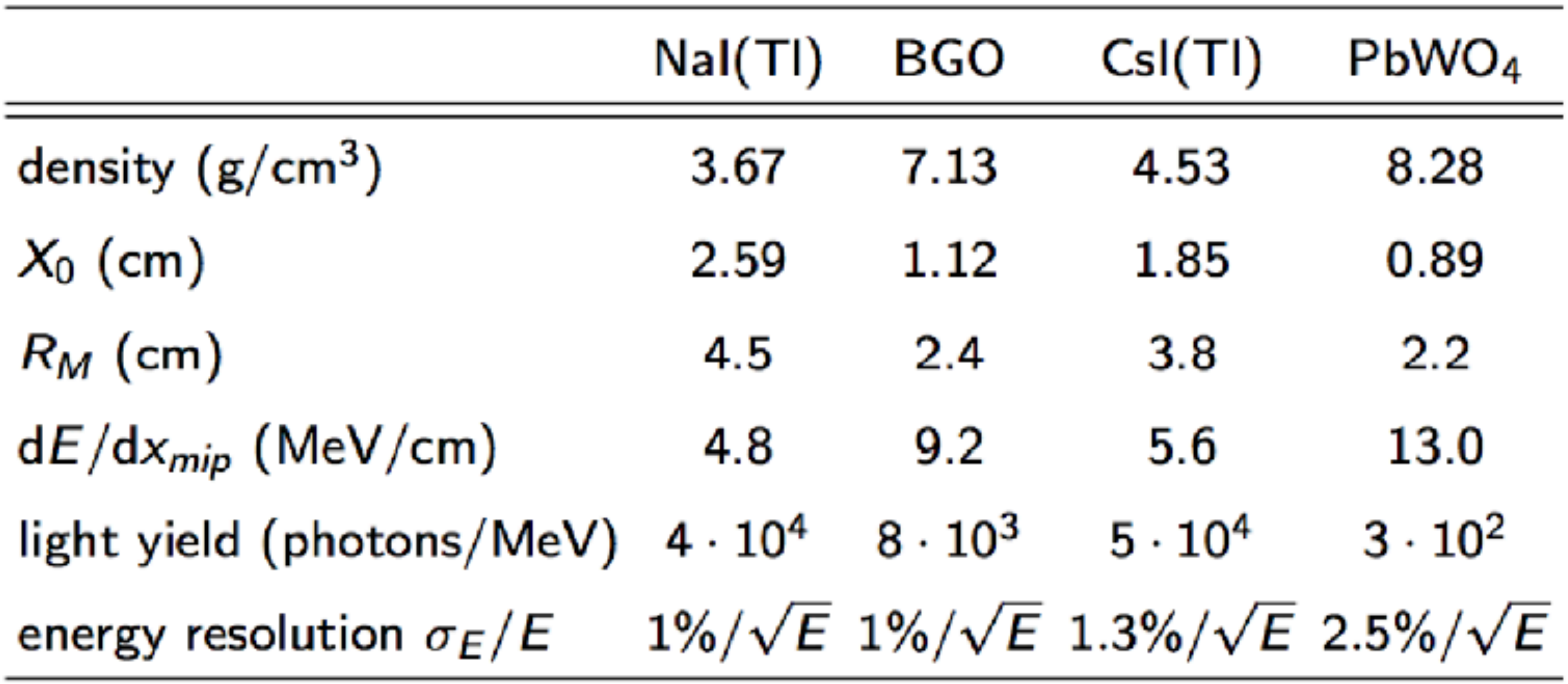
“Shashlik” design.
Alternating Pb absorber and scintillator.
Energy resolution sampling term of approximately 10%/sqrt(E/GeV)

ATLAS LAr ECAL



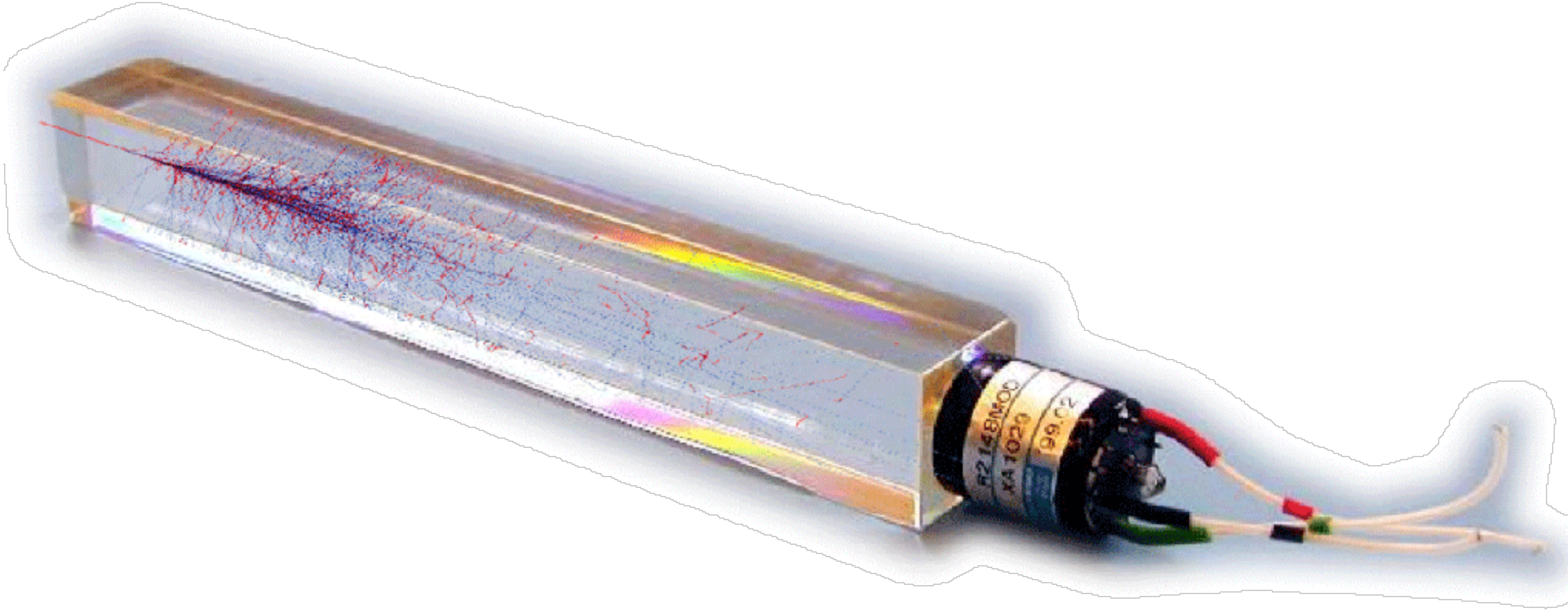
Homogenous calorimeters

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



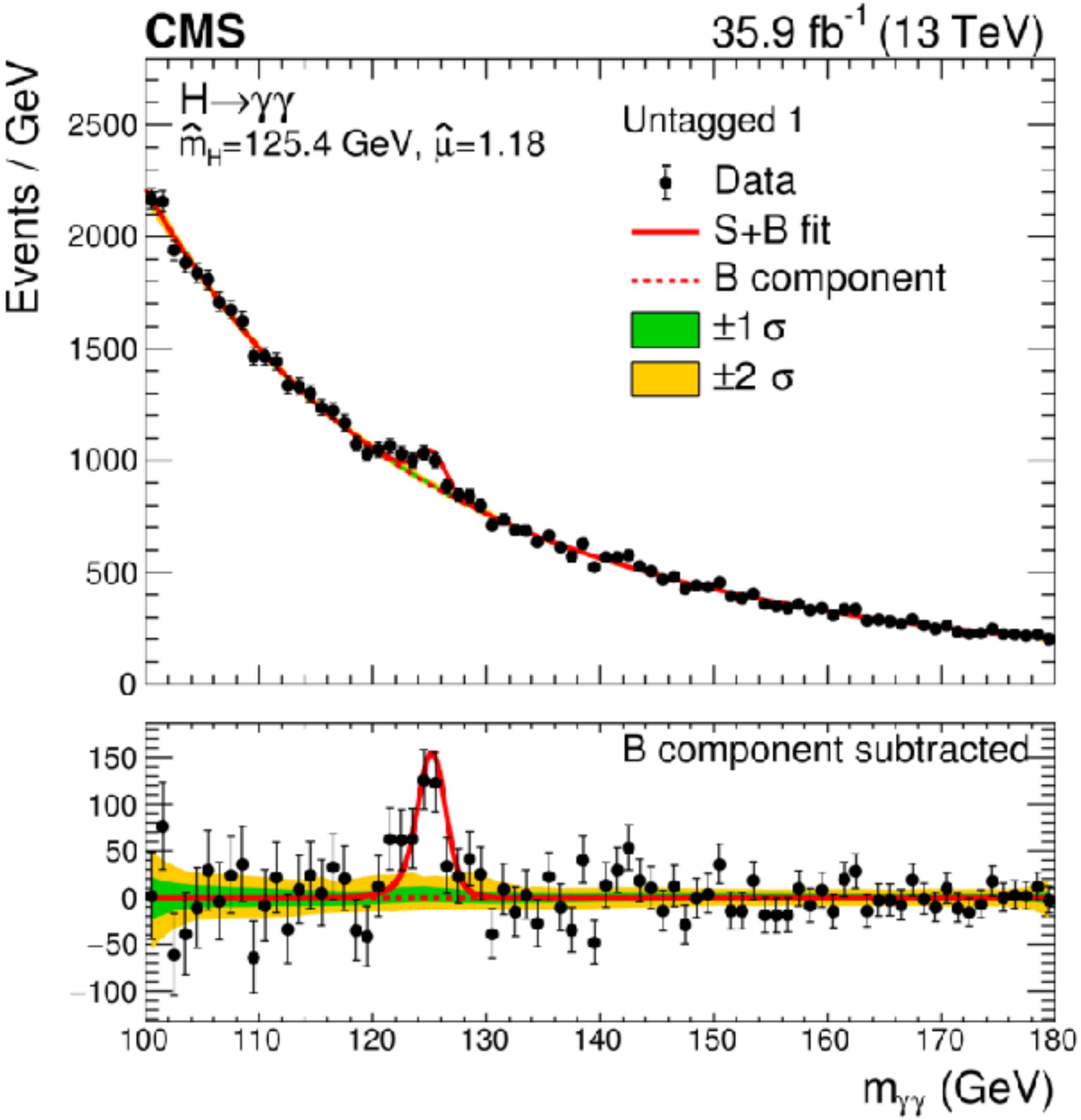
	NaI(Tl)	BGO	CsI(Tl)	$PbWO_4$
density (g/cm^3)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_M (cm)	4.5	2.4	3.8	2.2
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$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

