Detectors for High Energy Physics.

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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 !

Maybe not the ideal detector physicist

Overview

I. **Detectors in Particle Physics**

Part 1

II. **Interaction with Matter**

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

Part 2

IV. **Calorimeters**

Part 3

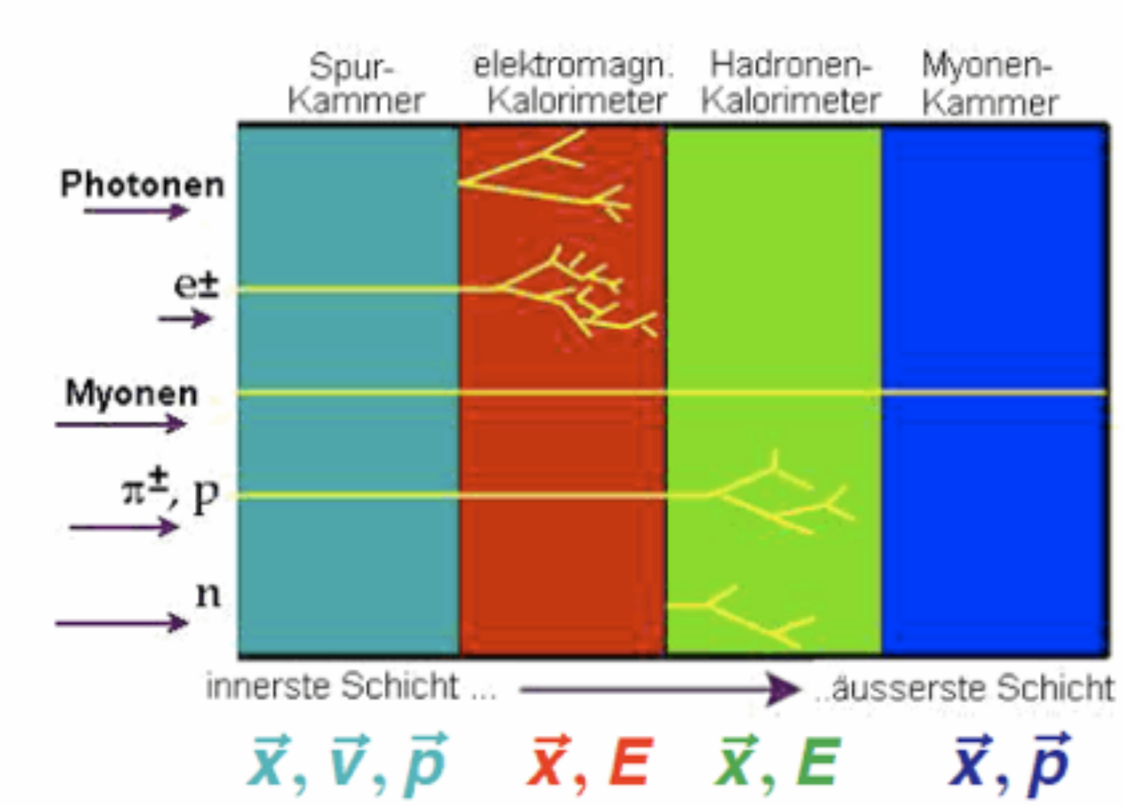
V. **Upgrade Plans**

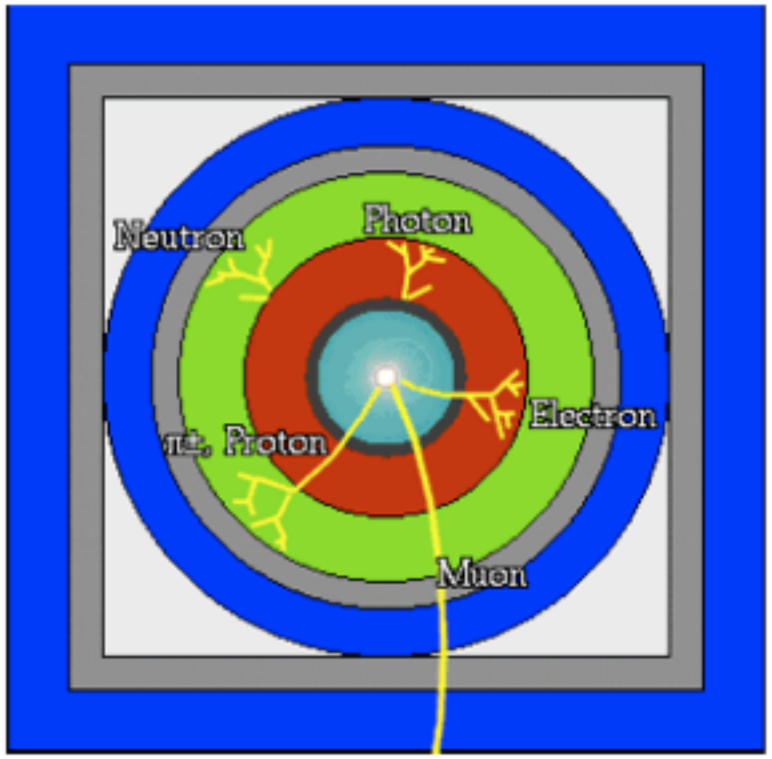
I. Overview:

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 due to electro-magnetic interaction



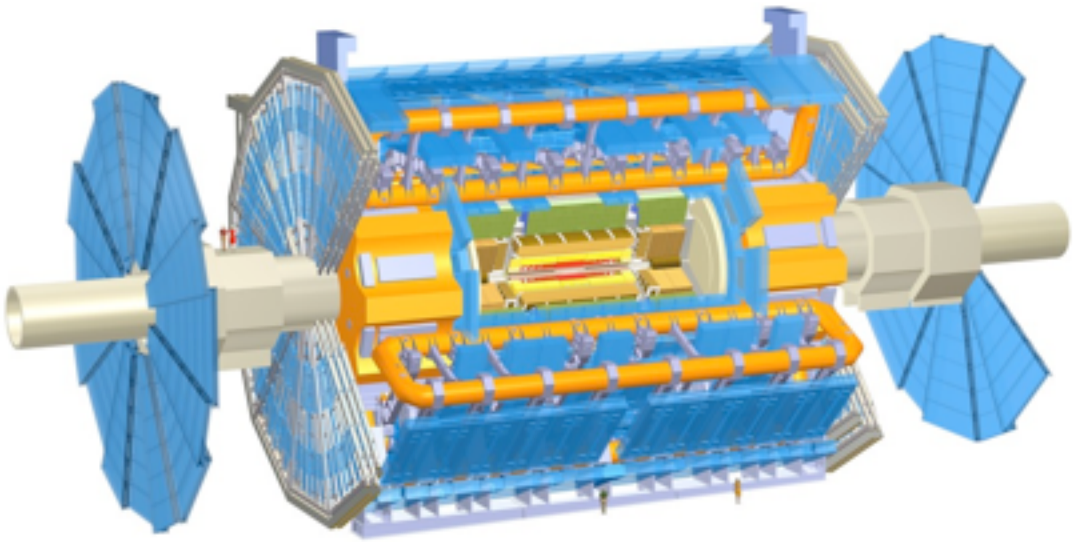


Tracker: Momentum of charged particles due to magnetic field and precise measurement of track

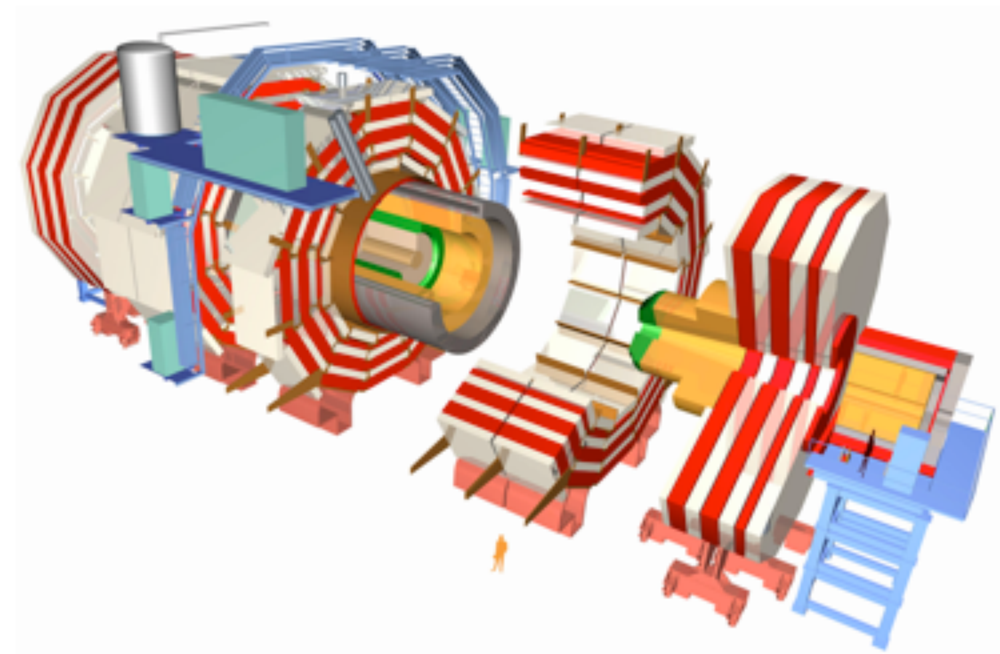
Calorimeter: Energy measurement of photons, electronics and hadrons through total absorption

Myon-Detectors: Identification and precise momentum measurement of myons outside of the magnet

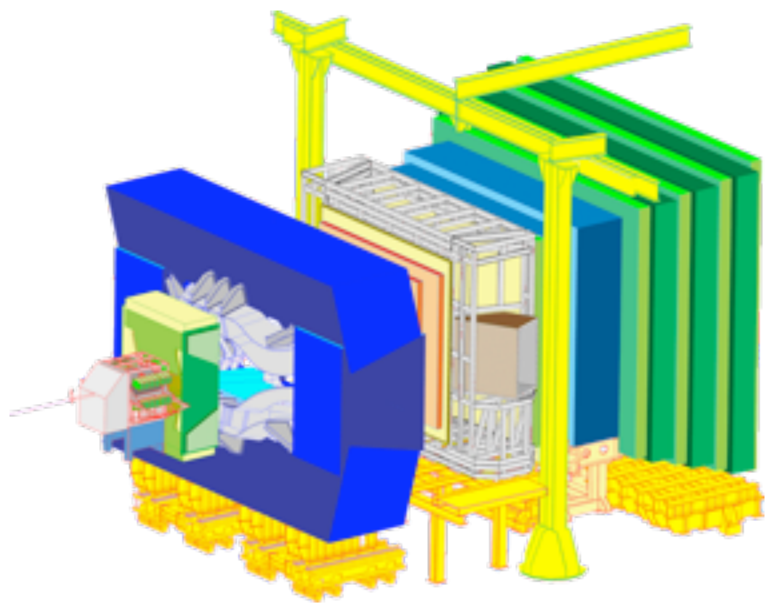
The Big Ones at LHC ....



