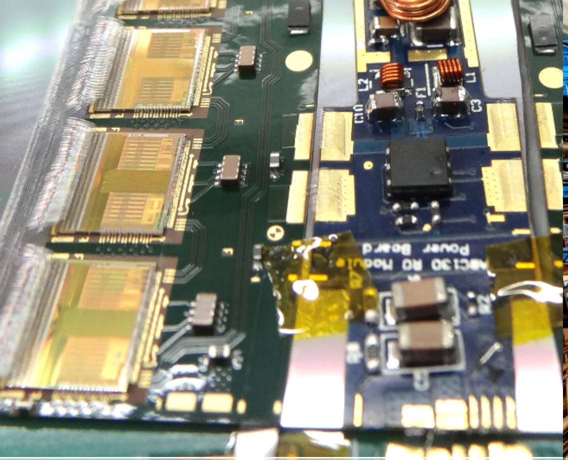
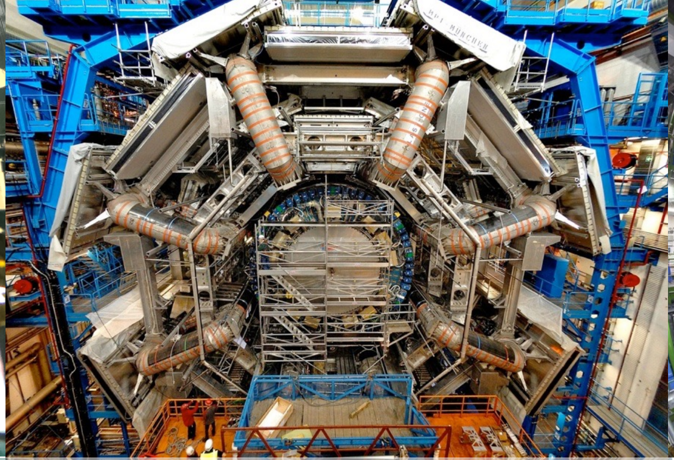
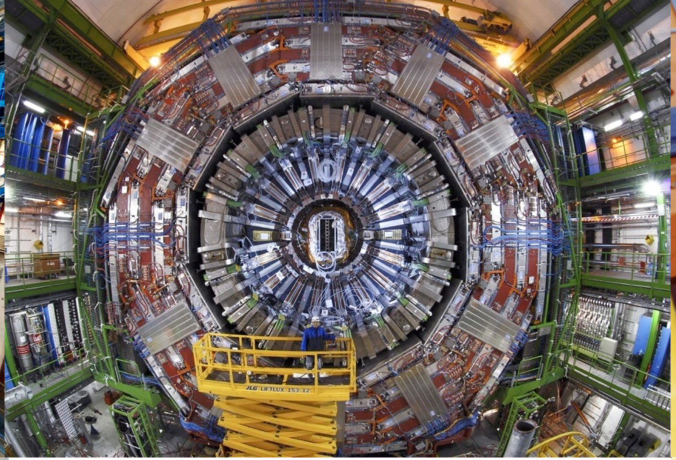
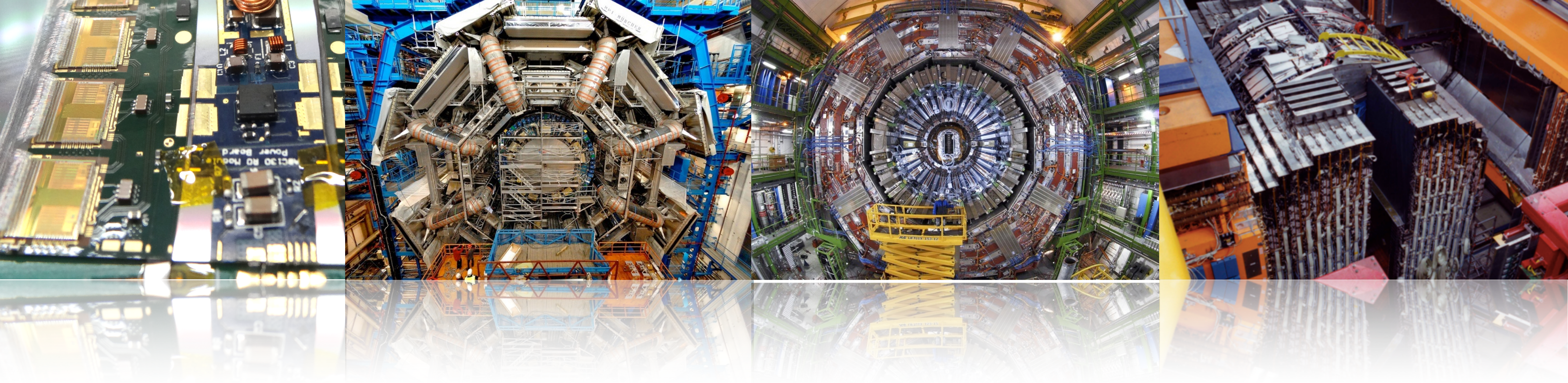





Detectors for High energy Physics

Ingrid-Maria Gregor
DESY/Universität Bonn
Summerstudents 2019
30.07.2019



Detectors for High energy Physics

Part 1

Ingrid-Maria Gregor
DESY/Universität Bonn

Summerstudents 2019
30.07.2019

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**

III. **Calorimeters**

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

V. **Examples from the real life**

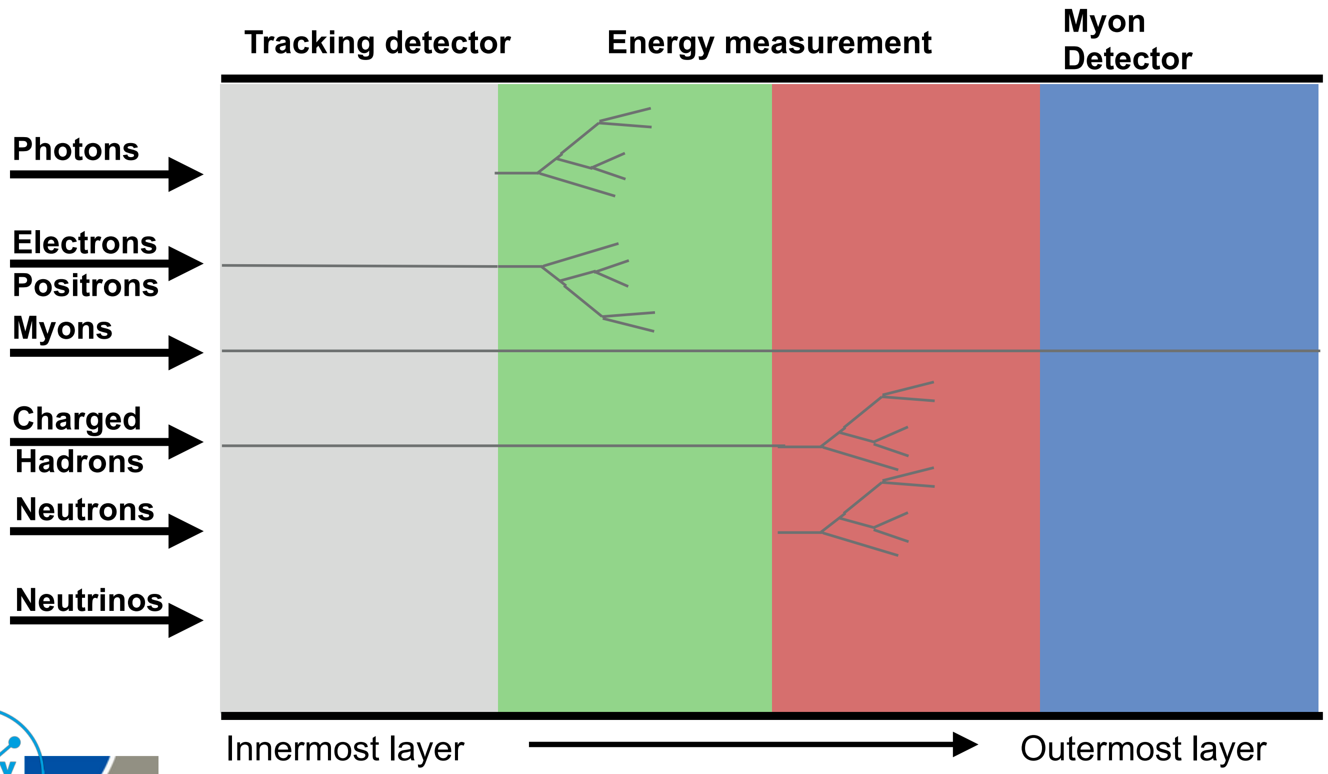
} *Tuesday*

} *Wednesday*

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



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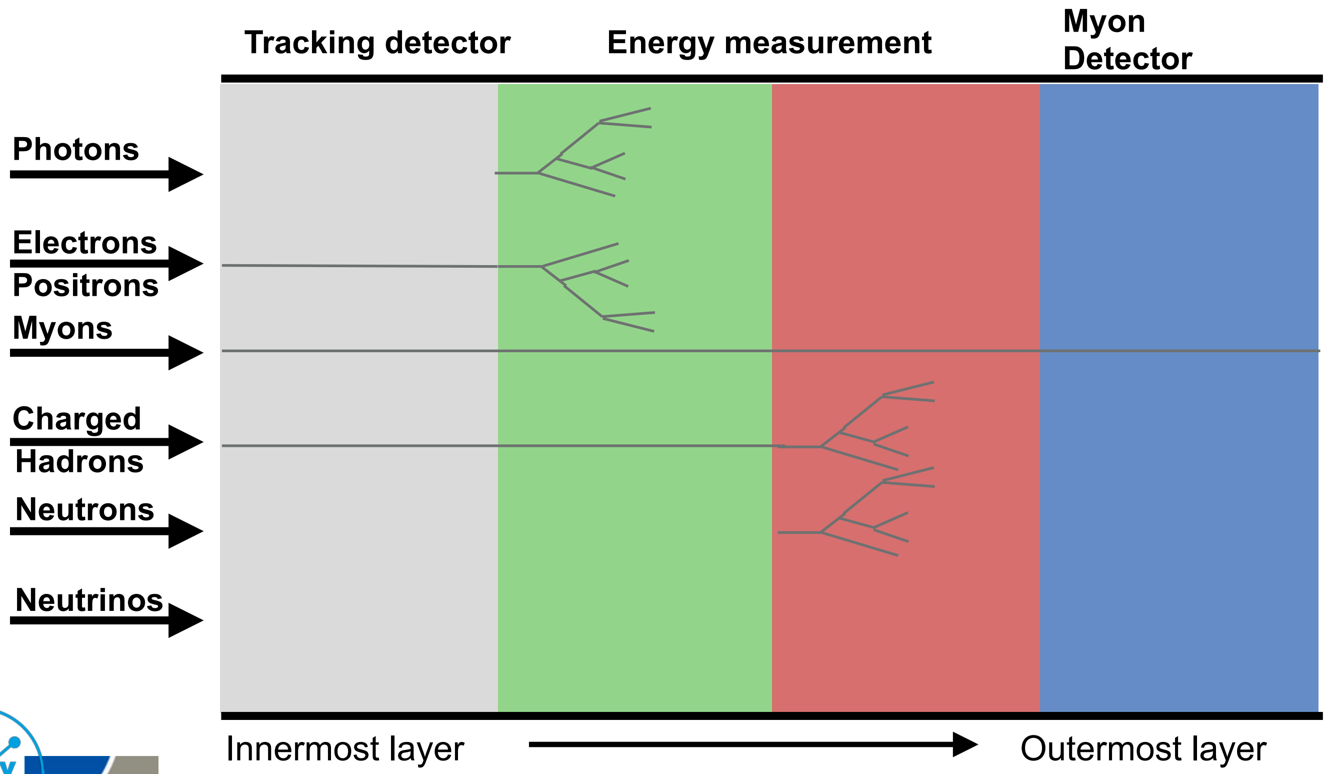
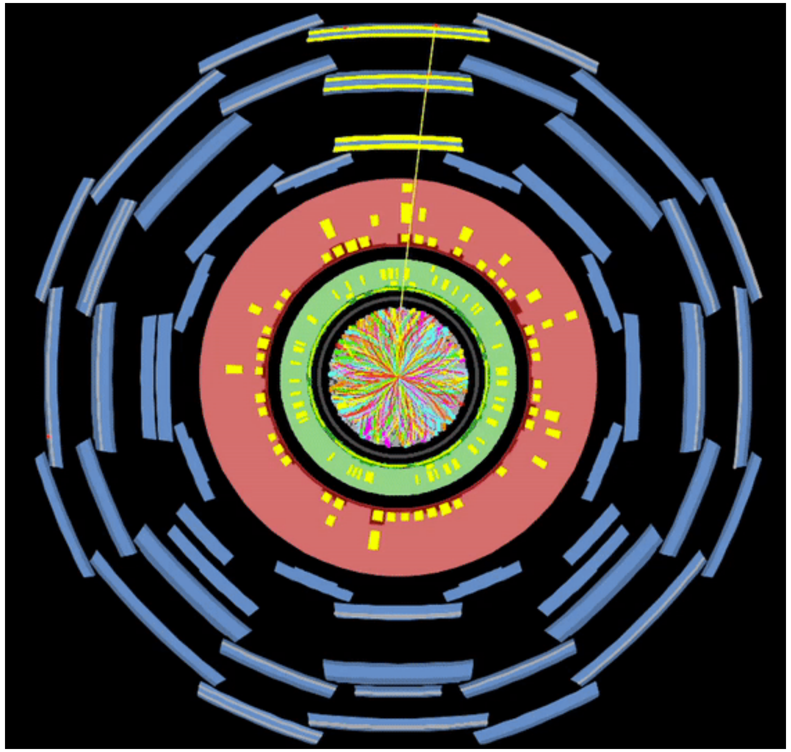
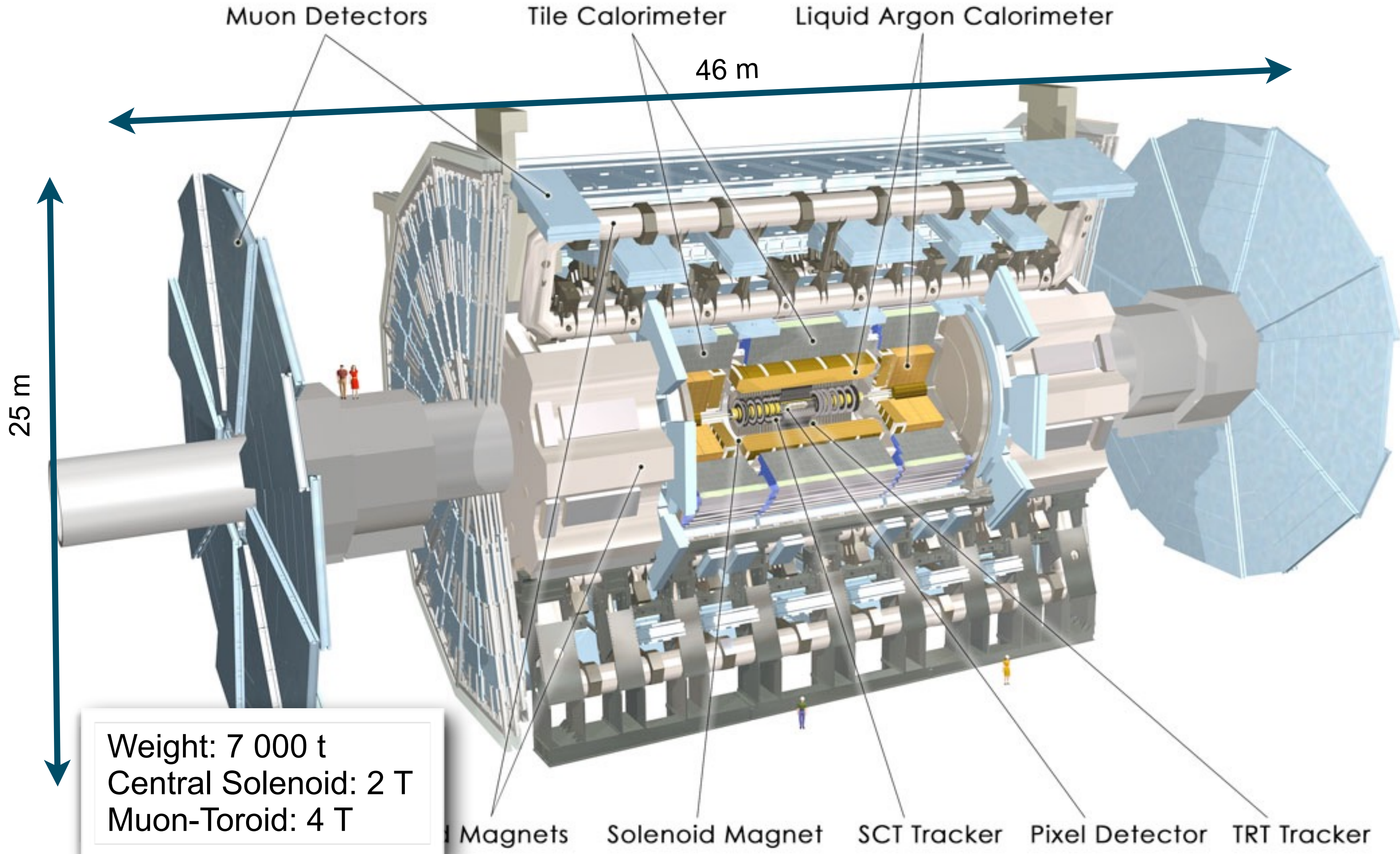




