Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

Monday

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

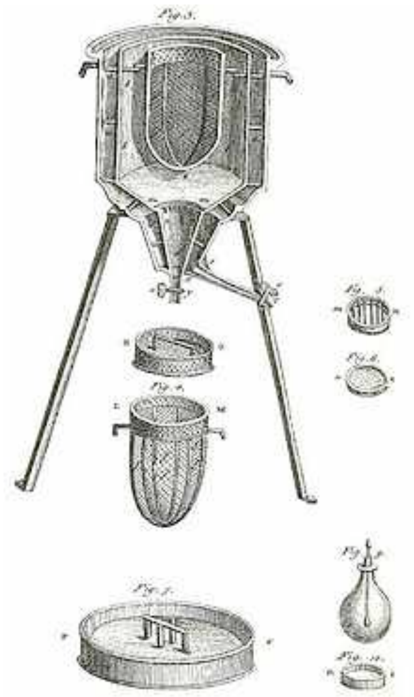
VI. **Examples from the real life**

Wednesday

III. Calorimeters

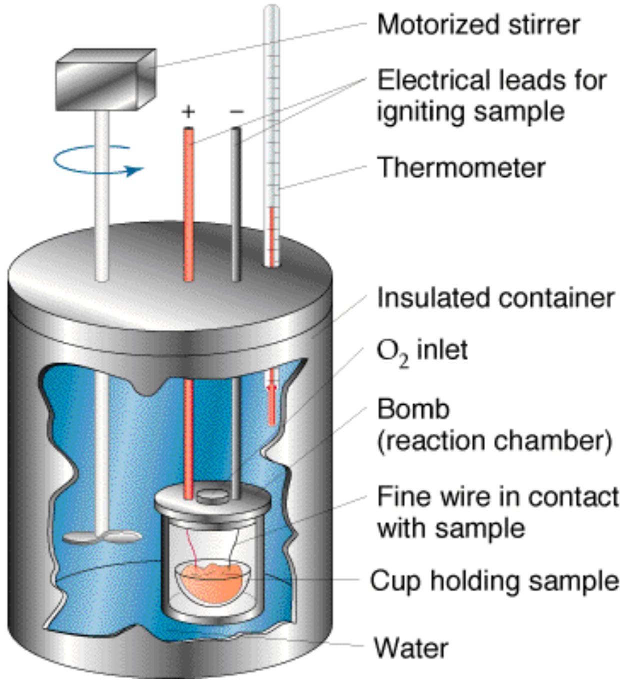
Calorimetry

Calorimetry: The Idea behind it ....



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

- Calorimetry originated in thermo-dynamics
  - The total energy released within a chemical reaction can be measured by measuring the temperature difference
- In particle physics:
  - Measurement of the energy of a particle by measuring the total absorption



Picture: Francois G. Amar

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

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

Calorimetry: Overview

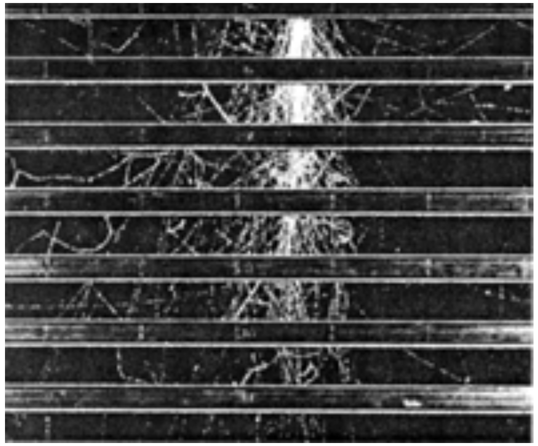
- Basic mechanism for calorimetry in particle physics:
  - formation of electromagnetic
  - or hadronic showers.
- The energy is converted into ionization or excitation of the matter.

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) !

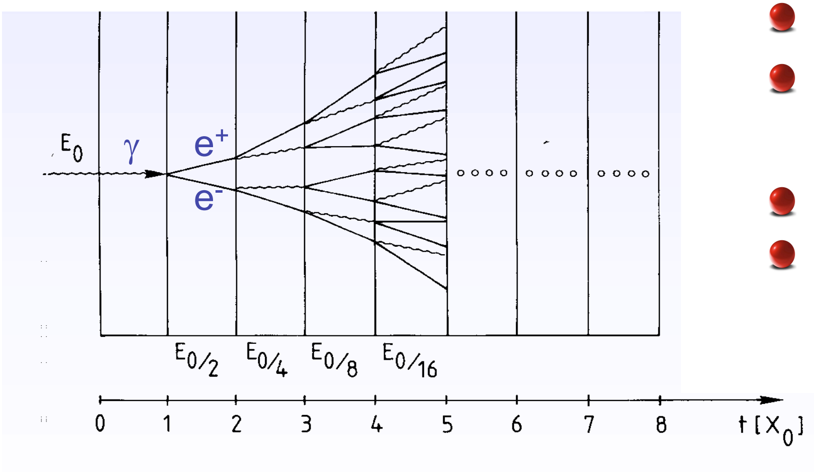
Electromagnetic Showers

Cloud chamber photo of electromagnetic cascade between spaced lead plates.



Pic: MIT cosmic ray group

- High energetic particles: forming a shower if passing through (enough) matter.
- An alternating sequence of interactions leads to a cascade:
  - Primary γ with E_0 energy pair-produces with 54% probability in layer X_0 thick
  - On average, each has $E_0/2$ energy
  - If $E_0/2 > E_c$, they lose energy by Bremsstrahlung



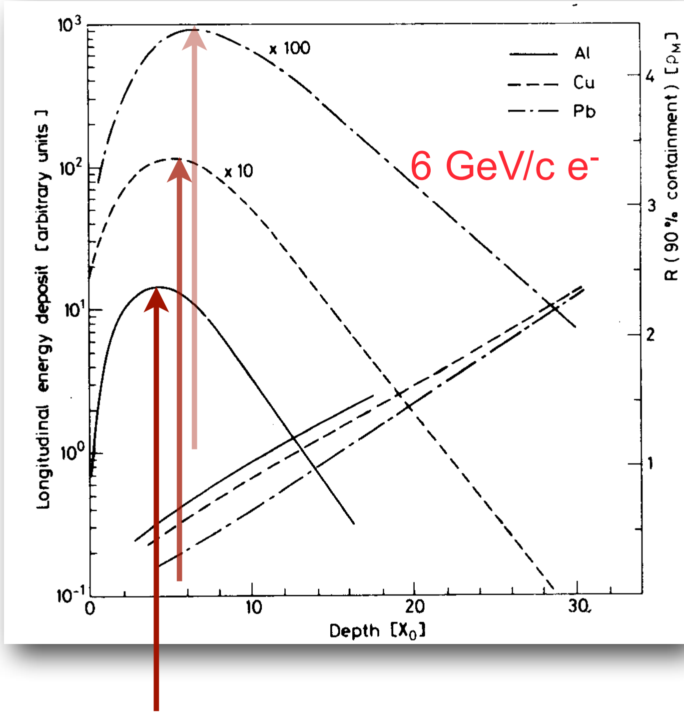
- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Bremsstrahlung with an average energy between $E_0/(2e)$ and $E_0/2$ is radiated
- Radiated γs produce again pairs
- After t radiation lengths
  - number of particles $N \simeq 2^t$
  - each with average energy $E_N \simeq \frac{E_0}{2^t}$

EM Shower Properties

- Shower continues until energy of particles below critical energy.

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

$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \qquad N_{max} \simeq \frac{E_0}{E_c}$$

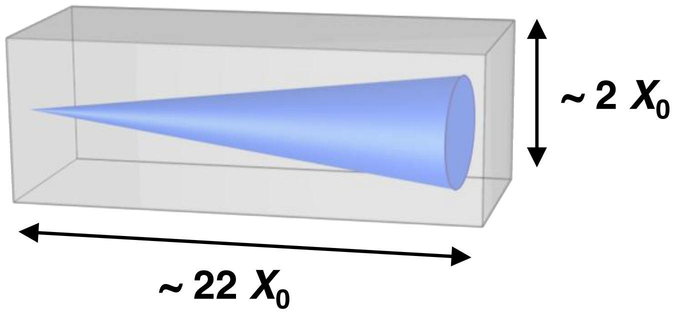


Shower maximum at t_{max}

- Simple model only, for more details MC simulation required.
- Shower curve should rise rapidly to a peak value and then fall to zero.
- The broad peak of the experimental curve can be interpreted in terms of a spread of energies of the incoming particles.
- Long tail due to muon interactions producing knock-on electrons capable of making a contribution to the cascade process.

EM Shower Properties

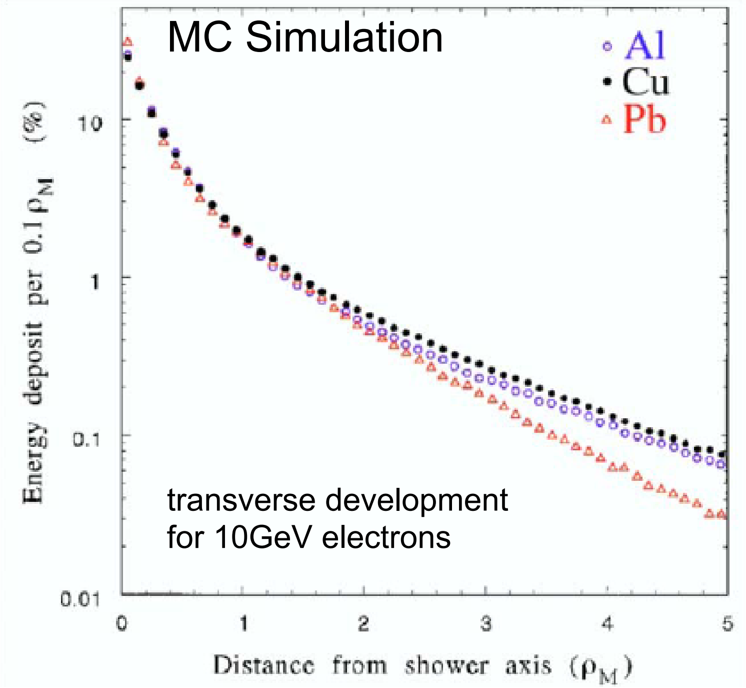
- Longitudinal development governed by the radiation length X_0.
- Lateral spread due to electron undergoing multiple Coulomb scattering:
  - 95% of the shower cone is located in a cylinder with radius 2 RM
  - Beyond this point, electrons are increasingly affected by multiple scattering



