Calorimetry in Subatomic Physics

M.C. Vetterli

Simon Fraser University
and TRIUMF

TSI-GRIDS (TRIUMF)
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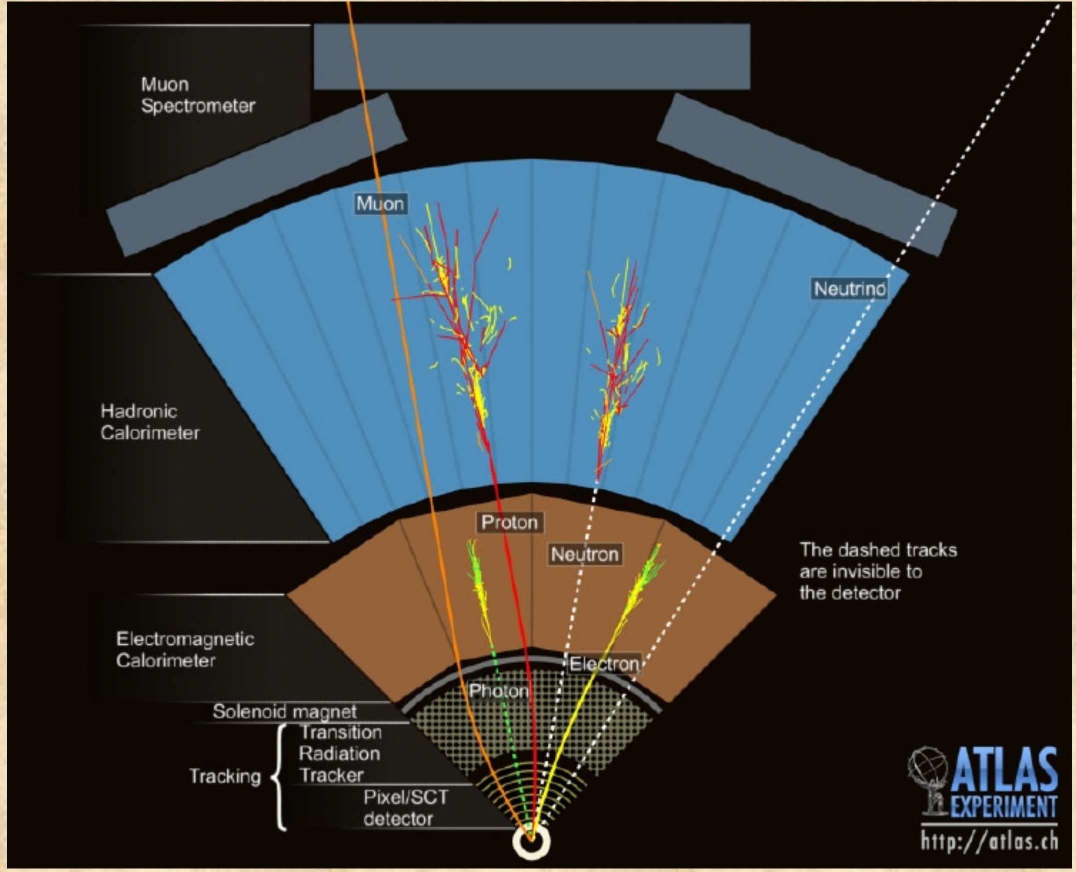
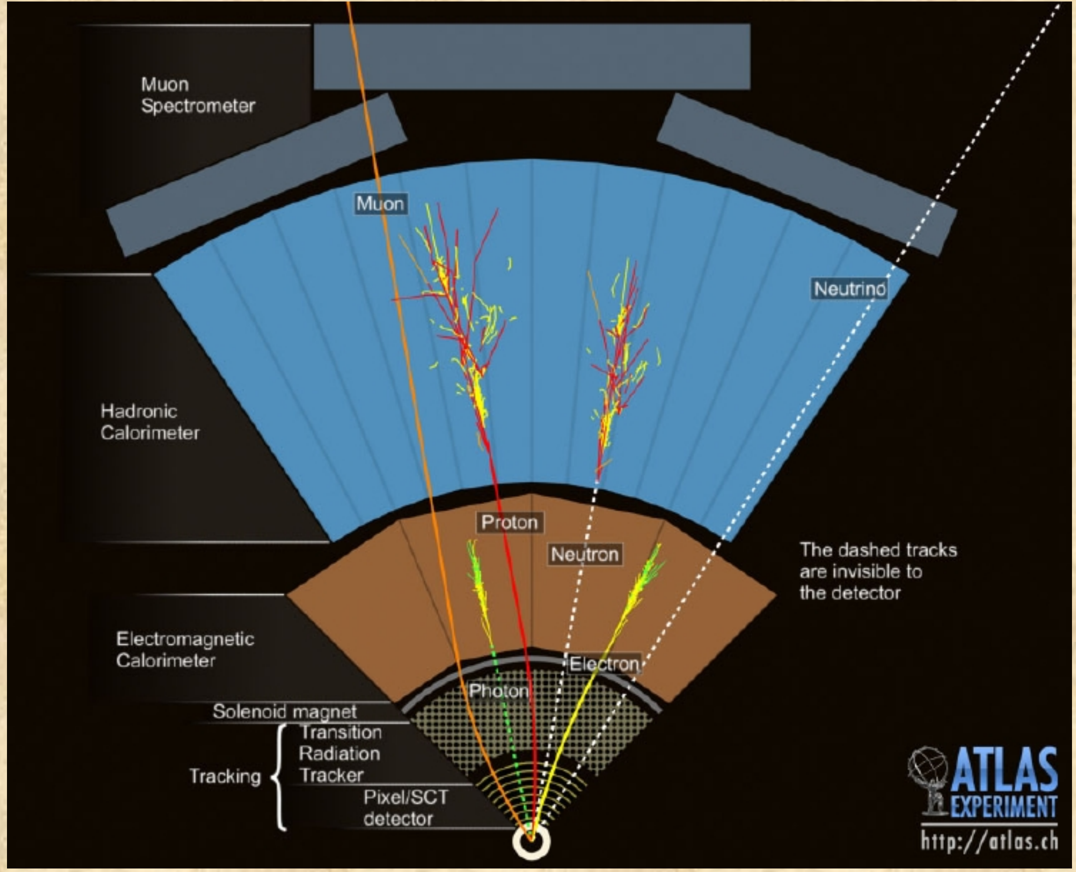


Calorimetry in Subatomic Physics

Outline

1) *What do we want to measure?*
2) *EM Calorimeters*
3) *Hadronic Calorimeters*
4) *Calibration*



There is something wrong with this picture.
There will be a test at the end of the lecture. 😄

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Calorimetry in Subatomic Physics

In addition to the first two references from the first lecture:

1) Fernow, Richard: "Introduction to experimental particle physics"
Cambridge University Press; ISBN 0-521-37940-7

2) Grupen, Claus & Shwartz, Boris: "Particle Detectors"
Cambridge Monographs; ISBN 978-0-521-18795-4

3) Wigmans, Richard: "Calorimetry; Energy Measurement in Particle Physics"
Oxford University Press; ISBN 0-19-850296 6

Various Energy Regimes

- Calorimeters measure the total energy of subatomic particles
- At low/intermediate energies (nuclear physics, TRIUMF), calorimeters are relatively simpler (e.g. no jets)
- NaI, CsI, Ge, total absorption Cerenkov detectors.
  We don't even usually call these detectors calorimeters.
- Particle astrophysics and cosmology require yet other types of instrument, usually detecting very small signals (direct DM detectors) or very large energies (e.g. super high-E cosmic rays; air showers).
- You will hear about Ultra Cold Neutrons in another lecture.
- I will focus on what people usually think of when they hear "calorimeter", i.e. total energy measurements in particle physics.

What do we want to measure?

- Calorimeters measure the total energy of subatomic particles
- The measurement is destructive; the particle(s) is/are absorbed

- EM calorimeter: optimized for electrons, photons
- Hadronic calorimeter: optimized for
  - single particles: p, n, π, d, etc. (charged AND neutral particles)
  - jets (quarks & gluons)
  - taus (decay to pions)
- Missing Transverse Energy (neutrinos, new particles)

  Infer the presence of something by measuring what is NOT there, using conservation of momentum. => hermetic calorimeter systems.

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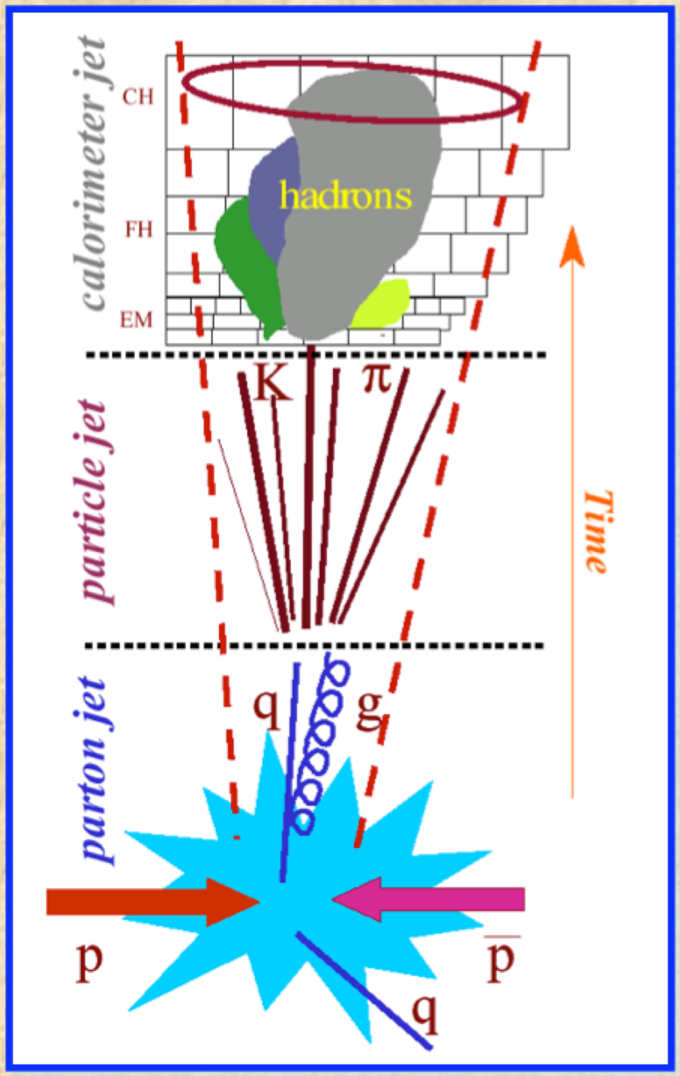
What do we want to measure?

- Electrons, photons, and single particles are pretty straight-forward, but… What is a jet exactly? "A collimated stream of particles originating from a quark or a gluon following a parton shower"
- A "parton shower" is completely different from a "calorimeter shower" (often confusing in meetings)
- (parton vs particle/truth vs calo) jet
- Theorists and experimentalists usually meet at the particle level.

=> VERY complicated!!