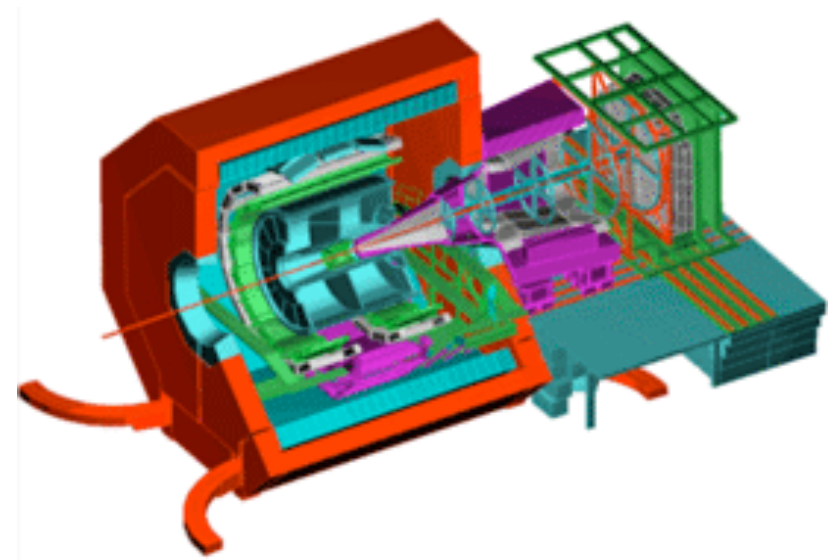
Berlin, Bonn, DESY, Dresden, Dortmund, Freiburg, Göttingen, Heidelberg, Mainz, Mannheim, München, MPI München, Wuppertal



Aachen, DESY, Karlsruhe

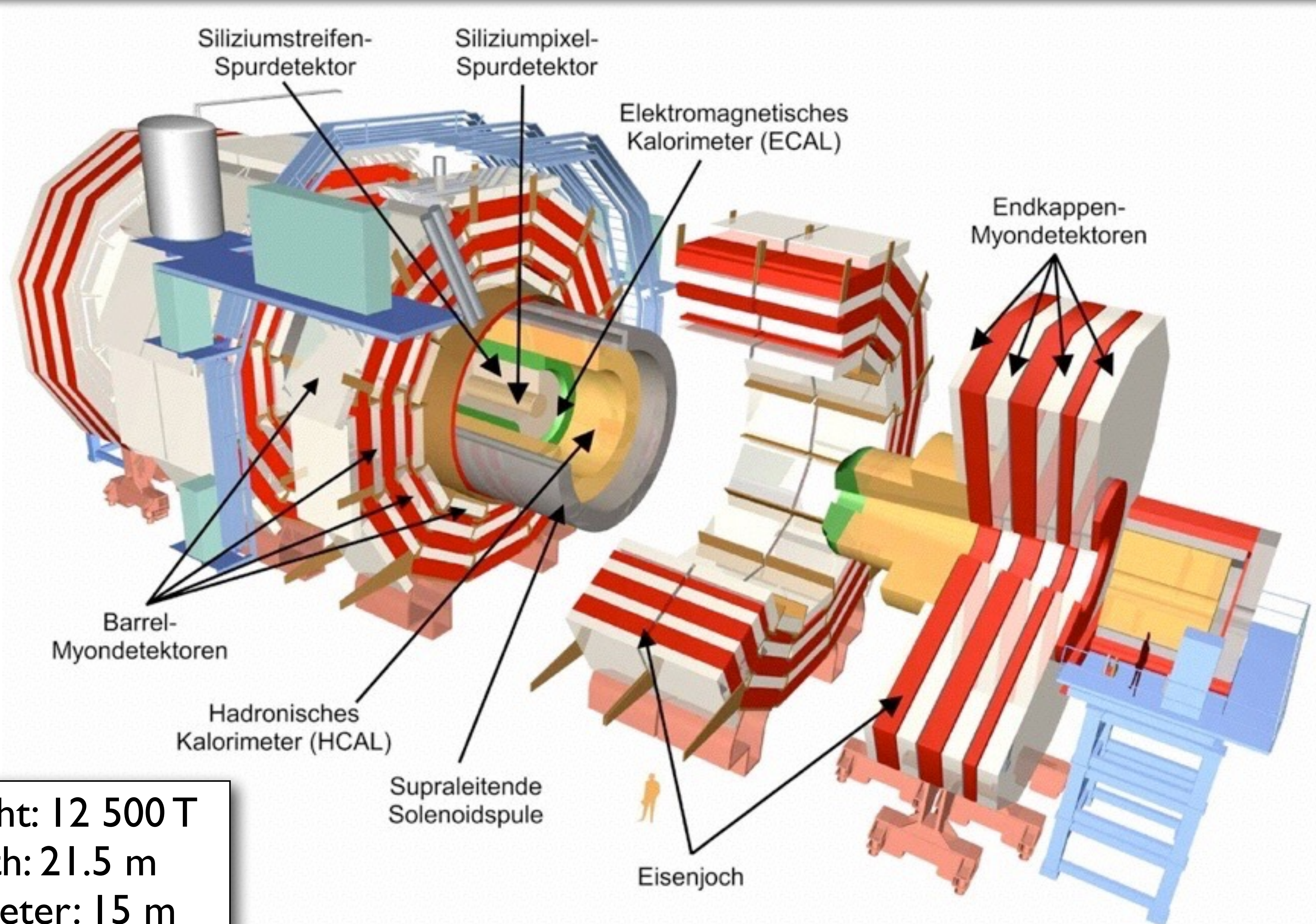


Dresden, Heidelberg, MPI Heidelberg



GSI Darmstadt, Frankfurt, Heidelberg, Kaiserslautern, Köln, Mannheim, Münster, Worms

CMS: The heavy detector



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

CMS Cross Section

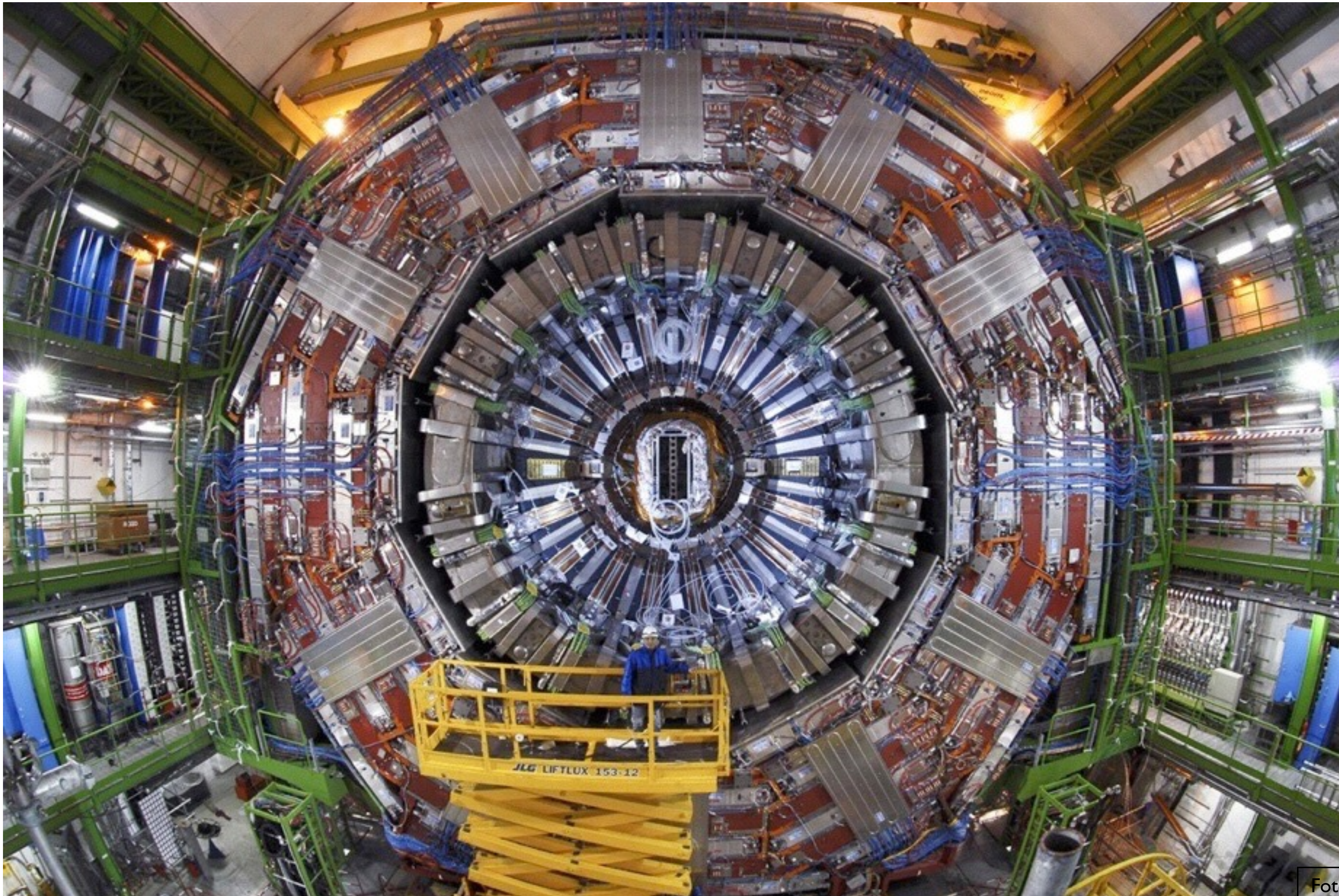
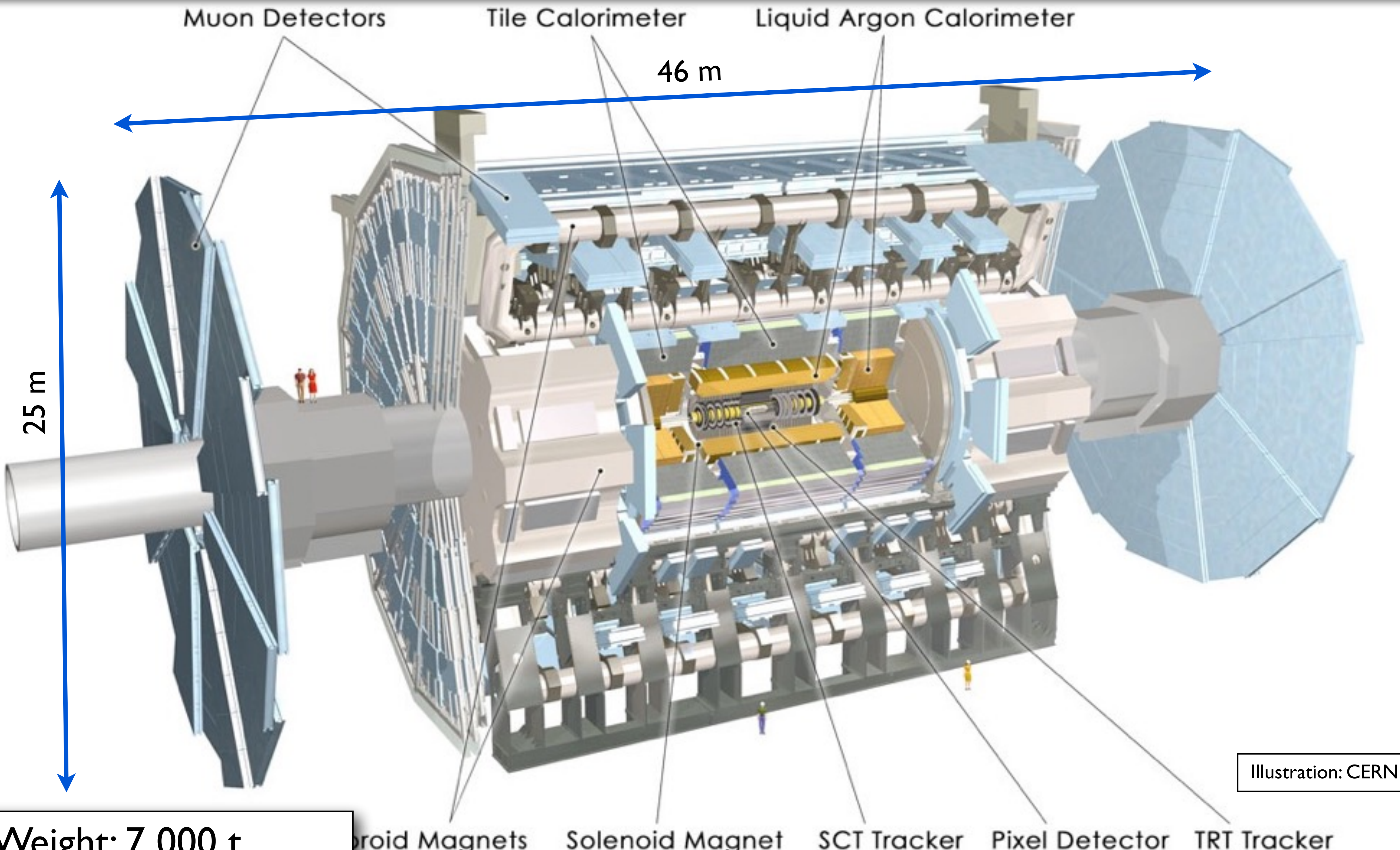