ATLAS@LHC



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

Illustration: CERN

ATLAS@LHC

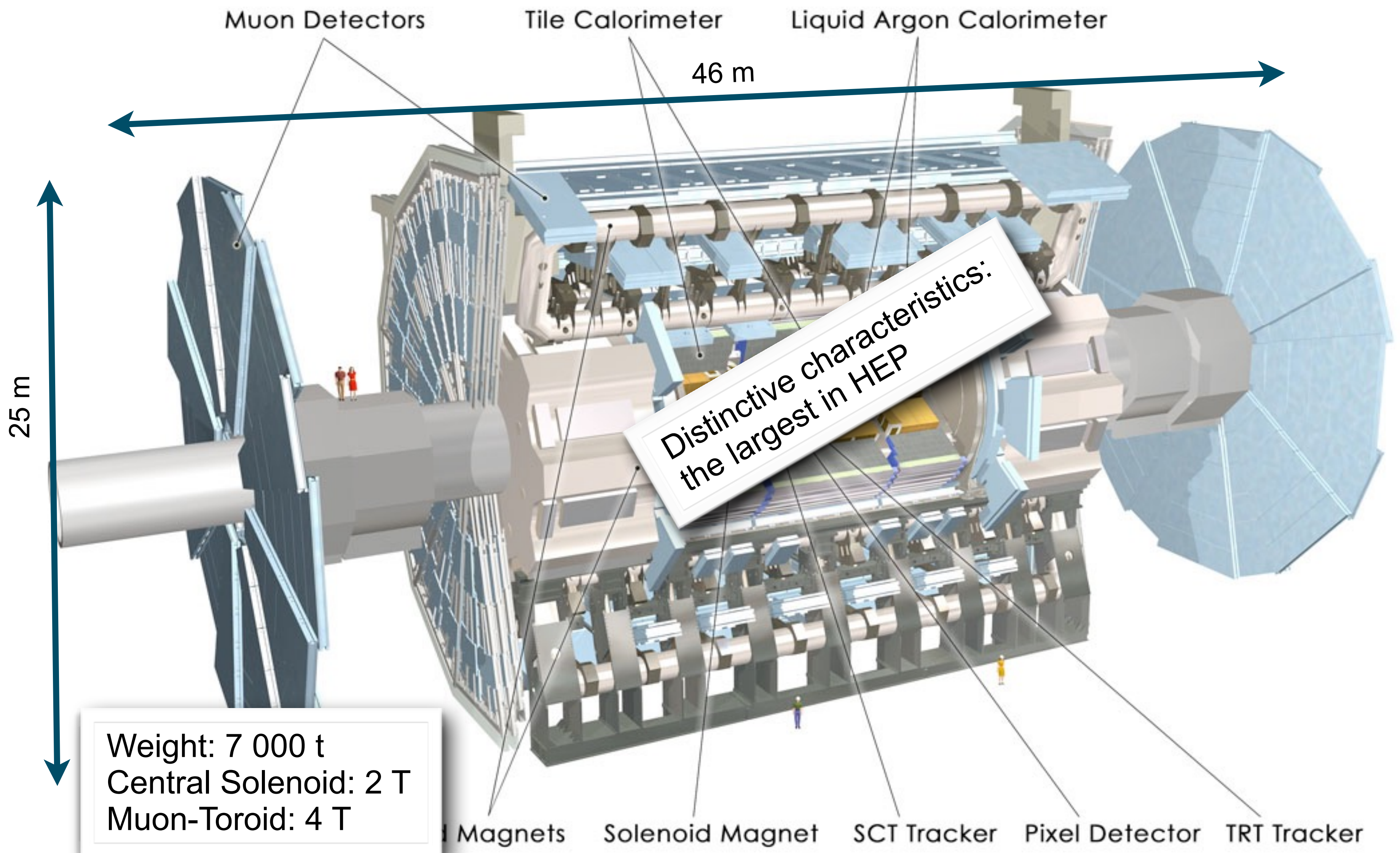


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Illustration: CERN

ATLAS Cross Section

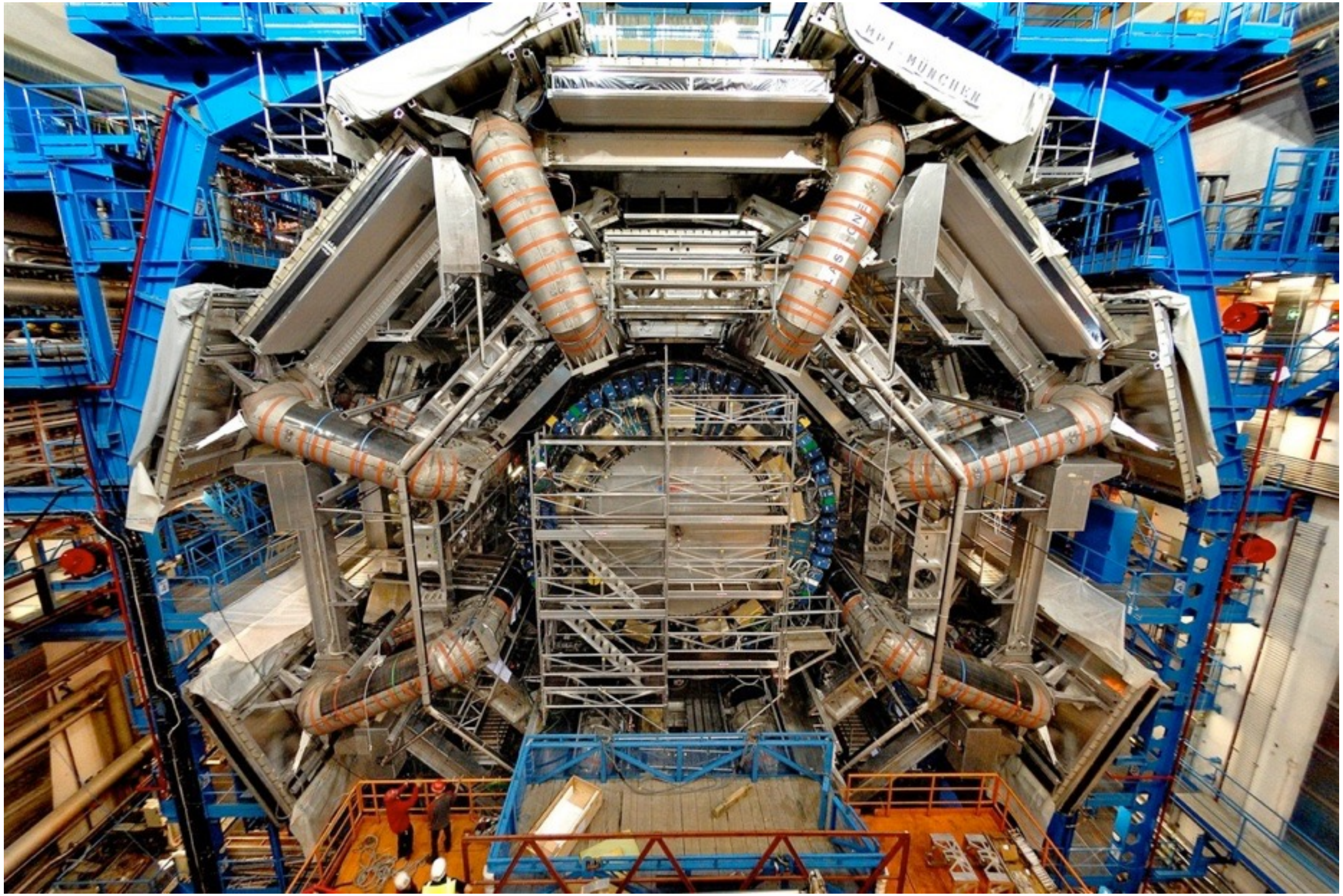
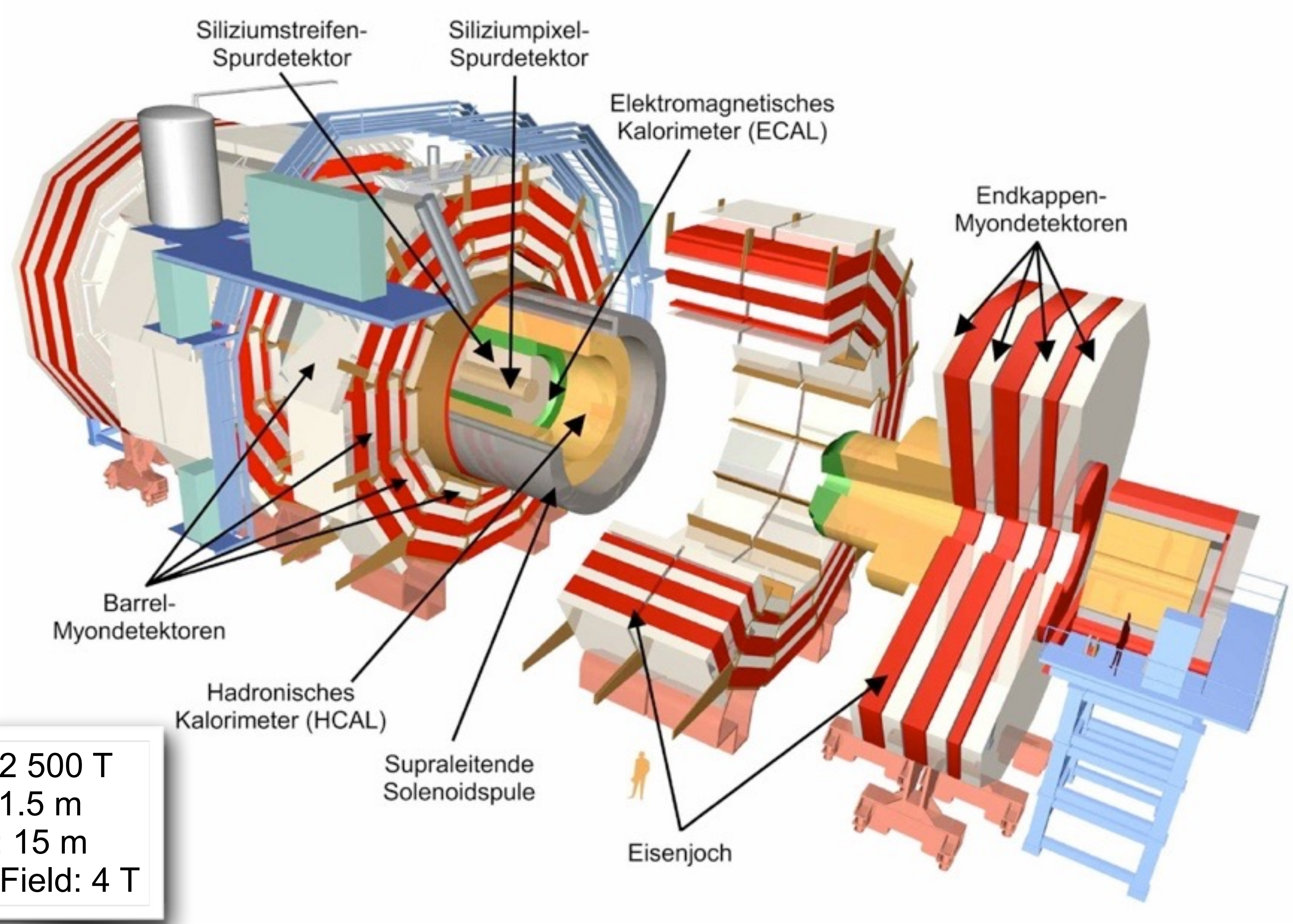


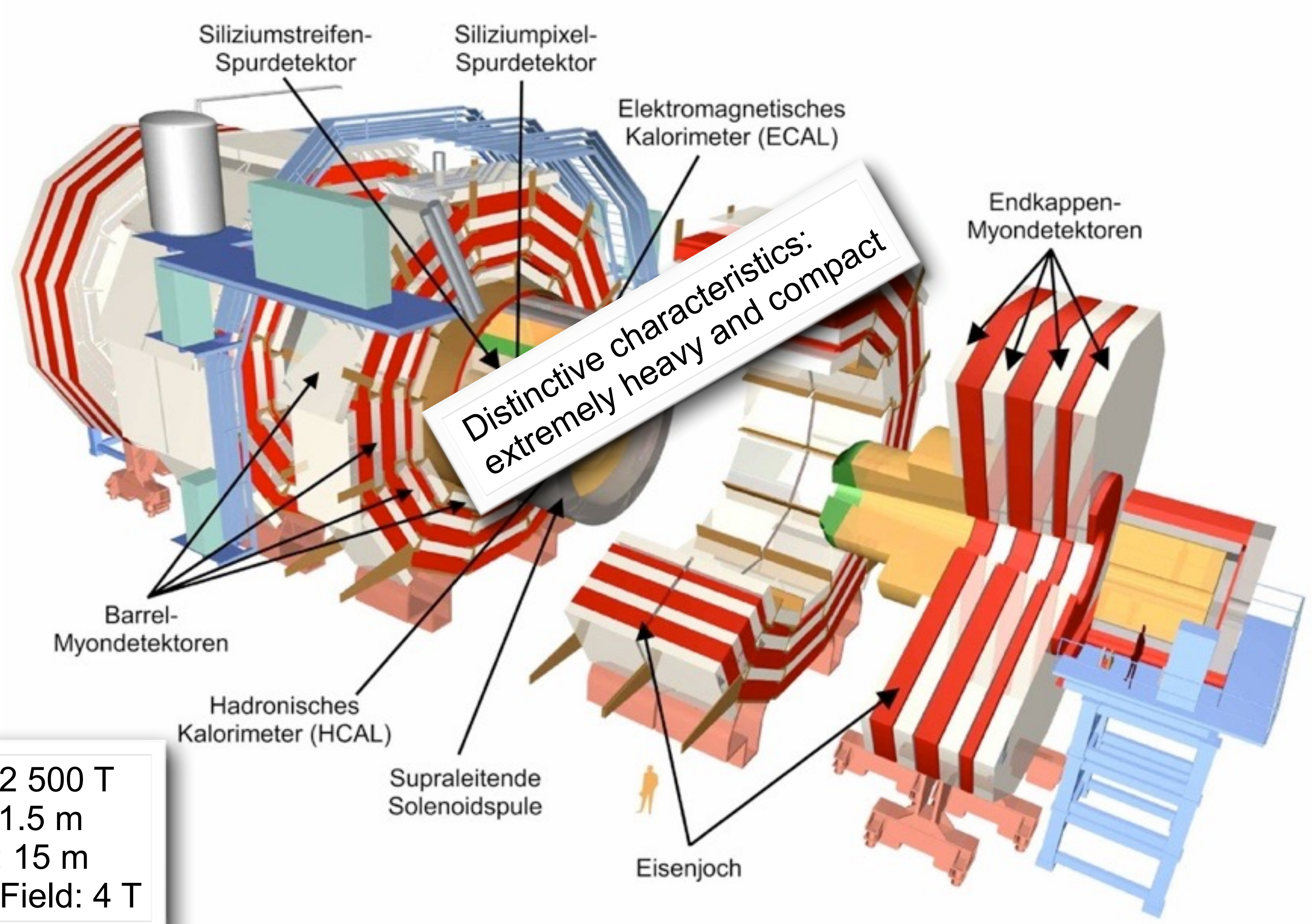
Foto: CERN

CMS@LHC



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

CMS@LHC



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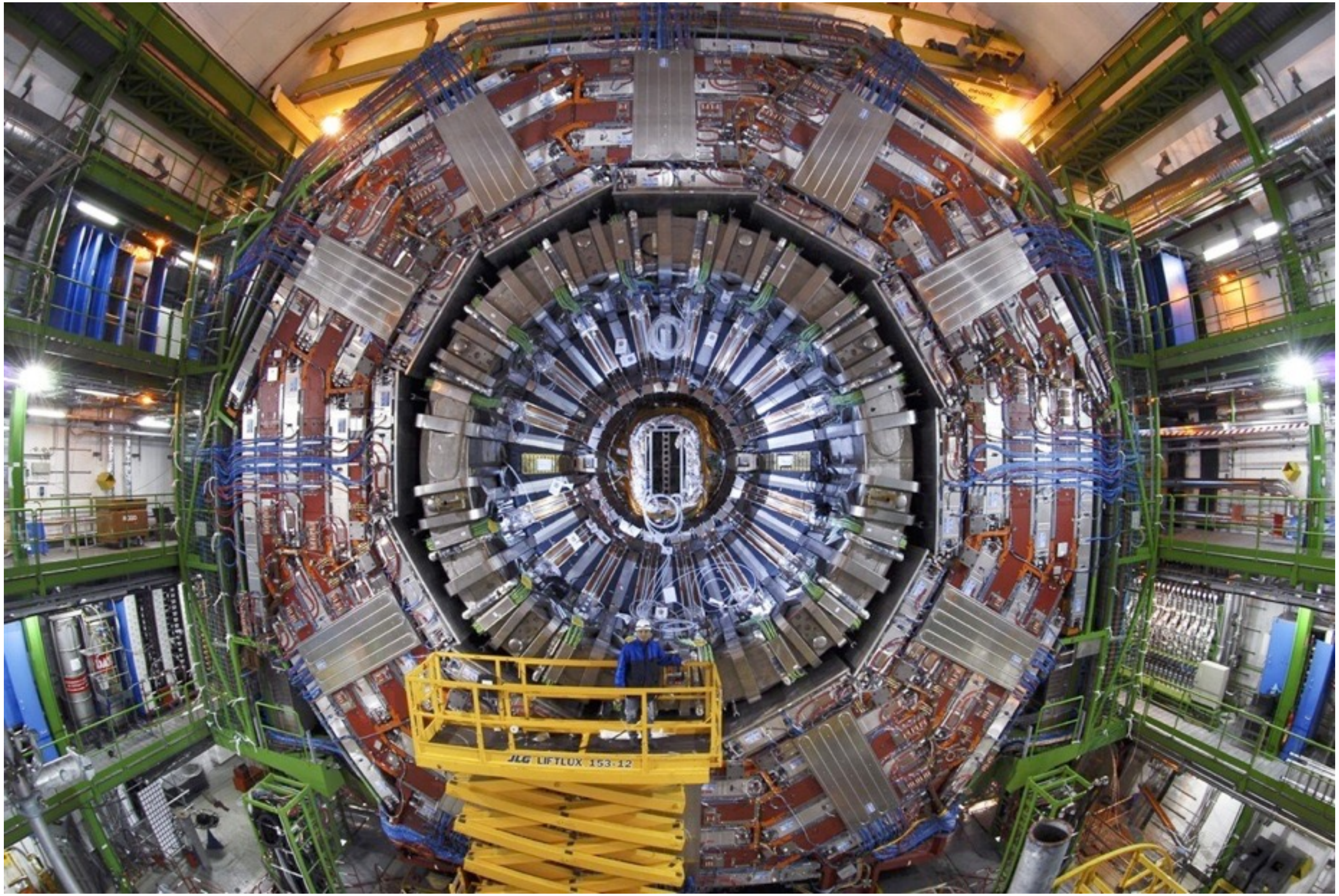
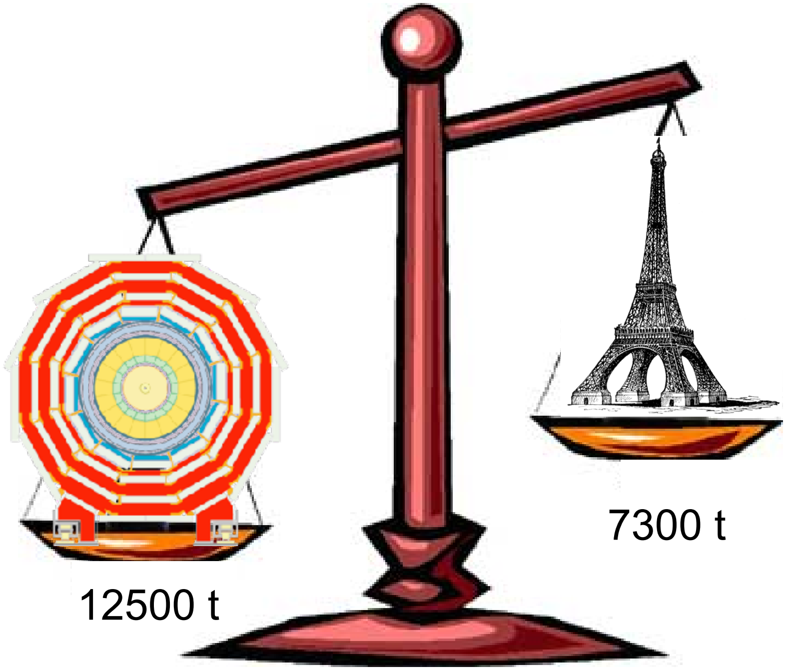


Foto: CERN

Size and Weight

CMS is 65% heavier than the Eiffel tower

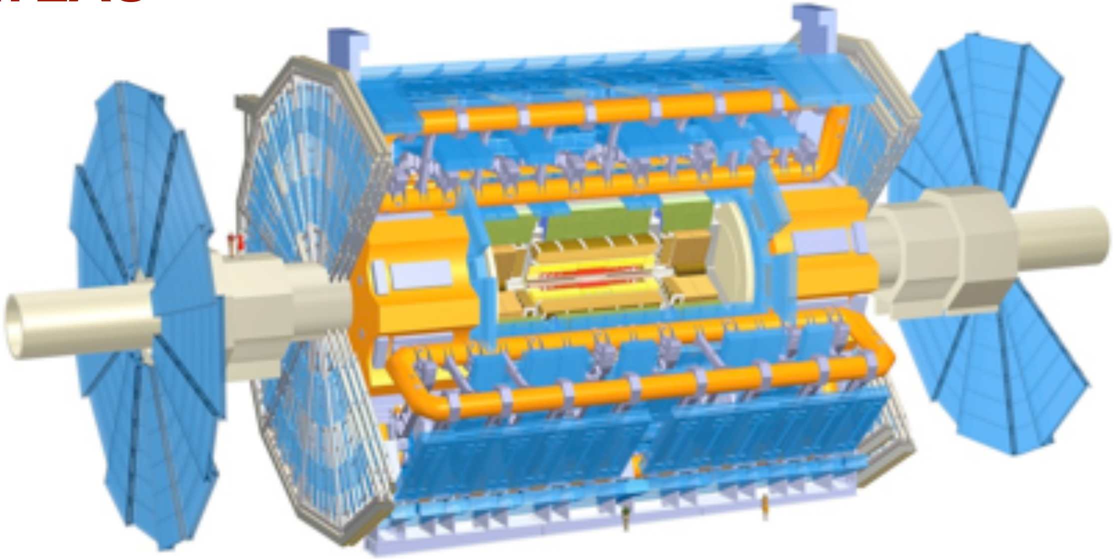
Brandenburger Tor in Berlin



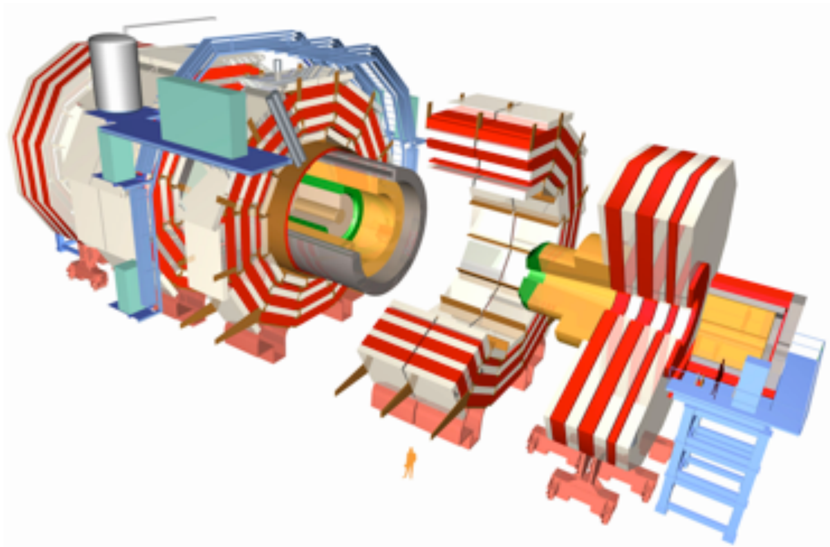
In Hamburg

The Big Ones at LHC ....

