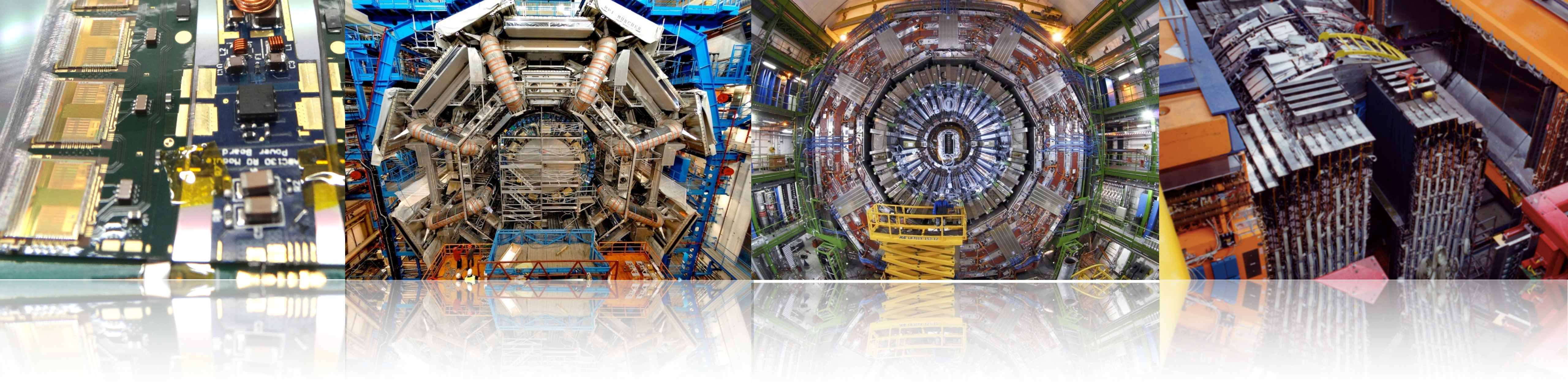

Instrumentation and Detectors

Part 3

AEPSHEP 2022

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DESY/Universität Bonn

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

Sunday

III. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers
- Muon Detectors

Monday

IV. **Calorimeters**

V. **Examples of what can go wrong**

Wednesday

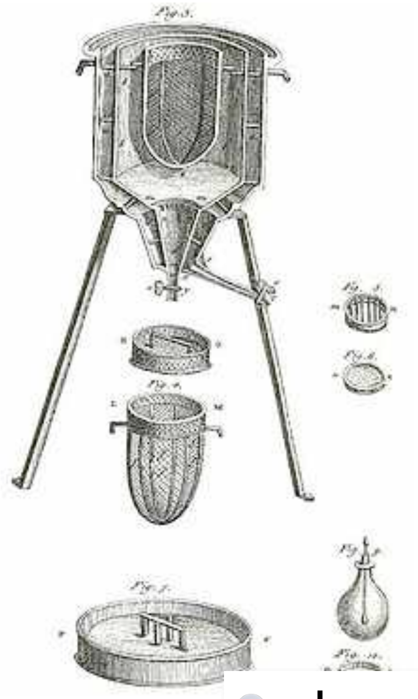
III. Calorimeters

Calorimetry

Calorimetry: The Idea behind it ....

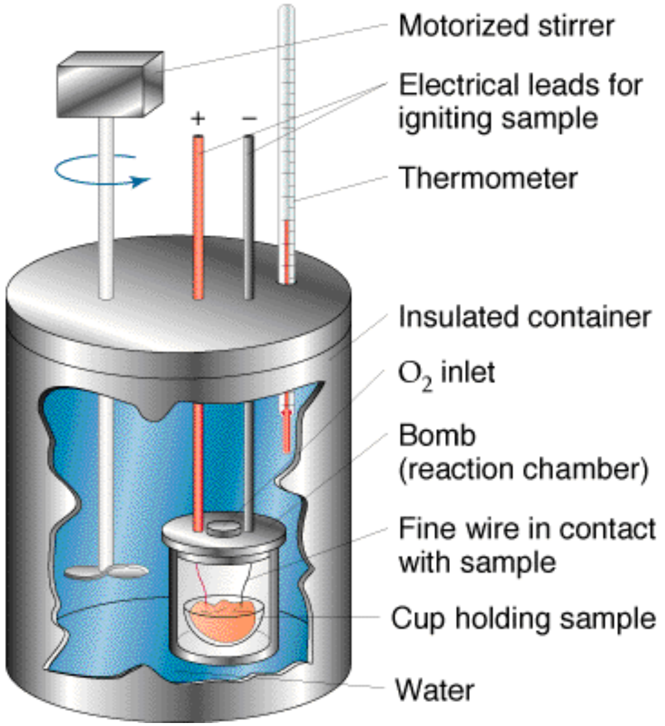
What is the effect of a 1 GeV particle in 1 litre water (at 20°C)?

- 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*.

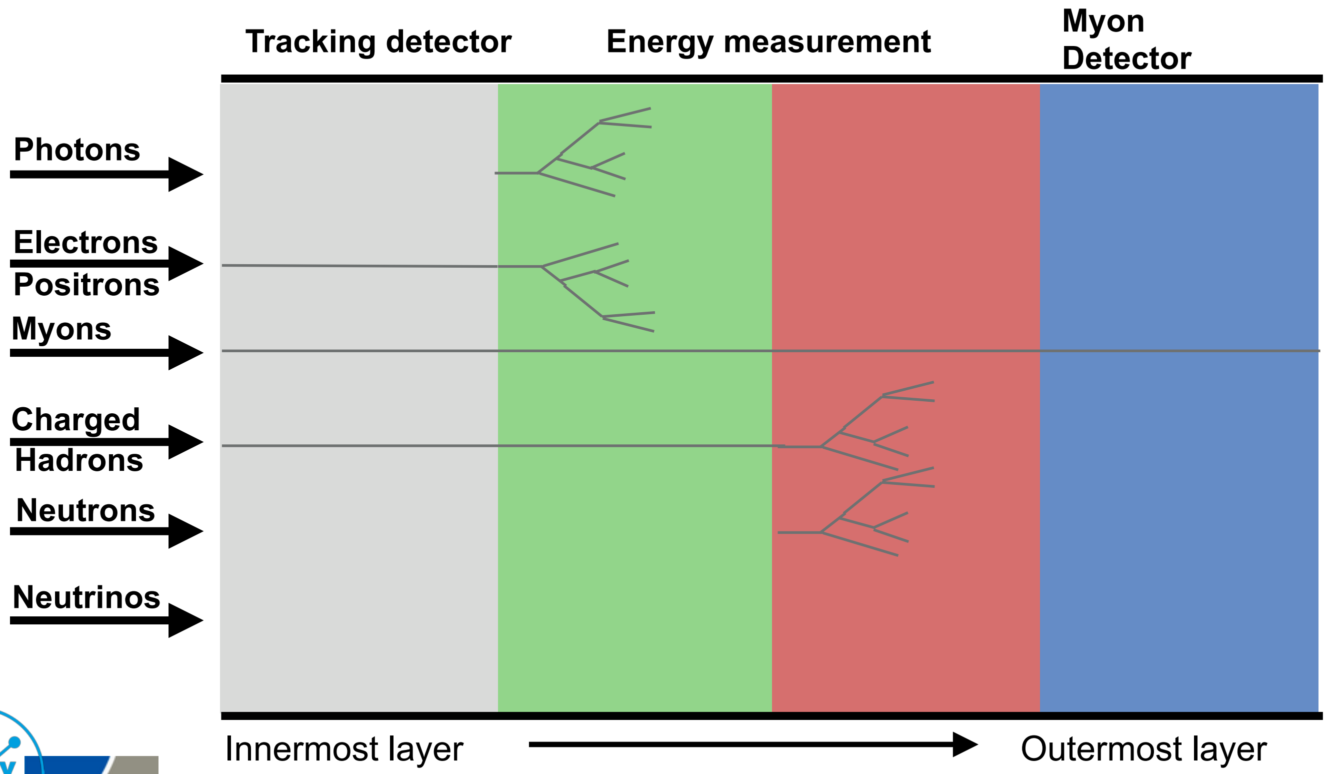
- In particle physics:
  - Measurement of the energy of a particle by measuring the total absorption

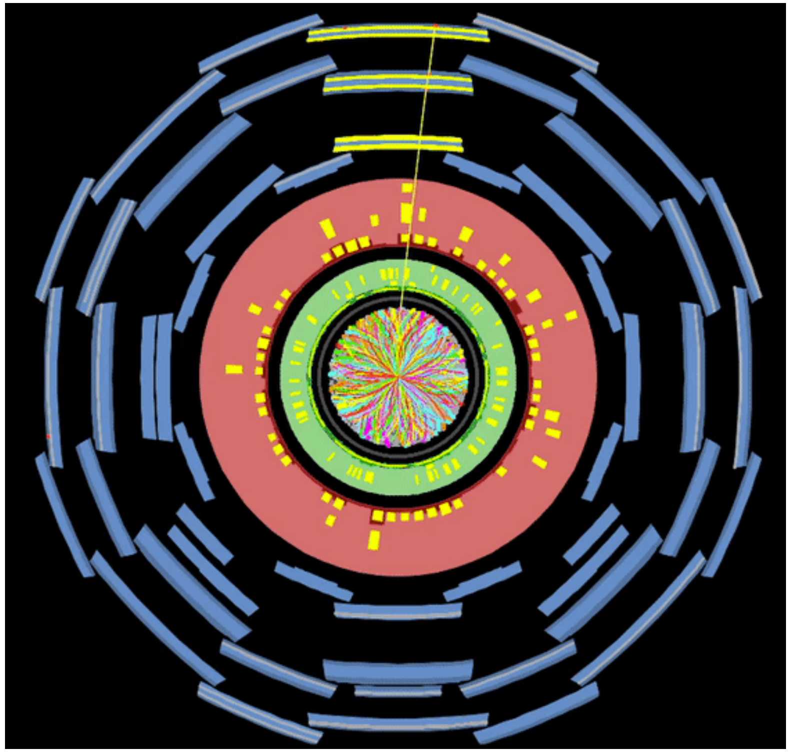


Picture: Francois G. Amar

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





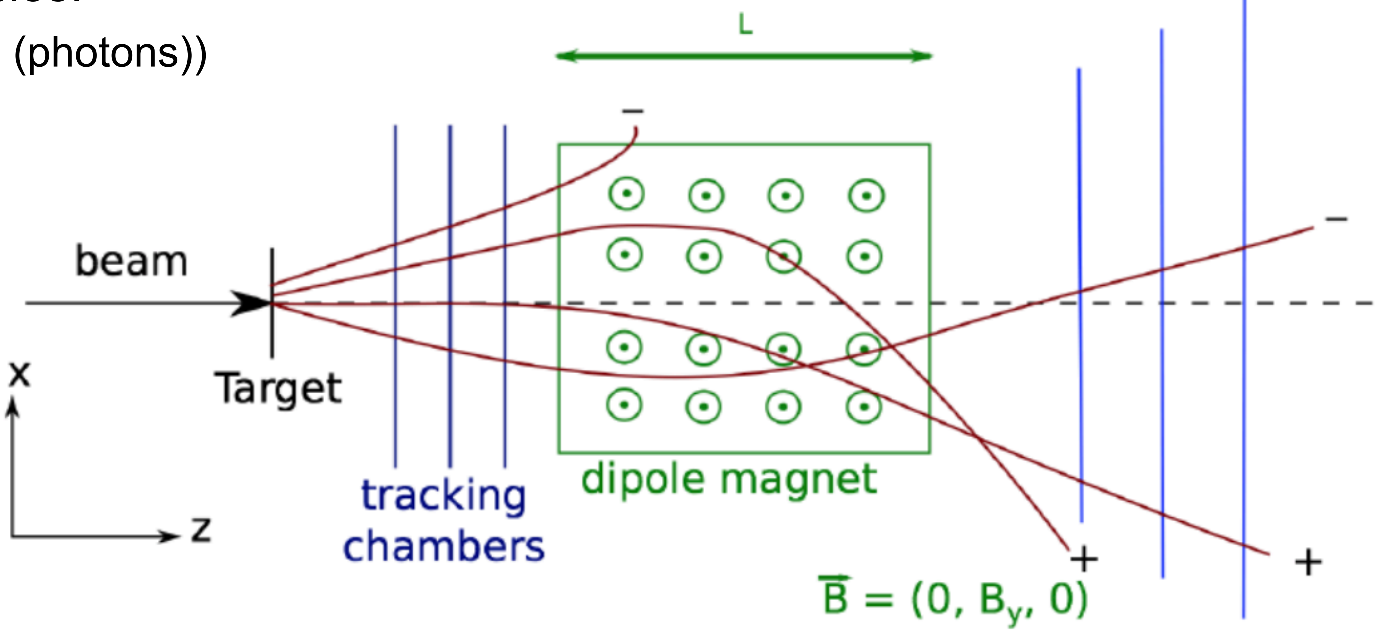
Transverse slice through ATLAS plane

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 !!
$n, \gamma, K^0, \ldots.$

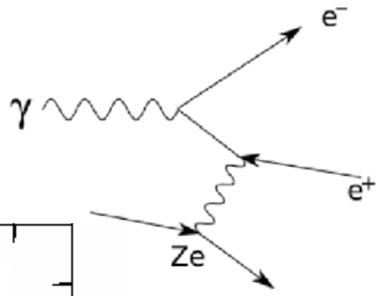
Calorimetry: Overview

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

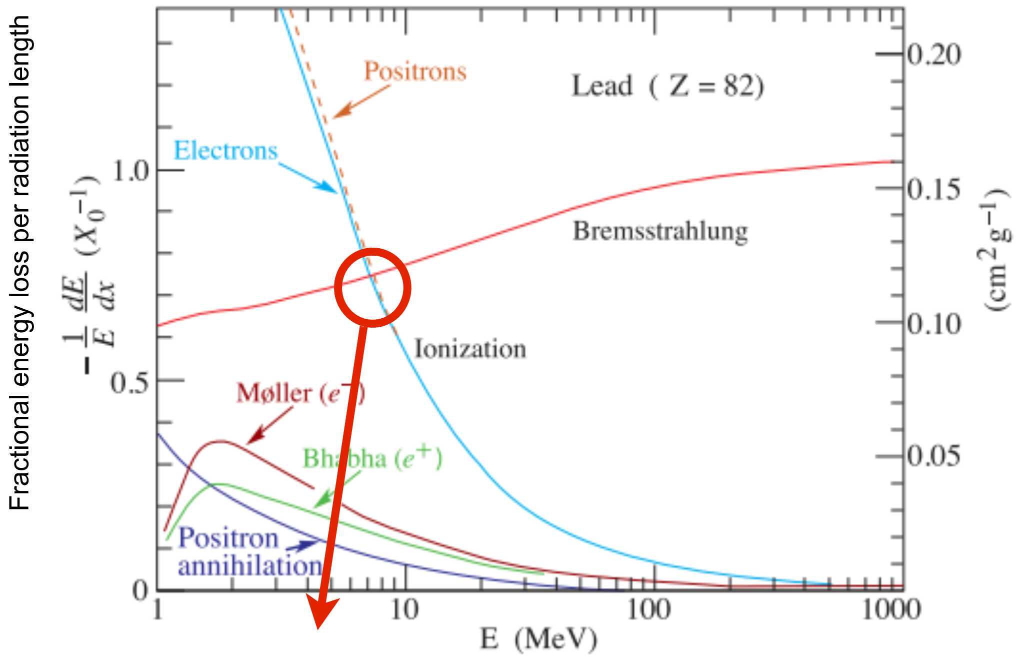
Charge — **Scintillation light** — **Cerenkov light**

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

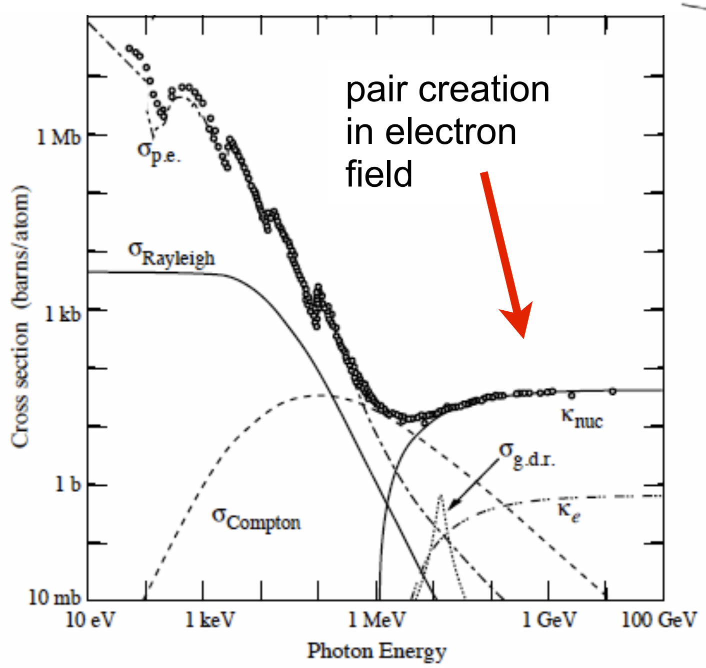
Reminder: Basic Processes



Electrons/positrons



Photons



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

$$\frac{dE}{dx}(E_c)_{\text{Brems}} = \frac{dE}{dx}(E_c)_{\text{ion}}$$

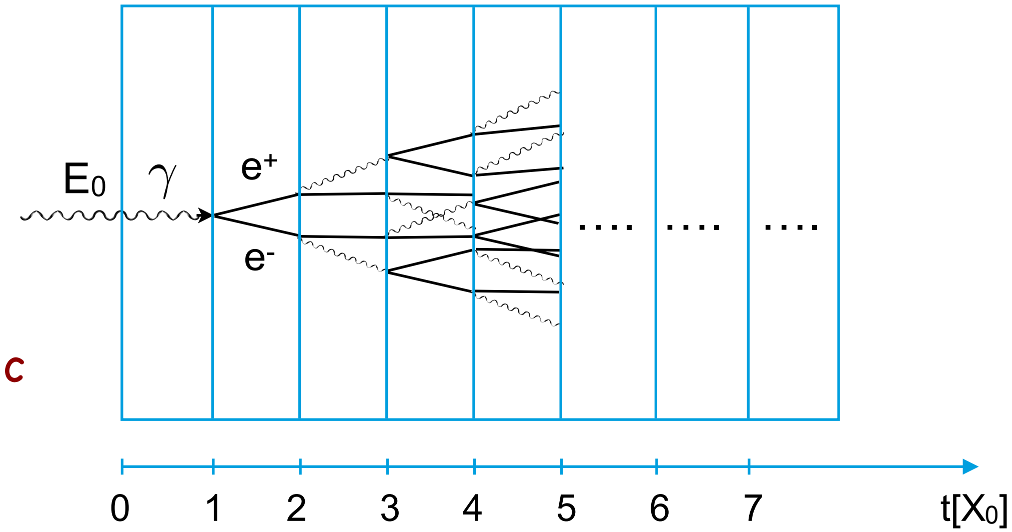
- Dominant effect for energies above a few MeV: **Pair production**

- **Radiation length** defines the amount of material a particle ha travel through until the energy of an electron is reduced by Bremsstrahlung to 1/e of its original energy

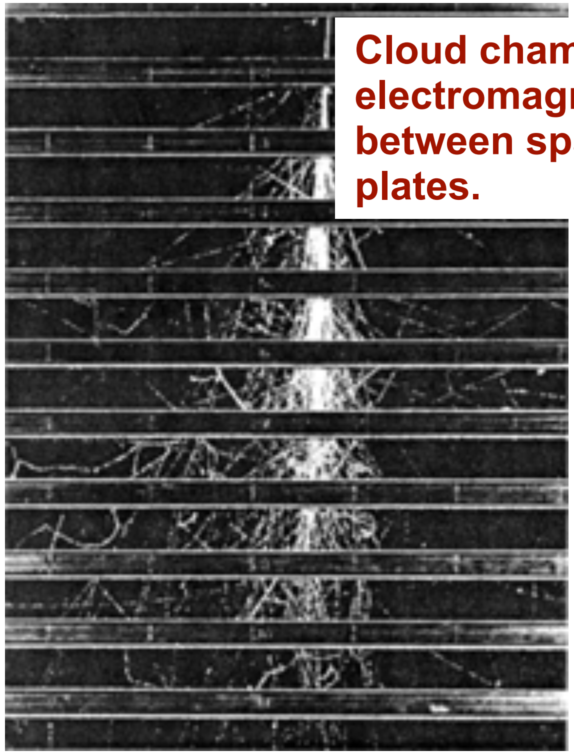
$$\langle E_e(x) \rangle \propto e^{\frac{x}{X_0}}$$

Pics: particle data group, June 2020

Electromagnetic Showers



X_0 is the characteristic scale



Pic: MIT cosmic ray group

- High energetic particles: form shower if passing through (enough) matter.

