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

Losses of Resolution:

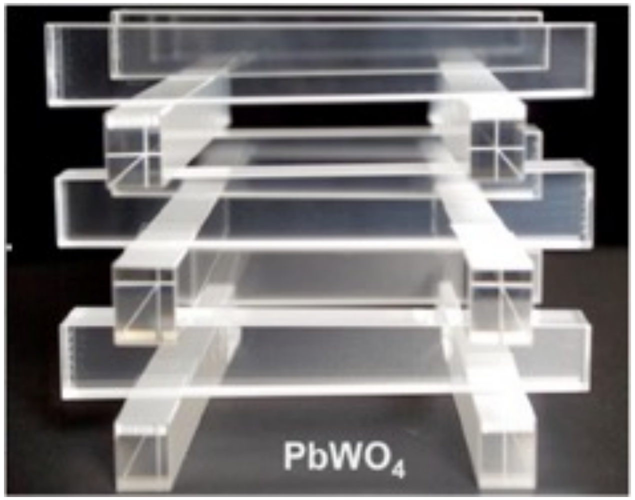
- **Shower not contained** in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.
- **Statistical fluctuations** in number of photoelectrons observed in detector.
- **Sampling fluctuations** if the counter is layered with inactive absorber.
- ….

Calos: Active Material

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.

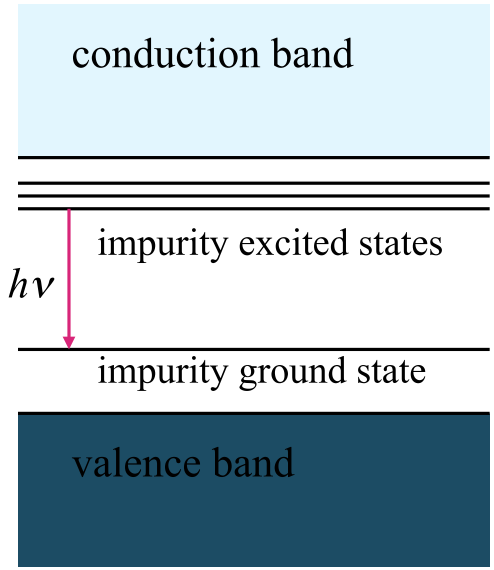
Picture: CDF@Fermilab



- $PbWO_4$: 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

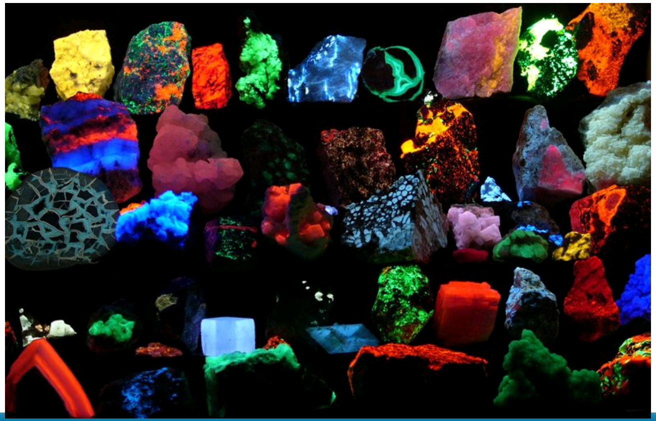
SCINTILLATORS TO MEASURE THE ENERGY

- 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



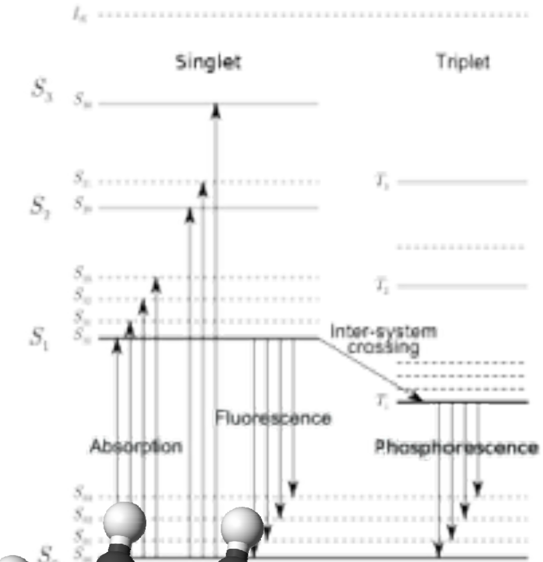
Advantages:
- Good efficiency
- Good linearity
- Radiation tolerance

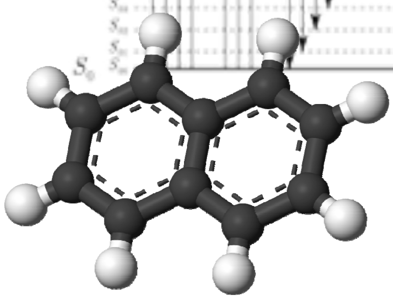
Disadvantage:
- Relatively slow
- Crystal structure needed (small and expensive)

Scintillators to Measure the Energy

Active material

Organic scintillators

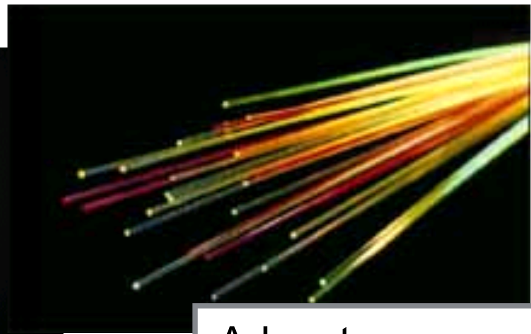




source: Wikipedia

- Organic cintillators 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

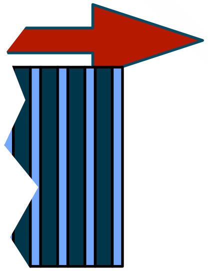
- Organic scintillators can be mixed with polystyrene to form a rigid plastic.
  - Easy to mold
  - Cheaper than crystals



Advantages:
- very fast

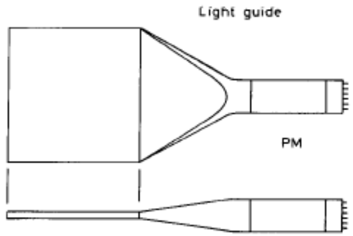
Disadvantage:
- inefficient
- non-linear
- not good for photons

Light transport

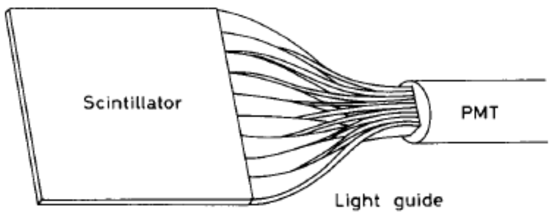


- The photons are being reflected towards the end of the scintillator
- A light guide brings the light to a Photomultiplier

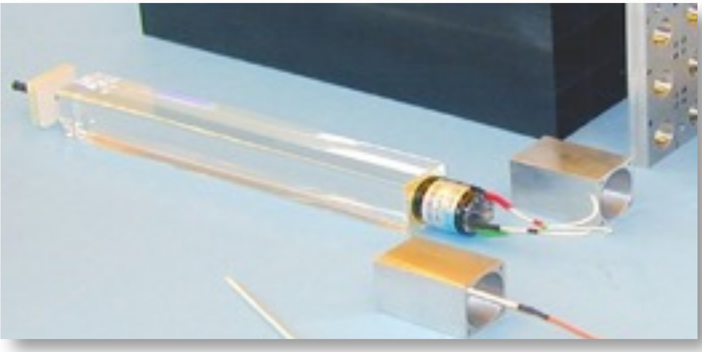
- Light guides: transfer by total internal reflection (+outer reflector)



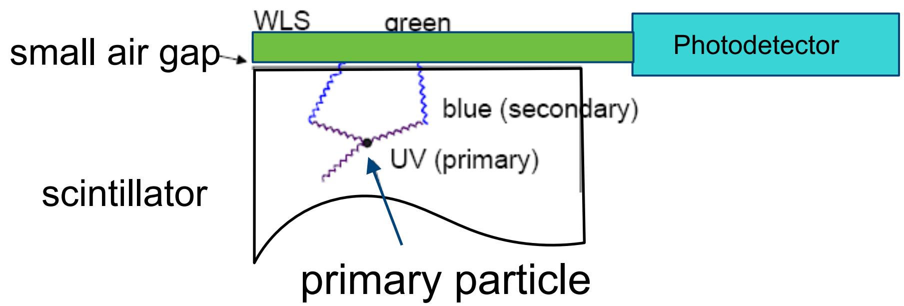
"fish tail"



adiabatic

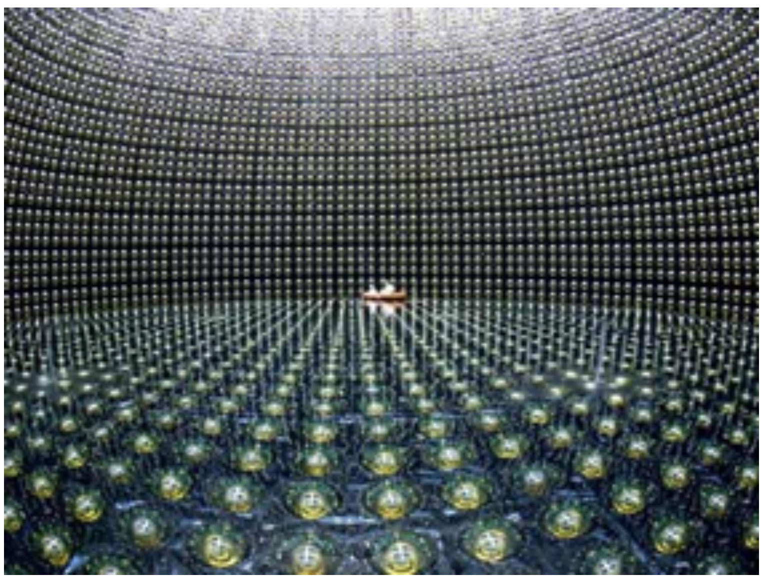


- UV light enters the light guide material
- Light is transformed into longer wavelength (wavelength shifter)
- -> Total internal reflection inside the WLS material
- -> 'transport' of the light to the photo detector

