CALORIMETERS

LECTURE 4 PART 4

CONTENT

1. Introduction
    1. Calorimeter principles
    2. The need for calorimetry
    3. Calorimeter types
    4. Homogenous calorimeters
    5. Sampling calorimeters
2. Electromagnetic calorimeters
    1. Electromagnetic showers
    2. Shower development and energy dependence
    3. Critical energy and Moliere radius
    4. Energy resolution
    5. Energy resolution parametrization
    6. Comparison of EM calorimeters
3. Hadron calorimeters
    1. Principles
    2. Hadronic shower
    3. Hadronic shower dimension
    4. *Compensating calorimeters
    5. Comparison of hadron calorimeters
4. Examples
    1. The Lead-Tungstate CMS ECAL
    2. CMS HCAL
    3. ATLAS LAR EM calorimeter
    4. H1 Spaghetti calorimeter

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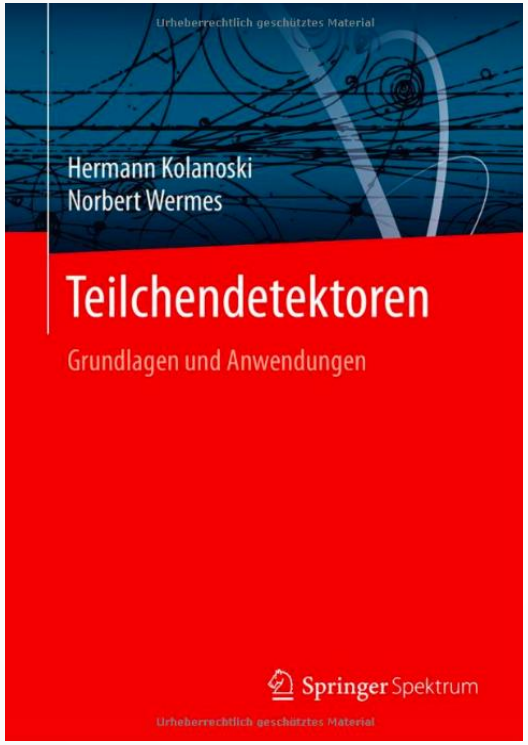
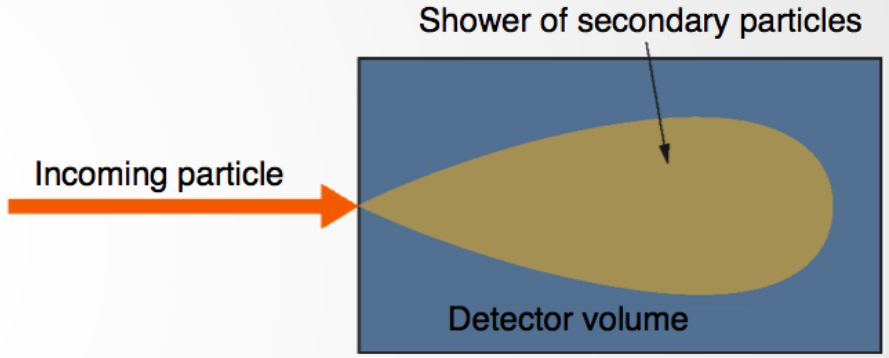


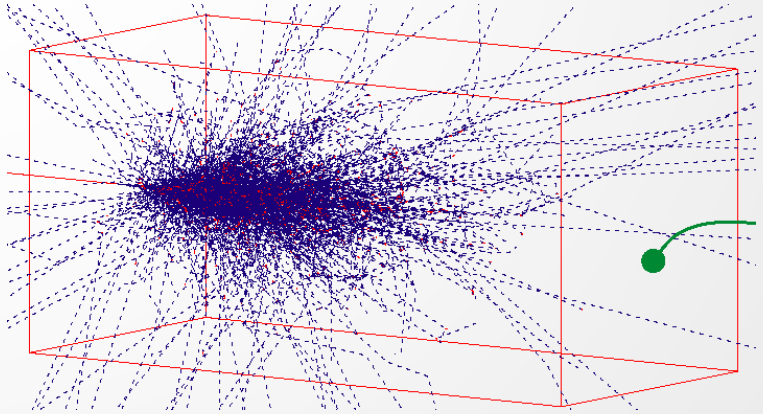
1. INTRODUCTION

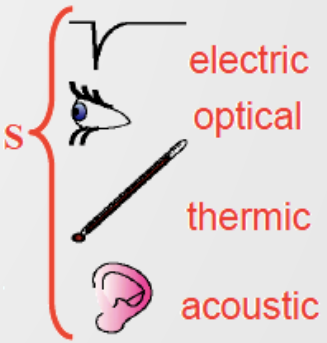
1.1 CALORIMETER PRINCIPLES

- A calorimeter is a detector which fully absorbs the particles.
  - The signals produced are a measure for the energy of the particle, but the particle is lost for further inspection
  - The particle initiates a particle shower. Each secondary particle deposits energy and produces further particles until the full energy is absorbed.
  - The composition and shape of the showers depend on the type and energy of the primary particle ($e^{\pm}$, γ or hadrons)
  - Ideally (but not in practice), the response is linear: Calorimeter signal ∝ deposited energy ∝ energy of primary particle.
- Calorimetry is a widespread technique in particle physics:
  - instrumented targets: neutrino exp. / proton decay / cosmic ray
  - 4π detectors for collider experiments
- Calorimetry makes use of various detection mechanisms:
  - Scintillation, Cherenkov radiation, Ionization, Cryogenic phen.

Convert energy E of incident particles to detector response S∝E







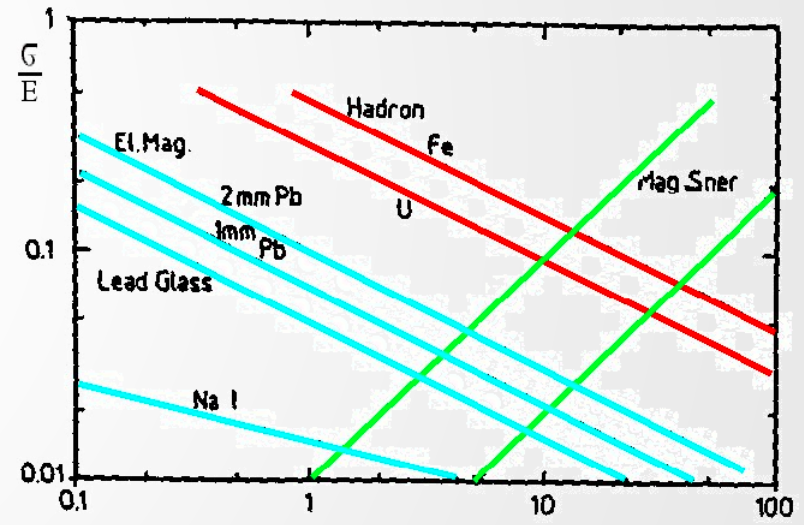
1.2 THE NEED FOR CALORIMETRY

- Calorimetry measures charged and neutral particles
- Performance of calorimeters improves with energy and is ~constant over 4π
  - while a magnetic spectrometer has a strong anisotropy due to B field
- Calorimetry is based on a statistical process. A particle produces on average N secondary particles, where N is proportional to the energy. The energy resolution is dominated by statistical fluctuations of N → the relative energy resolution improves with increasing energy.
  - Calorimeter measurement
  - Spectrometer measurement (tracking)

$$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}} \qquad \frac{\sigma_p}{p} \sim p$$

- The required thickness of a calorimeter scales only with the logarithm of the particle energy.
- Calorimeters can be used to identify particle types due to their shower shapes.
- Calorimeters are important components for the trigger system at hadron colliders. Within a few ns complex information on particle energy, particle direction, topology of the event, and possible missing energy is available!