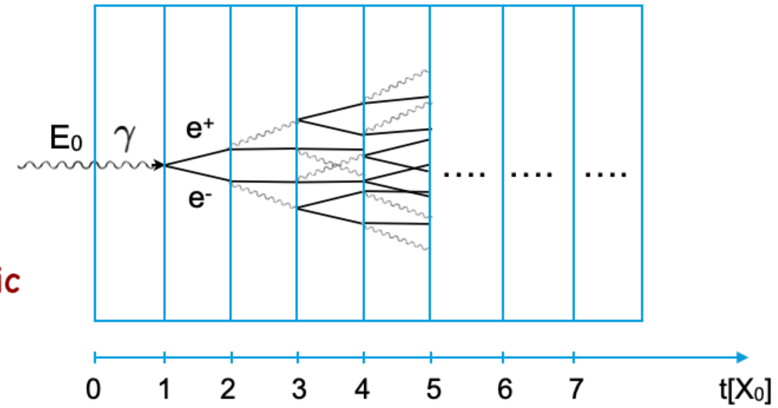
- Alternating sequence of interactions leads to a cascade:
  - Primary γ with E_0 energy produces e+e- pair in layer X_0 thick
  - On average, each has $E_0/2$ energy
  - If $E_0/2 > E_c$, they lose energy by Bremsstrahlung

- 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

Electromagnetic shower is characterised by

- Number of particles in shower
- Location of shower maximum
- Longitudinal shower distribution
- Transverse shower distribution



X_0 is the characteristic scale

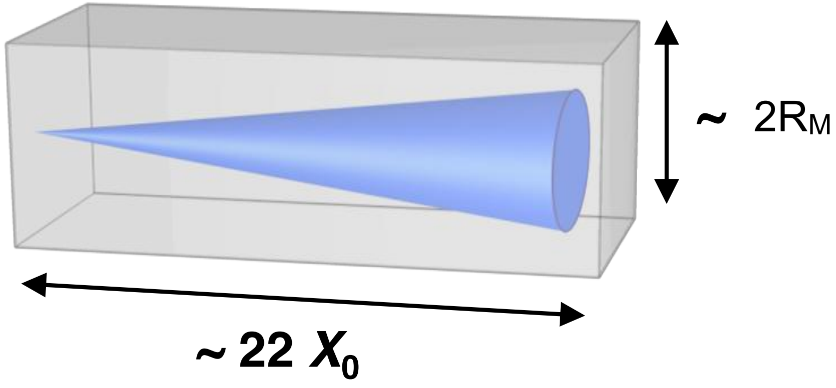
Simplified model (assuming e~2)

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



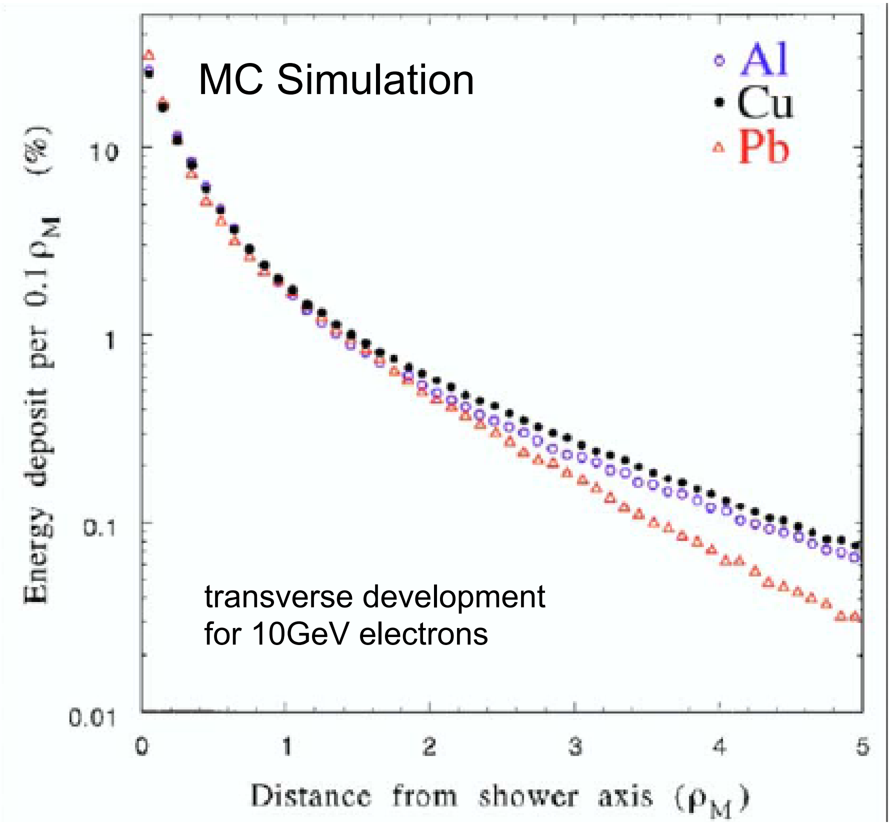
- Longitudinal development governed by the radiation length X_0.
- Lateral spread due to electron undergoing multiple Coulomb scattering:
  - 95% of the shower cone is located in a cylinder with radius 2 R_M
  - Beyond this point, electrons are increasingly affected by multiple scattering

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

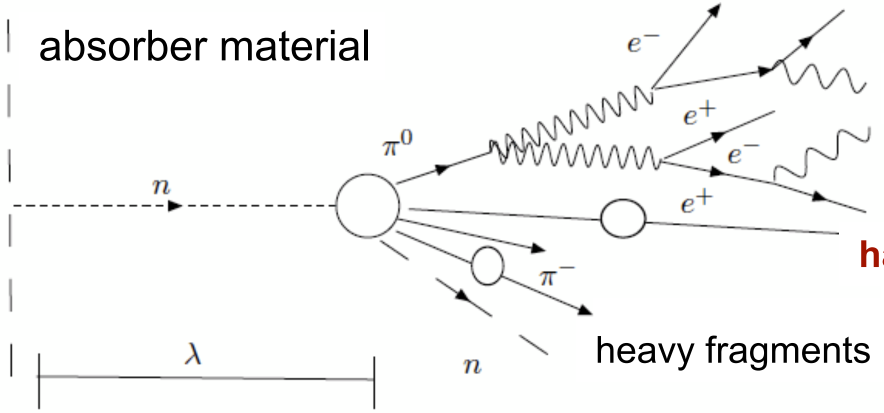
$$R_M = X_0 \frac{E_s}{E_c} = 21.2MeV * \frac{X_0}{E_c}$$

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

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



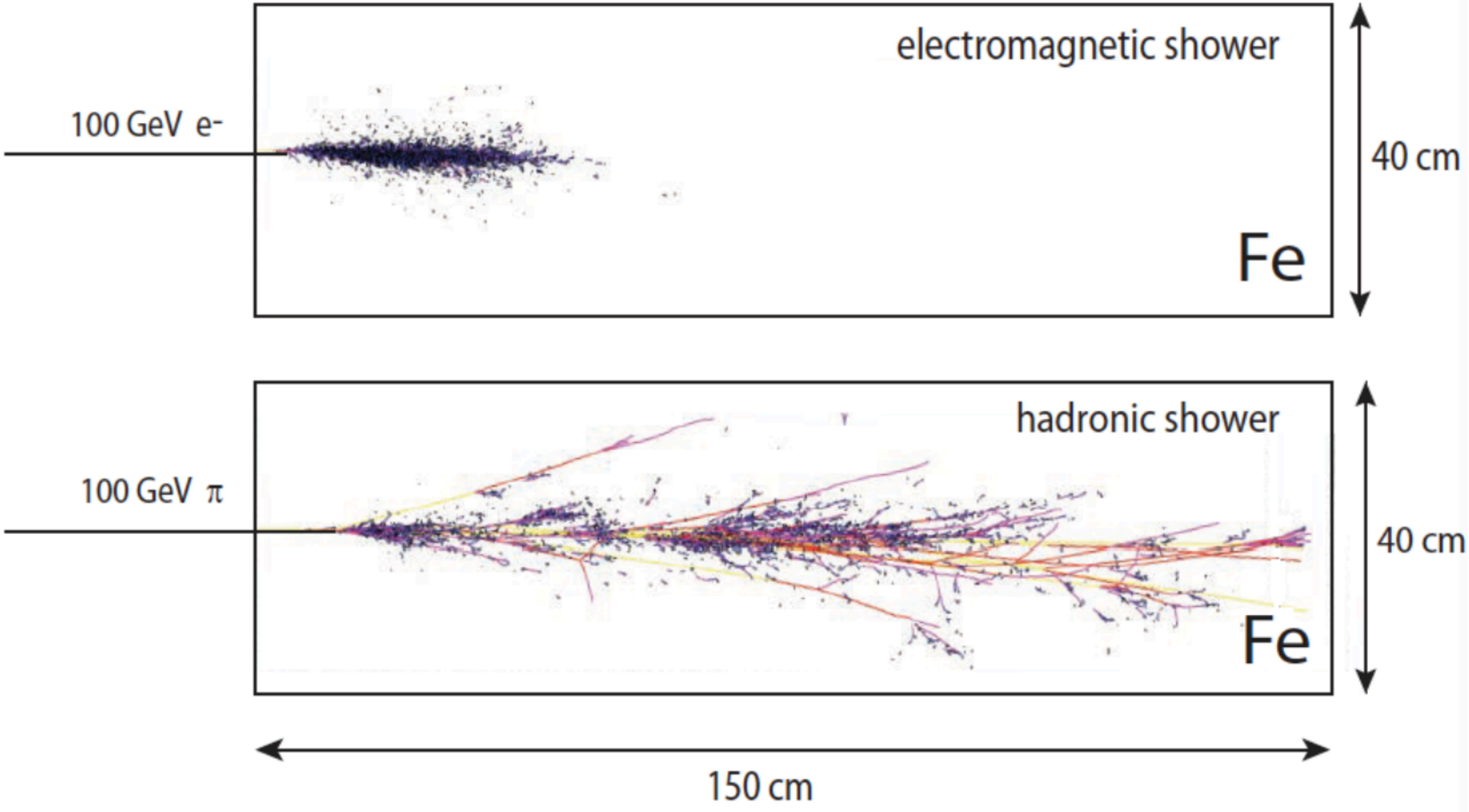
Pic: T. Ferbel. Experimental Techniques in High Energy Physics.

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

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

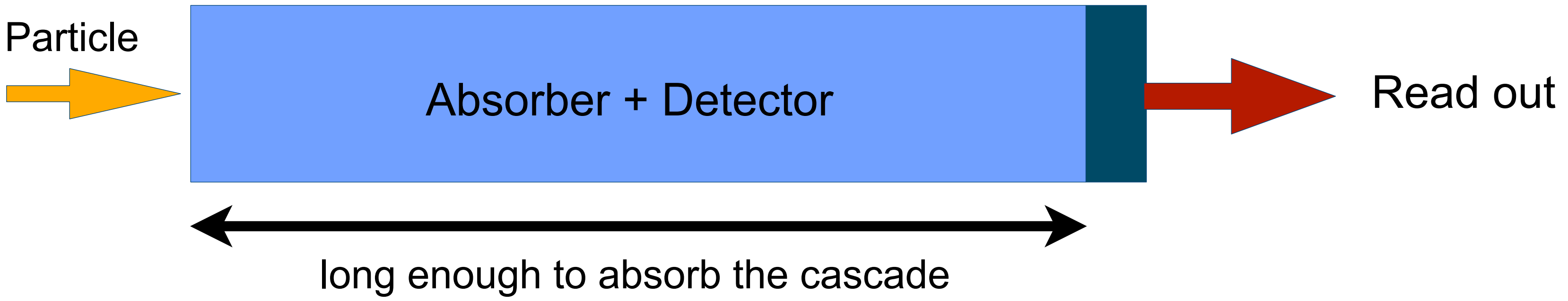
Hadronic vs. EM Shower

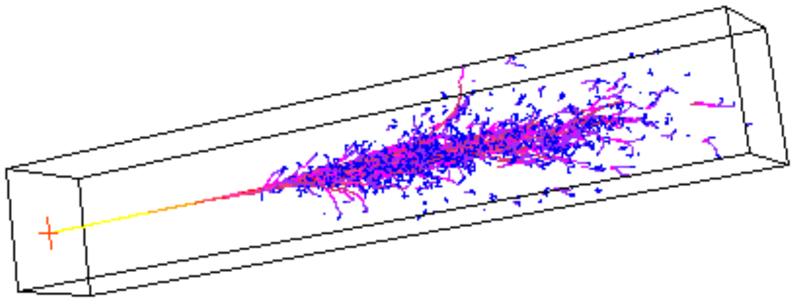


Calorimeter Types

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



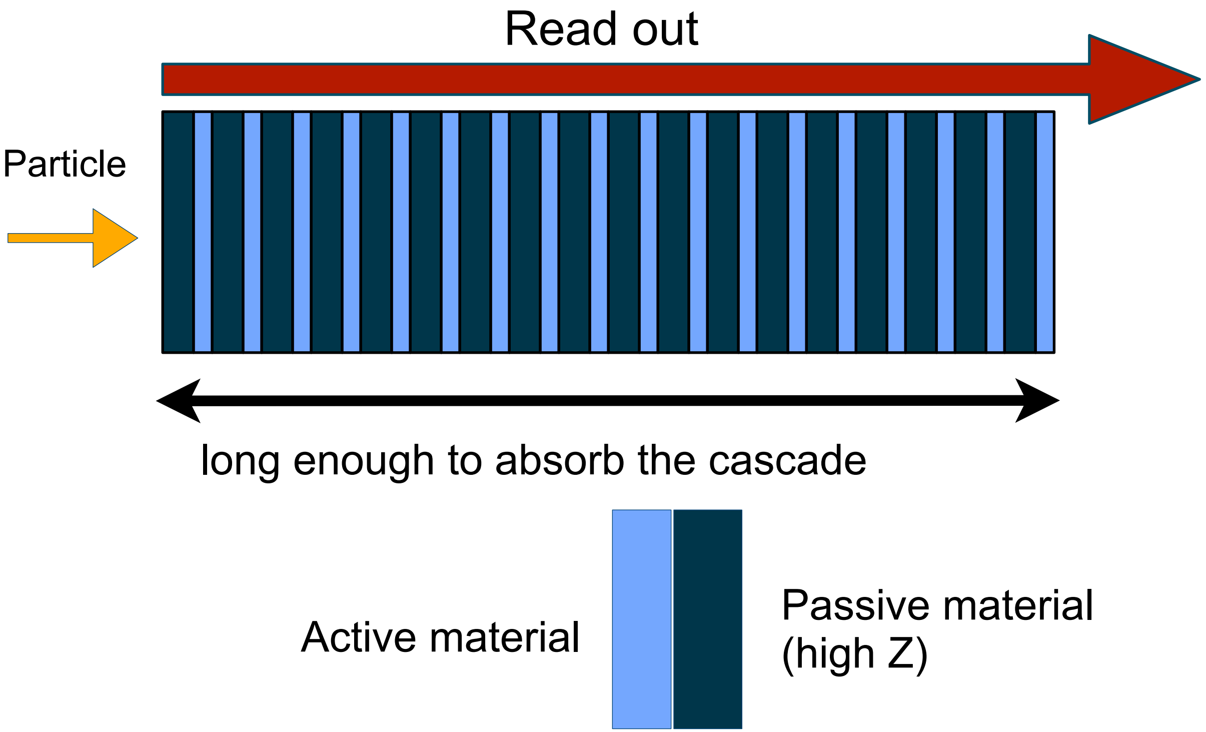


Pic: Cornell

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

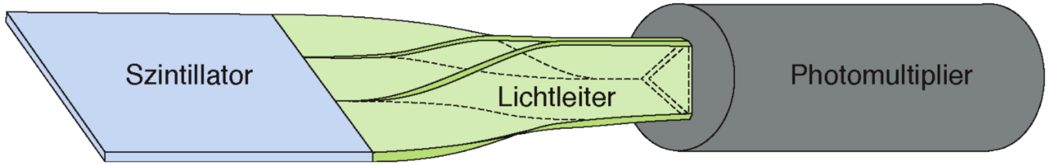
Calorimeter: Energy Resolution

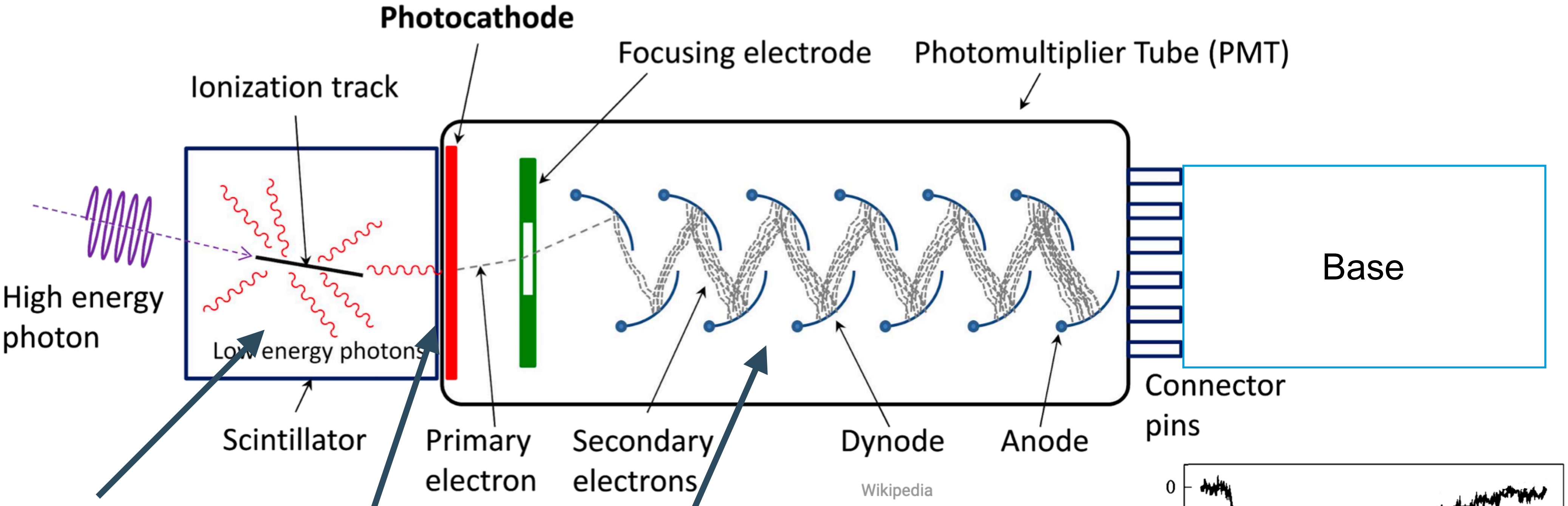
- The relative **energy resolution** of a calorimeter is parametrised:

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

- **Stochastic** term c_s
  - Counting aspect of the measurement: Simple statistical error
  - Depends on intrinsic shower fluctuations, photoelectron statistics, dead material in front of calo, and sampling fluctuations
- **Noise** term c_n
  - Constant, energy-independent noise contribution to the signal
  - Resolution term scales with 1/E
  - Electronic noise, radioactivity
- **Constant** term c_c
  - Inhomogeneities with in the detector sensitivity, calibration uncertainties and radiation damage

Basic Concept





Scintillator Types:

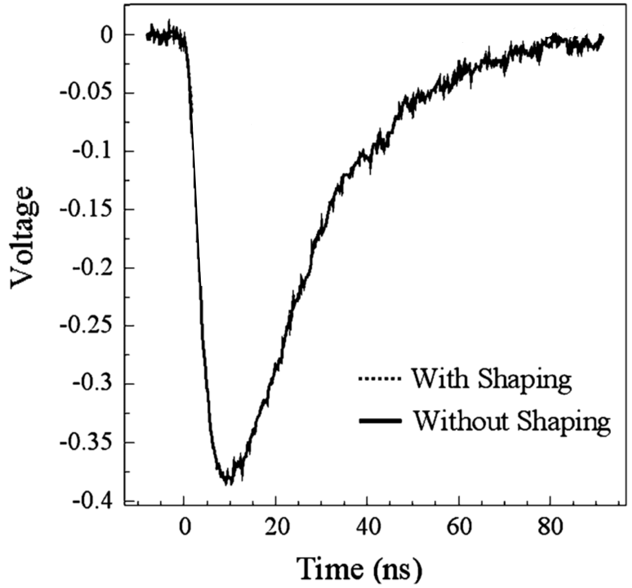
- Organic Scintillators
- Inorganic Crystals
- Gases

Light Transport

- Light guides
- Direct coupling

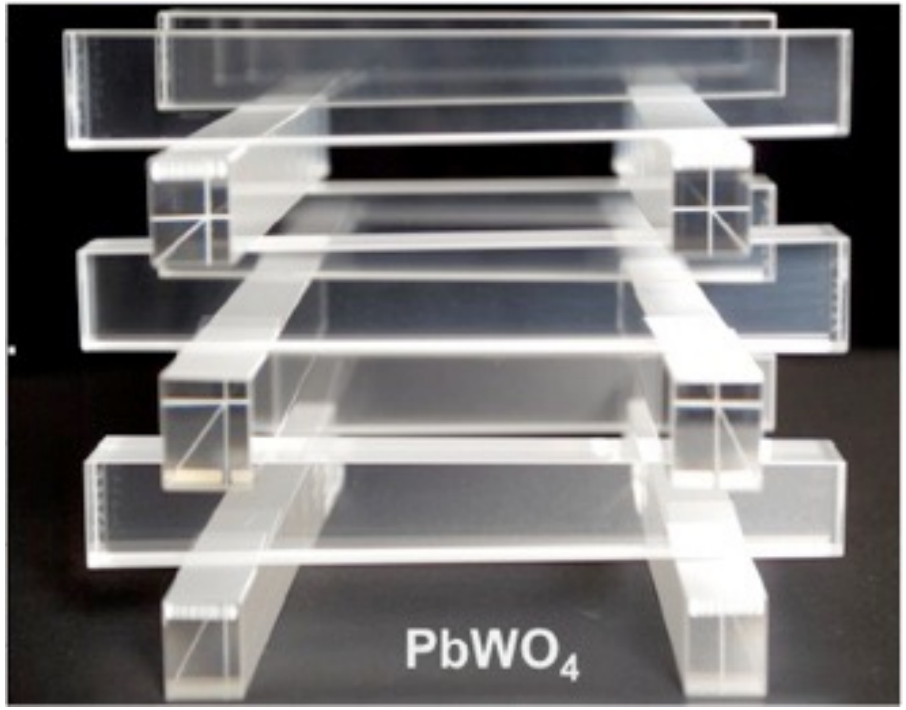
Photosensors:

- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photon
- Counter Silicon



Calorimeters: Active Material

- Detectors based on registration of excited atoms or molecules
- An incident photon or particle ionises the medium
  - Ionised electrons slow down causing excitation.
  - Excited states immediately emit light.
  - Inorganic and organic materials!

