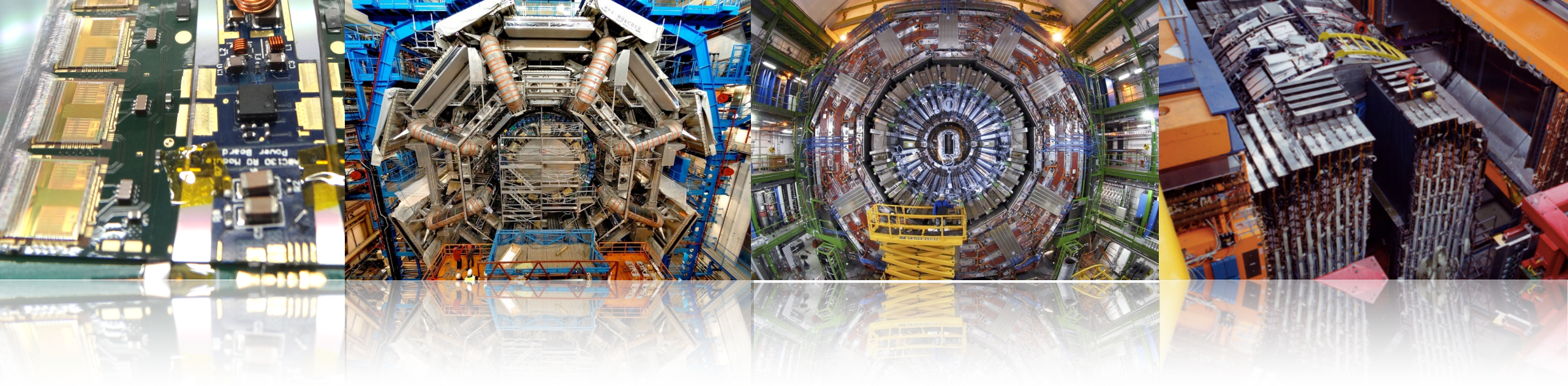


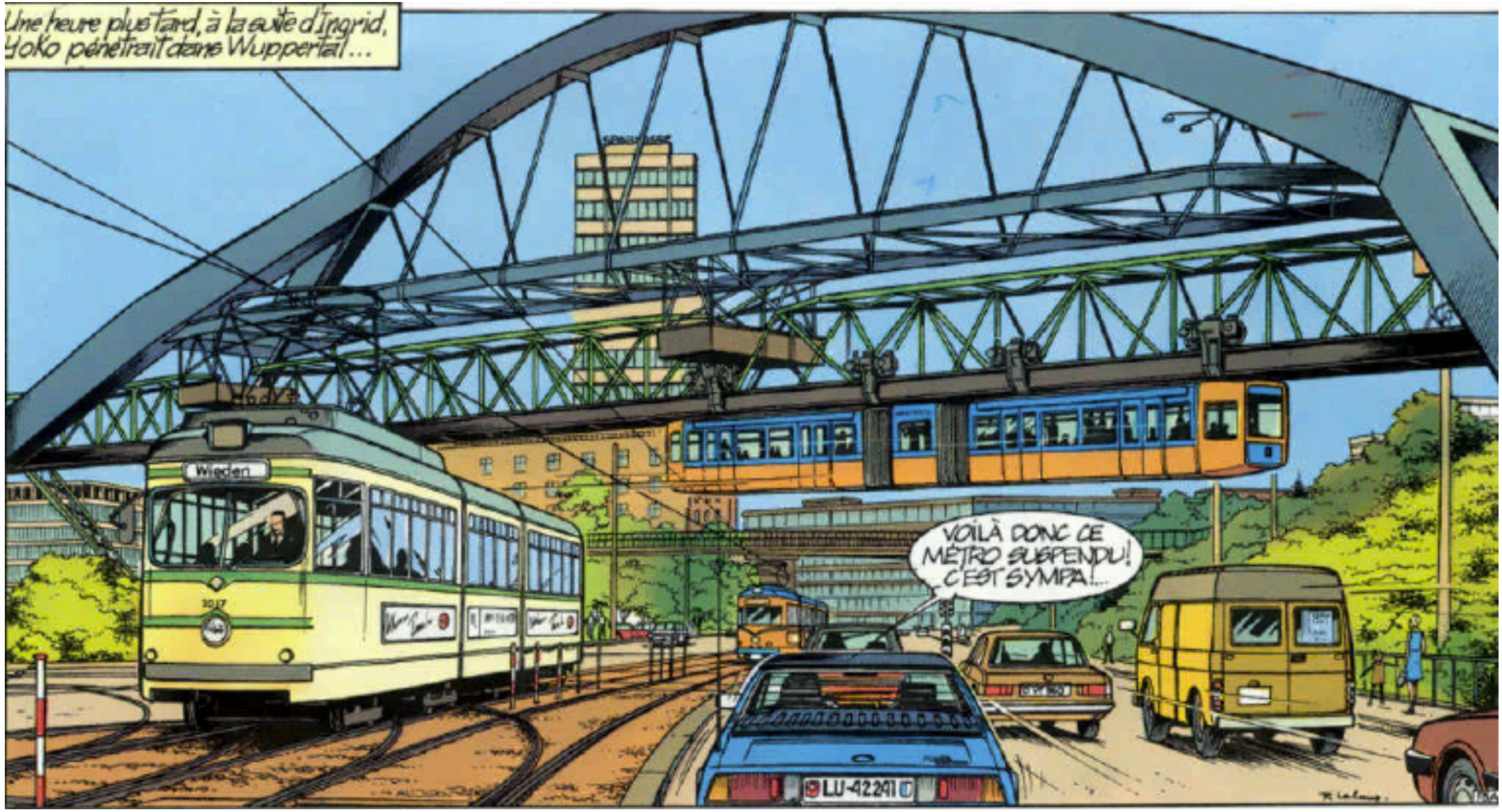
Instrumentation and Detectors

Part 1

Ingrid-Maria Gregor
DESY/Universität Bonn

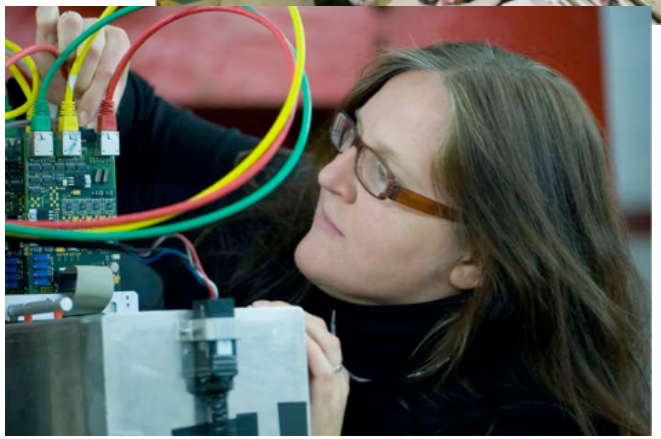
BND School

Wuppertal ....


Une heure plus tard, à la suite d'Ingrid, Yoko pénétrait dans Wuppertal...
Wiedenl
VOILÀ DONC CE MÉTRO SUSPENDU! C'EST SYMPA!...
LU-42241

Ingrid-Maria Gregor

- Studied here in Wuppertal
- Physics Engineering
  - First visit to CERN to install DELPHI pixel detector
- Decided to continue to study Physics
  - Multi-channel dosimeter to be used for Brachytherapy
- PhD - completed in October 2001
  - A radiation tolerant optical link for the ATLAS Pixel Detector
- Postdoc DESY - HERMES Experiment 2002-2005
  - Detector development and Hermes data analysis
- Staff Scientist DESY since May 2005
  - ZEUS calorimeter coordinator
  - EUDET Pixel Telescope development
  - ATLAS group leader since 2014
  - Building one end-cap for the ITk
- Joint professorship between DESY and Uni Bonn since 2019



Disclaimer

- Particle Detectors are very complex, a lot of physics is behind the detection of particles:
  - particle physics
  - material science
  - electronics
  - mechanics, ….

- To get a good understanding, one needs to work on a detector project ...

- This lecture can only give a glimpse at particle detector physics, cannot cover everything
- Biased by my favourite detectors !

Pic: DC Comics

Maybe not the ideal detector physicist

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

Monday

III. **Calorimeter**

Tuesday

IV. **Tracking Detectors Overview**

- Gas detectors
- Muon Detectors
- Semiconductor trackers

Wednesday I

V. **Current Pixel and Strip Detector Projects**

Wednesday II

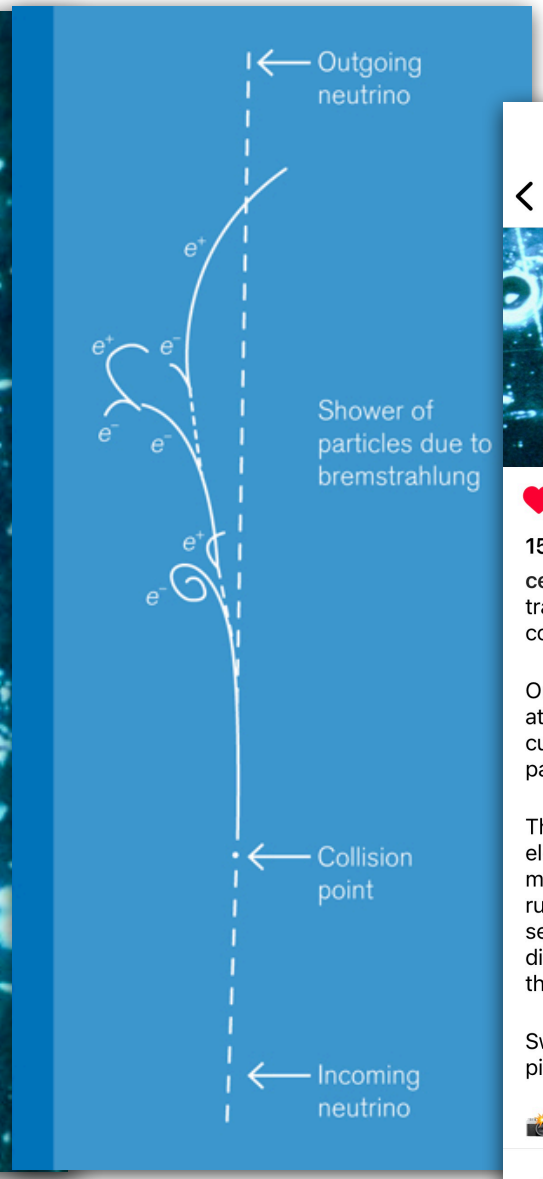
VI. **Examples of what can go wrong**

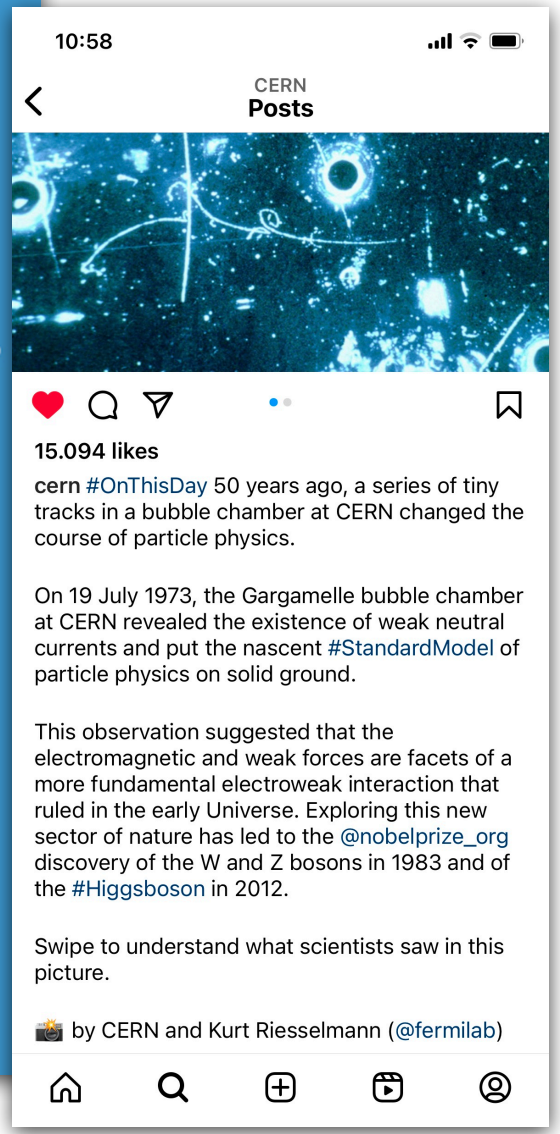
1. Overview: Detectors for particle physics

Discovery of neutral currents

Gargamelle, 19.7. 1973

50

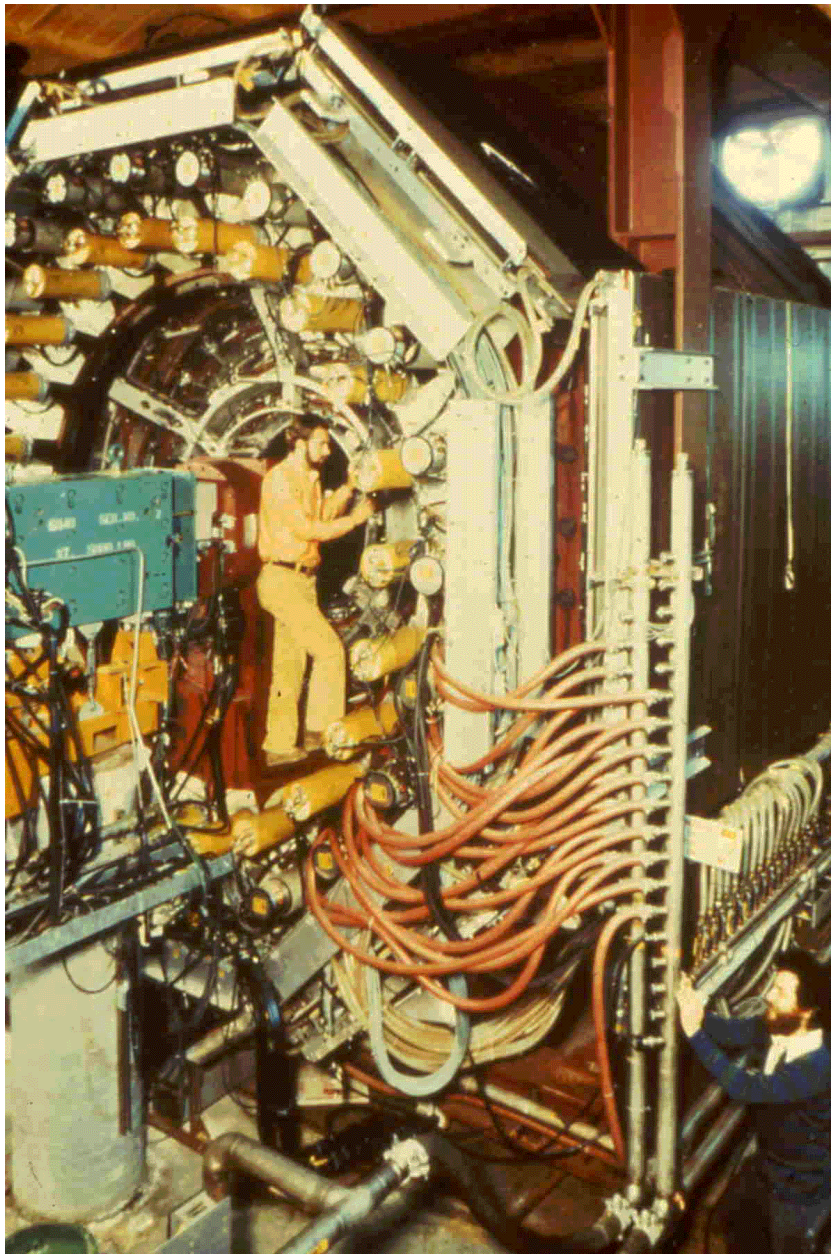




Mark-I Detector@SLAC

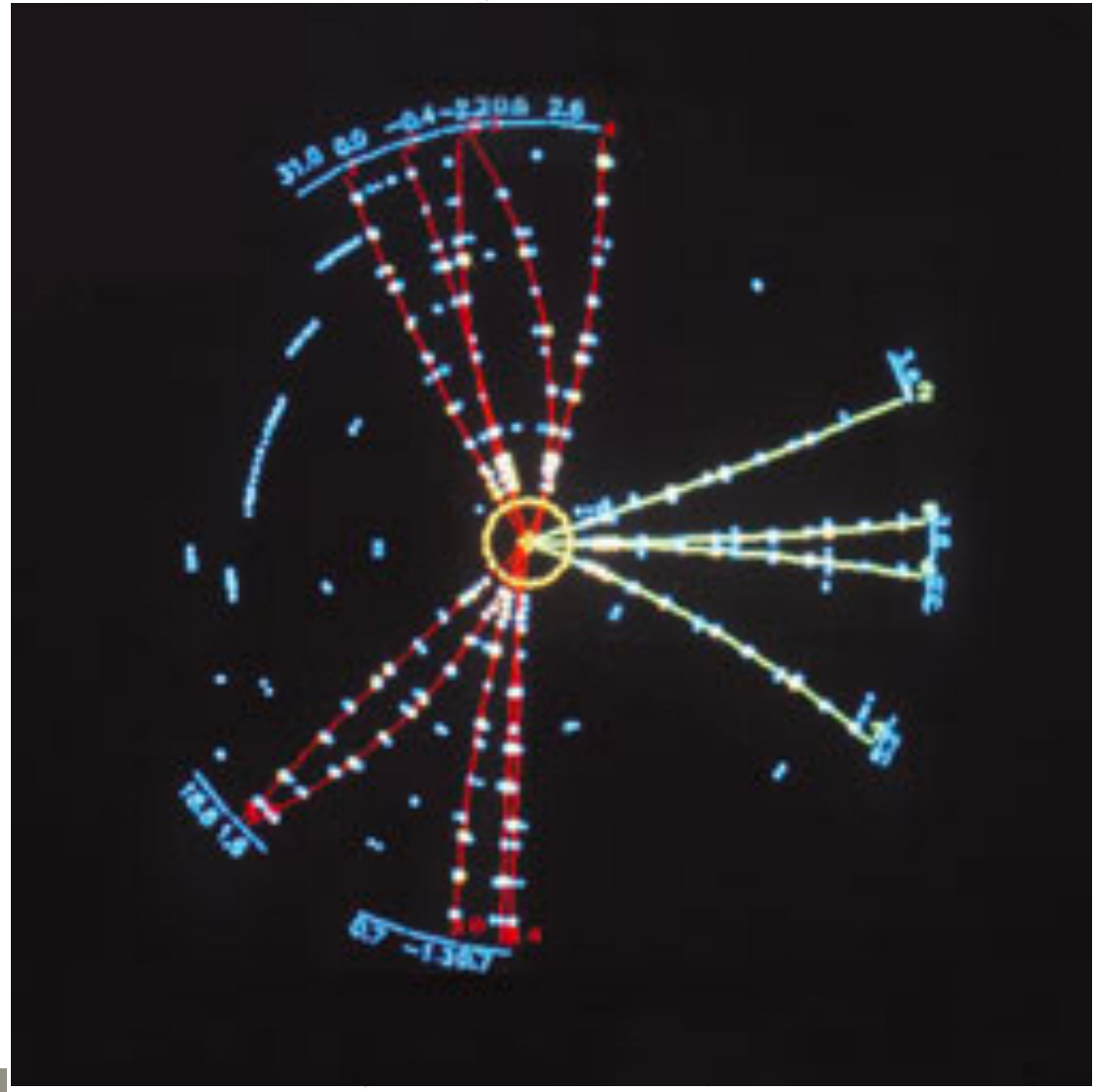
- Mark I detector: first 4π detector

Discoveries of the J/ψ particle and tau lepton, which both resulted in Nobel prizes (for Burton Richter in 1976 and Martin Lewis Perl in 1995)



Discovery of the Gluon

18.06.1979

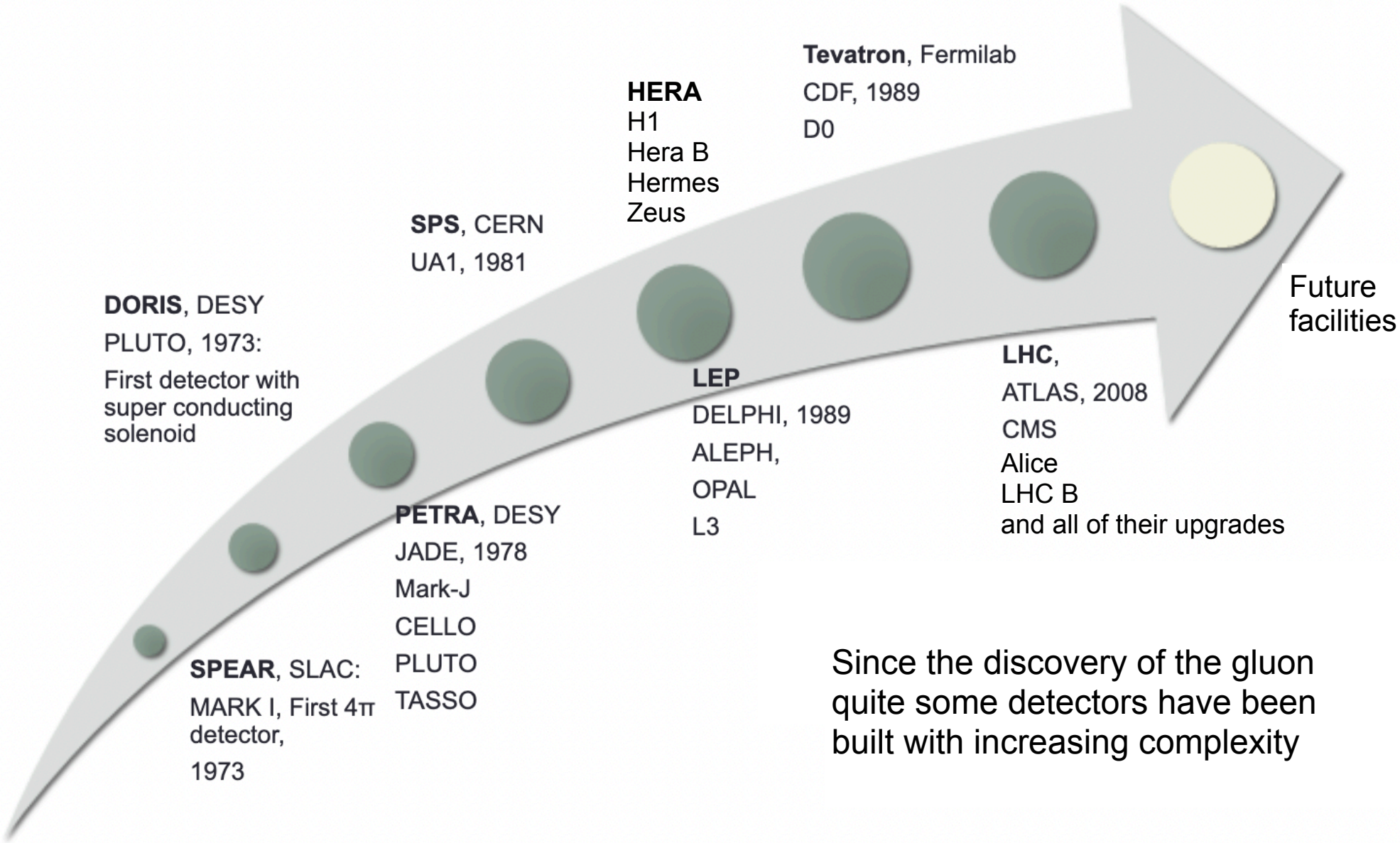


- Field theory predicted that the outgoing quarks radiate field quanta (gluons)
  -> 3 jet events

The quantum of the strong force was discovered and studied at lepton colliders

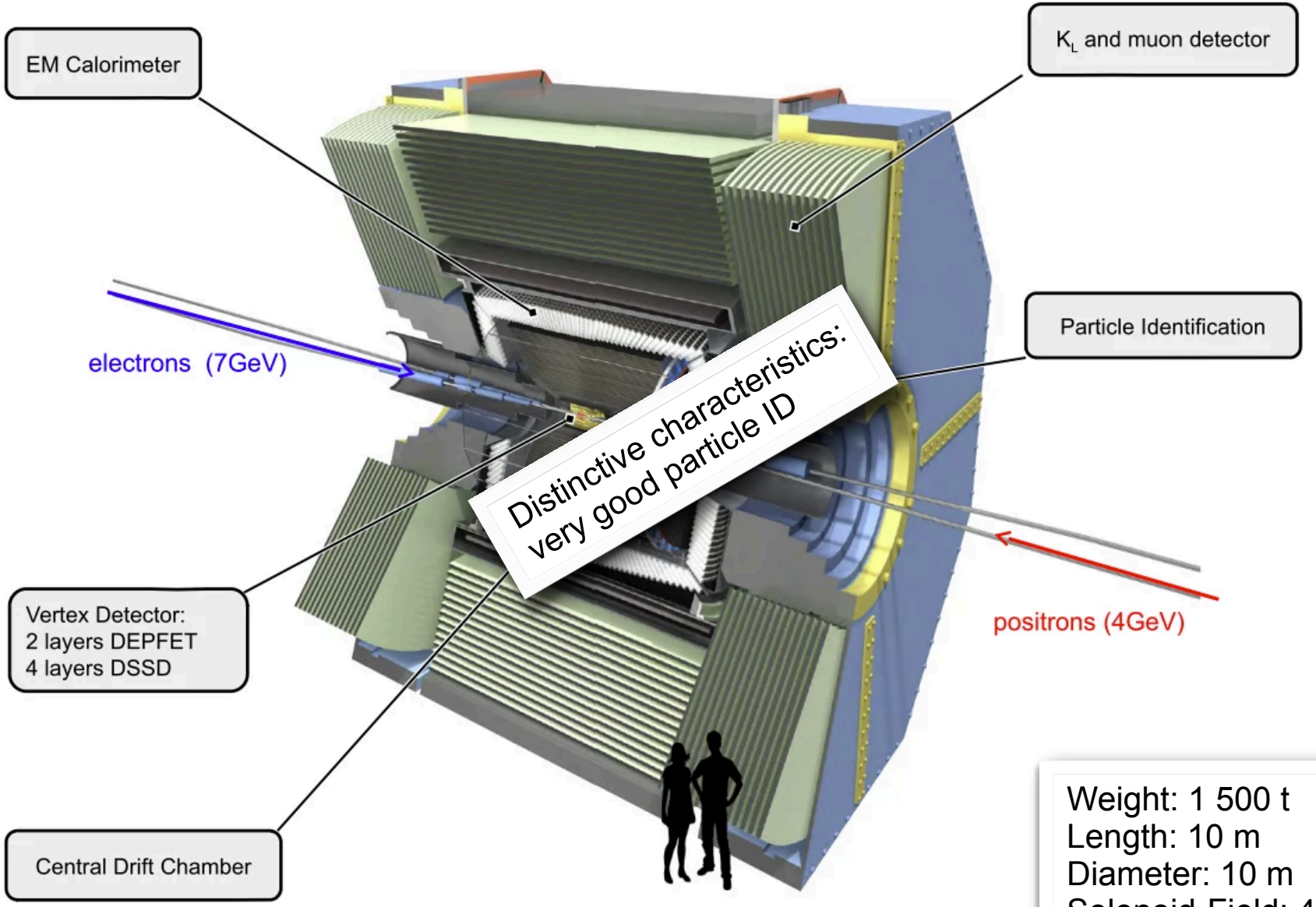
Petra experiments: JADE, Mark J, PLUTO, TASSO

Evolution of Detectors



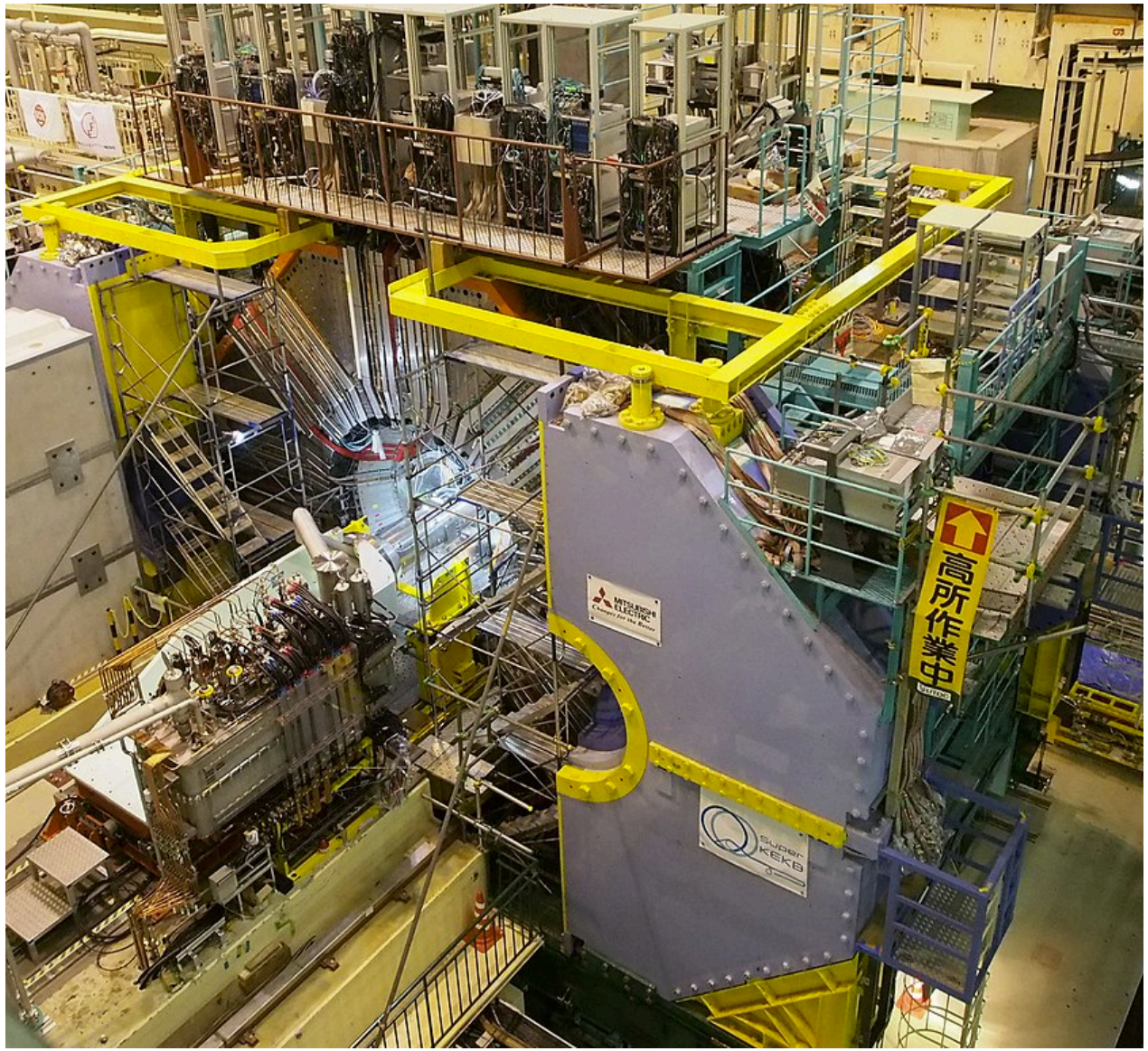
Since the discovery of the gluon quite some detectors have been built with increasing complexity

