Calorimetry:
Basics of Calorimetry for High-Energy Physics

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Outline

- Lecture 1
    - Basics of calorimetry for High-Energy Physics
- Lecture 2
    - Modern HEP Calorimetry Systems
- Lecture 3
    - Particle-Flow Calorimeters
- Lecture 4
    - Dual Readout Calorimeters

- Overview
- Electromagnetic showers
- Hadronic showers
- Homogenous calorimeters
- Sampling calorimeters
- Energy resolution

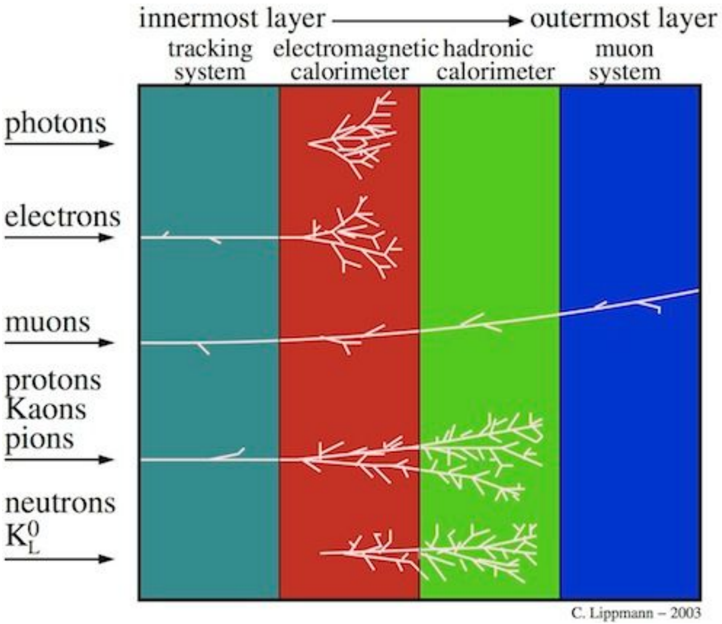
Overview

Goal of this lecture

Introduce how calorimeters in High-Energy Physics experiments…

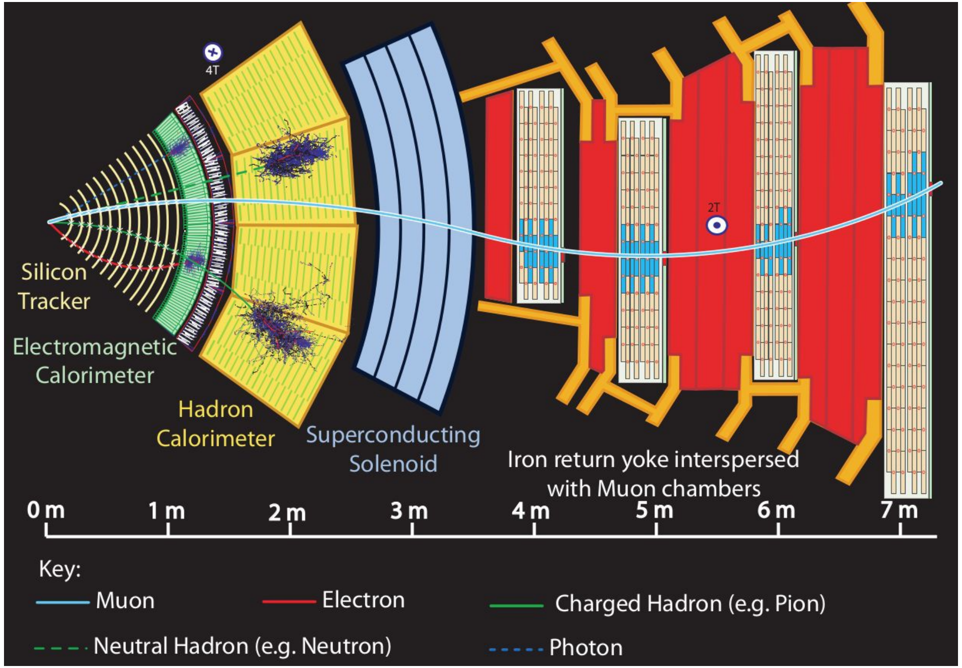
- … measure neutral particles
- … improve energy measurement of high-energetic charged particles
- … help identify particles

Radial structure of a high-energy physics detector



C. Lippmann – 2003

CMS detector slice



What is calorimetry?

- In nuclear and particles physics, calorimetry is the **detection of particles** and **measurements of their properties** though **total absorption** in a block of matter

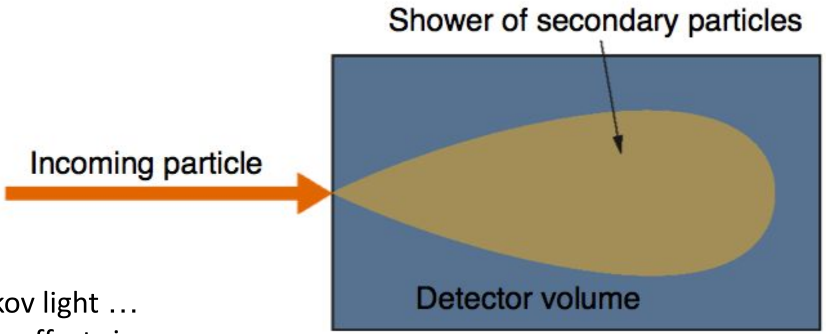
- Calorimetric measurement process is **destructive**
  - Particles are no longer available for inspection by other devices (except for muons)

- Name “Calorimetry” originates from the conversion of the particle energy into heat during the absorption process (Latin calor 'heat')

- However:
  - In accelerator experiments, the particle energies go up to O(TeV)
  - 1 calorie (= 1 g water warmed up by 1°C) is equivalent to 10^7 TeV
  - Rise in temperature of detector material is negligible
  - Other methods than temperature measurements are needed to determine the particle properties

Calorimetry: Concepts

- General idea
  - Primary particle creates shower of secondary particles in dense detector material
  - Each secondary particle deposits energy and produces further particles until the full energy is absorbed
  - Energy conversion into a measurable signal



- Shower particles interact with detection material
  - Via ionisation, atomic excitation, production of Cherenkov light …
  - Depending on the calorimeter type, mostly one of these effects is measured and a signal is deduced

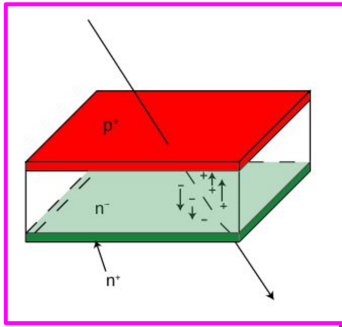
- "Practical" calorimeter
  - Measured signal ∝ deposited energy ∝ energy of primary particle

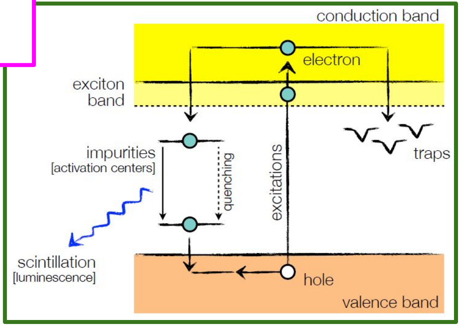
- Primary particles that can be measured
  - Stable charged and neutral particles with sufficient long lifetime of $c\tau > 500\mu m$: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^0, n, γ

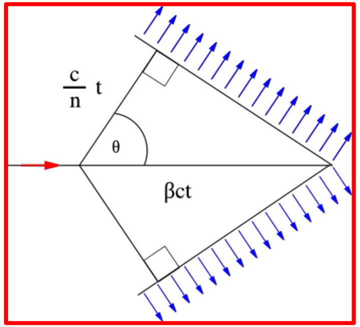
Calorimetry: Signal generation and detection

- **Signal generation**
  - Shower particles can
    - Ionise the detector material
      - electron-ion pairs (gases, liquids) via ionisation
      - create electrons-hole pairs (solids) via ionisation
    - Excite atoms in the detector material:
      De-excitation of atoms can produce scintillation light
    - Emit Cherenkov light in case of v>c/n
    - Create bremsstrahlung, □-rays electrons, interact hadronically

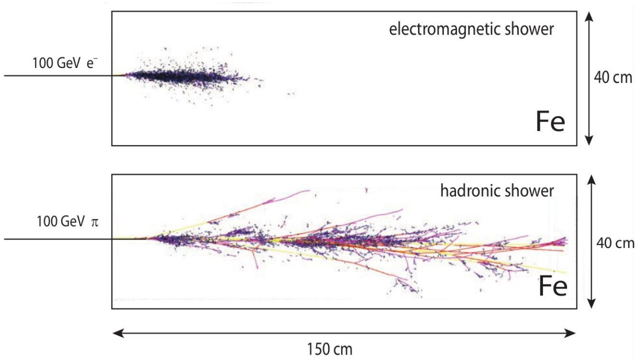
- **Signal detection methods**
  - Ionisation
    - Apply an electric field in the detector volume
    - The ionisation electrons and ions/holes move in the E field
    - Moving charges induce signal on metal electrodes of detector
    - Read out signals by readout electronics
  - Light
    - Cherenkov or scintillation light travels through transparent detector material
    - Read out light signal with photo detectors





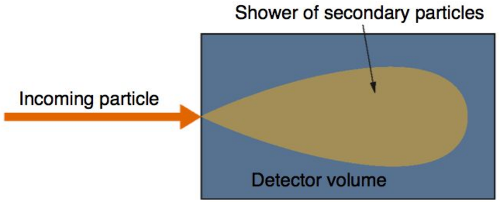


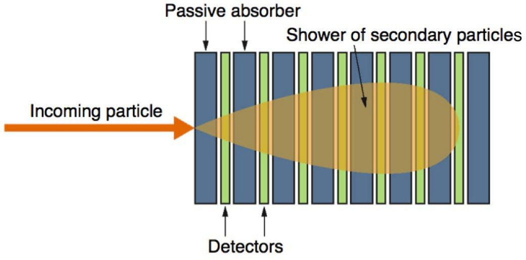
Calorimeter classes and types



Calorimeter classes

- **Electromagnetic** calorimeters
  - Measure electrons and photons through their EM interactions
  - Targeted at compact showers
- **Hadron** calorimeters
  - Measure hadrons through their strong interactions and EM interactions
  - Targeted at far reaching showers





Construction classes

- **Homogeneous** calorimeters
  - Built of only one type of material that performs both tasks, energy degradation and signal generation
- **Sampling** calorimeters
  - Alternating absorber / active medium (many configurations possible):
    - Absorber, a dense material used to degrade the energy of the incident particle
    - Active medium that provides the detectable signal

Attractiveness of calorimeters for HEP

1. Energy resolution of calorimeters improves with energy and independent from particle direction: Best suited for high E

Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$

Tracking detector: $\frac{\sigma_p}{p} \sim p$

e.g. ATLAS:

$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$

i.e. $\sigma_E/E = 1\%$ @ 100 GeV

e.g. ATLAS:

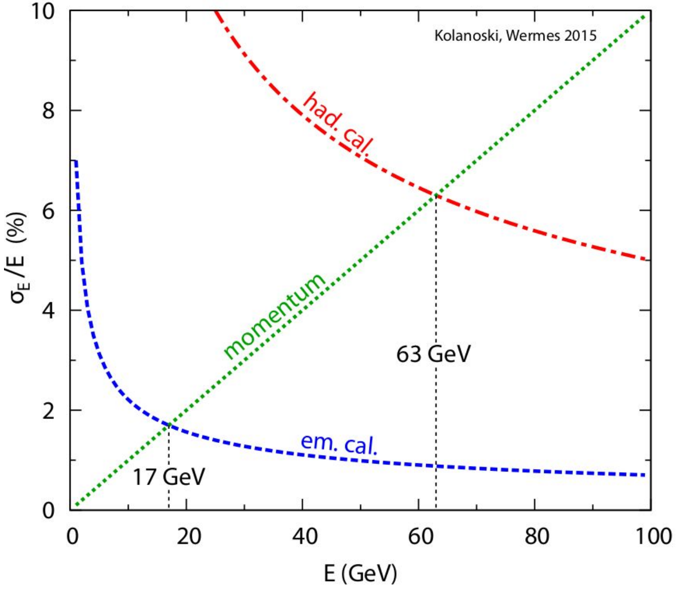
$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$

i.e. $\sigma_p/p = 5\%$ @ 100 GeV

2. Measure both charged and neutral particles
    - Even indirect detection of neutrinos via missing energy

3. Versatile detectors
    - Measure shower energy, position, direction, arrival time, particle identification from shower shapes
    - Fast signal (<100ns), easy to process and interpret → trigger

4. Space and cost effective
    - Shower depth (required detector depth) increases with ~log E
    - Comparison: Bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum



Example values used

$\sigma_E/E = 7\,\%/\sqrt{E}$ for electromagnetic showers

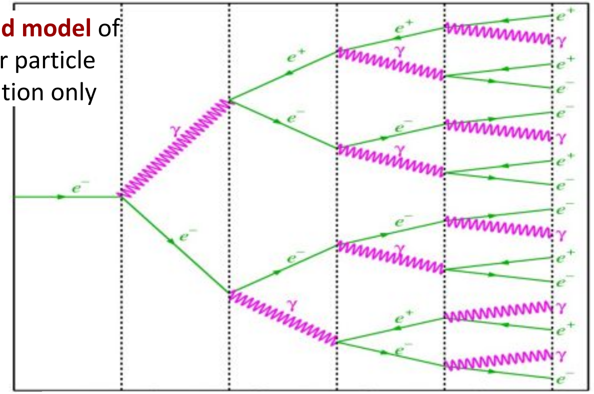
$\sigma_E/E = 50\,\%/\sqrt{E}$ for hadronic showers

$\sigma_p/p = 0.1\,\%\ p$ for E determination by p

Electromagnetic showers

Electromagnetic showers: Processes

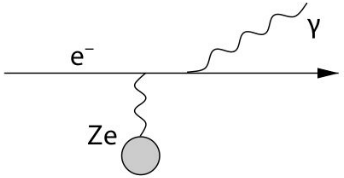
Simplified model of shower particle generation only



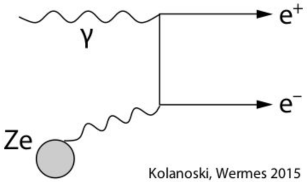
Note: Similar shower development for incoming photon

- An incoming $e^{\pm}$ emits a photon via **bremsstrahlung**
- The photon creates a $e^{+}e^{-}$ via **pair production**
  - Cross sections: $\sigma \propto Z^2$
- Rapidly increasing number of e^{+} and e^{-} and photons until critical energy E_c is reached
  - E_c: energy at which the energy loss via bremsstrahlung and ionisation are equal
- Remaining $e^{\pm}$ loose energy via ionisation, photons via Coulomb scattering and photo effect

Bremsstrahlung



Pair production



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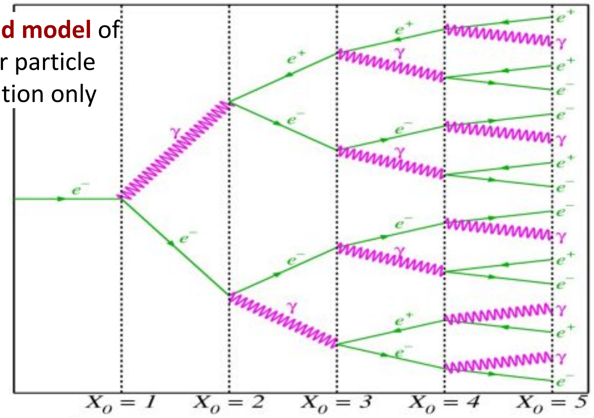
Interactions in Coulomb field of nucleus with charge number Z

E.m. shower development theoretically well known. Can be simulated precisely (e.g. EGS, Geant4).