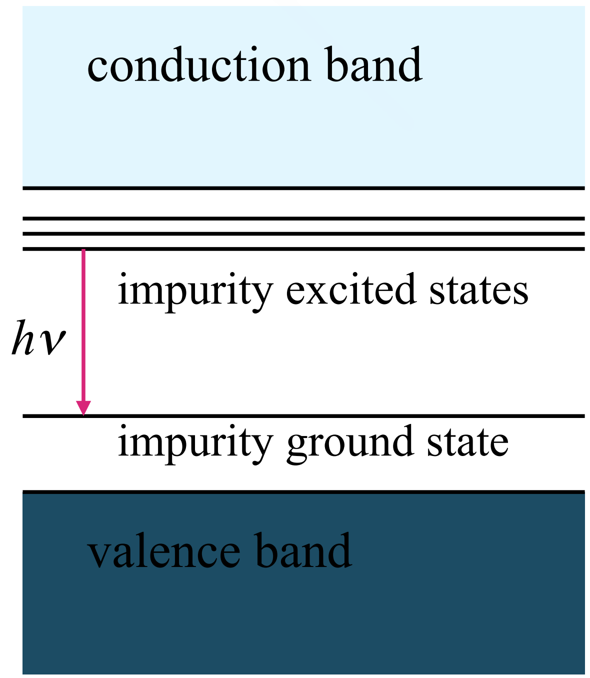


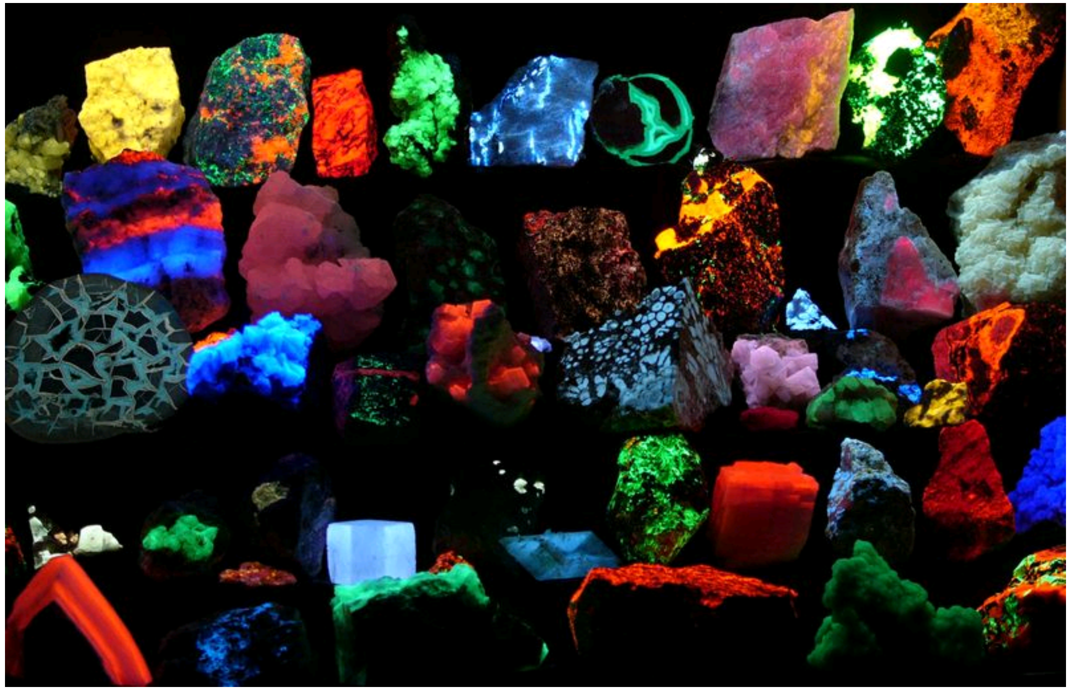
Picture: CDF@Fermilab

- $PbWO_4$: 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

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





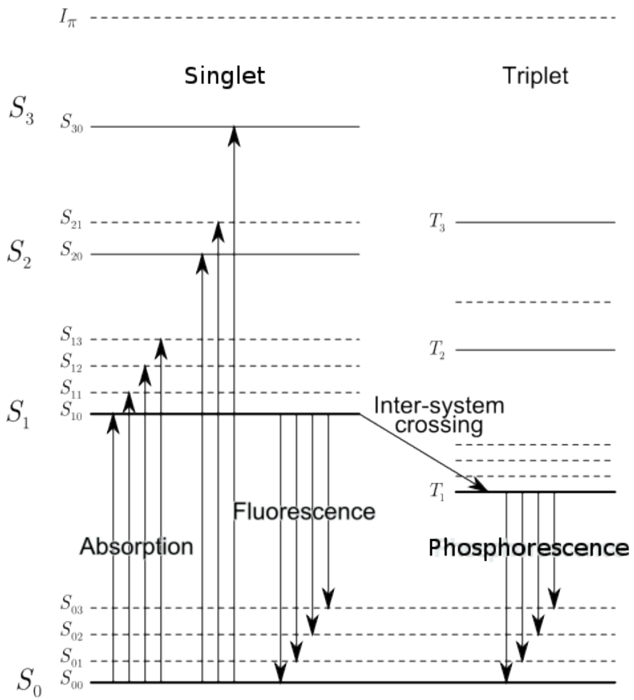
Advantages:
- Good efficiency
- Good linearity
- Radiation tolerance

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

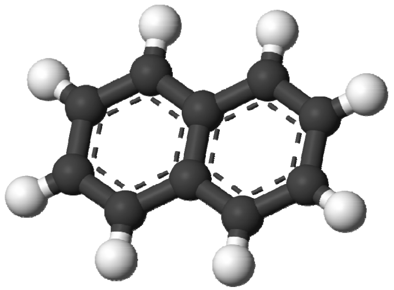
Organic Scintillators

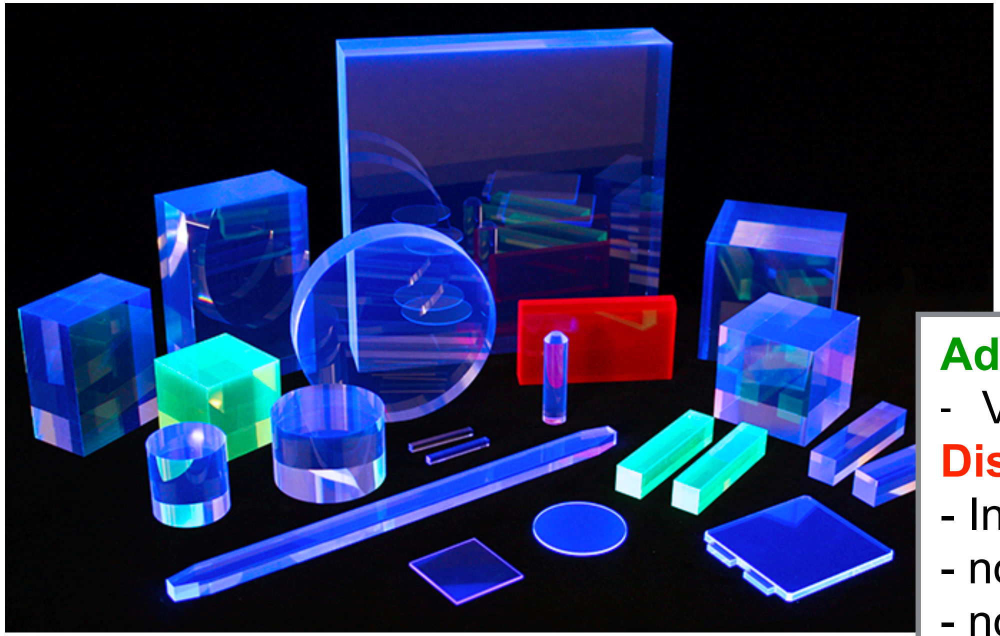
Active material

- 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



source: Wikipedia





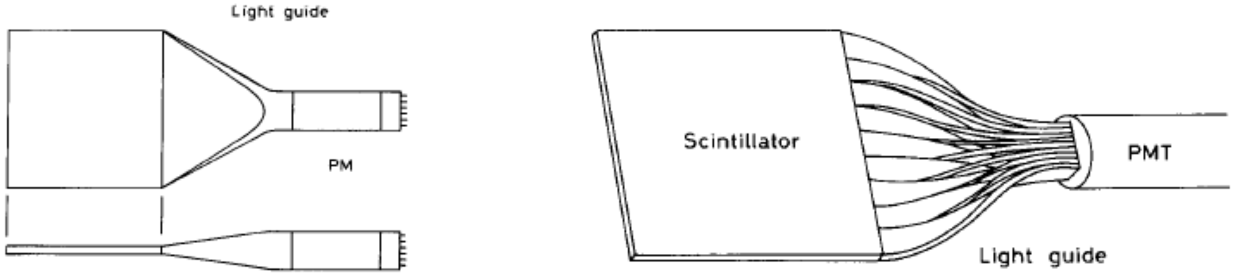
Advantages:
- Very fast

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

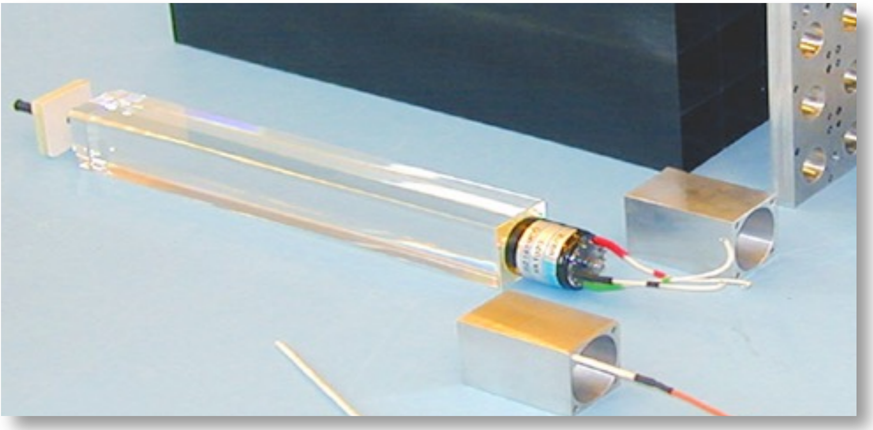
Light transport

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

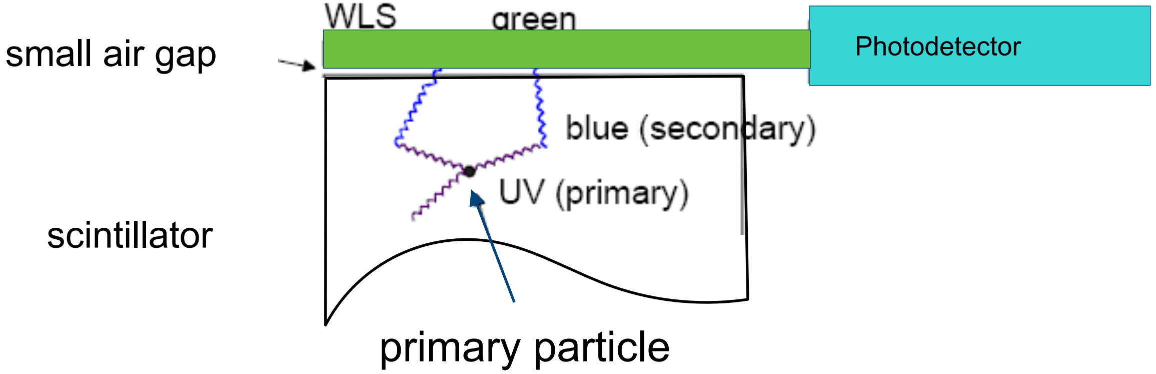
- Light guides: transfer by total internal reflection (+outer reflector)



"fish tail" adiabatic

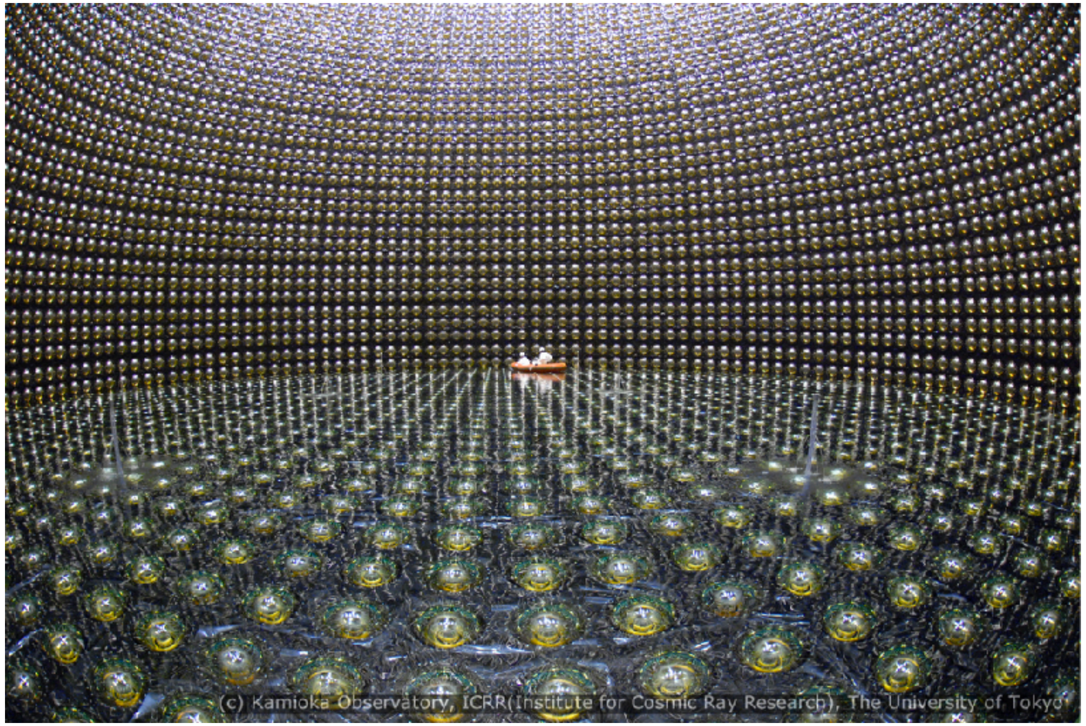


- UV light enters the light guide material
- Light is transformed into longer wavelength (wavelength shifter)
- -> Total internal reflection inside the WLS material
- -> 'transport' of the light to the photo detector

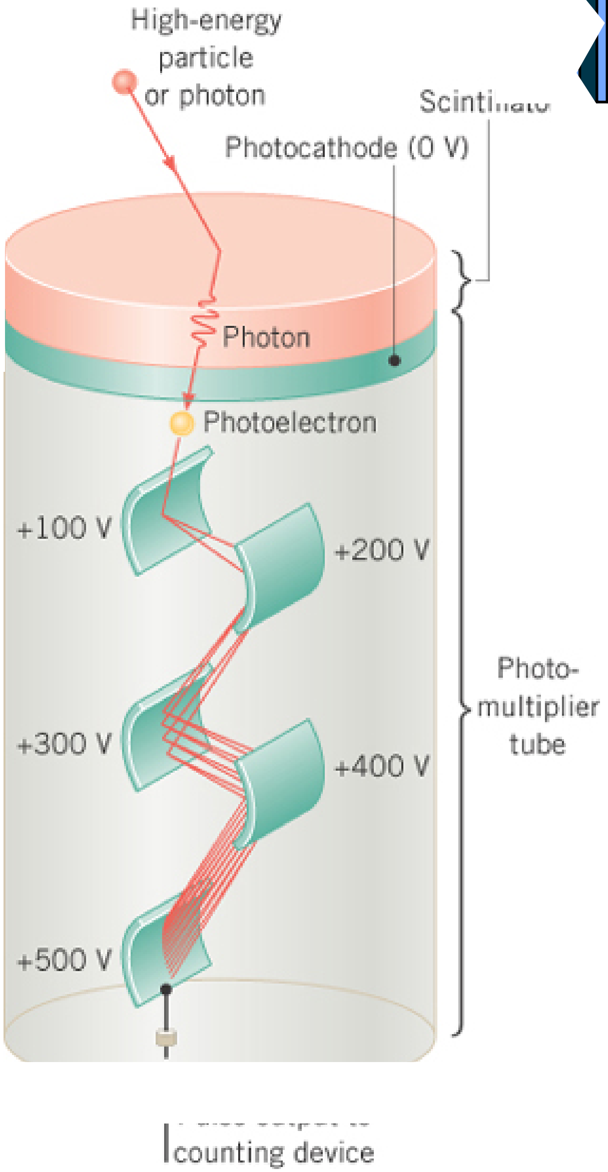


Detecting the Light

- 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

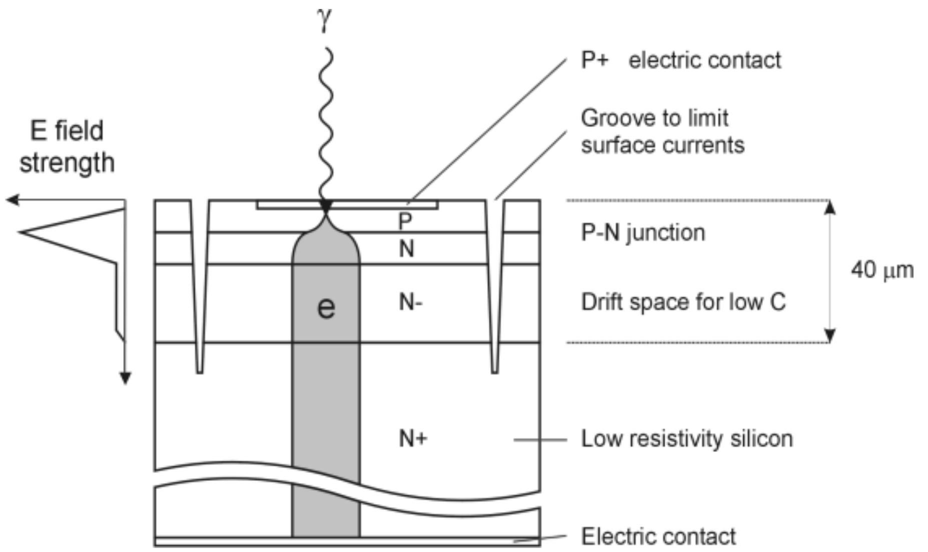


Source: Cutnell and Johnson, 7th edition image gallery

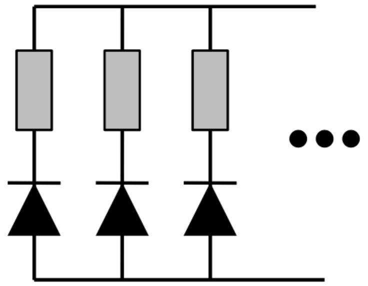
APD, SiPM

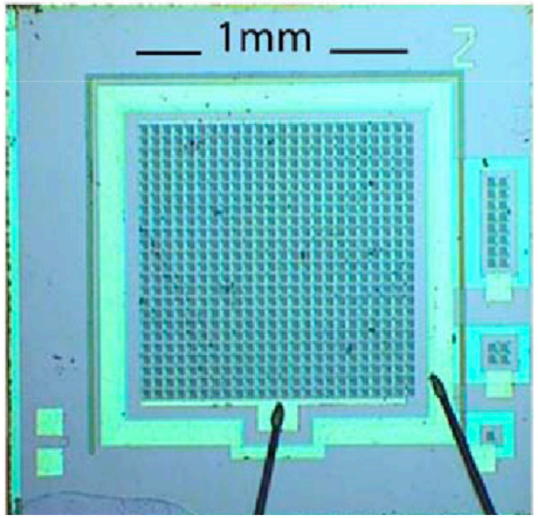
- Avalanche Photo Diodes (APDs) are silicon devices operated in reverse bias mode in the breakdown regime.
- Problem: low gain

- Therefore:
  - Add many APDs in parallel with separate quench resistors
  - Each SPAD (Single Photon APD) works in *Geiger Mode*
  - Breakdown of a *single* SPAD creates only a *small signal*
  - The *total signal* is *proportional* to the number of fired cells, i.e. *to the number of detected photons*