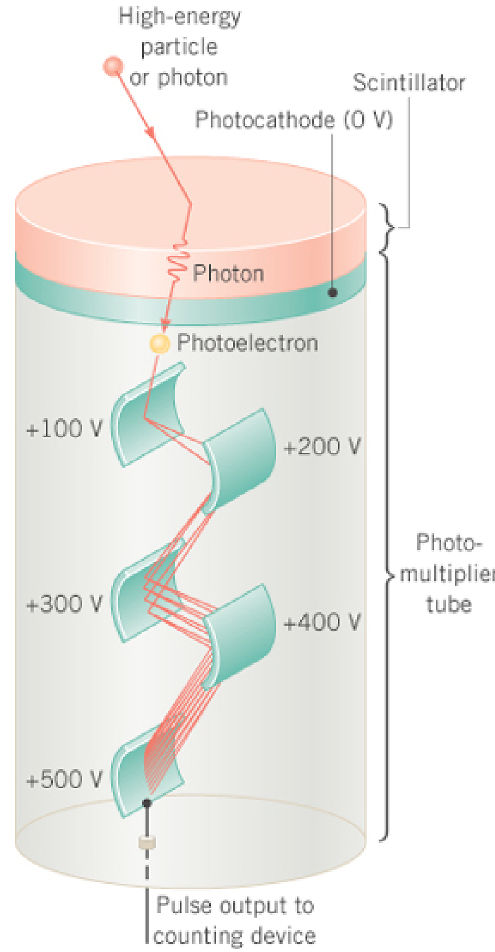


Detecting the Light

- 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

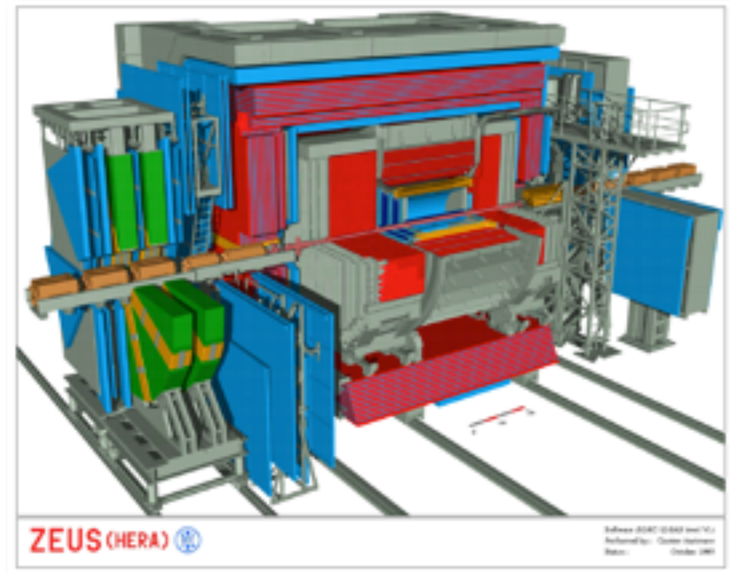


Source: Cutnell and Johnson, 7th edition image gallery

Example: ZEUS Calo

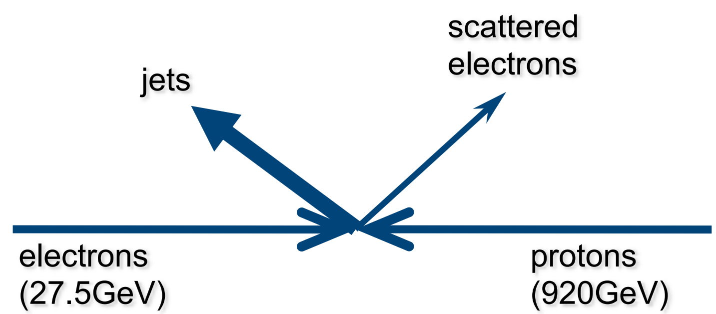
A rather hostile environment in ZEUS at HERA

- 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



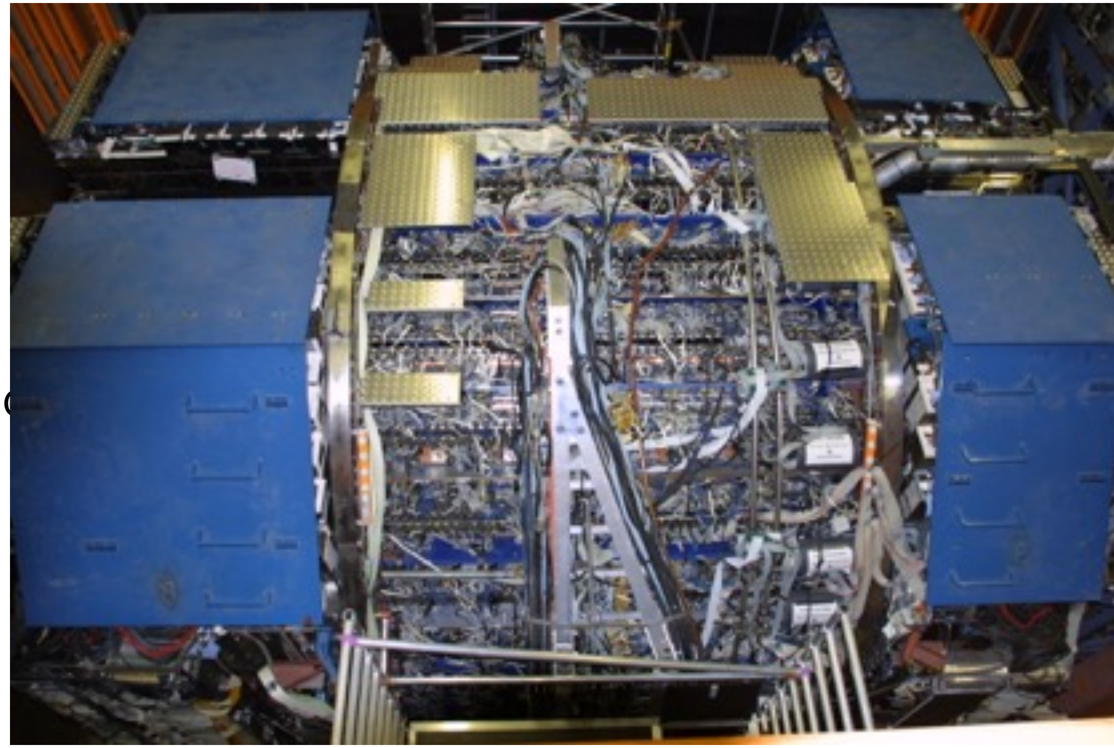
Keep in mind: this was developed in the middle of the 80s!

The ZEUS Calorimeter - Solution

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

e ±

27.5 (



GeV

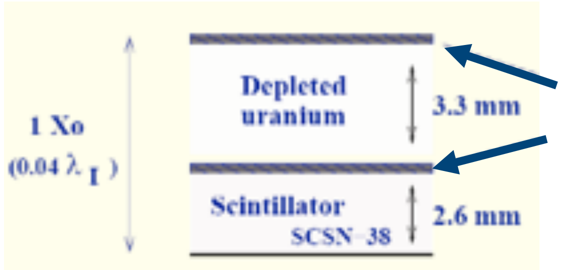
Uranium + Scintillator:

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

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

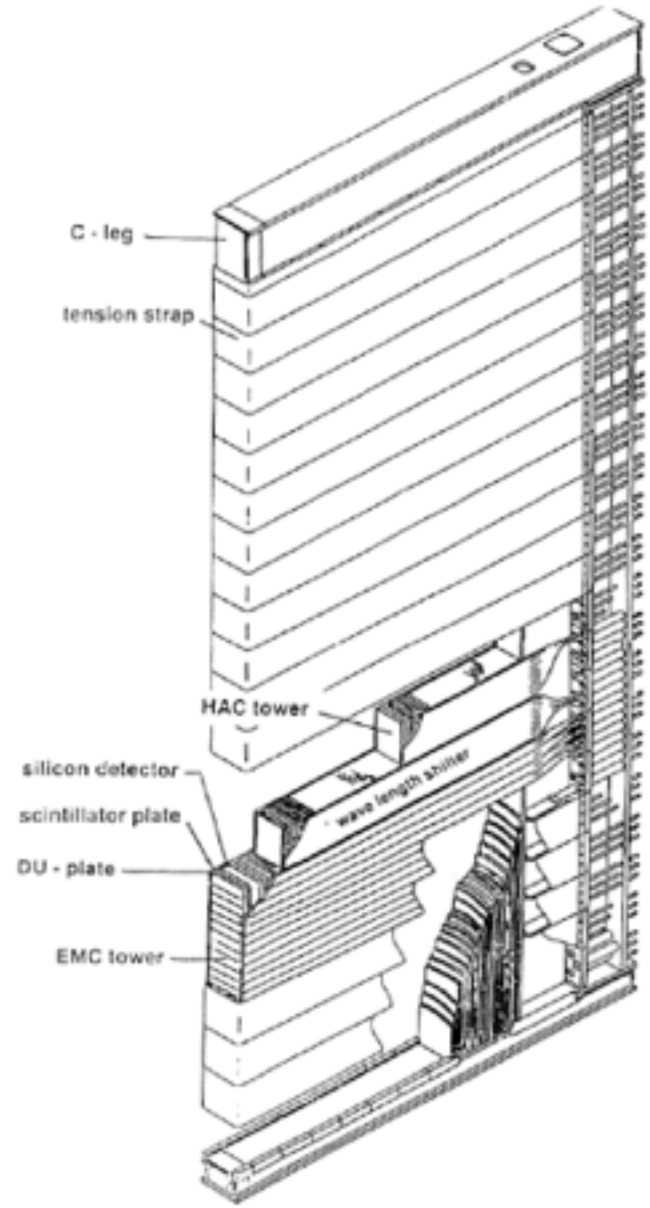
Design

- Layers:



