Calorimetry in High-Energy Physics

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Capacity buildiNG in Advanced physics
LA-CoNGA physics

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de la Unión Europea

References

Lectures

- I. Wingerter-Seez, C. Ochando and J-B Sauvan (special thanks), *Lectures on Calorimetry*, ESIPAP 2016, 2019-2021
- A. Zabi, *Instrumentation for High Energy Physics*, TES-HEP 2016
- R. Wigmans, *Calorimetry*, EDIT 2011

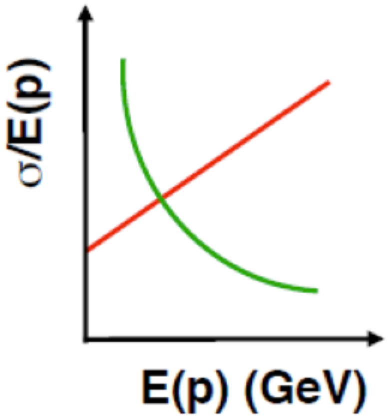
Books

- R. Wigmans, *Calorimetry, Energy measurement in Particle Physics*, Oxford science publication
- C. Gruppen & B. Shwartz, *Particle detectors*, Cambridge monographs on particle physics, nuclear physics and cosmology

What is a calorimeter (in HEP)?

- In HEP calorimetry is the detection of particles through **total absorption** in a block of matter
  - “Most particles end their journey in calorimeters”
- Calorimeters can **measure both charged and neutrals**
- Relative resolution improves with energy
- Complementary to tracking detectors

Resolution



Tracking

$$\frac{\sigma(p)}{p} = ap \oplus b$$

Calorimetry

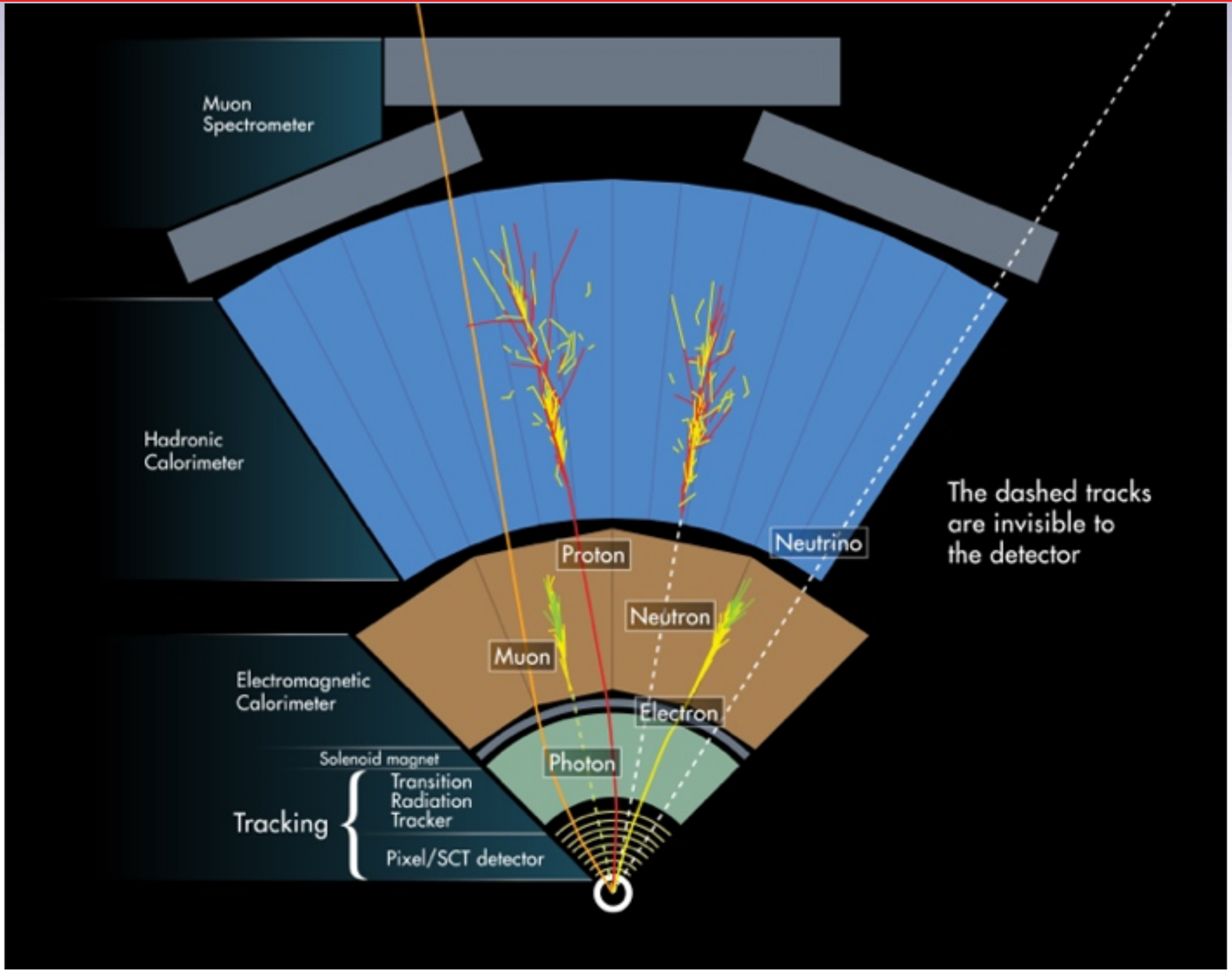
$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