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



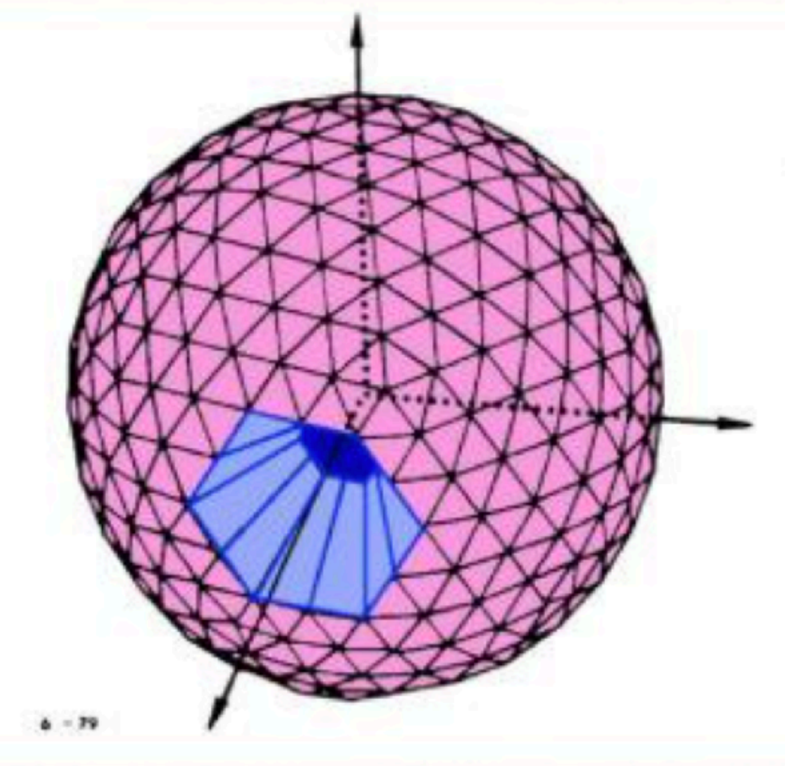


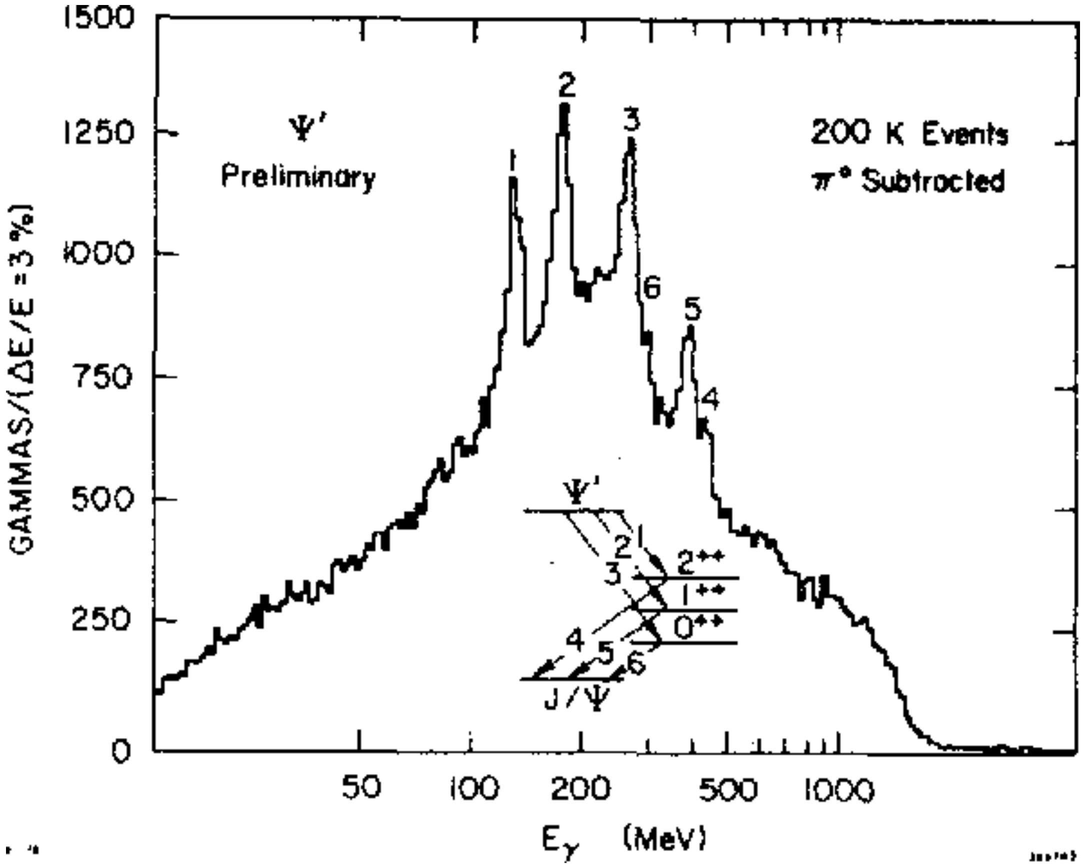
SiPM become more and more popular as replacement for standard photo multipliers.
Also in calorimeters

Examples of Homogeneous Calorimeter

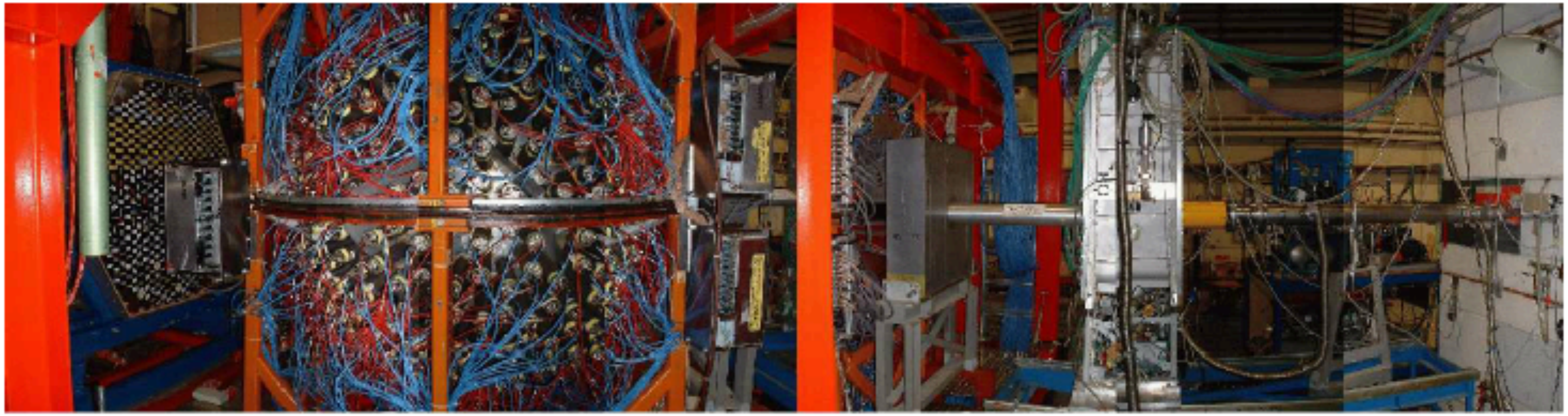
Crystal Ball Calorimeter

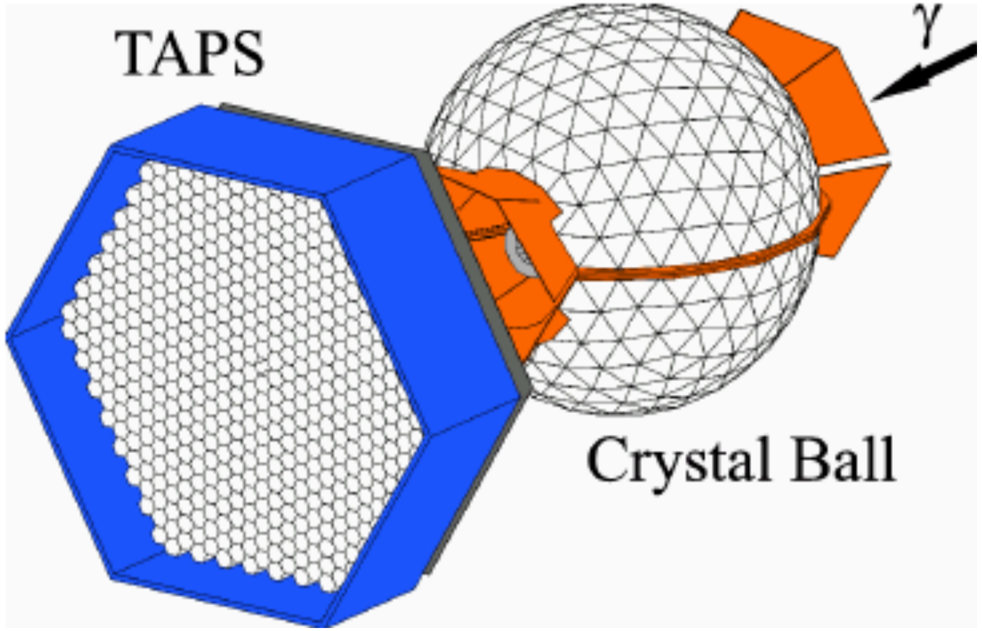
- Thallium-doped NaI(Tl) crystals arranged in a sphere ("ball") ⇒ excellent energy resolution
- (Almost) full 4π solid angle coverage
- Operated at electron-positron collider SPEAR at Stanford (now at Mainz!)
- Physics goal: Precise charmonium spectroscopy





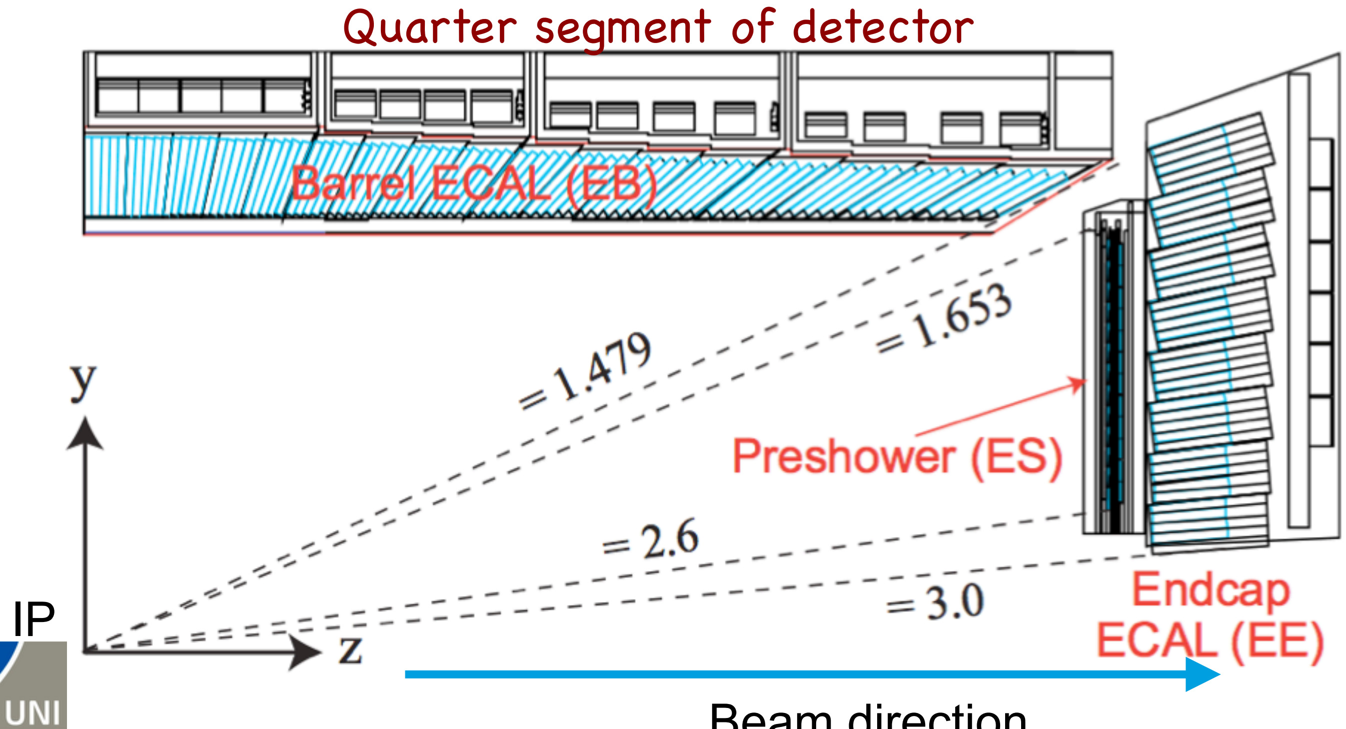
Crystal Ball Calorimeter

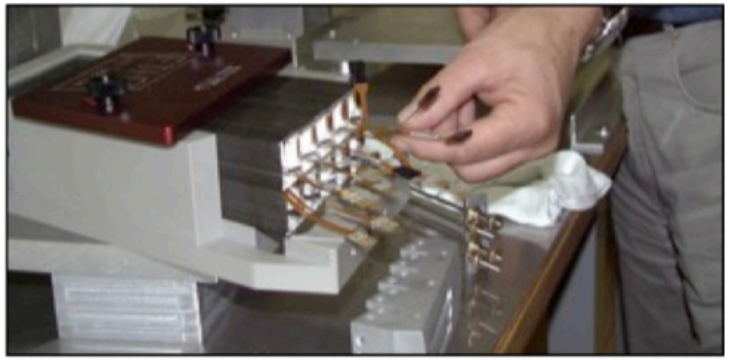


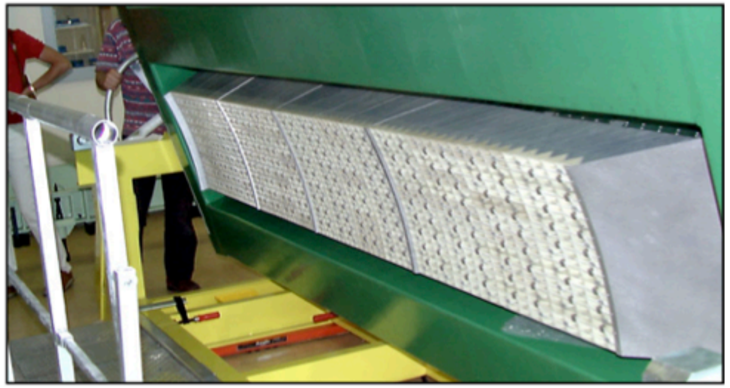


CMS ECAL

- Scintillator: $PbWO_4$ (Lead Tungsten)
  - high resolution Lead Tungsten crystal calorimeter -> **higher intrinsic resolution**
- Photosensor: Avalanche Photodiodes (APDs)
- Number of crystals: ~ 70000
- Light output: 4.5 photons/MeV





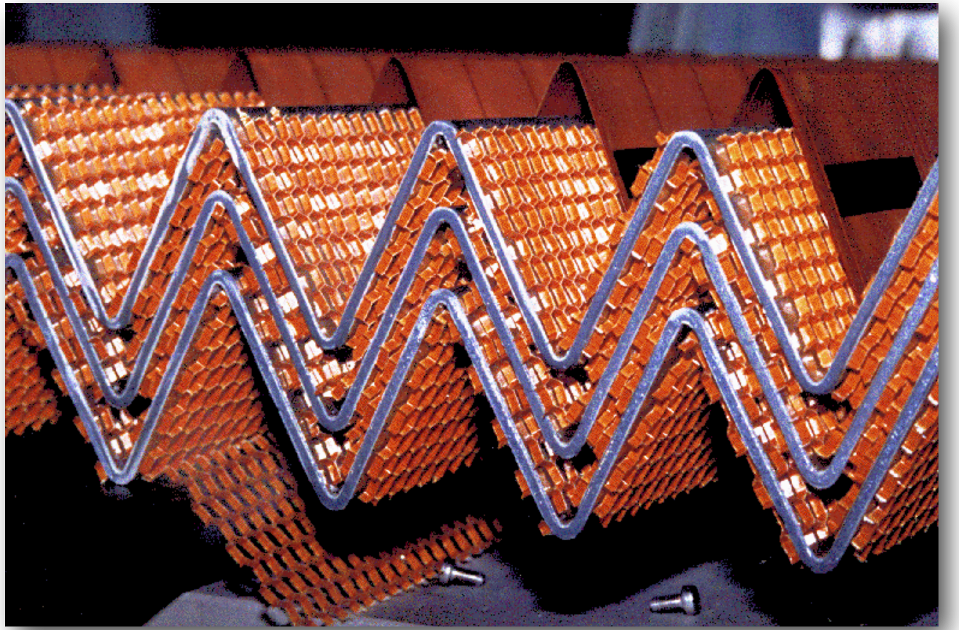


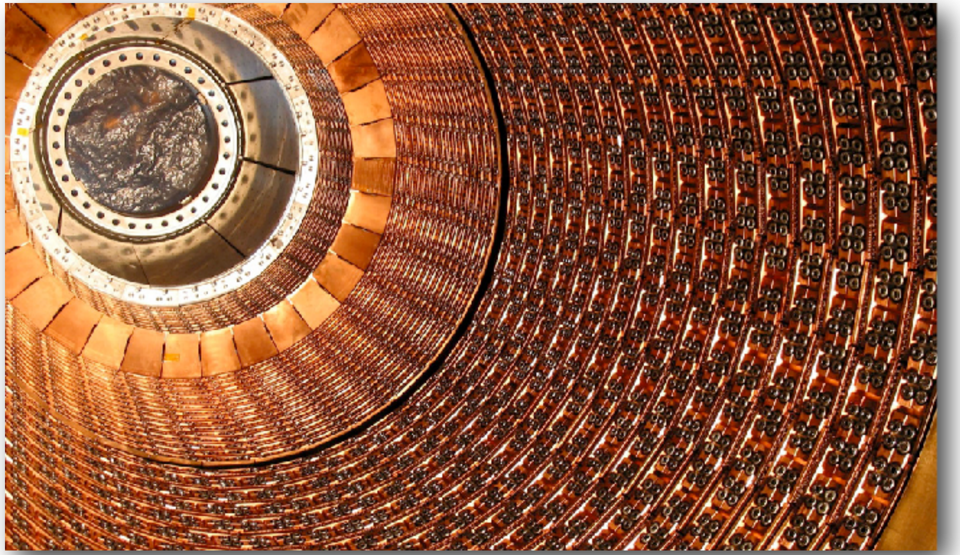
Examples of Sampling Calorimeter

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

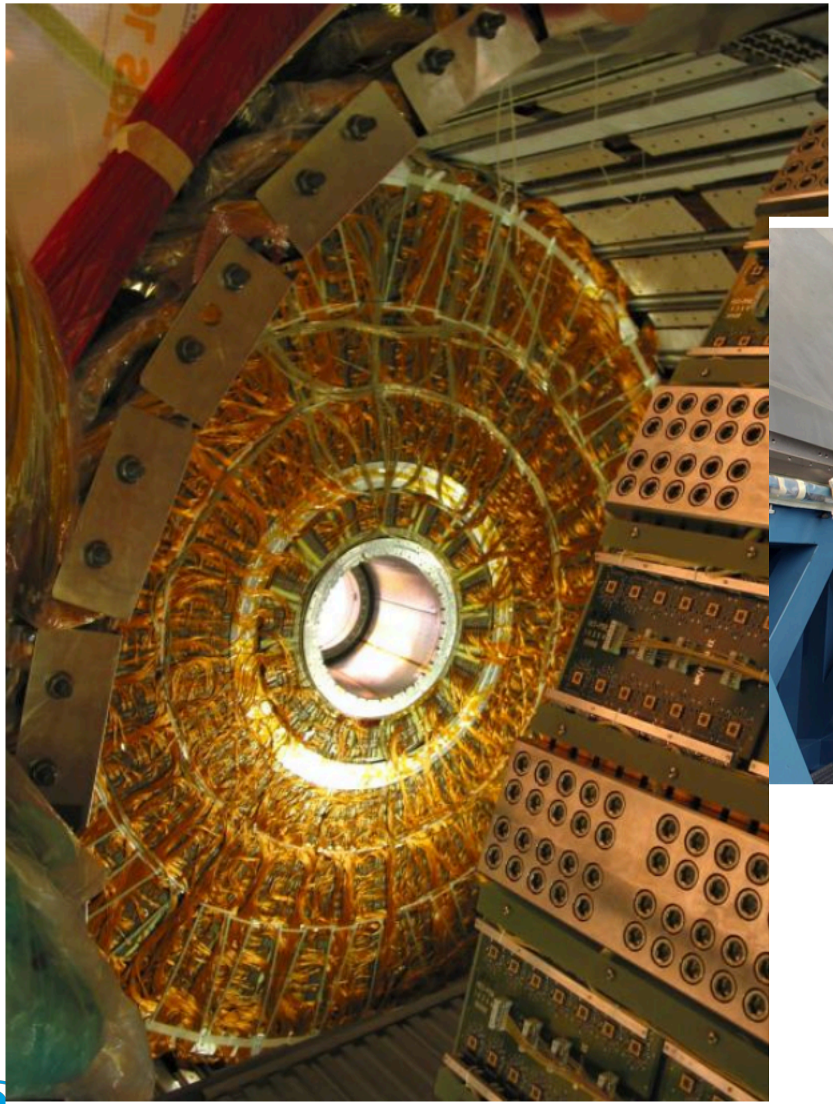
  - Tile calorimeter: covering outer region
  - “Conventional” steel absorber with plastic scintillators.

