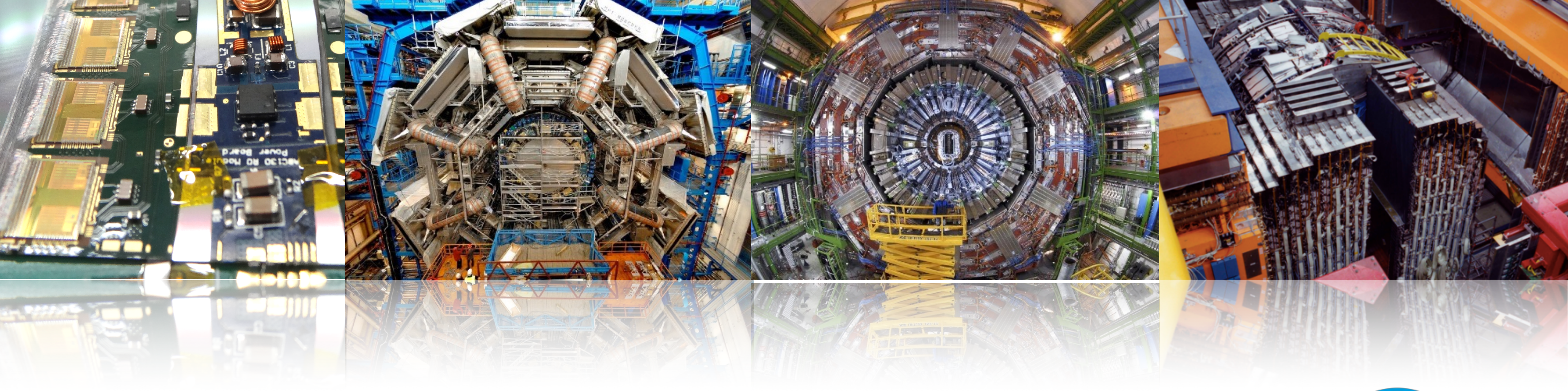


Detectors for High energy Physics

Ingrid Maria Gregor, Simon Spannagel

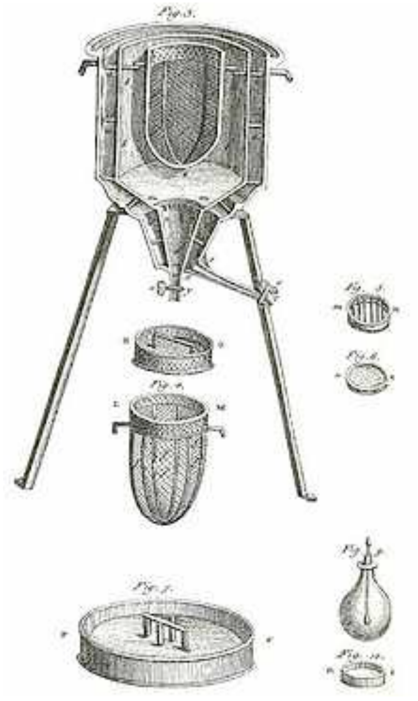
Part 3

DESY Summer Student 2025

IV. Calorimeters

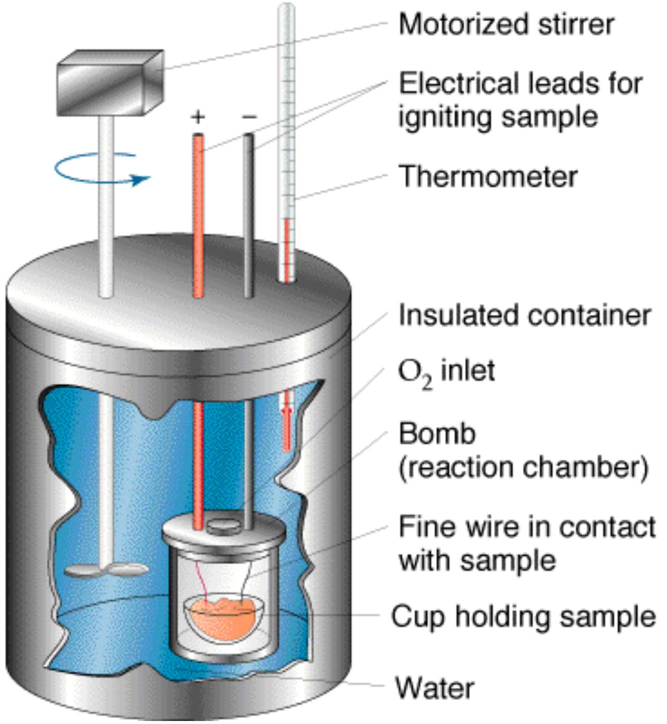
Calorimetry

Calorimetry: The Idea behind it ....



- Calorimetry originated in thermo-dynamics
  - The total energy released within a chemical reaction can be measured by measuring the temperature difference

Ice-calorimeter from Antoine Lavoisier's 1789 *Elements of Chemistry*.



Picture: Francois G. Amar

- What is the effect of a 1 GeV particle in 1 litre water (at 20°C)?

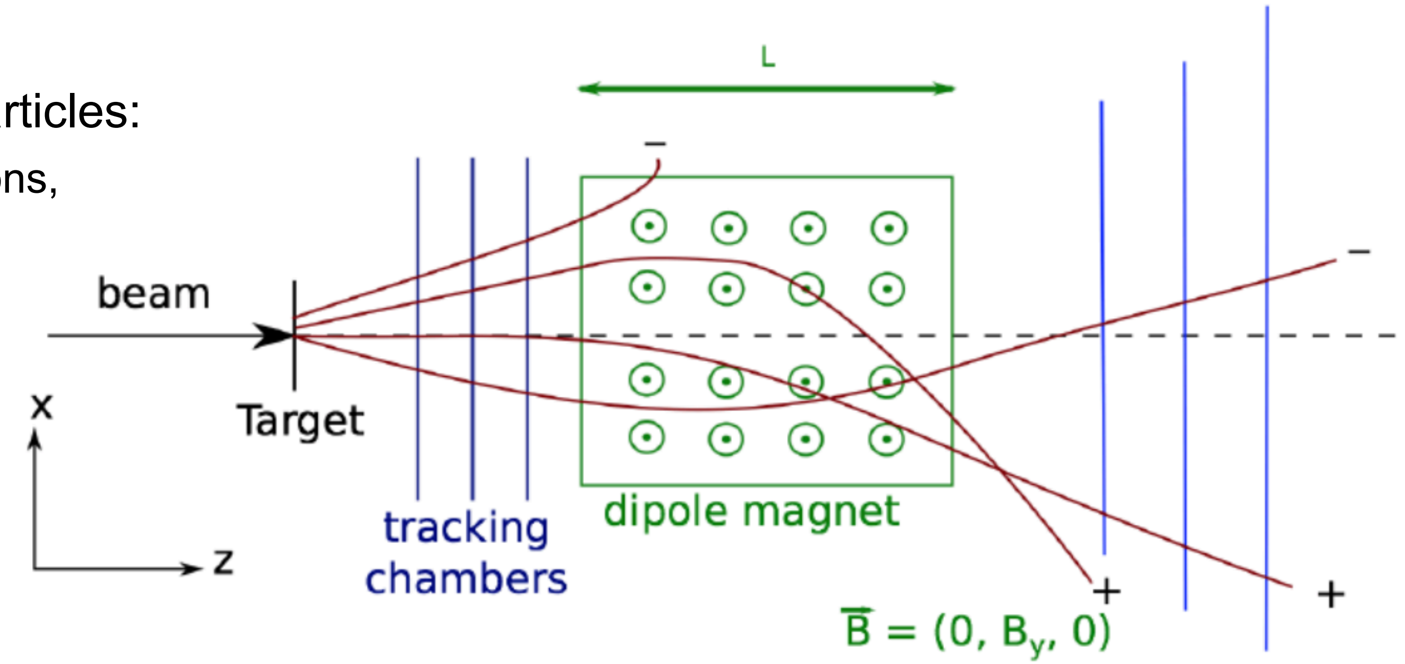
$$\Delta T = E / (c \cdot M_{water}) = 3.8 \cdot 10^{-14} K\ !$$

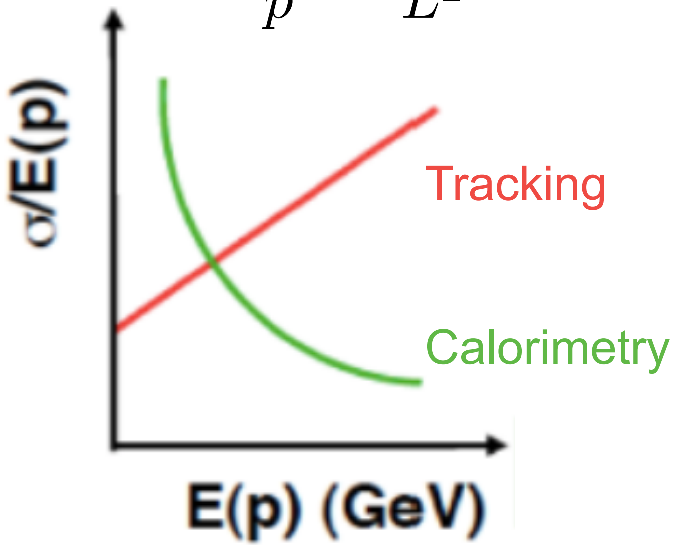
- In particle physics:
  - Measurement of the energy of a particle by measuring the total absorption

Why Calorimeters ?

- Measurement of energy or momentum of particles:
  - Focus on high energy particles (hadrons, leptons, (photons))
- Magnetic spectrometer:
  Momentum of charged particles measured in B-Field by tracking detectors

$$\frac{\sigma_p}{p} \propto \frac{p}{L^2}$$





- Problematic: with increasing p (or E) the momentum resolution gets worse (or L huge)
- **Calorimeters** are the solution

Calorimetry: Overview

- Basic mechanism for calorimetry in particle physics:
  - formation of electromagnetic
  - or hadronic showers.
- The energy is converted into ionisation or excitation of the matter.

Charge **Scintillation light** **Cerenkov light**

- Calorimetry is a “destructive” method. The energy and the particle get absorbed!
- Detector response ∝E
- Calorimetry works both for charged (e± and hadrons) and neutral particles (n,γ) !

Electrons: Energy Loss

- **Critical energy:** the energy at which the losses due to ionisation and Bremsstrahlung are equal

$$\frac{dE}{dx}(E_c) = \frac{dE}{dx}(E_c)$$

For electrons approximately:

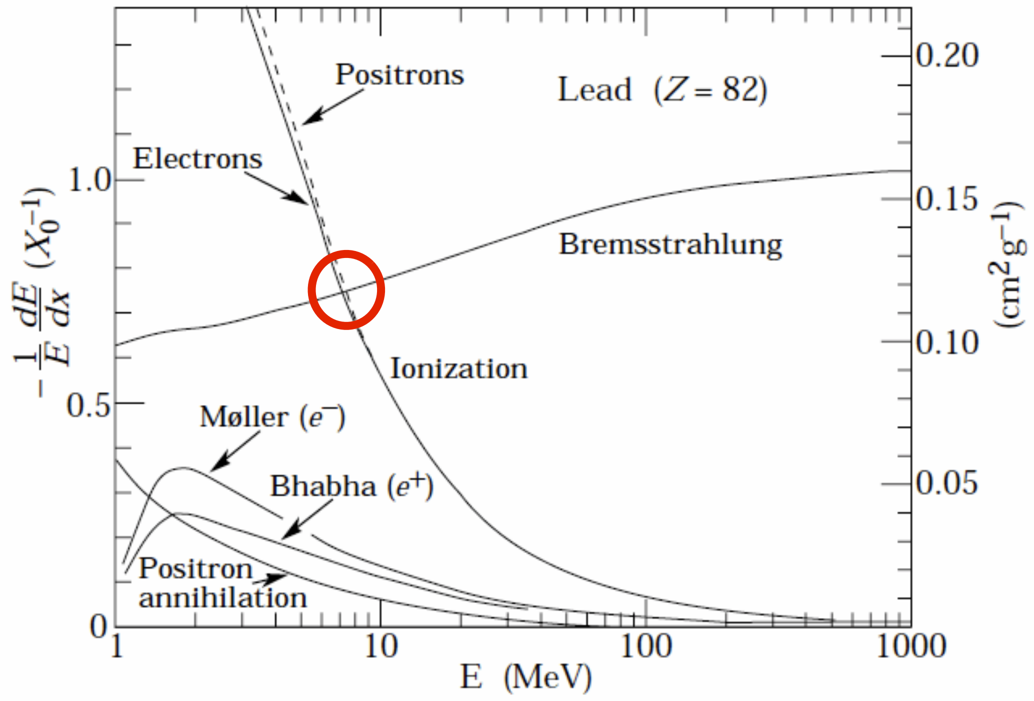
$$E_c^{\text{solid+liq}} = \frac{610 MeV}{Z + 1.24} \qquad E_c^{\text{gas}} = \frac{710 MeV}{Z + 1.24}$$

For electrons

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}}$$

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

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

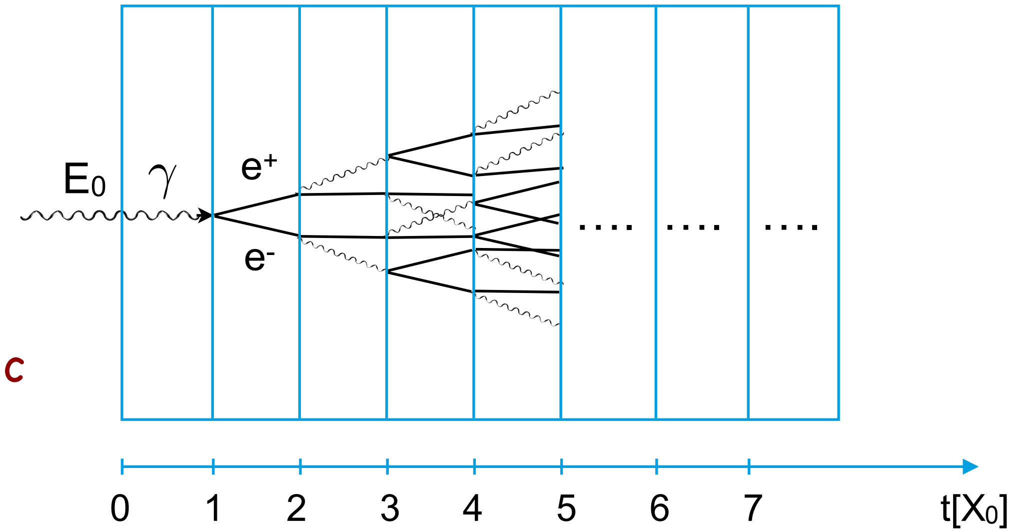


$$\Rightarrow \quad E = E_0 e^{-x/X_0}$$

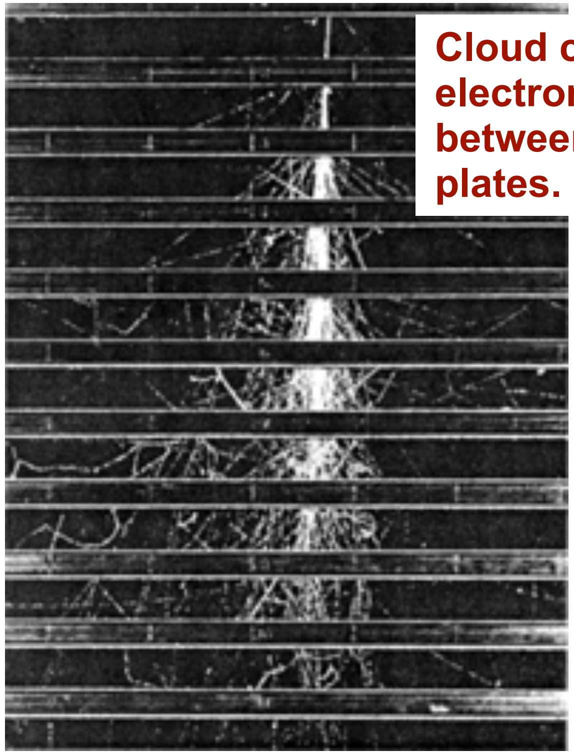
Parameters only depending on material the electron is passing through.

X_0:Radiation length

Electromagnetic Showers



X₀ is the characteristic scale

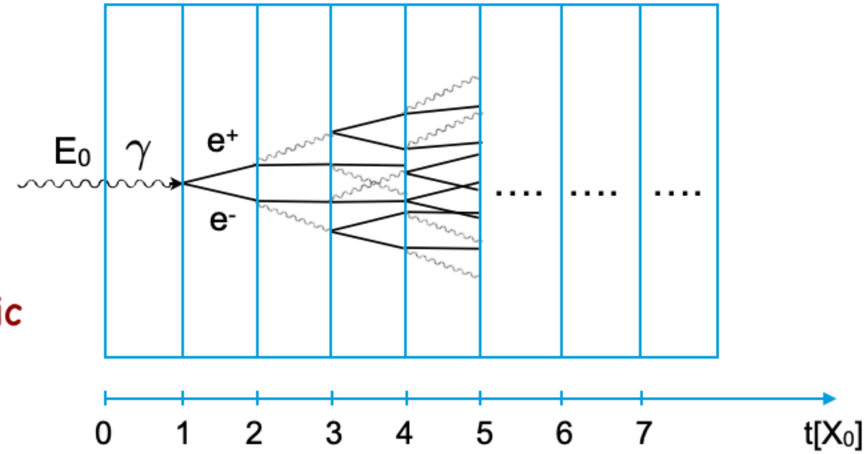


Cloud chamber photo of electromagnetic cascade between spaced lead plates.