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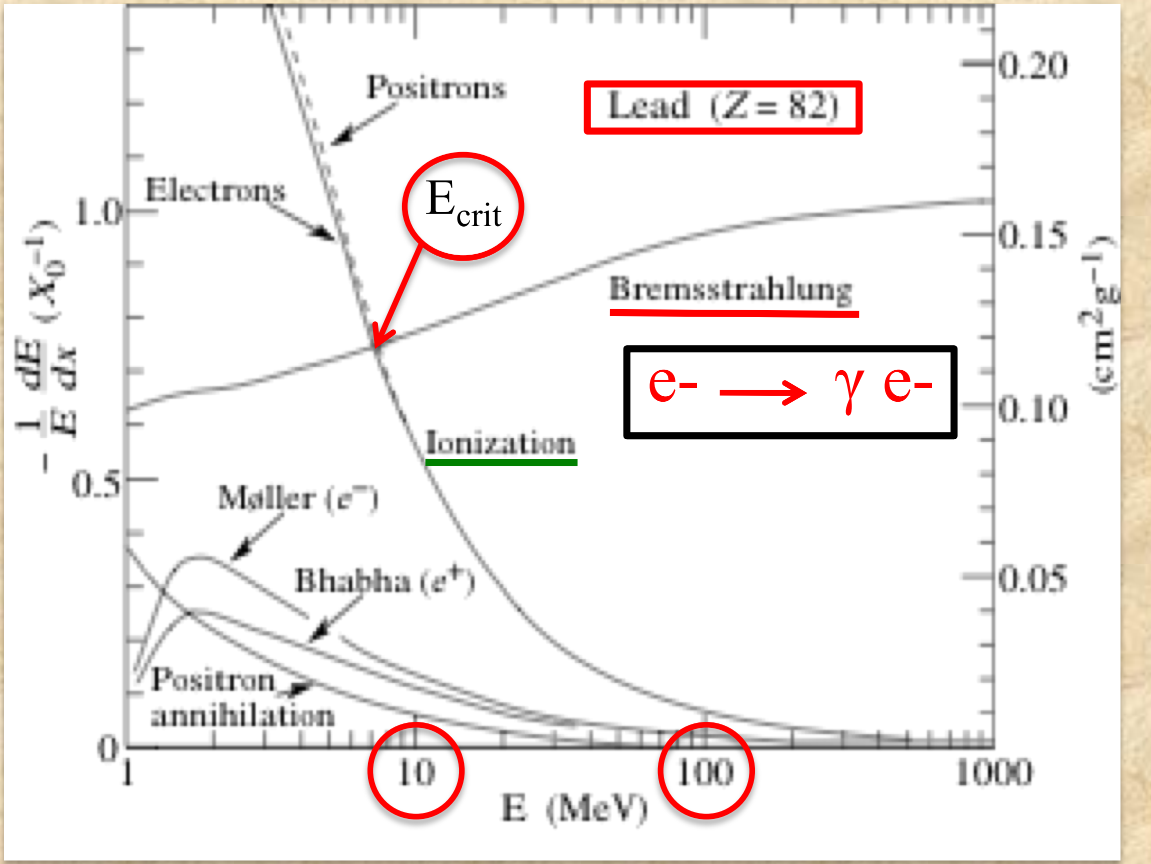
The Situation is Different for Electrons/Positrons

Accelerated charged particles radiate photons ➔ *Bremsstrahlung*
Electrons are light and are therefore more affected by EM fields
➔ *Main energy loss process for high-energy electrons*

$$\sigma_{Brem} \propto \frac{1}{m^2}$$

$$\frac{\sigma_{Brem}(e-)}{\sigma_{Brem}(\mu-)} \approx 42{,}800$$

Not really an issue for heavier particles



Bremsstrahlung

- Charged particles accelerated in an electric field radiate photons with wave number/momentum *k* (Bremsstrahlung).
- Electrons are the lightest charged particles. In practice, they are the only ones to radiate photons and this is the main energy-loss mechanism at high-energy.

$$\frac{d\sigma}{dk} = 5\,\frac{e^2}{\hbar c} Z_1^2 Z_2^2 \left(\frac{mc}{Mv_1}\right)^2 \frac{r_e^2}{k} \ln\frac{Mv_1^2\gamma^2}{k}$$

Goes as 1/(mass of incoming particle)^2
[m(μ)/m(e)]^2 > 40,000

(but at the LHC, we do have to worry about brems for high-energy muons)

The cross-section drops off with increasing photon energy as 1/*k*

=> brems photons are mostly soft

Heavy elements are more efficient at producing brems

=> calo absorbers usually Cu, Pb, Fe.

$$\bar{\theta}_\gamma \approx \frac{mc^2}{E}$$

Brems is forward peaked.

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Remember the Definition of a Radiation Length

$$L_R^{-1} = 4\sigma_0 n_a \ln(183 Z_2^{-1/3})$$

More often called X_0

- The radiation length L_R is the distance over which the initial electron loses all but 1/e of its energy.
- It is also 7/9 of the mean-free-path for pair-production by a high-E photon.
  => Photons go further before the first interaction.
- The behavior of calorimeters made of different materials scales pretty much with radiation length. It's like a unit of length.

$$\left.\frac{dE}{dx}\right|_{rad} \Big/ \left.\frac{dE}{dx}\right|_{coll} = \frac{Z_2 E_i}{1600 mc^2}$$

$$E_{crit} = \frac{1600}{Z_2} mc^2$$

Energy at which $E_{rad} = E_{coll}$

Properties of Materials

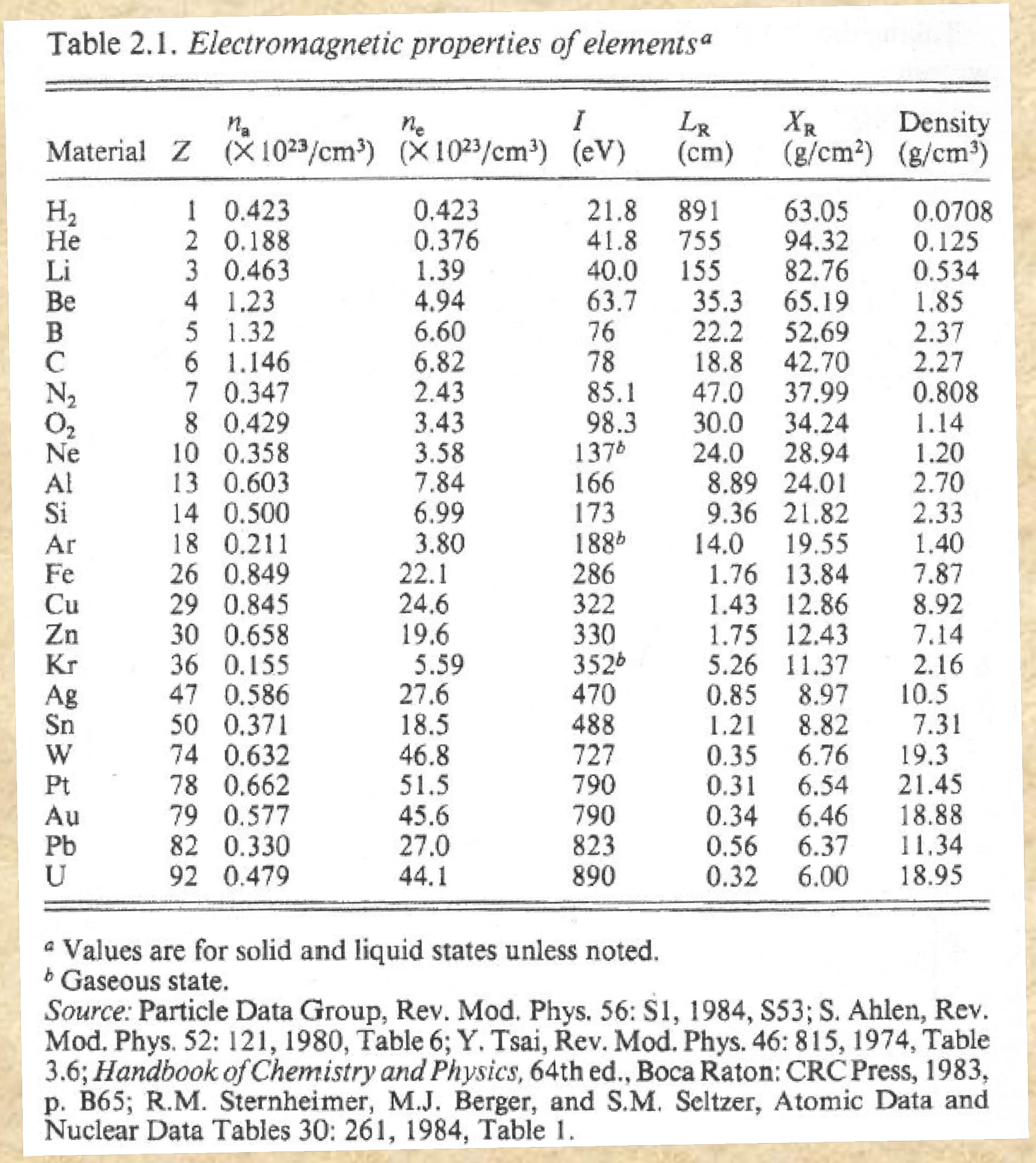


Table 2.1. *Electromagnetic properties of elements*[a]

Material	Z	n_a ($\times 10^{23}$/cm^3)	n_e ($\times 10^{23}$/cm^3)	I (eV)	L_R (cm)	X_R (g/cm^2)	Density (g/cm^3)
H_2	1	0.423	0.423	21.8	891	63.05	0.0708
He	2	0.188	0.376	41.8	755	94.32	0.125
Li	3	0.463	1.39	40.0	155	82.76	0.534
Be	4	1.23	4.94	63.7	35.3	65.19	1.85
B	5	1.32	6.60	76	22.2	52.69	2.37
C	6	1.146	6.82	78	18.8	42.70	2.27
N_2	7	0.347	2.43	85.1	47.0	37.99	0.808
O_2	8	0.429	3.43	98.3	30.0	34.24	1.14
Ne	10	0.358	3.58	137[b]	24.0	28.94	1.20
Al	13	0.603	7.84	166	8.89	24.01	2.70
Si	14	0.500	6.99	173	9.36	21.82	2.33
Ar	18	0.211	3.80	188[b]	14.0	19.55	1.40
Fe	26	0.849	22.1	286	1.76	13.84	7.87
Cu	29	0.845	24.6	322	1.43	12.86	8.92
Zn	30	0.658	19.6	330	1.75	12.43	7.14
Kr	36	0.155	5.59	352[b]	5.26	11.37	2.16
Ag	47	0.586	27.6	470	0.85	8.97	10.5
Sn	50	0.371	18.5	488	1.21	8.82	7.31
W	74	0.632	46.8	727	0.35	6.76	19.3
Pt	78	0.662	51.5	790	0.31	6.54	21.45
Au	79	0.577	45.6	790	0.34	6.46	18.88
Pb	82	0.330	27.0	823	0.56	6.37	11.34
U	92	0.479	44.1	890	0.32	6.00	18.95

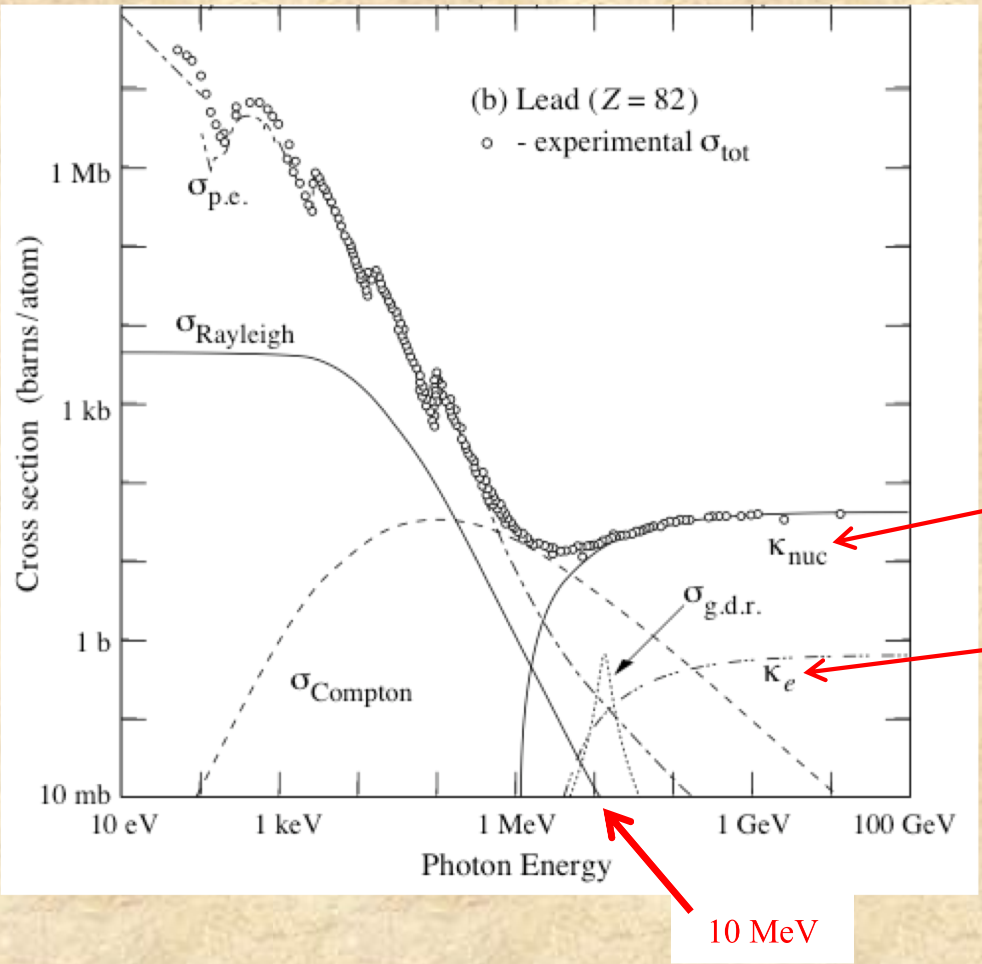
[a] Values are for solid and liquid states unless noted.