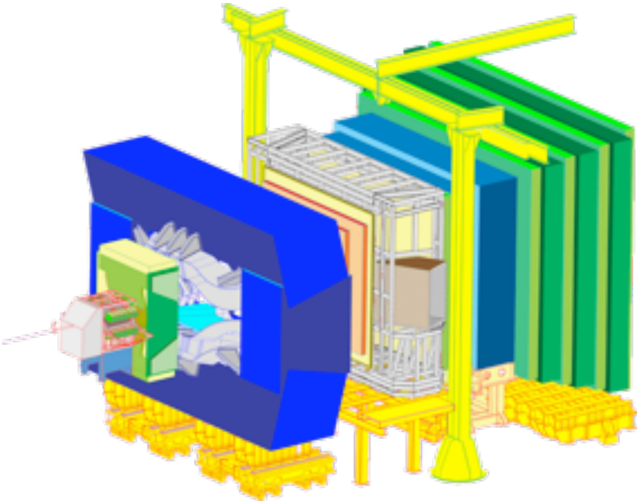
ATLAS



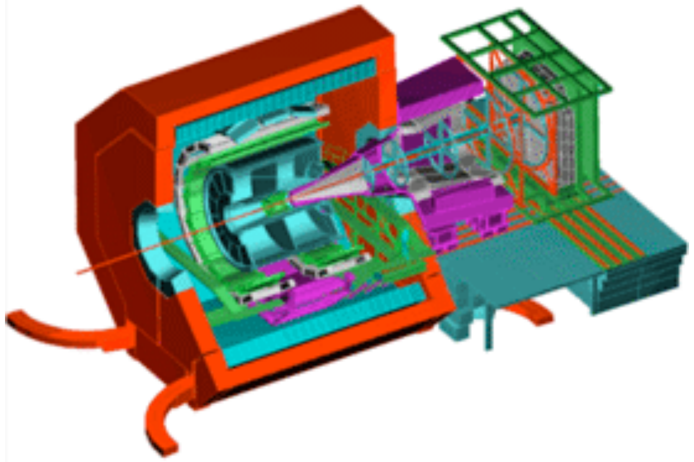
CMS



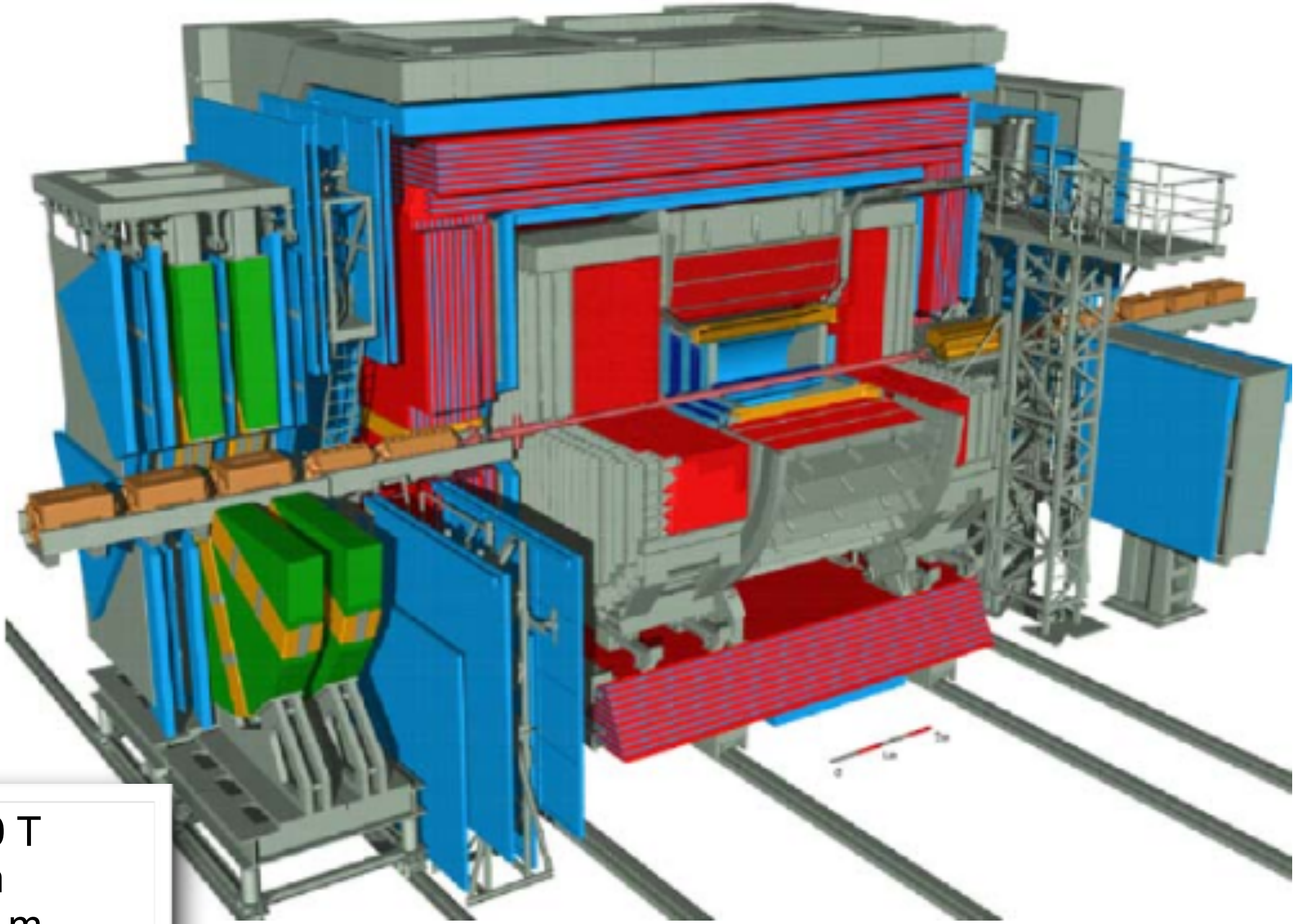
LHCb



ALICE

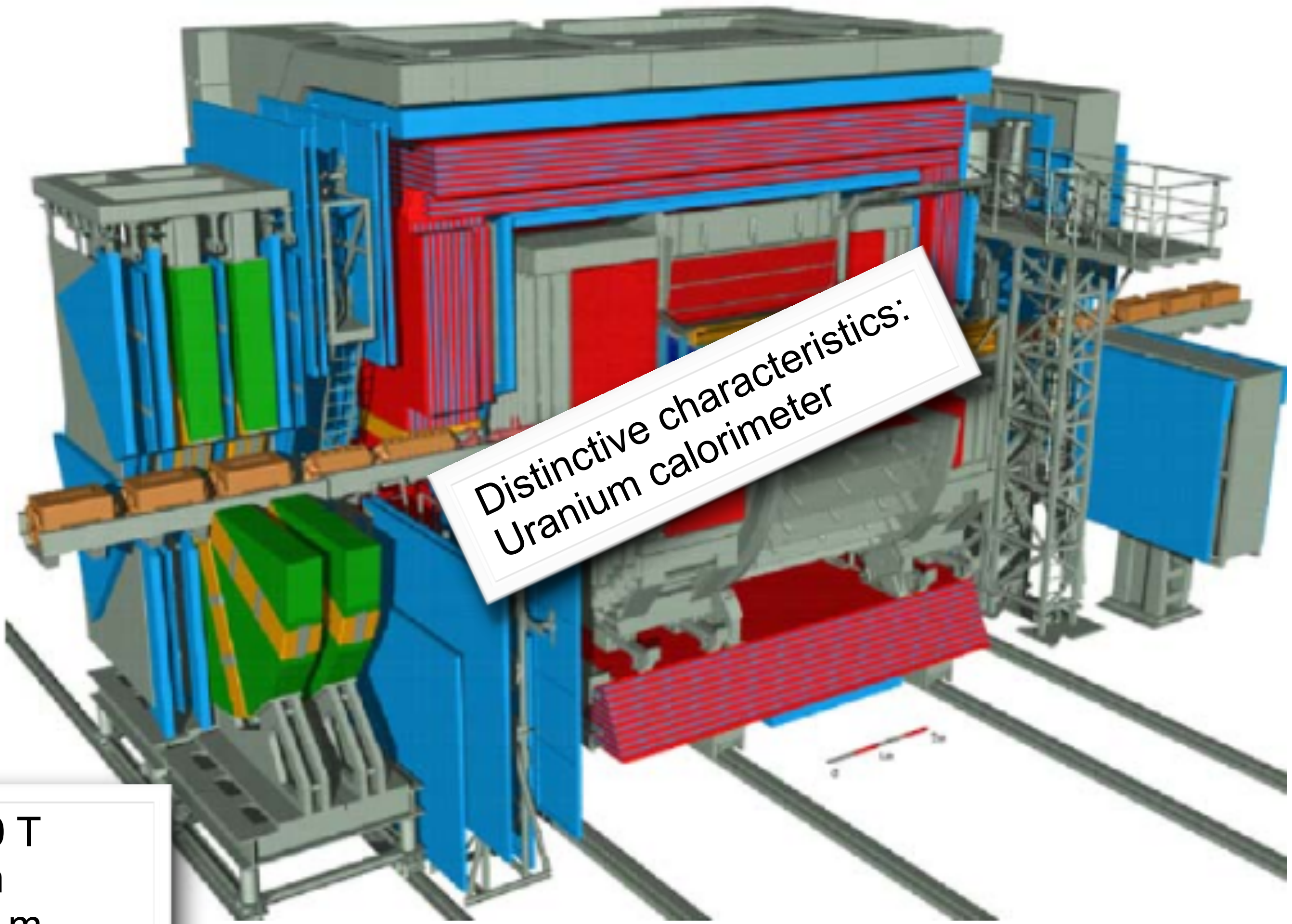


The ZEUS Detector@HERA



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

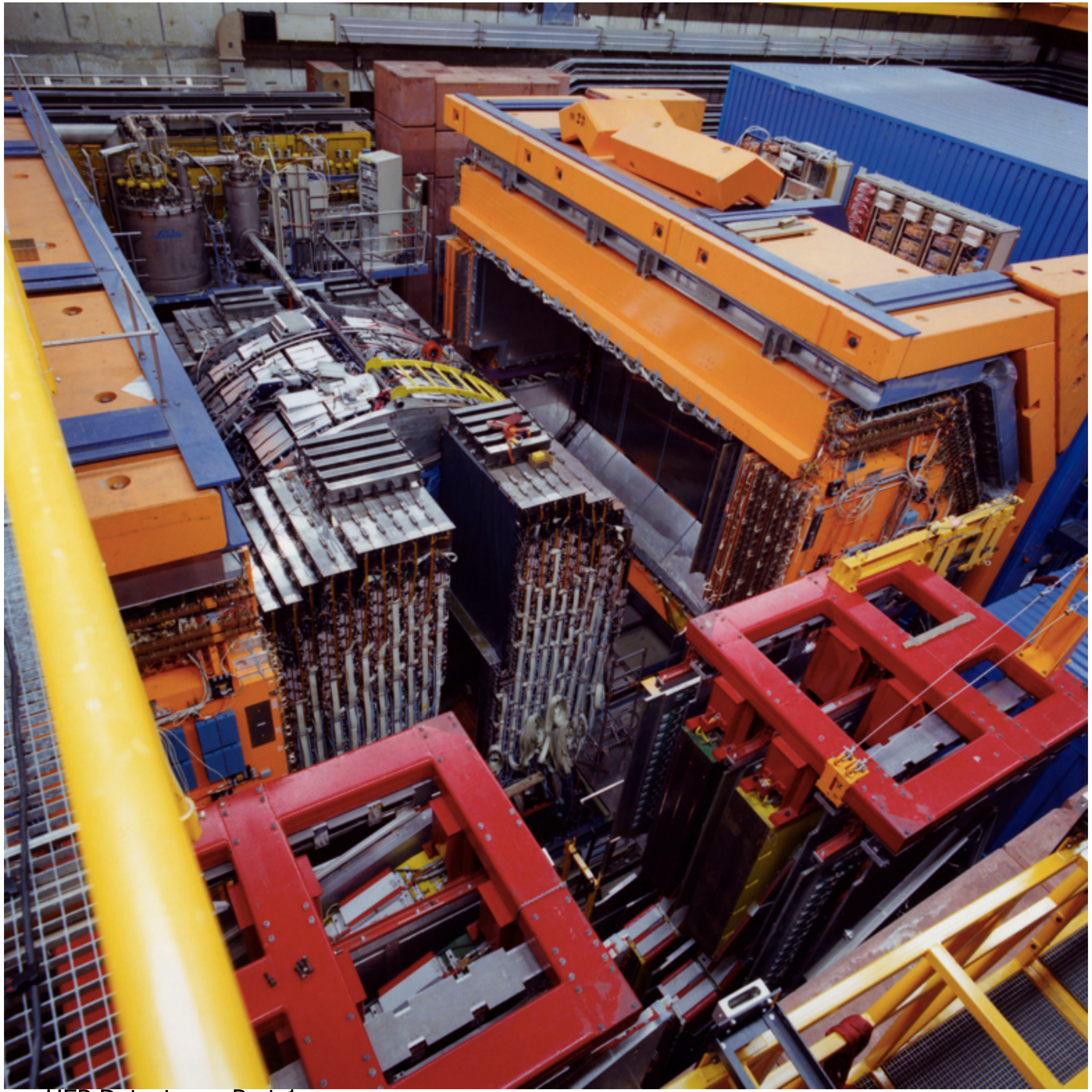
The ZEUS Detector@HERA



Distinctive characteristics:
Uranium calorimeter

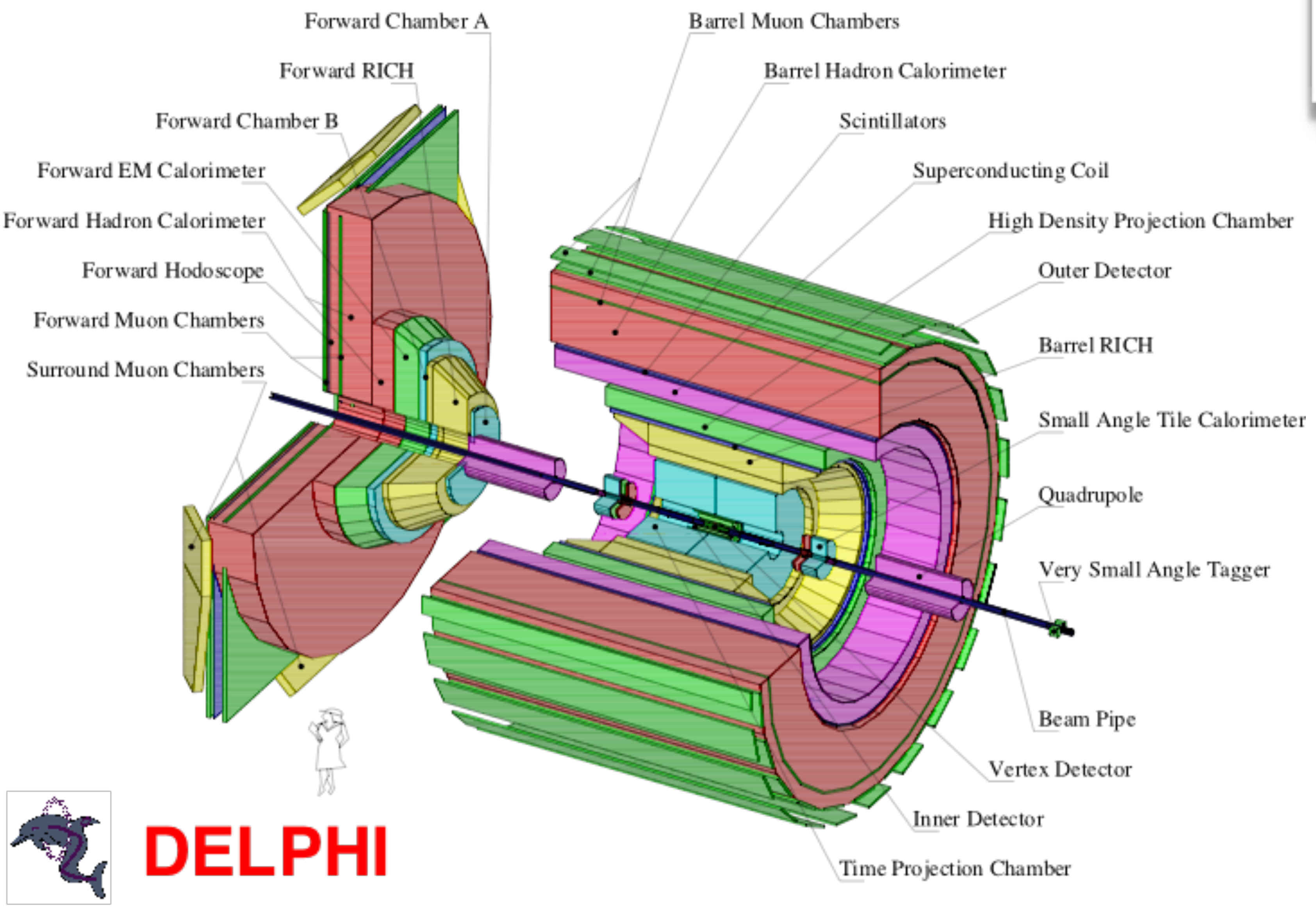
Weight: 3600 T
Length: 19 m
Diameter: 11 m
Solenoid-Field: 1.5 T

ZEUS



The DELPHI Detector @LEP

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



Pic: DELPHI Collaboration

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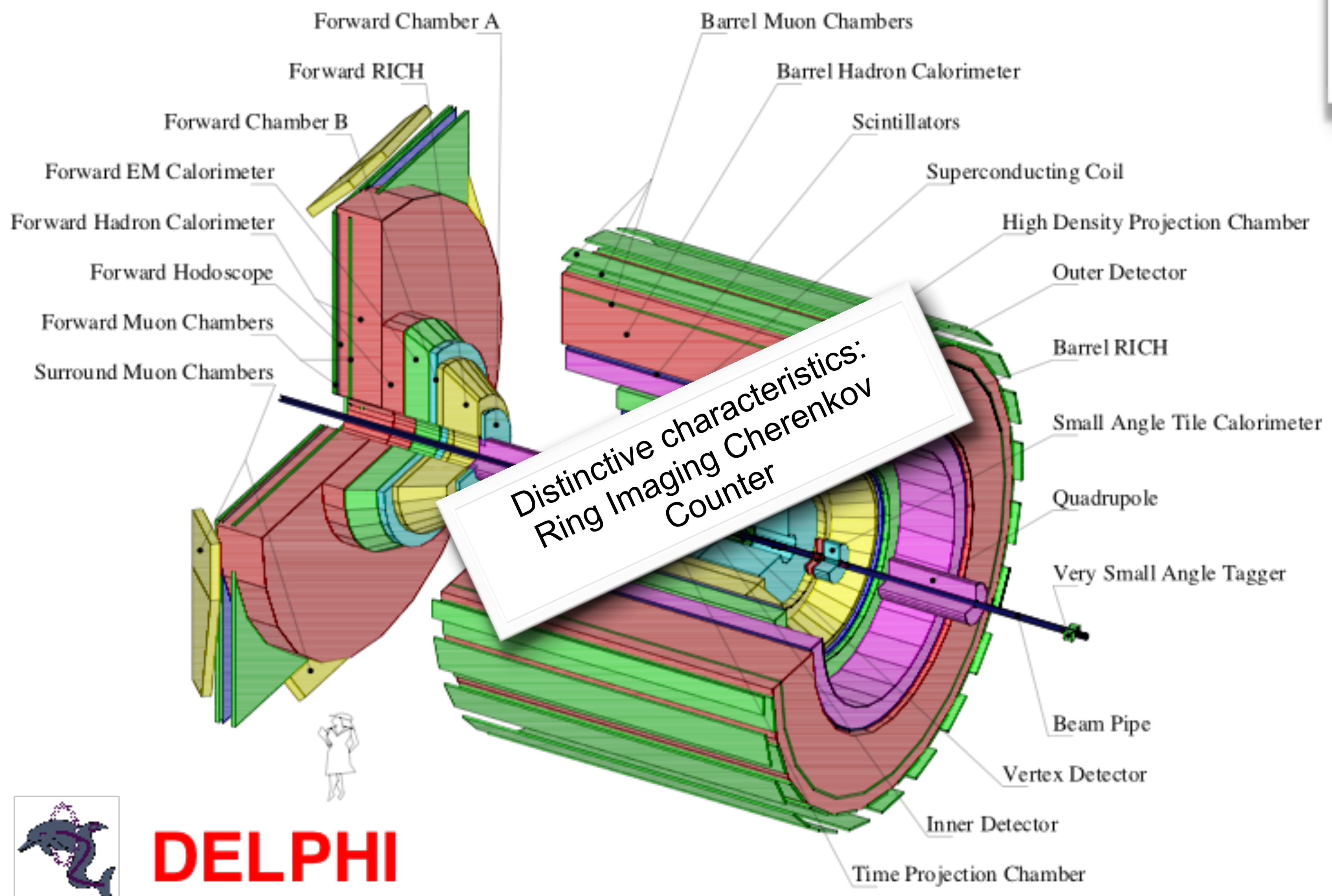
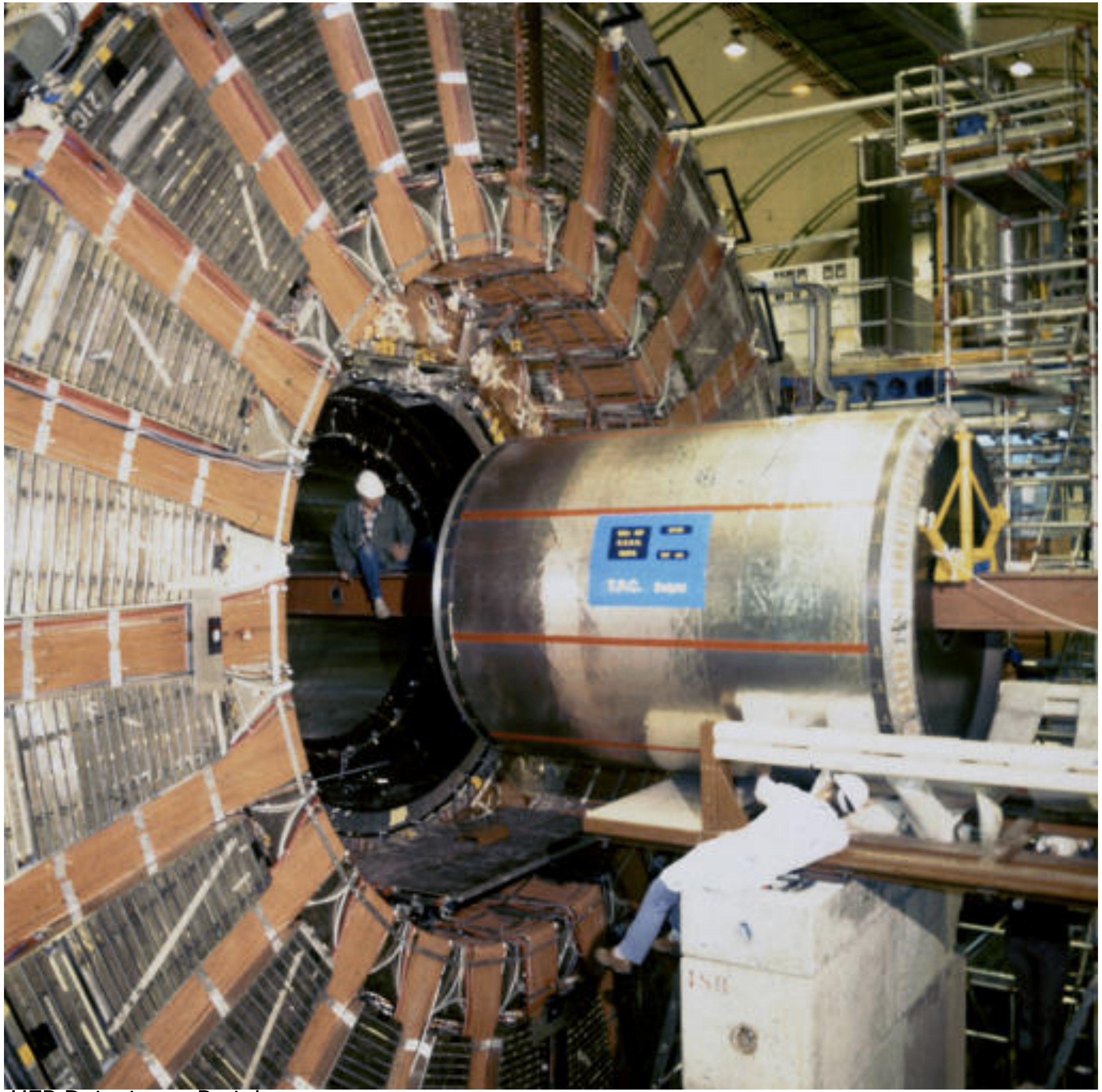
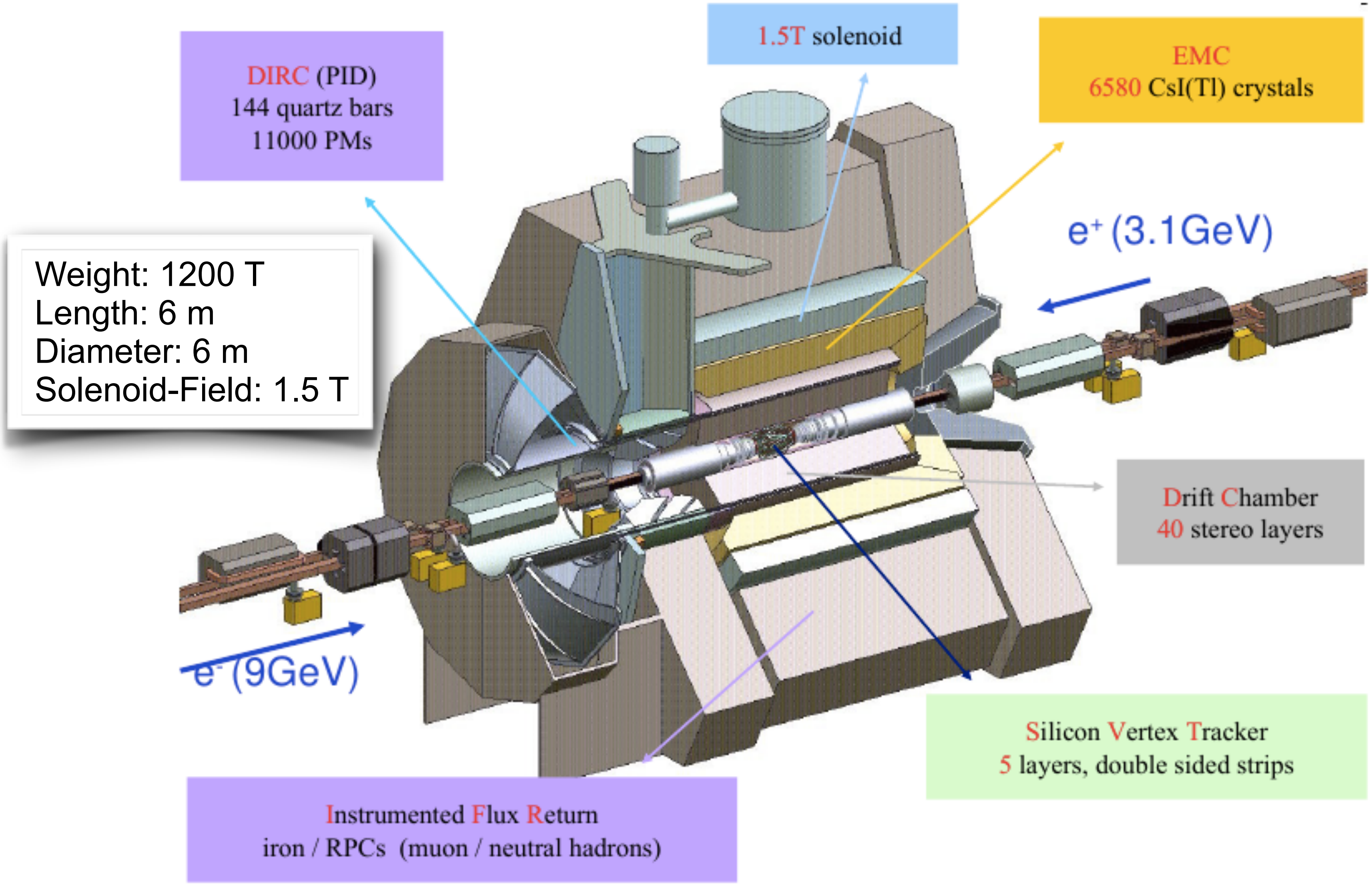