Pic: MIT cosmic ray group

- High energetic particles: form shower if passing through (enough) matter.
- Alternating sequence of interactions leads to a cascade:
  - Primary γ with E_0 energy produces e+e- pair in layer X_0 thick
  - On average, each has $E_0/2$ energy
  - If $E_0/2 > E_c$, they lose energy by Bremsstrahlung
- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Bremsstrahlung with an average energy between $E_0/(2e)$ and $E_0/2$ is radiated
- Radiated γs produce again pairs

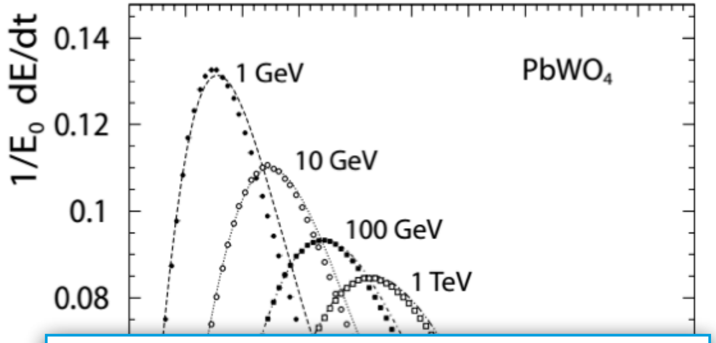
Analytic Model of electromagnetic Shower



X_0 is the characteristic scale

Electromagnetic shower is characterised by
- Number of particles in shower
- Location of shower maximum
- Longitudinal shower distribution
- Transverse shower distribution

- Introduce longitudinal variable $t = x/X_0$



- The shower end approximately when $E \approx E_c$

$$E_c = E(t_{\max}) = \frac{E_0}{2^{t_{\max}}}$$

- Maximum shower depth: $t_{\max} = \ln \frac{E_0}{E_c} / \ln 2$

- Maximum number of particles in shower

$$N_{\max} = \exp(t_{\max} \ln 2) = \frac{E_0}{E_c}$$

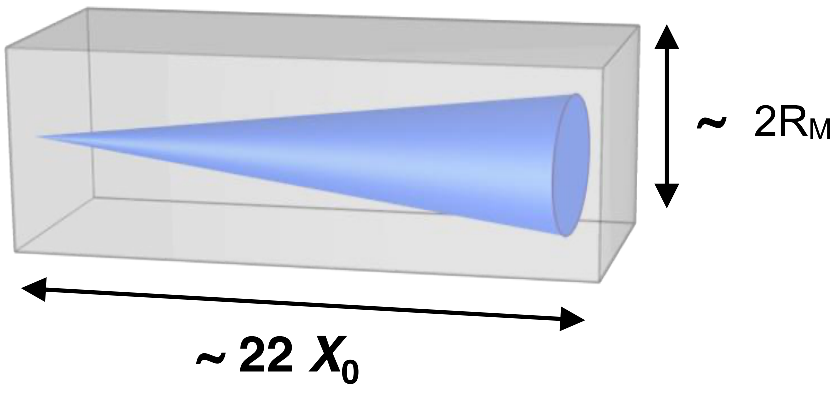
Example:
1 GeV photon in CsI crystal:

$$E_c \approx 10 \text{ MeV}$$
$$N_{\max} = E_0/E_c \approx 100$$
$$t_{\max} \approx 6.6 X_0$$

Wermes, Kolanoski

EM Shower Properties

- Longitudinal development governed by the radiation length X_0.
- Lateral spread due to electron undergoing multiple Coulomb scattering:
  - 95% of the shower cone is located in a cylinder with radius 2 RM
  - Beyond this point, electrons are increasingly affected by multiple scatteri

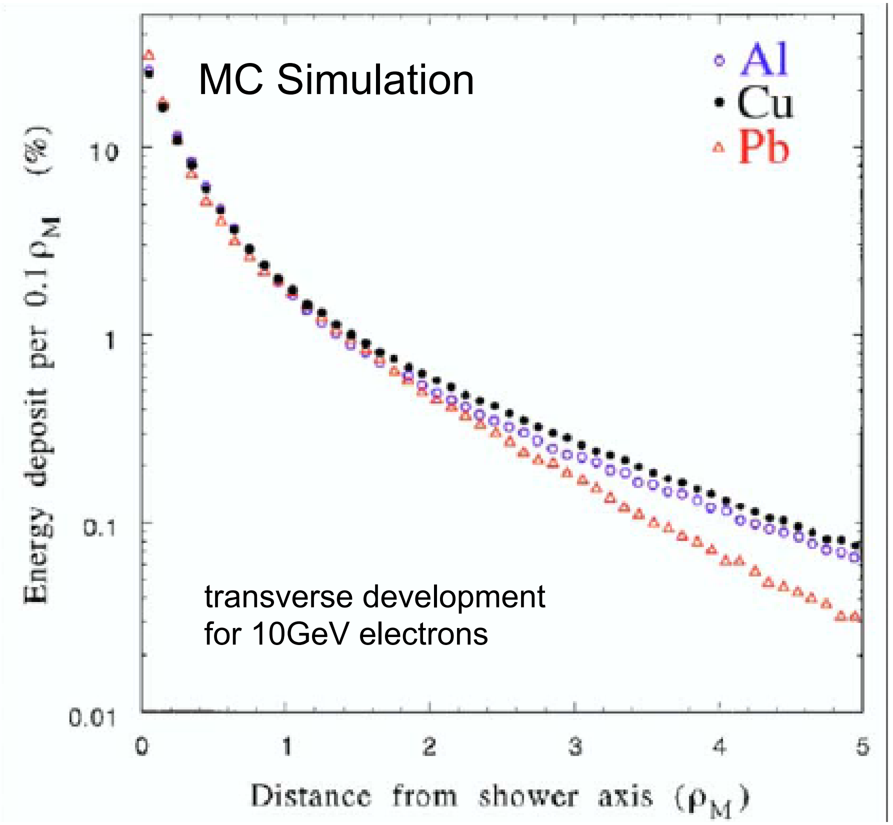


- Lateral width scales with the **Molière radius** ***R_M***
  - Important parameter for shower separation

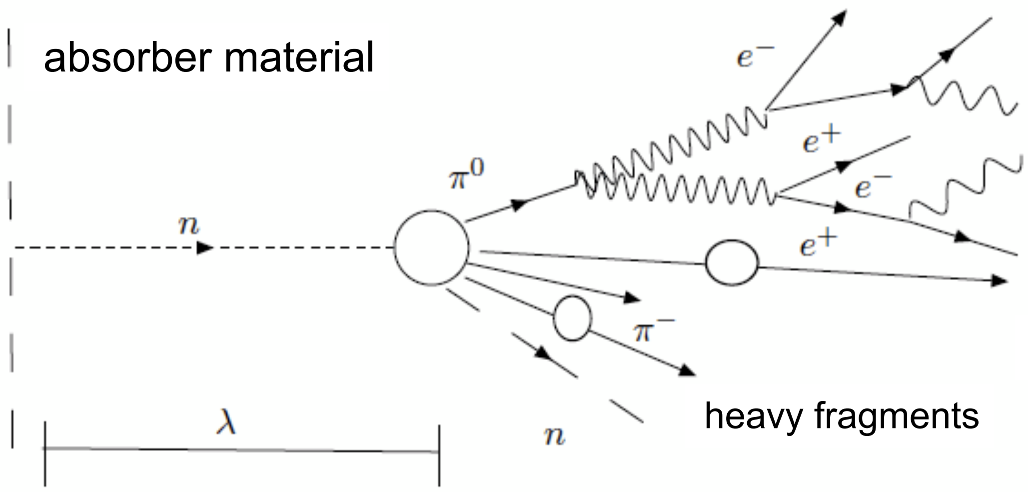
$$R_M = X_0 \frac{E_s}{E_c} = 21.2MeV * \frac{X_0}{E_c}$$

$$E_S = m_e c^2 \sqrt{4\pi/\alpha} = 21.2MeV$$

Example:
E_0= 100 GeV
in lead glass E_c=11.8 MeV
→N_c≈13, $t_{95\%}$≈23
X_0≈2 cm, R_M= 1.8·X_0≈3.6 cm



Hadronic Cascade: The Details



Pic: T. Ferbel. Experimental Techniques in High Energy Physics.

Hadronic showers are way more complicated than em showers.

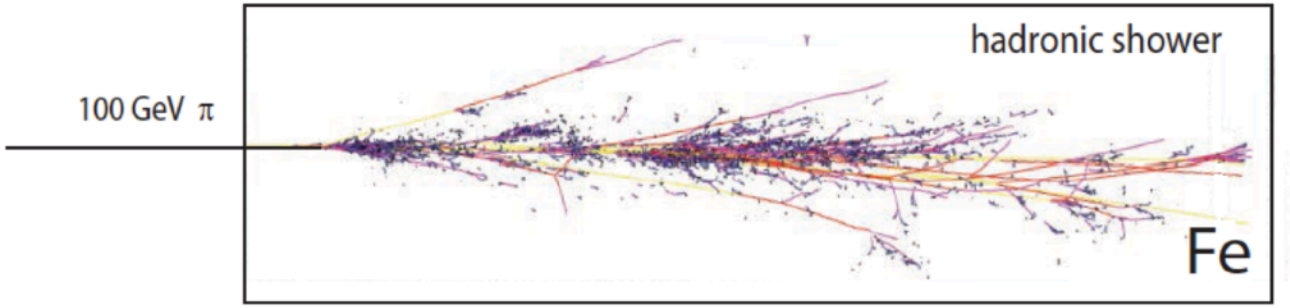
- Different processes are created by the impinging hadron:
  - high energetic secondary hadrons taking a significant part of the momentum of the primary particle [e.g. O(GeV)]
  - a significant part of the total energy is transferred into nuclear processes: nuclear excitation, spallation, ... ➠ Particles in the MeV range
  - neutral pions (1/3 of all pions), decay instantaneously into two photons ➠ start of em showers
  - Breaking up of nuclei (binding energy) neutrons, neutrinos, soft γ's, muons

EM fraction ~30%
Ionisation fraction up to 40%
Invisible fraction ~30%

invisible energy
-> large energy fluctuations
-> limited energy resolution

Hadronic Cascade

- Within the calorimeter material a hadronic cascade is build up: in inelastic nuclear processes more hadrons are created



The length scale of the shower is given in means of the nuclear reaction length λ_I

$$\lambda_I = \frac{A}{N_A \sigma_{total}}$$

total cross section for nuclear processes

Interaction length:
Probability that no hadronic reaction happens on the path x happened:

$$P = e^{-\frac{x}{\lambda_I}}$$

Compare X_0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.

	λ_I	X_0
Polystyren	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

Hadronic Shower development

Longitudinal shower development:

Strong peak near λ_{int} ...
followed by exponential decrease ....

Shower depth:

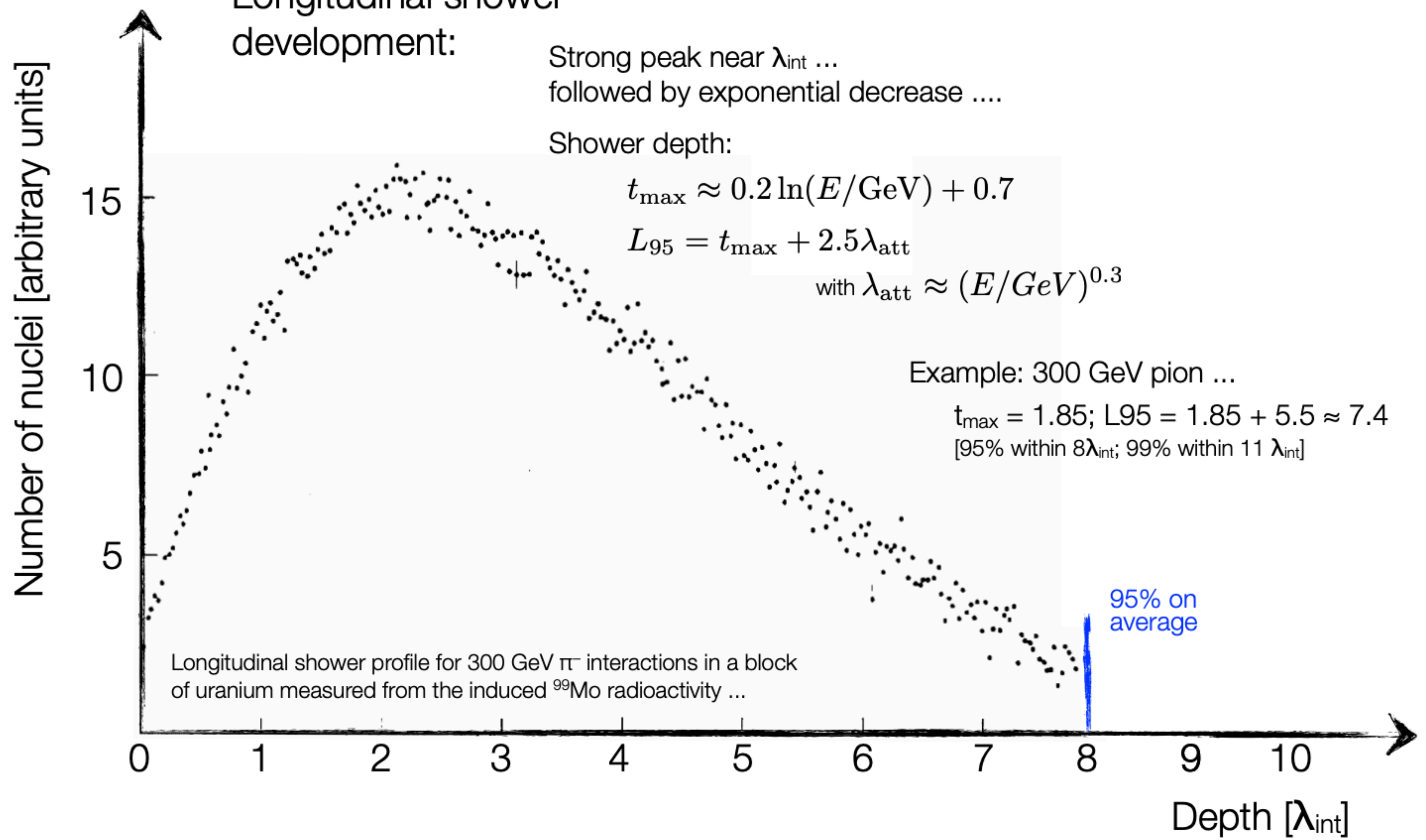
$$t_{max} \approx 0.2 \ln(E/\mathrm{GeV}) + 0.7$$

$$L_{95} = t_{max} + 2.5\lambda_{att}$$

with $\lambda_{att} \approx (E/GeV)^{0.3}$

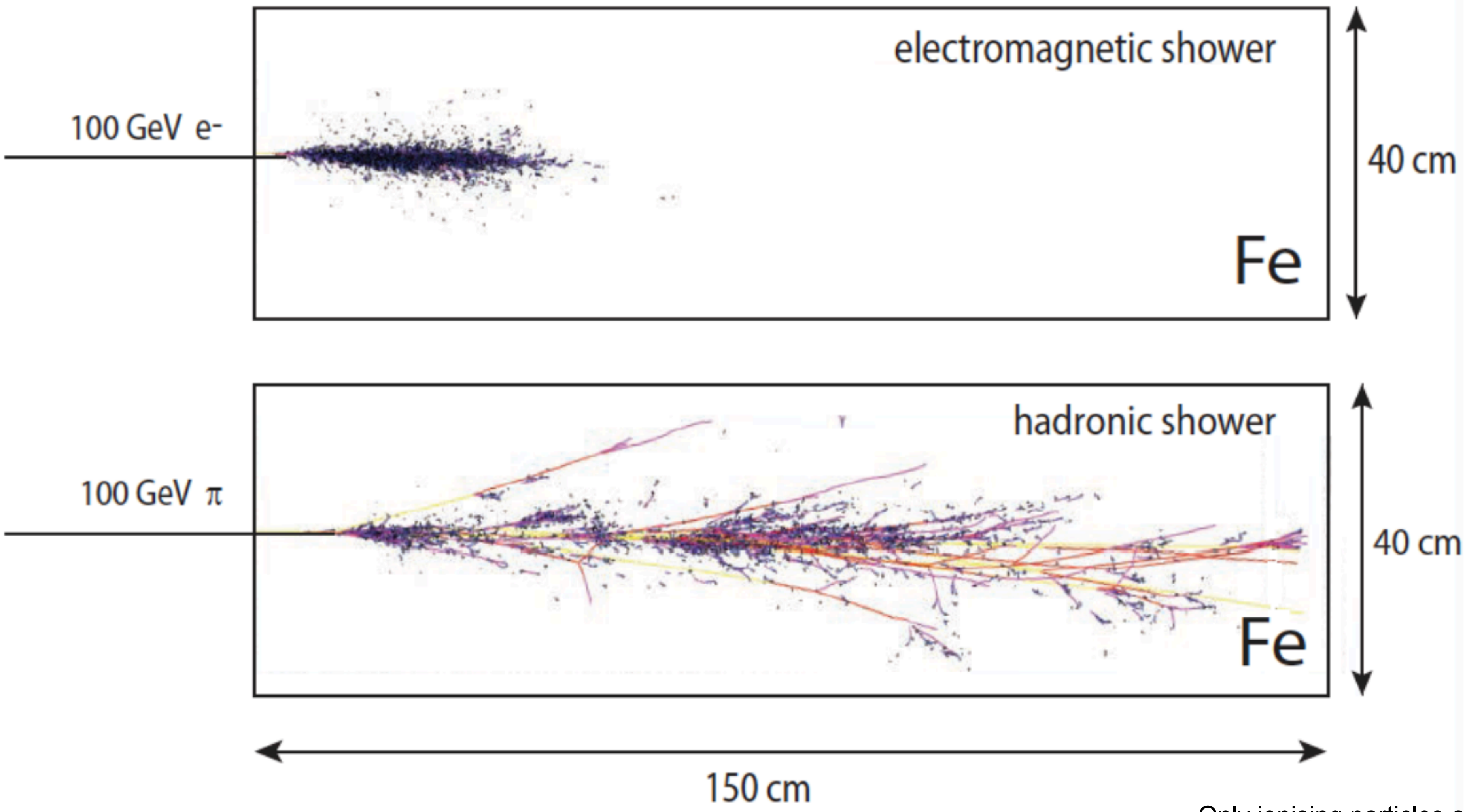
Example: 300 GeV pion ...

t_{max} = 1.85; L95 = 1.85 + 5.5 ≈ 7.4
[95% within 8λ_{int}; 99% within 11 λ_{int}]



Longitudinal shower profile for 300 GeV π⁻ interactions in a block of uranium measured from the induced [99]Mo radioactivity ...