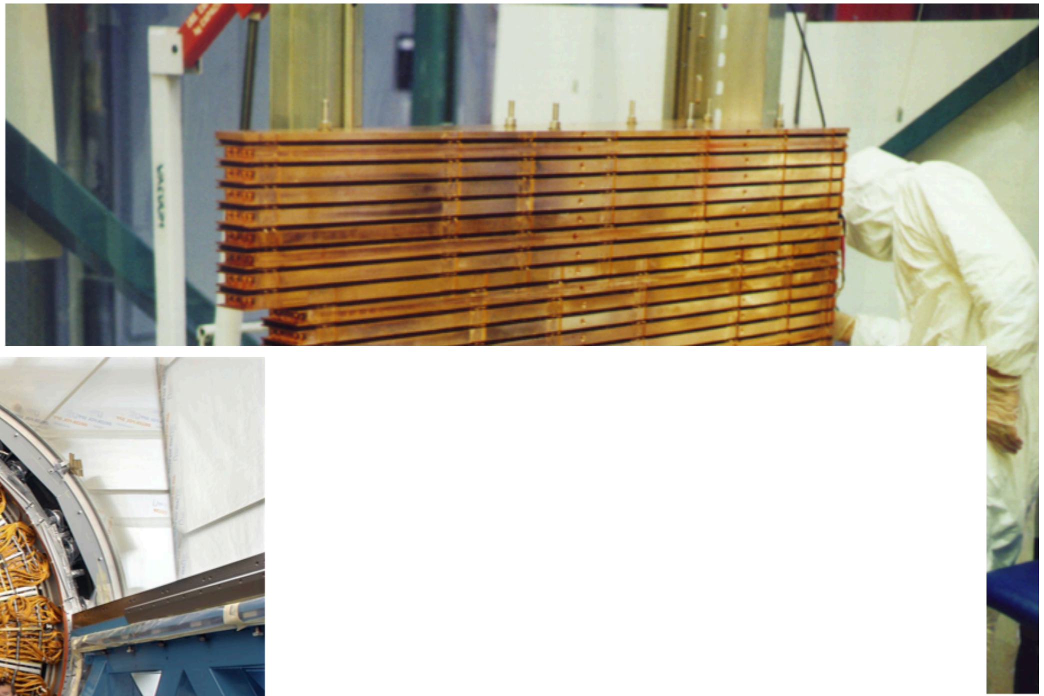


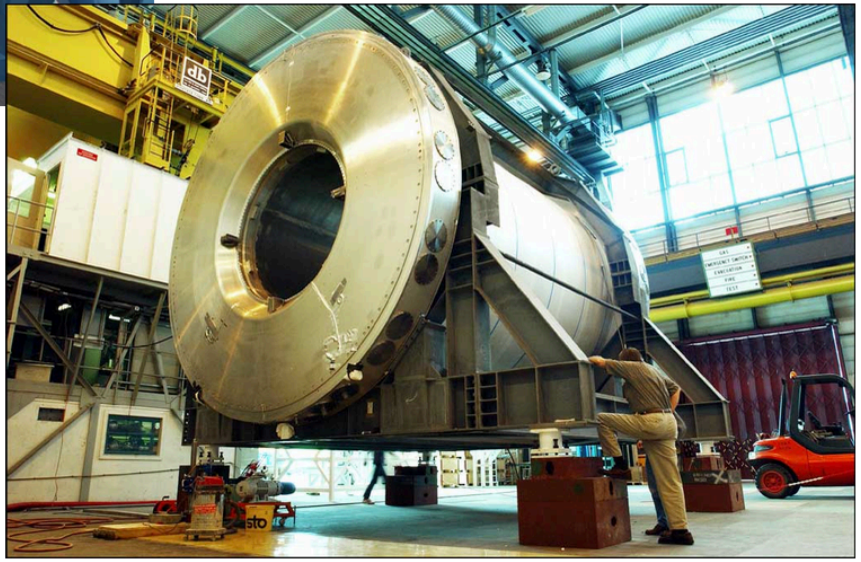


ATLAS Hadronic endcap Liquid Argon Calorimeter. (CERN)

ATLAS LAr Calorimeter

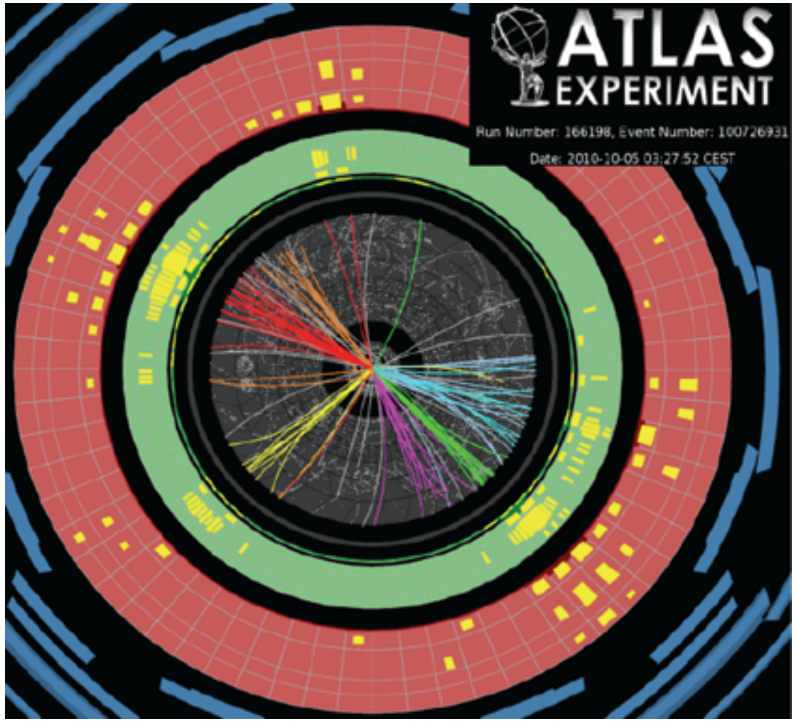


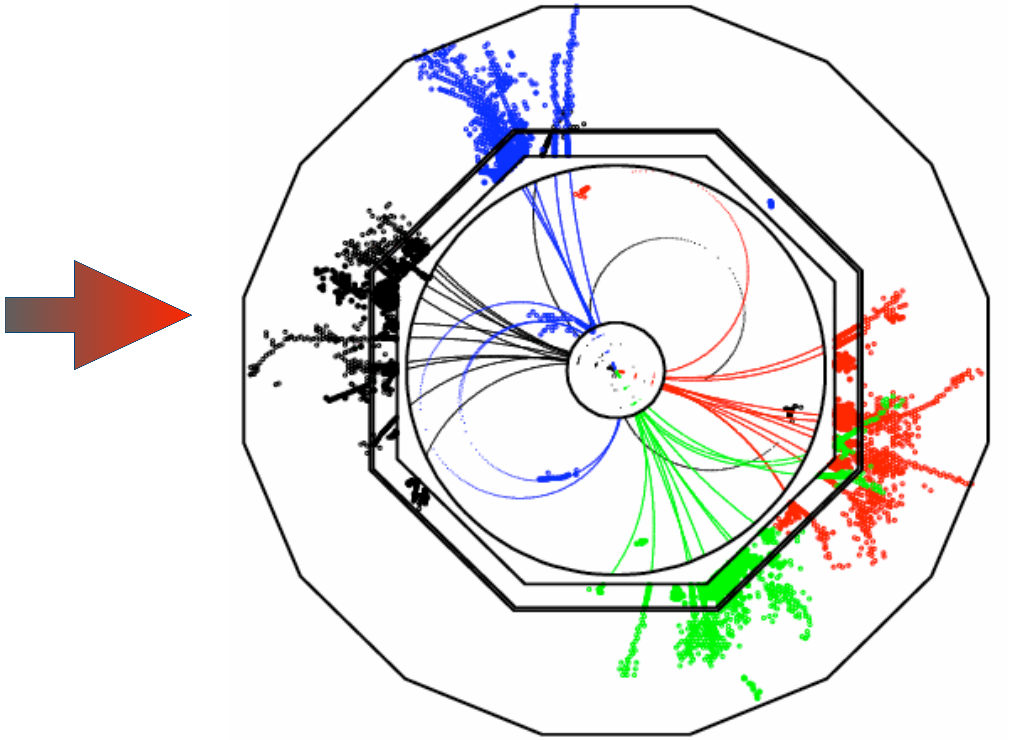




The Future

Current Hadron Calos ... and Dreams





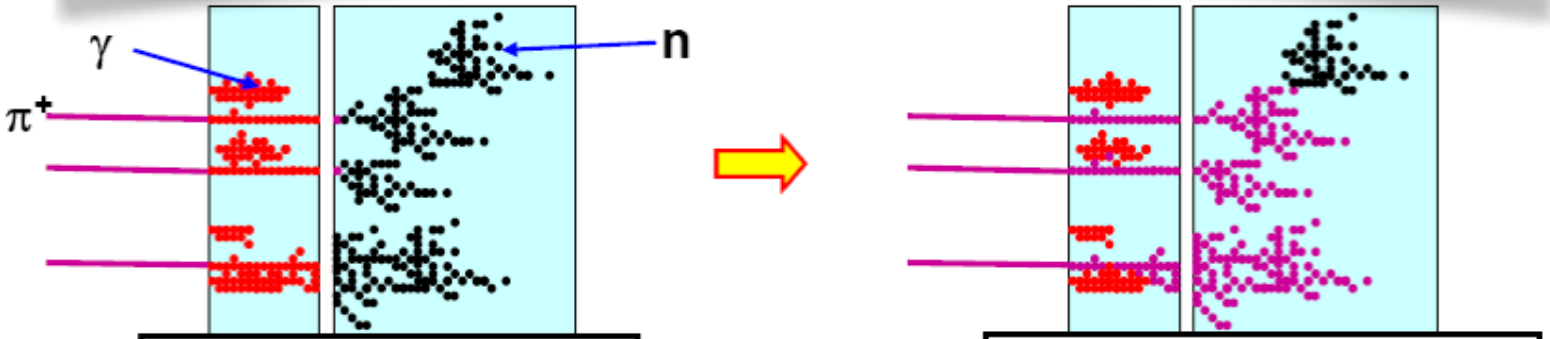
- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT) O(10k) channels for full detectors

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

Particle Flow

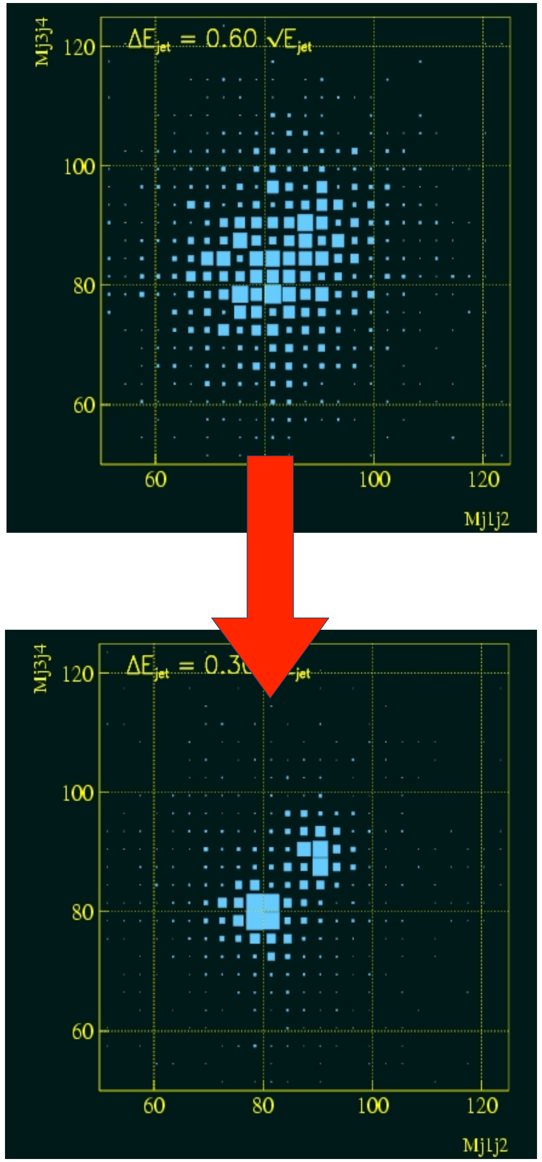
- Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution
- Reconstruct **every** particle in the event

- 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



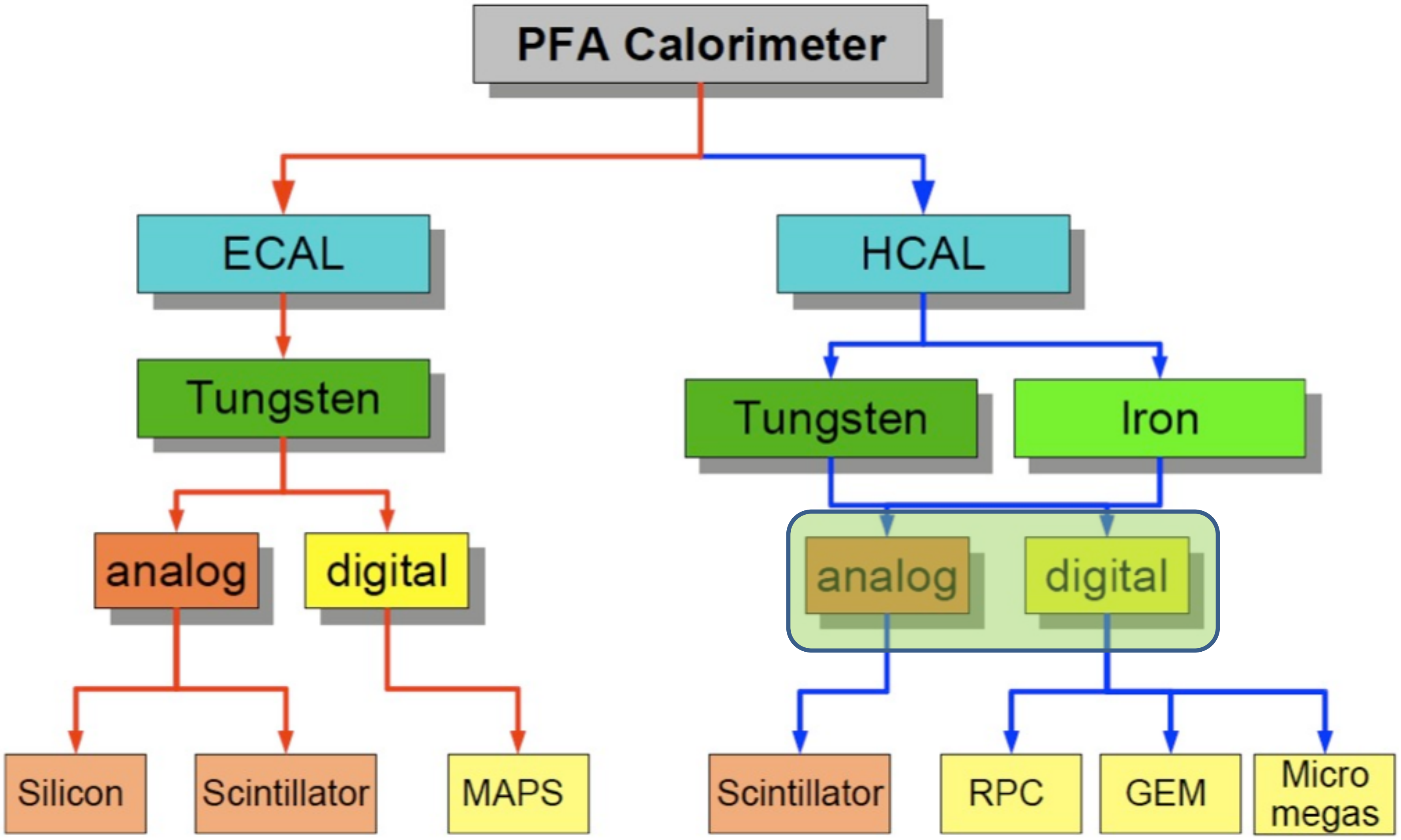
$$E_{JET} = E_{ECAL} + E_{HCAL}$$

$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$



PFLOW calorimetry = Highly granular detectors + Sophisticated reconstruction software

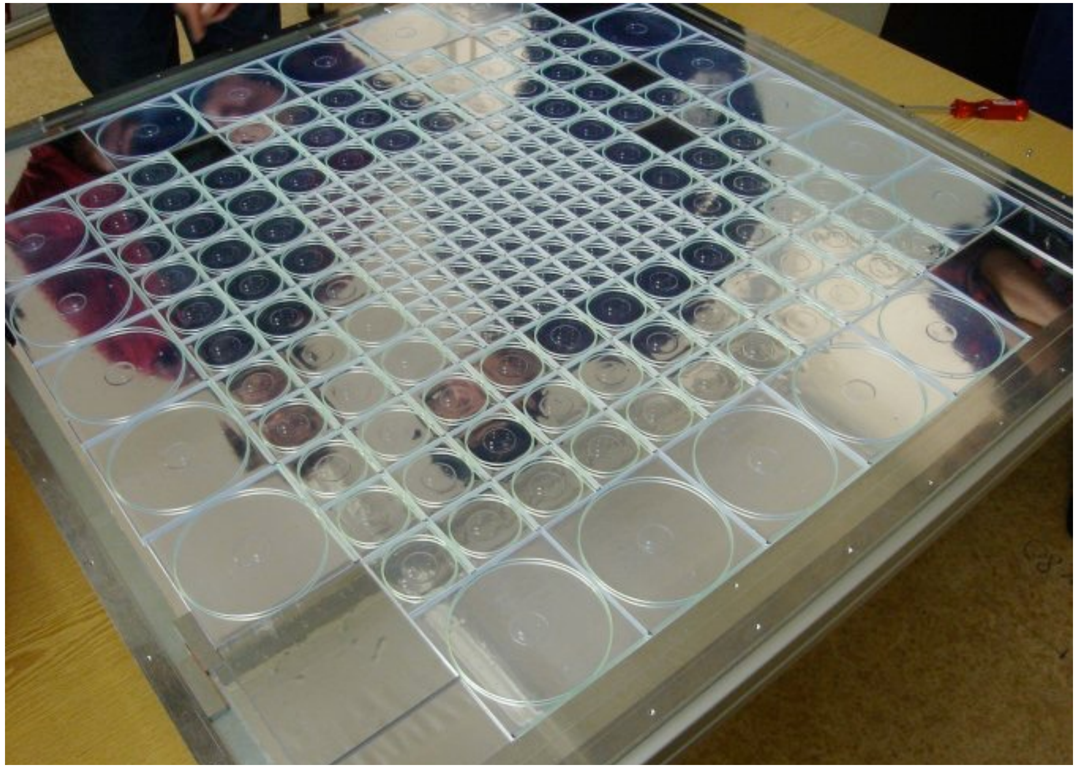
The zoo of PFLOW calorimeters



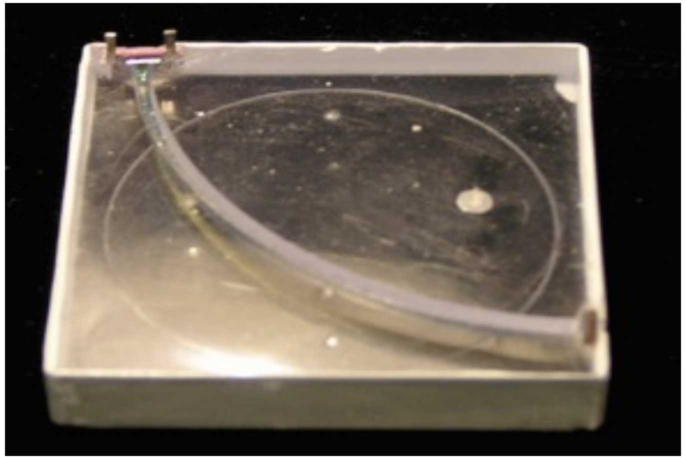
New Concepts: Highly Granular Calos

- 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

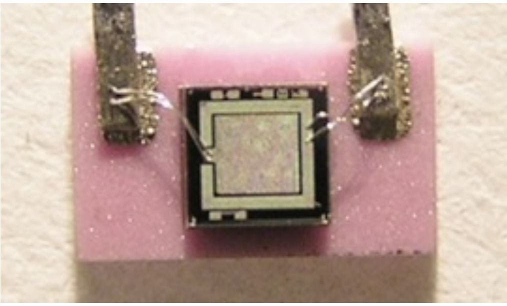
Pictures: CALICE collaboration



tiles in one layer



scintillator tile with WLS fiber

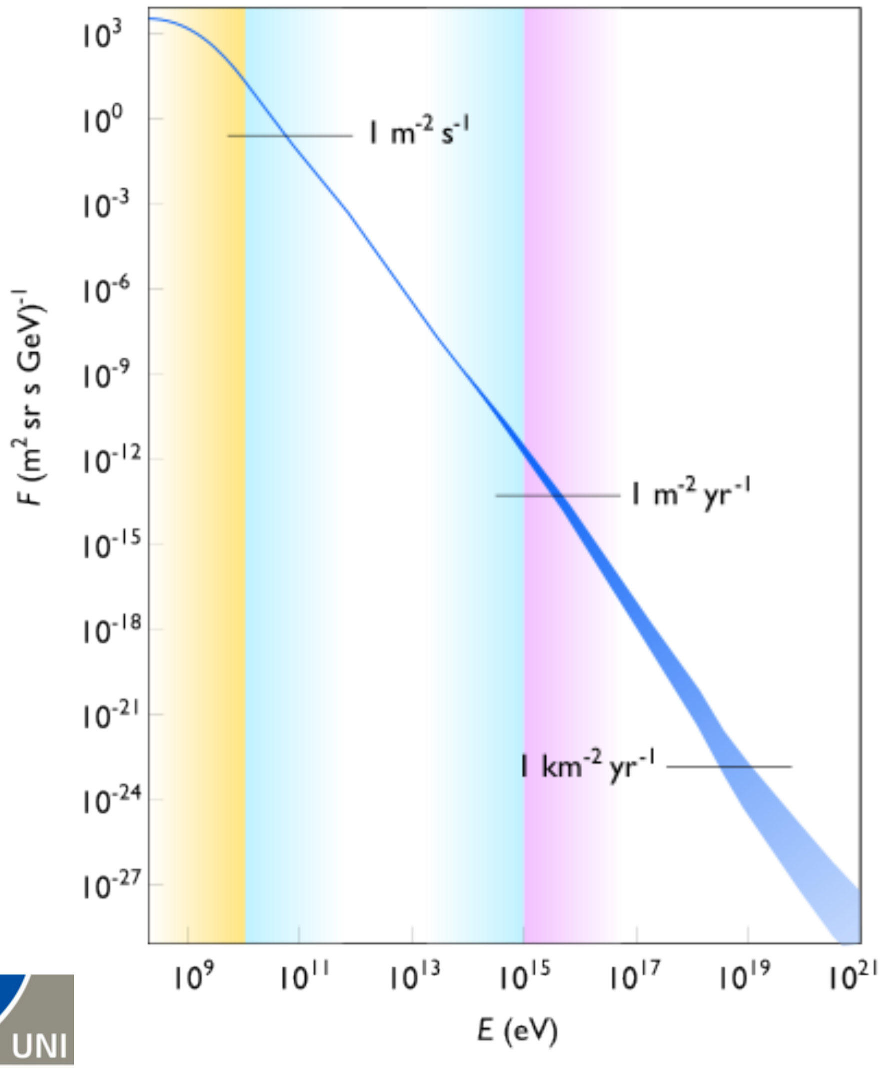


Silicon photo-multiplier

Calorimeter in the Pampa

Calos: not only at accelerators!