Pic: DELPHI Collaboration

Delphi



The BaBar Detector



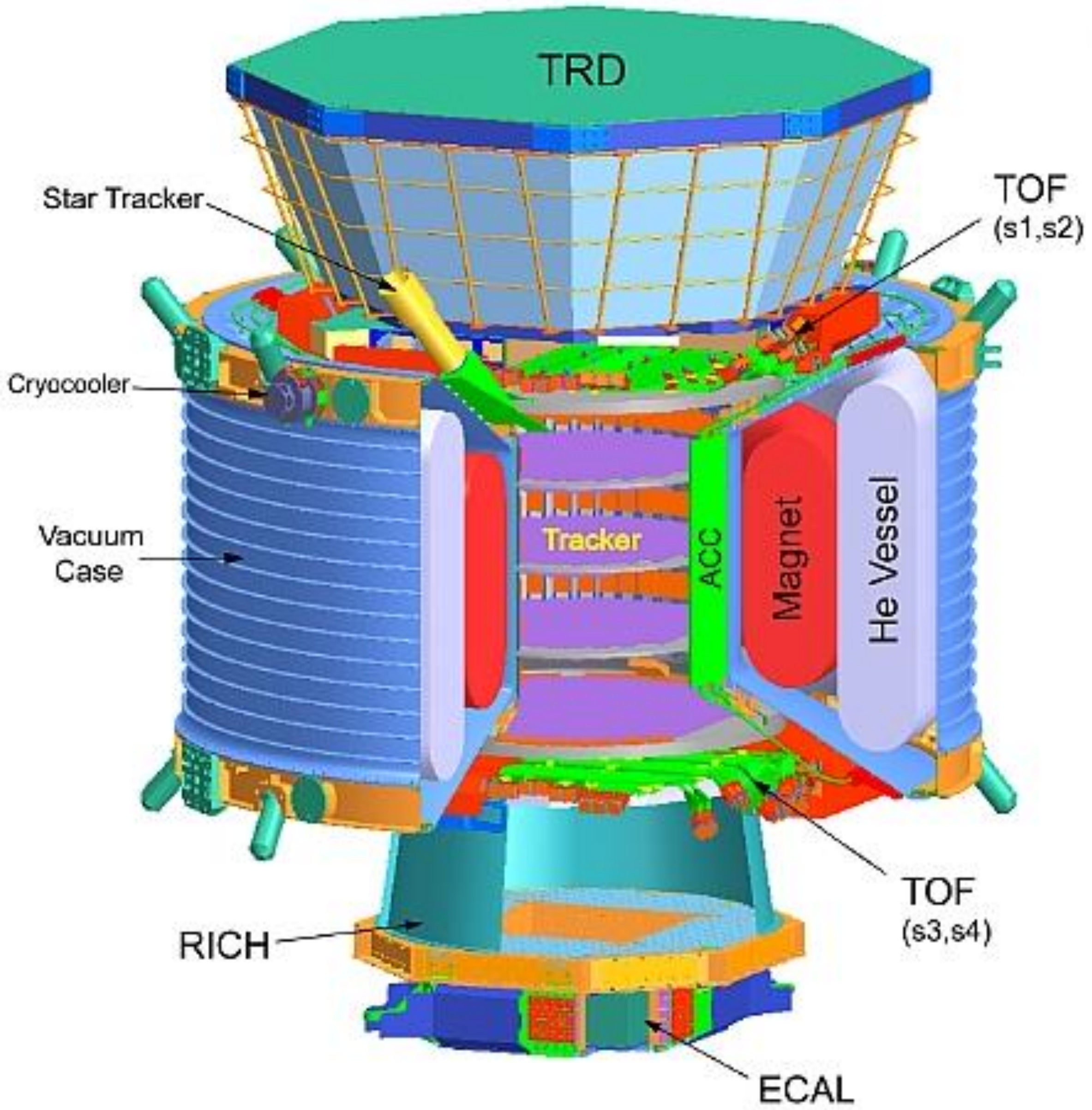
Pic: BaBar Collaboration

BaBar

BaBar
™ and © Nelvana, All Rights Reserved
Collaboration Home Page

AMS@ISS

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



picture: AMS collaboration

AMS@ISS

Weight: 1200 T
Length: 6 m
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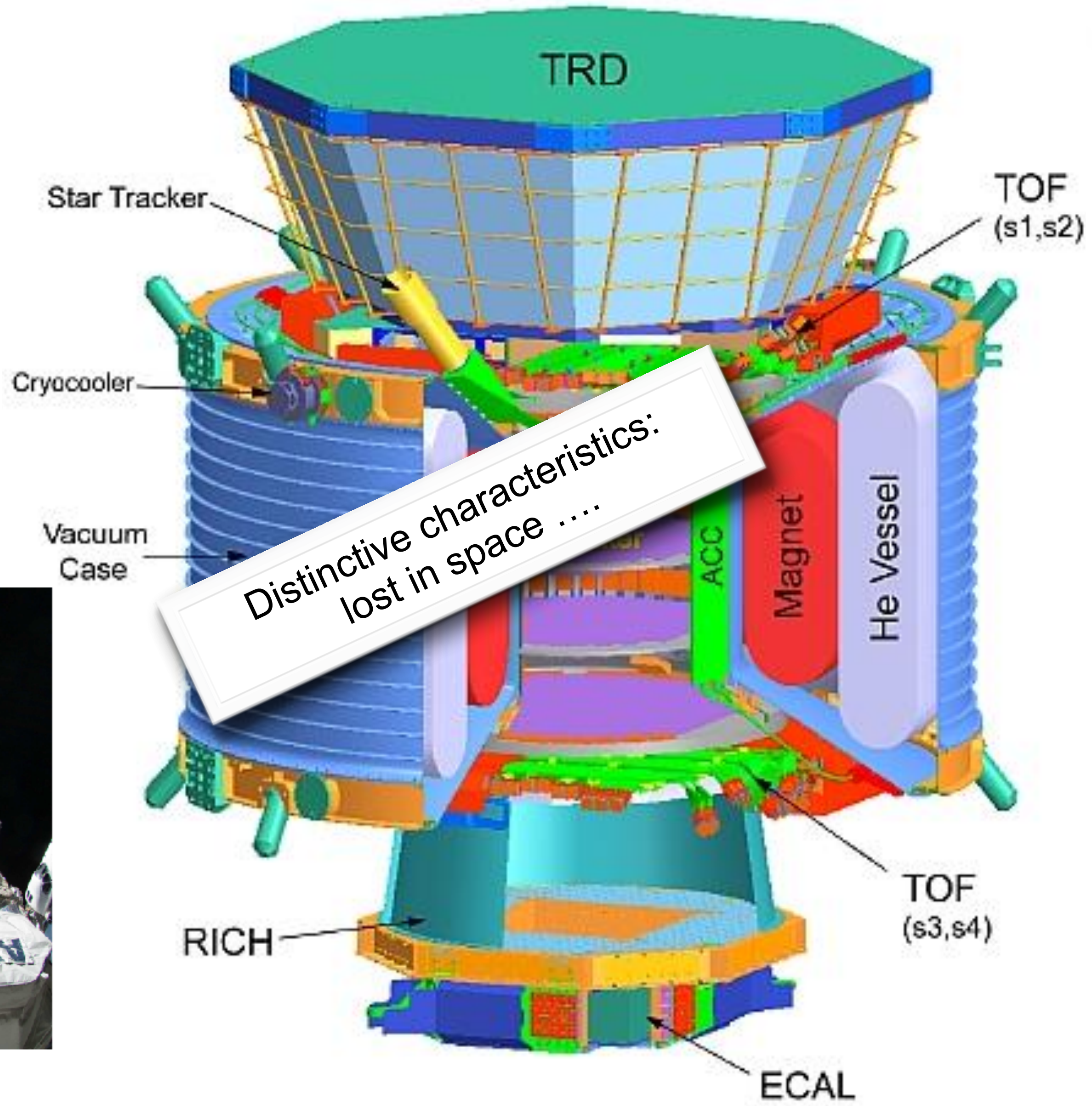

Distinctive characteristics:
lost in space ….

picture: AMS collaboration

Example: ATLAS at CERN

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

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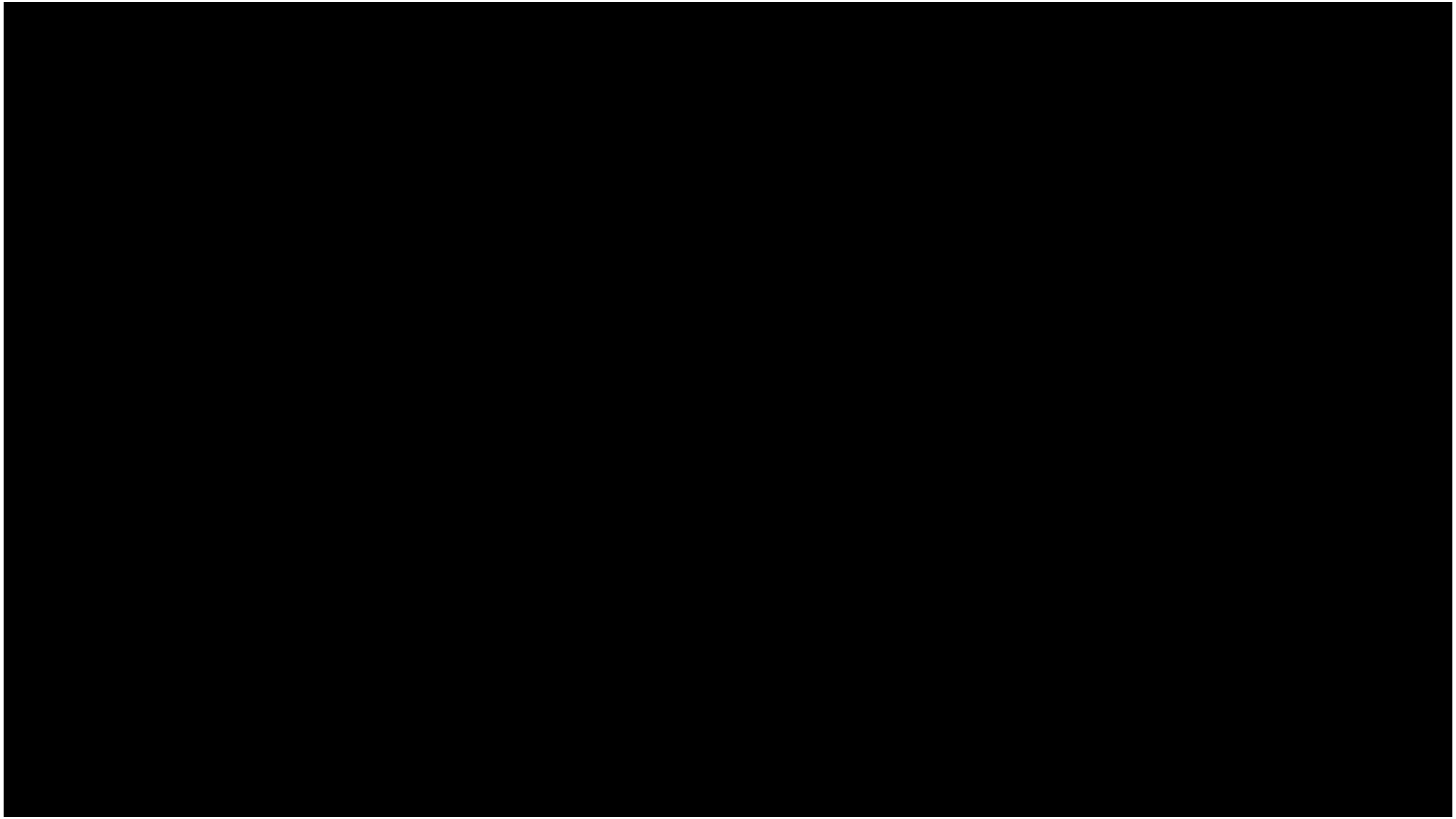

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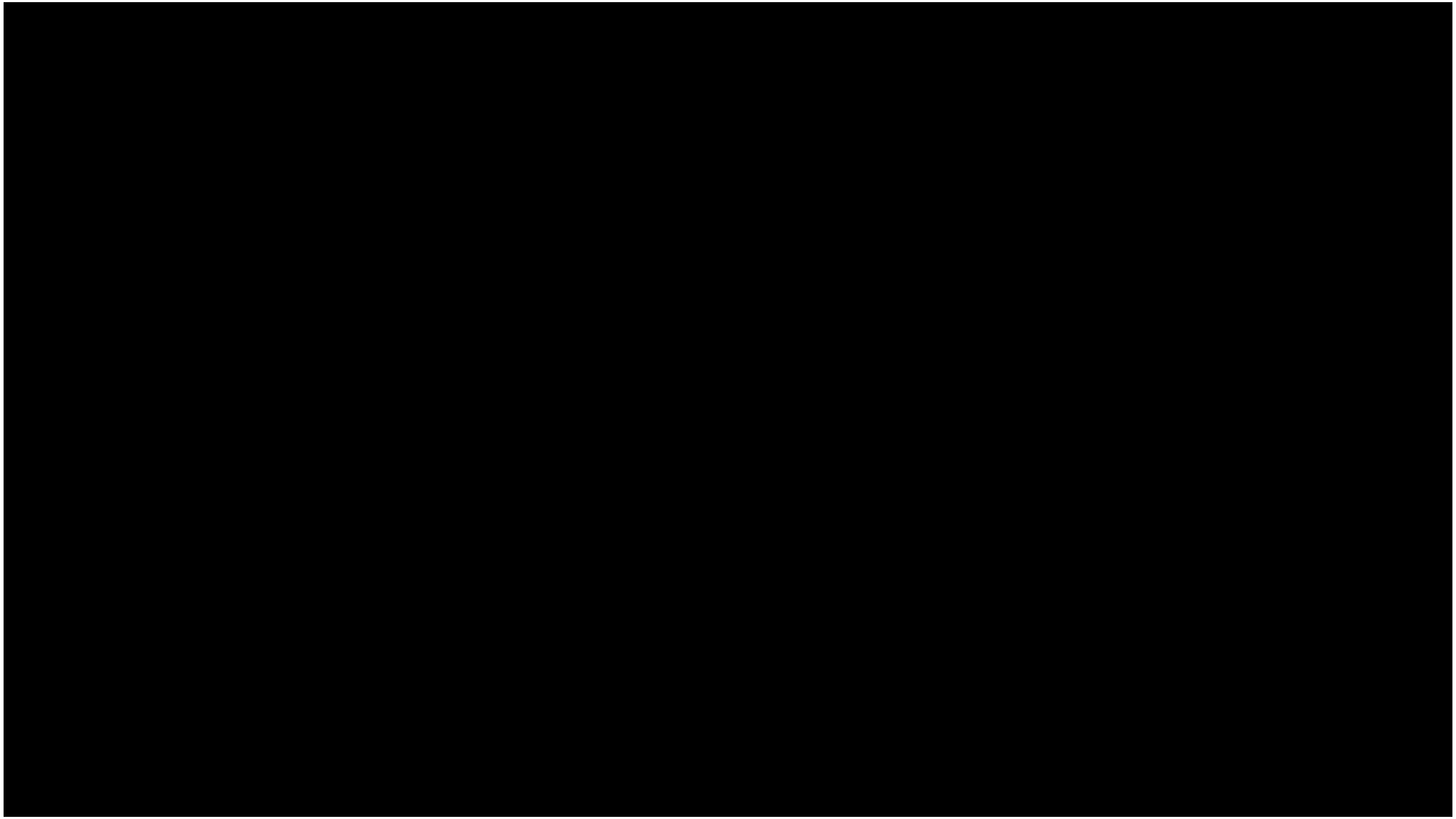

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Cameras for Particle Physics

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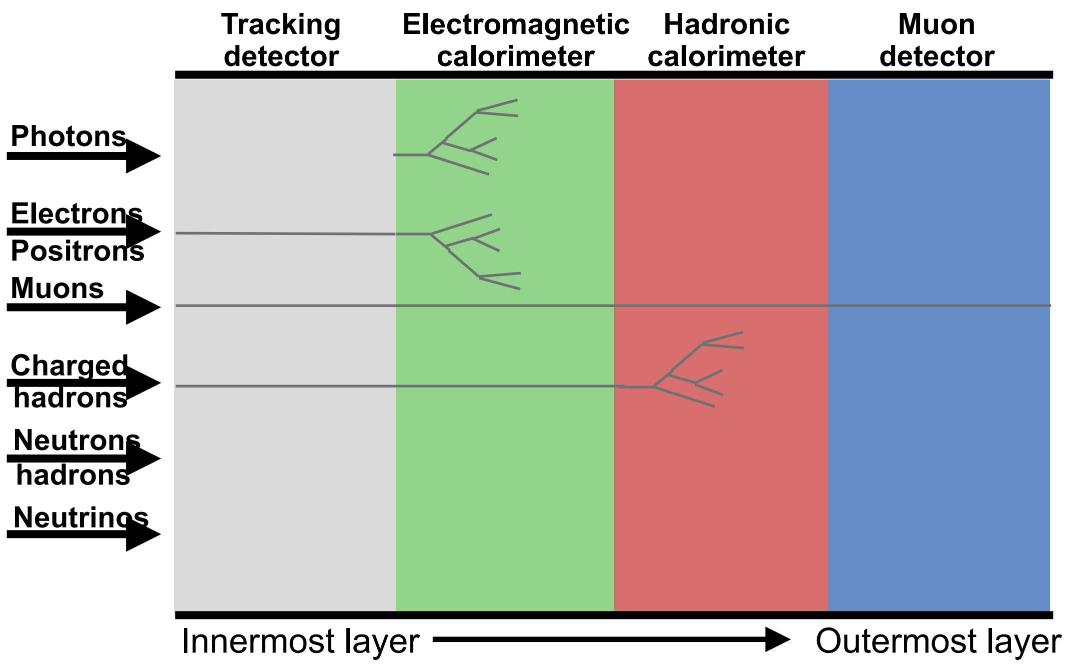
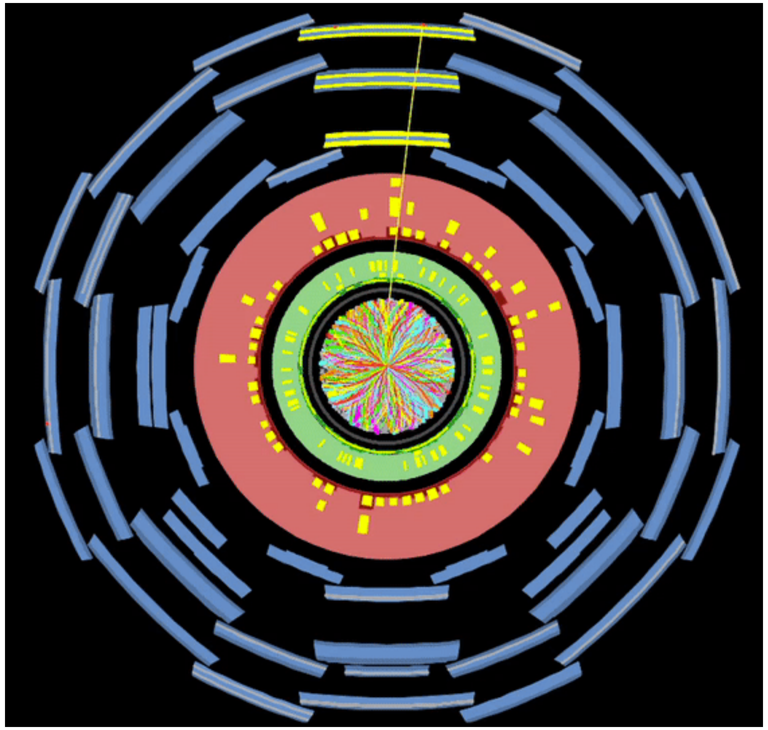




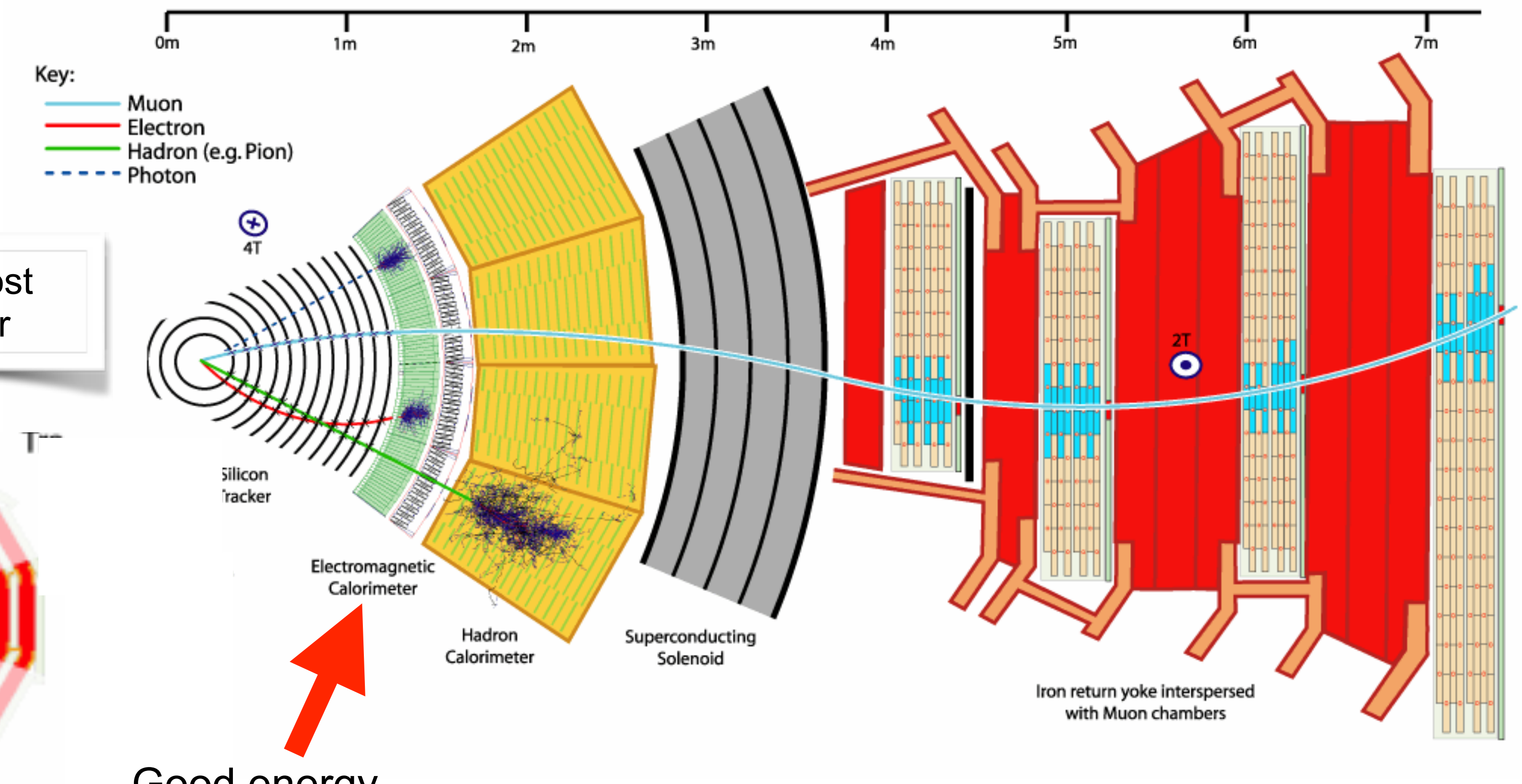
HEP Detector Overview

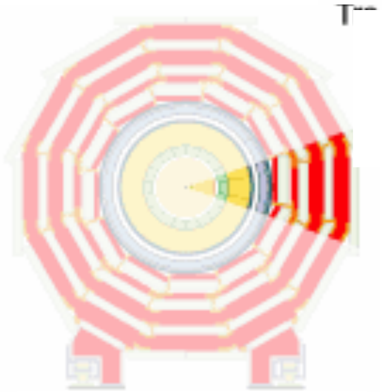
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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





Transverse slice through CMS

Good energy resolution up to highest energies

picture: CMS@CERN

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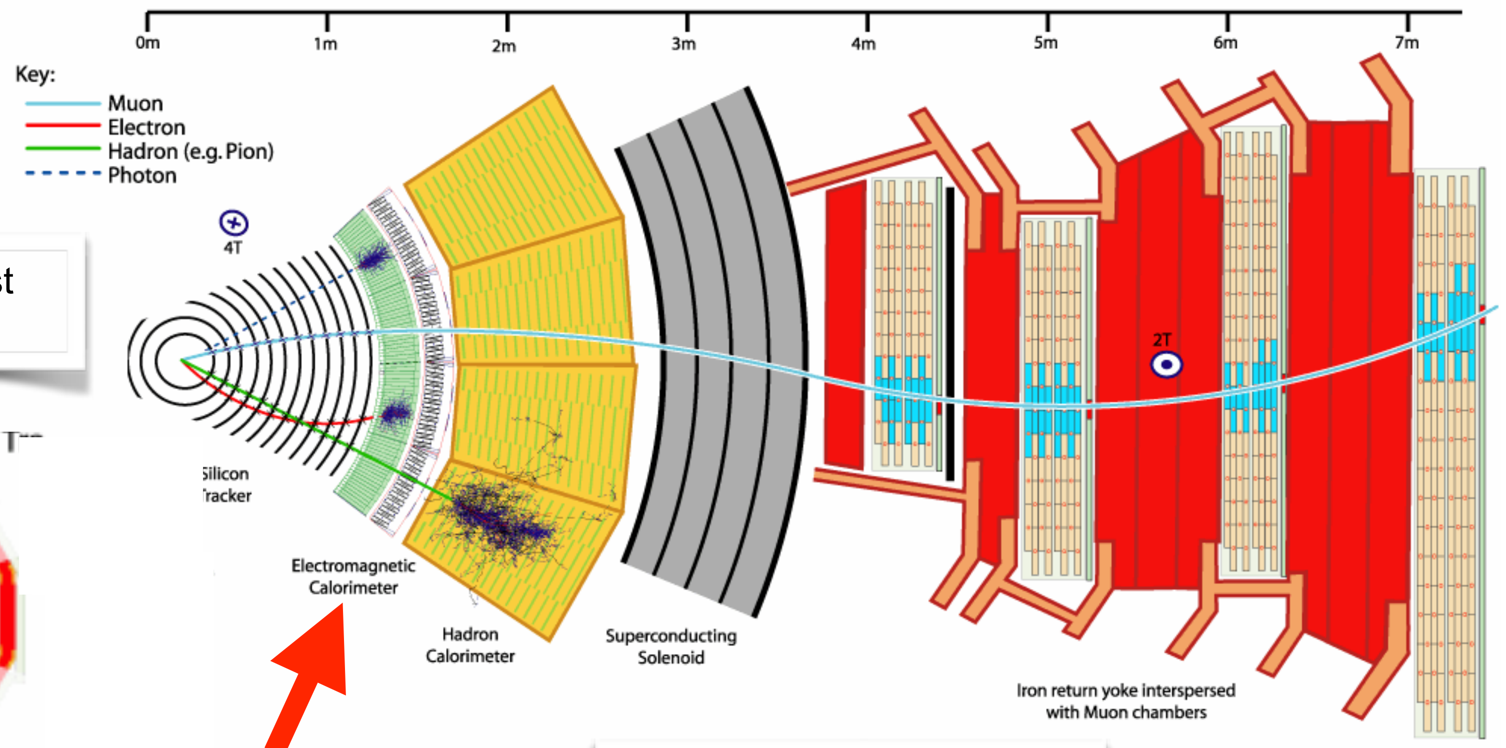
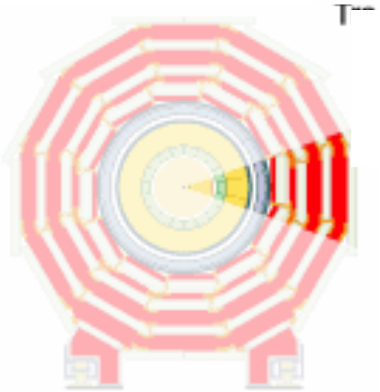




Transverse slice through CMS

Good energy resolution up to highest energies

Radiation hard (hadron collider)

picture: CMS@CERN

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

Analogy

- Planes leave tracks in sky under certain conditions ….