Hadronic vs. EM Shower



Wermes, Kolanoski

Only ionising particles are plotted.

Energy Resolution

- The relative **energy resolution** of a calorimeter is parametrised:

Stochastic term c_s: resolution depends on intrinsic shower fluctuations, photoelectron statistics, dead material in front of calo, and sampling fluctuations

Constant term c_c: Energy independent term contributing to the resolution: due to inhomogeneities with in the detector sensitivity, calibration uncertainties and radiation damage

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{c_s}{\sqrt{E}}\right)^2 + \left(\frac{c_n}{E}\right)^2 + (c_c)^2$$

Noise term c_n: Electronic noise, radioactivity, i.e. effect is dependent of the energy

Losses of Resolution:

- **Shower not contained** in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.
- **Statistical fluctuations** in number of photoelectrons observed in detector.
- **Sampling fluctuations** if the counter is layered with inactive absorber.
- ….

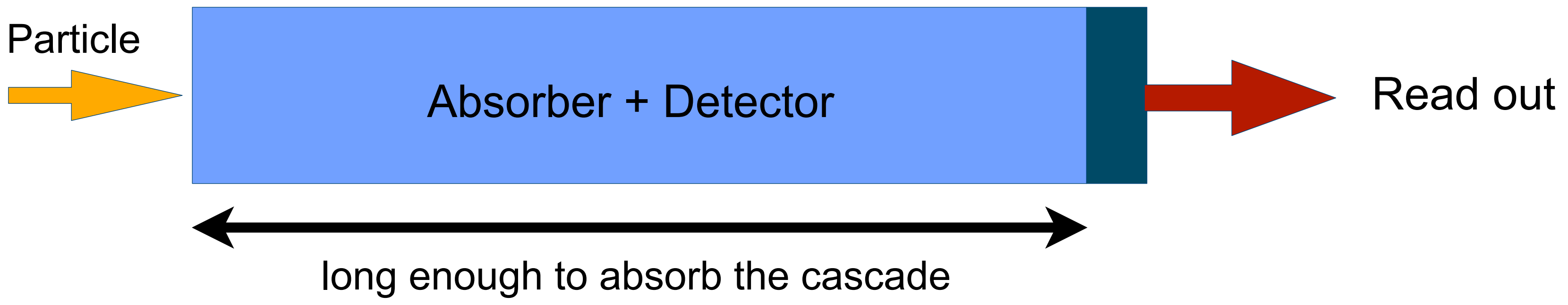
In literature also:

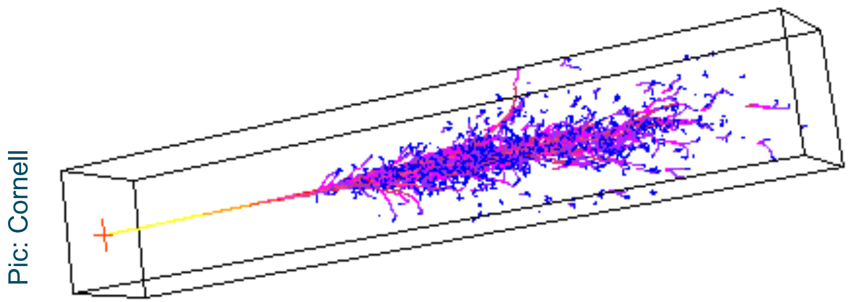
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Calorimeter Types

Calorimeter Types

- Two different types of calorimeters are commonly used: Homogeneous and Sampling Calorimeter
  - **Homogeneous Calorimeter**
    - The absorber material is active; the overall deposited energy is converted into a detector signal
    - Pro: very good energy resolution
    - Contra: segmentation difficult, selection of material is limited, difficult to built compact calorimeters



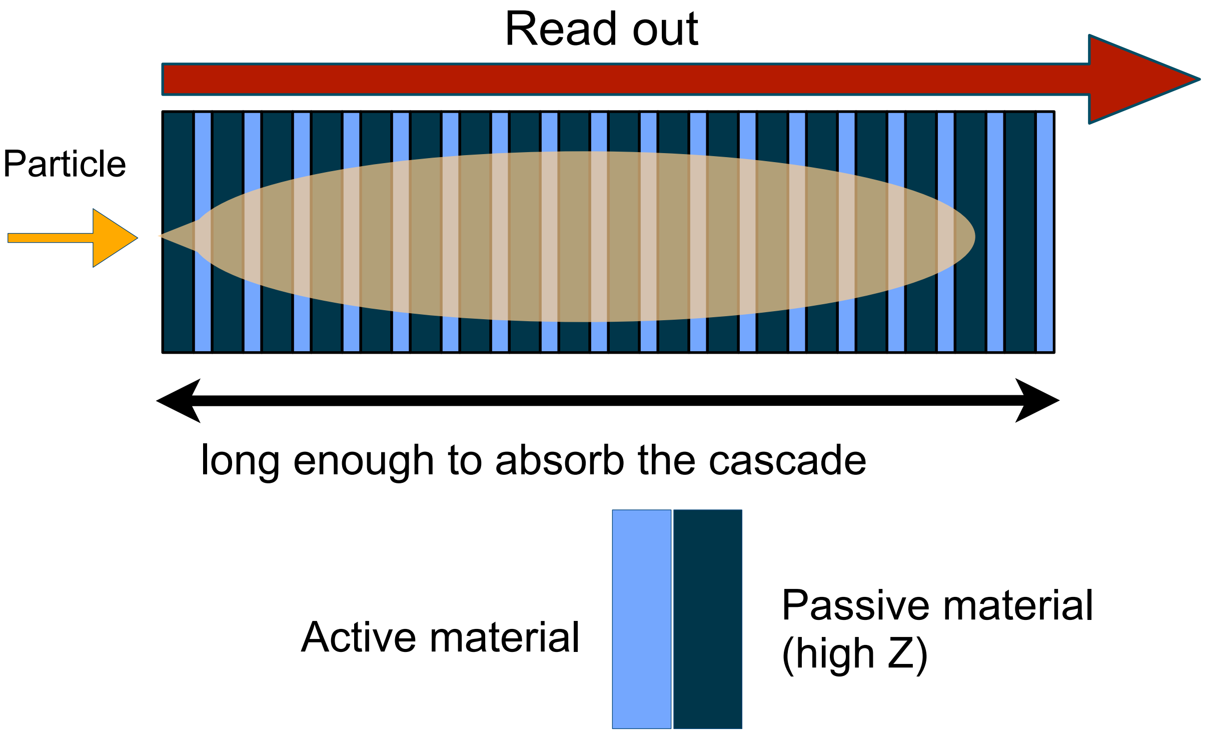


Example: Crystal calorimeter

Sampling Calorimeter

Sampling Calorimeter

- A layer structure of passive material and an active detector material; only a fraction of the deposited energy is "registered"
- **Pro**: Segmentation (transversal and lateral), compact detectors by the usage of dense materials (tungsten, uranium,…)
- **Contra**: Energy resolution is limited by fluctuations



Important parameter:
Sampling Fraction

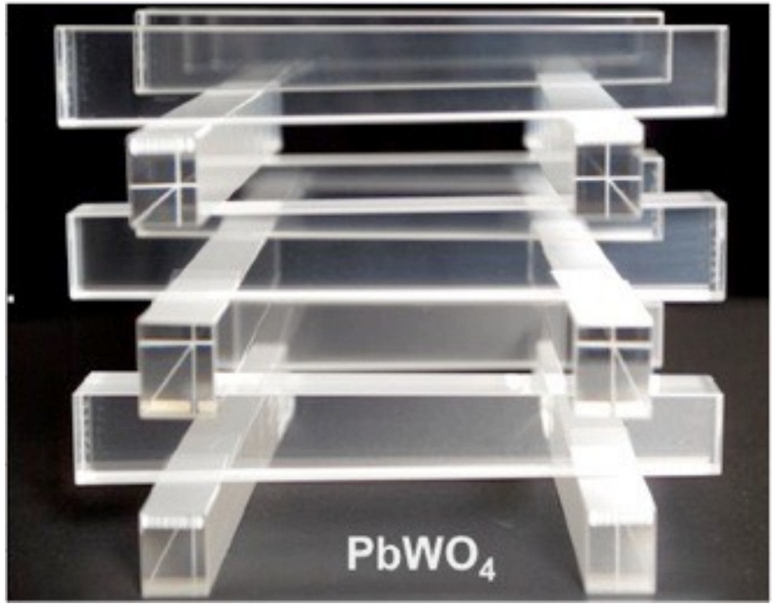
The fraction of the energy of a passing particle seen by the active material.

Typically in the percent range

Example: ZEUS Uranium Calorimeter

Calos: Active Material

- Detectors based on registration of excited atoms
- Emission of photons by excited atoms, typically UV to visible light.
  - Observed in noble gases (even liquid !)
  - Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, organic scintillators) -> Most important category.
  - Inorganic Crystals -> Substances with largest light yield. Used for precision measurement of energetic Photons.

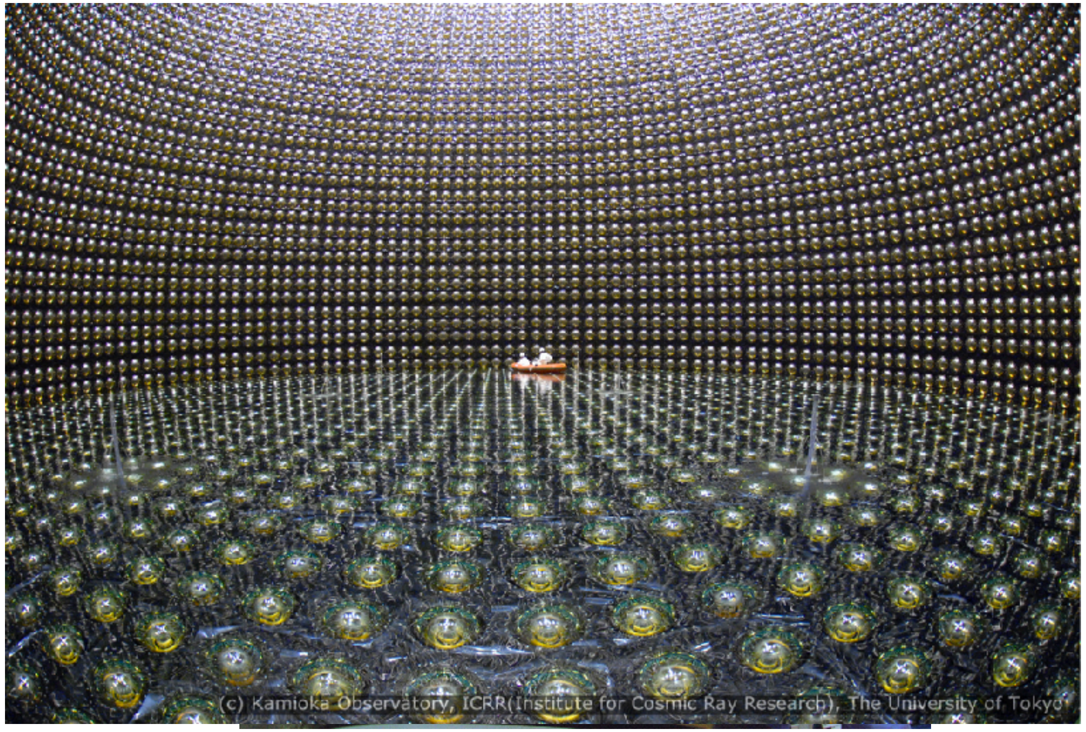


Picture: CDF@Fermilab

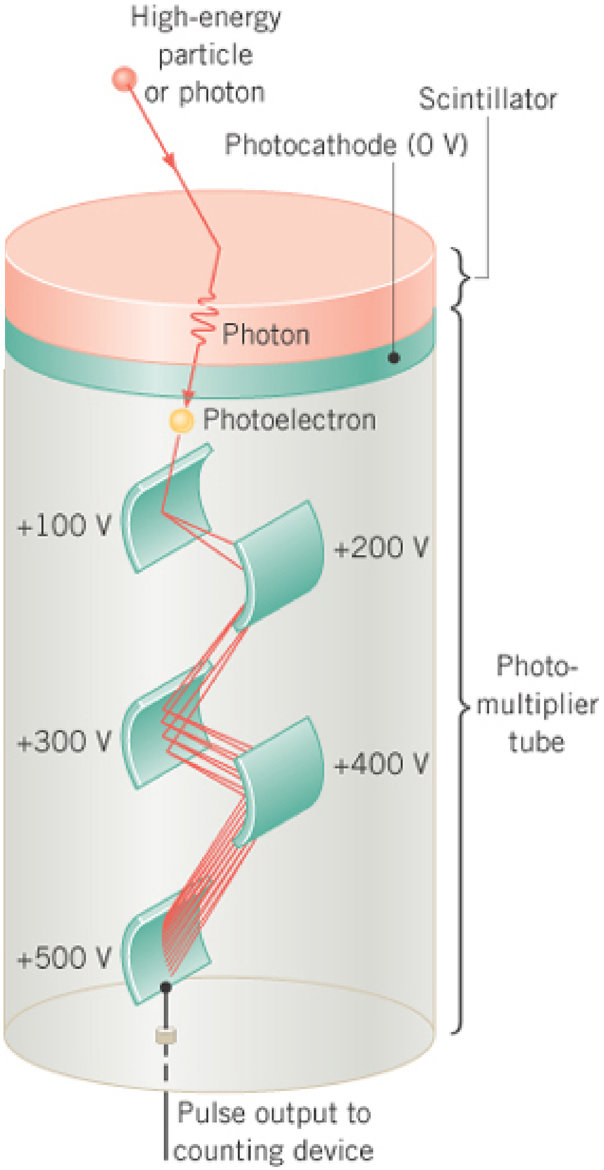
- $PbWO_4$: Fast, dense scintillator,
  - Density ~ 8.3 g/cm³ (!)
  - ρ_M 2.2 cm, X_0 0.89 cm
  - low light yield: ~ 100 photons / MeV

Detecting the Light

- The classic method to detect photons are photomultipliers
  - Conversion of a photon into electrons via photo-electric effect when the phot
  - The following dynode system is used to amplify the electron signal
  - Usable for a large range of wave lengths (UV to IR)
  - good efficiencies, single photon detection possible
  - large active area possible (SuperKamiokande O 46cm)



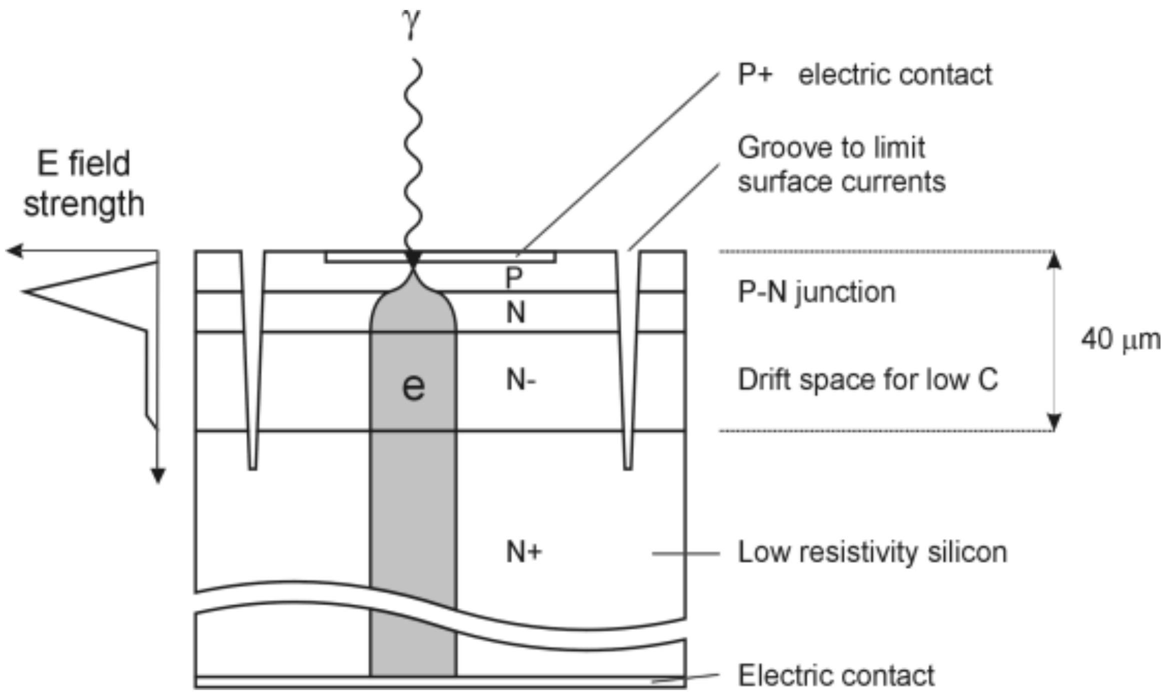
Pic: ICRR/University of Tokyo



Source: Cutnell and Johnson, 7th edition image gallery

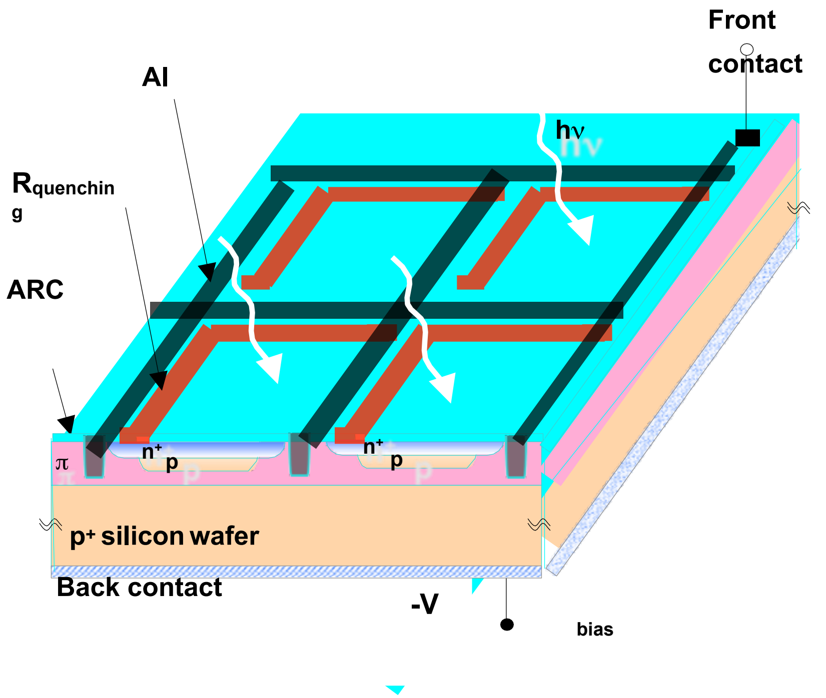
Avalanche Photo Diodes & SiPMs

- Standard Photomultipliers are bulky and expensive
- SiPM become more and more popular as replacement for standard photo multipliers.



