Detectors for High Energy Physics

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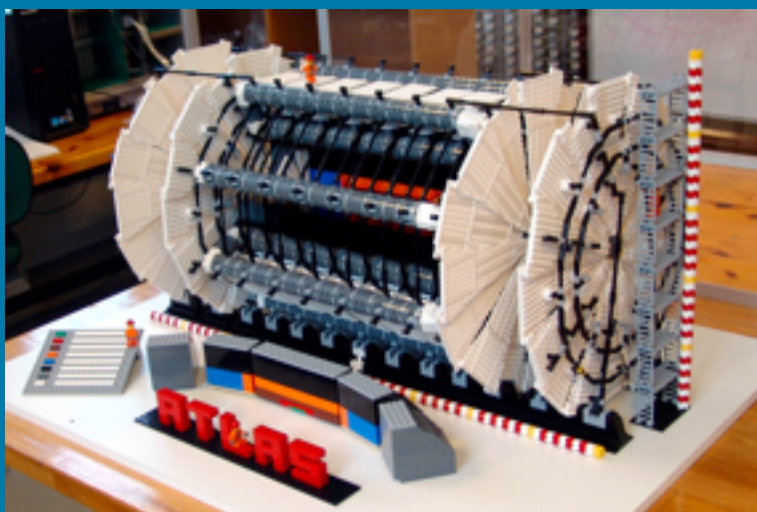
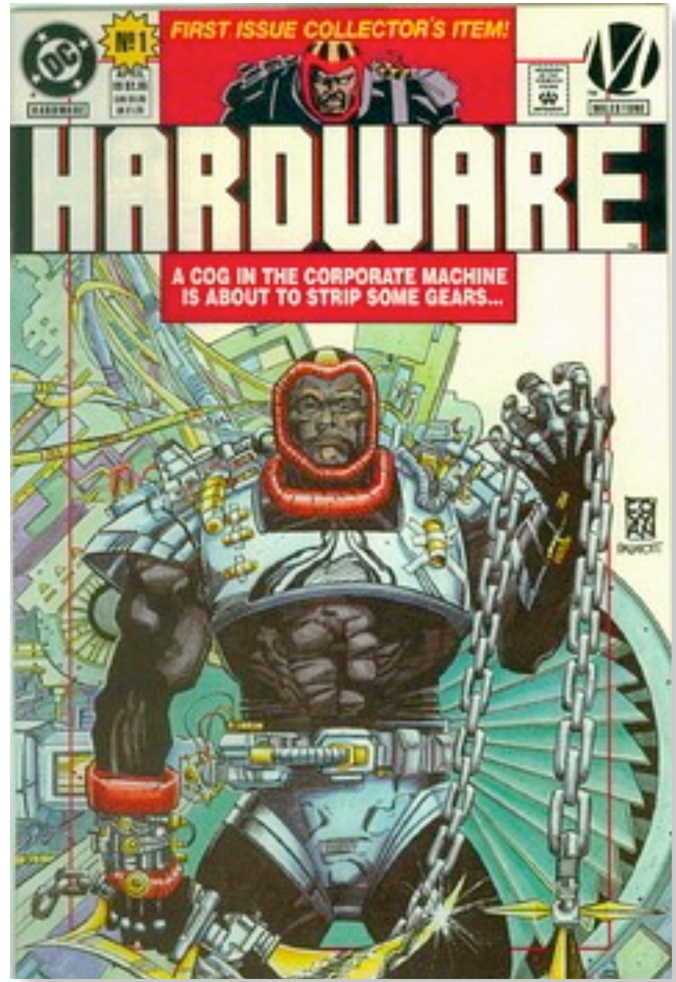


DESY Summer Student Program 2017
Hamburg
July 26th/27th

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 favorite detectors !