ATLAS

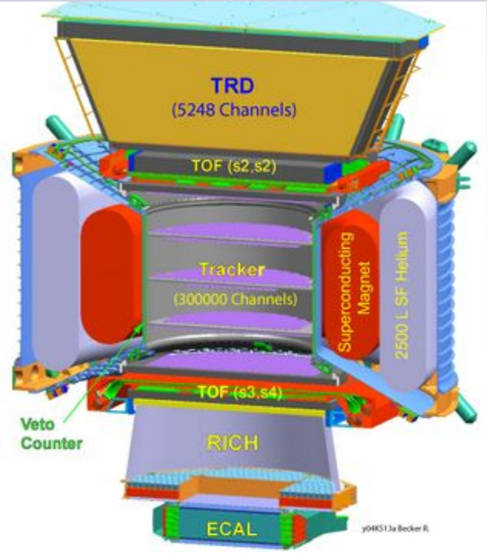
Muon spectrometer

Calorimeters

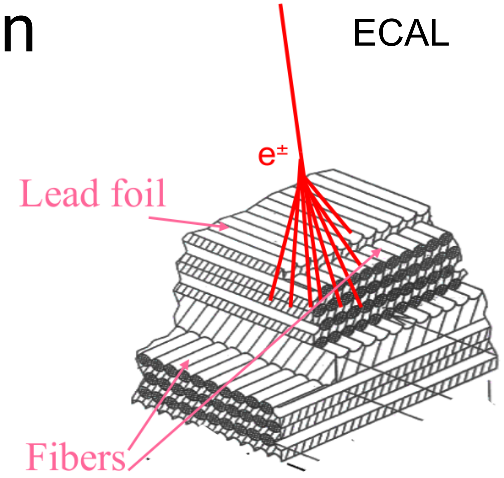
Trackers



AMS

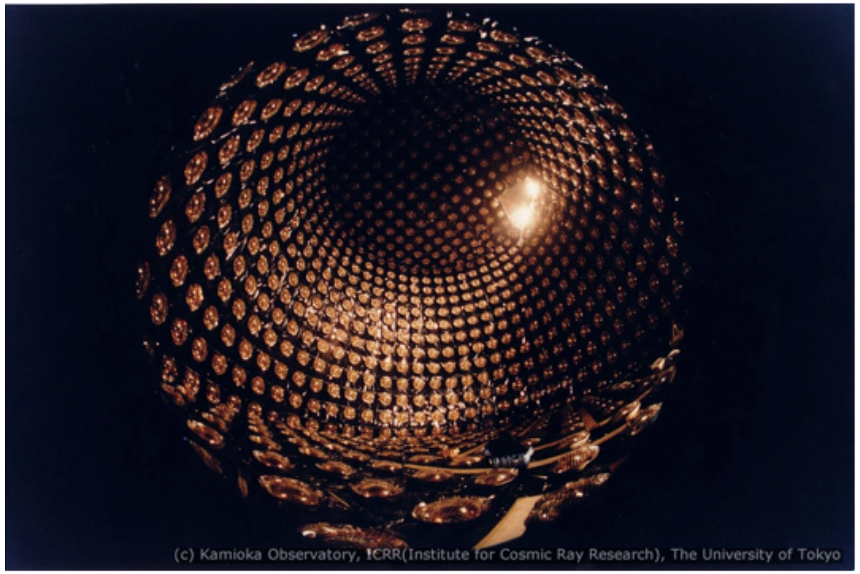


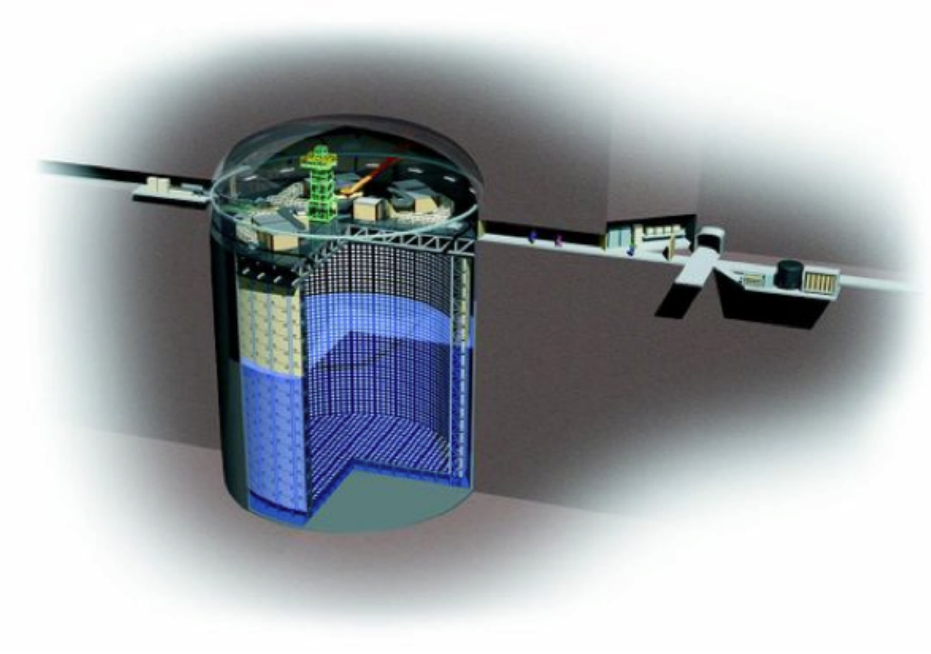
- AMS: experiment on the International Space Station
- Search presence of **antimatter and dark matter**
- Electromagnetic calorimeter
  - Measure high energy electrons/positrons
  - Discriminate against protons



Super-Kamiokande

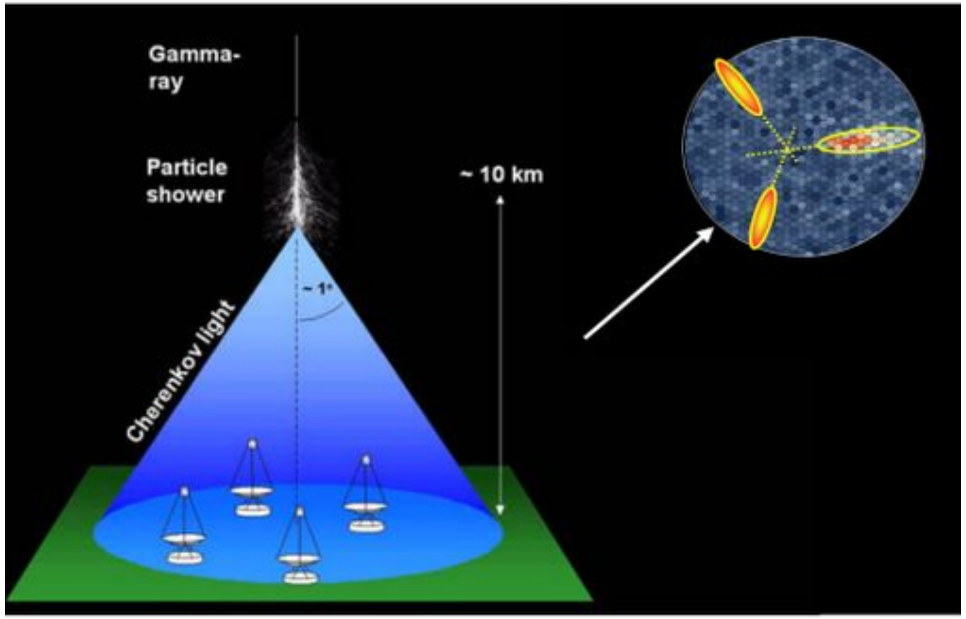
- Tank of 50 ktons of ultrapure water in underground mine
  - Scattering of neutrinos with electron or nuclei of water → **Cerenkov light**
  - 11k photomultipliers
- Measurement of solar neutrinos flux deficit, discovery of **neutrino oscillation**, ...


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



HESS

- Explore cosmic gamma rays
  - Interaction with the **atmosphere**
  - Emission of **Cerenkov light**
- Telescopes record this Cerenkov light on the ground



Electromagnetic and hadronic showers

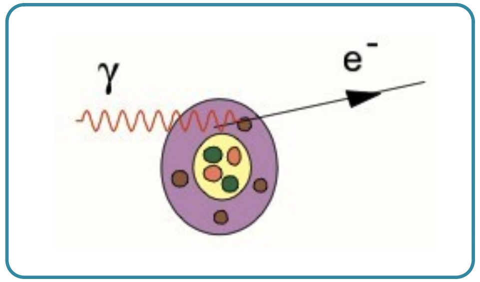
Electromagnetic interactions with matter

Photons

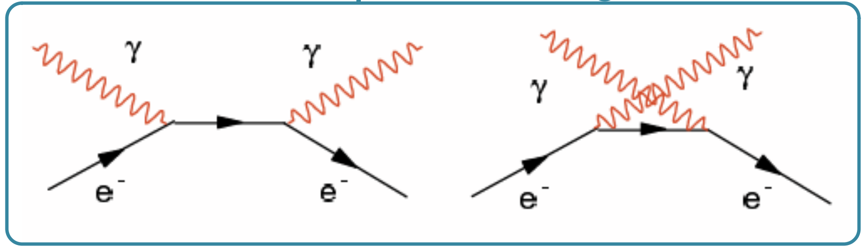
Electrons

Low energy

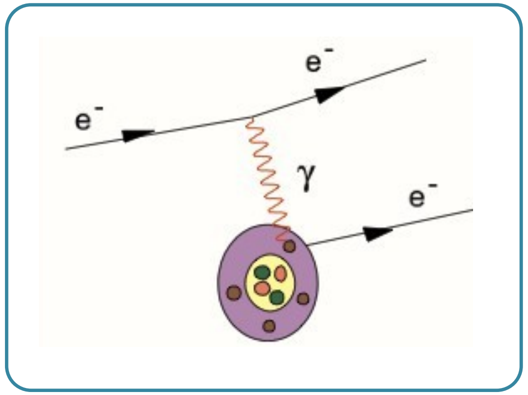
Photoelectric effect



Compton scattering

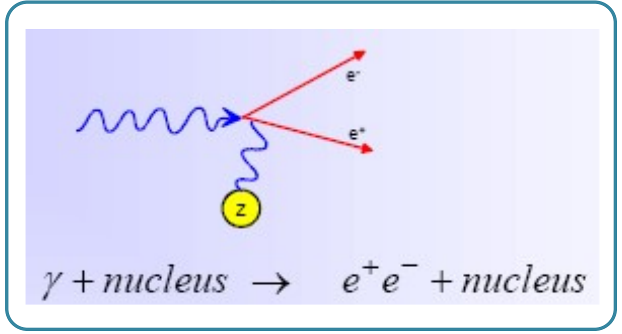


Ionisation

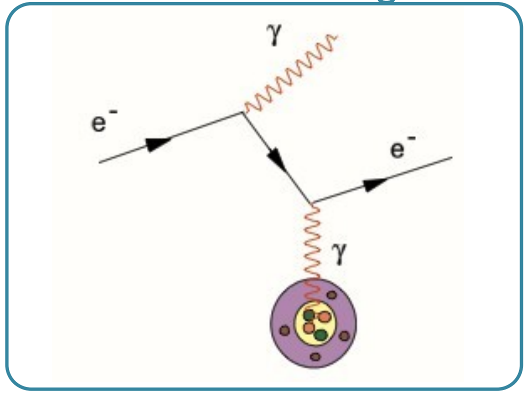


High energy

Pair production

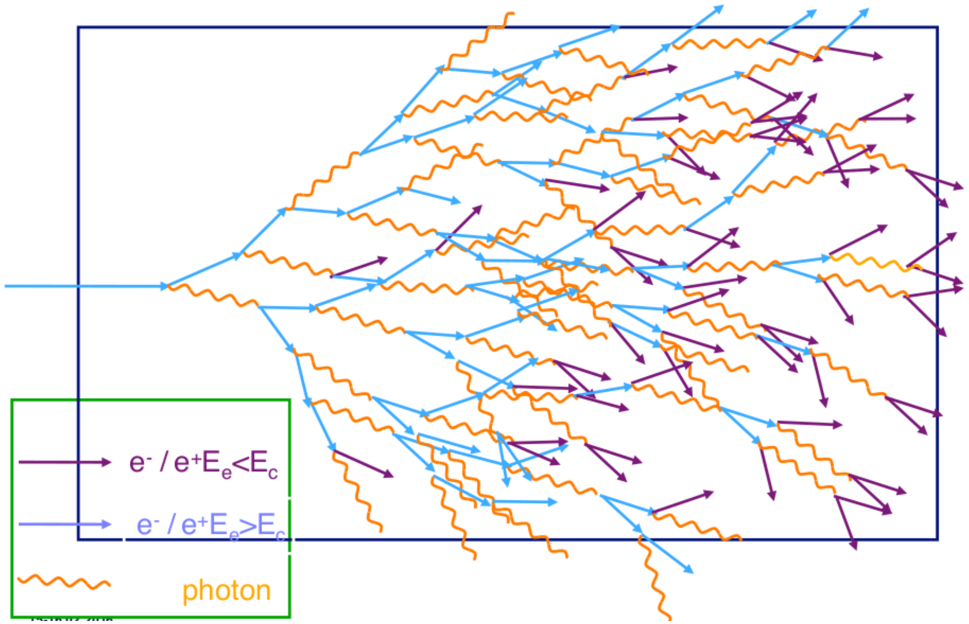


Bremsstrahlung



Electromagnetic showers

- High energy particle creates a **cascade** of lower energy electrons and photons (bremsstrahlung and pair production)
  - **Number of particles proportional to E_0**
- When the **critical energy** is reached, secondary particles are slowly **stopped** (electrons) or **absorbed** (photons)