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

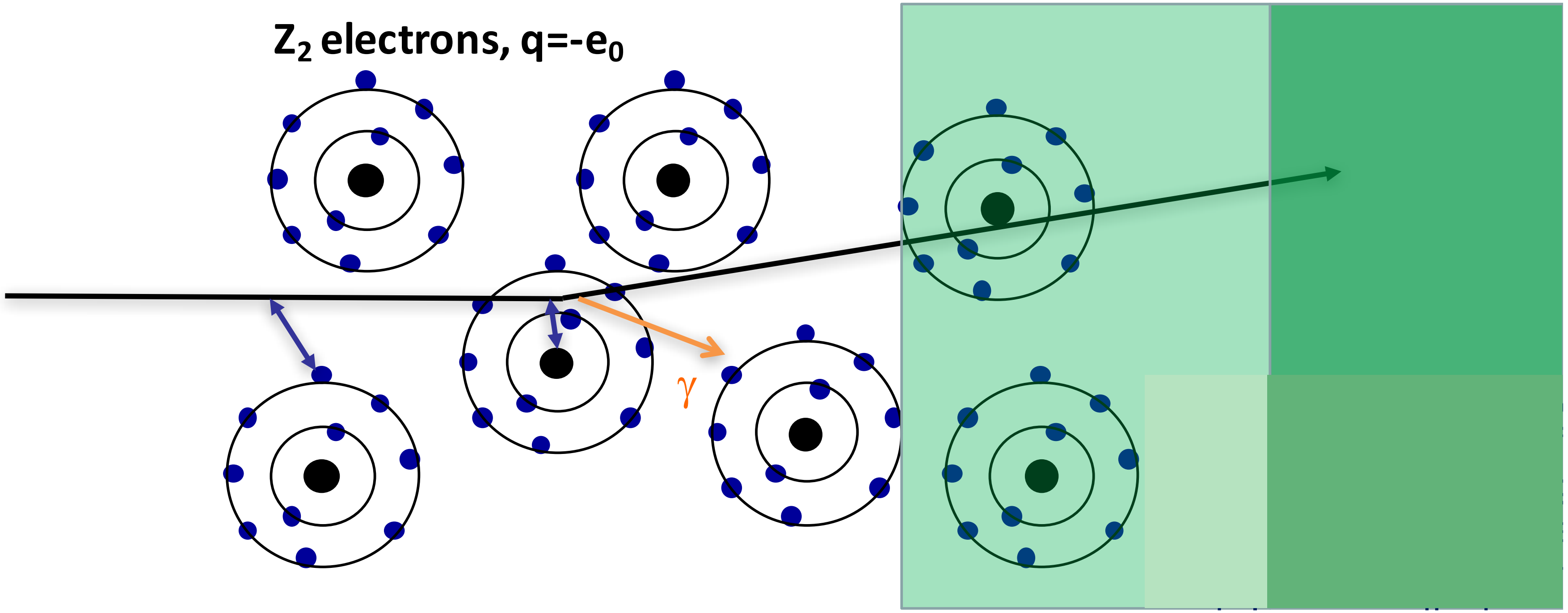
neutrons

http://www.particlezoo.net/

Interactions of charged particles

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



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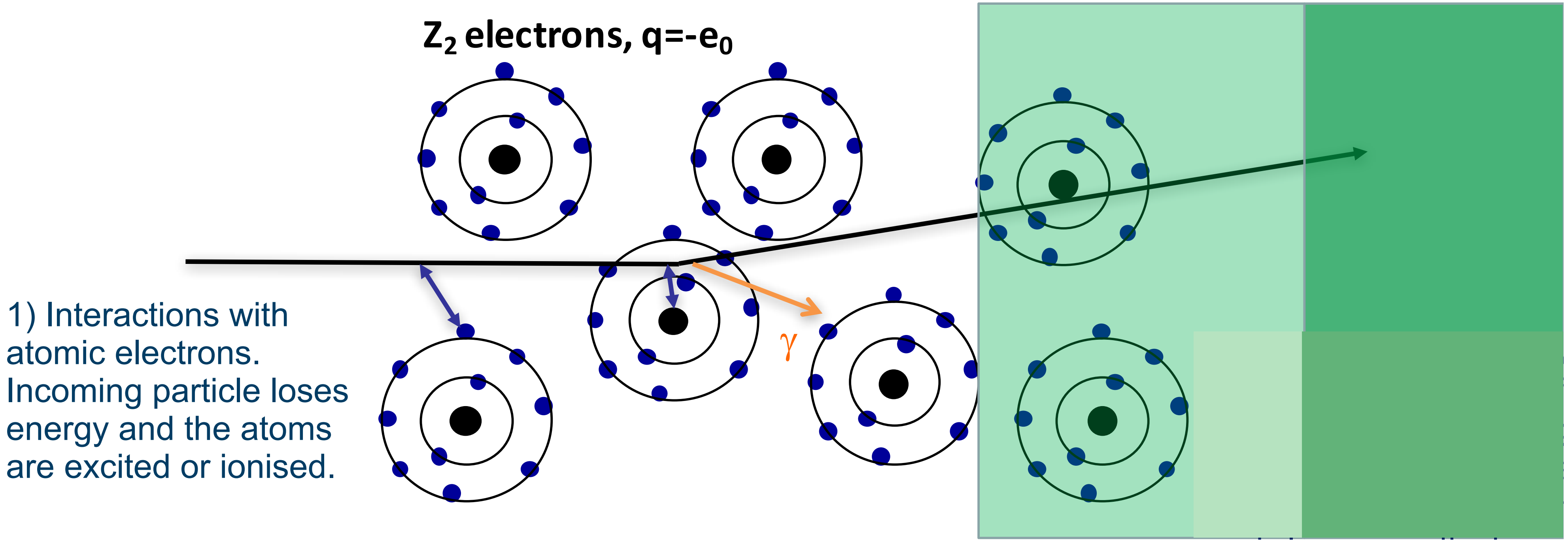

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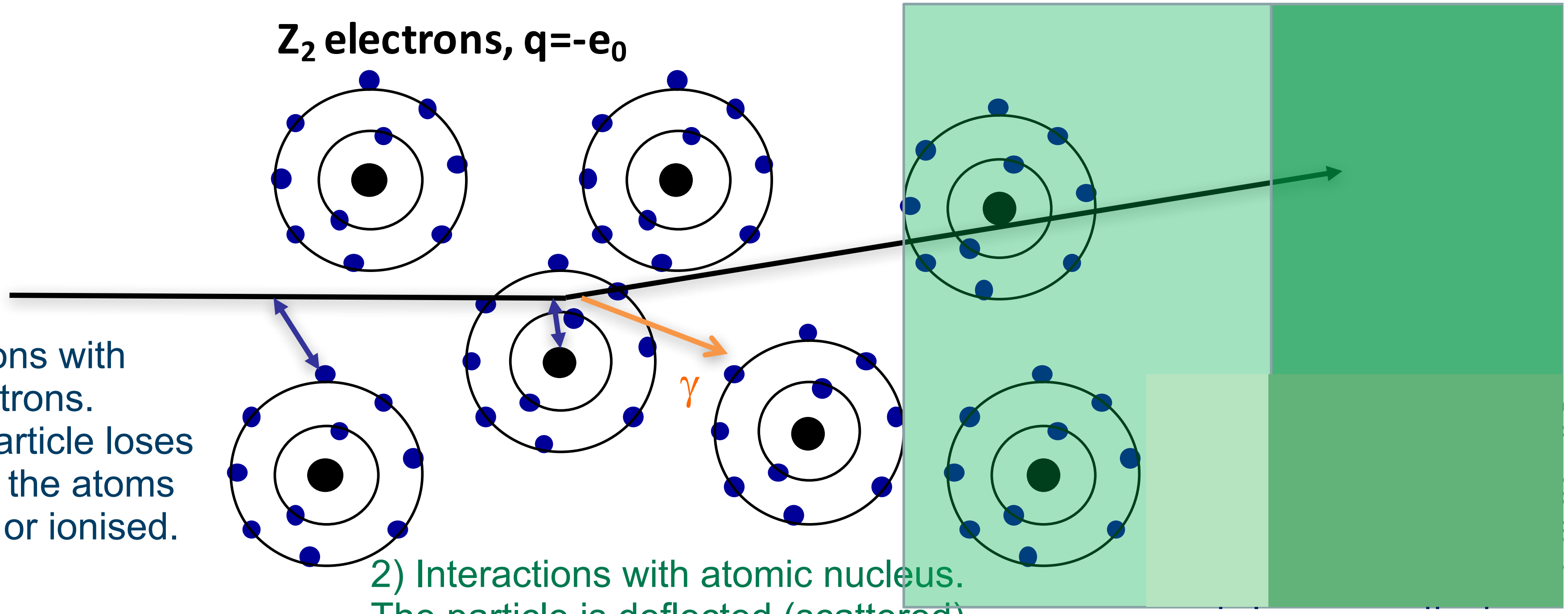

1) Interactions with atomic electrons. Incoming particle loses energy and the atoms are excited or ionised.

2) Interactions with 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.

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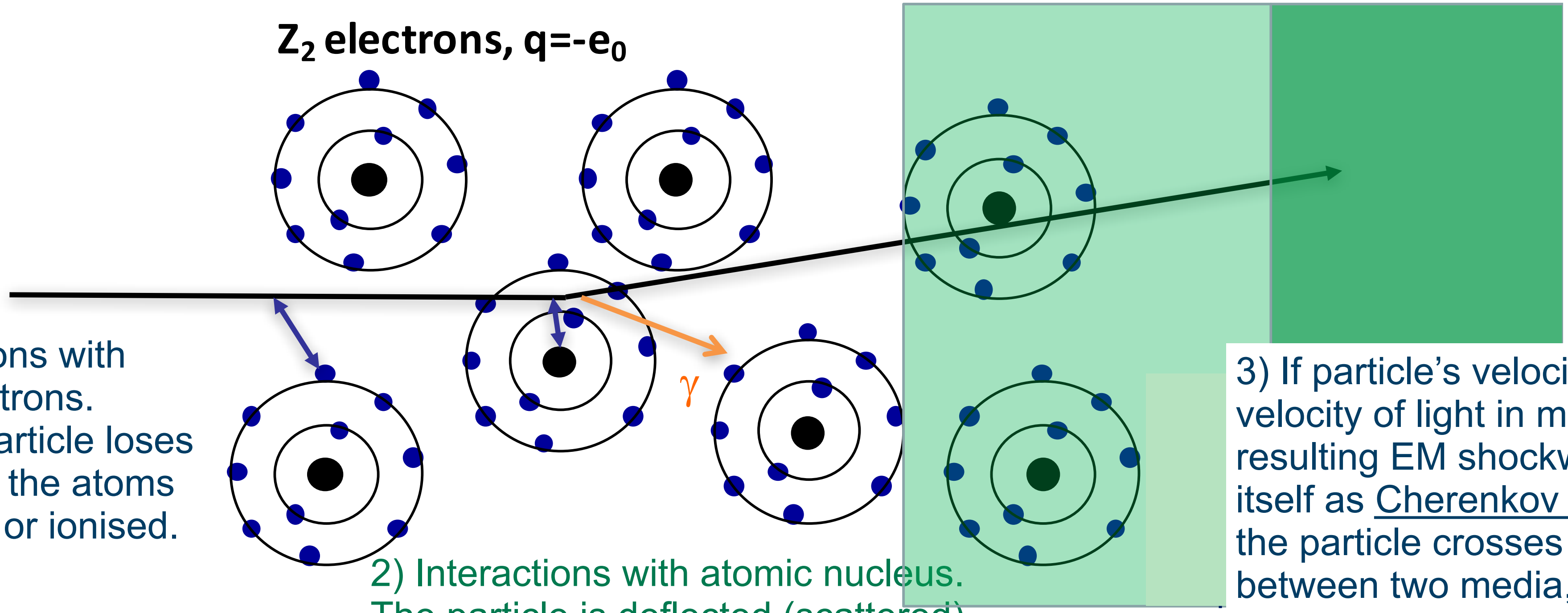

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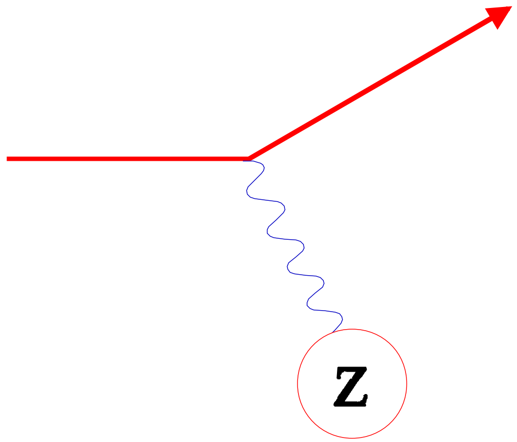
3) If particle's velocity is larger than velocity of light in medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability in the order of 1% to produce an X ray photon, called Transition radiation.

Heavy Charged Particle

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



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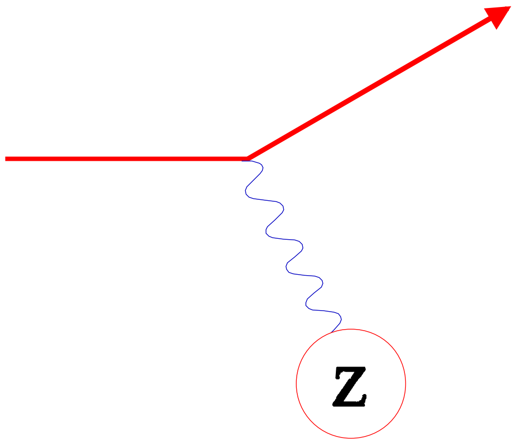

- Incoming particle interacts elastically with a target of nuclear charge Z.

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

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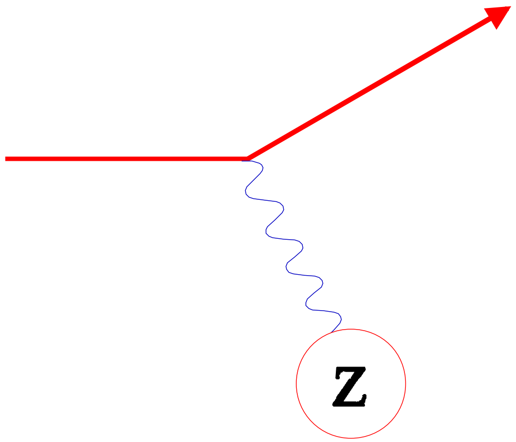

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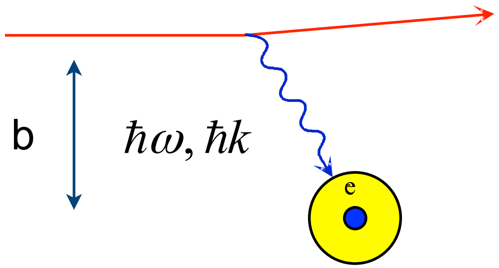
Rutherford Formula

- 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

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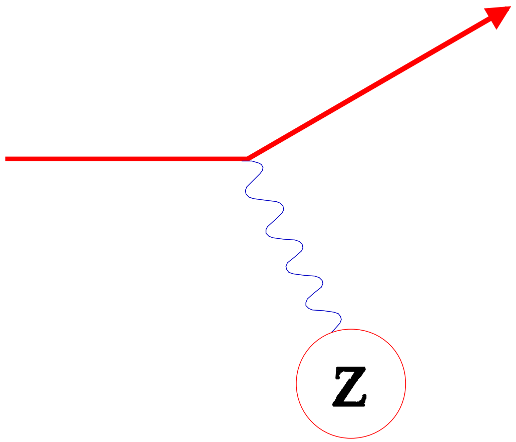

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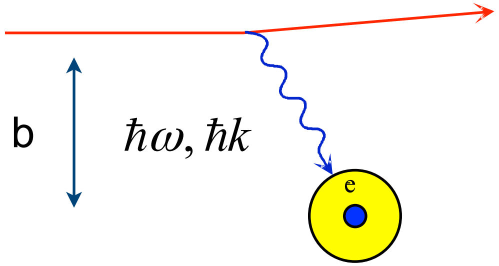

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N: electron density

→ **Bethe-Bloch Formula**

Interactions of "heavy" Particles with Matter

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

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

Plot: PDG, June 2018

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

Plot: PDG, June 2018

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I^2 Excitation energy

Plot: PDG, June 2018

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

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

I^2 Excitation energy

Plot: PDG, June 2018

Interactions of "heavy" Particles with Matter

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

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

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

Plot: PDG, June 2018

Interactions of "heavy" Particles with Matter

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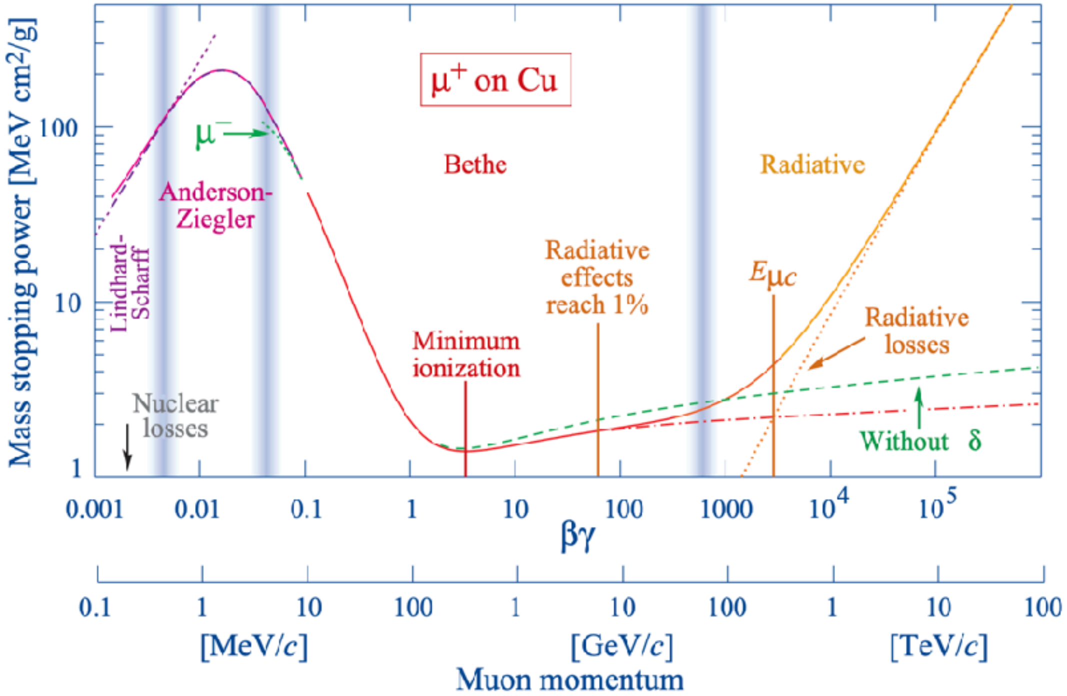

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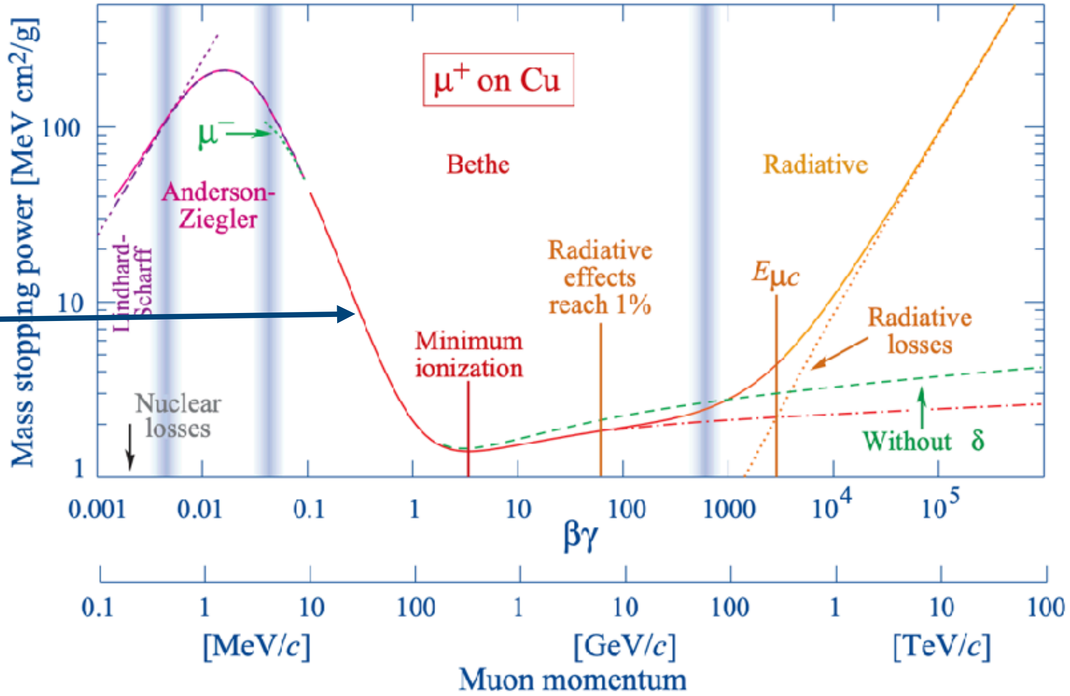
"kinematic term"