CMS ECAL



$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

CMS ECAL


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
2500
2000
1500
1000
500
0
B component subtracted
150
100
50
0
−50
−100
100
110
120
130
140
150
160
170
180
$m_{\gamma\gamma}$ (GeV)

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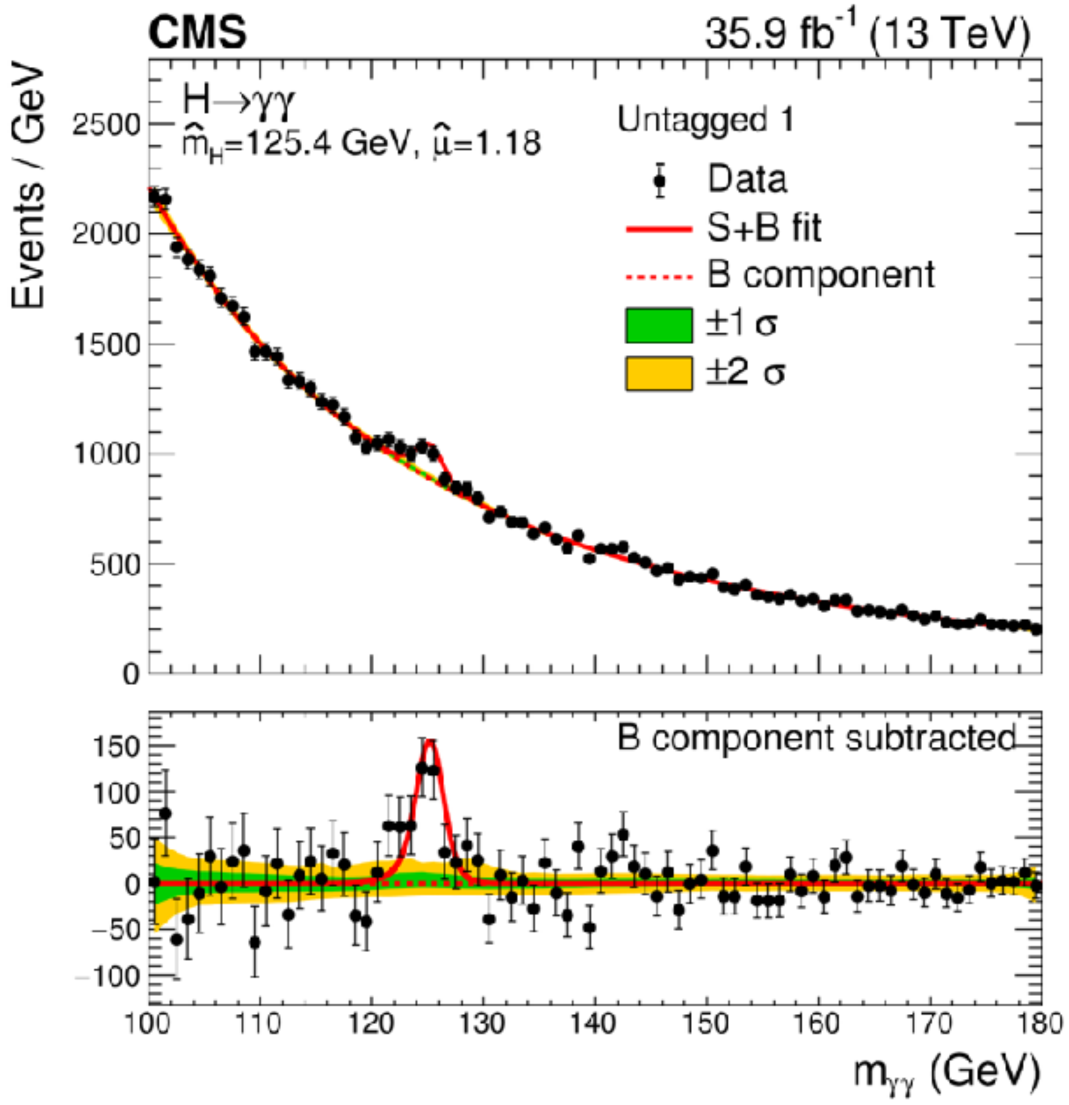
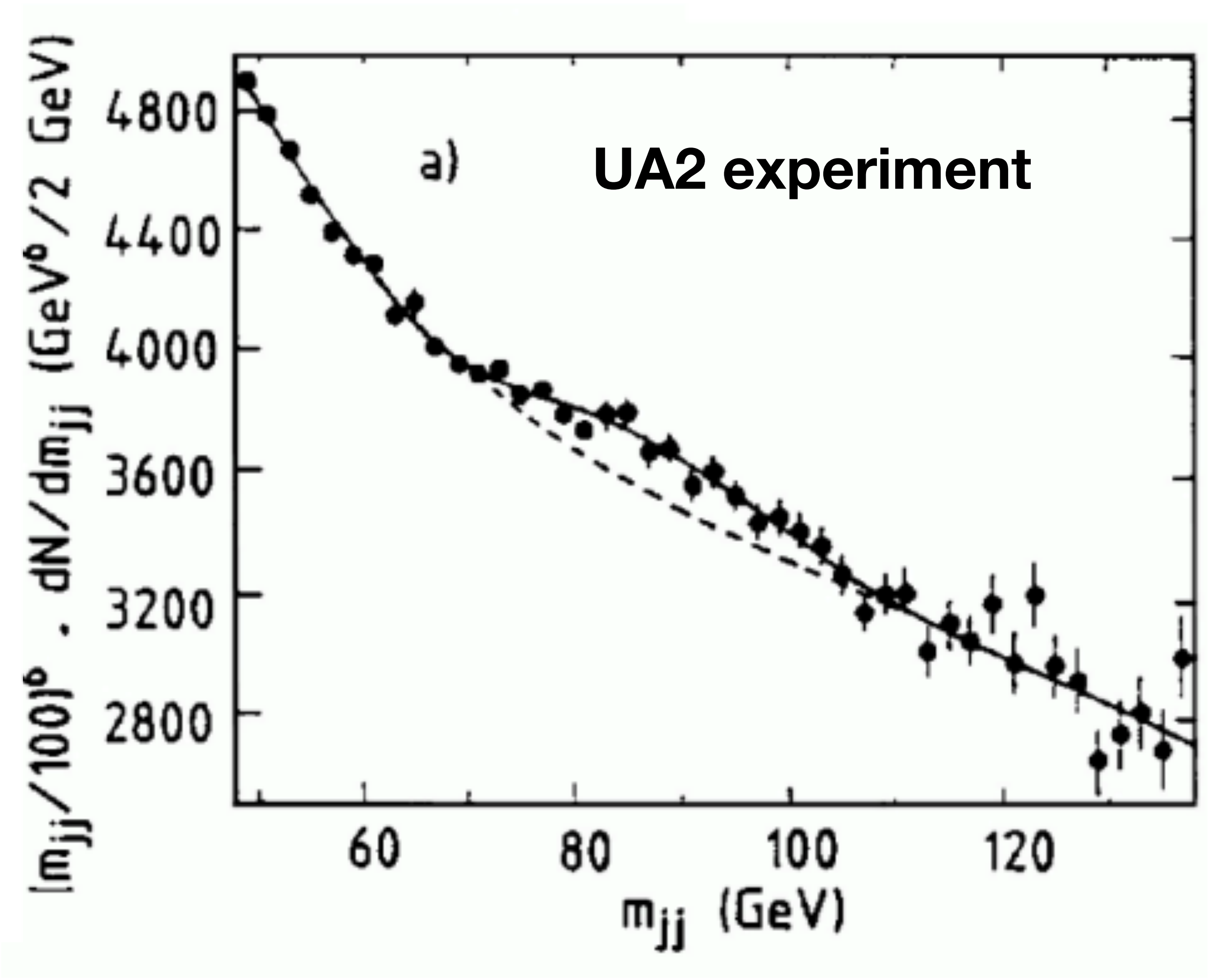
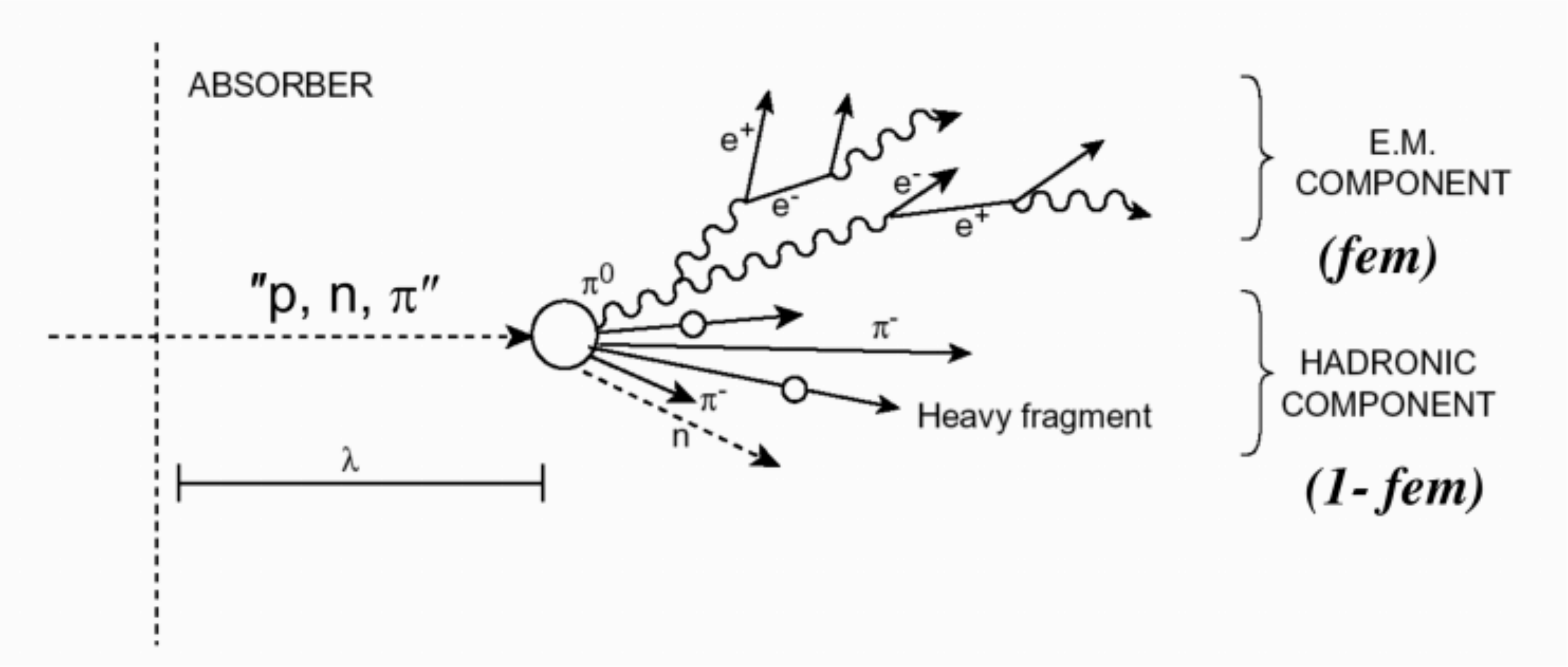