[b] Gaseous state.

Source: Particle Data Group, Rev. Mod. Phys. 56: S1, 1984, S53; S. Ahlen, Rev. Mod. Phys. 52: 121, 1980, Table 6; Y. Tsai, Rev. Mod. Phys. 46: 815, 1974, Table 3.6; *Handbook of Chemistry and Physics,* 64th ed., Boca Raton: CRC Press, 1983, p. B65; R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables 30: 261, 1984, Table 1.

Note the very wide variation in L_R between light and heavy elements

Photon Interactions



High-energy photons produce ***e⁺e-*** *pairs*

$$\boxed{\gamma \longrightarrow e^+e^-}$$

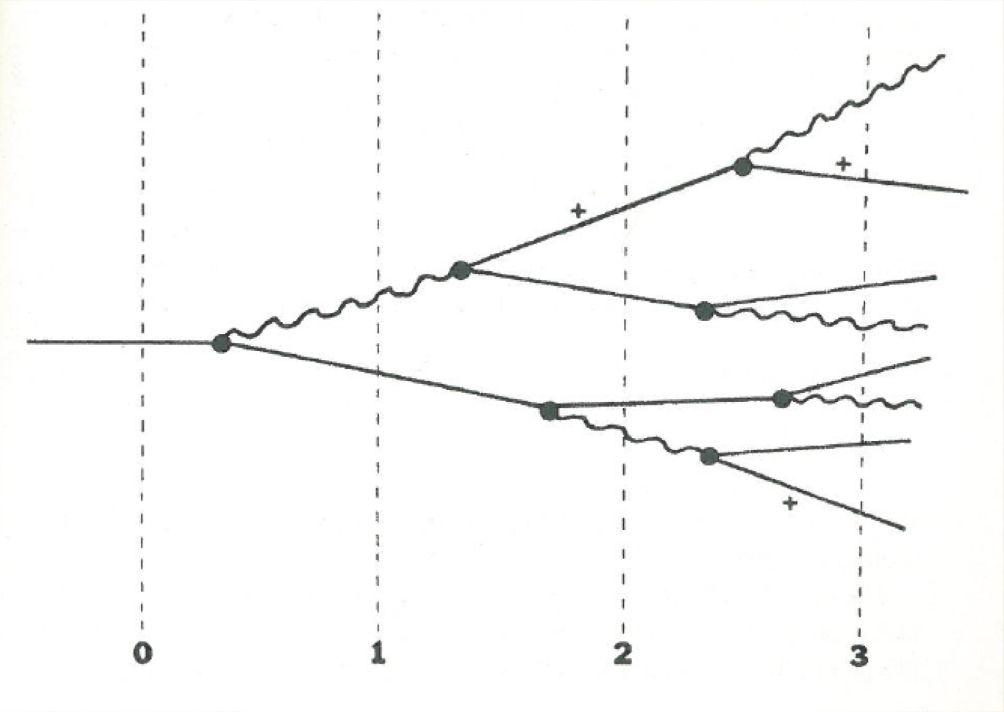
κ_{nuc}: *pair production in the field of a nucleus*

κ_e: *pair production in the field of an atomic electron*

A Simple EM Shower Model

Assume:

- An electron travels 1 X_0, then gives up half its energy to bremsstrahlung.
- A photon with $E>E_c$ travels 1 X_0 and undergoes pair production (E split equally between the e- & e+).
- Electrons with $E<E_c$ lose all their remaining energy to collisions.



Radiation Length

A Simple EM Shower Model

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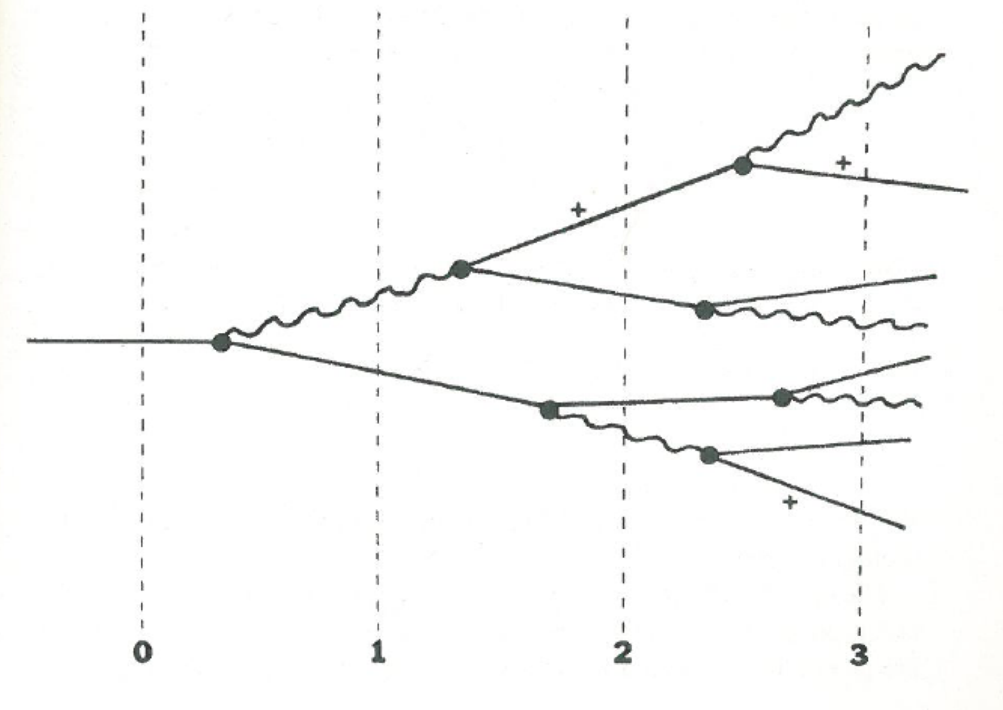
For an incident high-E electron (E_0):

- After 1 X_0, we have 1e- & 1γ ($E_0/2$)
- After 2 X_0, we have 2e-, 1e+, & 1γ ($E_0/4$)
- And so on…



Radiation Length

A Simple EM Shower Model - Predictions

- Number of particles after *t* radiation lengths: $N(t) = 2^t = e^{t\ln 2}$
- Average energy of a particle at depth *t*: $E(t) = E_0/2^t$
- Depth for energy *E'*: $t(E') = \dfrac{\ln(E_0/E')}{\ln 2}$

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A Simple EM Shower Model - Predictions

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- Shower maximum at $E(t) = E_c$: $t_{max} = \frac{\ln(E_0/E_c)}{\ln 2}$ After which there is no more multiplication; all ionization
- Number of particles at maximum: $N_{max} = e^{t_{max} \ln 2} = E_0/E_c$

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Monte Carlo simulations can clearly do better but these equations are not too bad. Fits to data give:

$$\boxed{t_{max} = 3.9 + \ln E_0} \qquad \boxed{N_{max} = 8.46\, E_0^{0.935}}$$

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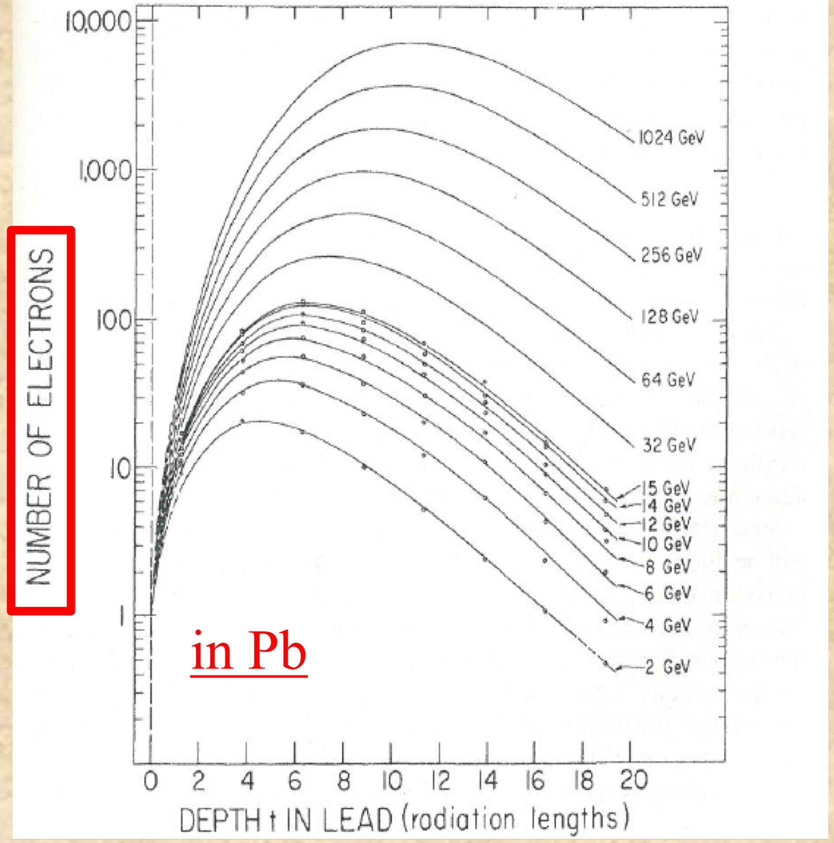
EM Shower Profiles

Figure 11.2 Shower profiles in lead. The number of electrons should be multiplied by a normalization factor of 0.79. (D. Müller, Phys. Rev. D 5: 2677, 1972.)



in Pb

Note the relatively slow decrease after the shower maximum in the MC simulation (abrupt in toy model)

EM Shower Profiles

Moliere Radius: Scale of the transverse shower development $\boxed{\rho_m \approx 7A/Z \; g/cm^2}$

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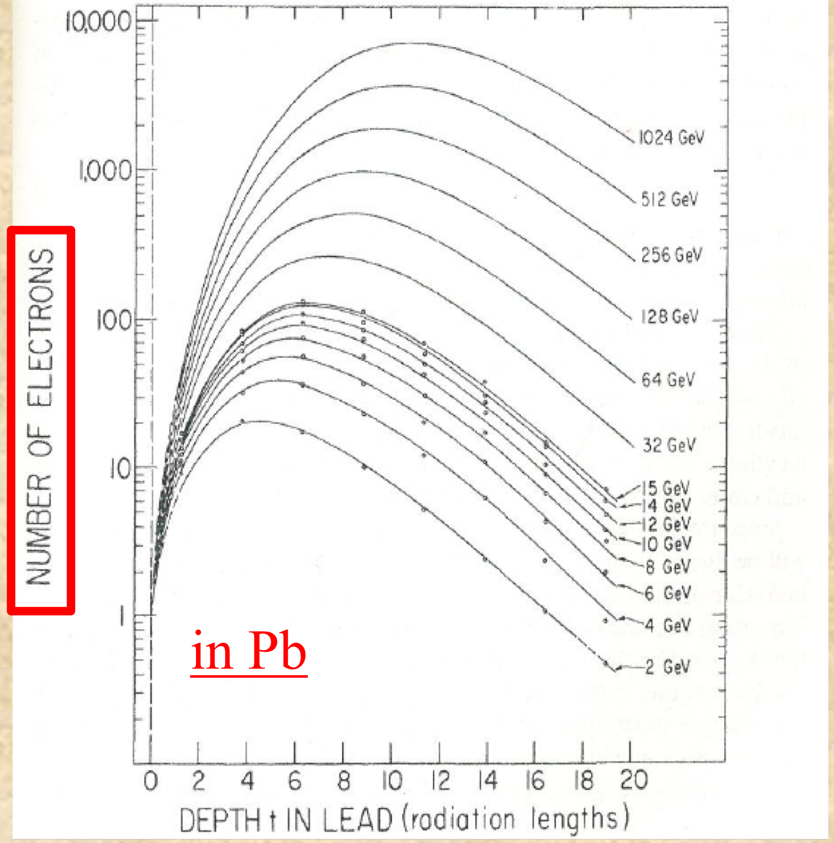
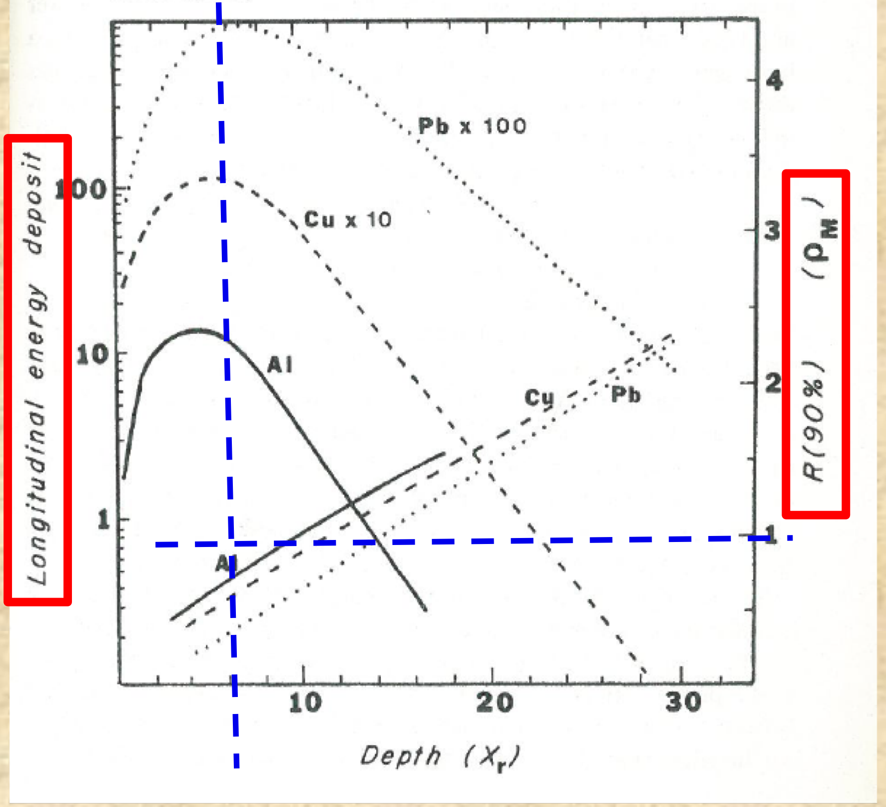


