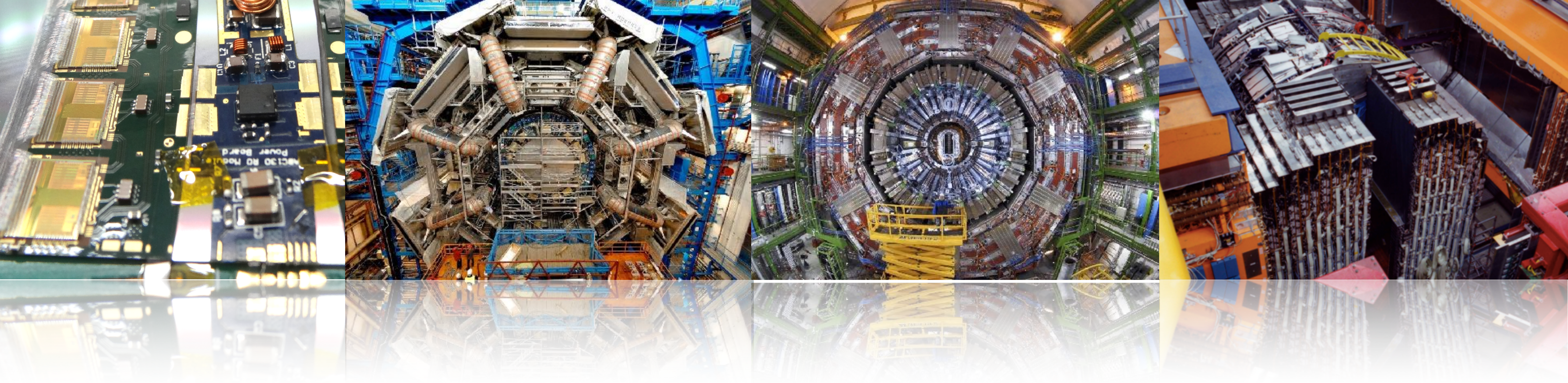

Detectors for High energy Physics

Part 2

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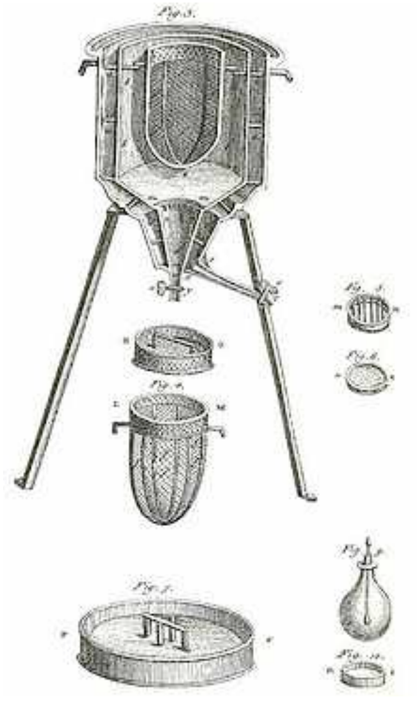
Summerstudents 2022
08.08.2022

III. Calorimeters

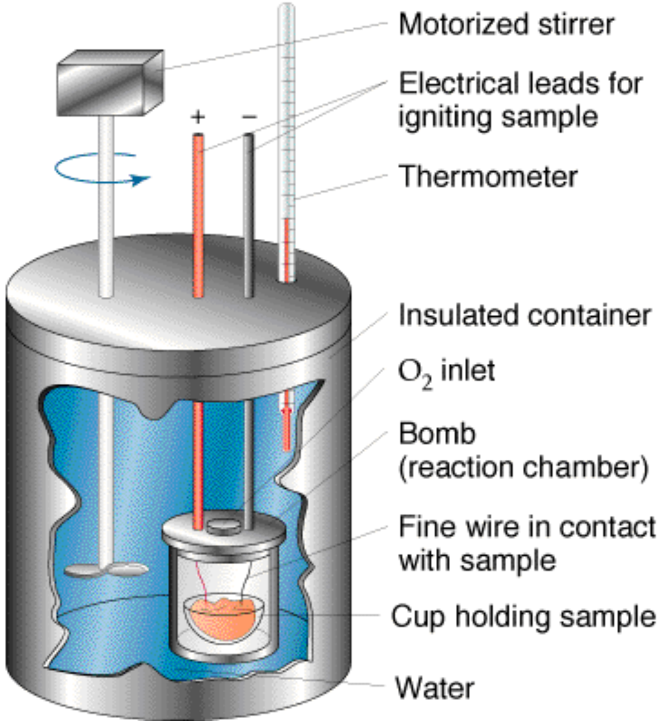
Calorimetry

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

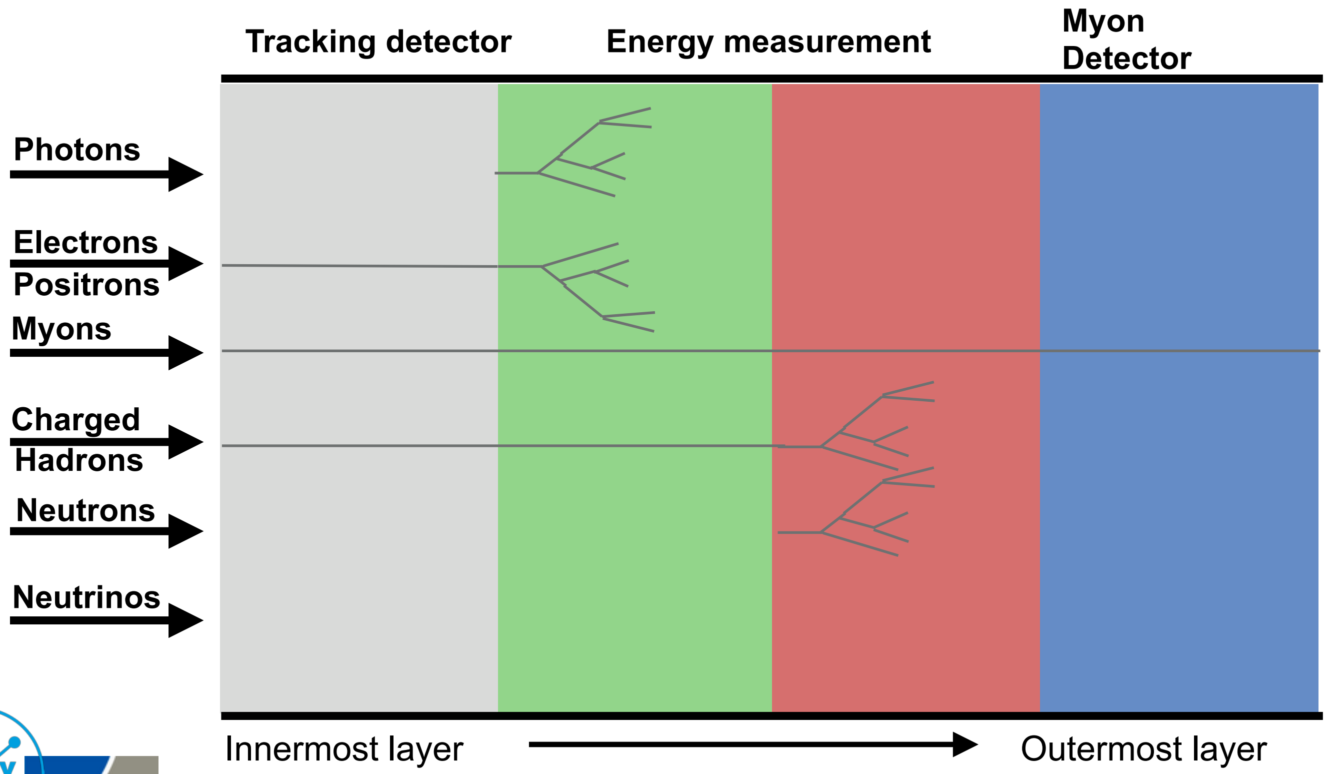
- What is the effect of a 1 GeV particle in 1 litre water (at 20°C)?

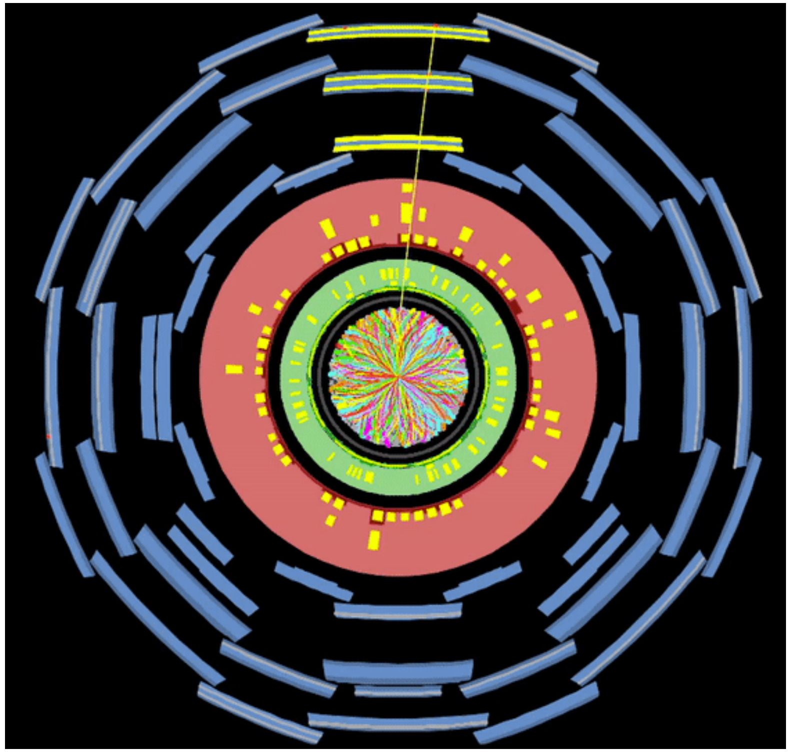
$$\Delta T = E / (c \cdot M_{water}) = 3.8 \cdot 10^{-14} K\ !$$

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

Particle Physics Detectors

- There is not one type of detector which provides all measurements we need -> “Onion” concept -> different systems taking care of certain measurement
- Detection of collision production within the detector volume
  - resulting in signals (mostly) due to electro-magnetic interactions





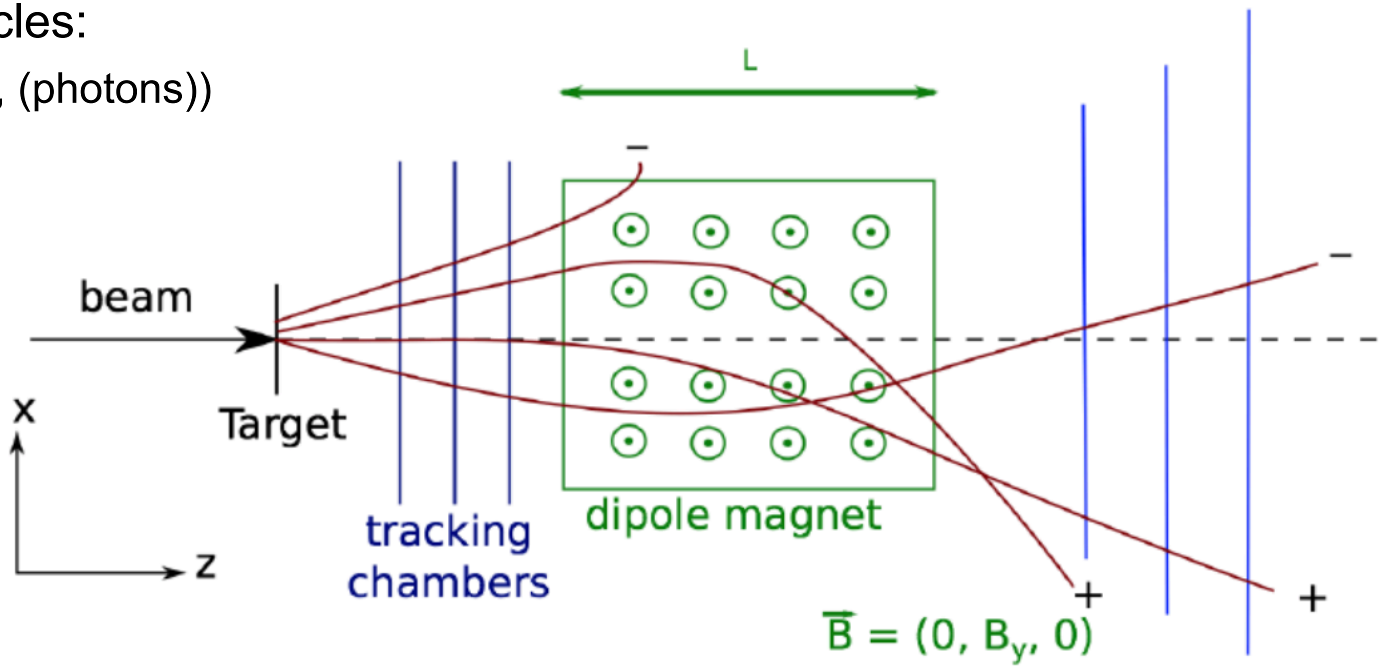
Transverse slice through ATLAS plane

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

What else ?

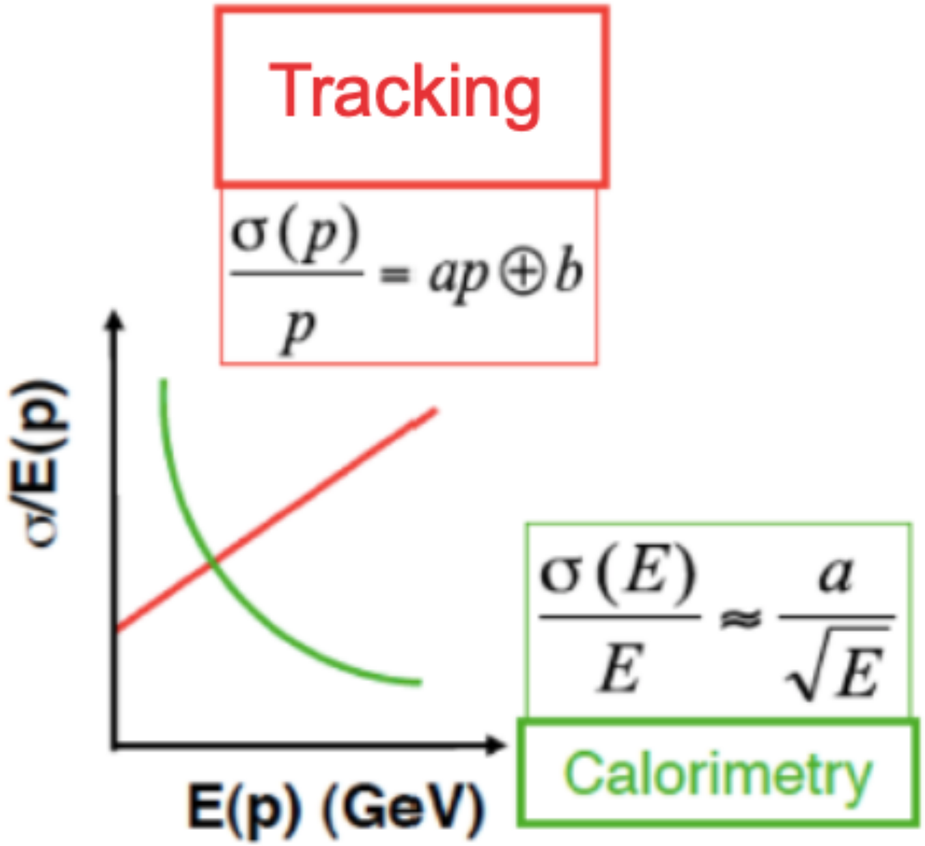
They work also for neutral particles !!
$n, \gamma, K^0, \ldots.$

Why Calorimeters ?

- Calos are the ideal instrument to measure the full energy of particles, especially at high momentum

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$$

Resolution improves with the energy !



- Other advantages:
  - Depth of shower grows only with ln(E)
  - Calorimeter can cover full solid angle
  - Fast timing signal from calorimeter -> can be used for triggering
  - Distinction of hadronic and electromagnetic showers showers using segmentation in depth

Calorimetry: Overview

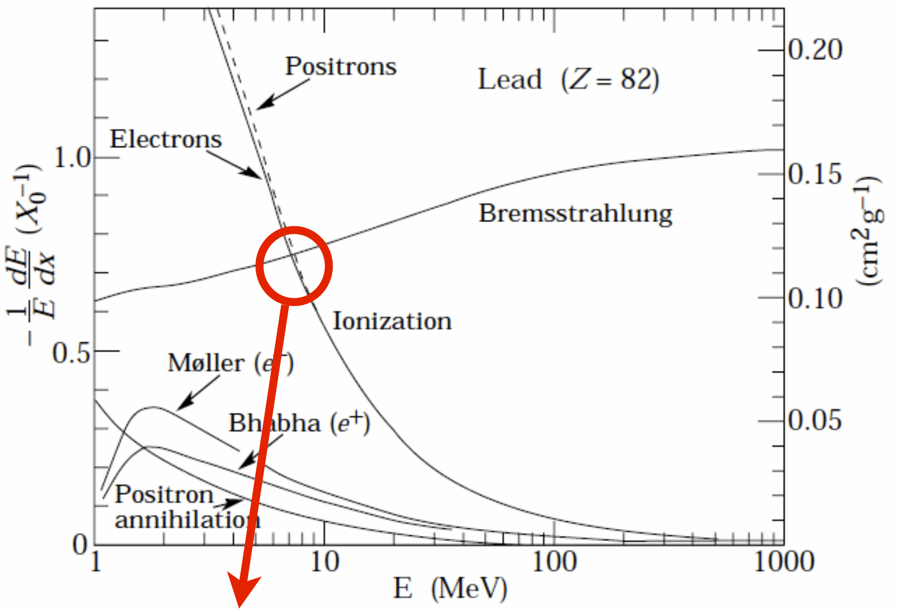
- Basic mechanism for calorimetry in particle physics:
  - formation of electromagnetic
  - or hadronic showers.
- The energy is converted into ionisation or excitation of the matter.