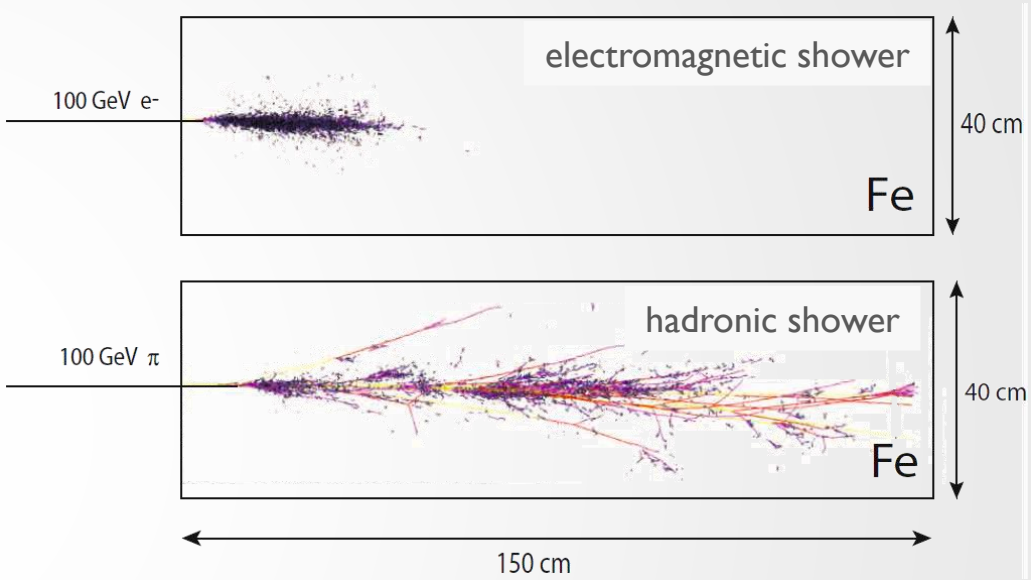
Schematic comparison of the resolution of calormetry and spectrometer measurements



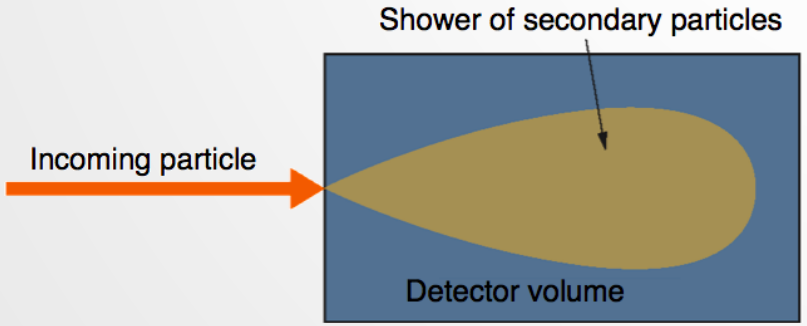
At high energies, calorimetry is absolutely needed!

1.3 CALORIMETER TYPES

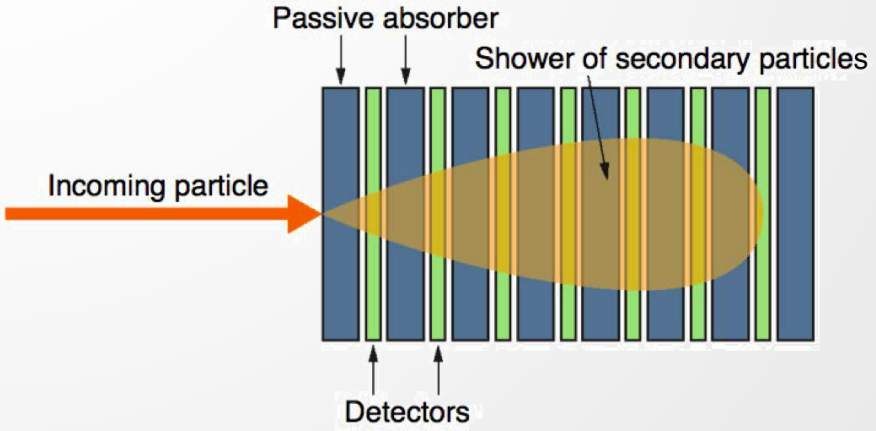
- Two different calorimeters by construction:
  - Homogeneous Calorimeters
  - Sampling Calorimeters
- Two different applications:
  - Electromagnetic calorimeters measure the energy of electrons, positrons and photons
  - Hadronic calorimeters measure the energy of hadrons



Homogenous calorimeter (principle)



Sampling calorimeter (principle)

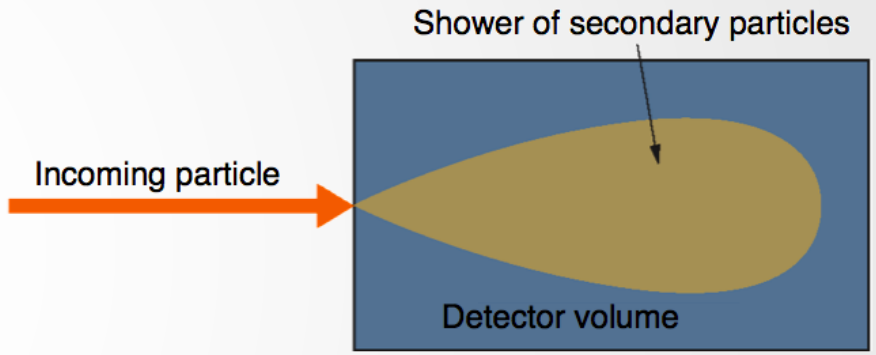


1.4 HOMOGENOUS CALORIMETERS

- Homogenous calorimeter: the detector material is at the same time the absorbing material and the detector.
- Examples for different signal exploited:

Signal	Material
Scintillation	BGO*, BaF_2, CeF_3, $PbWO_4$
Cherenkov light	Lead glass
Ionization	Liquid noble gasses (Ar, Kr, Xe), Germanium (in nuclear physics)

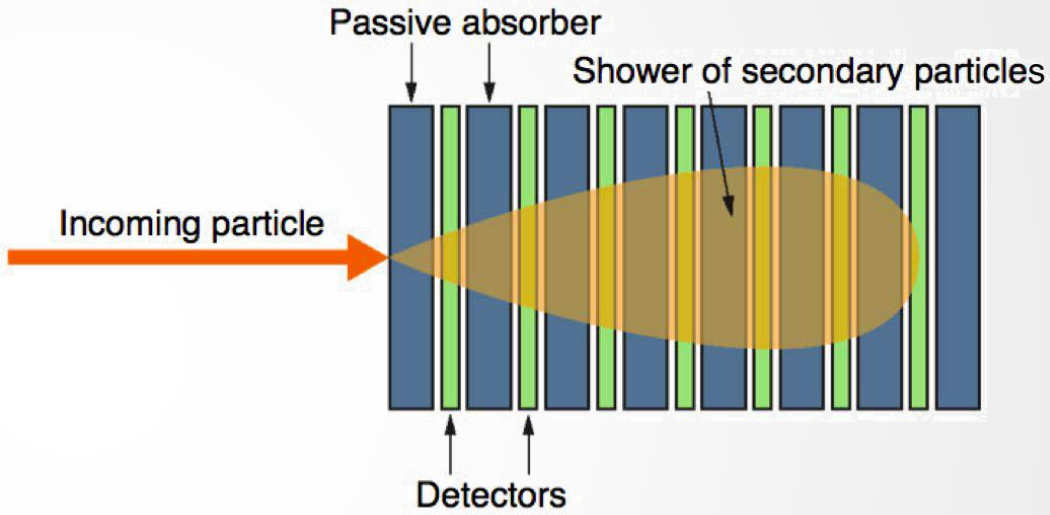
* Bismuth Germanate $Bi_4Ge_3O_{12}$



- Advantage: Best possible energy resolution achievable
- Disadvantage: Expensive
- Homogenous calorimeters are only used as electromagnetic calorimeters that measure the energy of $e^{\pm}$ and photons

1.5 SAMPLING CALORIMETERS

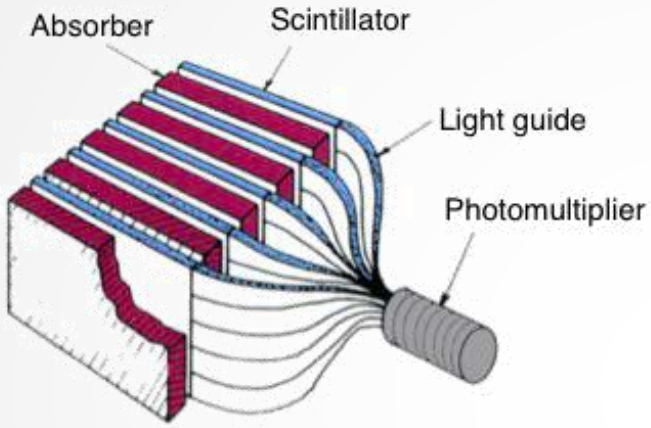
- A sampling calorimeter consists of alternating layers of passive absorbers and active detectors.
- Typical absorbers are materials with high density,
  - e.g.: Fe, Pb, U
- Typical active detectors:
  - Plastic or crystal scintillators
  - Silicon detectors
  - liquid noble gas ionization chambers
  - Gas detectors

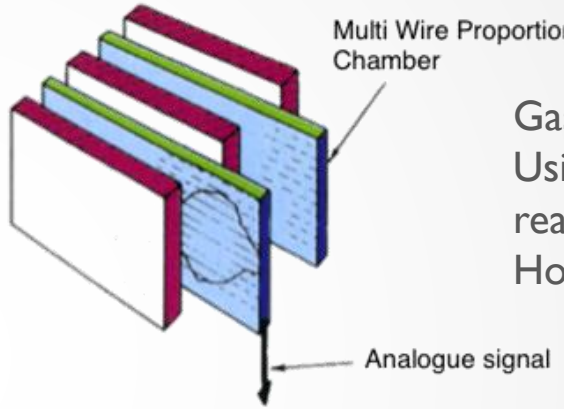


- Advantages:
  - Can optimally choose the absorber and detector material independently and according to the application.
  - By choosing a very dense absorber material the calorimeters can be made very compact.
  - The passive absorber material is cheap
- Disadvantages:
  - Only part of the particles energy is deposited in the detector layers and measured
  - Energy resolution is worse than in homogeneous calorimeter ("Sampling-Fluctuations").