Foto: CERN

ATLAS: The BIG One



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

ATLAS Cross Section

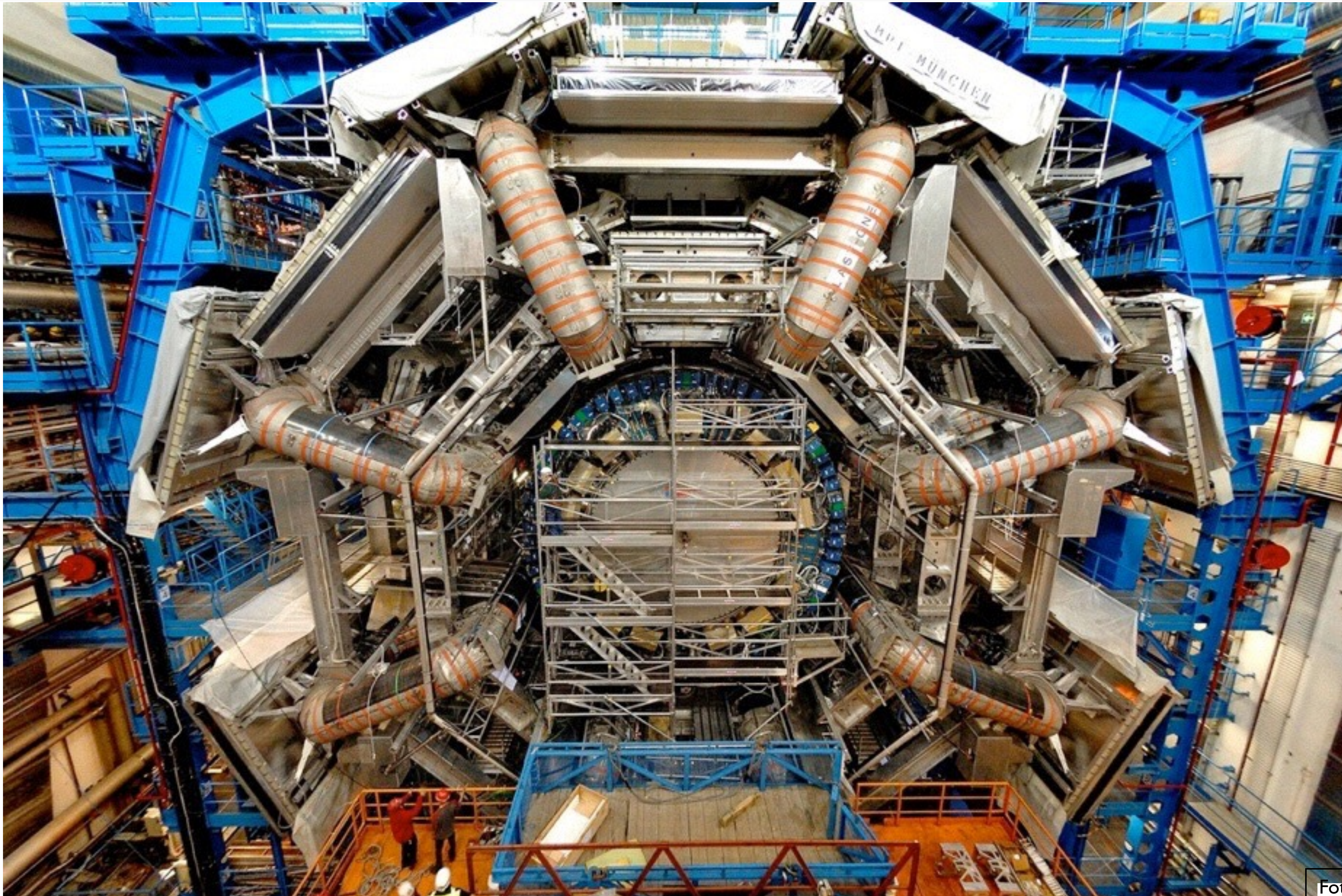
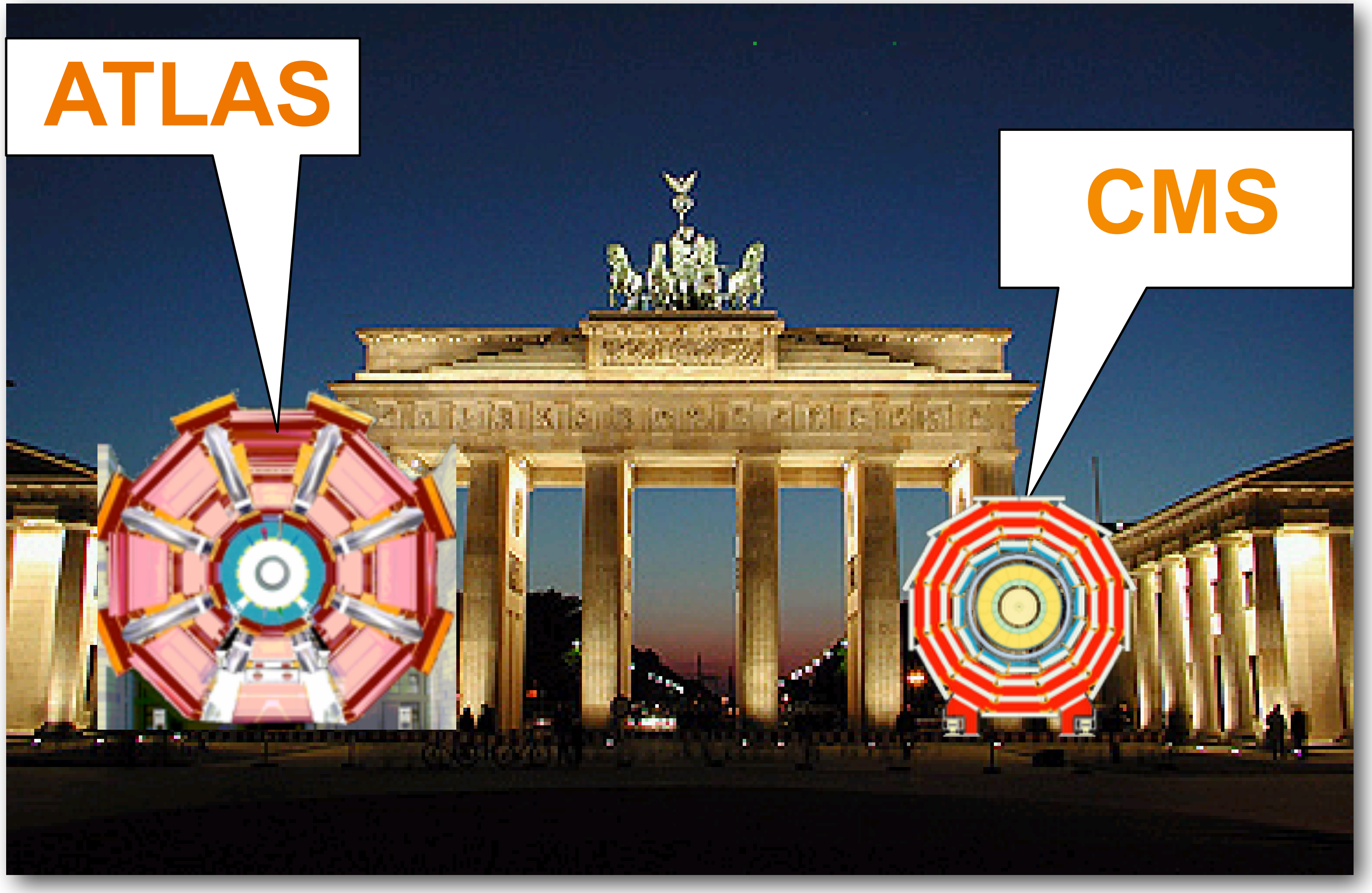