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

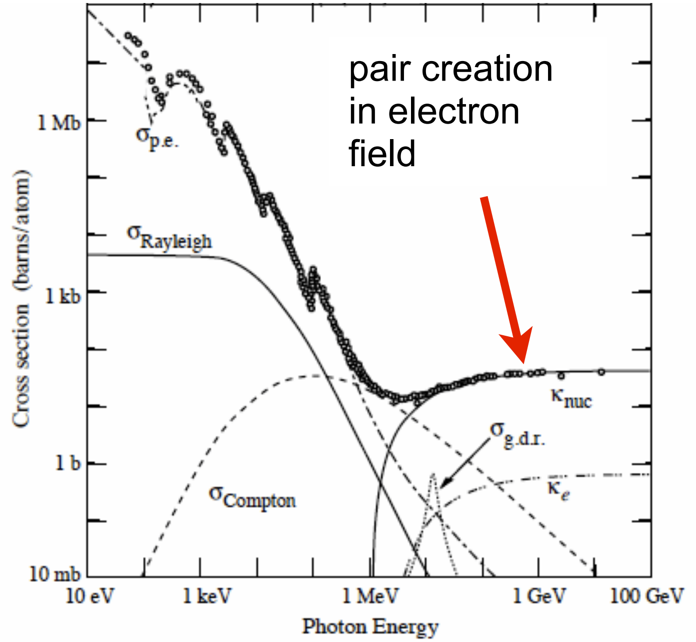
- Calorimetry is a “destructive” method. The energy and the particle get absorbed!
- Detector response $\propto E$
- Calorimetry works both for charged (e± and hadrons) and neutral particles (n,γ) !

Reminder

Electrons



Photons

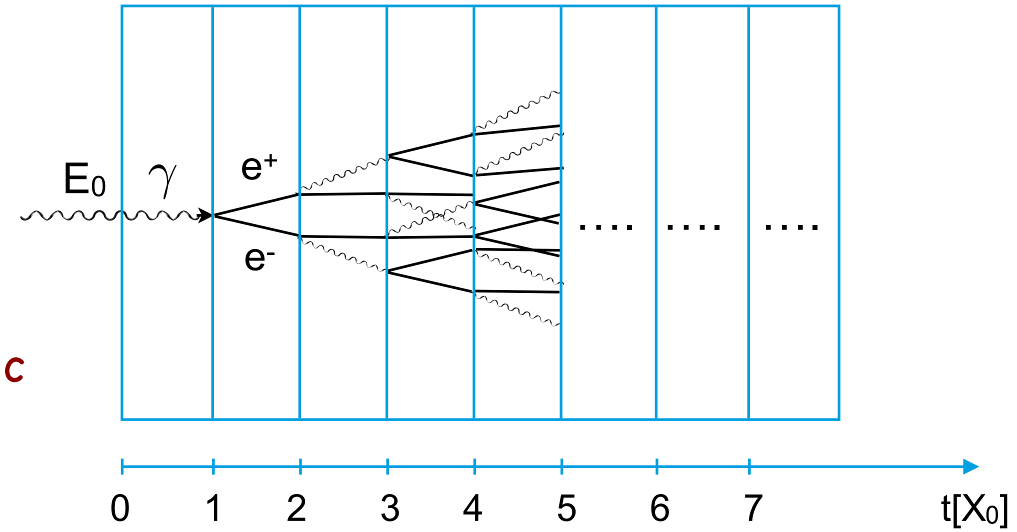


- **Critical energy:** the energy at which the losses due to ionisation and Bremsstrahlung are equal
- **Radiation length** defines the amount of material a particle has to travel through until the energy of an electron is reduced by Bremsstrahlung to 1/e of its original energy

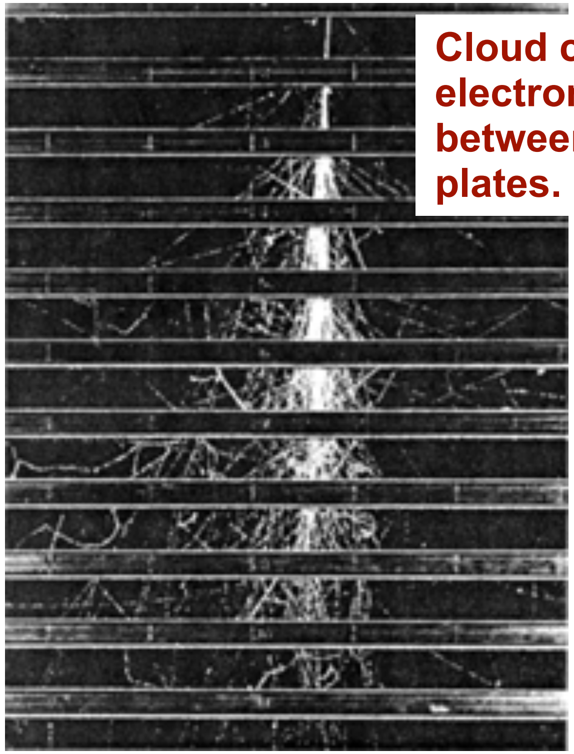
$$\langle E_e(x) \rangle \;\propto\; e^{\frac{x}{X_0}}$$

empirical: $$X_0 = \frac{716.4\,A}{Z(1+Z)\,ln(287/\sqrt{Z})}\,\frac{g}{cm^2} \propto \frac{A}{Z^2}$$

Electromagnetic Showers



X_0 is the characteristic scale



Cloud chamber photo of electromagnetic cascade between spaced lead plates.

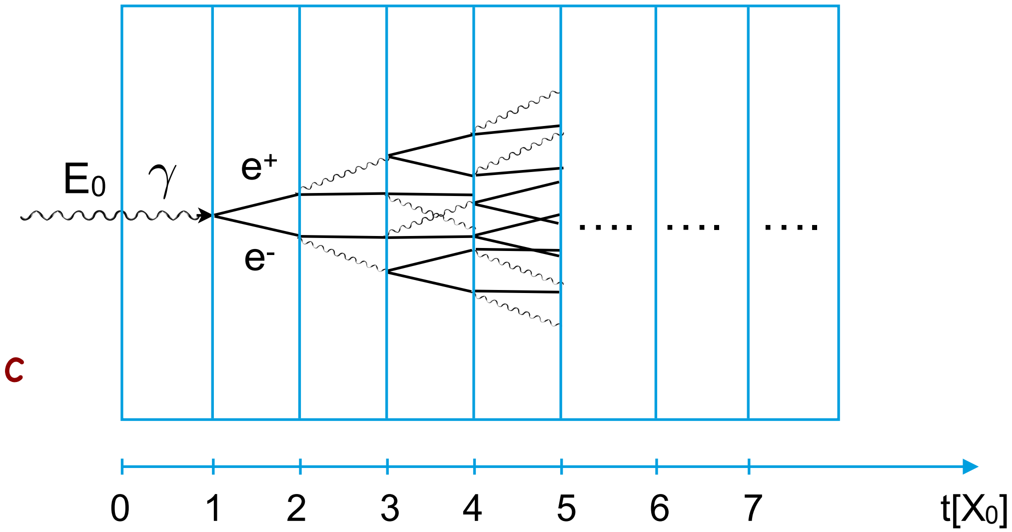
Pic: MIT cosmic ray group

- 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

Simplified model (assuming e~2)

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 $t = x/X_0$

- Number of particles after traversing depth t: $N(t) = 2^t$
- Each particle has energy: $E(t) = \frac{E_0}{N(t)} = \frac{E_0}{2^t} \rightarrow t = \ln(E_0/E)/\ln 2$
- The shower end approximately when $E \approx E_c$ $\quad E_c = E(t_{\max}) = \frac{E_0}{2^{t_{\max}}}$
- Maximum shower depth: $t_{\max} = \ln \frac{E_0}{E_c} / \ln 2$
- Maximum number of particles in shower

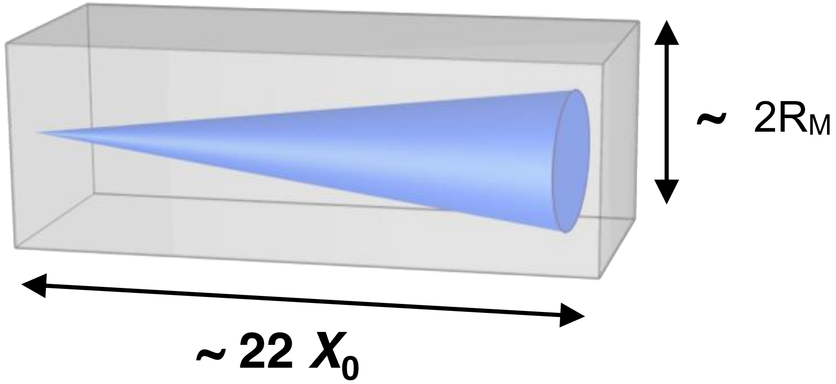
$$N_{\max} = \exp(t_{\max} \ln 2) = \frac{E_0}{E_c}$$

Example:
1 GeV photon in CsI crystal:

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

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

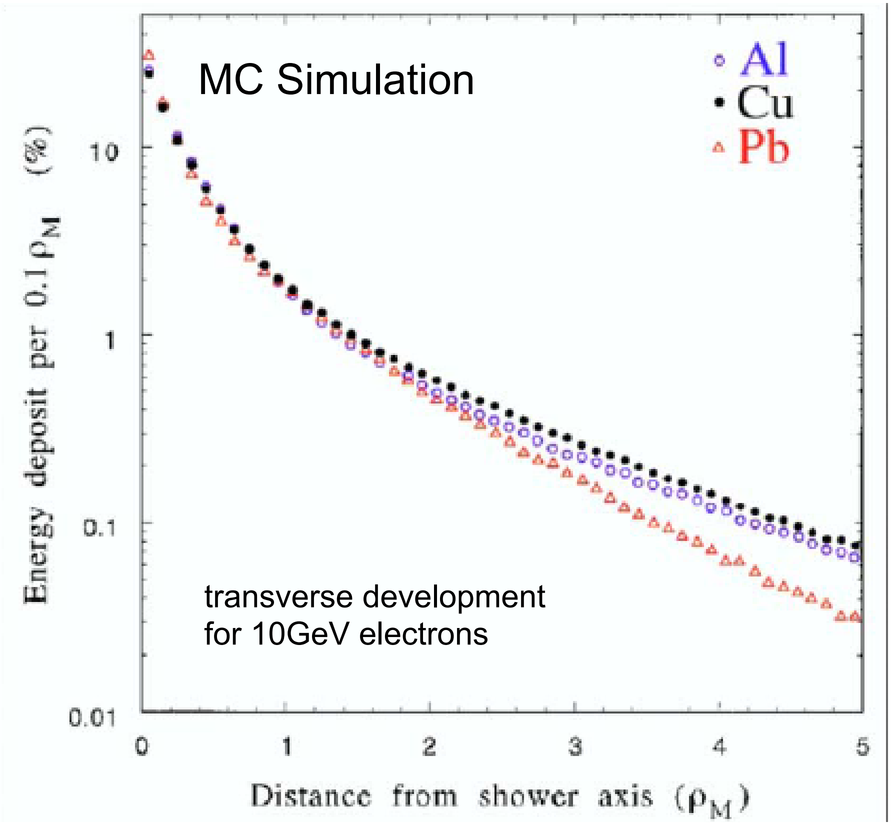


- Lateral width scales with the **Molière radius R_M**
  - Important parameter for shower separation

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

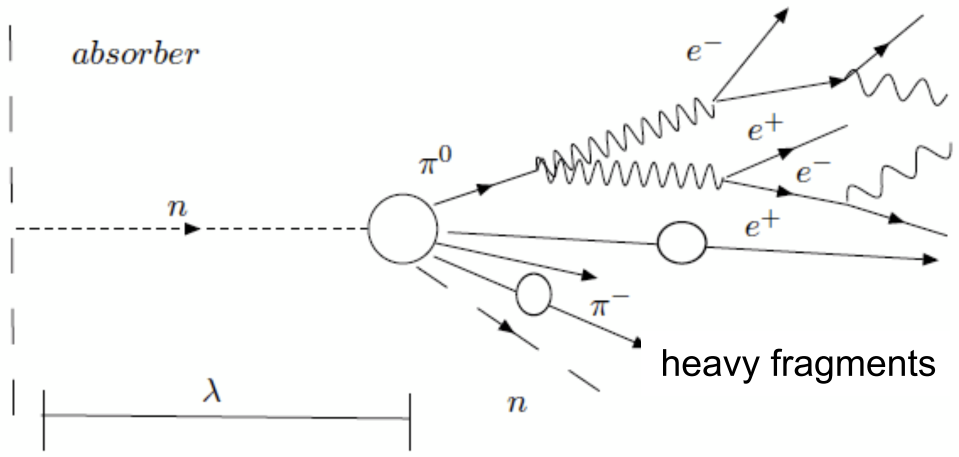
$$E_S = m_e c^2 \sqrt{4\pi/\alpha} = 21.2MeV$$

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



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

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

total cross section for nuclear processes

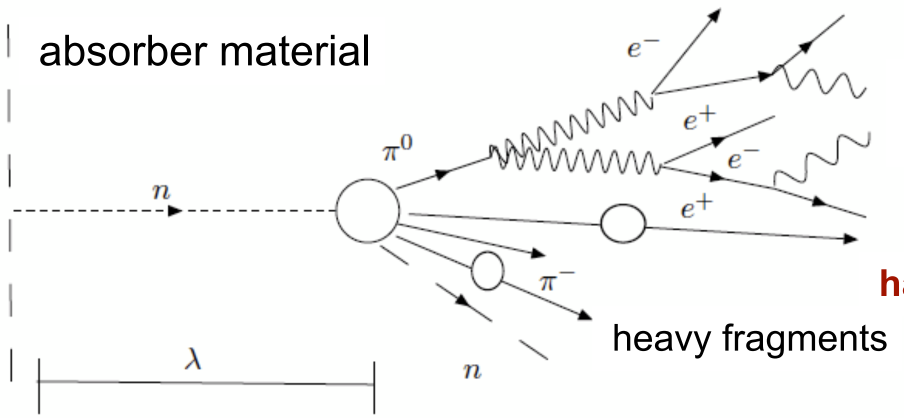
Interaction length:
Probability that no hadronic reaction happens on the path x happened:

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

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 Cascade: The Details



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

Hadronic showers are way more complicated than em showers.