1.5 SAMPLING CALORIMETERS

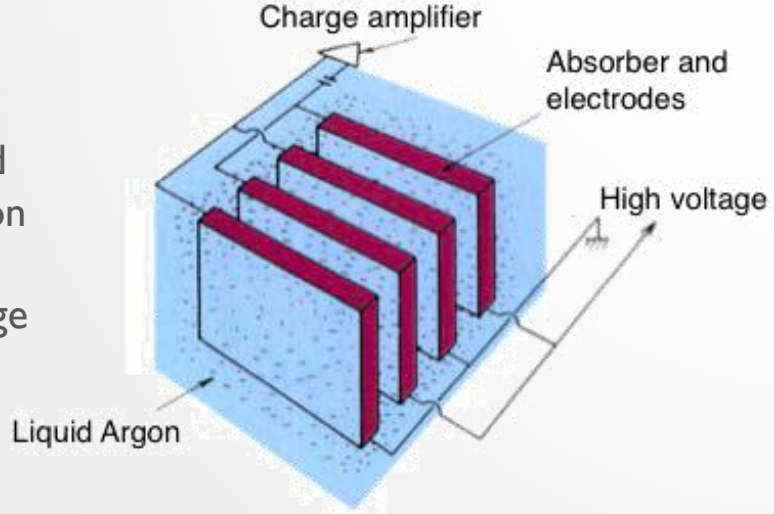
Scintillators
e.g. CMS HCal (plastic)
low maintenance
not very radiation hard

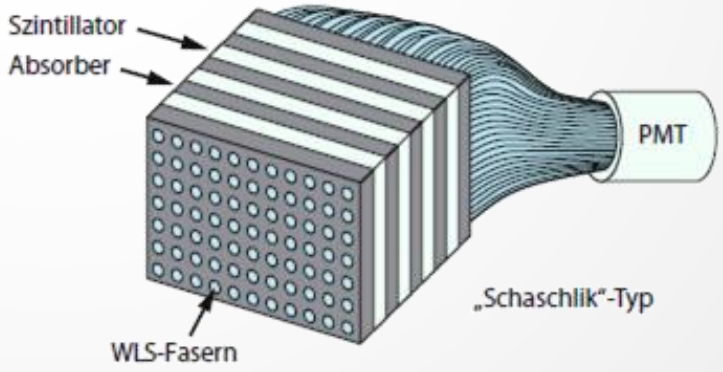




Gas detectors:
Using MWPC one can
read out the ionisation charge.
However, count rate often enough

LAr ATLAS calorimeter
cryogenic -185°C
active area is segmented
for high spatial resolution
Ar must be purified but
no/little radiation damage





Kolanoski, Wermes 2015

"Schaschlik "
e.g. Hera-B calorimeter
wave length shifting fibres
run through a sandwich
of absorbers and scintillators

2. ELECTROMAGNETIC CALORIMETERS

2.1 EM SHOWERS IN CALORIMETERS

- Electromagnetic calorimeters measure the energy of electrons, positrons and photons.
- High energy electrons, positrons and photons interact via Bremsstrahlung and pair production
  - shower development scales with radiation length X_0
  - energy loss is fast, e.m. calorimeters are not thick
- EM calorimeters exist as homogeneous or sampling

1. high energies: bremstrahlung $\sigma_{brem} \propto Z^2$, $X_0 \propto Z^{-2}$
2. low energies: ionization loss

- E_c is defined as the energy where 1. and 2. are equal
- Simple shower model: Total length $s = t_{max} X_0$ where $t_{max} = \log_2(E_{max}/E_c)$.

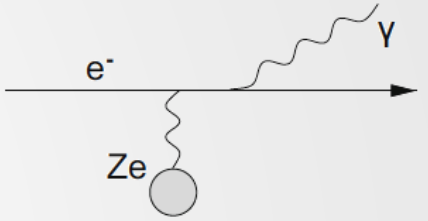
Remember from lecture 3:

$$\frac{dE}{dx} = -\frac{E}{X_0}$$

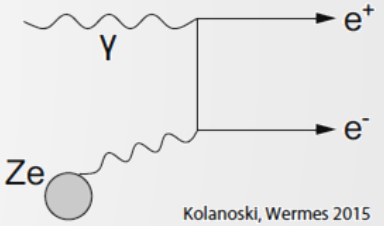
$$\rho X_0 = \frac{716.408 \text{ g cm}^{-2} A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

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

electron bremstrahlung



photon pair creation



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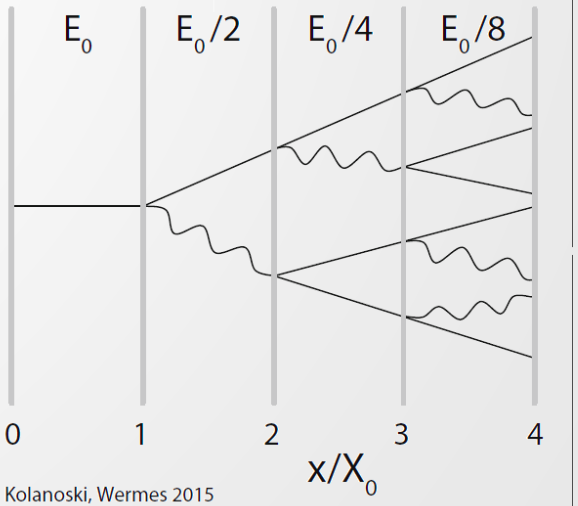

