Calorimetry

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16 June 2026

CNiD School on Instrumentation and Detectors for Nuclear, Particle and Astroparticle Physics

References and further material

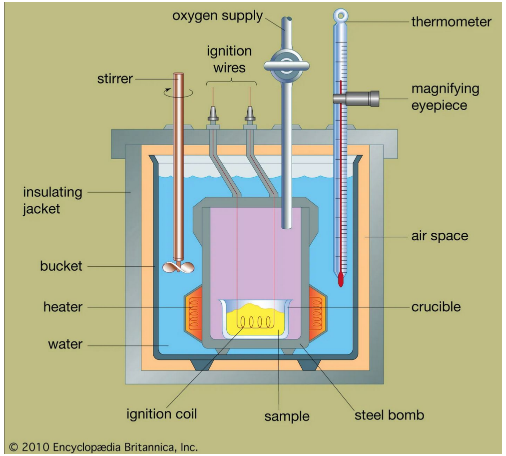
- **Books:**
  - "Calorimetry – Energy Measurement in Particle Physics" (aka "the bible of calorimetry") by Richard Wigmans
  - Slightly simpler/more modern: "Calorimetry for Collider Physics, an Introduction" by Michele Livan and Richard Wigmans (available for download)
  - "Handbook of Particle Detection and Imaging – Calorimeters" by Felix Sefkow and Frank Simon (shorter and very informative)
  - PDG review: Particle Detectors at Accelerators

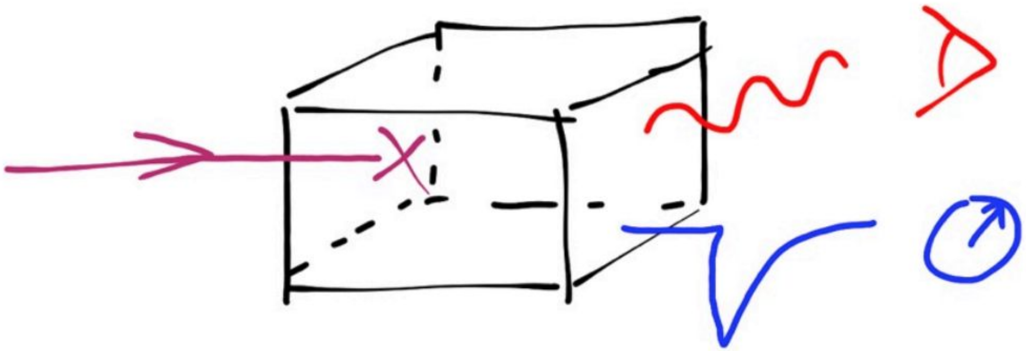
- **Selected presentations:**
  - David Barney: Calorimetry by examples (CERN Academic Training Lectures 2016)
  - Ludwik Dobrzynski : Instrumentation in HEP – Calorimetry (Split School of High Energy Physics 2015)
  - Frank Simon: Calorimetry - Refresher Course (IEEE NSS 2013)
  - David Cockerill: Introduction to Calorimeters (Southampton Lecture 2016)
  - Marco Delmastro: Future detectors: technologies for calorimetry (L'école de GIF 2025)
  - Silvia Masciocchi: Electromagnetic and hadronic calorimeters (HGSFP Heidelberg 2017)

- All used in the preparation of this talk, and great references for a deep-dive into the topic

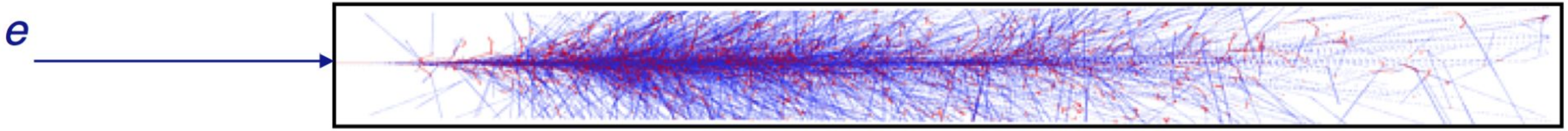
Introduction – What's a calorimeter?

- Original idea: device to measure the heat released by a chemical reaction
  - Detect the increase of temperature of a known amount of water
- In nuclear and particle physics: device to **measure the energy of a particle**
  - Not by measuring temperature changes: effect of a 100 GeV particle in 1 litre of water (at 20°C) is 10^{-12} K
  - Instead, convert the particle energy into something "detectable"
  - Usual choices: electric charge or photons (in or close to visible range)
- Particles ionize or excite the detector, producing **scintillation photons** or **ionization electrons**, both with O(eV) energies





Introduction – What's a calorimeter?



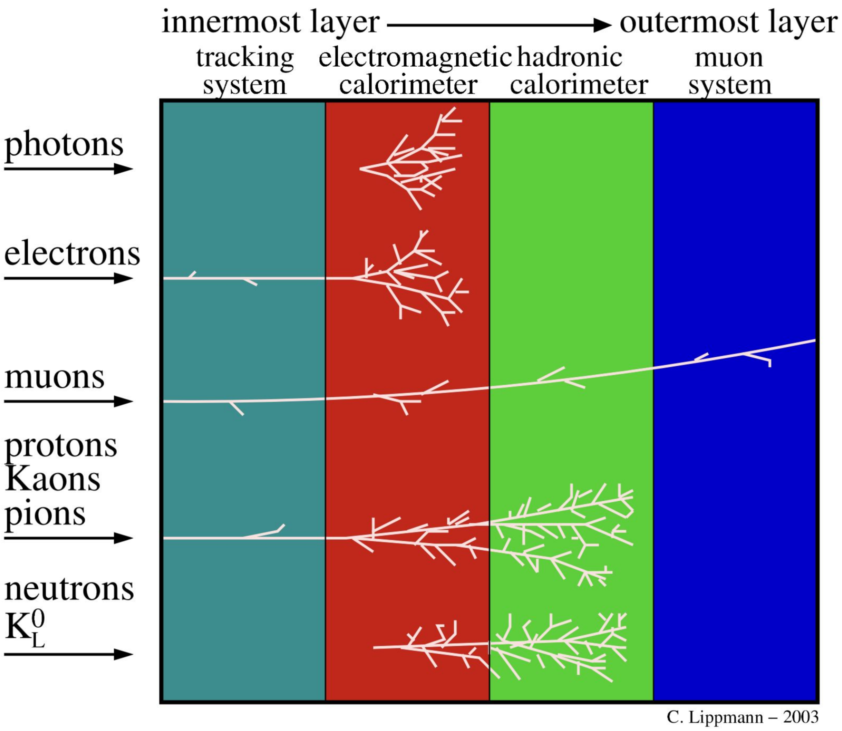
- More technical definition: A calorimeter is a device whose response to an incident particle is a signal proportional to the energy deposited by the particle
  - **Cascade process:** primary particle produces many secondary particles
    - Shower development depends on particle type and on detector material
  - Destructive process: the particle is **fully stopped** in the detector
  - **Total absorption:** need to be thick enough to absorb all the energy of the particle shower
  - Proportionality: most of the particle energy is dissipated as heat, while only a minor fraction constitutes the readable signal → Output signal must be proportional to the particle energy

- Calorimetry works for both charged (**e±** and **hadrons**) and neutral particles (**neutrons**, **photons**)
  - Complementary information to momentum measurement by tracking detectors
  - Only way to get direct kinematical information for neutral particles

Types of calorimeters: Electromagnetic / Hadronic

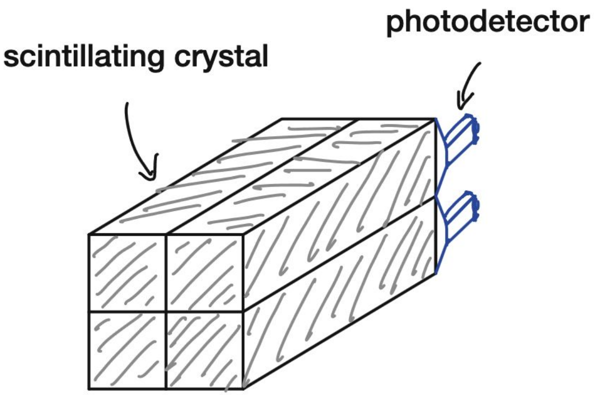
- Calorimeters are the "end of the road"
  - Where do you stop? = Who you are?
  - **Electron/photons:** will stop in the Electromagnetic (EM) calorimeter (**ECAL**)
  - **Charged/neutral hadrons:** will stop in the Hadronic calorimeter (**HCAL**) but will also deposit energy in the ECAL
  - Muons: will deposit some energy in the calorimeters but will not be stopped

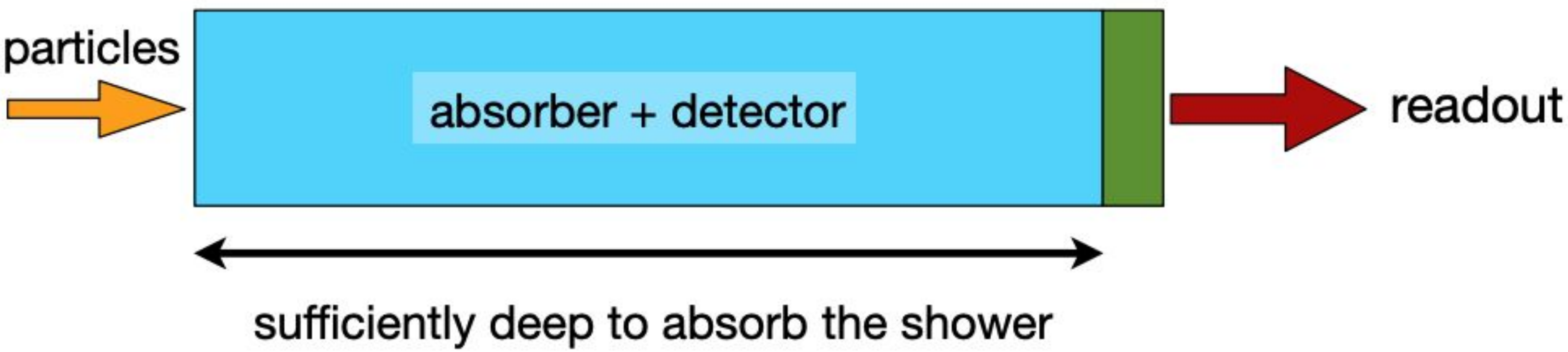
- Tracking system:
  - Provides charge and momentum measurement for charged particles
  - Minimum material: avoid energy losses before the particle reach the calorimeters



Types of calorimeters: Homogenous / Sampling

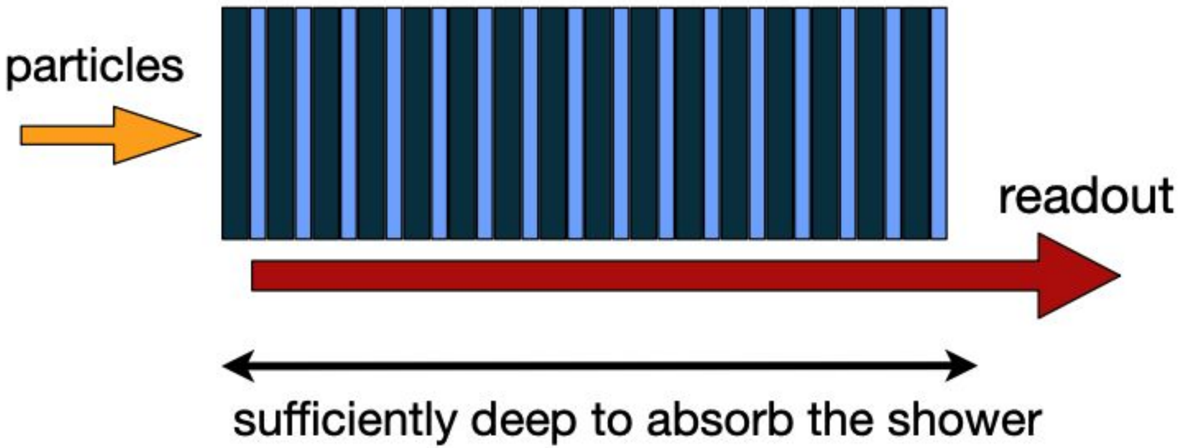
- Ideal calorimeter: Fully contain the incoming particle's energy and convert all that energy into a measurable signal which is linear to the deposited energy
- **Homogenous calorimeter:**
    - Shower develops in the same material which produces the signal
    - Typical examples: scintillating crystals (eg: lead tungstate crystals)
    - Measurement of all the energy produced, but challenging readout and construction

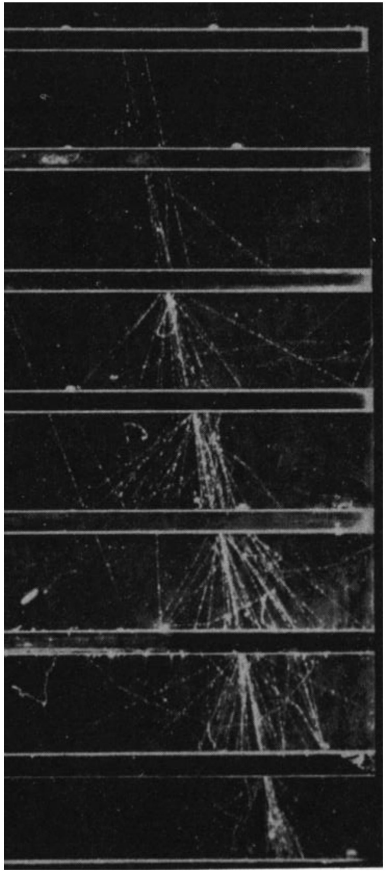




Types of calorimeters: Homogenous / Sampling

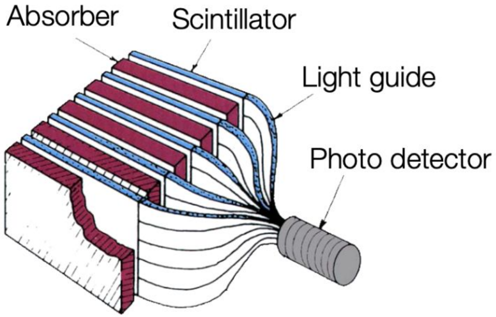
- **Sampling calorimeter:**
  - The shower mostly develops in the absorber material, but signal is produced in an active medium interleaved with the absorber
  - Not measuring all the energy produced, only a fraction → Potentially lower resolution
  - Signal is readout as the shower develops → More information
  - More flexible choice of active medium and absorber materials