Electromagnetic showers: Radiation length

Simplified model of shower particle generation only



x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
<E>	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

$$N = 2^t$$

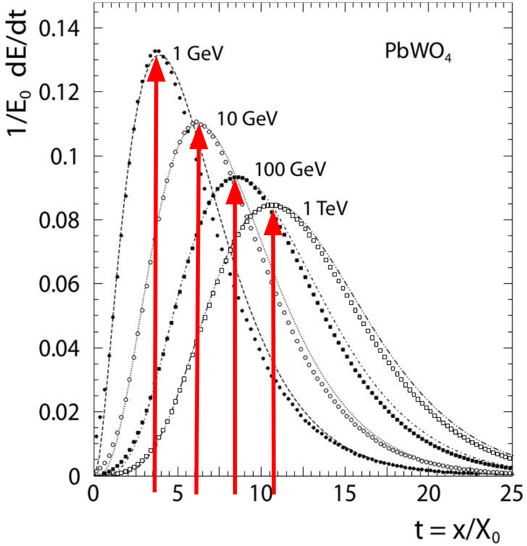
$$E_c = \frac{E_0}{2^{t_{max}}} \Rightarrow t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

Kolanoski, Wermes 2015

- X_0: Radiation length
  - Lengths after which the energy of the primary particle E_0 is reduced to 1/e (~37%)
  - Number of particles doubles each X_0
  - X_0 decreases with increasing nuclear charge Z

Material	Z	Radiation length X_0 (mm)
Air 20°C 1 atm	-	~304 000
Water	-	361
Iron	26	17.6
Tungsten	74	3.5
Lead	82	5.6
Uranium	92	3.2

Electromagnetic showers: Longitudinal development



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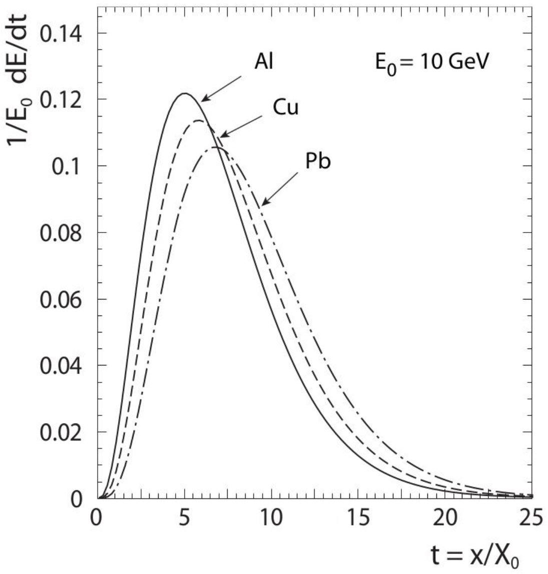
Important feature of calorimeters:

➡ Shower depth increases only logarithmically with incident particle energy

➡ Calorimeters can be compact

E_c = 9.64MeV
for electrons



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- Empirical formula for depth of shower t
  - Shower maximum at $t_{max}\,[X_0] \cong \ln(E_0/E_c) \begin{cases} -0.5 \text{ (electrons)} \\ +0.5 \text{ (photons)} \end{cases}$
- 95% of shower energy deposited after $t_{98\%} \cong t_{max} + 13.6 \pm 2.0$
- Number of particles N scales linearly with energy E_0 of primary particle: $N \propto E_0/E_c$

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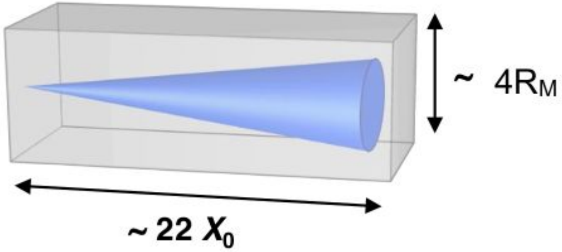
- t_{max} in units of X_0 depends on material through differences in critical energy E_c
- Shower decay after t_{max} is slower for materials with higher Z

Electromagnetic showers: Lateral spread

- Longitudinal development governed by the radiation length X_0
- Lateral spread due to $e^\pm$ undergoing multiple scattering and γ undergoing Compton scattering
    - 95% of the shower cone is located in a cylinder of 2 times the **Molière radius ρ_M (also R_M)**
- Molière radius $\rho_M = E_s/E_c \cdot X_0 = 21\text{MeV}/E_c \cdot X_0$
    - Energy scale $E_s = \sqrt{(4\pi/\alpha\ (m_e c^2))} = 21.2$ MeV
- Molière radius important parameter for
    - Measurement of shower position
    - Shower separation
    - Detector design: Granularity in the order of Molière radius or finer



Material	**Z**	**Molière radius ρ_M (mm)**
Aluminium	13	44.0
Iron	26	16.9
Copper	29	15.2
Tungsten	74	9.3
Lead	82	16.0
Uranium	92	10.0

Electromagnetic showers: Lateral spread

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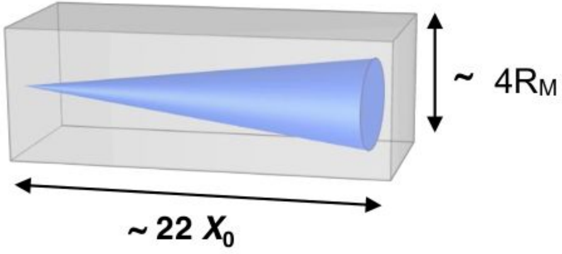
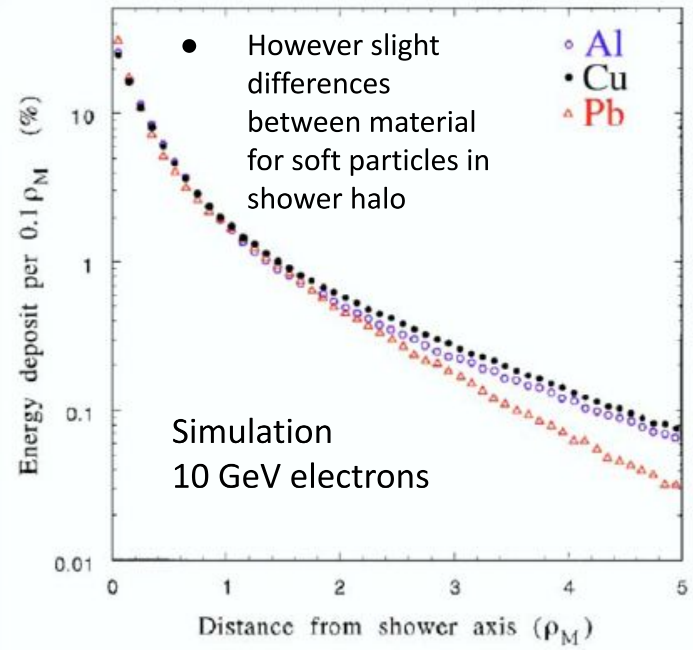




- However slight differences between material for soft particles in shower halo

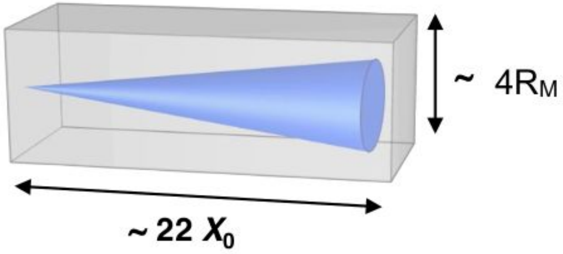
Simulation
10 GeV electrons

Electromagnetic showers: Example

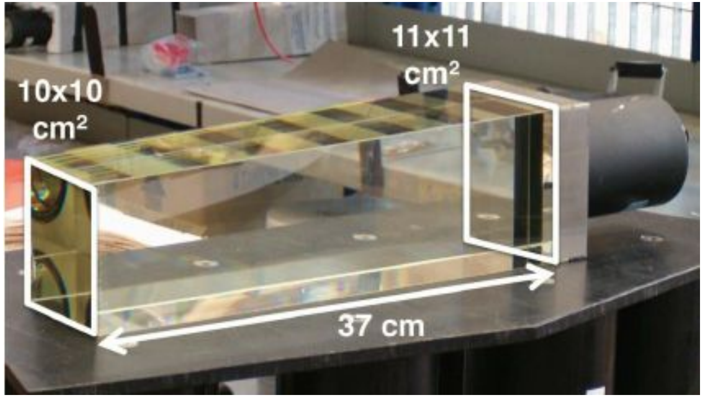
- Electron with E_0 = 100 GeV, in lead glass ($PbO + SiO_2$)
  - E_c = 11.8 MeV
  - $X_0 \approx 2$ cm

$N_{max} \approx E_0/E_c$	~8500	
$t_{max} \approx \ln(E_0/E_c) - 0.5$	$\sim 8.5\ X_0$	≈ 17 cm
$t_{98\%} \approx t_{max} + 13.6 \pm 2.0$	$\sim(22\pm2)\ X_0$	≈ 44±4 cm
$\rho_M \approx E_s/E_c * X_0$	~3.6cm	
$\rho_{95\%} \approx 2\ \rho_M$	~7.2cm	

Rule of thumb for modern HEP detector design: need about 25 X_0



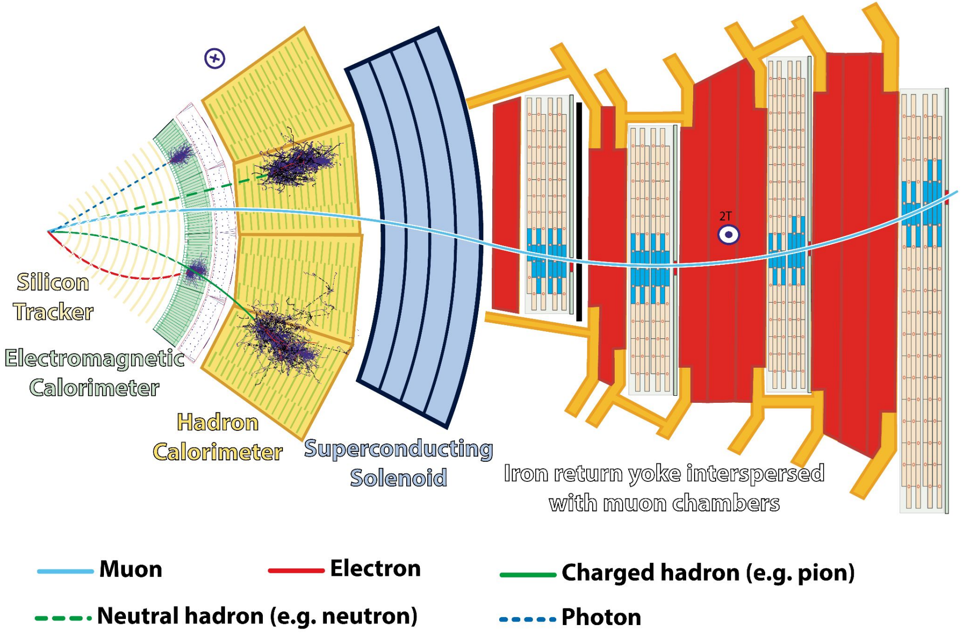
OPAL calorimeter: lead glass blocks (37cm - 52cm)
(Now in NA62)



Hadronic showers

Hadronic showers: Introduction

- Hadronic showers:
  - From primary charged hadrons (p, $\pi^{\pm}$,$K^{\pm}$) and neutral hadrons (n, K^0)
- Hadron shower development:
  - Similar to electromagnetic shower development, but with hadronic interactions
  - Hadronic interactions governed by nuclear force, with smaller cross section than electromagnetic cross section

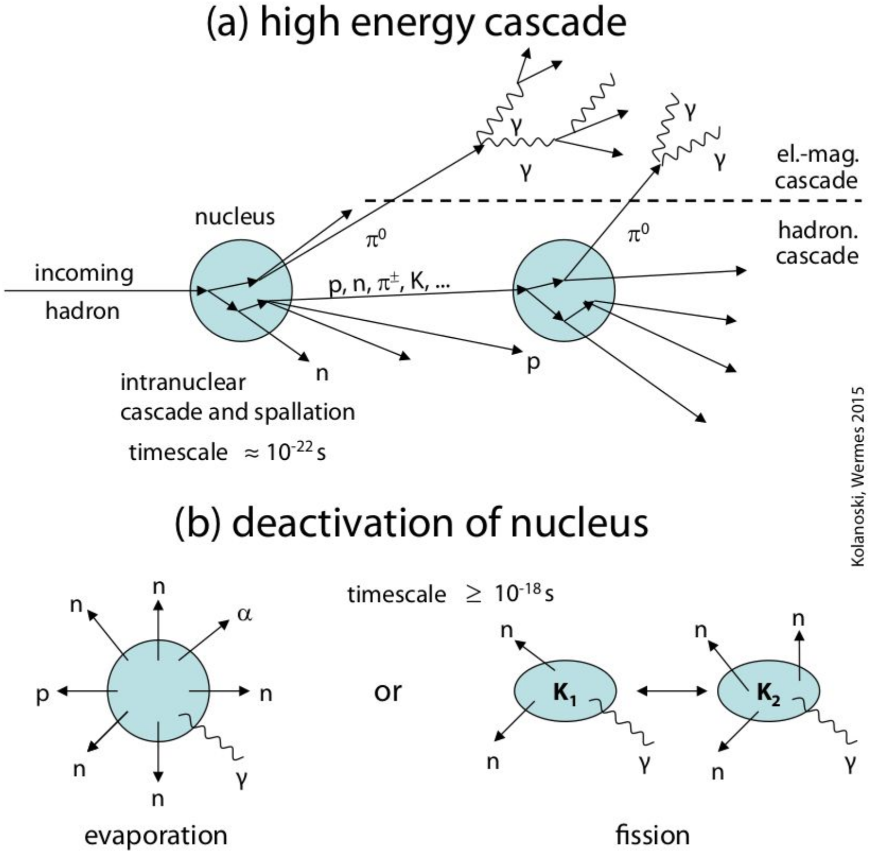


Impact on experiment layout:

- "Slim" e.m. calorimeter located in front of "thick" hadronic calorimeter

Hadronic showers: Processes

- Series of **inelastic** hadronic interactions of primary and secondary hadrons with the nuclei of the target material
- **Multitude of possible processes**:
    - Intra-nuclear cascade: Components of the nucleus receive enough energy to interact with each other and to produce pions or other hadrons
    - Inter-nuclear cascade: Particles escaping the nucleus hit another nucleus
    - Spallation
    - Nuclear excitation
    - Nuclear evaporation
    - Nuclear fission
- **Elastic** interactions
    - Do not produce secondary particles
    - Do not contribute to the hadronic shower development
- Between interactions and at end of shower, shower particles loose energy via ionisation and atomic excitation