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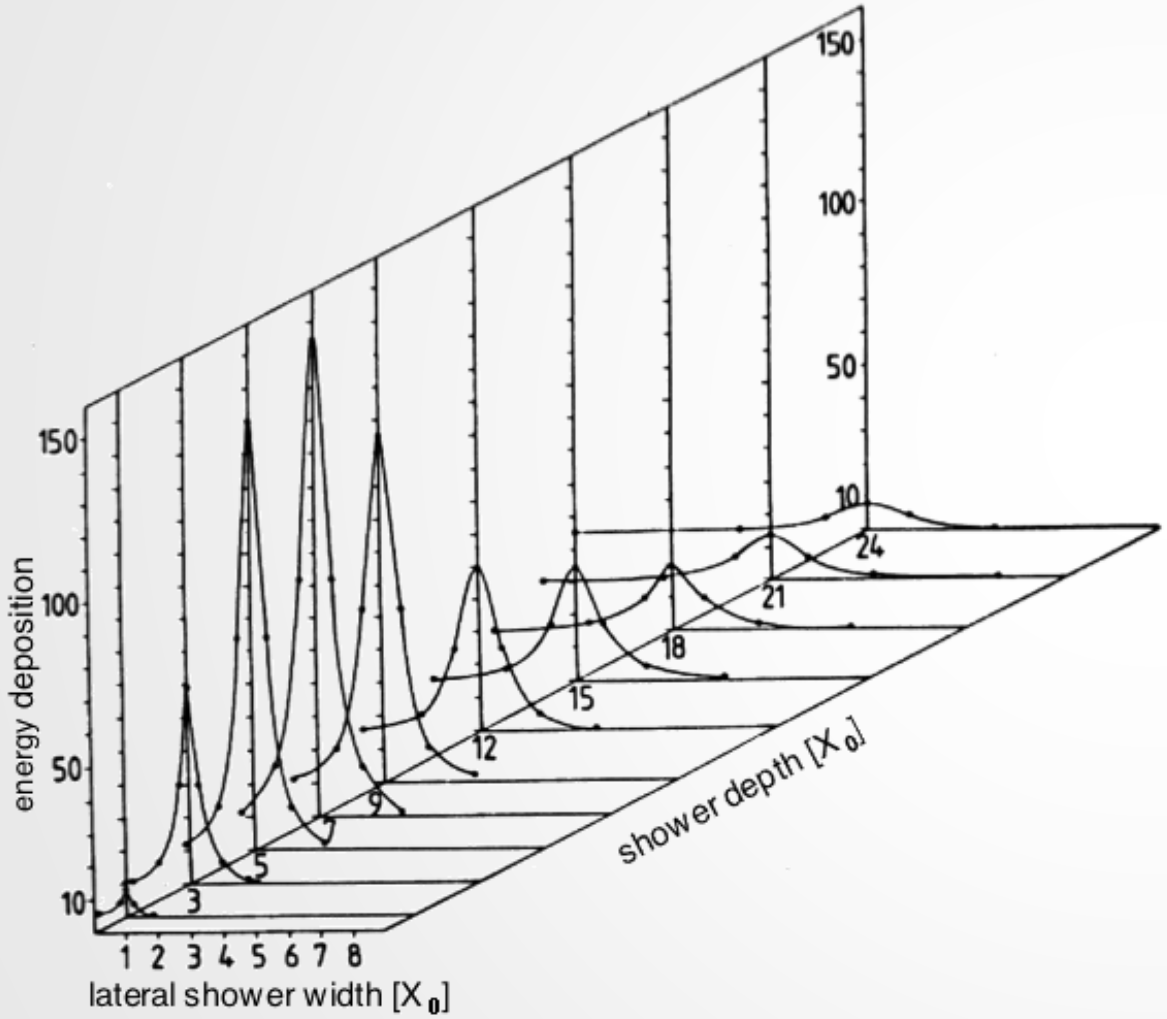
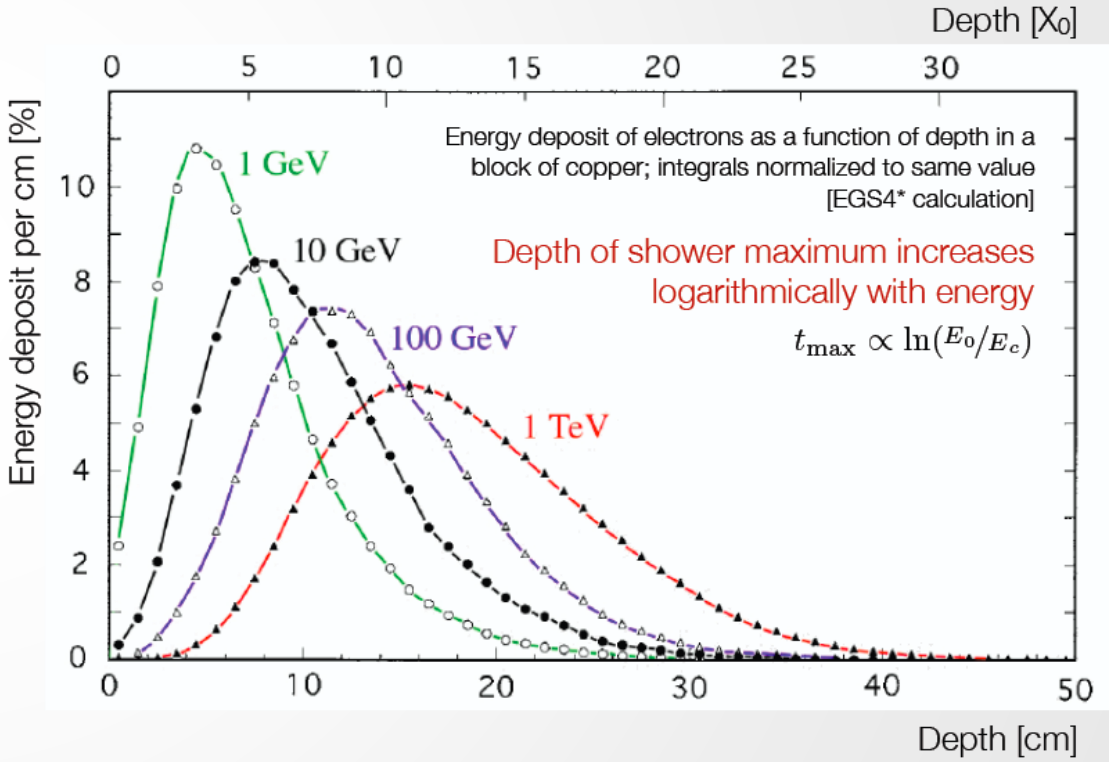
2.2 SHOWER DEVELOPMENT AND ENERGY DEPENDENCE





2.3 CRITICAL ENERGY & MOLIERE RADIUS

* C. Leroy, F.-G. Rancoita, Rep.Prog.Phys. 63, 505–606 (2000)

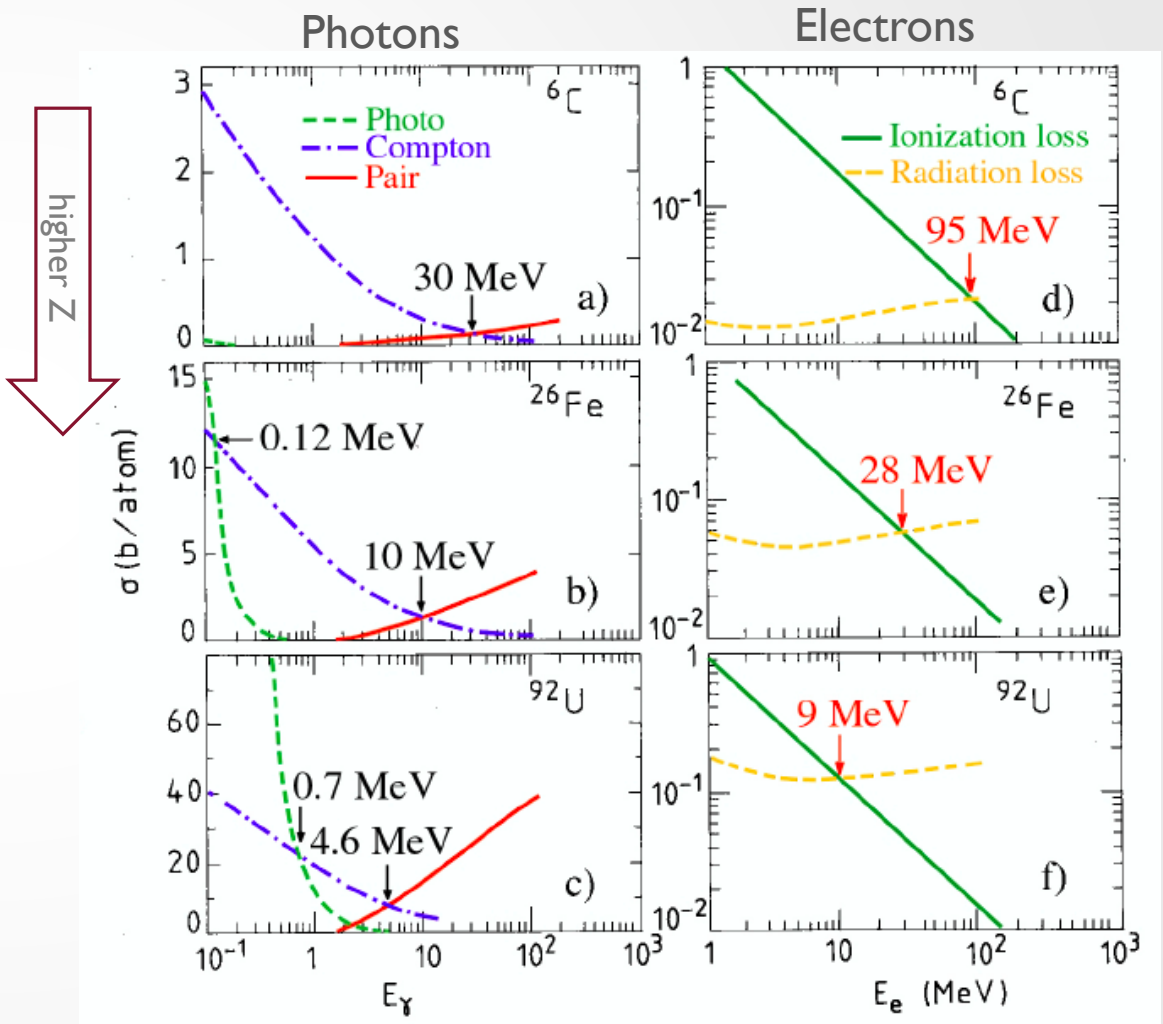
- Important for the calorimeter is
  - the longitudinal dimension of the shower.
    - About 95% of the energy of the incident particle is contained within the depth T (semi empirical formula*):

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

    - Rule of thumb: need about 25 X_0
- In the transversal plane, 90 (95%) of a shower is contained within 1 (2) Moliére radii. R(95%) = $2\rho_M$

$$\rho_M = \frac{\sqrt{\frac{4\pi}{\alpha}}\, m_e c^2}{E_c} = \frac{21\,[\text{MeV}]}{E_c\,[\text{MeV}]} \cdot X_0$$

  - The transversal shower profile has a central core in which most of the energy is deposited.
  - It is surrounded by a halo.
  - The width of the core is determined by small angle scattered $e^{\pm}$, whereas the halo develops due to low energy photons, which fly a long distance in the detector and by large angle Rutherford scattering



high Z materials have high multiplicities of low energy particles. Even though built for TeV!