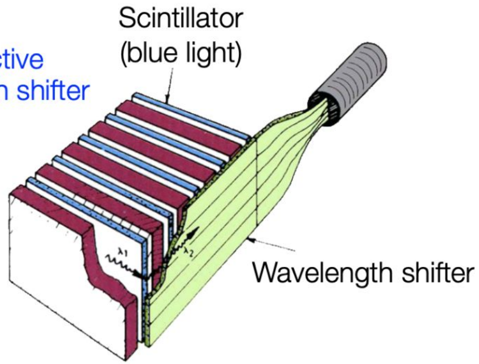


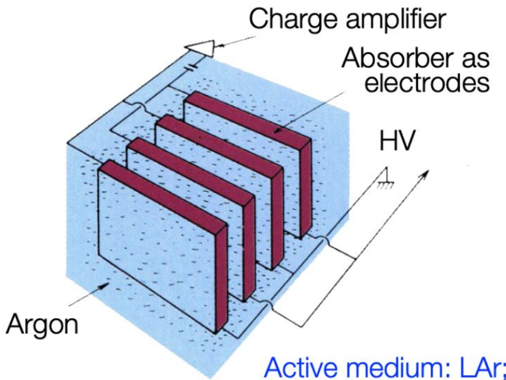
Sampling calorimeters: some examples

Scintillators as active layer;
signal readout via photo multipliers



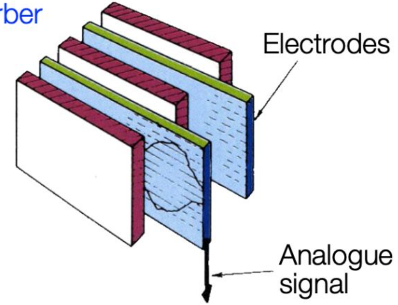
Scintillators as active layer; wave length shifter to convert light





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

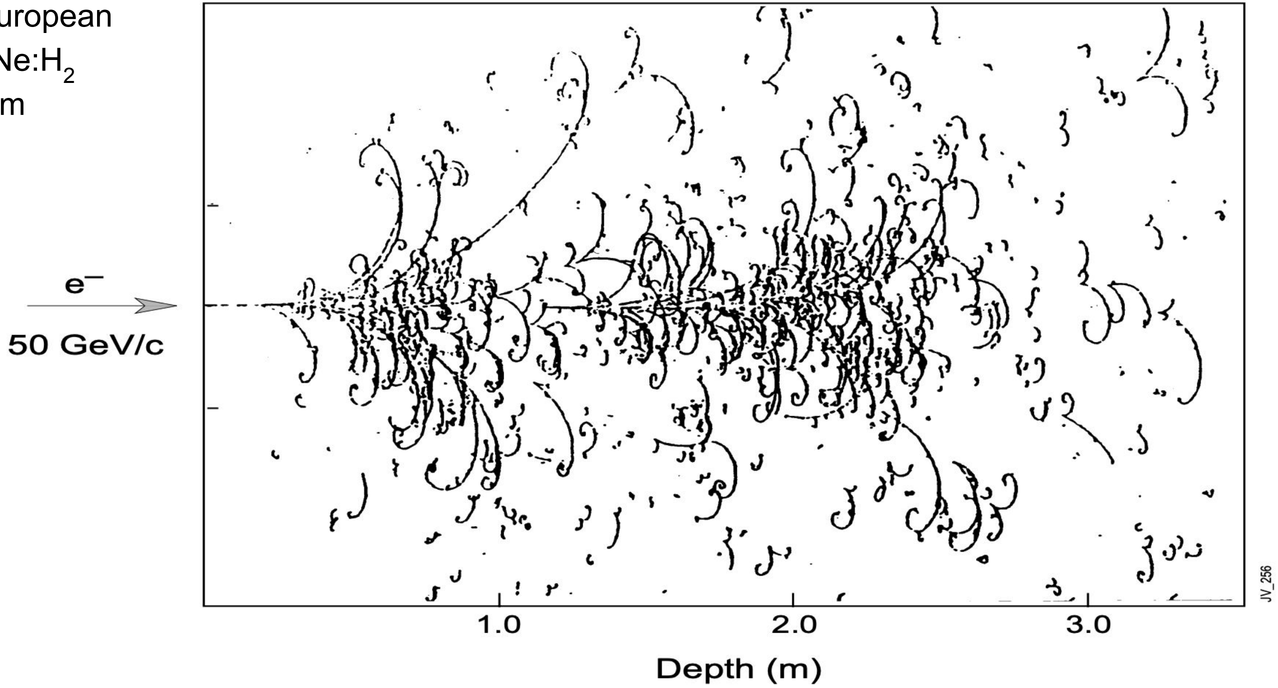
Ionization chambers between absorber plates



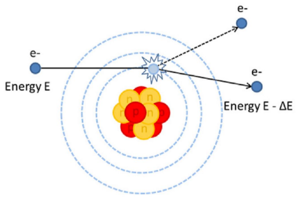
Electromagnetic showers

- Incident particles interact with the material and produce secondary particles
- Important to understand the involved physics processes to optimize the design of your detector

Electron shower in the Big European Bubble Chamber, filled with Ne:H_2 (70%:30%), 3T field, x_0=34 cm



Energy loss mechanisms: Ionization

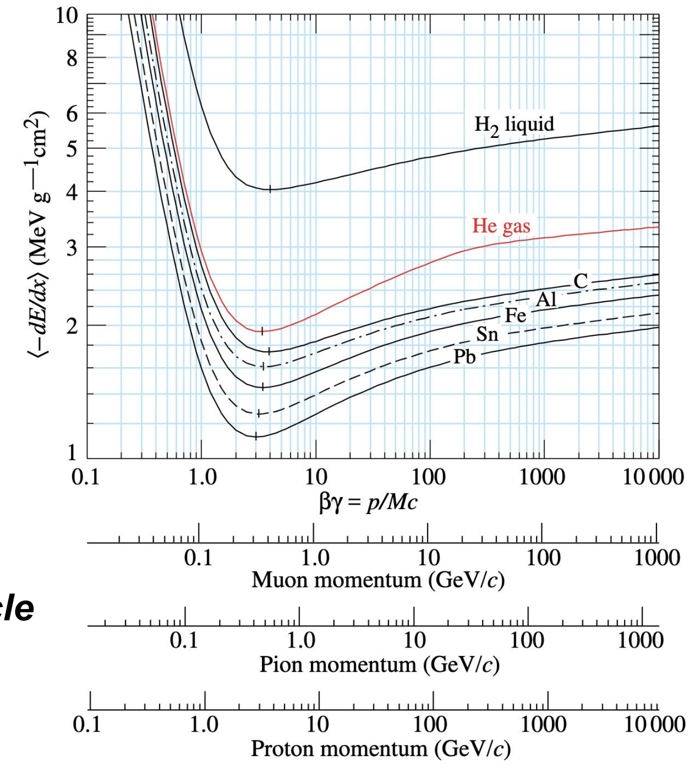


Diagrams from Clin Oncol 33 (2021) 455

- Energy loss by ionization for a particle (z, β,γ) in a given material (A,Z) is given by the **Bethe-Bloch formula**:

$$-\frac{dE}{\rho\,dx} = C\,\frac{1}{\beta^2}\frac{Z}{A}z^2\left[\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2}\right)-2\beta^2-\delta-2\frac{C}{Z}\right]$$

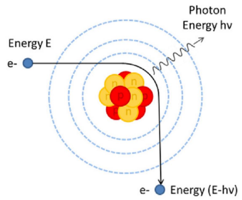
- Formula valid for all particle types, adjusting for the relativistic $\beta\gamma$ values
- Proportional to Z/A → Small differences for most materials
- Minimum at βγ~3.5 (β=0.94) → **MIP: *Minimum ionizing particle***
- Relativistic energies: increasing logarithmically on E/m
- Low energy: large increase (dependence on $1/\beta^2$)



Energy loss mechanisms: Bremsstrahlung

- **Radiation of photons** in the presence of the electric field of the atomic nuclei
- One of the processes responsible for the production of secondary particles
- Energy loss by bremsstrahlung:

$$\left\langle -\frac{dE}{d\chi} \right\rangle = 4\pi N_A z^2 \frac{Z^2}{A} \left[\frac{1}{4\pi\varepsilon_0 m_e c^2} \frac{e^2}{mc^2} \right]^2 E \ln \frac{183}{Z^{1/3}}$$



Diagrams from [Clin Oncol 33 (2021) 455]

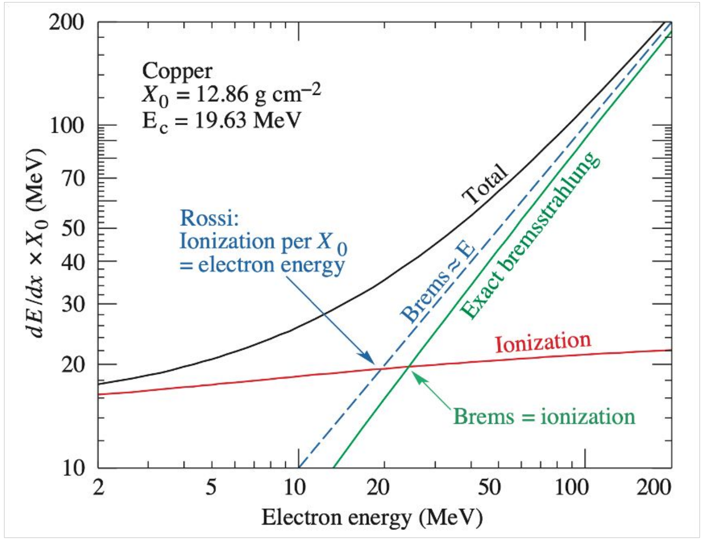
- Directly proportional to particle's E and the material Z^2/A
- Process is characterized by the **radiation length** (**X_0**): distance in the medium where a high energy electron loses on average 1/e (63%) by radiation

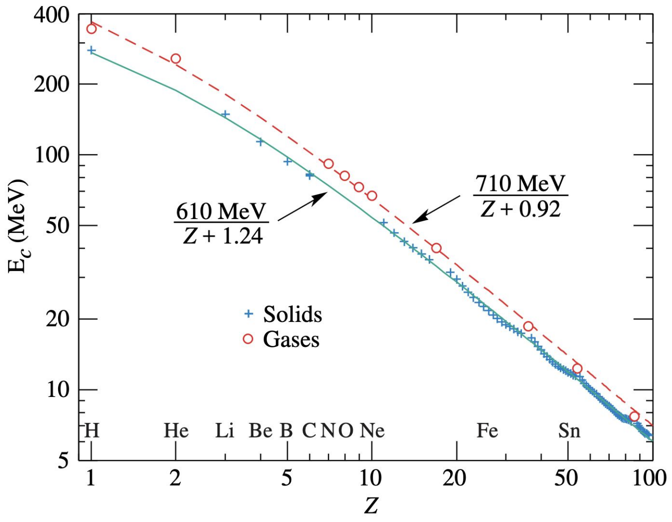
$$\left\langle -\frac{dE}{d\chi} \right\rangle = \frac{E}{X_0}$$

- Some typical X_0 values:
  - Air: 300 m
  - Plastic scintillator: 40 cm
  - Iron: 1.76 cm
  - $PbW0_4$: 0.9 cm

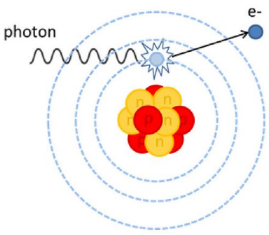
Electron critical energy

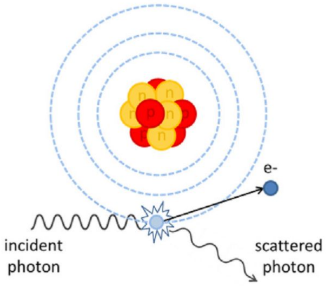
- Two competing processes:
  - **Ionization:** dominant at low energies (logarithm increase vs. E)
  - **Bremsstrahlung:** dominant at high energies (linear increase vs. E)
- **Critical energy (E_c):** energy for which the energy loss by radiation and ionization are the same
  - Alternative definition: losses by radiation are equal to the particle energy
- Only depends on material properties, with well known values for solids and gases