Electromagnetic showers: radiation length (X_0)

Allows nearly material-independent shower parametrisation

- Electrons loose half of their energy in about **2/3×X_0**
- Photons convert in about **9/7×X_0**
- High-energy particle duplication at every X_0
  (e → eγ or γ→ ee)

Electron energy loss

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}$$

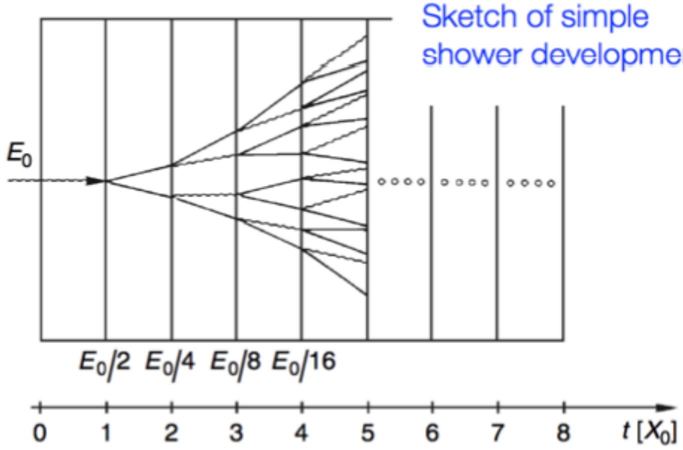
$$E = E_0 e^{-x/X_0}$$

$$x(E_0/2) = X_0 \ln(2)$$

Pair prod. probability

$$\frac{dw}{dx} = \frac{1}{\lambda_{pair}} e^{-x/\lambda_{pair}}$$

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



Sketch of simple shower development

Approximation:

$$X_0 = \frac{180\,A}{Z^2}\,g.cm^{-2}$$

Expressed in **cm** or **g.cm^{-2}**
(conversion using density)

O(1 cm) for dense materials

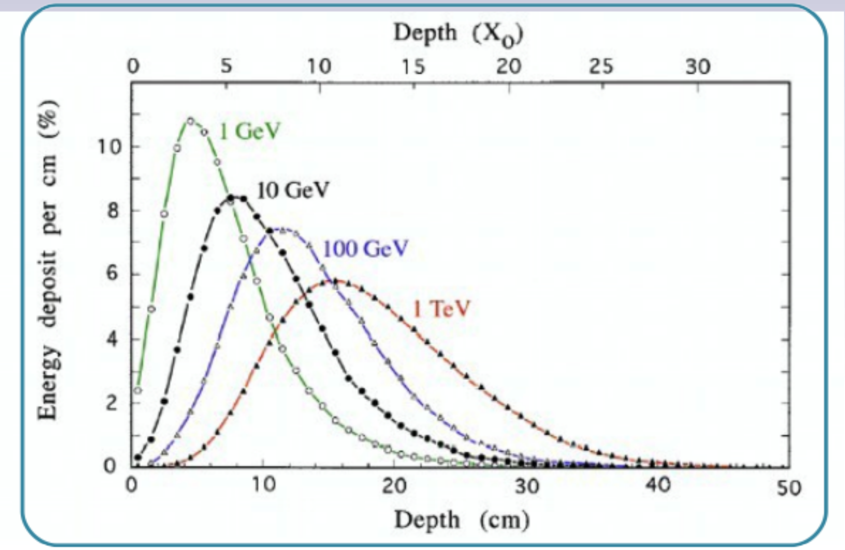
EM shower properties

- Shower depth grows with log(E)
  - EM calorimeters can be compact (~15-30 X0, preferably high-Z materials)

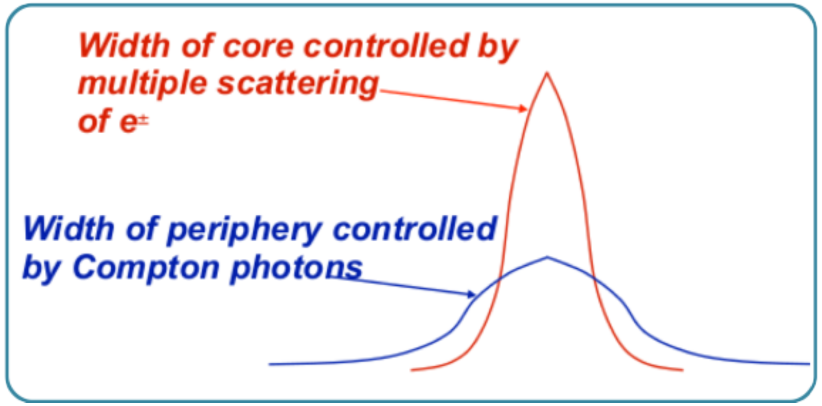
- Lateral spread described by Molière radius
  - ~90% of the energy in a cilinder of R_M (~95% in 2 R_M)
  - Few cm for typical materials used

$$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\, g\,.\,cm^{-2}$$

Longitudinal profile



Lateral profile



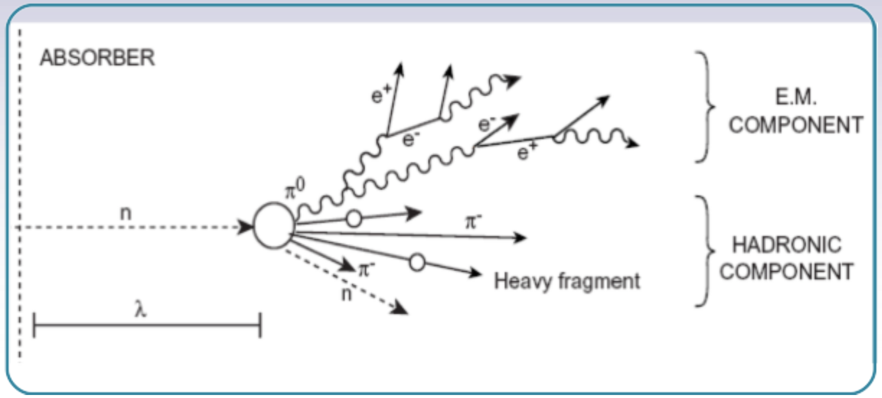
Width of core controlled by multiple scattering of e±

Width of periphery controlled by Compton photons

Hadronic showers

- **Many processes,** depending on particle and material
  - EM interactions
  - Hadron production, nuclear de-excitation, spallation, muon and pion decays, ...

First hadronic interaction



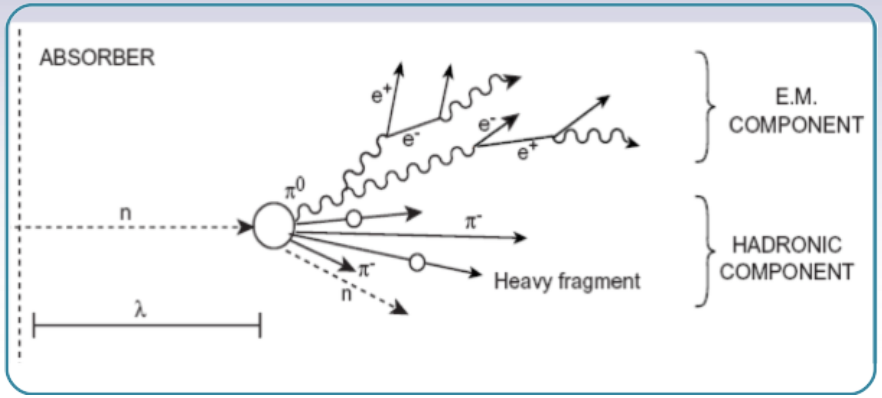
Hadronic showers

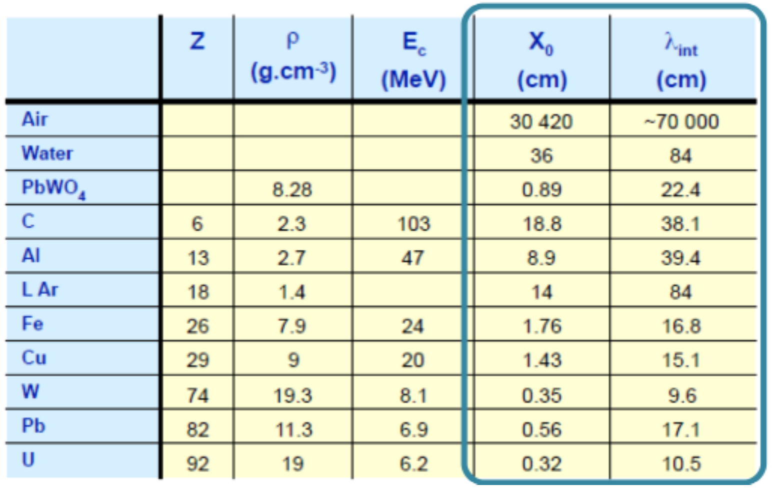
- **Many processes,** depending on particle and material
  - EM interactions
  - Hadron production, nuclear de-excitation, spallation, muon and pion decays, ...
- Described by **nuclear interaction length λ_{int},** mean free path between inelastic interactions