Pic: DC Comics

Maybe not the ideal detector physicist

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

Wednesday

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

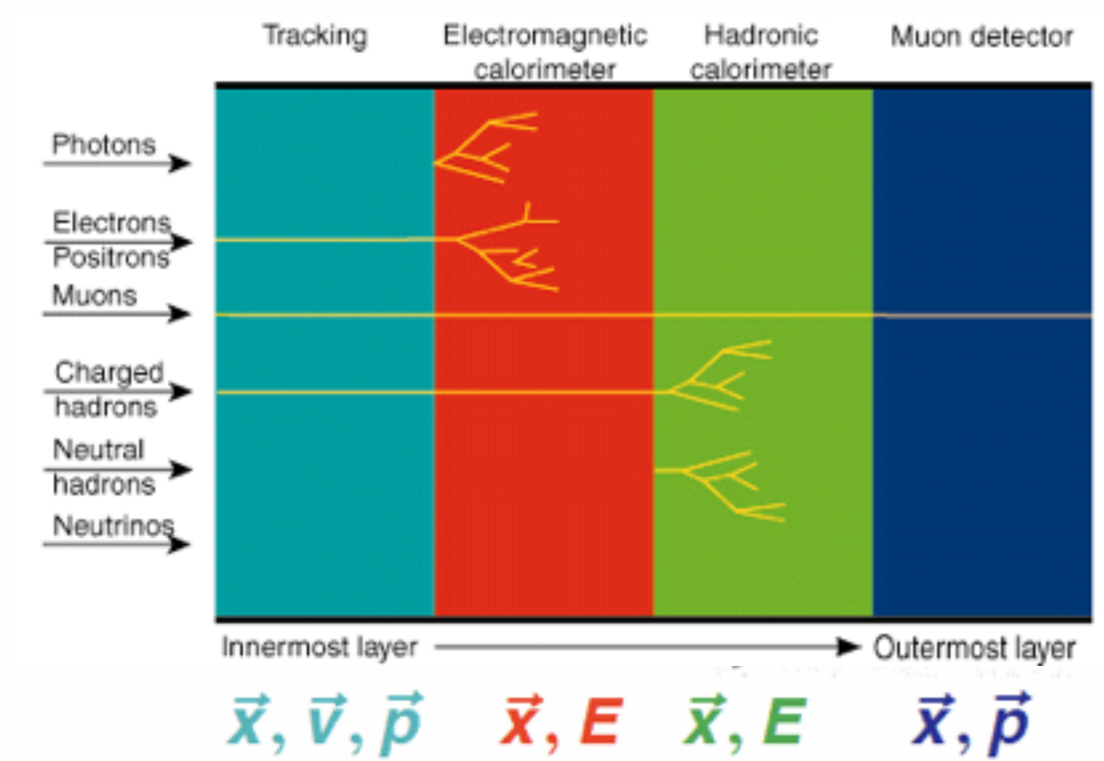
V. **Examples from the real life**

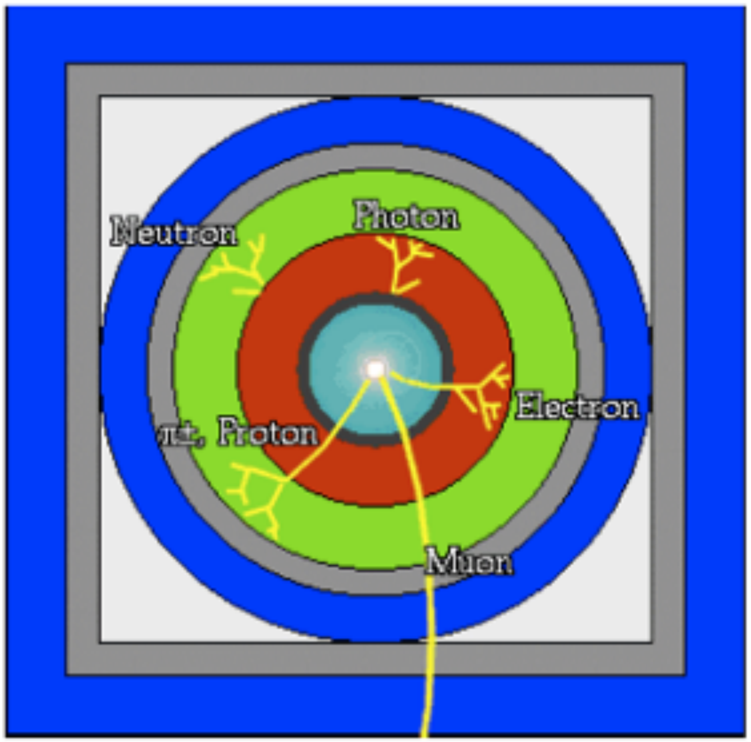
Thursday

I. Overview: Detectors for particle physics

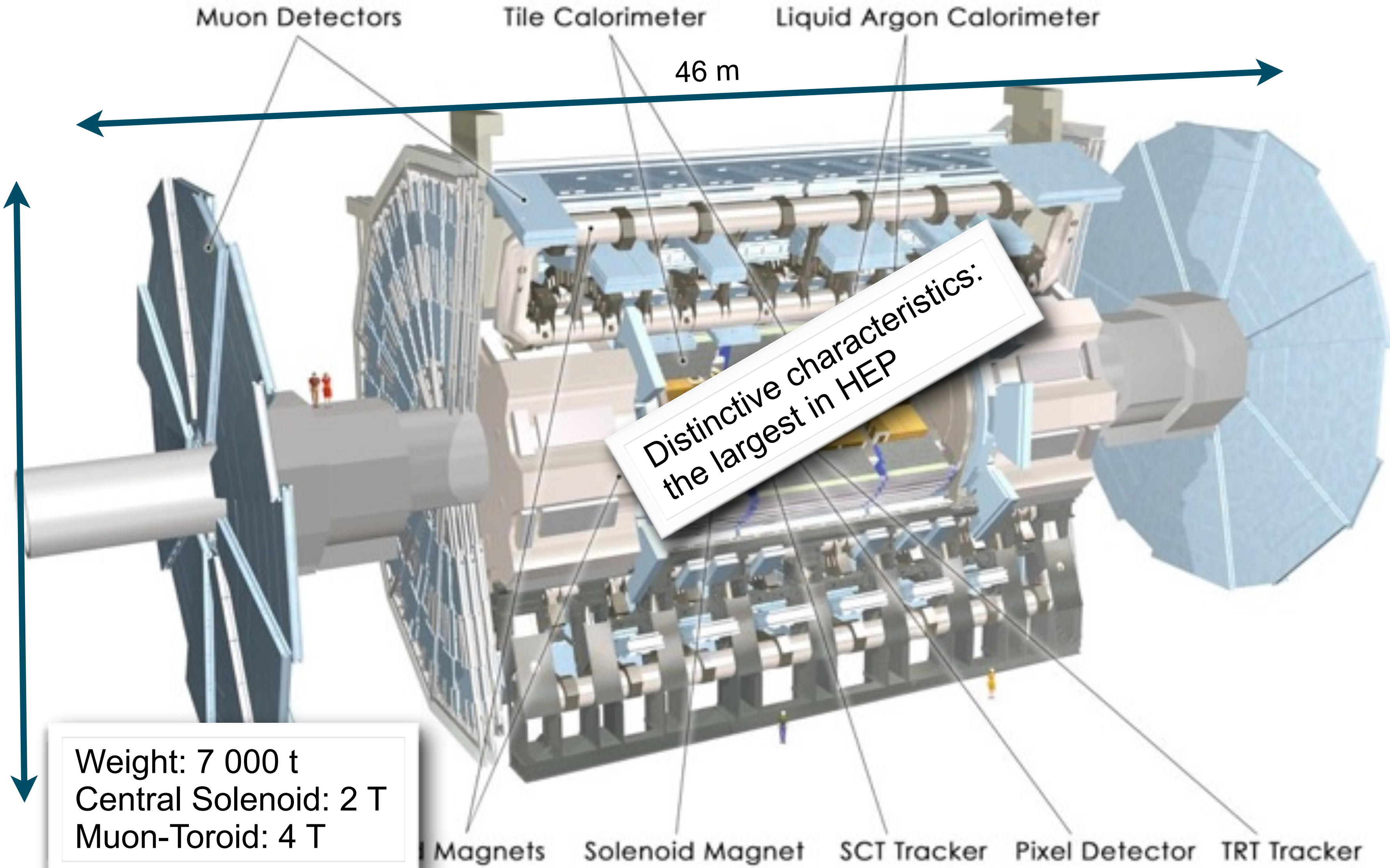
Particle Physics Detectors

- 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





ATLAS@LHC



Distinctive characteristics:
the largest in HEP

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

Illustration: CERN

ATLAS Cross Section

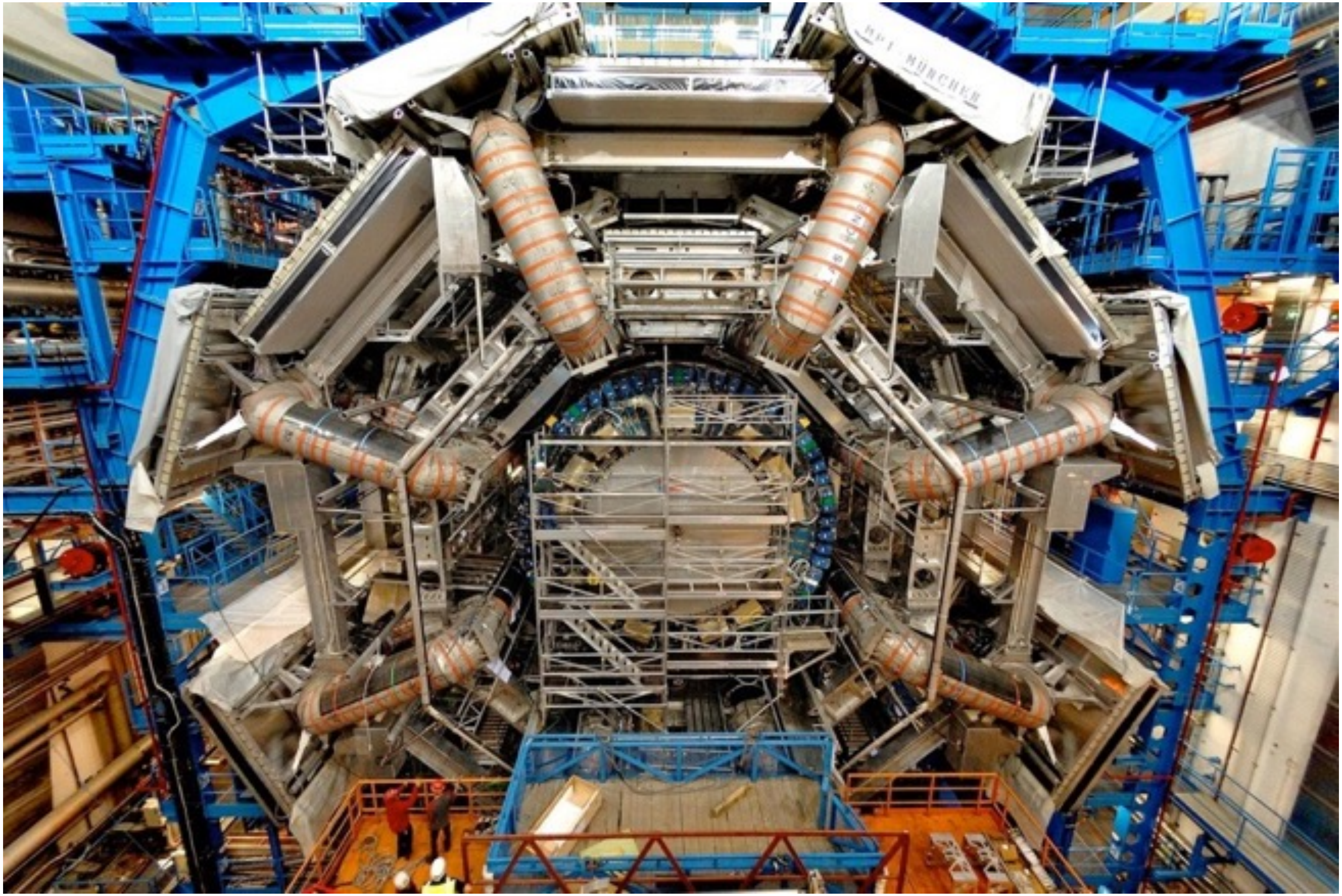
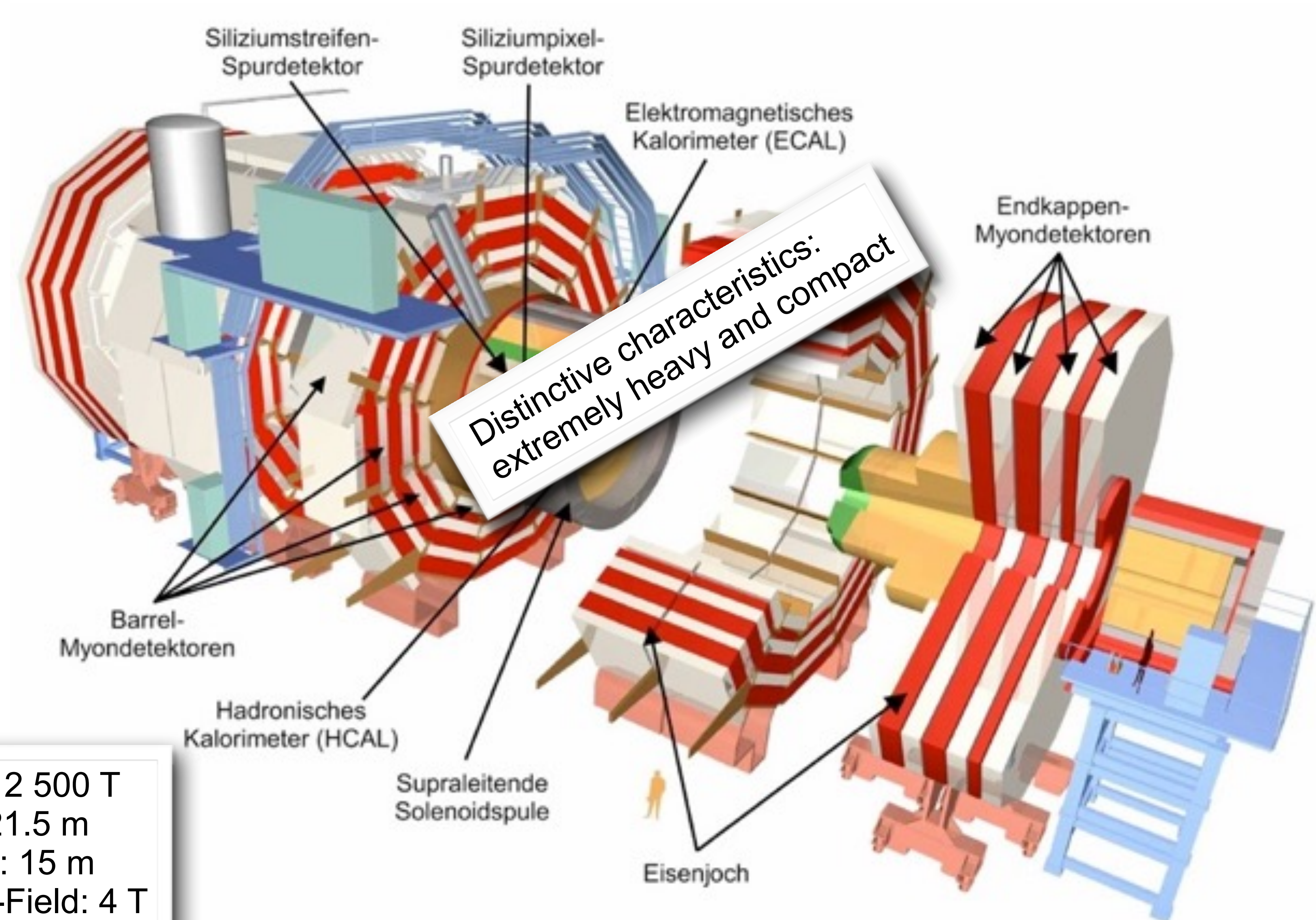