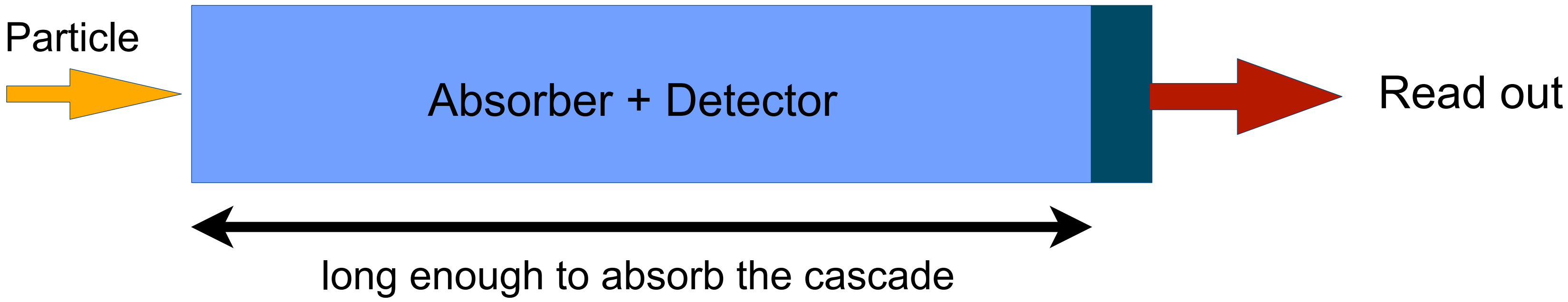
- Different processes are created by the impinging hadron:
  - high energetic secondary hadrons taking a significant part of the momentum of the primary particle [e.g. O(GeV)]
  - a significant part of the total energy is transferred into nuclear processes: nuclear excitation, spallation, ... ➠ Particles 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

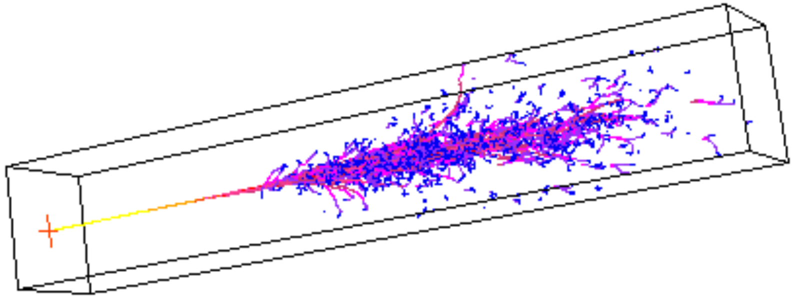
invisible energy
-> large energy fluctuations
-> limited energy resolution

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





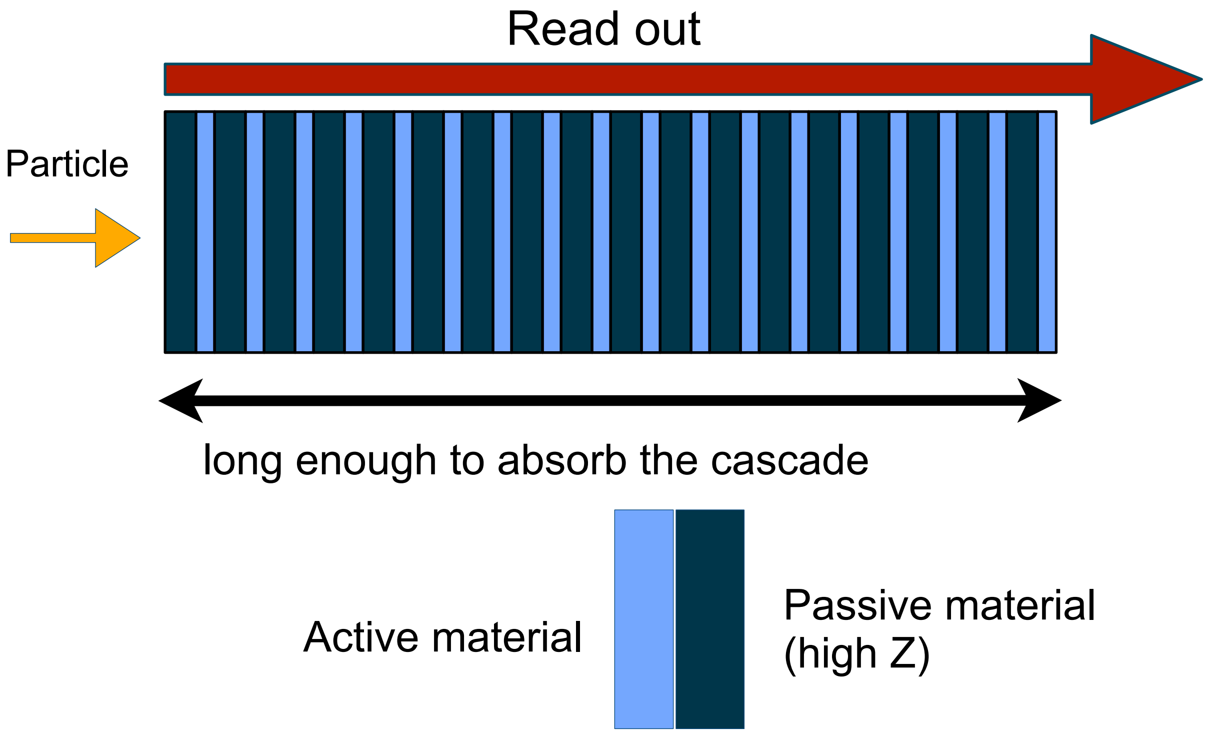
Pic: Cornell

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

Calorimeter: Important Parameter (1)

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

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

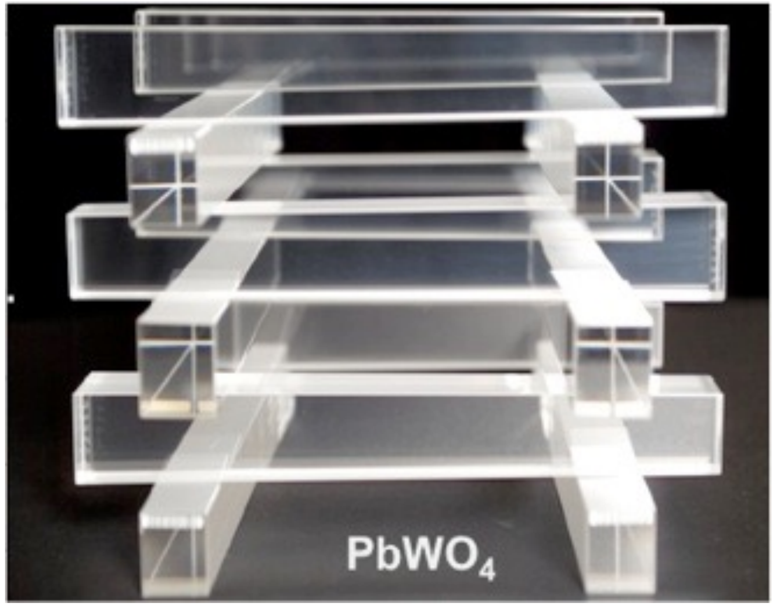
- **Stochastic** term $\mathbf{c_s}$
  - the resolution depends on intrinsic shower fluctuations, photoelectron statistics, dead material in front of calo, and sampling fluctuations
- **Noise** term $\mathbf{c_n}$
  - Electronic noise, radioactivity, i.e. dependent of the energy
- **Constant** term $\mathbf{c_c}$
  - Energy independent term contributing to the resolution: due to inhomogeneities with in the detector sensitivity, calibration uncertainties and radiation damage

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.
- ….

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.

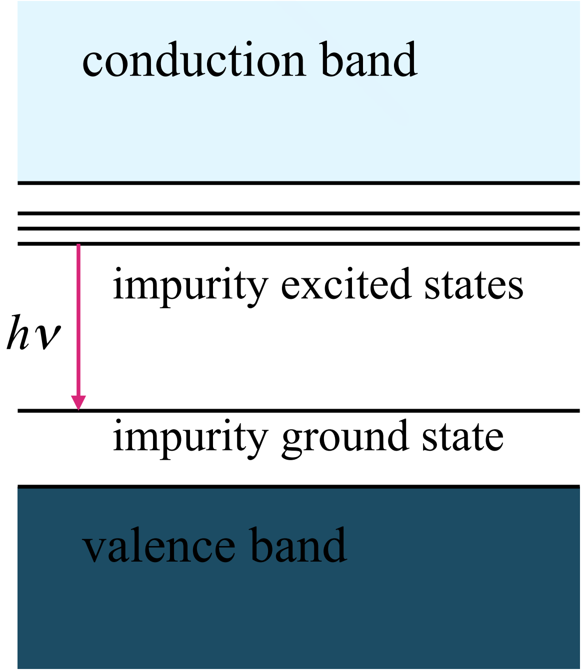


Picture: CDF@Fermilab

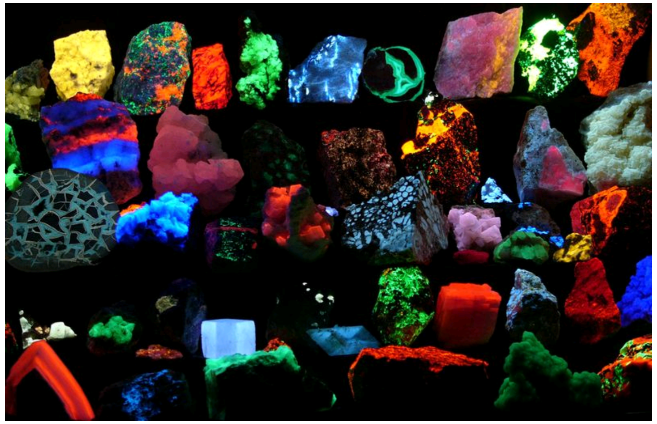
- $PbWO_4$: Fast, dense scintillator,
  - Density ~ 8.3 g/cm^3 (!)
  - ρ_M 2.2 cm, X_0 0.89 cm
  - low light yield: ~ 100 photons / MeV

Scintillators to measure the energy

- An incident photon or particle ionises the medium (on band structure level).
- Ionised electrons slow down causing excitation.
- Excited states immediately emit light.



Inorganic scintillators



- Fluorescence is known in many natural crystals.
  - UV light absorbed
  - Visible light emitted
- Artificial scintillators can be made from many crystals.
  - Doping impurities added
  - Improve visible light emission

Advantages:
- Good efficiency
- Good linearity
- Radiation tolerance

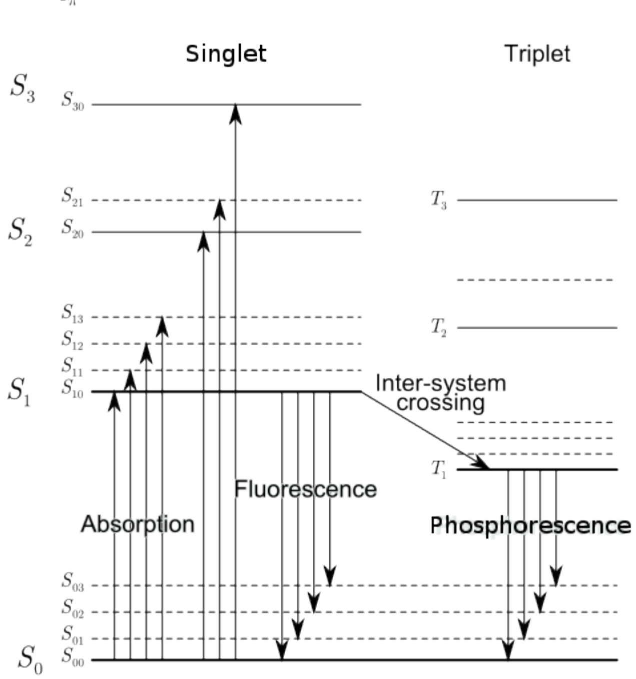
Disadvantage:
- Relatively slow
- Crystal structure needed (small and expensive)

Scintillators to Measure the Energy

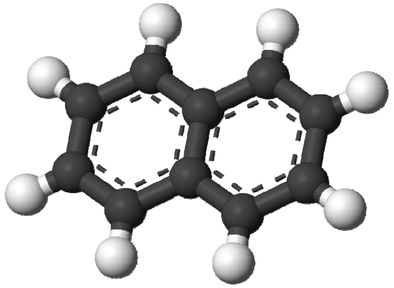
Active material

- Very common: Measurement of the deposited energy using scintillation

Organic scintillators



source: Wikipedia



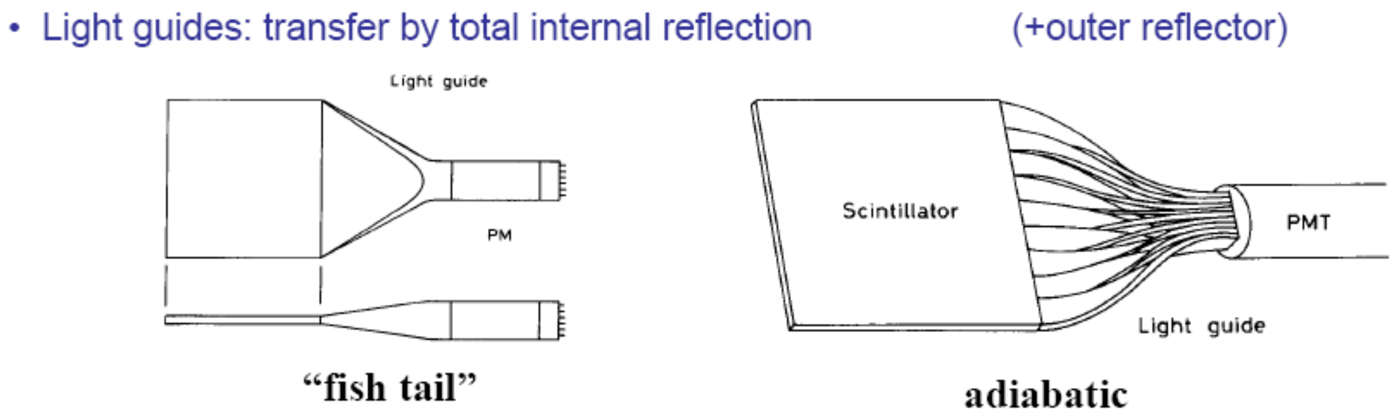
- Organic scintillators are aromatic hydrocarbon compounds (containing benzene ring compounds)
- The scintillation mechanism is due to the transition of electrons between molecular orbitals
  - organic scintillators are fast ~ few ns.
- Excited states radiate photons in the visible and UV spectra.
  - Fluorescence is the fast component
  - Phosphorescence is the slow component

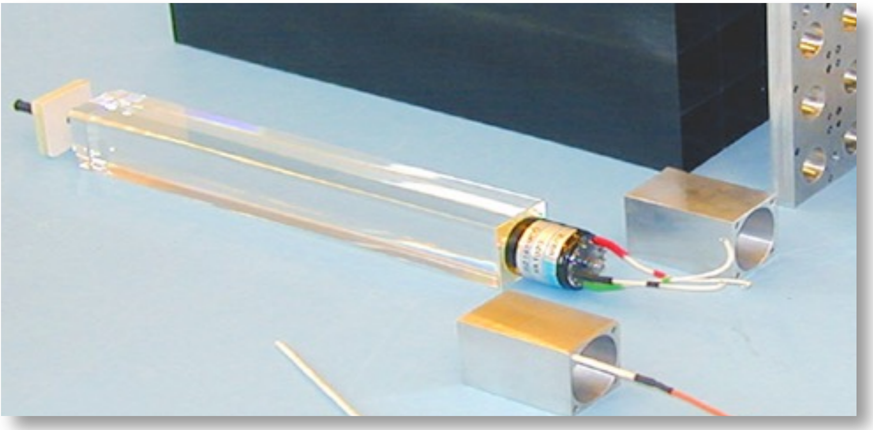
Advantages:
- very fast

Disadvantage:
- inefficient
- non-linear
- not good for photons

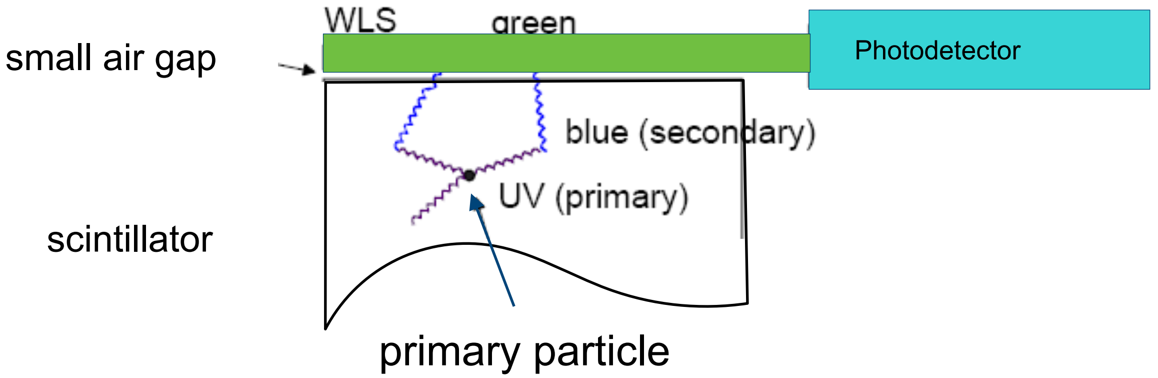
Light transport

- The photons are being reflected towards the end of the scintillator
- A light guide brings the light to a Photomultiplier



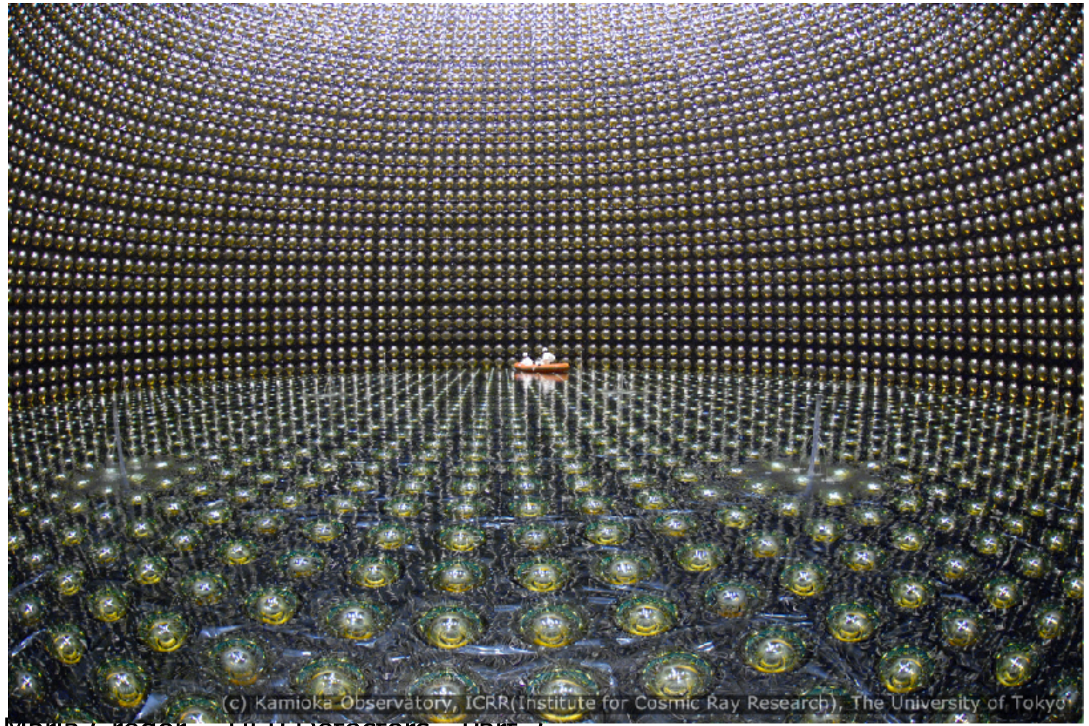


- UV light enters the light guide material
- Light is transformed into longer wavelength (wavelength shifter)
- -> Total internal reflection inside the WLS material
- -> 'transport' of the light to the photo detector