UA2 experiment

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

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

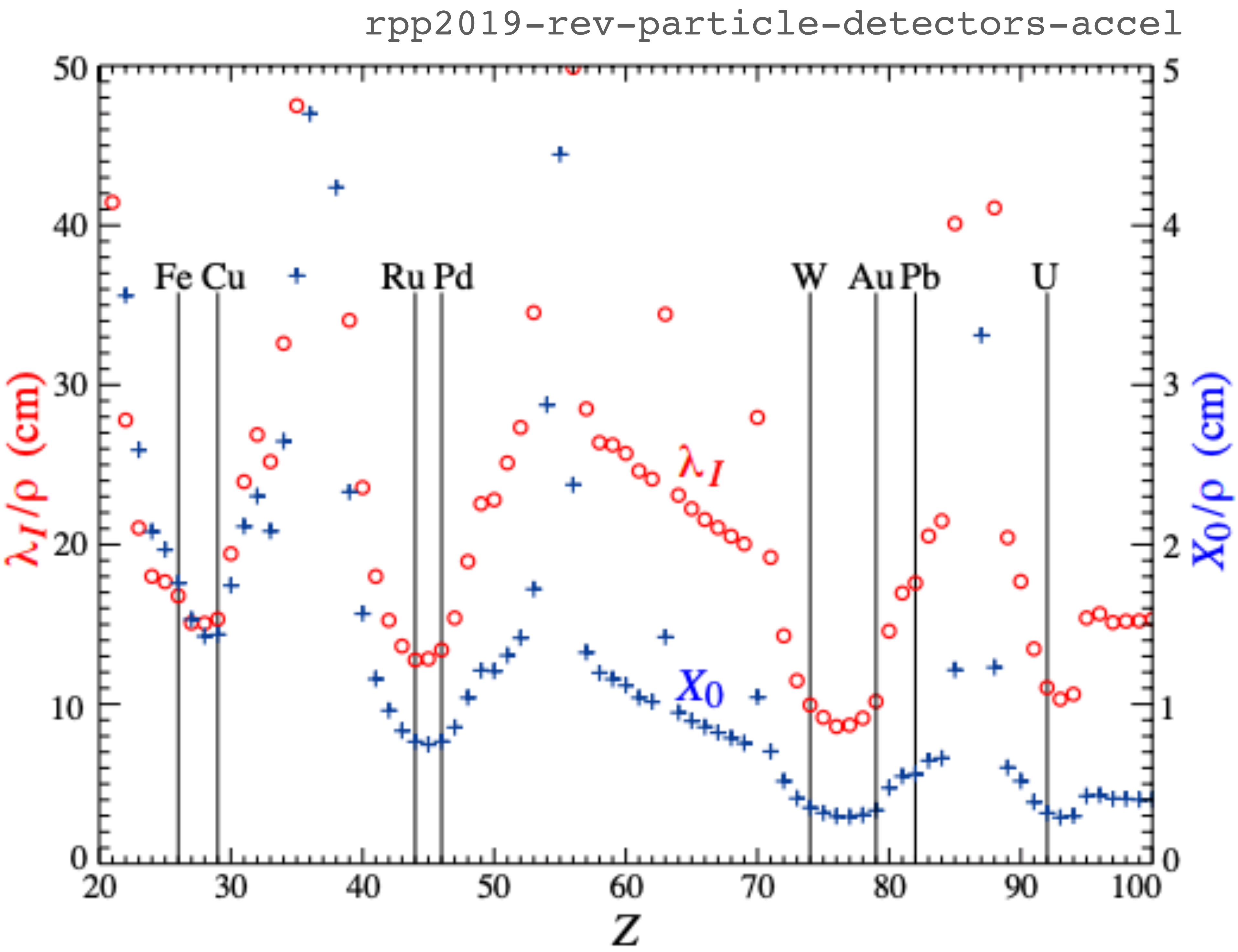
- Typically order of magnitude larger than X_0

- Typically require about 10λ for containment

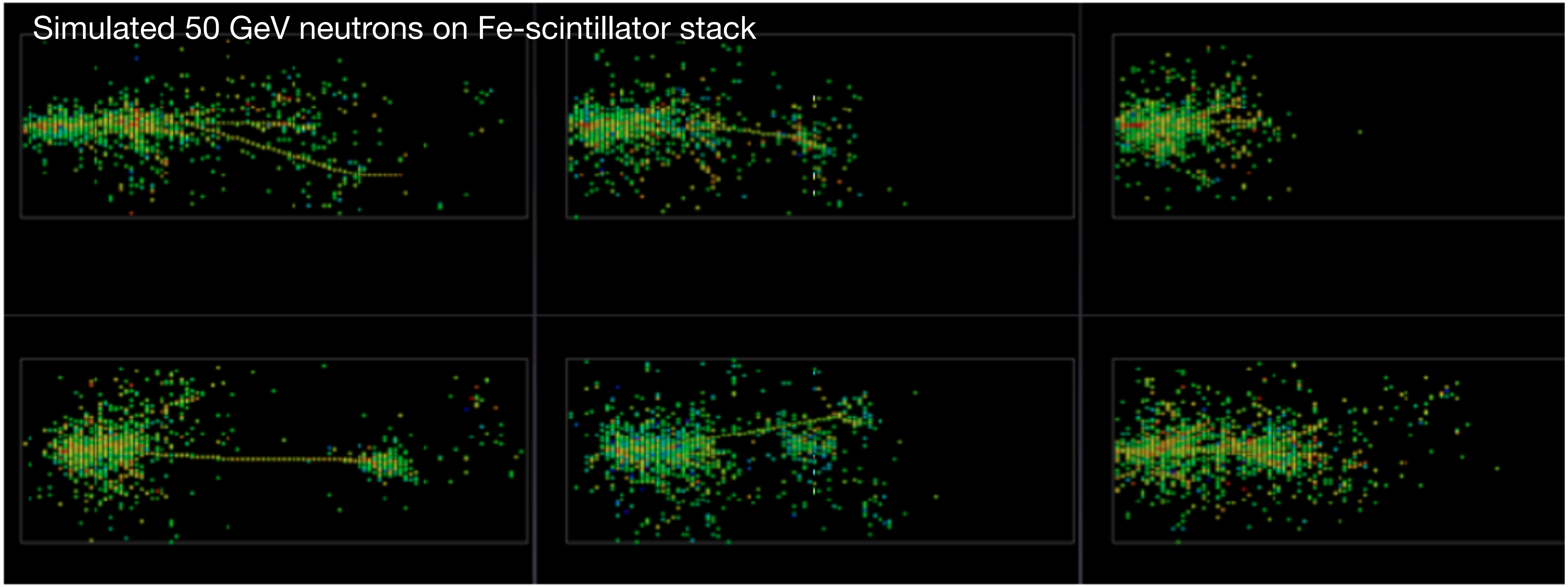
- Hadronic calorimeters are always of the sampling type

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

Material dependence



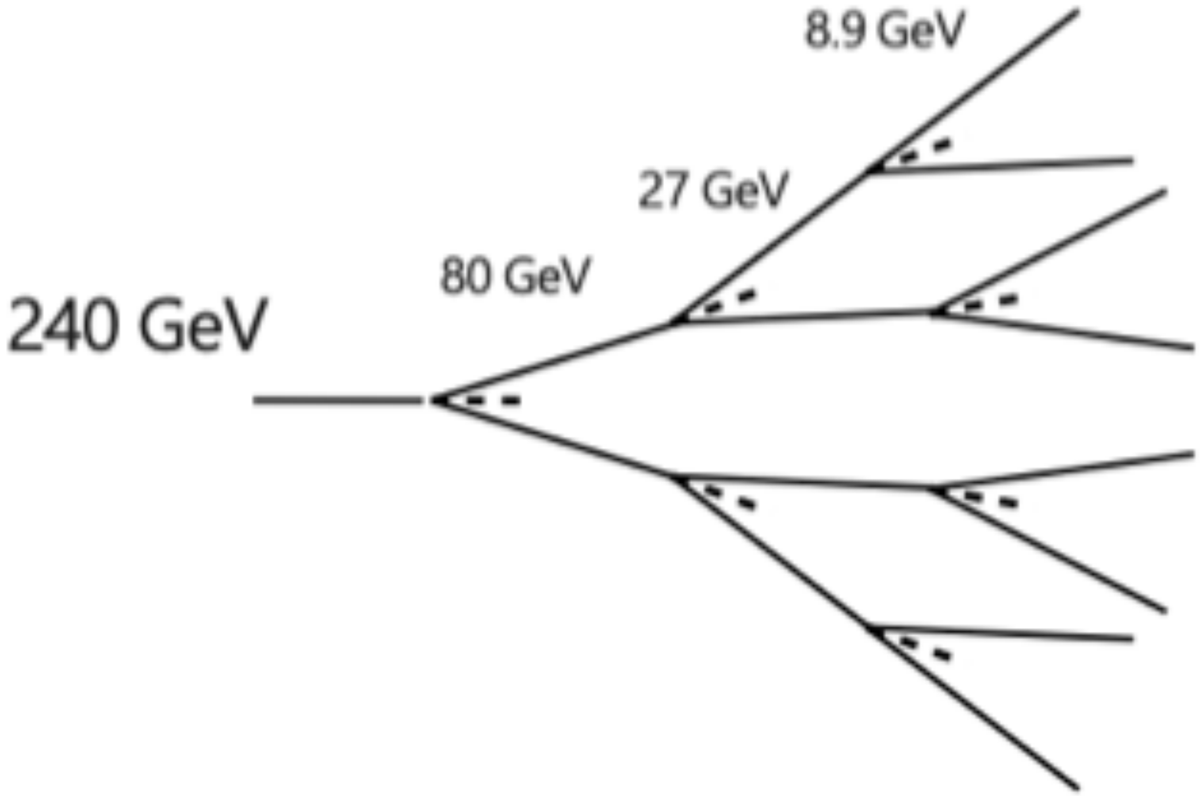
Hadron shower characteristics



- 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 $\langle E \rangle < 3m_\pi$