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



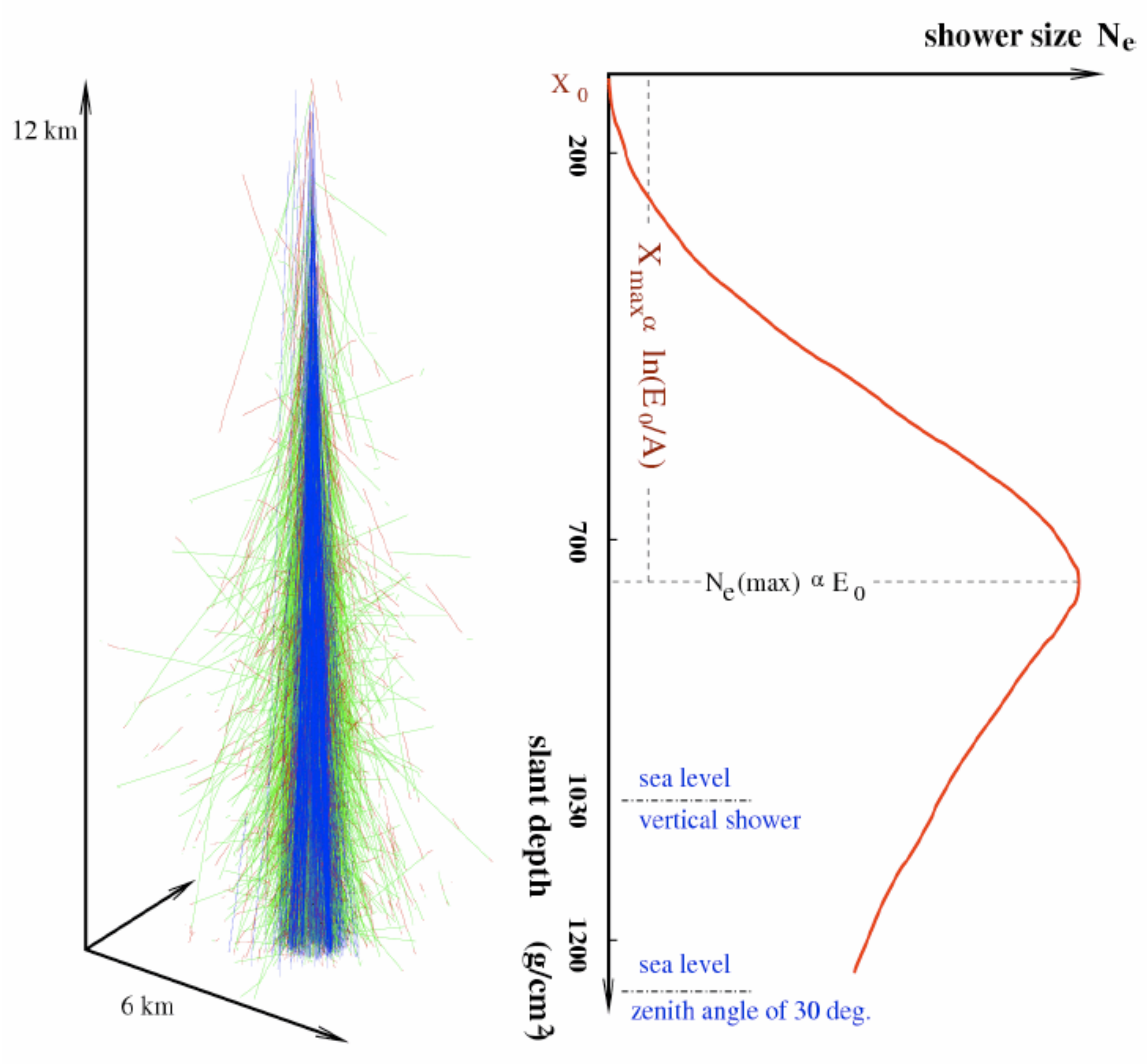
Pic: Wikipedia

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/cm^2

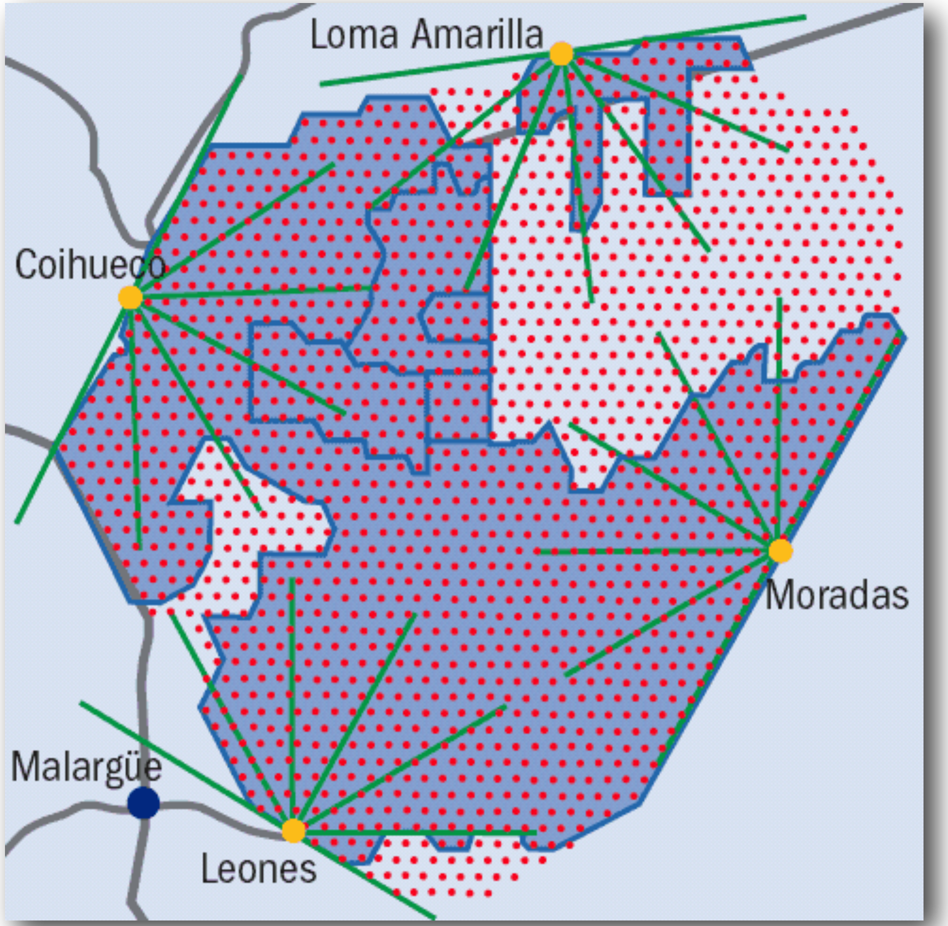
Radiation length X_0 ~ 36.6 g/cm^2

Density: ~ 1035 g/cm^2

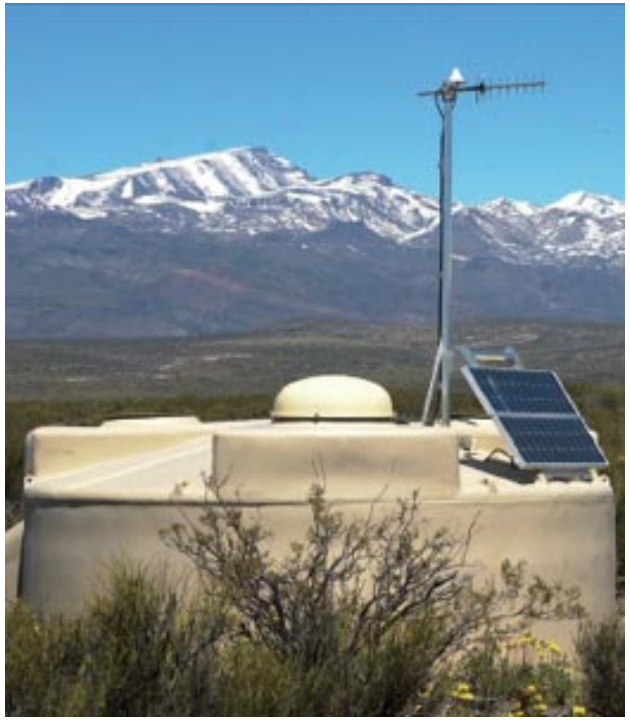
~ 11 λ_I, ~ 28 X_0

Example: AUGER-South: Argentinian Pampa

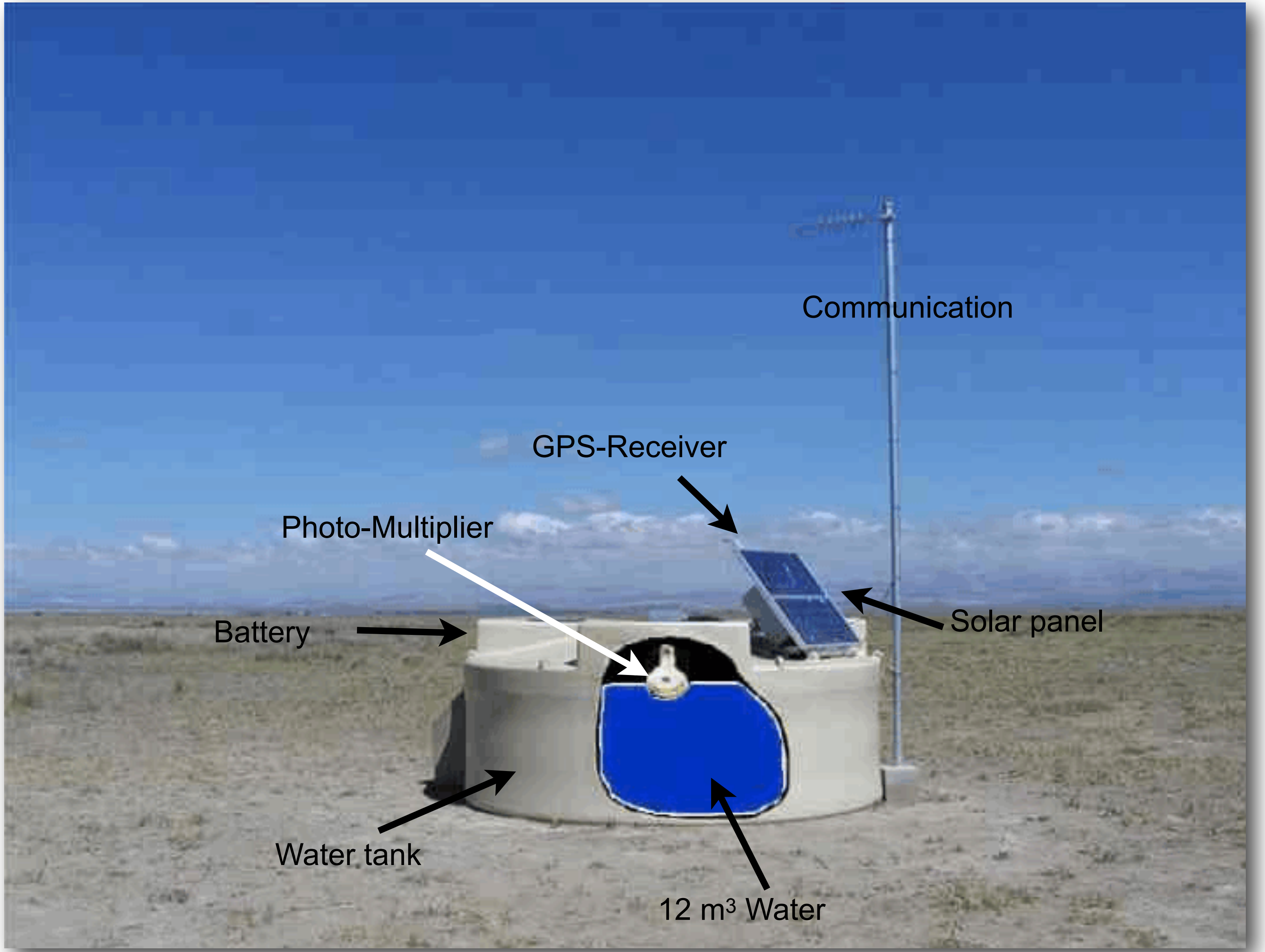
Pics: Pierre Auger Observatory



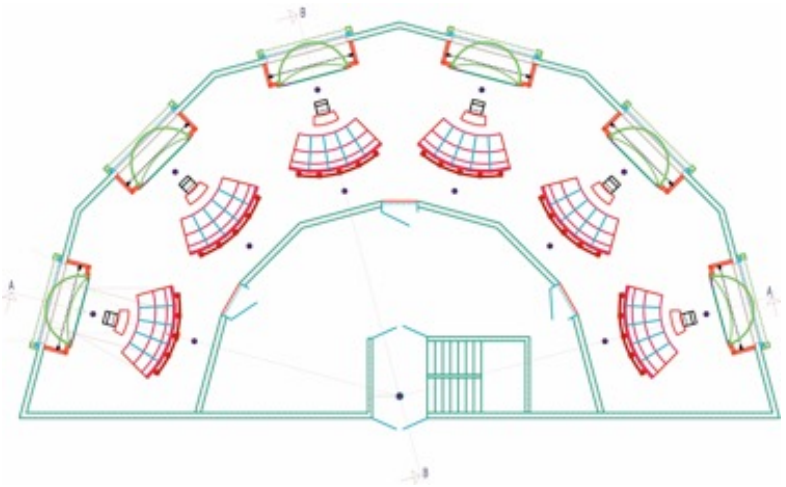
- 1600 water-Cherenkov detectors on ground
- 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

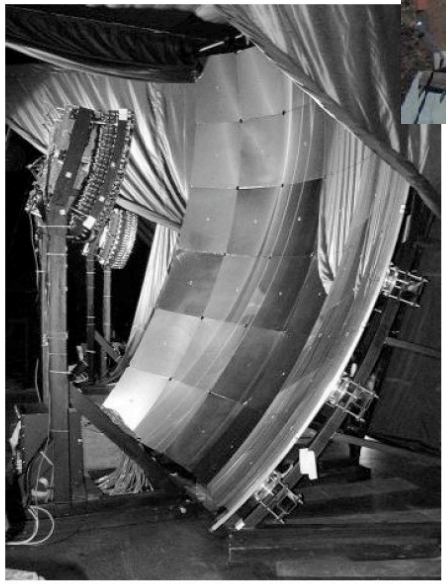


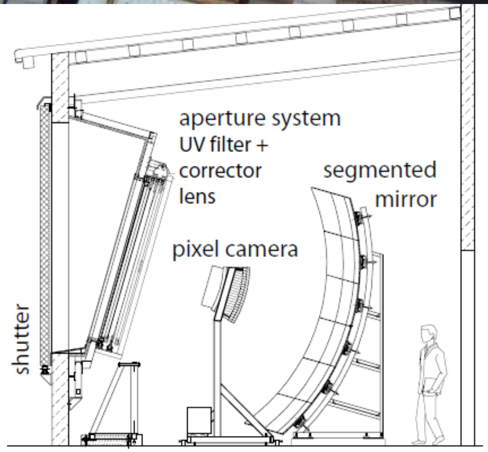
AUGER-Detektor: Ground Array



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.

Real Life Examples
Building an Experiment (Example LHC)

How to do a particle Physics Experiment

- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger
  - recording devices
- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data

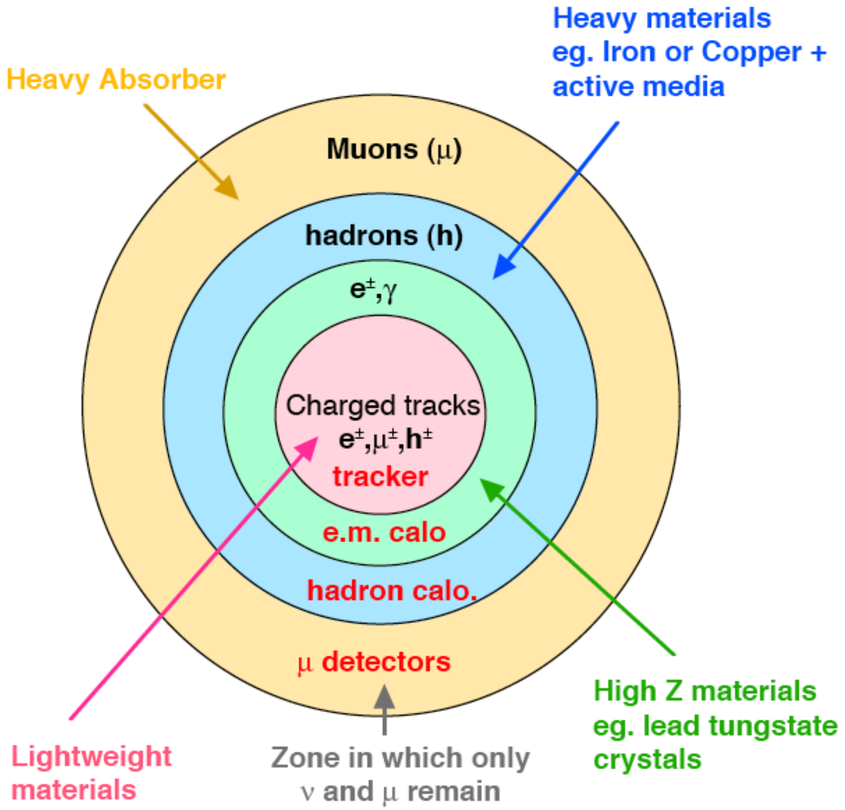
typical HERA collaboration: ~400 people
LHC collaborations: >2000 people

Pic: DESY

- many people to:
  - design, build, test, operate accelerate
  - design, build, test, calibrate, operate, understand the detector
  - analyse data
- lots of money to pay all this ….

Conceptual Design of HEP Dete

- Need detailed understanding of
  - processes you want to measure (“physics case”)
  - signatures, particle energies and rates to be expected
  - background conditions
- Decide on magnetic field
  - only around tracker?
  - extending further ?
- Calorimeter choice
  - define geometry (nuclear reaction length, X0)
  - type of calorimeter (can be mixed)
  - choice of material depends also on funds



at a collider experiment

- Tracker
  - technology choice (gas and/or Si?)
  - number of layers, coverage, …
  - pitch, thickness, ….
  - also here money plays a role

Detailed Monte Carlo Simulations need to guide the design process all the time !!

A magnet for a LHC experiment

- **Wish list**
  - big: long lever arm for tracking
  - high magnetic field
  - low material budget or outside detector (radiation length, absorption)
  - serve as mechanical support
  - reliable operation
  - cheap
  - ….