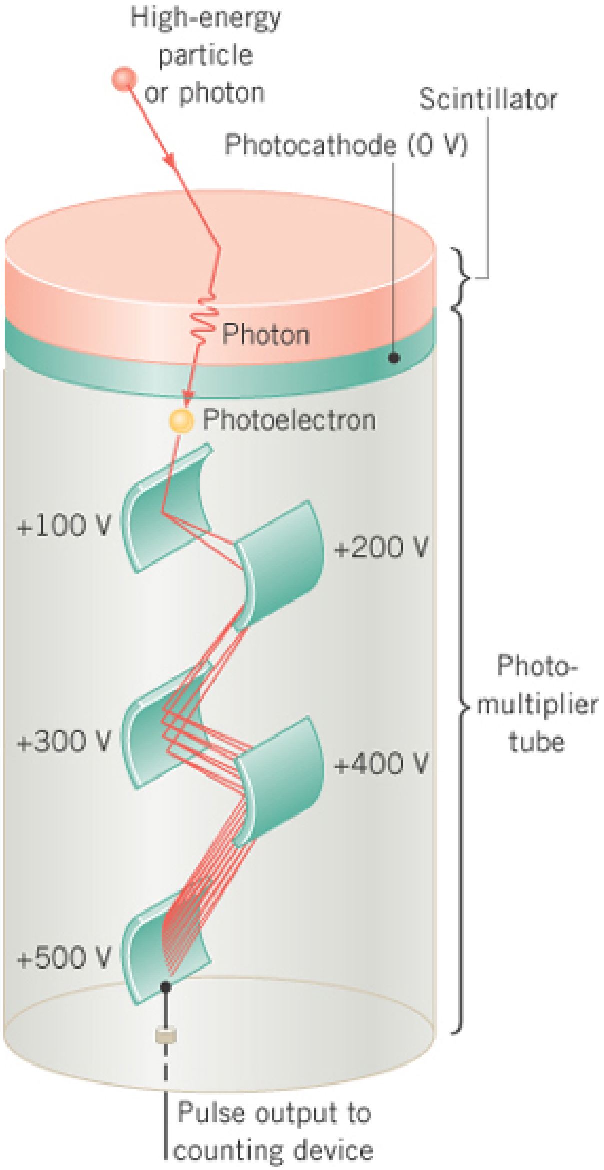


Detecting the Light

- The classic method to detect photons are photomultipliers
  - Conversion of a photon into electrons via photo-electric effect when the photon impinges on the photo cathode
  - 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



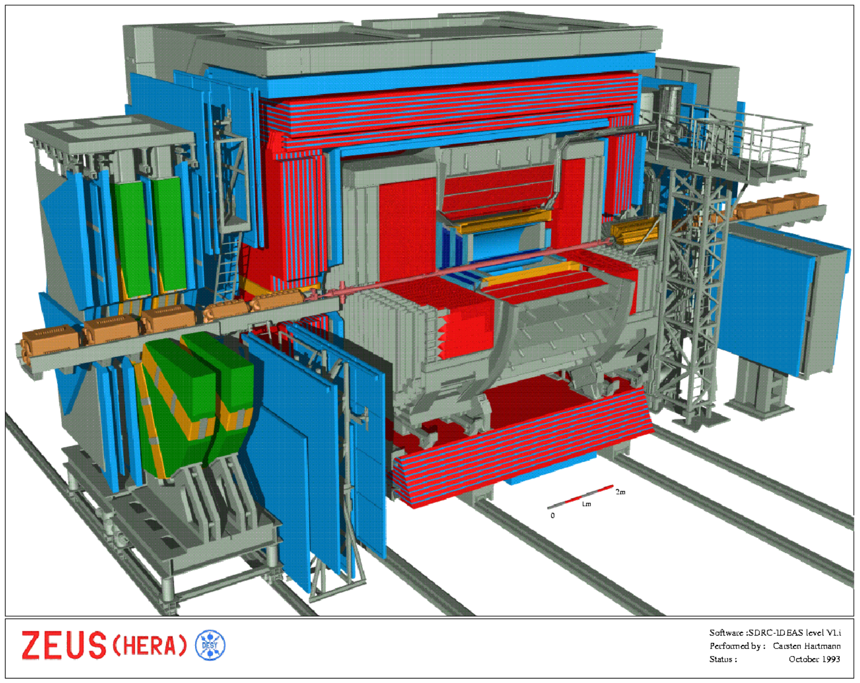
Source: Cutnell and Johnson, 7th edition image gallery

Examples

Example: ZEUS Calo

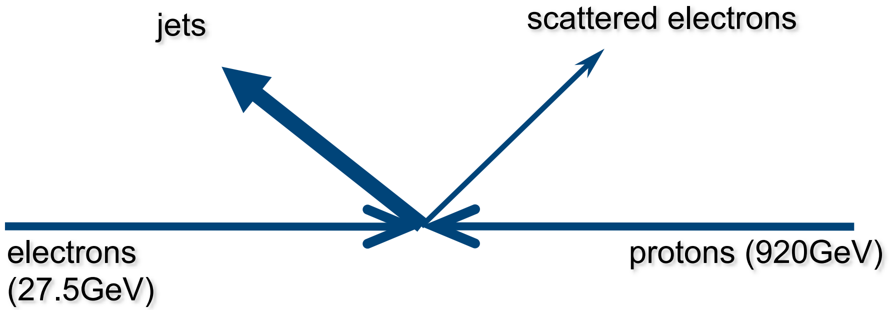
A rather hostile environment in ZEUS at HERA

- bunch crossing every 96ns
- high beam gas rate
- very energetic particles produced



Requirements for the ZEUS calorimeter:

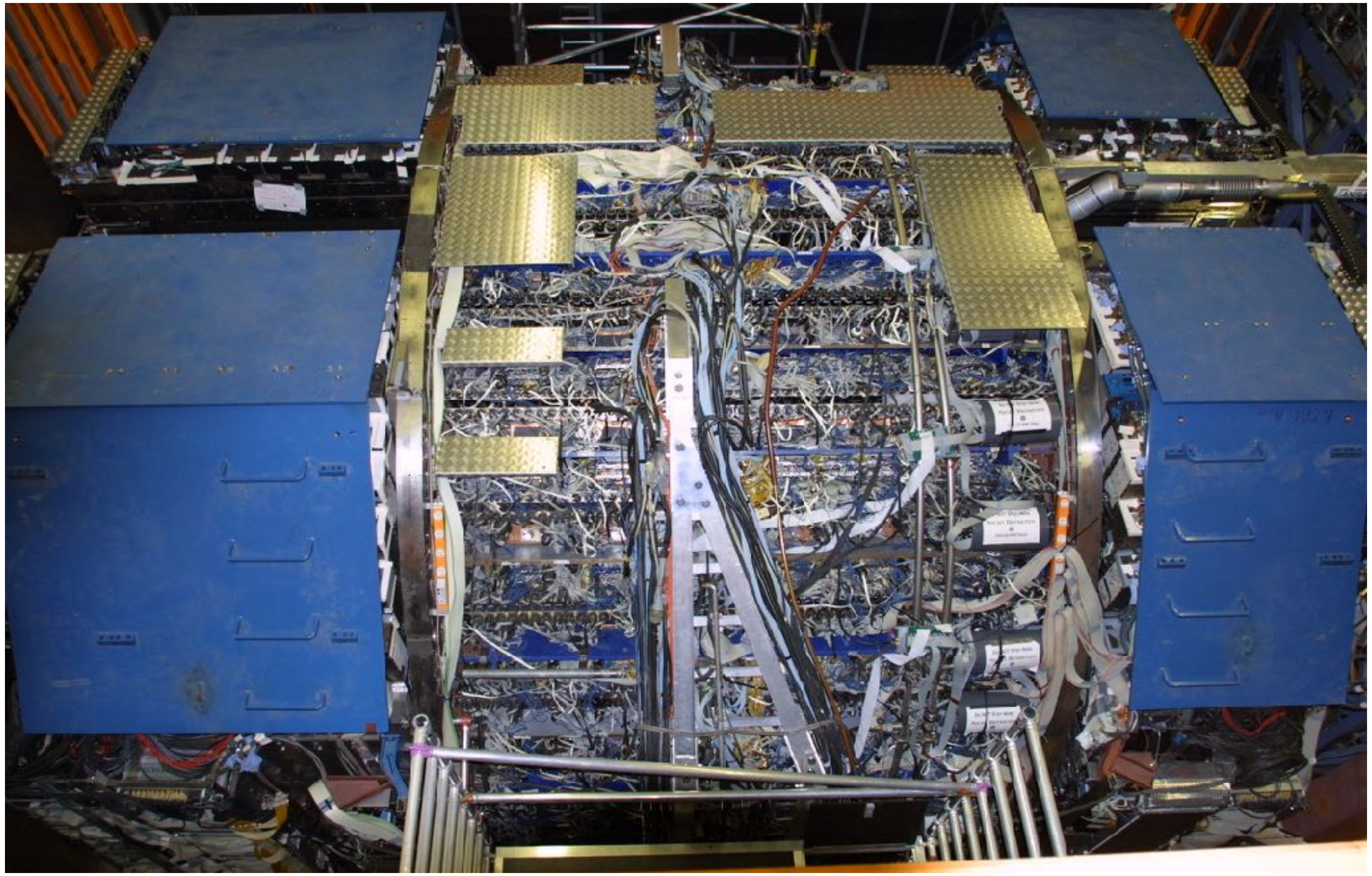
- hermeticity
- dead time free readout
- time resolution in nanosecond range
- uniform response
- radiation tolerance (15 years of running)
- electron-hadron separation
- good position resolution
- good electron and jet energy resolution



Keep in mind: this was developed in the middle of the 80s!

The ZEUS Calorimeter - Solution

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



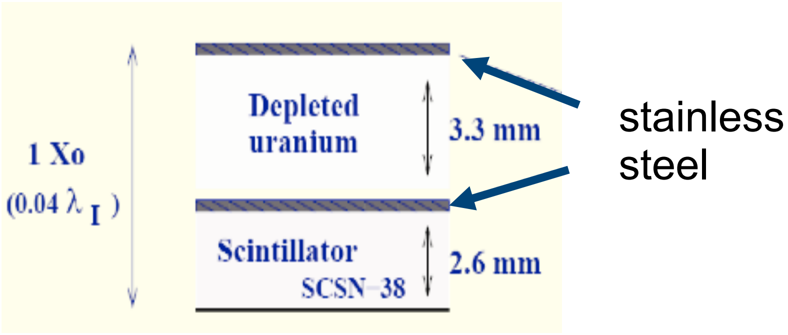
Uranium + Scintillator:

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

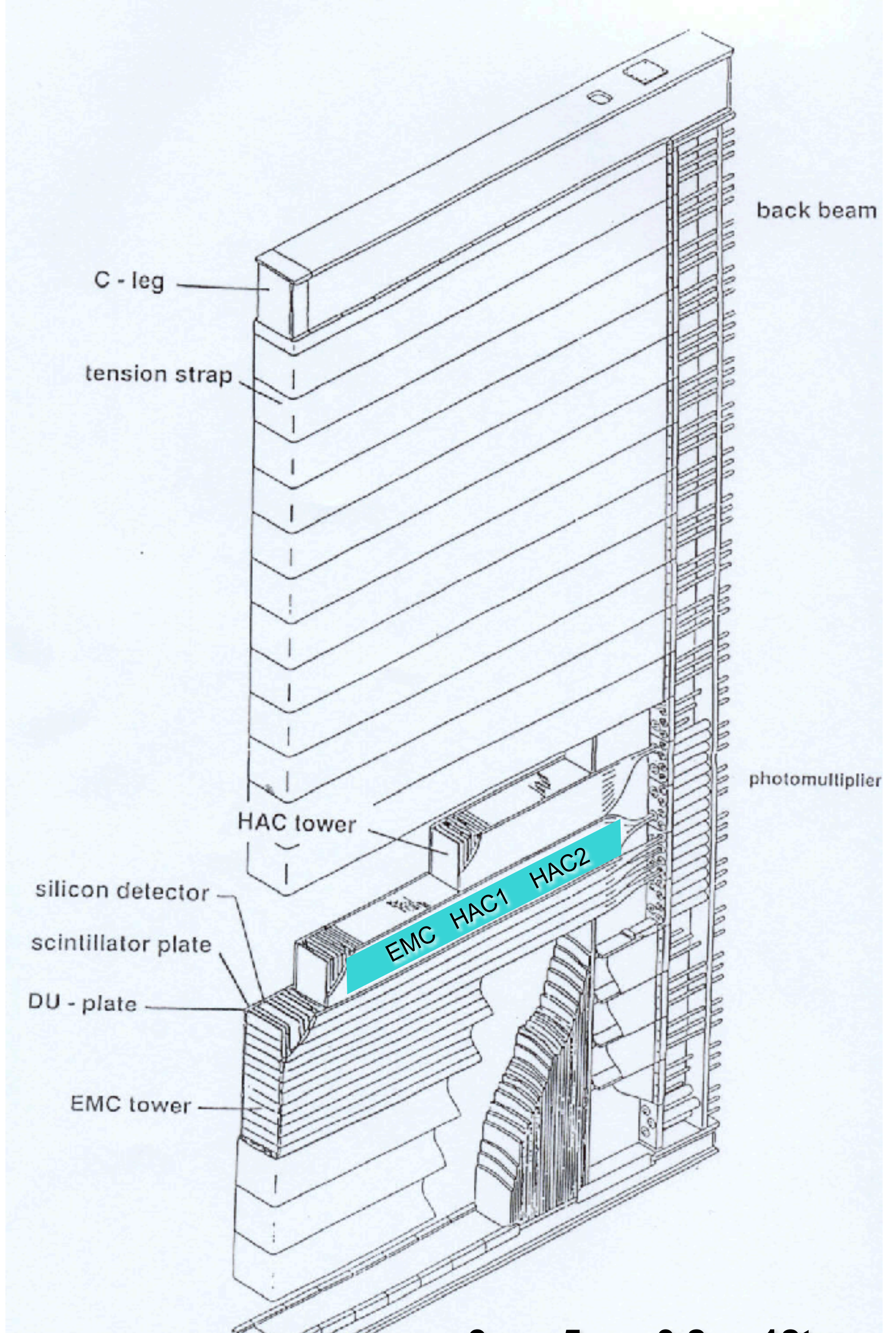
- Very hermetic: covering up to $\eta<4.2$ in the forward direction and $\eta<-3.8$ in the rear direction.
- Readout by 12,000 phototubes (PMTs)

Design

- Layers:



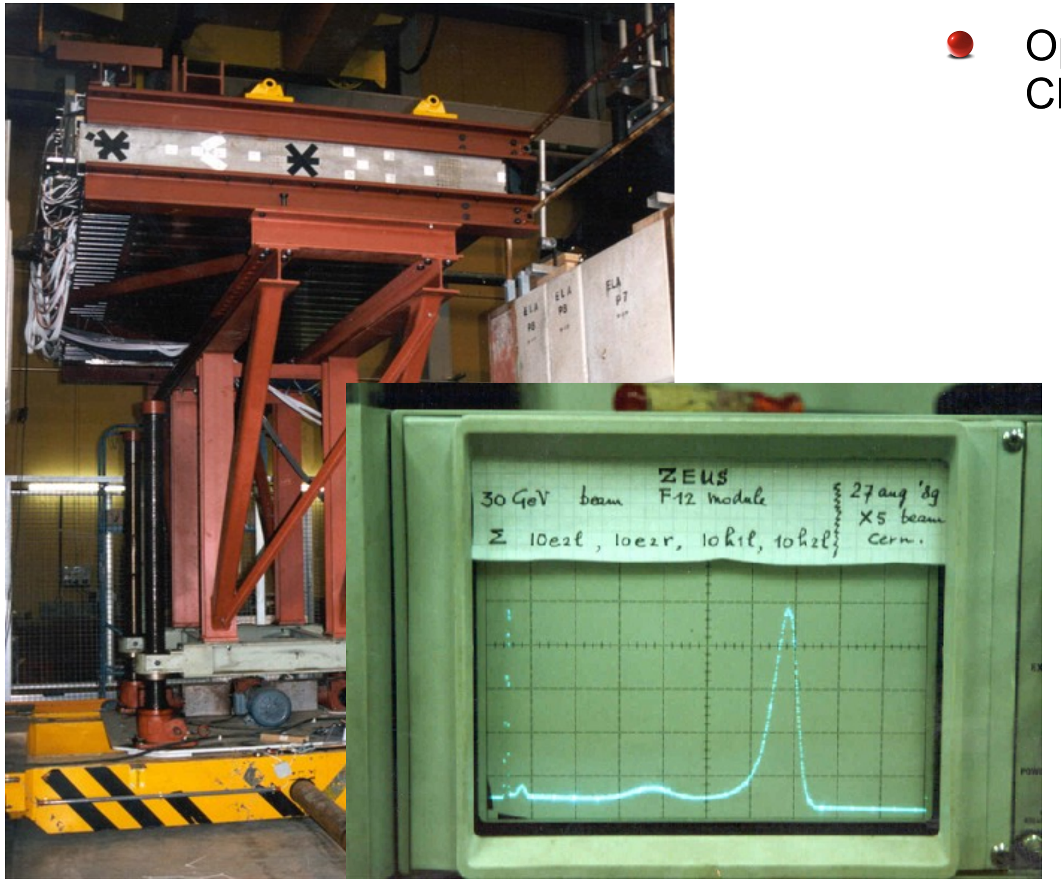
- Choice of active and passive thicknesses -> compensation (e/h = 1.0
- Uniformity in structure + natural radioactivity -> good calibration
- F/B/RCAL with ~6000 cells
  - EM cell size: 5x20 (10x20) cm2 in F/BCAL (RCAL)
  - HA cell size: 20x20 cm2