Figure 11.3 Longitudinal development of electromagnetic showers in different materials. Right scale shows radii for 90% shower containment. (C. Fabjan and T. Ludlam, adapted with permission from the Annual Review of Nuclear and Particle Science, Vol. 32, © 1982 by Annual Reviews, Inc.)



Note the relatively slow decrease after the shower maximum in the MC simulation (abrupt in toy model)

Note the shower width increases with depth, but most of the shower (95%) is within 2 ρ_m; Almost independent of incident energy.

Homogeneous Calorimeters

- Some materials can generate EM showers (e.g. high-Z) but also detect the photons and the ionization. Since the absorber and the detection medium are the same, these are called homogeneous calorimeters.
- Main advantage is resolution, but they are expensive and difficult to make on a large scale.
- Sensitive to: scintillation light (scintillator crystals, liquid noble gases), ionization (liquid noble gases), Cerenkov light (lead glass, heavy transparent crystals)
- Example #1: CMS EM calo

  80,000 lead-tungstate ($PbWO_4$ or PWO) crystals (barrel: 22 x 22 x 230 mm^3)

  $X_0 = 0.89$ cm ; $\rho_m = 2.19$ cm

  radiation resistant, but relatively low light output (~50 photons/MeV)

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{155\,MeV}{E} \oplus 0.55\%$$

(See slide 23)

Materials for Homogeneous Calorimeters

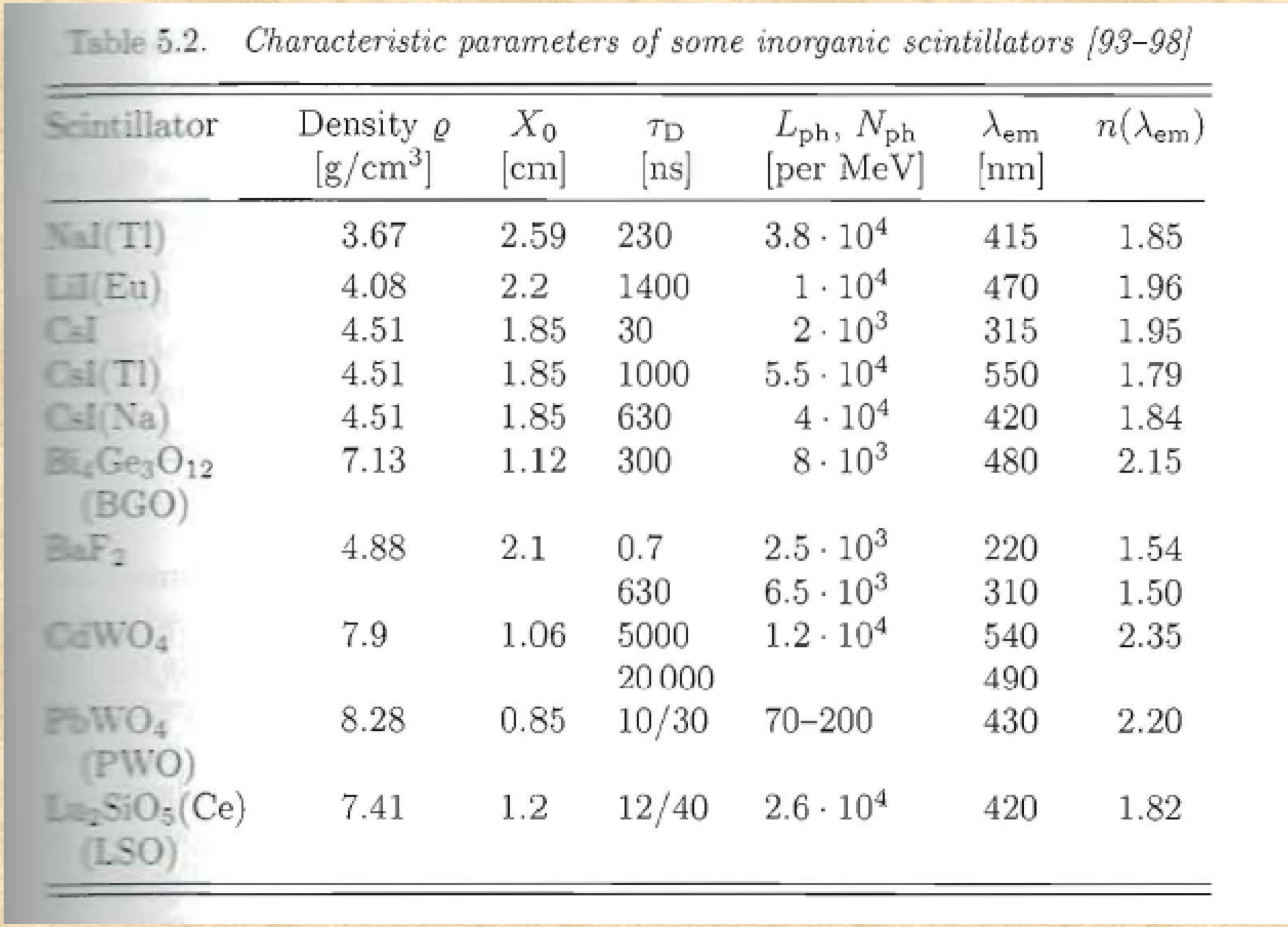


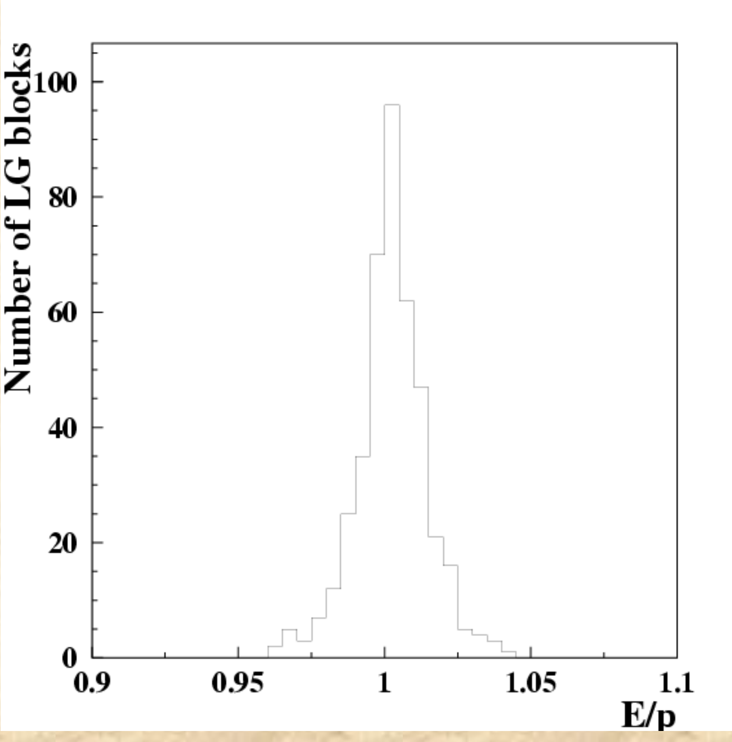
Table 5.2. *Characteristic parameters of some inorganic scintillators [93–98]*

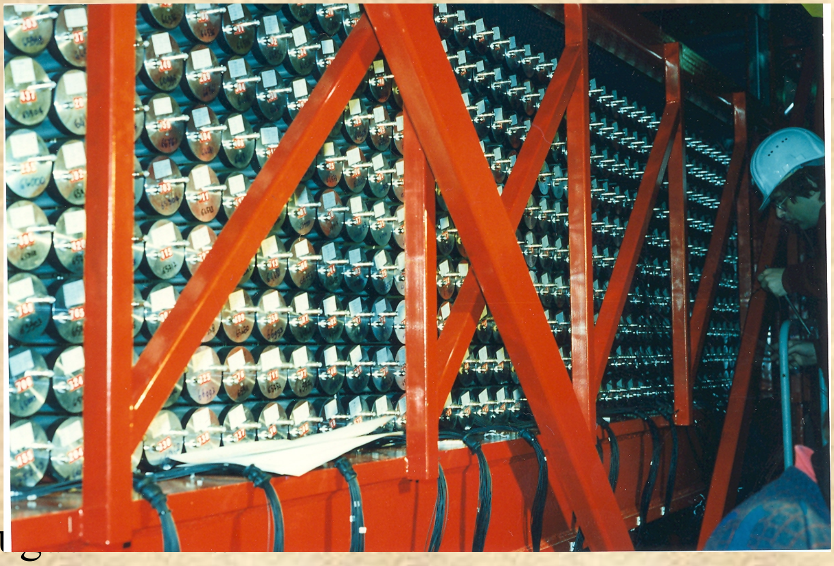
Scintillator	Density ϱ [g/cm^3]	X_0 [cm]	τ_D [ns]	L_{ph}, N_{ph} [per MeV]	λ_{em} [nm]	$n(\lambda_{em})$
NaI(Tl)	3.67	2.59	230	$3.8 \cdot 10^4$	415	1.85
LiI(Eu)	4.08	2.2	1400	$1 \cdot 10^4$	470	1.96
CsI	4.51	1.85	30	$2 \cdot 10^3$	315	1.95
CsI(Tl)	4.51	1.85	1000	$5.5 \cdot 10^4$	550	1.79
CsI(Na)	4.51	1.85	630	$4 \cdot 10^4$	420	1.84
$Bi_4Ge_3O_{12}$ (BGO)	7.13	1.12	300	$8 \cdot 10^3$	480	2.15
BaF_2	4.88	2.1	0.7	$2.5 \cdot 10^3$	220	1.54
			630	$6.5 \cdot 10^3$	310	1.50
$CdWO_4$	7.9	1.06	5000	$1.2 \cdot 10^4$	540	2.35
			20 000		490	
$PbWO_4$ (PWO)	8.28	0.85	10/30	70–200	430	2.20
Lu_2SiO_5(Ce) (LSO)	7.41	1.2	12/40	$2.6 \cdot 10^4$	420	1.82

Homogeneous Calorimeters

Example #2: HERMES calo (27 GeV electrons on a fixed target at DESY)
2 x 420 F101 lead glass blocks [9x9 cm^2 x 50 cm (18 X_0)]
F101 is radiation resistant

$$\frac{\sigma(E)}{E}\,[\%] = \frac{(5.1 \pm 1.1)}{\sqrt{E\,[GeV]}} + (1.5 \pm 0.5)$$





Sampling Calorimeters

- When the absolute best resolution is not needed, it is simpler and much cheaper to use a sampling calorimeter.
- Alternate the absorber (high-Z, high-density material to efficiently produce calo showers) and the detector.
- In this way you sample only a fraction of the calo shower, but the signal is still proportional to the initial particle energy.
- Some example geometries:
  - metal– scintillator sandwich
  - metal – Liquid Argon (e.g. ATLAS)
  - metal – proportional wire chambers
- Many geometries possible using light guide/wavelength shifter to remove the readout from the magnetic field if needed.