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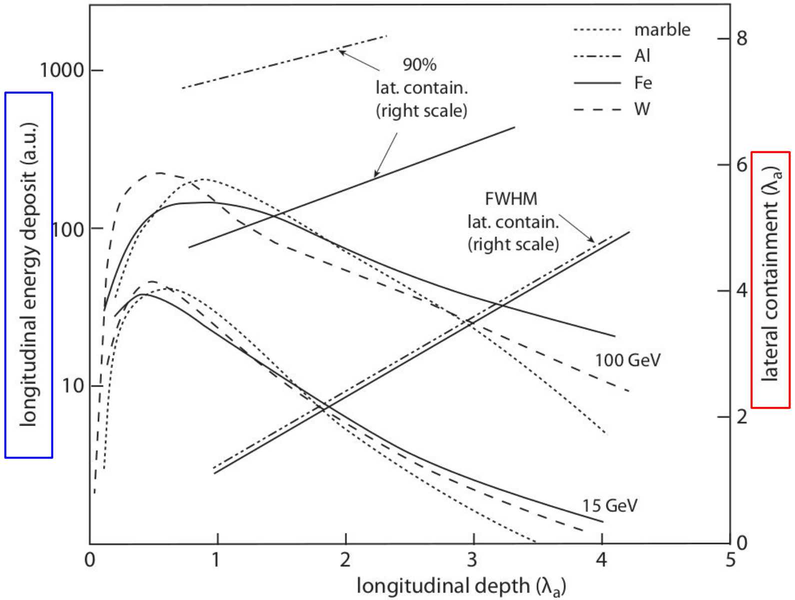
Note: Hadronic shower development much more complicated than e.m. shower development, more difficult to simulate

Hadronic showers: Longitudinal & lateral development



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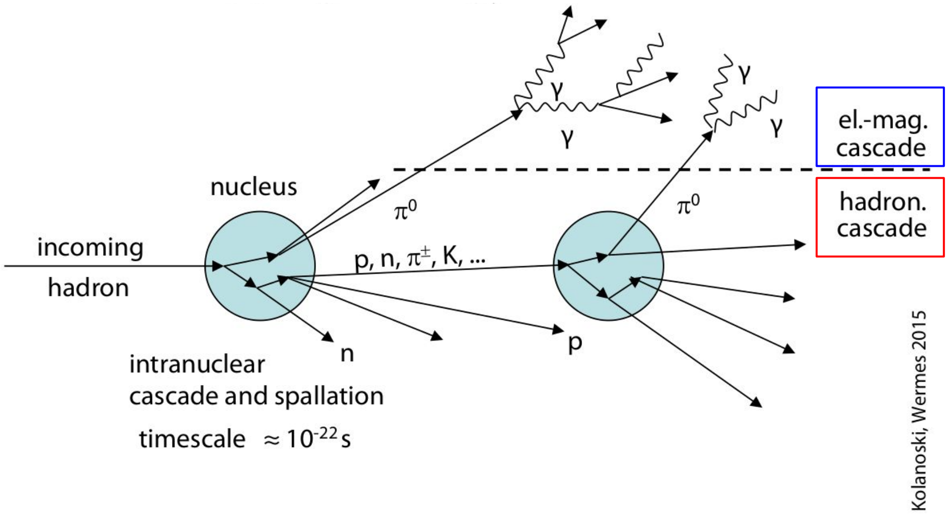
(Starting at point of first interaction)

Material	Z	Nuclear interaction length λ_a(mm)
Air 20°C 1 atm	-	~747 000
Iron	26	168
Tungsten	74	96
Lead	82	170
Uranium	92	105

- Shower development scales with nuclear interaction length
- Empirical estimates:
  - $t_{max} \cong 0.2 \ln(E/GeV) + 0.7$ → in units of λ_a
  - $t_{95\%} \cong t_{max} + 2.5\,(E/GeV)^{0.13}$

Rule of thumb for modern HEP detector design: need about 10 λ_a

Hadronic showers: Shower substructure



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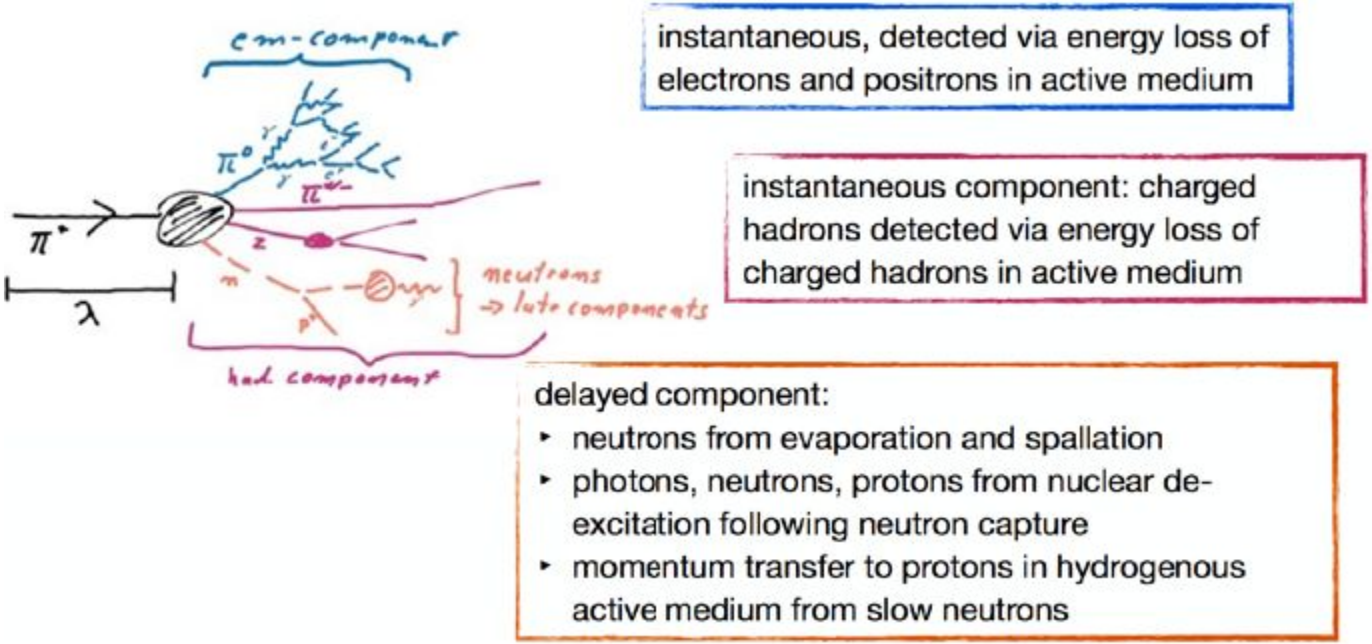
Shower substructure:

- Secondary neutral mesons (π^0,η) decay into photons
  - Electromagnetic sub-showers within hadronic shower
  - Apriori not know which energy fraction carried by electromagnetic sub-shower

Hadronic showers: Time structure

- Hadronic showers have a complex structure also in time
- Importance of delayed component in signal formation strongly depends on target nucleus
- Sensitivity to time structure depends on the choice of active medium (e.g. H content)



instantaneous, detected via energy loss of electrons and positrons in active medium

instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

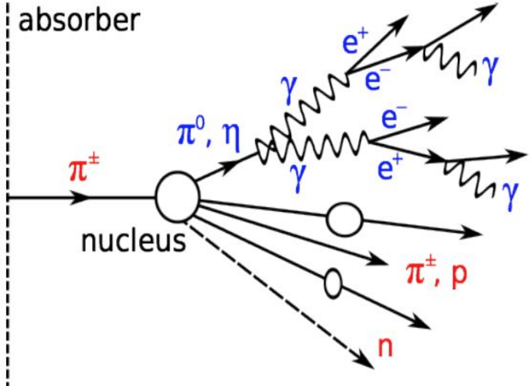
delayed component:
- neutrons from evaporation and spallation
- photons, neutrons, protons from nuclear de-excitation following neutron capture
- momentum transfer to protons in hydrogenous active medium from slow neutrons

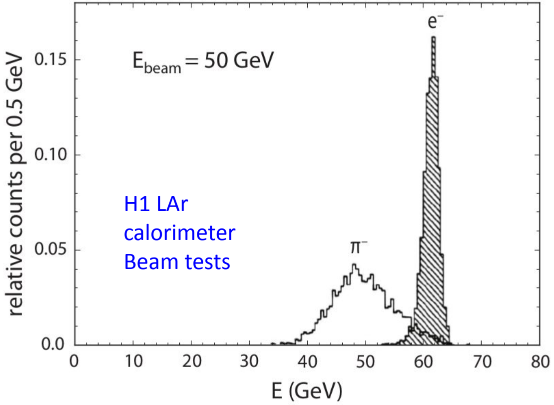
Hadronic showers: Energy response

- Absorption of 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
- No such energy loss mechanism in the e.m. shower

- Response of calorimeter
  - to purely hadronic component (h) usually smaller than
  - to purely e.m. component (e)

- e/h response ratio figure of merit of a hadron calorimeter
  - A priori e/h ≠ 1 and energy dependent
  - An ideal calorimeter has similar response for both shower components: e/h=1





H1 LAr calorimeter Beam tests

Compensation

- Hadron calorimeter response to hadronic and electromagnetic shower components:
  - $R_h = e \cdot E_e + h \cdot E_h$
- Fraction of energy deposited electromagnetically
  - Fluctuates between events and
  - Increases on average with energy of primary hadron:
    - $E_e / E = f_{EM} = k \cdot \ln(E(\mathrm{GeV}))$, $k \sim 0.1$
    - Response of calorimeter to hadron shower becomes non-linear
    - Energy resolution degrades

a= stochastic term of energy resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + d\left(\frac{e}{h} - 1\right)$$

But

- e/h depends on geometry and material
- e/h=1 can be reached by increasing the hadronic signal
  - **Hardware** compensation
    - Increase neutron activity by use of special absorber (e.g. Uranium)
    - Increase sensitivity to slow neutrons (e.g. use Hydrogen enriched scintillator)
    - Choose favourable sampling fraction (thickness of absorber vs. active layers)
  - **Software** supported compensation
    - Identify dense (e.m.) and sparse regions (had.) in the shower and assign energy weights
      - Requires granularity
  - Software compensation never as good as hardware compensation

Energy resolution

Energy measurement: Intrinsic resolution

- For an ideal calorimeter with infinite dimensions, the energy resolution is determined by **stochastic fluctuations** of the **number of charged particles N** contributing to the signal

$$\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

- Maximum number of particles contributing to the signal

$$N_{\max} = E/\eta$$

- η: threshold energy = minimum energy to create detectable secondary particle
  - Germanium: $\eta = 2.9$ eV
  - Silicon: $\eta = 3.6$ eV
  - Gas: $\eta = 30$ eV
  - Plastic scintillator: $\eta = 100$ eV

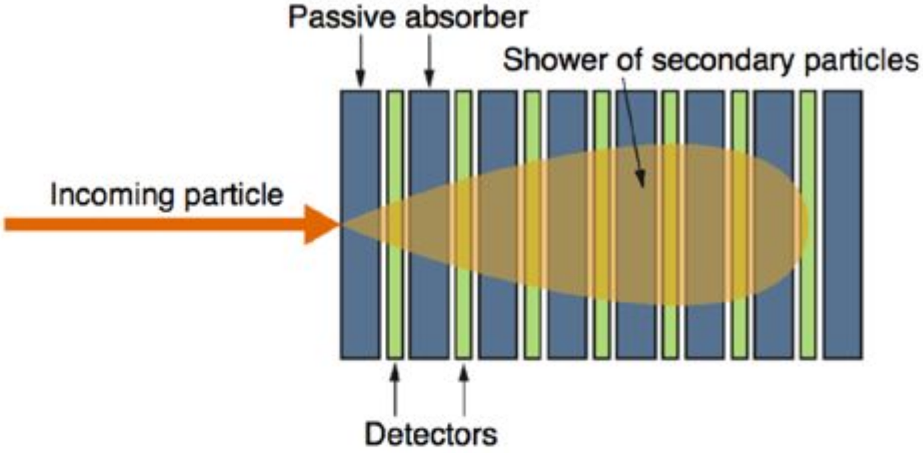
- In a realistic calorimeter further terms arise, with different energy dependencies (see later)

Energy measurement: Sampling fluctuations

- **Sampling fluctuations**
  - Sampling calorimeters measure only a small fraction (few %) of the deposited energy
  - Energy fraction f_s deposited in detection layers varies from event to event
  - This deteriorates the energy resolution
  - Driven by variation in number of charged secondary particles traversing the detector layers

$$f_s = \frac{E_{vis}}{E_{dep}}$$

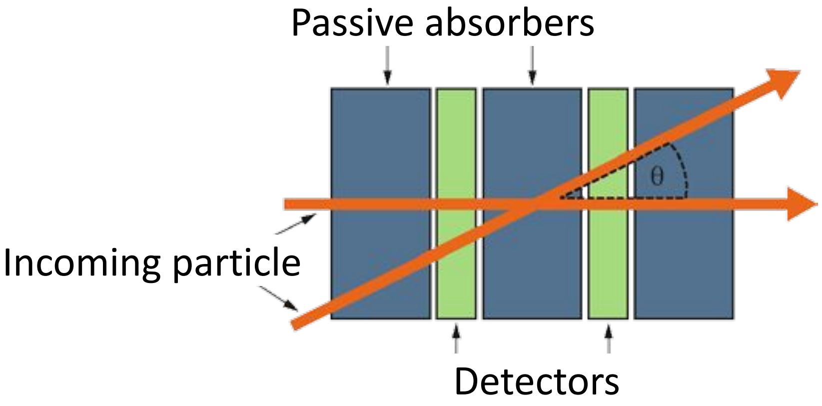
$$\frac{\sigma_E}{E} \approx \frac{\sqrt{N_{vis}}}{N_{vis}} = \frac{1}{\sqrt{N_{vis}}}$$



Energy measurement: Other fluctuations

- **Landau fluctuations**
  - Thin detector layers
    → Asymmetric energy loss distribution (Landau instead of Gaussian distribution)
    → Important in gas and thin silicon detectors

- **Track-length fluctuations**
  - Secondary particles cross the detector planes under various angles
  - From event to event the total track length of secondary particles fluctuates
    → Deposited energy varies accordingly
    → Contribution to the energy resolution

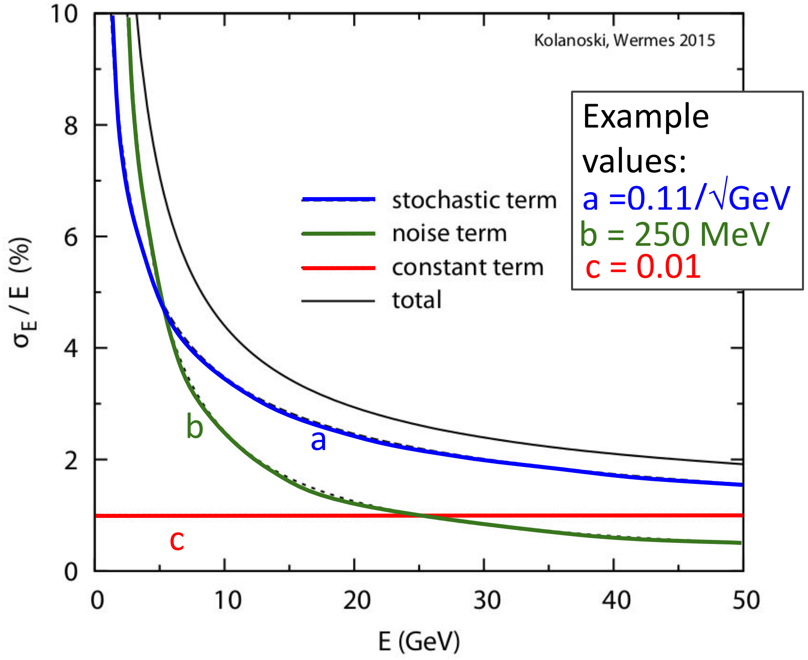


Energy resolution: Parametrisation

- The energy resolution is parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2} \quad = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Stochastic term **a**
  - All stochastic fluctuations,
    e.g. intrinsic fluctuations, sampling fluctuations
- Noise term **b** → dominates at low E
  - Electronic noise
  - Energy independent term
- Constant term **c** → dominates at high E
  - Mechanical and electronic imperfections,
    inhomogeneous response, calibration errors, dead channels, leakage
  - Linearly dependent of energy