2.4 ENERGY RESOLUTION

- In an ideal homogeneous calorimeter with infinite dimensions the energy resolution is determined by the statistical fluctuations of the number of shower particles N

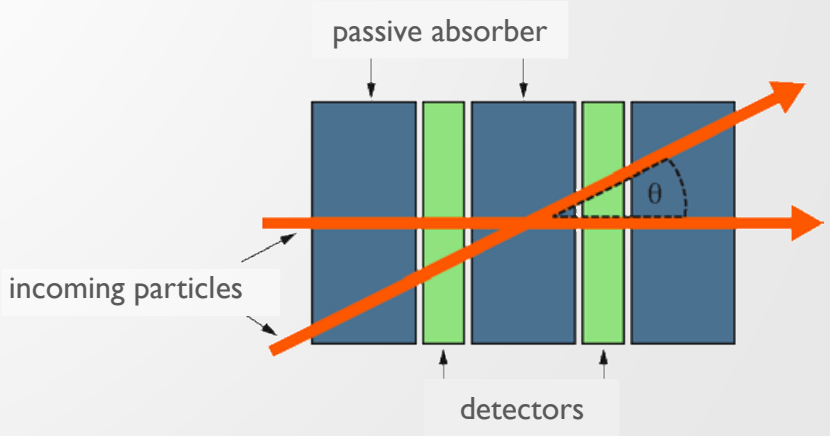
$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

- Maximal number of "detectable" particles is given : $N_{max} = E/\eta$
- E is the energy of the primary particle and η is the threshold energy of the detector, i.e. the minimal energy to produce a single detectable secondary particle.
- Examples for the threshold energy:
  - Ge (Si) detectors: η ≈ 2.9 eV (3.6 eV), Gas detectors: η ≈ 30 eV, Plastic scintillators: η ≈ O(100 eV)

1. Sampling fluctuations
   - In sampling calorimeters only a small part of the deposited energy is measured.
   - The fractions of how much is energy is deposited in the absorber and in the detector varies from event to event:

$$\frac{\sigma_E}{E} \approx \frac{\sqrt{N_{vis}}}{N_{vis}} = \frac{1}{\sqrt{N_{vis}}}$$

2. Landau fluctuations:
   - In case of thin detector layers due to the asymmetric energy loss distribution (Landau instead of Gaussian distribution), e.g. important in gas and silicon detectors.
3. Track length fluctuations:
   - Secondary particles are scattered and cross the detector planes under various angles.
   - From event to event the total track length of secondary particles fluctuates
   - ⟶ contribution to the energy resolution.



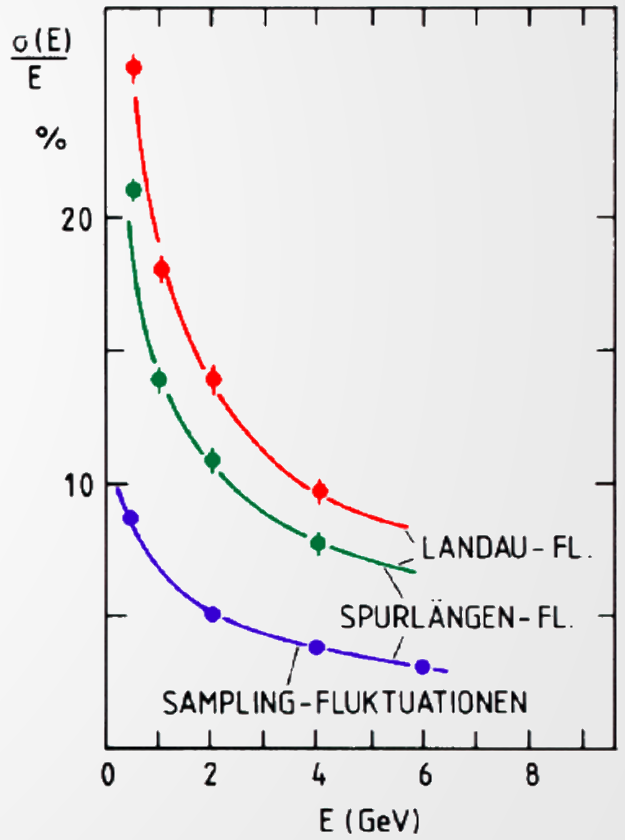
2.5 ENERGY RESOLUTION PARAMETRISATION

- The energy resolution of a calorimeter can be parameterized using

$$\frac{\sigma(E)}{E} \approx \sqrt{\left(\frac{c_1}{\sqrt{E}}\right)^2 + \left(\frac{c_2}{E}\right)^2 + c_3{}^2}$$

  - E ..... particle energy in GeV
  - c_1, c_2, c_3 …Empirical, detector dependent constants or fit parameters
- The three terms are
  - the intrinsic resolution is $\propto c_1/\sqrt{E}$
  - the term $\propto c_2/E$ is mainly due to electronic noise (independent of E) (+ pile up fluctuations in high luminosity environments)
  - the constant term c_3 is caused by inhomogeneous response, calibration errors, dead channels, longitudinal leakage, etc.
- At high energies the constant term dominates the energy resolution!

contributions to the energy resolution



2.6 COMPARISON OF EM CALORIMETERS

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
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
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

Homogeneous

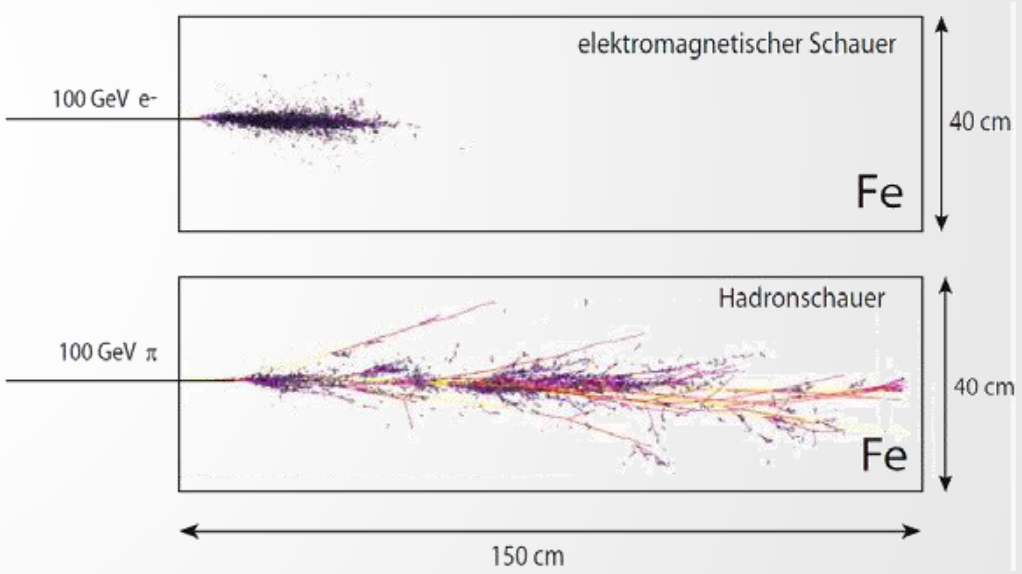
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	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