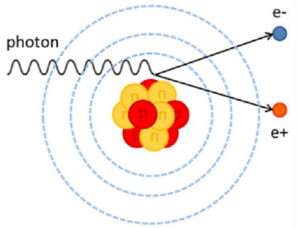




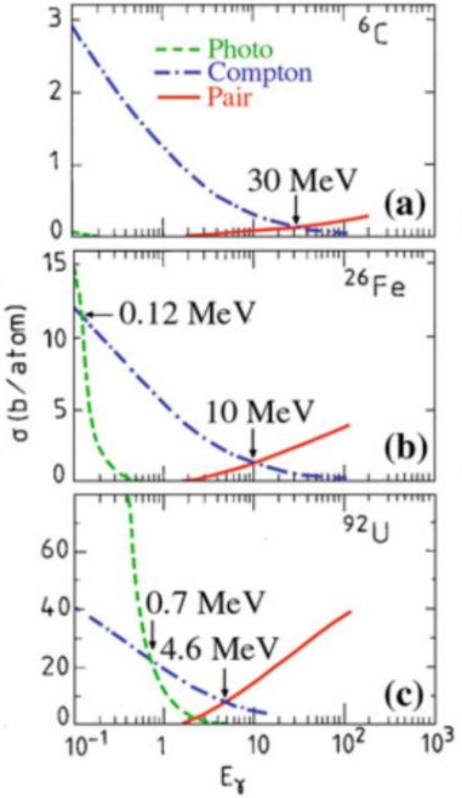
Photon energy loss





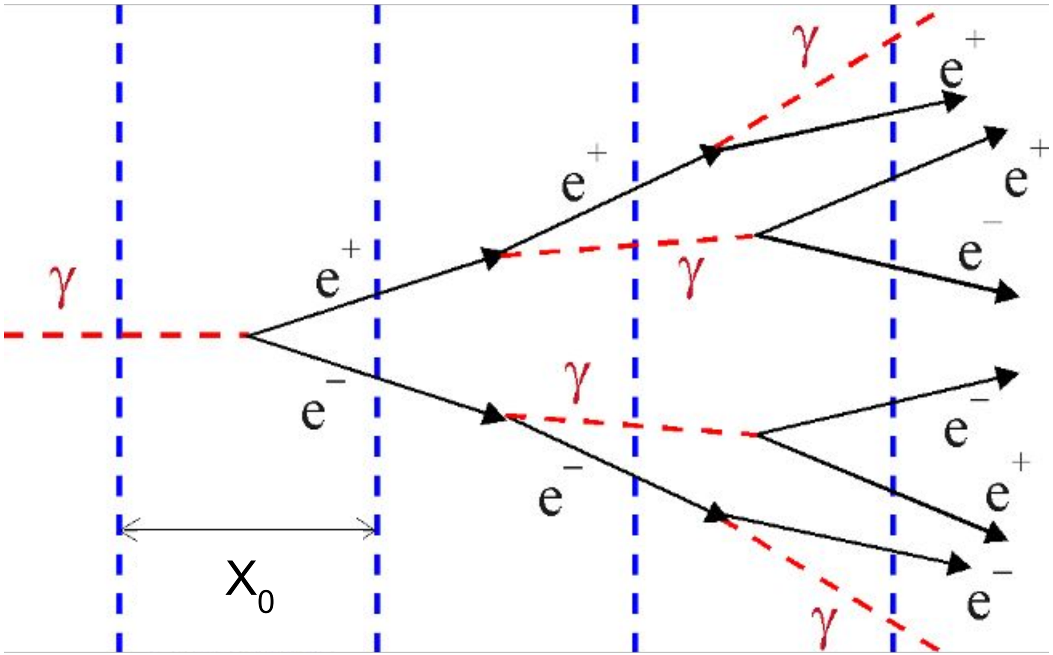


- **Photoelectric effect:**
  - Proportional to Z^5 and E^{-5} → Dominant at low E
- **Compton scattering:**
  - Photon scattered by an atomic electron, which is freed
  - Proportional to Z and E^{-1} → Dominates at intermediate energies
- **Pair production:**
  - Create electron-positron pairs in an electric field
  - Proportional to Z (Z+1) and ln(E) → Dominant at high energies
  - **Mean free path before pair production: 9/7 X_0**
- Preference for high Z materials:
  - Short transition from pair production (multiplication phase) to photoelectric effect (localized abortion)

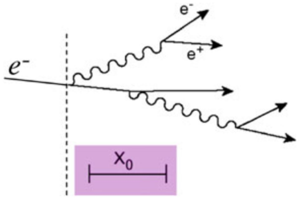


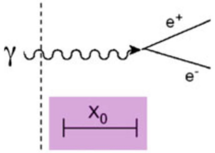
Diagrams from Clin Oncol 33 (2021) 455

An qualitative EM shower model



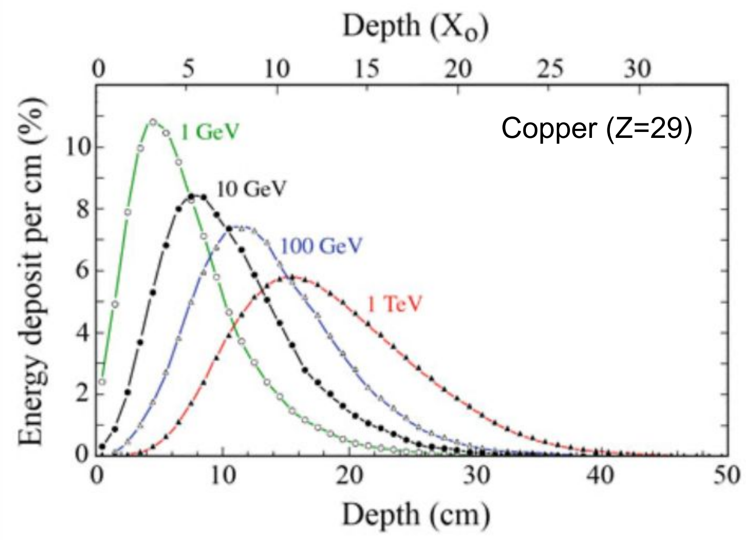
- Simplistic model, but deriving useful rules of thumb
- Pair production mean path: $\sim X_0$
- Electron or photon with (high) energy E_0 hits the calorimeter
- Each X_0, bremsstrahlung or pair production → **"generation length"**
- After *t* generations we have:
  - *2t* particles in the shower
  - Assuming equal energy sharing: $E(t)=E_0/2^t$





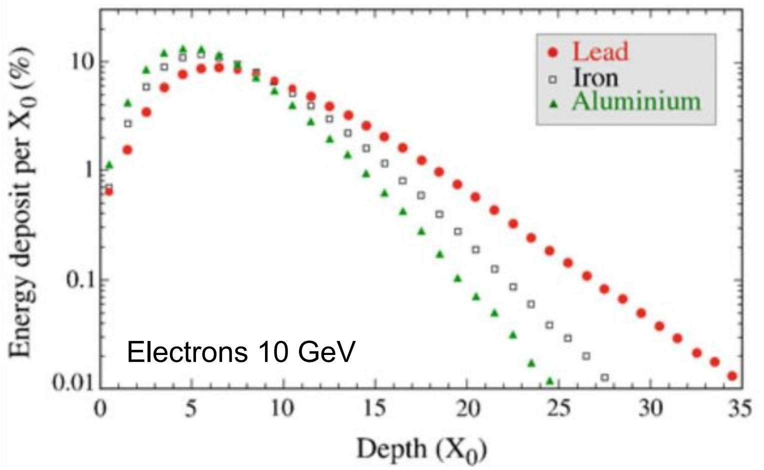
- Multiplicative process stops when $E(t)<E_c$ → Ionization, Compton and photoelectric effect take over
- Predicts shower maximum proportional to $\ln(E_0/E_c)$

EM shower: longitudinal development



- Shower maximum indeed showing a logarithmic dependence on particle energy
- Tails are larger for highly energetic particles
- **About 25 X_0 needed for good shower containment**

- For heavier elements (smaller critical energy):
  - Deeper shower maximum
  - Slower shower extinction



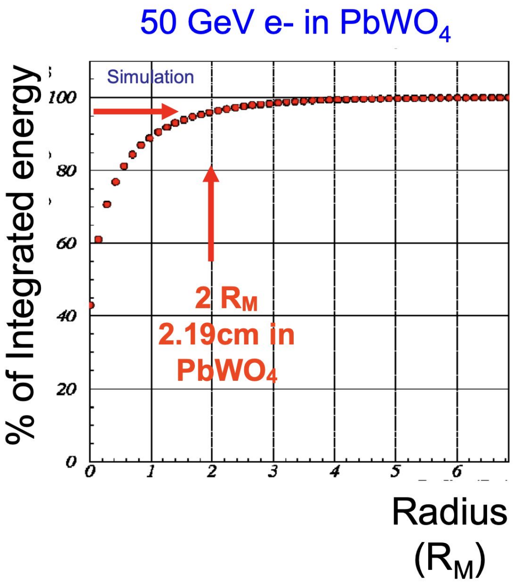
EM shower: lateral development

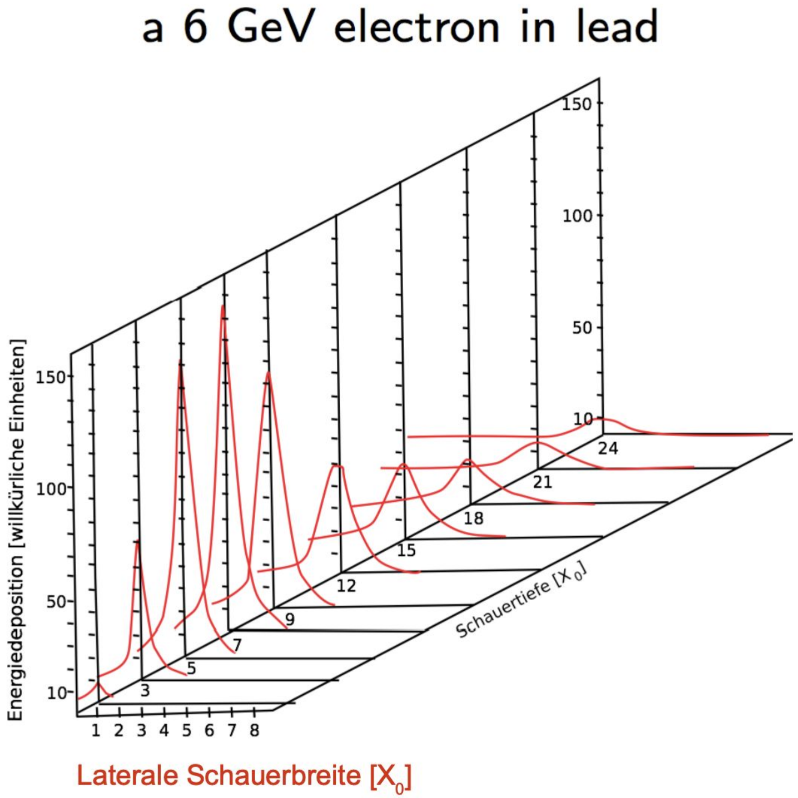
- The **Molière radius (R_M)** is frequently used to describe the transverse development
- Approximately material independent:

$$R_M = \frac{21\ MeV}{E_C} X_0 \approx 7\frac{A}{Z}$$

- 90% of the shower is contained within one R_M

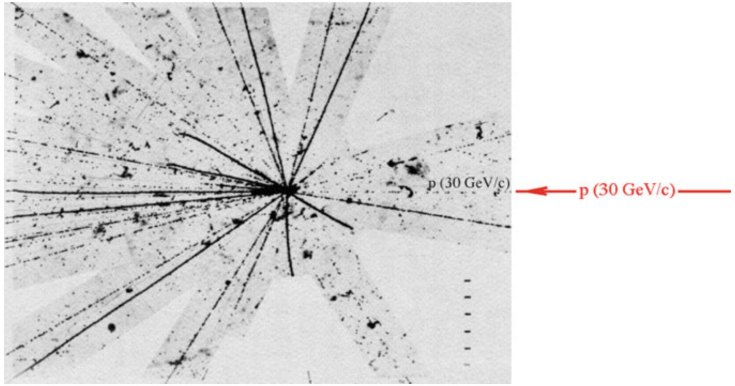
- Typical vales:
  $PbWO_4$: 2.2 cm
  Lead: 1.6 cm

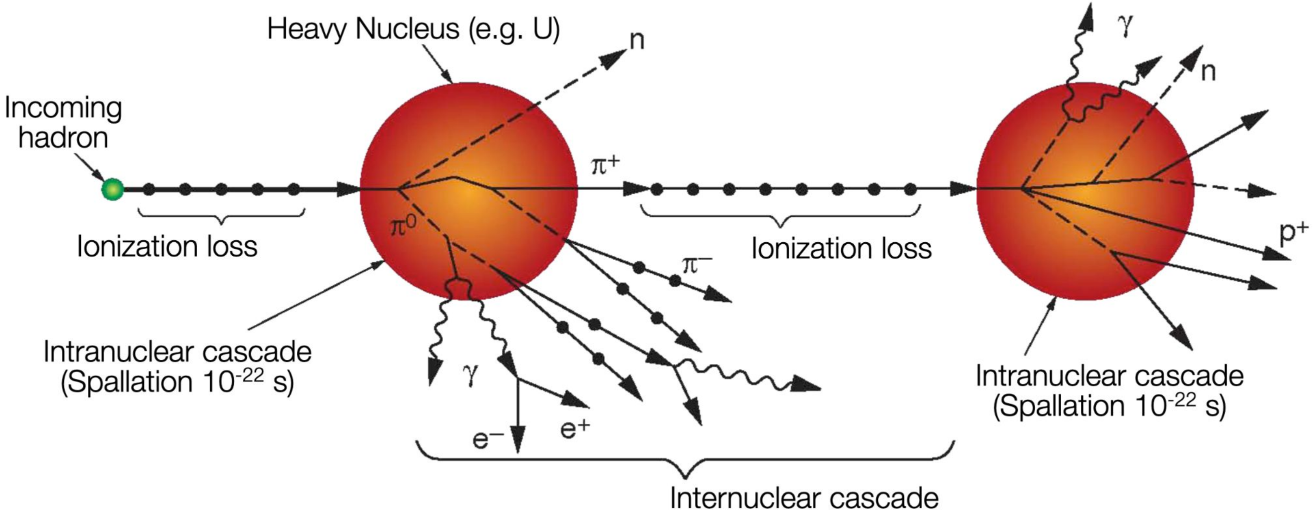




Hadronic showers

- Much more difficult than EM showers: strong interactions of the shower particles with the medium nuclei
- Pions are the most important contribution in the hadronic shower composition, but the large majority of the energy is deposited through protons and neutrons.
- Neutral pion decay via $\pi^0 \to \gamma\gamma$ initiating an EM shower