Example values:
a =0.11/√GeV
b = 250 MeV
c = 0.01

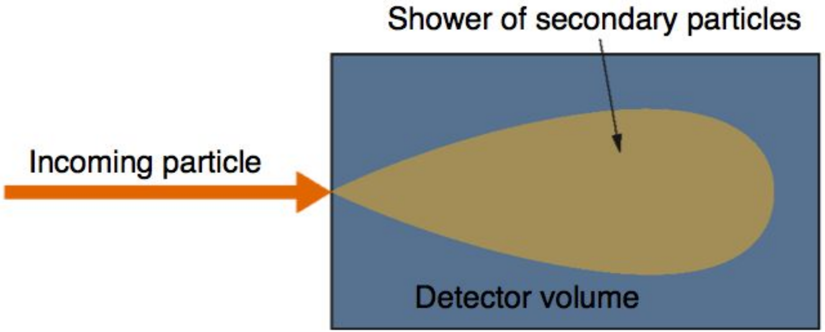
Homogeneous calorimeter examples

Homogeneous calorimeters

- One material used for both purposes
  - passive material that absorbs particle and
  - material that produces detectable signal

- Pros:
  - Very good energy resolution (measure the full shower energy)
- Cons:
  - Limited selection of materials
  - High costs
  - Detector element needs to be deep enough to absorb the full shower
  - Segmentation is difficult (limited information on shower shape),

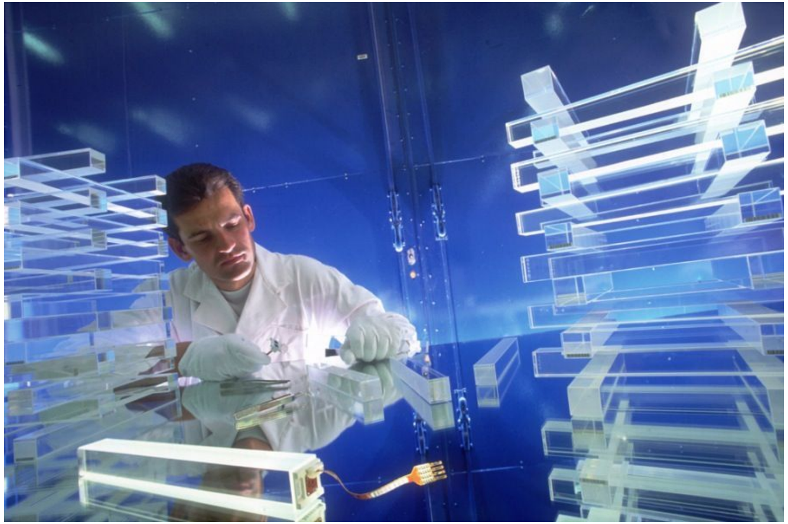
Homogenous concept only for electromagnetic calorimeters



Signal	**Material**
Scintillation	Bismuth Germanate $Bi_4Ge_3O_{12}$= BGO Lead Tungstate $PbWO_4$ BaF_2 , CeF_3, CsI(Tl)
Cherenkov light	Lead glass (PbO+ SiO_2)
Ionisation	Liquid noble gasses (Ar, Kr, Xe), Germanium (in nuclear physics)

Homogeneous calorimeters: Scintillators

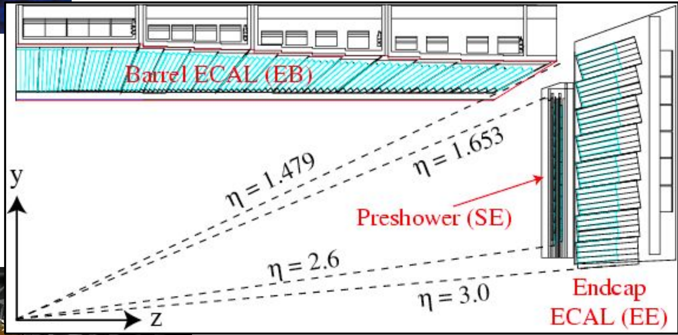
$PbWO_4$ (95% lead) monocrystals for CMS ECAL



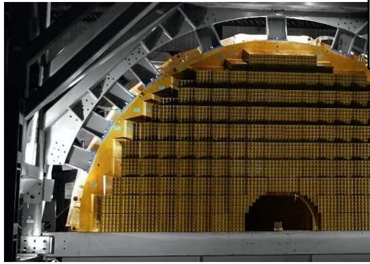
ALICE PHOS

- $PbWO_4$: Lead tungstate crystal
  - Signal: Scintillation
  - Very radiation hard
- Light detection (in CMS ECAL):
  - Avalanche Photo Diodes (APD): Barrel
  - Vacuum Phototriodes (VPT) Endcap

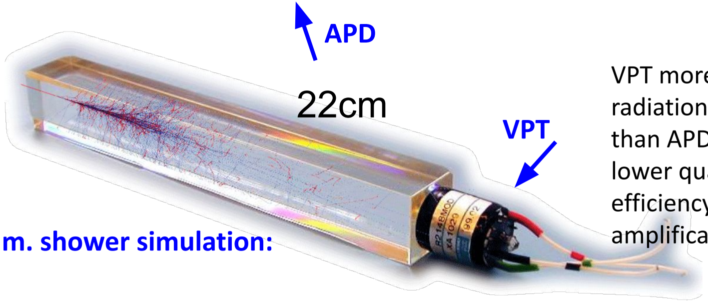
CMS ECAL: Crystal orientation in direction of interaction point



CMS ECAL Endcap (EE)



E.m. shower simulation:



VPT more radiation hard than APDs but lower quantum efficiency and amplification

Typical resolutions:

$$\boxed{\frac{\sigma_E}{E} \approx \frac{(2\text{–}5)\%}{\sqrt[4]{E/\mathrm{GeV}}}}$$

Homogeneous calorimeters: Crystals

	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5

- Higher light yield provides better energy resolution
- Selected material needs to fit time and radiation requirement of experiment
- Materials need to be transparent for scintillation signal

BaBar@PEPII/ Belle@KEKB

- 10ms interaction rate
- High light yield
- Low radiation dose

L3@LEP

- 25µs bunch crossing
- Medium light yield
- Low radiation dose

CMS@LHC

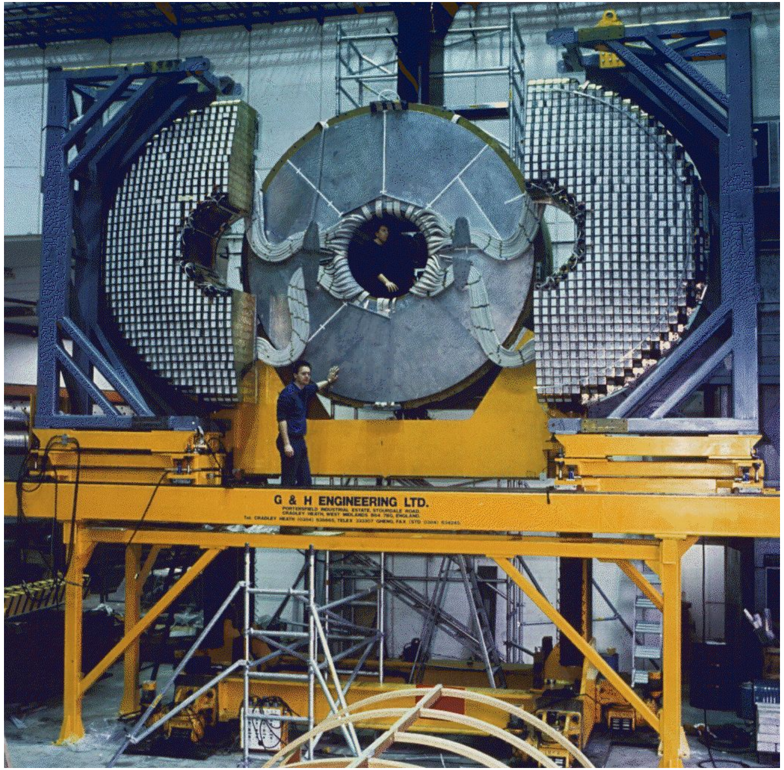
- 25ns bunch crossing
- Lower light yield
- High radiation dose

Homogeneous calorimeters: Cherenkov

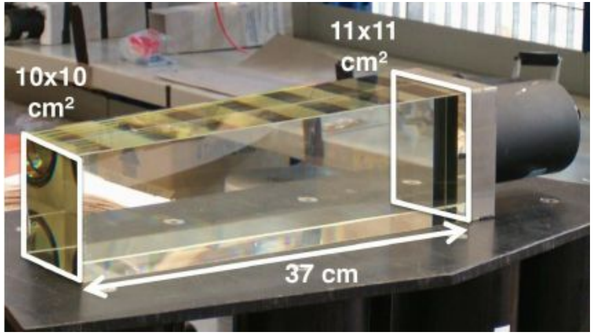
Lead glass ($PbO + SiO_2$) calorimeter in OPAL detector

- Lengths between 37 and 52 cm
- Signal: Cherenkov light
    - Created for electron energy > 0.7MeV
- Light yield smaller than of scintillating crystal, leading to worse energy resolution than in crystals with scintillation signal
- Light detection: Vacuum photo-triodes (VPT)

OPAL calorimeter endcap



OPAL calorimeter: lead glass (Now in NA62)



Typical resolutions:

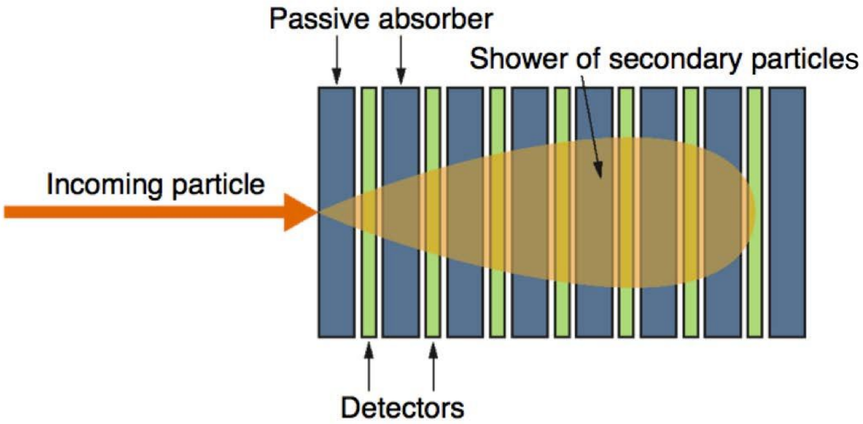
$$\boxed{\frac{\sigma_E}{E} \approx \frac{(5\text{–}10)\%}{\sqrt{E/\mathrm{GeV}}}}$$

Sampling calorimeter examples

Sampling calorimeters

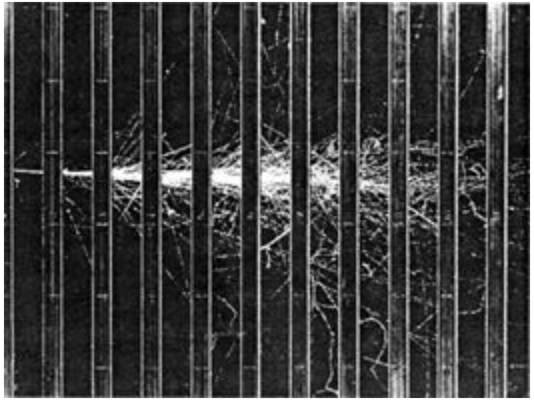
Sampling calorimeter: alternating layers/elements of passive absorbers and active detectors

- Typical absorbers: materials with high density:
  - Fe, Pb, W, U
- Typical active detectors:
  - Plastic scintillators
  - Silicon detectors
  - Noble liquid ionisation chambers
  - Gas detectors

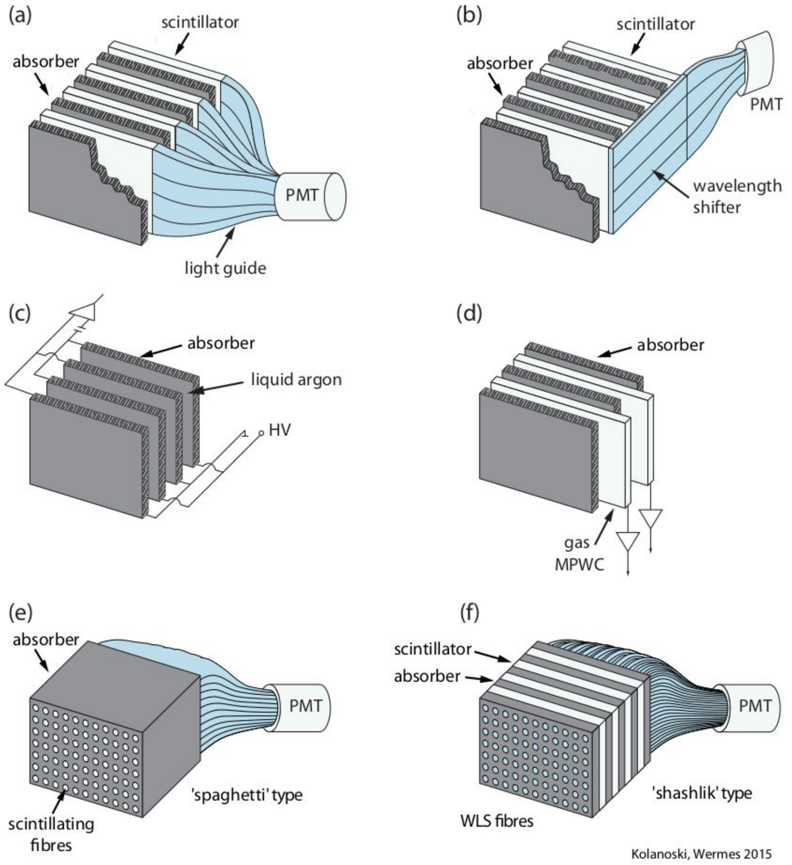


- Pros:
  - Optimise absorber and detector material independently, targeted to application
  - Dense absorber material allows for compact calorimeter
  - Absorber material relatively cheap
- Cons:
  - Only fraction of shower energy is measured
  - Deteriorates energy resolution

Electromagnetic cascade of 4 GeV photon in cloud chamber filled with 1.3cm lead plates



Sampling calorimeters: Main layouts



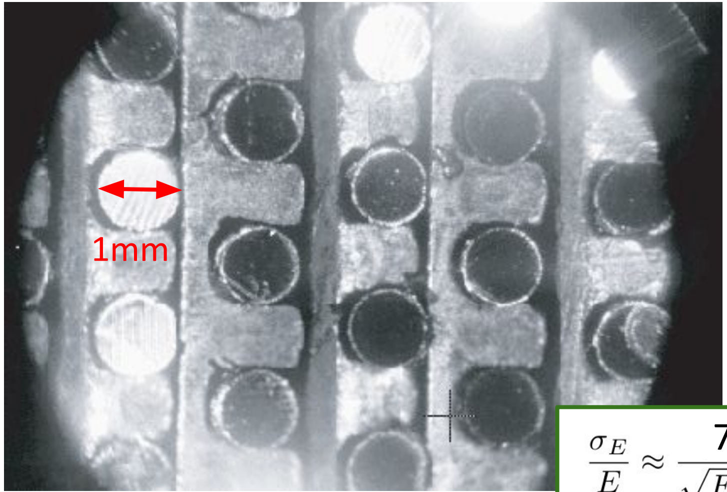
Kolanoski, Wermes 2015

- “Sandwich”
  - (a)+(b): Scintillator
  - (c): Ionisation chamber based on liquid Argon (LAr), silicon
  - (d): Gas Detector: here: Multi-Wire-Proportional Chamber
- “Spaghetti”
  - (e): Absorber with scintillating fibres
- “Shashlik”
  - (f): Scintillating layers and wavelength shifting fibres