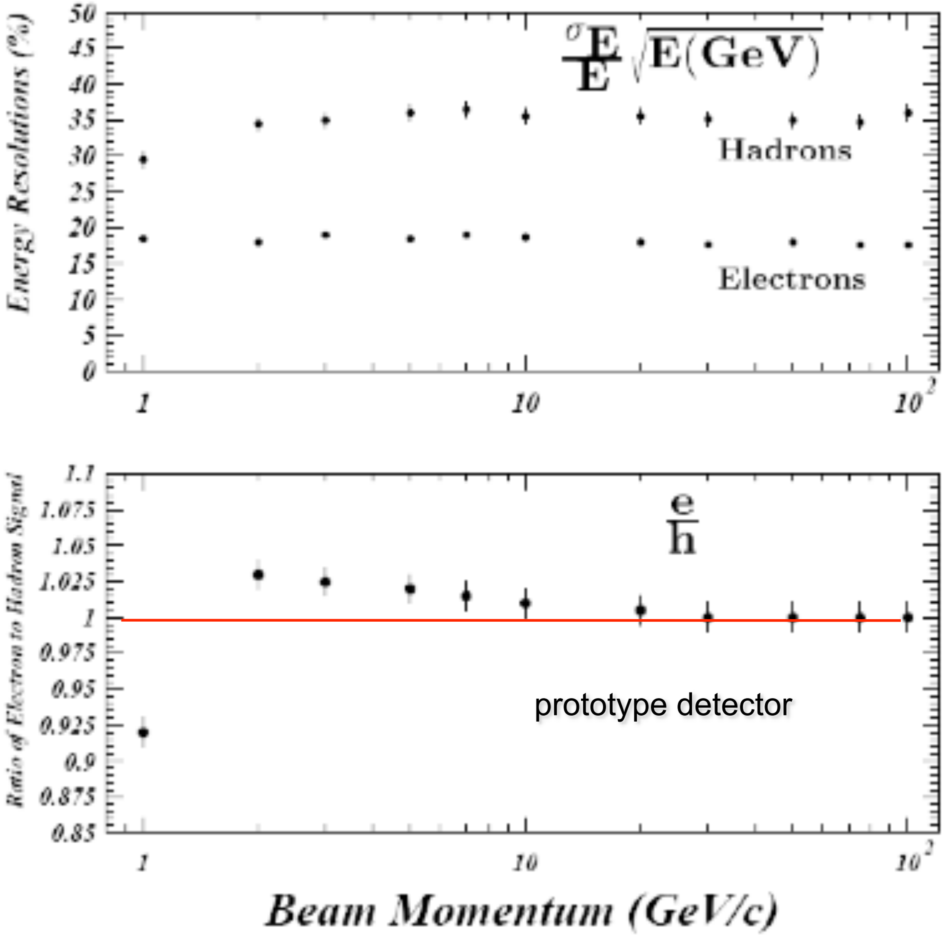
3m x 5m x 0.2m, 12tons
total of 80 modules

- Cell read out on both sides with wavelength shifters
  - redundancy
  - transverse position measurement within the cell

Test beam at CERN



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



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

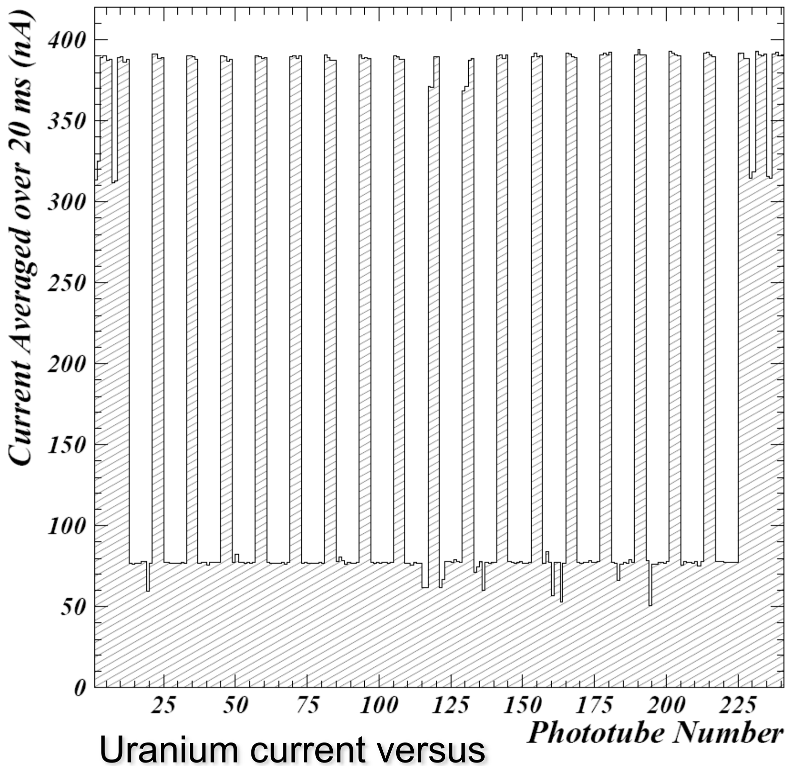
Hadrons: $$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

Production modules were all calibrated at CERN

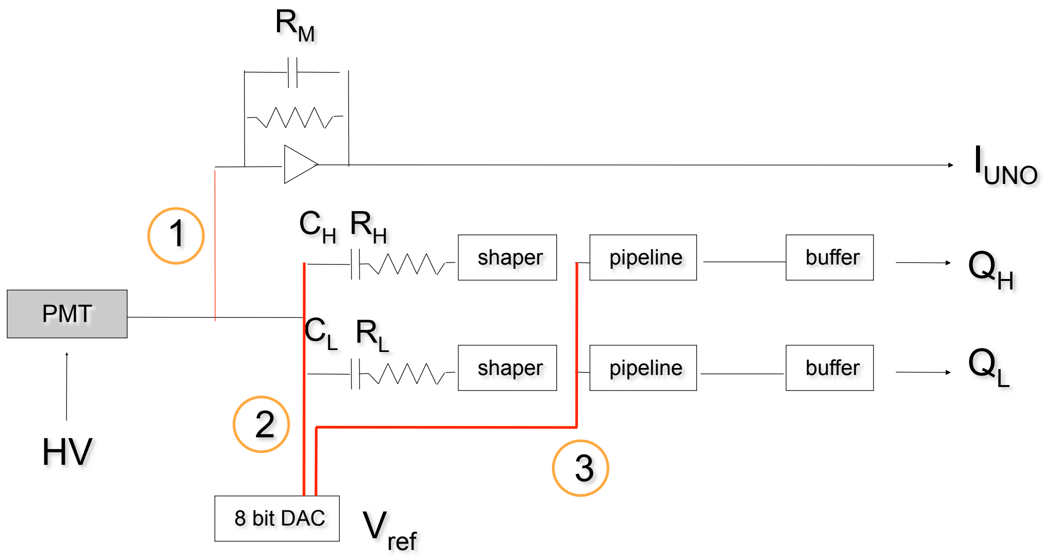
Calibration Methods

Stable radioactivity
- good for calibration

- Natural uranium activity provides absolute energy calibration in situ!
  - 98.1% U238 + 1.7% Nb + 0.2% U235
  - Half-Life of U238 is 4.5 *109 years
- Detectable uranium induced signal current
- Uranium noise signal
  - ~ 2MHz (EM Calo)
  - ~10MHz (Hadronic Calo)
  - with Uranium noise calibration can be tracked very easy



Uranium current versus channels of one module



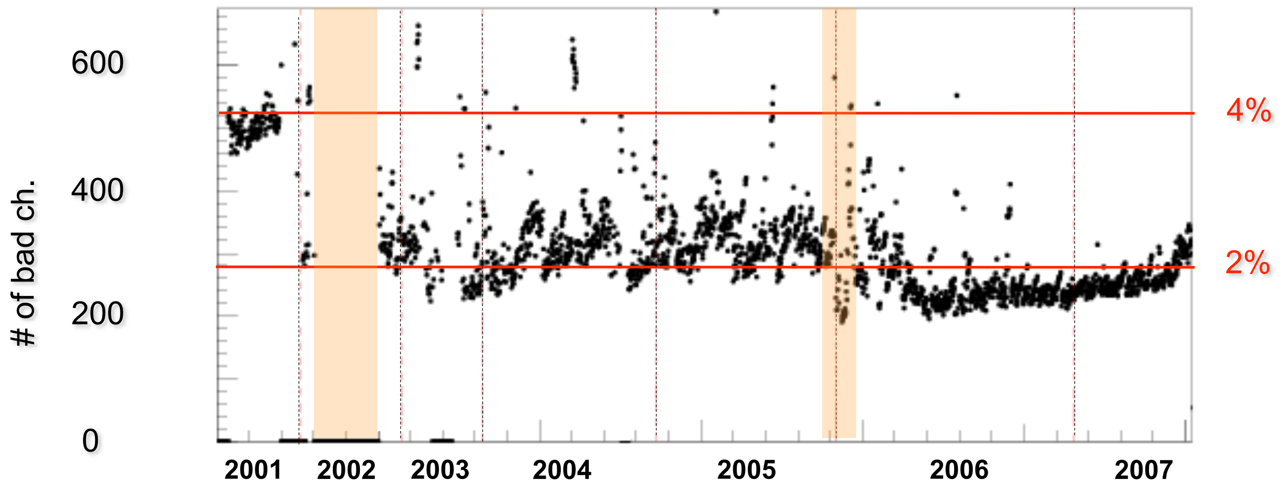
1 Uranium noise

2 Charge injection

3 Pedestals and Gains

Channels out of range
-> declared as “bad” until readjusted

Hardware Performance



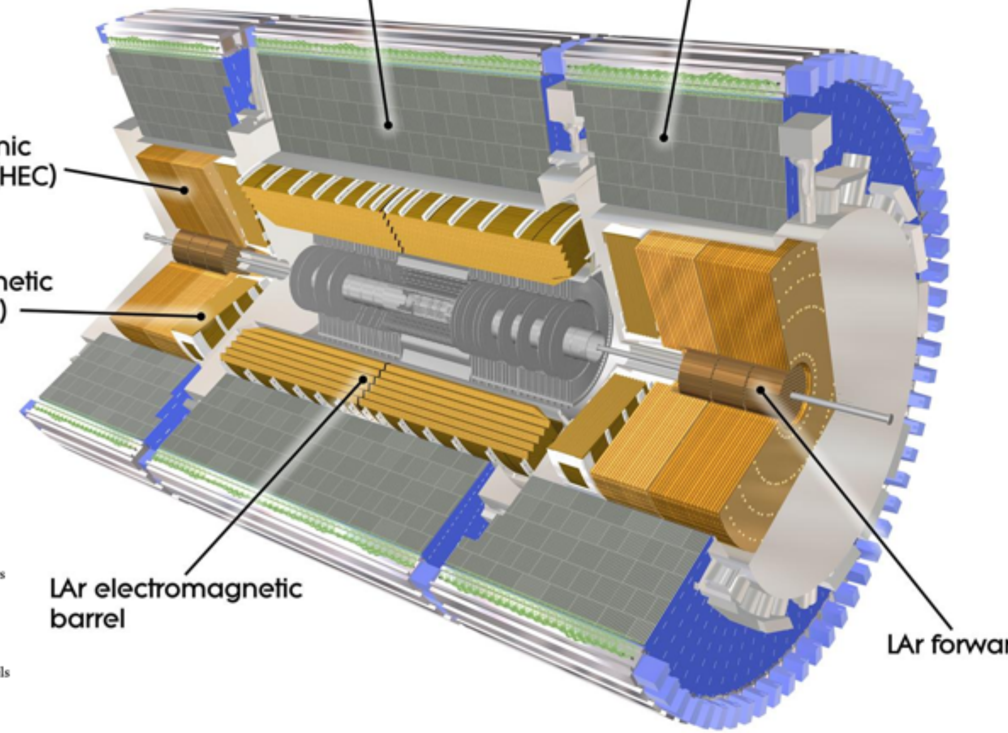
- Number of bad channels versus run number (over years)
- “Bad channels” are excluded from data taking -> reducing the calo performance in that area
- Read out from both sides -> bad channel is not complete loss of information
- Ups and downs visible in bad channel behaviour over the years

- At the time of the shutdown (30.06.2007):
  - only ~ 2% bad channels (one side) and only 2 holes (both sides failed) -> 0.3 per mille
- **In general very stable and robust system**

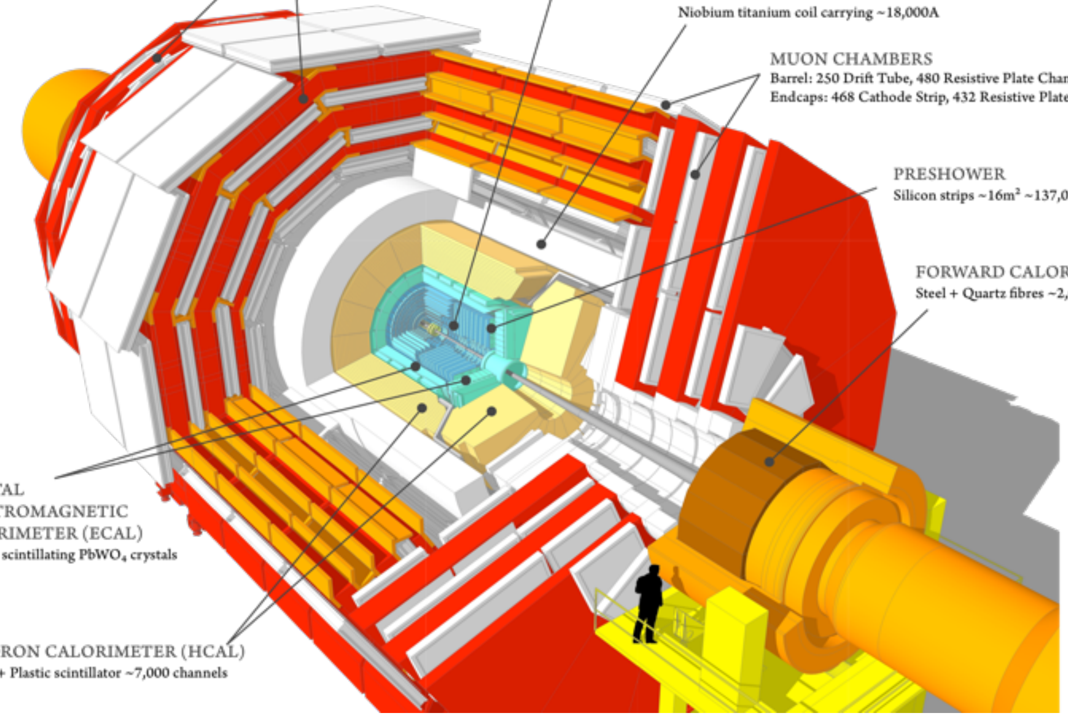
- Front End Cards:
  - About 1000 necessary for the running, ~10% spares
  - Main failure mode: buffer or pipeline chip (socketed)
  - Cards easy to debug and maintain
  - Failure rate: <1/month (12 channels – one side)
  - Very successful