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

$$R_M = X_0 \frac{E_S}{E_c} = 21.2MeV \cdot \frac{E_S}{E_c}$$

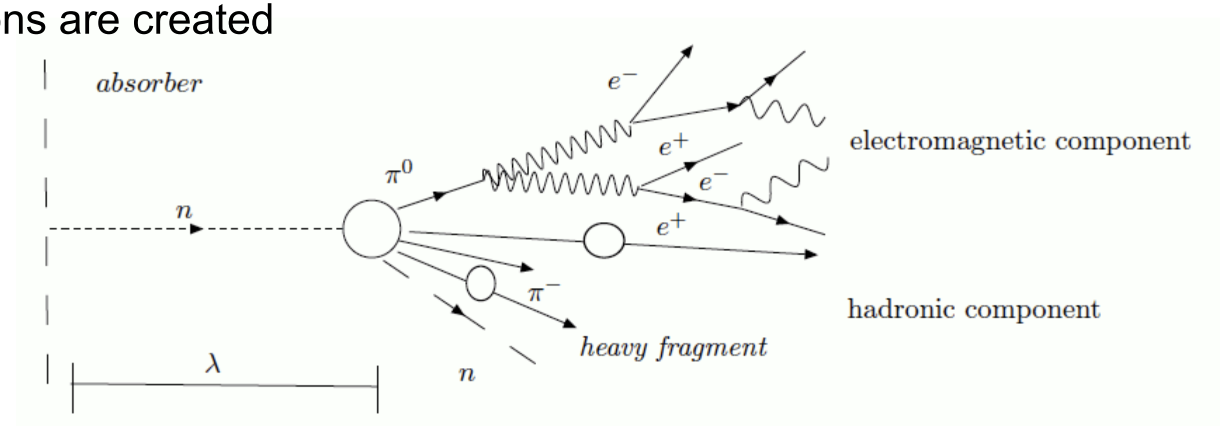
$$E_S = m_e c^2 \sqrt{4\pi/\alpha} = 21.2MeV$$



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

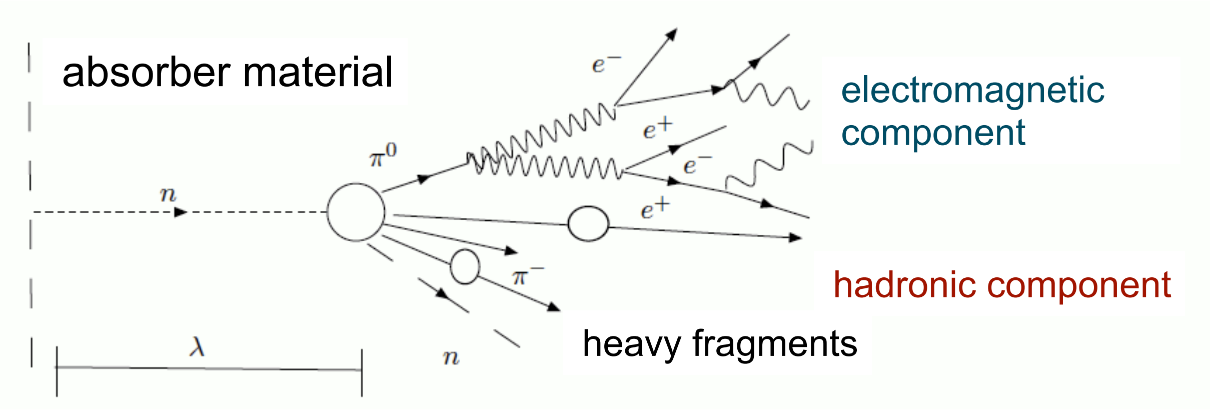
$$\lambda_l = \frac{A}{N_A \sigma_{total}}$$

total cross section for nuclear processes

	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

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

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 transfered into nuclear processes: nuclear excitation, spallation, ... ➠ Particles in the MeV range
  - Neutrale 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

Hadronic cascades

The concept of compensation

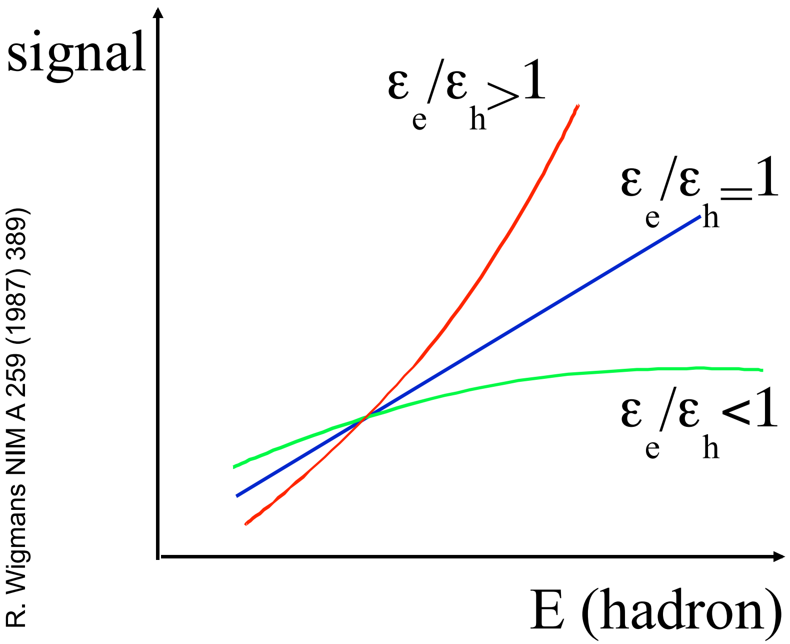
- A hadron calorimeter shows in general different efficiencies for the detection of the hadronic and electromagnetic components ε_h and ε_e.

$$R_h = \varepsilon_h E_h + \varepsilon_e E_e$$

ε_h: hadron efficiency
ε_e: electron efficiency

- The fraction of the energy deposited hadronically depends on the energy

$$\frac{E_h}{E} = 1 - f_{\pi^0} = 1 - k \ln E \ (GeV) \qquad k \approx 0.1$$



R. Wigmans NIM A 259 (1987) 389)

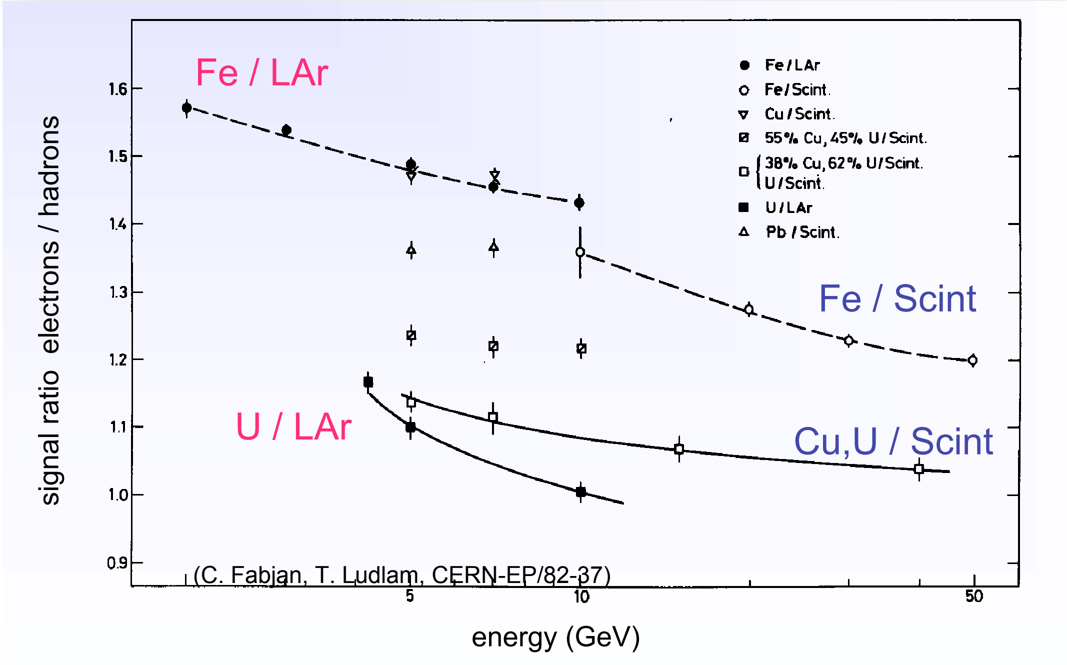
Response of calorimeter to hadron shower becomes non-linear

Energy resolution degraded !

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \times \left| \frac{\varepsilon_e}{\varepsilon_h} - 1 \right|$$

Improved Energy Resolution: Compensation

- The detector parameter e/π is defined by geometry and material.
- To reach e/π = 1 (Compensation), the signal produced by hadrons has to be increased
- Introduce active material with sensitivity for slow neutrons: Scintillator with H
- also possible: increase of the neutron activity by the use a special absorber i.e. Uranium



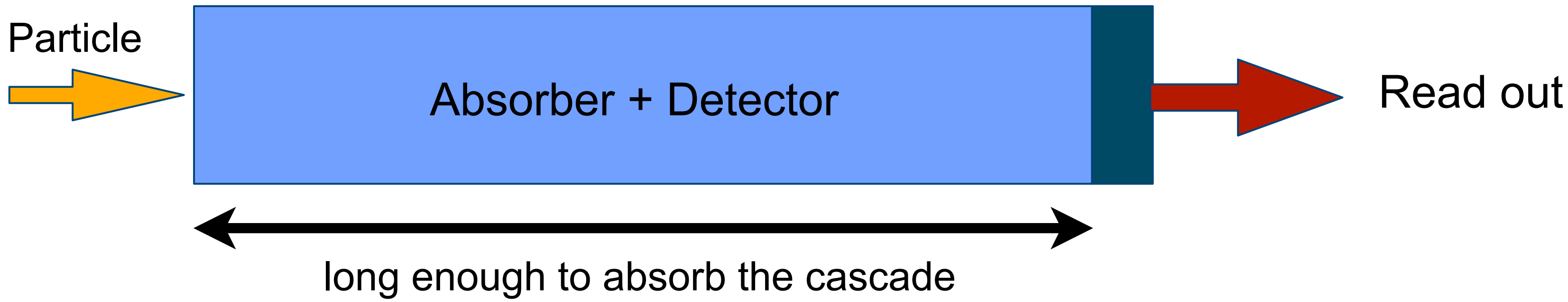
- Compensation is enabled by choosing the right Sampling-fraction

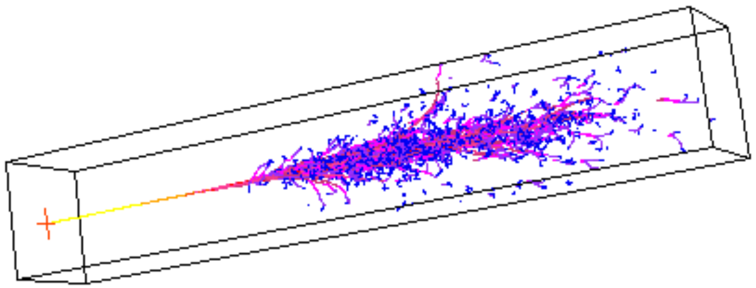
But:

- careful with amount of material in front of calorimeter!