Note: Orientation of active components to particle direction varies in existing detectors

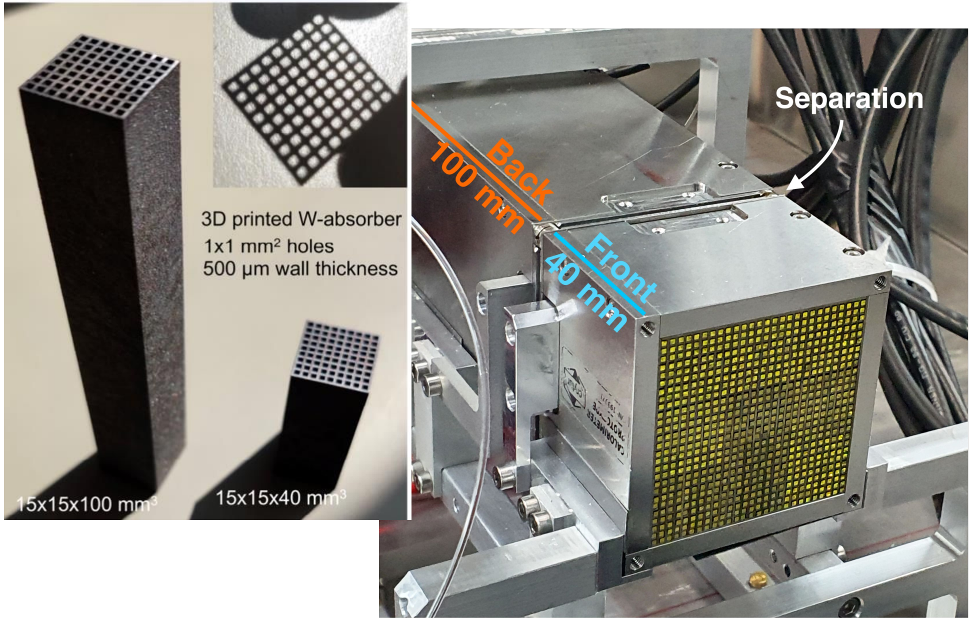
Sampling calorimeters: Spaghetti Calorimeters

- SPACAL H1 @ HERA
  - Active layers: Scintillating fibres
    0.5mm or 1mm diameter (for ECAL or HCAL part)
  - Light generation and readout combined
  - Absorber: lead: Plates with grooves
  - No longitudinal segmentation



Nucl. Instr. Methods A., 386, 397–408 (1997)

$$\frac{\sigma_E}{E} \approx \frac{7\,\%}{\sqrt{E/\mathrm{GeV}}}$$

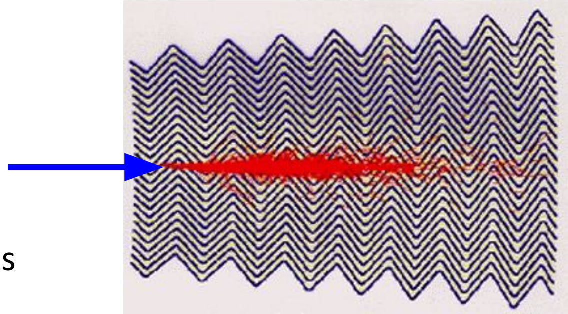


- LHCb SPACAL prototype for HL-LHC
  - Radiation-hard scintillating crystal fibres
  - Tungsten absorber
  - Can now be 3D printed, fibres inserted

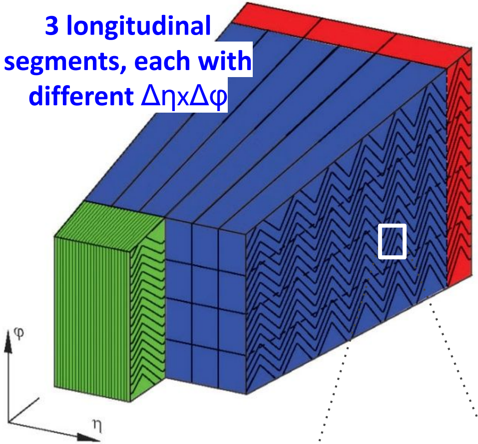
Sampling calorimeters: Example ATLAS LAr ECAL

- Sampling calorimeter with Accordion structure
  - No cracks in azimuthal angle
- Absorber: Lead
- Active medium: Liquid Argon at 90K
  - Radiation resistant
- Signal used: Ionisation
- Honeycomb spacers position electrodes between lead absorber plates

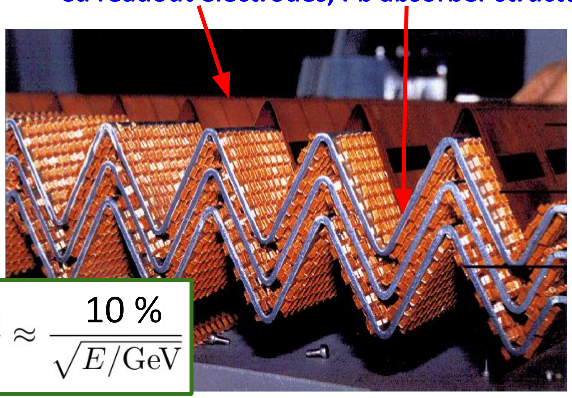
Particle shower simulation



3 longitudinal segments, each with different Δη×Δφ

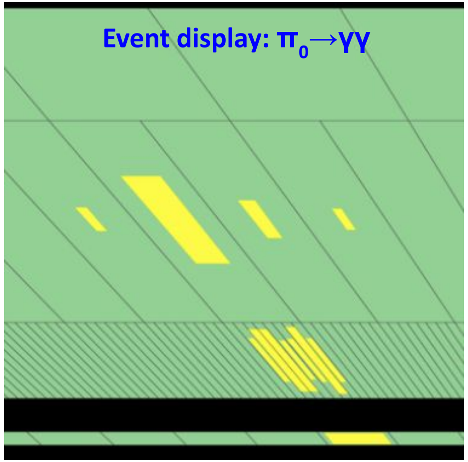


Cu readout electrodes, Pb absorber structure

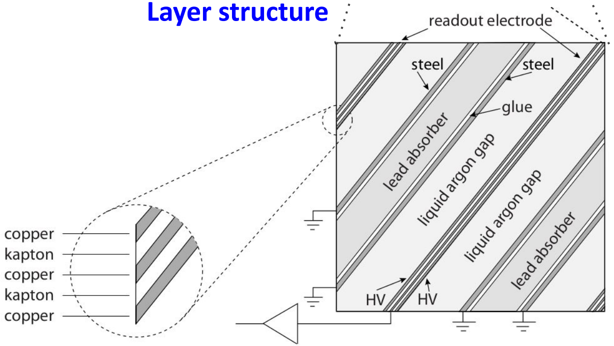


$$\frac{\sigma_E}{E} \approx \frac{10\ \%}{\sqrt{E/\mathrm{GeV}}}$$

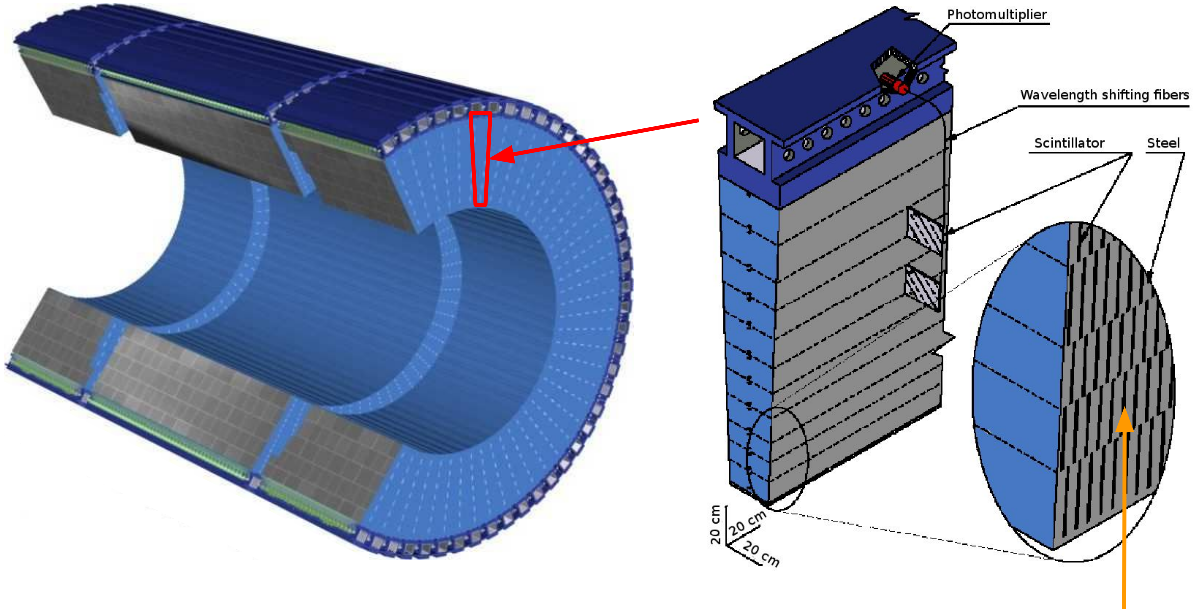
Event display: $\pi_0 \rightarrow \gamma\gamma$



Layer structure

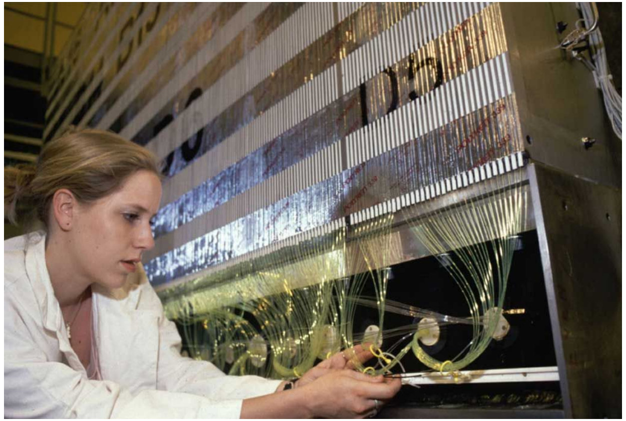


Sampling calorimeters: Example ATLAS TileCal (HCAL)



- Iron plates as absorber
- Plastic scintillating tiles as the active material 10 λ_a
- Scintillation light transmitted by wavelength shifting fibres to photomultiplier tubes (PMTs)

Particles from Interaction point



$$\frac{\sigma_E}{E} \approx \frac{56\ \%}{\sqrt{E/\mathrm{GeV}}}$$

Scintillator tiles in vertical orientation to incoming particle direction

Sampling calorimeters: Example CMS Barrel HCAL

Absorber:

- Brass (70% Cu / 30% Zn)
- Thickness 50.5-56.5 mm
- Used over a million World War II brass shell casings from the Russian Navy
- Depth: between 5.5 and 10 λ_a + catcher layer behind magnet

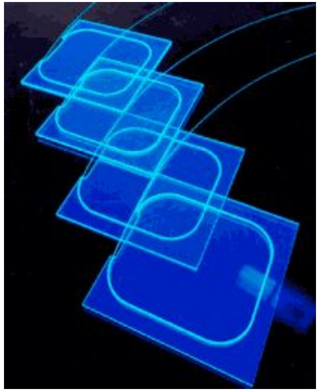
Detector:

- Plastic scintillator with embedded wavelength shifting fibers
- Thickness 3.7 mm
- Scintillation light 410-425 nm: blue-violet
- The fibers absorb light and re-emit it at 490 nm: green
- Hybrid Photodiodes convert light into electrical signals

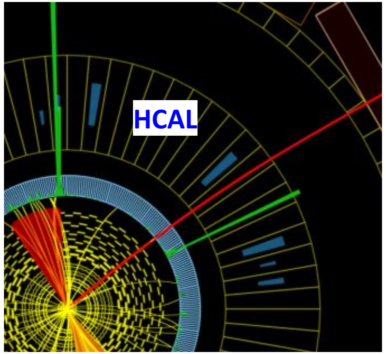
Readout in towers

- No longitudinal segmentation in barrel, 2 segments in endcap

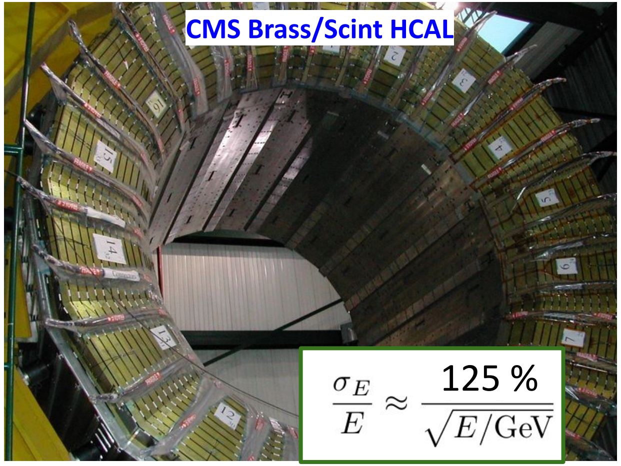
Scintillator tiles with wavelength shifting fibres



Event display



Brass shell casings → absorber

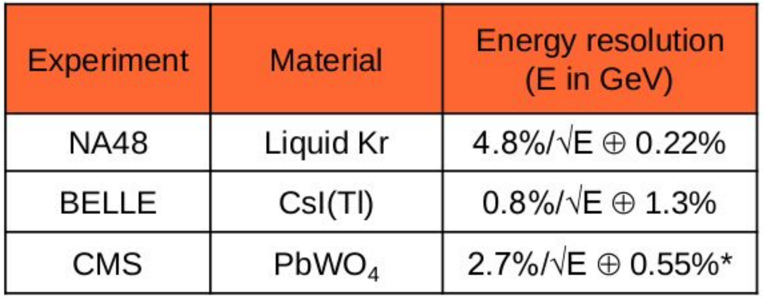


CMS Brass/Scint HCAL

$$\frac{\sigma_E}{E} \approx \frac{125\ \%}{\sqrt{E/\mathrm{GeV}}}$$

Energy resolution examples: ECAL

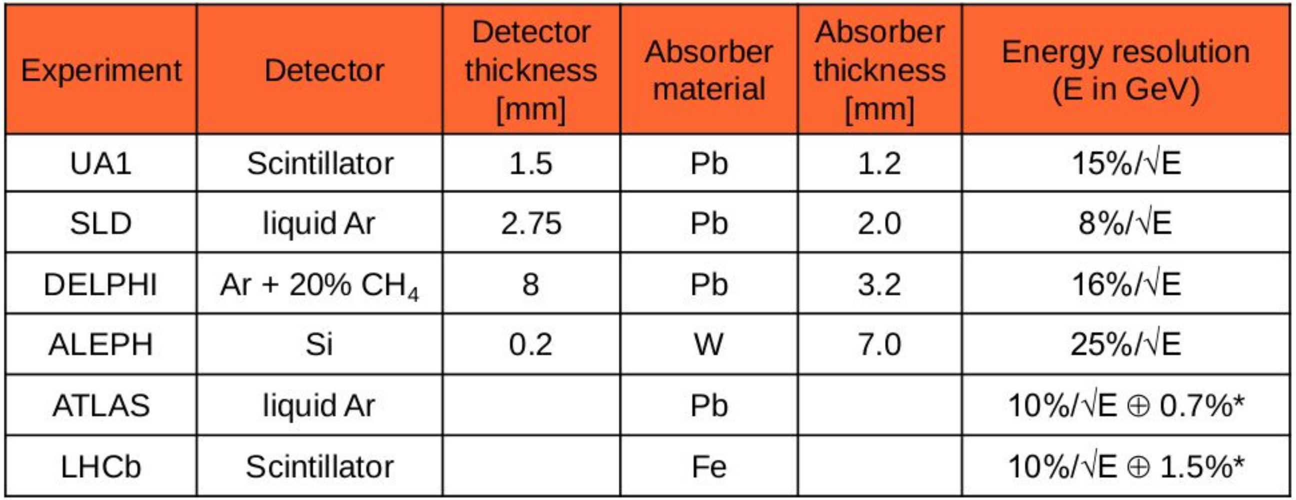
Homogeneous calorimeters:



Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

Energy resolution superior in homogeneous calorimeters w.r.t. sampling calorimeters

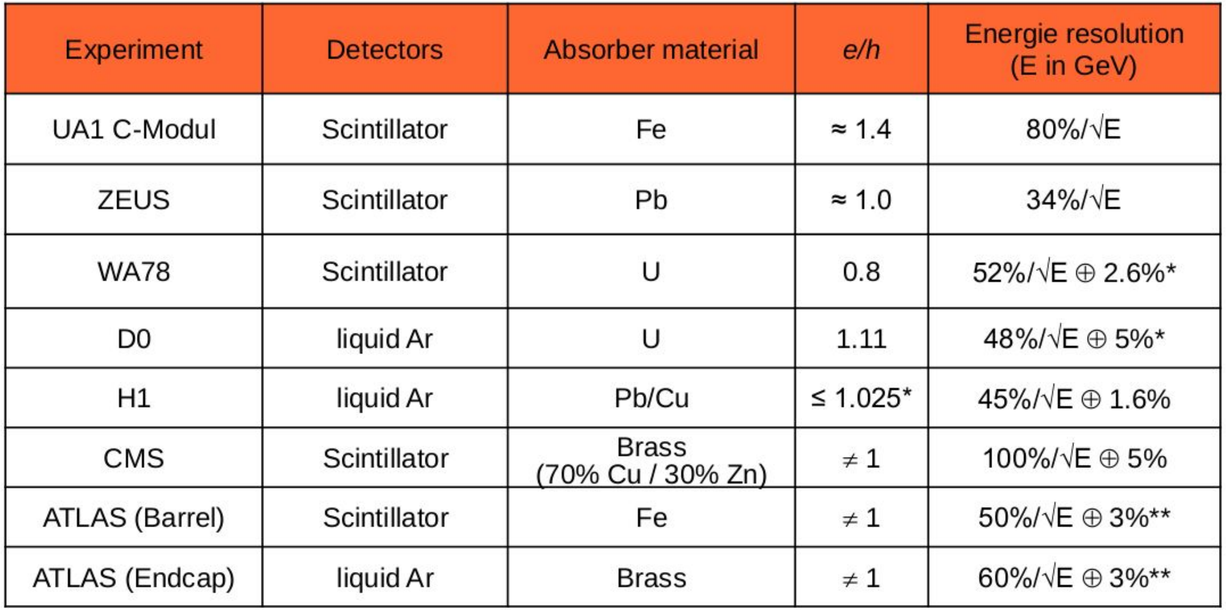
Sampling calorimeters:



Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	15%/√E
SLD	liquid Ar	2.75	Pb	2.0	8%/√E
DELPHI	Ar + 20% CH_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 1.5%*

* Design values

Energy resolution examples: HCAL



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

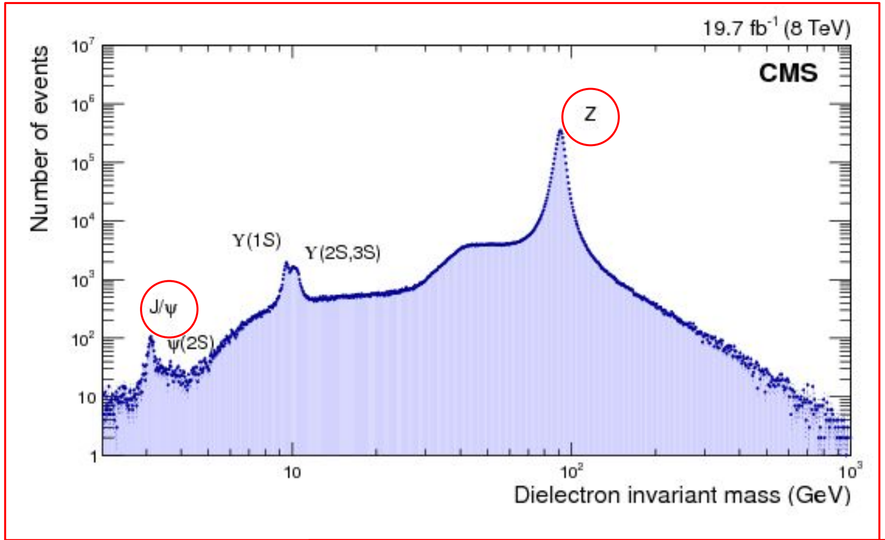
Energy resolution superior for compensating calorimeters and deep calorimeters that fully contain the showers

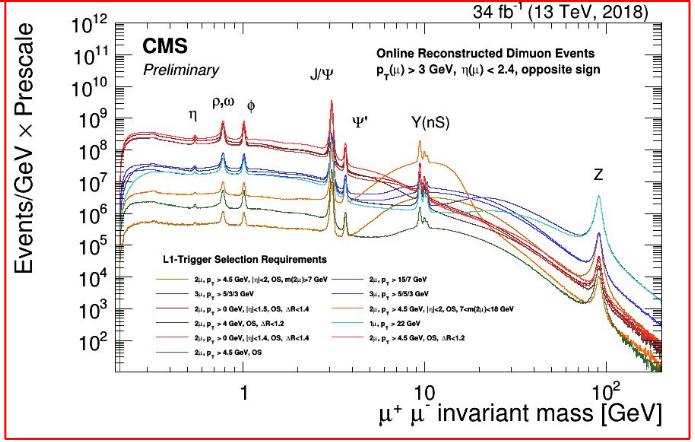
Calibration

Calibration

- Before detector operation:
  Beam tests
  - Test calorimeters with variety of particles of known type and energy

- During detector operation:
  Study known physics processes of collider
  - ECAL
    - Bhabha scattering at e^+e^- colliders
    - π^0 reconstruction from two photons
    - Reconstruction of known resonances J/Ψ, Z from e^+e^-
      - Comparison to other decay channels ($\mu^+\mu^-$)
    - Signal from minimum ionising particles (MIPs)
    - Radioactive sources with known gamma lines (when noise level is in keV range)
  - HCAL, combined with ECAL
    - Hadronic decay of vector boson $W^\pm$ and Z into two jets





Summary

- Calorimeters measure the energy and direction of charged and neutral particles
    - Electromagnetic Calorimeters (ECAL)
        - Measure electrons and photons through their EM interactions
    - Hadron Calorimeters (HCAL)
        - Measure hadrons through their strong and EM interactions: Very complex showers
    - Advantages
        - Required depth increases only logarithmically with particle energy ⟶ Compact, cost effective
        - Fast, easy to process and interpret ⟶ Trigger

- Two types of calorimeters in HEP
    - Homogeneous Calorimeters ⟶ only used for ECALs
        - Only one material for energy degradation AND signal generation
    - Sampling Calorimeters ⟶ used for ECAL and HCAL
        - Alternating detector elements of
            - absorber material to degrade the energy of the incident particle, and
            - active material that provides the detectable signal

- Energy resolution
    - Improves with energy about like ⟶
    - Better than tracker at high energies

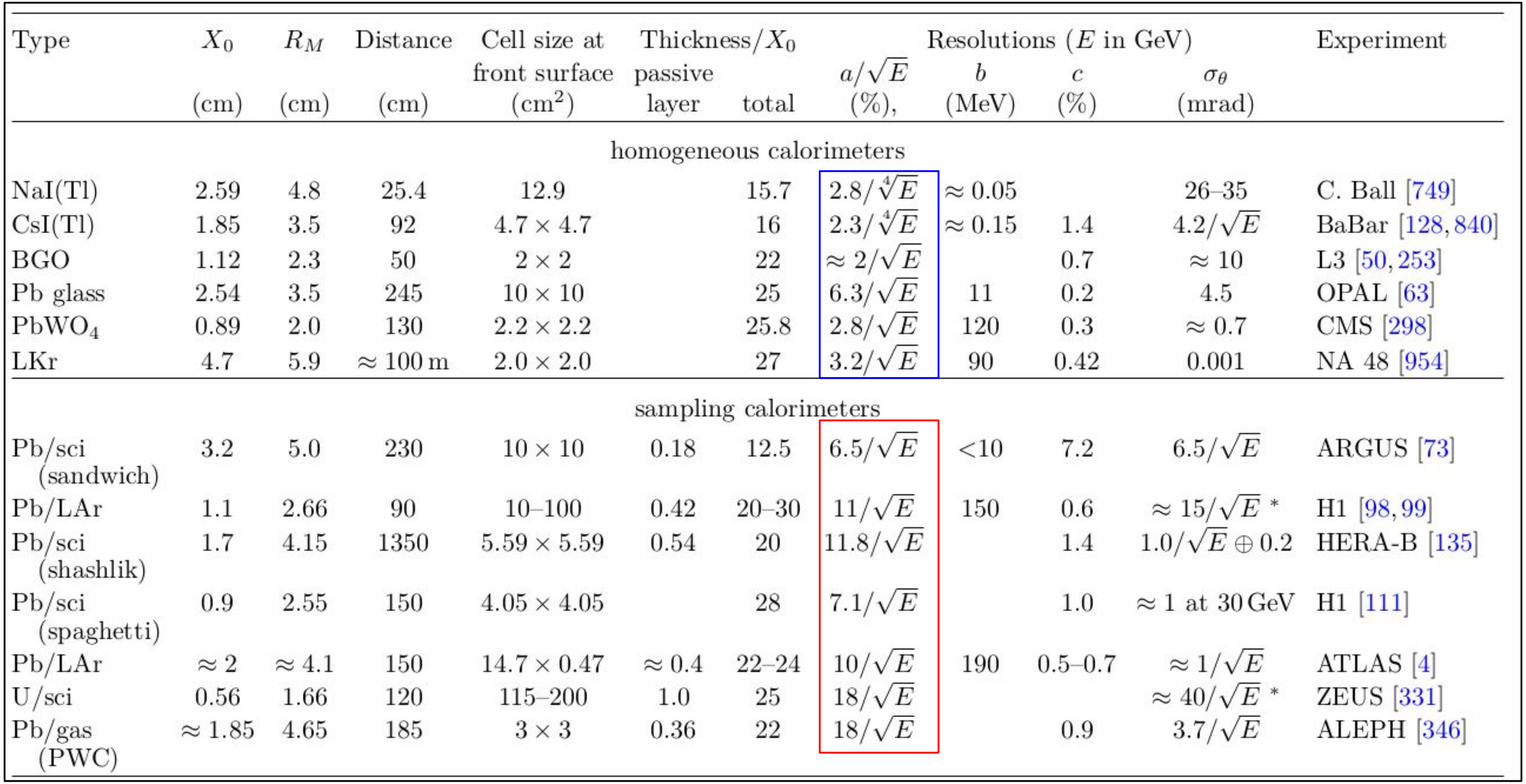
$$\frac{\sigma_E}{E} \approx \begin{cases} \dfrac{2\text{–}15\,\%}{\sqrt{E/\mathrm{GeV}}} & \text{(ECAL)} \\[2ex] \dfrac{35\text{–}120\,\%}{\sqrt{E/\mathrm{GeV}}} & \text{(HCAL)} \end{cases}$$

References

- Book “Particle detectors: fundamentals and applications” by Hermann Kolanoski, Norbert Wermes Link
- Calorimetry I lecture at EDIT 2020 school by Erika Garutti Link
- Calorimetry lecture 2017 by Thomas Bergauer Link
- Calorimetry for particle physics, C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, 2003 Link
- Detector lectures at CERN Summer Student Lecture Programme 2023 by Werner Riegler Link
- Book “Calorimetry - Energy measurement in particle physics” by Richard Wigmans Link

Backup

Energy resolution examples: ECAL



Type	X_0 (cm)	R_M (cm)	Distance (cm)	Cell size at front surface (cm^2)	Thickness/X_0 passive layer	Thickness/X_0 total	Resolutions (E in GeV) $a/\sqrt{E}$ (%),	b (MeV)	c (%)	σ_θ (mrad)	Experiment
homogeneous calorimeters											
NaI(Tl)	2.59	4.8	25.4	12.9		15.7	$2.8/\sqrt[4]{E}$	≈ 0.05		26–35	C. Ball [749]
CsI(Tl)	1.85	3.5	92	4.7×4.7		16	$2.3/\sqrt[4]{E}$	≈ 0.15	1.4	$4.2/\sqrt{E}$	BaBar [128, 840]
BGO	1.12	2.3	50	2×2		22	$\approx 2/\sqrt{E}$		0.7	≈ 10	L3 [50, 253]
Pb glass	2.54	3.5	245	10×10		25	$6.3/\sqrt{E}$	11	0.2	4.5	OPAL [63]
$\mathrm{PbWO_4}$	0.89	2.0	130	2.2×2.2		25.8	$2.8/\sqrt{E}$	120	0.3	≈ 0.7	CMS [298]
LKr	4.7	5.9	≈ 100 m	2.0×2.0		27	$3.2/\sqrt{E}$	90	0.42	0.001	NA 48 [954]
sampling calorimeters											
Pb/sci (sandwich)	3.2	5.0	230	10×10	0.18	12.5	$6.5/\sqrt{E}$	<10	7.2	$6.5/\sqrt{E}$	ARGUS [73]
Pb/LAr	1.1	2.66	90	10–100	0.42	20–30	$11/\sqrt{E}$	150	0.6	$\approx 15/\sqrt{E}$ *	H1 [98, 99]
Pb/sci (shashlik)	1.7	4.15	1350	5.59×5.59	0.54	20	$11.8/\sqrt{E}$		1.4	$1.0/\sqrt{E} \oplus 0.2$	HERA-B [135]
Pb/sci (spaghetti)	0.9	2.55	150	4.05×4.05		28	$7.1/\sqrt{E}$		1.0	≈ 1 at 30 GeV	H1 [111]
Pb/LAr	≈ 2	≈ 4.1	150	14.7×0.47	≈ 0.4	22–24	$10/\sqrt{E}$	190	0.5–0.7	$\approx 1/\sqrt{E}$	ATLAS [4]
U/sci	0.56	1.66	120	115–200	1.0	25	$18/\sqrt{E}$			$\approx 40/\sqrt{E}$ *	ZEUS [331]
Pb/gas (PWC)	≈ 1.85	4.65	185	3×3	0.36	22	$18/\sqrt{E}$		0.9	$3.7/\sqrt{E}$	ALEPH [346]