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

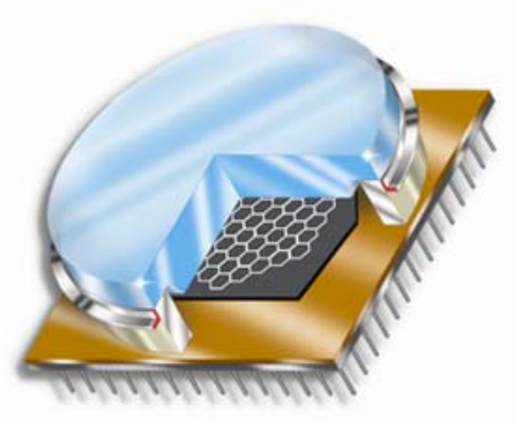


CMS

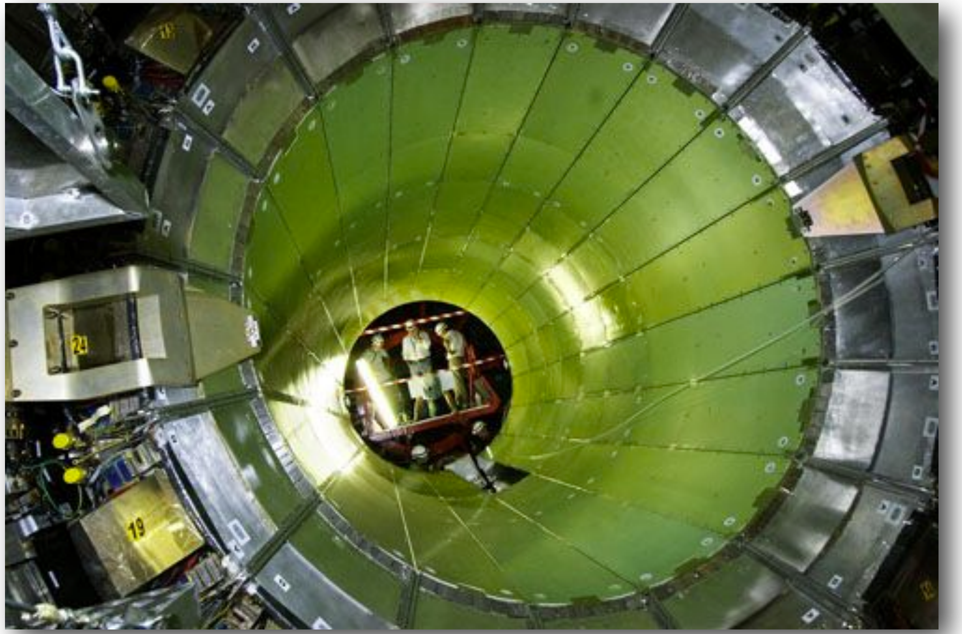


CMS Calorimeter

- **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)

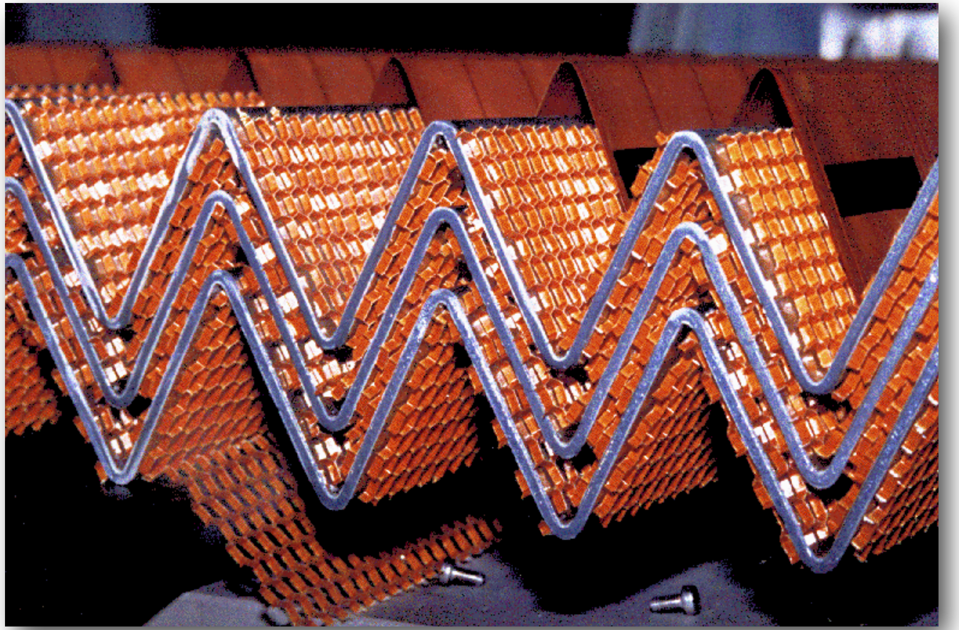


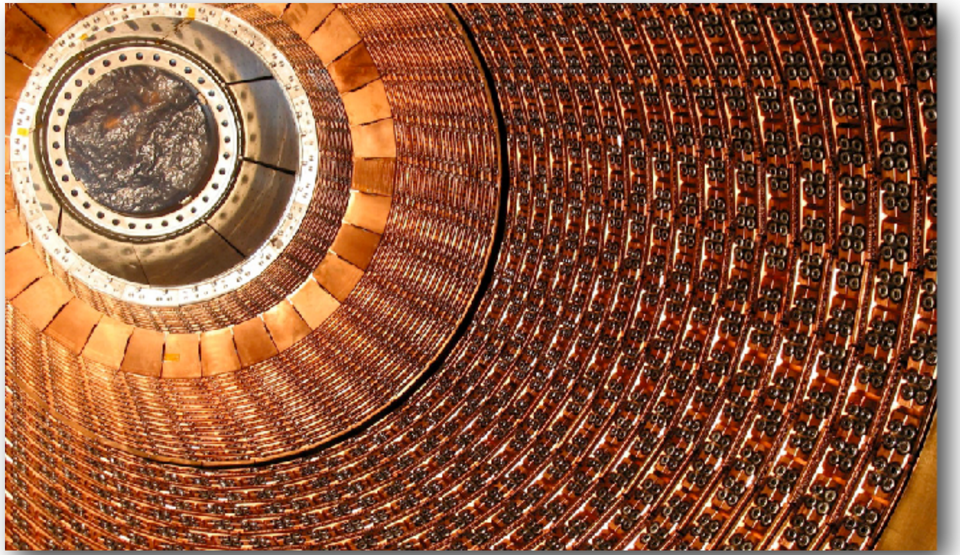
CMS ECAL during installation (CERN)

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

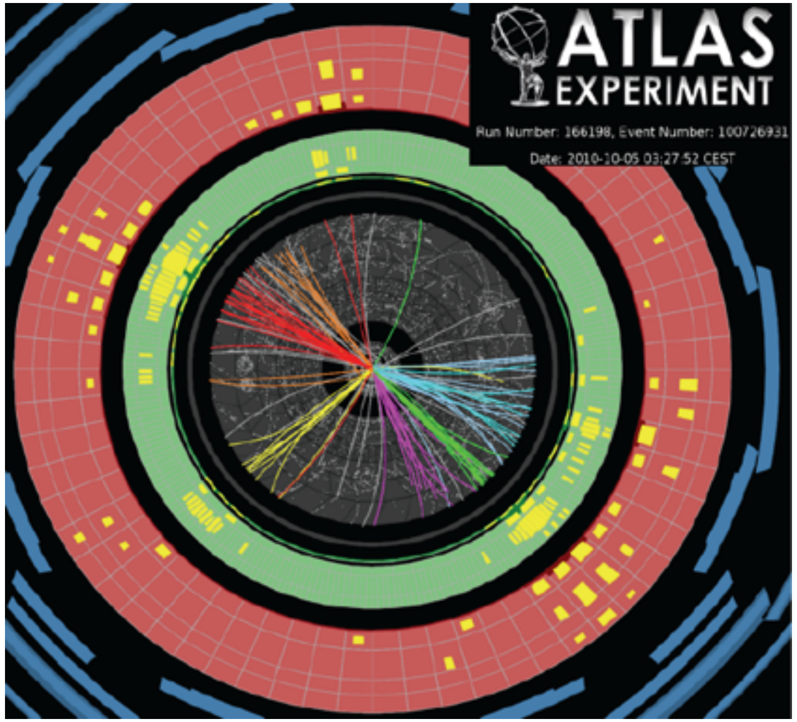
  - Tile calorimeter: covering outer region
  - "Conventional" steel absorber with plastic scintillators.

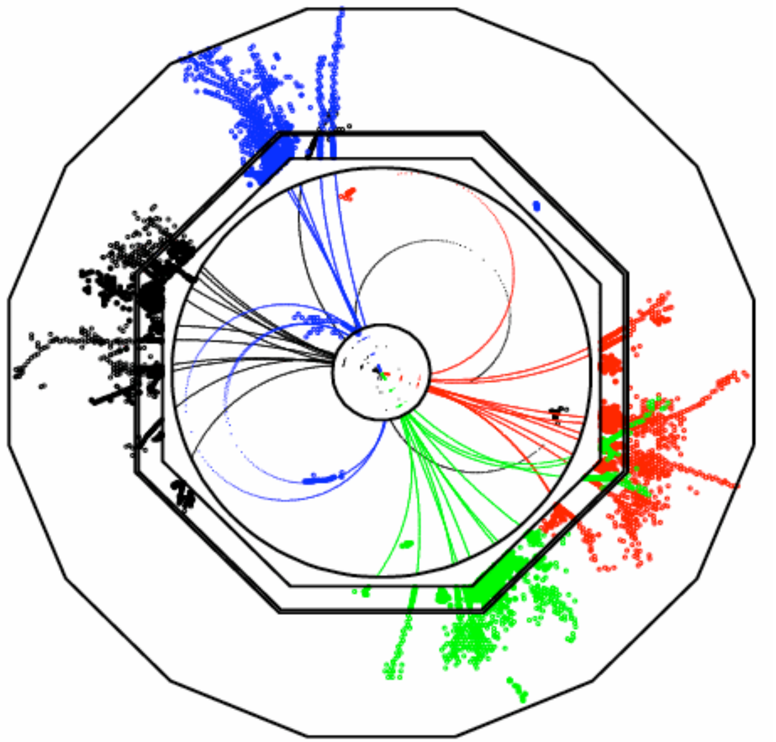




ATLAS Hadronic endcap Liquid Argon Calorimeter. (CERN)

Current Hadron Calos ... and Dreams





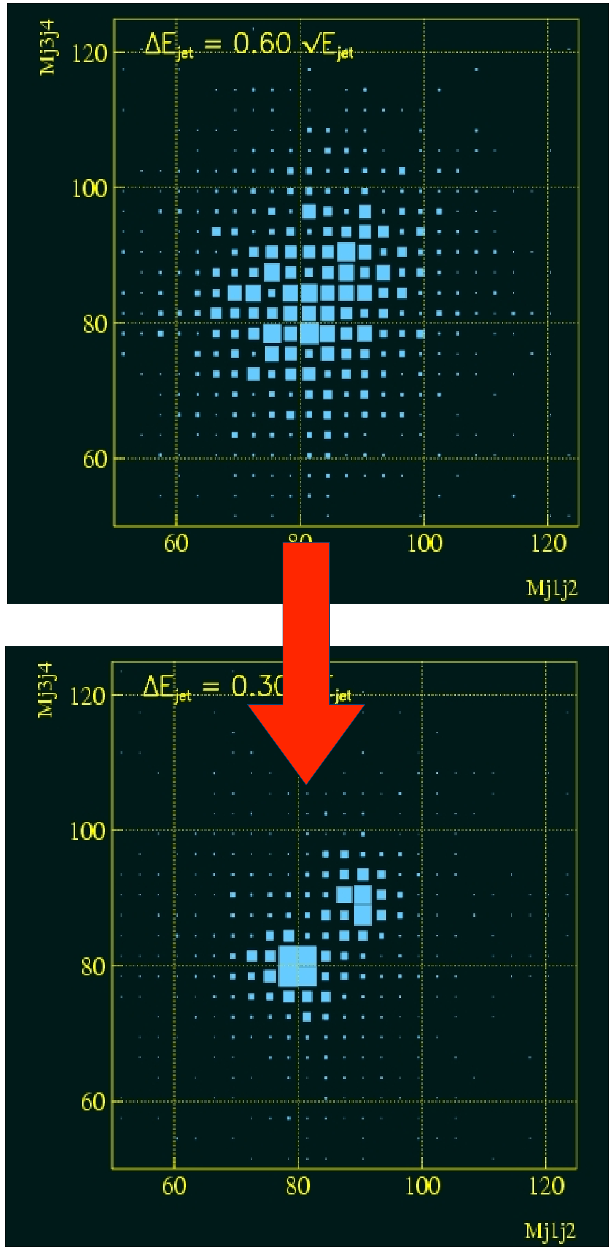
- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT) O(10k) channels for full detectors
- Extreme granularity to see shower substructure: small detector cells with individual readout for Particle Flow O(10M) channels for full detectors

Particle Flow Calorimeter

- Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution

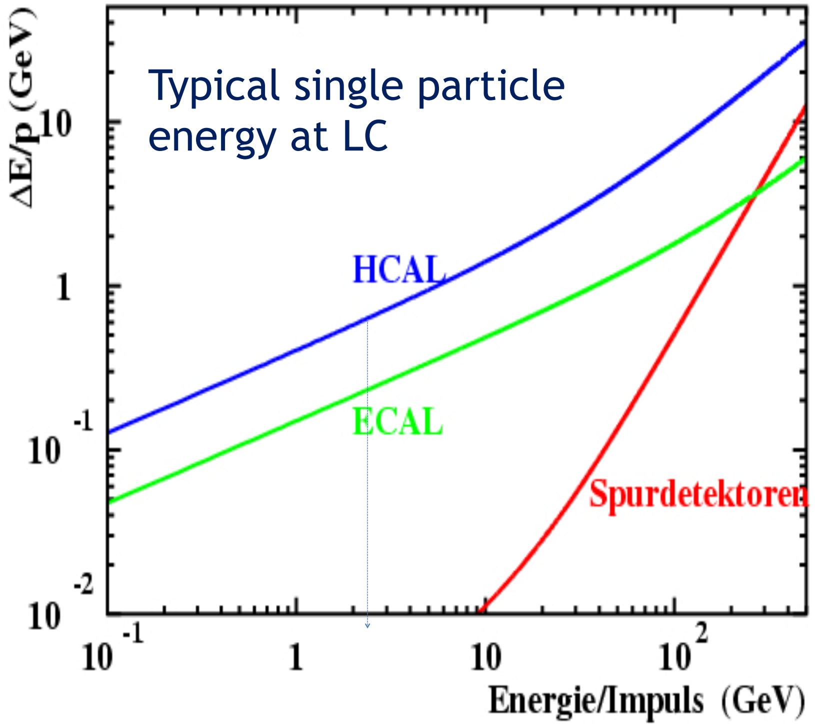
- Used in three main contexts:
  - “Energy flow” -> Use tracks to correct jet energies
  - “Particle flow/Full event reconstruction” e.g. CMS
    -> Aim to reconstruct particles not just energy deposits
  - “High granularity particle flow” e.g. ILC
    -> Technique applied to detector concept optimised for particle flow

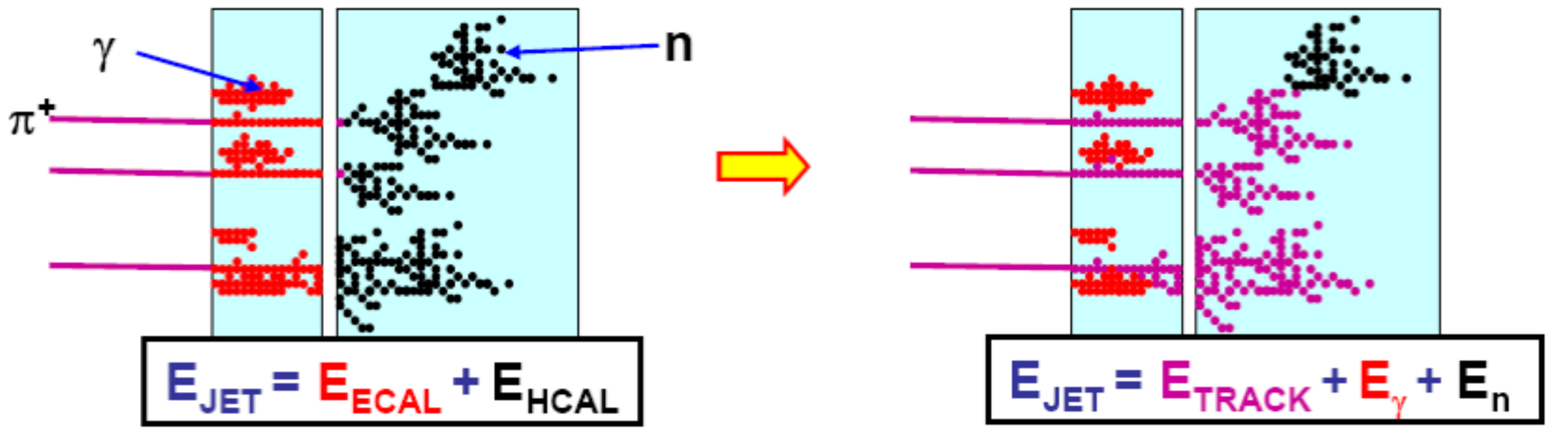
- Need
  - a calorimeter optimised for photons: separation into ECAL + HCAL
  - to place the calorimeters inside the coil (to preserve resolution)
  - to minimise the lateral size of showers with dense structures
  - the highest possible segmentation of the readout
  - to minimise thickness of the active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