Foto: CERN

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

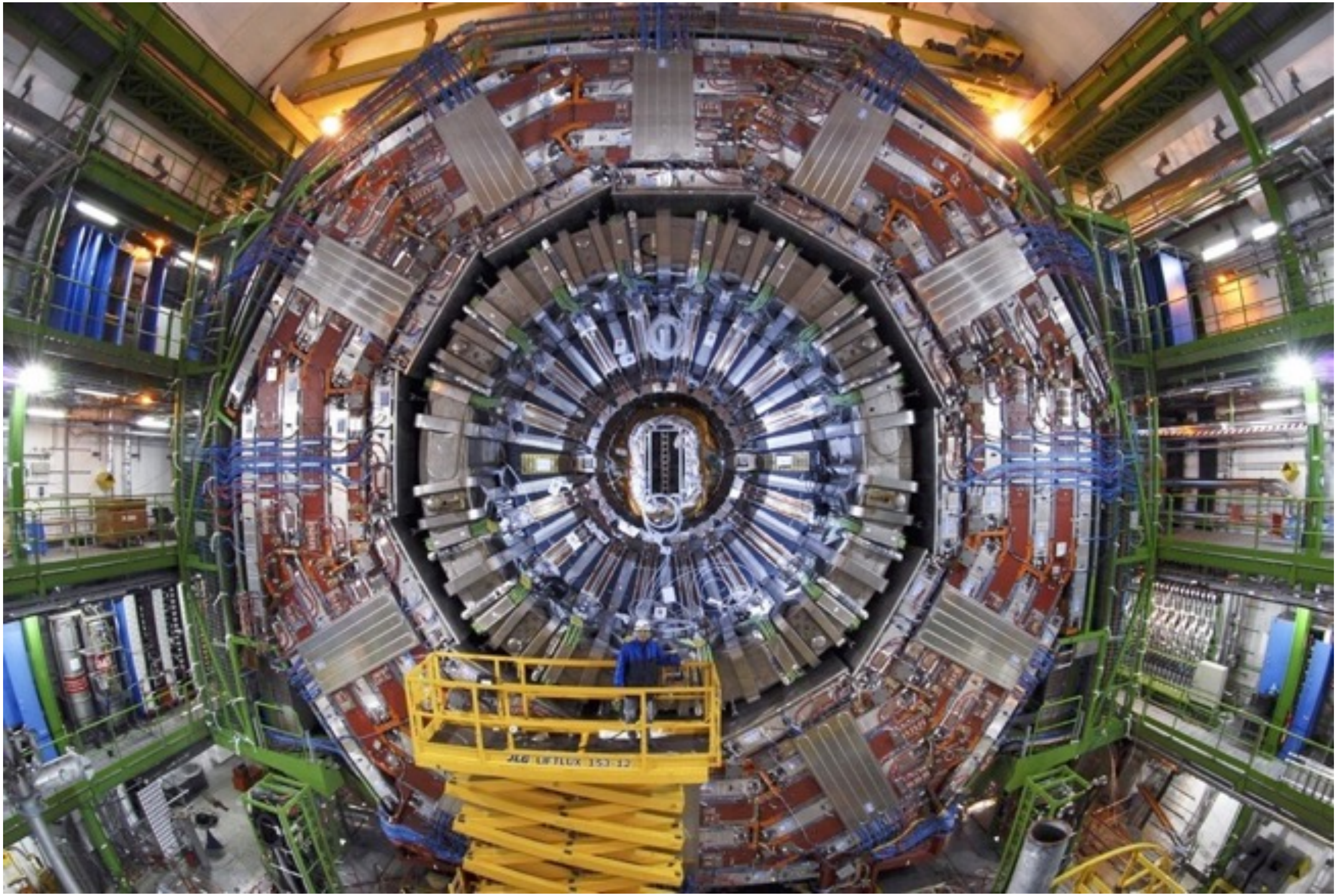


Foto: CERN

Size and Weight

Brandenburger Tor in Berlin

CMS is 65% heavier than the Eiffel tower

12500 t

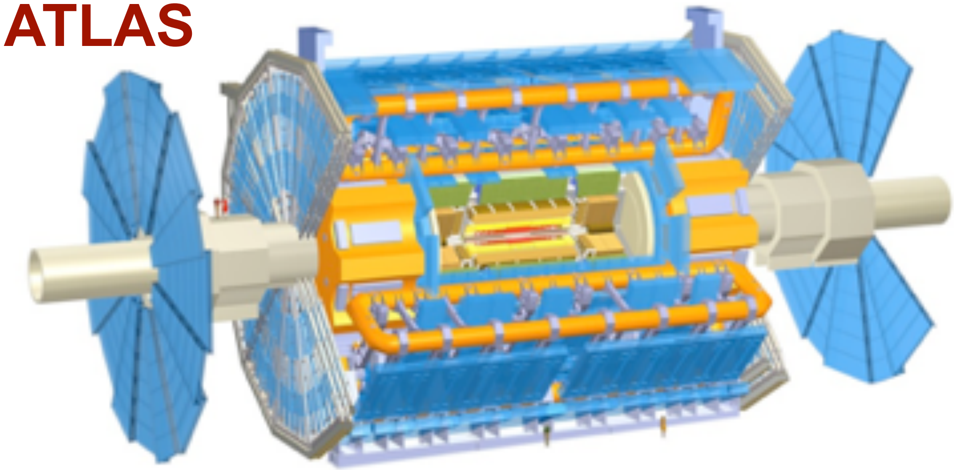
7300 t

mit Hamburg

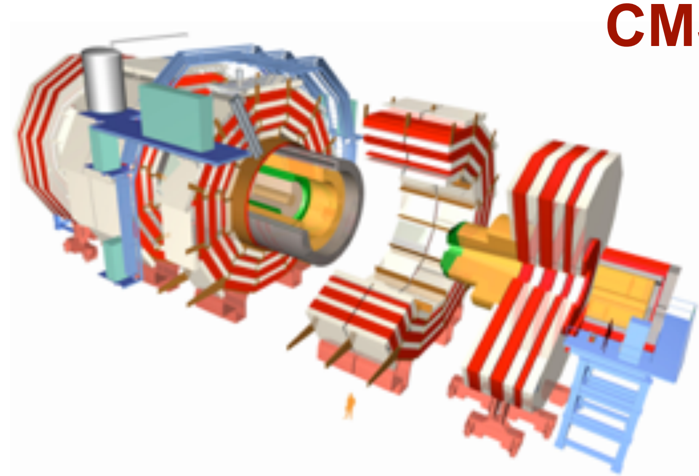
Blue sky !

The Big Ones at LHC ....