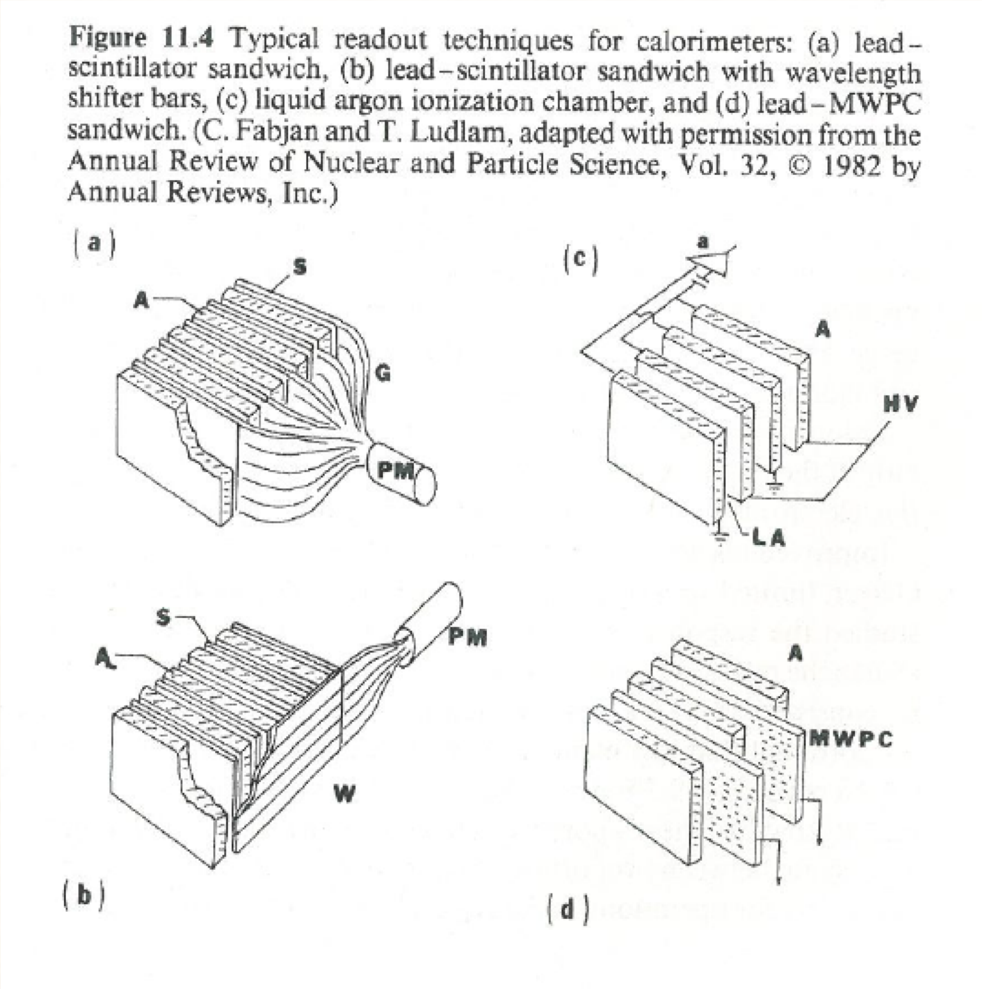


Figure 11.4 Typical readout techniques for calorimeters: (a) lead–scintillator sandwich, (b) lead–scintillator sandwich with wavelength shifter bars, (c) liquid argon ionization chamber, and (d) lead–MWPC sandwich. (C. Fabjan and T. Ludlam, adapted with permission from the Annual Review of Nuclear and Particle Science, Vol. 32, © 1982 by Annual Reviews, Inc.)

Resolution

The resolution of a calorimeter has many components:

- Fluctuation in the fraction of the energy deposited in the active area (sampling fluctuations)
- Leakage of energy both laterally, but mostly out the back at higher E
- Noise in the active layers
- Photocathode statistics / gain variations
- Electronic noise
- Pileup (big at the LHC)

If the fluctuations follow Poisson statistics: $\sigma(N)/N = 1/\sqrt{N}$

$$\boxed{\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

a: sampling fluctuations / stochastic term
b: noise term (electronic noise, pileup)
c: overall calibration error (e.g. variation of response from cell to cell
$\oplus$ means adding in quadrature

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Resolution

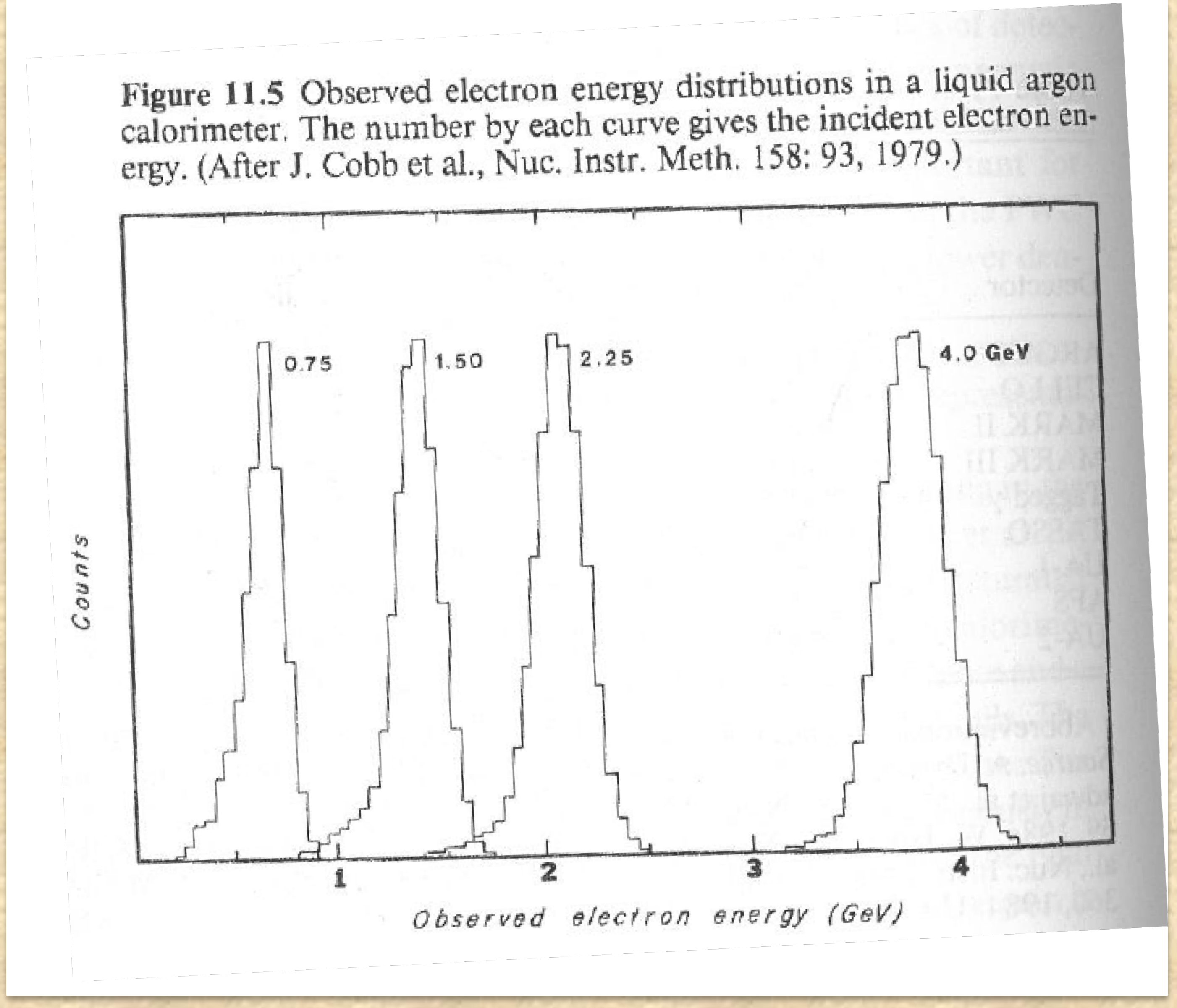
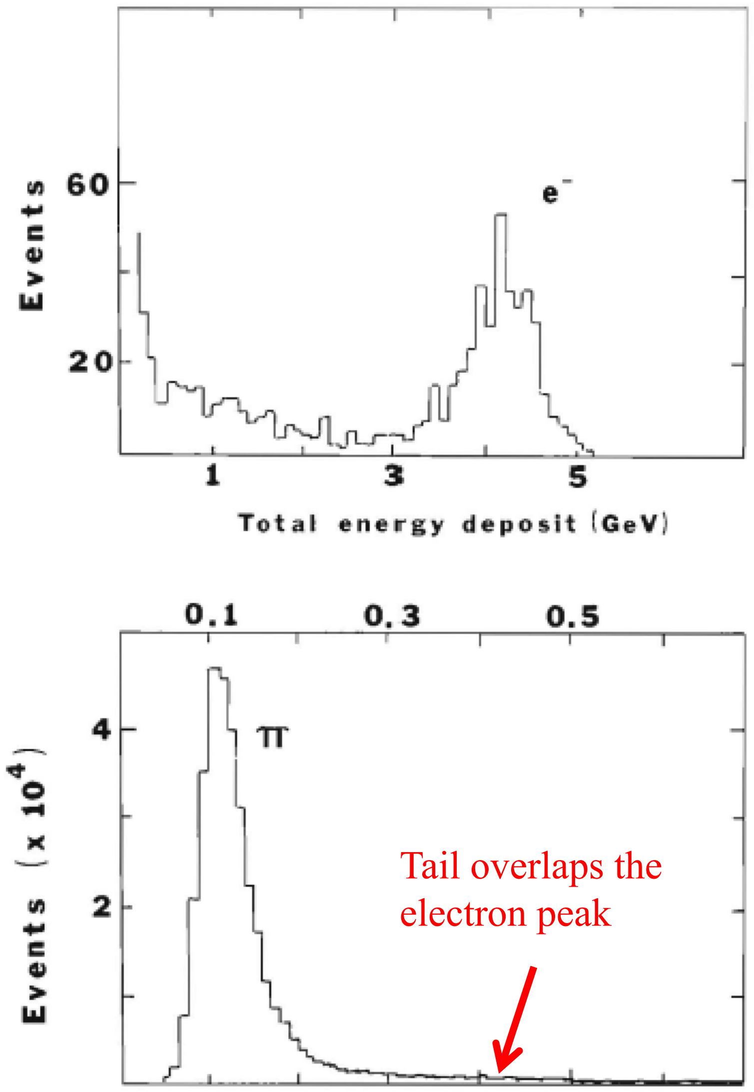


Figure 11.5 Observed electron energy distributions in a liquid argon calorimeter. The number by each curve gives the incident electron energy. (After J. Cobb et al., Nuc. Instr. Meth. 158: 93, 1979.)