$$\lambda \approx 35\, A^{1/3}\ \mathrm{g \cdot cm^{-2}}$$

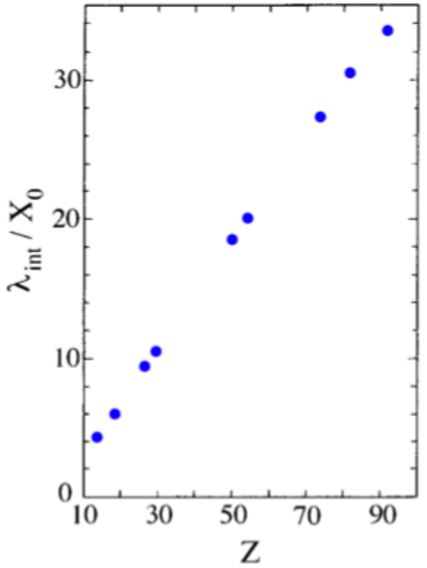
  - λ_{int} > X0 -> hadronic showers start later and are more diffuse than EM ones

First hadronic interaction



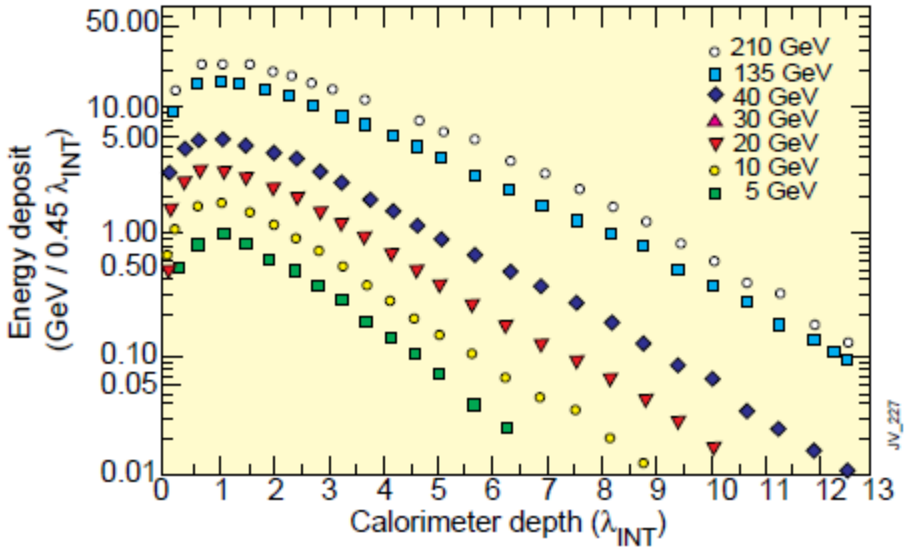


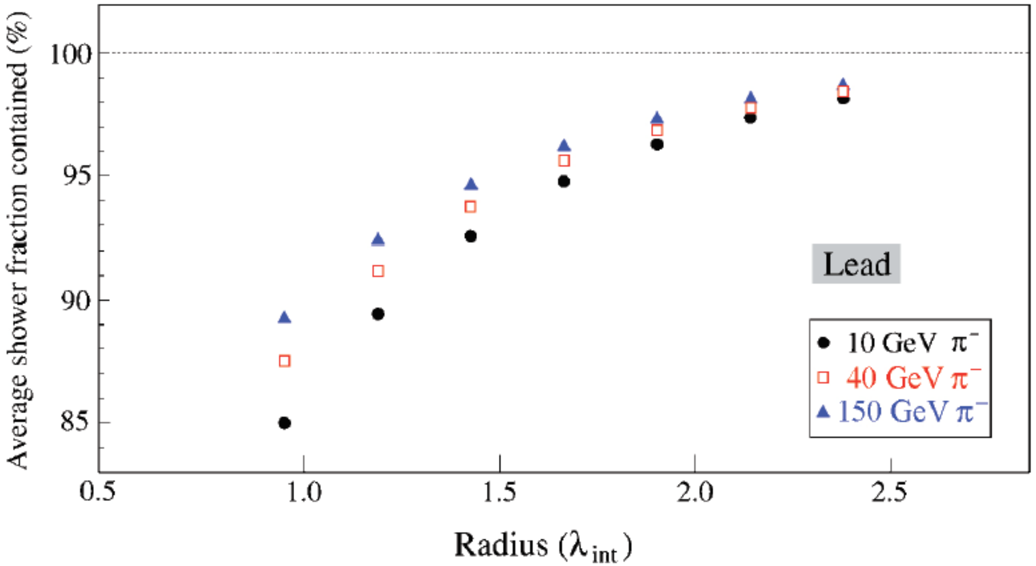
	Z	ρ (g.cm-3)	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5



Hadronic shower properties

- Hadronic calorimeters usually have 5-8 λ_{int}
- Lateral shower spread from EM core and tails from non-EM components
  - Well described by λ_{int}

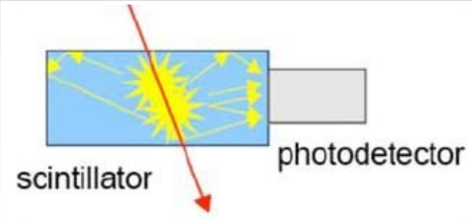


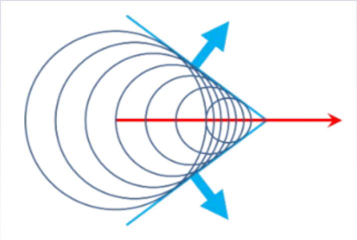


Detection techniques and calorimeter types

Detection techniques

- Energy loss produces light
    - Scintillation or Cerenkov
    - Light converted to electric current
        - Photomutipliers, photodiodes, etc





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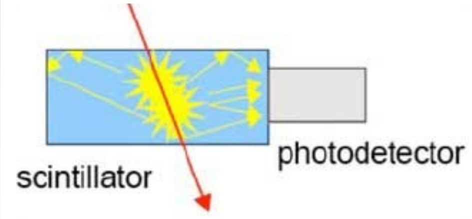
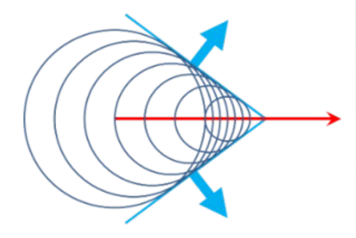
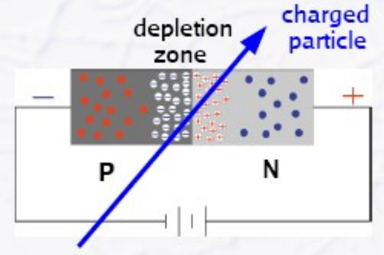




- Directly collect charges
  - From ionisation in gas or noble liquids
  - From electron/hole pairs in semiconductors



Detection techniques

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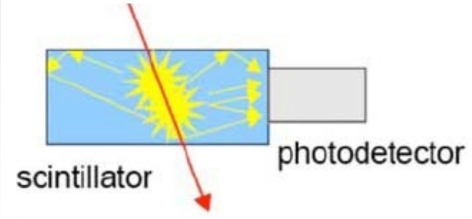

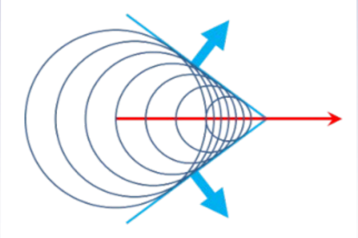

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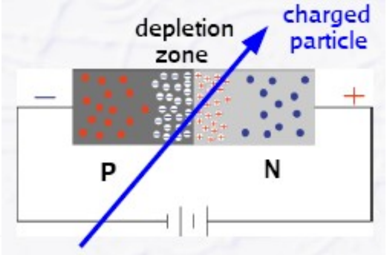
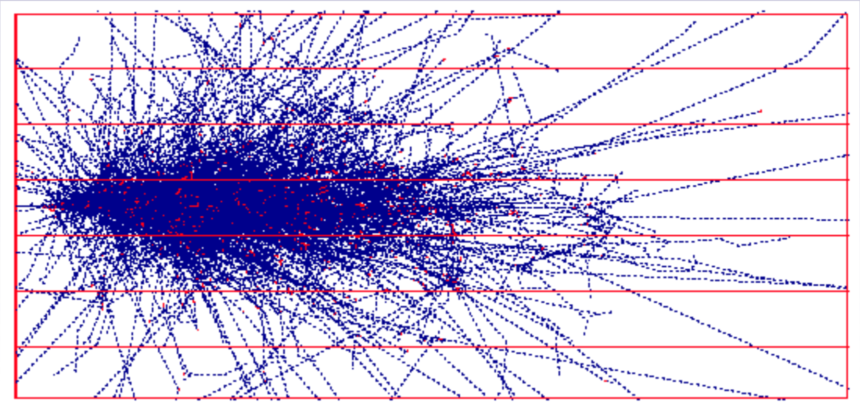