Eierlegende Wollmilchsau

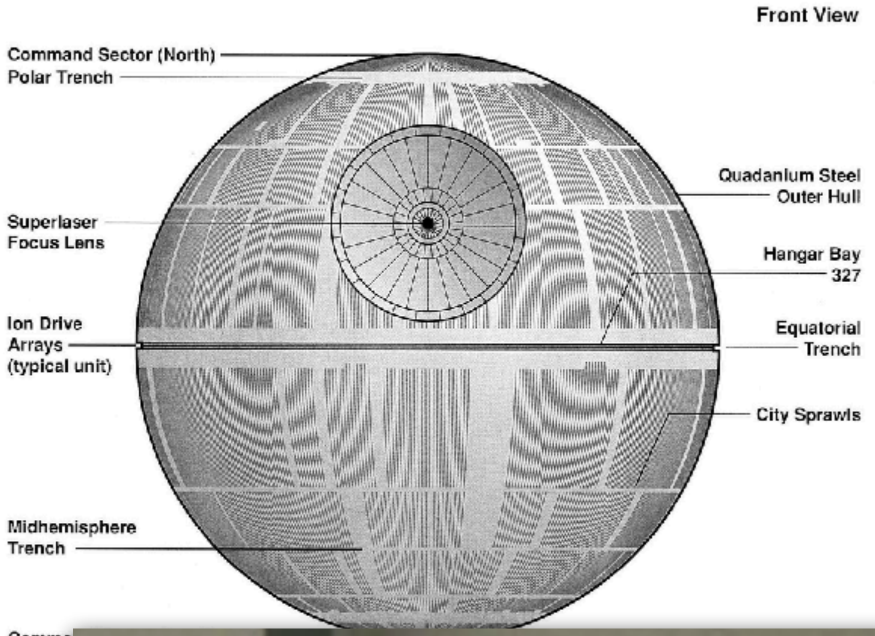
- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

- **CMS decision**
  - single magnet with the highest possible field in inner tracker (momentum resolution)
  - muon detector outside of magnet

And what can go wrong....

Disclaimer

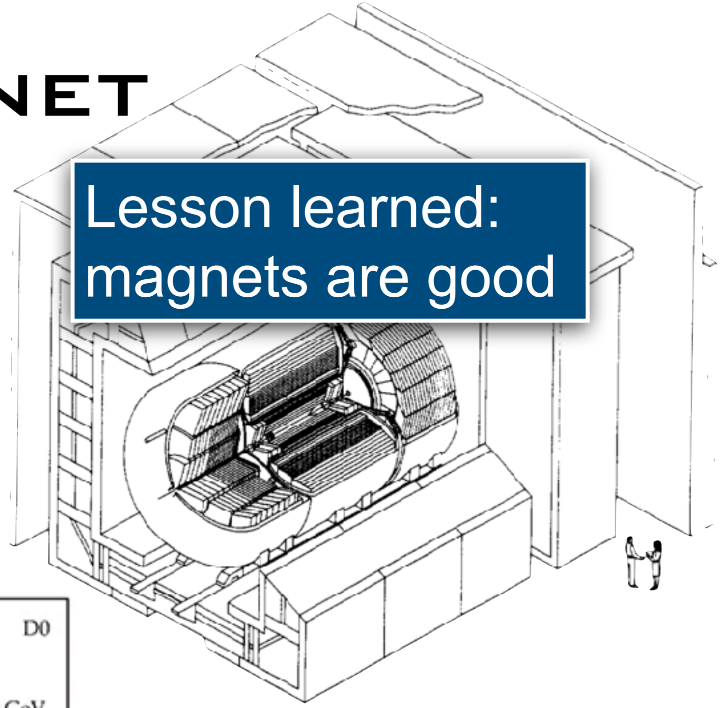
- Designing a large (silicon) detector for particle tracking or identification is a very complex business
- Many very nice examples exist
- Also some examples of failures



- Some stuff you don’t find in textbooks
- Collection of failures might give the impression of overall incompetence
  - Overwhelming majority of detectors run like a chime
  - Unbelievable effort to get large accelerators and experiments in a global effort to run so nicely
  - Even sociologists are interested in how we do this …

D0 without Inner Tracking Magnet

- D0 Experiment at Tevatron constructed to study proton-antiproton collisions
- **Top quark discovery** in 1995 together with CDF experiment

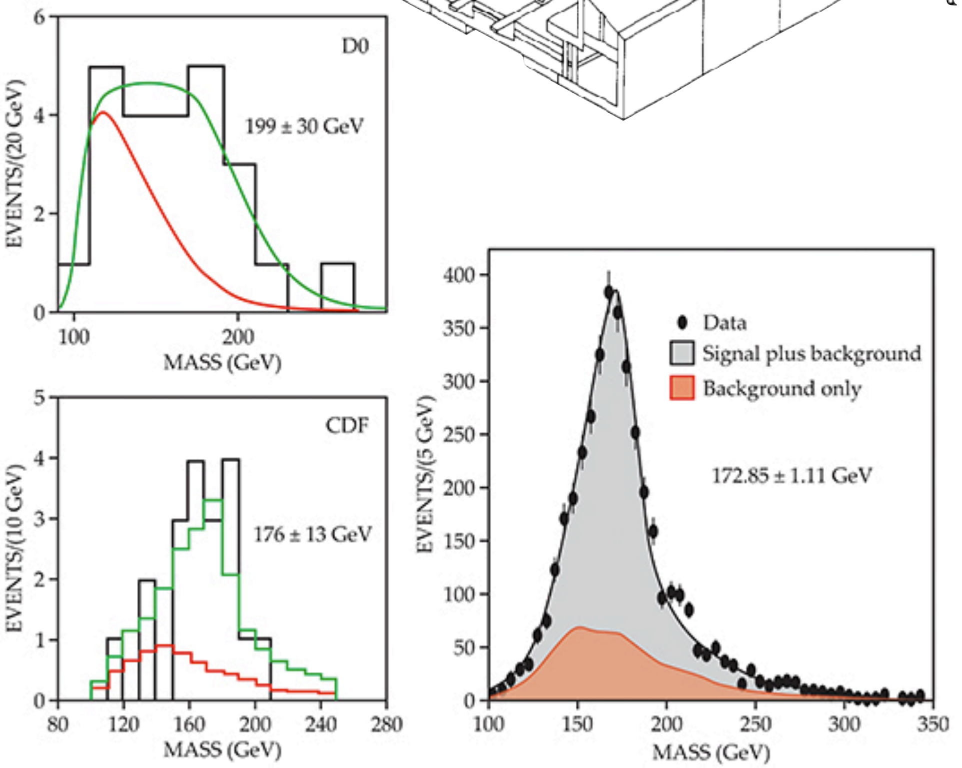


Lesson learned: magnets are good

- Original design for Run I: no magnet for tracking
  - “Focussing on parton jets for deciphering the underlying physics than emphasis on individual final particle after hadronisation”
  - Very compact tracking system
  - Uranium-liquid argon calorimeter for identification of electrons, photons, jets and muons

- Effect of low momentum charged particles greatly underestimated resulting in analysis difficulties.

Run II system included a silicon microstrip tracker and a scintillating-fibre tracker located within a 2 T solenoidal magnet.



Top quark discovery

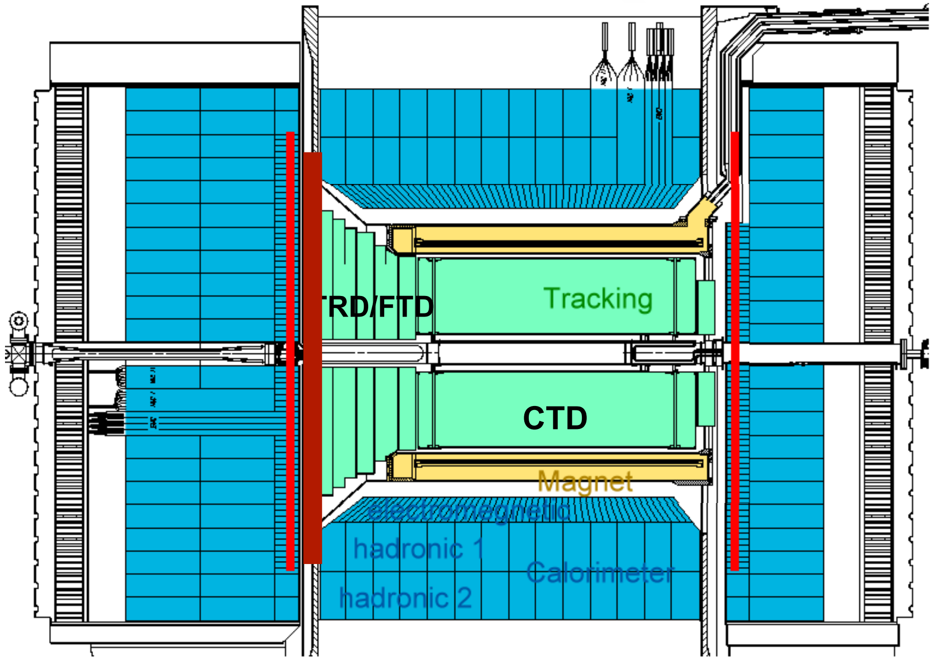
ZEUS TRD

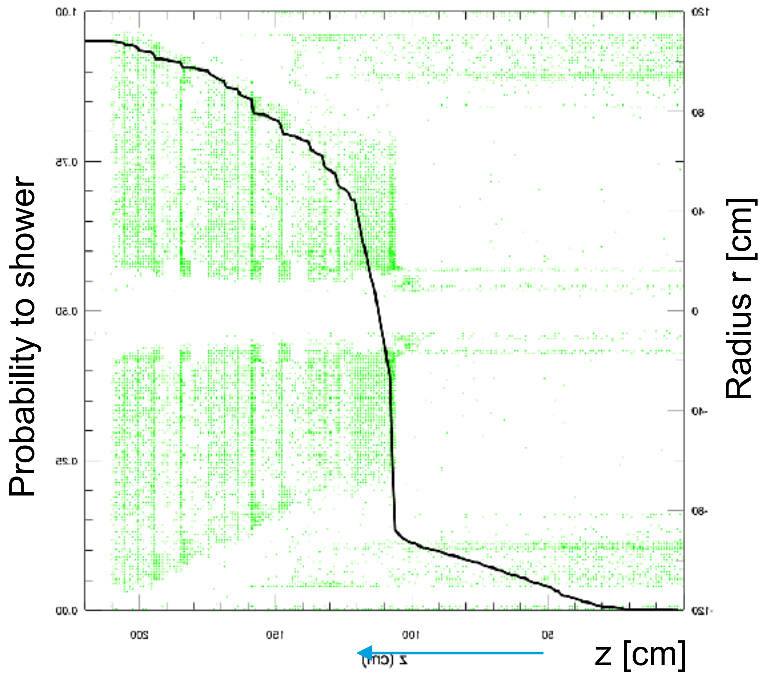
- Zeus Transition Radiation detector for electron identification.
- Aim: h/e rejection ratio of about 10^{-2} for electron tracks embedded in jets (1 - 30 GeV/c).

  - However - central tracking detector (wire chamber) had 2cm end-plate for wire fixation
    - Electrons 100% probability to shower and thus were not present in showers anymore

  - Reason for mishap: no proper Monte Carlo simulation tools available at time of detector design

    - TRD used for Here Run I Replaced by Straw Tube Tracker for Run II



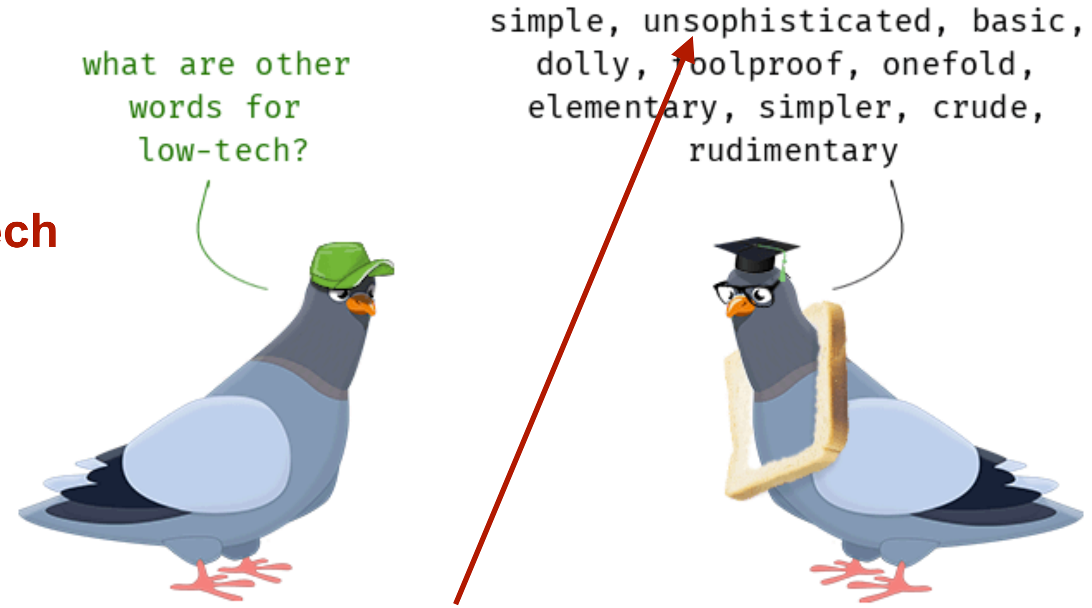


Lesson learned:
Monte Carlos simulations should include everything

"Low Tech" Failures

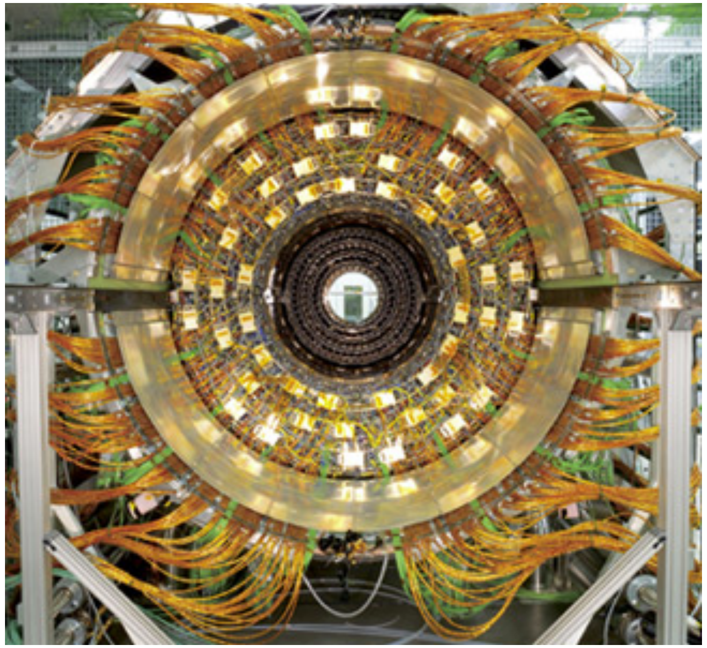
What is "Low" Tech ?

- In particle physics experiments almost everything is **high tech**
  - Need extreme reliability
  - Radiation tolerance
  - Precision
  - Mostly running longer than originally planned



For particle physics experiments this is not true !

- However - some areas considered as "low tech" and people (and funding agencies) don't like to invest research money into those areas
  - Cables for powering
  - Power plants
  - Cooling
  - Data transfer (optical and electrical)
  - Non sensitive materials (mechanics)
  - Glues
  - …..

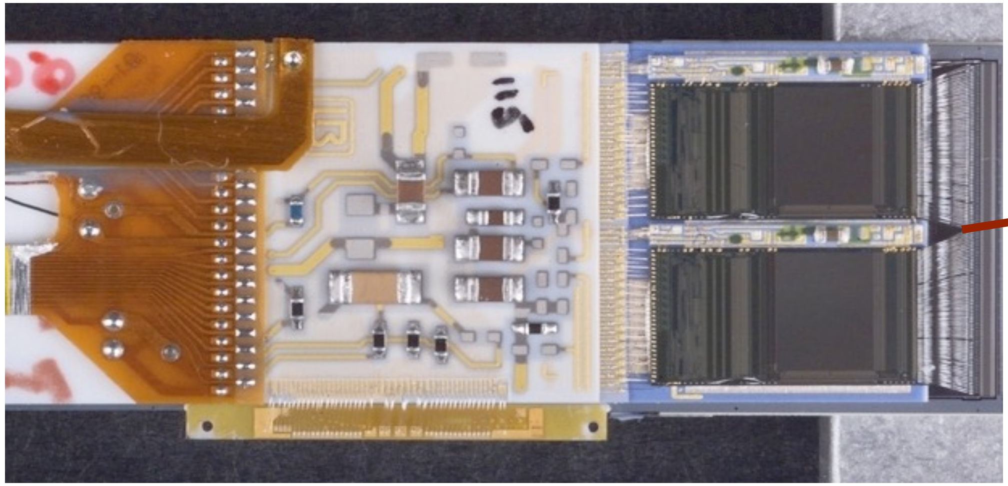


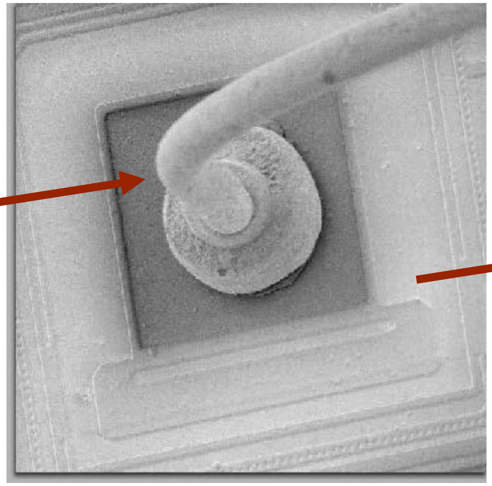
Wire-Bonds and Wire Breakage

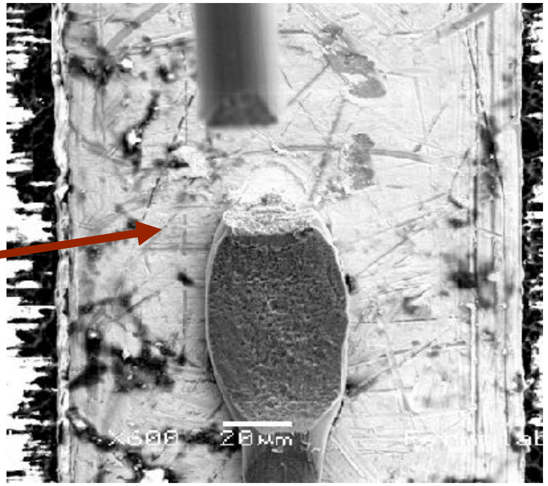
Problems with Wire Bonds (CDF, D0)

during running

- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- Observation: During synchronous readout conditions, loss of modules (no data, Drop in current)



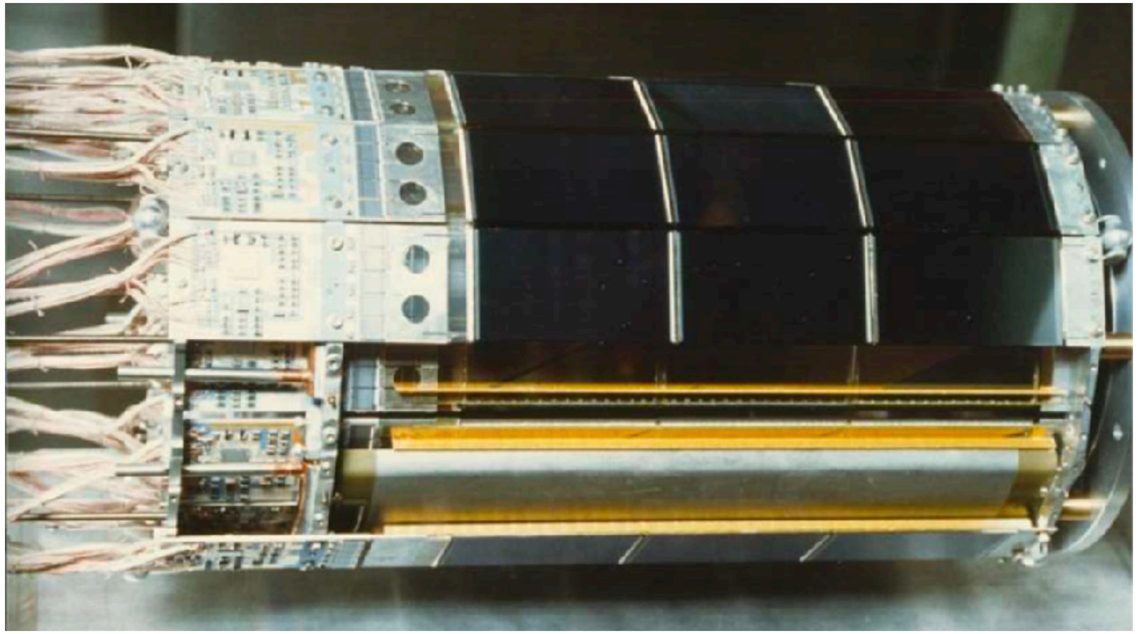




- Tests revealed:
  - Bonds start moving due to Lorentz Force in magnetic field
  - Wire resonance in the 20 kHz range
  - Current is highest during data readout
  - Already a few kicks are enough to get the bond excited

Implemented “Ghostbuster” system which avoids long phases with same readout frequency

OPAL MVD 1994



- OPAL MVD ran for a short while without cooling water flow.
- Temperature of the detector rose to **over 100°C.**
  - Most of the modules to fail or to be partially damaged.