Pion Rejection

- EM calorimeters want to identify/focus on electrons and photons.
- Sometimes a pion will deposit a lot of energy (e.g. a δ-ray)
- However, this can usually be handled by looking at the shower shape

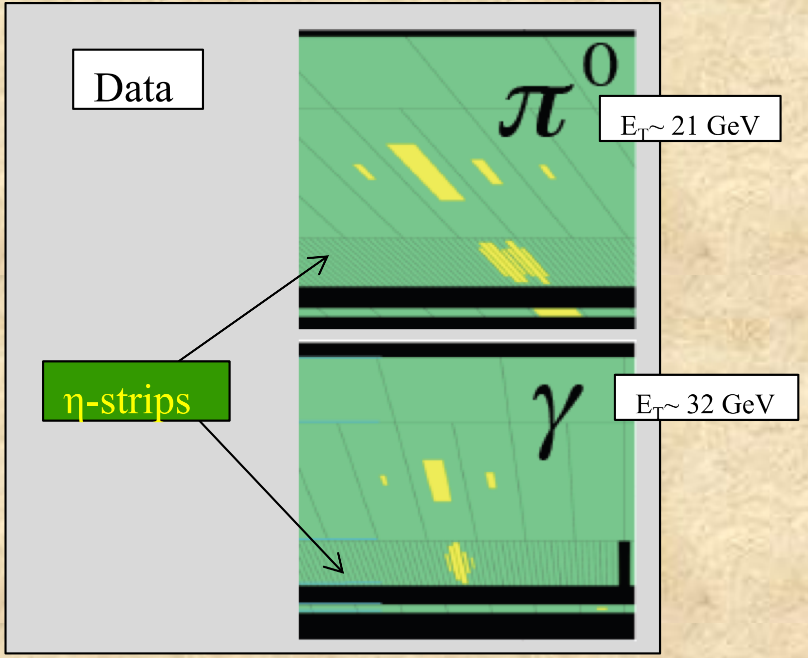
Figure 11.7 Deposited energy spectrum of electrons and pions in a lead–scintillator calorimeter. Note the different energy scales for the two curves. (After G. Abshire et al., Nuc. Instr. Meth. 164: 67. 1979.)

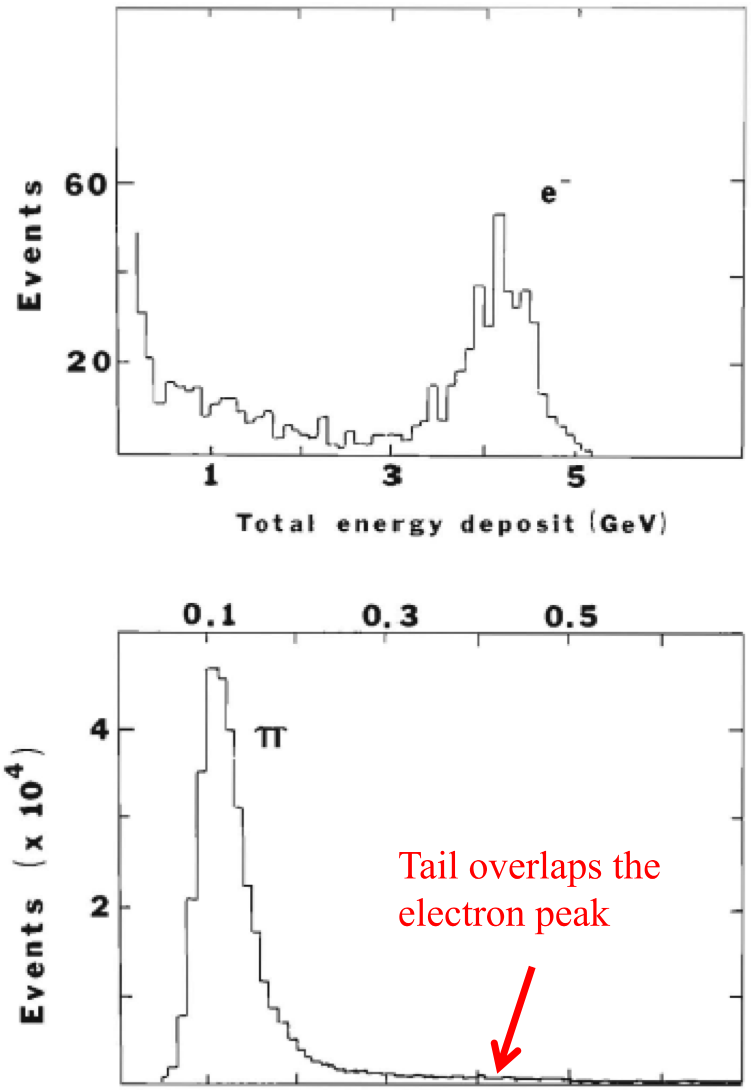


Tail overlaps the electron peak

Pion Rejection

- EM calorimeters want to identify/focus on electrons and photons.
- Sometimes a pion will deposit a lot of energy (e.g. a δ-ray)
- However, this can usually be handled by looking at the shower shape
- Neutral pions are a more difficult problem ($\pi^0 \longrightarrow \gamma\gamma$). calo segmentation!





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Tail overlaps the electron peak

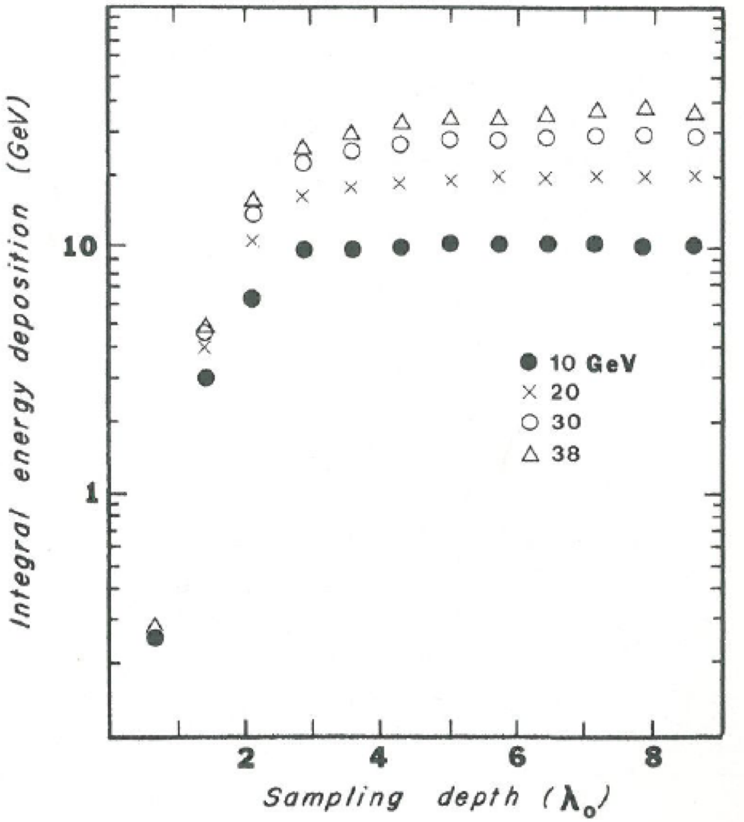
Hadronic Calorimeters

- Because of the relatively large mass of the hadrons, they do not radiate bremsstrahlung.
- Hadrons lose energy through nuclear interactions, which create, among other things electromagnetic objects.
- All hadronic calorimeters, at least at high-energy, are sampling calorimeters.
- Hadronic calorimeters are placed behind the EM calorimeter.
- The hadronic shower properties are characterized by λ the nuclear absorption length or the nuclear interaction length. This is the equivalent of the radiation length for EM showers.

$$\lambda = A/N_A\sigma_{abs}$$

- Notice that the shower depth is a smaller number of interaction lengths than radiation lengths for EM showers. But the physical length is longer. (e.g. for Pb: $X_0 = 0.5617$ cm, $\lambda_{int} = 17.59$ cm, $\rho_m = 1.6$ cm)

Figure 11.9 Integral energy deposition versus total sampling depth for hadronic showers. (After A. Sessoms et al., Nuc. Instr. Meth. 161: 371, 1979.)



Hadronic Calorimeters

A simple model of a hadronic shower, say for a pion:

- the pion will undergo a nuclear reaction with a nucleus in the calorimeter absorber (e.g. spallation reactions)
- in this process other hadrons are created/released (p, n, mostly π)
- however, energy is lost to overcoming the binding energy of the nucleons in the nucleus This "invisible energy" is lost. => the hadronic response cannot be 1.

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- π^+ π^- and π^0 are created in equal numbers on average (isospin symmetry)
- the charged pions will propagate and undergo further nuclear reactions
- however, the neutral pions will decay immediately to two photons, which will create mini EM-showers within the hadronic shower.
- higher-energy hadrons have more interaction steps so that the showers have more π^0s; the response for higher-energy hadrons is better.

Energy Sharing in a Hadronic Shower

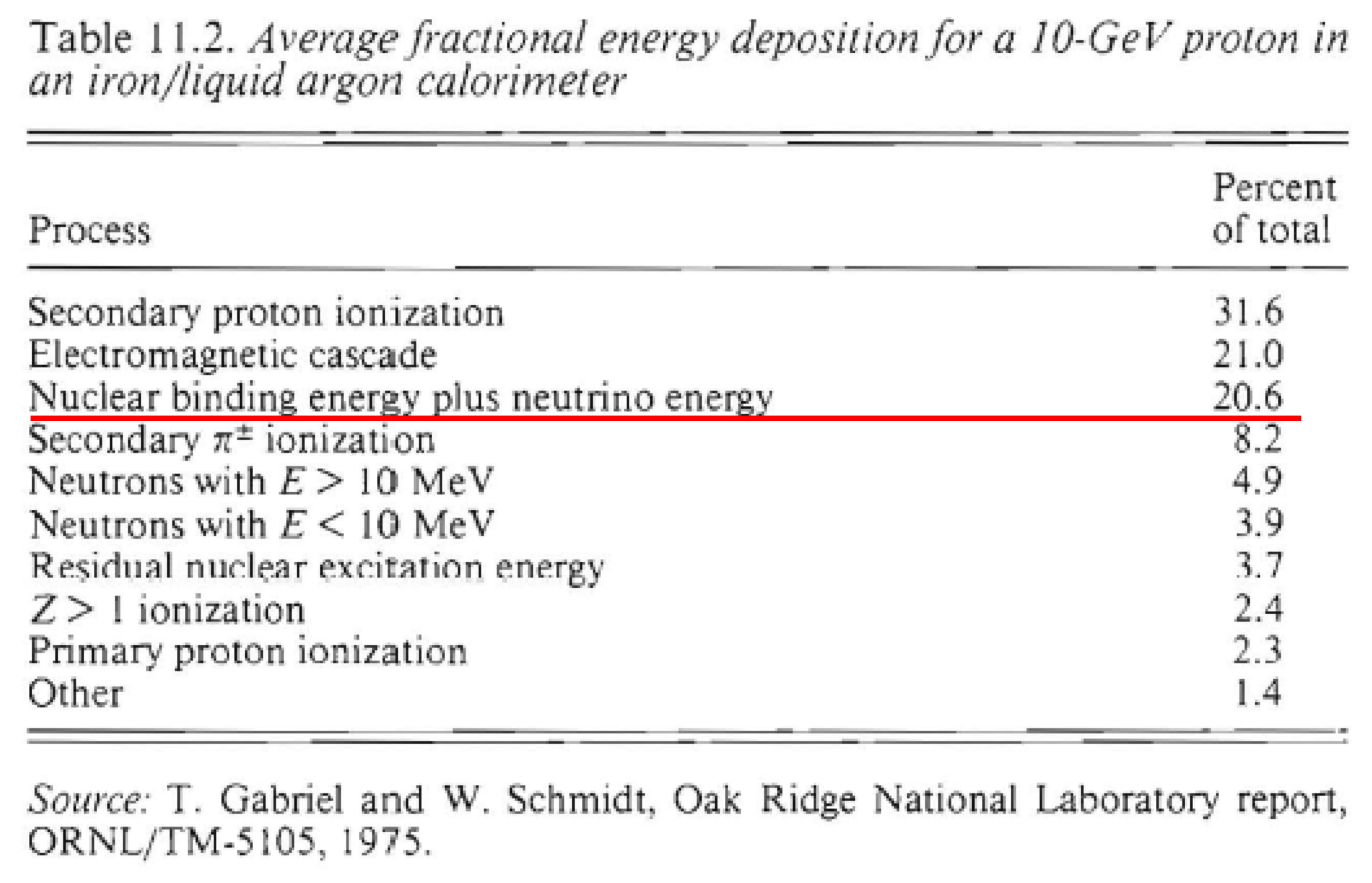

Table 11.2. *Average fractional energy deposition for a 10-GeV proton in an iron/liquid argon calorimeter*

Process	Percent of total
Secondary proton ionization	31.6
Electromagnetic cascade	21.0
Nuclear binding energy plus neutrino energy	20.6
Secondary $\pi^{\pm}$ ionization	8.2
Neutrons with $E > 10$ MeV	4.9
Neutrons with $E < 10$ MeV	3.9
Residual nuclear excitation energy	3.7
$Z > 1$ ionization	2.4
Primary proton ionization	2.3
Other	1.4

Source: T. Gabriel and W. Schmidt, Oak Ridge National Laboratory report, ORNL/TM-5105, 1975.