D. Renker, Nucl. Instr. Methods A 571 (2007) 1-6

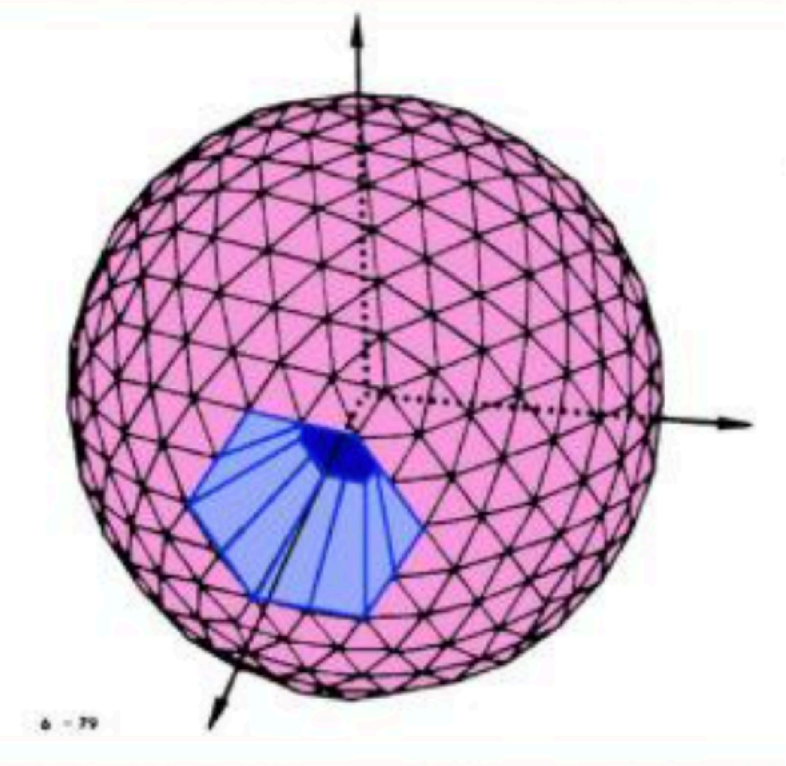
SiPM are matrices of APDs:

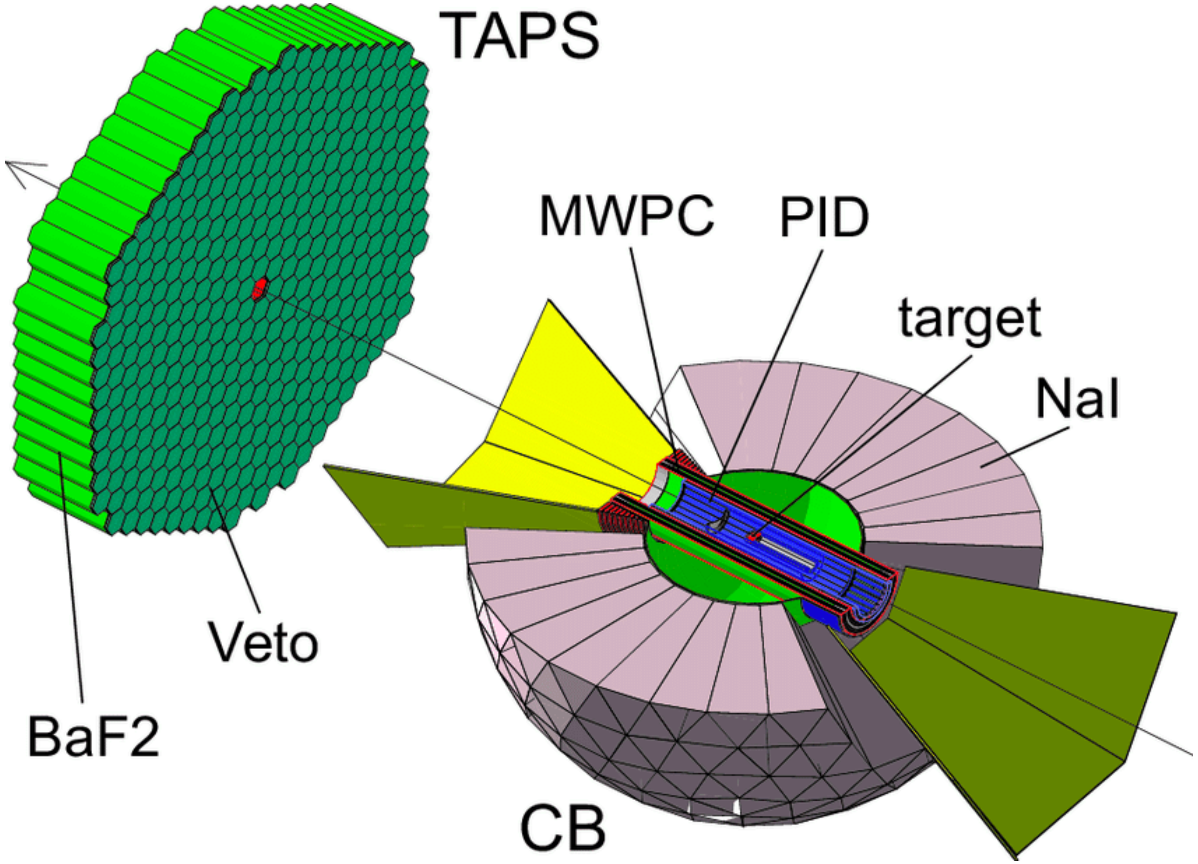


Examples of Calorimeter

Crystal Ball Calorimeter

- Thallium-doped NaI(Tl) crystals arranged in a sphere ("ball") ⇒ excellent energy resolution
- (Almost) full 4π solid angle coverage
- Operated at electron-positron collider SPEAR at Stanford (now at Mainz!)
- Physics goal: Precise charmonium spectroscopy

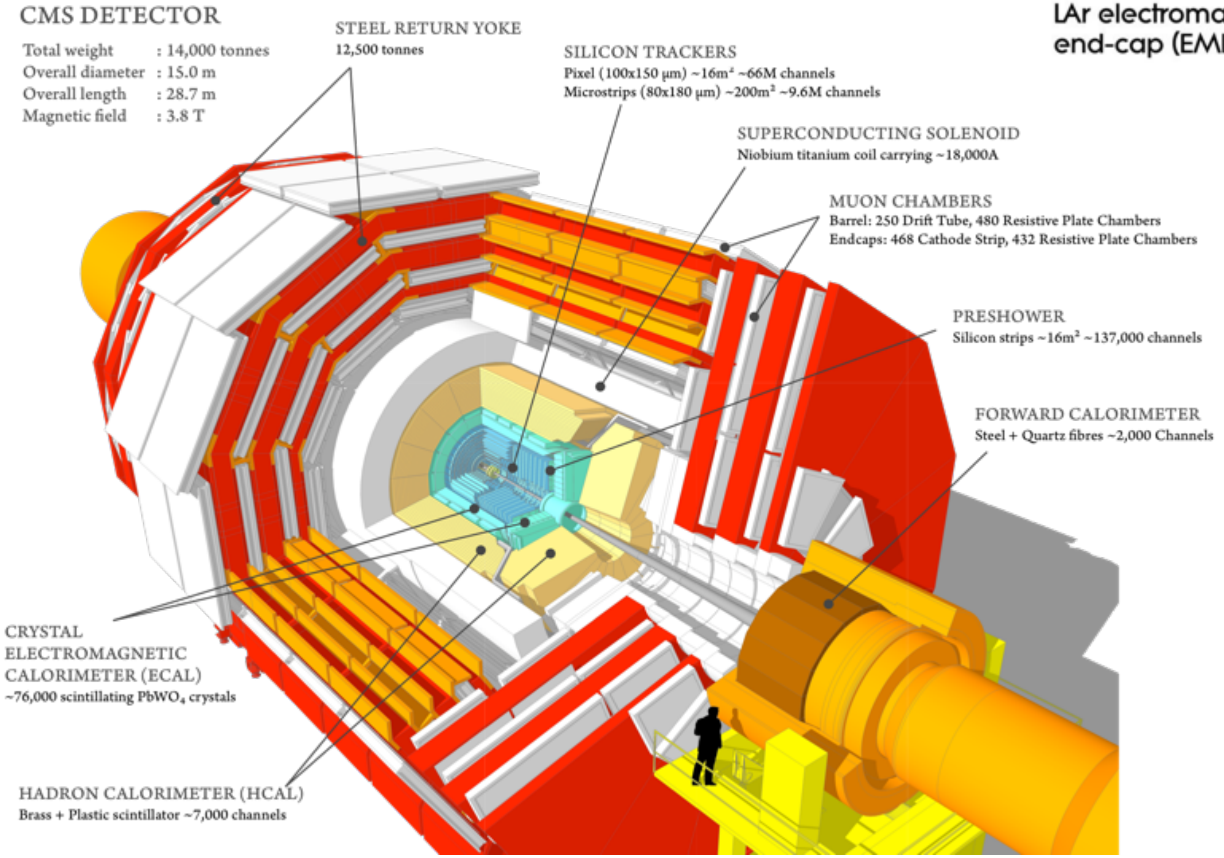




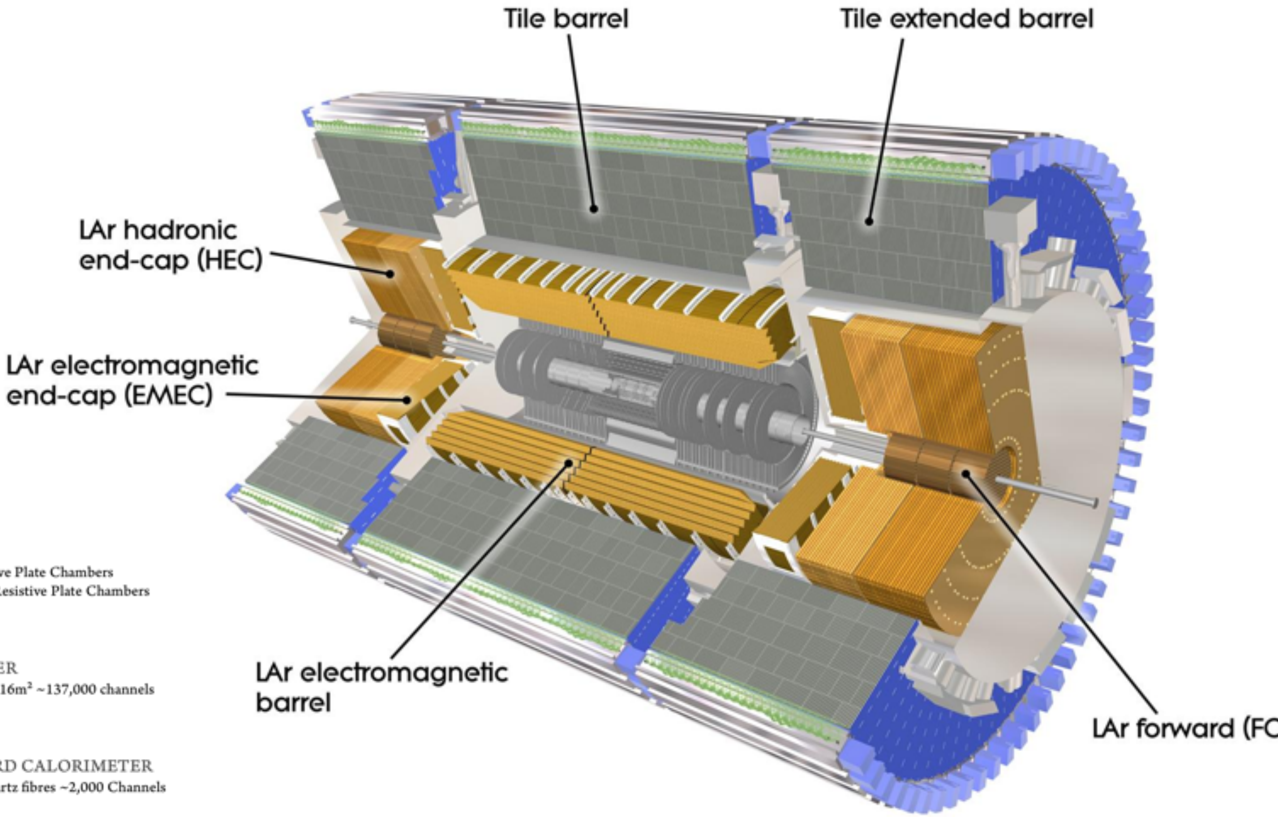
Overview of Calorimeters

- In order to maximise the sensitivity for $H \rightarrow \gamma\gamma$ decays, the experiments need to have an excellent e/γ identification and resolution

CMS



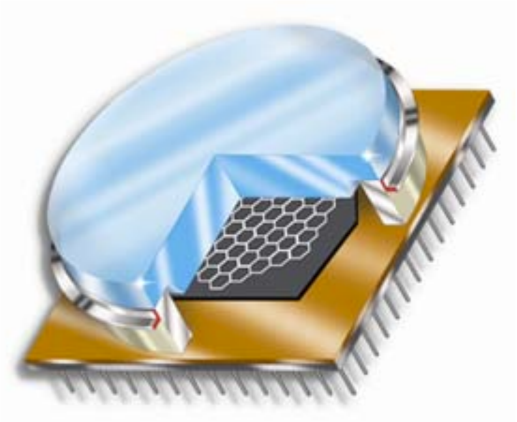
ATLAS



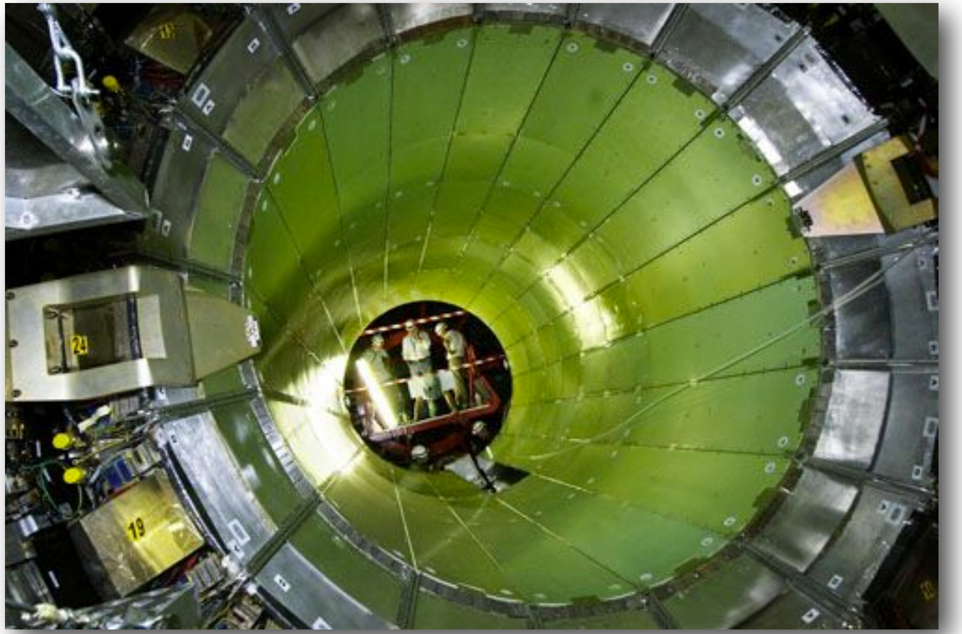
CMS Calorimeter

- **ECAL:** homogeneous calo
  - high resolution Lead Tungsten crystal calorimeter -> **higher intrinsic resolution**
  - 80000 crystals each read out by a photodetector
  - constraints of magnet -> HCAL absorption length not sufficient
  - tail catcher added outside of yoke

- **HCAL:** sampling calo
  - 36 barrel “wedges”, each weighing 26 tonnes
  - brass or steel absorber
  - plastic scintillators
  - read out by hybrid photodetectors



CMS Lead tungsten crystals, each 1.5kg (CERN)