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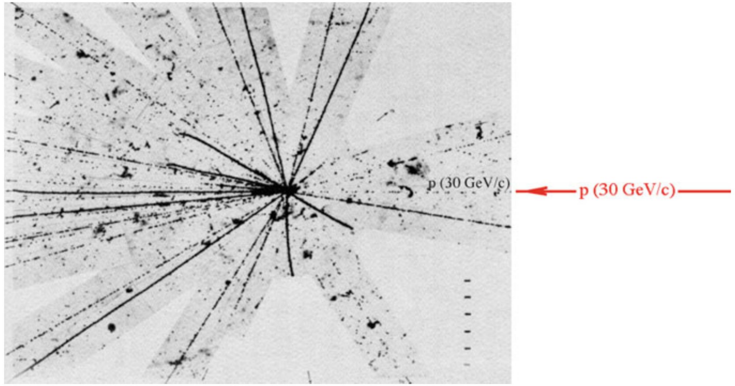
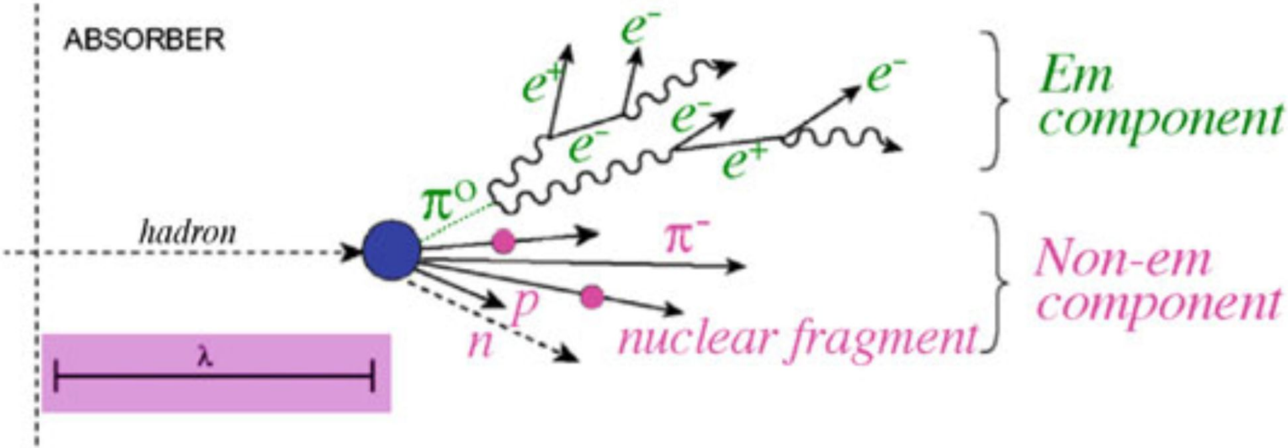
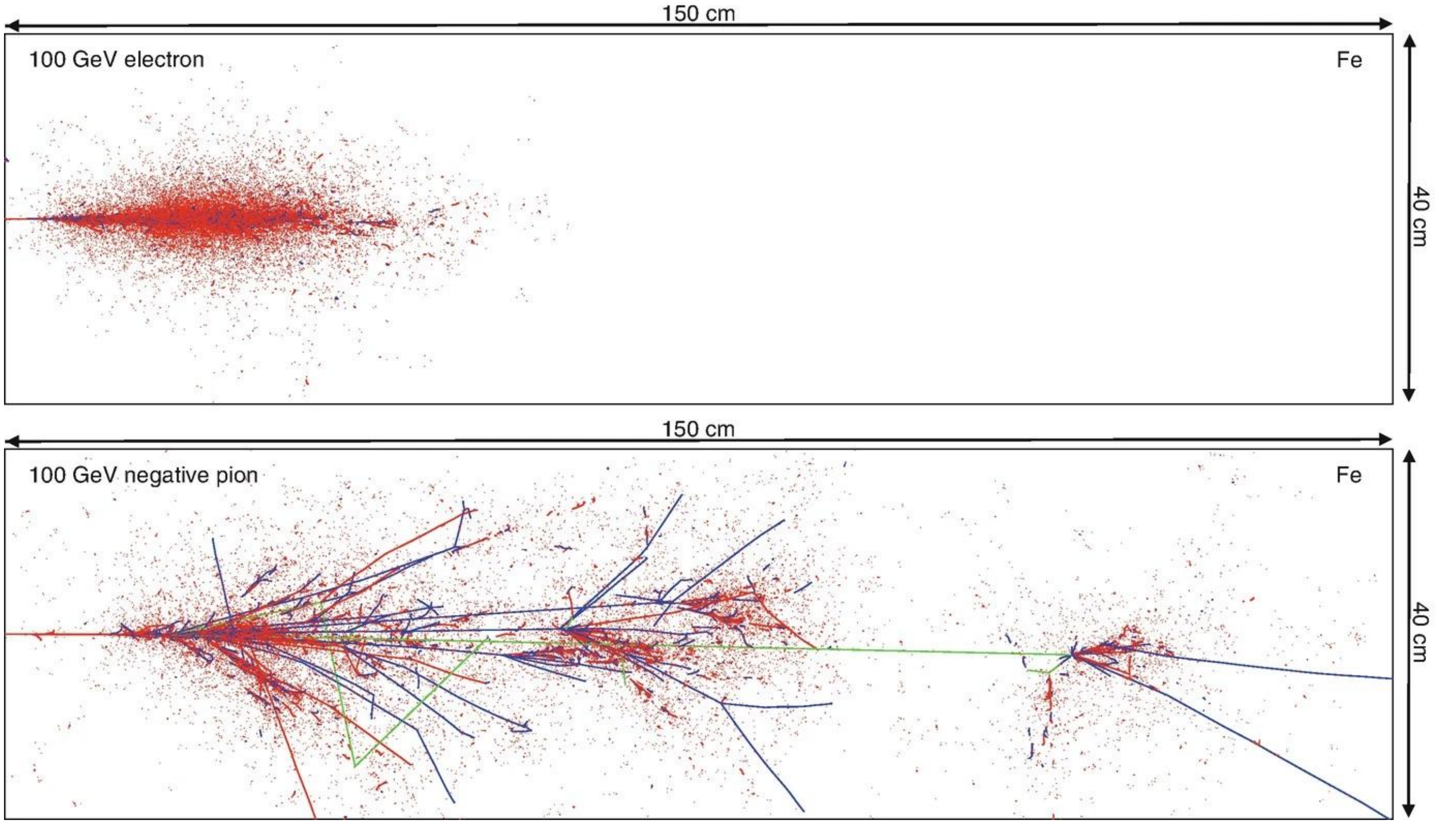




Comparing shower development



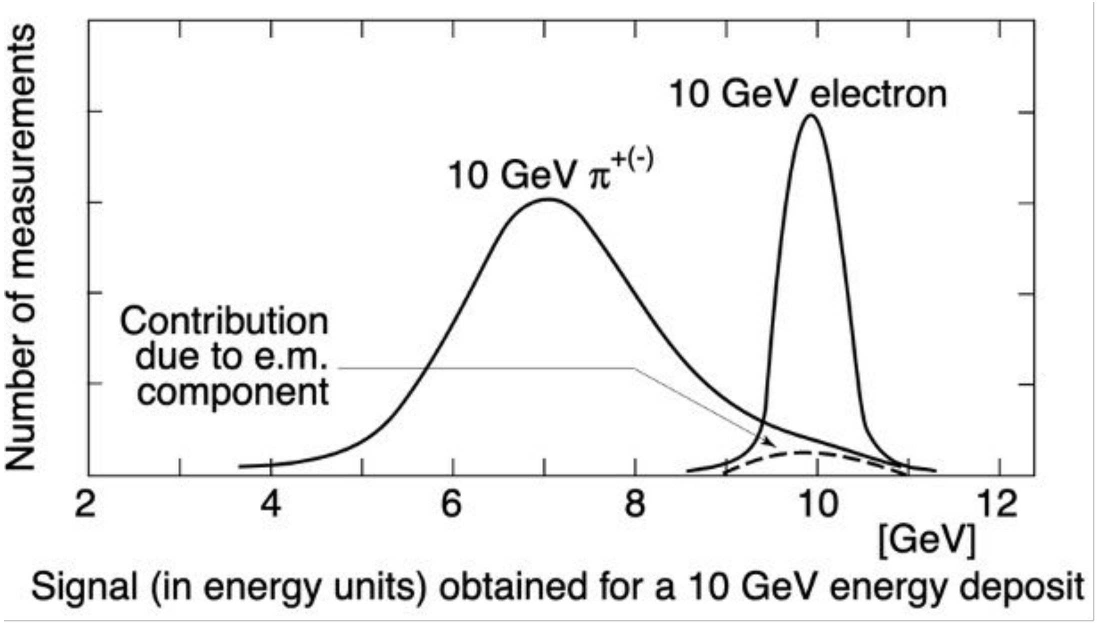
EM component

Non-EM component (charged only)

Non-EM component (neutral – except γ,n)

Hadronic showers

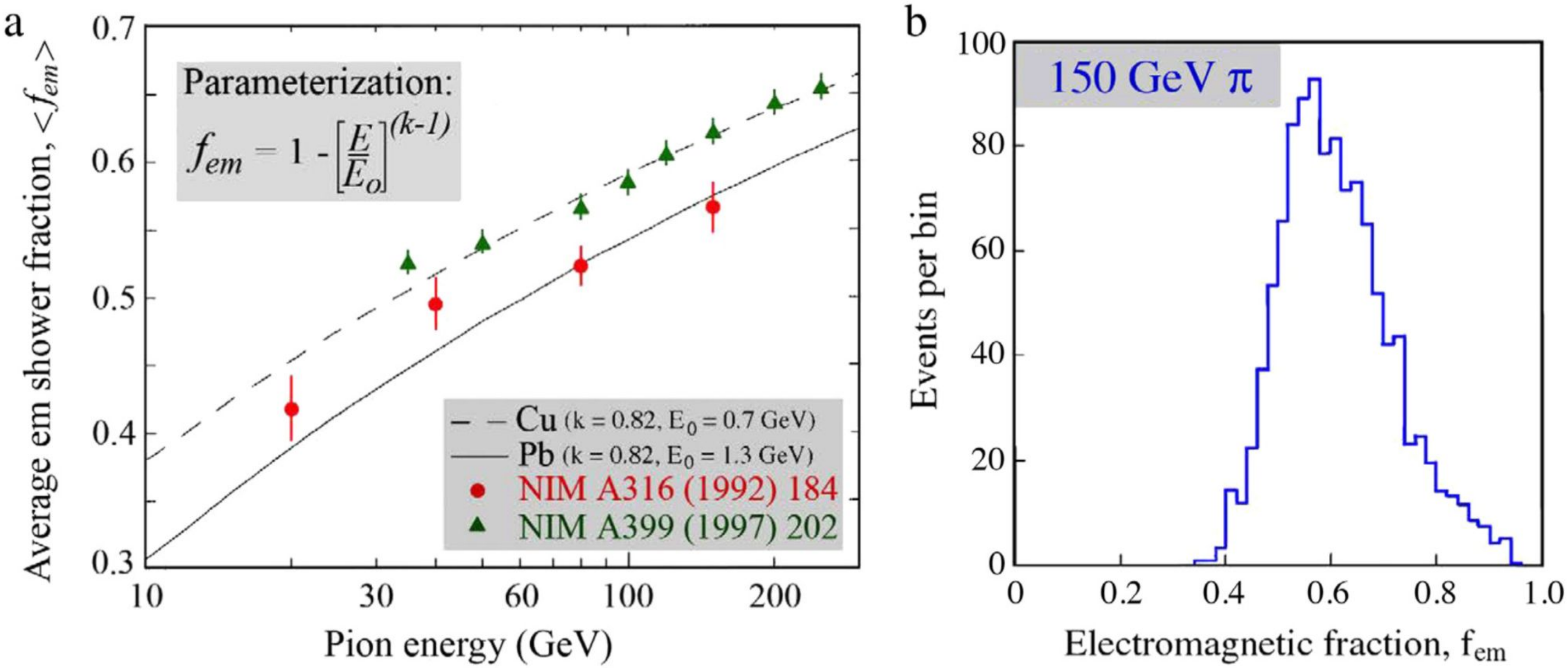
- A fraction of the energy is used in breaking the medium nuclei and other processes leading to invisible energy (not detectable or too slow to be in the signal readout time window) → Worse energy resolution



Charged hadrons	(20%)
Nuclear fragments, protons	(25%)
Neutrons, soft γs	(15%)
Breakup of nuclei	(40%)

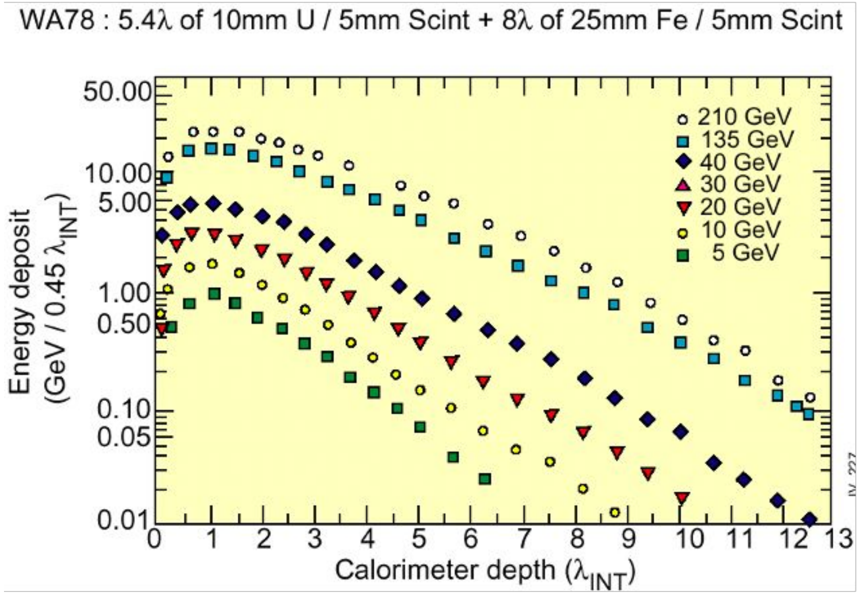
Hadronic showers: EM fraction

- EM fraction is large (40-60%) and fluctuates depending on the number of pions in the shower
- Increases with particle energy, with non-Gaussian tails