BELLE@KEK

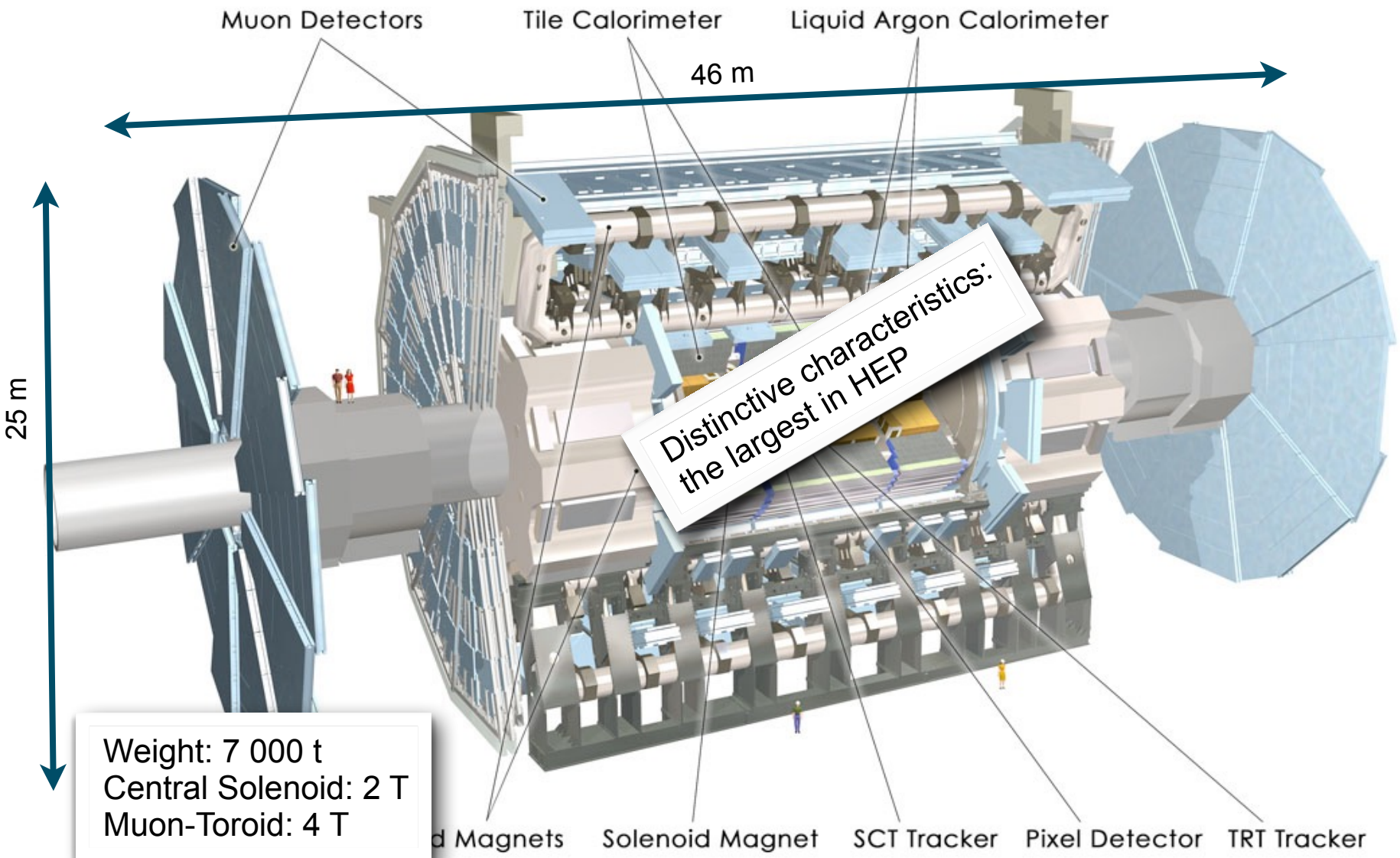


Weight: 1 500 t
Length: 10 m
Diameter: 10 m
Solenoid-Field: 4 T

BELLE@KEK



ATLAS@LHC



Weight: 7 000 t
Central Solenoid: 2 T
Muon-Toroid: 4 T

Illustration: CERN

ATLAS Cross Section

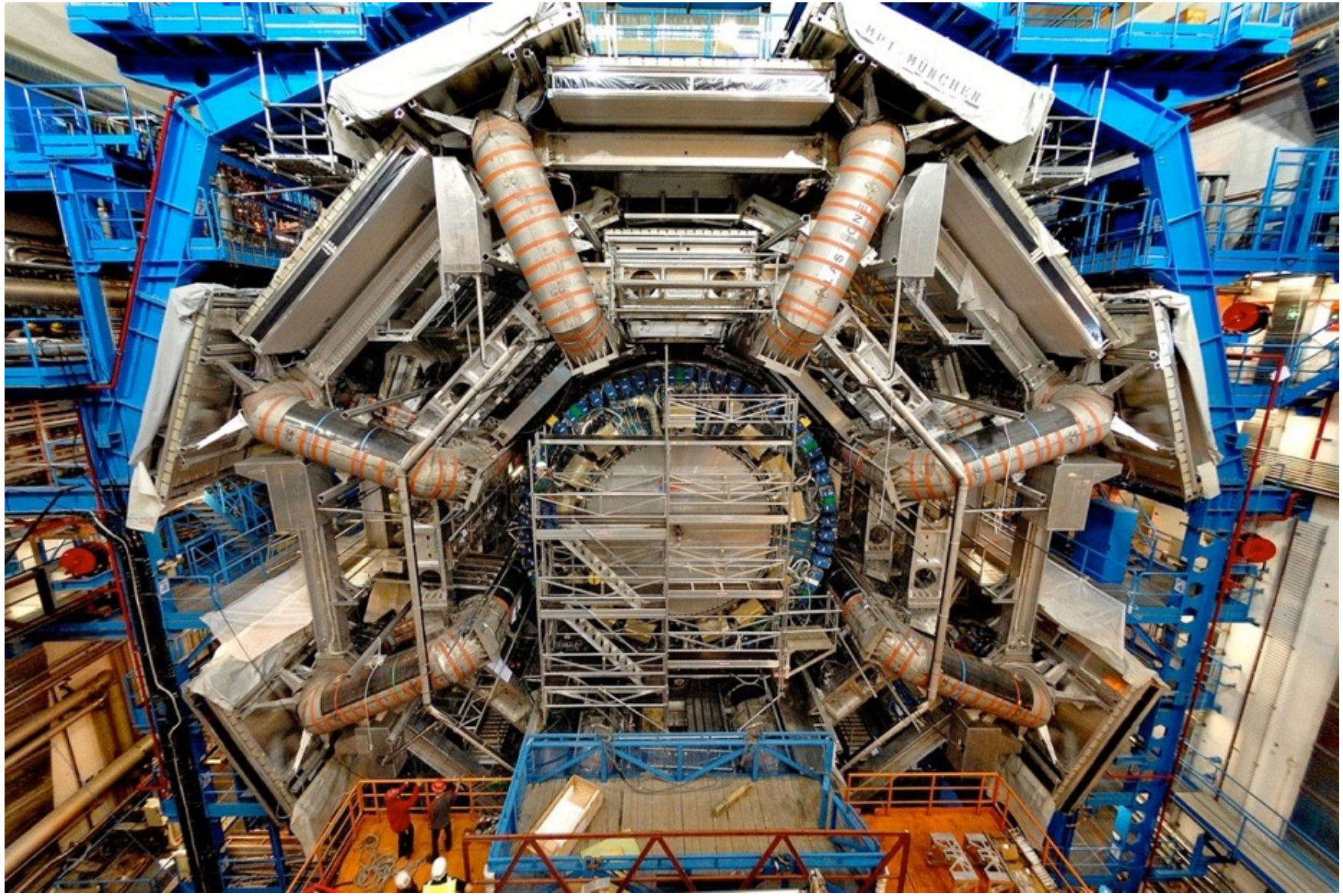
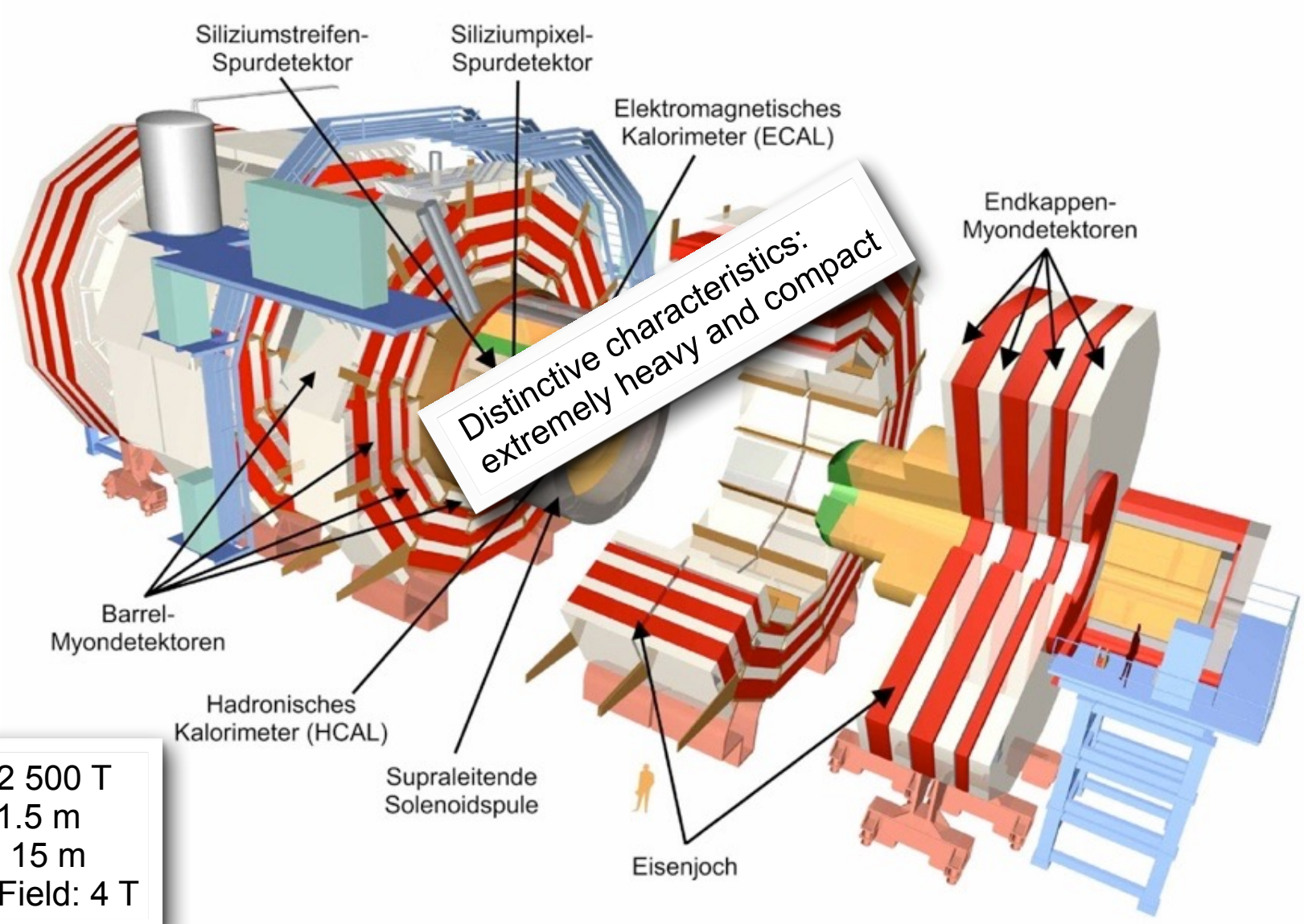


Foto: CERN

CMS@LHC



Distinctive characteristics:
extremely heavy and compact

Weight: 12 500 T
Length: 21.5 m
Diameter: 15 m
Solenoid-Field: 4 T

CMS Cross Section

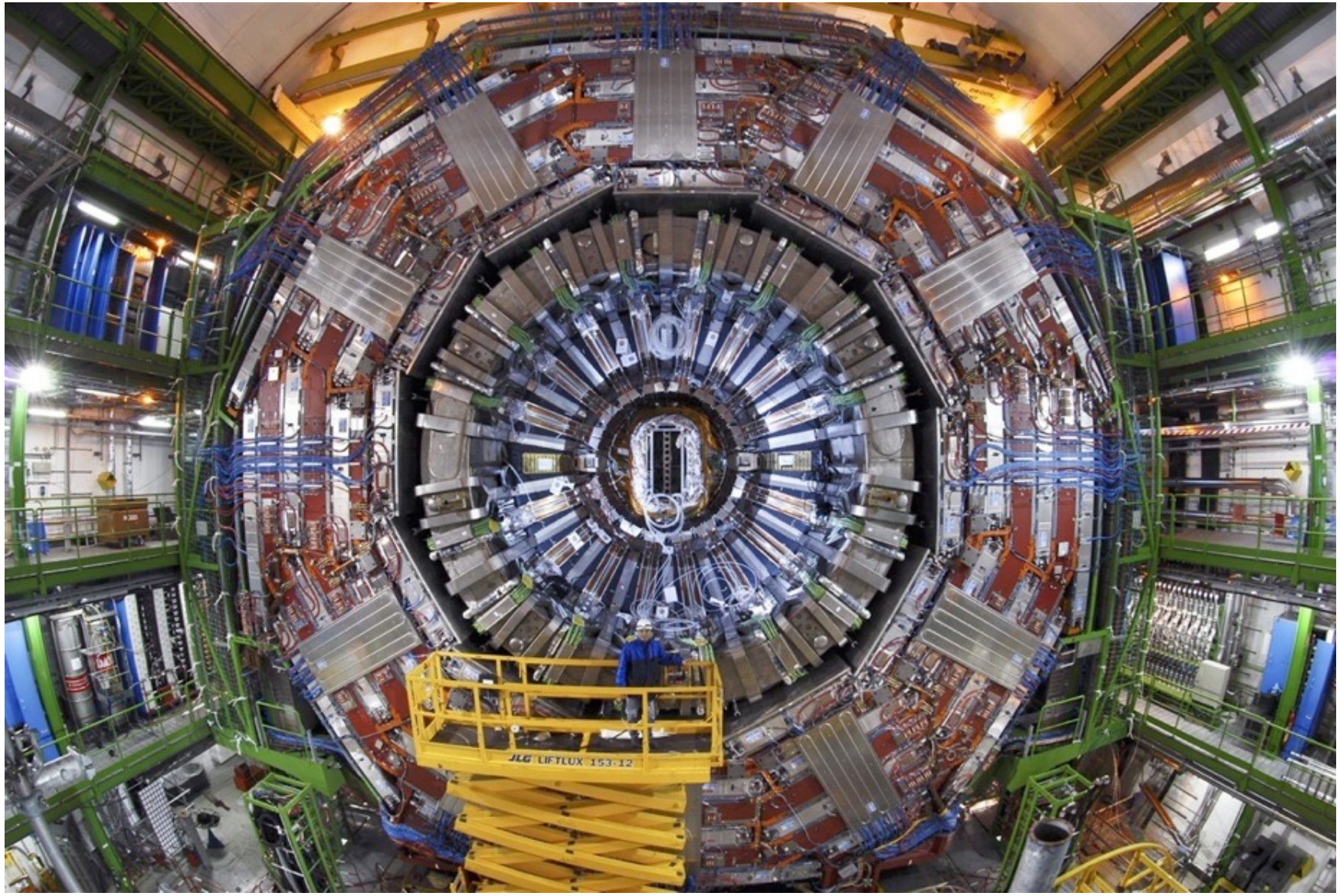
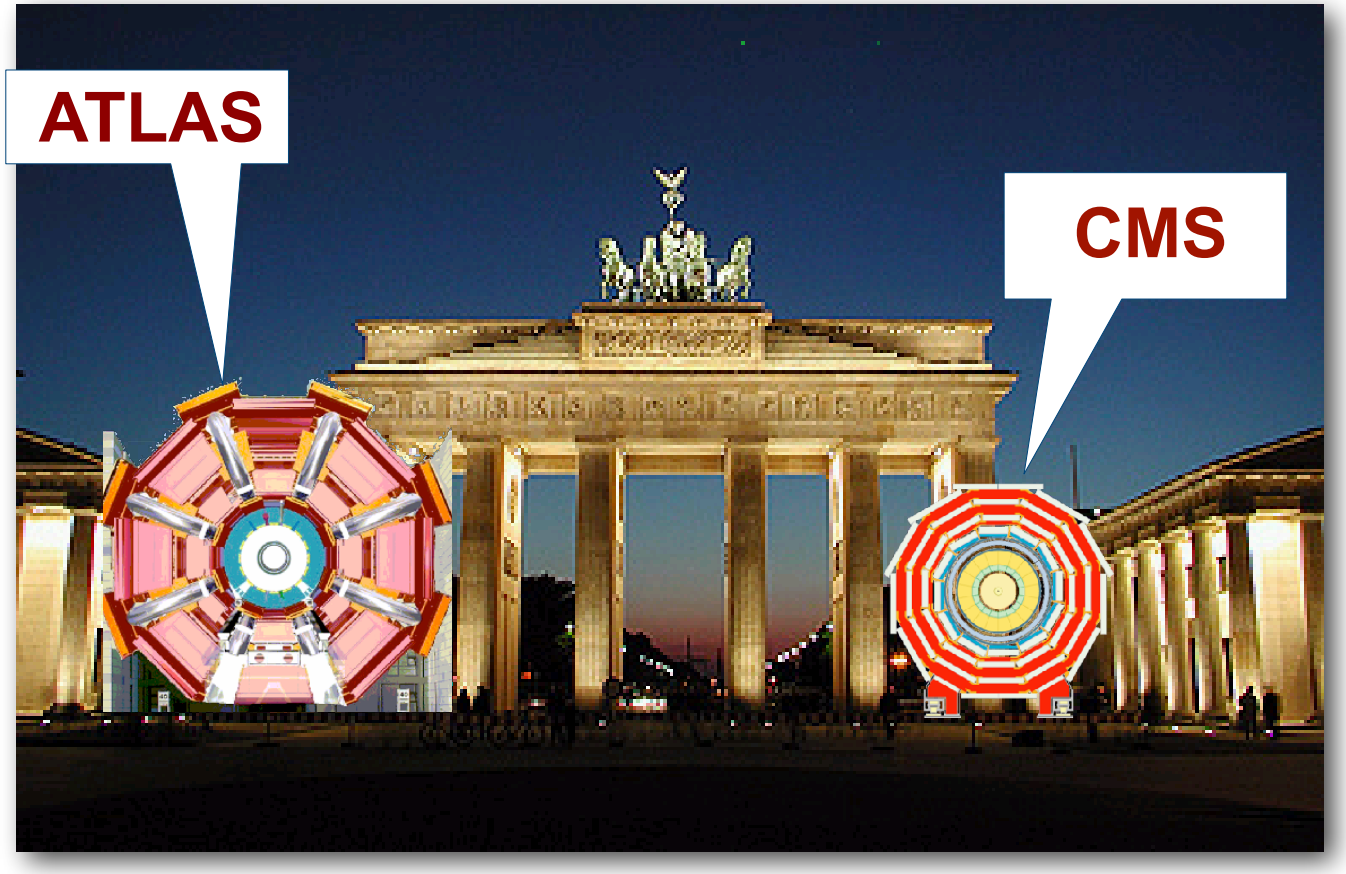
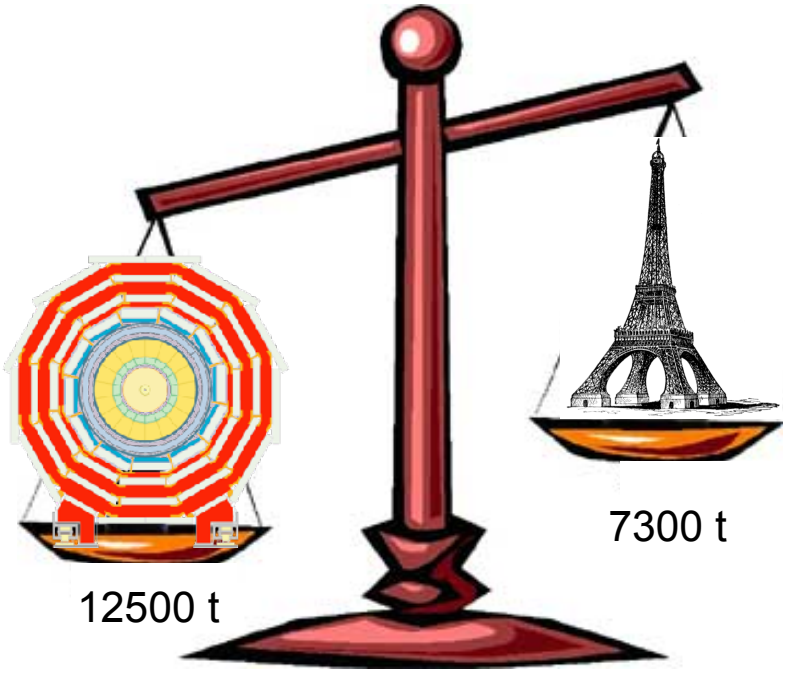


Foto: CERN

Size and Weight



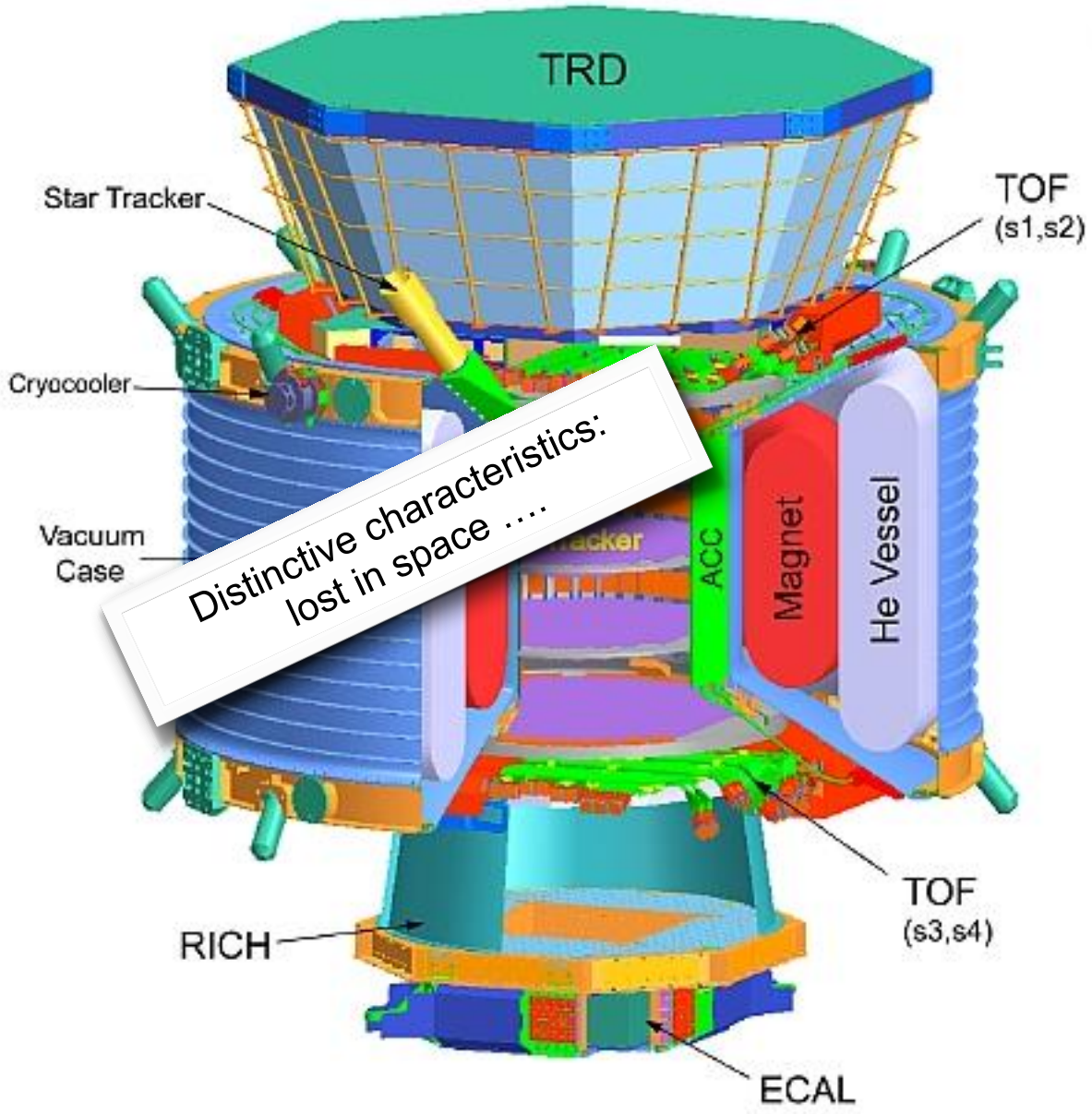
Brandenburger Tor in Berlin



CMS is 65% heavier than the Eiffel tower

AMS@ISS

Weight: 6700 kg
Length: 6 m
Diameter: 6 m
Solenoid-Field: 1.5 T



Distinctive characteristics:
lost in space ….

picture: AMS collaboration

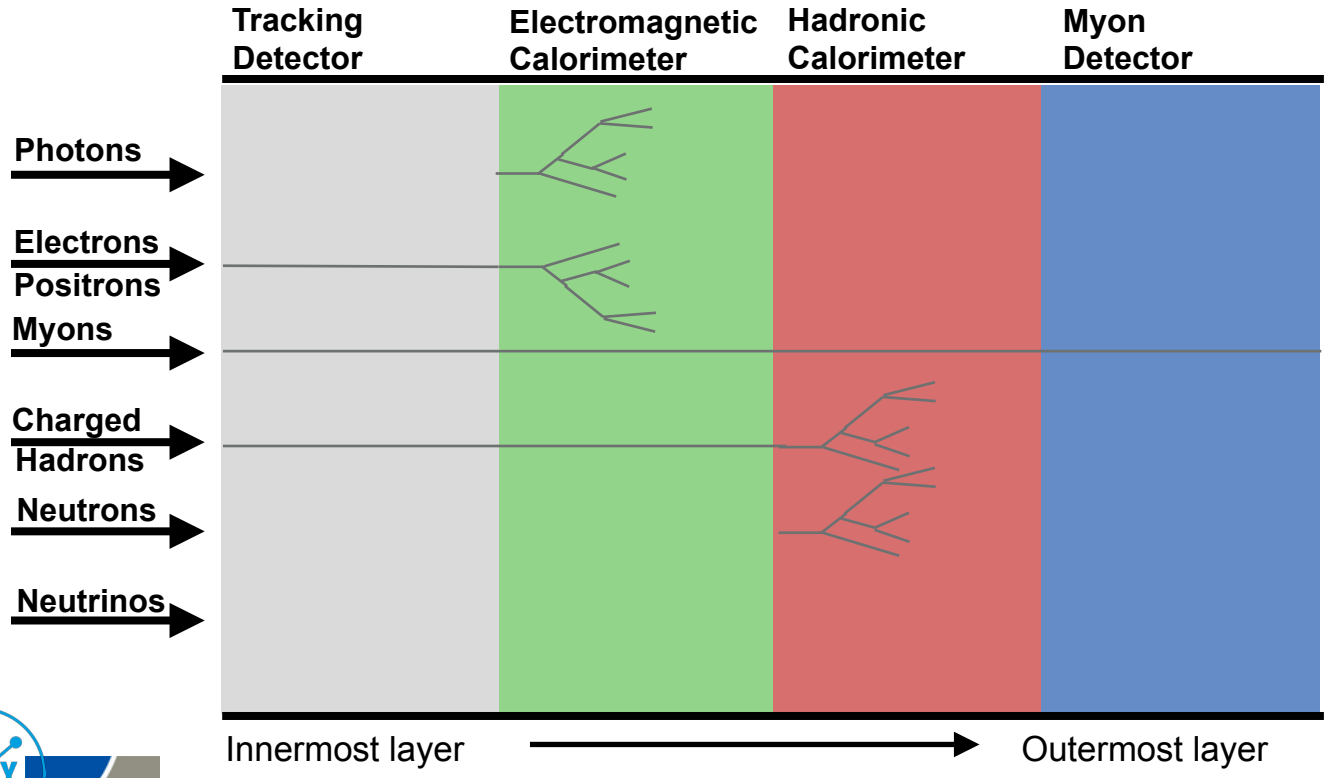
Icecube Experiment

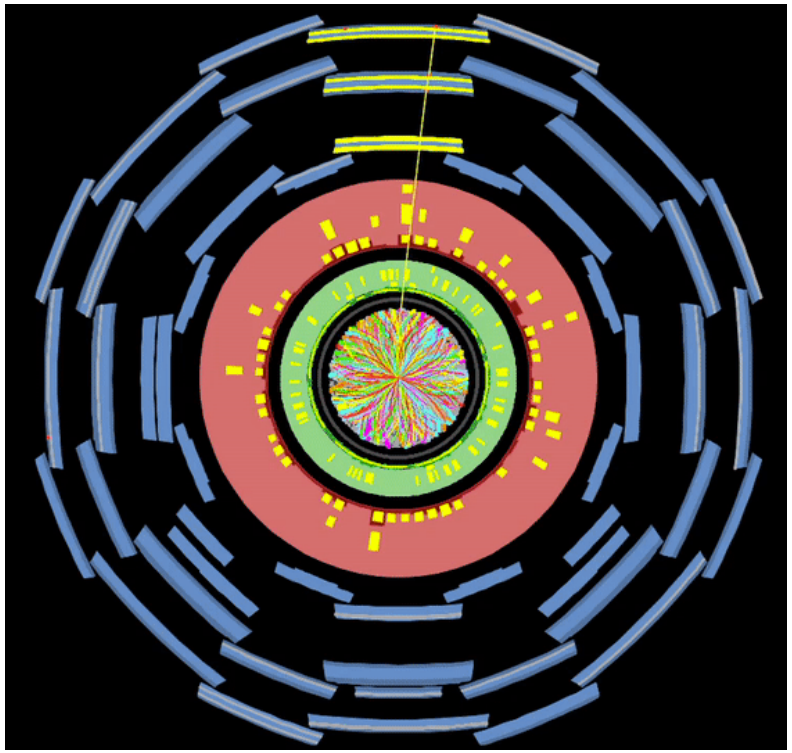
Example: ATLAS at CERN

Full movie: ATLAS experiment - Episode 2 - The Particles Strike Back
http://cds.cern.ch/record/1096390?ln=en