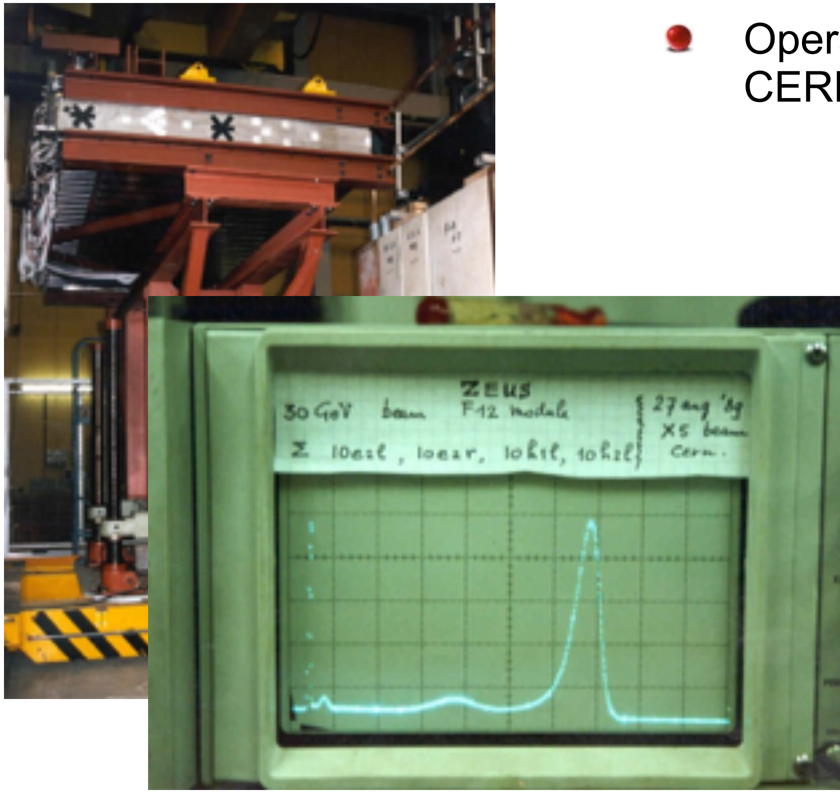
stainless steel

- 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) cm^2 in F/BCAL (RCAL)
  - HA cell size: 20x20 cm^2
- Cell read out on both sides with wavelength shifters
  - redundancy
  - transverse position measurement within the cell

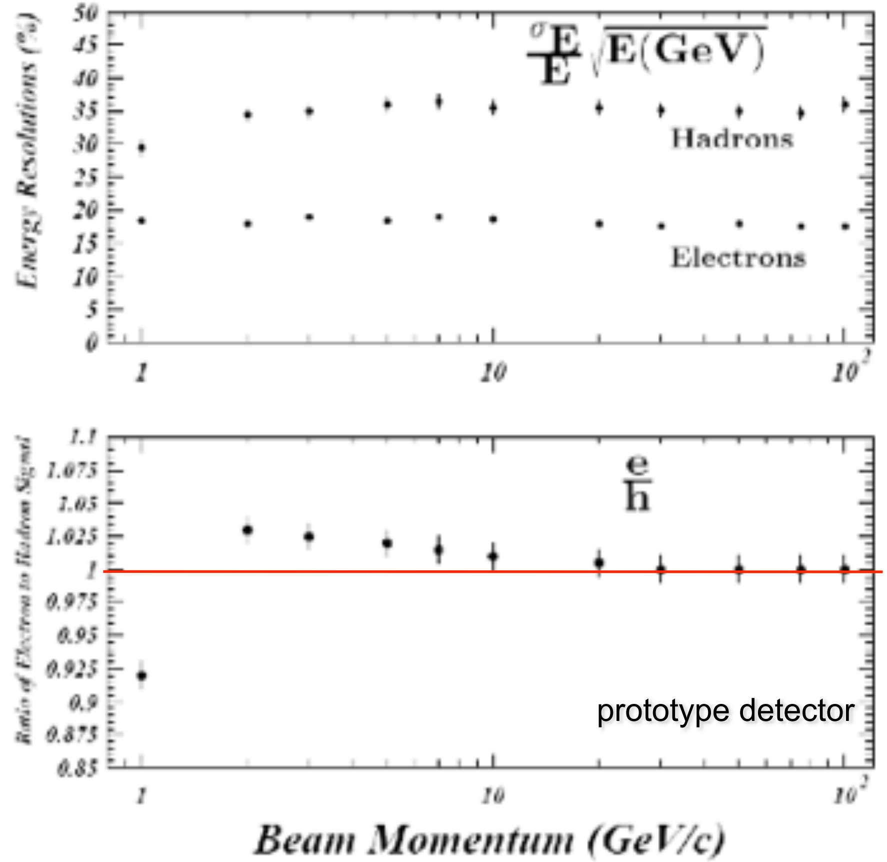


3m x 5m x 0.2m, 12tons
total of 80 modules

Test beam at CERN



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



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

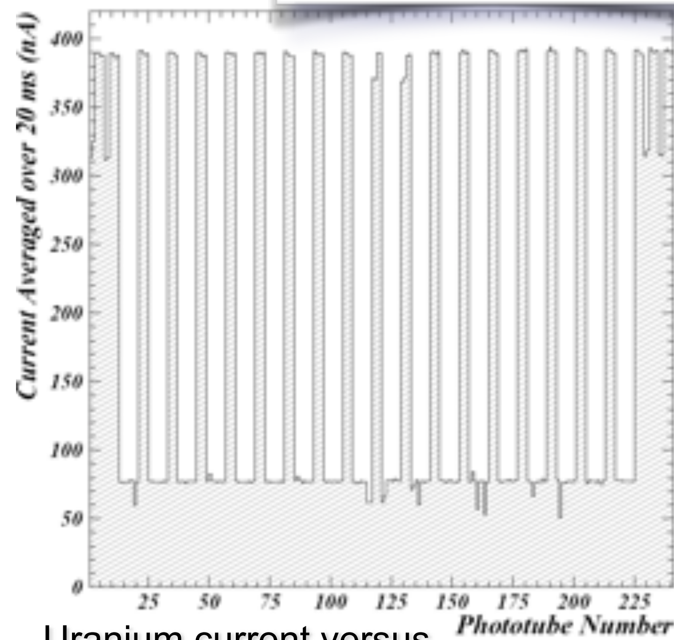
Hadrons: $$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E(GeV)}}$$

Production modules were all calibrated at CERN

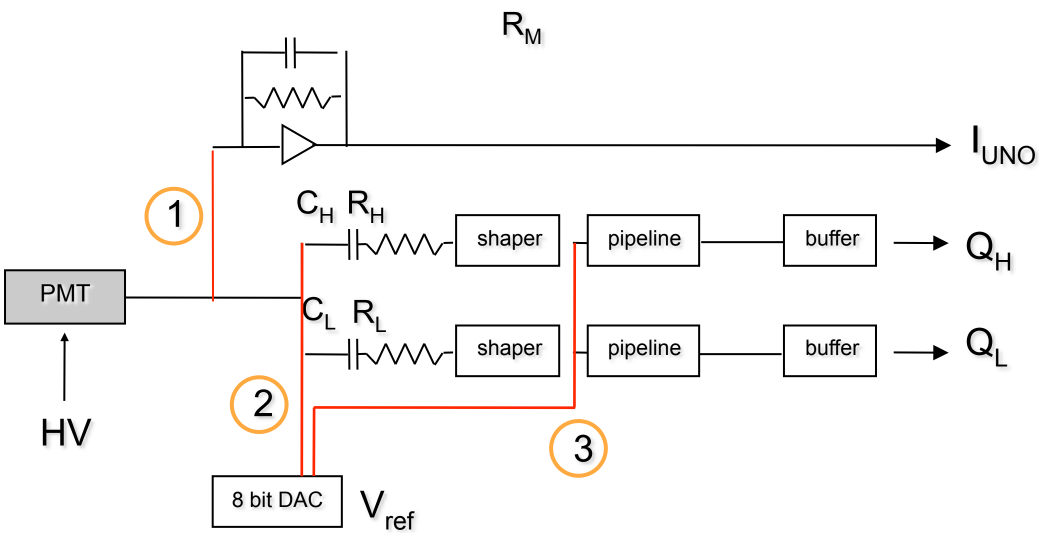
Calibration Methods

Stable radioactivity
- good for calibration

- Natural uranium activity provides absolute energy calibration in situ!
  - 98.1% U^{238} + 1.7% Nb + 0.2% U^{235}
  - Half-Life of U^{238} is 4.5 *10^9 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