3. HADRON CALORIMETERS

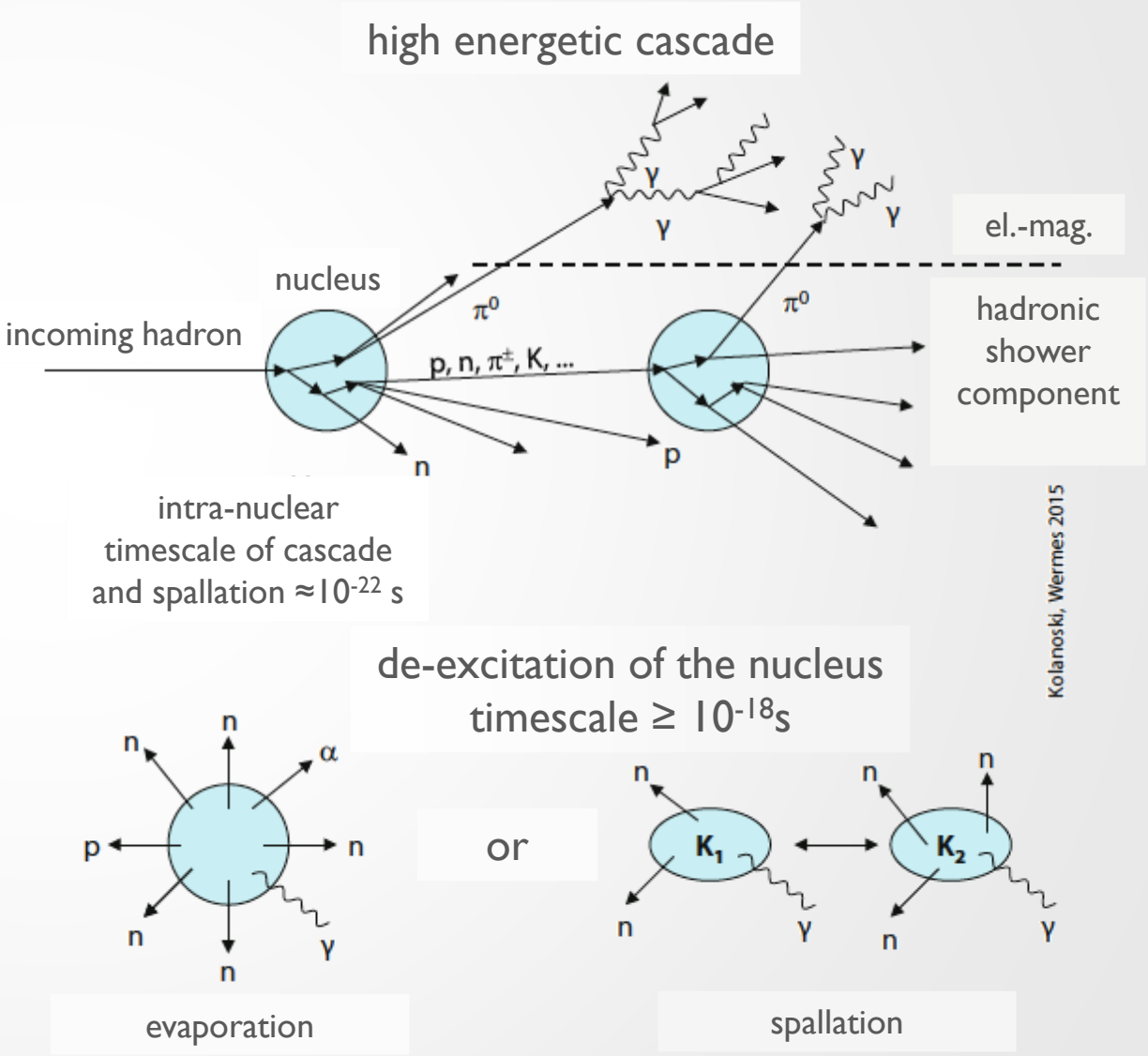
3.1 PRINCIPLES

- Hadron calorimeters measure the energy of charged and neutral hadrons.
- Shower development similar to EM calorimeters
  - Extra complication: The strong interaction with detector material
  - shower development scales with nuclear absorption length λ_a
  - hadron calorimeters need to be much "thicker"
- Importance of calorimetric measurement of hadrons:
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy
- Hadron calorimeters exist only as sampling calorimeters.
- In an experimental set-up the EM calorimeter is always in front of the hadron calorimeter
  - The CMS ECAL constitutes about 1 nuclear radiation length in front of HCAL



3.2 HADRONIC SHOWER

- Hadrons interact inelastically with a single nuclei in the nucleus
- Secondary hadronic decay products interact with other nuclei, leading to shower formation.
- If neutral pions are produced, they decay to photons with subsequent electromagnetic showers.
- Between hadronic interactions, charged shower particle also ionize the material, leading to an EM cascade (also, nuclei can de-excite emitting γ)
- The fluctuation of the shower components is large and, depending on the charge and the momenta of the particles, each has a different reconstruction efficiency.
- This limits the resolution in reconstructing the energy of the incident particle.



3.3 HADRONIC SHOWER DIMENSION

C. Leroy, F.-G. Rancoita, Rep.Prog.Phys. 63, 505–606 (2000)

- Hadronic shower dimensions described by the nuclear absorption length λ_a.
  - 95% of a shower is contained in approximately 7.6 λ_a (about 80 cm in U).
  - Rule of thumb: 10 λ_a required
- ≈95% of the total energy is deposited in a cylinder with radius λ_a.
- The transversal profile consists of a high energy core. Full width at half maximum (FWHM) ≈ 0.1 – 0.5 λ_a and a halo of low energy particles.
- The absorption of the purely hadronic shower involves energy loss processes which do not create measurable signals:
  - Nuclear binding energy
  - Production of neutrinos and high energy muons
  - Kinetic energy of debris of nuclei
- Hadronic showers also always produce an EM component!
- The fraction of the shower energy which goes into the EM shower is determined at the first interactions (beginning of the shower).
  - large event-by-event fluctuations
  - EM and hadronic response not identical – worsening of resolution $\propto E$, no improvement with $E^{1/2}$!

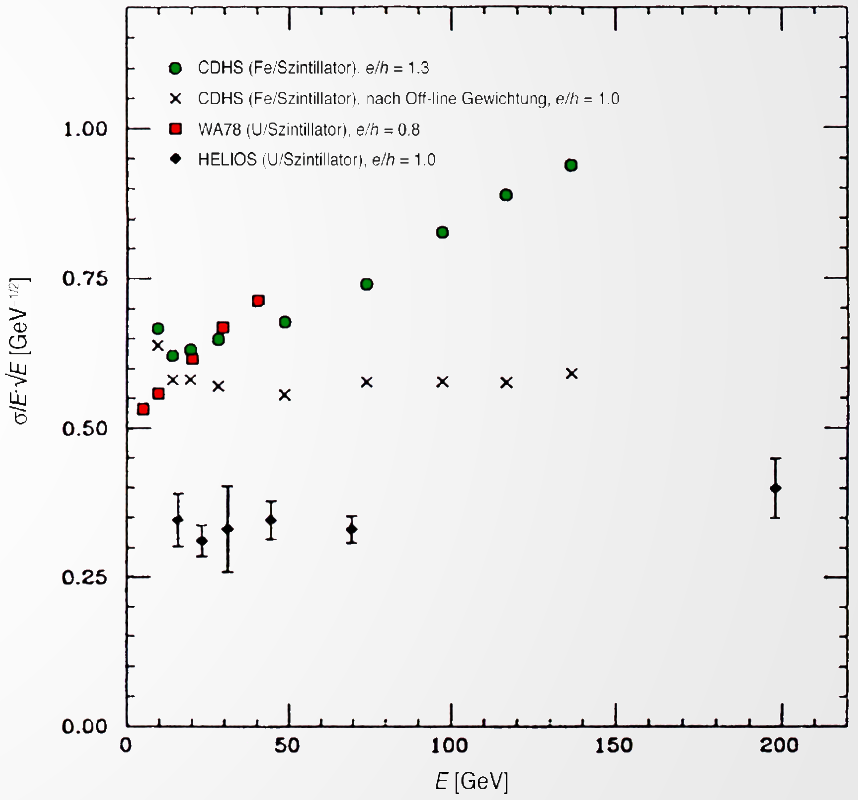
Material	λ_a [cm]
Fe	16.8
Pb	17.1
U	10.5
Cu	15.1
Al	39.4
W	9.6
Polystyrol	79.5
Ar	83.7
Si	45.5

*3.4 COMPENSATING CALORIMETERS

- By a careful choice of
  - the calorimeter active material - absorber with large Z (U or Pb) and detector with low Z
  - the detector geometry - optimized thickness of detector and absorber, and
  - signal processing - disregard slow hadronic processes such as neutron capture with γ emission >100ns

  a ratio of the shower responses e/h ≈ 1 can be achieved.
  - This is called a compensating calorimeter
- Because the ratio E_{EM}/E_{had} is dependent on the incident energy, a non-compensating calorimeter is non-linear.
  - Compensating calorimeters are linear over a large energy range
  - Linear calorimeters have better resolution

resolution of compensating and non-compensating calorimeters



Legend:
Helios/NA34 (low transverse momentum lepton and photon measurements)
WA1/CDHS (DIS of neutrinos)
WA78@SPS (charmed strange baryon production)