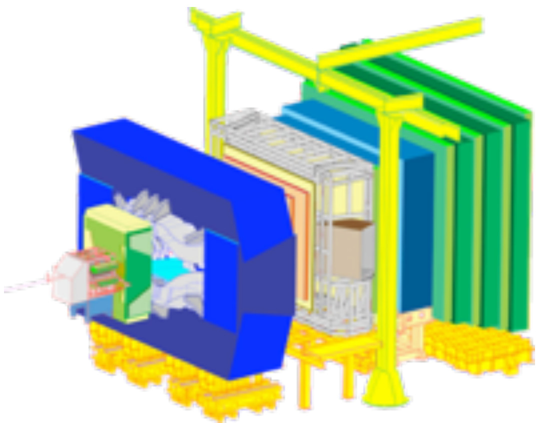
ATLAS



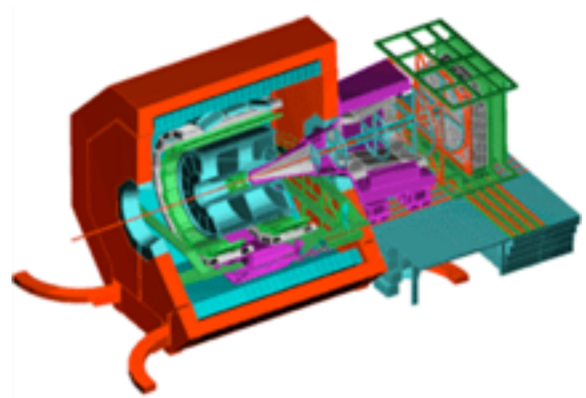
CMS



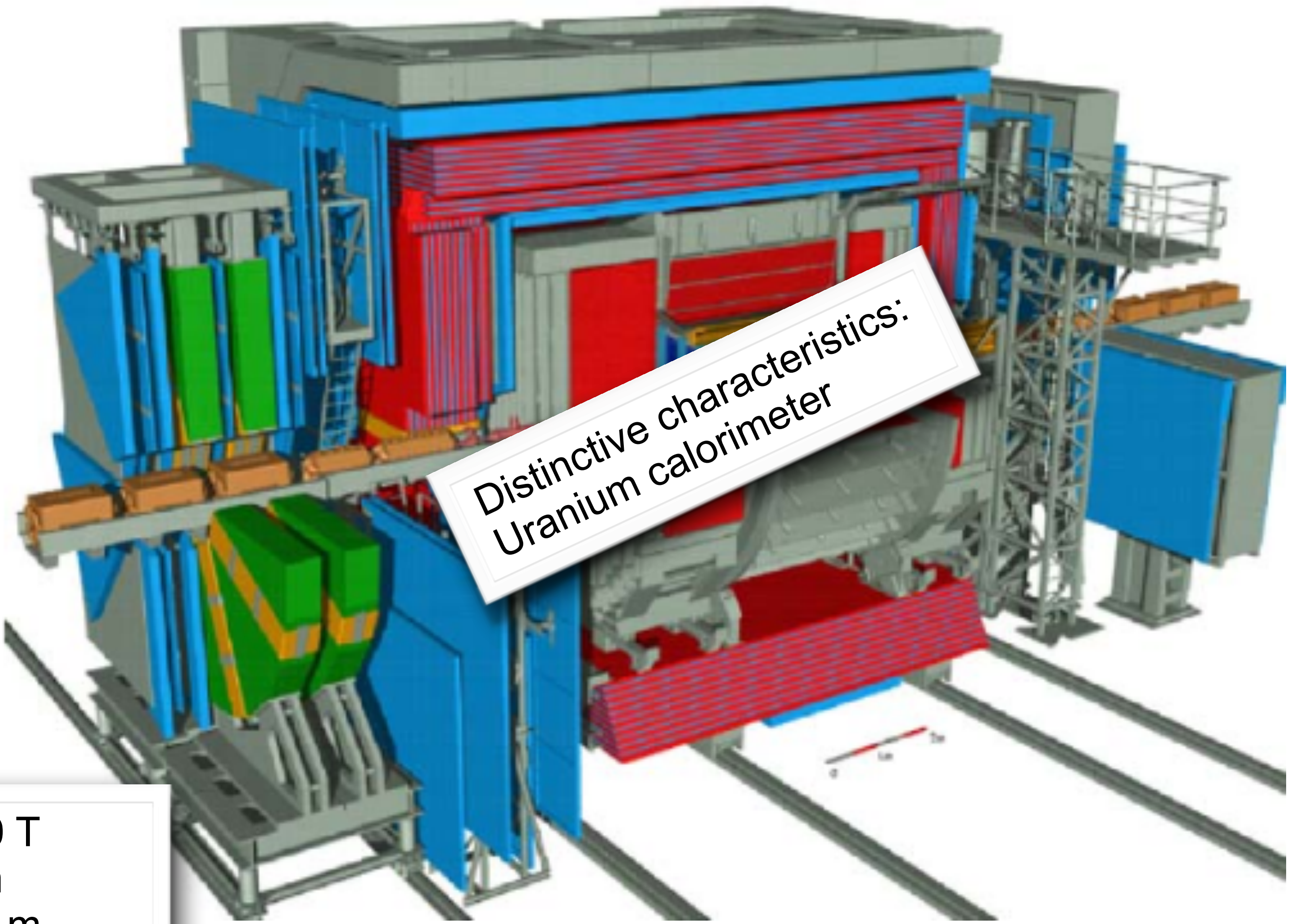
LHCb



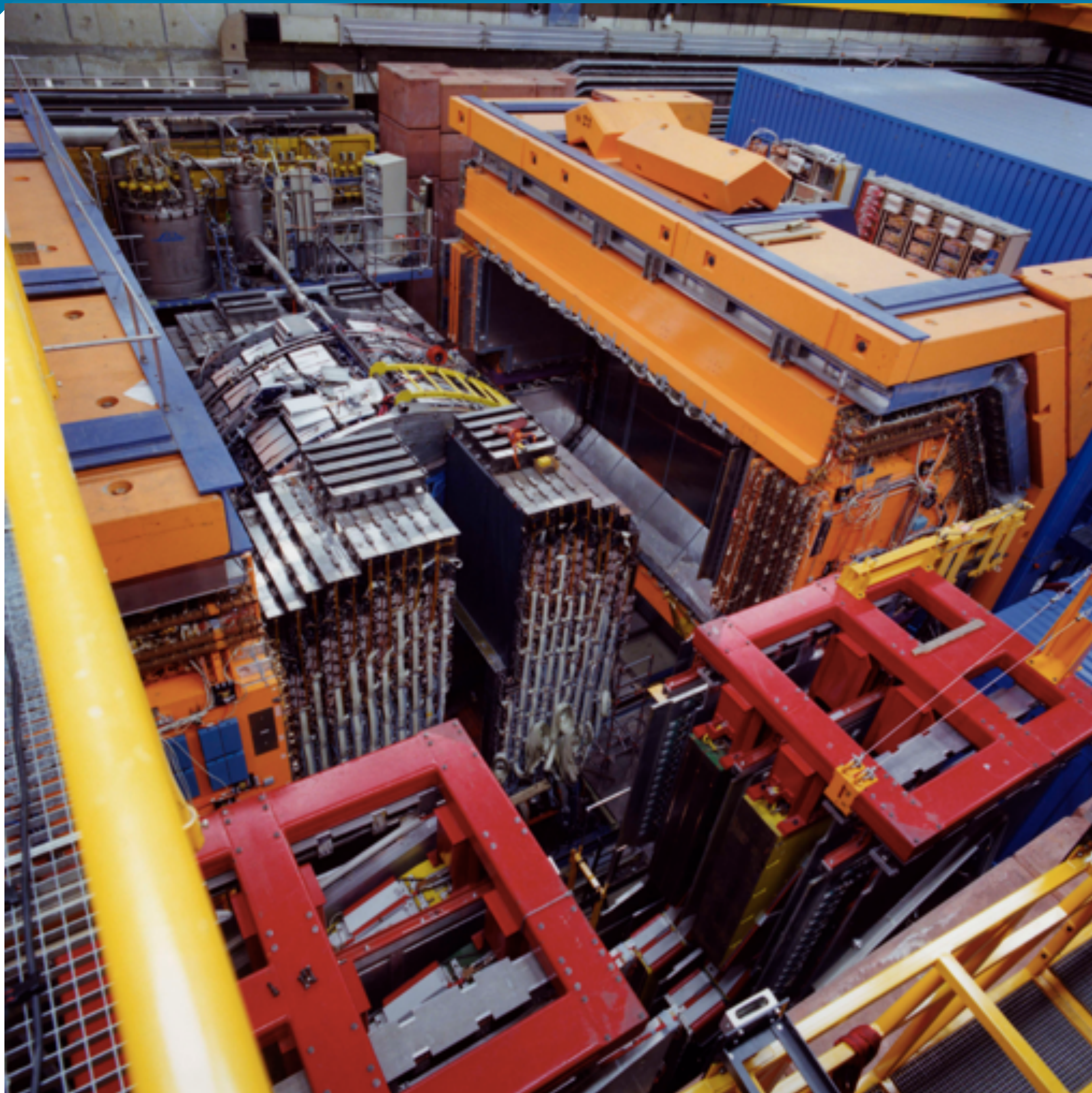
ALICE



The ZEUS Detector@HERA



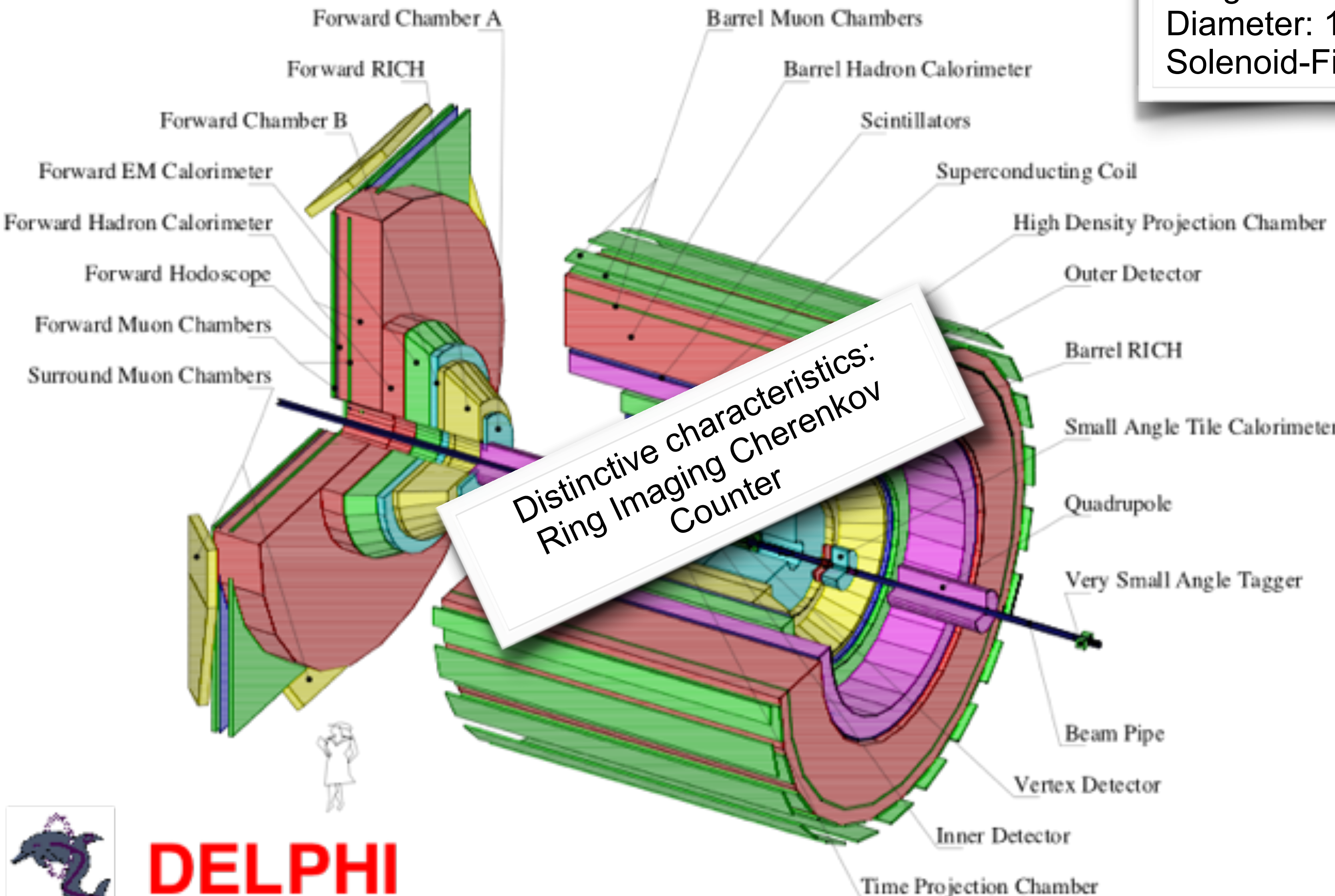
Weight: 3600 T
Length: 19 m
Diameter: 11 m
Solenoid-Field: 1.5 T