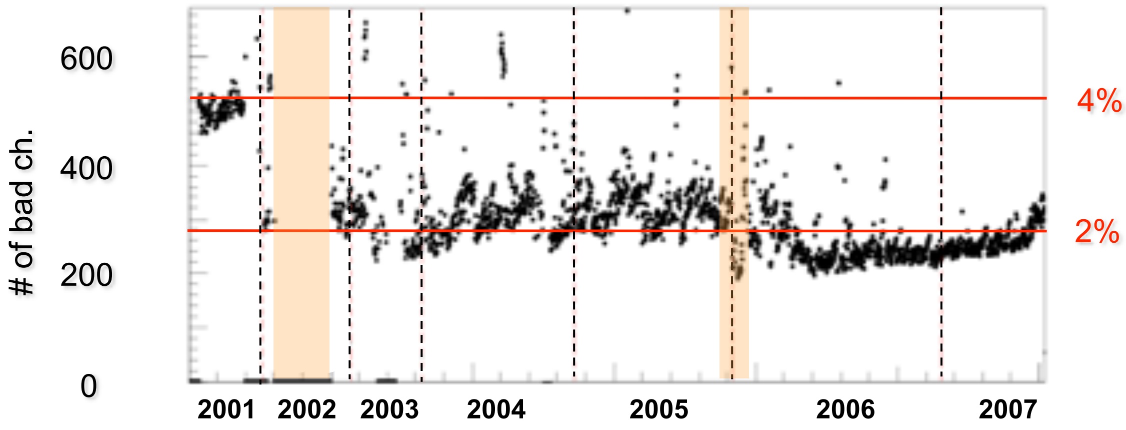
1 Uranium noise

2 Charge injection

3 Pedestals and Gains

Channels out of range
-> declared as "bad" until readjusted

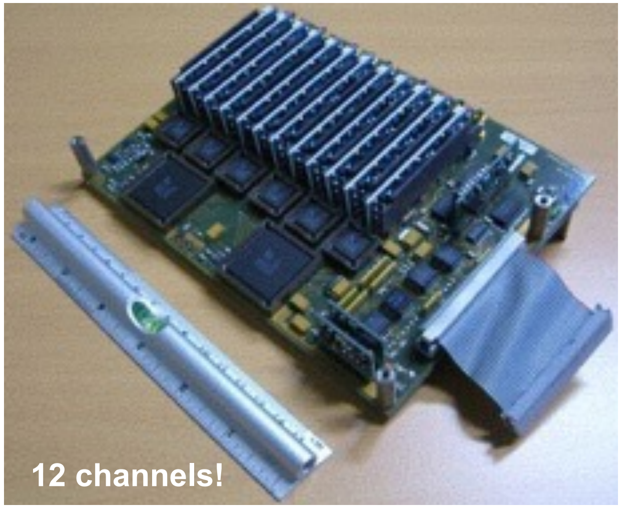
Hardware Performance



- 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**

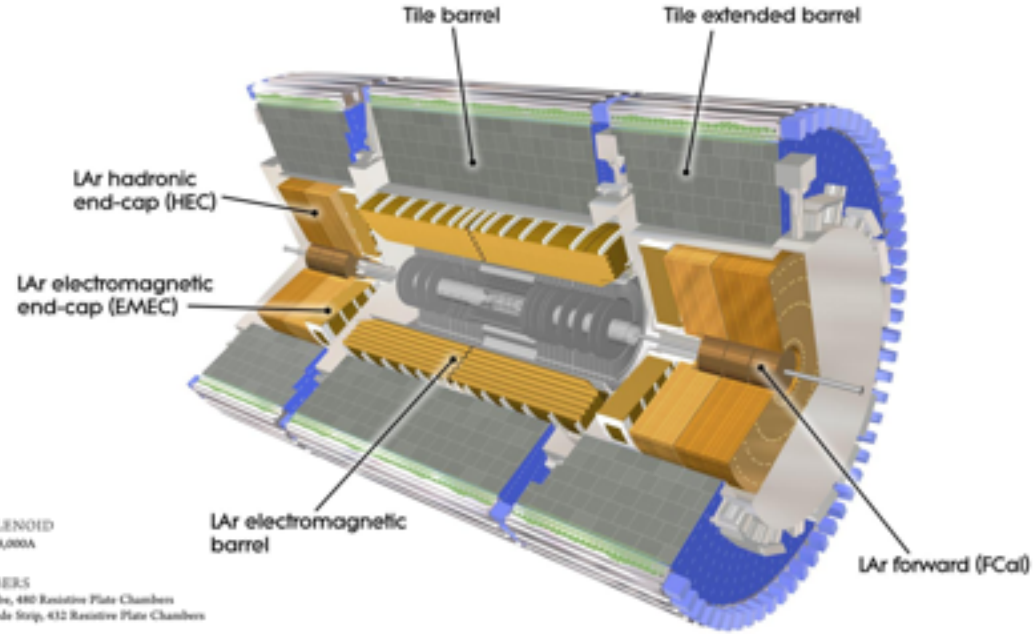
- Front End Cards:
  - About 1000 necessary for the running, ~10% spares
  - Main failure mode: buffer or pipeline chip (socketed)
  - Cards easy to debug and maintain
  - Failure rate: <1/month (12 channels – one side)
  - Very successful



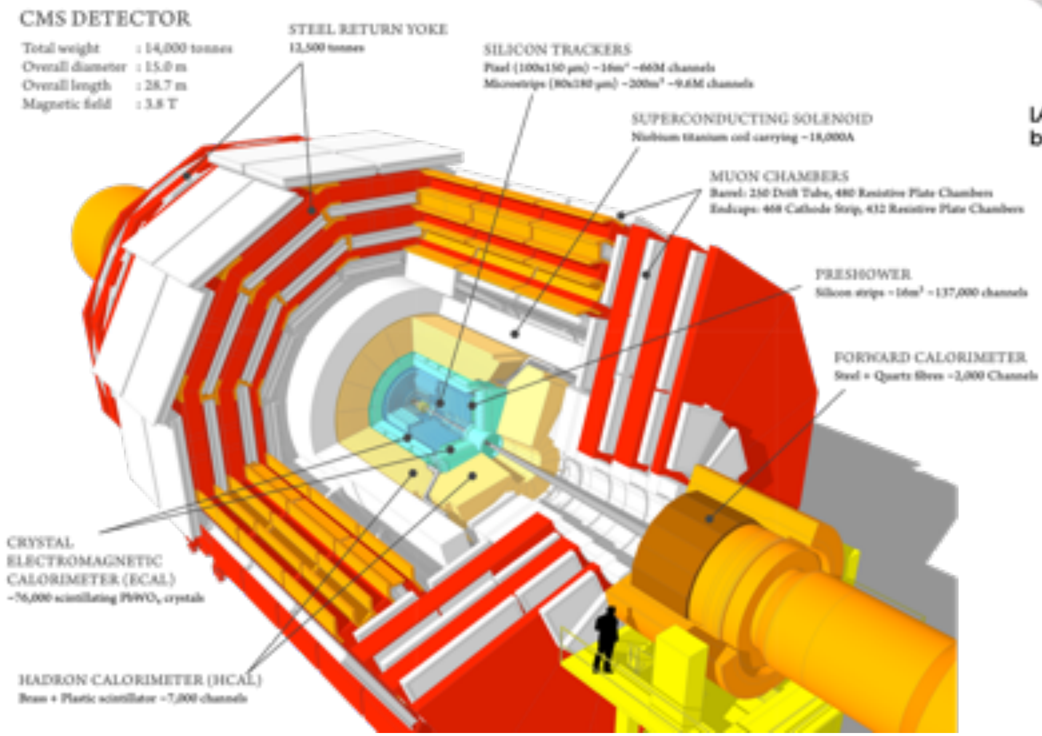
Overview of Calorimeters

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

ATLAS

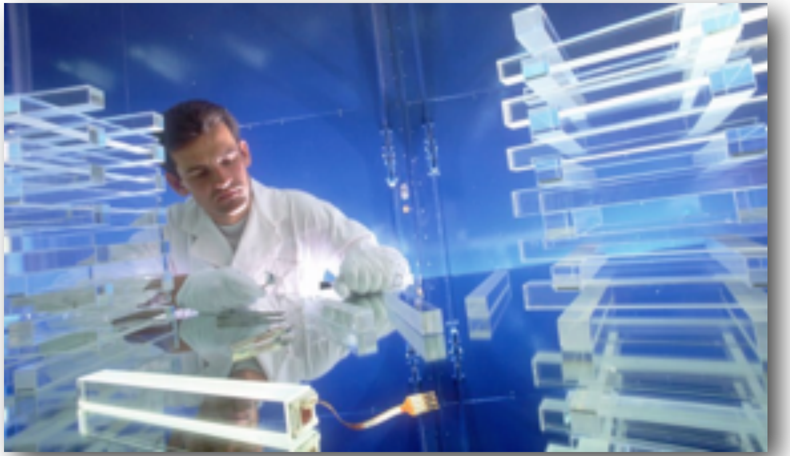


CMS

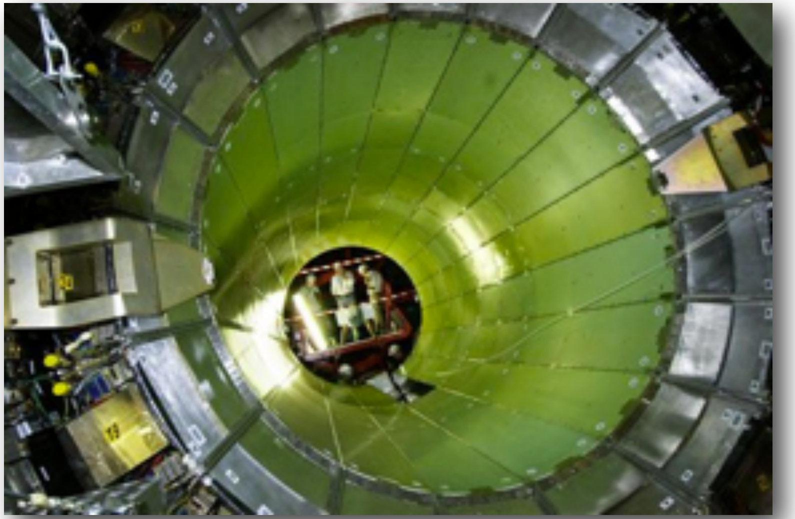


CMS Calorimeter

- **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)