- Chain of problem causing damage:
  - MVD expert modified the control/monitoring software between consecutive data taking runs.
  - Inserted bug which stopped software in a state with cooling water off but with the low voltage power on.
  - Stopped software also prevented the monitoring of the temperature from functioning
  - Should have been prevented by additional interlock but that was also disabled….

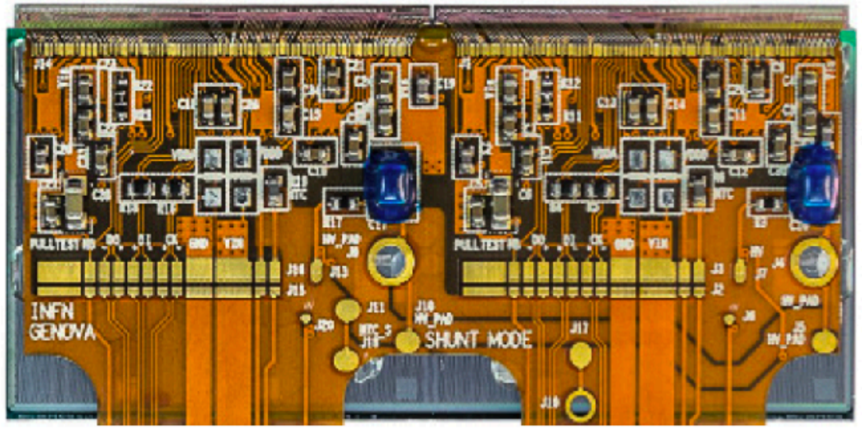
Lucky outcome:

- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

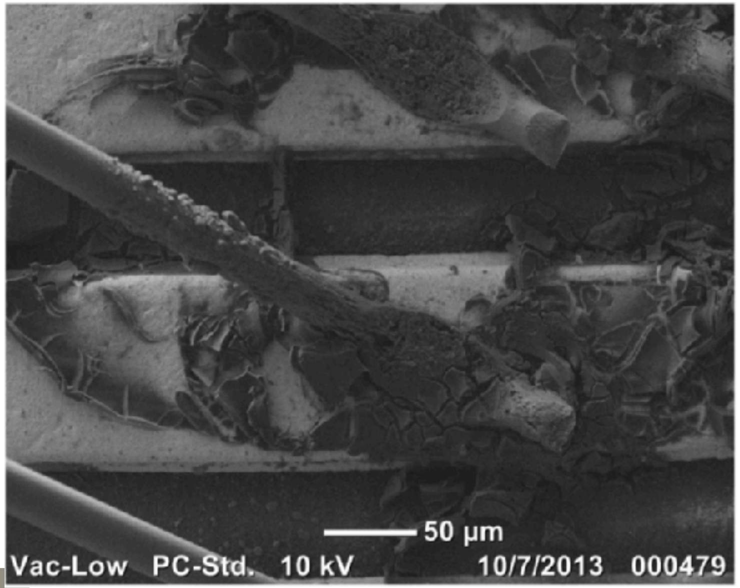
Mitigation plan:

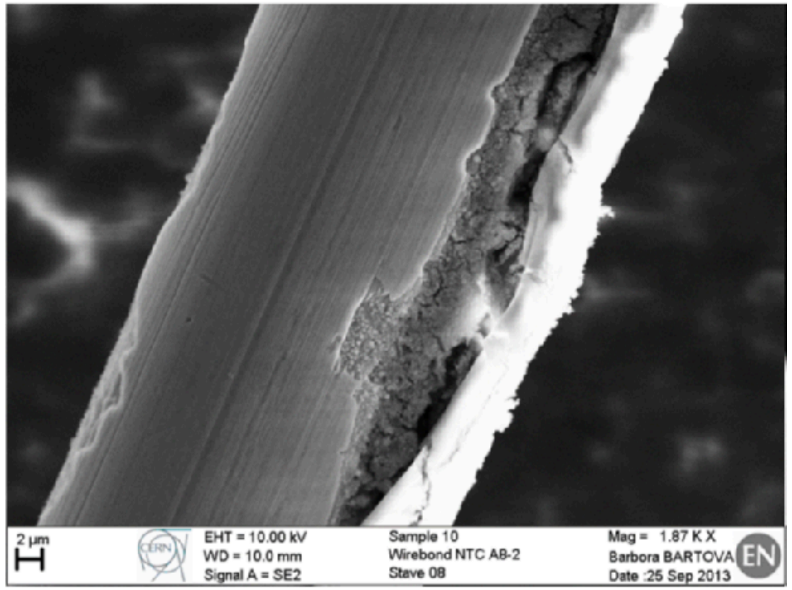
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

ATLAS IBL - Wire Bond Corrosion



- Additional pixel layer for ATLAS installed in 2015
- Five months **before** installation: corrosion residues observed at wire-bonds after cold tests (-25 C)
  - Severe damage of many wire-bonds
- Residue showed traces of chlorine: catalyst of a reaction between Aluminium (wire-bonds) and H_2O (in air)
- Origin of chlorine in system never fully understood





- Emergency repair and additional staves from spare parts

during production

https://indico.cern.ch/event/435798/contributions/1074098/attachments/1134177/1622192/encapsulation_study_-_Oxford.pdf

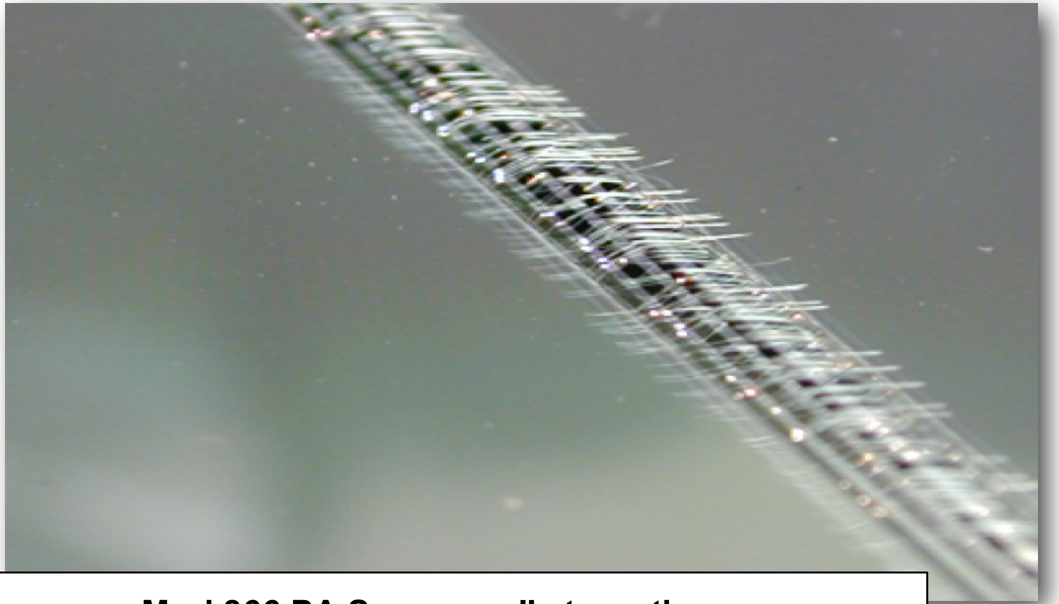
More Wire Bond Wreckage

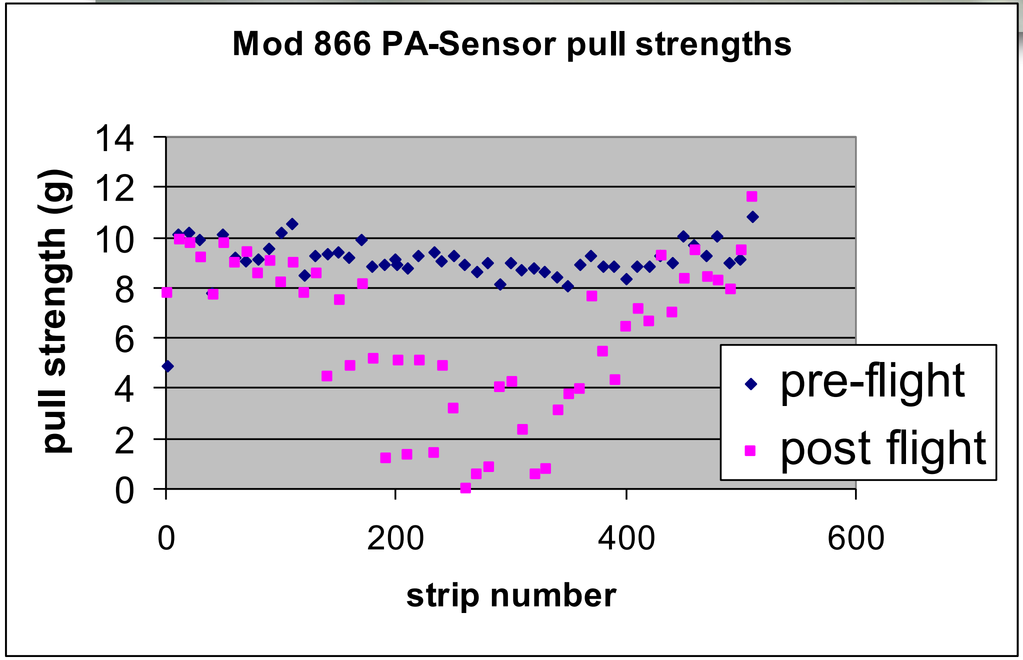
- During CMS strip tracker production quality assurance applied before and after transport
  - Quality of wires is tested by pull tests (measured in g)

- Wire bonds were weaker after transport with plane
- Random 3.4 g NASA vibration test could reproduce same problem

- Problem observed during production -> improved by adding a glue layer
- No further problems during production

during production

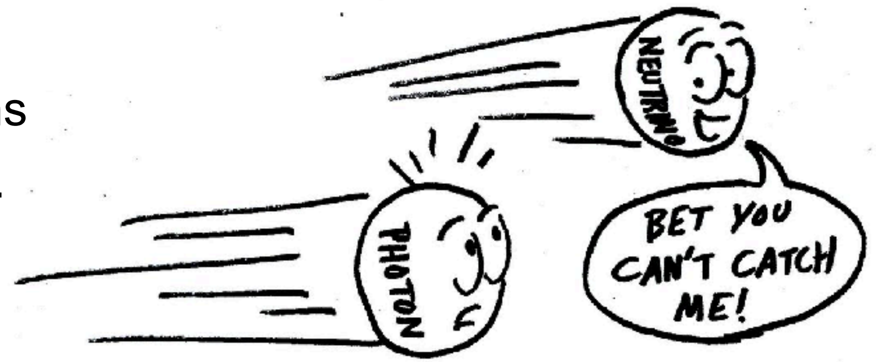




Other Problems and Famous Problems

Cable Problem with Press Coverage

- Oscillation Project with Emulsion-tRacking Apparatus — **OPERA:** instrument for detecting tau neutrinos from muon neutrino oscillations
- In 2011 they observed neutrinos appearing to travel faster than light.
  - Very controversial paper also within collaboration



The top 10 biggest science stories of the decade

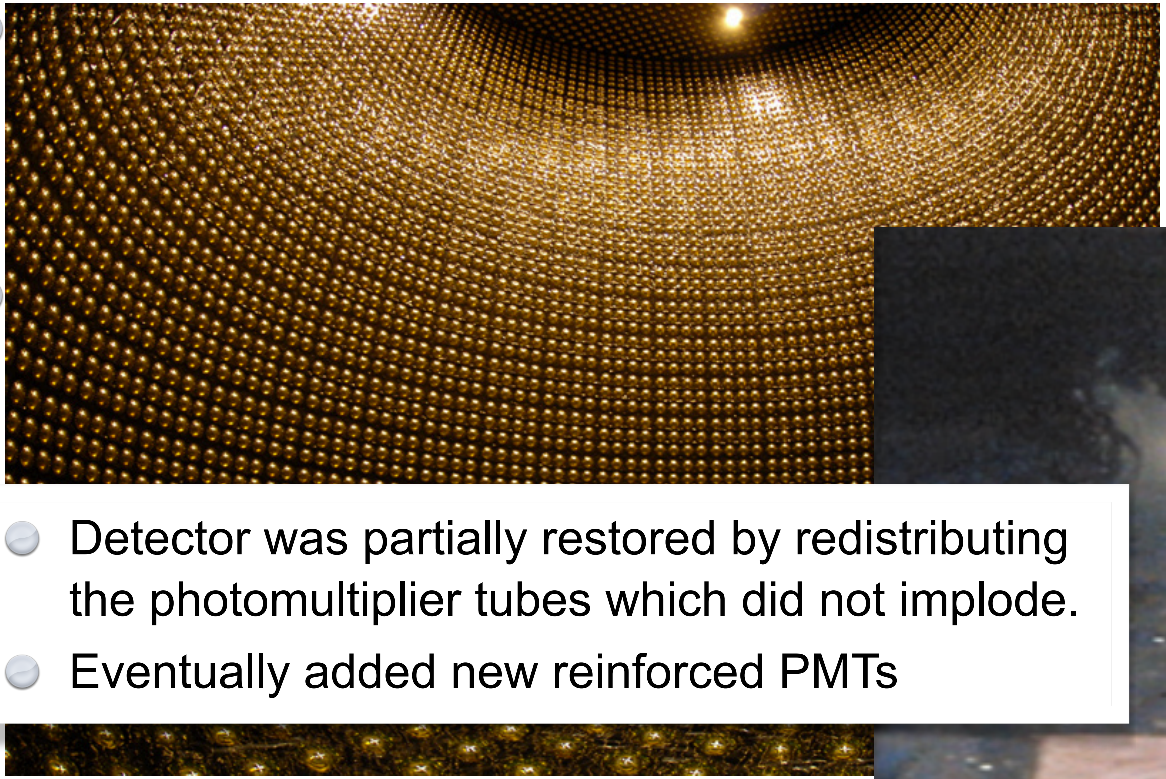
- Kink from a GPS receiver to OPERA master clock was loose
  - Increased the delay through the fibre resulting in decreasing the reported flight time of the neutrinos by 73 ns,
  - making them seem faster than light.

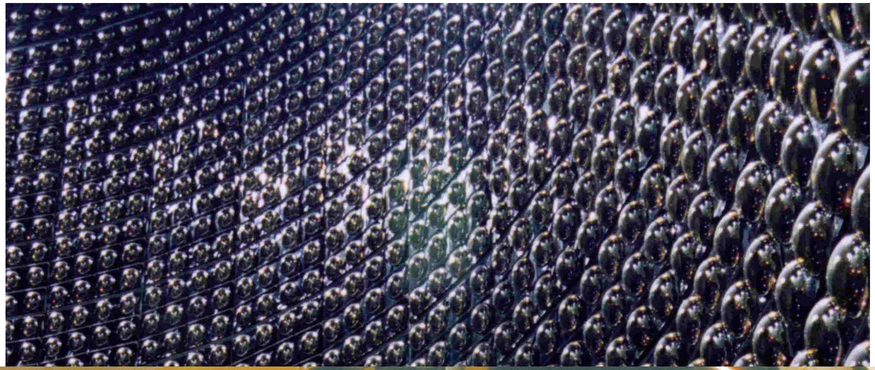
After finding the problem, the difference between the measured and expected arrival time of neutrinos was approximately 6.5 ± 15 ns.

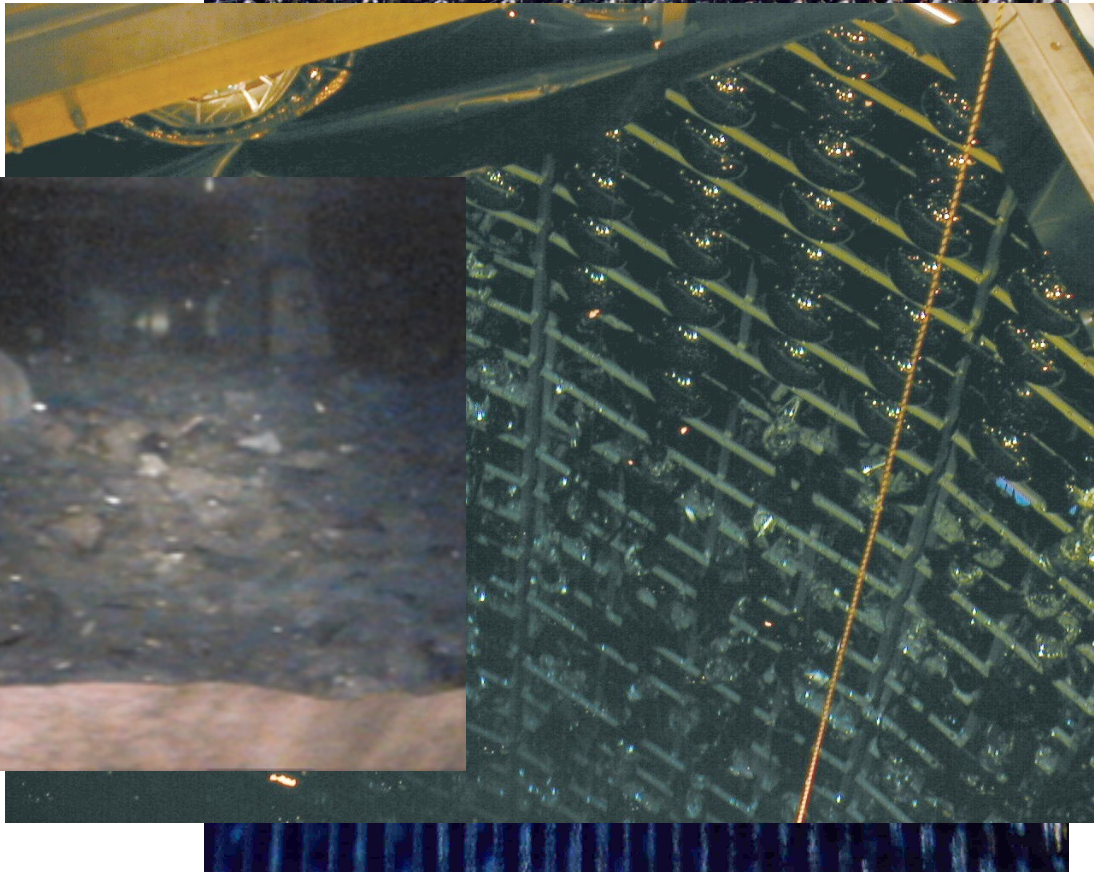
Maybe Most Famous Damage ....

during commissioning

- Underground water Cherenkov detector with 50,000 tons of ultrapure water as target material
- Nov 2001: One PMT imploded creating shock wave destroying about 7700 of PMTs





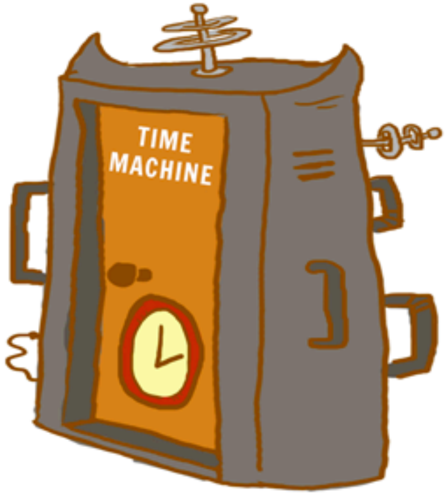


- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.
- Eventually added new reinforced PMTs

Pic: unknown source….

Lessons Learned ?

- Spend enough time on simulating all aspects of your detector with ALL materials implemented
- Don’t underestimate the “low tech”
  - Cables
  - Cooling
  - Mechanics including FEA
  - Radiation damage of non-sensitive materials
  - …..
- Make sure the overall timeline is not completely crazy (tough job)
- When mixing materials — ask a chemist once in a while
- …..



Solving and preventing theses kind of problems is also part of the fascination of detector physics!!

Summary

- I could only give a **glimpse** at the wealth of particle detectors. More detectors are around: medical application, synchrotron radiation experiments, astro particle physics, ...
- All detectors base on similar principles
  - Particle detection is indirectly by (electromagnetic) interactions with the detector material
- Large detectors are typically build up in layers (onion concept):
  - Inner tracking: momentum measurement using a B-field
  - Outside calorimeter: energy measurement by total absorption
- Many different technologies:
  - Gas- and semiconductors (light material) for tracking
  - Sampling and Homogeneous calorimeters for energy measurement
- Similar methods are used in astro particle physics
- **Always looking for new ideas and technologies!**

Detector Literature

Text books:

- **N. Wermes, H. Kolanoski: Particle Detectors: Fundamentals and Applications,** Oxford University Press (30. August 2020)
- Frank Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer Verlag 2018
- C.Grupen: Particle Detectors, Cambridge UP 22008, 680p
- D.Green: The physics of particle Detectors, Cambridge UP 2000
- K.Kleinknecht: Detectors for particle radiation, Cambridge UP, 21998
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web:
Particle Data Group: *Review of Particle Properties: pdg.lbl.gov*
further reading:
The Large Hadron Collider - The Harvest of Run 1; Springer 2015