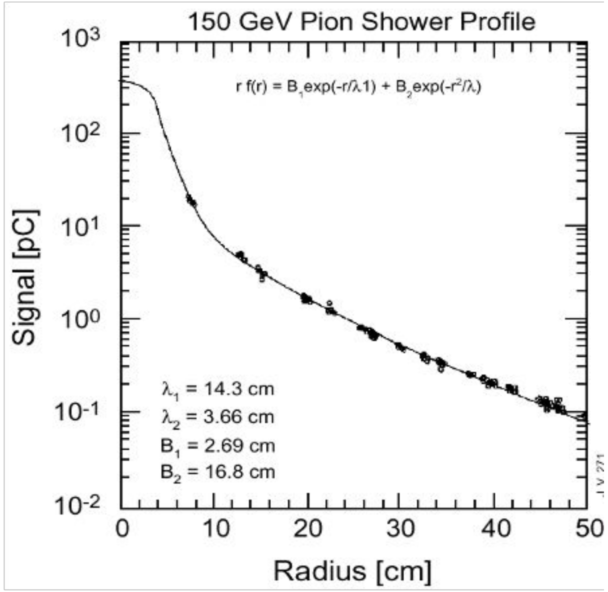


Hadronic showers: Scaling variables

- **Interaction length (λ_{INT}):** average distance hadrons travel before inducing a nuclear interaction
- Good containment of showers requires ~10 λ_{INT} thickness and ~1 λ_{INT} width



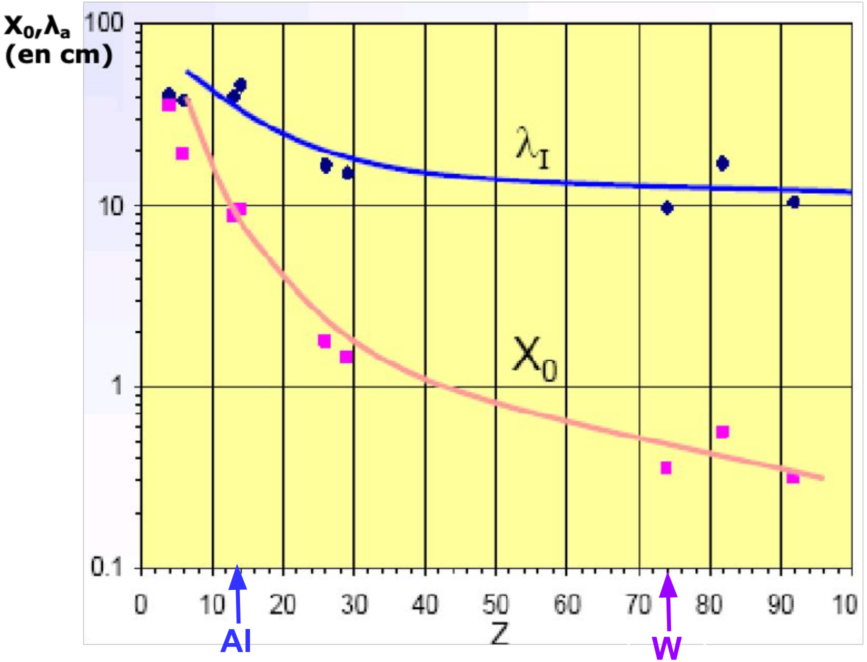
Longitudinal development

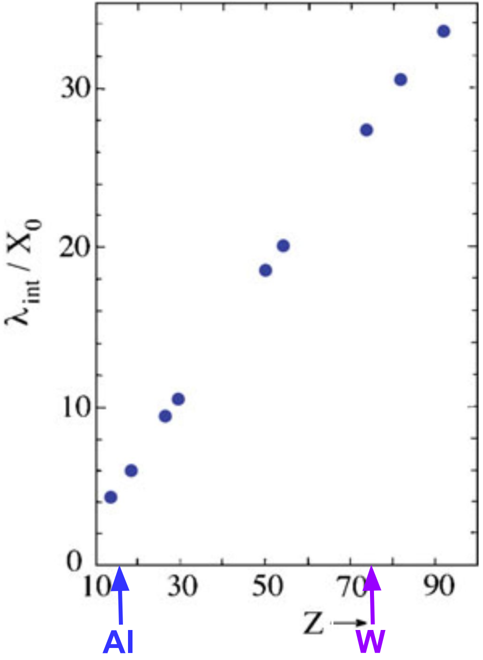


Transverse development

Hadronic showers: Scaling variables

- λ_{INT} is proportional to $A^{1/3}$ and much larger than X_0 (proportional to A/Z^2)
- Relative sensitivity to EM and HAD shower components strongly depend on the material choice



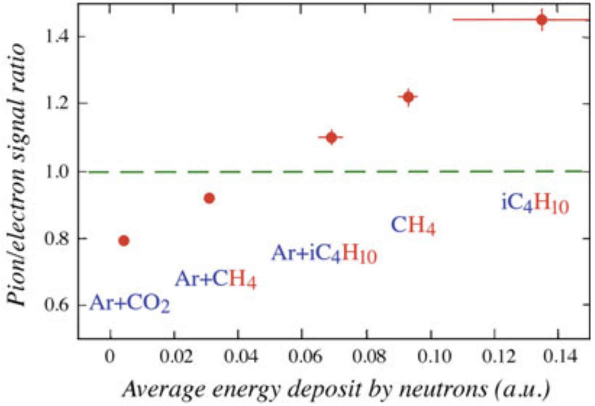


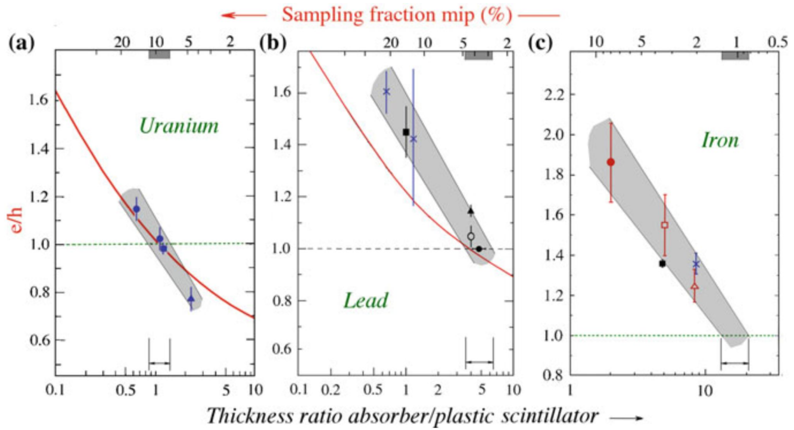
Scaling Parameters

Material	Z	A	ρ (g/cm²)	X_0 (cm)	R_M (cm)	λ_{INT} (cm)
Air				~30,000	~7,400	~70,000
Water				36	9	84
$PbWO_4$			8.28	0.89	2.0	22.4
Carbon	6	12	2.27	18.8	4.8	38
Aluminium	13	27	2.7	8.9	4.4	39.4
Silicon	14	28	2.33	9.36	4.8	45.5
Iron	26	56	7.87	1.76	1.69	16.8
Copper	29	64	8.96	1.43	1.52	15.1
Tungsten	74	184	19.3	0.35	0.93	9.6
Lead	82	207	11.35	0.56	1.6	17.1
Uranium	92	238	18.95	0.32	1.0	10.5

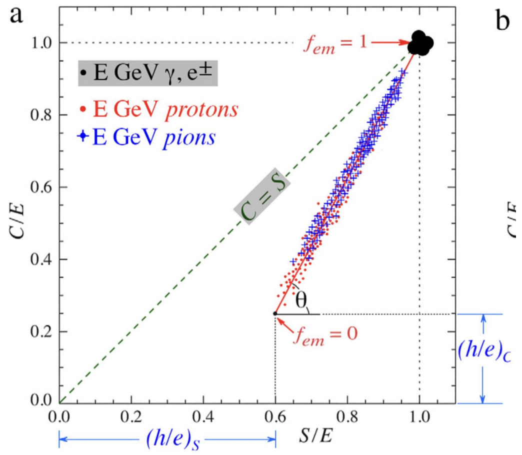
- 25 X_0 (EM shower containment): 2 m for aluminium, 23 cm in $PbWO_4$, and 9 cm in tungsten
- 10 λ_{INT} (HAD shower containment): 4 m for aluminium, 1.7 m for iron, and 96 cm in tungsten

Compensation





- Lower response of the non-EM components (h) than EM component (e): e/h<1 → non-linearities, poor resolution, non-Gaussian response
- **Compensation:** several techniques to **bring e/h closer to 1**
- Hardware options: Materials more sensitive to neutrons (with hydrogen), tuning of the sampling faction
- Highly 3D segmented calorimeters: Apply **calibration corrections** for each calorimeter cell
- **Dual readout:** separate Scintillation (S) and Cherenkov (C) components



Energy Resolution

- Ideal case:

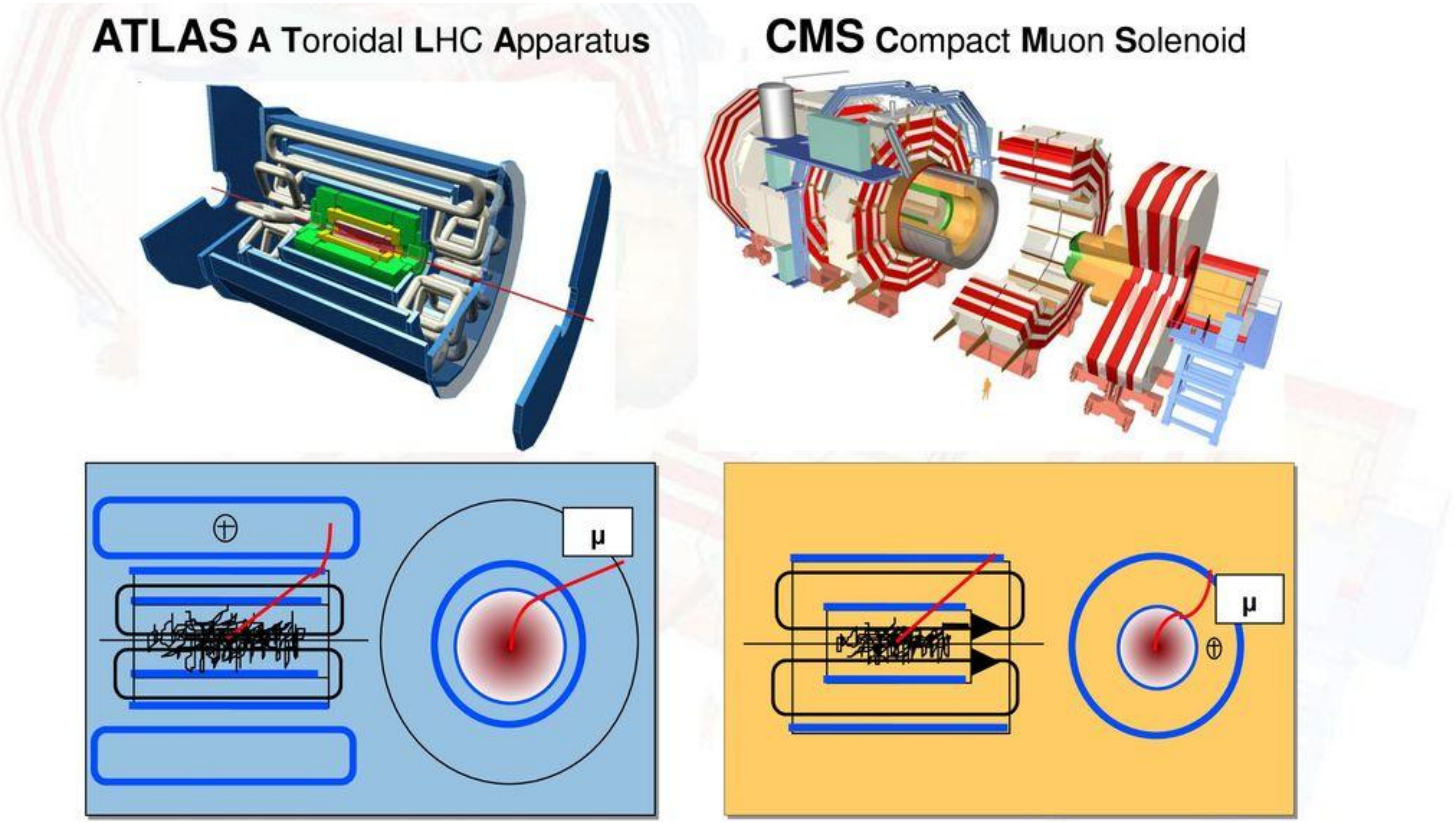
$$E \propto N \rightarrow \sigma(E) \propto \sqrt{N} \rightarrow \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

- Real-life case:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- **a) Stochastic term:** intrinsic statistical shower fluctuations, sampling fluctuations, signal quantum fluctuations (e.g. photo-statistics)
- **b) Noise term:** electronic noise, sampling fraction variations
- **c) Constant term:** inhomogeneities, imperfections in calorimeter construction (gaps, dimensions variations etc.), fluctuations in longitudinal energy containment, etc.