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

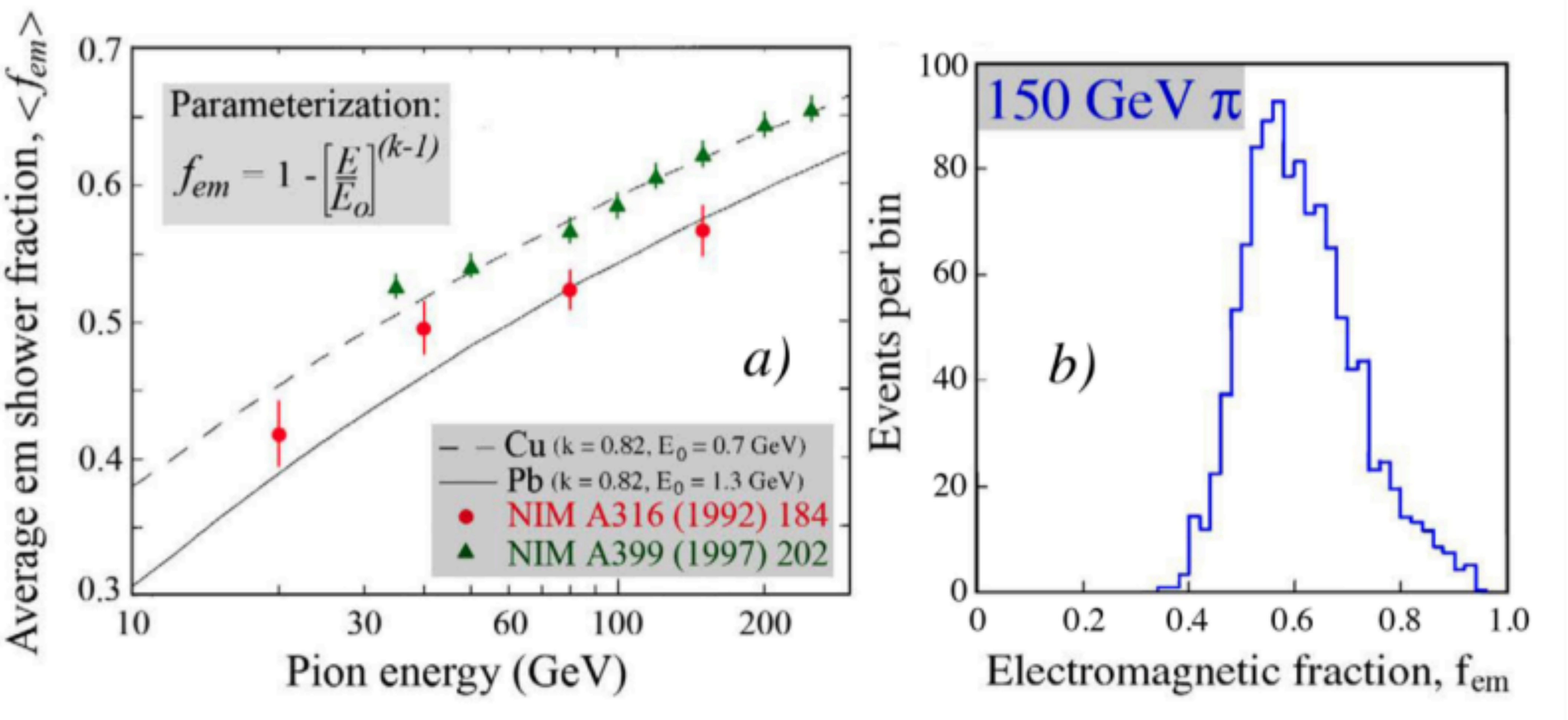
…f_{EM} increases with energy

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

Challenge of hadron calorimeters

Energy dependence of f_{EM}

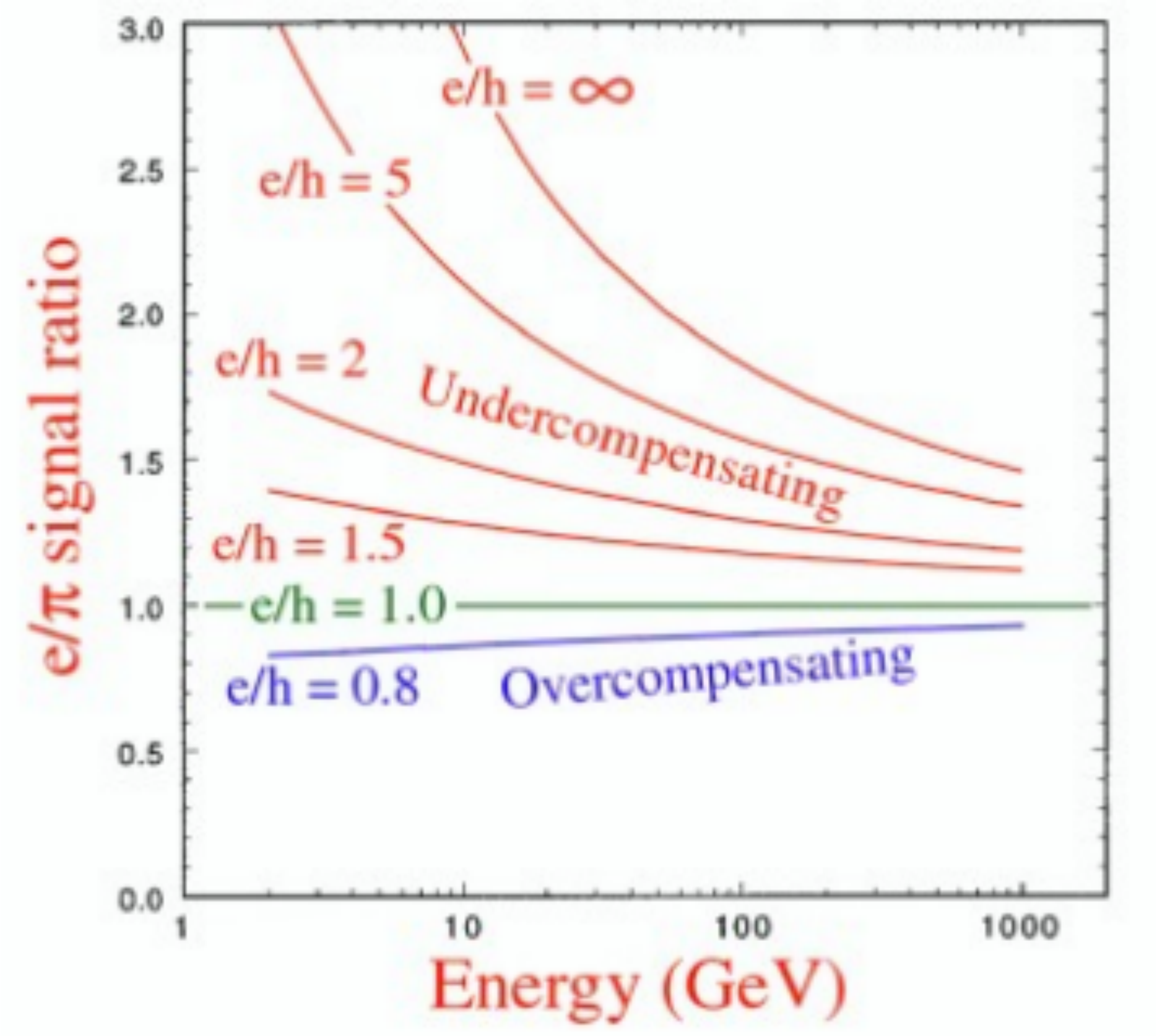
Fluctuations in f_{EM}



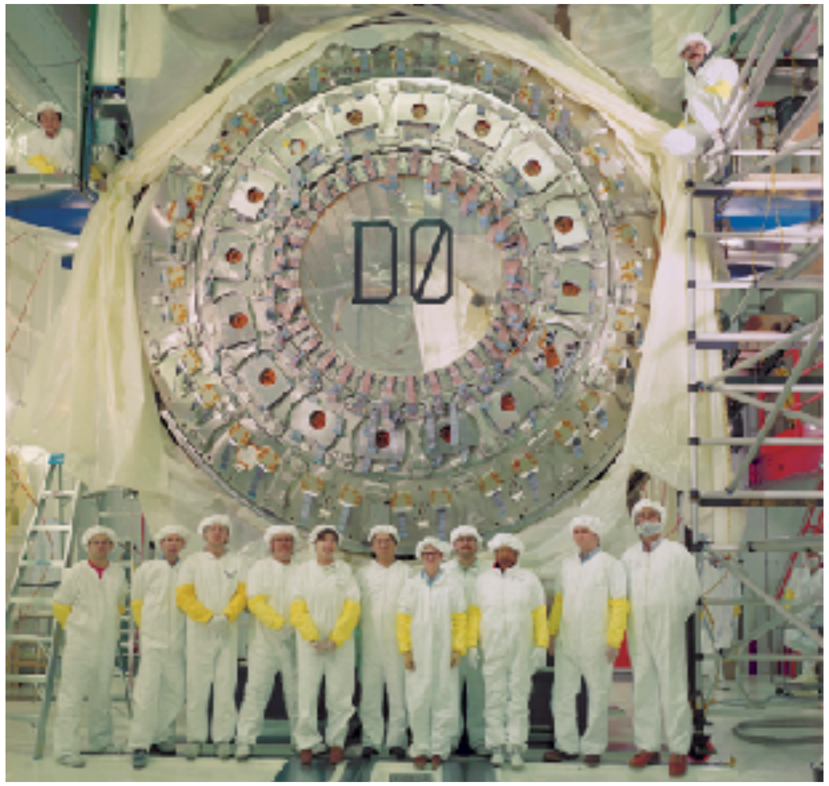
And the calorimeter response to the hadronic component tends to be smaller than to the electromagnetic component.