Particle Physics Detectors

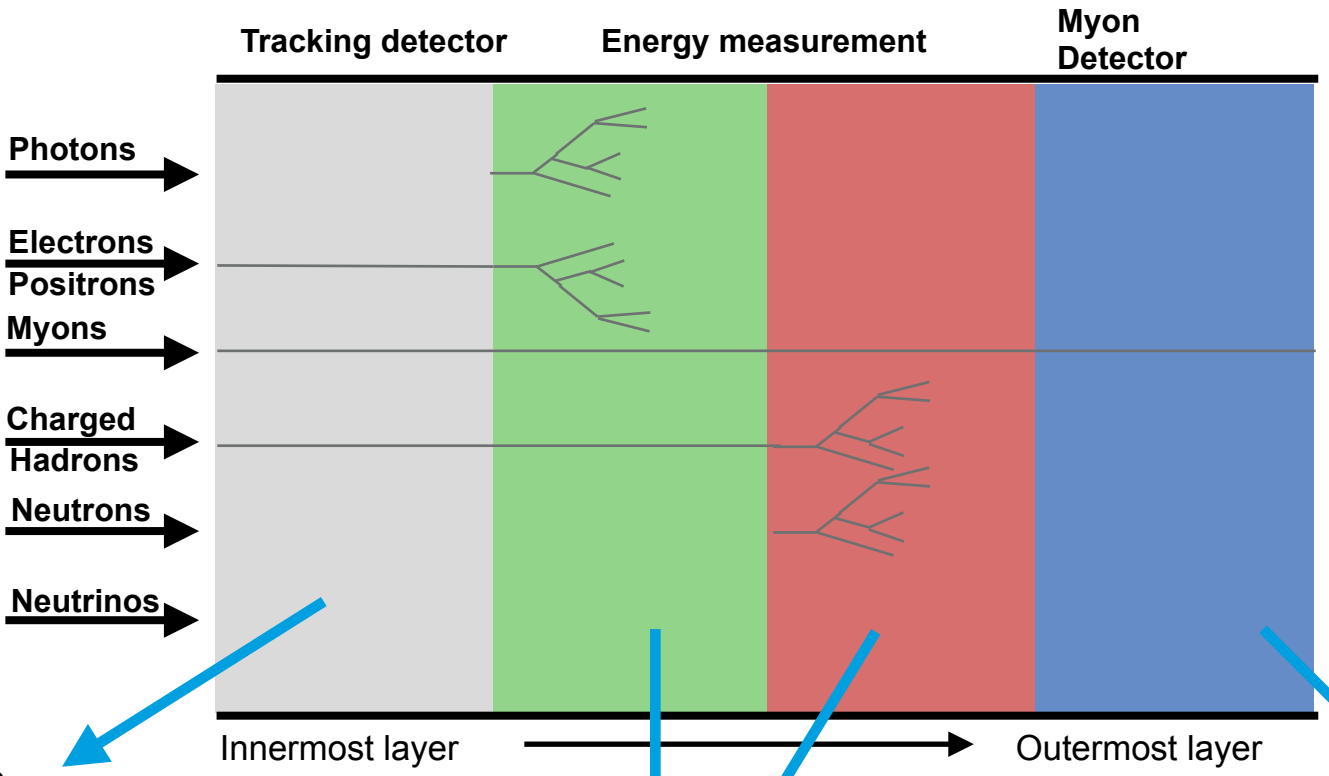
- There is not one type of detector which provides all measurements we need -> “Onion” concept -> different systems taking care of certain measurement
- Detection of collision production within the detector volume
  - resulting in signals (mostly) due to electro-magnetic interactions





25 m

Particle Physics Detectors



Tracking detectors

- Silicon detectors:
  - pixel
  - strip
- Gas detectors
  - wire chambers
  - time projection chambers
  - ….

Calorimeter

- Electromagnetic cal
- Hadronic cal

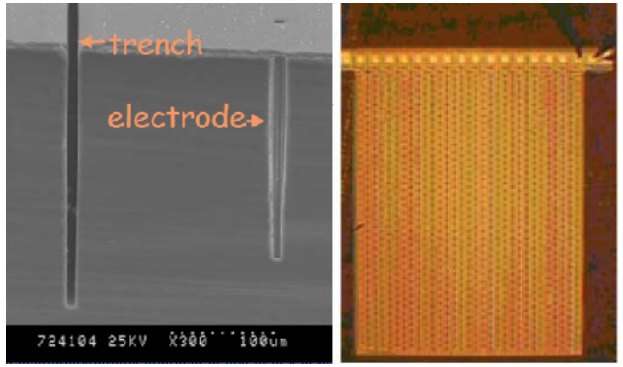
- Homogeneous
- Sampling

Muon detectors
= outside tracker

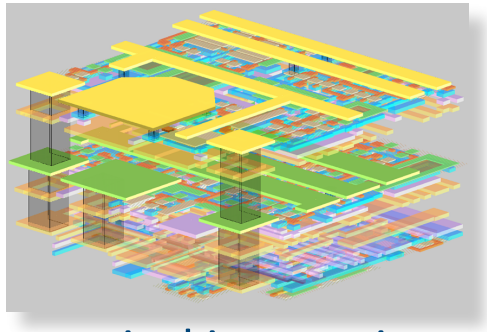
- Gas detectors
  - Wire chambers
  - …

HEP Detector R&D

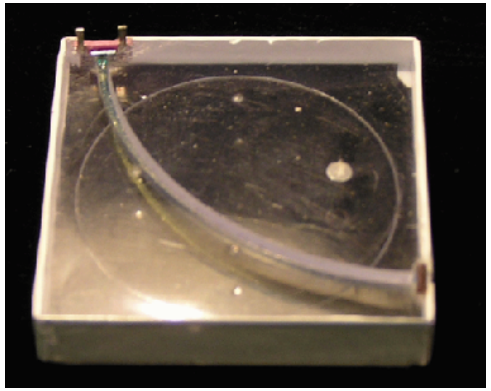
- Many different new or advanced detector technologies are under investigation:
  - radiation hard silicon sensors (x10 of LHC)
  - new pixel sensor technologies (planar, 3D sensors, diamond, CMOS!!)
  - new silicon strip technologies
  - silicon photomultipliers (SiPM)
  - micro-pattern gas detectors
  - heavy fibres, new scintillating crystals
  - new diamond devices for luminosity monitoring,
  - use of quartz plates in calorimetry
  - high resolution calorimetry (EM and Hadronic; PFA, analog vs. digital ….)
  - optimal detector geometry
  - magnetic field configurations...

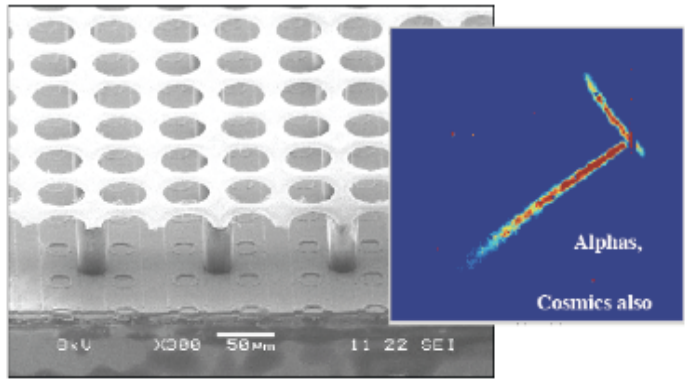


3D sensors



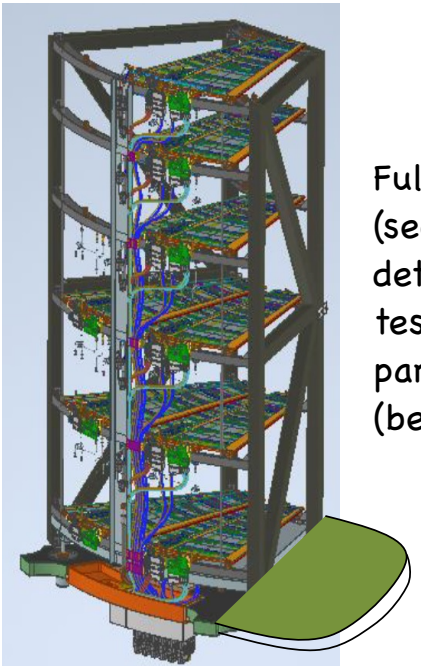
vertical integration



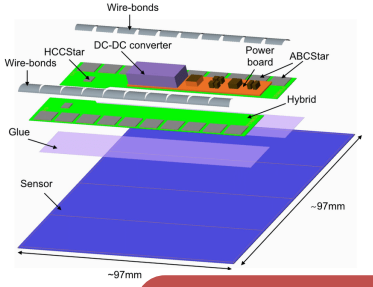


- Extensive amount of studies of all this new technologies to qualify them
  - Opportunities for master and PhD theses

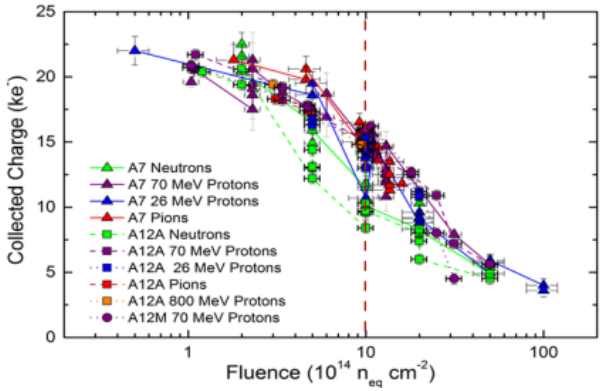
Detector Development Cycle



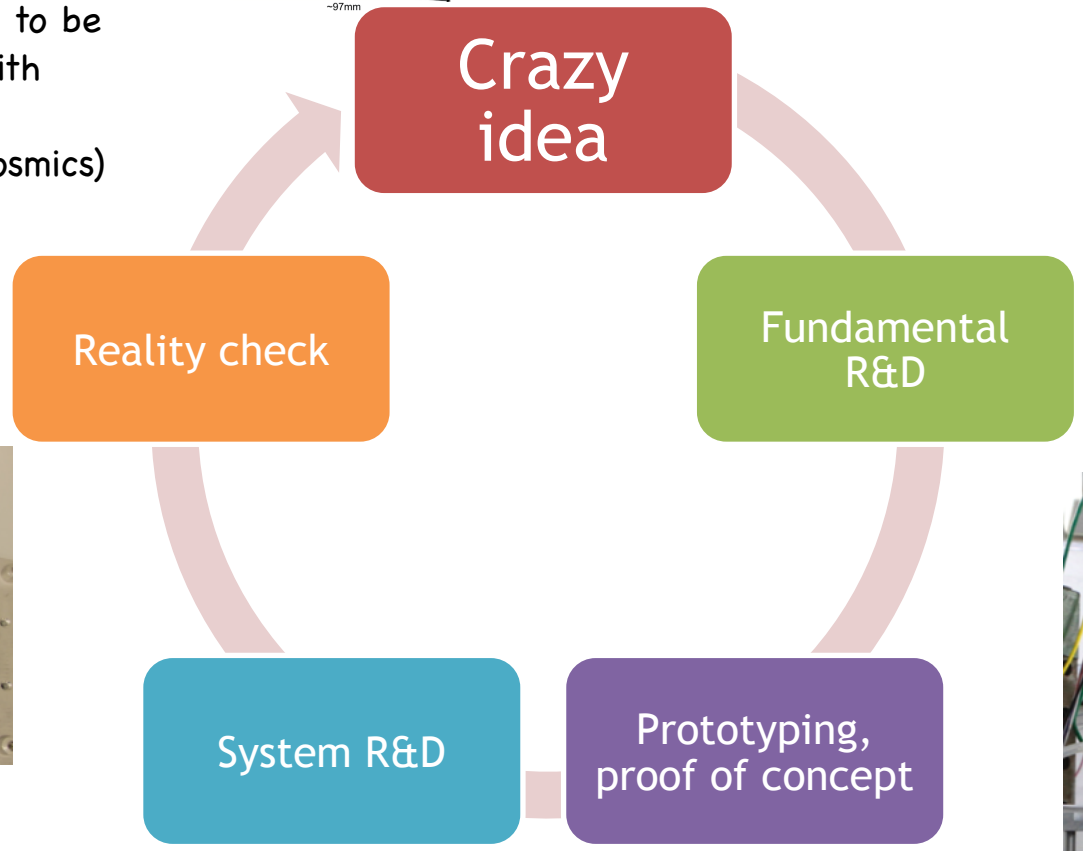
Full system (segment of detector) to be tested with particles (beam, cosmics)

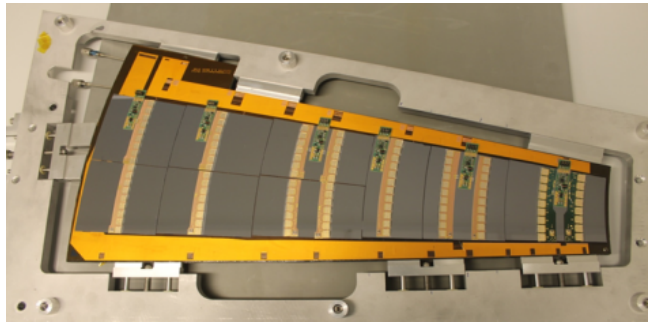


Crazy-idea-detector: use glue to build the detector….

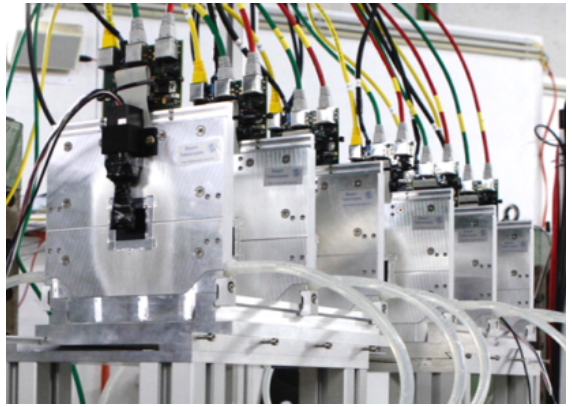


Does the crazy-idea-detector "see" passing particles





Towards large-size systems incl. cooling, powering, monitoring ….



Can we build a small-size detector out of it ? Test with "real" particles!

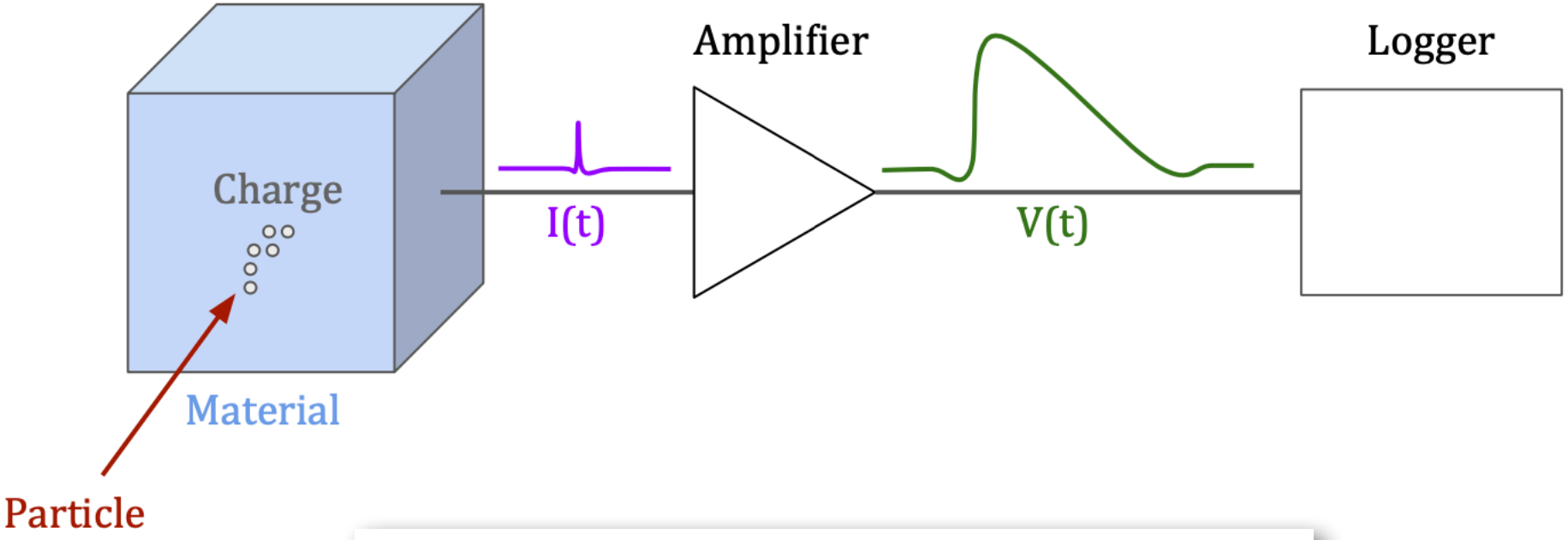
II. The Basics of All Detection Processes:

Interactions with Matter

Analogy

- Planes leave tracks in sky under certain conditions ….

Basic Detection Principle

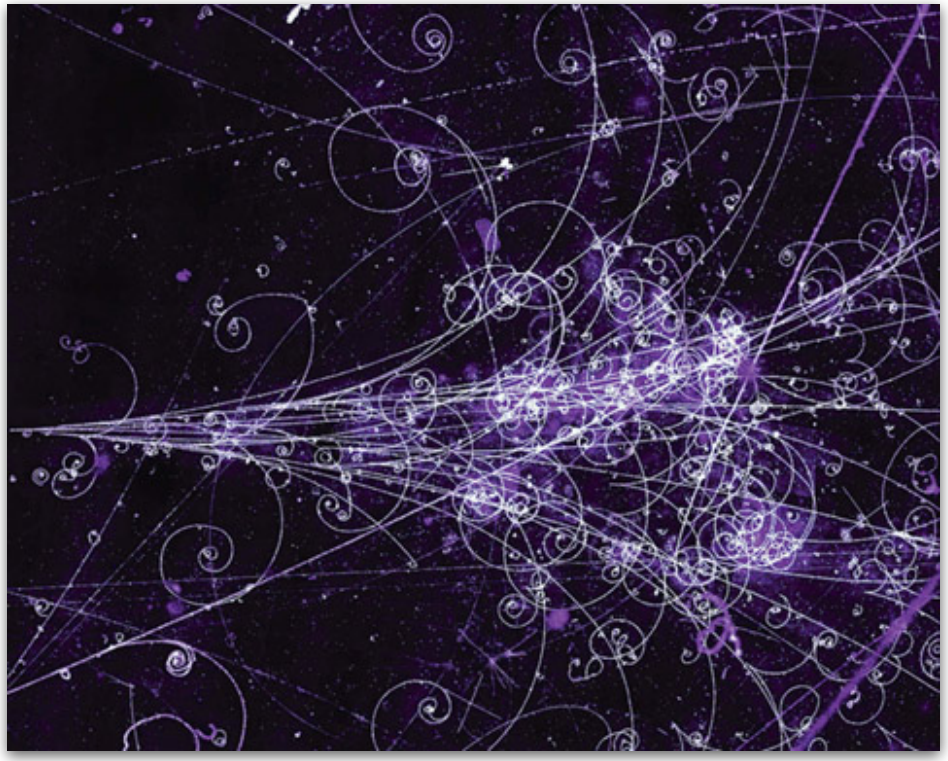


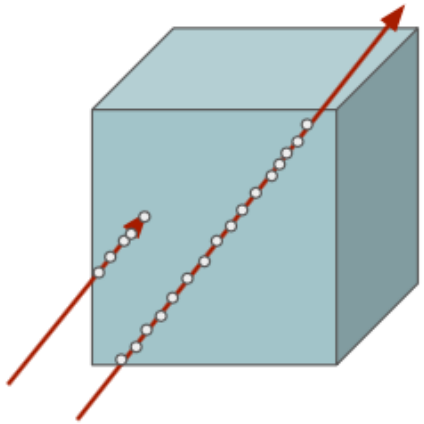
To interpret the result, we need to know **how particles interact with matter**. So that's where we start.

Interactions of charged particles

Charged Particles

- For charged particles the electromagnetic interaction is dominating
- Charged particles penetrating matter can initiate the following processes:
  - Ionisation of atoms
  - Excitation of atoms
  - Bremsstrahlung (only relevant for electrons and positrons)
  - Cherenkov radiation
  - Transition radiation

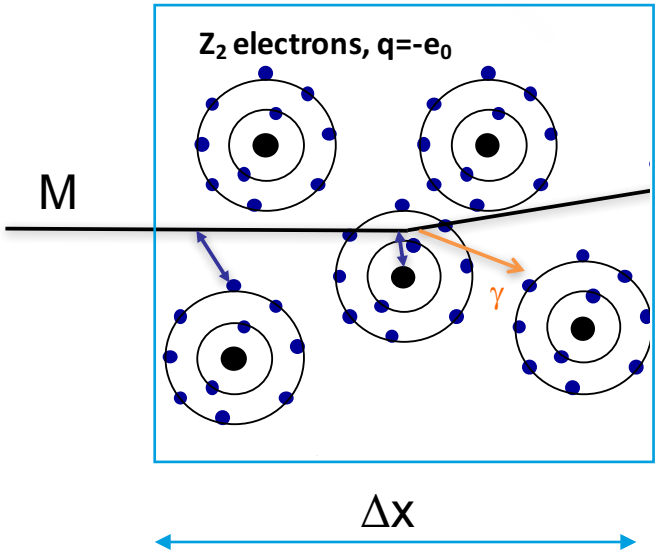




- All these processes **cause energy loss of the penetrating particles**.
- The relative contribution of these various processes to the total energy loss depends on the kinetic energy of the particle, the detector material, etc.

Interaction of Charged Particles

- A charged particle traverses material of thickness Δx
- Upon exiting, the energy of the particle has decreased by ΔE
- The basis of ~all particle detectors: **collect ΔE from the material**



- The deposited energy ΔE probably depends on:
  - Δx
  - Material density ρ
  - Particle mass M and charge ze
  - Particle kinetic energy T and velocity β

The key to detector design is understanding **dE/dx**

$$\left[\left\langle\frac{dE}{dx}\right\rangle\right] = \frac{\text{MeV}}{\text{cm}}$$ *Linear* stopping power

or

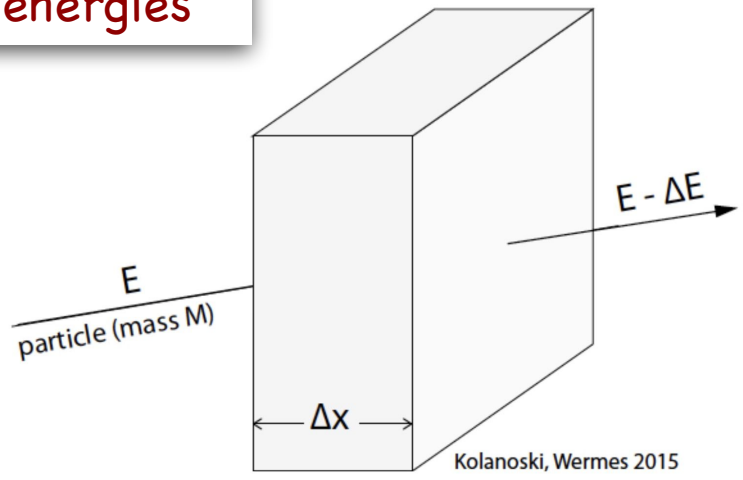
$$\left[\left\langle\frac{dE}{d\tilde{x}}\right\rangle\right] = \frac{\text{MeV}}{\text{gcm}^{-2}}$$ *Mass* stopping power

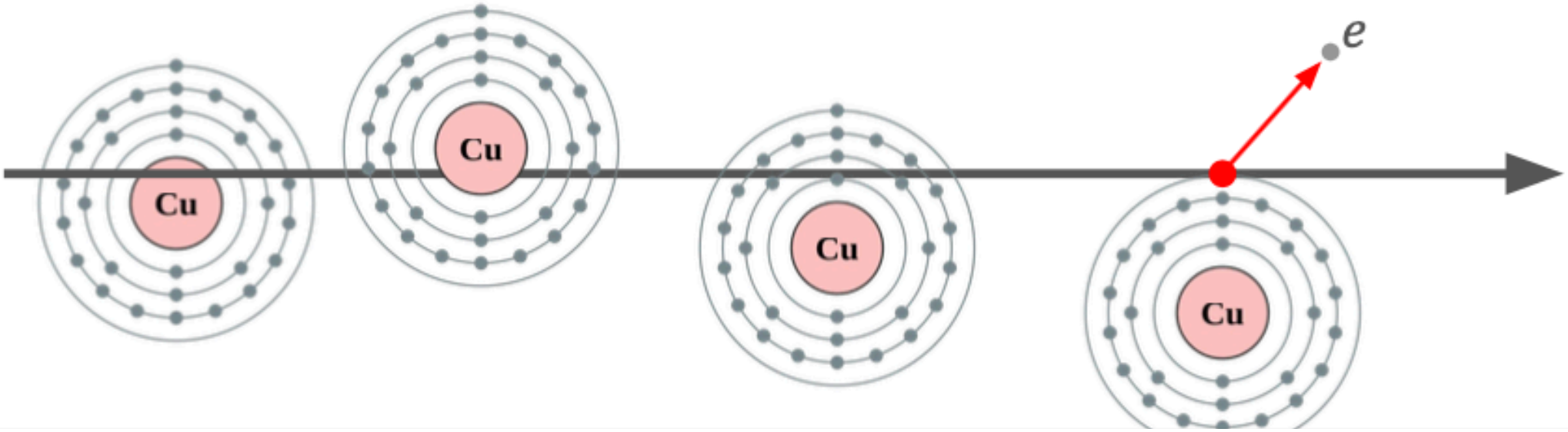
$$\tilde{x} = \rho x$$

Ionisation

The primary contributor to dE/dx at typical energies

- Particle can collide with **atomic electron** (*EM* interaction)
- If enough energy is transferred, the electron escapes, **ionising** the atom and causing small $-dE$
  - can also excite the atom, if transferred energy is small
- In general, this happens frequently, with small energy transfers (<100eV), so energy loss is ~continuous





Interactions of "heavy" Particles with Matter

- Mean energy loss is described by the Bethe-Bloch formula

$$-\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

Material; is the fraction of nucleons that are protons

Properties of the **particle**

W_{max} Maximum kinetic energy which can be transferred to the electron in a single collision

I^2 Excitation energy

$\frac{\delta}{2}$ Density term due to polarisation: leads to saturation at higher energies