Particle Flow paradigm

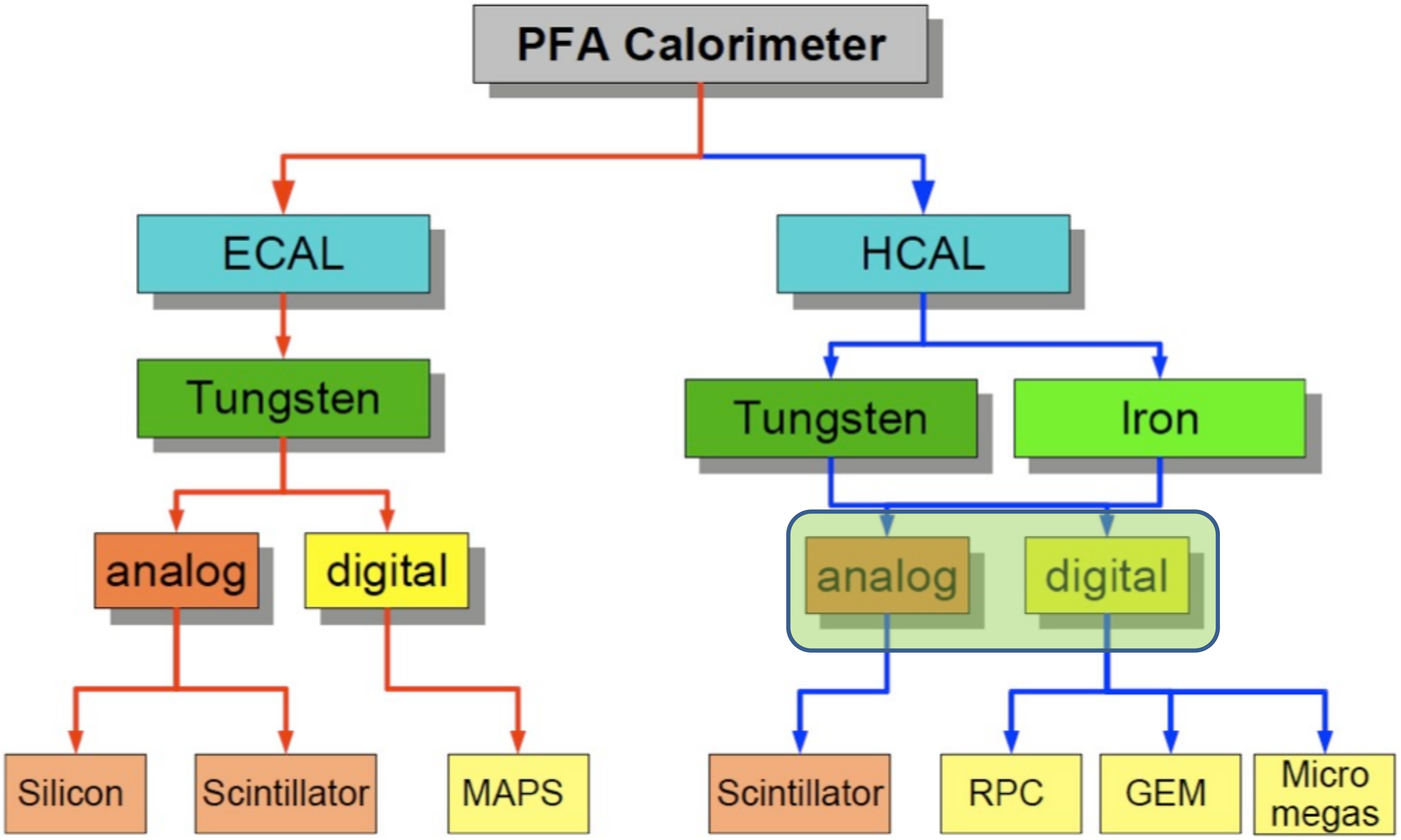
- Reconstruct **every** particle in the event
- Up to ~100 GeV **Tracker** is superior to calorimeter
  - use tracker to reconstruct **$e^\pm$,$\mu^\pm$,$h^\pm$** (<65%> of E_{jet}
  - use **ECAL** for γ reconstruction (<25%>)
  - use (**ECAL+**) **HCAL** for **h^0** reconstruction (<10%>)
- HCAL E resolution still dominates E_{jet} resolution
- But much improved resolution (only 10% of E_{jet} in HCAL)





PFLOW calorimetry = Highly granular detectors + Sophisticated reconstruction software

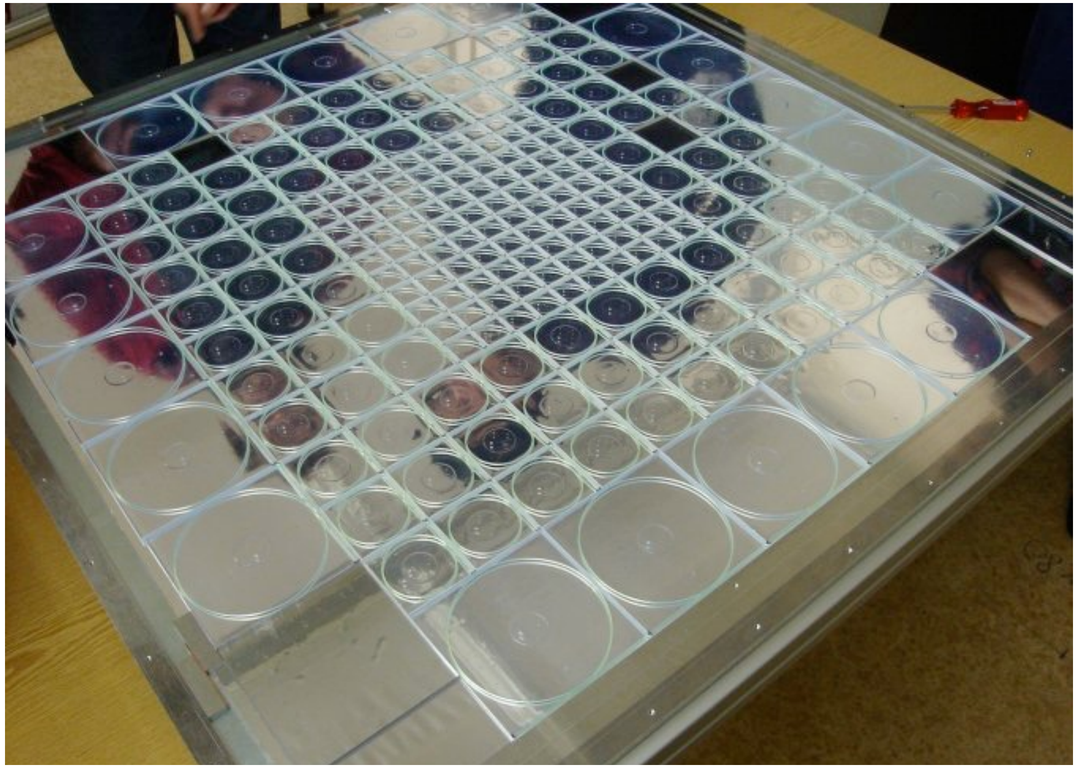
The zoo of PFLOW calorimeters



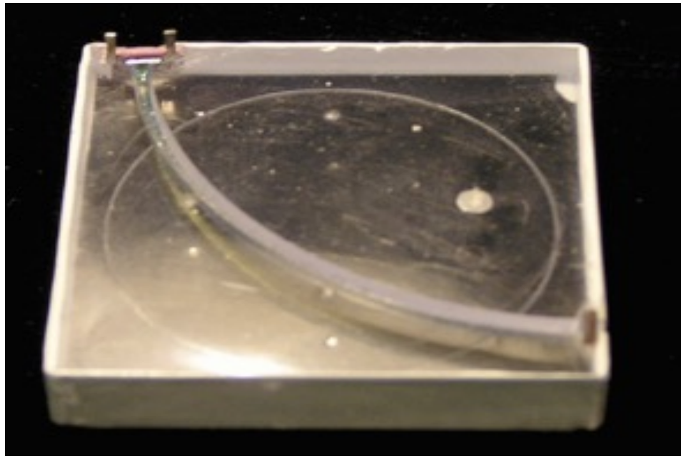
NEW CONCEPTS: HIGHLY GRANULAR CALOS

- CALICE (CAlorimeter for a LInear Collider Experiment) HCAL prototype:
  - highly granular readout: 3 x 3 cm^2 scintillator tiles, 38 layers (~4.7 λ_{int}), each tile with individual SiPM readout

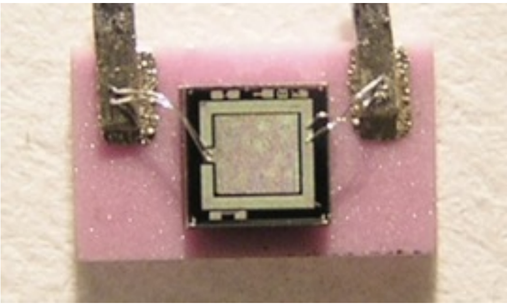
Pictures: CALICE collaboration



tiles in one layer



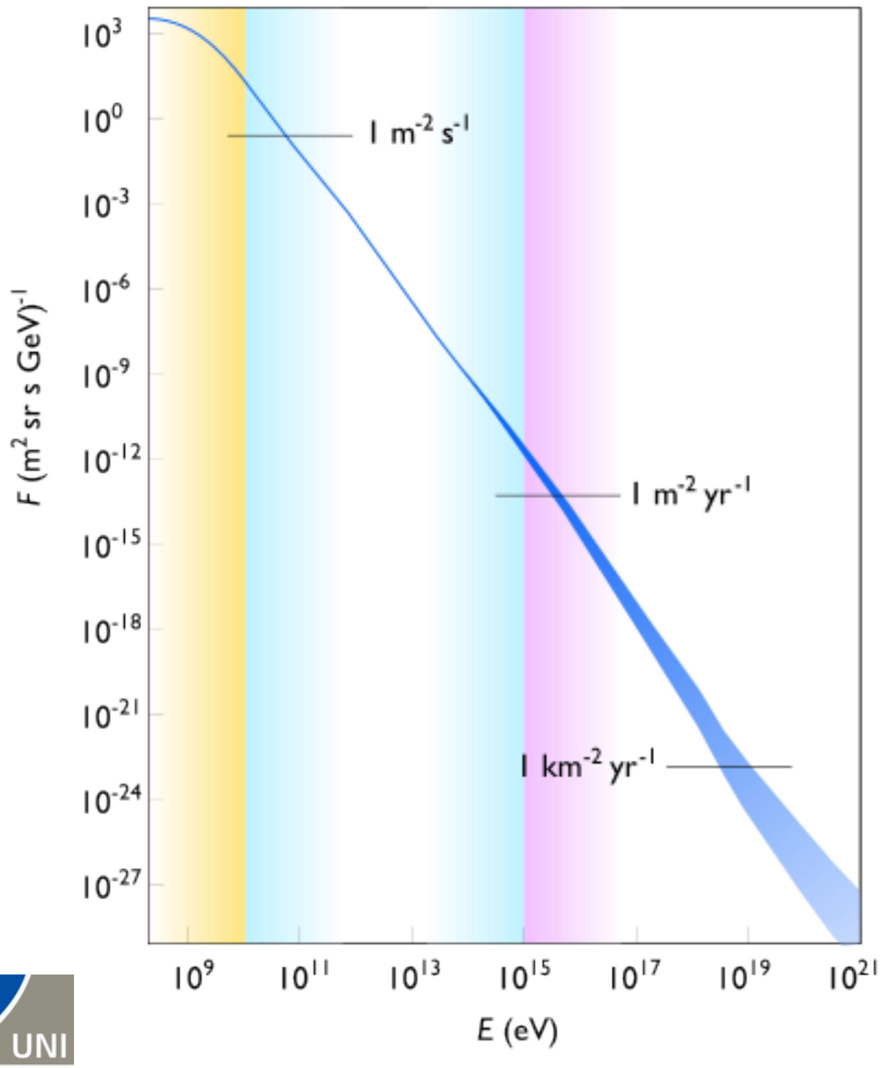
scintillator tile with WLS fiber



Silicon photo-multiplier

Calos: not only at accelerators!