Foto: CERN

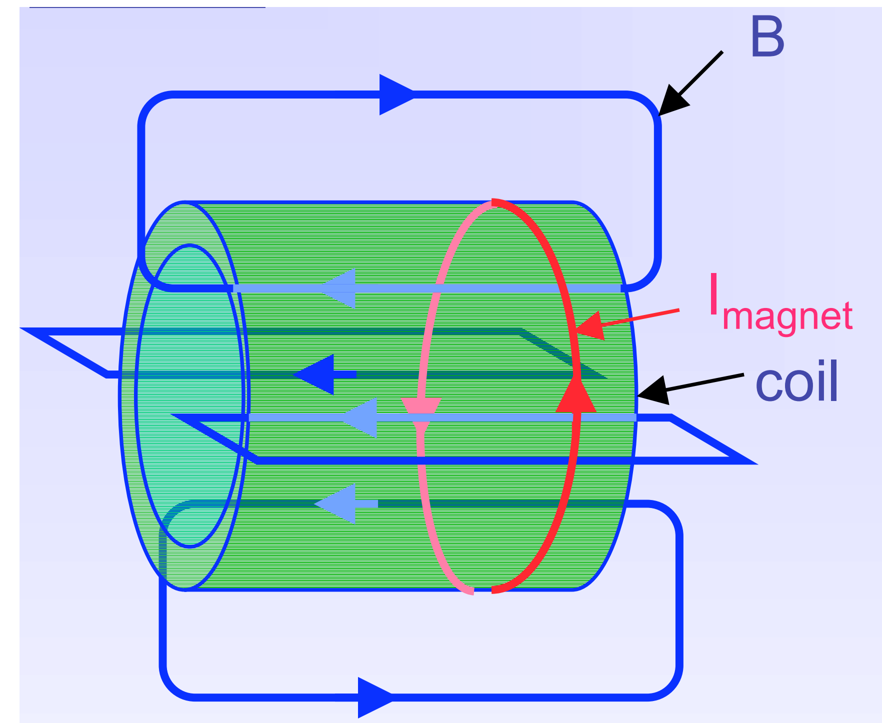
Size and Weight



Brandenburger Tor in Berlin

CMS is 30% heavier than the Eiffel tower

Magnet: CMS -> Solenoid

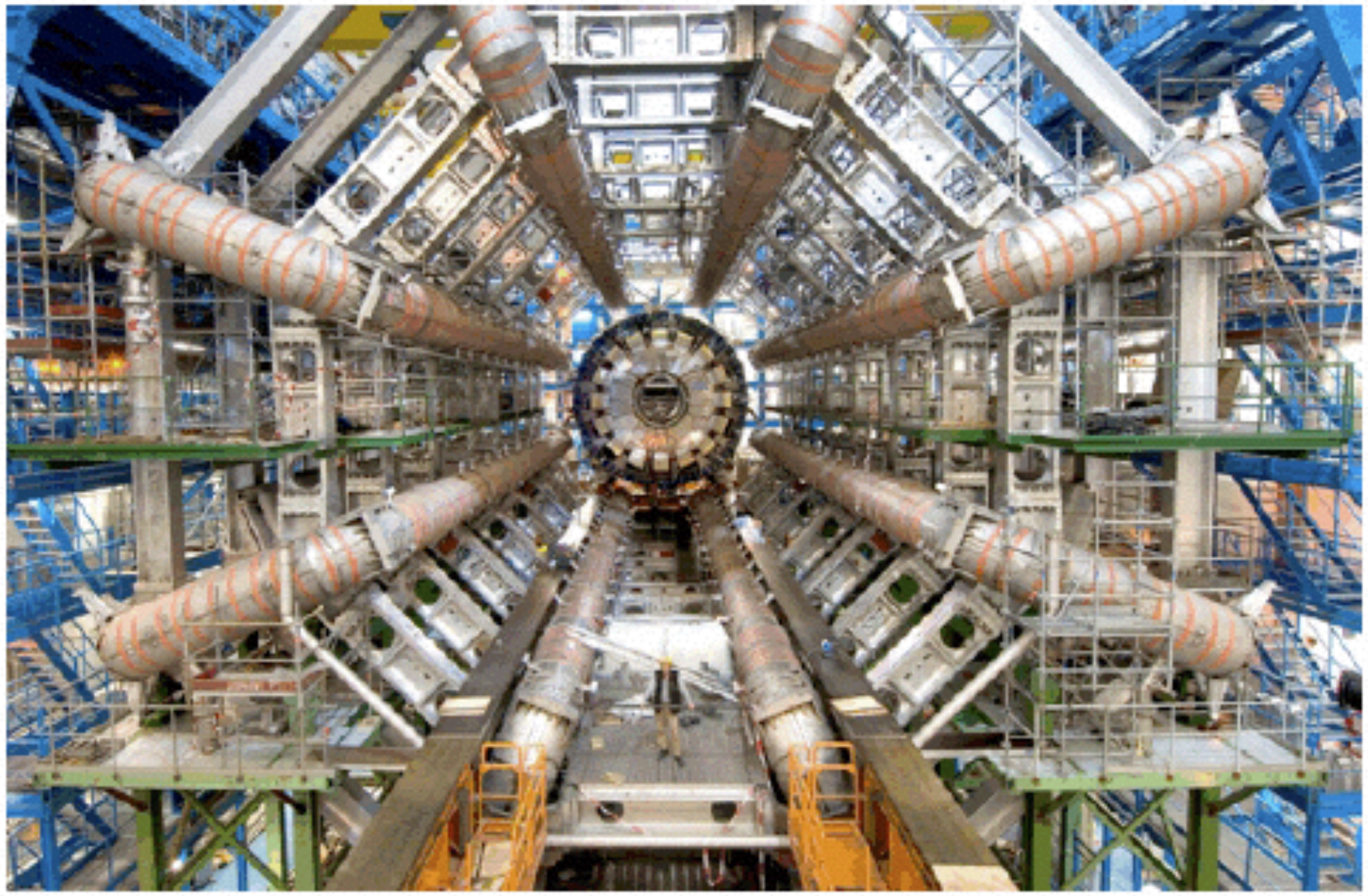


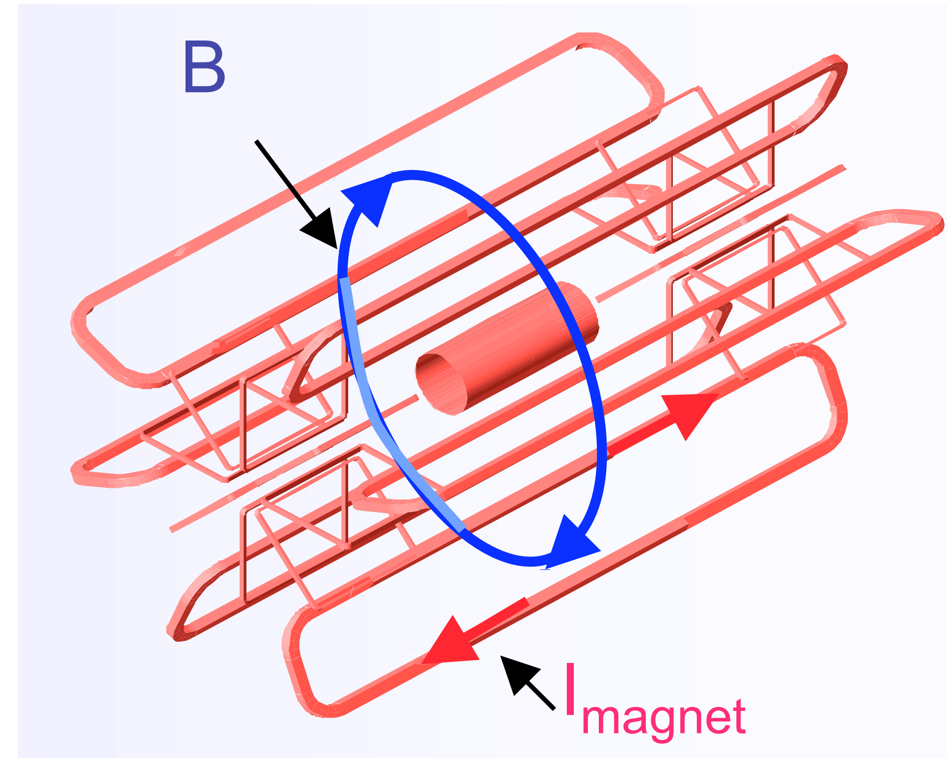
- Largest Solenoid in the world:
  - super conducting, 4 T field
  - encloses trackers and calorimeter
  - 13 m long, inner radius 5.9 m, I = 20 kA, weight of coil: 220 t

+ large homogeneous field inside coil
+ weak opposite field in return yoke
- size limited (cost)
- relative high material budget

Magnet: ATLAS -> Toroid

the largest magnet in the world





- Central Toroid field within Muon-System: 4 T
  - Closed field, no yoke
  - Complex field
- 2 T Solenoid-field for trackers

+ field always perpendicular to $\vec{p}$
+ relative large field over large volume
- non uniform field
- complex structure

Example: ATLAS at CERN

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

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

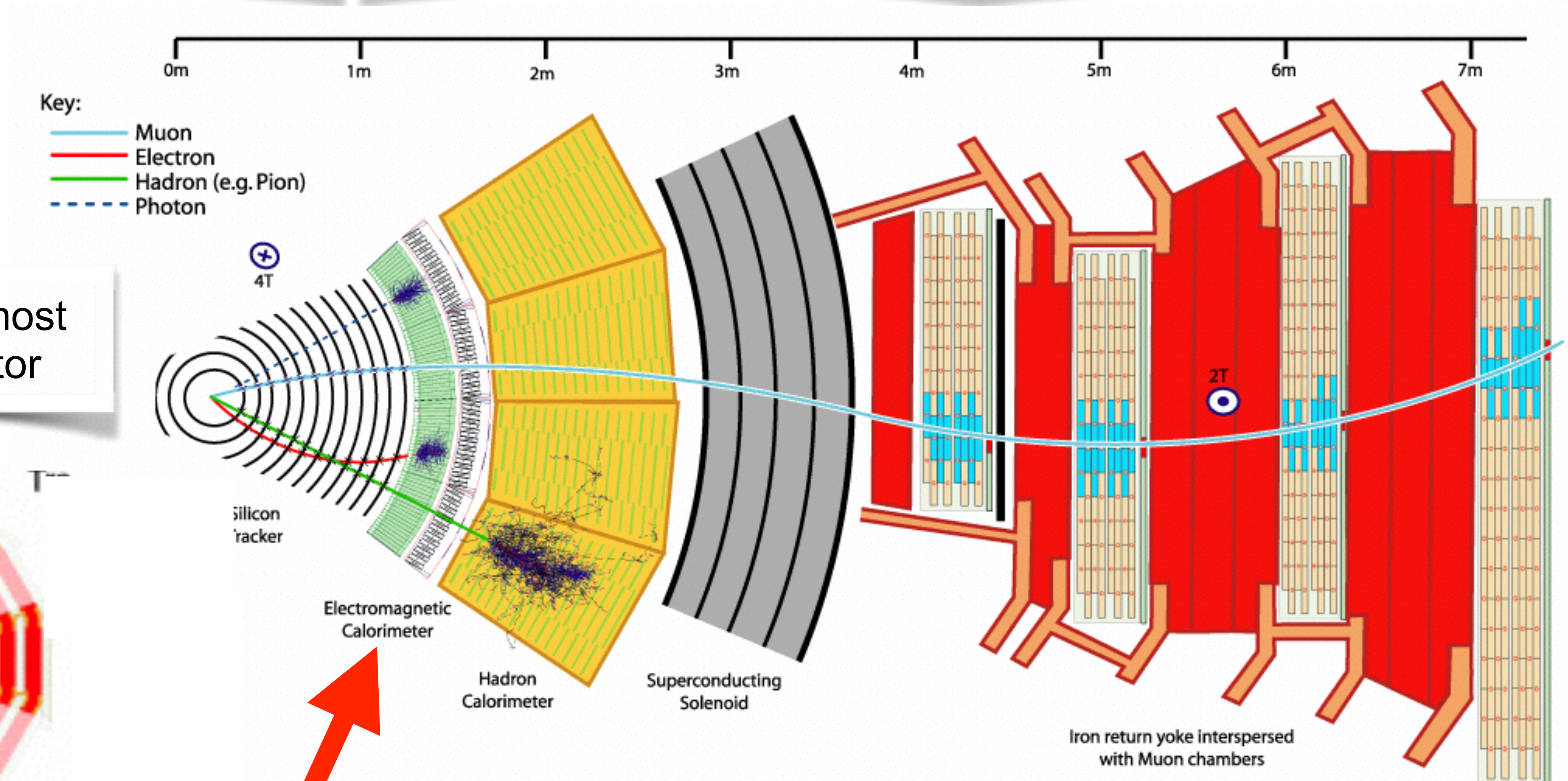
LHC Detector Overview

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

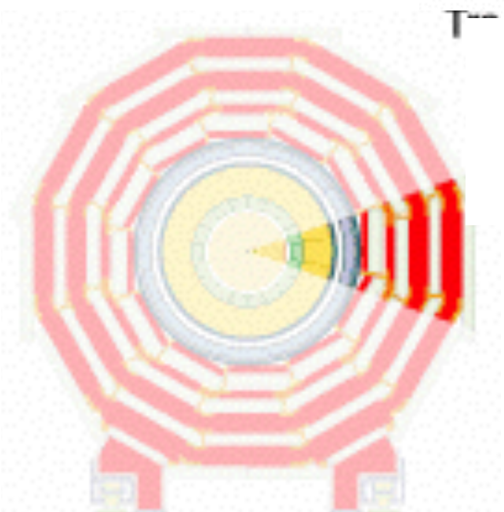
Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

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)

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II. The Basics of All Detection Processes:

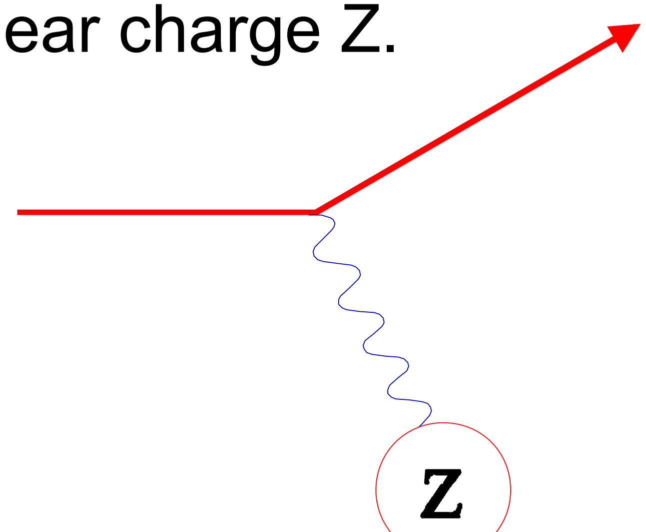
Interactions with Matter

Analogy

- Planes leave tracks in sky under certain conditions ….

Heavy Charged Particle

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



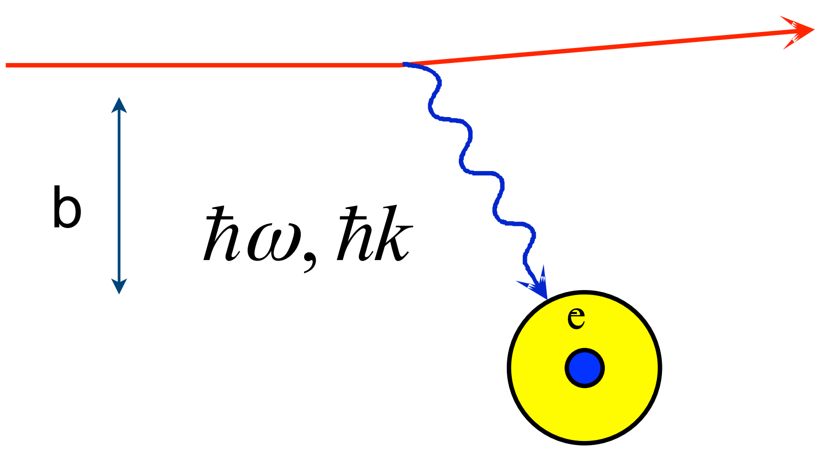
Cross section

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

"heavy" Particles with Matter

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

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

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

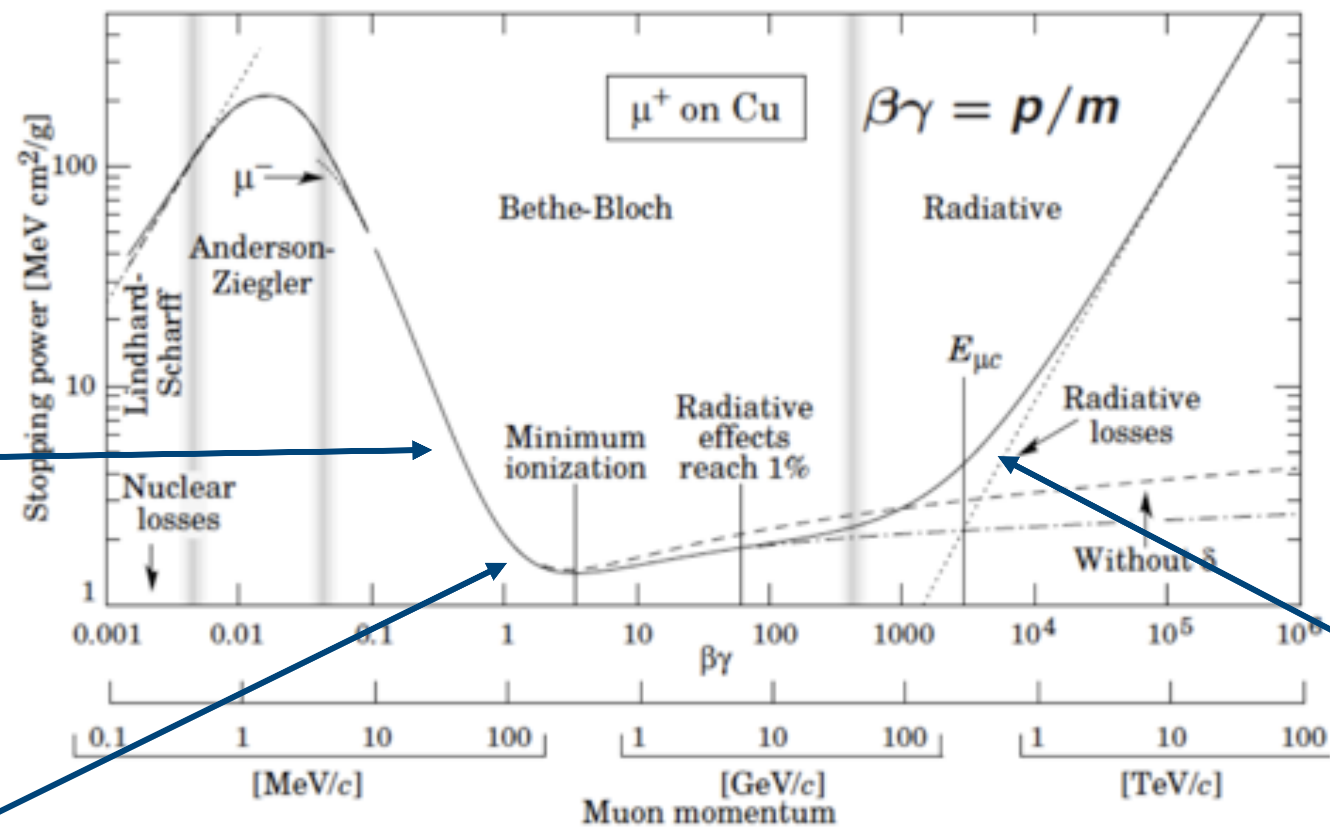
$\frac{\delta}{2}$ Density term due to polarization: leads to saturation at higher energies