$\frac{C}{Z}$ Shell correction term, only relevant at lower energies

$$2\pi N_A r_e^2 m_e c^2 = 0.1535 \mathrm{MeV cm^2/g}$$

r_e : classical electron radius

m_e : electron mass

N_A : Avogadro's number

I : mean excitation potential

Z : atomic number of absorbing material

A : atomic weight of absorbing material

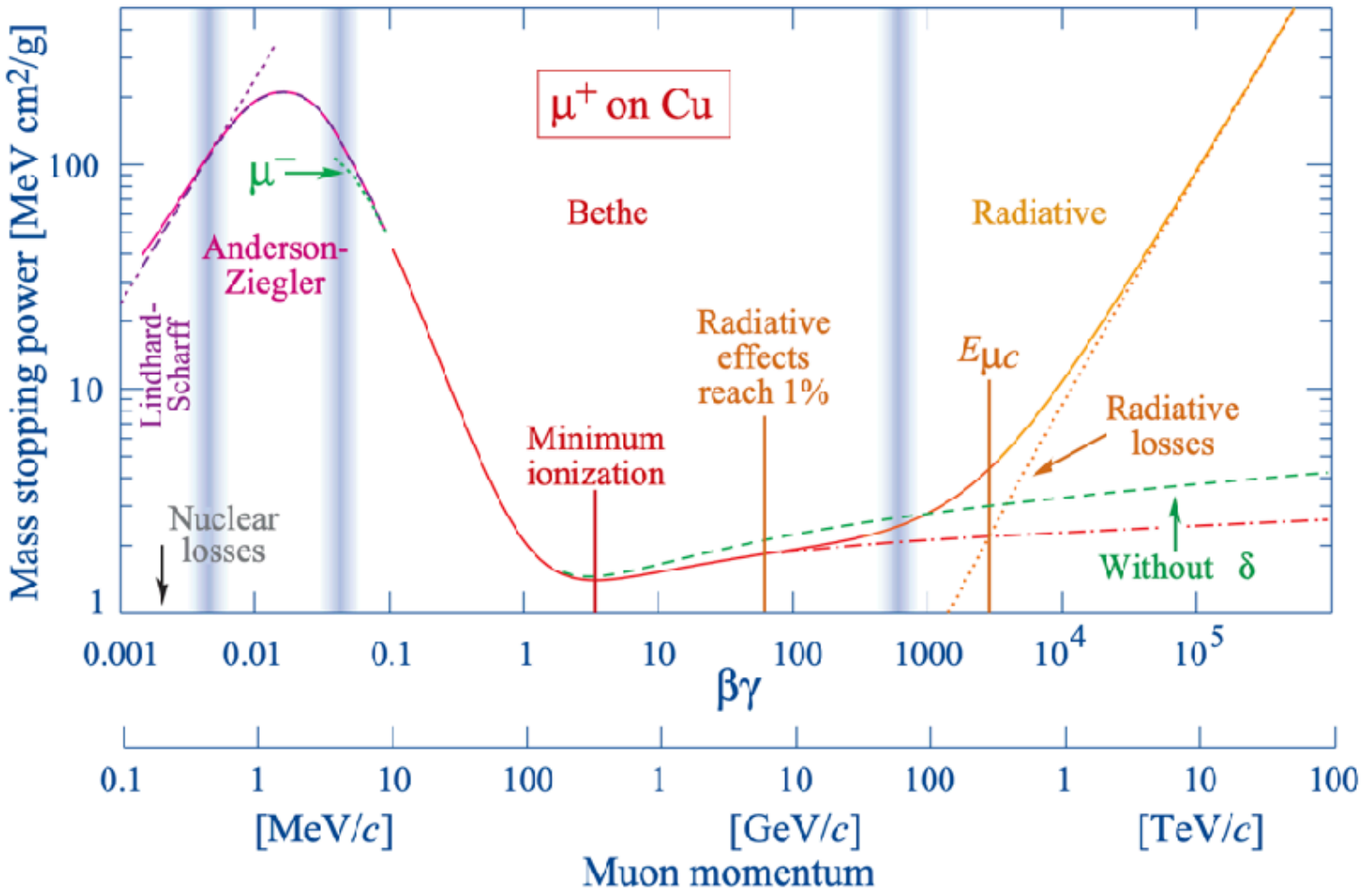
ρ : density of absorbing material

z : charge of incident particle in units of e

β : v/c of the incident particle

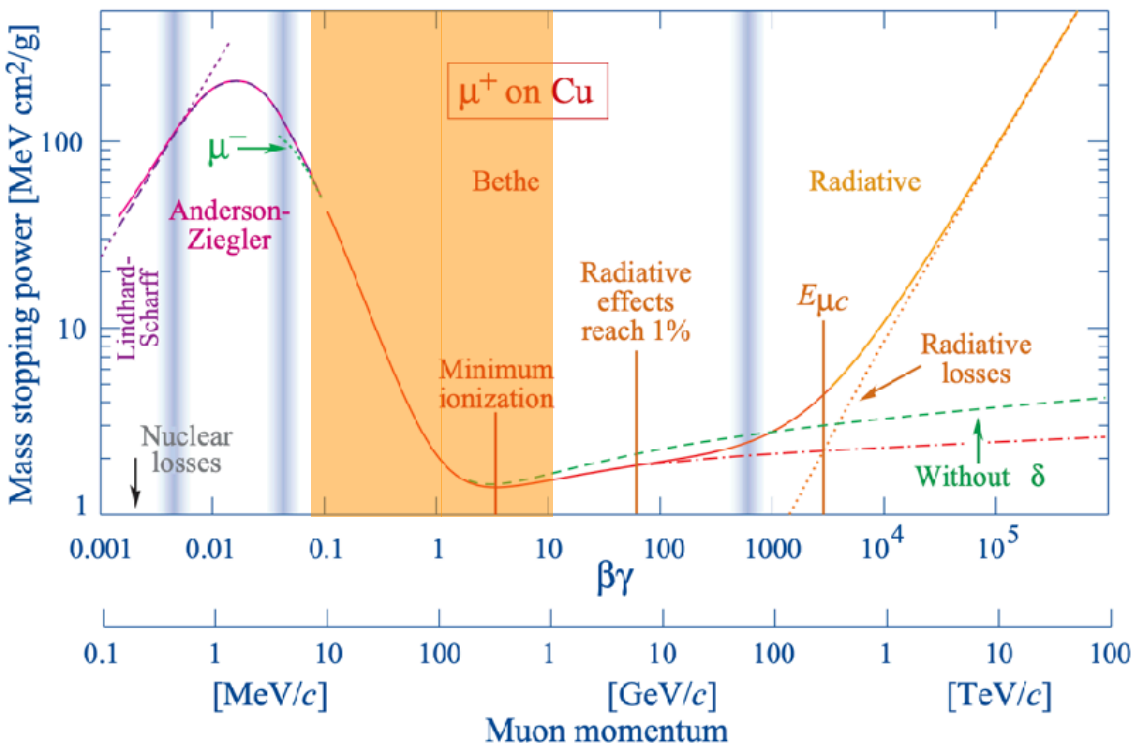
γ : $1/\sqrt{1-\beta^2}$

Understanding Bethe Bloch



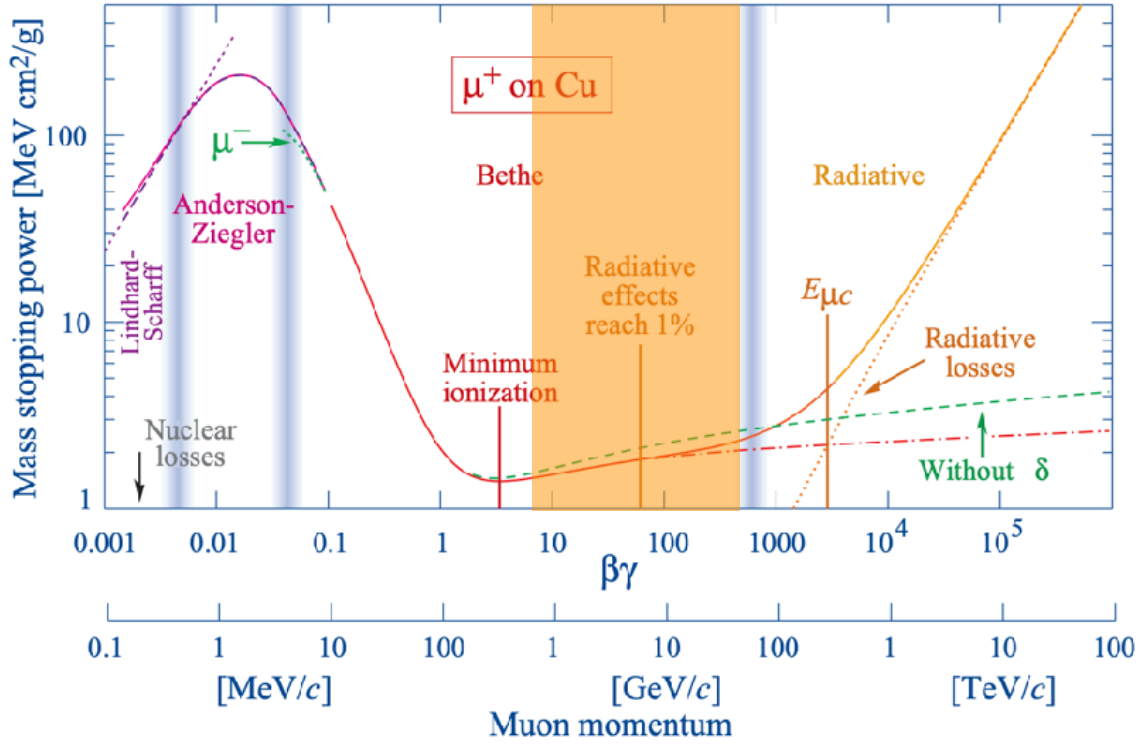
Understanding Bethe Bloch

- Kinematic term (βγ~0.1-1.0):
  - dE/dx ~ β^{-2}
  - slower particles feel electric force of atomic electron for longer time
- Minimum ionising particles (βγ~1.0-10.0)
  - Most physics tracks happen in this range
  - Semi-classical intuition: after $\beta\gamma$~1, the track no longer gets "faster" as T increases, so there's a minimum time spent near atomic electrons

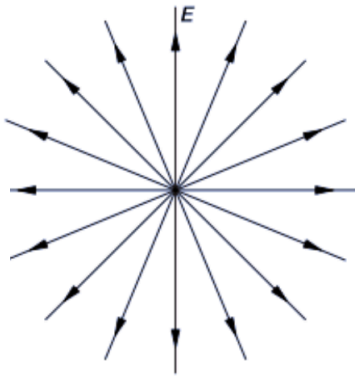


Understanding Bethe Bloch

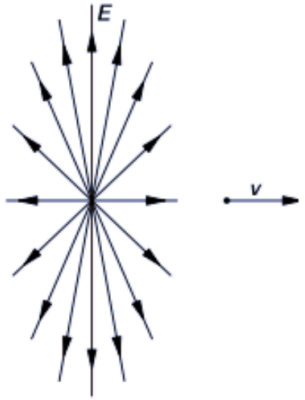
- Rise after βγ~5:
  - dE/dx~ln(βγ)2
  - due to more energy transfer from rare high-dE collisions
  - logarithmic rise due to lateral extension of electric field due to Lorentz transform Ey→γEy



v=0



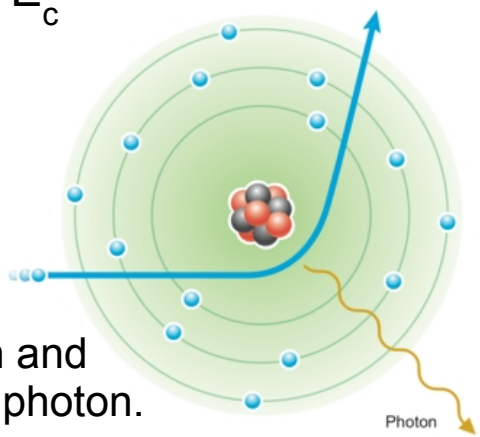
v=0.9c



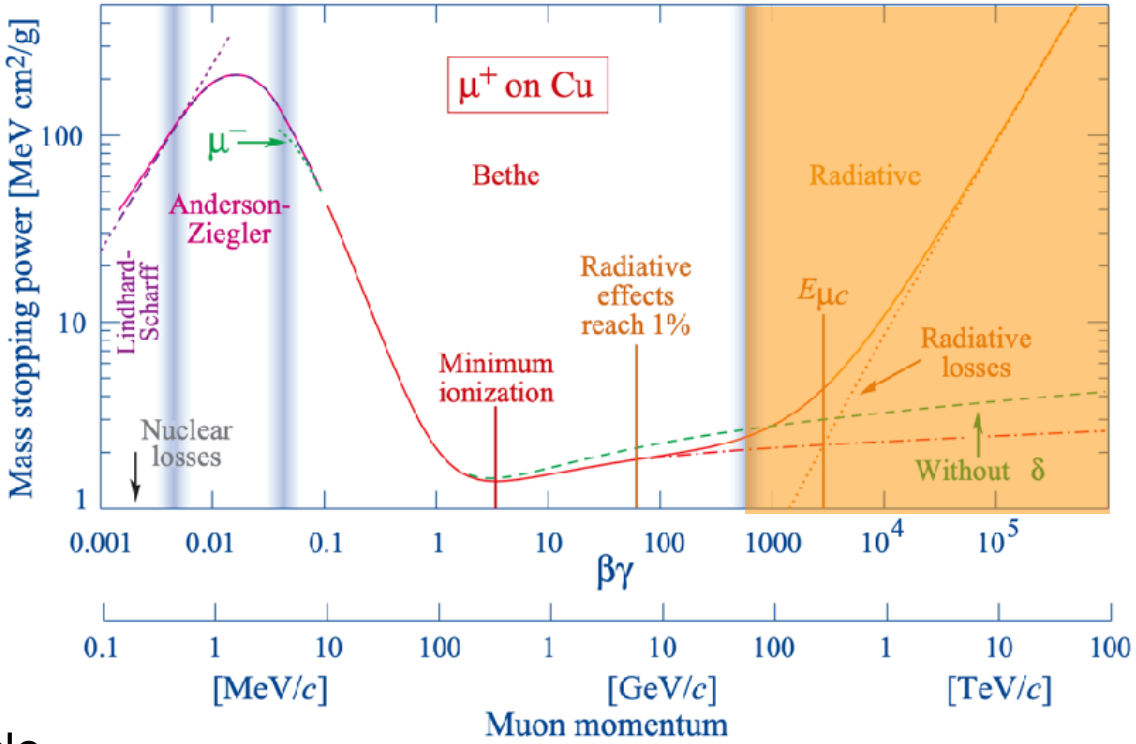
https://www.feynmanlectures.caltech.edu/II_26.html

Understanding Bethe Bloch - large βγ

- dE/dx diverges at large E
  - Radiative losses equal ionisation losses at the critical energy E_c



Incident electron and Bremsstrahlung photon.



- Bremsstrahlung: photon emission by a charged particle accelerated in Coulomb field of another charged particle (nucleus)
  - due to conservation of energy (with $h\nu = dE$)

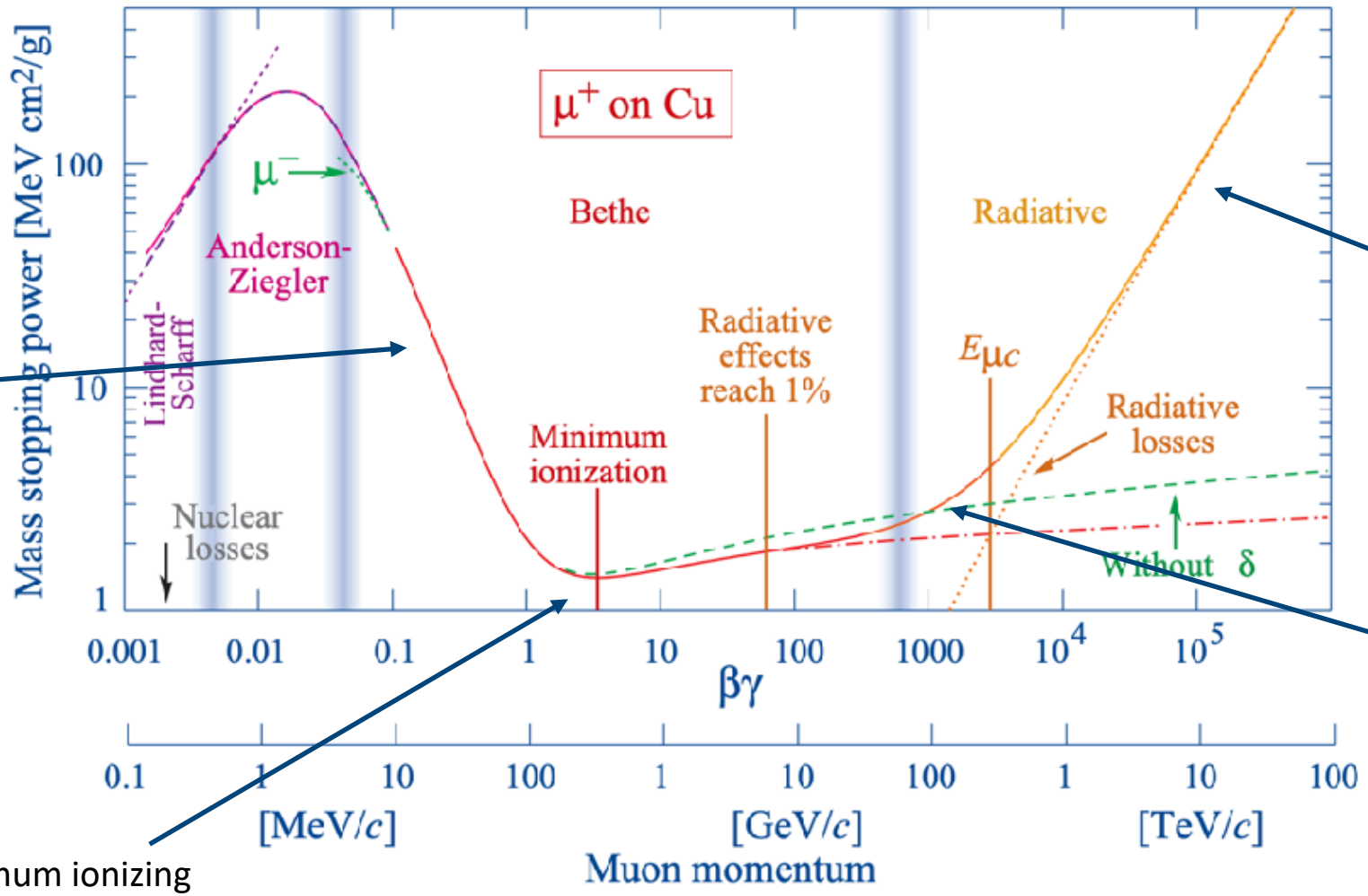
$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{Z^2 E}{m^2}$$

- Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV).

Summary Bethe Bloch

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"kinematic term"



Bremsstrahlung

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$$

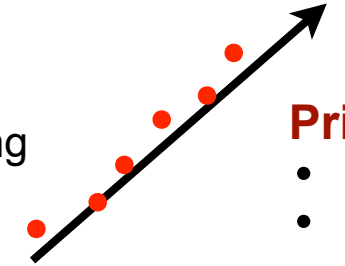
"relativistic rise"

"minimum ionizing particles" $\beta\gamma \approx 3\text{-}4$

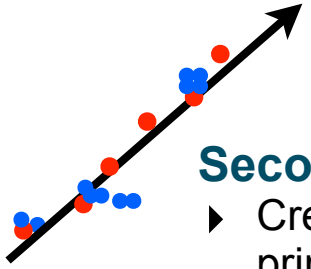
Plot: PDG, June 2018

A Closer Account of Energy Loss

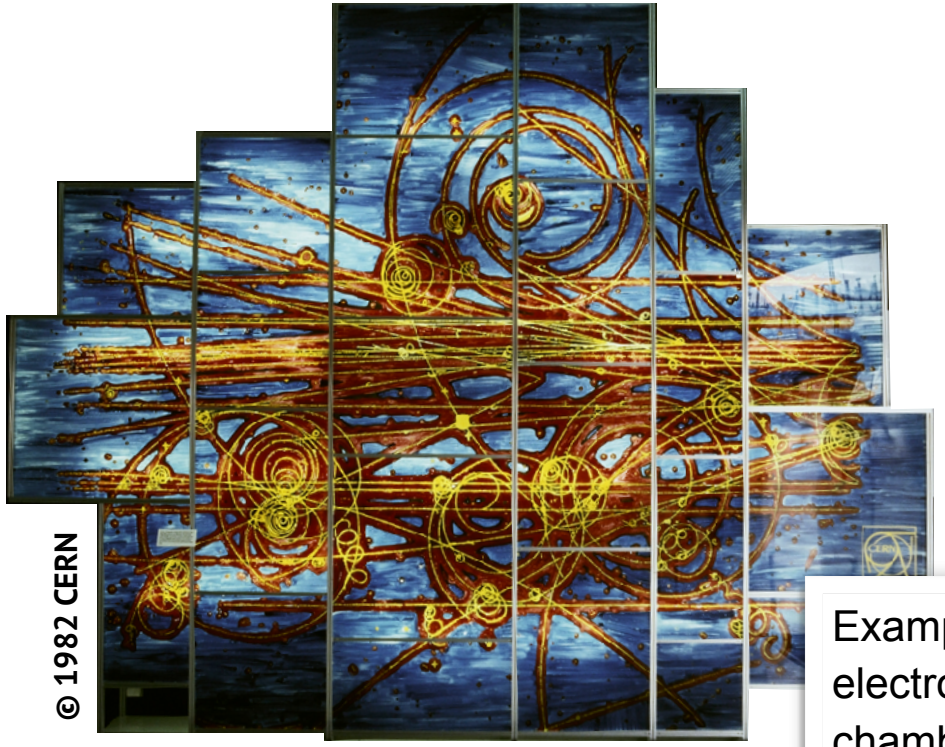
- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



Primary ionisation
- Poisson distributed
- Large fluctuations per reaction



Secondary ionisation
- Created by high energetic primary electrons
- sometime the energy is sufficient for a clear secondary track: δ-Electron



Example of a delta electron in a bubble chamber: visible path

Total ionisation = **primary ionisation** + **secondary ionisation**

Liquid hydrogen bubble chamber 1960 (~15cm).

Energy Loss in Thin Layers

- Bethe Bloch formula describes average energy loss
- Fluctuations about the mean value are significant and non-Gaussian
  - A broad maximum: collisions with little energy loss (more probable)
  - A long tail towards higher energy loss: few collisions with large energy loss T_{max}, δ-electrons.
    -> Most probable energy loss shifted to lowed values

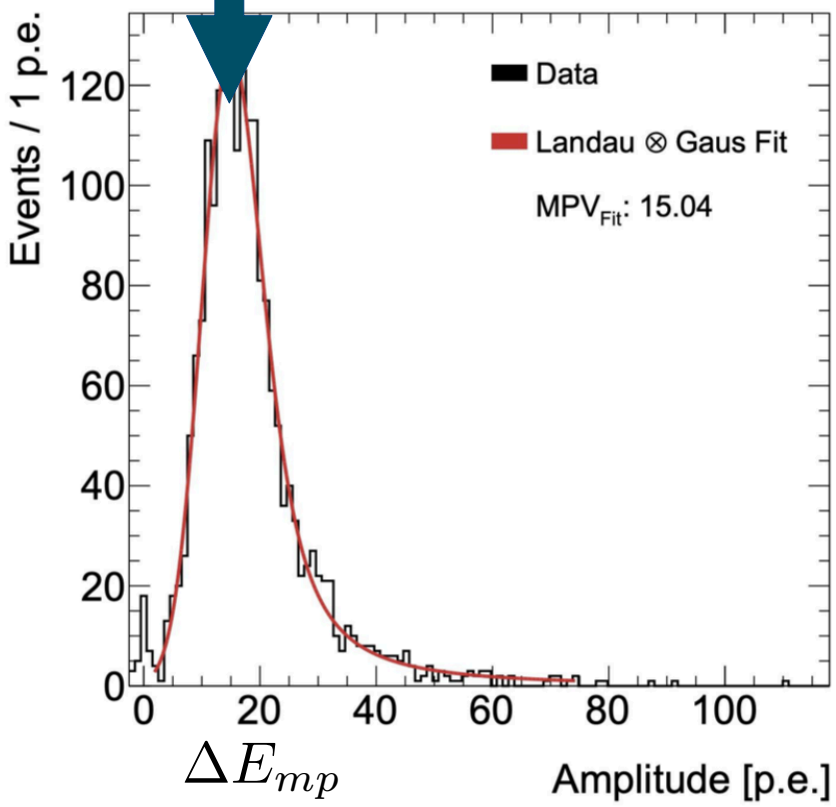
The Landau distribution is used in physics to describe the fluctuations in the energy loss of a charged particle passing through a thin layer of matter

$$P(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\lambda + e^{-\lambda})\right]$$

$$\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$$

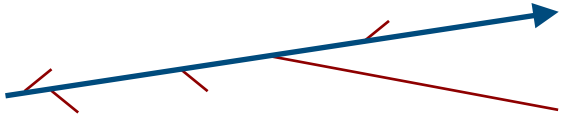
ξ is a material constant

most probable peak!

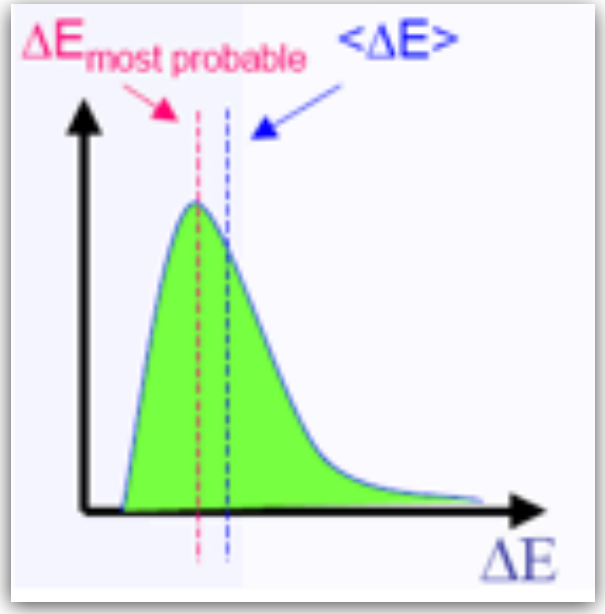


Landau Tails

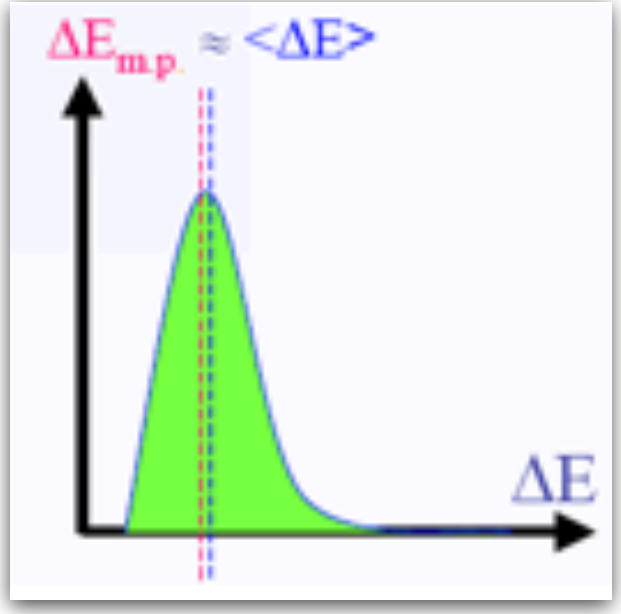
- Real detector measures the energy ΔE deposited in a layer of finite thickness δx
- For thin layers or low density materials
  - few collisions; some with high energy transfer



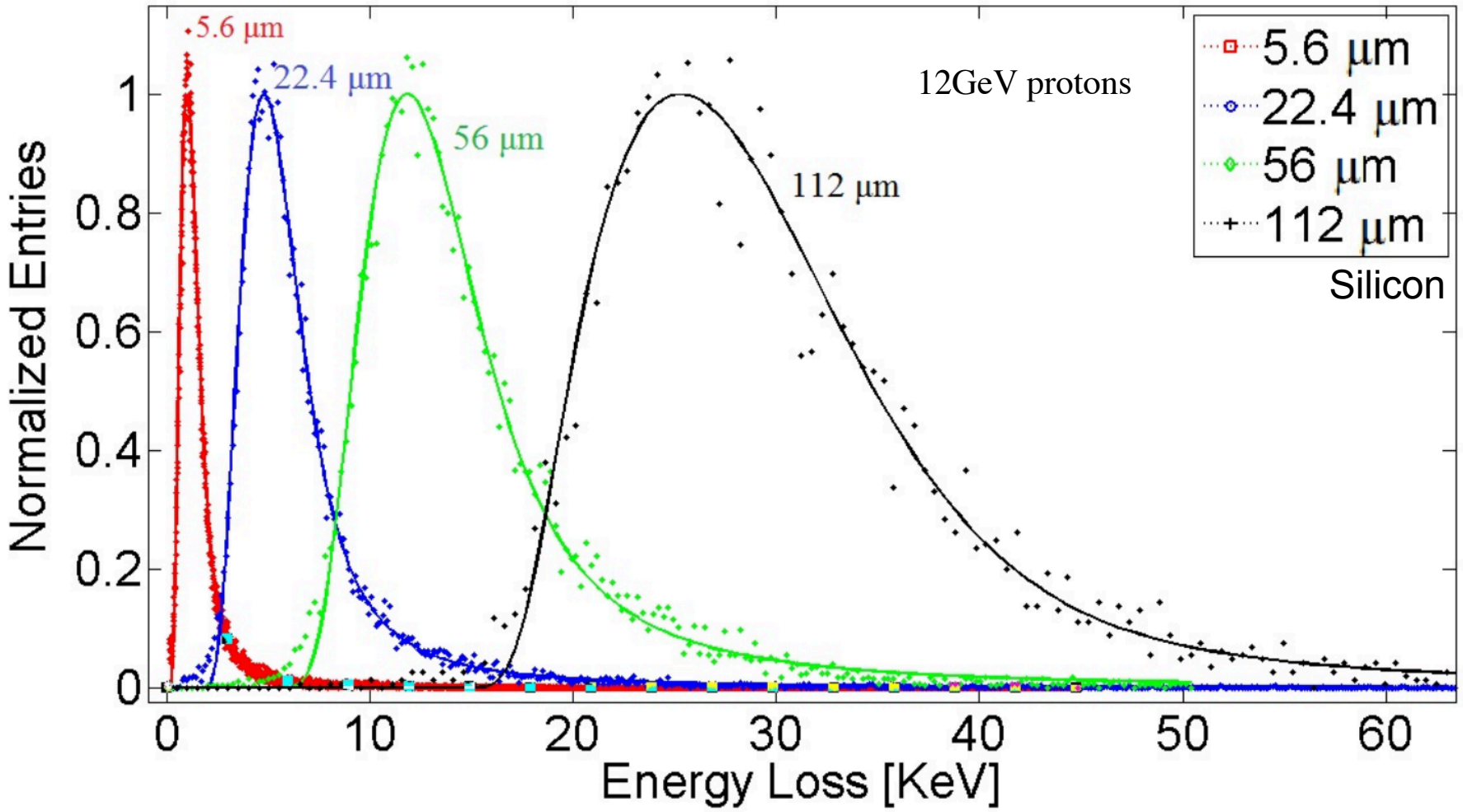
    - Energy loss distributions show large fluctuations towards high losses
    - Long Landau tails



- For thick layers and high density materials
  - Many collisions
  - Central limit theorem: distribution -> Gaussian



Landau at Different Thicknesses



2011 JINST 6 P06013

Radiation Length X_0

dE/dx for an **electron**

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

$$-\frac{dE}{dx} = \frac{E}{X_0} \rightarrow \boxed{E = E_0\, e^{-x/X_0}}$$

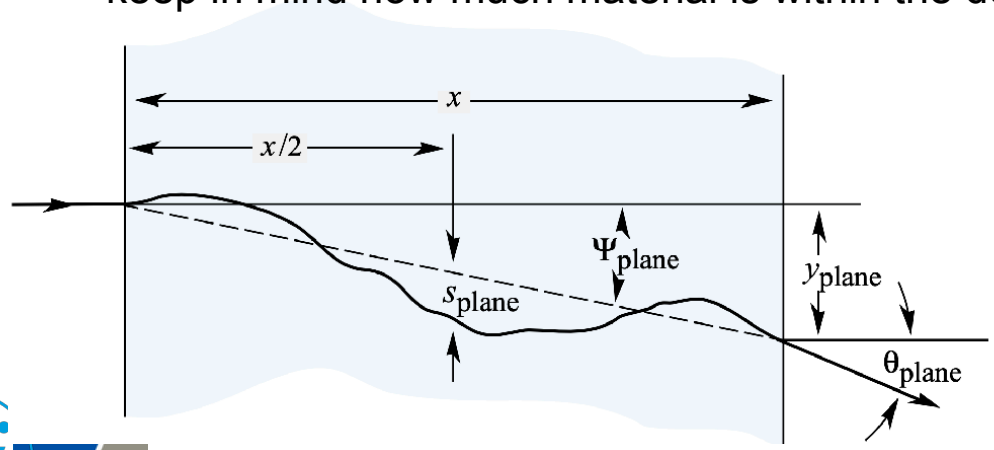
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Parameters only depending on material the electron is passing through.