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- in this process other hadrons are created/released (p, n, mostly π)
- however, energy is lost to overcoming the binding energy of the nucleons in the nucleus This "invisible energy" is lost. => the hadronic response cannot be 1.
- π^+ π^- and π^0 are created in equal numbers on average (isospin symmetry)
- the charged pions will propagate and undergo further nuclear reactions
- however, the neutral pions will decay immediately to two photons, which will create mini EM-showers within the hadronic shower.
- higher-energy hadrons have more interaction steps so that the showers have more π^0s; the response for higher-energy hadrons is better.
- the transverse momentum in nuclear reactions is much larger than for brems or pair production
  - => hadronic showers are much wider than EM showers.
  - => can use this, along with longitudinal profile to distinguish them.

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Hadronic Shower Profiles vs Depth

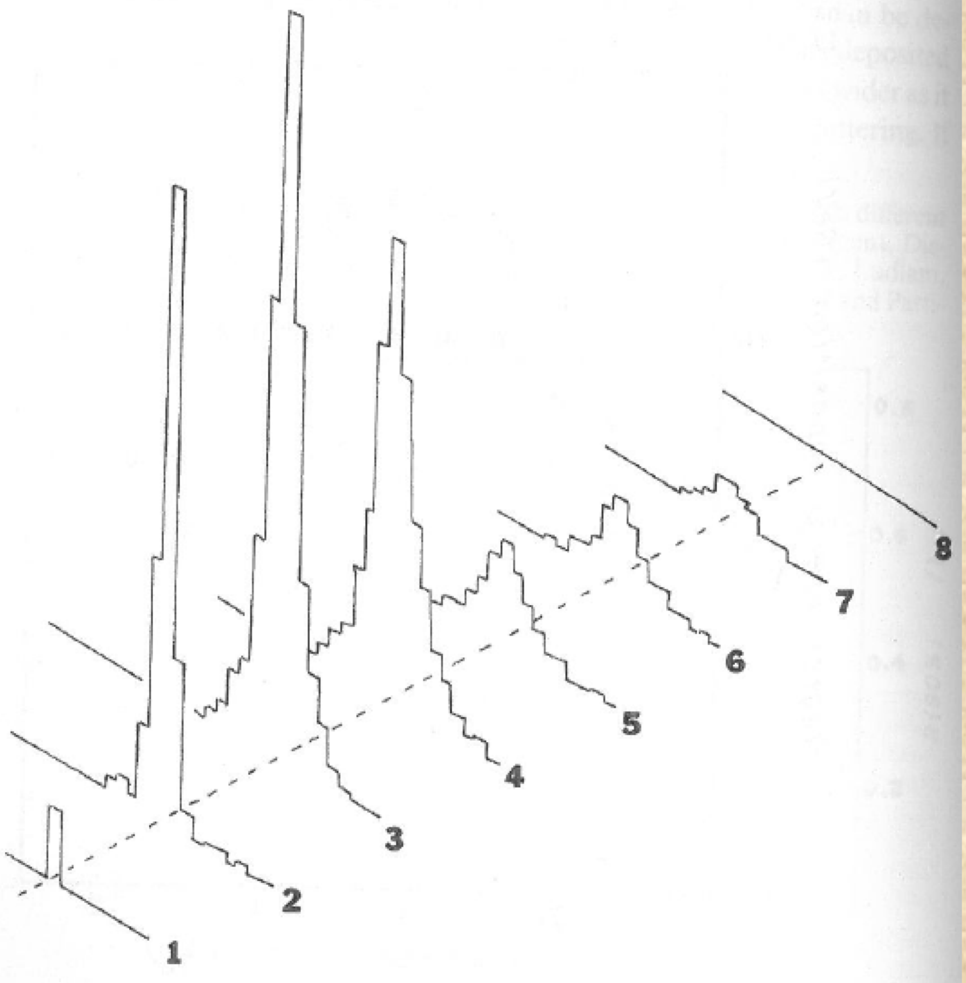
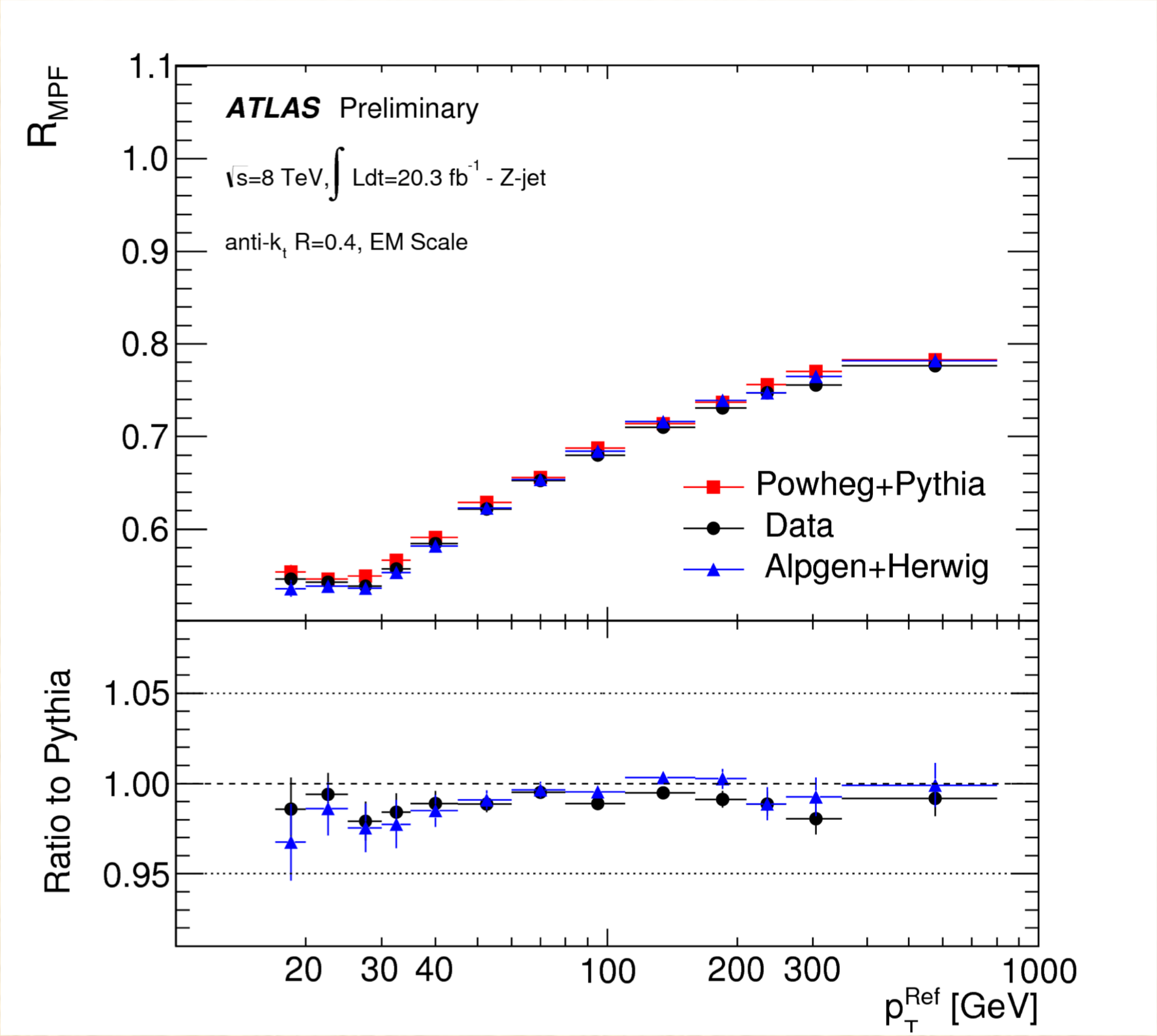


Figure 11.10 Transverse shower profiles at various depths in a hadronic shower. The showers originated from the interaction of a 20-GeV hadron in layer 2. (After A. Sessoms et al., Nuc. Instr. Meth. 161: 371, 1979.)

Hadronic Response vs p_T



Note: The rise at low-pt is an artifact of the jet reconstruction threshold

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Measurement of Total Energy

Hadronic Showers:

Jets: π, K, p, n, etc.

Nuclear interactions

Ionization

- ***Long***
- ***Broad***
- ***"Invisible energy"***

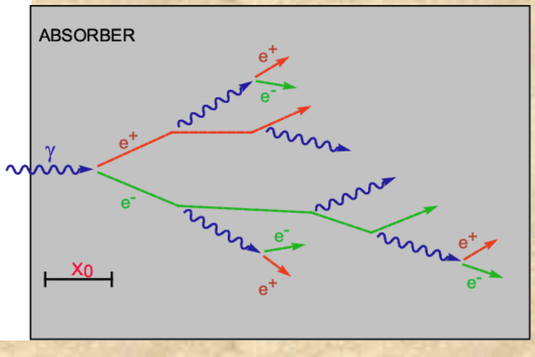
Sophisticated Computer Simulation

Shower shape, particularly longitudinal profile, can separate e-/γ from hadrons ➔ particle ID

Electromagnetic Showers:

- e- ⟶ γ + e-
- γ ⟶ e^+e^-
- *etc.* ⟶ *EM shower*

- ***Short***
- ***Narrow***
- ***All energy deposited***

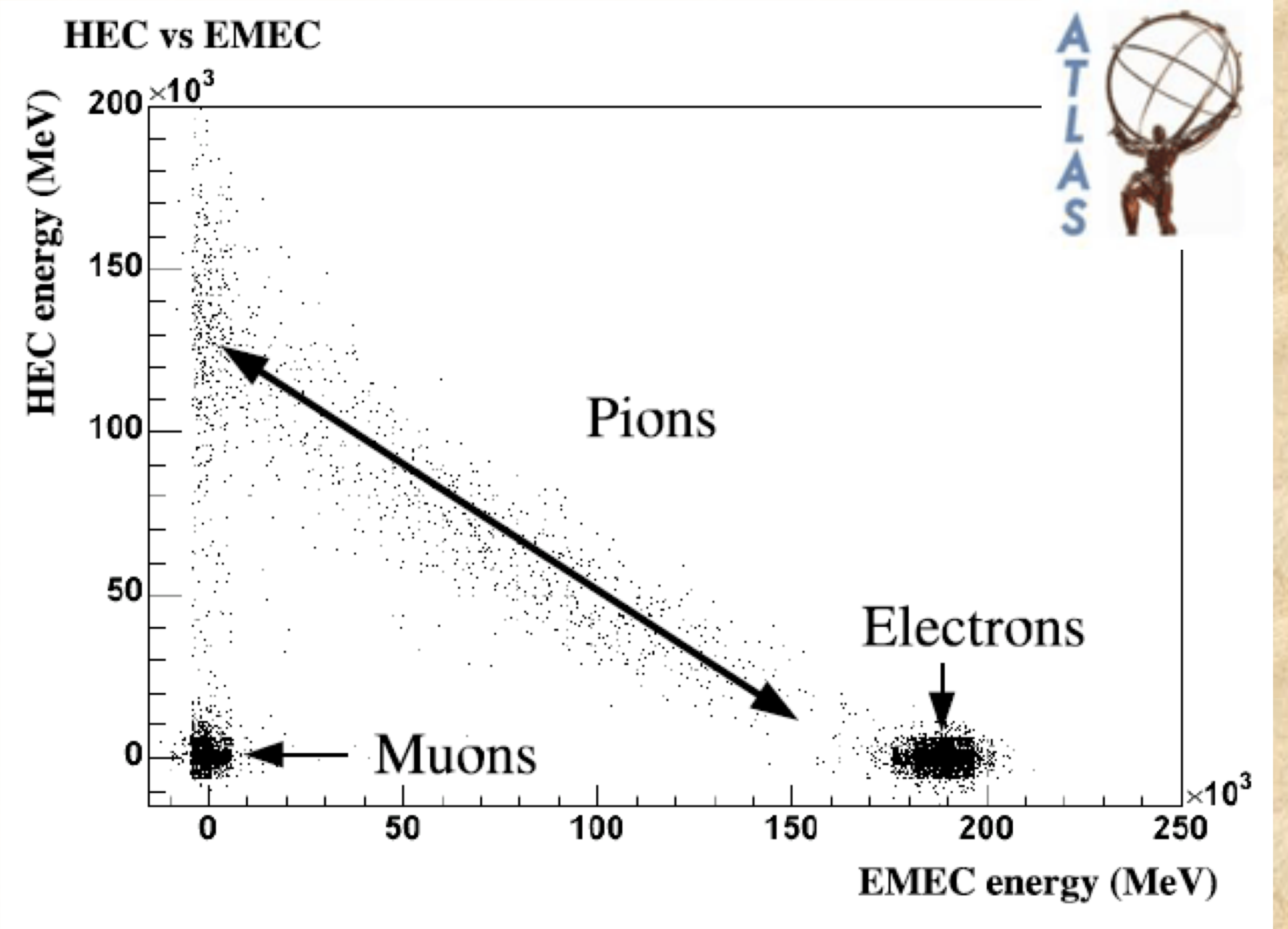


ATLAS Calorimeters in CERN Testbeam

Electrons deposit all their energy in the em calo

Pion energy is shared between em & hadronic

Muons don't deposit much energy in either



Calibration

- Test beams
- EM in-situ: Z => e+e- and J/ψ => e+e-
- Hadronic in-situ: transverse momentum balance in γ + jet and Z + jet events
- Direct Balance and Missing E_T Projection Fraction (MPF) techniques
- Response is different for quark-induced and gluon-induced jets. The latter have more, softer particles from the parton shower.
- The hadronic in-situ techniques measure mainly quark jets but there are many more gluon-induced jets in the data.
- At ATLAS, we get a better than 1% uncertainty on the in-situ measurements themselves over most of the energy/momentum range.
  But other effects increase the total/final uncertainty (e.g. flavour dependence)