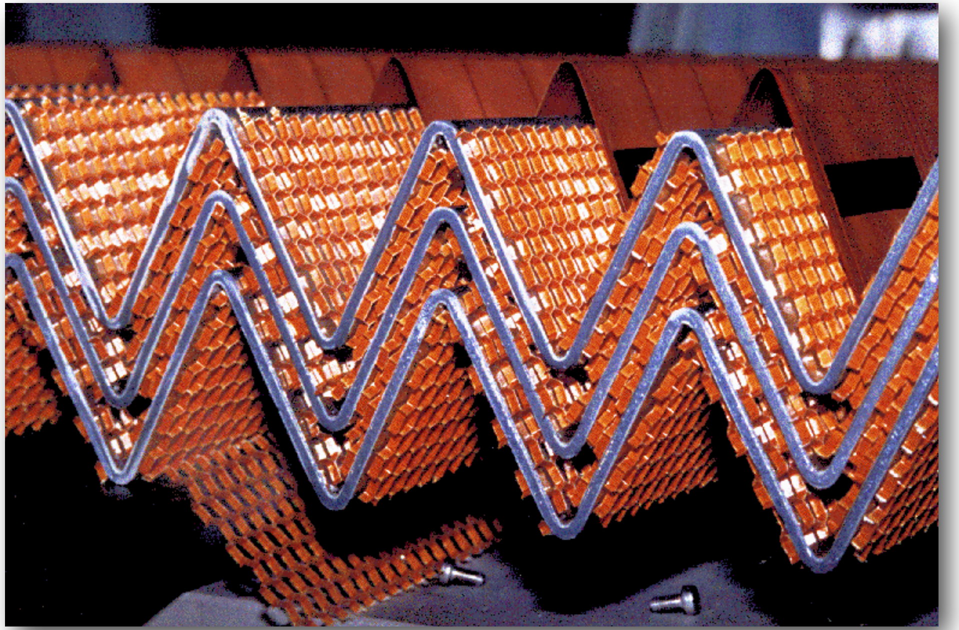


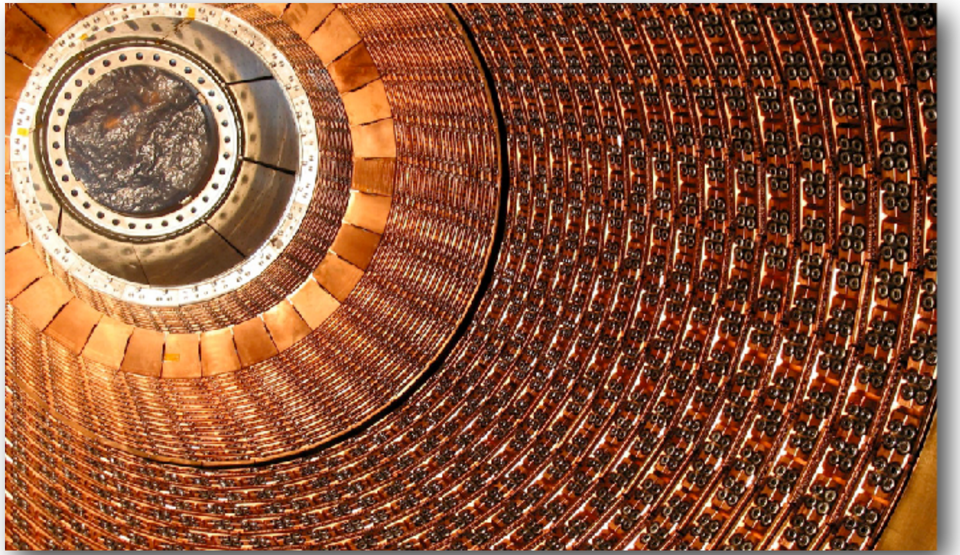
CMS ECAL during installation (CERN)

ATLAS Calorimeter

- **ECAL + HCAL:** sampling calo
  - Liquid argon LAr calorimeter > high granularity and longitudinally segmentation (better e/ ID)
  - Electrical signals, high stability in calibration & radiation resistant (gas can be replaced)
  - Solenoid in front of ECAL -> a lot of material reducing energy resolution
  - Accordion structure chosen to ensure azimuthal uniformity (no cracks)
  - Liquid argon chosen for radiation hardness and speed

  - Tile calorimeter: covering outer region
  - "Conventional" steel absorber with plastic scintillators.



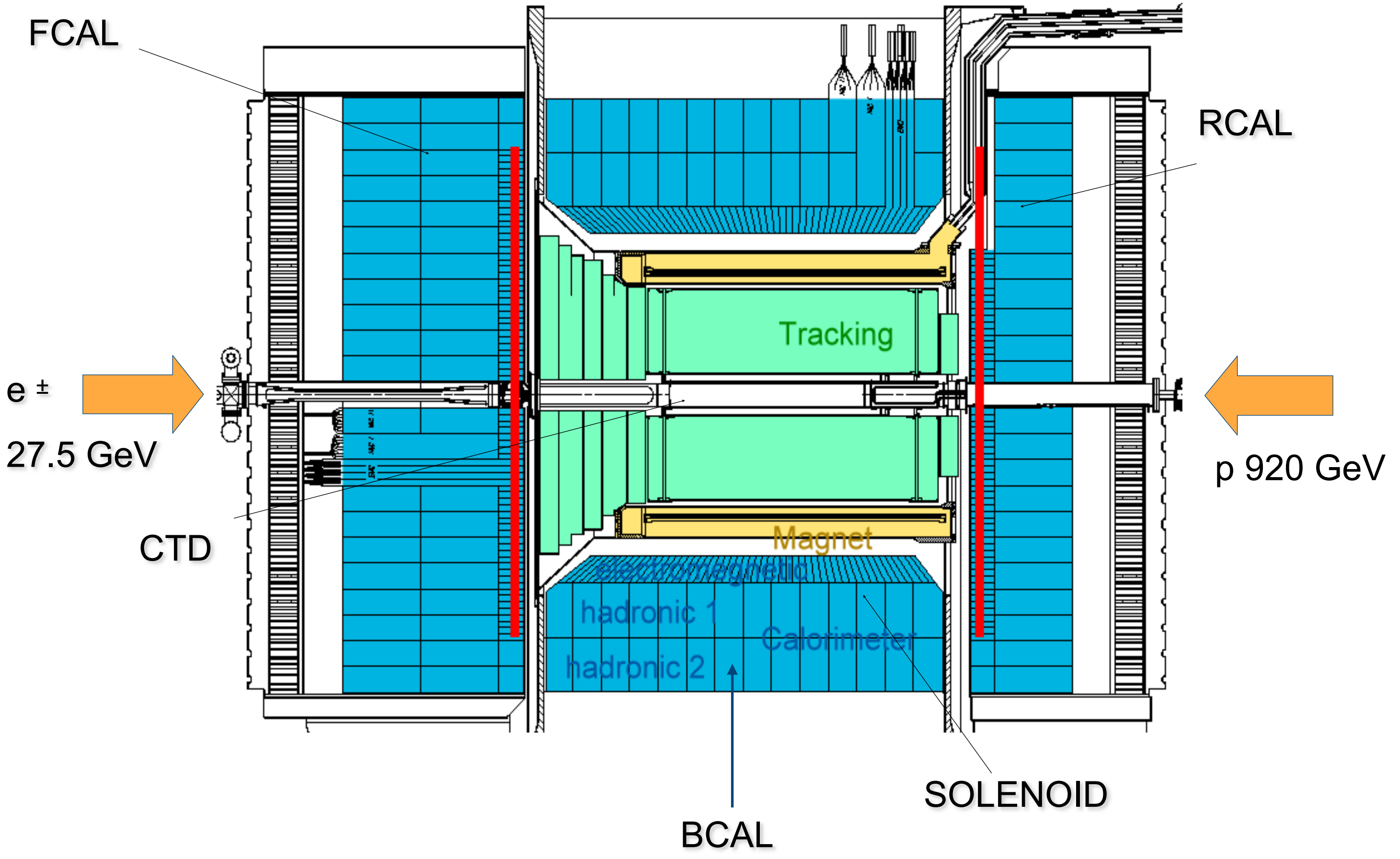


ATLAS Hadronic endcap Liquid Argon Calorimeter. (CERN)

The ZEUS Calorimeter - Solution

Sampling Calorimeter

- Highly-segmented, uranium scintillator sandwich calorimeter read out with photomultiplier tubes (PMTs)

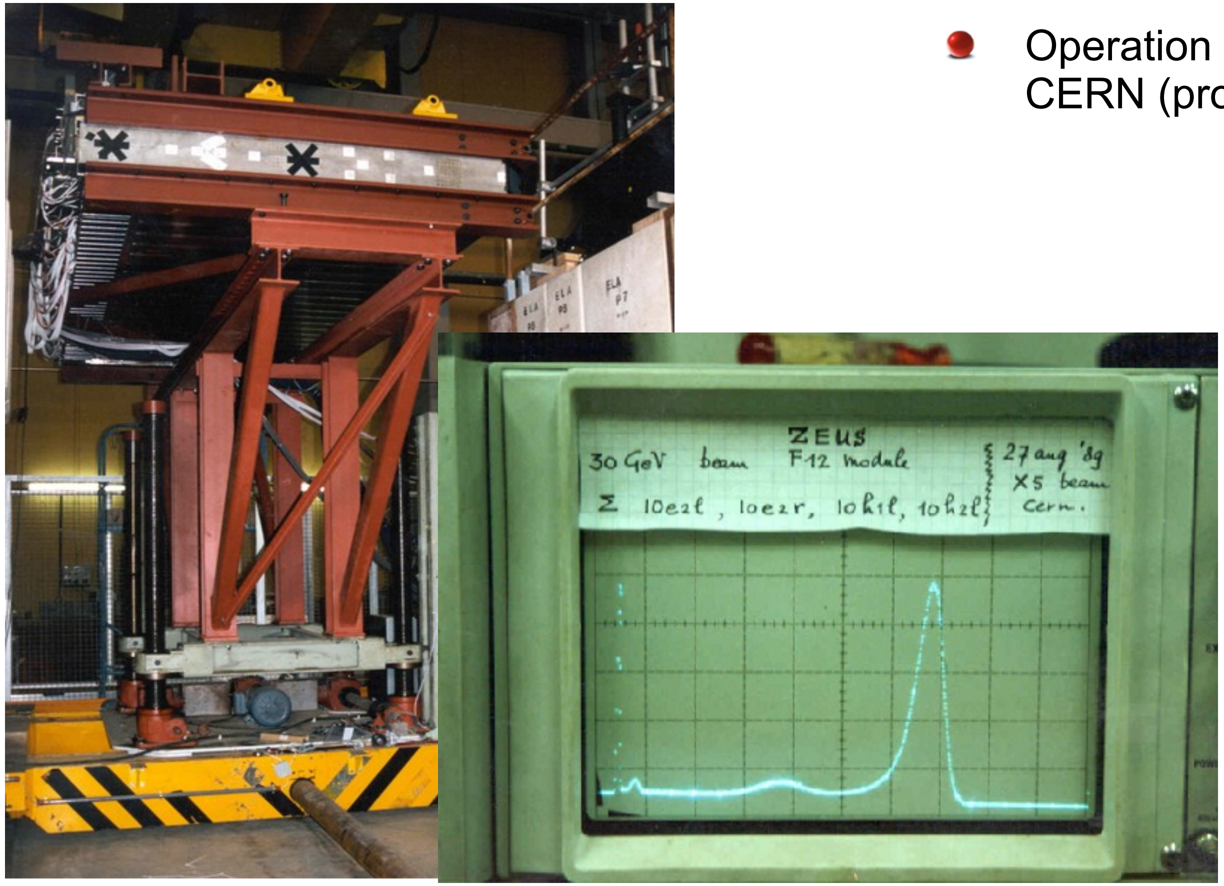


Uranium + Scintillator:

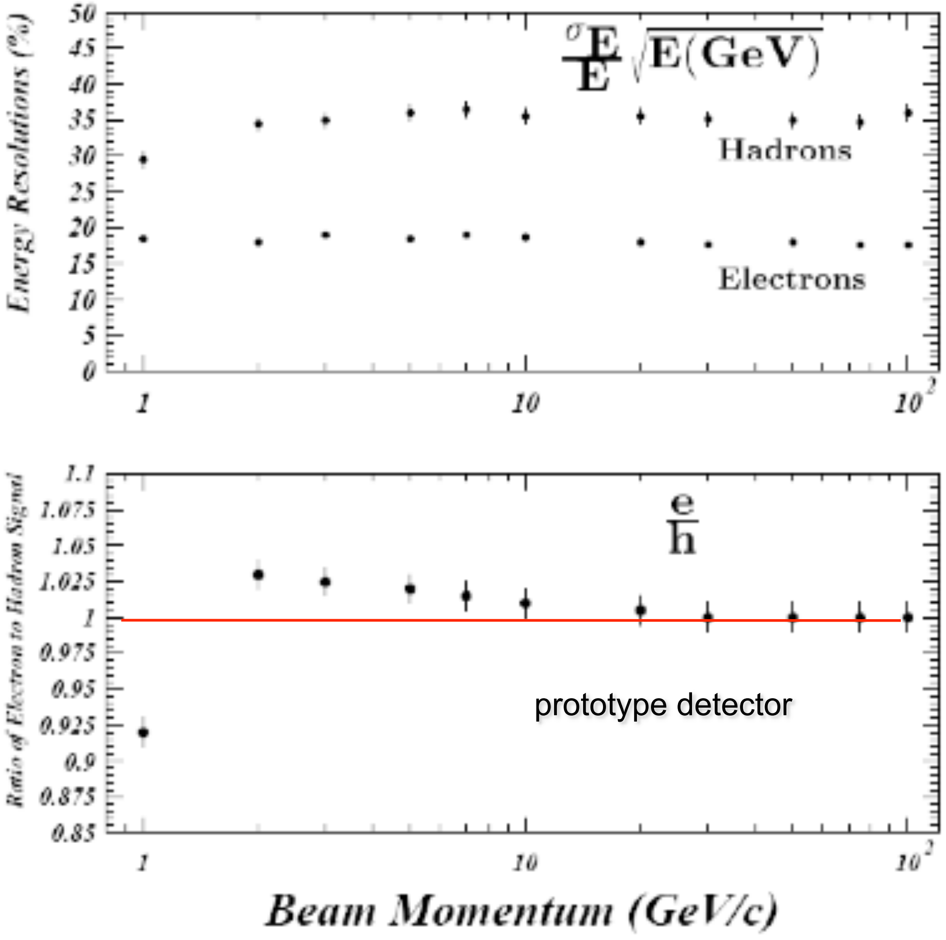
- compensation
- high Z material -> more compact size of calorimeter
- natural radioactivity provides means of calibration

- Very hermetic: covering up to $\eta<4.2$ in the forward direction and $\eta<-3.8$ in the rear direction.
- Readout by 12,000 phototubes (PMTs)

Test beam at CERN



- Operation characteristics were determined in test beams at CERN (prototype detector)

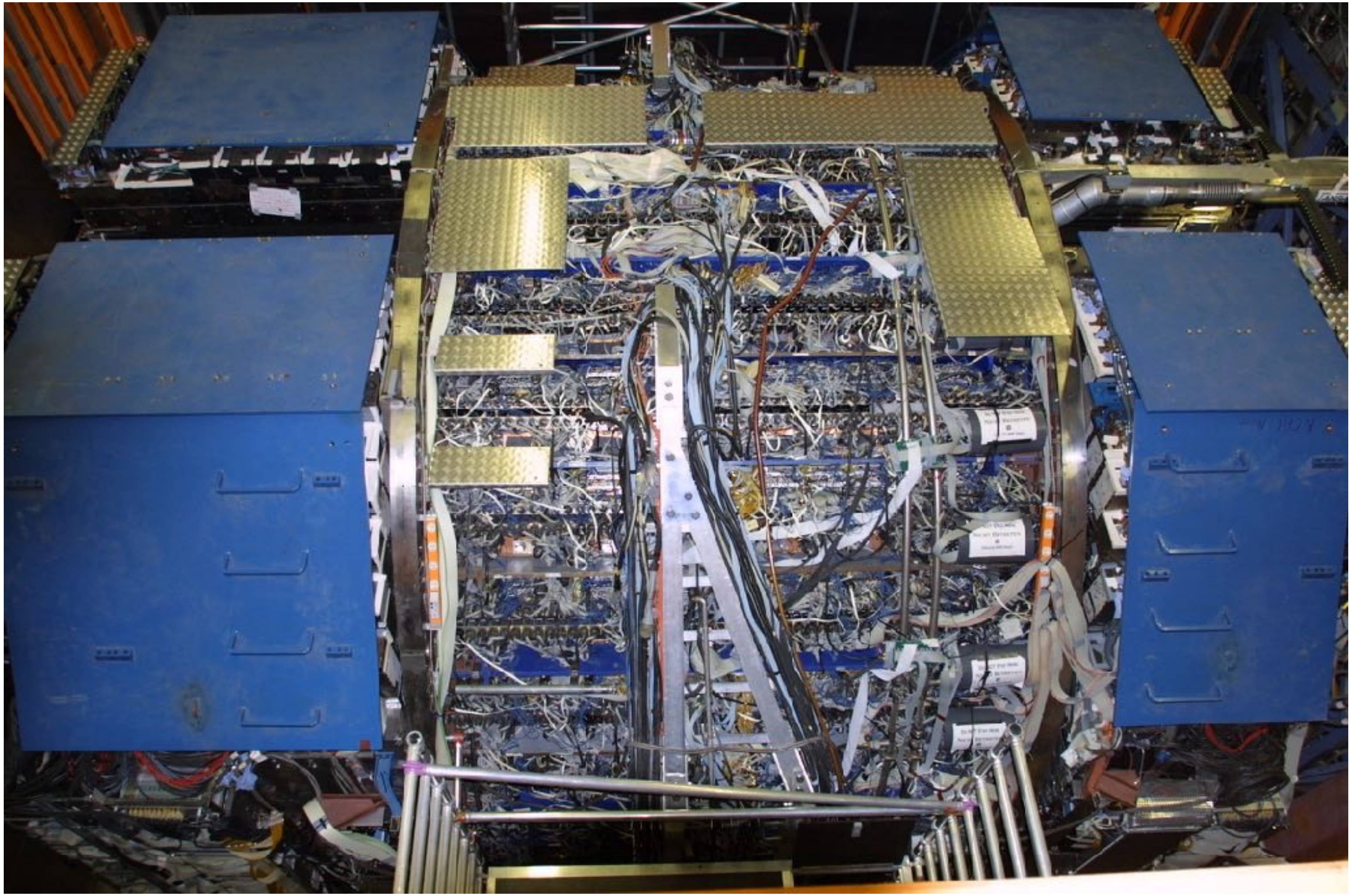


Electrons: $$\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E(GeV)}}$$

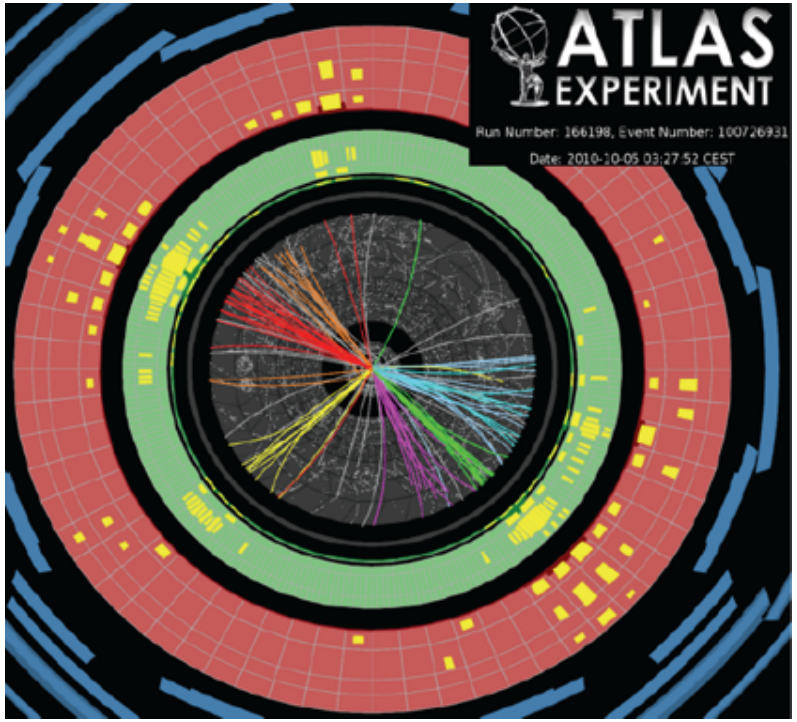
Hadrons: $$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