I^2 Excitation energy

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

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

"kinematic term"



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

"relativistic rise"

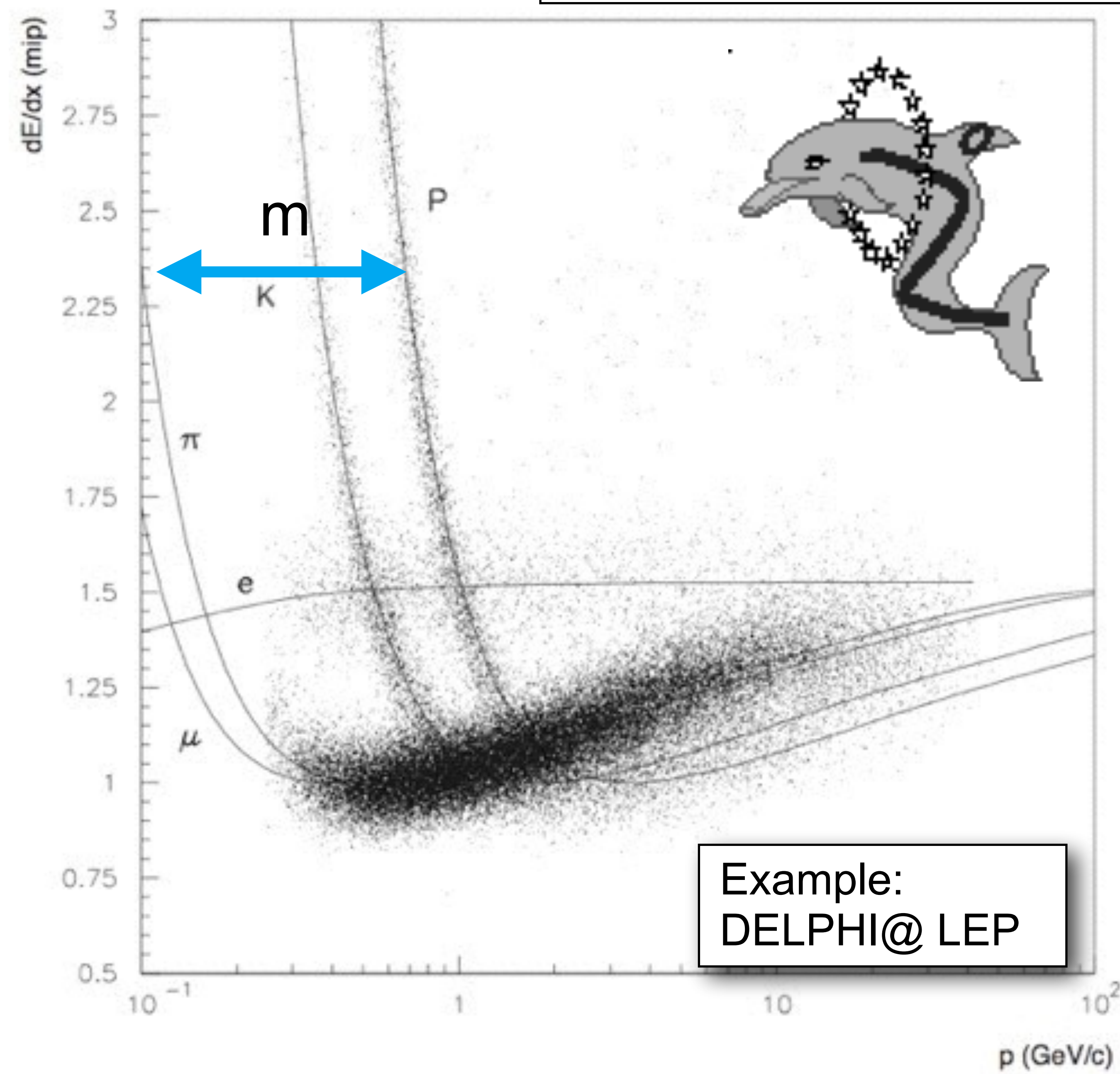
"minimum ionizing particles" $\beta\gamma \approx$ 3-4

Particle Identification 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 !**

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

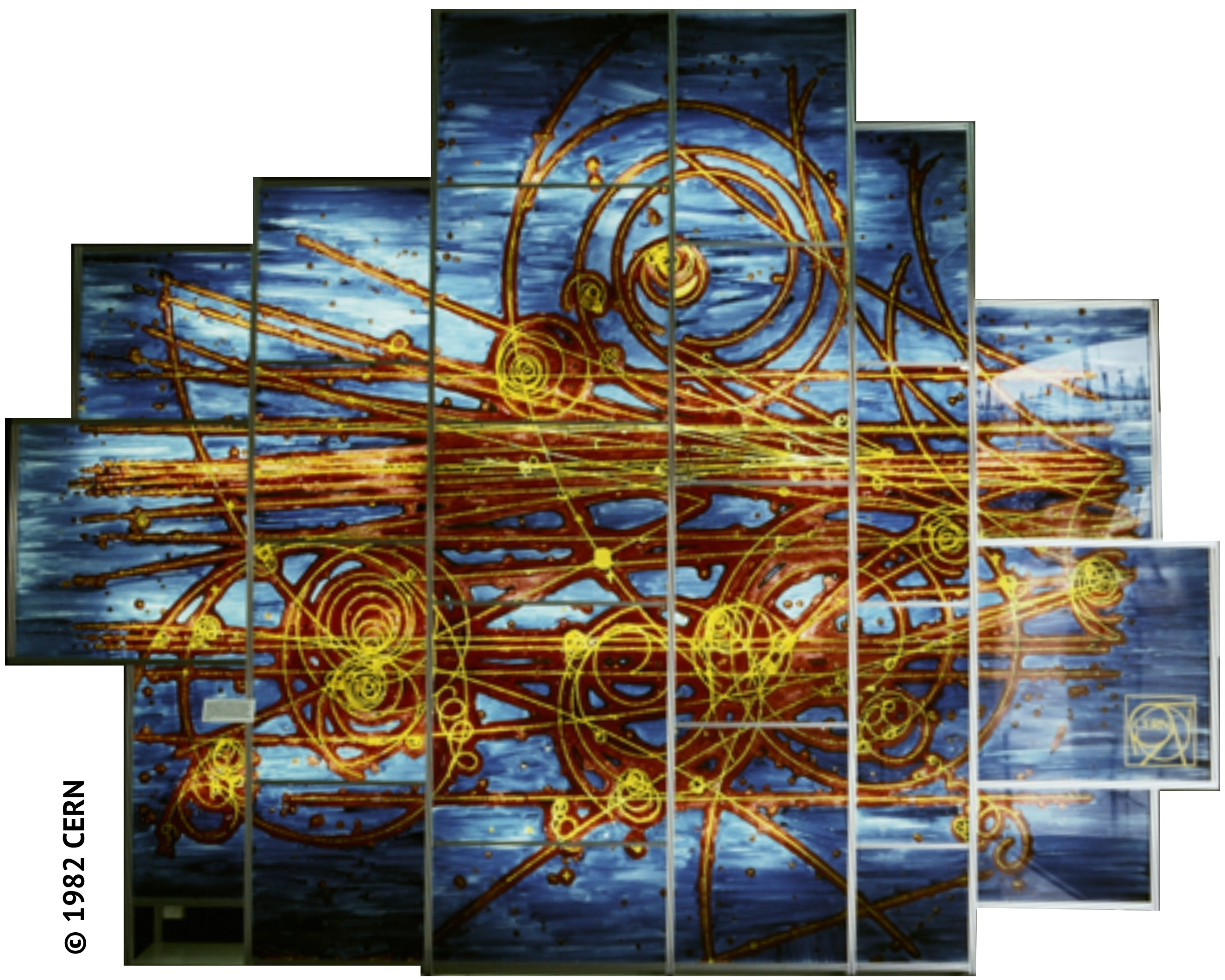


Example:
DELPHI@ LEP

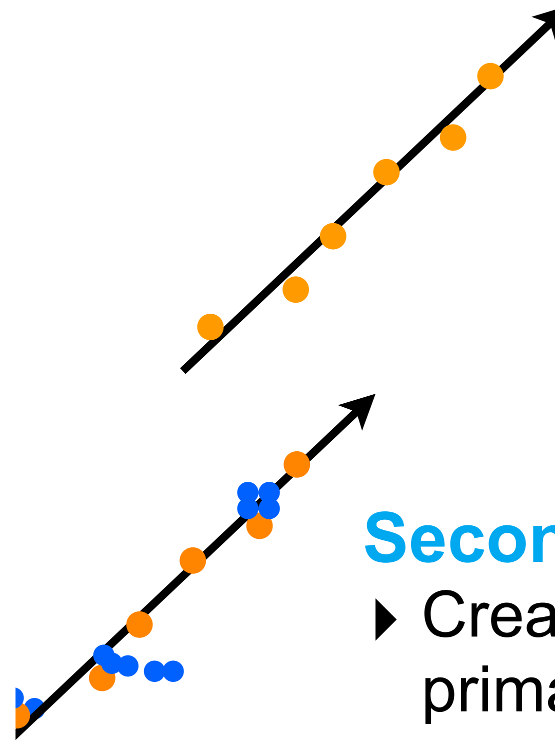
$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}]$$

A Closer Account

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



© 1982 CERN



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

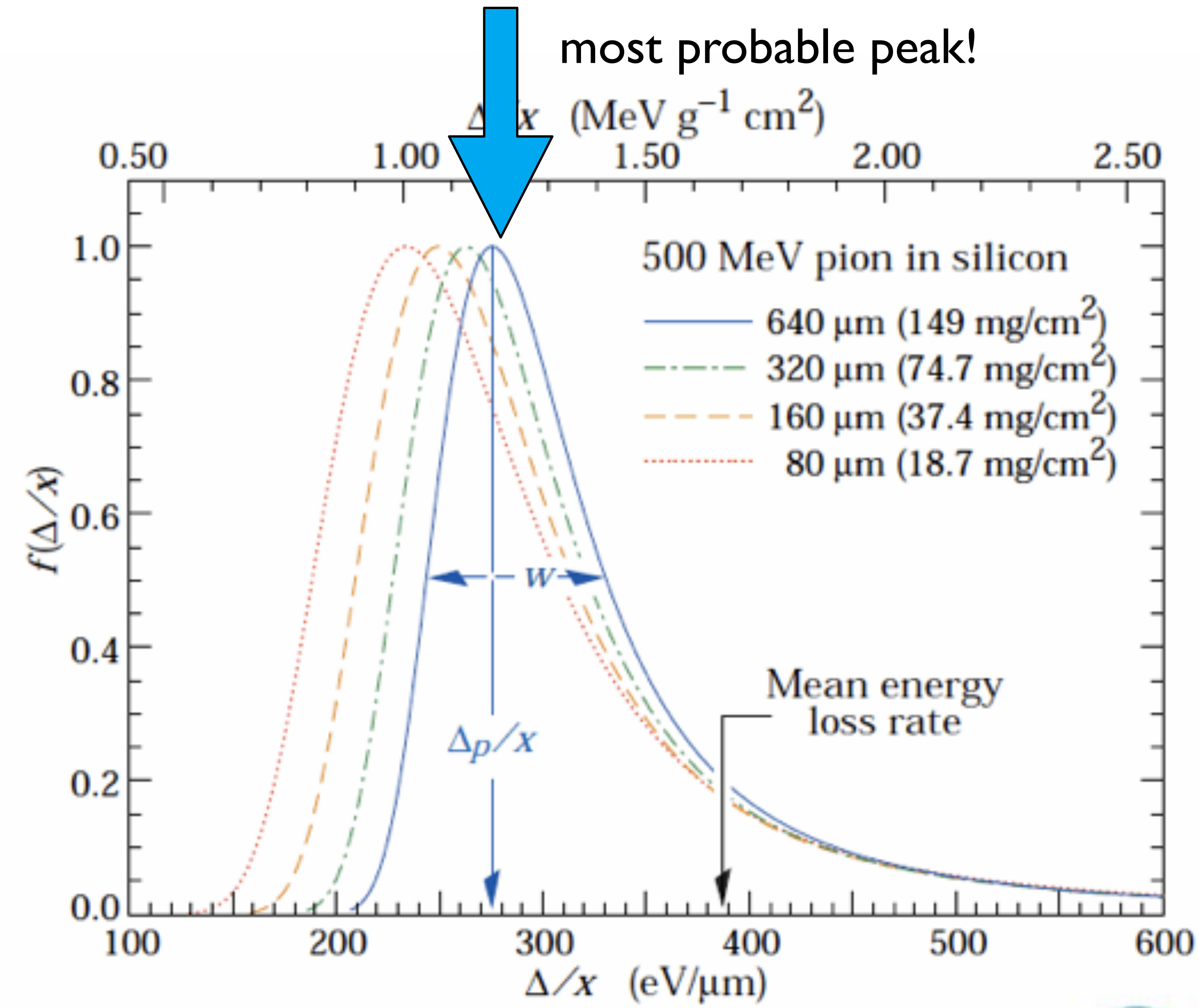
Total ionisation =
primary ionisation
+
secondary ionisation