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.

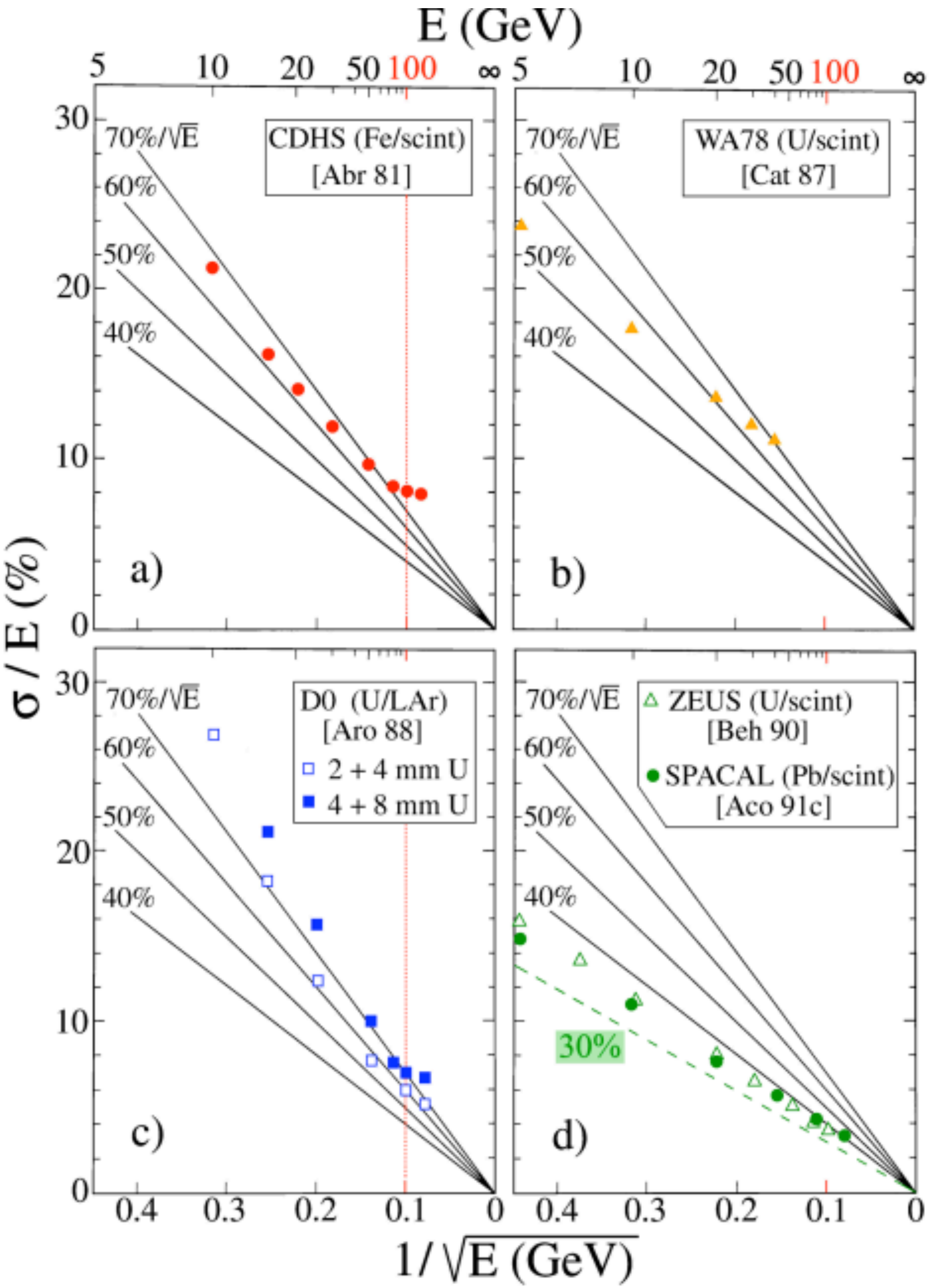
3. Boost the hadronic response

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

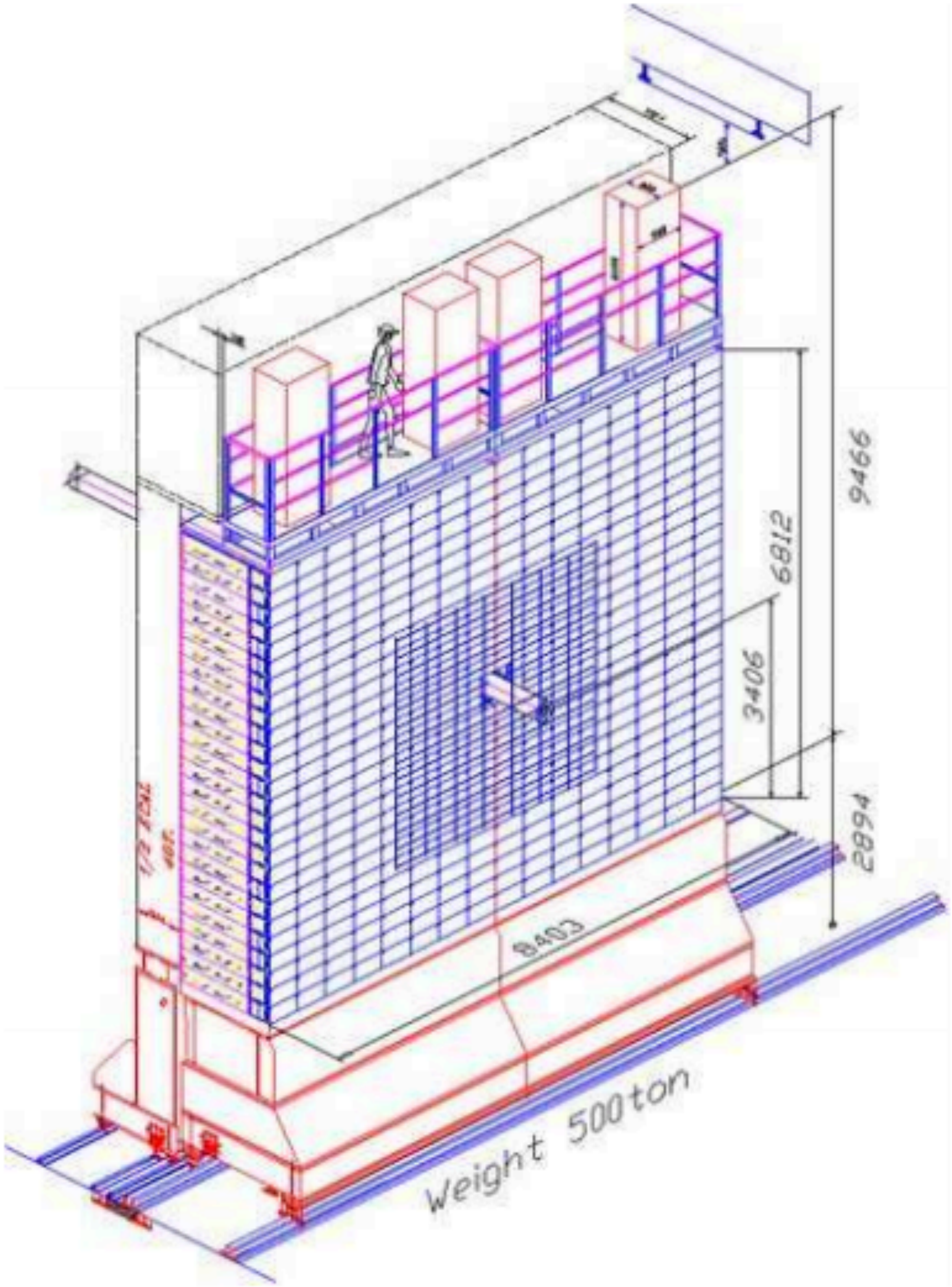
   Uranium (nuclear fission triggered by neutrons).

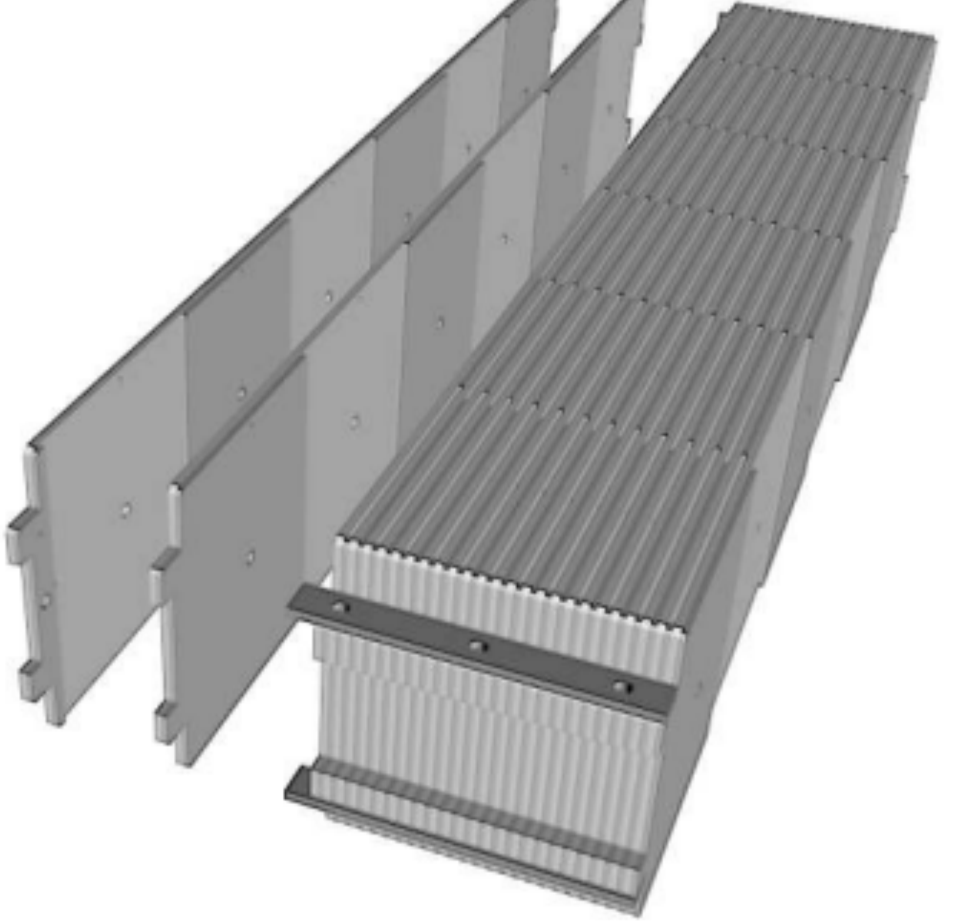
Not compatible with good EM resolution!