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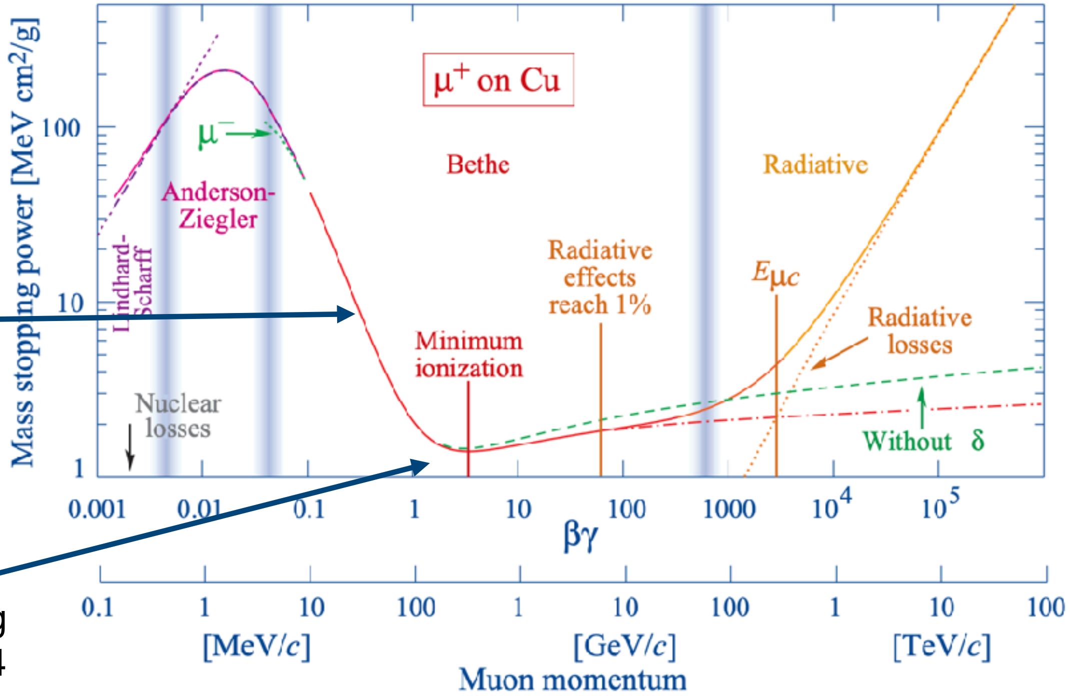

"minimum ionizing particles" $\beta\gamma \approx 3\text{-}4$

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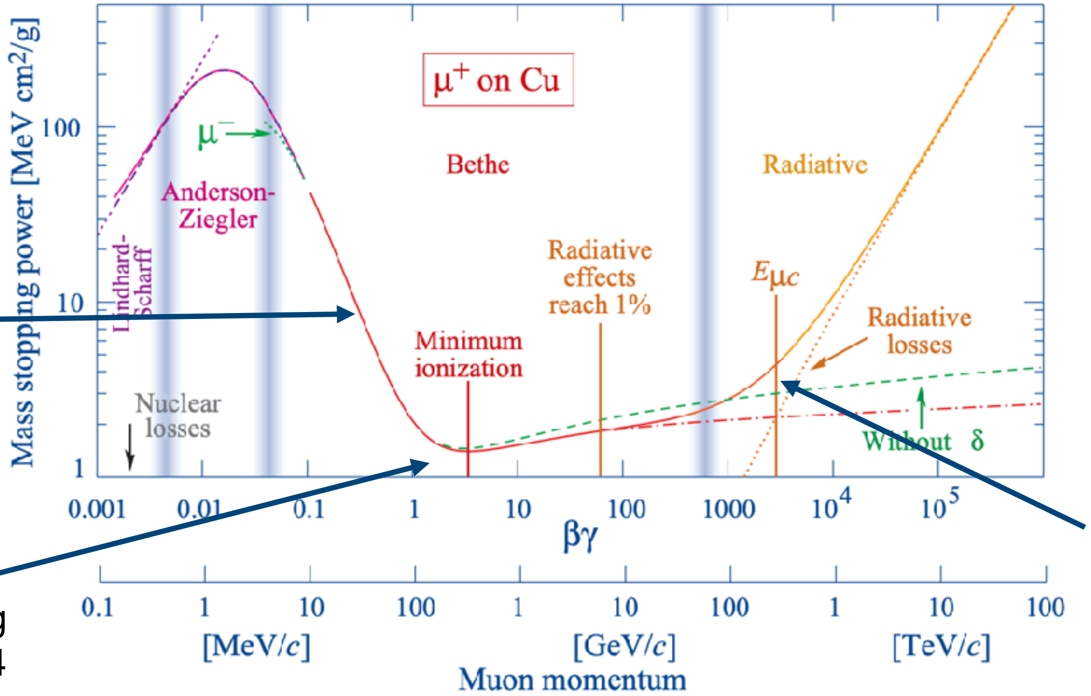

"minimum ionizing particles" βγ ≈ 3-4

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

"relativistic rise"

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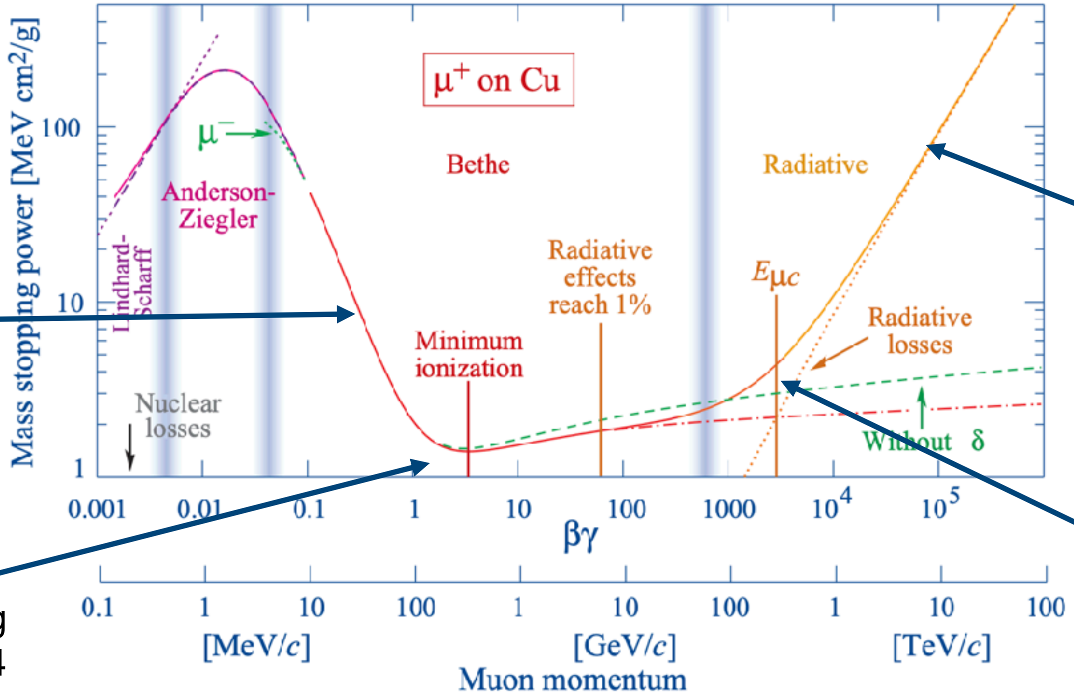


$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$ "kinematic term"

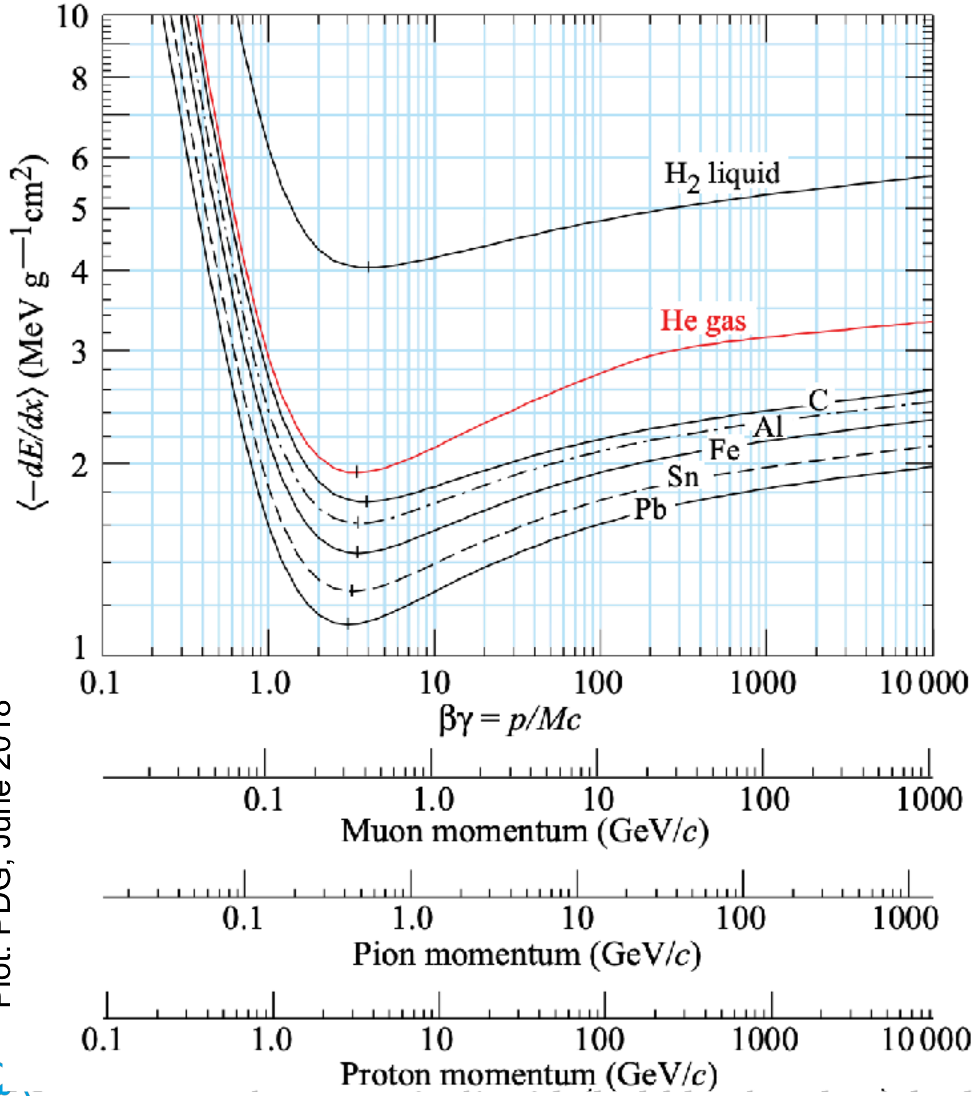
Bremsstrahlung

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

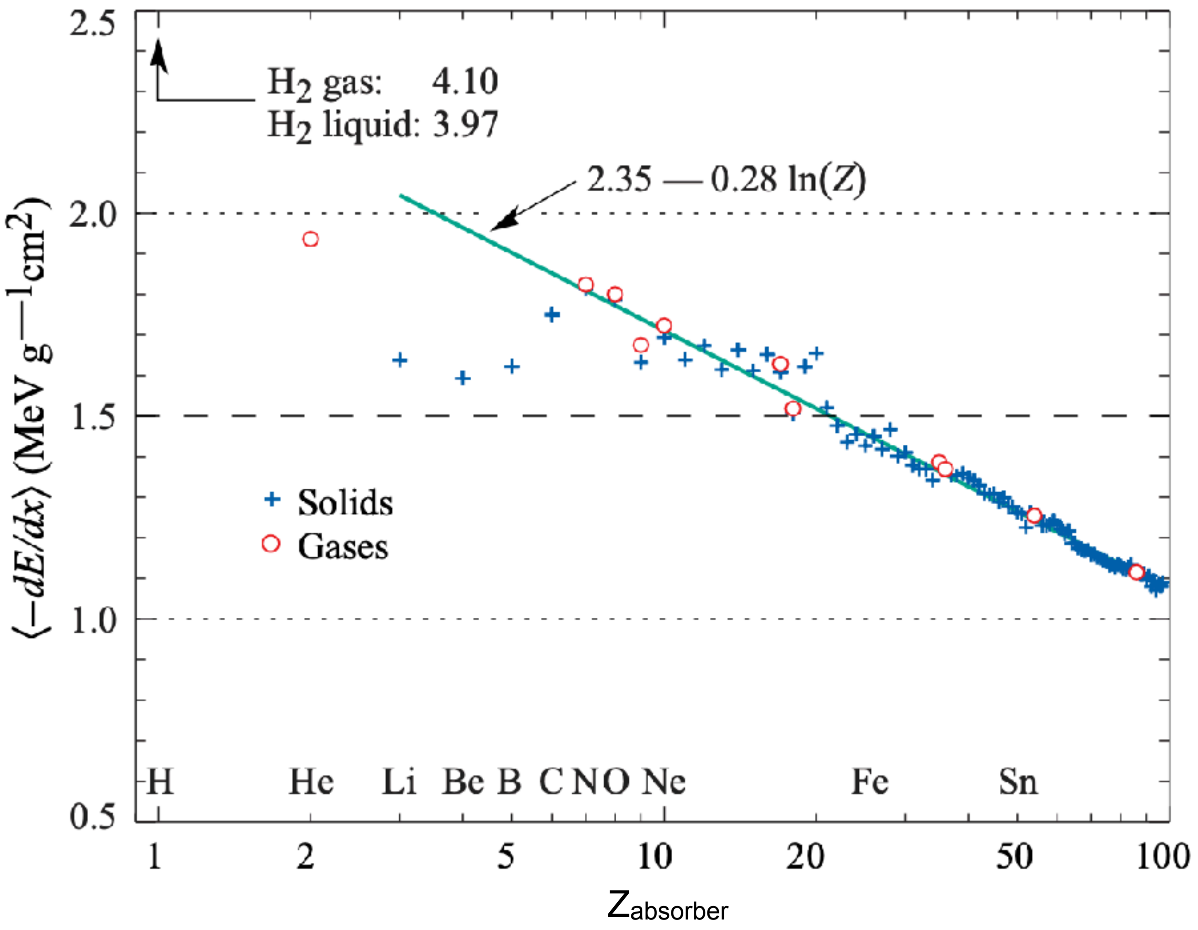
"minimum ionizing particles" $\beta\gamma \approx 3\text{-}4$

Plot: PDG, June 2018

Material Dependence of the Energy Loss



Plot: PDG, June 2018



Rule of thumb: energy loss of MIPs ($\beta\gamma$ ~ 3): 1-2 MeV g^{-1} cm^2

Important Constants

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV$/c^2$
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times$ c^2	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075$ MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$\sqrt{\rho\langle Z/A\rangle} \times 28.816$ eV (ρ in g cm^{-3})
N_e	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408$ g cm$^{-2})^{-1}$ for $A = 1$ g mol^{-1}
X_0	Radiation length	g cm^{-2}
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

- Median ionisation energy I: I ~ 16 $Z^{0.9}$ eV for Z > 1

- Maximal energy transfer:

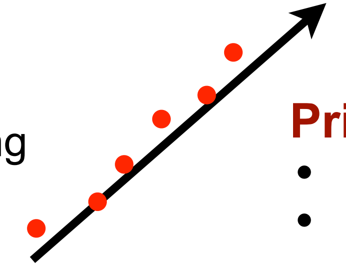
$$T_{max} \sim 2m_ec^2\beta^2\gamma^2$$

für m >> m_e

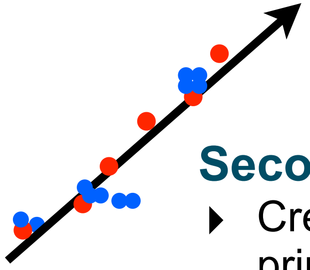
Particle Data Group, June 2018

A Closer Account of Energy Loss

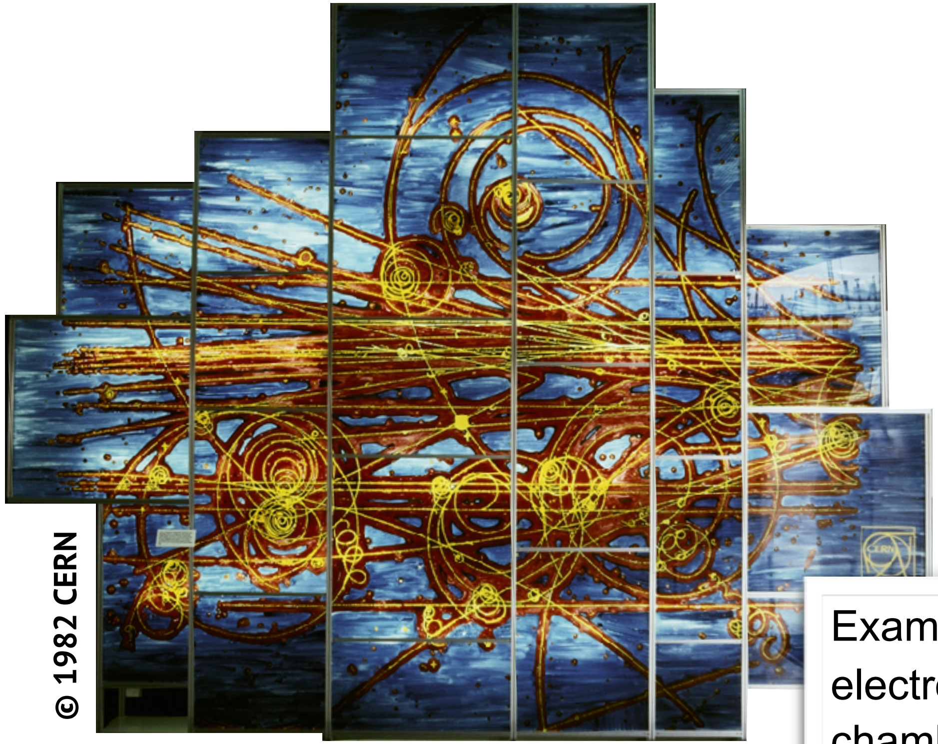
- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



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

Liquid hydrogen bubble chamber 1960 (~15cm).

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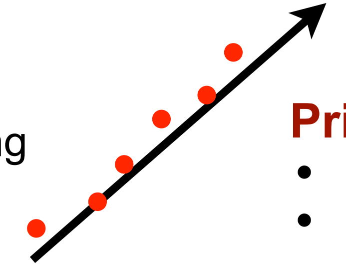

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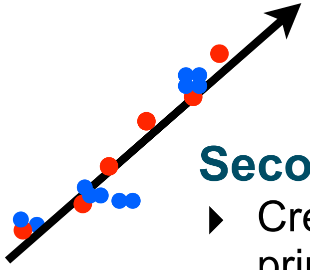

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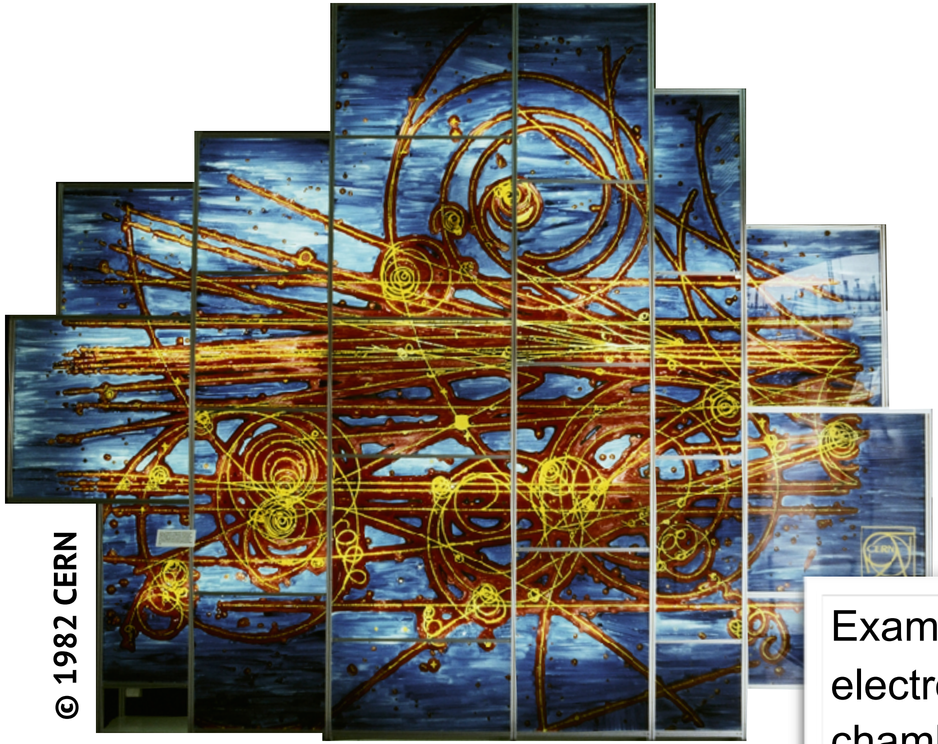


Example of a delta electron in a bubble chamber: visible path

Liquid hydrogen bubble chamber 1960 (~15cm).

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

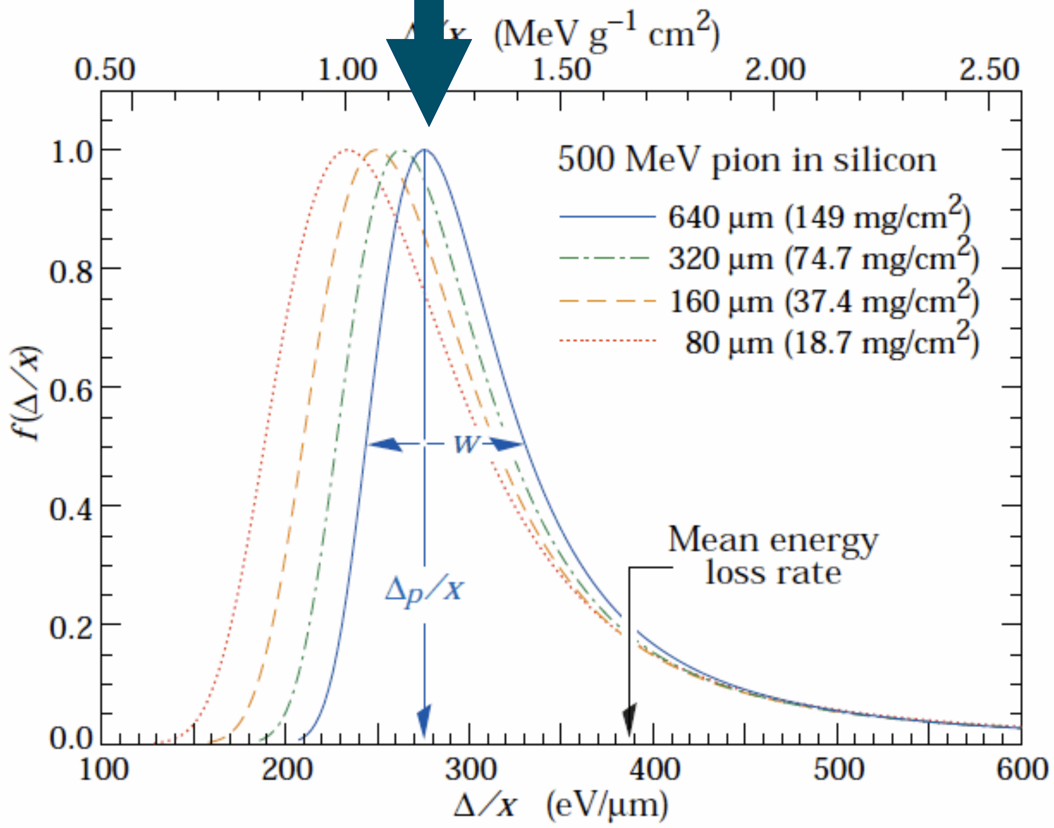
Energy Loss in Thin Layers

- 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 Tmax, δ-electrons.