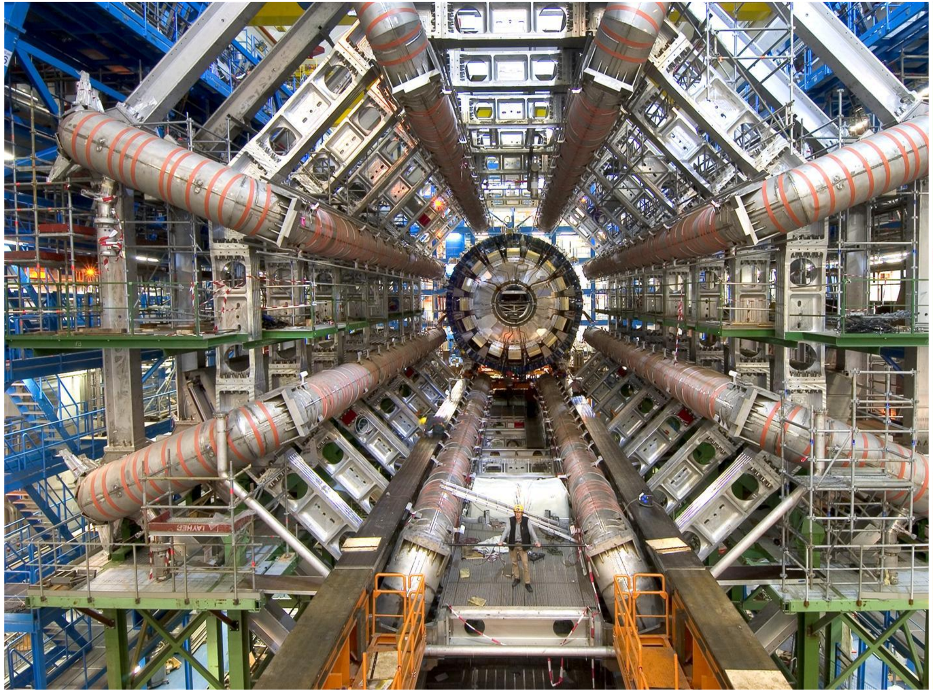
ATLAS and CMS calorimeters

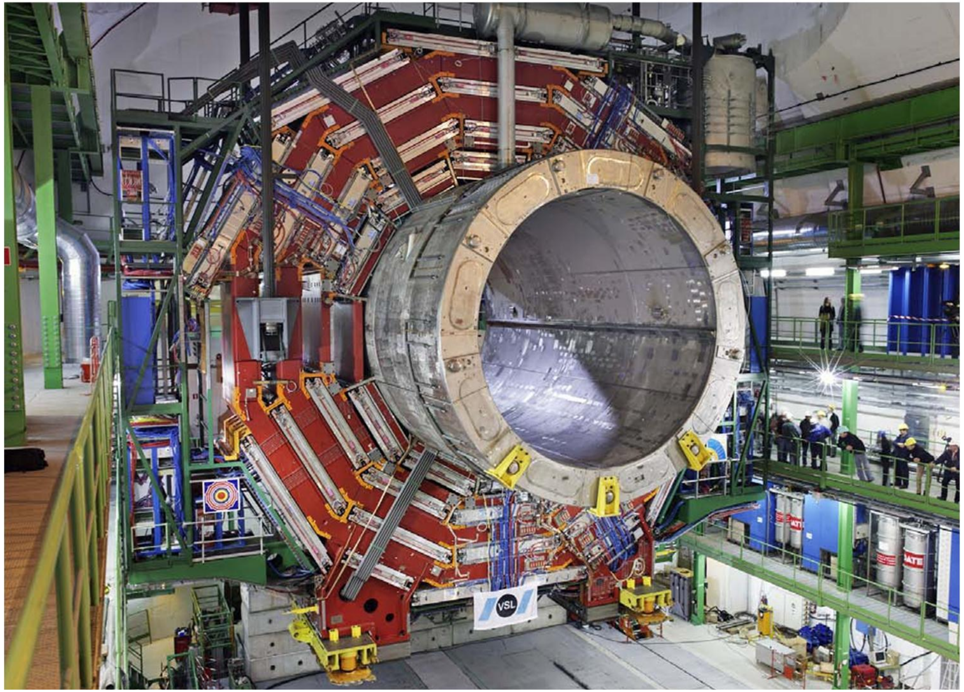


ATLAS and CMS calorimeters

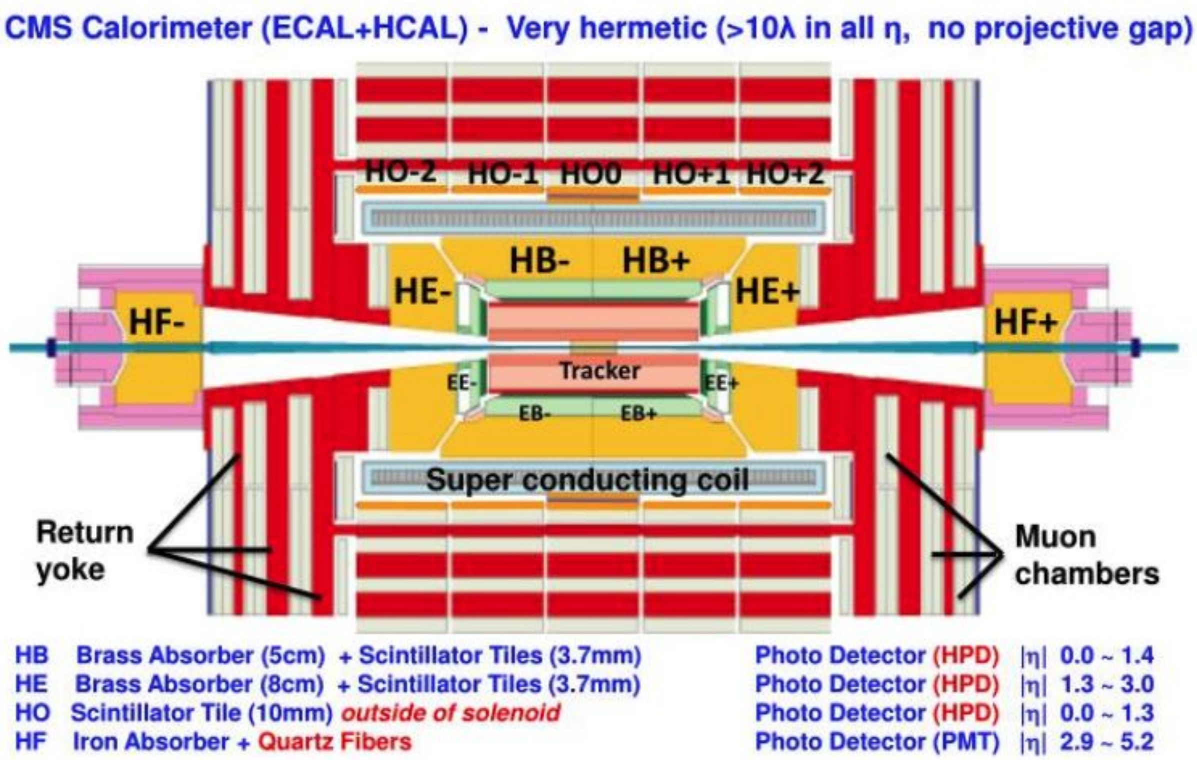
ATLAS A Toroidal LHC Apparatus

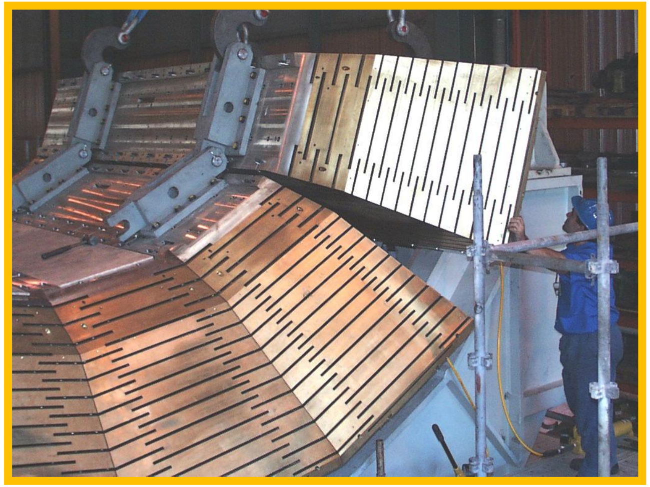
CMS Compact Muon Solenoid



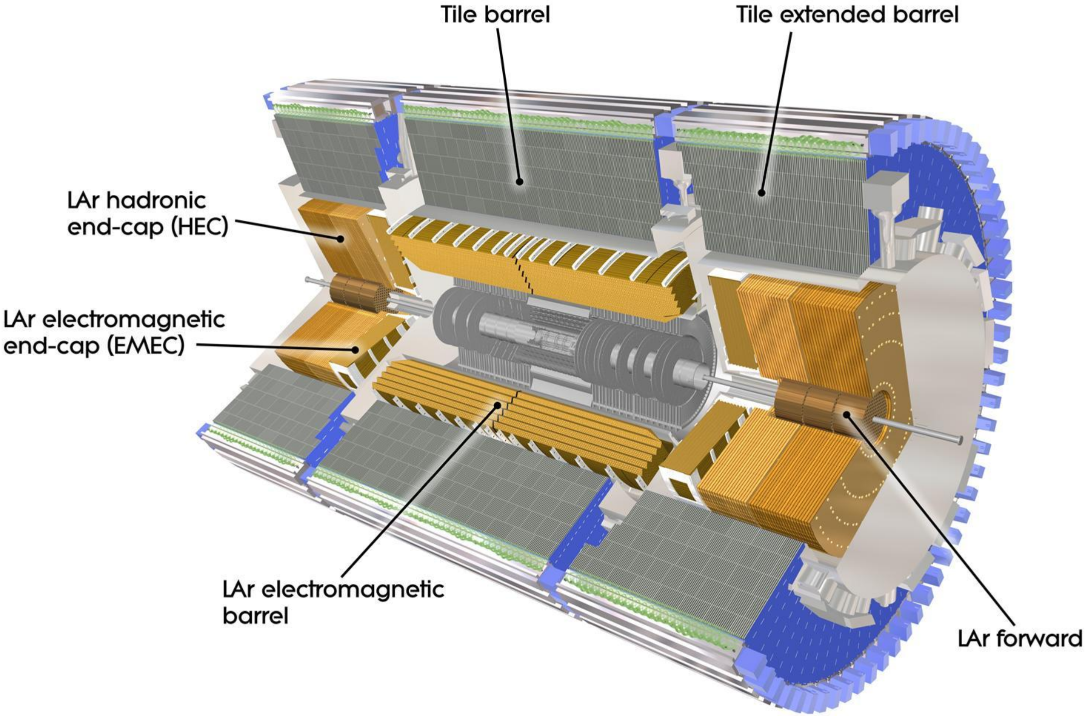


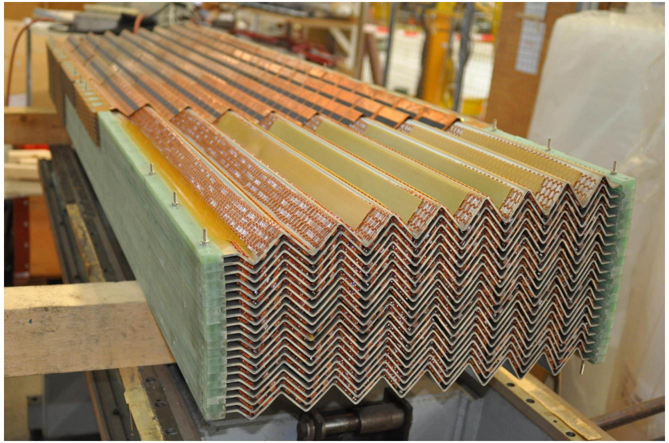
ATLAS and CMS calorimeters

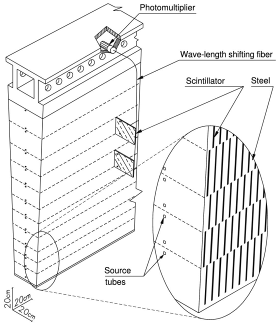


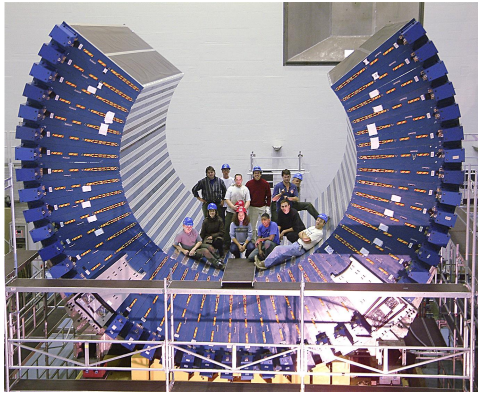


ATLAS and CMS calorimeters









ATLAS and CMS calorimeters

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term *a*	10%	10 to 12%	3%	5.5%
Local constant term *b*	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29\ mm^2$. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

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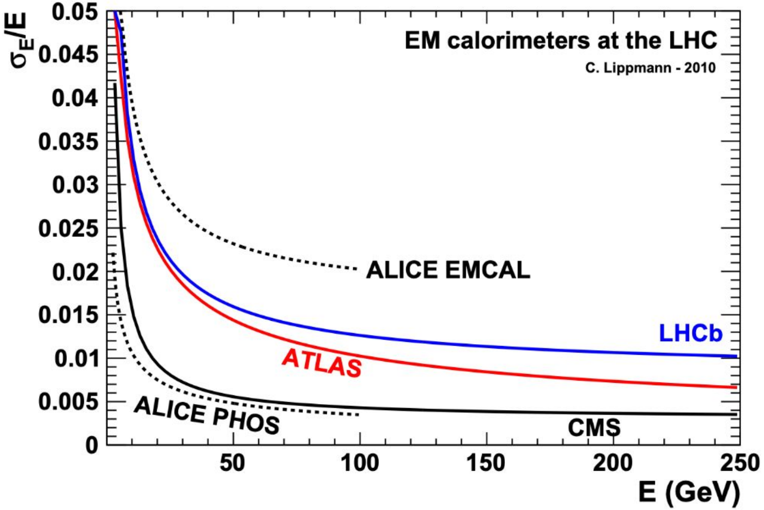

ATLAS and CMS calorimeters

TABLE 9 Main parameters of the ATLAS and CMS hadronic calorimeters

	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Channels		
Barrel/Ext. barrel	9852	2592
End caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	0.1×0.1 to 0.2×0.1	0.087×0.087
End caps	0.1×0.1 to 0.2×0.2	0.087×0.087 to 0.18×0.175
Forward	0.2×0.2	0.175×0.175
Samplings ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	3	1
End caps	4	2
Forward	3	2
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

Note that the CMS barrel calorimeter (HB) is complemented by a tail catcher behind the coil (HO) to minimize problems with longitudinal leakage of high-energy particles in jets.