ZEUS

THE DELPHI DETECTOR @LEP

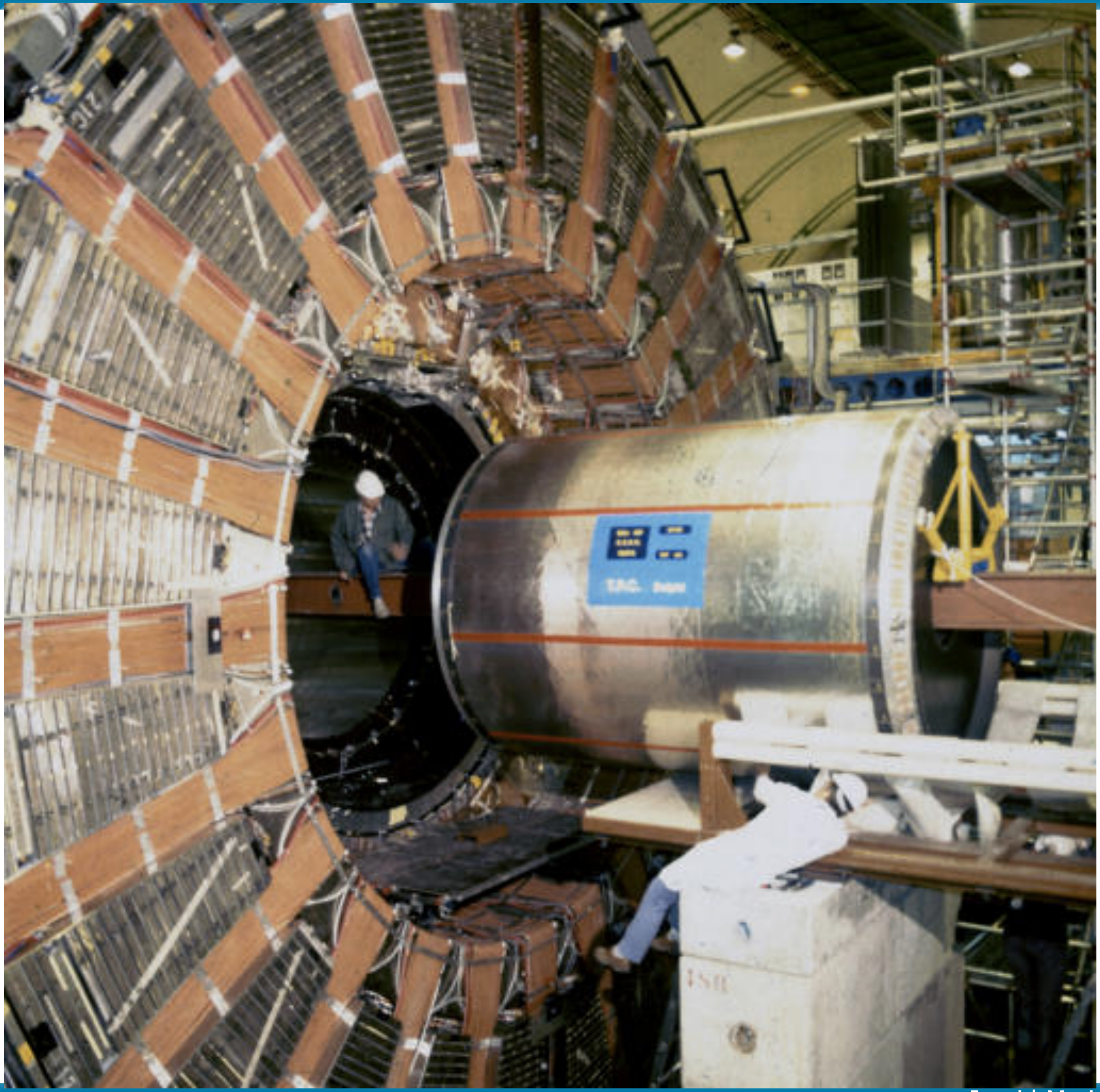
Weight: 3500 T
Length: 10 m
Diameter: 10 m
Solenoid-Field: 1.2 T



Distinctive characteristics: Ring Imaging Cherenkov Counter

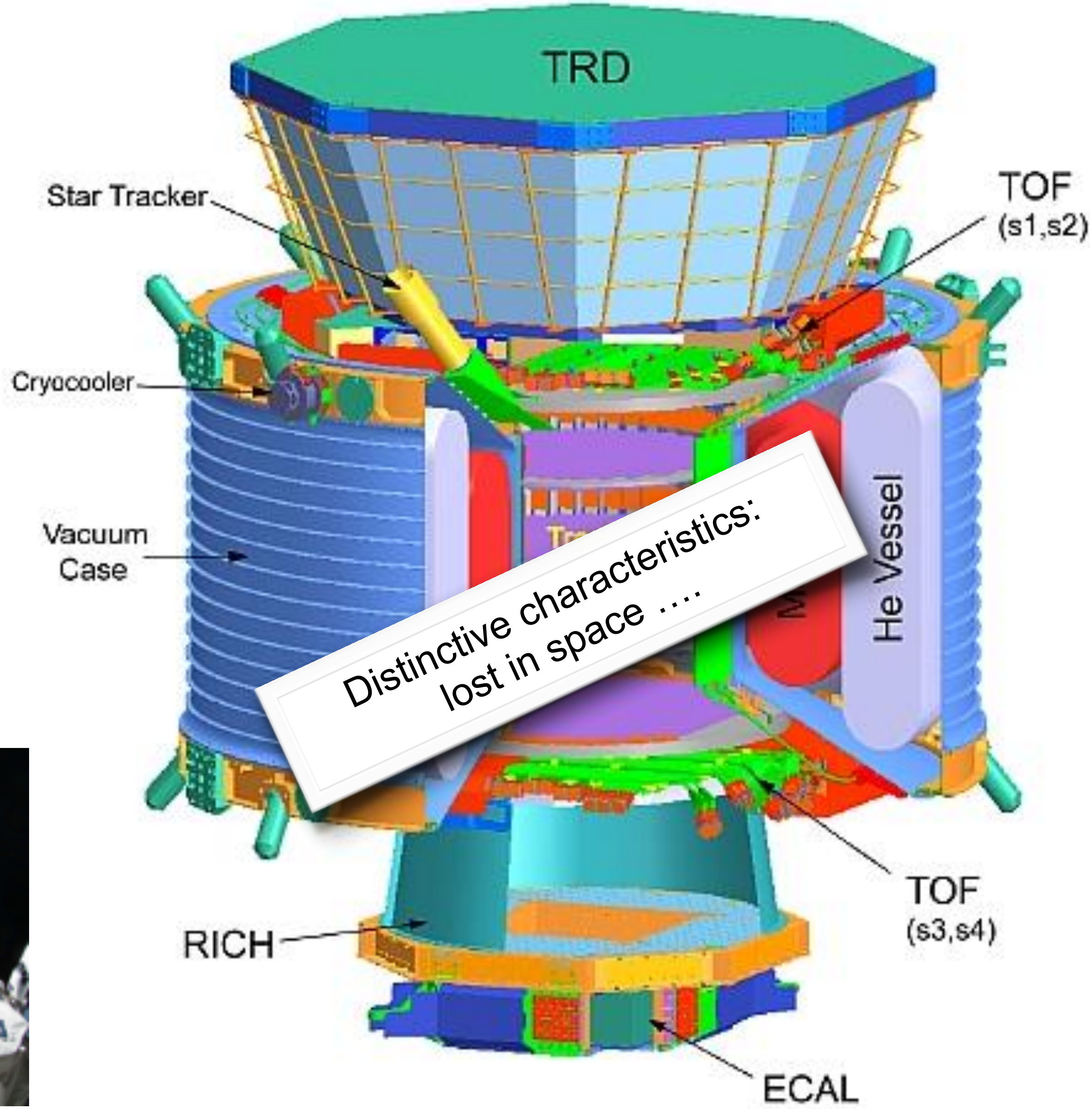
DELPHI

Pic: DELPHI Collaboration


T.A.C.

AMS@ISS

Weight: 1200 T
Length: 6 m
Diameter: 6 m
Solenoid-Field: 1.5 T



Distinctive characteristics:
lost in space ....