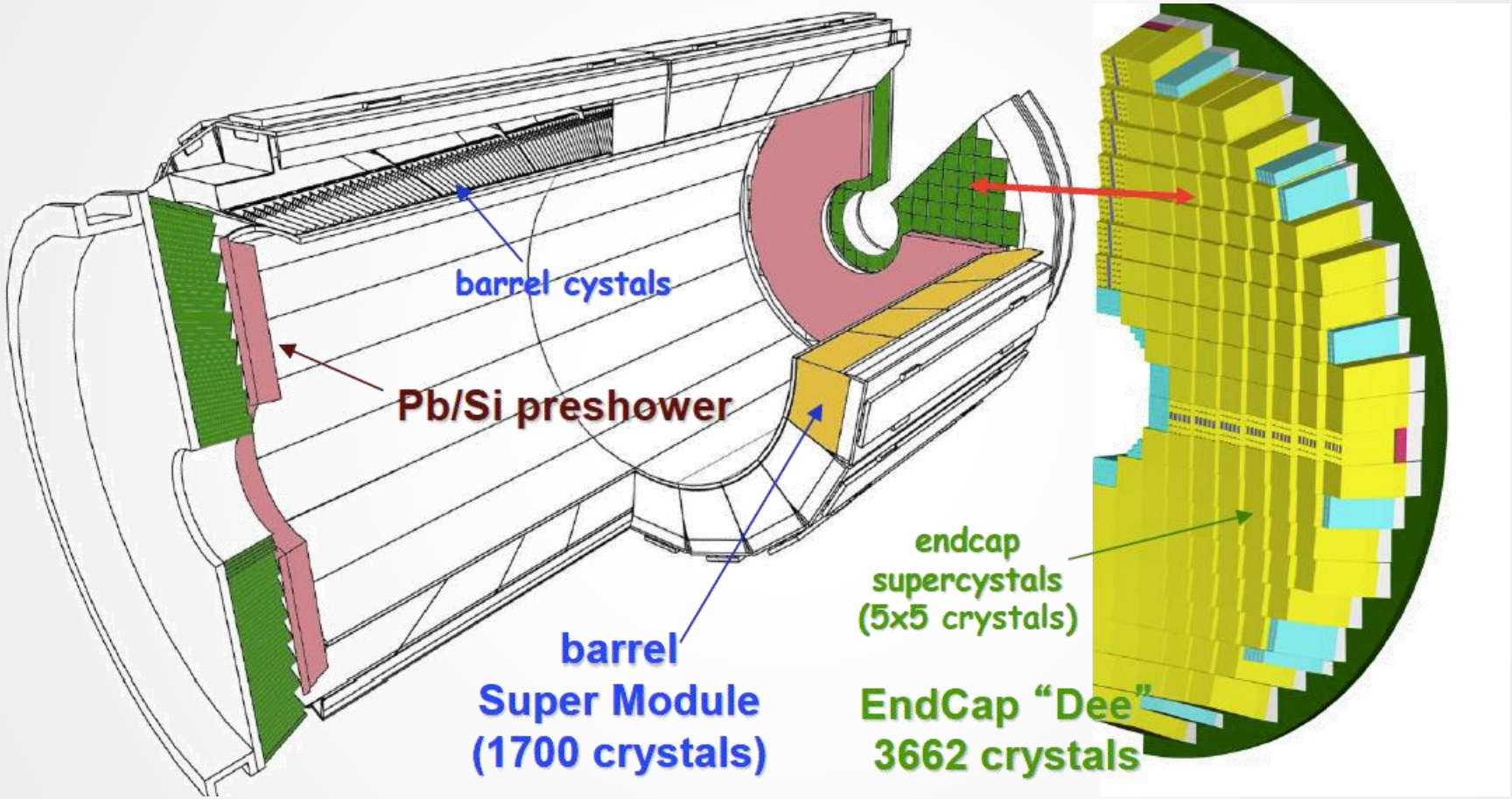
3.5 COMPARISON OF HADRON CALORIMETERS

Experiment	Detectors	Absorber material	*e/h*	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	80%/√E
ZEUS	Scintillator	Pb	≈ 1.0	34%/√E
WA78	Scintillator	U	0.8	52%/√E ⊕ 2.6%*
D0	liquid Ar	U	1.11	48%/√E ⊕ 5%*
H1	liquid Ar	Pb/Cu	≤ 1.025*	45%/√E ⊕ 1.6%
CMS	Scintillator	Brass (70% Cu / 30% Zn)	≠ 1	100%/√E ⊕ 5%
ATLAS (Barrel)	Scintillator	Fe	≠ 1	50%/√E ⊕ 3%**
ATLAS (Endcap)	liquid Ar	Brass	≠ 1	60%/√E ⊕ 3%**

* After software compensation
** Design values

4. EXAMPLES

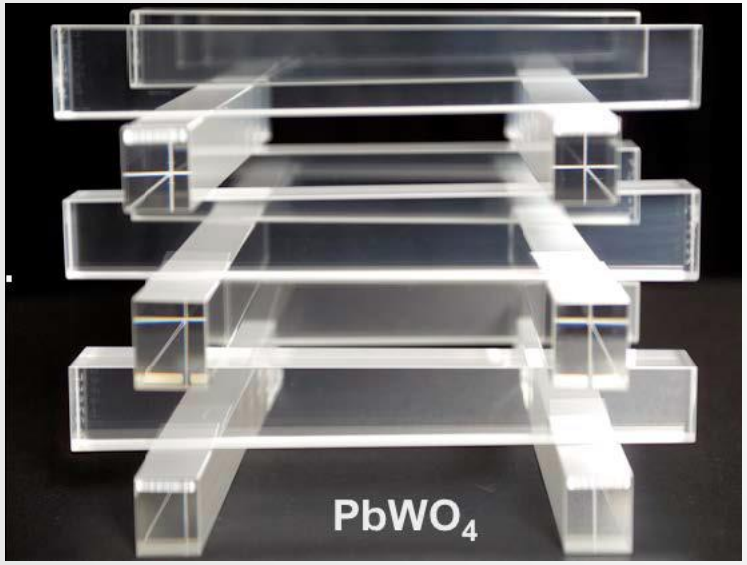
4.1 THE LEAD-TUNGSTATE CALORIMETER OF CMS



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23 cm^3)

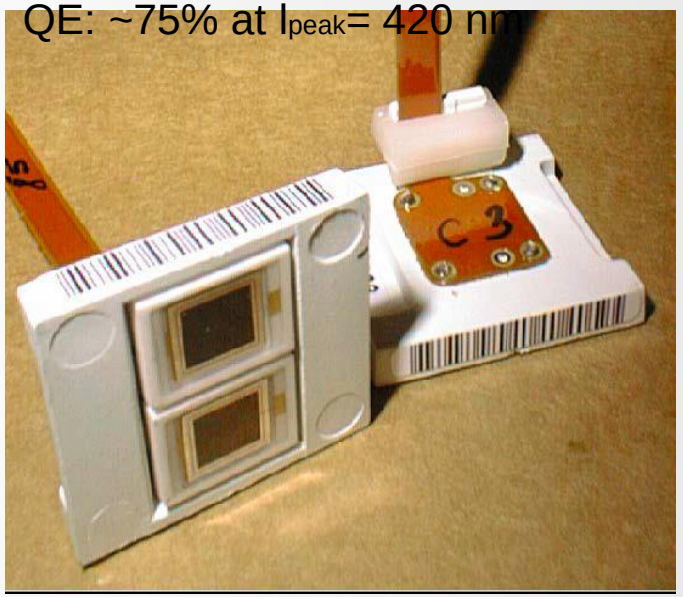
EndCaps: $1.48 < |\eta| < 3.0$, 4 Dees
14648 crystals (3x3x22 cm^3)

4.1 THE LEAD-TUNGSTATE CALORIMETER OF CMS



Endcaps: - Vacuum phototriodes (VPT)
Better radiation resistance than APDs
Active area ~ 280 mm^2/crystal
Amplification 8 -10 (B=4T)
Q.E.~20% at 420 nm

Barrel: Avalanche photodiodes (APD)
Two 5x5 mm^2 APDs/crystal
Amplification: 50
QE: ~75% at l_{peak}= 420 nm



Test beam measurement:

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

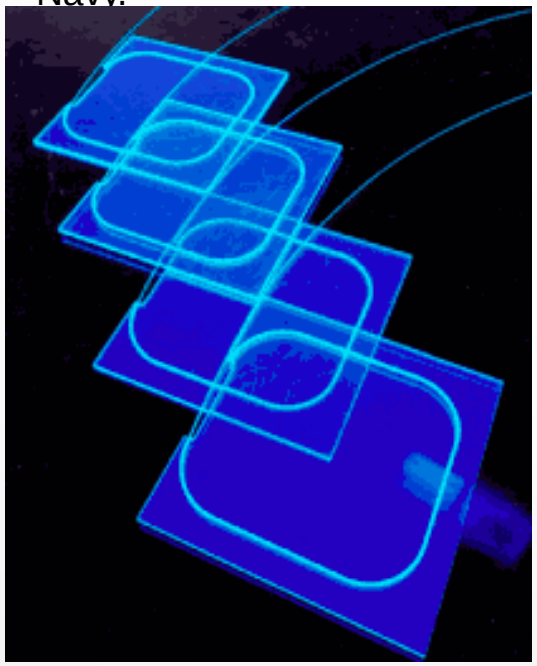
4.2 CMS HCAL

Absorber: Brass (70% Cu / 30% Zn), thickness 50.5 mm and 56.5 mm

Detector: Plastic Scintillator

(Kuraray SCSN81), Thickness 3.7 mm

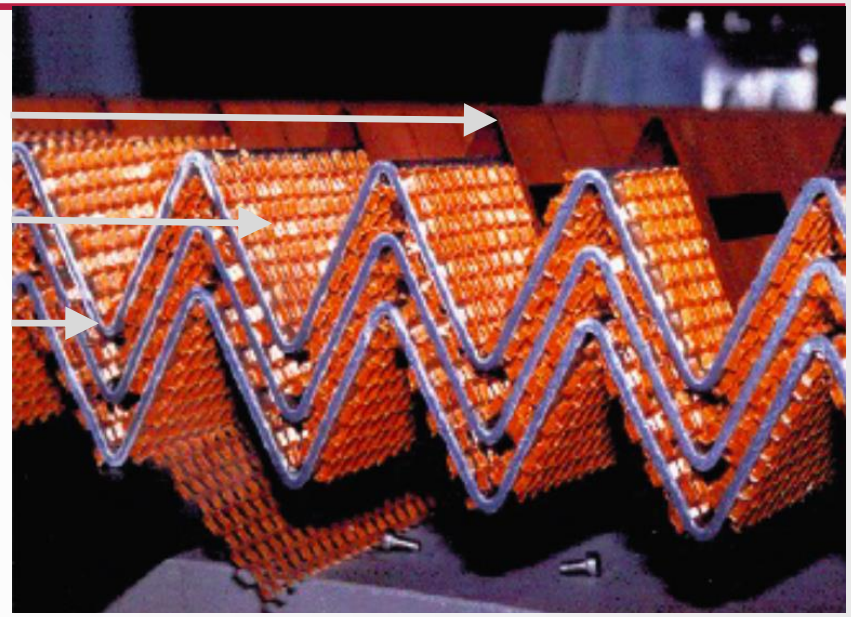
Used over a million World War II brass shell casements from the Russian Navy.