Homogeneous

Sampling

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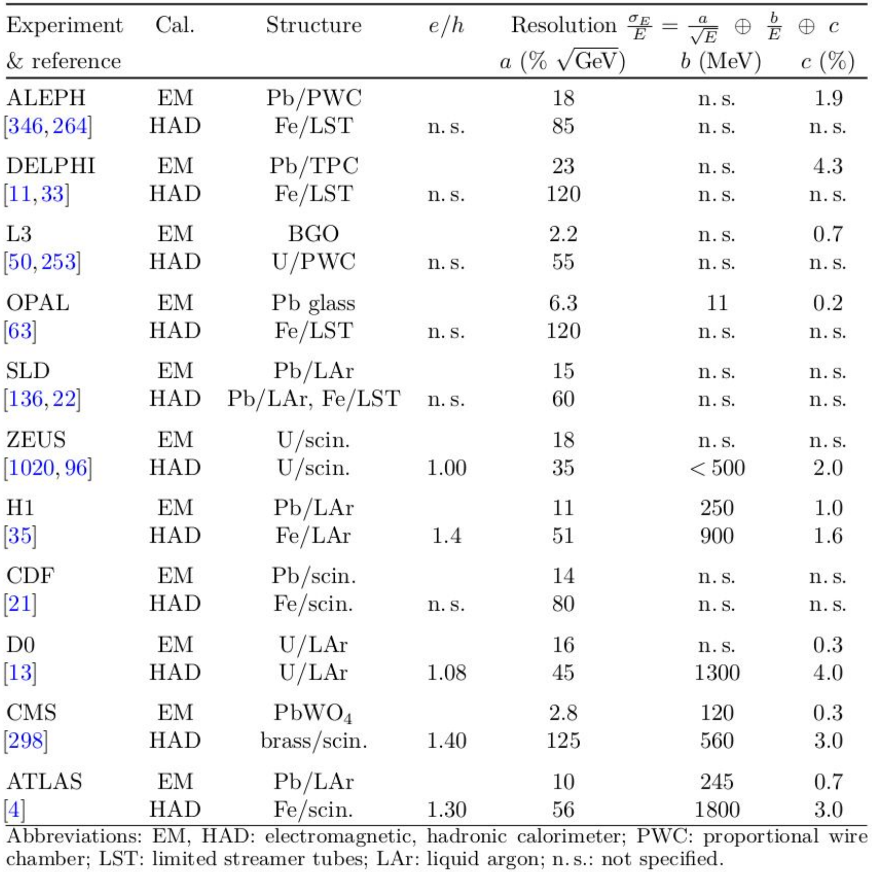
Energy resolution examples: ECAL+HCAL



Experiment & reference	Cal.	Structure	e/h	Resolution $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$ a (% $\sqrt{\text{GeV}}$)	 b (MeV)	 c (%)
ALEPH	EM	Pb/PWC		18	n. s.	1.9
[346, 264]	HAD	Fe/LST	n. s.	85	n. s.	n. s.
DELPHI	EM	Pb/TPC		23	n. s.	4.3
[11, 33]	HAD	Fe/LST	n. s.	120	n. s.	n. s.
L3	EM	BGO		2.2	n. s.	0.7
[50, 253]	HAD	U/PWC	n. s.	55	n. s.	n. s.
OPAL	EM	Pb glass		6.3	11	0.2
[63]	HAD	Fe/LST	n. s.	120	n. s.	n. s.
SLD	EM	Pb/LAr		15	n. s.	n. s.
[136, 22]	HAD	Pb/LAr, Fe/LST	n. s.	60	n. s.	n. s.
ZEUS	EM	U/scin.		18	n. s.	n. s.
[1020, 96]	HAD	U/scin.	1.00	35	< 500	2.0
H1	EM	Pb/LAr		11	250	1.0
[35]	HAD	Fe/LAr	1.4	51	900	1.6
CDF	EM	Pb/scin.		14	n. s.	n. s.
[21]	HAD	Fe/scin.	n. s.	80	n. s.	n. s.
D0	EM	U/LAr		16	n. s.	0.3
[13]	HAD	U/LAr	1.08	45	1300	4.0
CMS	EM	$PbWO_4$		2.8	120	0.3
[298]	HAD	brass/scin.	1.40	125	560	3.0
ATLAS	EM	Pb/LAr		10	245	0.7
[4]	HAD	Fe/scin.	1.30	56	1800	3.0

Abbreviations: EM, HAD: electromagnetic, hadronic calorimeter; PWC: proportional wire chamber; LST: limited streamer tubes; LAr: liquid argon; n. s.: not specified.

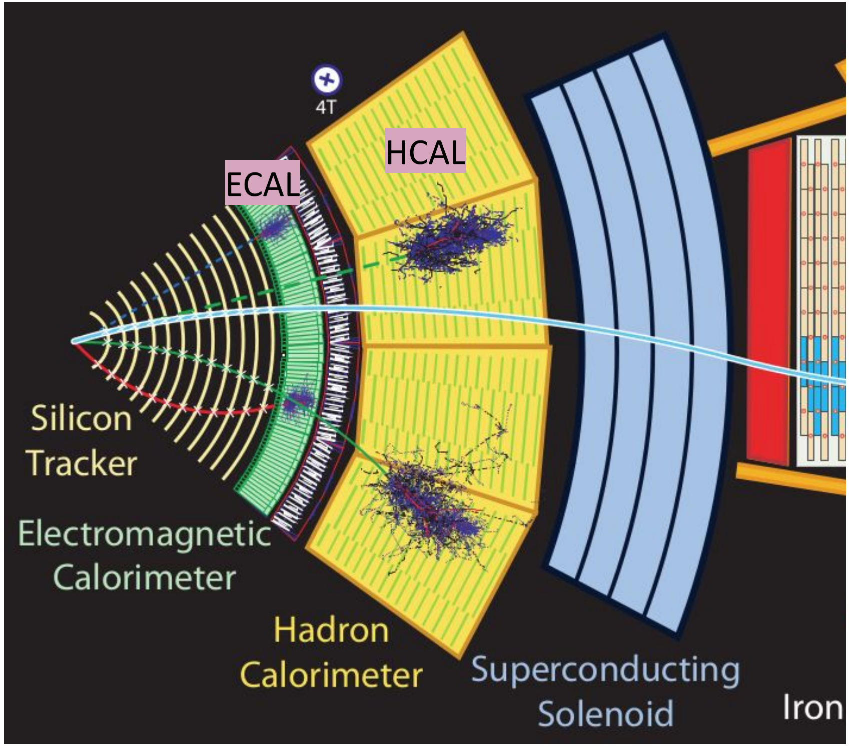
Kolanoski, Wermes 2015

Considerations for calorimeter construction and operation

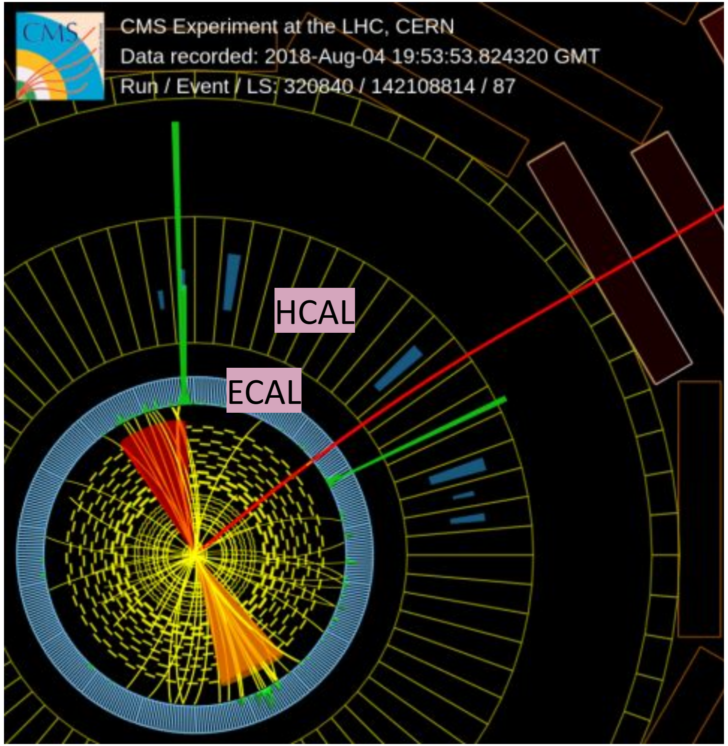
- Energy and position resolution
  - Optimised for most interesting physics processes, leading to different choices
  - Example: LHC experiments gave high importance to H->$\gamma\gamma$ measurement of ECALs
- Longitudinal segmentation
  - Separation of electromagnetic and hadronic showers
- Tail catcher
  - Improve HCAL energy measurement in case of shower leakage
  - Can be muon chambers, active layers in return yoke of magnet
- Pre-sampler
  - Detect if shower has started before calorimeter
  - Tracker and other material can add up to few X_0
  - Important for high-energy photons with mean free path for pair production of 9/7 X_0
- Lateral structure
  - Shower separation
  - Shower direction and axis measurement
- Signal collection and time resolution
  - In view of collision rate, pile up rejection
- Calibration
- Radiation hardness

Side remark: Readout cell size

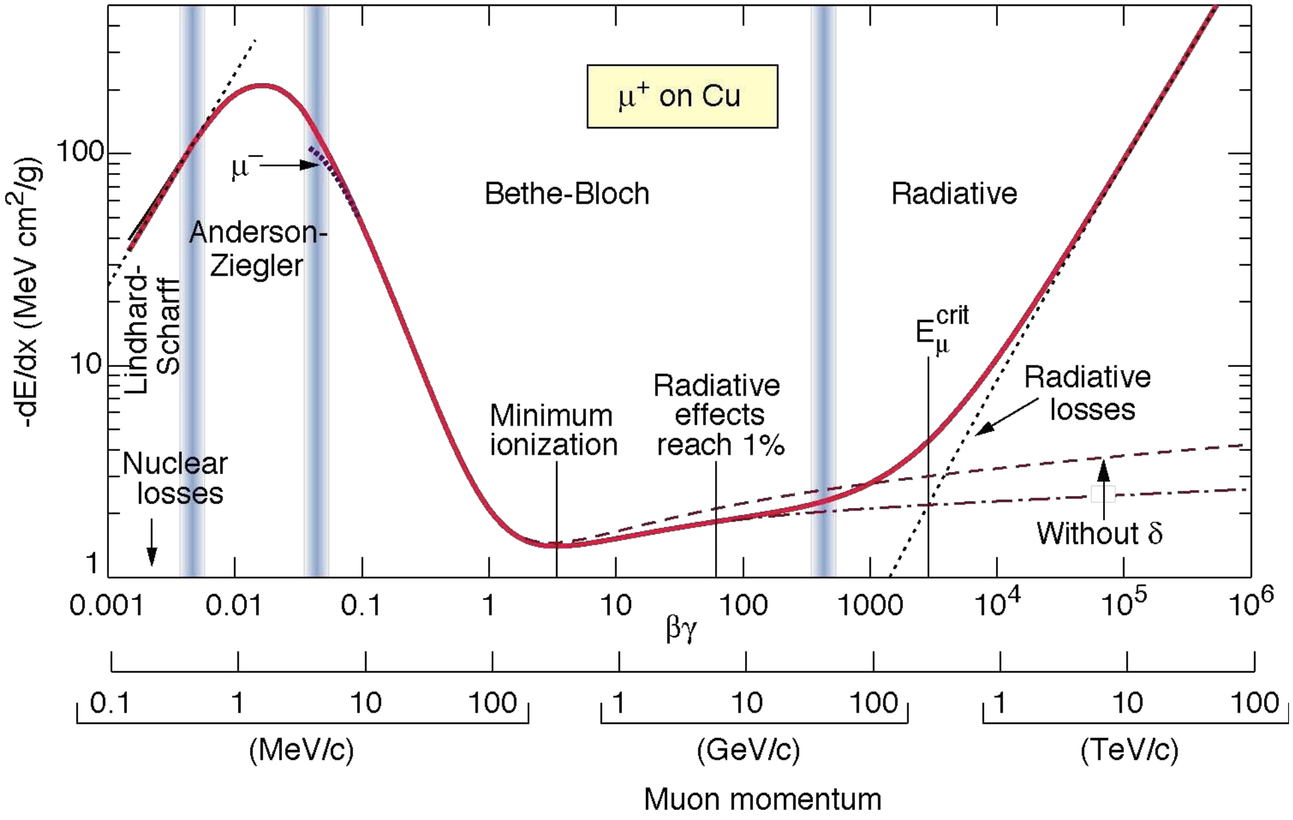
CMS: Simulated showers on top of detector concept



CMS: Event display indicating readout cell size

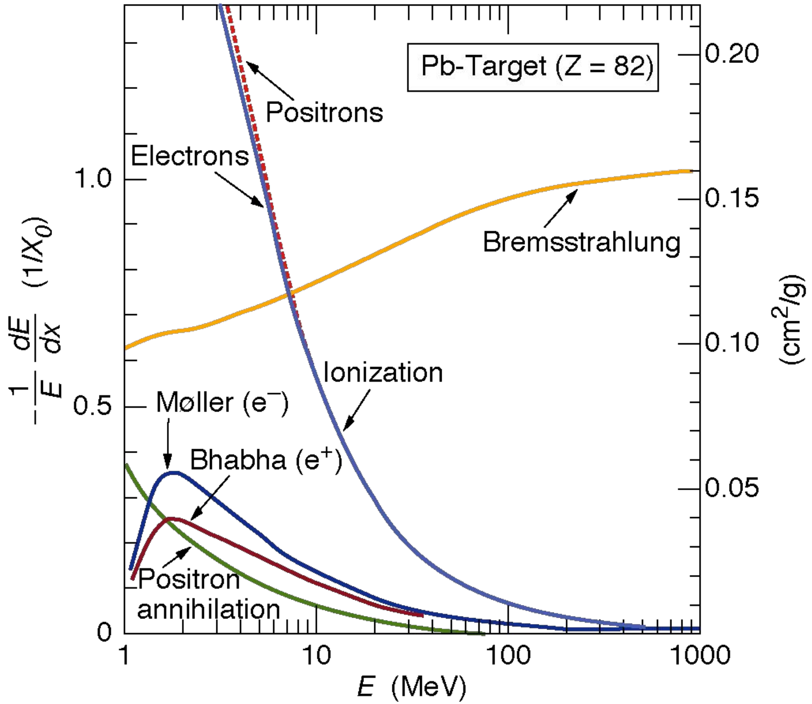


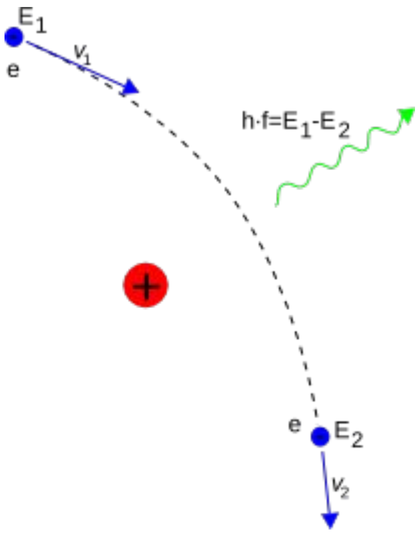
Ionisation



μ+ on Cu
-dE/dx (MeV cm²/g)
100
10
1
Lindhard-Scharff
Anderson-Ziegler
μ−
Bethe-Bloch
Radiative
Minimum ionization
Radiative effects reach 1%
E_μ^crit
Radiative losses
Without δ
Nuclear losses
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
(MeV/c)
(GeV/c)
(TeV/c)
Muon momentum