picture: AMS collaboration

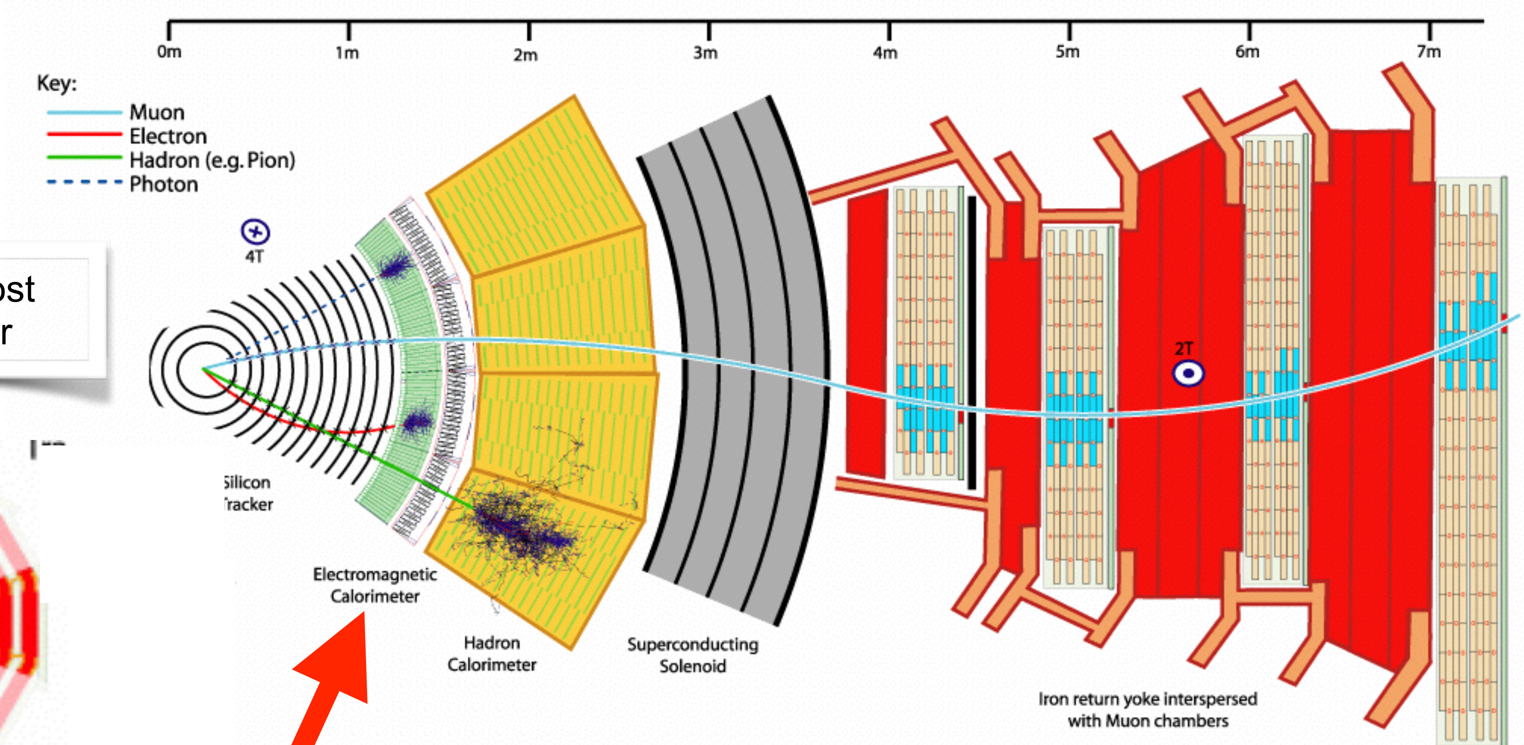
HEP Detector Overview

Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

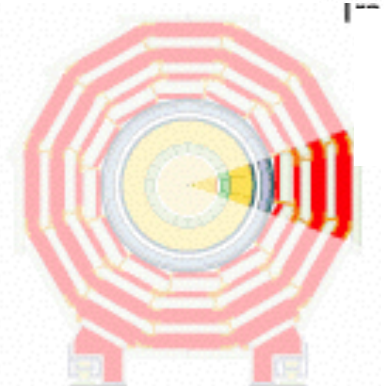
Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Vertex: Innermost tracking detector



picture: CMS@CERN



Transverse slice through CMS

Good energy resolution up to highest energies

Radiation hard (hadron collider)

II. The Basics of All Detection Processes: Interactions with Matter

Analogy

- Planes leave tracks in sky under certain conditions ….

Particles Leave Signals in Matter

- Different effects are involved when a particle passes through matter, depending on mass, charge and energy of the particle.
- Following the effects will be explained for

heavy charged particles (with masses>$m_{electron}$)

electrons/positrons

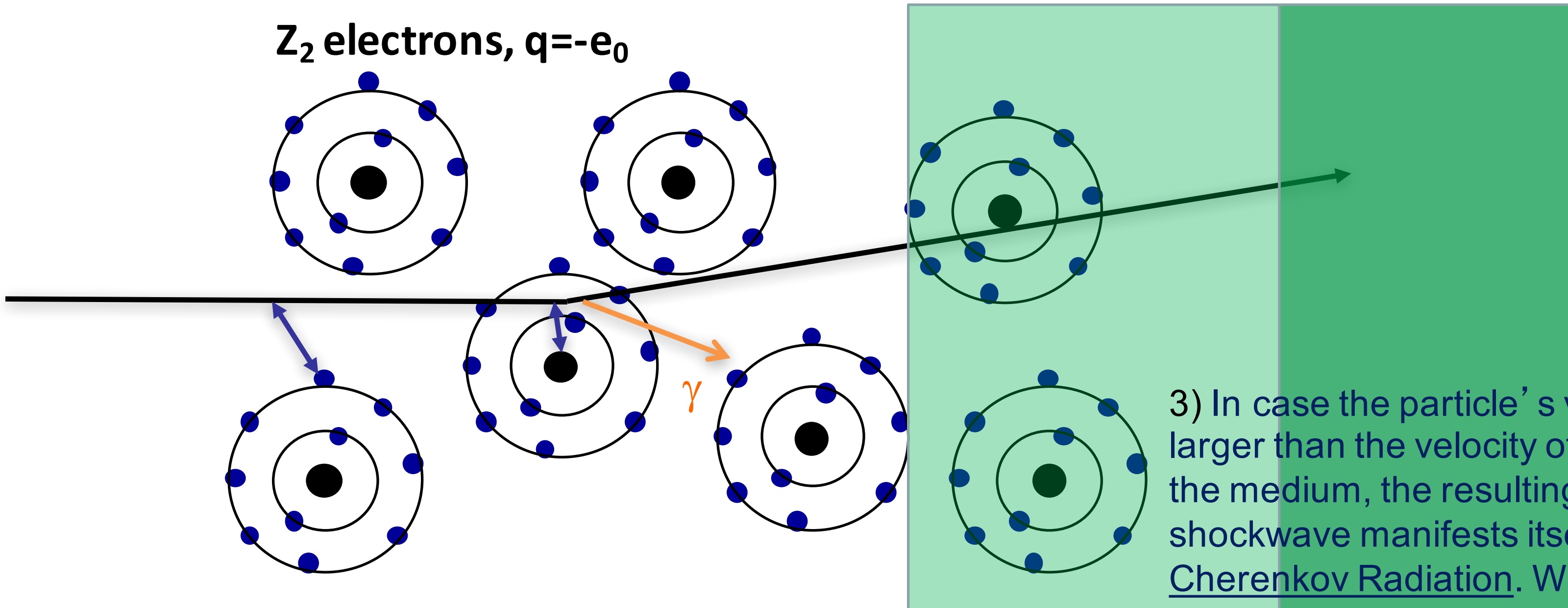
photons

neutrons

http://www.particlezoo.net/

Interaction of Charged Particles

- Three type of electromagnetic interactions:
  1. Ionization (of the atoms of the traversed material)
  2. Emission of Cherenkov light
  3. Emission of transition radiation



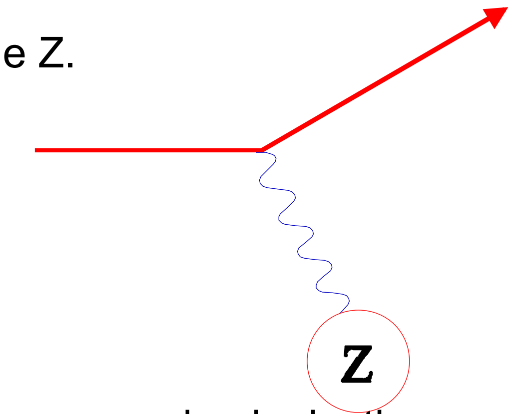
1) Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized

2) Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

3) In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability in the order of 1% to produce an X ray photon, called Transition radiation.

Heavy Charged Particle

- Incoming particle interacts elastically with a target of nuclear charge Z.



Cross section

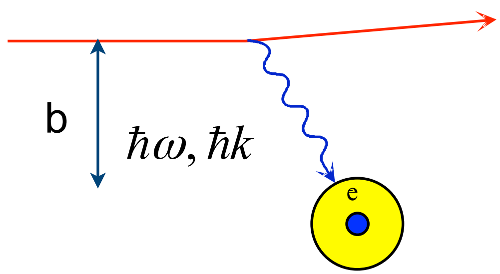
$$\frac{d\sigma}{d\Omega} = 4z^2 Z^2 r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \frac{\theta}{2}}$$

Rutherford Formula

- Heavy charged particles transfer energy mostly to the atomic electrons causing ionisation and excitation.

$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty N E \frac{d\sigma}{dE} h d\omega$$

N: electron density



- Simple model ($M \gg m_e$):
  - consider energy transfer of particle to single electron (distance b)
  - multiply with the number of independent electrons passed (Z)
  - integrate over all distances b

→ **Bethe-Bloch Formula**

Interactions of "heavy" Particles with Matter

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

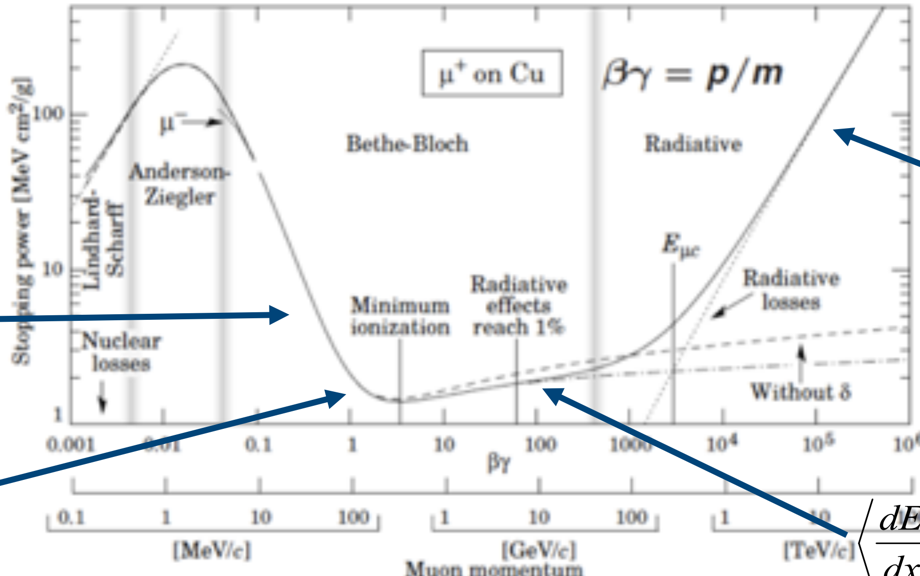
$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}]$$