Thickness of material an electron travels through until the energy is reduced by Bremsstrahlung to 1/e of its original energy

- The radiation length is also an important quantity in multiple scattering
- A very important number when building detectors, one always has to keep in mind how much material is within the detector volume

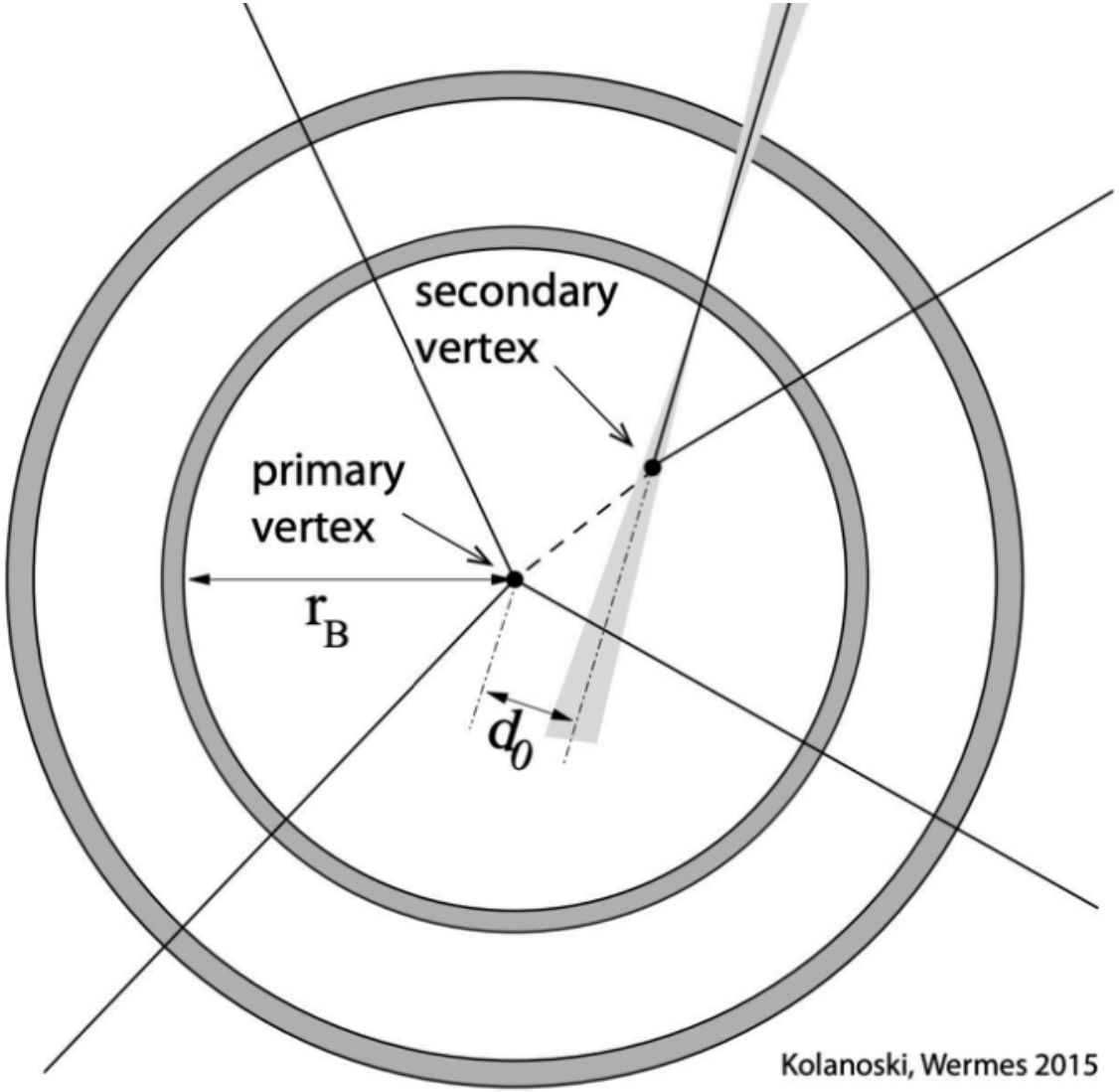
- Usually quoted in [g/cm²], typical values are:
  - Air: 36.66 g/cm² ->~ 300 m
  - Water: 36.08 g/cm² -> ~ 36 cm
  - Silicon: 21.82 g/cm² -> 9.4 cm
  - Aluminium: 24.01 g/cm² -> 8.9 cm
  - Tungsten: 6.76 g/cm² -> 0.35 cm



$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$$

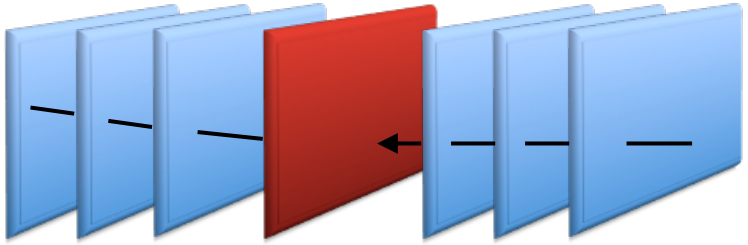
$$\theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

Consequence of Multiple

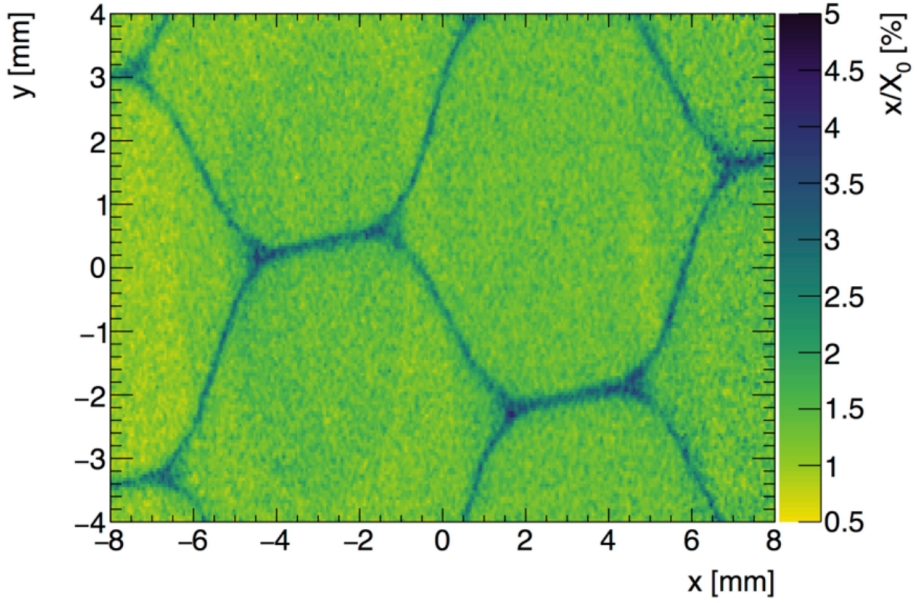


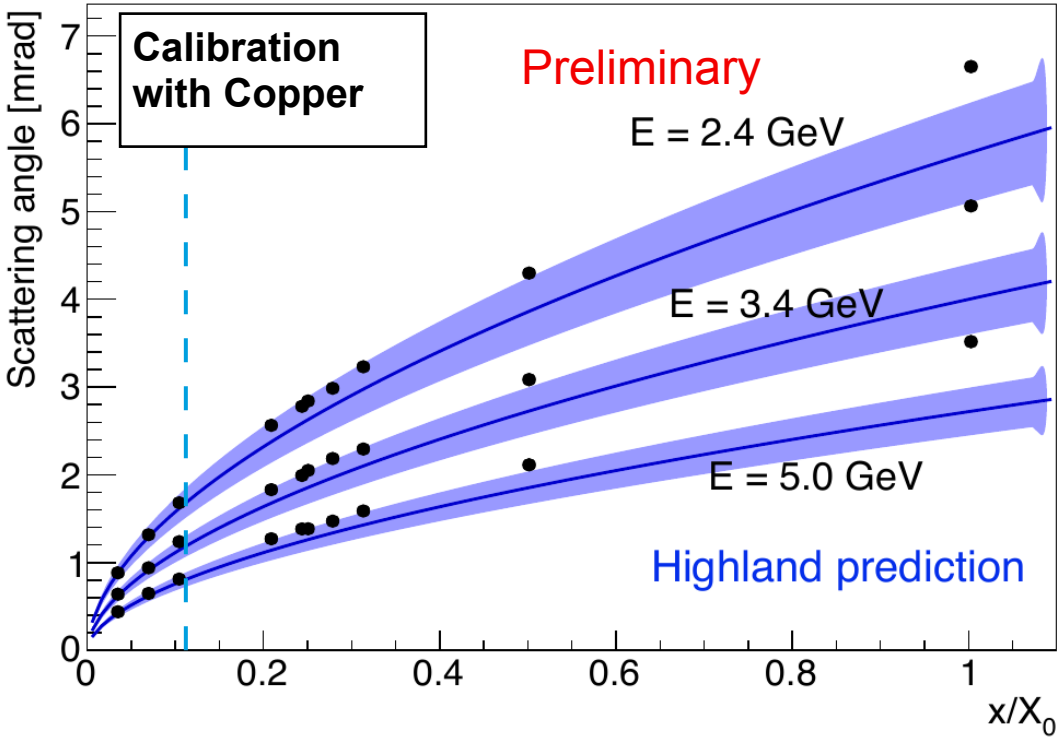
Using Multiple Scattering

- Possibility to provide *x/X_0 maps* of complex targets -> input for detector simulations
  - Currently only coarse information of modules available as radiation length for composite materials typically not available



Measuring kink angle

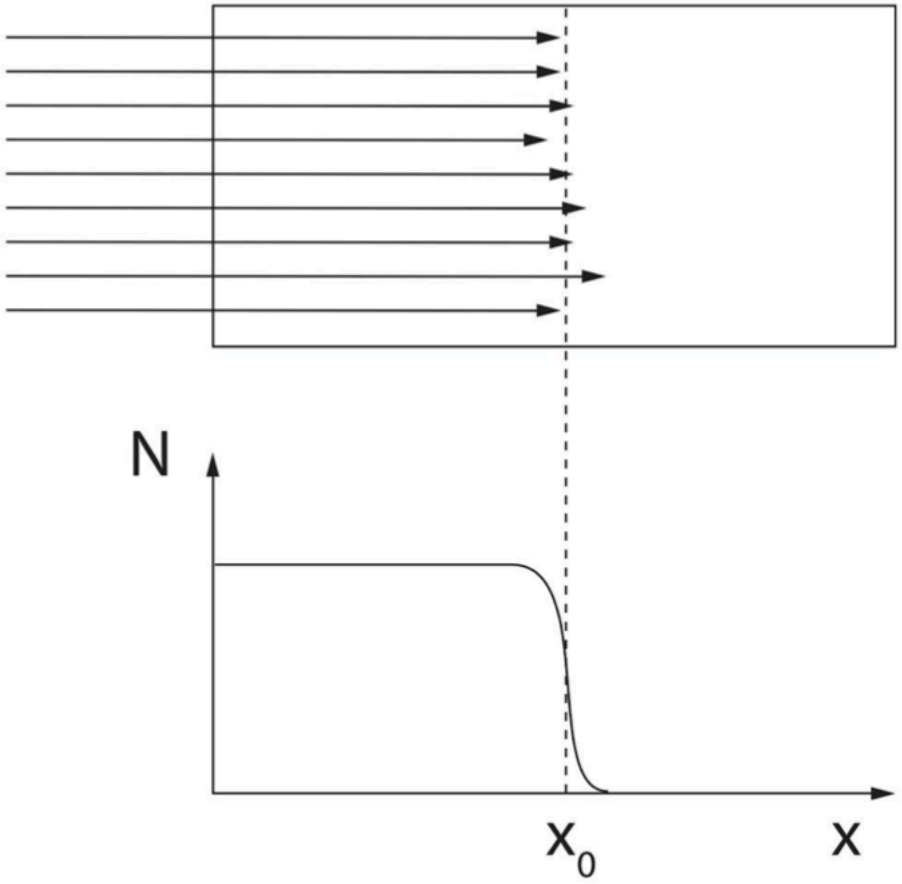




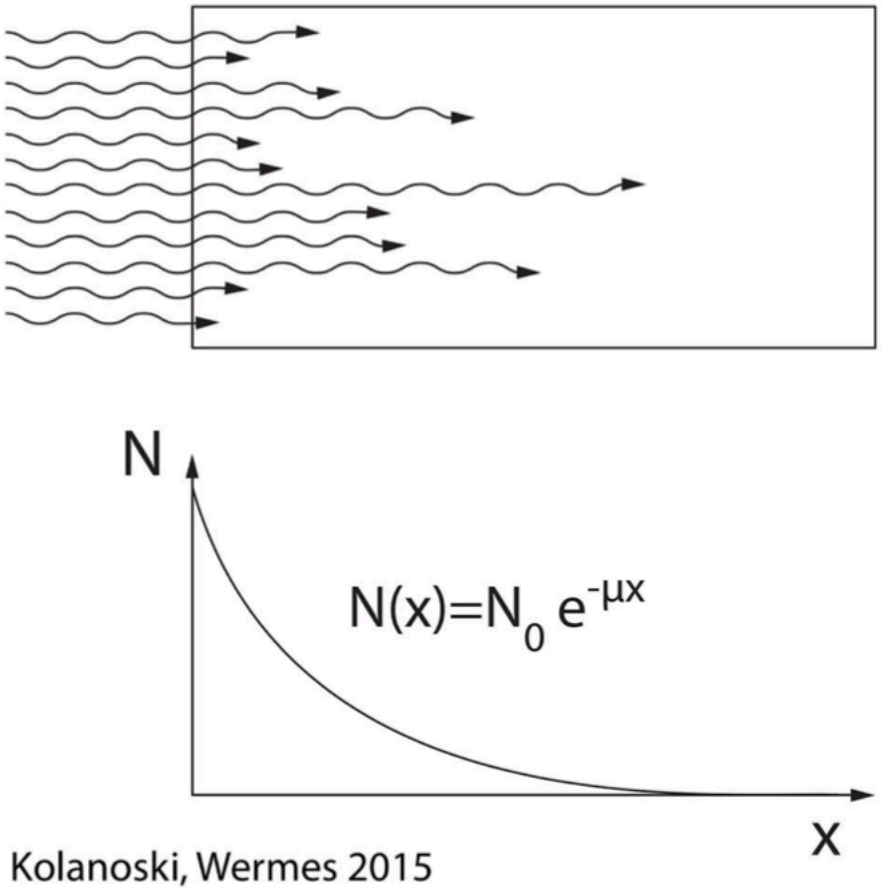
Interactions of Photons

Big Difference

Charged particles



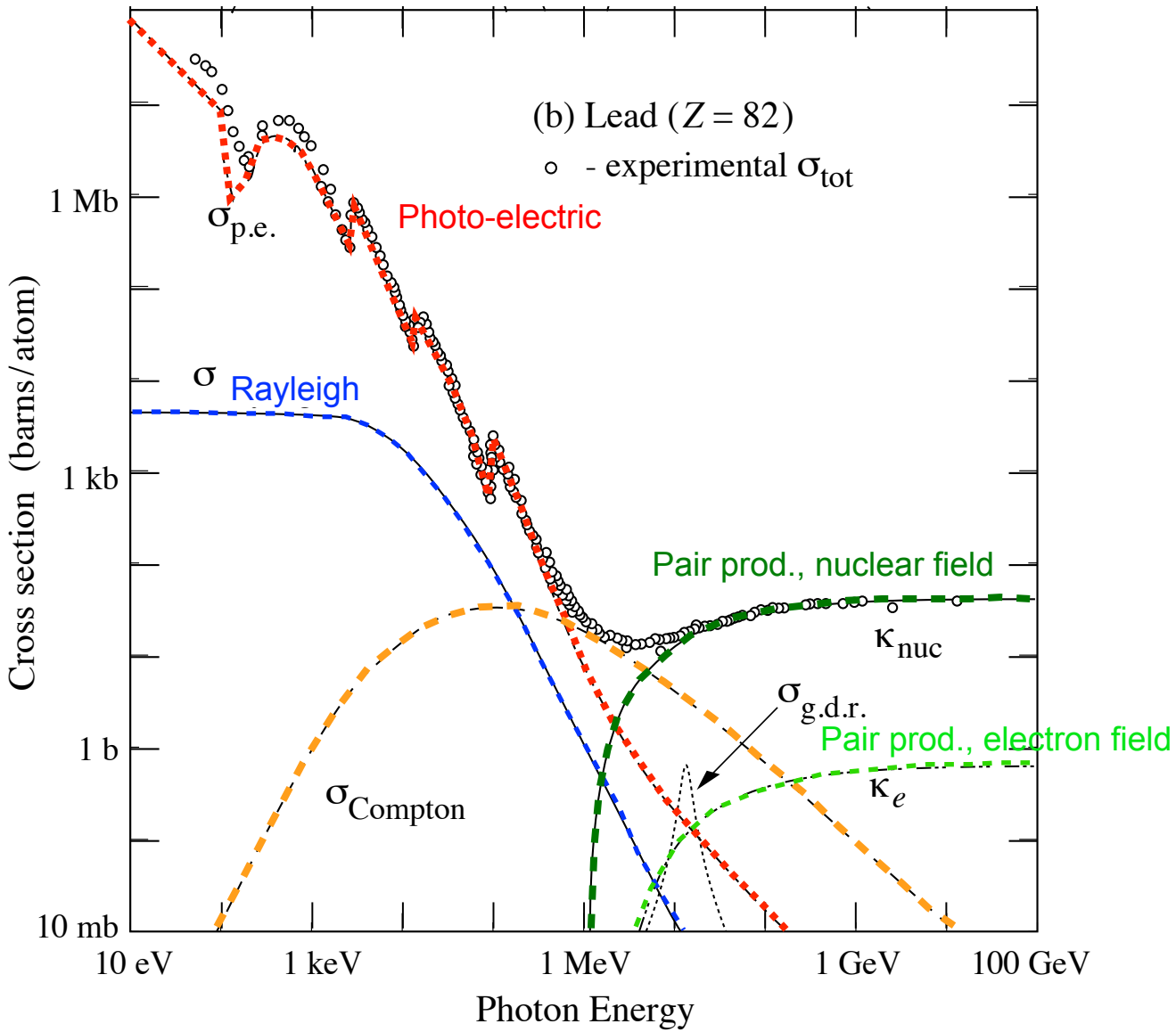
Photons



Kolanoski, Wermes 2015

Photons: Interactions

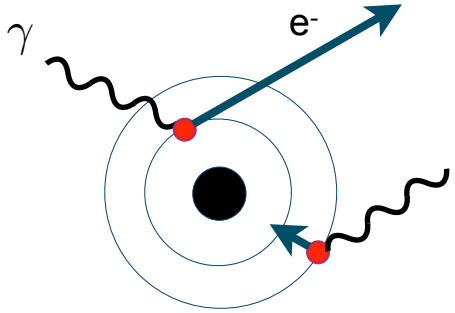
- Photons appear in detector systems
  - as primary photons,
  - created in Bremsstrahlung and de-excitations
- Photons are also used for medical applications, both imaging and radiation treatment.
- Photons interact via **six** mechanisms depending on the photon energy:
  - < few eV: molecular interactions
  - **< 1 MeV: photoelectric effect**
  - < 1 MeV: Rayleigh scattering
  - **~ 1 MeV: Compton scattering**
  - **> 1 MeV: pair production**
  - > 1 MeV: nuclear interactions



Photons: Main Interactions

- Most dominating effects:

Photo-Effect

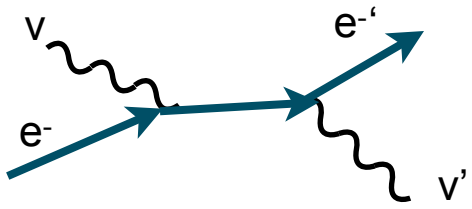


A γ is absorbed and photo-electron is ejected.

- the γ disappears,
- the photo-electron gets an energy

$$E_{\mathrm{p.e}} = E_\gamma - E_{\mathrm{binding}}$$

Compton-Scattering

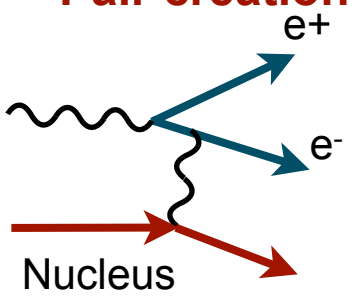


$$\gamma + e \rightarrow \gamma' + e'$$

Elastic scattering of a photon with a free electron

$$E'_\gamma = \frac{1}{1 + \epsilon(1 - \cos\theta_\gamma)}$$

Pair creation



Only possible in the Coulomb field of a nucleus (or an electron) if

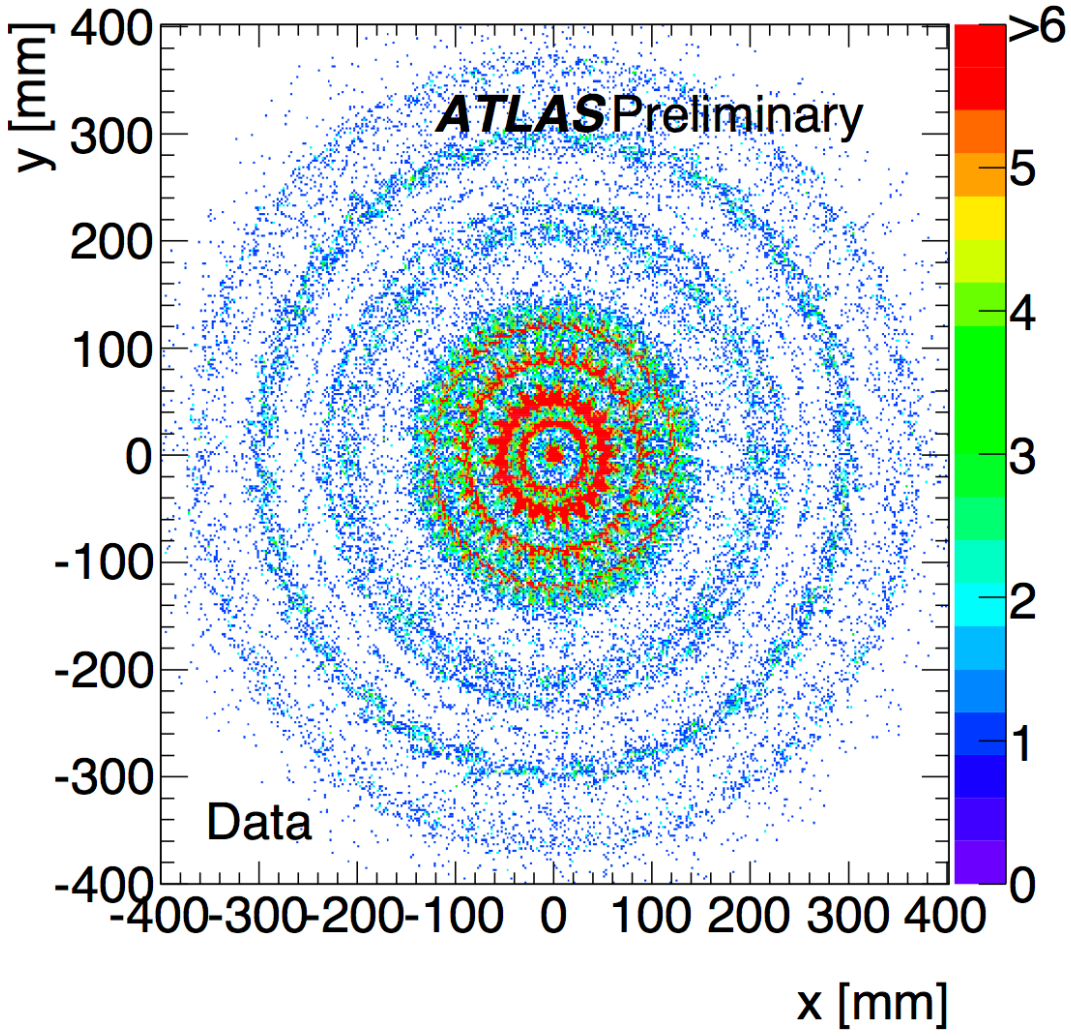
$$E_\gamma \geq 2 m_e c^2$$

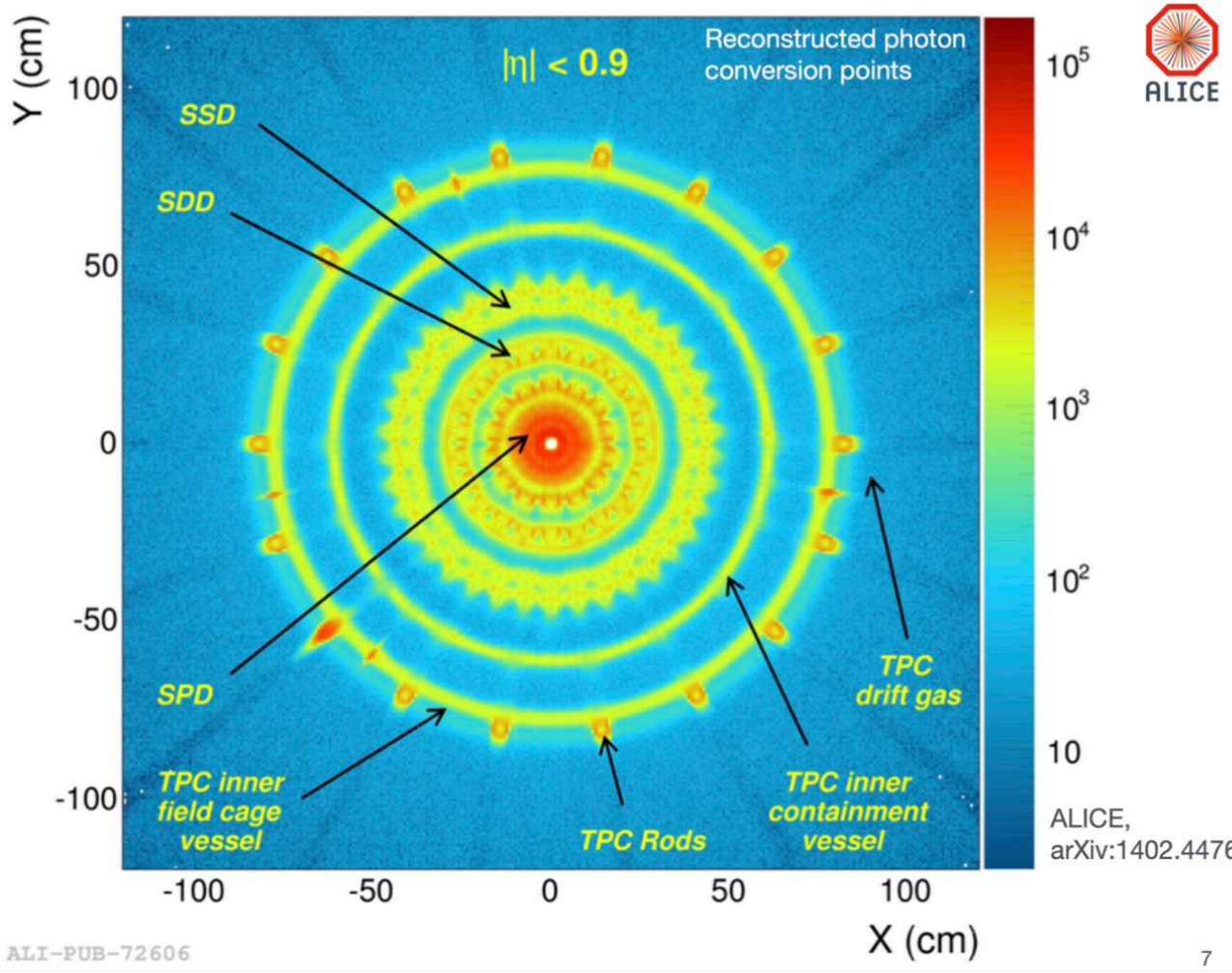
~1.022 MeV

➪ Reduction of photon intensity with passage through matter:

$$I(x) = I_0 e^{-\mu x}$$

Examples how to Use this





A short summary

$\pi^- + p$

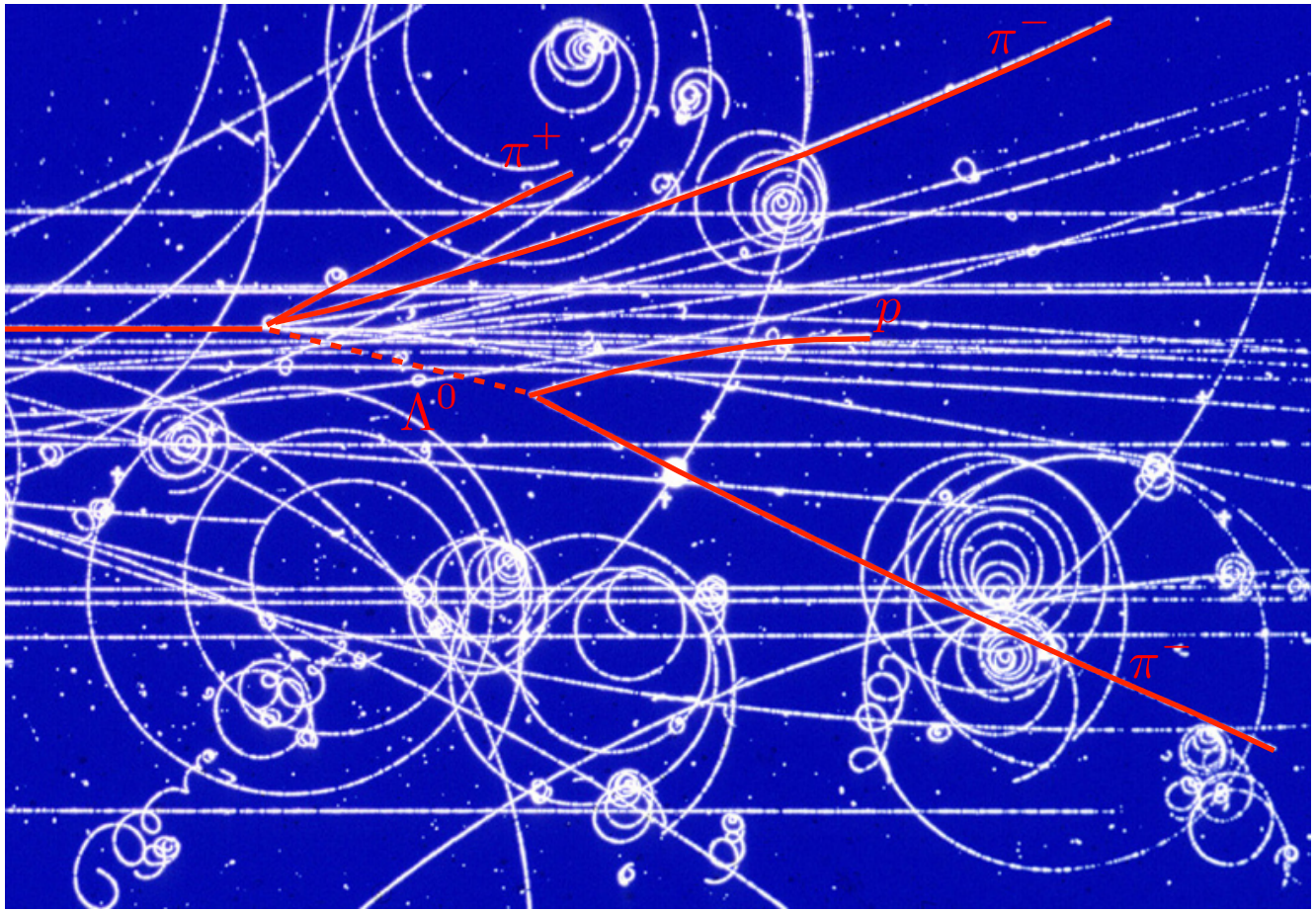
16 GeV

.

.

.

.



Lifetime of lambda:
2.6 10^{-10} sec
-> a few cm

$$\pi^- + p \rightarrow K_s^0 + \Lambda$$

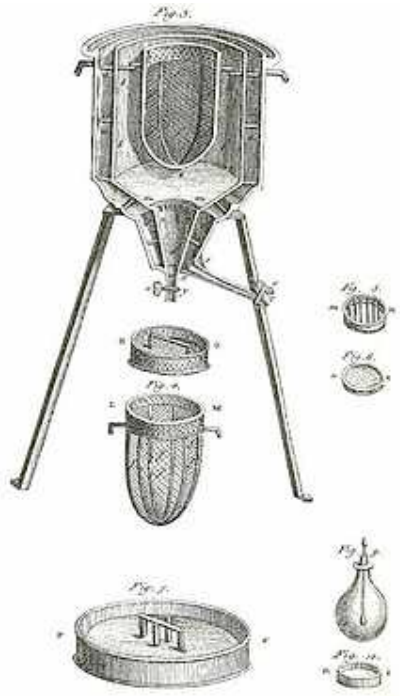
?

The decay of a lambda particle in the 32 cm hydrogen bubble chamber

III. Calorimeters in a Nutshell

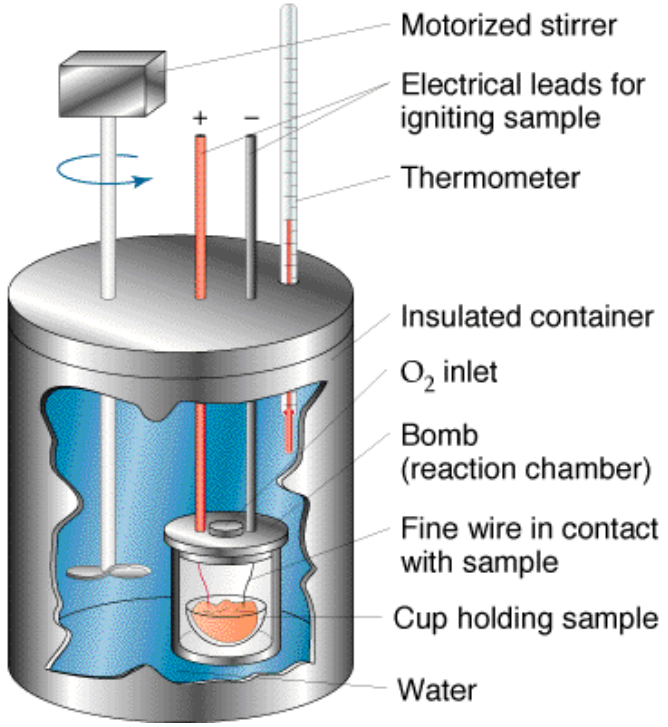
Calorimetry

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



Picture: Francois G. Amar

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

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

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

Calorimetry: Overview

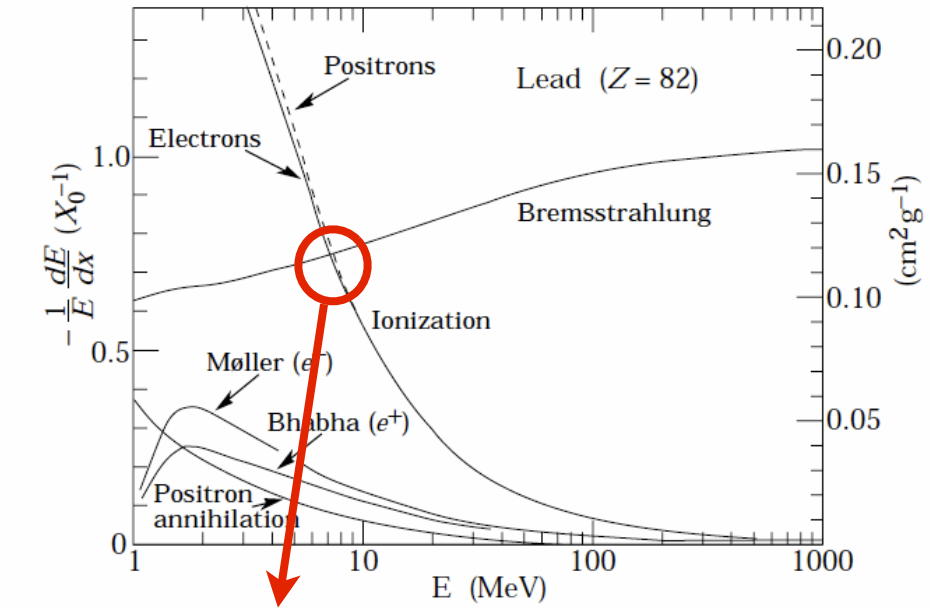
- Basic mechanism for calorimetry in particle physics:
  - formation of electromagnetic
  - or hadronic showers.
- The energy is converted into ionisation or excitation of the matter.

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

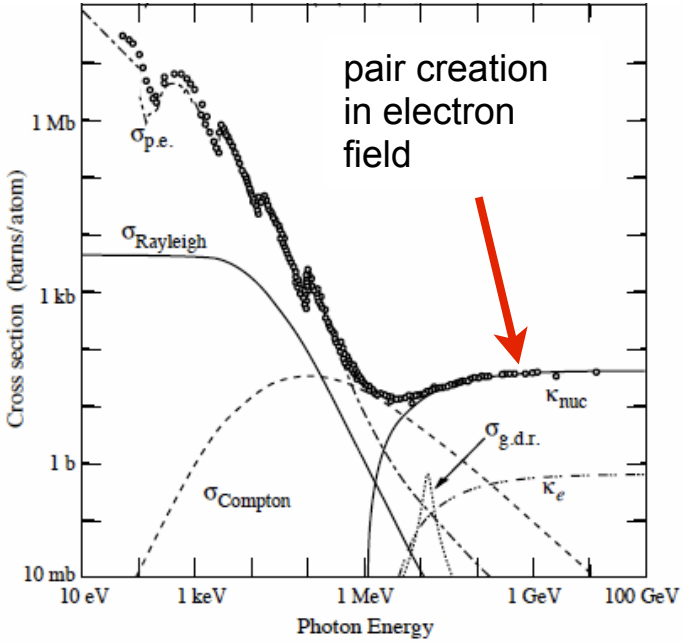
  - Calorimetry is a “destructive” method. The energy and the particle get absorbed!
  - Detector response $\propto E$
  - Calorimetry works both for charged (e± and hadrons) and neutral particles (n,γ) !

Reminder

Electrons



Photons

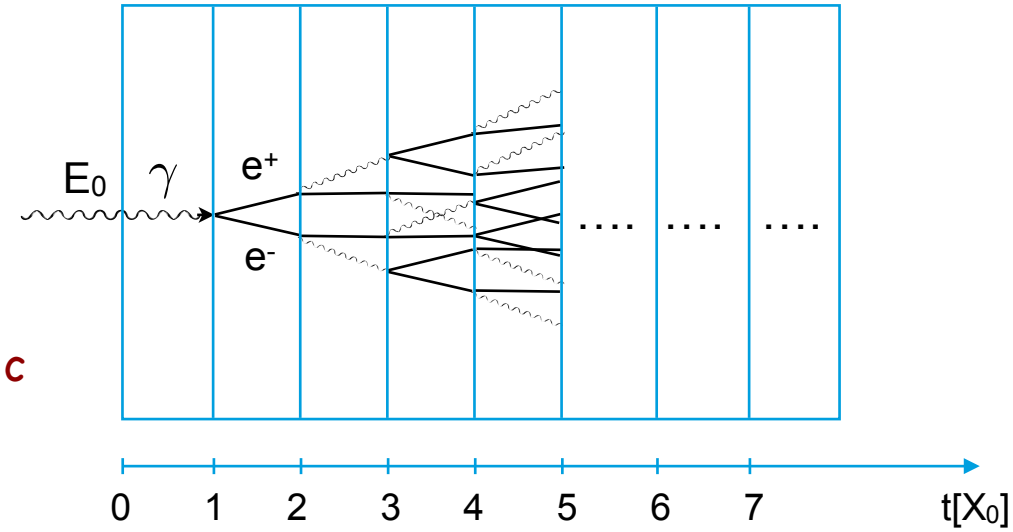


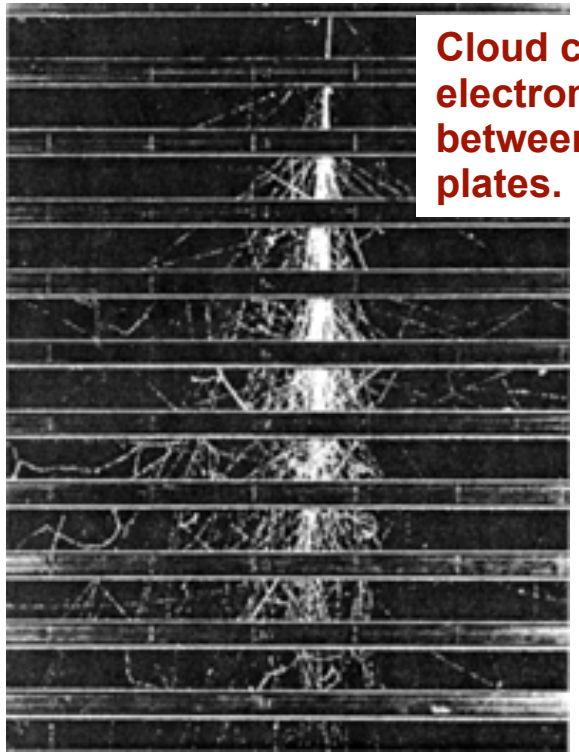
- **Critical energy:** the energy at which the losses due to ionisation and Bremsstrahlung are equal
- **Radiation length** defines the amount of material a particle has to travel through until the energy of an electron is reduced by Bremsstrahlung to 1/e of its original energy $\langle E_e(x)\rangle \propto e^{\frac{x}{X_0}}$

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

Electromagnetic Showers

X_0 is the characteristic scale





Cloud chamber photo of electromagnetic cascade between spaced lead plates.

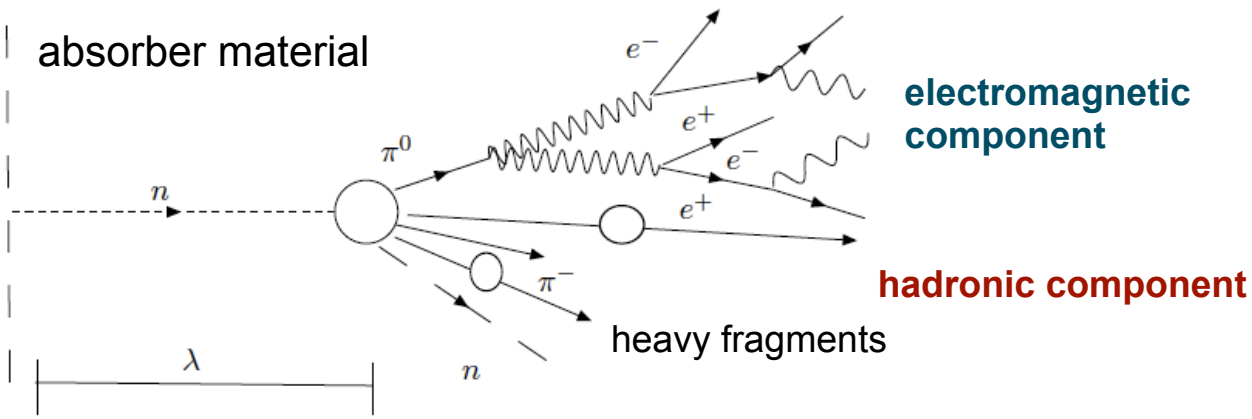
Pic: MIT cosmic ray group

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

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

- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Bremsstrahlung with an average energy between $E_0/(2e)$ and $E_0/2$ is radiated
- Radiated γs produce again pairs

Hadronic Cascade: The Details



Hadronic showers are way more complicated than em showers.

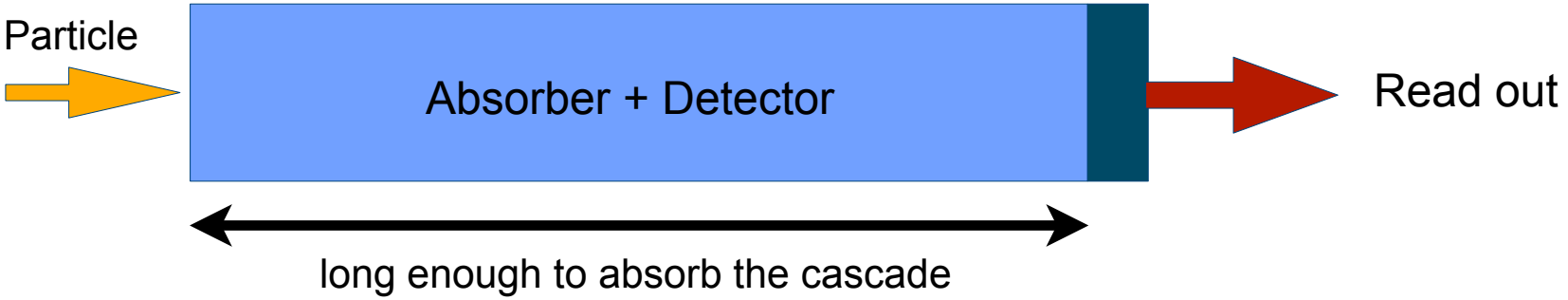
Pic: T. Ferbel. Experimental Techniques in High Energy Physics.

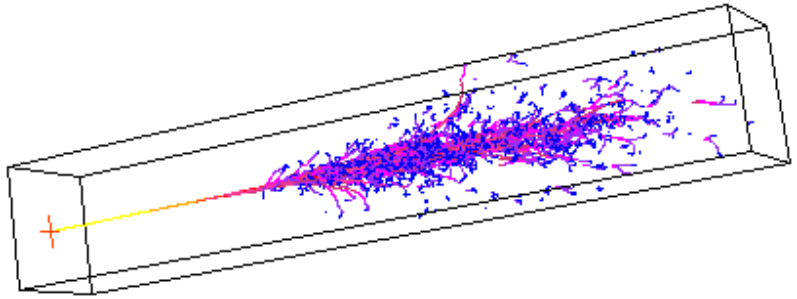
- Different processes are created by the impinging hadron:
  - high energetic secondary hadrons taking a significant part of the momentum of the primary particle [e.g. O(GeV)]
  - a significant part of the total energy is transferred into nuclear processes: nuclear excitation, spallation, ... ➠ Particles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

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

Calorimeter Types

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





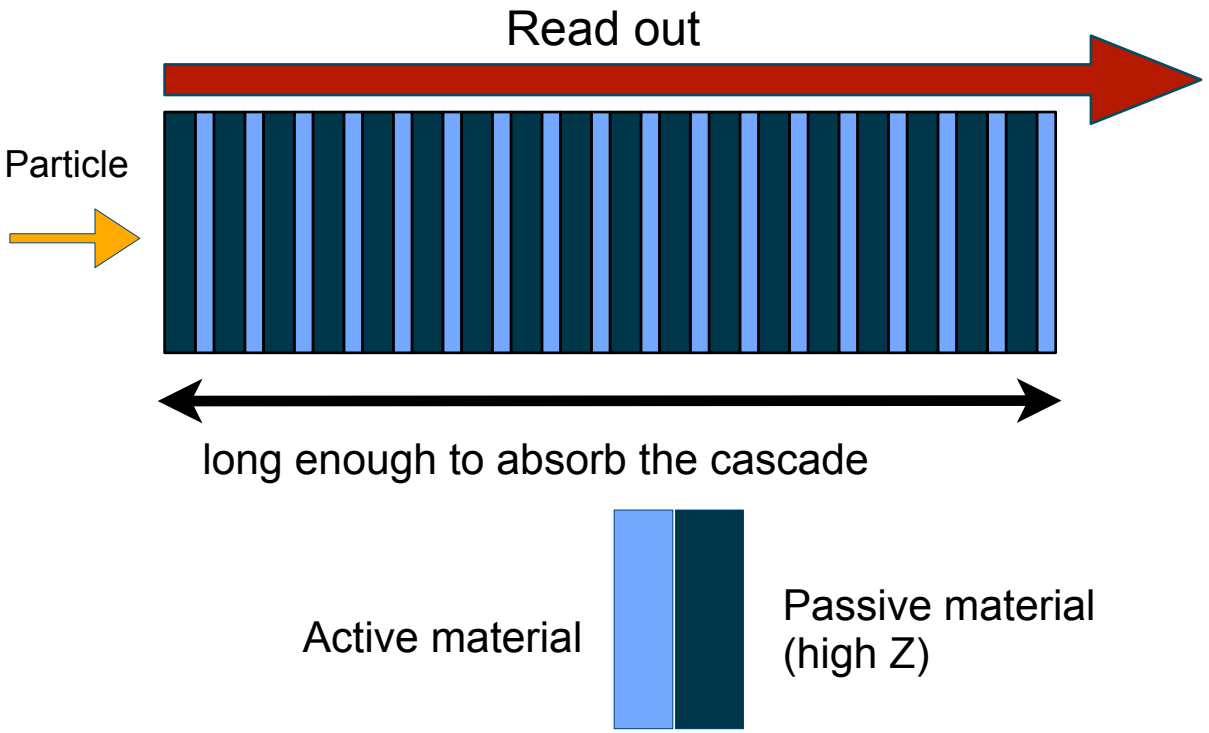
Pic: Cornell

Example: Crystal calorimeter

Sampling Calorimeter

Sampling Calorimeter

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



Important parameter:
Sampling Fraction

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

Typically in the percent range

Example: ZEUS Uranium Calorimeter

Calorimeter: Important Parameter (1)

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

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

  - **Stochastic** term 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 inhomogeneities with in the detector sensitivity, calibration uncertainties and radiation damage

Losses of Resolution:

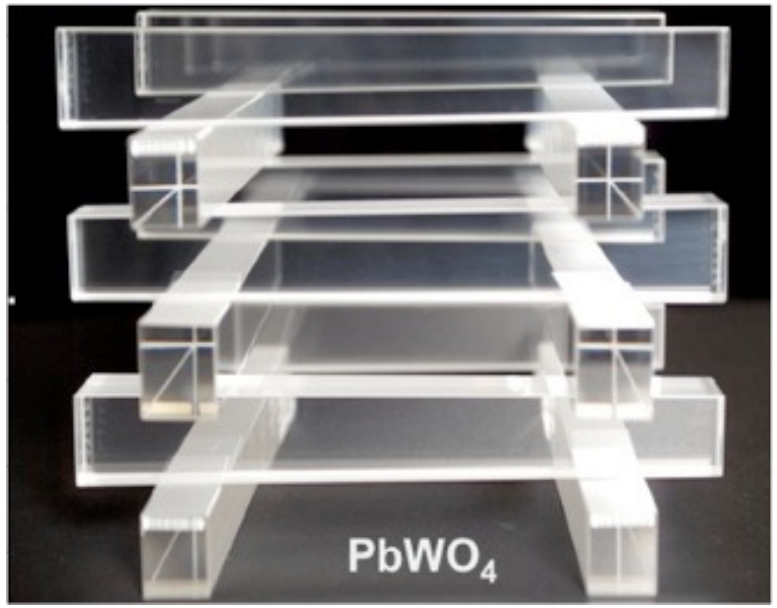
- **Shower not contained** in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.
- **Statistical fluctuations** in number of photoelectrons observed in detector.
- **Sampling fluctuations** if the counter is layered with inactive absorber.
- ….

Calos: Active Material

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.

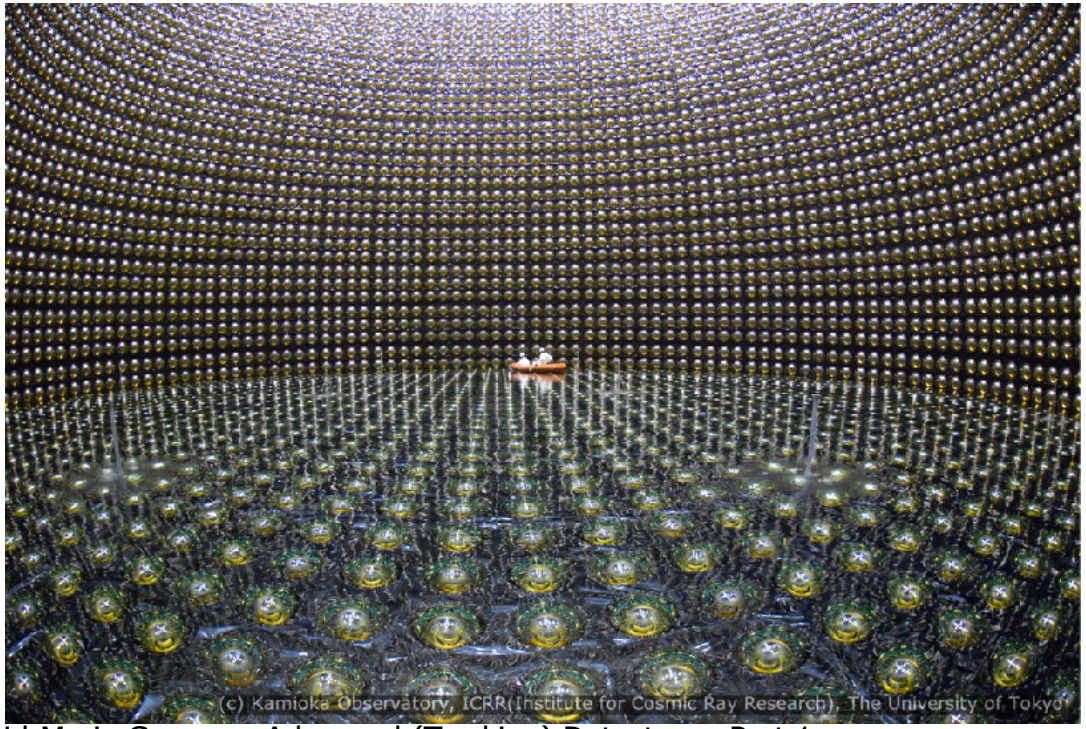
Picture: CDF@Fermilab



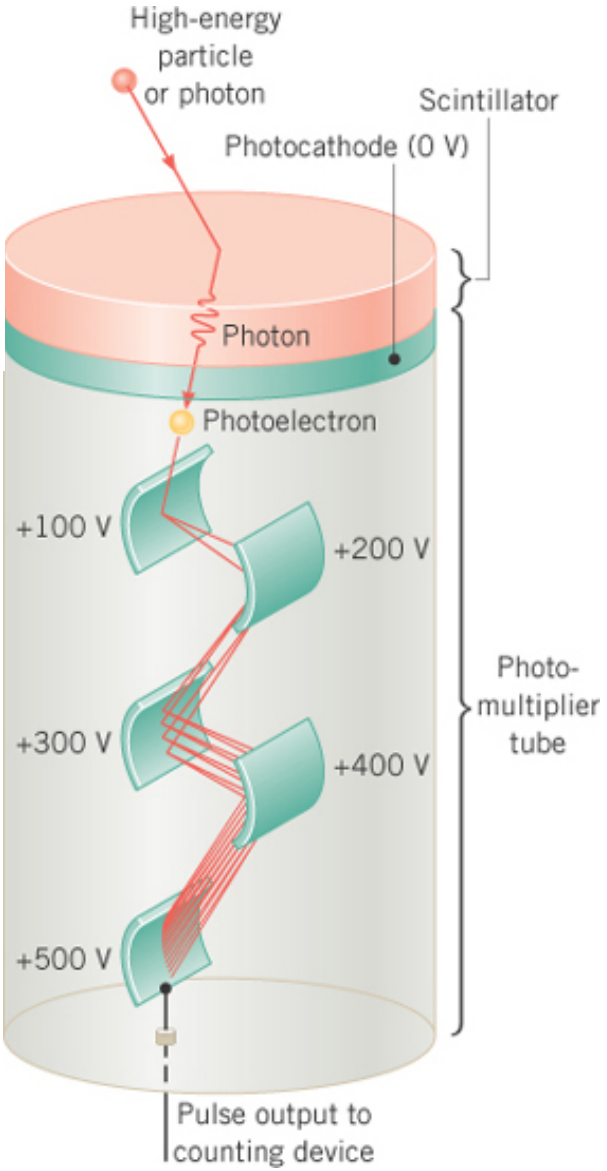
- $PbWO_4$: Fast, dense scintillator,
  - Density ~ 8.3 g/cm^3 (!)
  - ρ_M 2.2 cm, X_0 0.89 cm
  - low light yield: ~ 100 photons / MeV