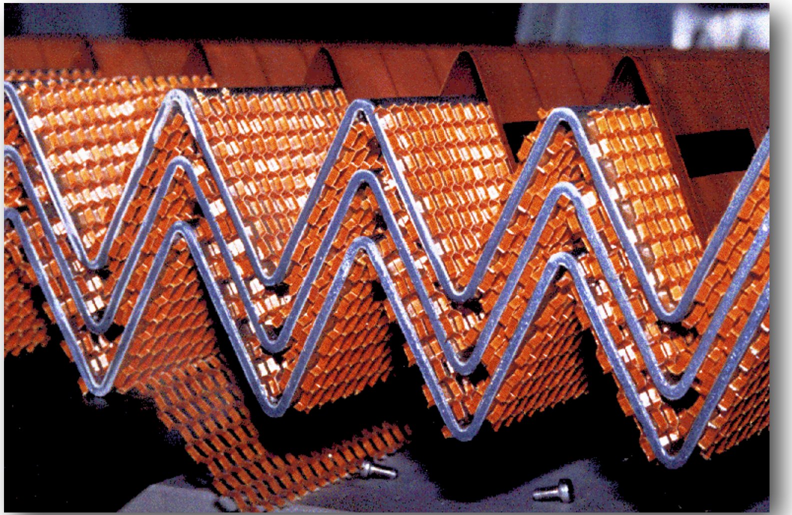


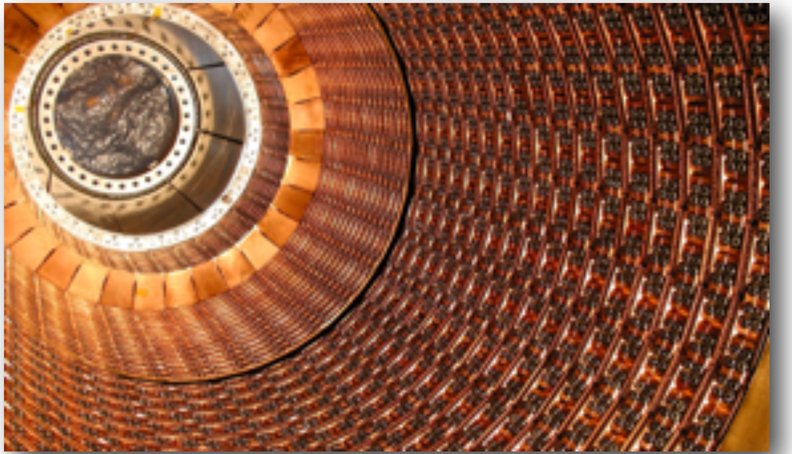
CMS ECAL during installation (CERN)

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)

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	$\|\eta\| < 1.475$	10	0.7
	EM end-cap	$LAr + Pb$	63,744	$1.375 < \|\eta\| < 3.2$	10	0.7
	FCal	$LAr + Cu$	2016	$3.1 < \|\eta\| < 4.9$	28.5	3.5
CMS	ECAL barrel	$PbWO_4$	61,200	$\|\eta\| < 1.479$	2.8	0.3
	ECAL end-cap	$PbWO_4$	14,648	$1.479 < \|\eta\| < 3.0$	2.8	0.3
LHCb	ECAL	Scint. + Pb	6016	$0.756 < \eta_x < 2.19$ $1.037 < \eta_y < 2.19$	9	0.8
ALICE	PHOS	$PbWO_4$	17,920	$\|\eta\| < 0.12$, $220° < \phi < 320°$	3.3	1.1
	EMCal	Scint. + Pb	12,672	$\|\eta\| < 0.7$, $80° < \phi < 187°$	10	2

sampling

homogeneous

sampling

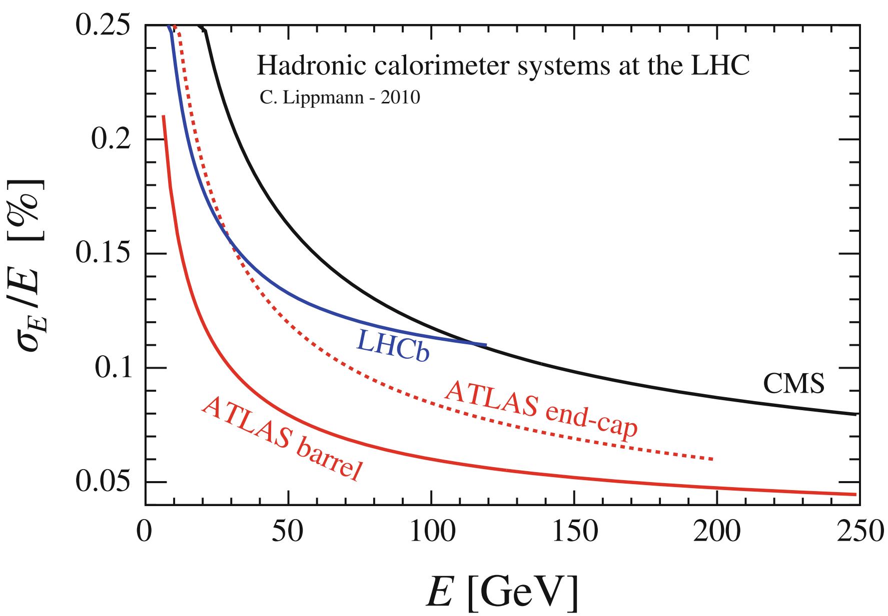
sampling

- 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

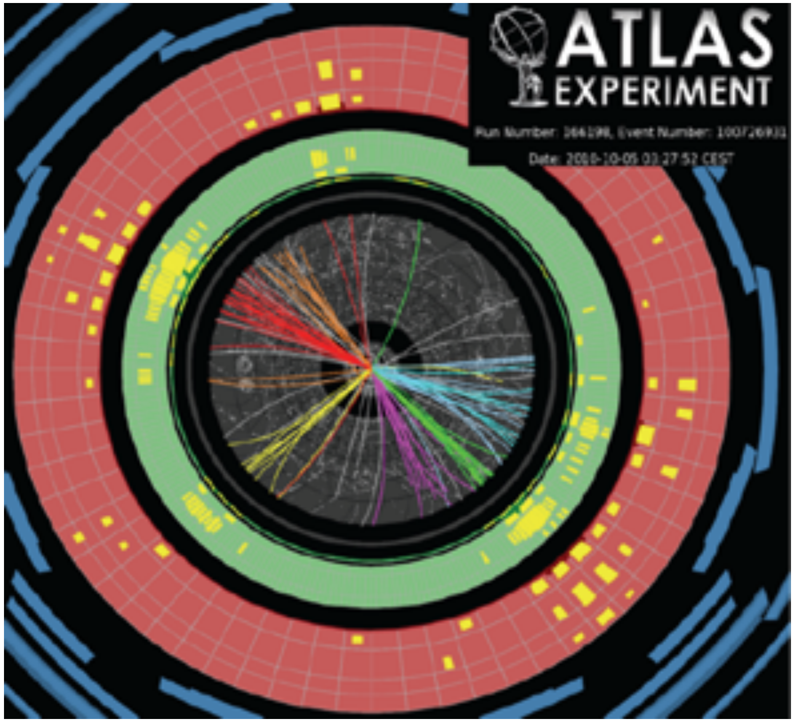
Hadronic Calos at LHC

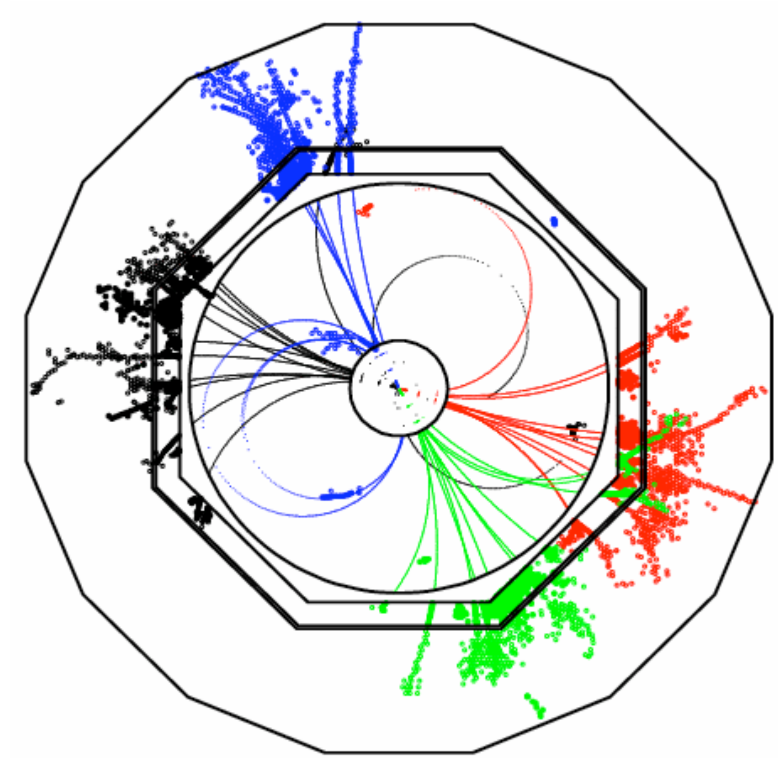
	Calorimeter	Material	Number of channels	Angular coverage	Energy resolution	
					c_s (%)	c_c (%)
ATLAS	Tile	Scint. + Pb	9852	$\|\eta\| < 1.7$	52	3
	HEC	$LAr + Cu$	5632	$1.5 < \|\eta\| < 3.2$	84	–
	FCal	$LAr + W$	1508	$3.1 < \|\eta\| < 4.9$	94	7.5
CMS	HB	Scint. + steel/brass	2592	$\|\eta\| < 1.3$	90	9
	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