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



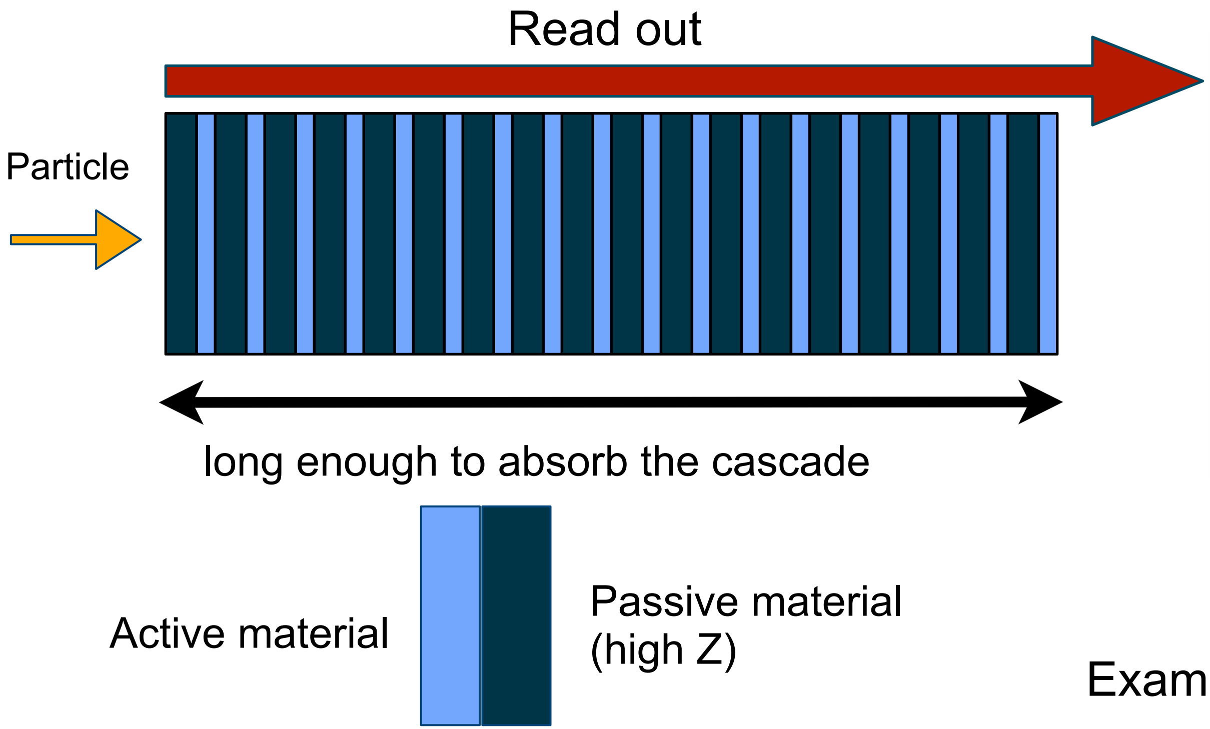


Pic: Cornell

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 **energy resolution** of a calorimeter is parametrized:

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

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

Losses of Resolution:

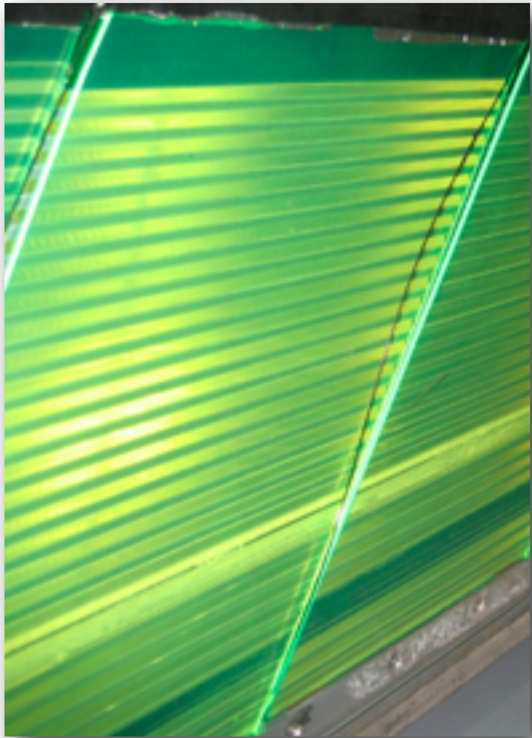
- **Shower not contained** in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.
- **Statistical fluctuations** in number of photoelectrons observed in detector.
- **Sampling fluctuations** if the counter is layered with inactive absorber.
- ….

Calos: Active Material

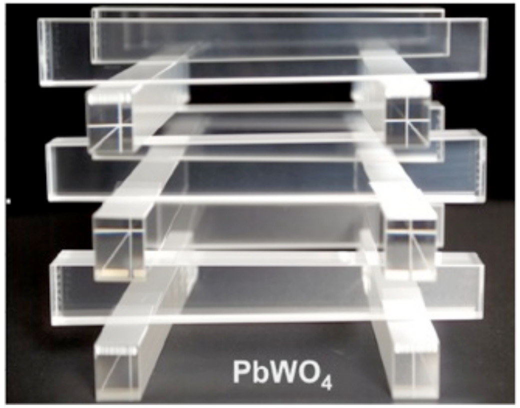
Active material

- 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.
    - Large scale industrial production, mechanically and chemically quite robust.
  - Inorganic Crystals -> Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.



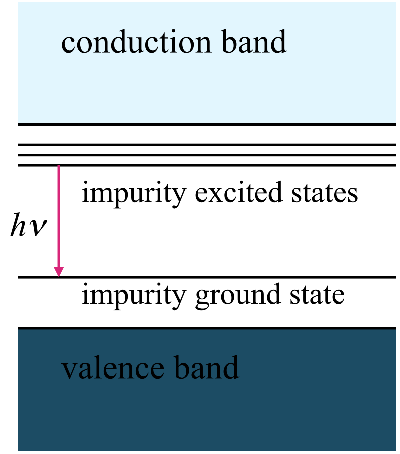
Picture: CDF@Fermilab



- $PbWO_4$: 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

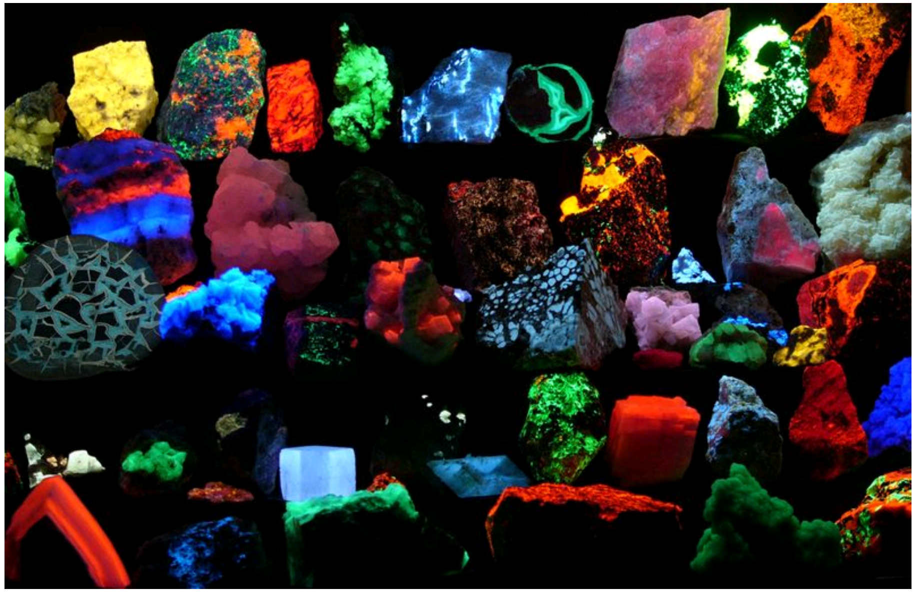
Scintillators to measure the energy

- An incident photon or particle ionizes the medium.
- Ionized electrons slow down causing excitation.
- Excited states immediately emit light.



Inorganic scintillators

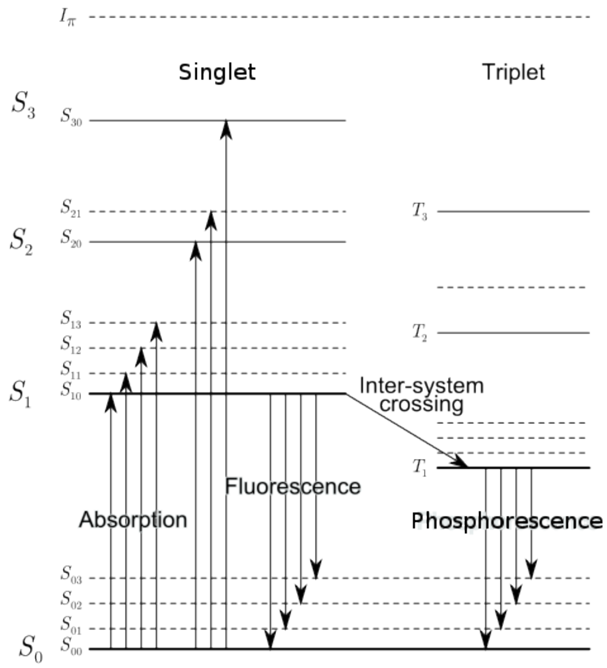
- Fluorescence is known in many natural crystals.
  - UV light absorbed
  - Visible light emitted
- Artificial scintillators can be made from many crystals.
  - Doping impurities added
  - Improve visible light emission



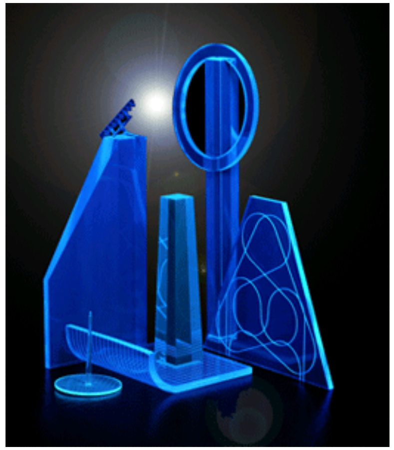
Scintillators to Measure the Energy

Inorganic scintillators

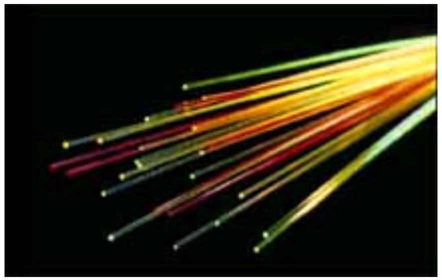
source: Wikipedia



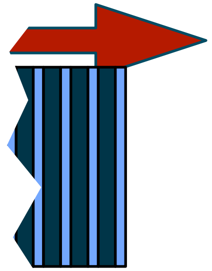
- Scintillators emit light when ionizing particles pass the material
- Excited states radiate photons in the visible and UV spectra.
  - Fluorescence is the fast componen
  - Phosphorescence is the slow component



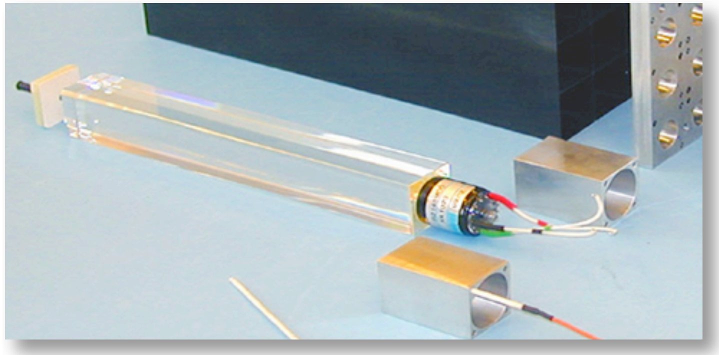
- Organic scintillators can be mixed with polystyrene to form a rigid plastic.
  - Easy to mold
  - Cheaper than crystals
- Used as slabs or fibers