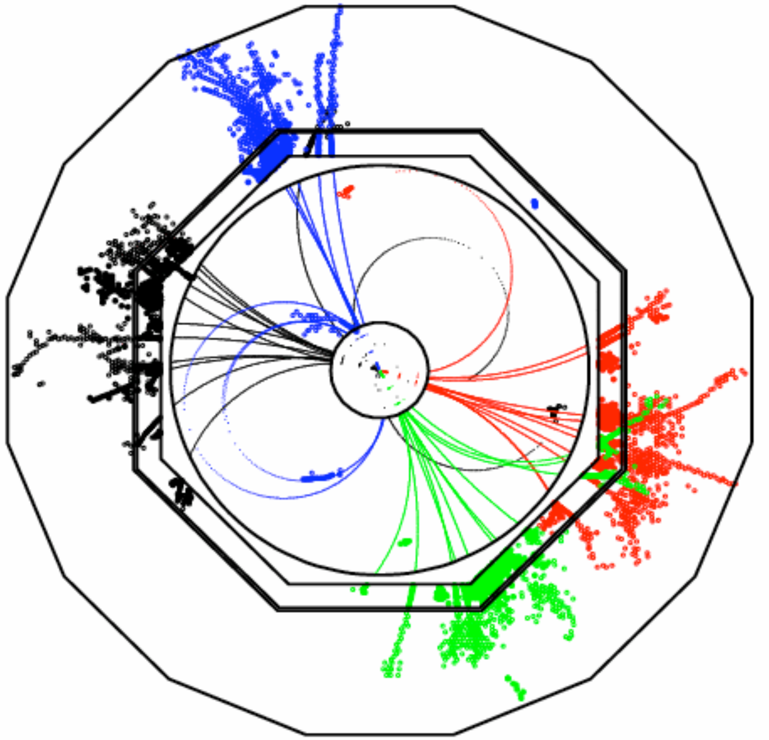
Production modules were all calibrated at CERN

Medusa ....



Current Hadron Calos ... and Dreams

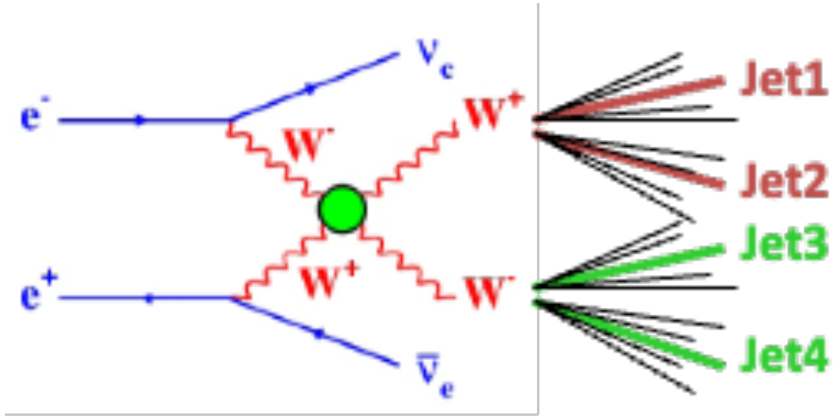


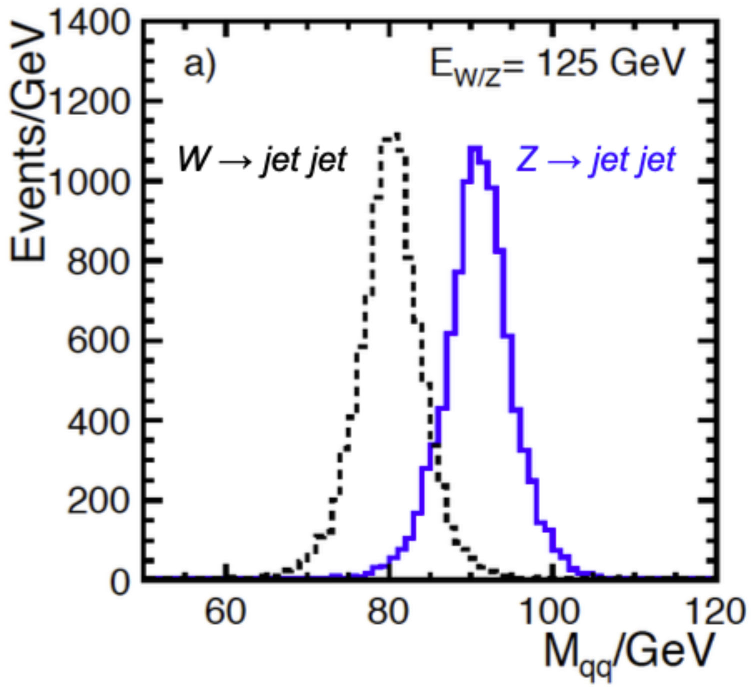


- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT)
  O(10k) channels for full detectors

- Extreme granularity to see shower substructure: small detector cells with individual readout for Particle Flow
  O(10M) channels for full detectors

The Jet Energy Challenge





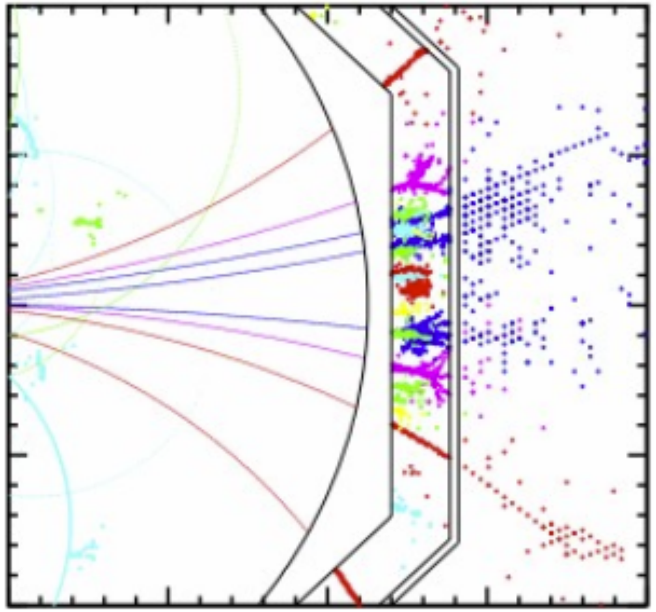
M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- Many interesting physics processes involve W or Z bosons predominantly decay into jets
- Goal: distinguish the decays *Z → jet jet* and *W → jet jet* by their reconstructed mass
- Required resolution: $\sigma(E_{jet})/E_{jet} \approx$ 3-4% for $E_{jet} \approx$ 40 to 500 GeV
- "typical" calorimeter:

$$\sigma(E_{jet})/E_{jet} \approx 60\%/\sqrt{E(\text{GeV})} \oplus 2\%$$
$$\Rightarrow \sigma(E_{jet})/E_{jet} \approx 10\% \text{ at } E_{jet} = 50 \text{ GeV}$$

- promising solution:
  Particle **F**low **A**lgorithms

Particle Flow Calorimeter



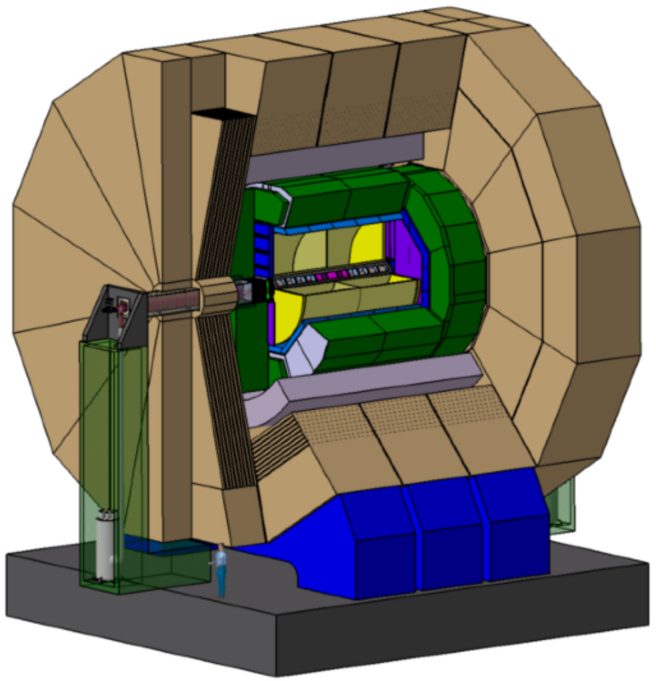
- Attempt to measure the energy/momentum of **every** particle with the dete best resolution
- Used in three main contexts:
  - "Energy flow" -> Use tracks to correct jet energies
  - "Particle flow/Full event reconstruction" e.g. CMS
    -> Aim to reconstruct particles not just energy deposits
  - "High granularity particle flow" e.g. ILC
    -> Technique applied to detector concept optimised for particle flow

- Need
  - a calorimeter optimised for photons: separation into ECAL + HCAL
  - to place the calorimeters inside the coil (to preserve resolution)
  - to minimise the lateral size of showers with dense structures
  - the highest possible segmentation of the readout
  - to minimise thickness of the active layer and the depth of the HCAL

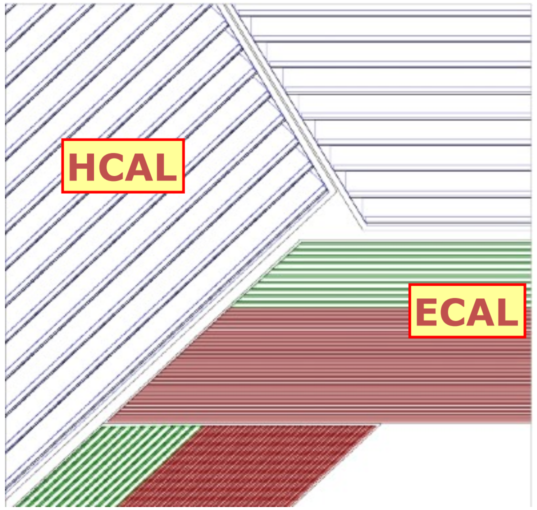
"Typical" jet:
~62% charged particles (mainly hadrons)
~27% photons
~10% neutral hadrons
~1% neutrinos

Example: Calo design at ILC

"no" material in front	– calorimeter inside the solenoid
large radius and length	– to better separate the particles
large magnetic field	– to sweep out charged tracks
small Moliere radius	– to minimize shower overlap
small granularity	– to separate overlapping showers



ILD: International Large Detector



ECAL:

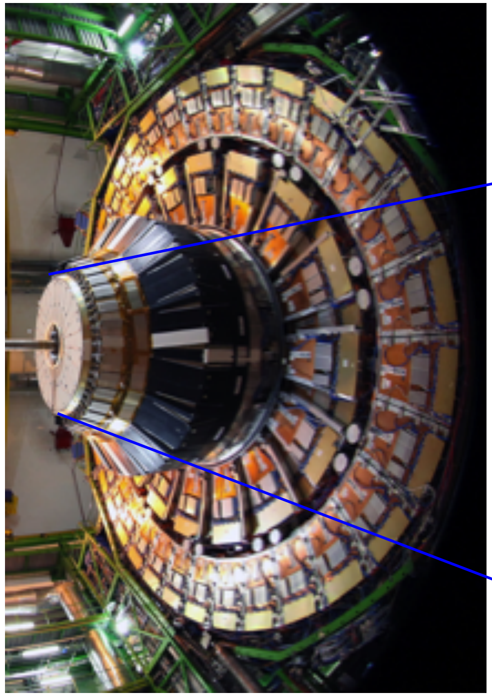
- SiW sampling calorimeter
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels

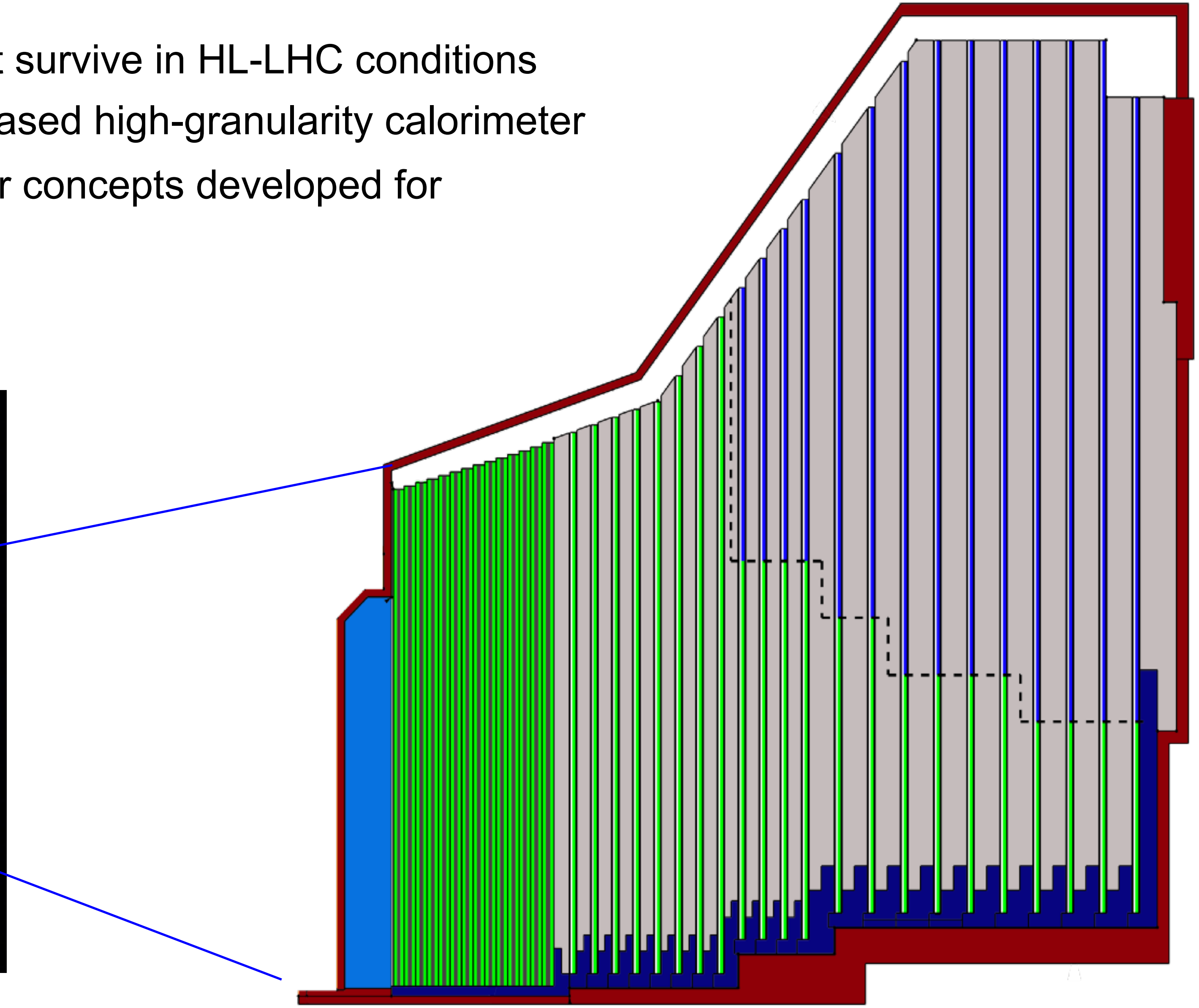
HCAL:

- Steel-Scintillator tile sampling calorimeter
- longitudinal segmentation: 48 layers (6 λ_I)
- transverse segmentation: 3x3 cm^2 tiles

CMS High Granularity Calorimeter Endcap

- Current CMS calorimeter endcap will not survive in HL-LHC conditions
- 2015, decided to replace it with silicon-based high-granularity calorimeter
- Synergy with high granularity calorimeter concepts developed for electron-positron colliders (CALICE)