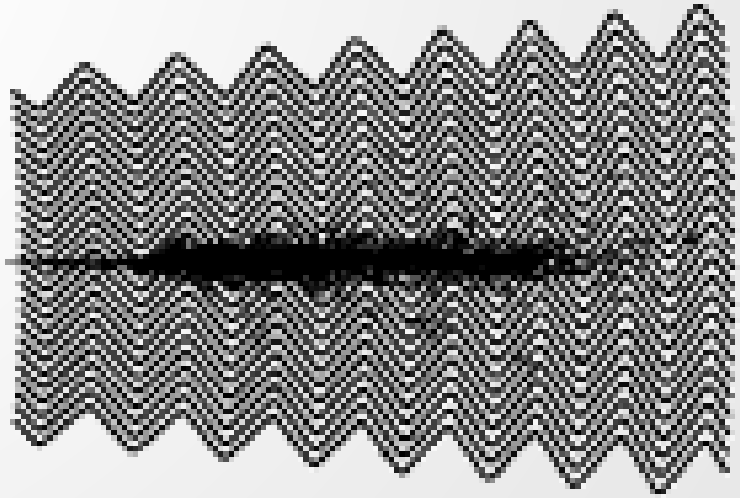


- Plastic scintillators with WLS fibers:
  - scintillator light: 410-425 nm (blue-violet)
  - fibers absorb re-emit it at 490 nm (green).
  - Hybrid Photodiodes (now SiPM) are used to convert light into electrical signals.
  - Energy resolution about $100\%/\sqrt{E} \oplus 5\%$

4.3 ATLAS LAR EM CALORIMETER

- The ATLAS 'accordion' LAr calorimeter covers most of the instrumented area.
- It is a sampling calorimeter with liquid argon (LAr) and Pb absorber
- Electrodes between two layers of lead (2.1mm) allow transversal segmentation, the accordion increases the length of the ionization path
- The granularity is finest at the beginning of the shower development (strips) and coarsest at the end.





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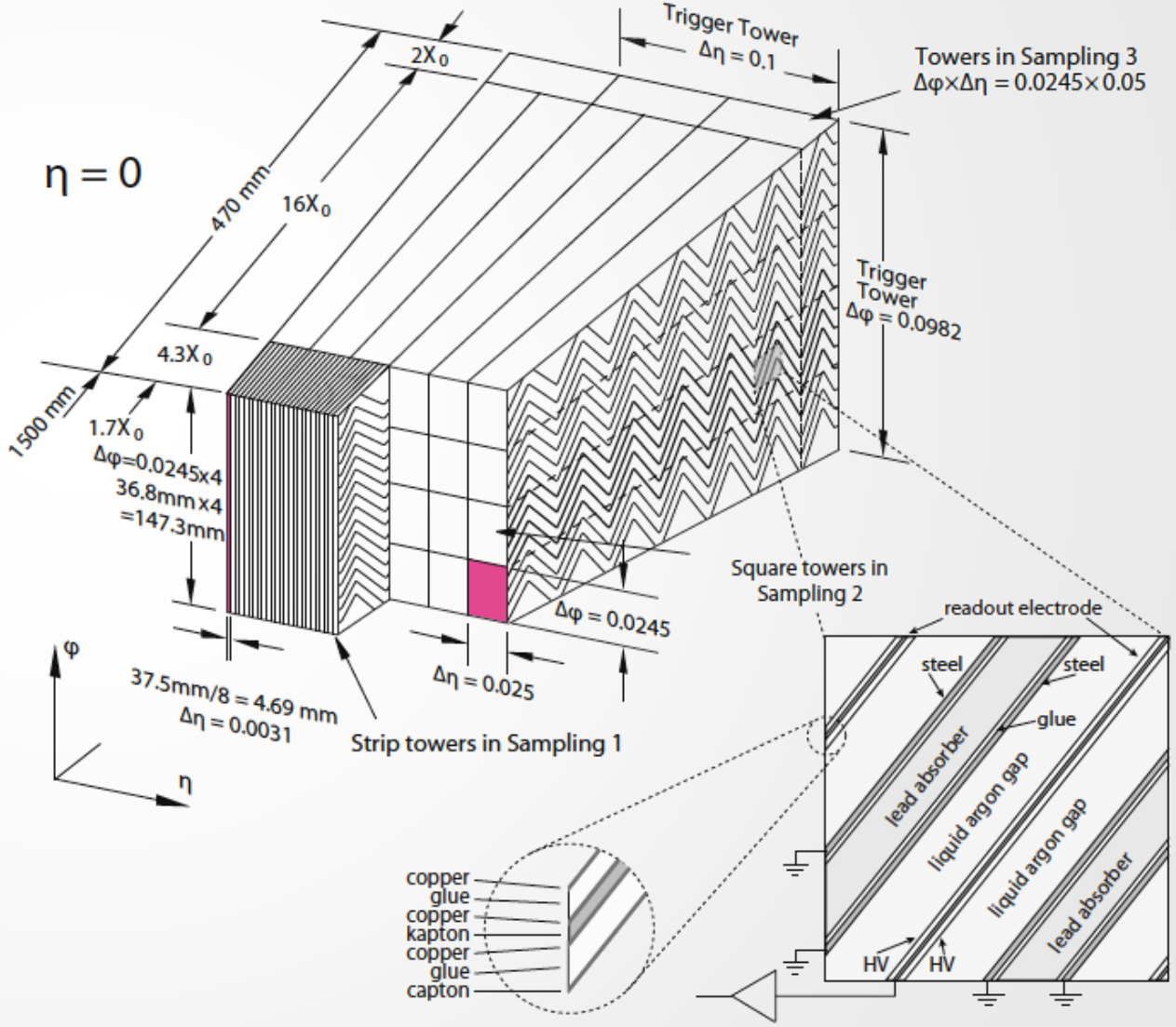
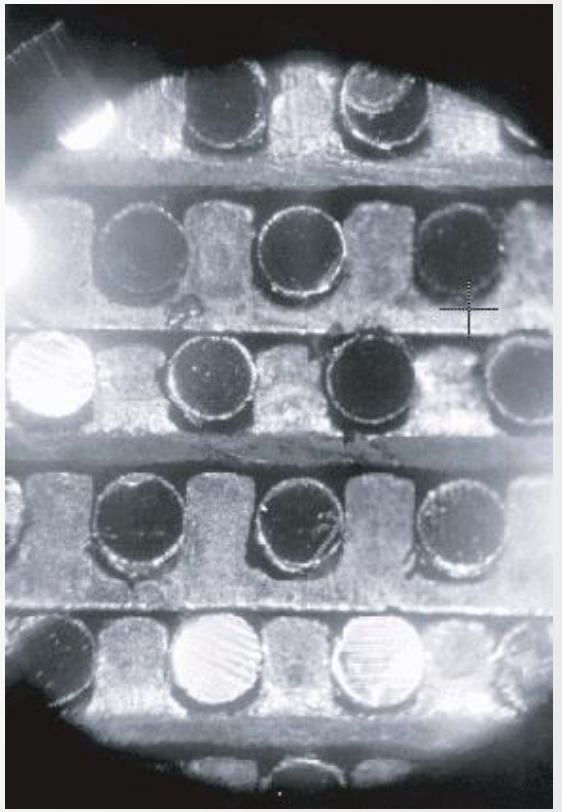


4.4 H1 SPAGHETTI CALORIMETER

- In this type of calorimeter parallel bundles of scintillating fibers are embedded in an absorber matrix (e.g. Pb).
  - Fiber diameter typically 0.5–1 mm.
- Advantages:
  - cheap, compensation possible, excellent hermeticity of the detector
- main disadvantage
  - no longitudinal segmentation
- Prototypes: 1 mm thick fibers in Pb matrix, distance between fibers 2.22 mm
- energy resolution:
  - $\sigma(E)/E$ (e.m.)= $15.7\%/\sqrt{E} \oplus 2\%$ and
  - $\sigma(E)/E$ (hadron.)= $33.3\%/\sqrt{E} \oplus 2.2\%$.



THE END!