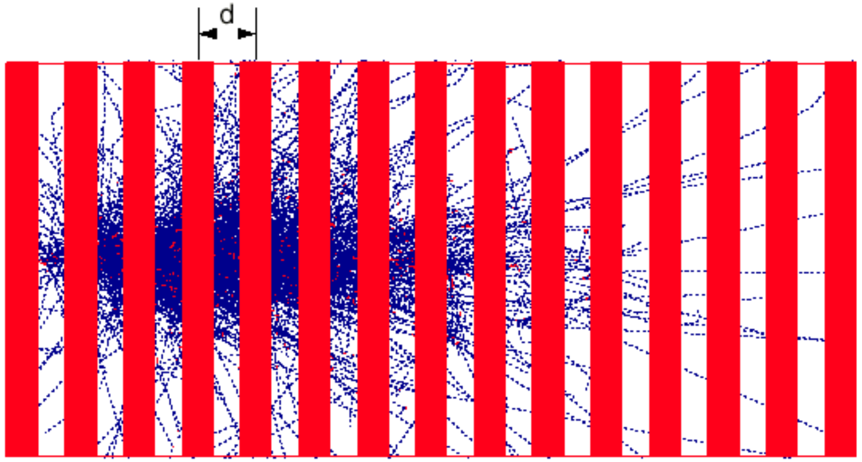
- Measure (very small) temperature increase
  - Bolometers, not covered in this lecture

- Dedicated electronics to collect signals in each case (not covered)

Homogeneous and sampling calorimeters



- Homogeneous calorimeter
  - Single medium for shower development and signal collection
  - “All” energy deposited is collected
    - Excellent energy resolution
  - Usually (very) expensive

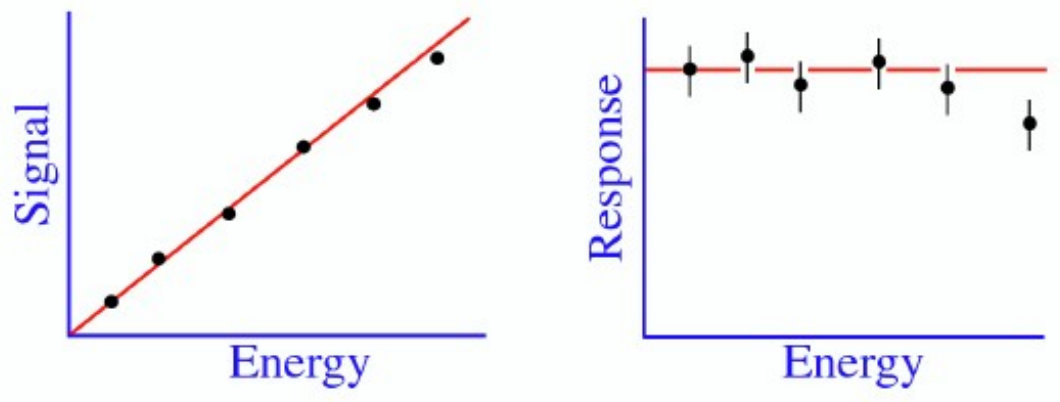


- Sampling calorimeter
  - Absorber (dense material) for shower development
  - Active material for signal collection
    - Only energy in active material is measured
  - Cheaper but worse energy resolution
  - All hadronic calorimeters (I know of) are of this type

Energy measurement

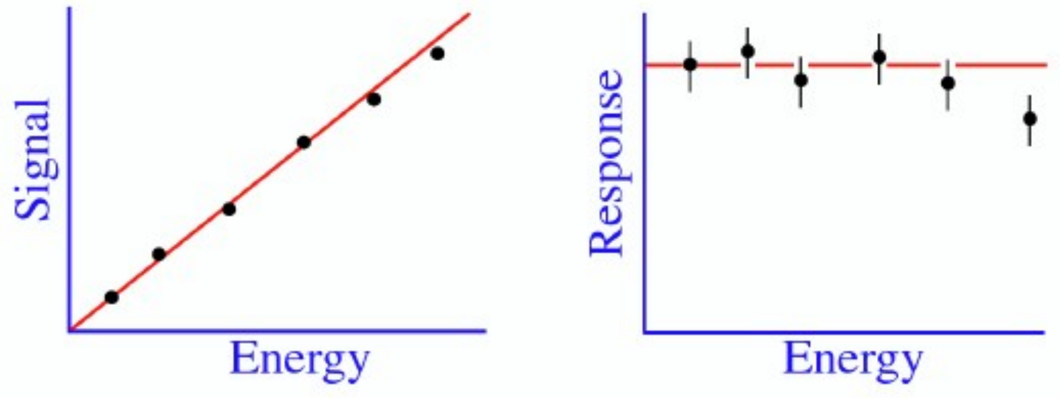
Calibration and calorimeter response

- Calibration from signal to energy usually from known sources
  - Light injection, radioactive decays, particle beams, ...



Calibration and calorimeter response

- Calibration from signal to energy usually from known sources
  - Light injection, radioactive decays, particle beams, ...
- A linear calorimeter has a constant response (<signal> / energy)
  - The signal is proportional to the deposited energy



- In general electromagnetic calorimeters are linear
- Hadronic calorimeters are not, the response depends on the particle

Energy resolution

Energy resolution determined by fluctuations of energy deposits and measurement process

Stochastic Constant

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

Noise

$\oplus$ = quadratic sum

N.B.: only a parametrisation, there can be other effects

- Stochastic term (Poisson fluctuations)
  - E ∝ number of particles n: $\frac{\sigma_n}{n} = \frac{\sqrt{n}}{n} = \frac{1}{\sqrt{n}} \rightarrow \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$
- Noise term: electronics or e.g. other particles
  - Independent of particle energy
- Constant term
  - Leakage, non-uniformities (construction, temperature, calibration, etc)

Energy resolution of some EM calorimeters

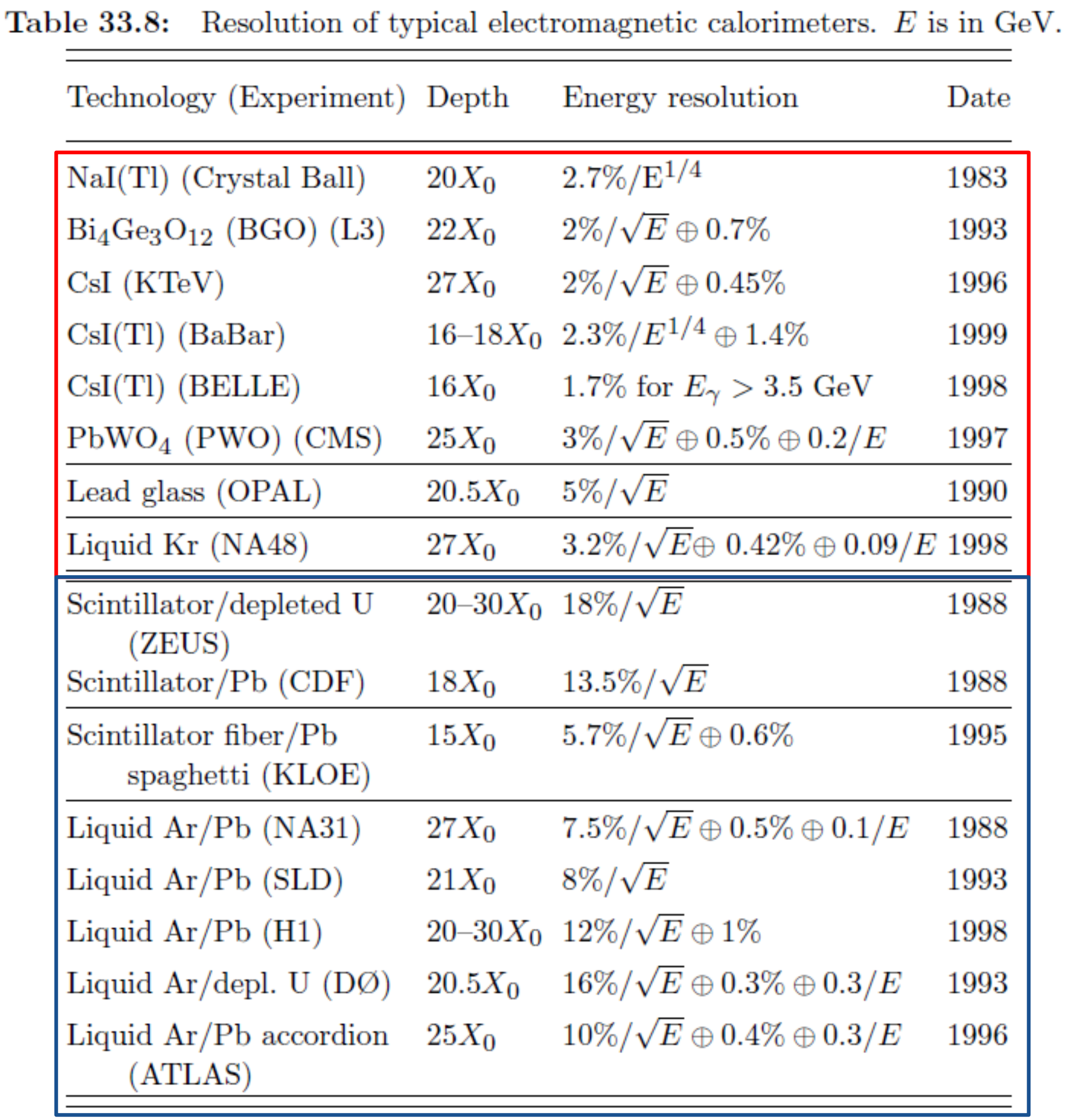
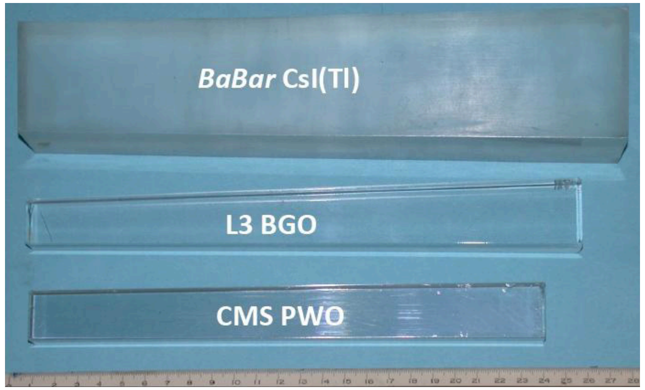