$T_{\max}$ 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



Bremsstrahlung

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

"kinematic term"

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

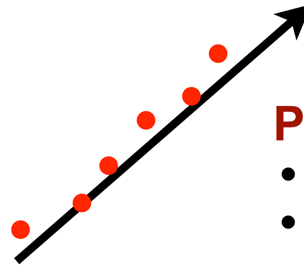
$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$

"relativistic rise"

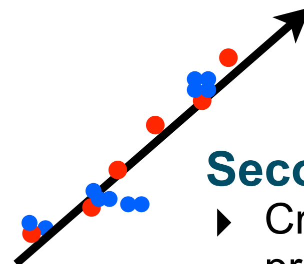
Plot: PDG, July 2012

A Closer Account of Energy Loss

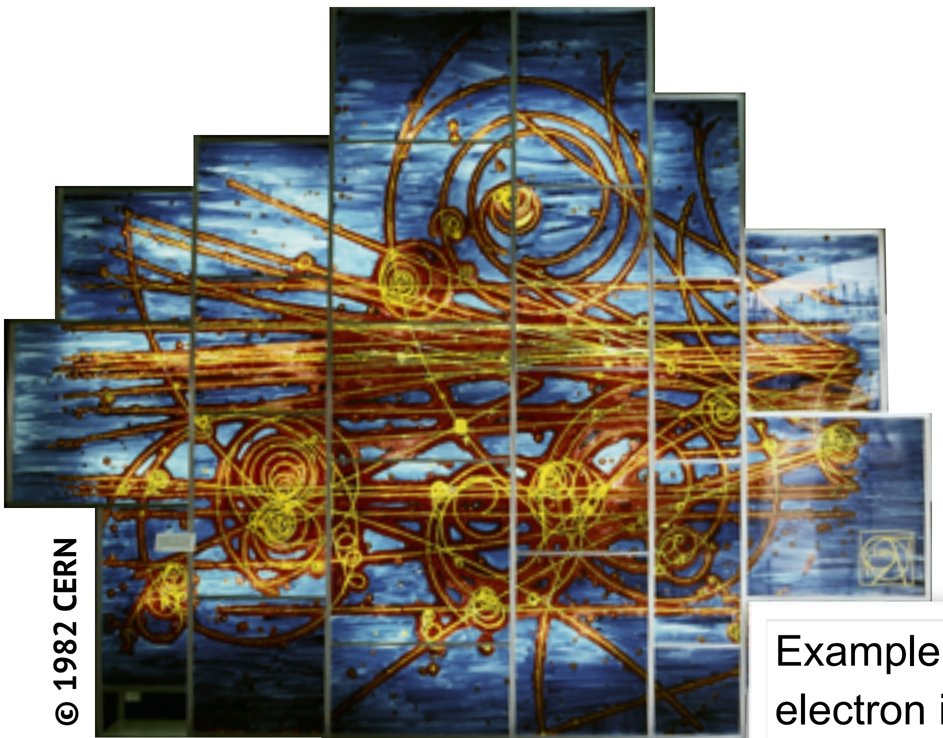
- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



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



© 1982 CERN

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

Liquid hydrogen bubble chamber 1960 (~15cm).

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

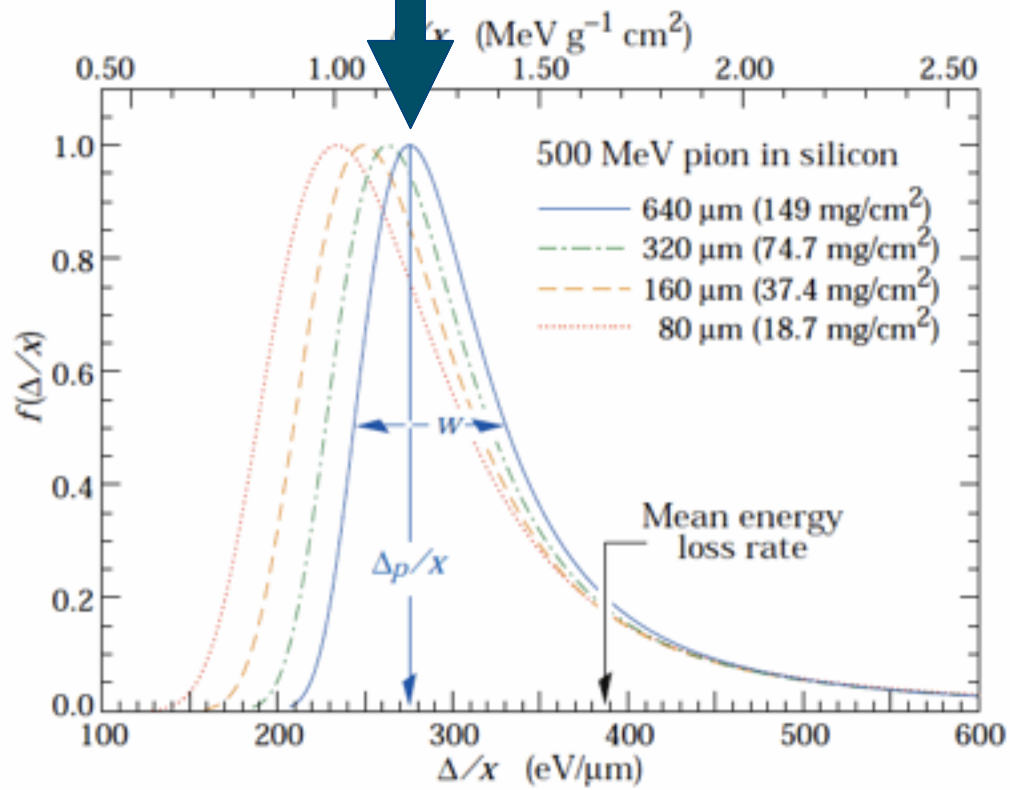
Energy Loss in Thin Layers

- In case of thin detectors the variation width within the energy transfer of the reactions leads to a large variation of the energy loss:
  - A broad maximum: collisions with little energy loss
  - A long tail towards higher energy loss: few collisions with large energy loss T_{max}, δ-electrons.

most probable peak!

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

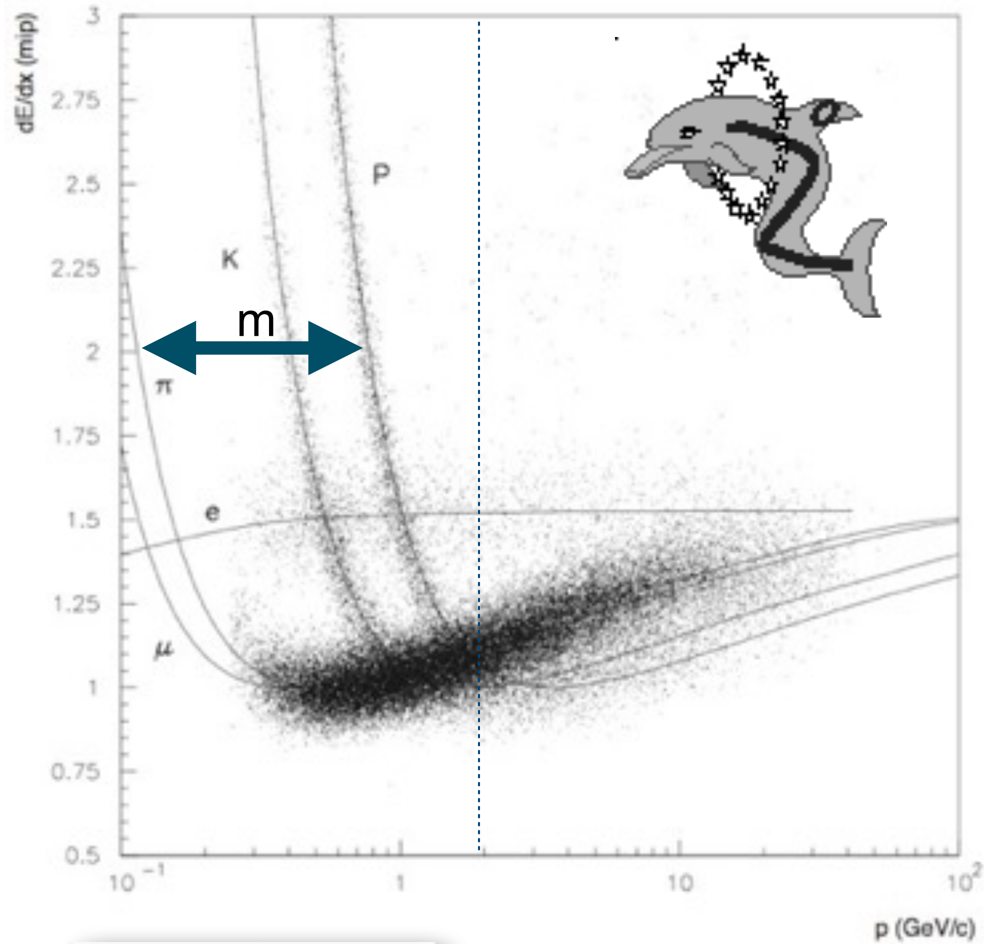
Thin absorber:
$\langle dE \rangle < \sim 10 T_{max}$



Particle Identification Using dE/dx

- The energy loss as a function of particle momentum $p = mc\beta\gamma$ **is** depending on the particle's mass.
- By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass.