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



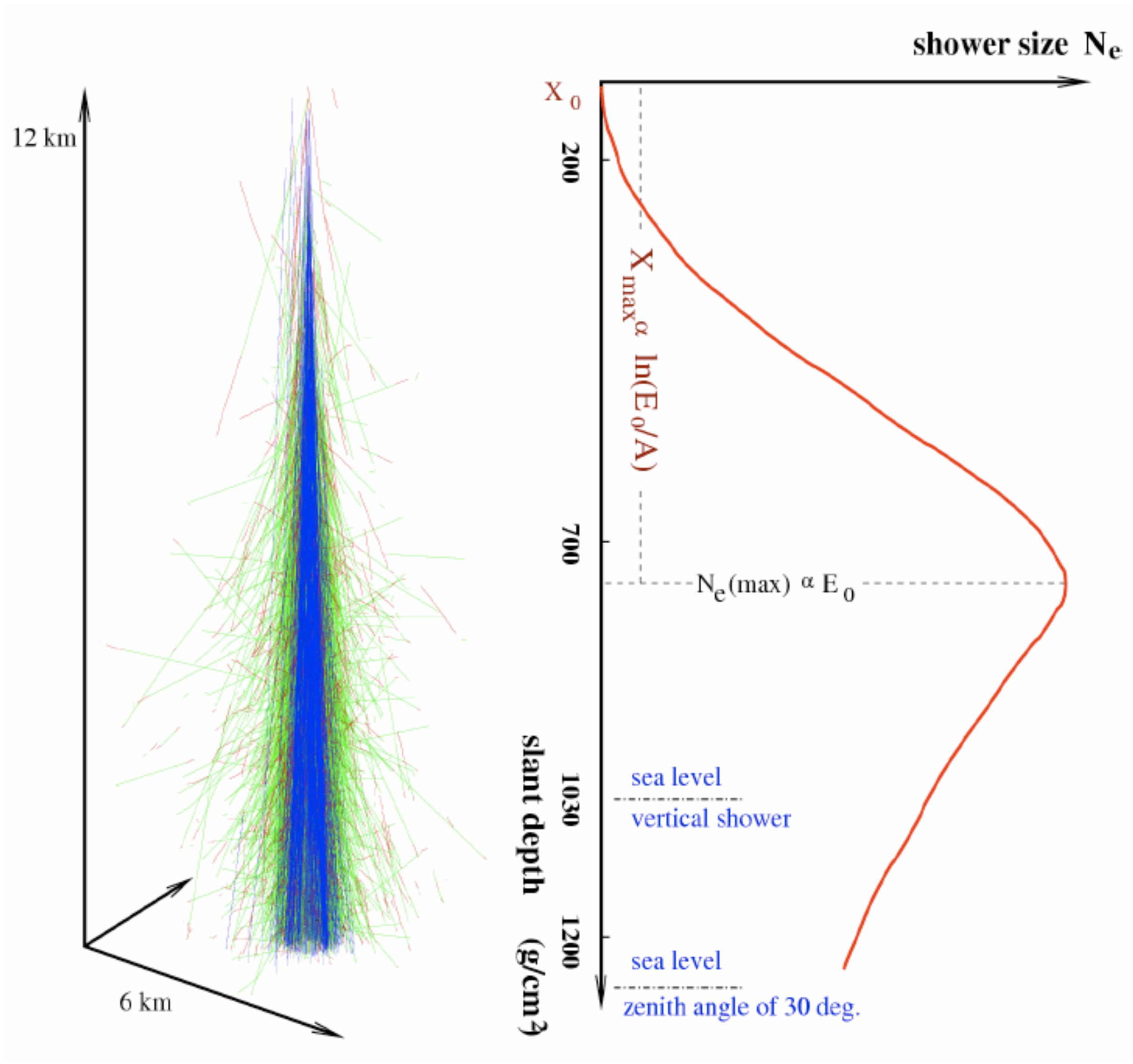
Pic: Wikipedia

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

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

Air shower



R.Engel, ISAPP2005

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

Use atmosphere as calorimeter

Nuclear reaction length λ_I ~ 90 g/cm²

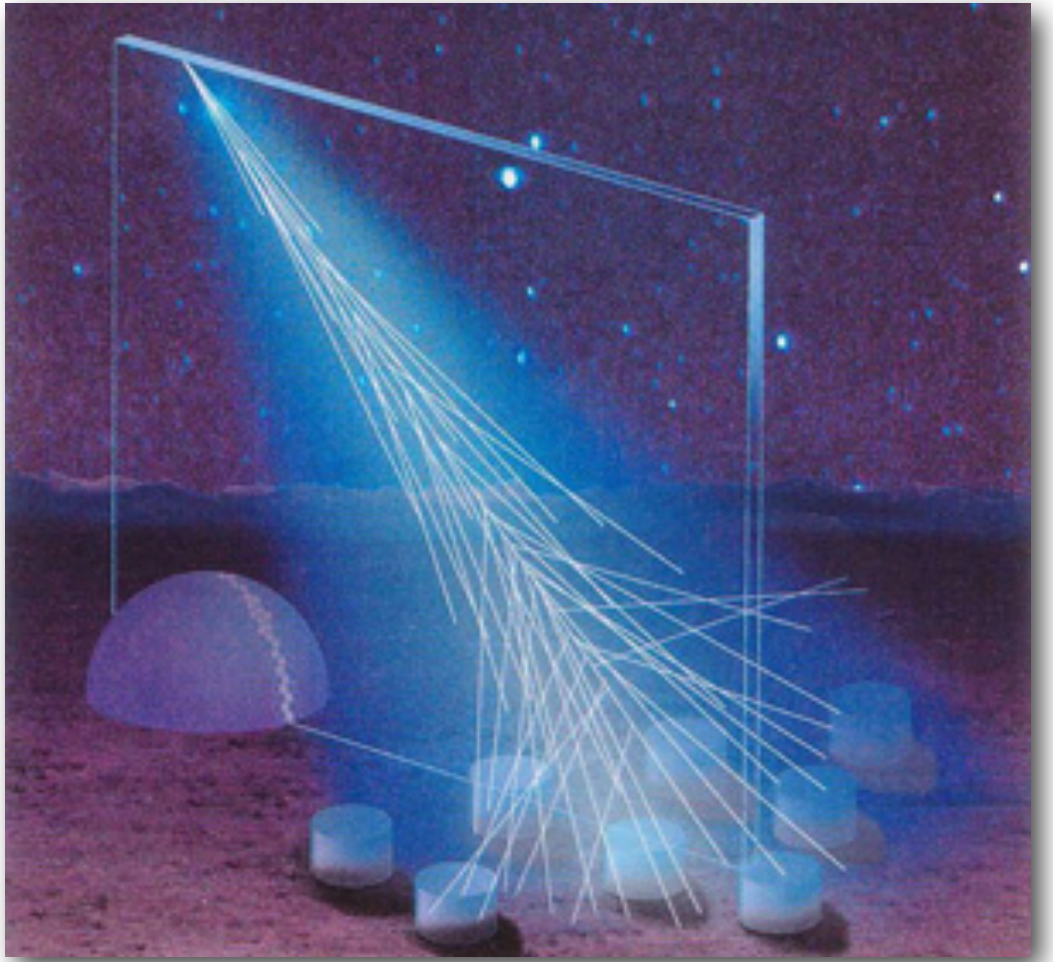
Radiation length X_0 ~ 36.6 g/cm²

Density: ~ 1035 g/cm²

~ 11 λ_I, ~ 28 X_0

Two Techniques

Pic: Pierre Auger Observatory



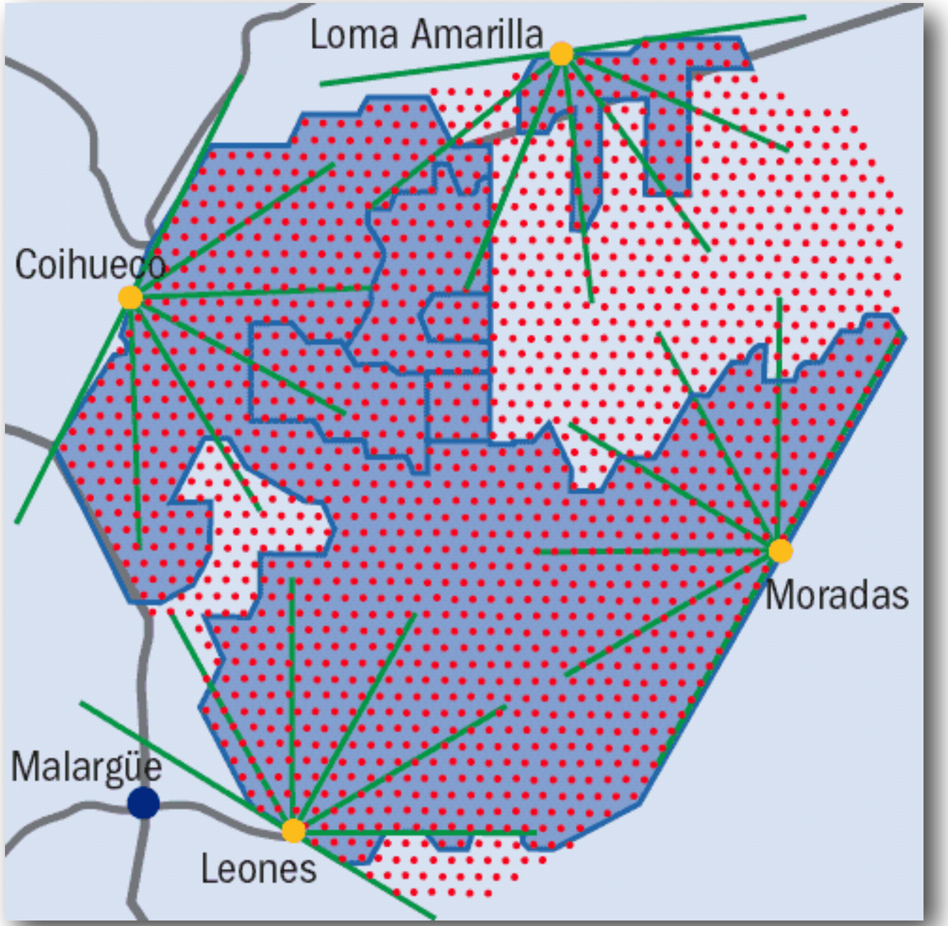
- The atmosphere as homogeneous calorimeter:
  - Energy measurement by measuring the fluorescence light

This is only possible with clear skies and darkness !

- A one-layer sampling calorimeter 11 λ absorber
  - Energy measurement using particle multiplicity

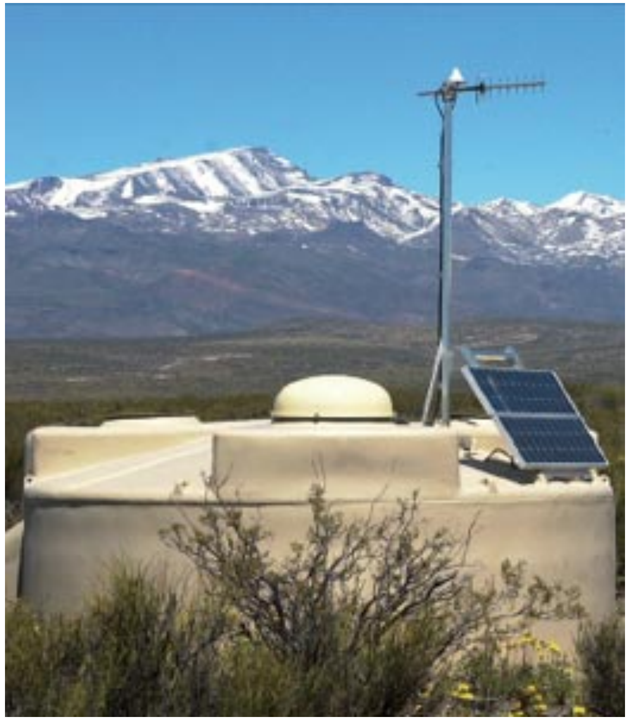
Always possible but has large uncertainties !

AUGER-SOUTH: ARGENTINIAN PAMPA

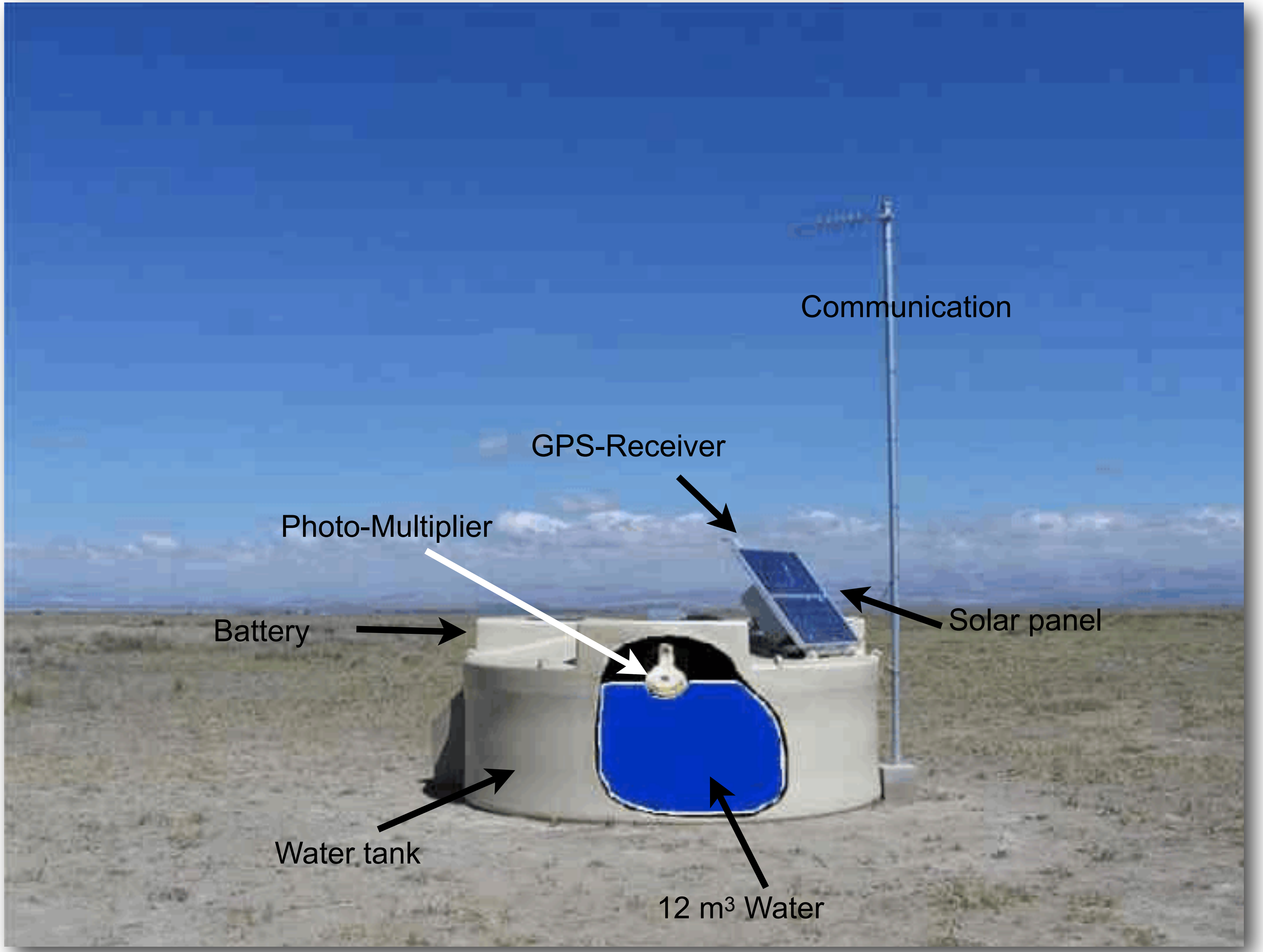


Pics: Pierre Auger Observatory

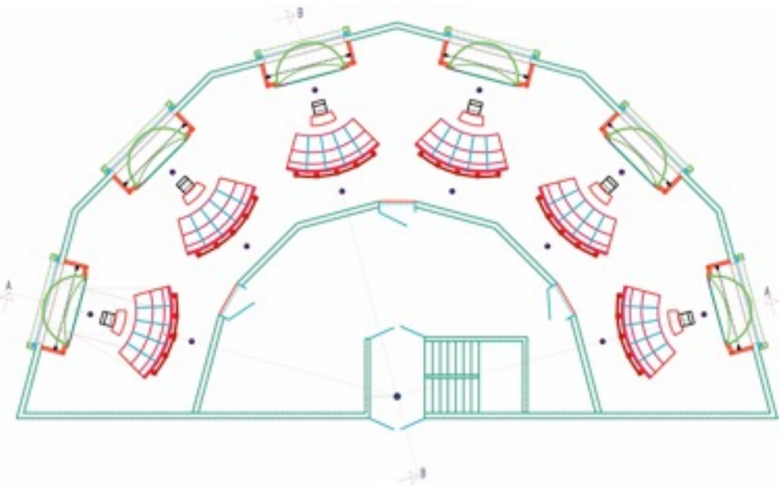
- 1600 water-Cherenkov detectors on ground
- 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

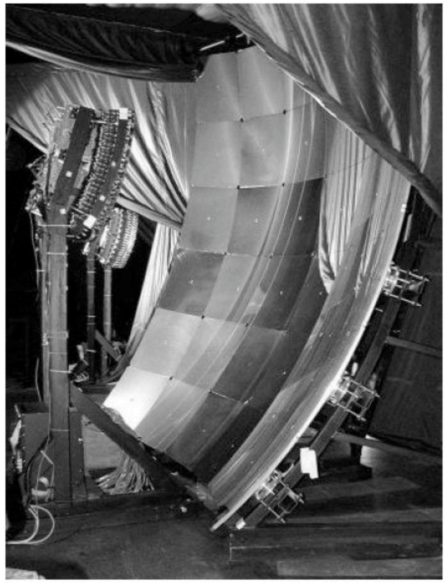


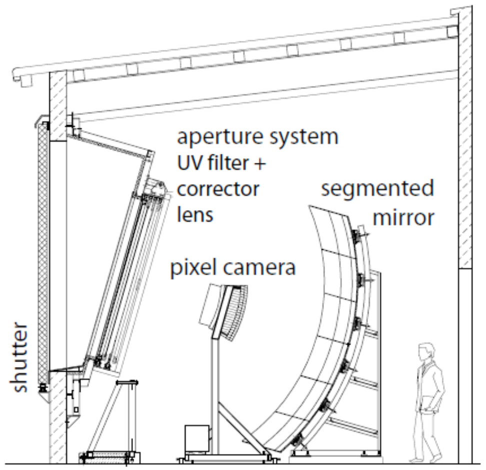
AUGER-Detektor: Ground Array



AUGER Hybrid Installation







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.

Calorimeters at LHC

- All LHC experiments have a calorimetric system with at least an electromagnetic and a hadronic part

Overview **EM** calorimeters at LHC

	Calorimeter	Material	Number of channels		Angular coverage	Energy resolution	
						c_s (%)	c_c (%)
ATLAS	EM barrel	$LAr + Pb$	109,568	sampling	$\lvert\eta\rvert < 1.475$	10	0.7
	EM end-cap	$LAr + Pb$	63,744		$1.375 < \lvert\eta\rvert < 3.2$	10	0.7
	FCal	$LAr + Cu$	2016		$3.1 < \lvert\eta\rvert < 4.9$	28.5	3.5
CMS	ECAL barrel	$PbWO_4$	61,200	homogeneous	$\lvert\eta\rvert < 1.479$	2.8	0.3
	ECAL end-cap	$PbWO_4$	14,648		$1.479 < \lvert\eta\rvert < 3.0$	2.8	0.3
LHCb	ECAL	Scint. + Pb	6016	sampling	$0.756 < \eta_x < 2.19$ $1.037 < \eta_y < 2.19$	9	0.8
ALICE	PHOS	$PbWO_4$	17,920	sampling	$\lvert\eta\rvert < 0.12$, $220° < \phi < 320°$	3.3	1.1
	EMCal	Scint. + Pb	12,672		$\lvert\eta\rvert < 0.7$, $80° < \phi < 187°$	10	2

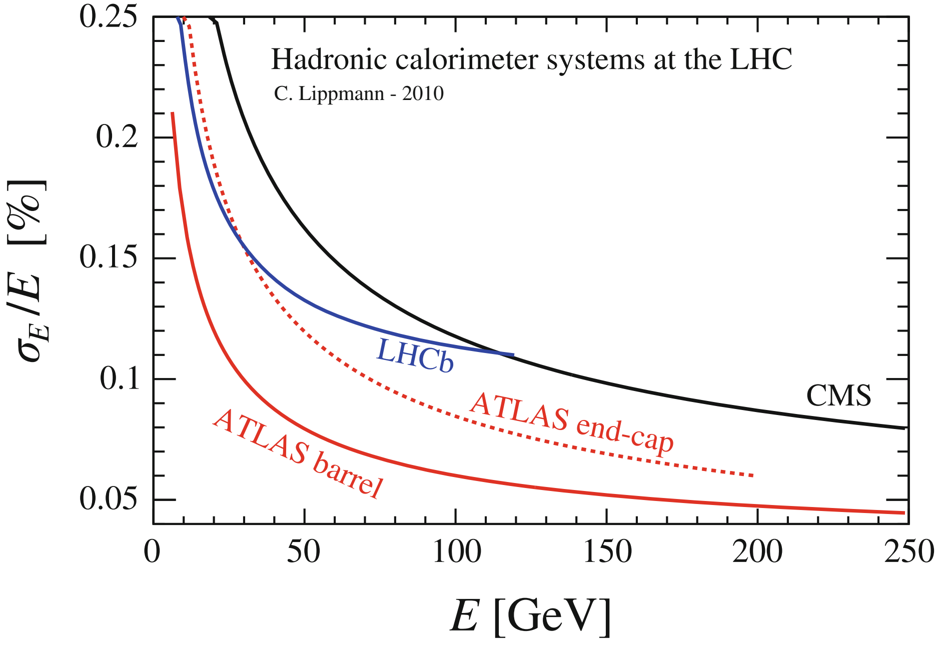
- As expected, the sampling based on lead as absorber have a slightly worse resolution than the homogeneous crystal calorimeters.

Source: LHC - the Harvest of Run 1

Hadronic Calos at LHC

	Calorimeter	Material	Number of channels	Angular coverage	Energy resolution	
					c_s (%)	c_c (%)
ATLAS	Tile	Scint. + Pb	9852	$\|\eta\| < 1.7$	52	3
	HEC	$LAr + Cu$	5632	$1.5 < \|\eta\| < 3.2$	84	–
	FCal	$LAr + W$	1508	$3.1 < \|\eta\| < 4.9$	94	7.5
CMS	HB	Scint. + steel/brass	2592	$\|\eta\| < 1.3$	90	9
	HE	Scint. + steel/brass	2592	$1.3 < \|\eta\| < 3$	90	9
	HO	Scint. + steel	2160	$\|\eta\| < 1.4$	–	–
	HF	Quartz fibre + steel	1728	$3 < \|\eta\| < 5.2$	120	–
LHCb	HCAL	Scint. + steel	1488	$\|\eta_x\| < 1.87$ $\|\eta_y\| < 2.07$	69	9

- All sampling calorimeter



State of the art of Particle Flow algorithm

- High granularity Particle Flow reconstruction is highly non-trivial

many complex steps (not all shown)