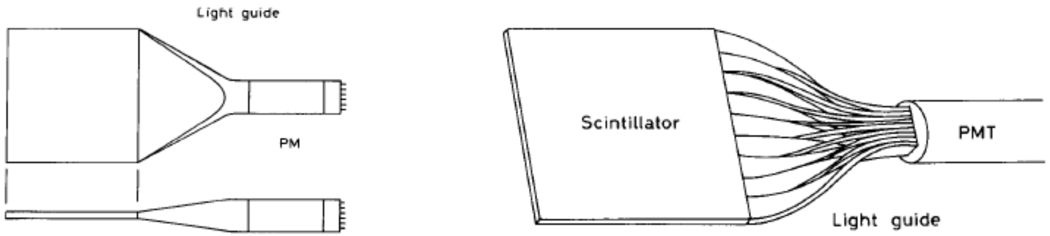
Light transport



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

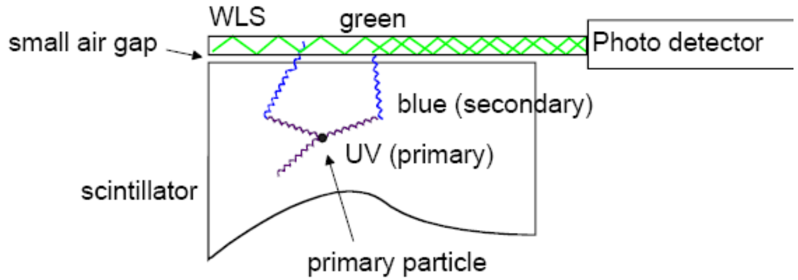


- Light guides: transfer by total internal reflection (+outer reflector)



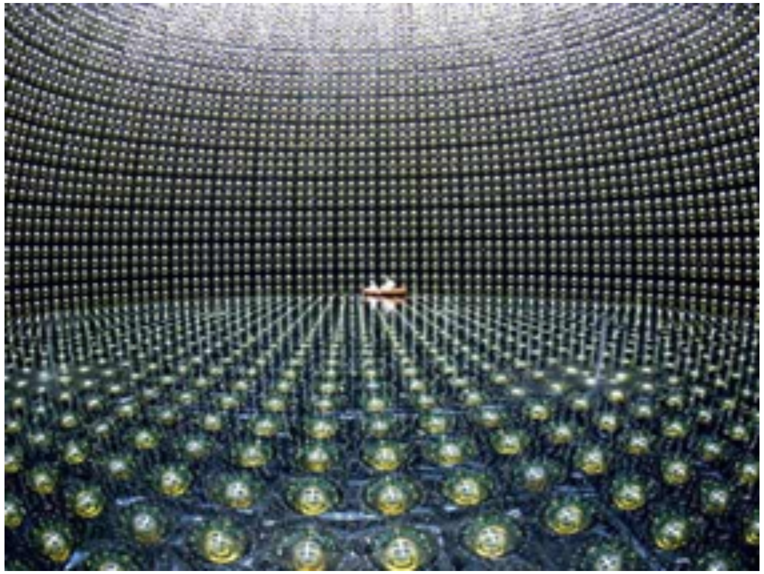
"fish tail" adiabatic

- 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

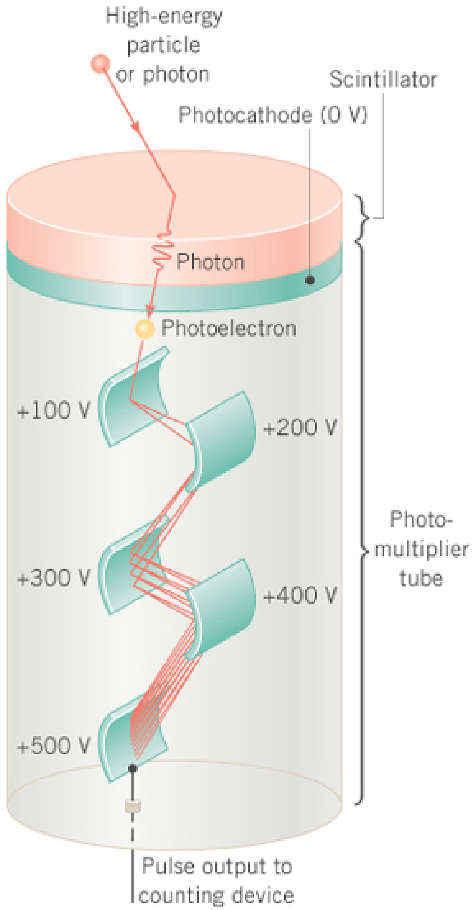


Detecting the Light

- 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

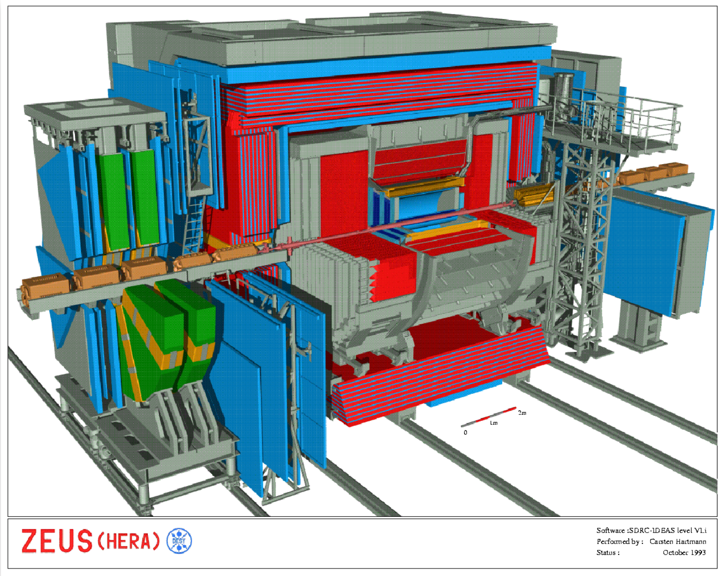


Source: Cutnell and Johnson, 7th edition image gallery

Example: ZEUS Calo

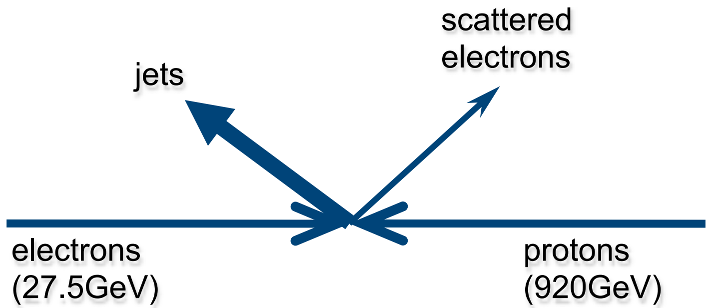
A rather hostile environment in ZEUS at HERA

- 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



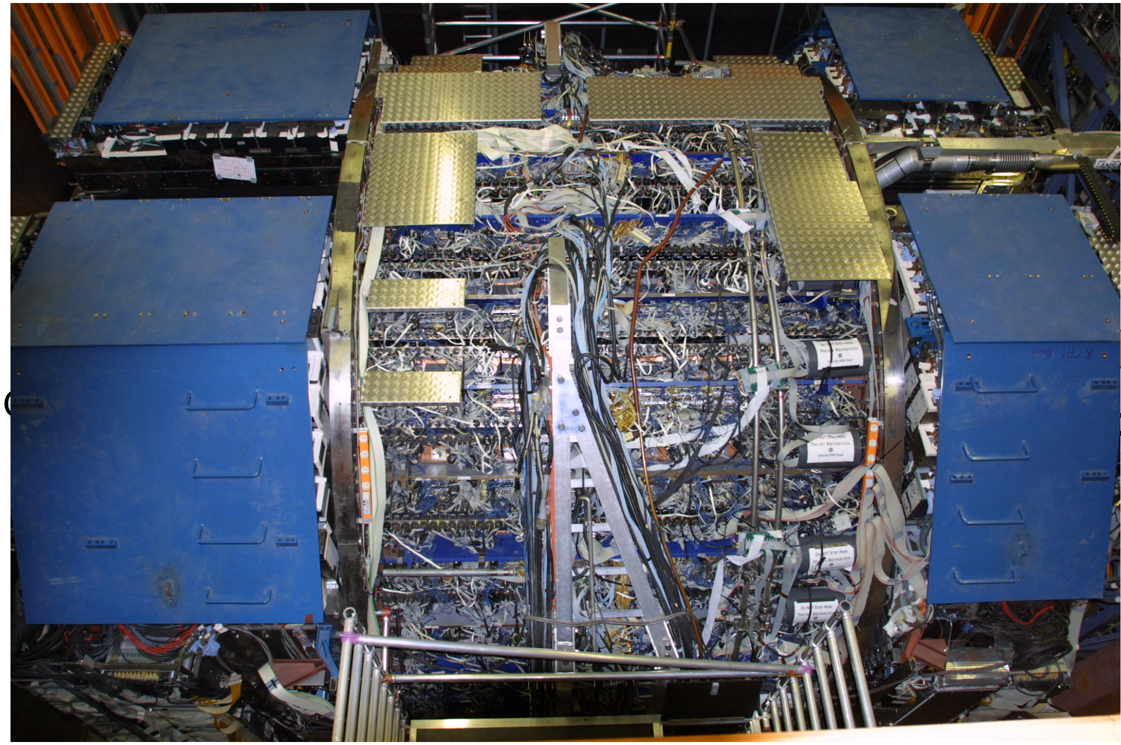
Keep in mind: this was developed in the middle of the 80s!

The ZEUS Calorimeter - Solution

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

e ±

27.5 (



GeV

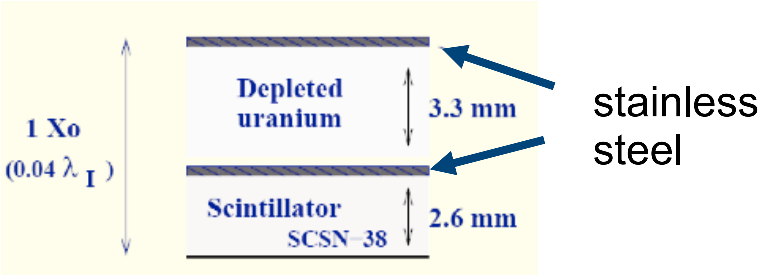
Uranium + Scintillator:

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

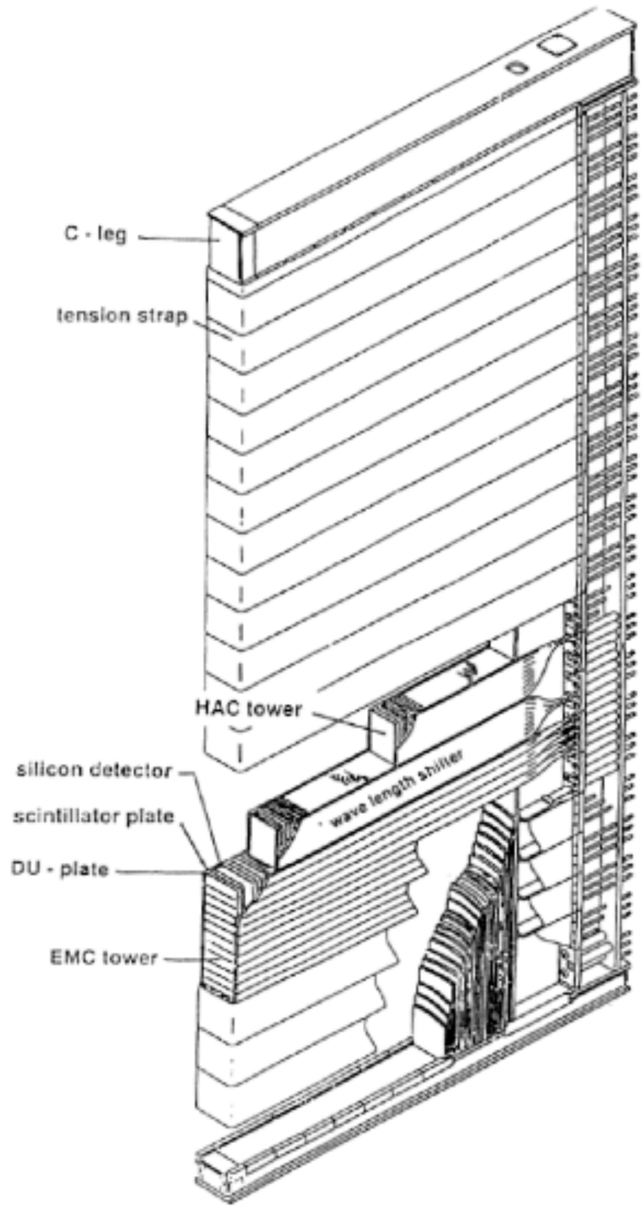
- Very hermetic: covering up to η<4.2 in the forward direction and η<-3.8 in the rear direction.
- Readout by 12,000 phototubes (PMTs)

Design

- Layers:

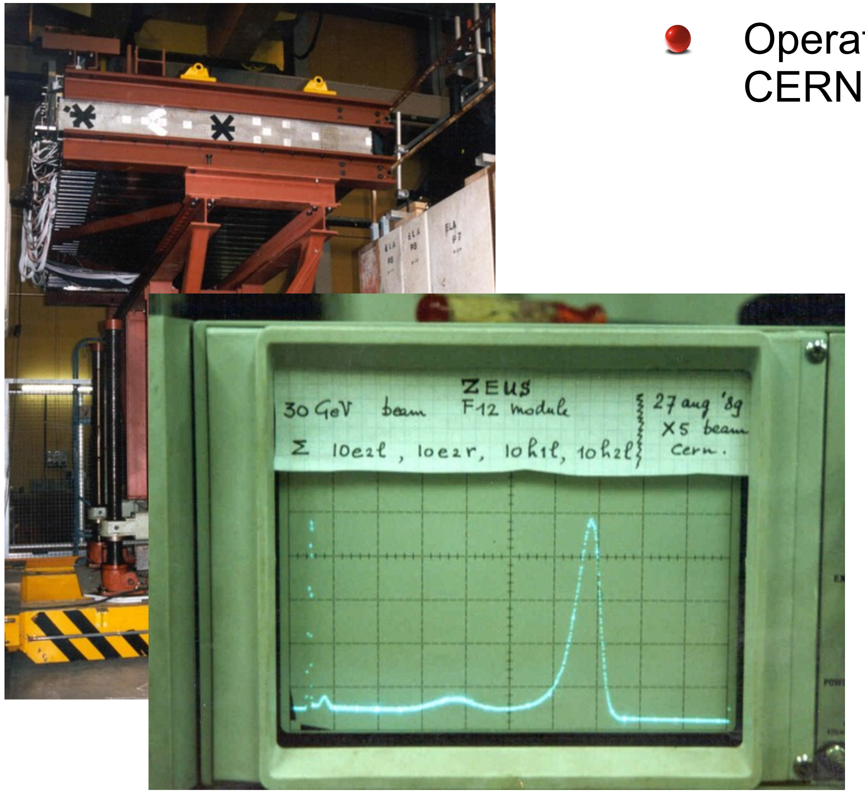


- choice of active and passive thicknesses -> compensation (e/h = 1.0)
- uniformity in structure + natural radioactivity -> good calibration
- F/B/RCAL with ~6000 cells
  - EM cell size: 5x20 (10x20) cm^2 in F/BCAL (RCAL)
  - HA cell size: 20x20 cm^2
- Cell read out on both sides with wavelength shifters
  - redundancy
  - transverse position measurement within the cell

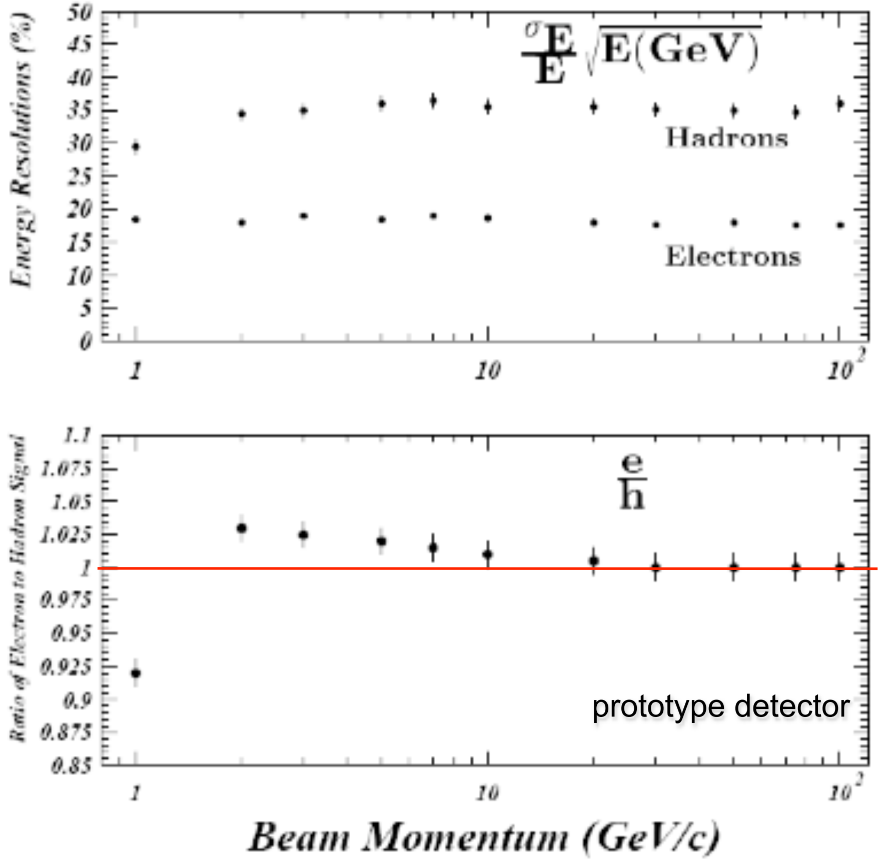


3m x 5m x 0.2m, 12tons
total of 80 modules

Test beam at CERN



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



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

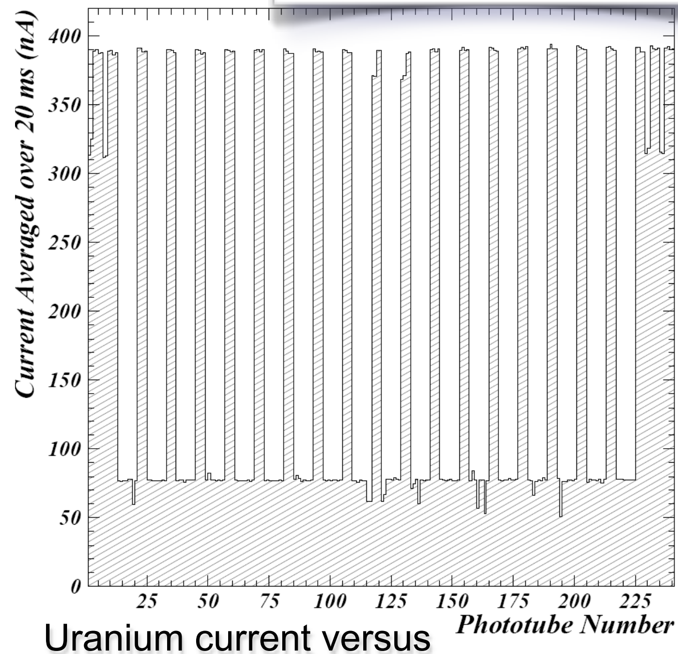
Hadrons: $$\frac{\sigma(E)}{E}=\frac{35\%}{\sqrt{E(GeV)}}$$

Production modules were all calibrated at CERN

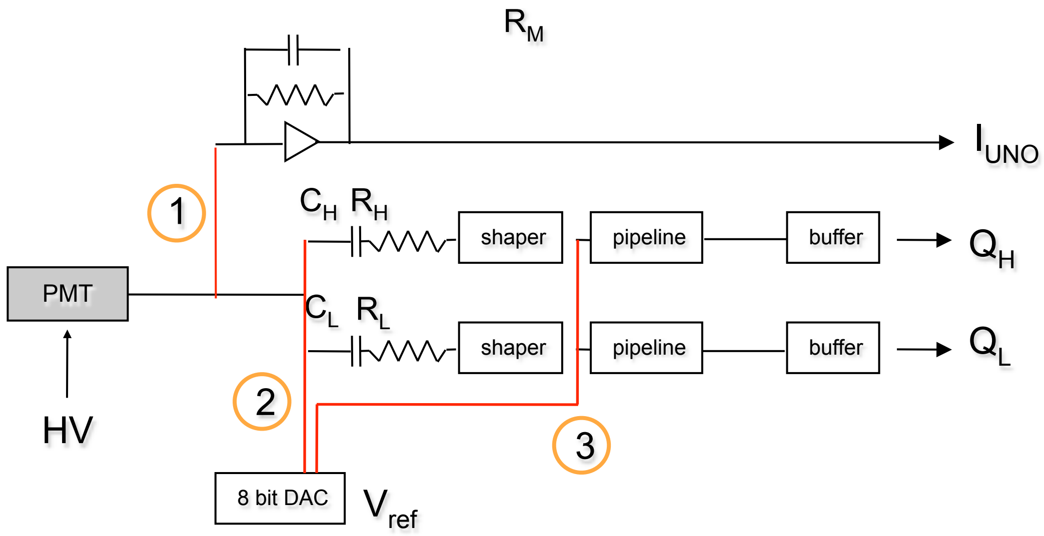
Calibration Methods

- 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

Stable radioactivity
- good for calibration



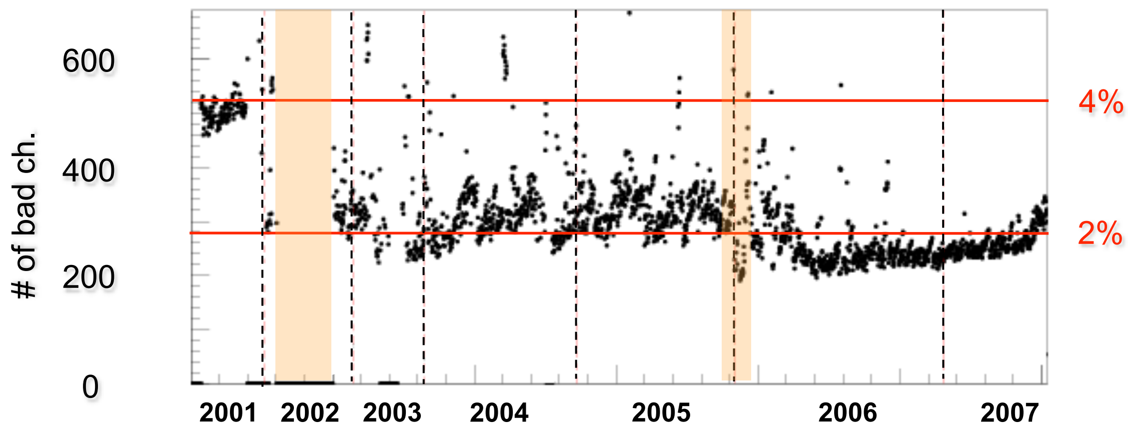
Uranium current versus channels of one module