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, 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

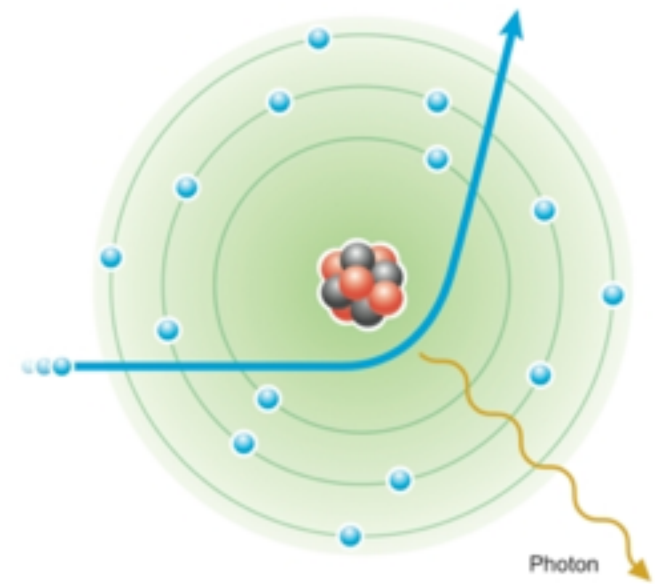
Thin absorber:
<dE> < ~10Tmax



Bremsstrahlung

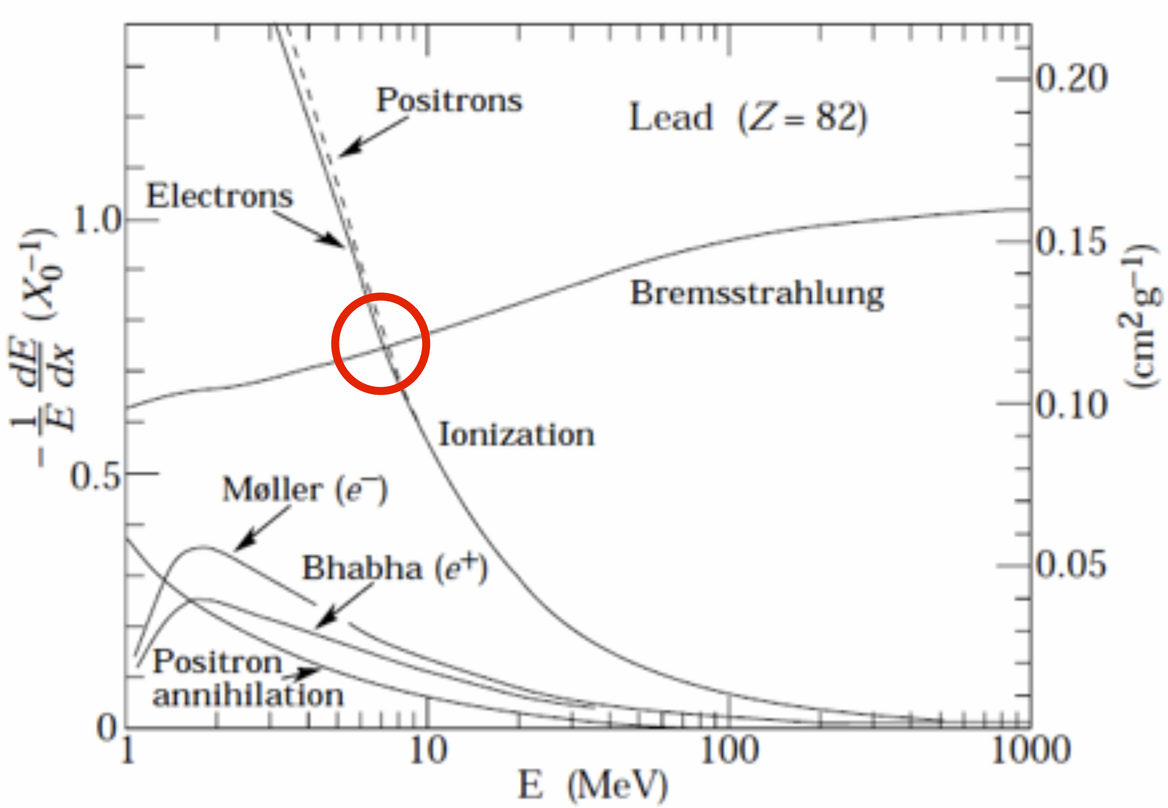
- Deflection of a charge in a strong nuclear E-field -> emission of a photon.

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



Incident electron and Bremsstrahlung photon.

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

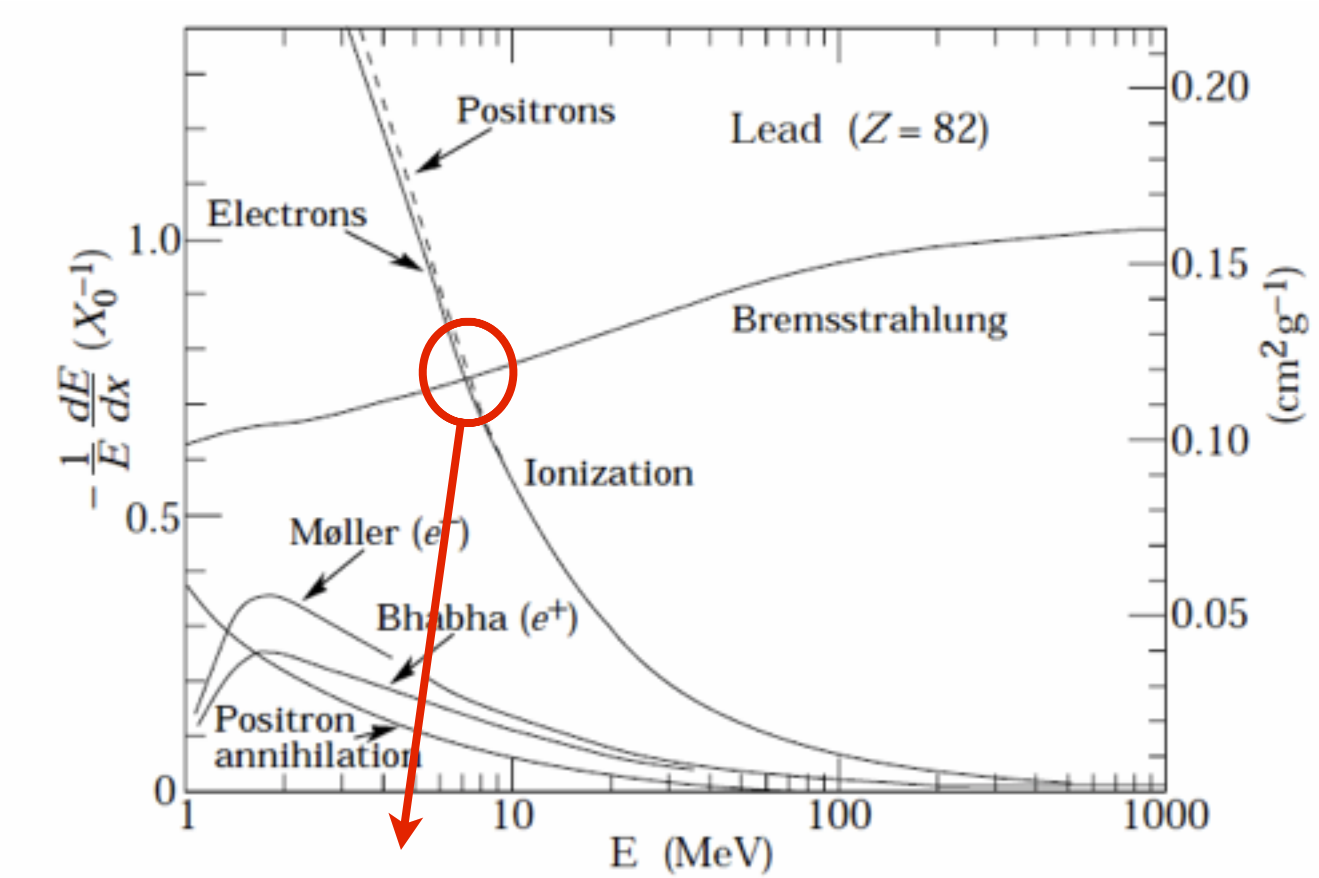


Energy loss for anything heavier than an electron is dominated by ionisation.

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

Electrons: Energy Loss

- Ionisation loss by electrons (positrons) differs because of the kinematics, spin and the identity of the incident electron with the electrons which it ionises.