Table 33.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

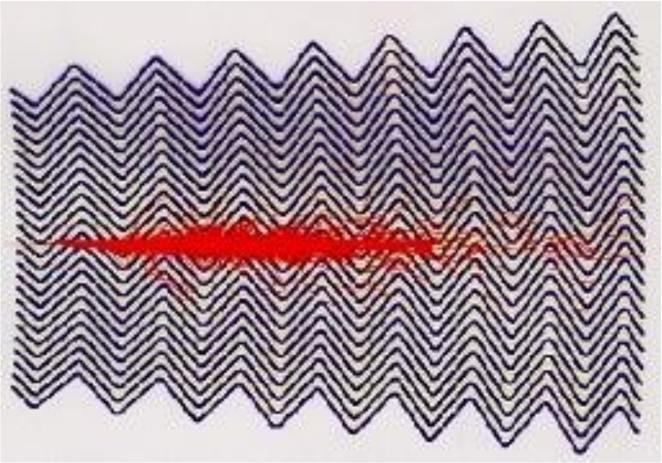
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	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
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

Homogeneous



Sampling

ATLAS Pb – liquid argon ECal

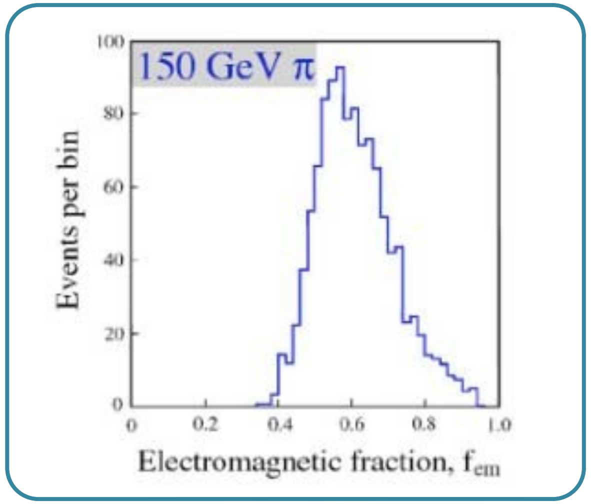


"Particle Detectors at Accelerators", https://pdg.lbl.gov/2020/reviews/contents_sports.html

Fluctuations in hadronic showers

- Electromagnetic energy fraction increases with energy and varies event-by-event

Fluctuations in EM fraction



Fluctuations in hadronic showers

- Electromagnetic energy fraction increases with energy and varies event-by-event
- Large part of energy losses is invisible or late
  - Nuclear binding and recoil (~15% in Fe, ~30% in Pb), evaporation neutrons (5-10%), muons, neutrinos, ...

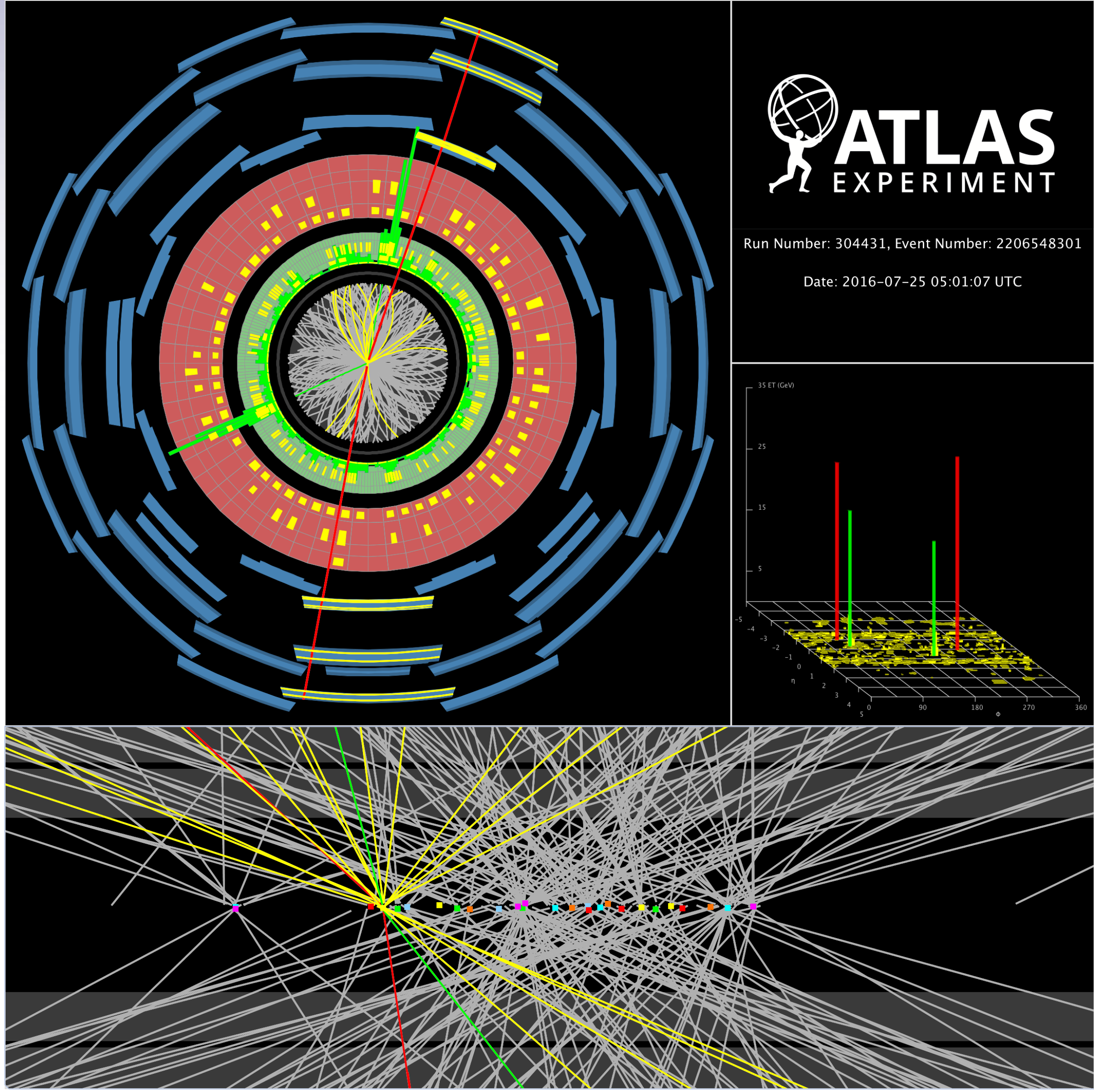
Fluctuations in hadronic showers

- Electromagnetic energy fraction increases with energy and varies event-by-event
- Large part of energy losses is invisible or late
  - Nuclear binding and recoil (~15% in Fe, ~30% in Pb), evaporation neutrons (5-10%), muons, neutrinos, ...
- **Non-linearity due to different response for EM and non-EM components**
  - Compensating calorimeters try to have e/h ~ 1
    - High-Z absorbers (Pb/U), ideally hydrogen in active material to boost neutron response
    - Large volume and long integration times (few 100 ns)
    - Can achieve resolutions around 20%/$\sqrt{E}$
- Typical resolutions around 50-100%/$\sqrt{E}$

Beyond energy measurement

Higgs boson (→ 2μ2e) candidate at LHC

- 25 p+p collisions at the same time
  - Up to ~60 in Run-2, 200 in HL-LHC
- Another event coming in 25 ns