Current Hadron Calos ... and Dreams



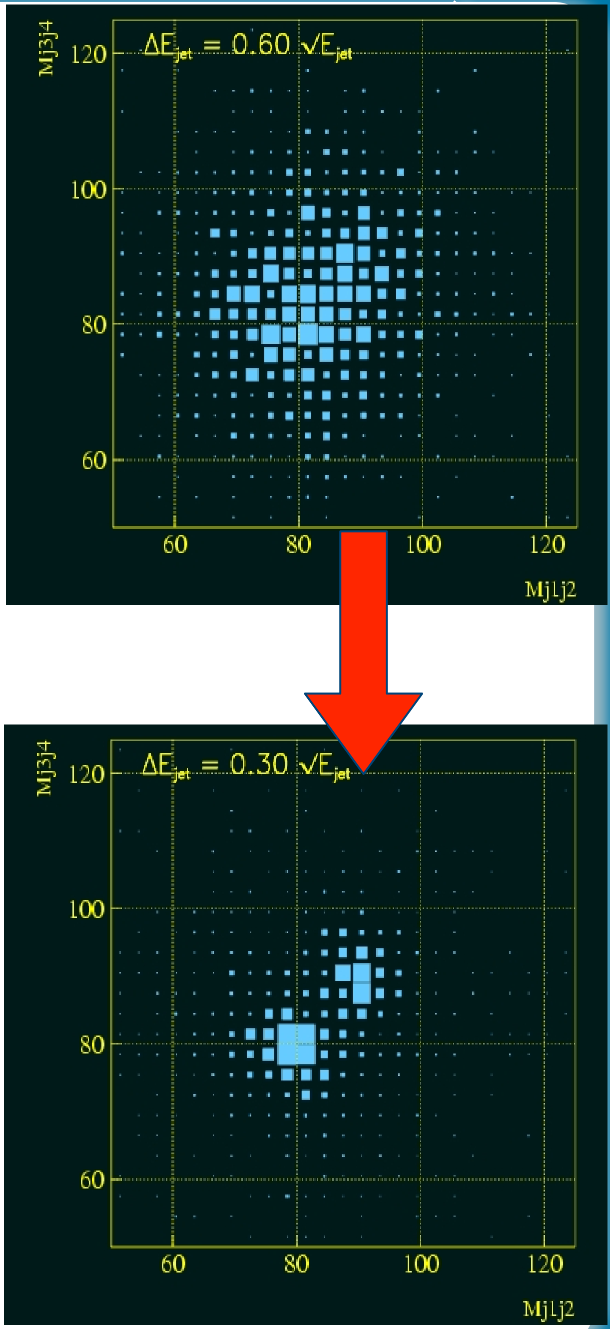


- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT)
  O(10k) channels for full detectors

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

Particle Flow Calorimeter

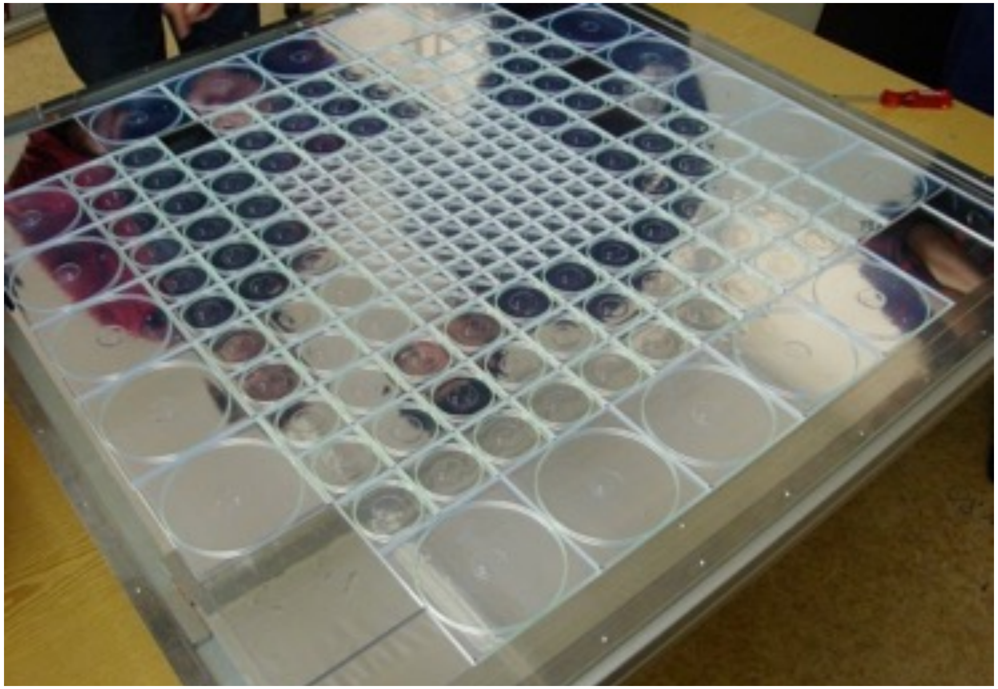
- Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution
- Need
  - a calorimeter optimised for photons: separation into ECAL + HCAL
  - to place the calorimeters inside the coil (to preserve resolution)
  - to minimise the lateral size of showers with dense structures
  - the highest possible segmentation of the readout
  - to minimise thickness of the active layer and the depth of the HCAL