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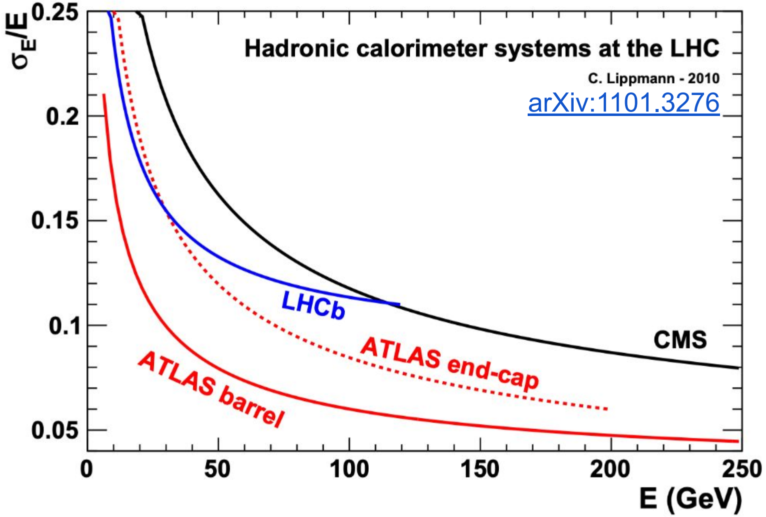
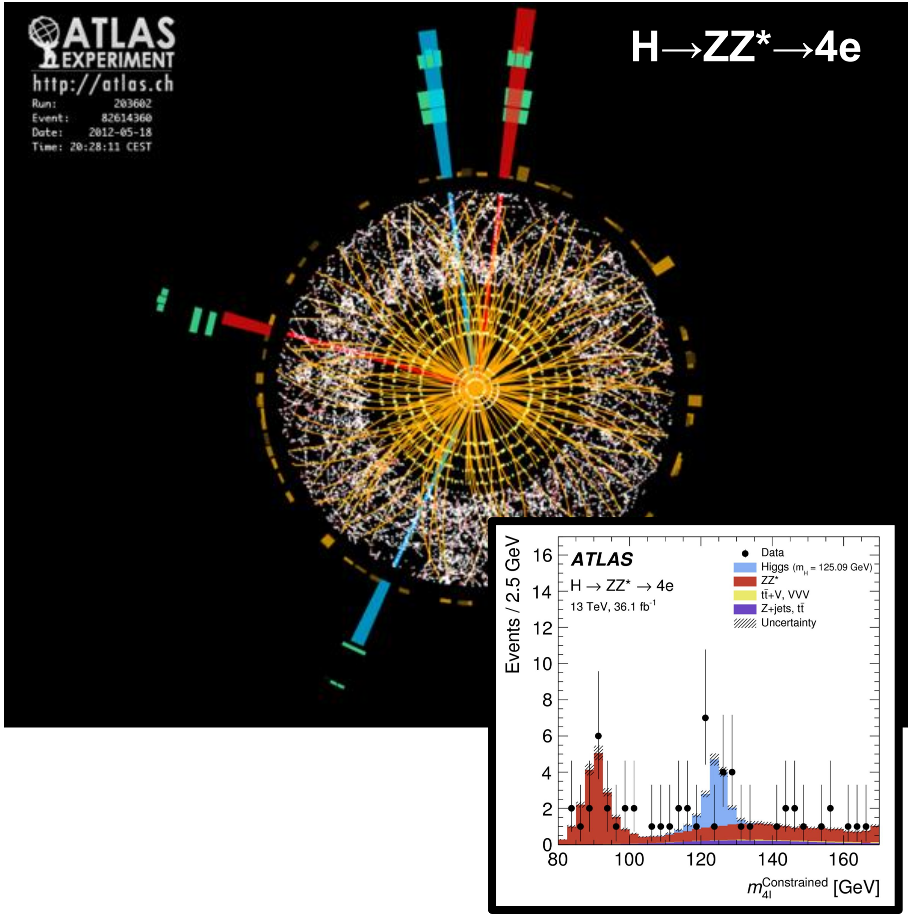
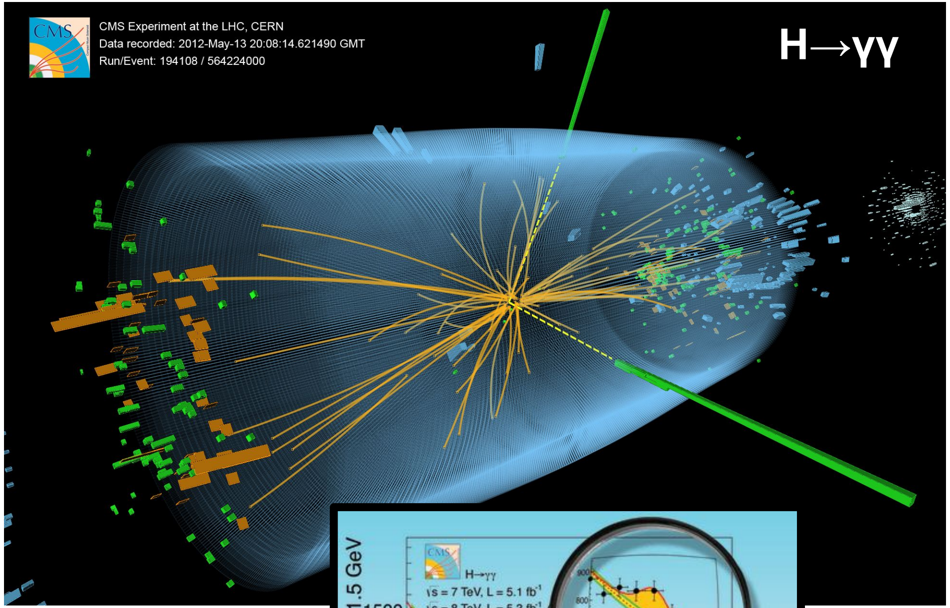
TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

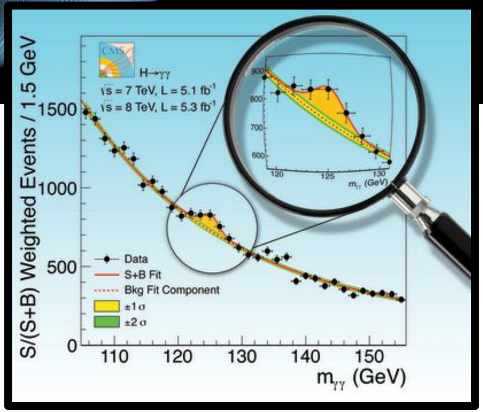
	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	< 1%		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV



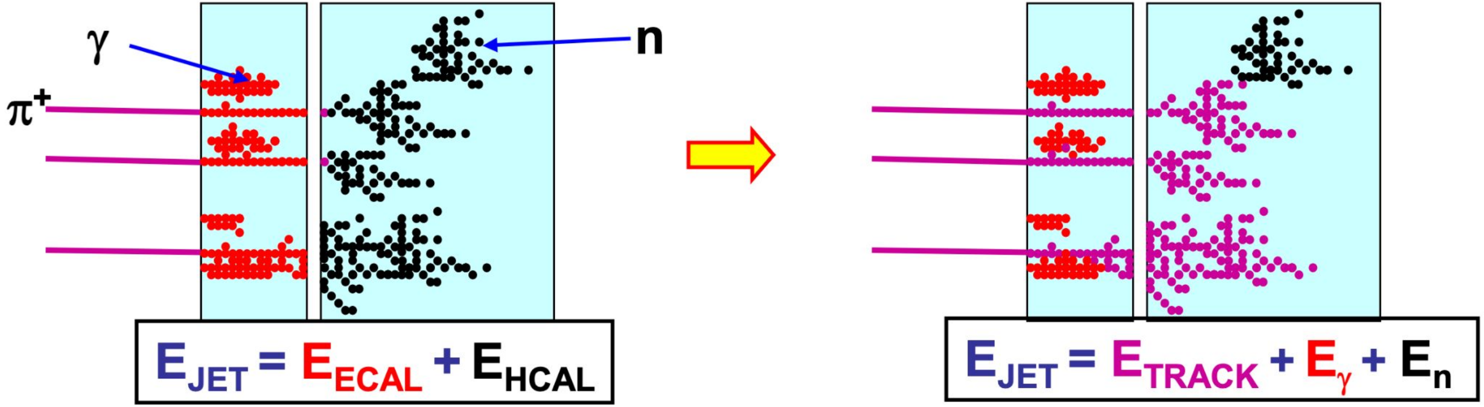
Finding the Higgs boson



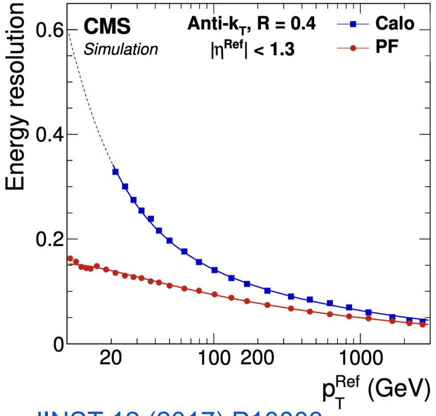




Particle Flow



- First proposed by Mark Thomson (current CERN DG)
- Typical hadronic jet composition:
  60% charged hadron, 30% photons, 10% neutral hadrons (n, K^0)
- **"Traditional" approach:** measure all components in ECAL and HCAL
- **Particle flow:** measure each component where resolution is best
  - Tracker for charged particles
  - ECAL for photons
  - Only using HCAL for the neutral particles



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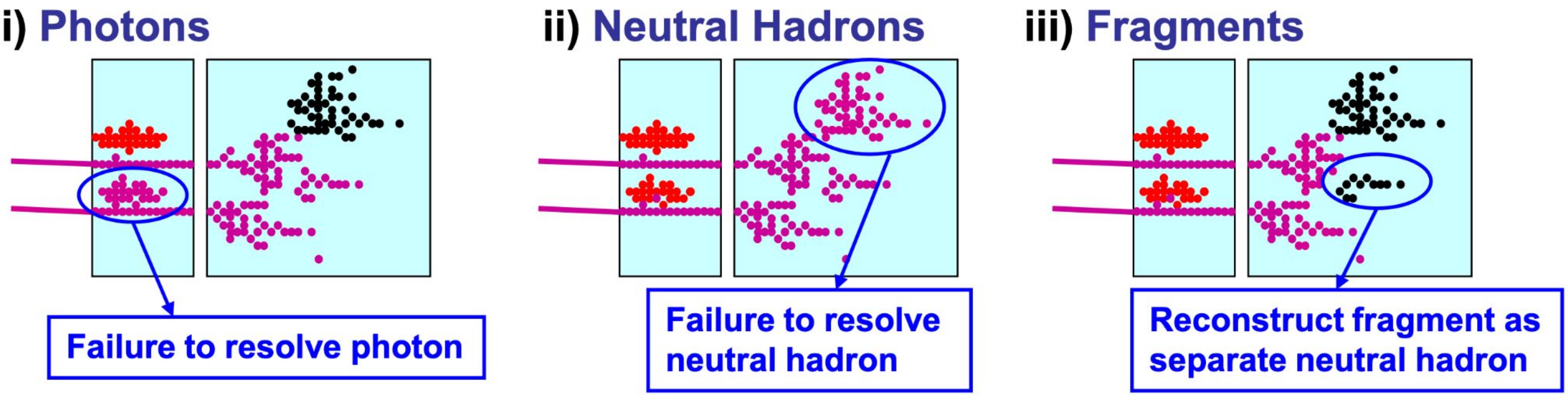
Particle Flow

- Key for success: **correctly identify each particle** in the jet
- Confusion: miss or double count the energy for some of the particles



- Need calorimeters with very high granularity (avoid having several particles inside the same readout channel), with a compromise for resolution:
  - Lateral granularity below Molière radius, and use materials with very low Molière radius
- Take care of all possible cases: complex algorithmics and careful tuning
- Particle Flow is the current approach to meet the jet performance targets of FCC

Signal read-out: PMTs

- For decades, photomultiplier tubes (PMTs) have been the choice for read-out scintillating light in calorimeters
- Conversion of single photons into electric signals, with large signal amplification (10^7-10^8)
- Drawbacks: sensitivity to magnetic fields, operated with high voltage, size, cost