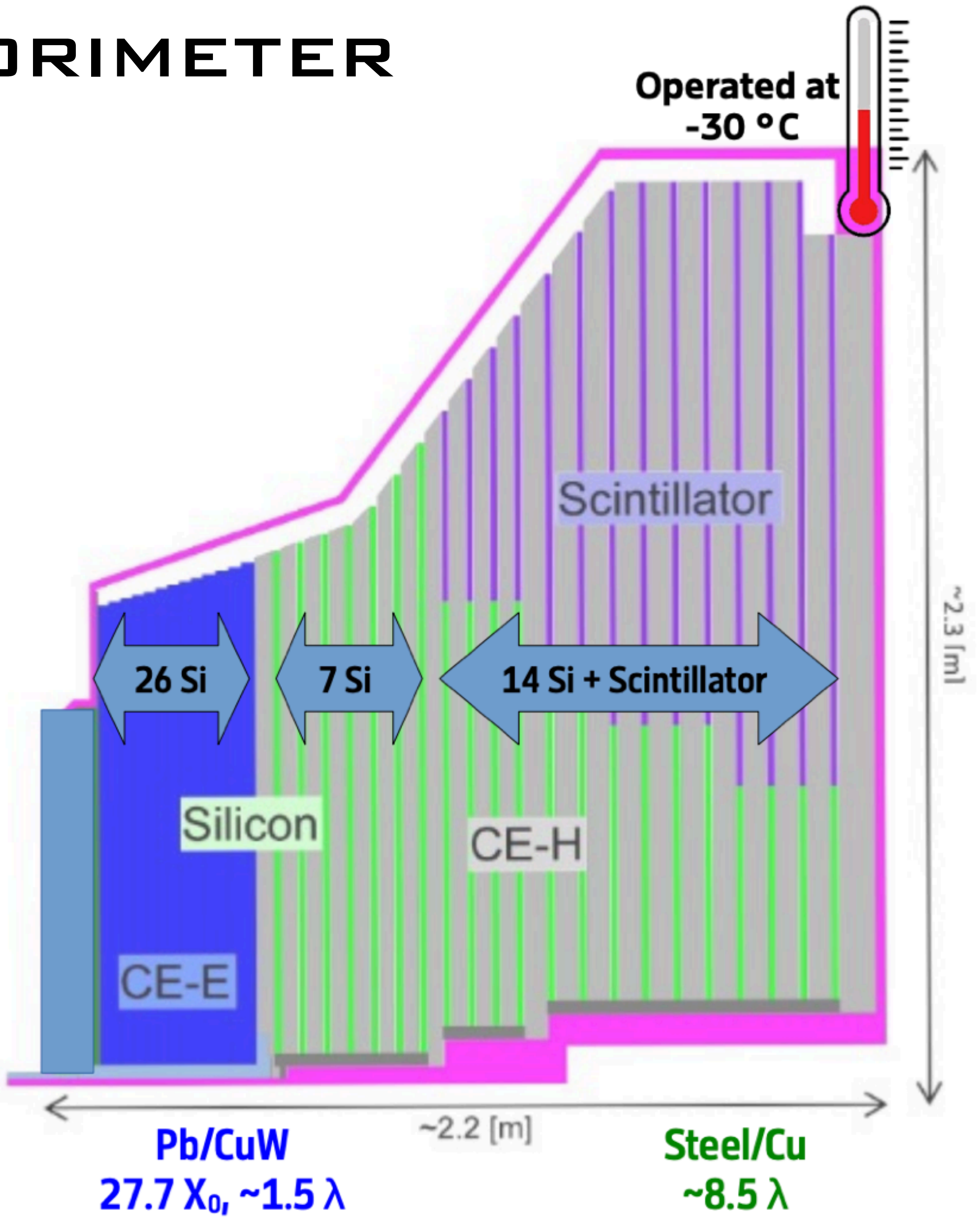


HGCAL - 5D Imaging Calorimeter

- 5D imaging calorimeter:
  - 3D spatial granularity, energy, timing information
- Two separated sections in one single detector

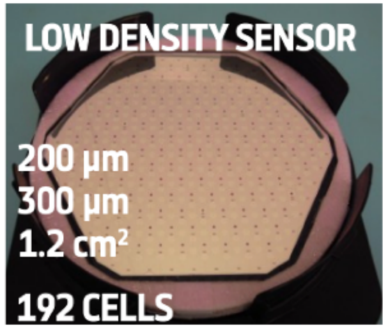
- **Active Materials**
  - Silicon Sensors (CE-E and CE-H)
    - Hexagonal 8” wafers • 6M pads (~620 m2)
  - Plastic Scintillators with SiPM readout (CE-H)
    - 240k scintillator tiles (~370 m2)

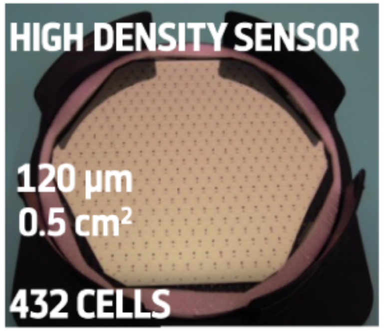
- **Passive materials**
  - Lead absorber plates, copper cooling plates, and CuW baseplates • Compact and dense object → 225 T

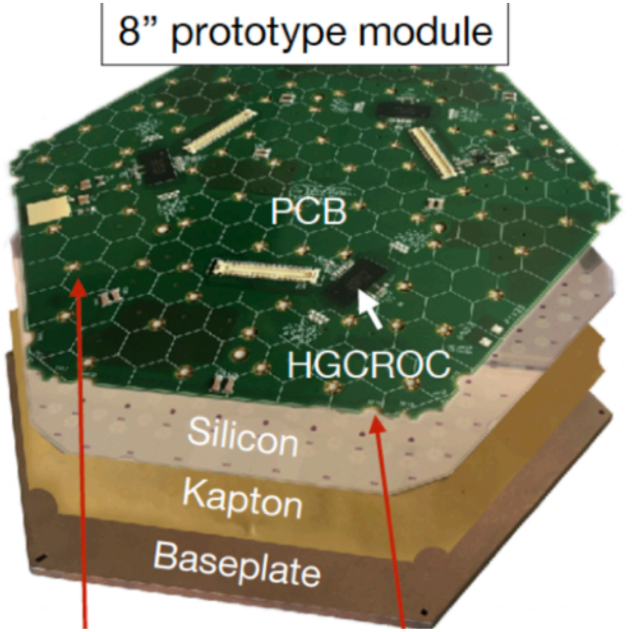


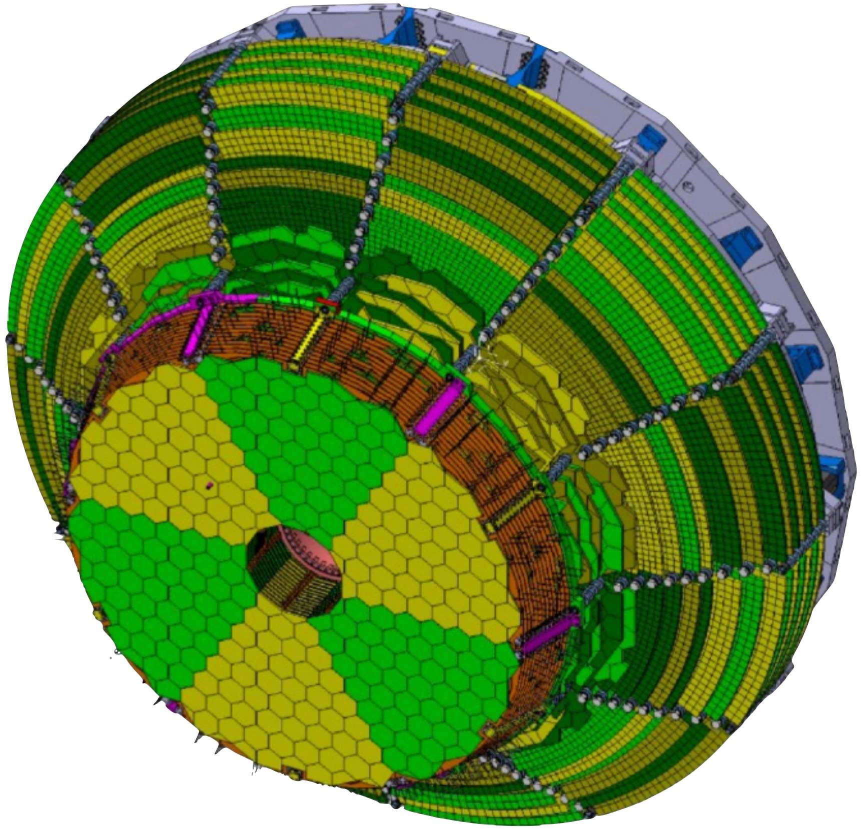
Active Material

Silicon Modules for highest radiation level





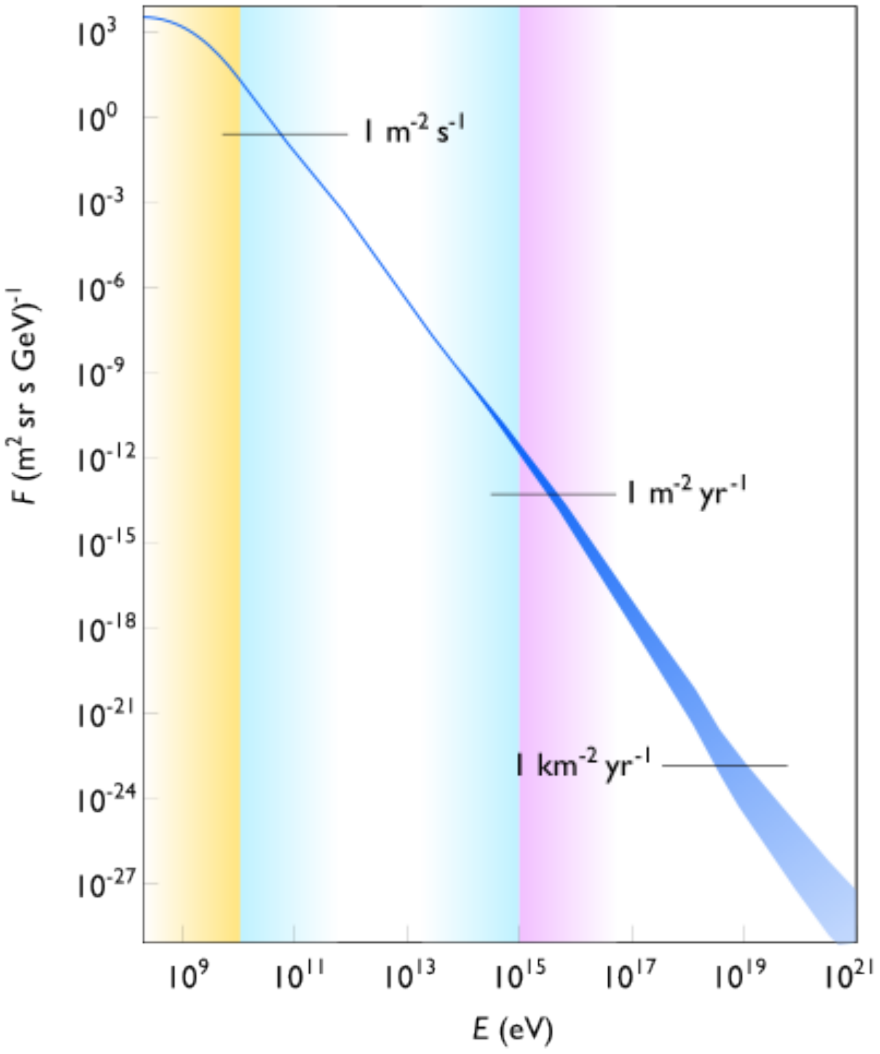




Plastic Scintillators with SiPM for medium radiation level

- **Status of project**
  - Intense prototyping phase towards conclusion
  - Pre-production start in 2024
  - To be ready in 2027

Calos: not only at accelerators!



Pic: Wikipedia

Requirements are different

- Search for extremely rare reactions
  - Large areas and volumina have to be covered
  - Background needs to be well suppressed
  - High efficiency: no event can be lost!
  - Data rate, radiation damage etc. are less of a problem

- The methods used in particle physics are more and more used in astro particle physics.

Flux of cosmic ray particles as a function of their energy.