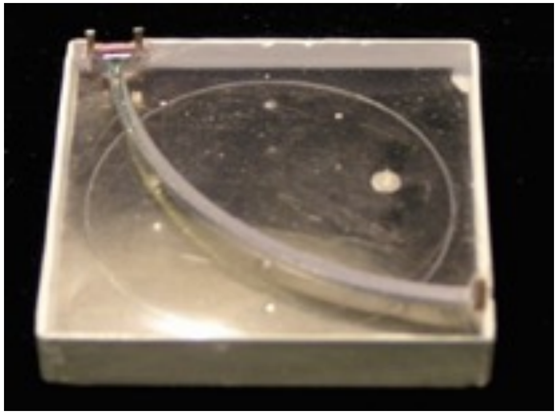
New Concepts: Highly Granular Calos

- 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

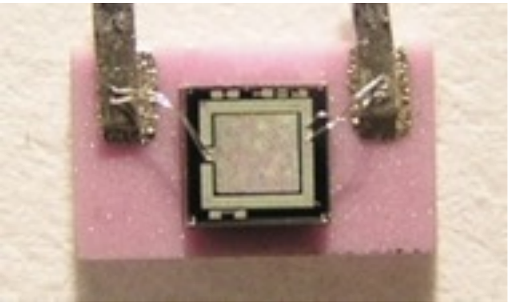
Pictures: CALICE collaboration



tiles in one layer

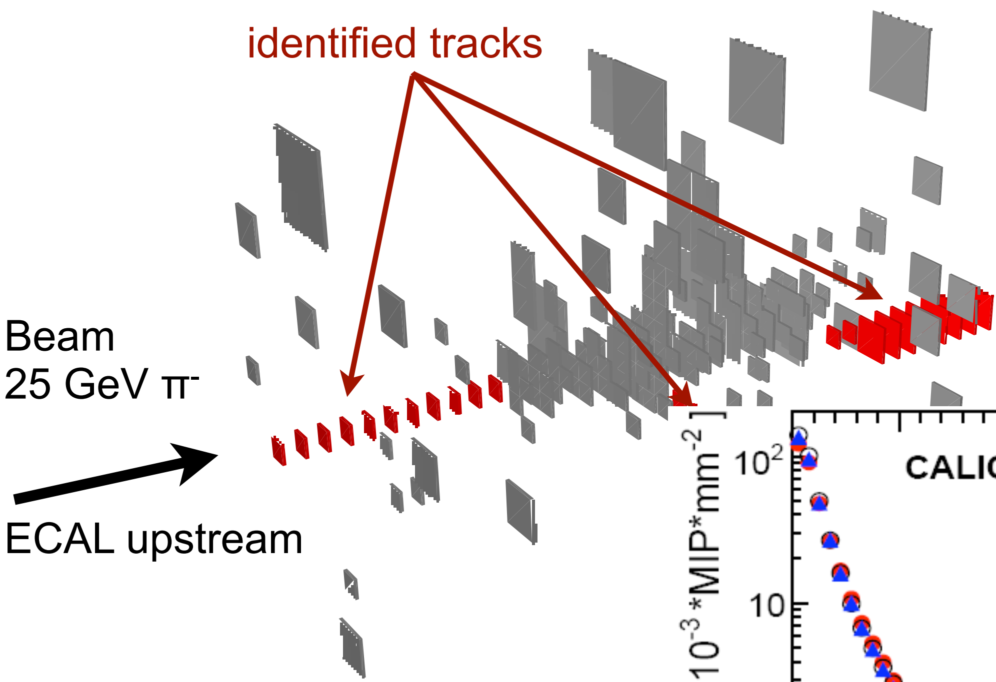


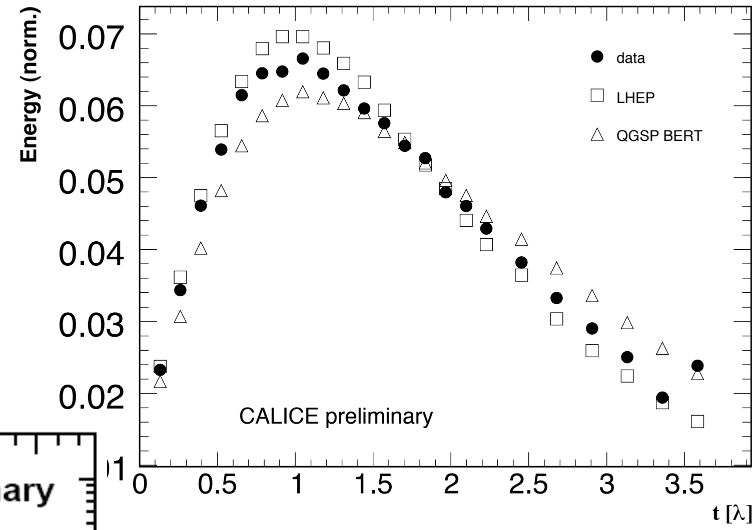
scintillator tile with WLS fiber

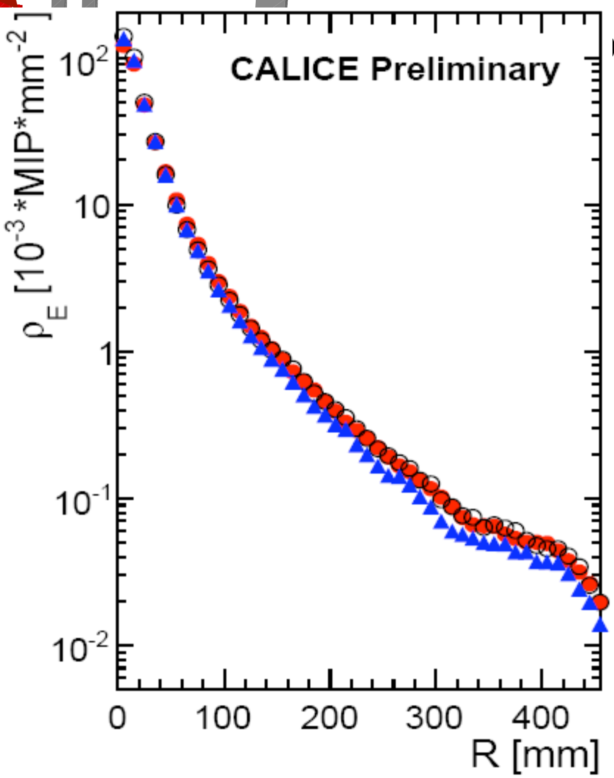


Silicon photo-multiplier

CALICE: Hadronic Shower Studies

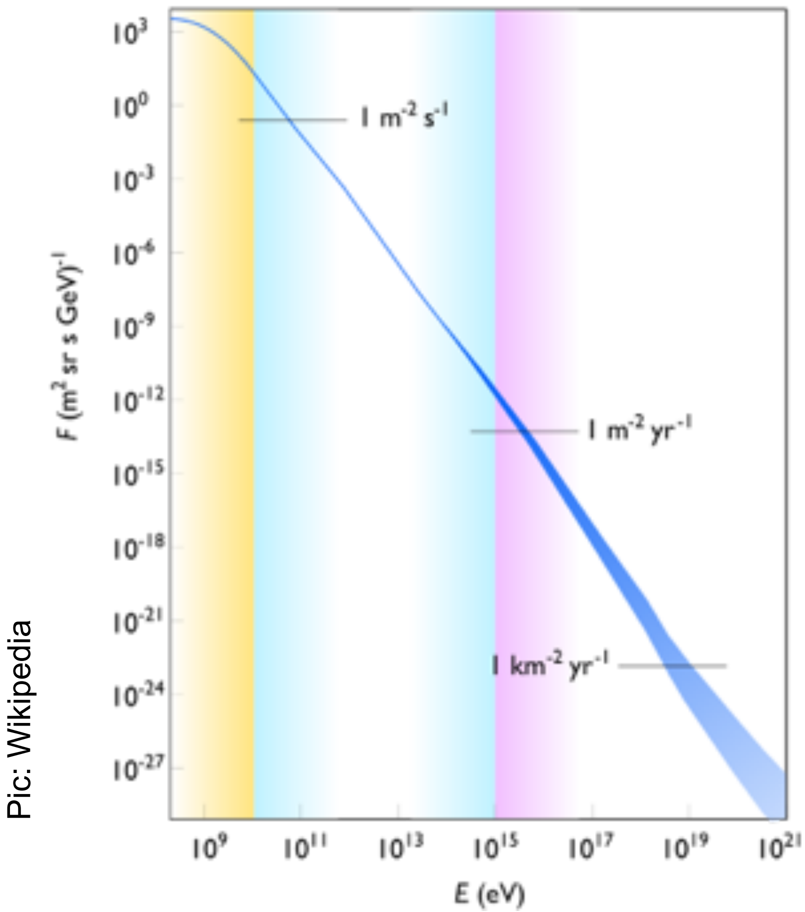






- Comparison of detailed test beam studies with simulations: improvement of existing shower models

Calos: not only at accelerators!



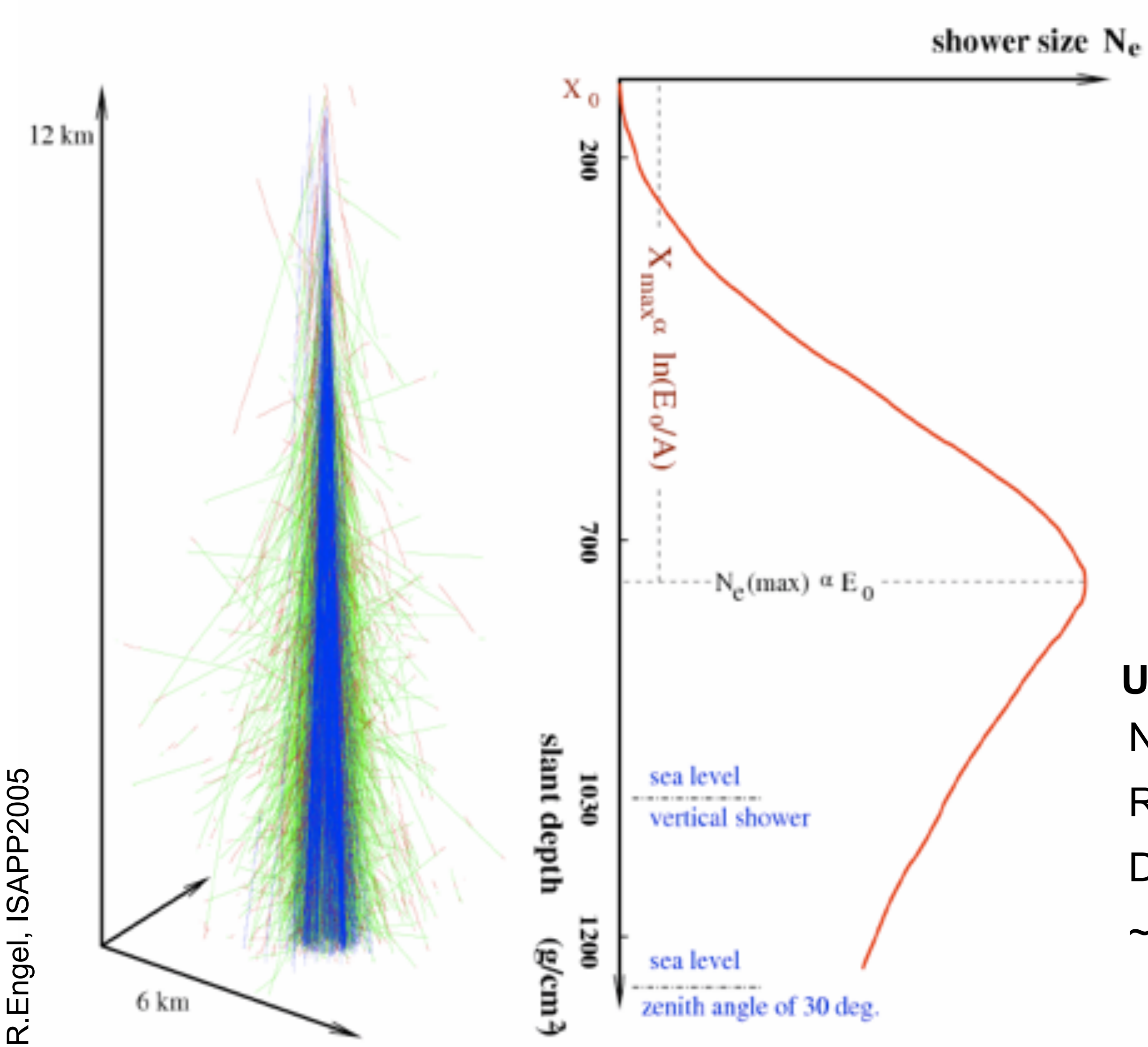
Flux of cosmic ray particles as a function of their energy.