Summary

- Calorimeters measure the total energy of subatomic particles
- Two different types: EM calos (EM interaction)
  Hadronic calos (Nuclear and EM interactions)
- There are homogeneous and sampling calorimeters. Each has different strengths and weakenesses.
- EM calorimeters have good E resolution and are calibrated to a response of 1.
- Hadronic calorimeters have poorer resolution because of invisible energy and larger fluctuations in the relevant processes. Response is less than 1.
- Calorimeters not only measure energy, but they are also used for particle ID and in the trigger.

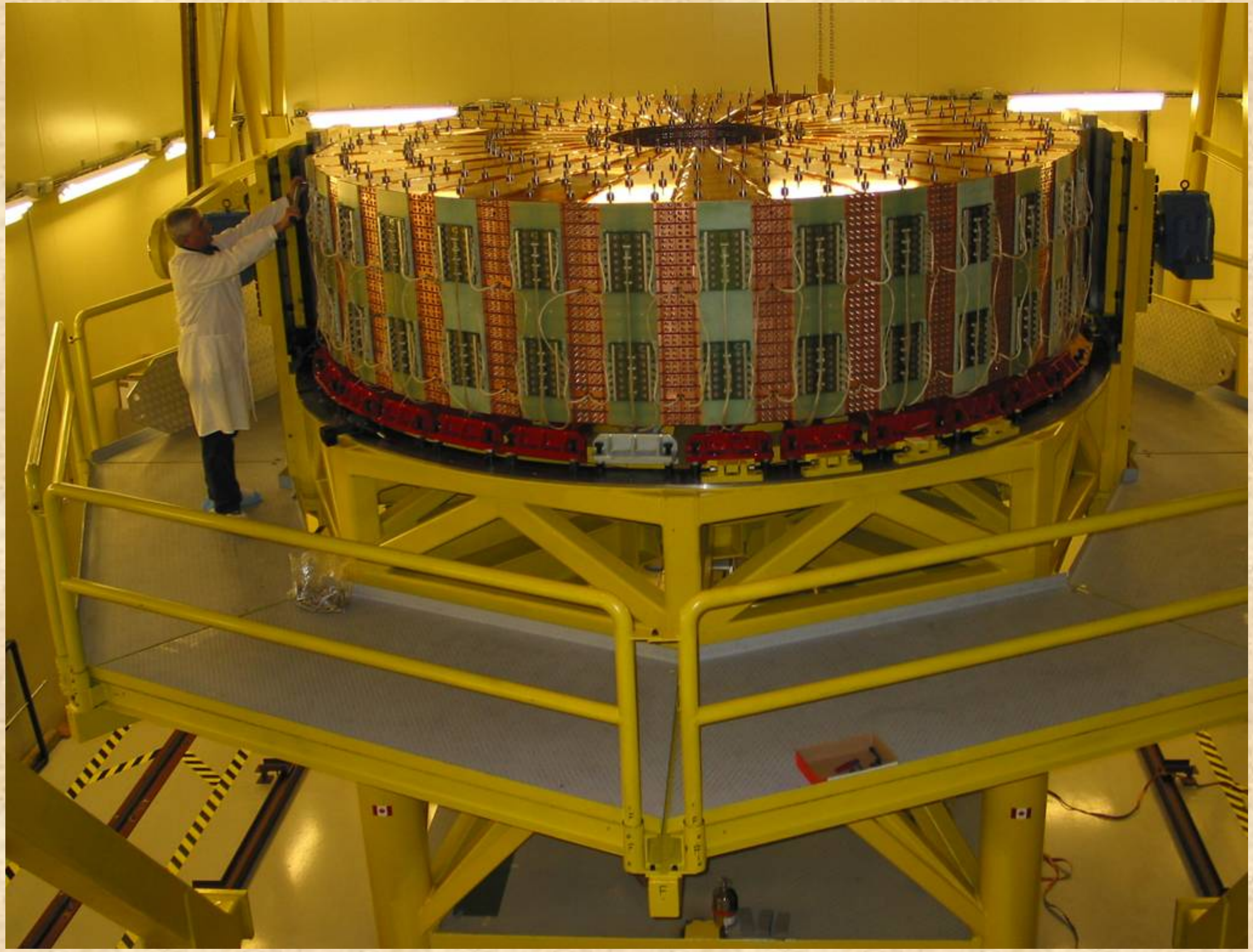
The ATLAS Hadronic Endcap Calorimeter

Absorber:

Cu Plates

Detection medium:

Liquid Argon



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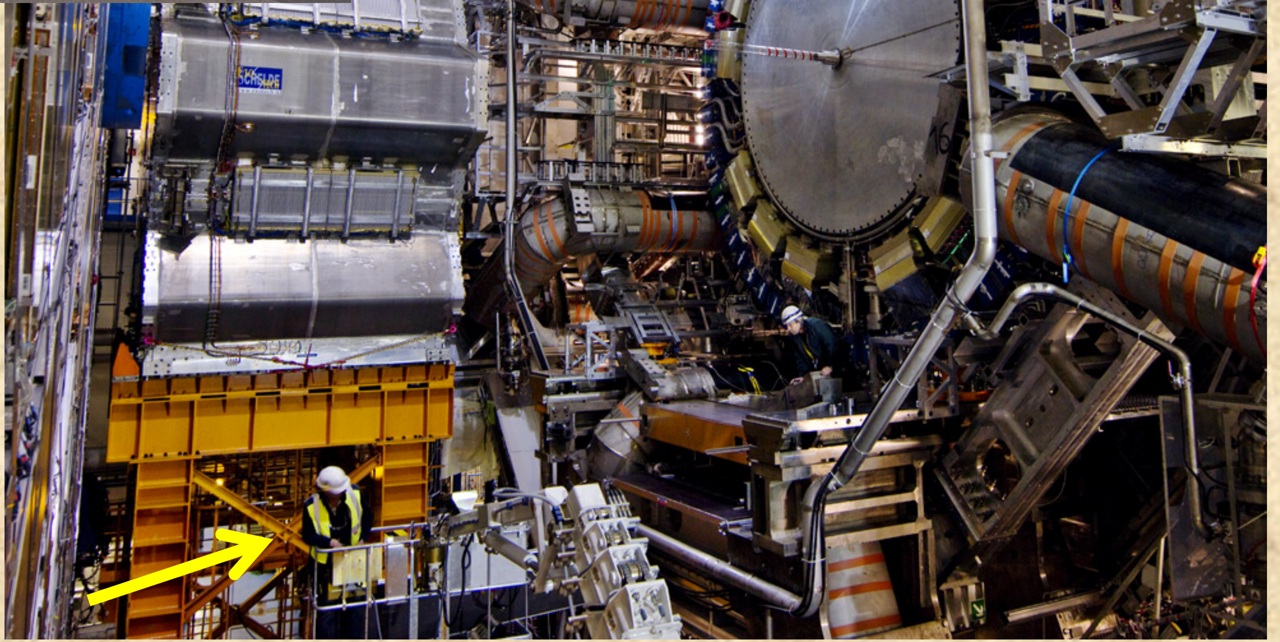
ATLAS Hadronic Endcap

In transport



Installed

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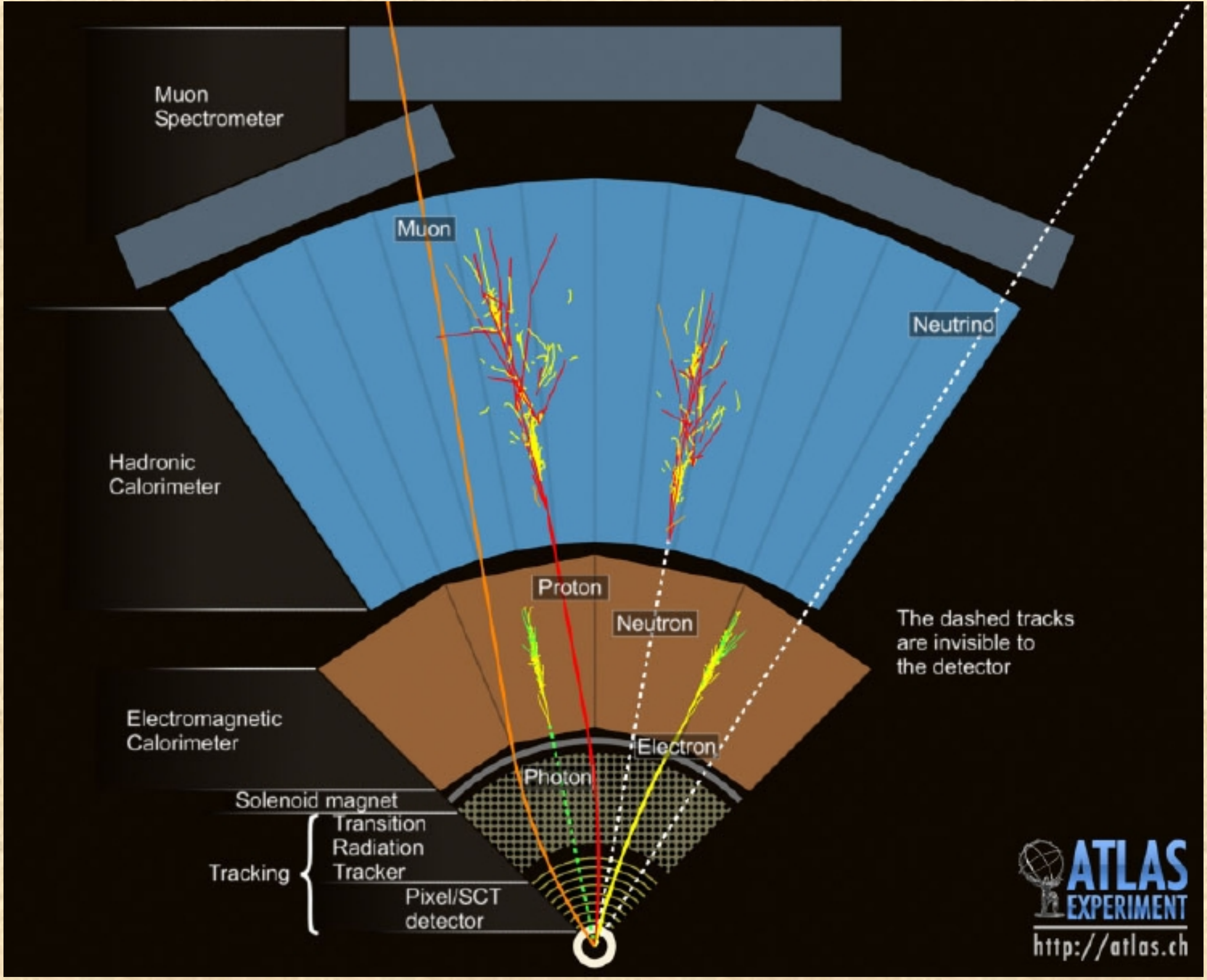
What is wrong with this diagram?



Pions deposit substantial energy in the EM calo!