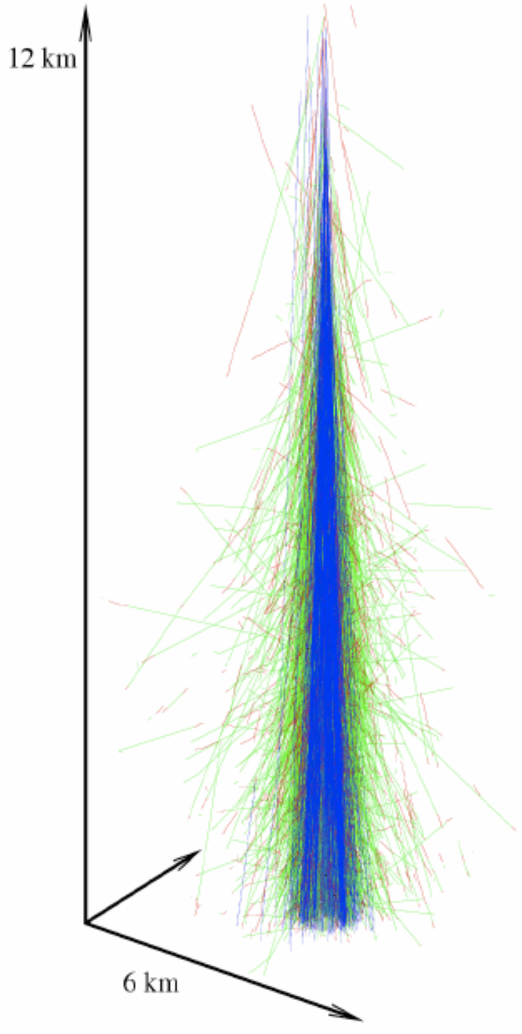
Air shower

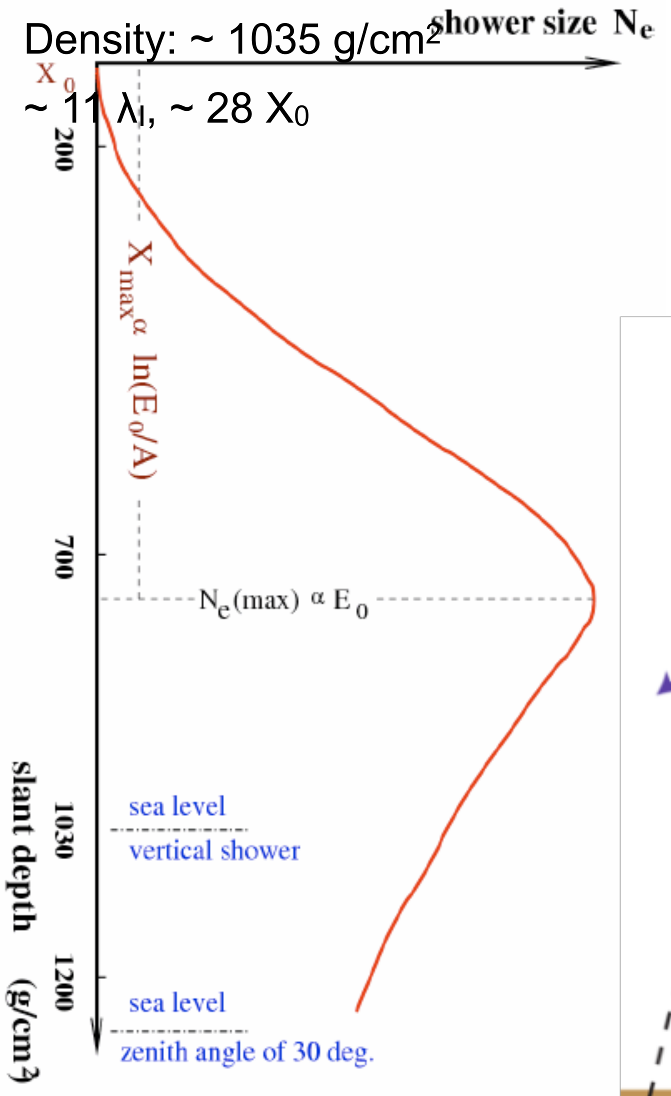
Nuclear reaction length λ_I ~ 90 g/cm²

Radiation length X_0 ~ 36.6 g/cm²

Density: ~ 1035 g/cm²

~ 11 λ_I, ~ 28 X_0

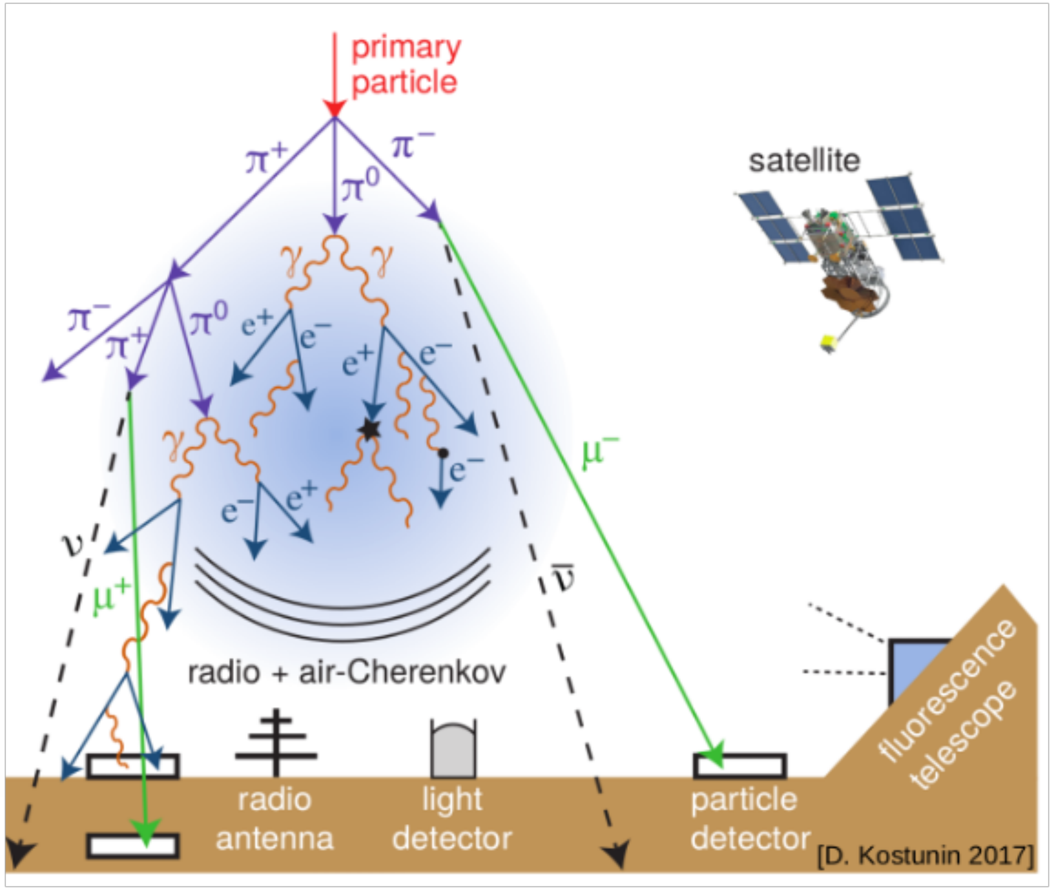




R.Engel, ISAPP2005

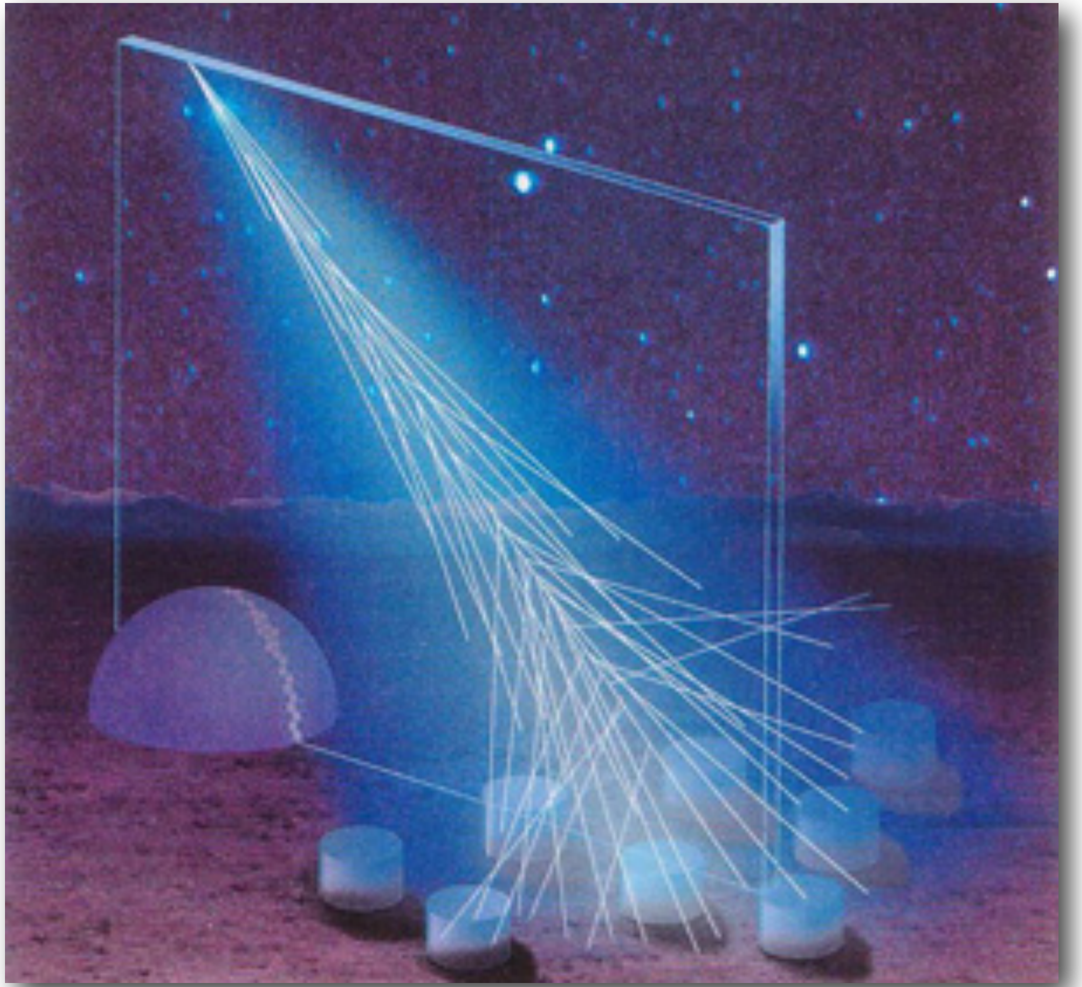
Use atmosphere as calorimeter

- Mainly electromagnetic: photons, electrons
- Shower maximum: ~ ln(E_0/A)



Two Main Techniques

Pic: Pierre Auger Observatory



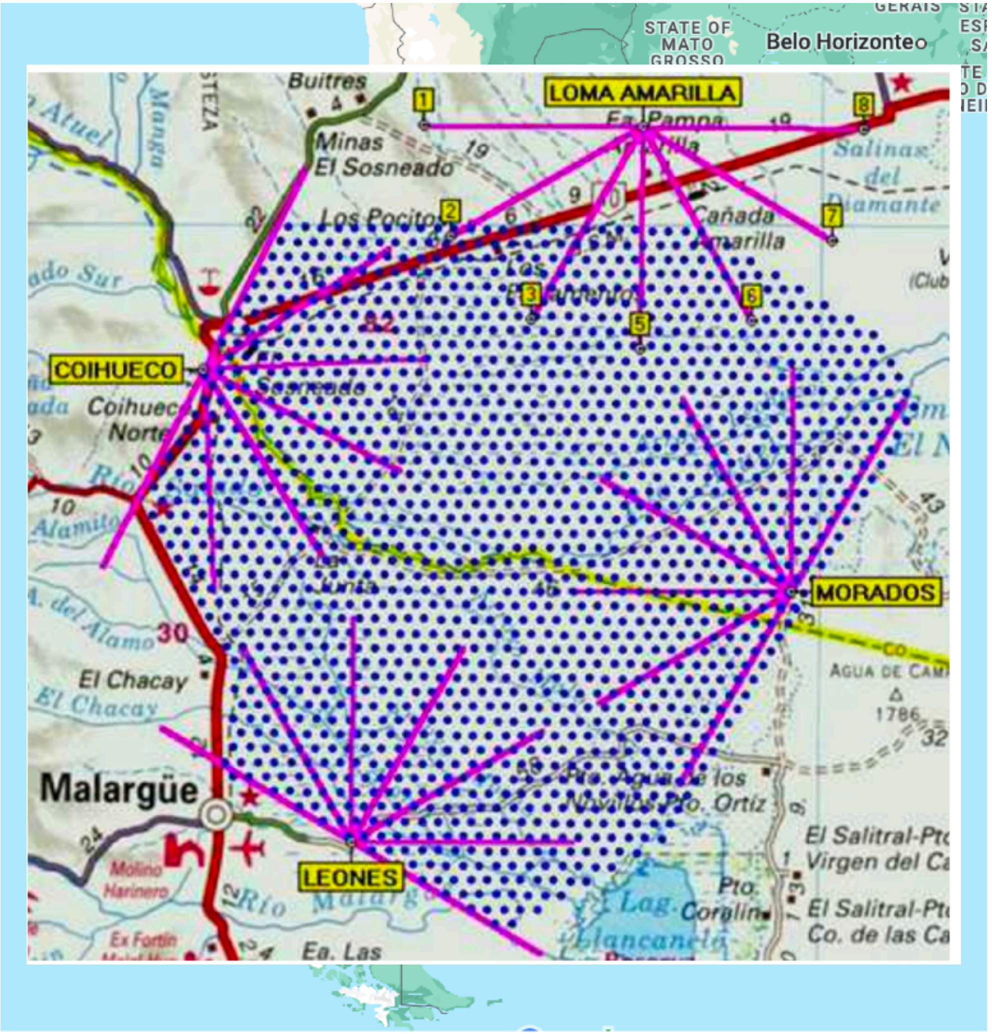
- The atmosphere as homogeneous calorimeter:
  - Energy measurement by measuring the **fluorescence** light

This is only possible with clear skies and darkness !

- A one-layer sampling calorimeter 11 λ absorber
  - Energy measurement using particle multiplicity on the **surface**

Always possible but has large uncertainties !

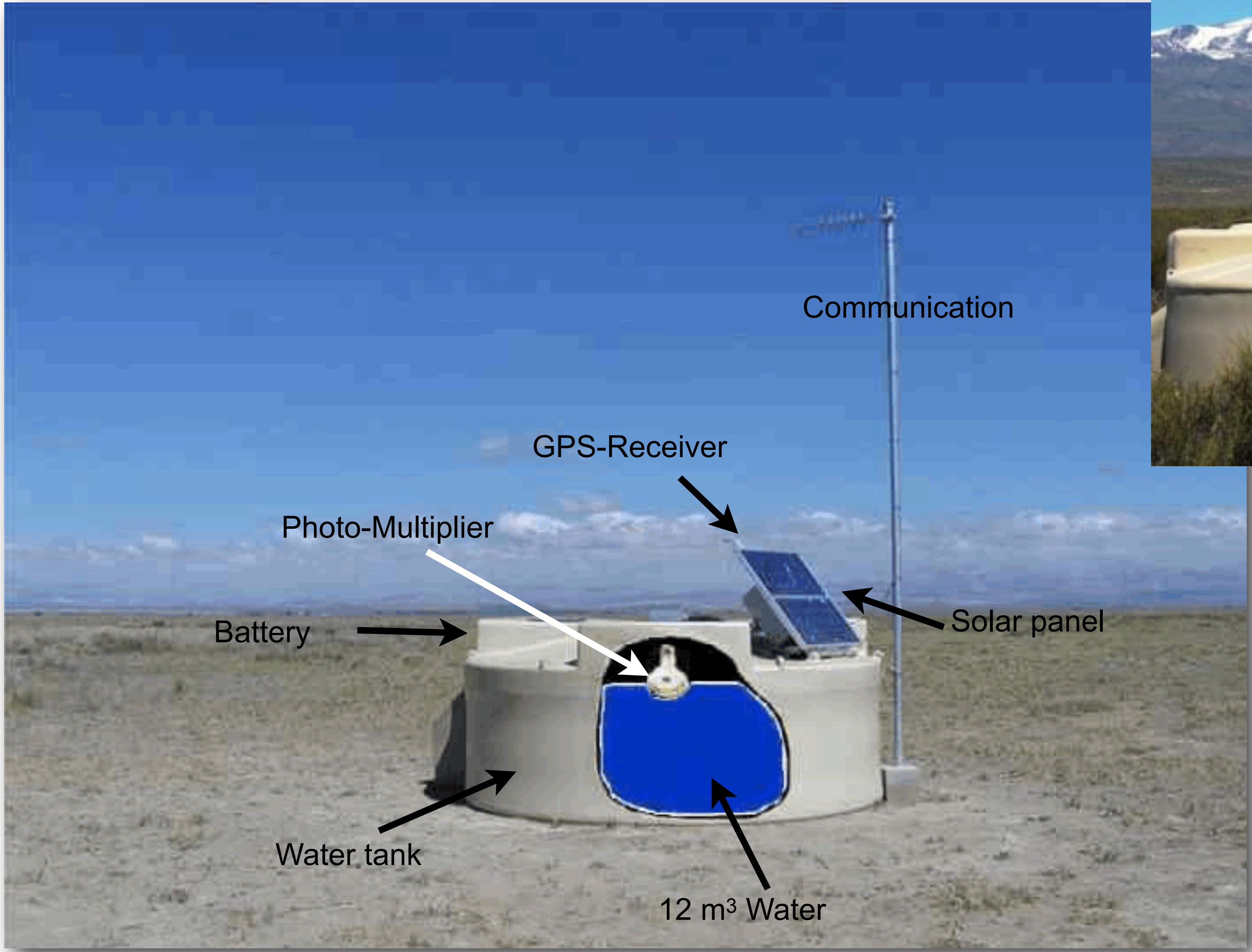
AUGER-SOUTH: ARGENTINIAN PAMPA

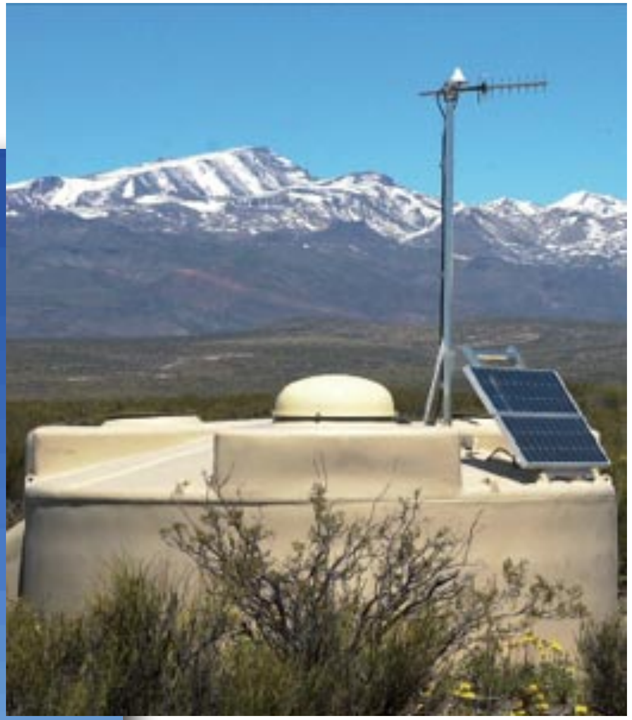


Pics: Pierre Auger Observatory

- Hybrid Installation
  - 1600 water-Cherenkov detectors on ground
  - 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

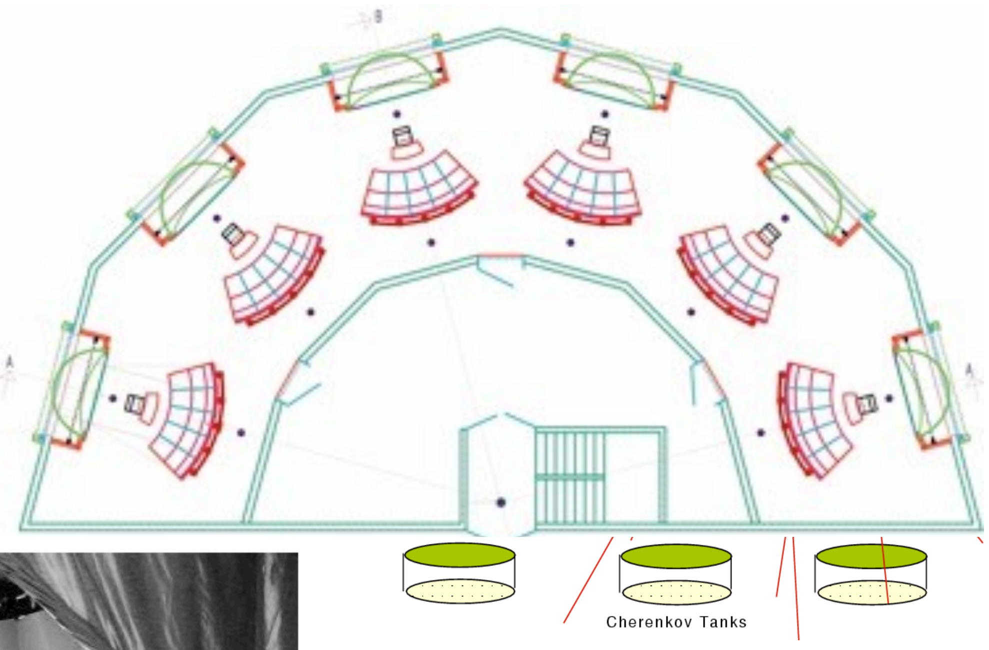
AUGER-Detektor: Surface Detector

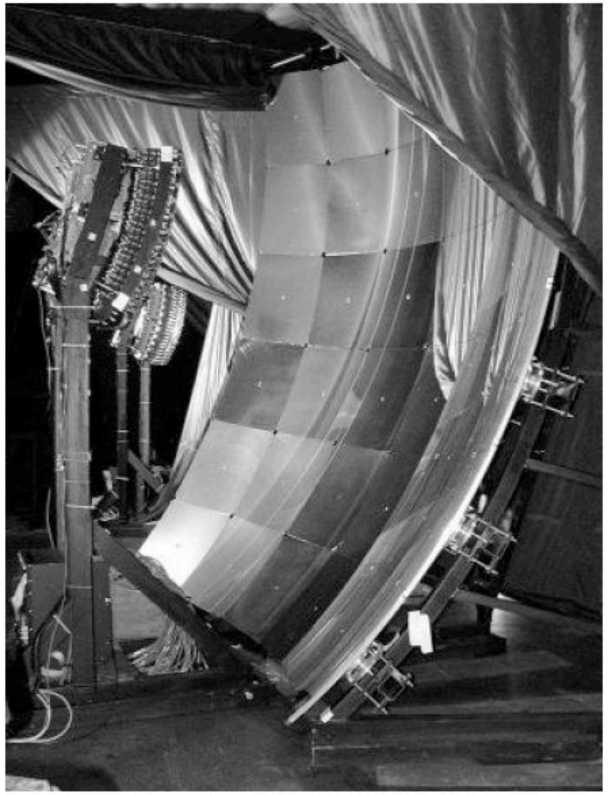


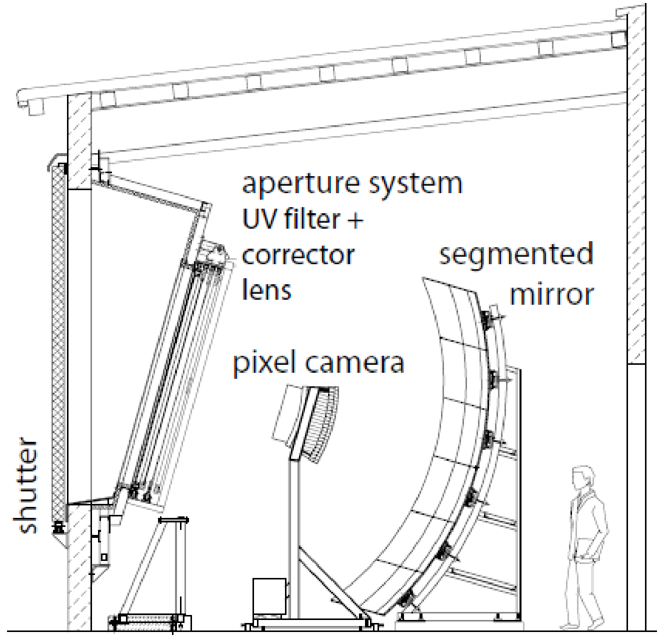


AUGER Hybrid Installati

- Four fluorescence stations with each 6 telescopes
- Each telescope has a field of view of 30°×30°.
- Mirror with an area of about 12m² focuses the fluorescence with an array of photomultipliers







Summary Calorimeters

Calorimeters can be classified into:

Electromagnetic Calorimeters,

- to measure electrons and photons through their EM interactions.

Hadron Calorimeters,

- Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,

- that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,

- that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.