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

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



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

Use atmosphere as calorimeter

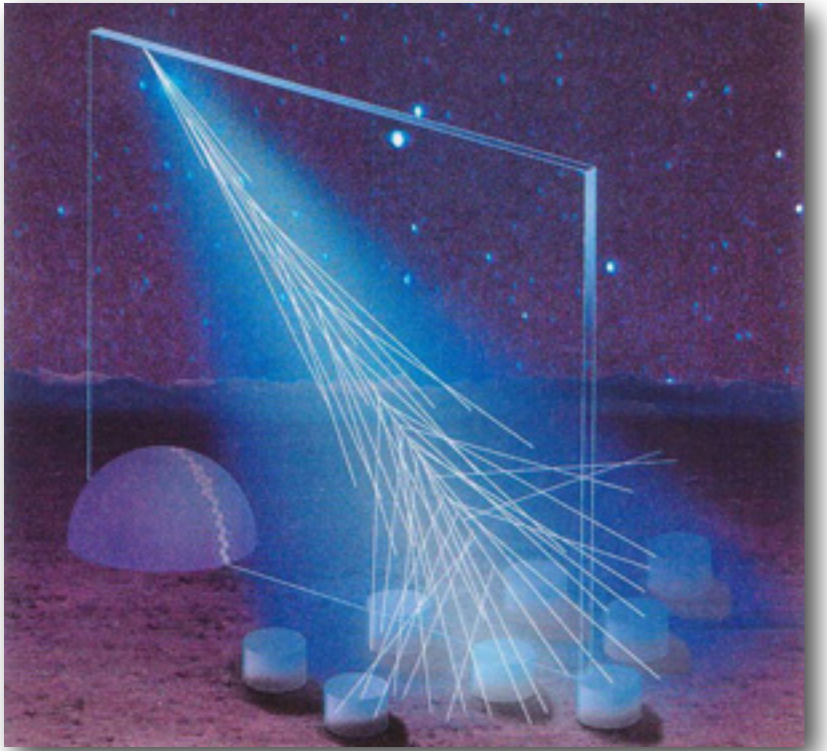
Nuclear reaction length $\lambda_I \sim 90$ g/cm^2

Radiation length $X_0 \sim 36.6$ g/cm^2

Density: ~ 1035 g/cm^2

$\sim 11\ \lambda_I$, $\sim 28\ X_0$

Two Techniques



Pic: Pierre Auger Observatory

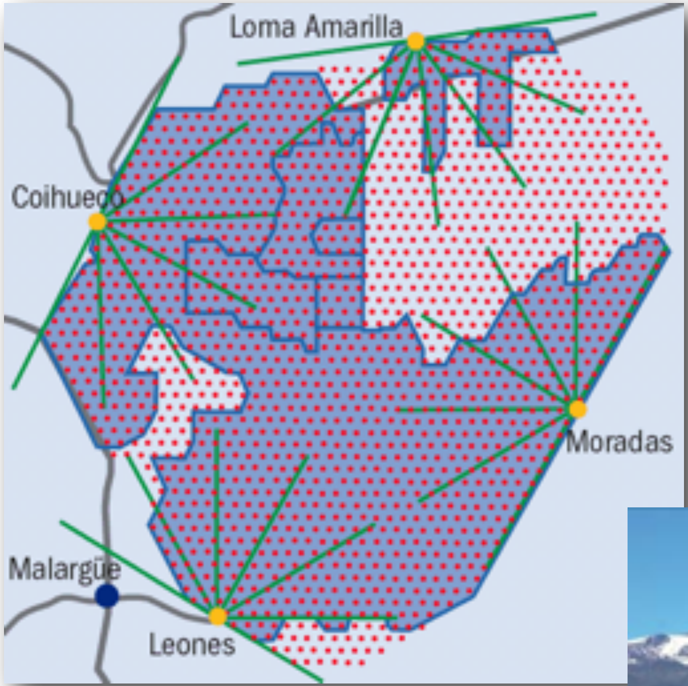
- The atmosphere as homogeneous calorimeter:
  - Energy measurement by measuring the fluorescence light

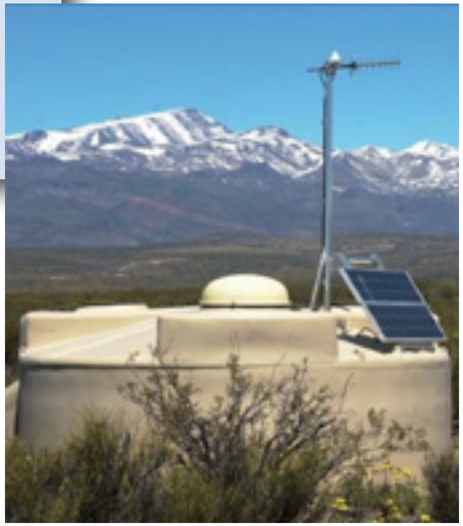
This is only possible with clear skies and darkness !

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

Always possible but has large uncertainties !

AUGER-South: Argentinian Pampa

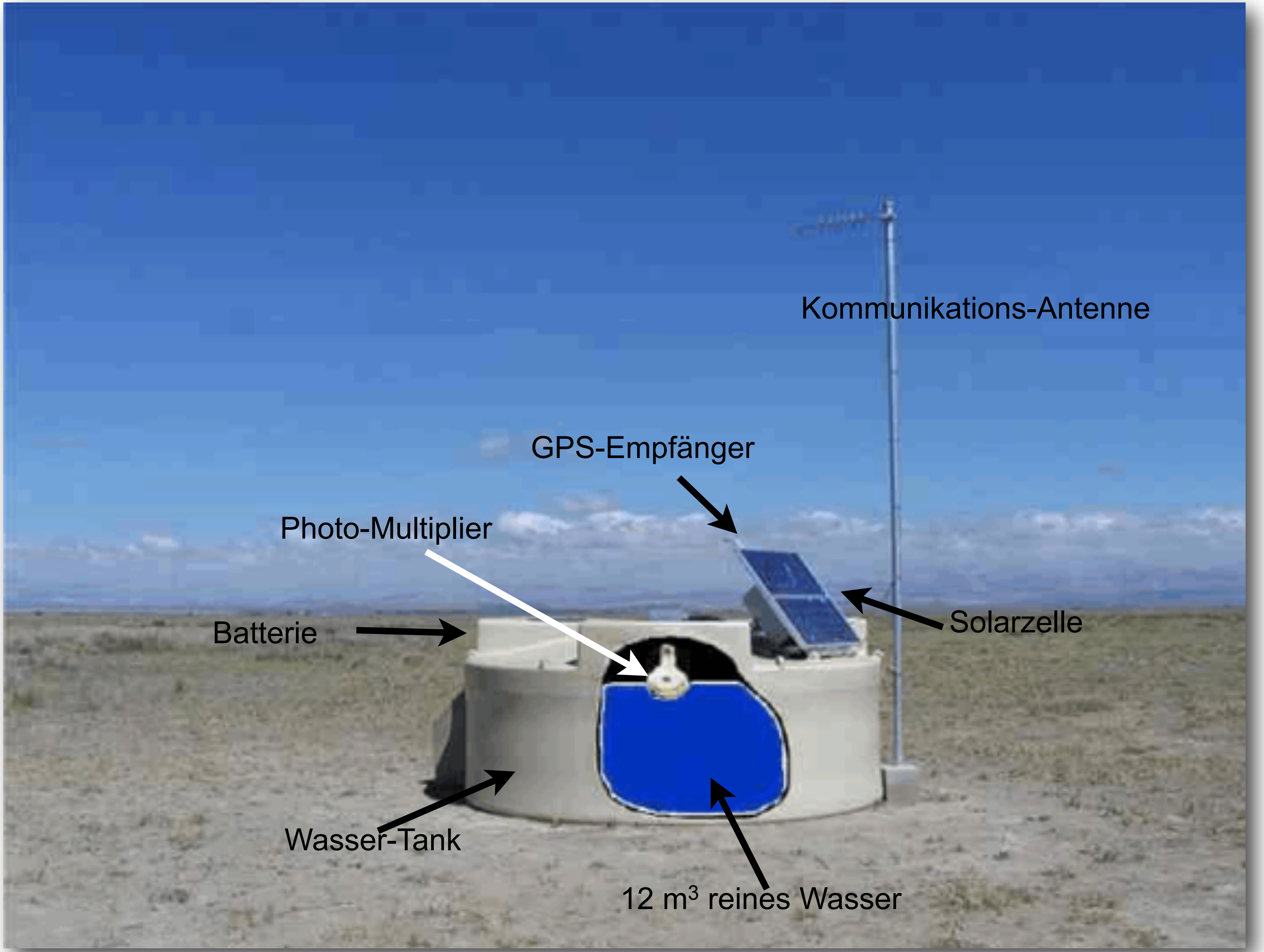




- 1600 water-Cherenkov detectors on ground
- 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

Pics: Pierre Auger Observatory

AUGER-DETEKTOR: GROUND ARRAY



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.

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

Wednesday

V. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers

VI. **Examples from the real life**

Thursday