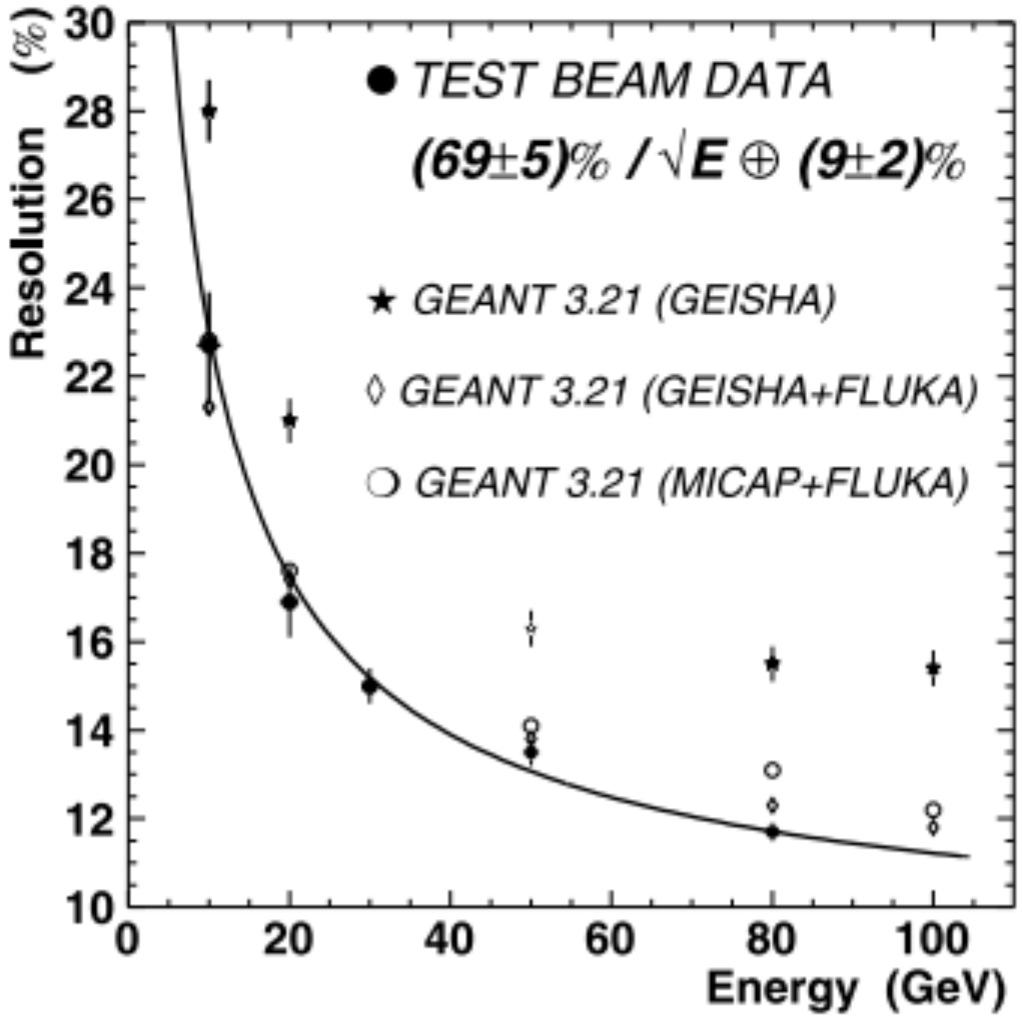
Some example performances



LHCb HCAL

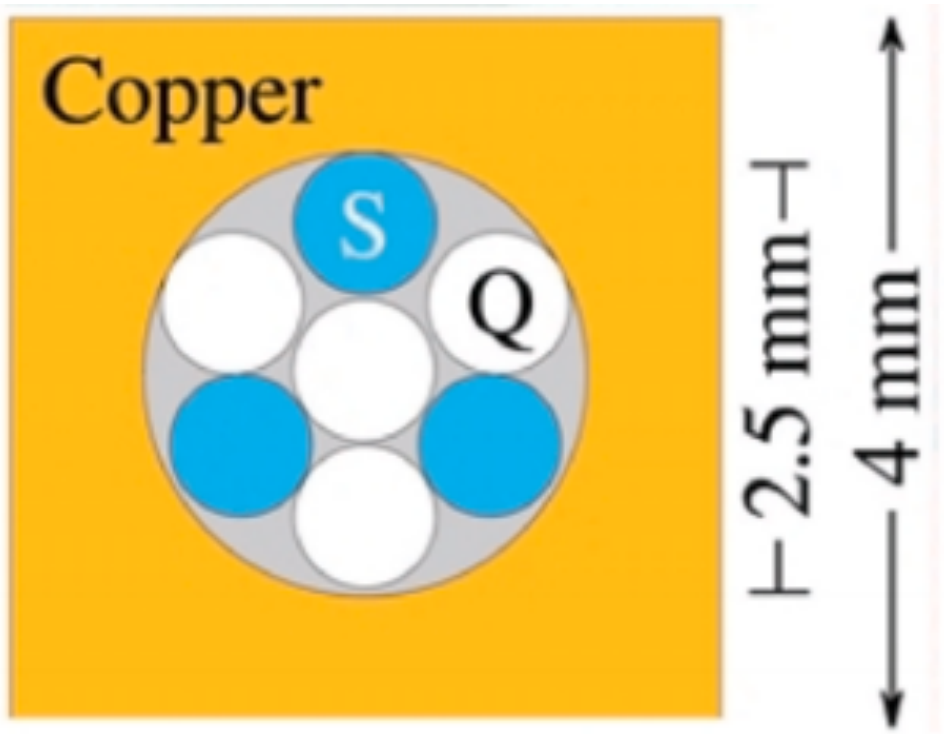

9466
6812
3406
2894
8403
Weight 500ton

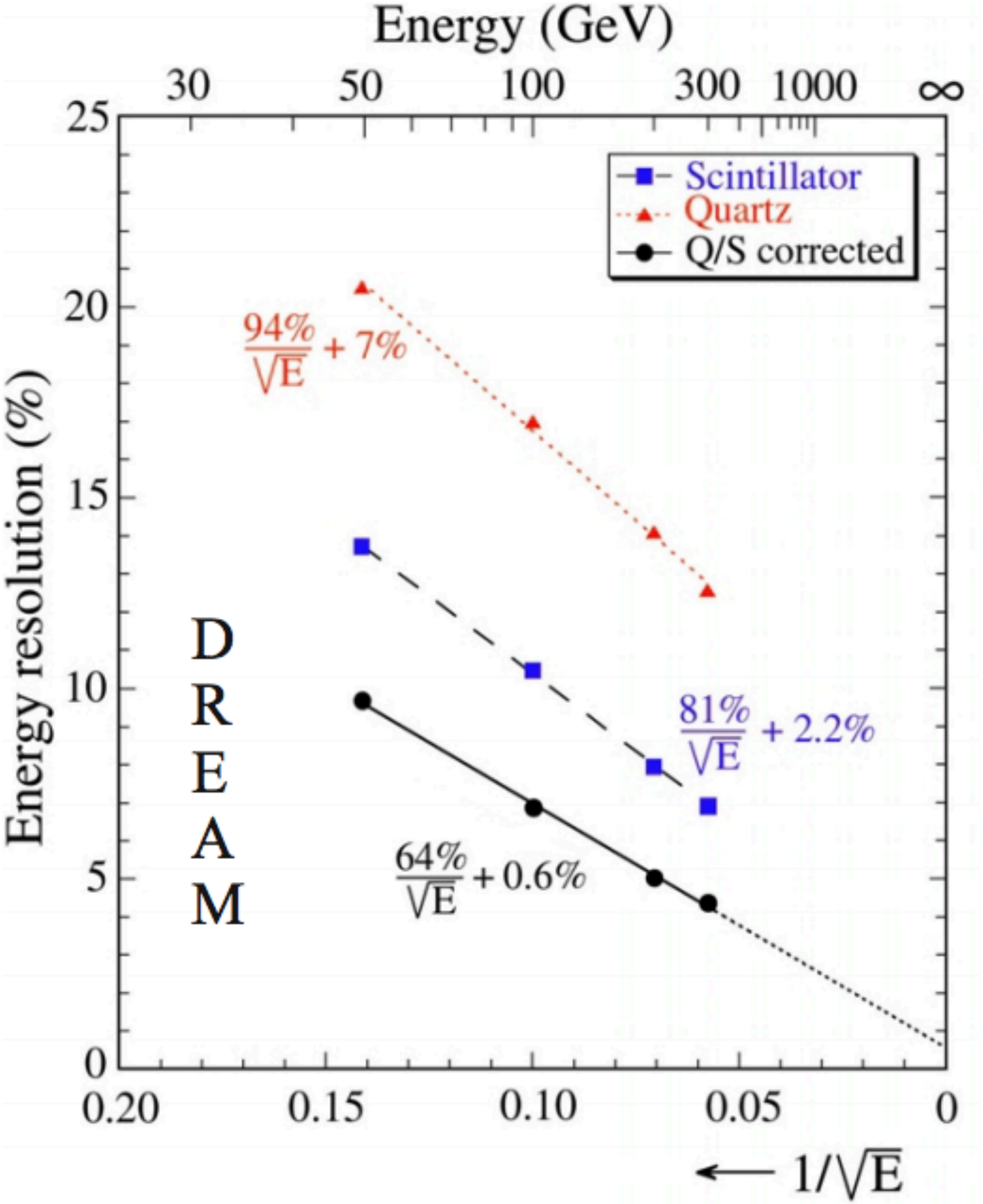



● TEST BEAM DATA
(69±5)% / √E ⊕ (9±2)%
★ GEANT 3.21 (GEISHA)
◊ GEANT 3.21 (GEISHA+FLUKA)
○ GEANT 3.21 (MICAP+FLUKA)
Resolution (%)
10
12
14
16
18
20
22
24
26
28
30
0
20
40
60
80
100
Energy (GeV)