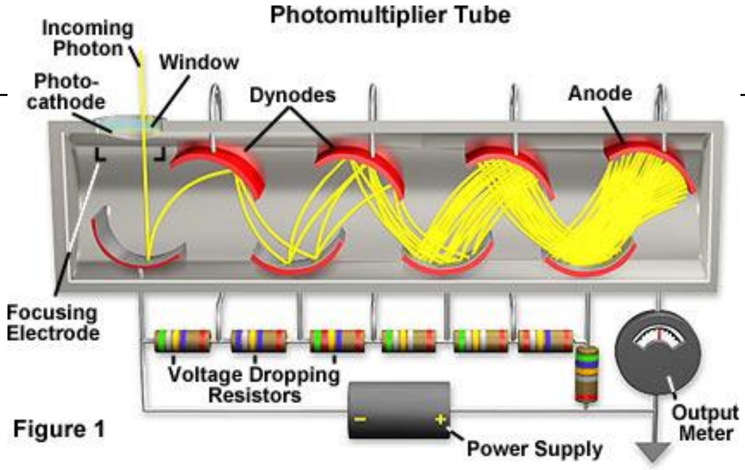


Figure 1

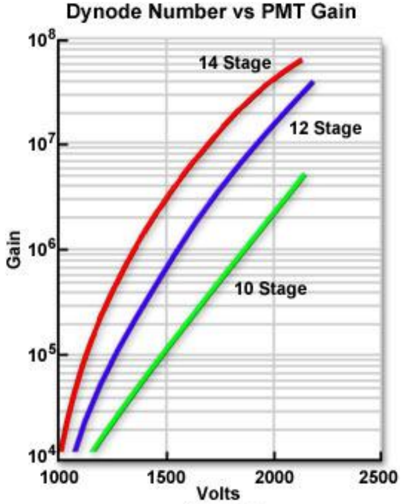
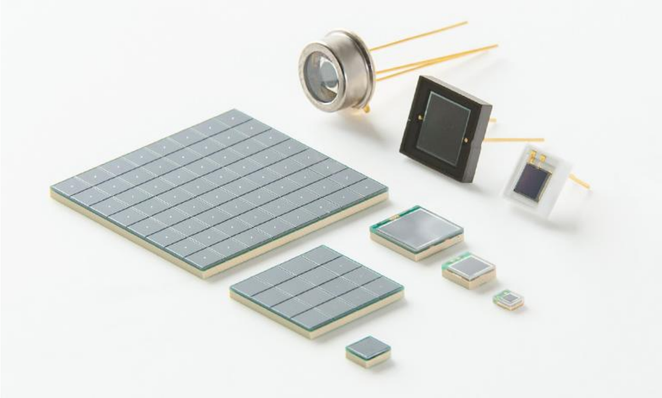
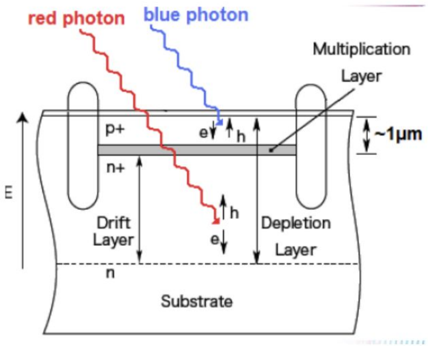


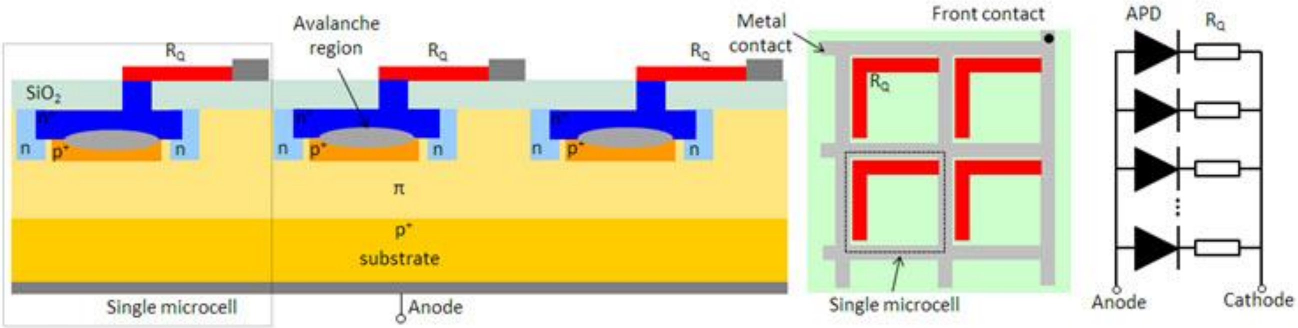
Figure 1

Signal read-out: SiPM

- **Silicon Photomultiplier (SiPM):** large number of very tiny pixels, each being a photon detector operating in the Geiger mode
- Important features:
  - Operation at low voltage, small size and cost → Compact design with many channels
  - Low dark count, high gain and photon detection efficiency
  - Insensitive to magnetic fields, good mechanical resistance

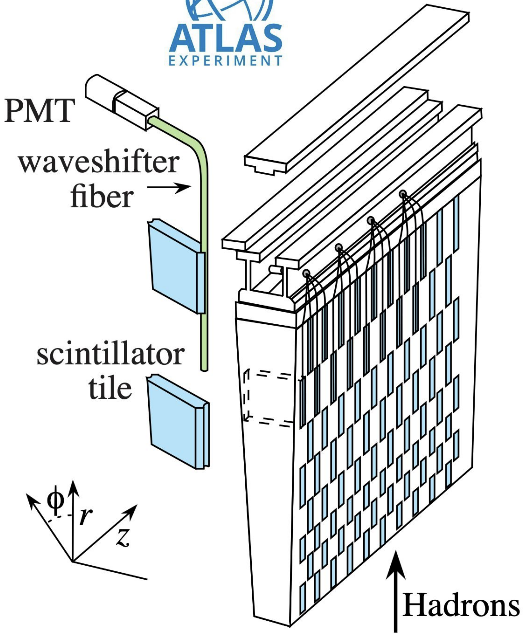


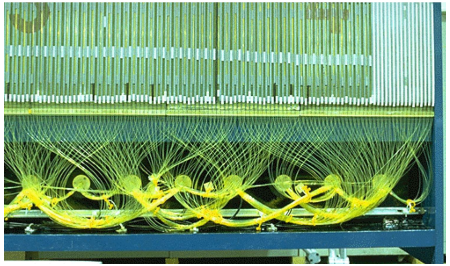




The future of calorimeters

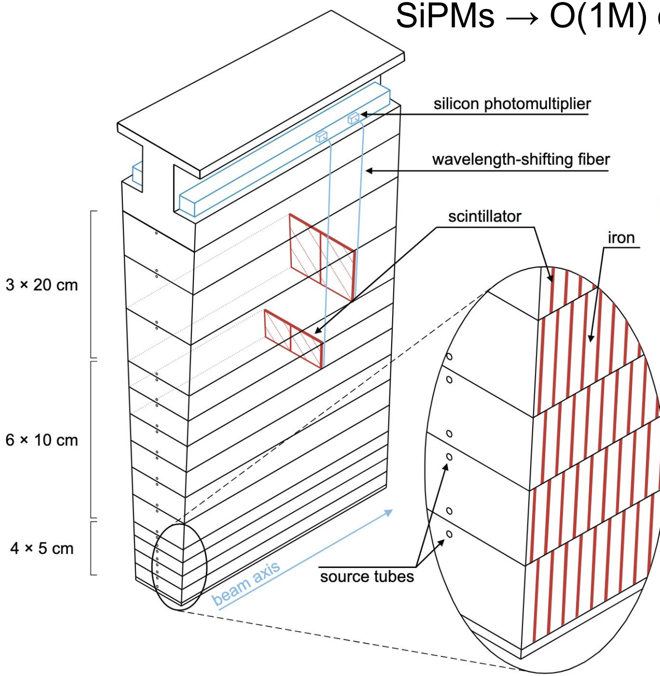
- New silicon-based photon sensors are enabling the leap towards high granularity!
- Example of TileCal:





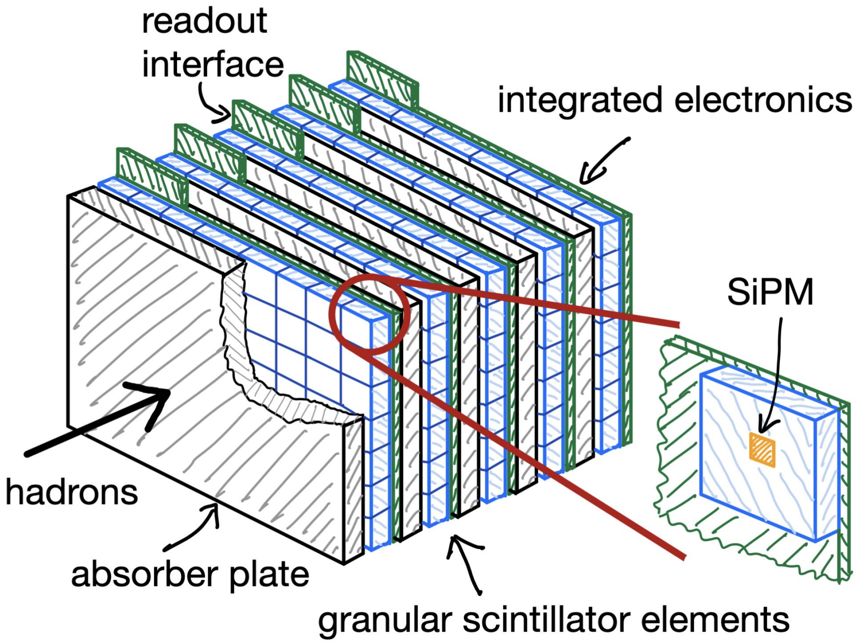
Bundles of ~50 fibers per PMT
→ 9,852 readout channels

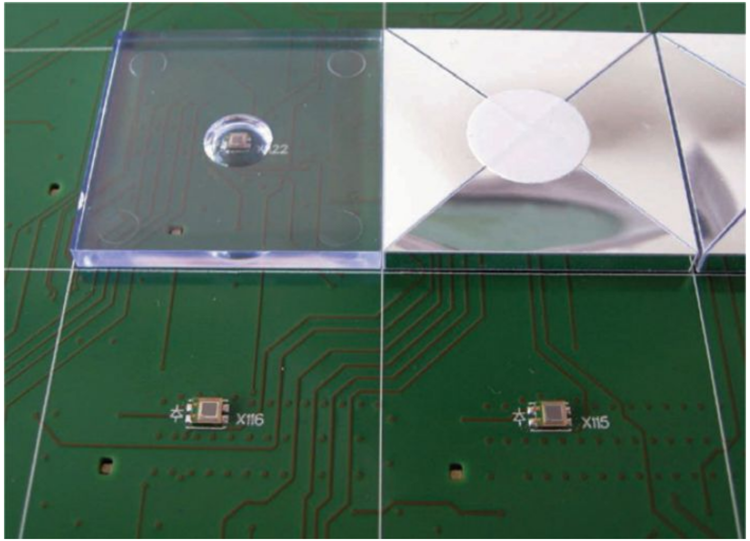
Individual fibers read out by SiPMs → O(1M) channels



The future of calorimeters

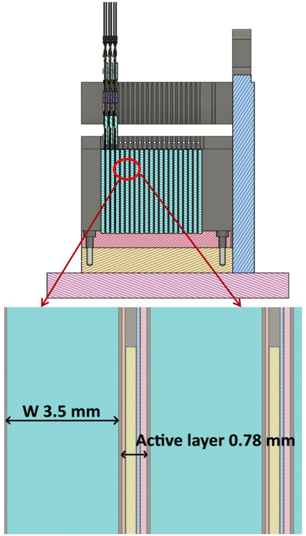
- “SiPM-on-tile” structure used in the CALICE analogue HCAL prototype, and in the CMS [High-Granularity Calorimeter (HGCAL) upgrade for the HL-LHC]

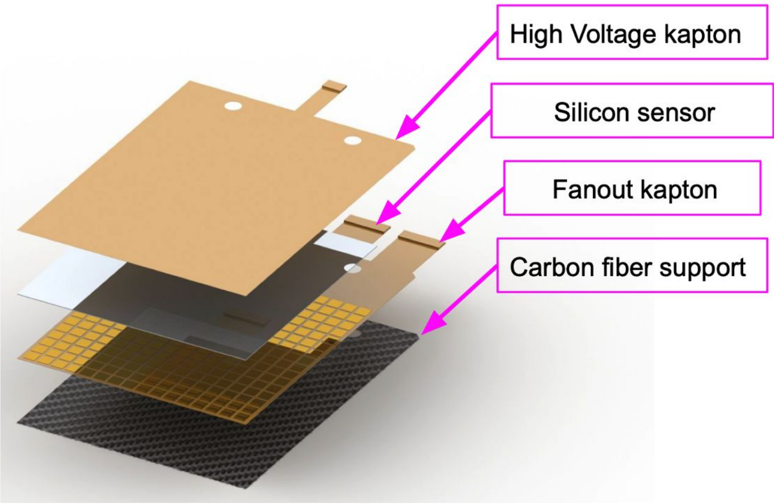


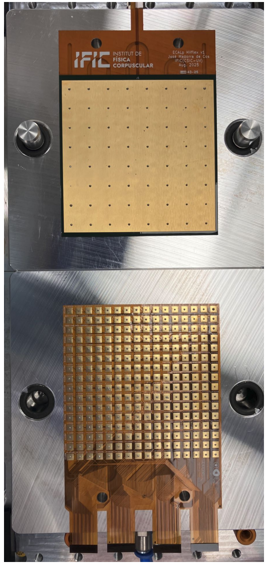


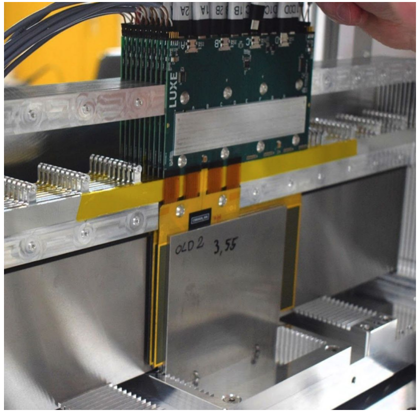
The future of calorimeters

- SiW ECAL and Forward luminosity calorimeters (FCAL) for FCC and LUXE
- 21 tungsten absorber plates 3.5 mm (1 X_0) thick + 1 mm gap between them → 21 X_0 in 10 cm
- Compact Silicon Sandwich (CSIS) modules: layers of 5.5×5.5 mm silicon diode sensor glued onto printed circuit boards (PCB), transferring their signals to frontend electronics









Summary

- Did not have time to cover important aspects: signal read-out, calibration, integration, operation, etc, → Much more information in the references in page 2

- Calorimeters are crucial detectors for modern nuclear and particle physics:
  - Measurement of electron energy
  - Only way to measure the energy and direction of neutral particles (such as photons)
  - Only way to study neutrinos and missing transverse energy
- Particle showers: complex (but well-understood) physics processes involved
- Wide variety of material and technology choices → Lots of room for design optimization, also depending on application and budget

- Many ongoing R&D developments, such as SiPM readout and Particle Flow, represent a revolution in the field
- **The era of ultra-highly granular calorimetry is only starting, and will be key for the physics discoveries of the future**