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

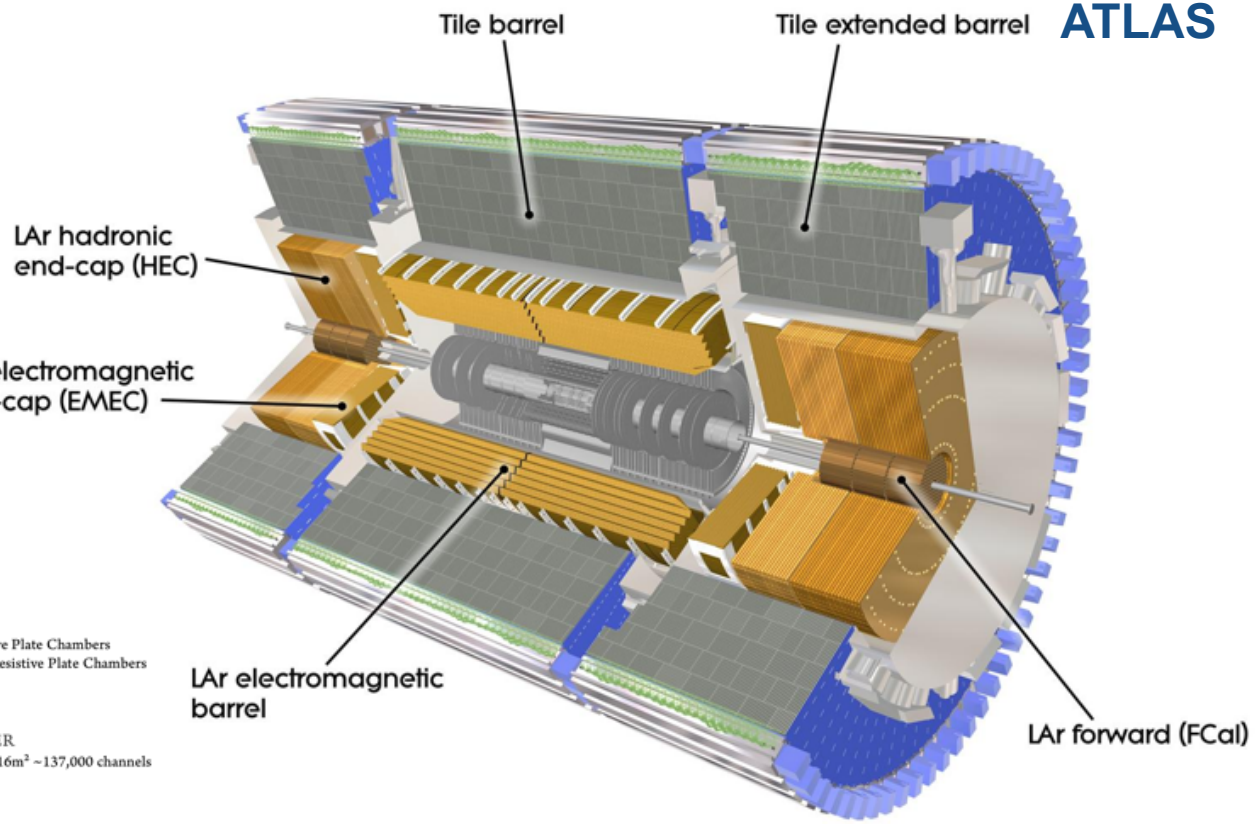


Source: Cutnell and Johnson, 7th edition image gallery

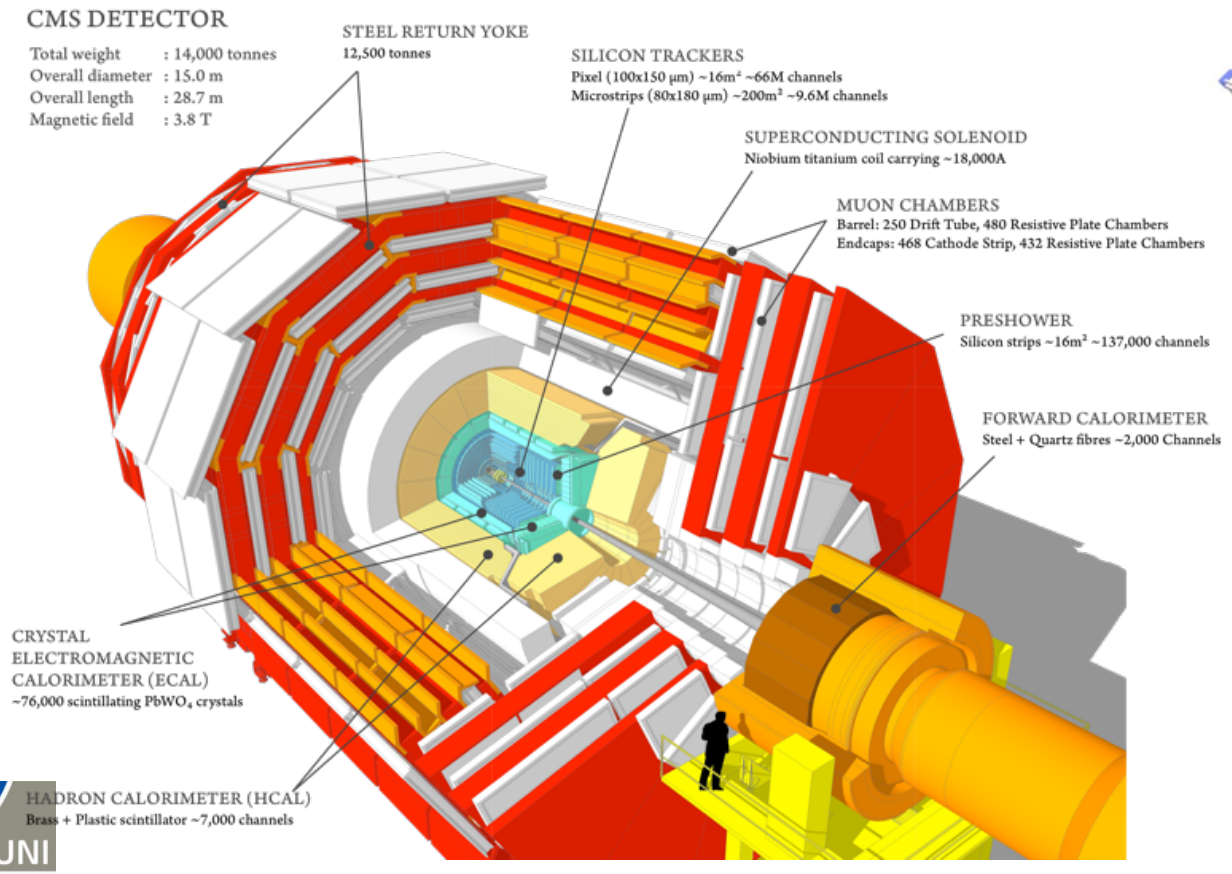
Overview of Calorimeti

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

ATLAS



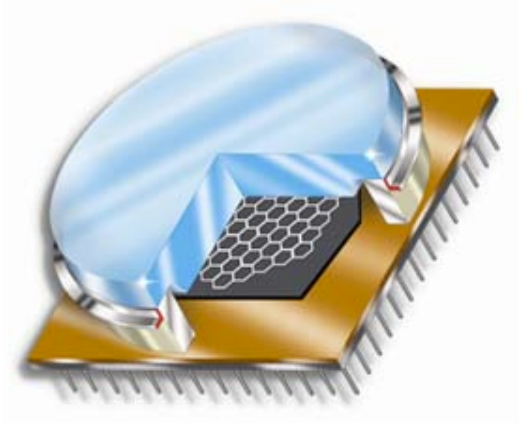
CMS

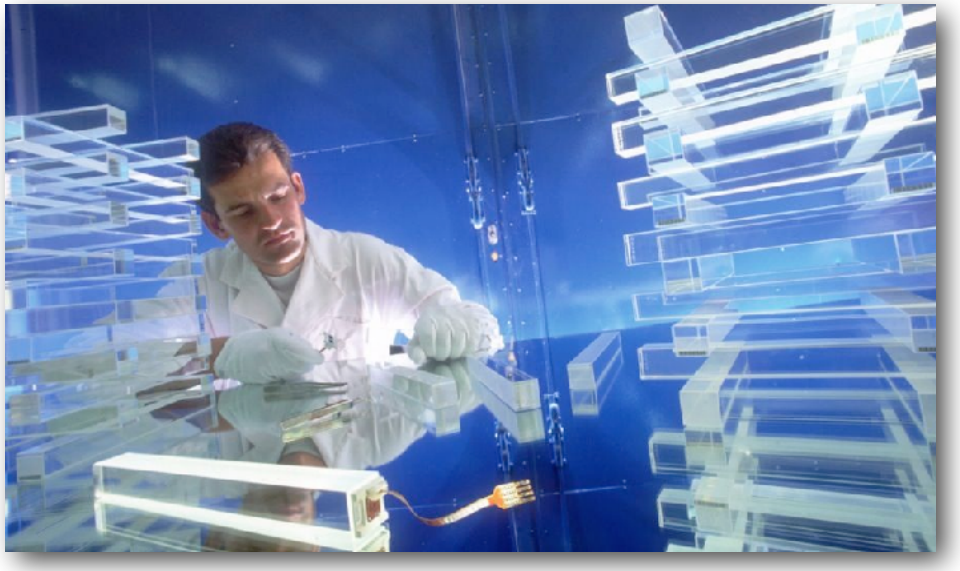


CMS Calorimeter

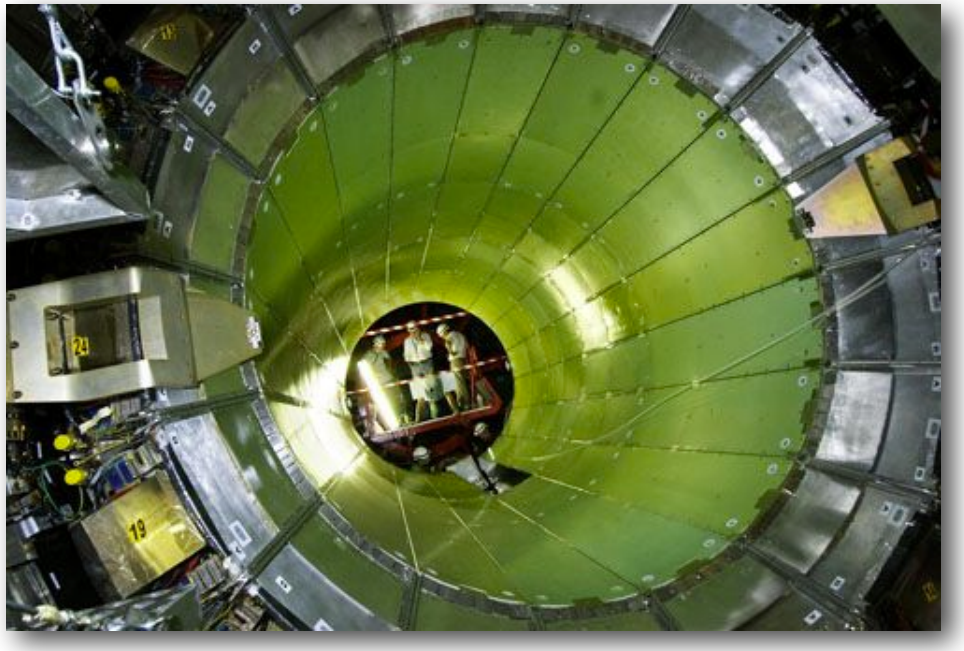
- **ECAL:** homogeneous calo
  - high resolution Lead Tungsten crystal calorimeter -> **higher intrinsic resolution**
  - 80000 crystals each read out by a photodetector
  - constraints of magnet -> HCAL absorption length not sufficient
  - tail catcher added outside of yoke

- **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)

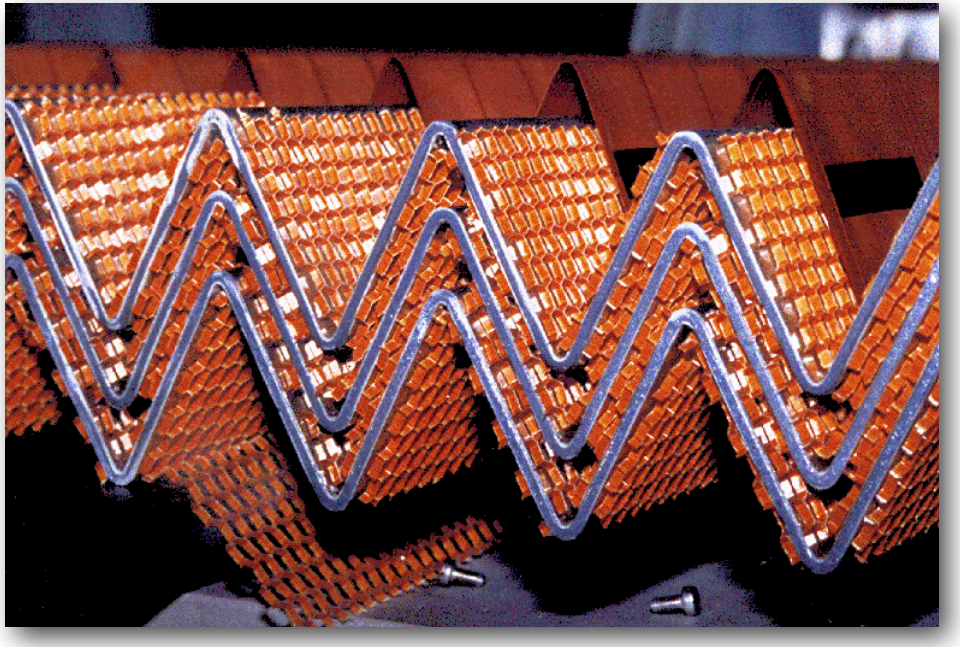


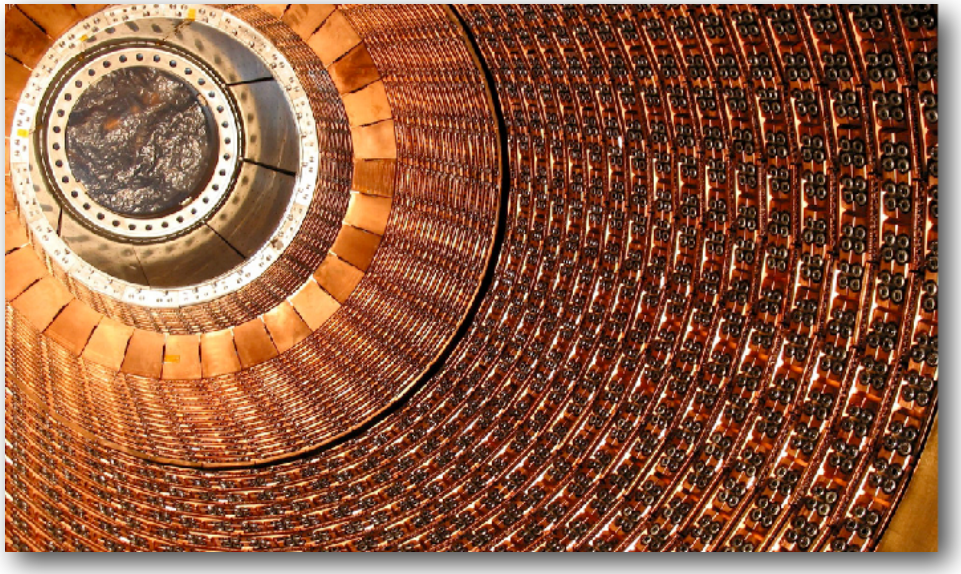
CMS ECAL during installation (CERN)

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

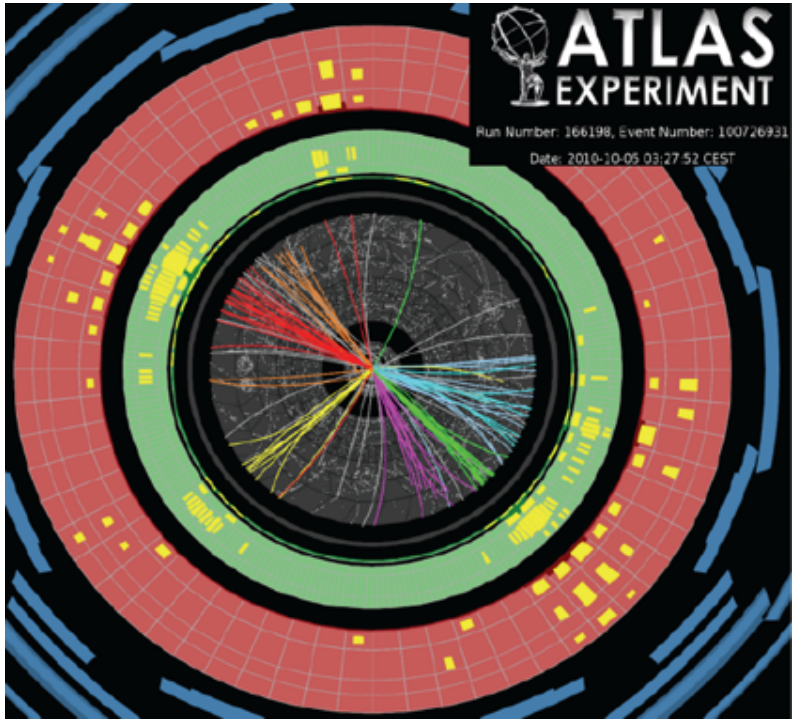
  - Tile calorimeter: covering outer region
  - “Conventional” steel absorber with plastic scintillators.

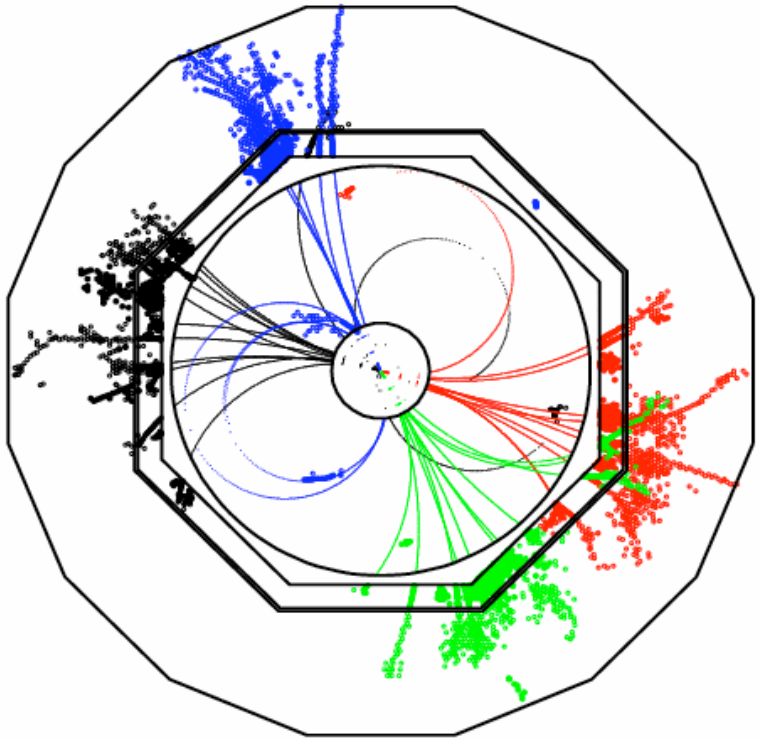




ATLAS Hadronic endcap Liquid Argon Calorimeter. (CERN)

Current Hadron Calos ... And Dreams

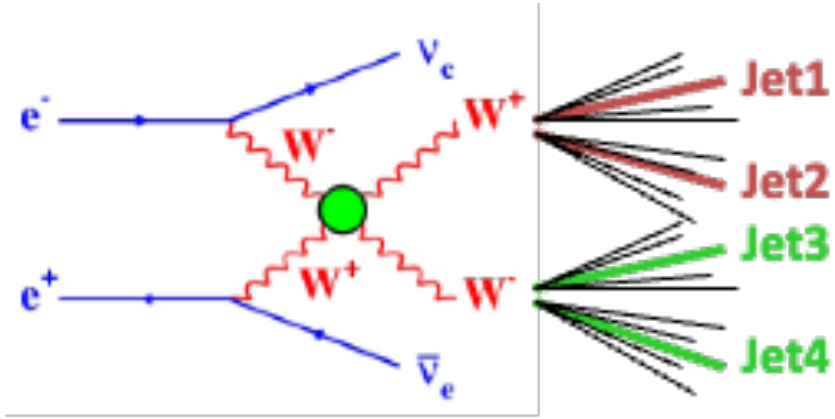


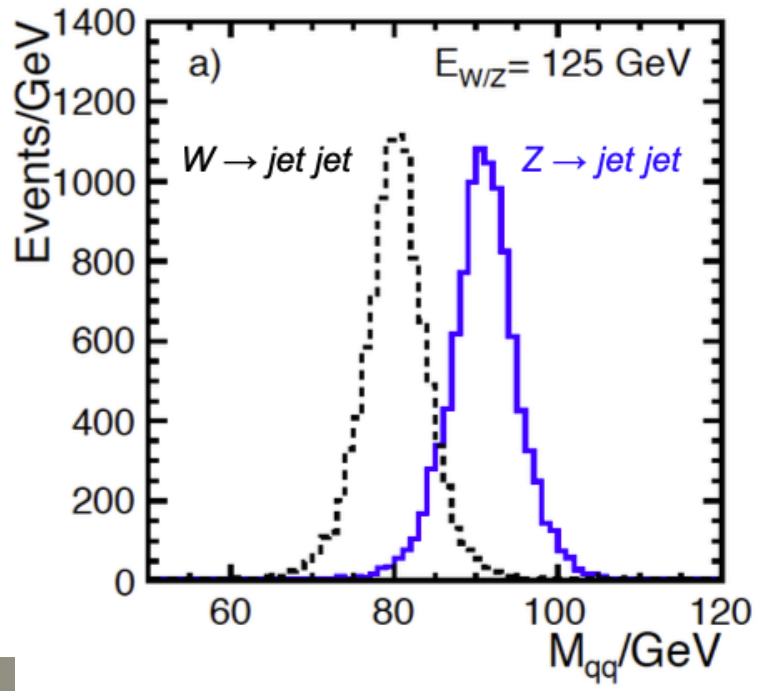


- Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT)
  O(10k) channels for full detectors

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

The Jet Energy Challenge





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

- Many interesting physics processes involve W or Z bosons predominantly decay into jets
- Goal: distinguish the decays *Z → jet jet* and *W → jet jet* by their reconstructed mass

- Required resolution: $\sigma(E_{jet})/E_{jet} \approx$ 3-4% for $E_{jet} \approx$ 40 to 500 GeV
- "typical" calorimeter:

$$\sigma(E_{jet})/E_{jet} \approx 60\%/\sqrt{E(\text{GeV})} \oplus 2\%$$

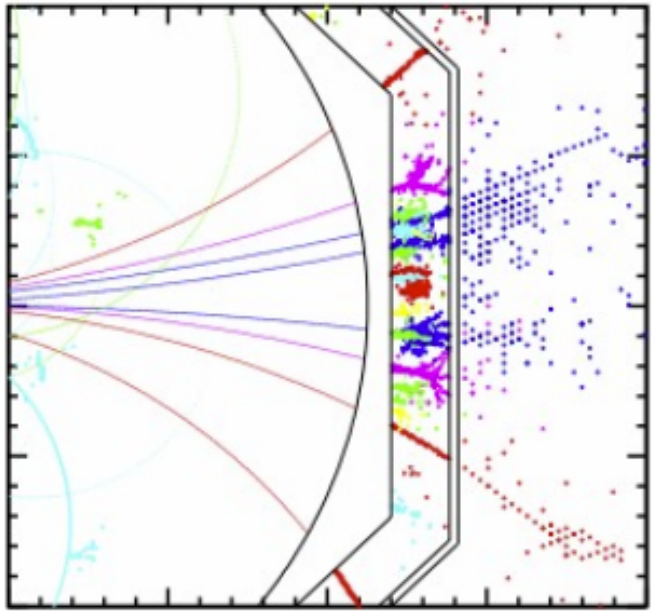
$$\Rightarrow \sigma(E_{jet})/E_{jet} \approx 10\% \text{ at } E_{jet} = 50 \text{ GeV}$$

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

Particle Flow Calorimeter

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

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

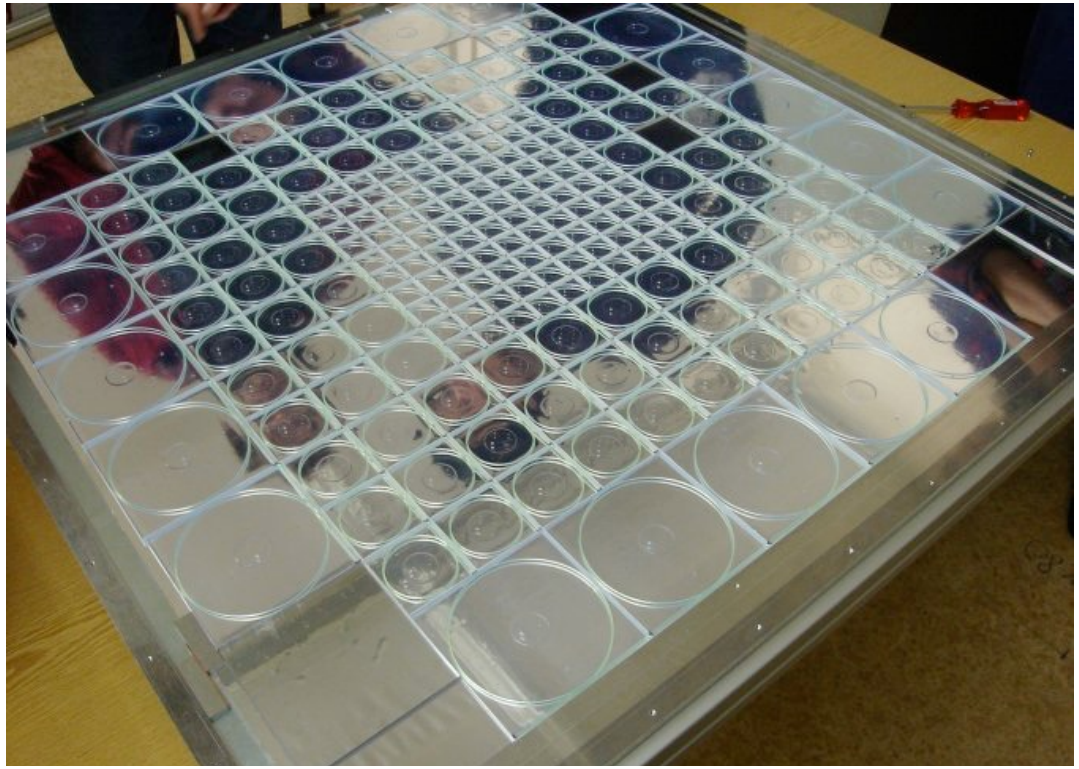


- Need
  - a calorimeter optimised for photons: separation into ECAL + HCAL
  - to place the calorimeters inside the coil (to preserve resolution)
  - to minimise the lateral size of showers with dense structures
  - the highest possible segmentation of the readout
  - to minimise thickness of the active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