Dual readout R&D (compensation)

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

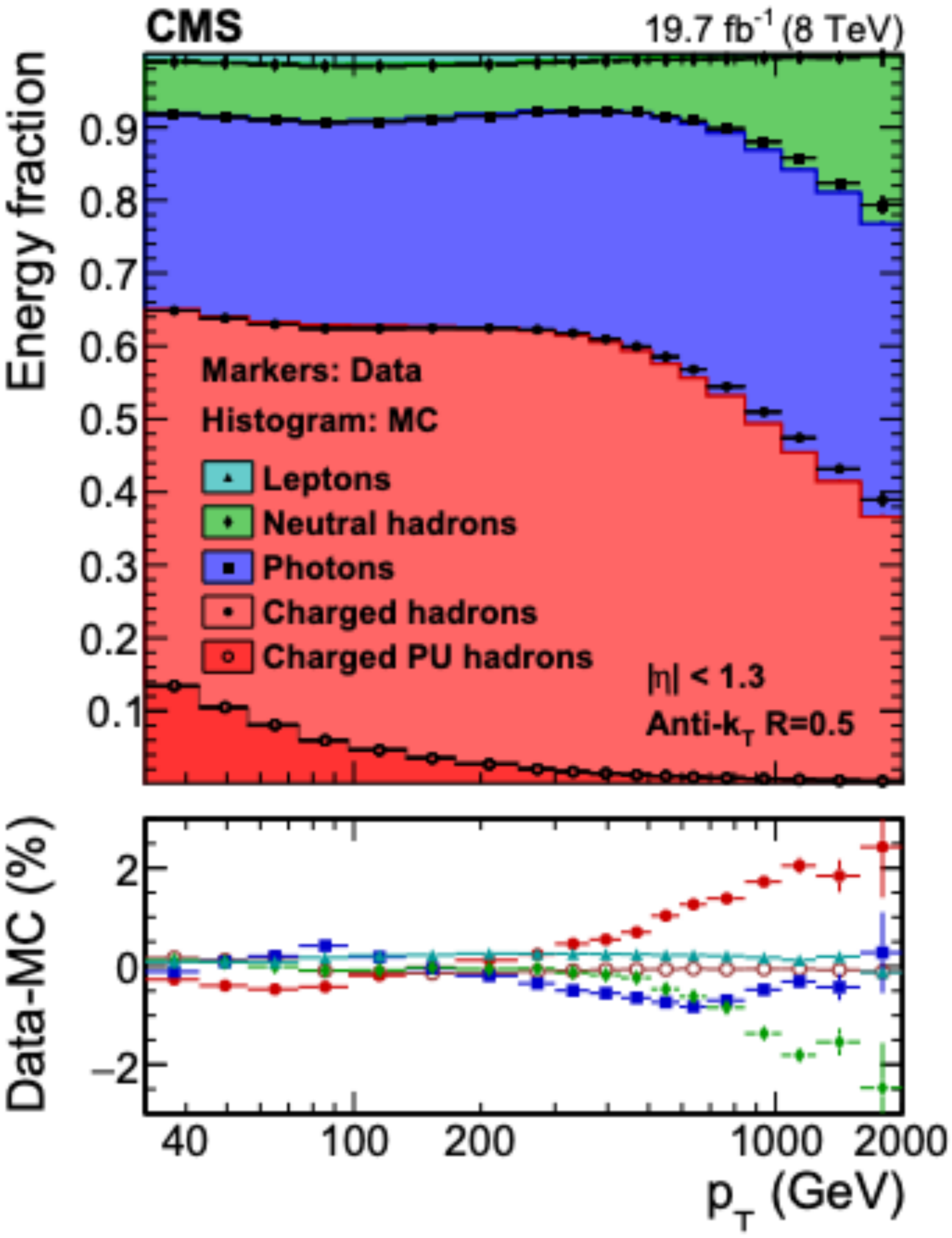


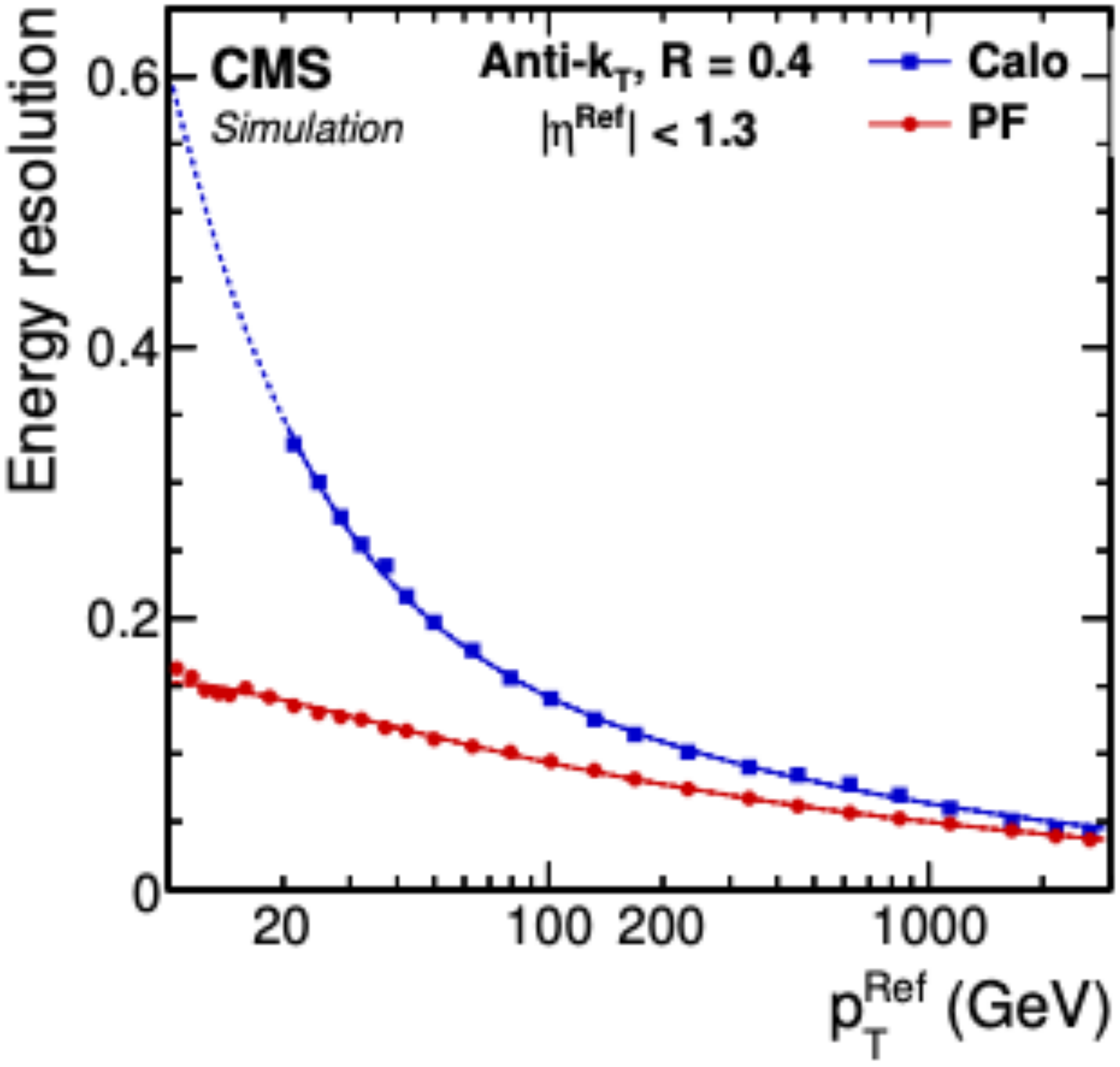


Area of ongoing R&D activity

Particle flow

JINST 12 (2017) P10003





Useful references

Book

Calorimetry: Energy Measurement in Particle Physics, Richard Wigmans

PDG reviews

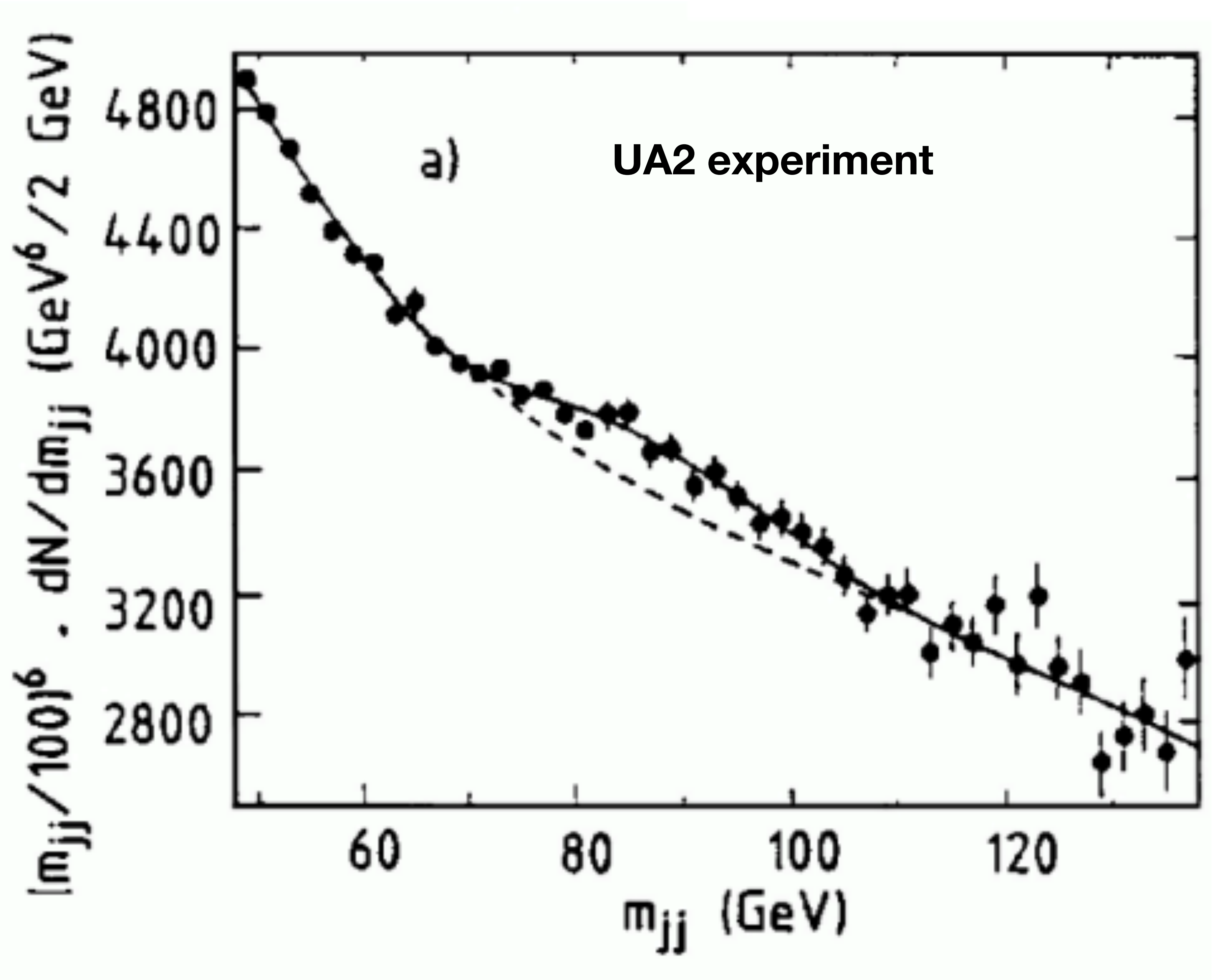
http://pdg.lbl.gov/2019/reviews/rpp2019-rev-passage-particles-matter.pdf
https://pdg.lbl.gov/2019/reviews/rpp2019-rev-particle-detectors-accel.pdf

Animated gifs of shower simulations

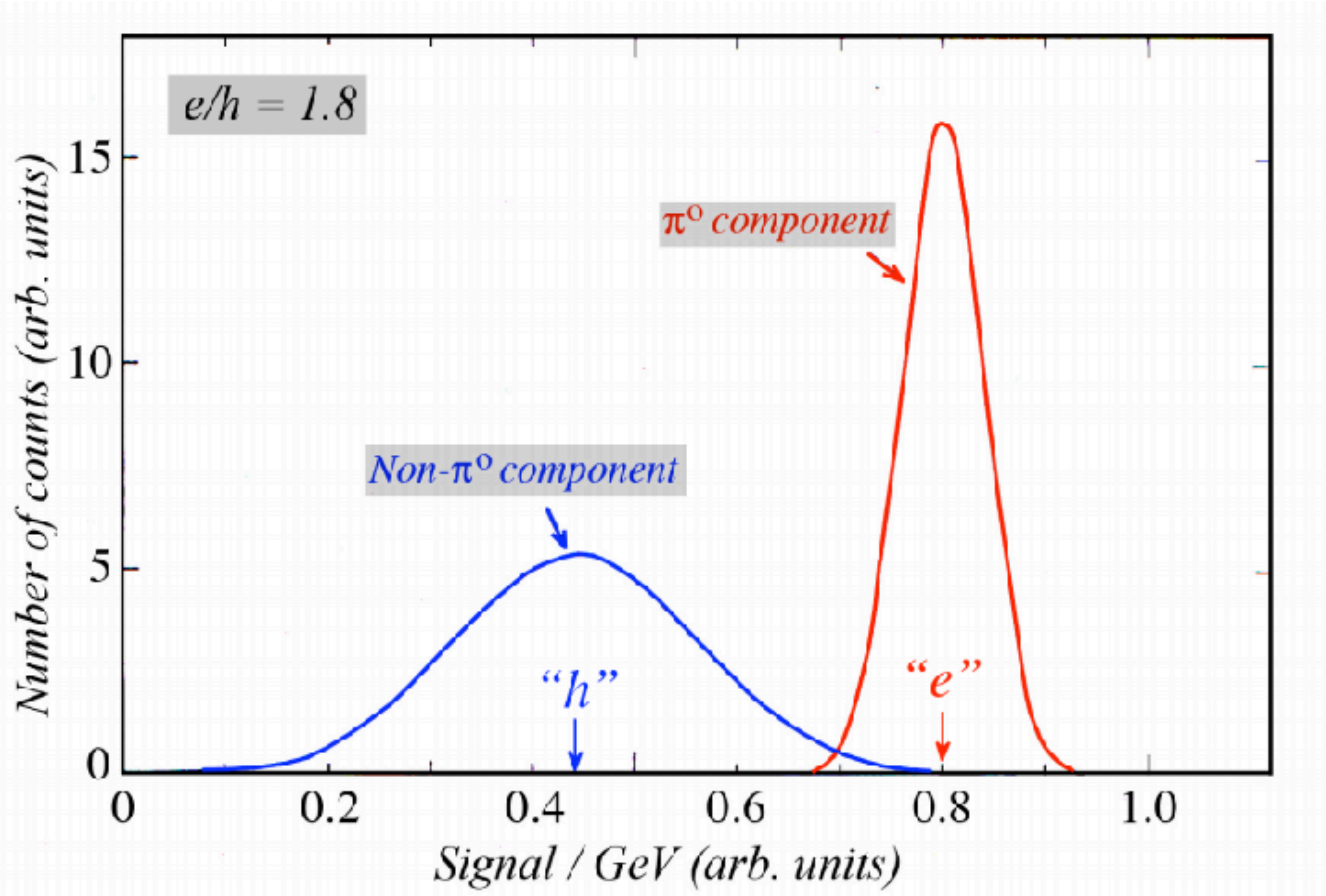