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:
$<dE> < \sim 10T_{max}$

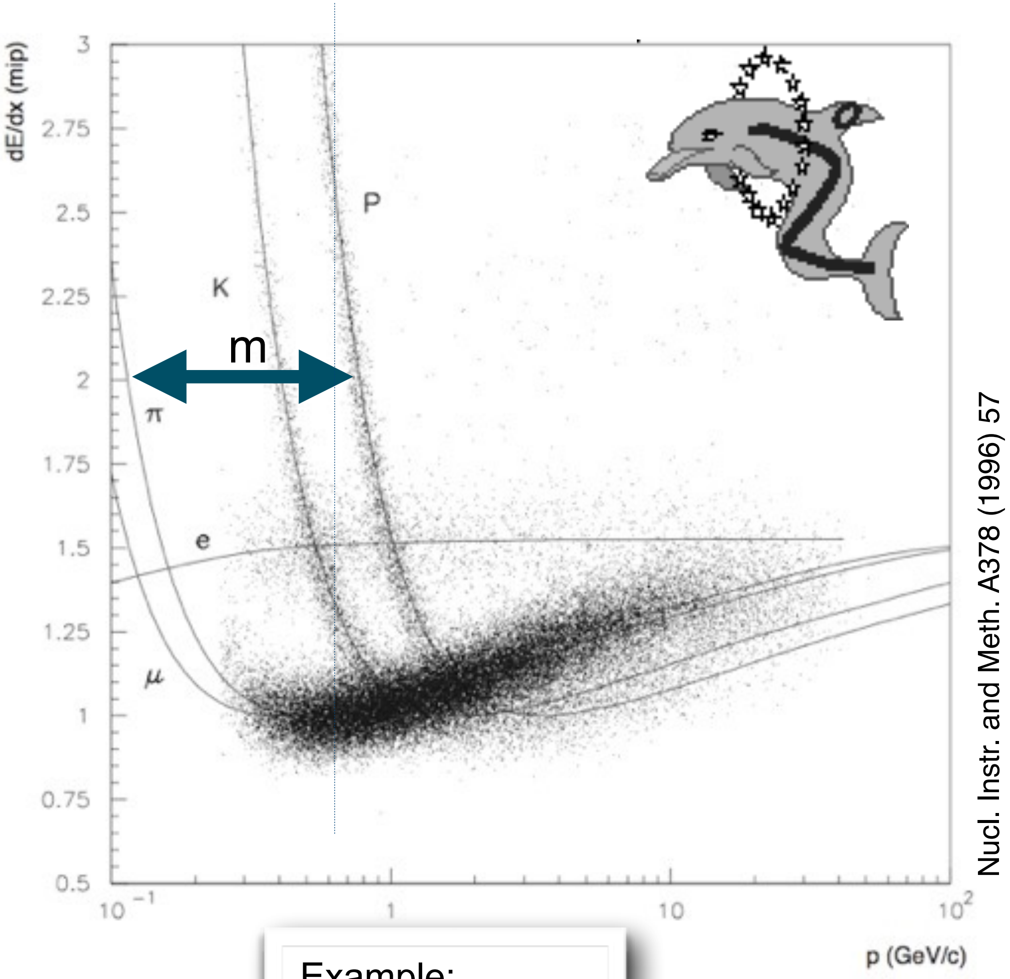
most probable peak!



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)**



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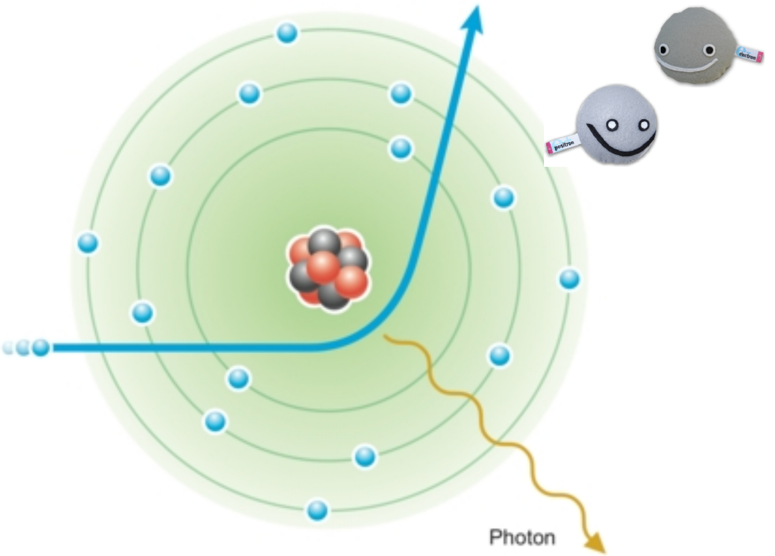
Example:
DELPHI@ LEP

Energy Loss for Electrons

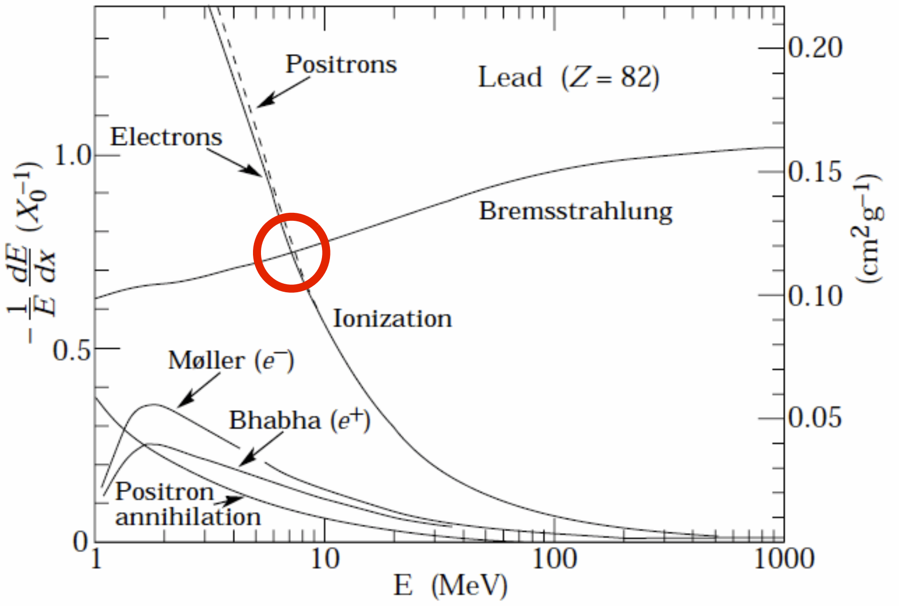
- Incident and target electron have same mass m_e
- Scattering of identical, undistinguishable particles
- Bremsstrahlung: photon emission by an electron accelerated in Coulomb field of nucleus

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



Incident electron and Bremsstrahlung photon.

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



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

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

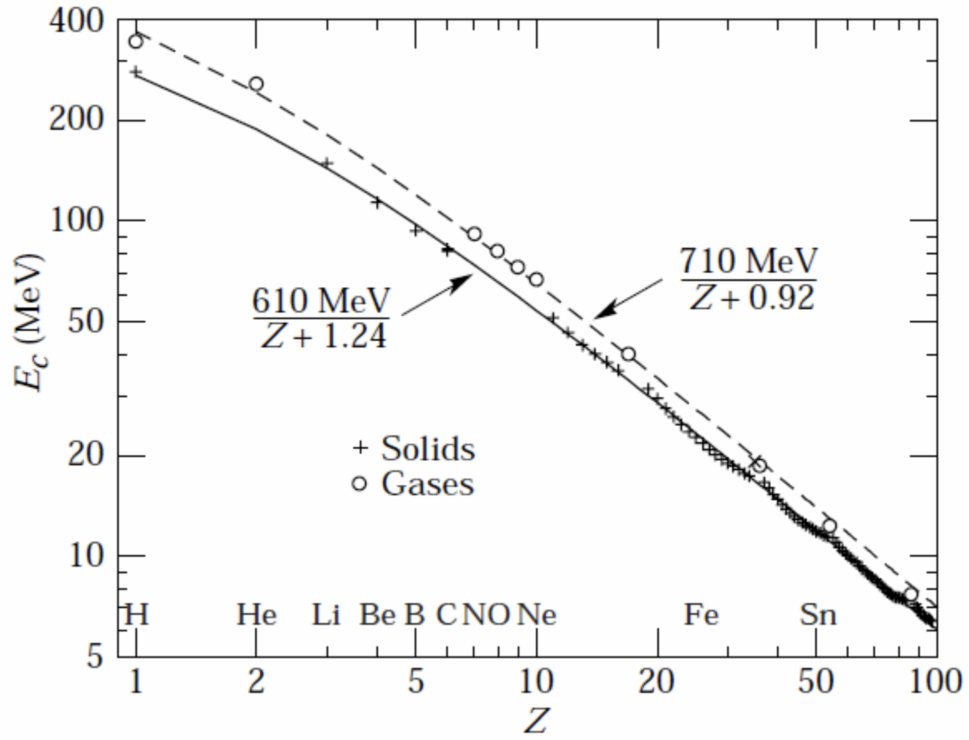
Electrons: Energy Loss

- **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

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

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

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

$$\rightarrow \quad E = E_0 \, e^{-x/X_0}$$

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

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

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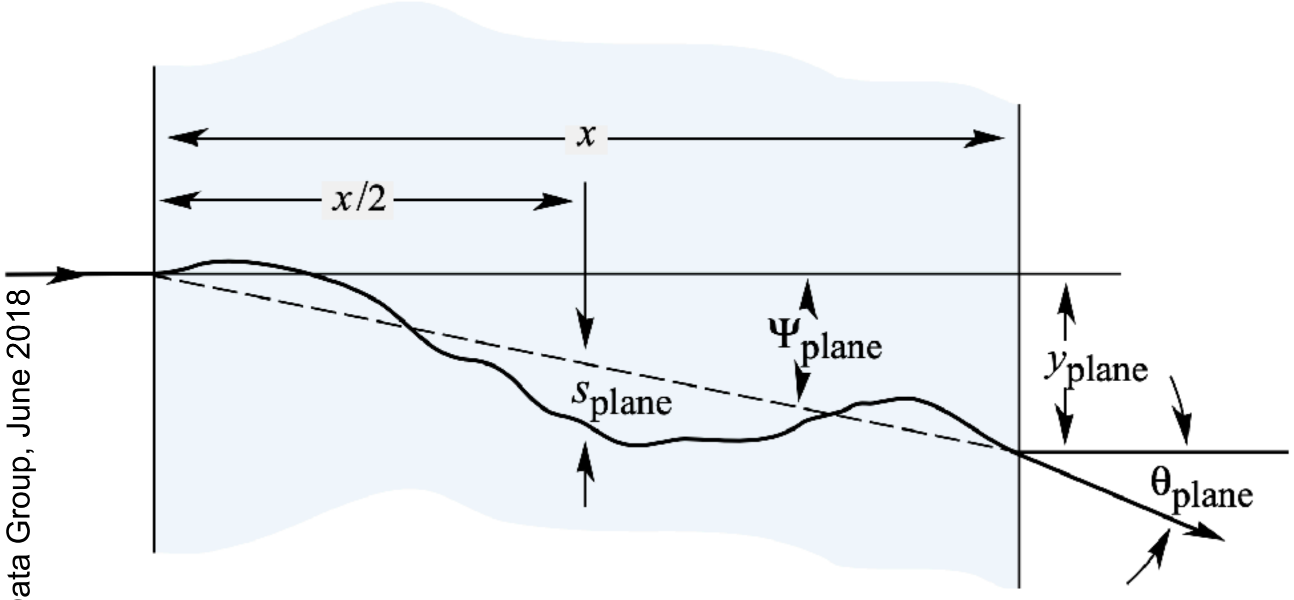
- Usually quoted in [g/cm²], typical values are:
  - Air: 36.66 g/cm² ->~ 300 m
  - Water: 36.08 g/cm² -> ~ 36 cm
  - Silicon: 21.82 g/cm² -> 9.4 cm
  - Aluminium: 24.01 g/cm² -> 8.9 cm
  - Tungsten: 6.76 g/cm² -> 0.35 cm

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.



Particle Data Group, June 2018

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

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

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

Gaussian approximation sufficient for many applications.

Cherenkov-Radiation

- Emission of photons when a charged particle is faster than speed of light within a medium (n>1).
- Typically in transparent material: threshold
- Suitable for particle identification!
  - Only depending on β if momentum known.

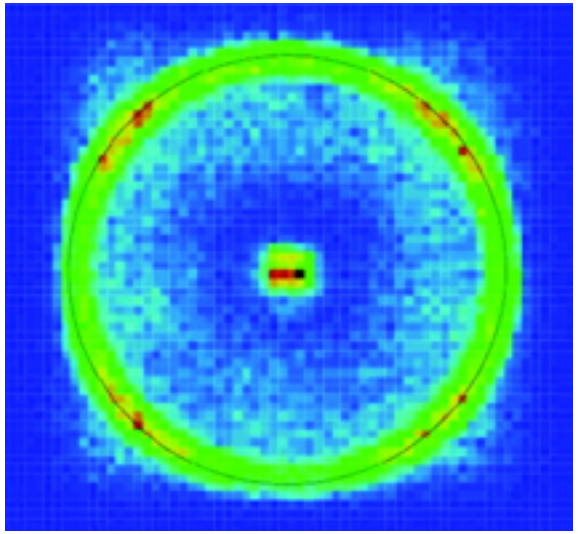
Emission under a characteristic Angle:

$$\cos\theta_c = \frac{ct/n}{vt} = \frac{1}{n\beta}$$

- Cherenkov angle: between 1^o (air) to 45^o (quartz).
- Number of photons is small -> good detectors are needed for the detection.

PIC: NASA

"Sonic boom for charged particles"



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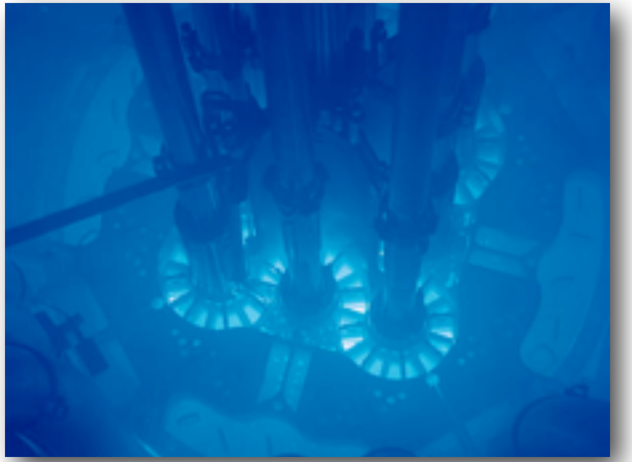
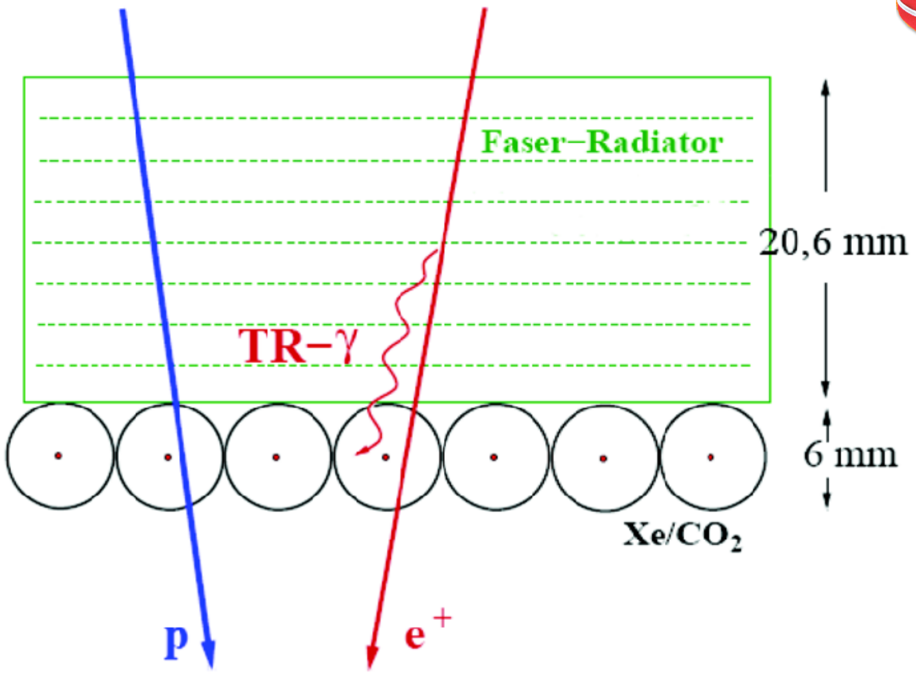
Cherenkov ring recorded by an array of silicon photomultipliers (pions).



Pic: Idaho National Lab

Transition Radiation

- **Transition Radiation**
  - Produced by relativistic charged particles when they cross interface of two media of different refraction indices
  - Explained by re-arrangement of electric field
  - Significant radiation only at large γ (O ~ 1000) in the keV range.
  - Very useful for electron/pion separation



Pic: PERDaix Collaboration

- Energy loss at a boundary is proportional to the relativistic gamma factor.
- A significant amount of transition radiation is produced for a gamma greater than 1000.
- Gamma factor of protons is, up to a momentum of 5GeV, still in the order of 10.
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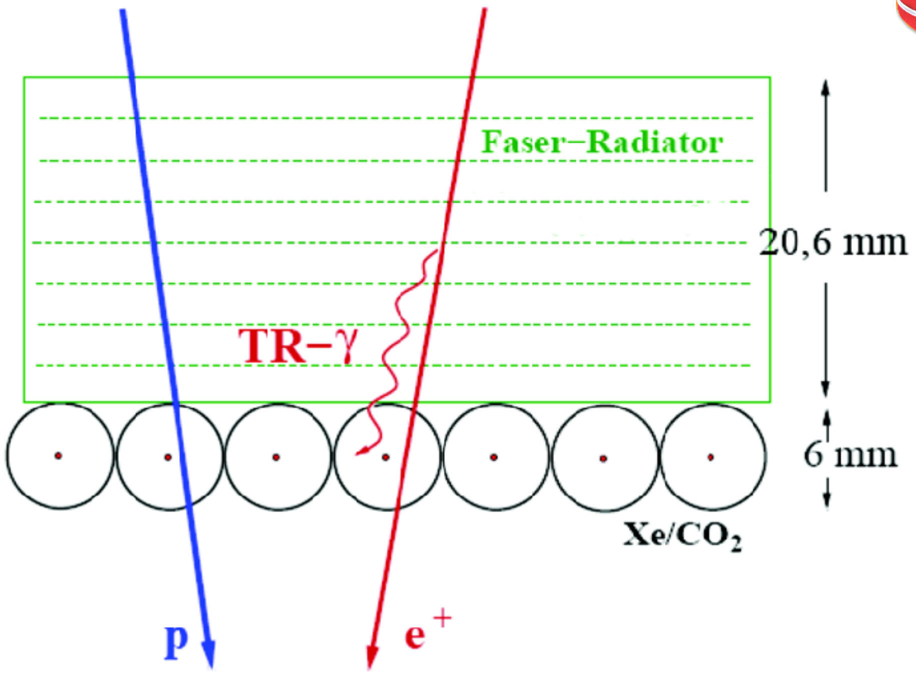

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Both effects are not really contributing to the energy loss of the particles!

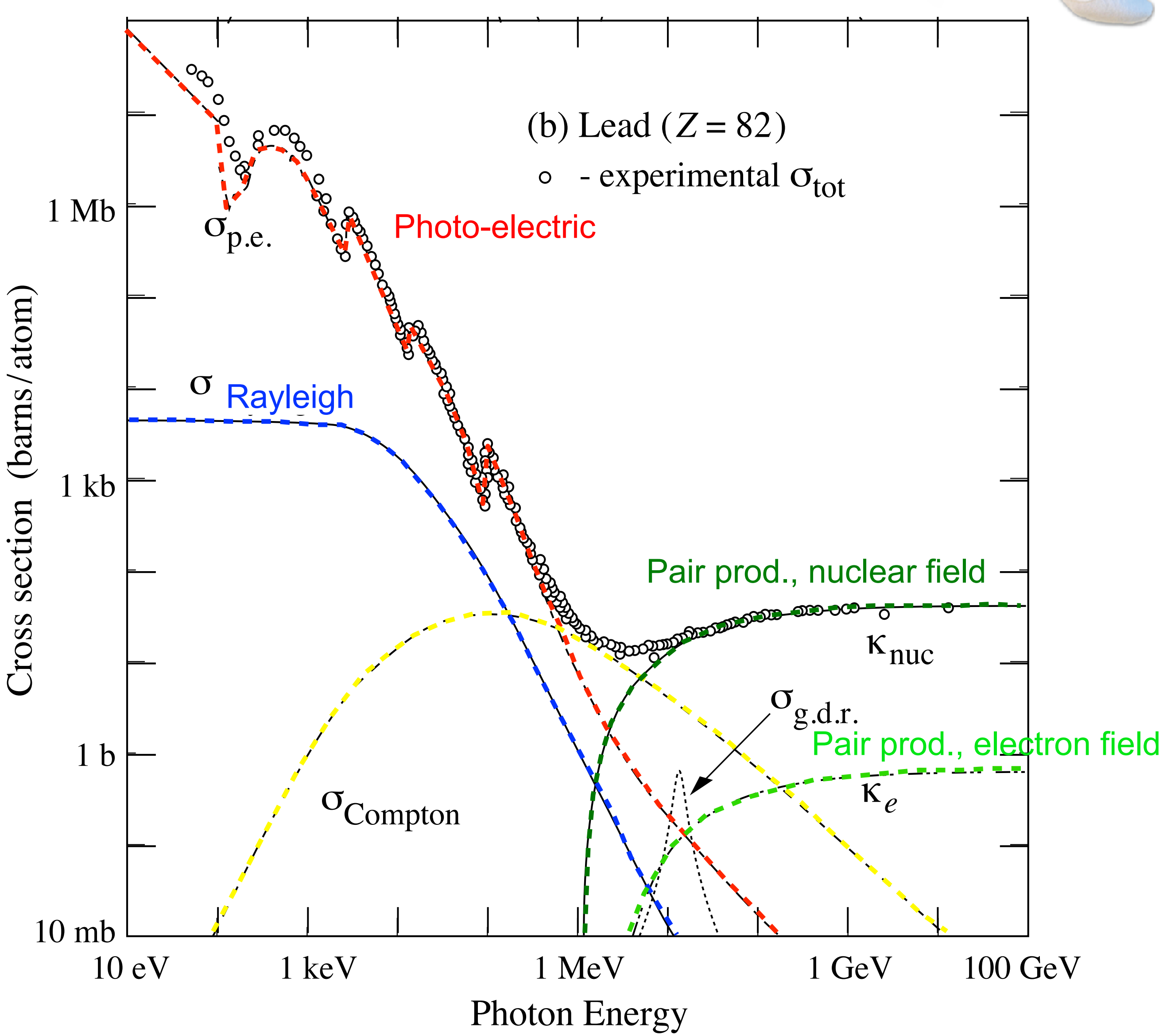
Interactions of Photons, Neutrons and Neutrinos

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: Interactions

- Most dominating effects:

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Photo-Effect **Compton-Scattering** **Pair creation**

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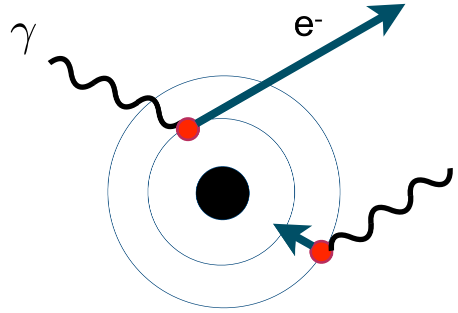

A γ is absorbed and photo-electron is ejected.
- the γ disappears,
- the photo-electron gets an energy

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

Compton-Scattering

Pair creation

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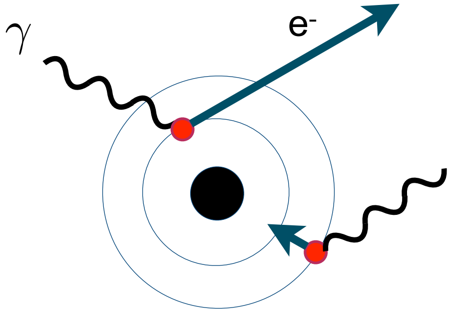

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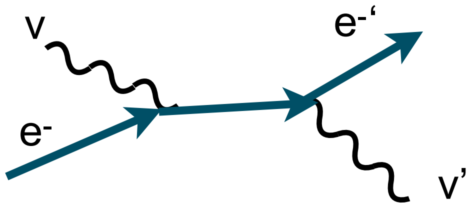

$$\gamma + e \rightarrow \gamma' + e'$$

Elastic scattering of a photon with a free electron

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

Pair creation

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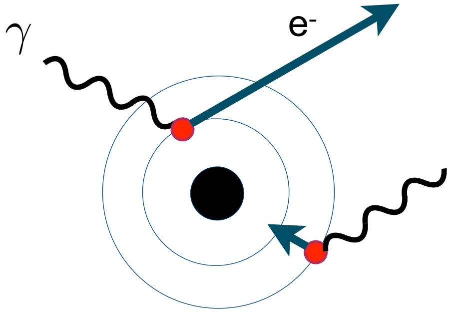

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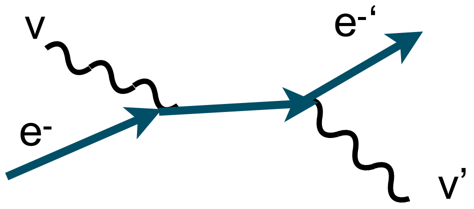

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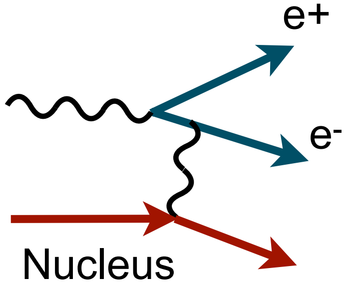

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$$E_{\mathrm{p.e}} = E_\gamma - E_{\mathrm{binding}}$$

Elastic scattering of a photon with a free electron

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

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

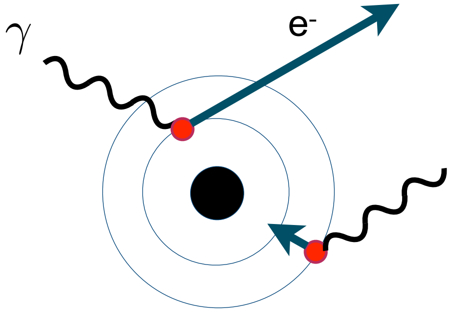
$$E_\gamma \geq 2m_e c^2$$

~1.022 MeV

Photons: Interactions

- Most dominating effects:

Photo-Effect

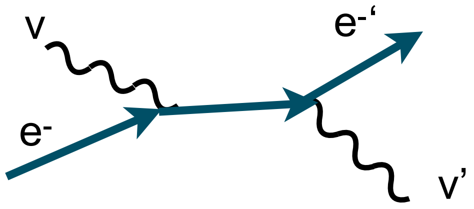


A γ is absorbed and photo-electron is ejected.