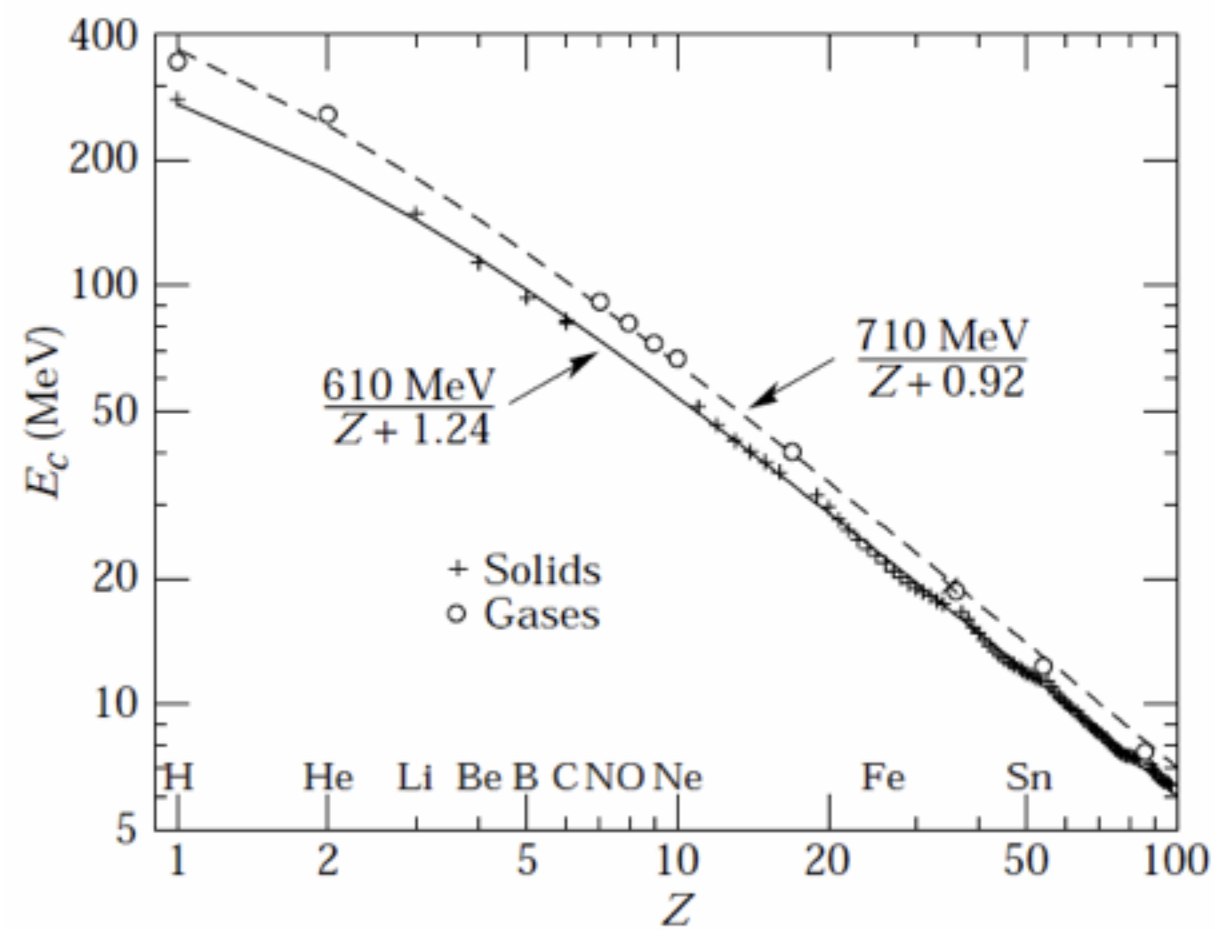


Bremsstrahlung is dominating at high energies

At low energies: ionisation, additional scattering

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

$$\frac{dE}{dx}(E_c) = \frac{dE}{dx}(E_c)$$



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

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

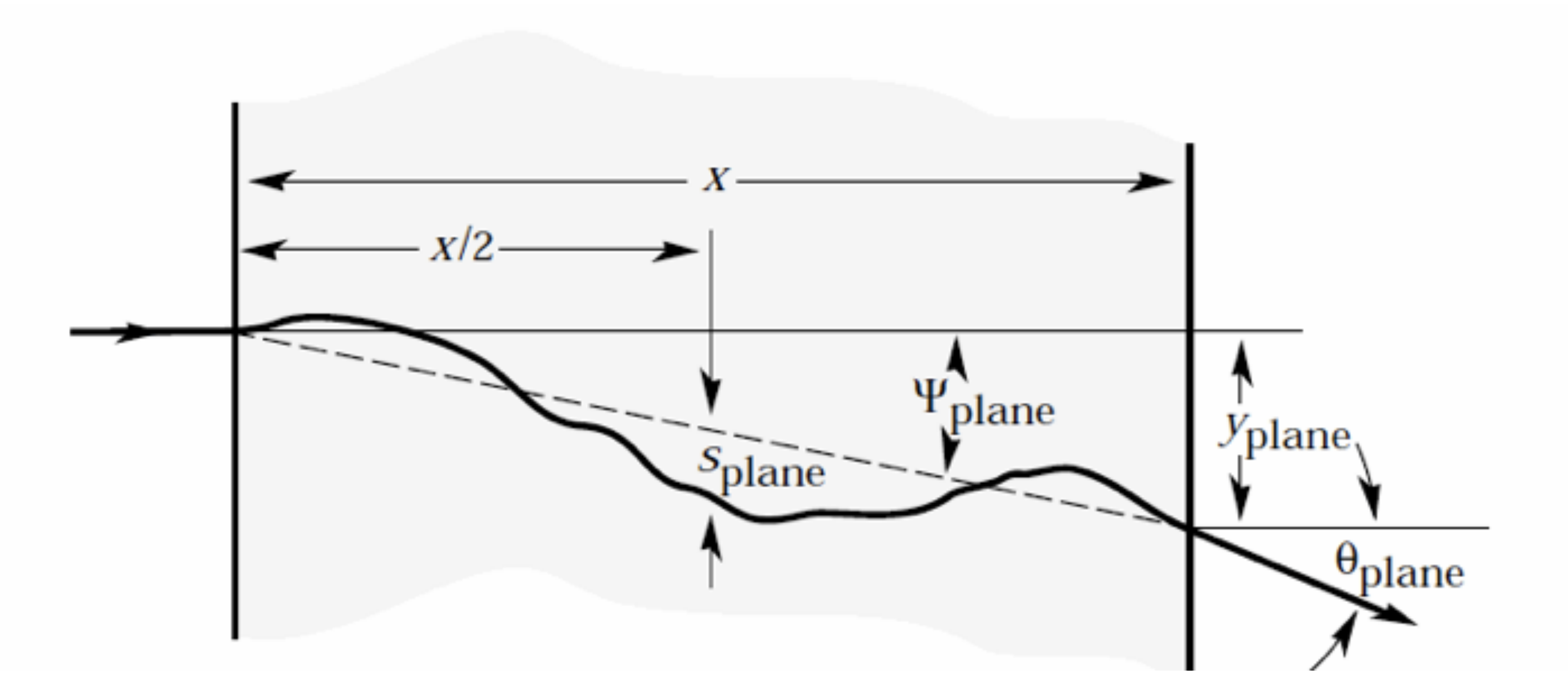
- A very important number when building detectors, one always has to keep in mind how much material is within the detector volume

Typical values are:

- Air: 36.66 g/cm^2 ->~ 300 m
- Water: 36.08 g/cm^2 -> ~ 36 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 due to Coulomb field



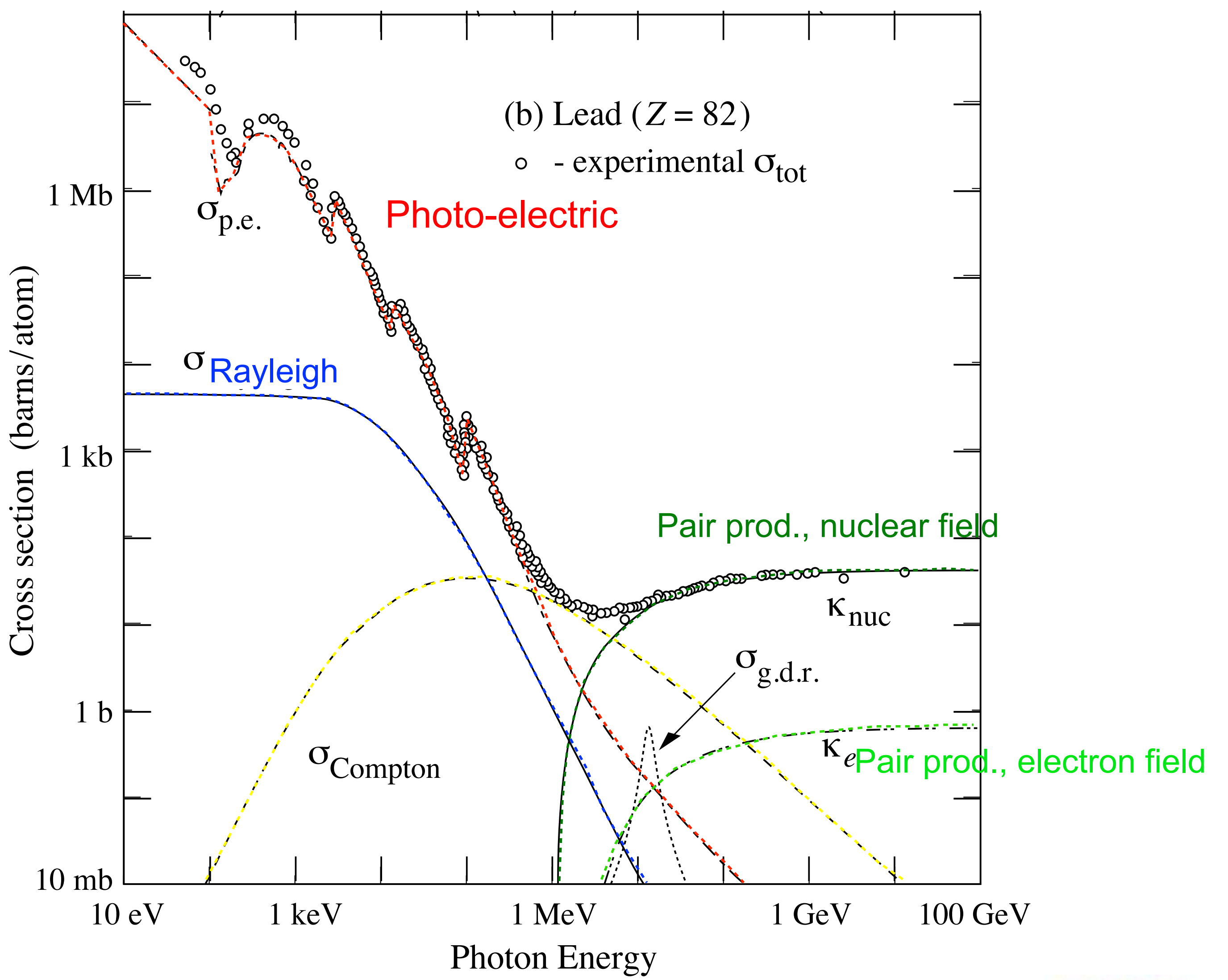
$$\theta_0 = \theta_{\mathrm{plane}}^{\mathrm{rms}} = \frac{1}{\sqrt{2}}\theta_{\mathrm{space}}^{\mathrm{rms}} \qquad \theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

- relevant for relativistic particles, for material thickness from 10^{-3} X_0 bis 100 X_0

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.

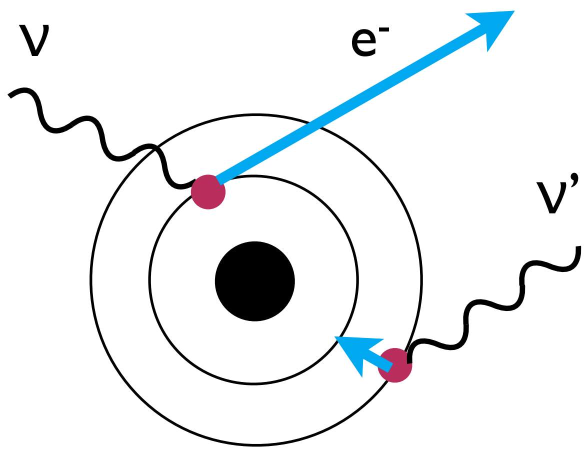
- Photons interact via 6 mechanisms depending on the photon energy:
  - < few eV: molecular interactions
  - < 1 MeV: photoelectric effect
  - < 1 MeV: Rayleigh scattering
  - ~ 1 MeV: Compton scattering
  - > 1 MeV: pair production
  - > 1 MeV: nuclear interactions



Photons: Interactions

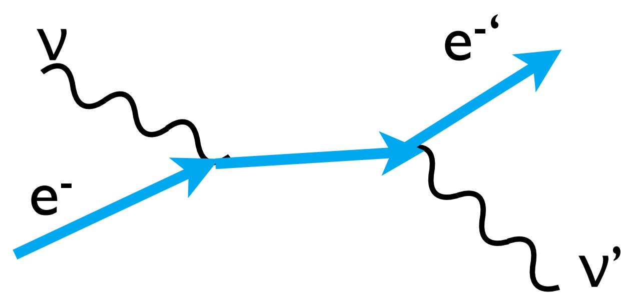
- Photons appear in detector systems as primary photons, they are created in bremsstrahlung and de-excitations, and they are used for medical applications, both imaging and radiation treatment.

Photo-Effect



Only possible in the close neighbourhood of a third collision partner
→photo effect releases mainly electrons from the K-shell.