https://www.mpp.mpg.de/~menke/elss/home.shtml

Backup slides

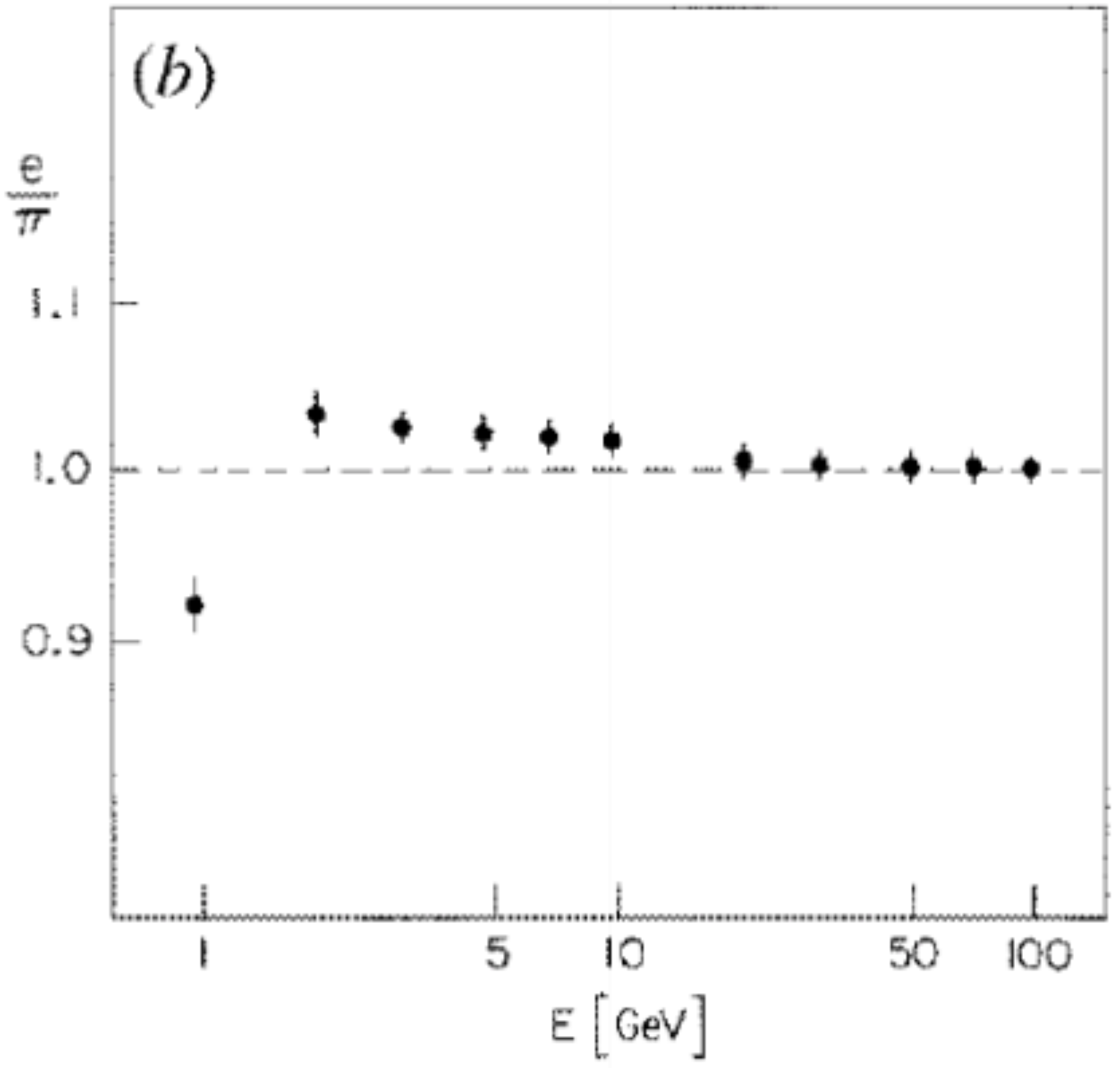
Hadronic showers



e/h example


e/h = 1.8
π° component
Non-π° component
"h"
"e"
Number of counts (arb. units)
0
5
10
15
0
0.2
0.4
0.6
0.8
1.0
Signal / GeV (arb. units)

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.

Lateral containment

- Secondary hadrons have p_T of a few hundred MeV
- Comparable to energy lost in 1λ
- Characteristic lateral extent of 1λ
- High energy showers have pronounced core with exponential halo.

Moliere radius

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