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

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

Compton-Scattering

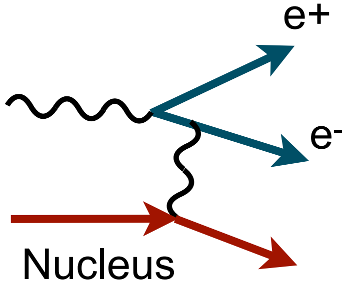


$$\gamma + e \rightarrow \gamma' + e'$$

Elastic scattering of a photon with a free electron

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

Pair creation



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➫ Reduction of photon intensity with passage through matter:

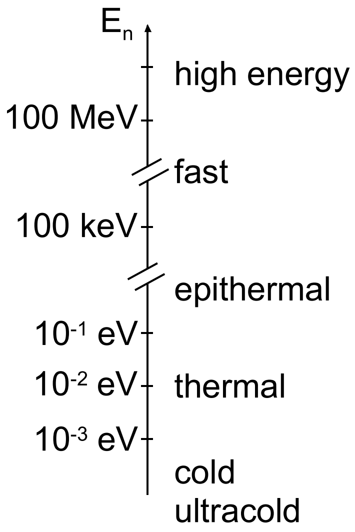
$$I(x) = I_0 e^{-\mu x}$$

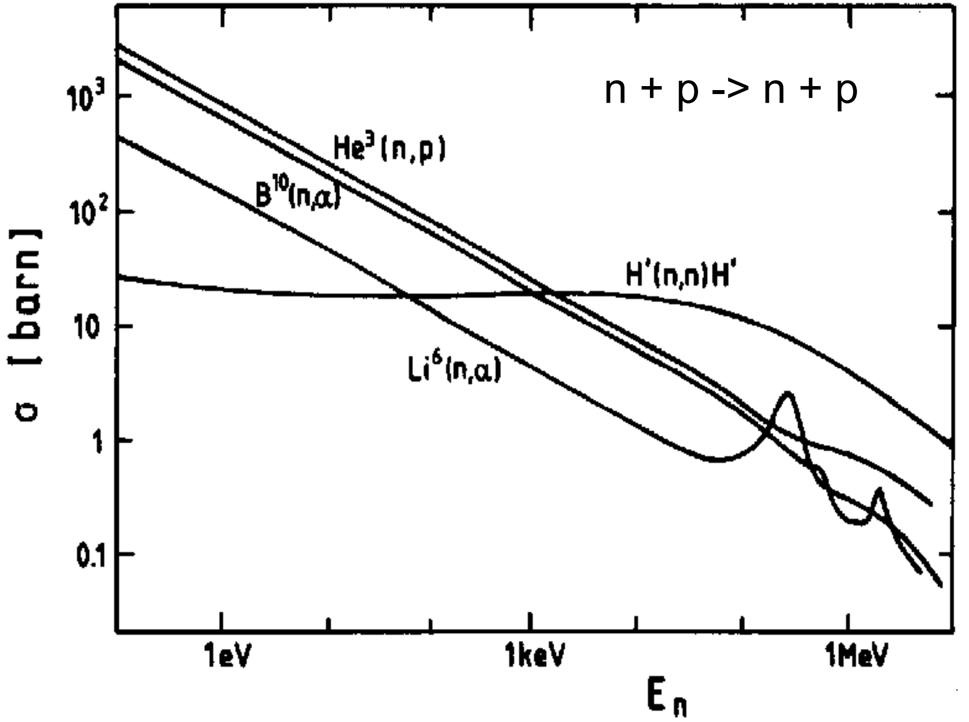
Interactions of Neutrons

- Neutron interaction is based only on strong (and weak) nuclear force.
- To detect neutrons, one has to create charged particles.
- Possible neutron conversion and elastic reactions …

$$\left.\begin{array}{r} n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} \\ n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} \\ n + {}^{3}\mathrm{He} \rightarrow p + {}^{3}\mathrm{H} \end{array}\right\} \quad E_n < 20\mathrm{MeV}$$

$$n + p \rightarrow n + p \qquad E_n < 1\mathrm{GeV}$$





Plot: H. Neuert, Kernphysikalische Messverfahren, 1966

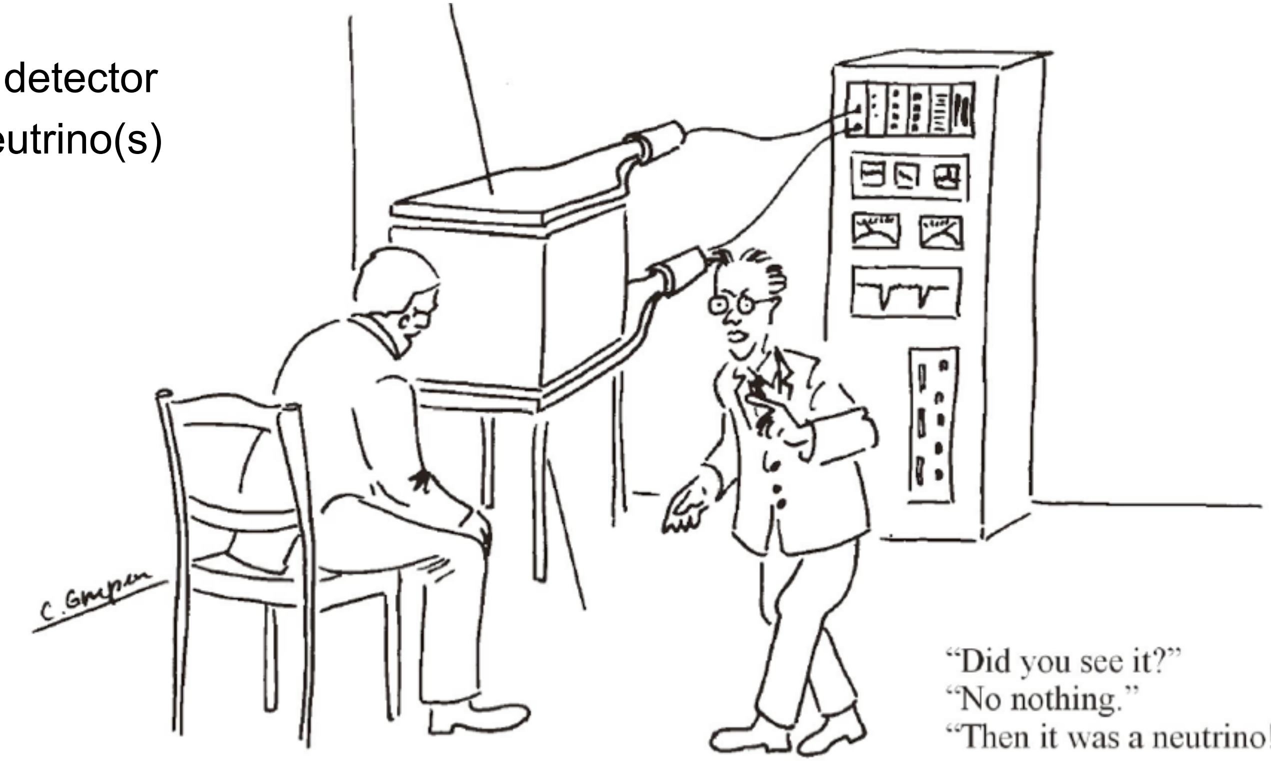
In addition there are…

- inelastic reactions → hadronic cascades E_n > 1 GeV
- same detection principals as for other hadrons (calorimeter)

A Short Word on Neutrinos...

- Neutrons react very weakly with matter
- Cross section for $\nu_e + n \rightarrow e^- + p$ is around 10^{-43} cm^{-2}.
  - 1m Iron: probability 10^{-17}

- In collider experiments fully hermetic detectors allow indirect detection
  - Sum up all visible energy and momentum in detector
  - Missing energy and momentum belong to neutrino(s)



“Did you see it?”
“No nothing.”
“Then it was a neutrino!”

Claus Grupen, Particle Detectors, Cambridge Uni. Press 1996

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.

Summary Part 1

Ionisation and Excitation:

- Charged particles traversing material are **exciting and ionising** the atoms.
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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….

A short summary

$\pi^- + p$

16 GeV

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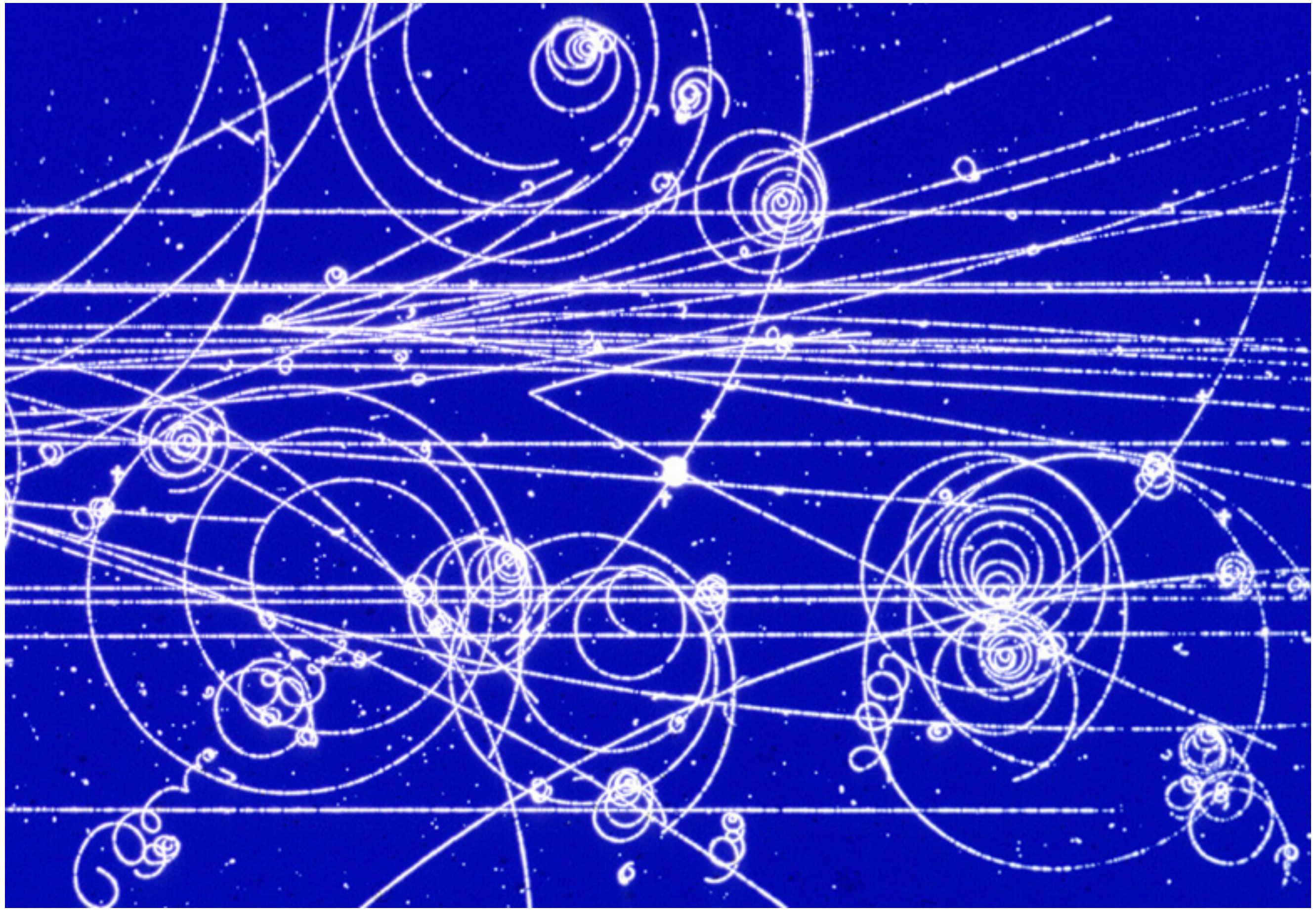

?

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

A short summary

$\pi^- + p$

16 GeV

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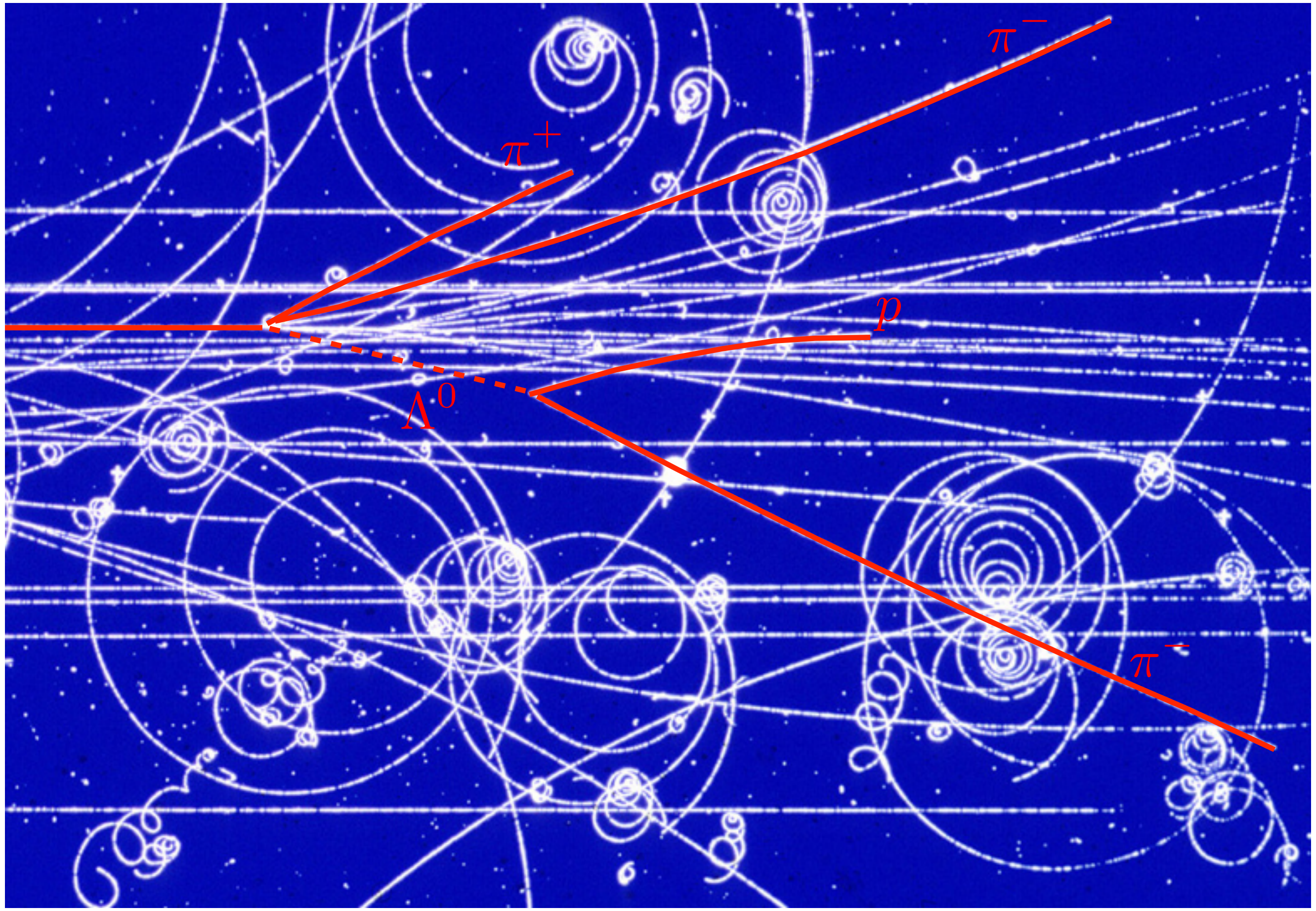
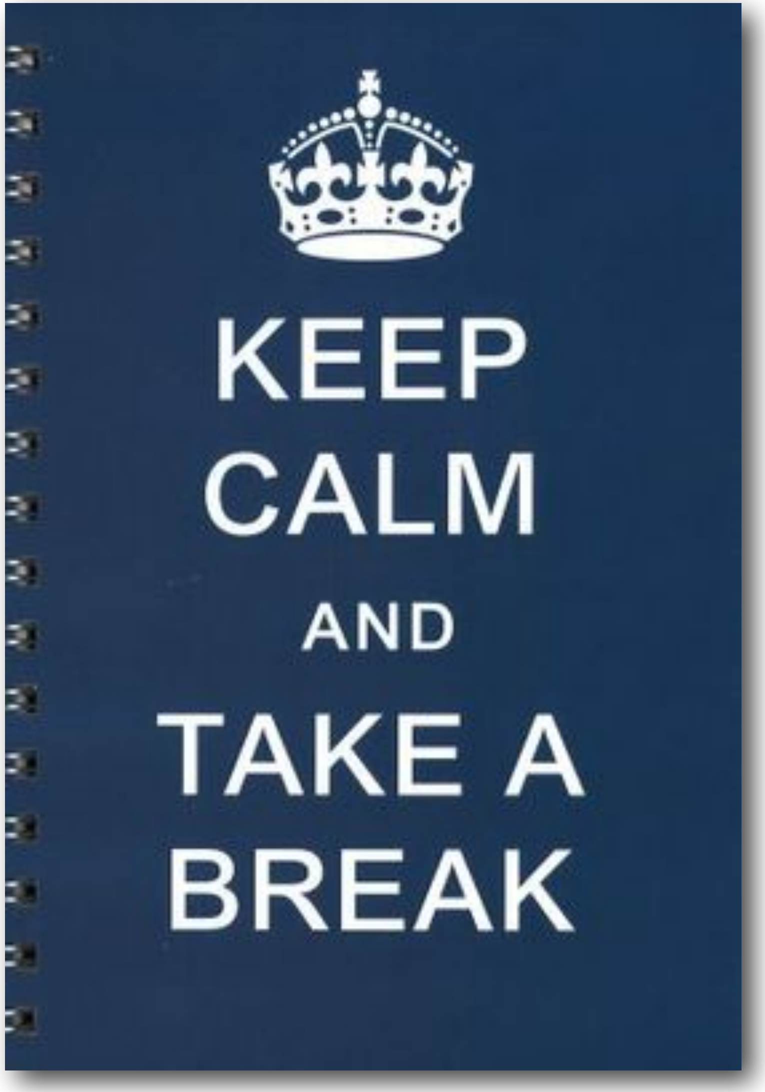


Lifetime of lambda:
2.6 10^{-10} sec
-> a few cm

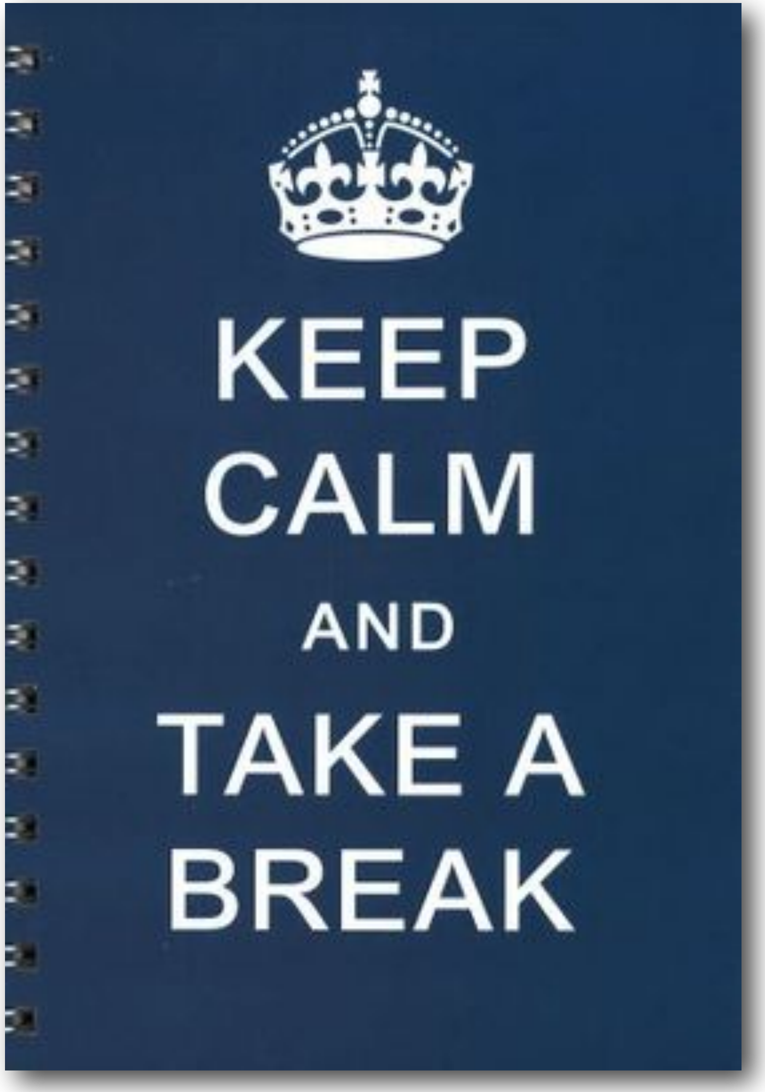
$$\pi^- + p \rightarrow K_s^0 + \Lambda$$?

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

AND NOW ... ?



AND NOW ... ?



15 minutes
coffee break ….