Higgs boson (→ 2μ2e) candidate at LHC

- 25 p+p collisions at the same time
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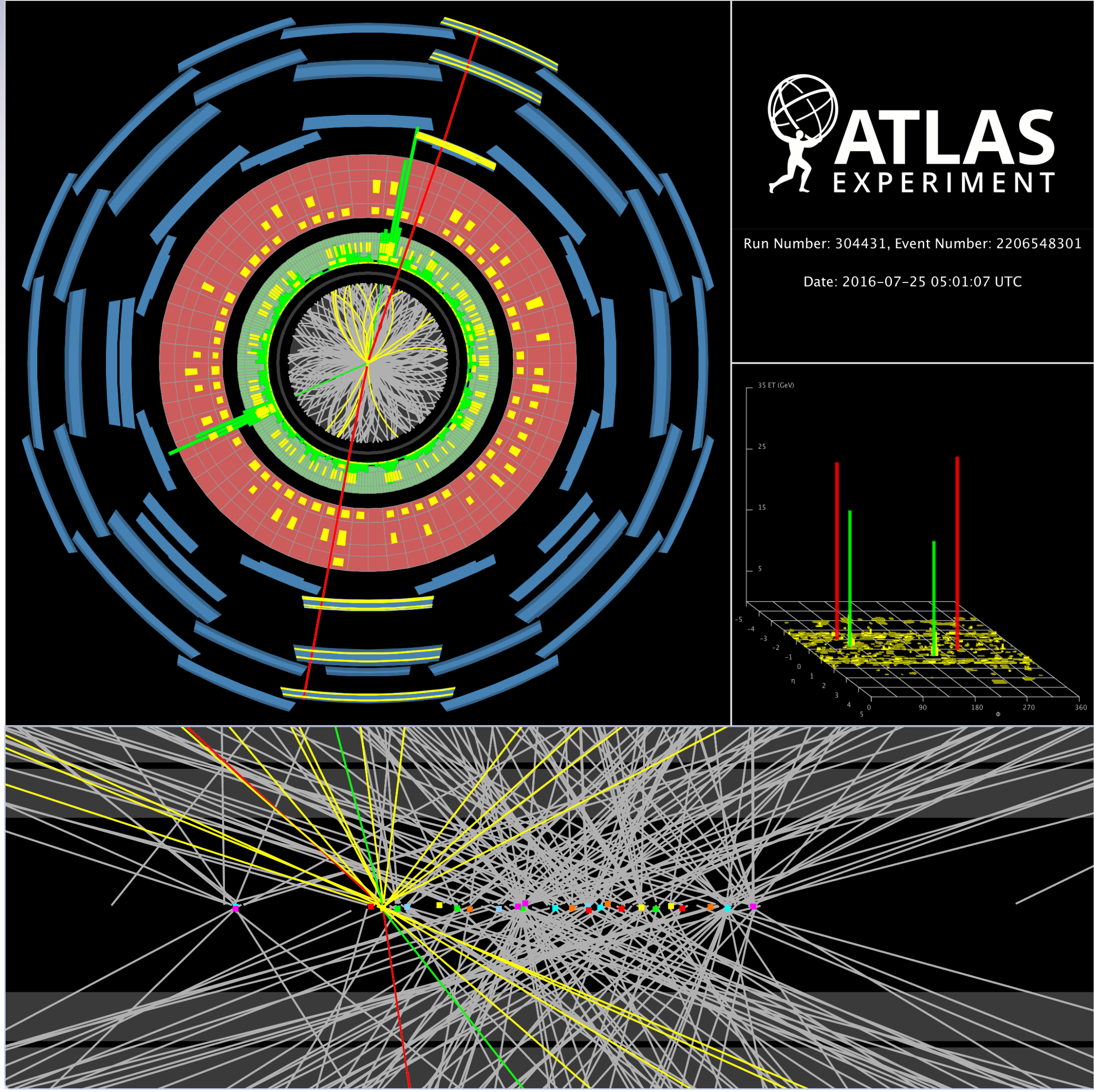
Depending on the environment, calorimeters need or provide:

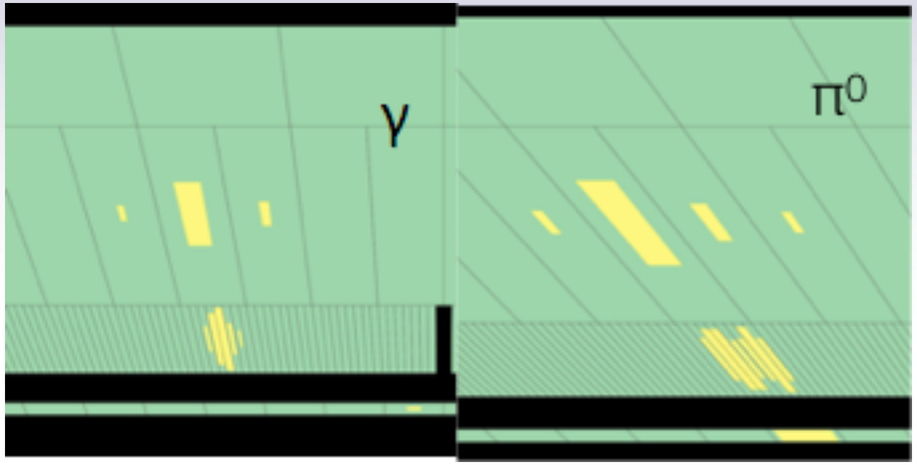
- High granularity, precise position measurements
- Fast signals, trigger and timing
- Particle identification
- Radiation hardness



ATLAS ECal: particle identification and vertexing

Lateral and longitudinal segmentation

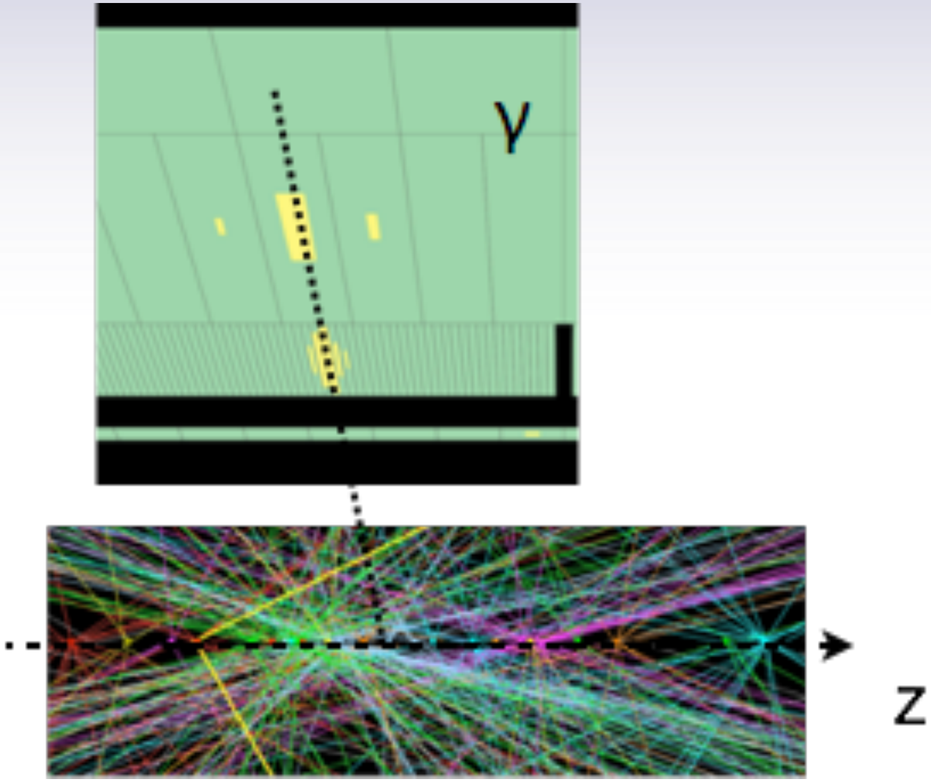
- 1st layer with 5 mm strips
  - Distinguish γ from $\pi^0 \rightarrow \gamma\gamma$