1. Uranium noise
2. Charge injection
3. Pedestals and Gains

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

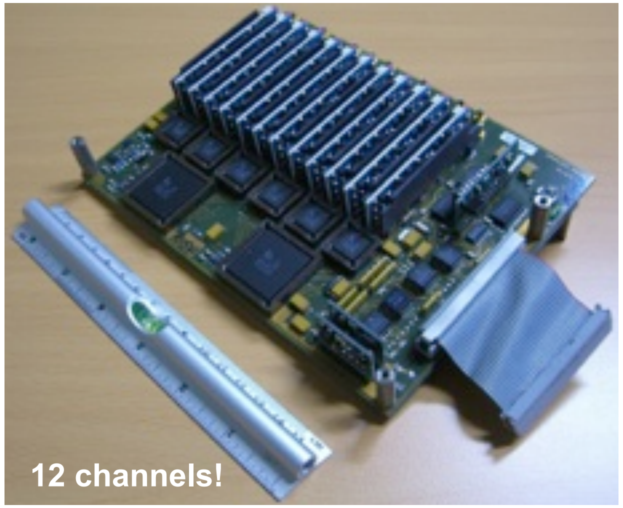
Hardware Performance



- 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**

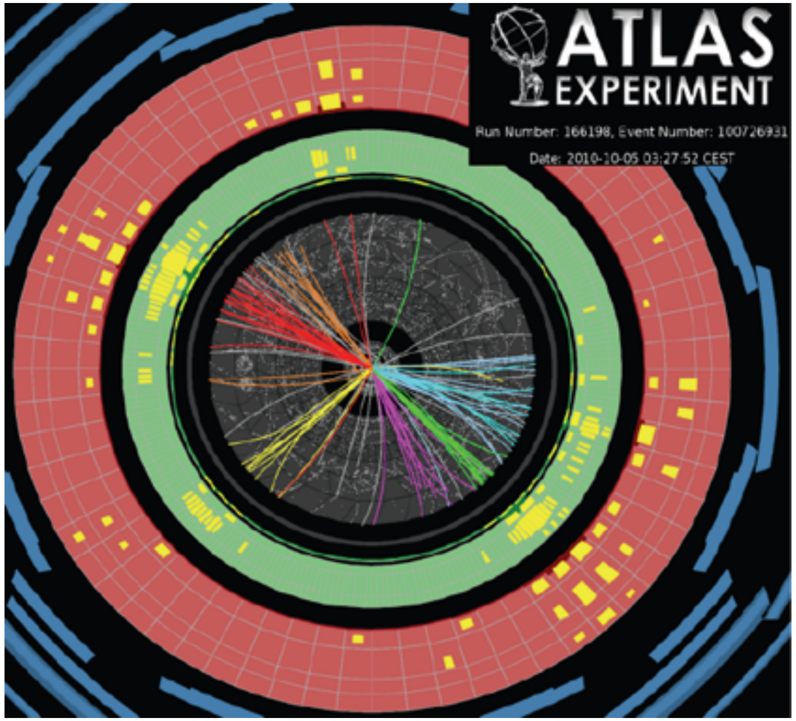
- Front End Cards:
  - About 1000 necessary for the running, ~10% spares
  - Main failure mode: buffer or pipeline chip (socketed)
  - Cards easy to debug and maintain
  - Failure rate: <1/month (12 channels – one side)
  - Very successful

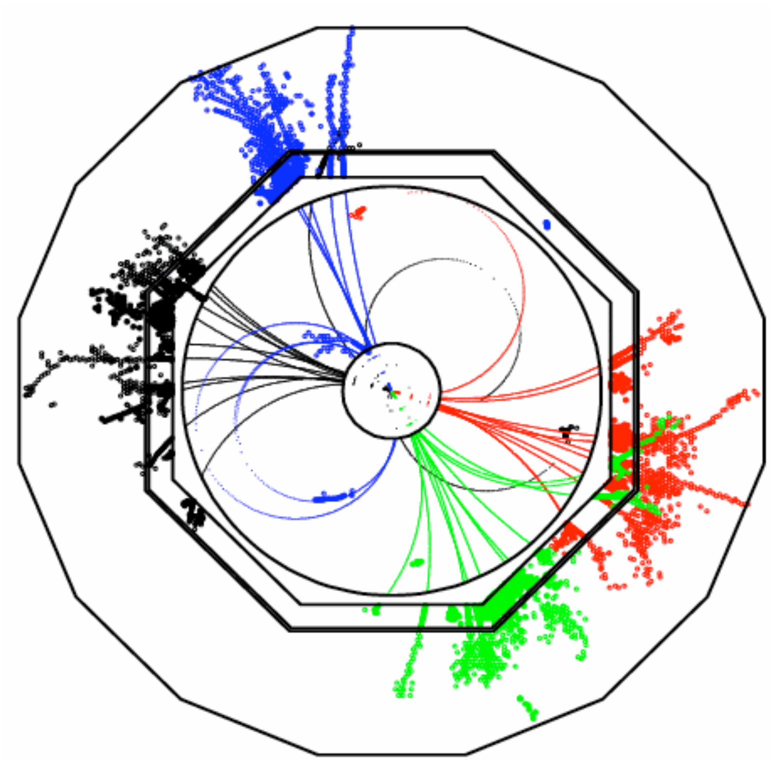


Lessons learned

- **Pipeline Chips on analog cards:**
  - In tests of prototype observed degradation in performance of pipeline chips
  - Range of duty cycle of the write clock over which the pipeline operates changed with elapsed time of operation
  - Replacement of all pipeline chips during first summer shutdown (1993)
- **Ageing of cables**
  - CAL was opened and closed for beam injection and beam dump -> radiation protection
  - In later years often failure in control cables (clock, QINJ)
  - Combination of mechanical stress and aging
  - Stopped CAL movement as PMT voltage showed no dramatic radiation damage
- **BCAL PMT bases**
  - Higher failure rate than anticipated (1 PMT/week/module)
  - Problem traced back to capacitor in Cockcroft-Walton base (HV creation within PMT)
  - Failed bases were replaced by newly designed
  - Failure rate of original bases decreased as time went on

Current Hadron Calos … and Dreams

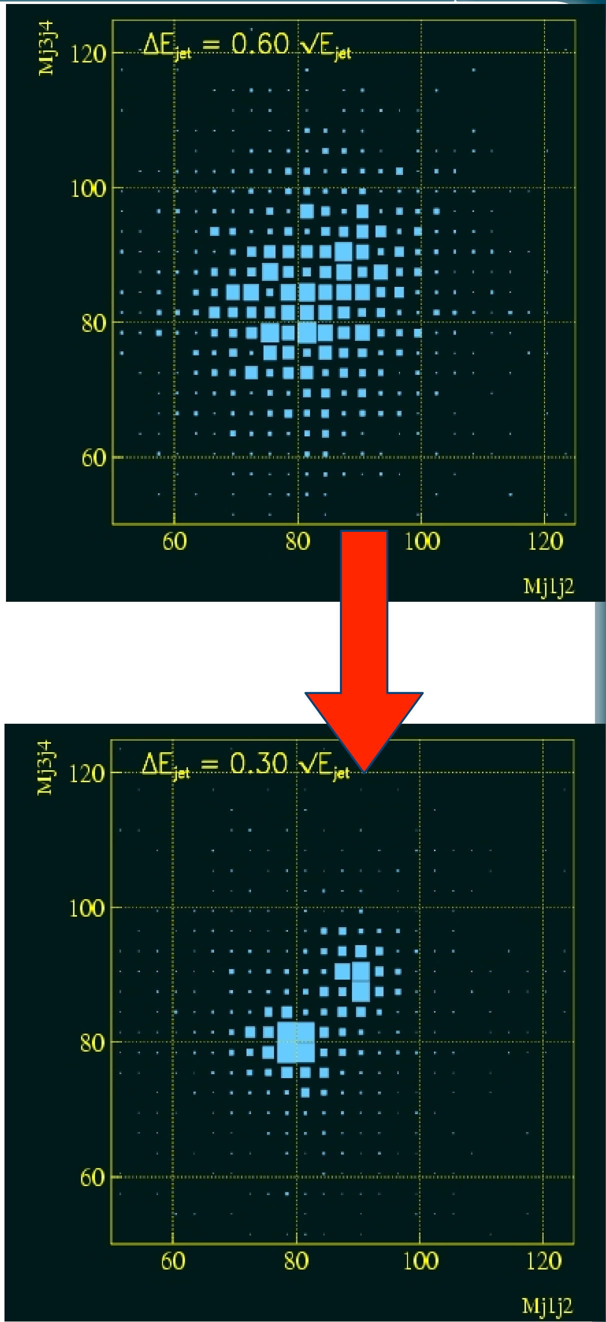




- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT) O(10k) channels for full detectors
- Extreme granularity to see shower substructure: small detector cells with individual readout for Particle Flow O(10M) channels for full detectors