Bremsstrahlung

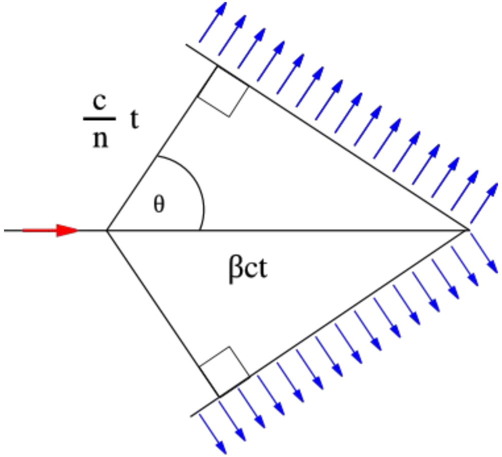


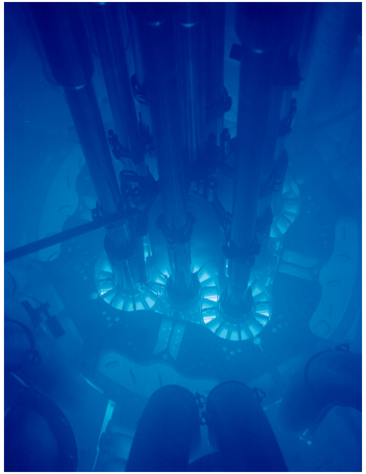


$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z(Z+1)}{A} z^2 \left(\frac{1}{4\pi\epsilon_0}\cdot\frac{e^2}{mc^2}\right)^2 E \cdot \ln 183 Z^{-1/3}$$

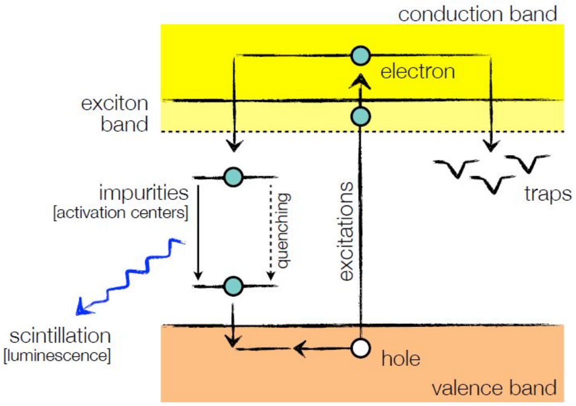
Cherenkov radiation

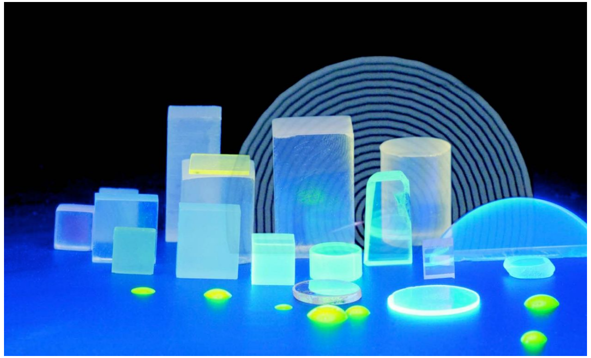
- Cherenkov radiation is emitted when particle velocity is larger than speed of light in the material
    - v > c/n
      with n = refractive index of material
- Electromagnetic shock wave of conical shape
- Emission angle θ
    - cos θ = 1/βn
      with β = v/c
- Contribution to energy loss 1%





Scintillation



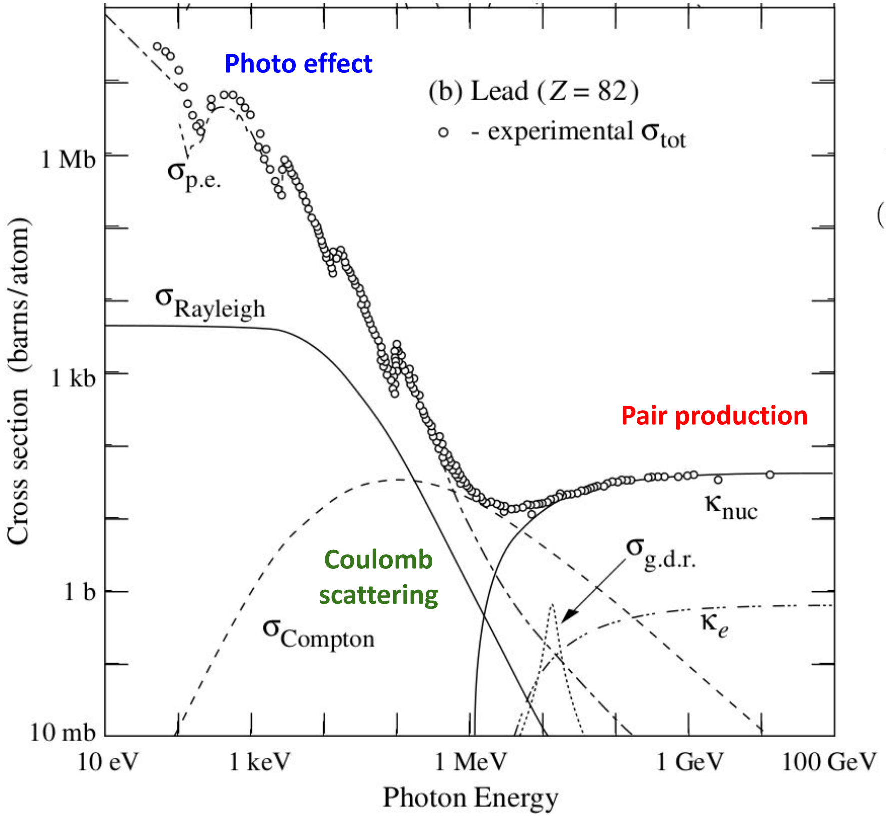


Scintillation: Emission of photons during de-excitation of atoms, typically UV to visible light

1. (Liquid) Noble Gases
2. Inorganic Crystals
   - Substances with largest light yield
   - Expensive
3. Polycyclic hydrocarbons (organic scintillators)
   - e.g. naphthalene, anthracene,
   - Large scale industrial production
   - mechanically and chemically quite robust

- Few % of the total energy loss converted into visible photons.
- Example: 1cm plastic scintillator, 1, dE/dx=1.5 MeV, ~15 keV in photons; i.e. ~ 15 000 photons produced.

Excursion: Photon interactions with matter



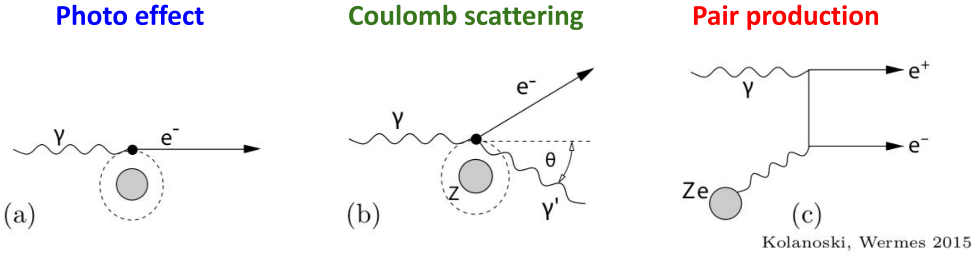


Photo effect

Coulomb scattering

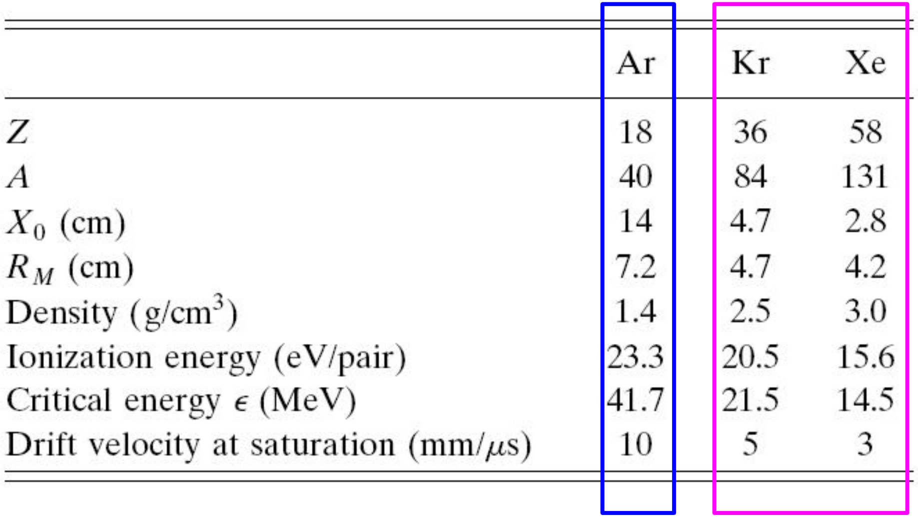
Pair production

Kolanoski, Wermes 2015

κ_{nuc} = pair production, nuclear field

κ_{e} = pair production, electron field

Liquid noble gases used in calorimeters



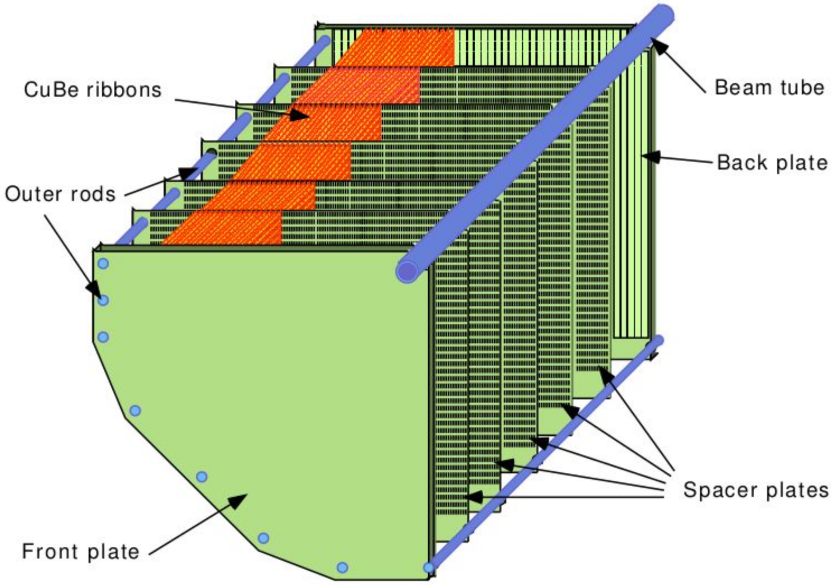
	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

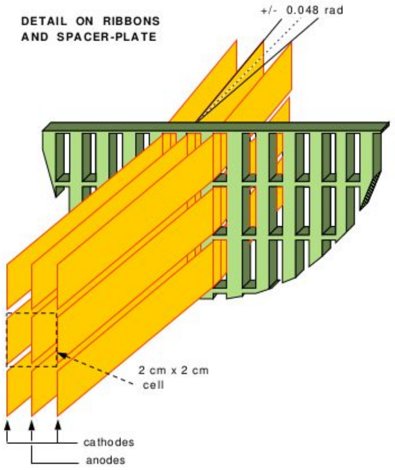
- Energy loss of charged particles
  - Half via ionisation
  - Half via scintillation
- Best energy resolution would be reached when collecting both charge and light signal, but rarely done due to complex technical implementation

- Liquid noble gases with high-Z: Liquid Krypton and Xenon
  - Small radiation length and Molière radius
  - Can serve both as converters and as active media → Application in homogenous calorimeters

- Liquid Argon common as active medium in sampling calorimeters

Homogeneous calorimeters: Liquid Noble Gas



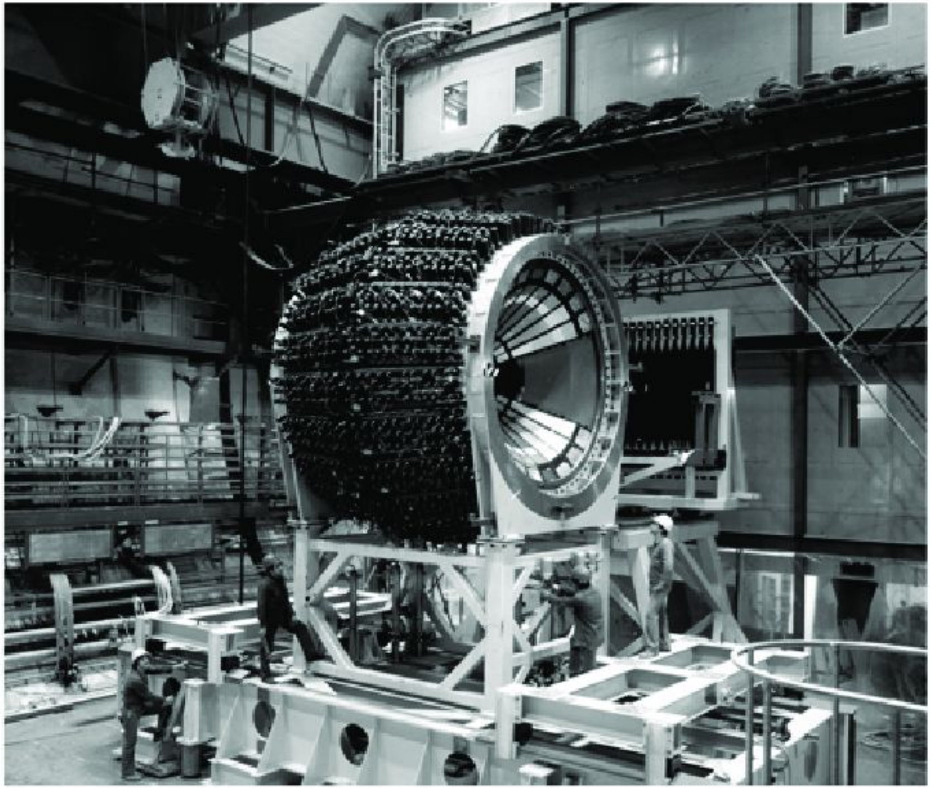


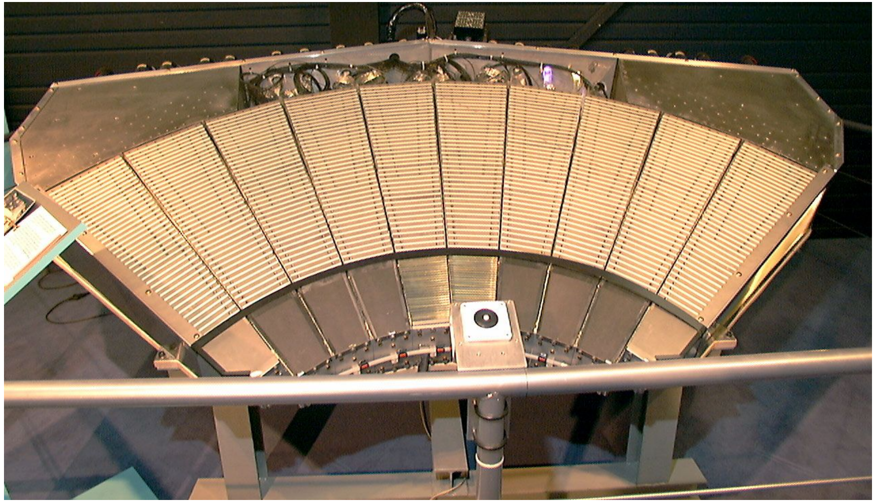
Typical resolutions:

$$\frac{\sigma_E}{E} \approx \frac{(3\text{–}5)\%}{\sqrt{E/\mathrm{GeV}}}$$

- Liquid Krypton calorimeter of NA48 (later re-used in NA62)
  - Quasi-homogeneous ionisation calorimeter, 27 X_0
  - Filled with 10 m^3 of liquid krypton as active medium and absorber
  - Ionisation charges collected on thin electrodes: Copper-Beryllium ribbons
  - Shower sampling with high granularity and hence high position resolution
  - Combines the advantages of a homogeneous calorimeter with those of a sampling calorimeter

Sampling calorimeters: Example UA2 @ S$\bar{p}$pS





- Built in orange-like structure with 24 slices
- Active layers:
  - Plastic scintillator + light guides
- Absorber
  - Inner part: lead absorber
  - Outer part: Iron absorber