➡ **Particle Identification at low energies (p<2GeV/c)**

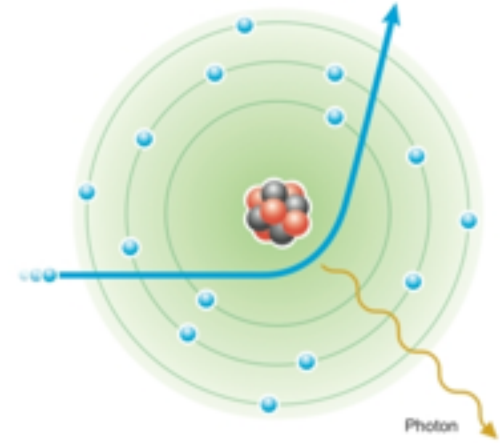


Nucl. Instr. and Meth. A378 (1996) 57

Example:
DELPHI@ LEP

Bremsstrahlung

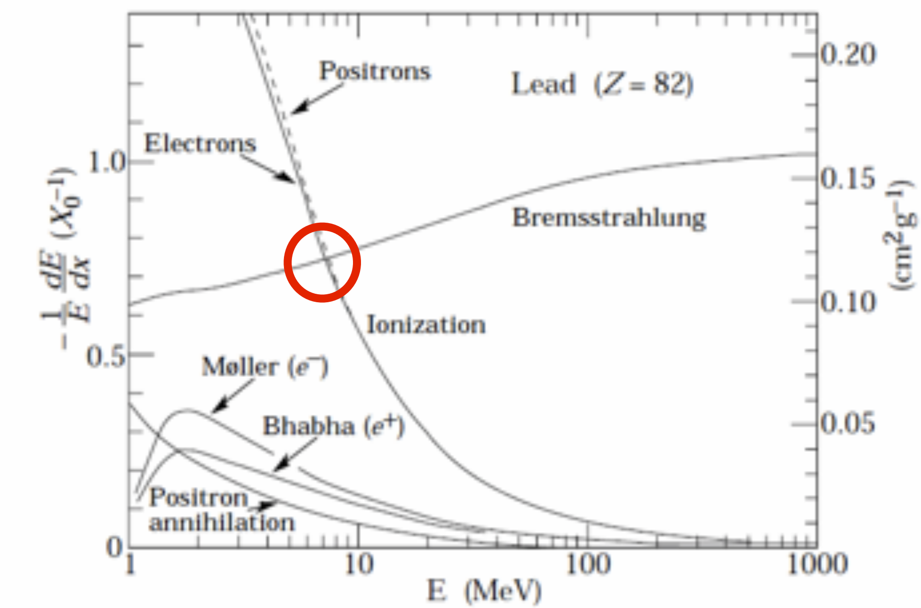
- Deflection of a charge in a strong nuclear E-field -> emission of a photon.



Incident electron and Bremsstrahlung photon.

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

- Effect plays a role only for $e^{\pm}$ and ultra-relativistic μ (>1000 GeV).

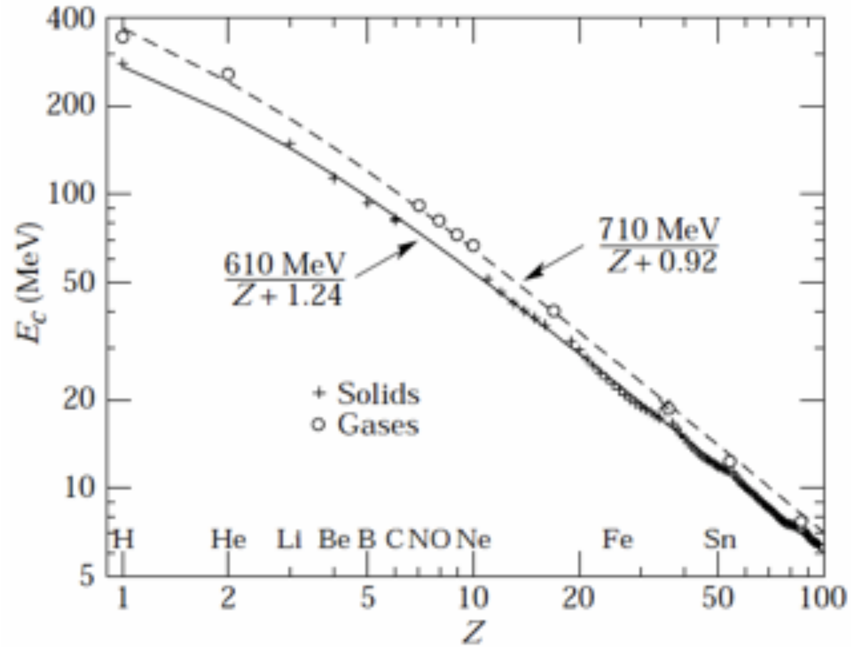


Energy loss for anything heavier than an electron is dominated by ionisation.

- Bremsstrahlung is dominating at high energies
- At low energies: ionisation, additional scattering

Electrons: Energy Loss

- **Critical energy:** the energy at which the losses due to ionisation and Bremsstrahlung are equal $$\frac{dE}{dx}(E_c) = \frac{dE}{dx}(E_c)$$



For electrons approximately:

$$E_c^{\text{solid+liq}} = \frac{610 MeV}{Z+1.24} \qquad E_c^{\text{gas}} = \frac{710 MeV}{Z+1.24}$$

For electrons

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

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

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

Parameters only depending on material the electron is passing through.

X_0:Radiation length

Electrons and Photons: Radiation Length

- Radiation length: an important parameter for particle detectors
- Thickness of material an electron travels through
  - until the energy is reduced by Bremsstrahlung to 1/e of its original energy

empirical:

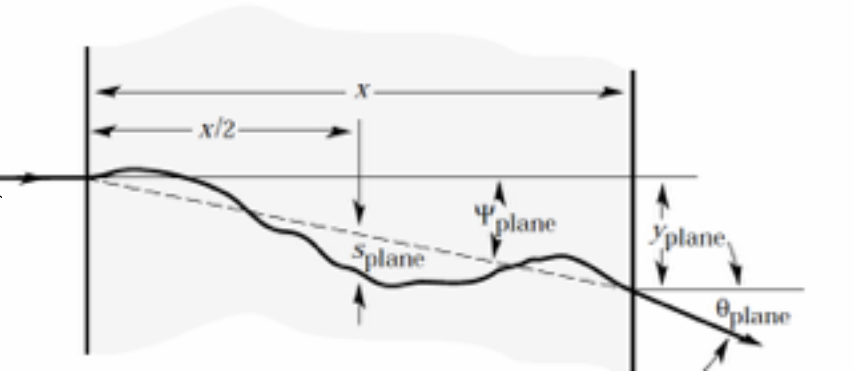
$$X_0 = \frac{716.4\, A}{Z(1+Z)\, ln(287/\sqrt{Z})} \frac{g}{cm^2} \propto \frac{A}{Z^2}$$

- 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/cm^2], typical values are:
  - Air: 36.66 g/cm^2 ->~ 300 m
  - Water: 36.08 g/cm^2 -> ~ 36 cm
  - Silicon: 21.82 g/cm^2 -> 9.4 cm
  - Aluminium: 24.01 g/cm^2 -> 8.9 cm
  - Tungsten: 6.76 g/cm^2 -> 0.35 cm

Multiple Scattering!

- Charged particles are forced to deviate from a straight track when moving through a medium: multiple scattering mostly due to Coulomb field.
- Cumulative effect of these small angle scatterings is a net deflection from the original particle direction.



Pic: PDG, June 2012

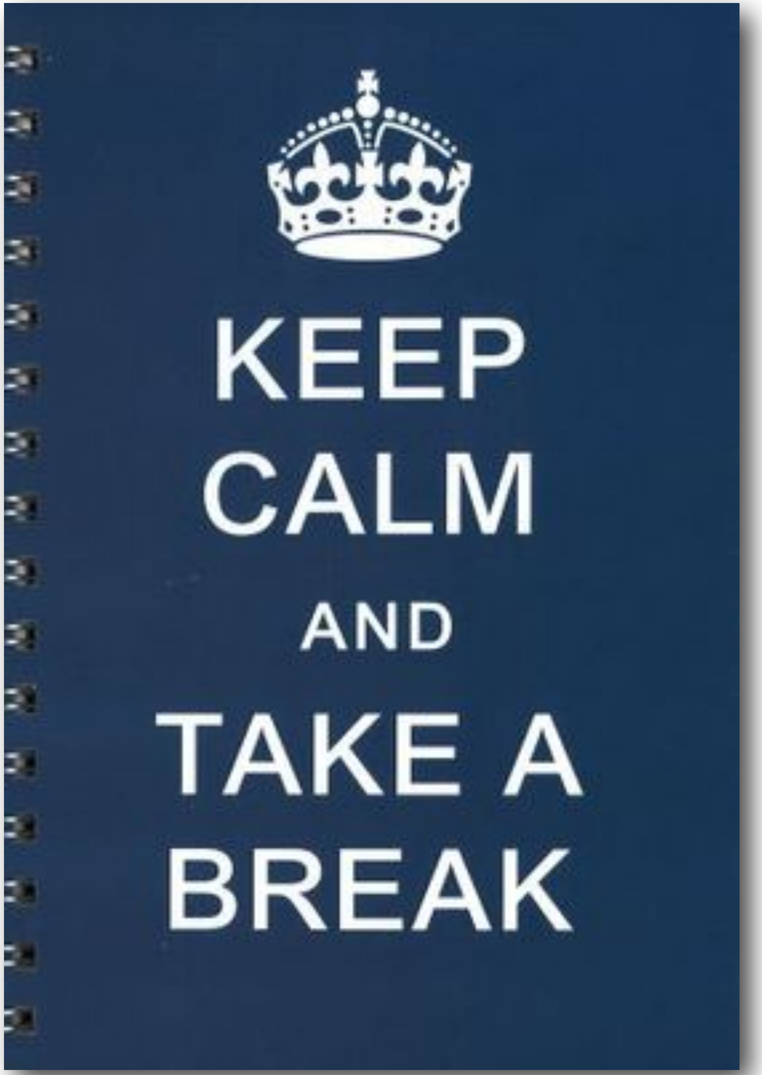
$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}} \theta_{\text{space}}^{\text{rms}}$$

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

- the smaller the momentum the larger the effect
- kind of Gaussian around original direction

Gaussian approximation sufficient for many applications.

AND NOW ... ?



10 minutes
coffee break ….