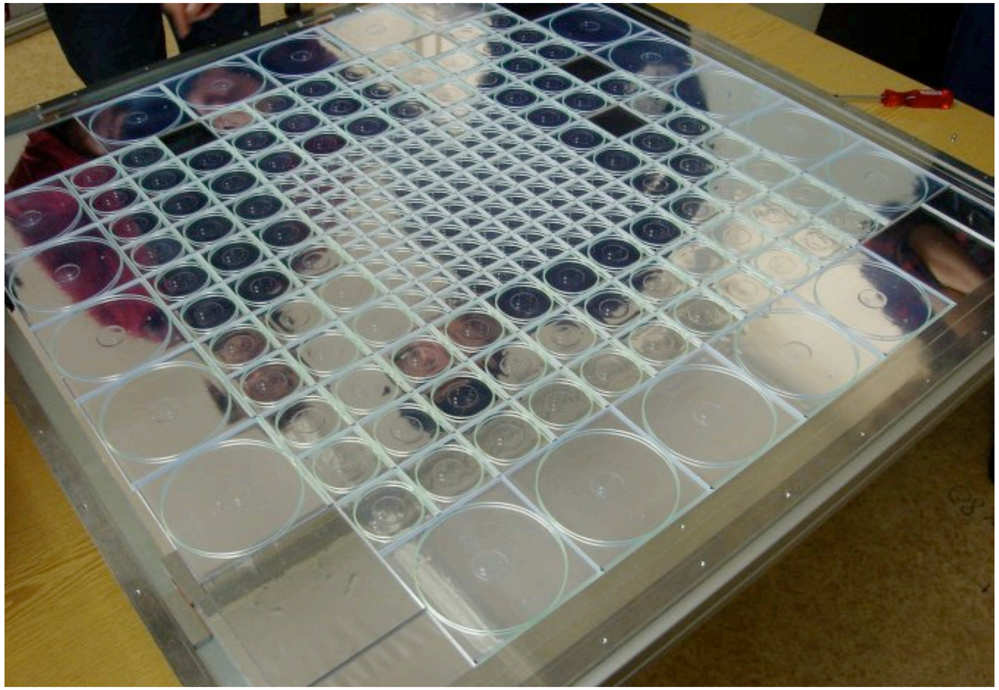
Particle Flow Calorimeter

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



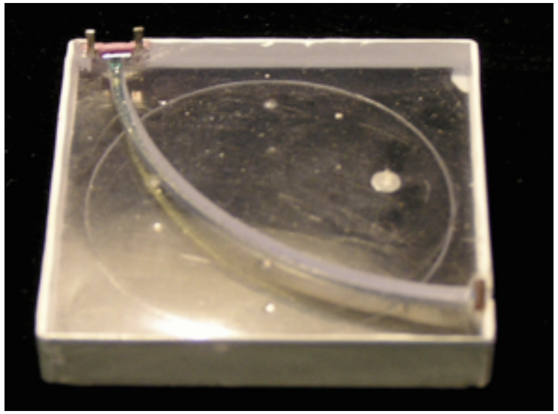
New Concepts: Highly Granular Calos

- 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

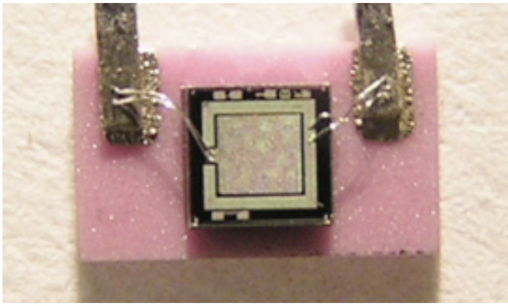


Pictures: CALICE collaboration

tiles in one layer

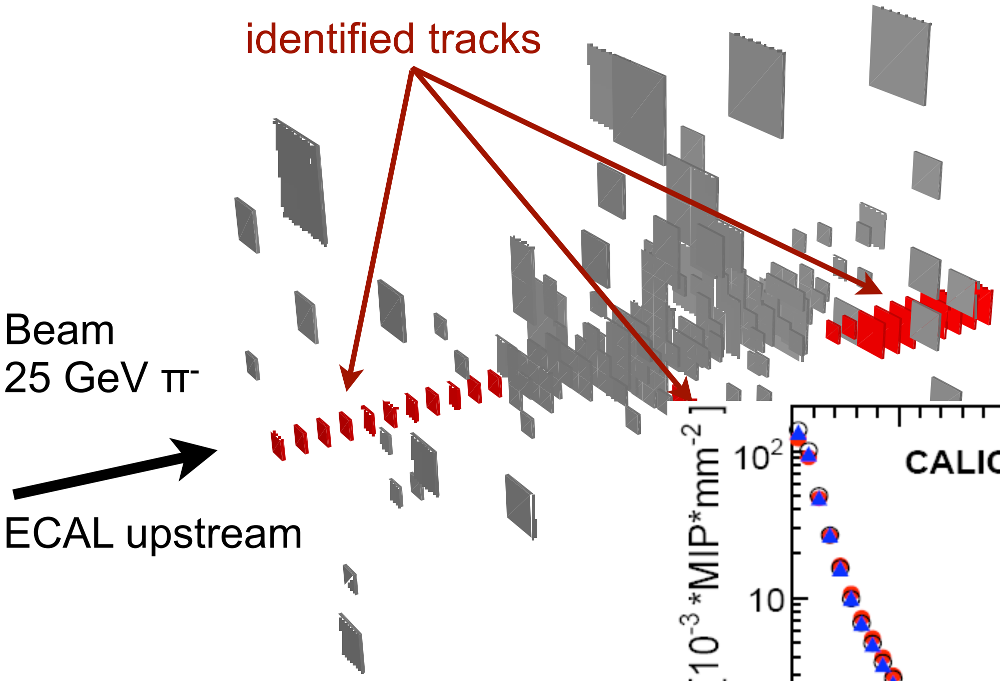


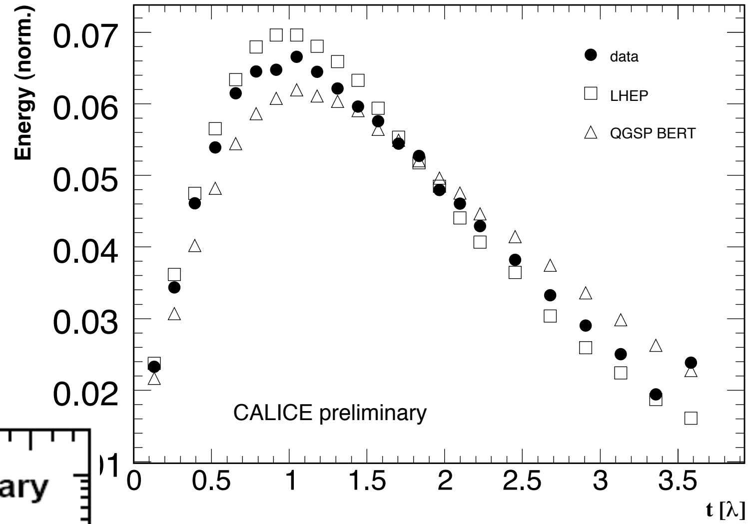
scintillator tile with WLS fiber

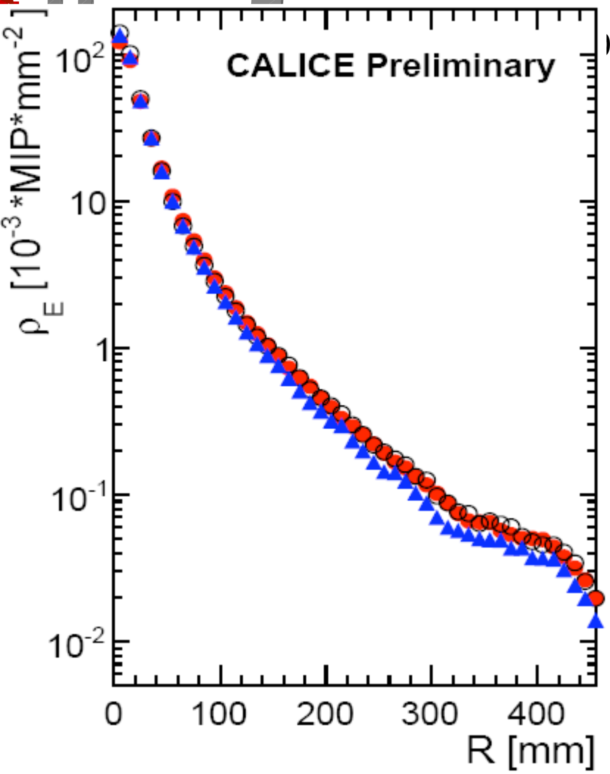


Silicon photo-multiplier

CALICE: Hadronic Shower Studies

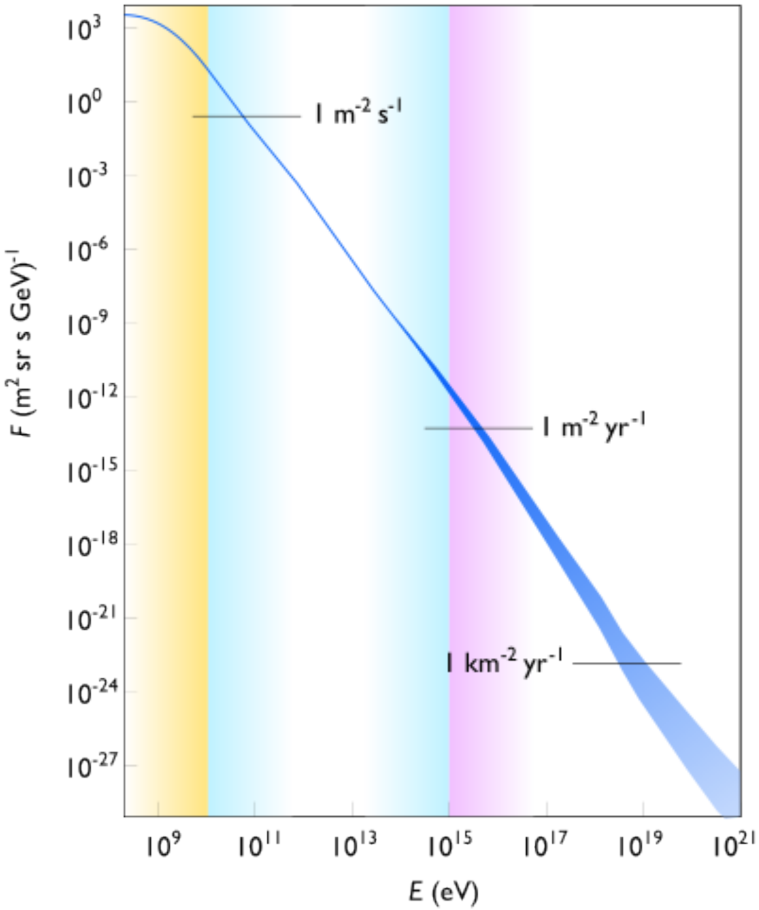






- Comparison of detailed test beam studies with simulations: improvement of existing shower models

Calos: not only at accelerators!