ATLAS ECal: particle identification and vertexing

Lateral and longitudinal segmentation

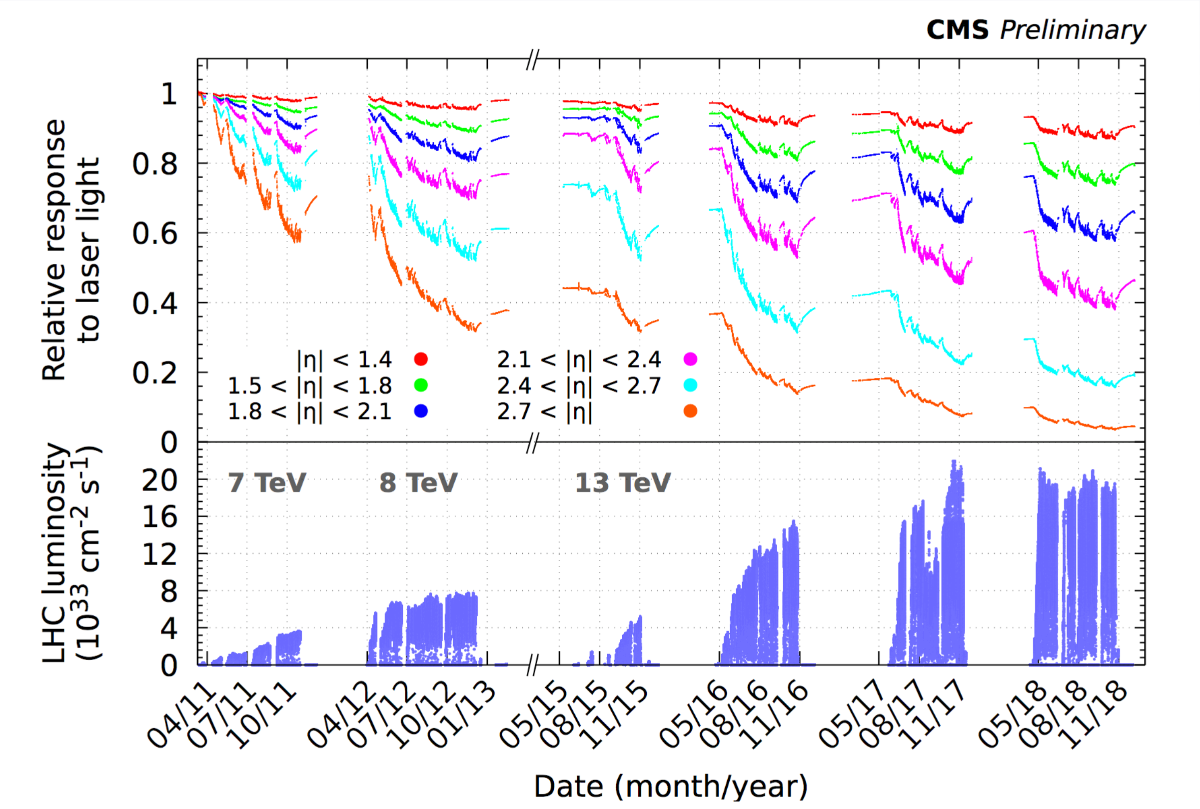
- 1st layer with 5 mm strips
  - Distinguish γ from $\pi^0 \rightarrow \gamma\gamma$
- 3 layers in depth
  - Shower depth: improve energy resolution
  - γ direction and vertex ($H \rightarrow \gamma\gamma$)



CMS ECal: transparency loss and laser monitoring

$PbWO_4$ crystal transparency affected by radiation

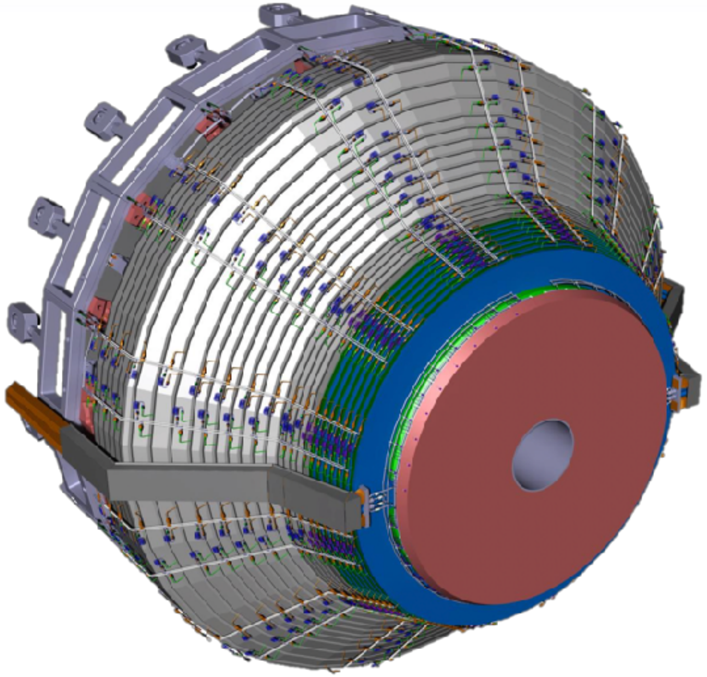
Laser light injected into every crystal during LHC abort gap @ 100 Hz

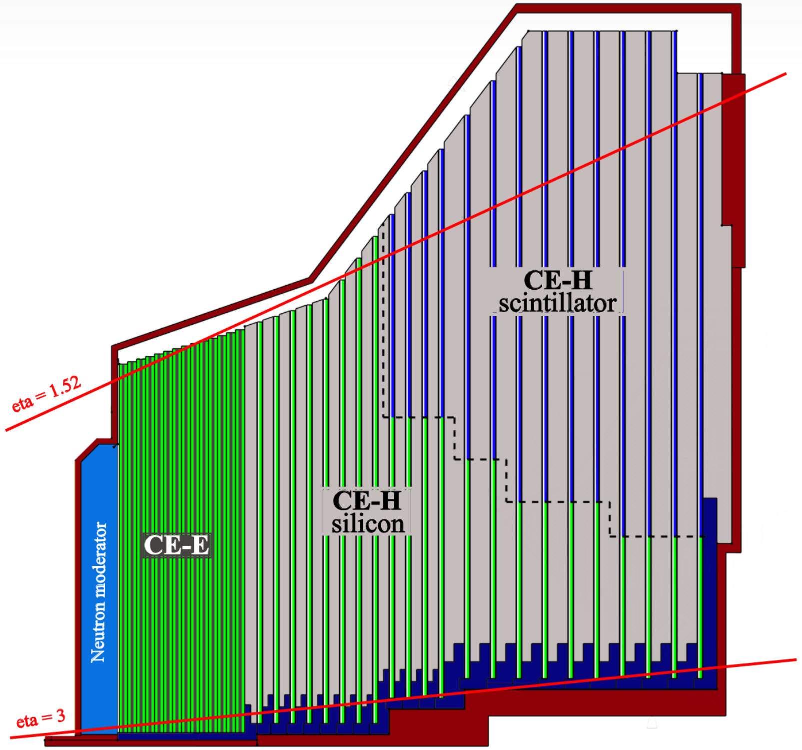


CMS HGCal for High-Luminosity LHC

Radiation hard detector measuring energy and time (down to 30 ps)

- **Silicon sensors** (6M channels) in ECAL and part of HCAL
- **Scintillating tiles + SiPM** readout in low-radiation region

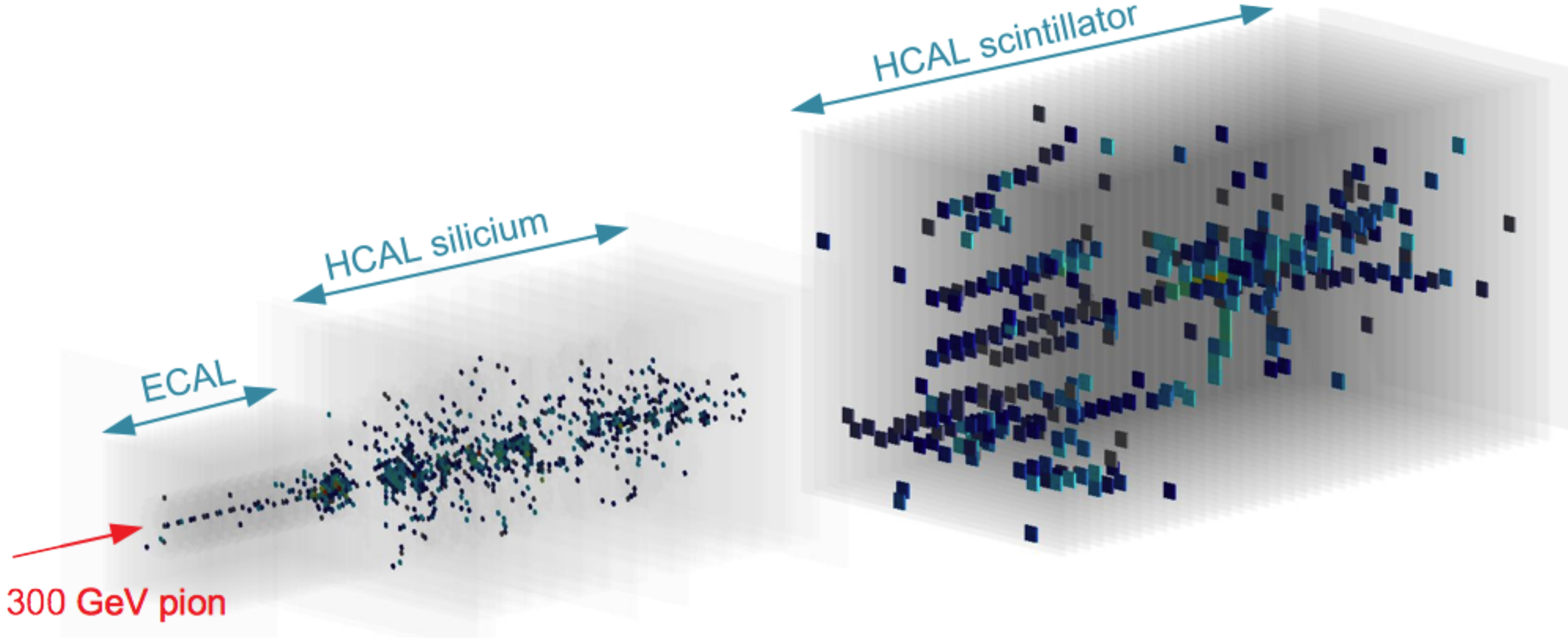




ECAL (CE-E):
28 layers, 25 X0, 1.3 λ
Pb, Cu, CuW absorbers

HCAL (CE-H):
22 layers, 8.5 λ
Steel, Cu absorbers

CMS HGCal pion shower



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LA-CoNGA physics

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