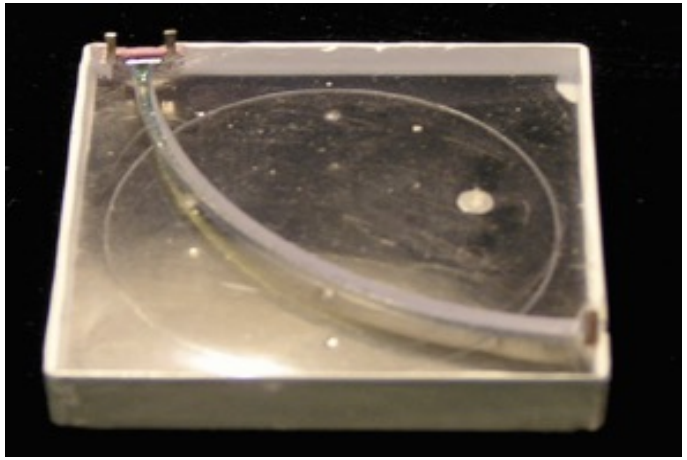
New Concepts: Highly Granular Calos

- 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

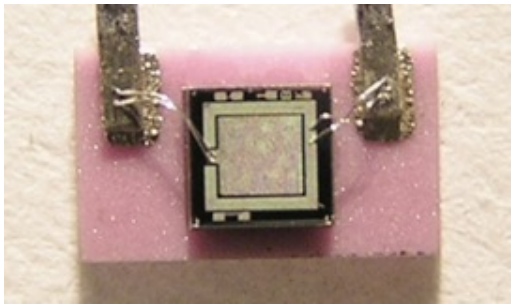
Pictures: CALICE collaboration



tiles in one layer



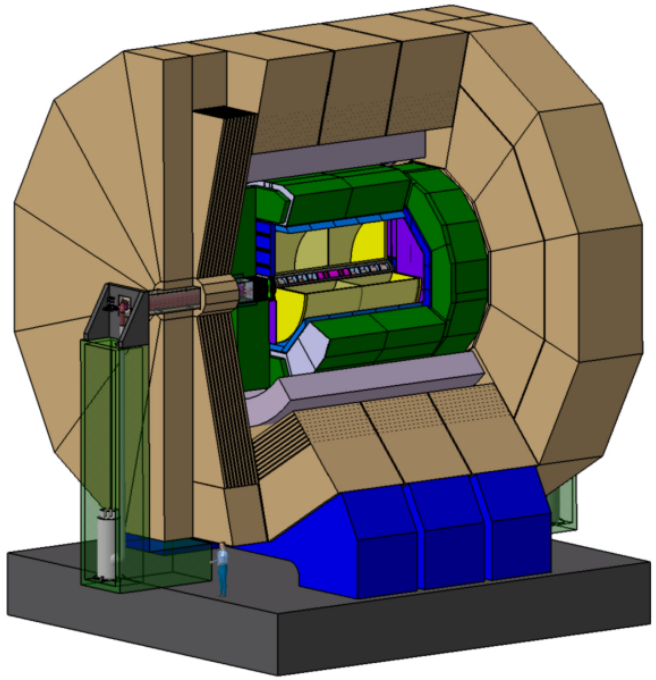
scintillator tile with WLS fiber



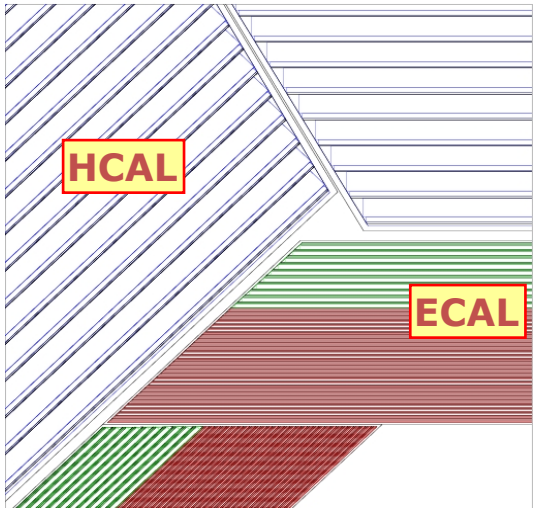
Silicon photo-multiplier

Example: Calo design at ILC

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



ILD: International Large Detector



ECAL:

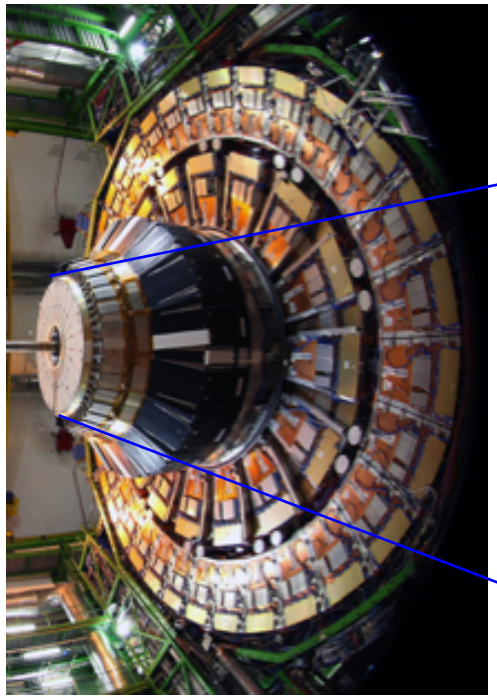
- SiW sampling calorimeter
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels

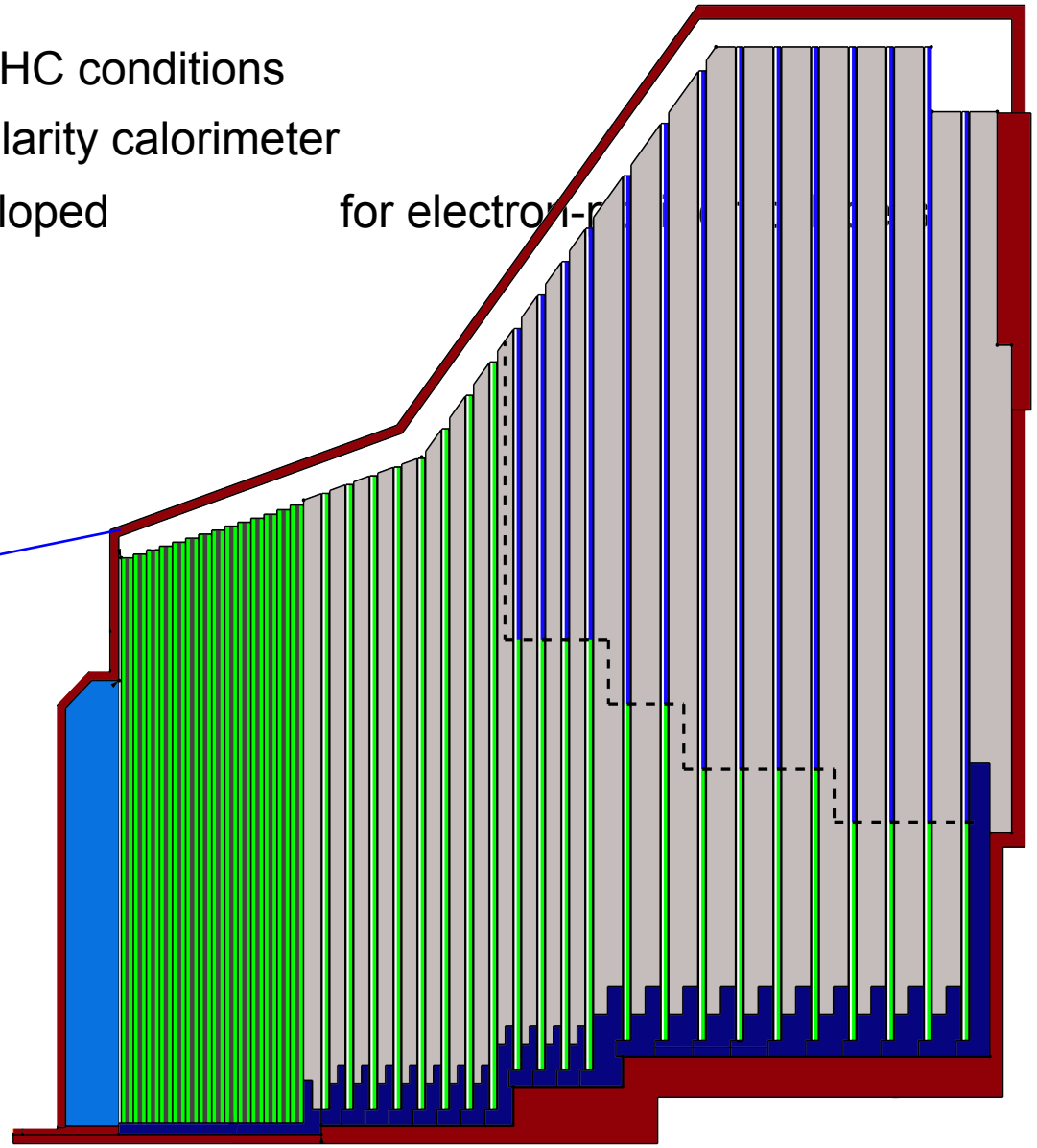
HCAL:

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

CMS High Granularity

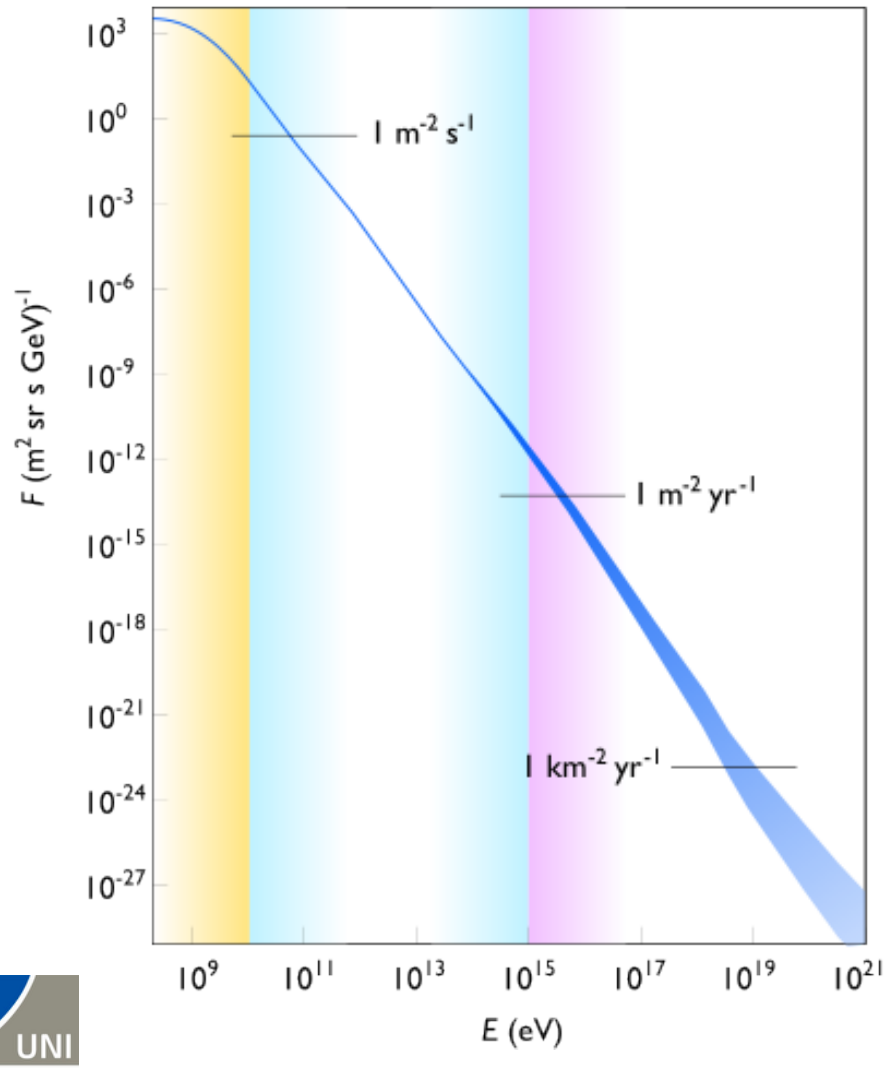
- Current CMS calorimeter endcap will not survive in HL-LHC conditions
- 2015, decided to replace it with silicon-based high-granularity calorimeter
- Synergy with high granularity calorimeter concepts developed for electron-





Calos: not only at accelerators!

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



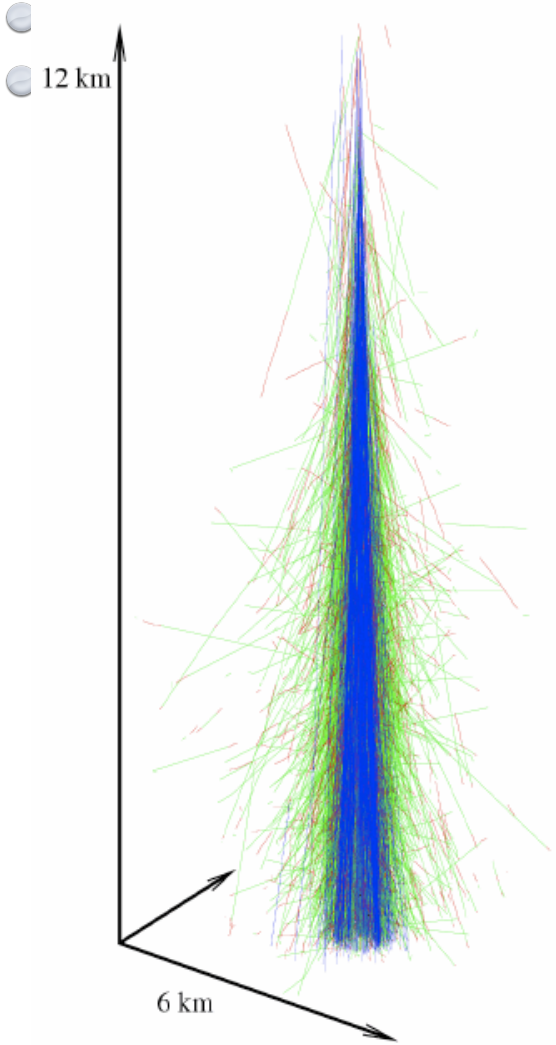
Pic: Wikipedia

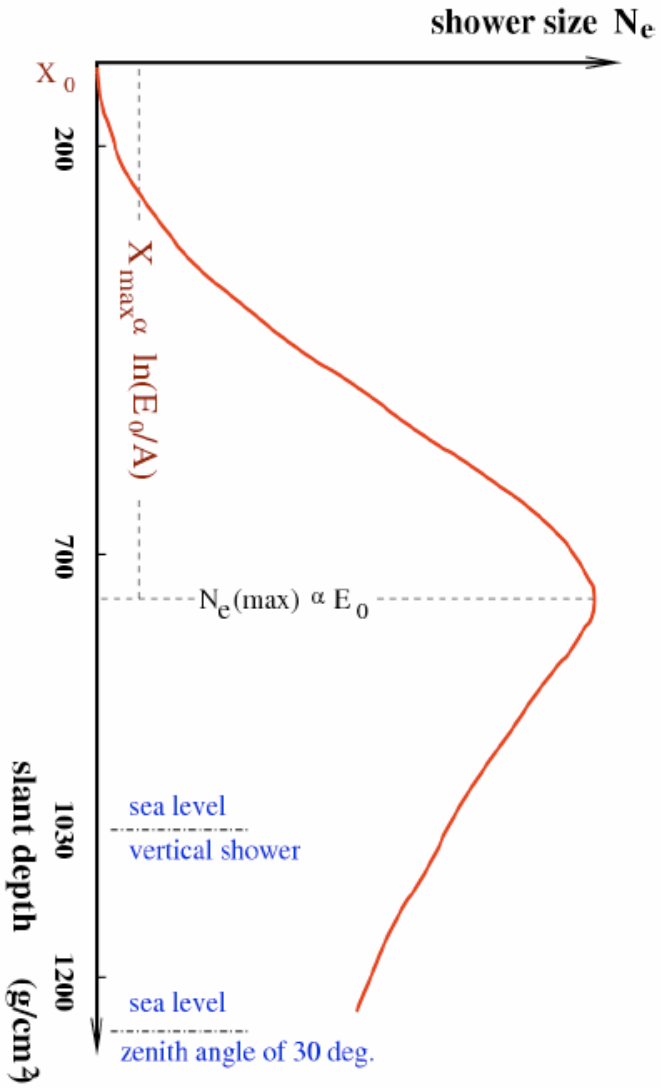
Flux of cosmic ray particles as a function of their energy.

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

Use atmosphere as calorimeter

Nuclear reaction length $\lambda_I \sim 90$ g/cm²

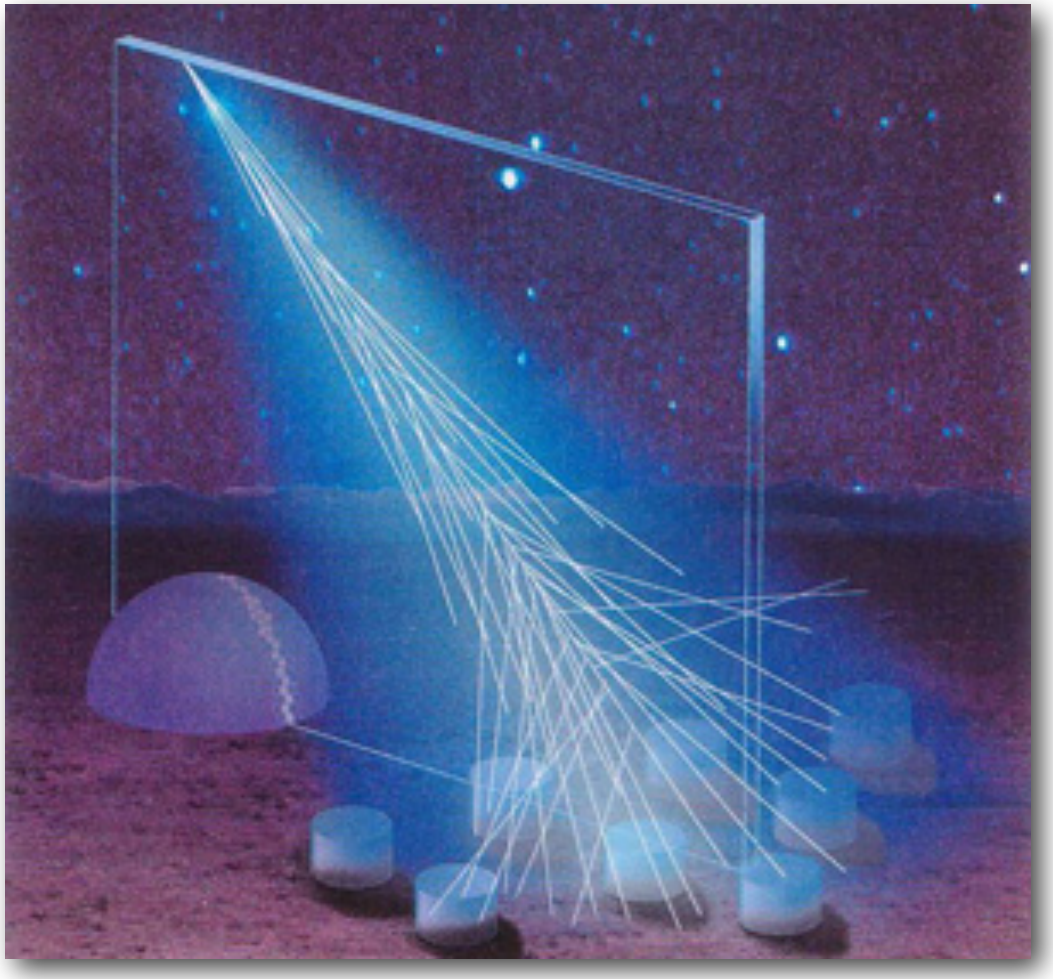
Radiation length $X_0 \sim 36.6$ g/cm²

Density: ~ 1035 g/cm²

~ 11 λ_I, ~ 28 X_0

Two Techniques

Pic: Pierre Auger Observatory



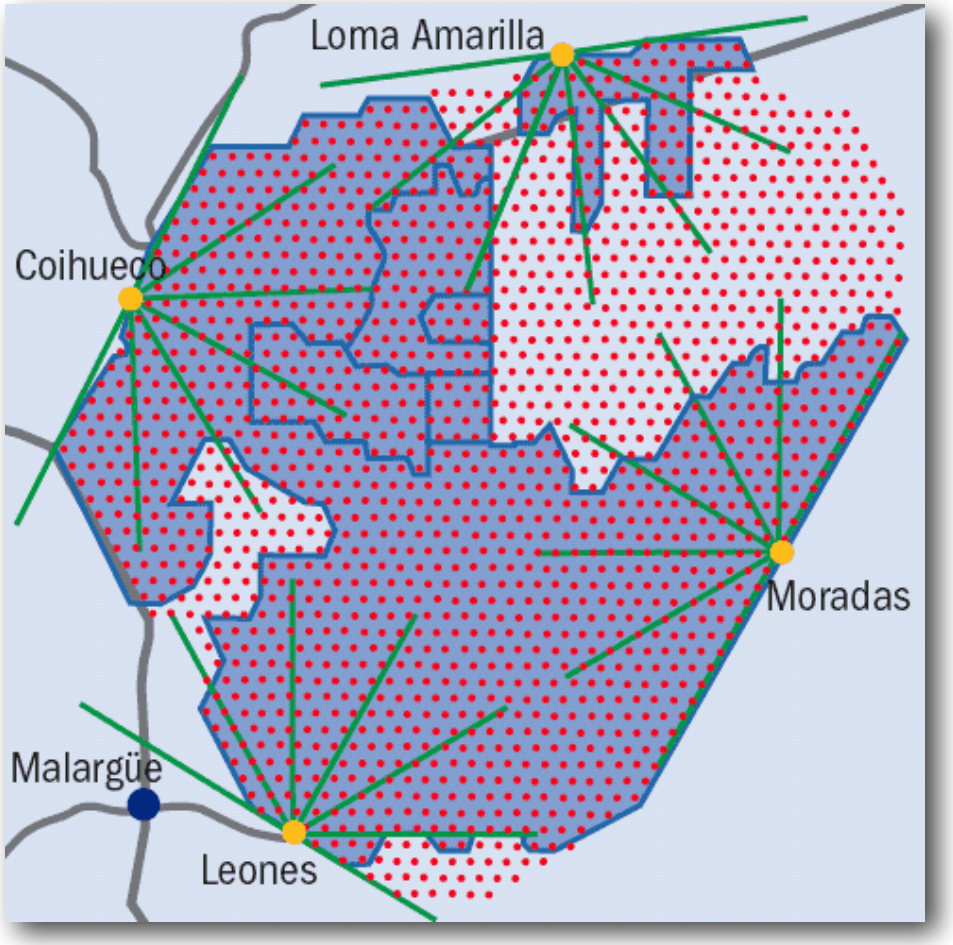
- The atmosphere as homogeneous calorimeter:
  - Energy measurement by measuring the **fluorescence** light

This is only possible with clear skies and darkness !

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

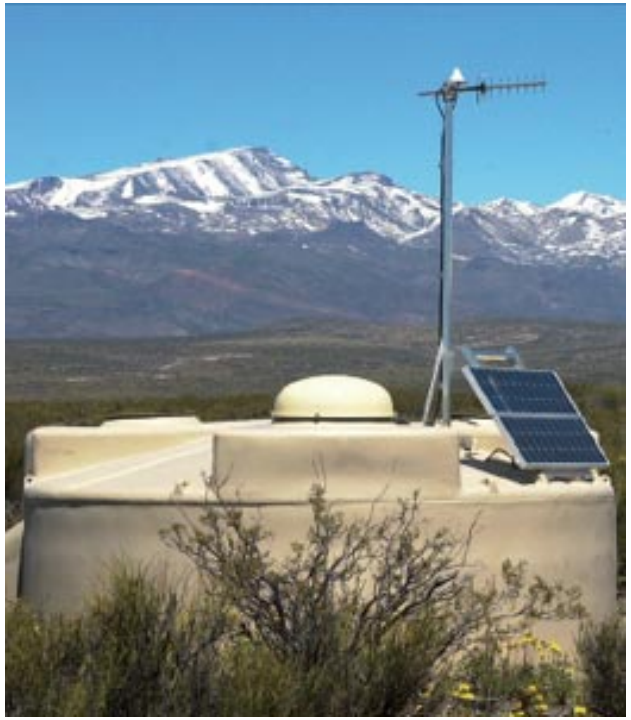
Always possible but has large uncertainties !

AUGER-SOUTH: ARGENTINIAN PAMPA

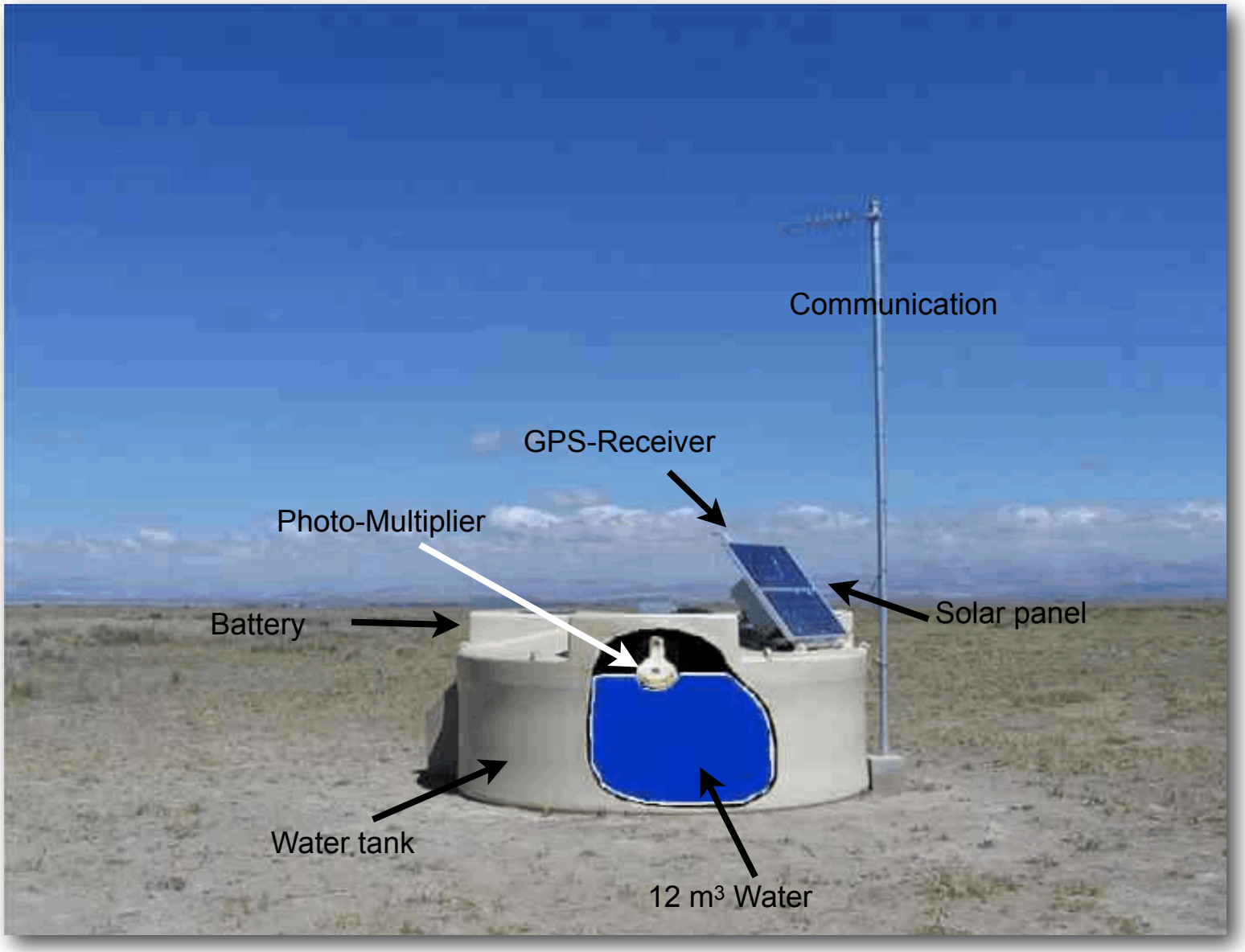


Pics: Pierre Auger Observatory

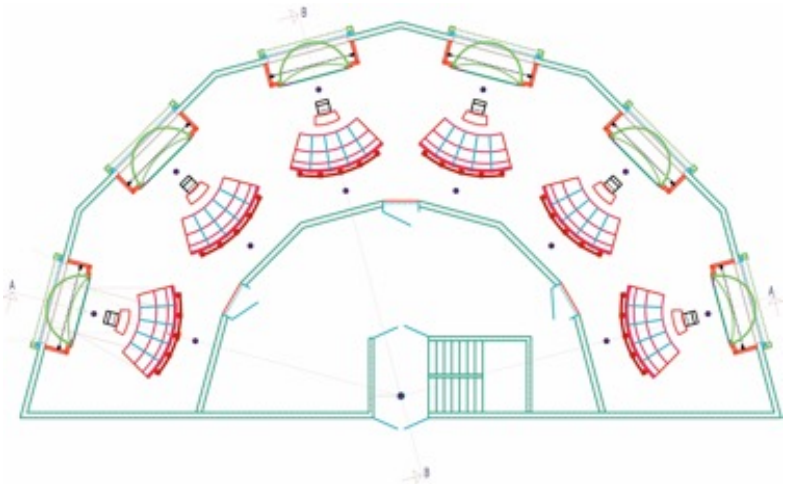
- 1600 water-Cherenkov detectors on ground
- 4 Flourorescence-stations with 6 telescopes
- Covered area:
  3000 km^2 (30 x Paris)
- Designed to measure energies above 10^{18}eV

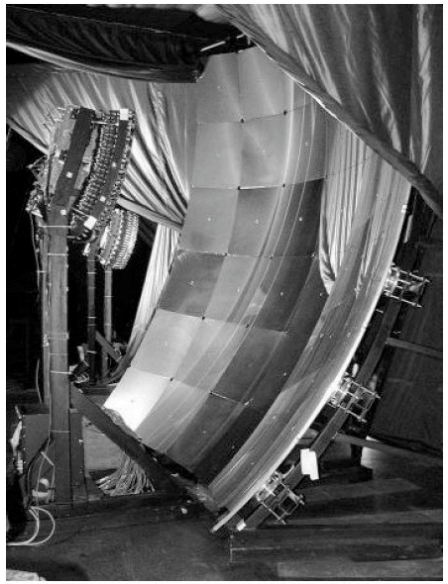


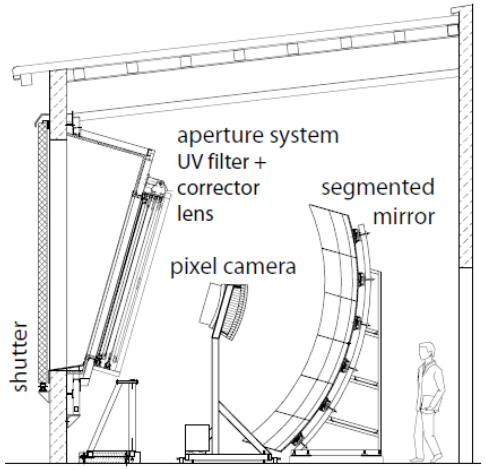
AUGER-Detektor: Ground Array



AUGER Hybrid Installation







Summary Part 1

Ionisation and Excitation:

- Charged particles traversing material are **exciting and ionising** 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 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.