Pic: Wikipedia

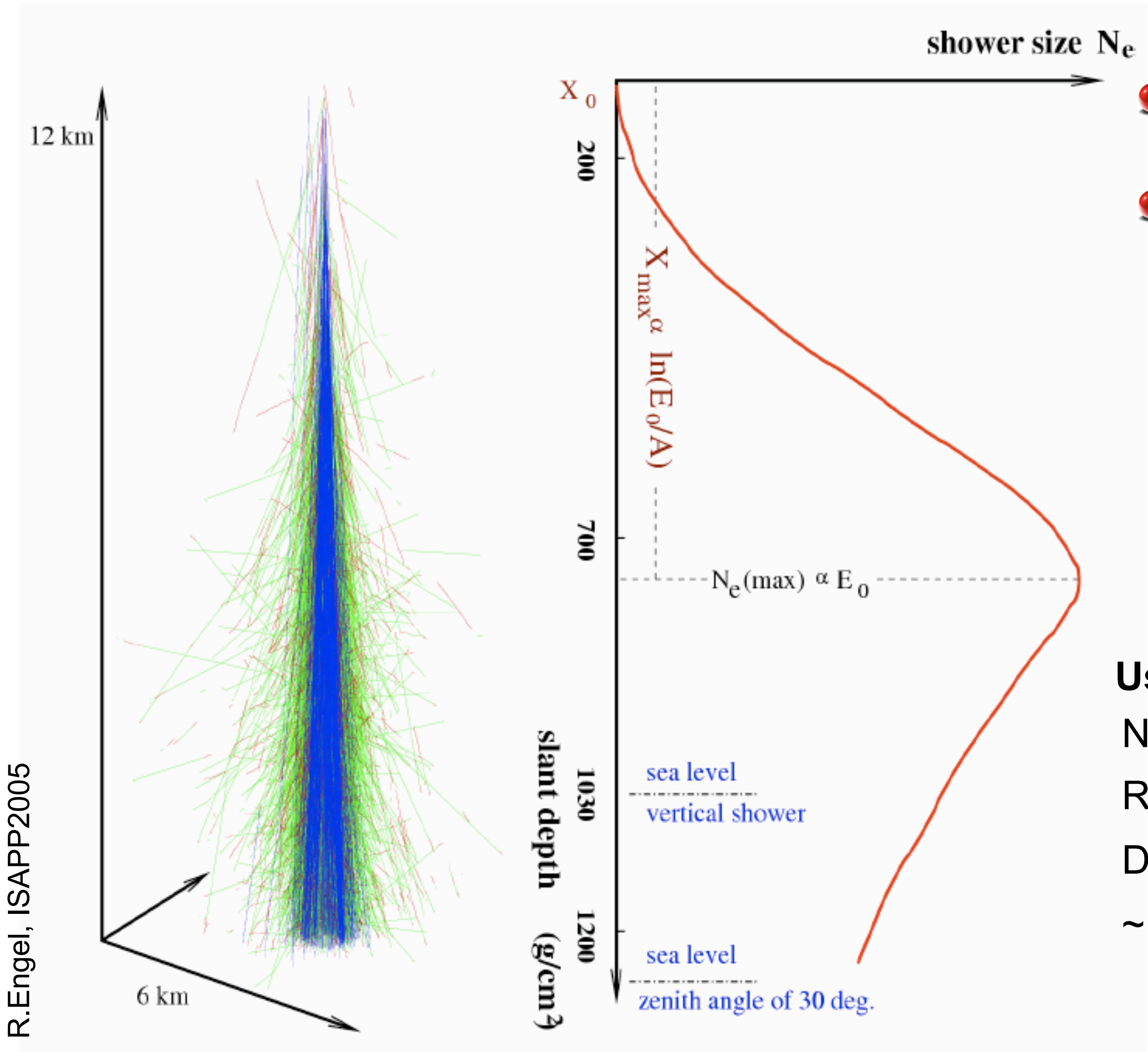
Flux of cosmic ray particles as a function of their energy.

- 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

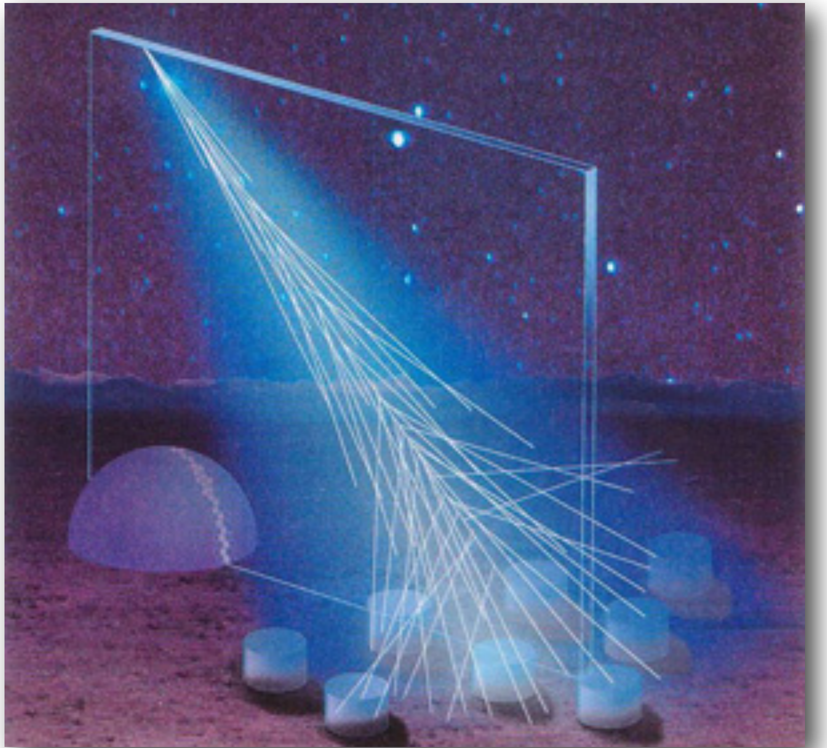
Nuclear reaction length $\lambda_I \sim 90\ g/cm^2$

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

Density: $\sim 1035\ g/cm^2$

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

Two Techniques



Pic: Pierre Auger Observatory

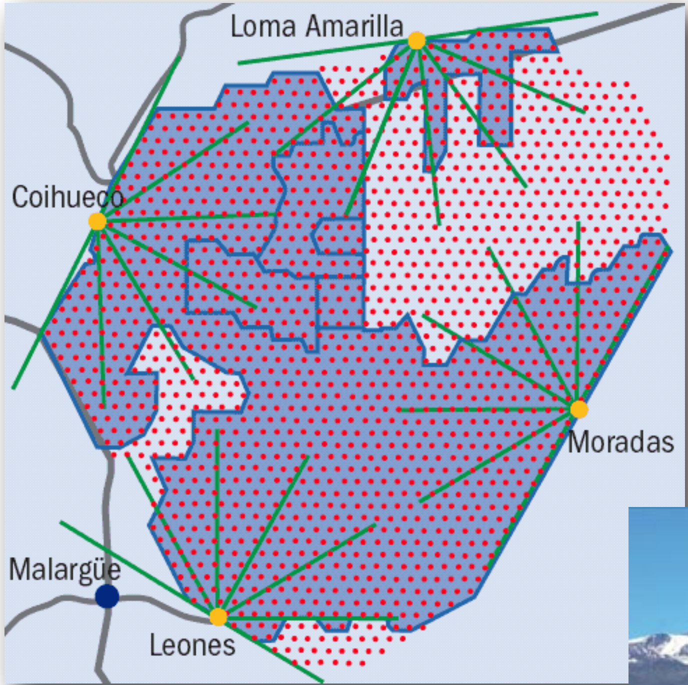
- The atmosphere as homogeneous calorimeter:
  - Energy measurement by measuring the fluorescence light

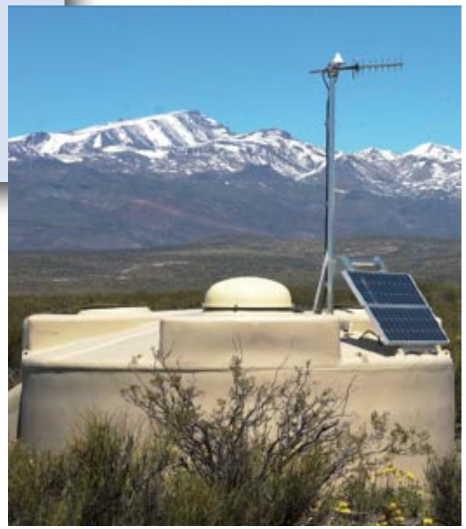
This is only possible with clear skies and darkness !

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

Always possible but has large uncertainties !

AUGER-South: Argentinian Pampa

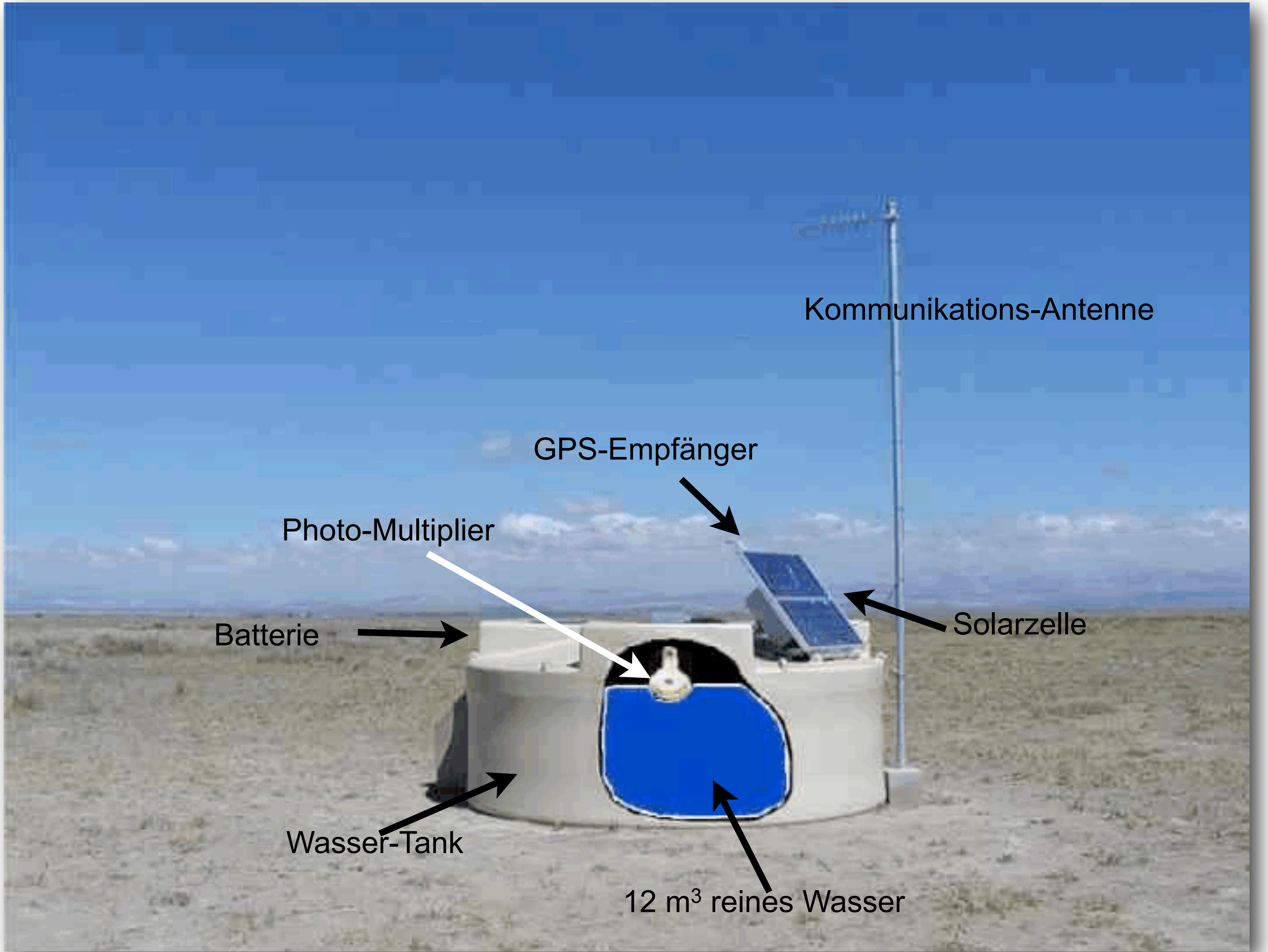




- 1600 water-Cherenkov detectors on ground
- 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

Pics: Pierre Auger Observatory

AUGER-Detektor: Ground Array



Summary Part 1

Ionization and Excitation:

- Charged particles traversing material are **exciting and ionizing** the atoms.
- Average energy loss of the incoming charged particle: good approximation described by the **Bethe Bloch** formula.
- The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

- Incoming particles are **scattering off** the atomic nuclei which are partially shielded by the atomic electrons.
- Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.
- The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus….

Summary Part 2

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

V. Tracking Detectors
- Gas detectors
- Semiconductor trackers

VI. Examples from the real life

} *Monday* (I.–III.)

} *Wednesday* (V.–VI.)