Compton-Scattering

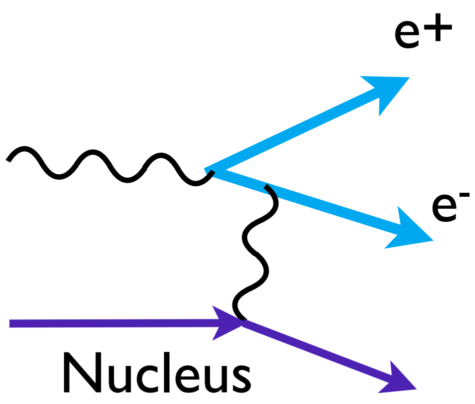


$$\gamma + e \rightarrow \gamma' + e'$$

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

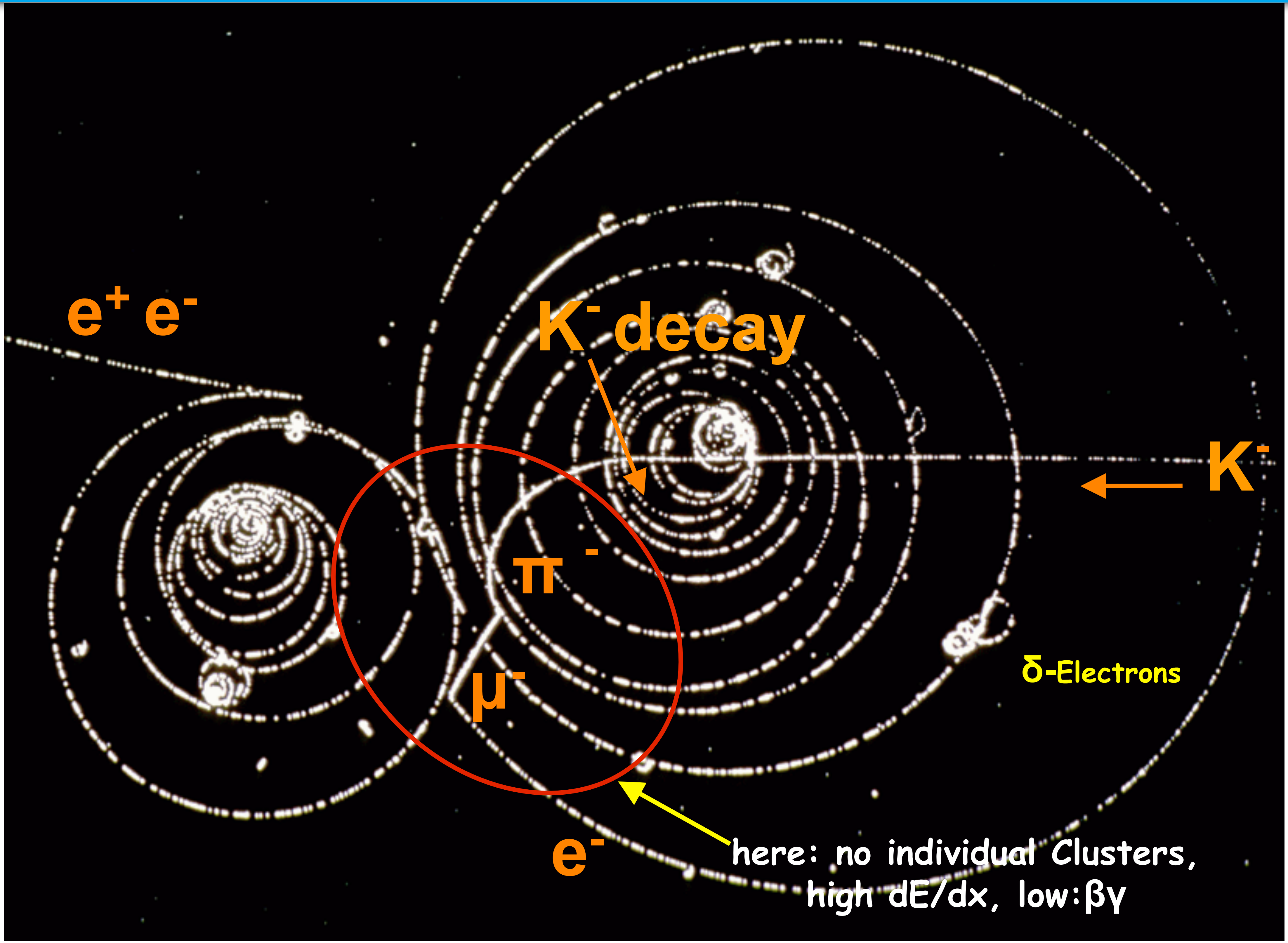
$$E_\gamma \geq 2m_e c^2$$

~1.022 MeV

➩ Reduction of photon intensity with passage through matter:

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

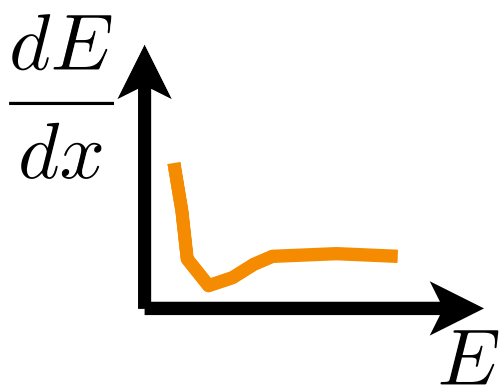
A Short Summary



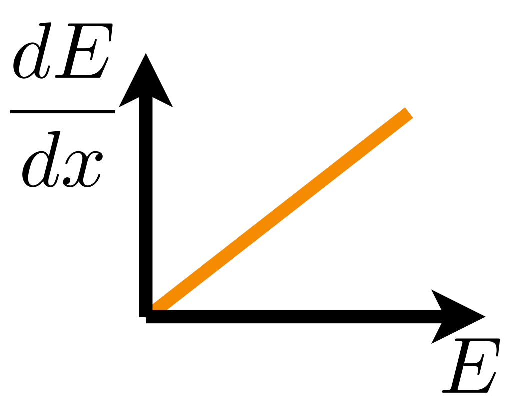
Overview

e^+/e^-

Ionisation

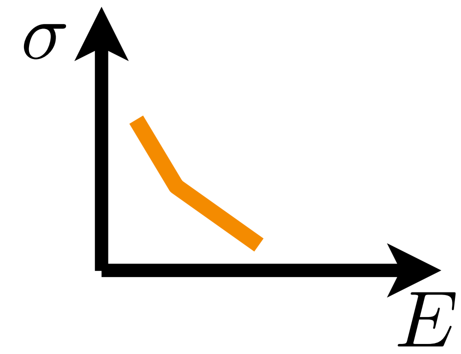


Bremsstrahlung

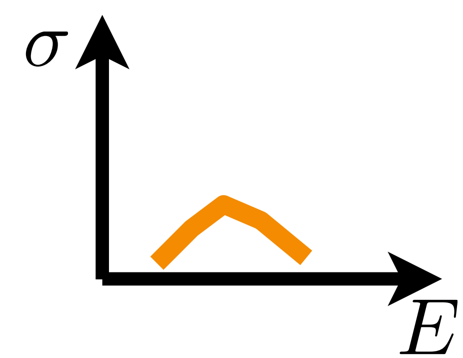


γ

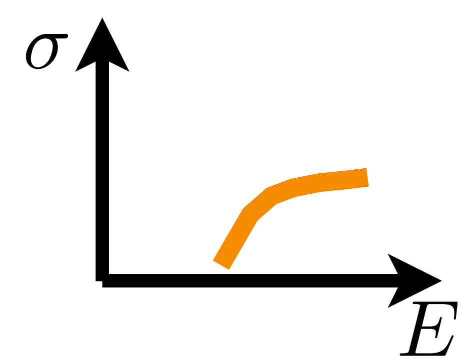
Photoelectric Effect



Compton Effect



Pair Production



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- Gas detectors
- Semiconductor trackers

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III. Tracking detectors

Tracking

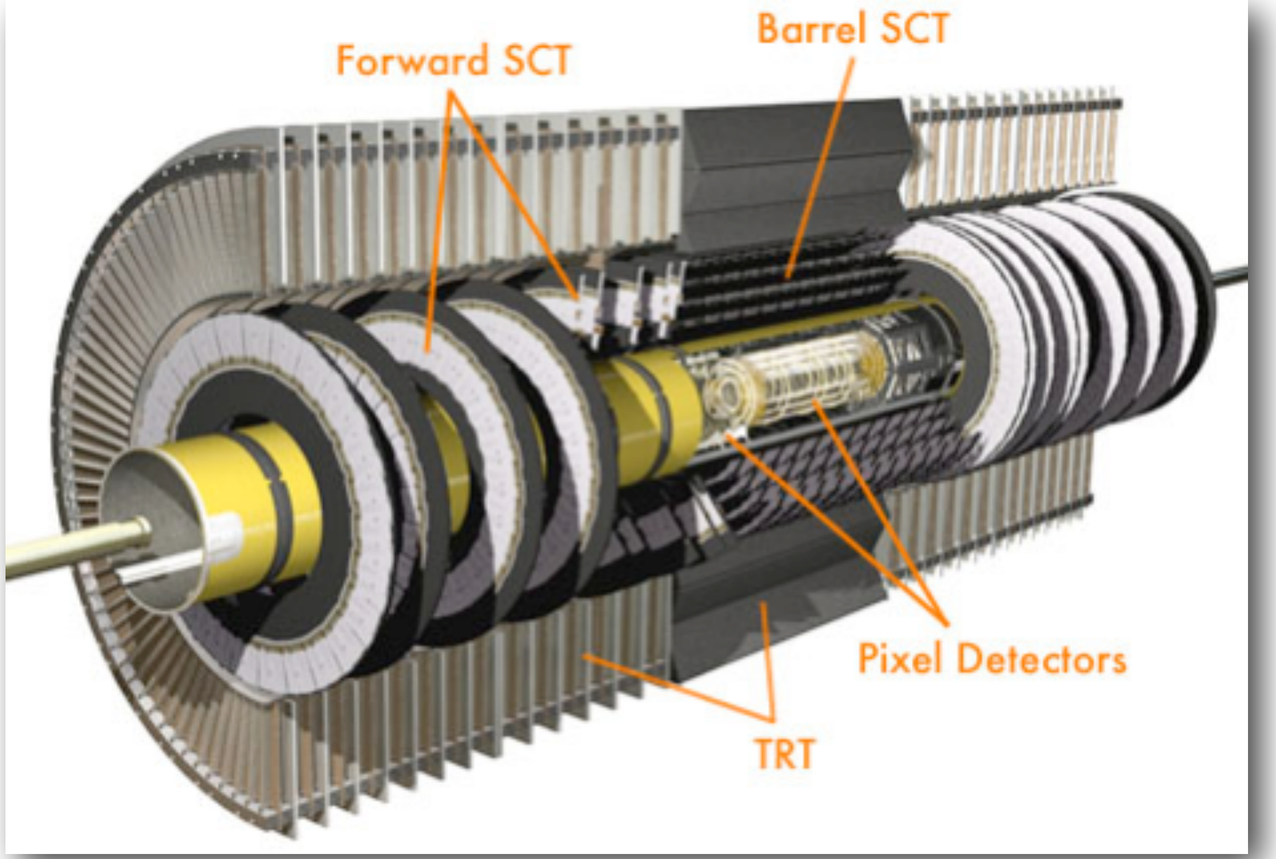
- “tracking” in google image search:

Tracking Detector

- “tracking detector” in google image search

GPS Tracking Detector

But the 1st image on list is:

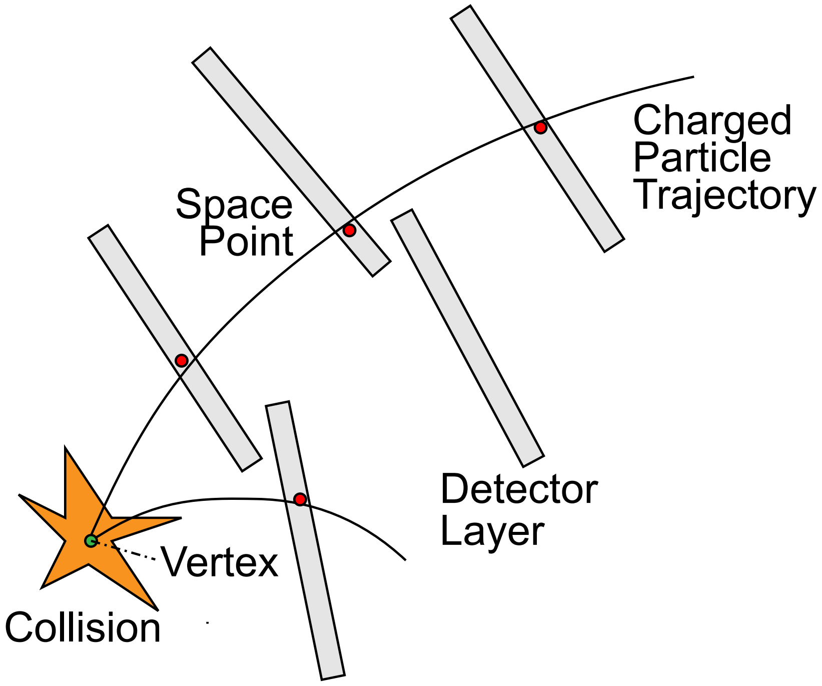


Pic: ATLAS Collaboration

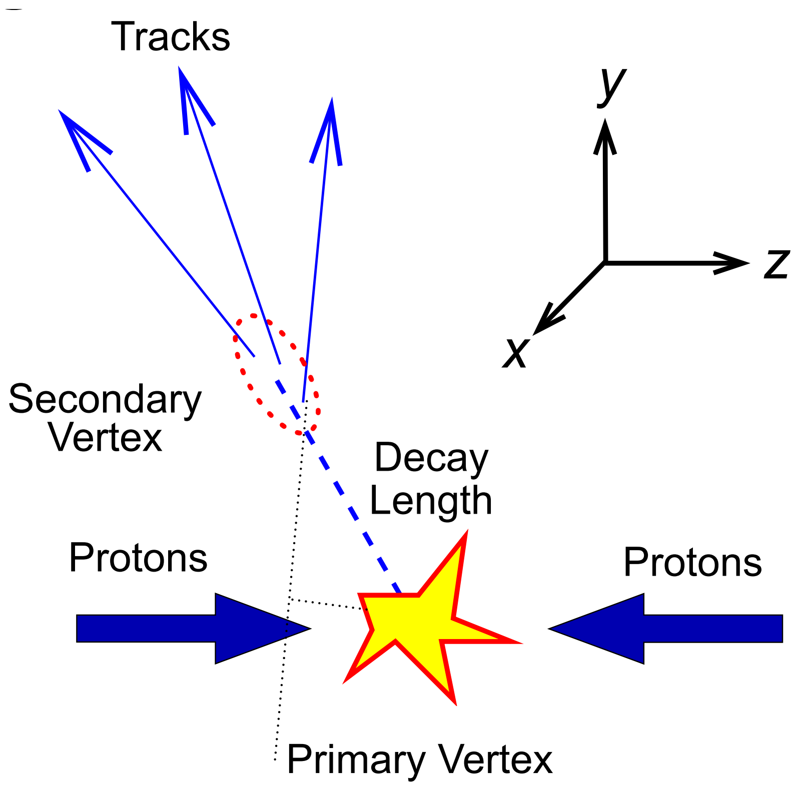
Tracking Detectors

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

- The trajectory should be disturbed minimally by this process (reduced material)

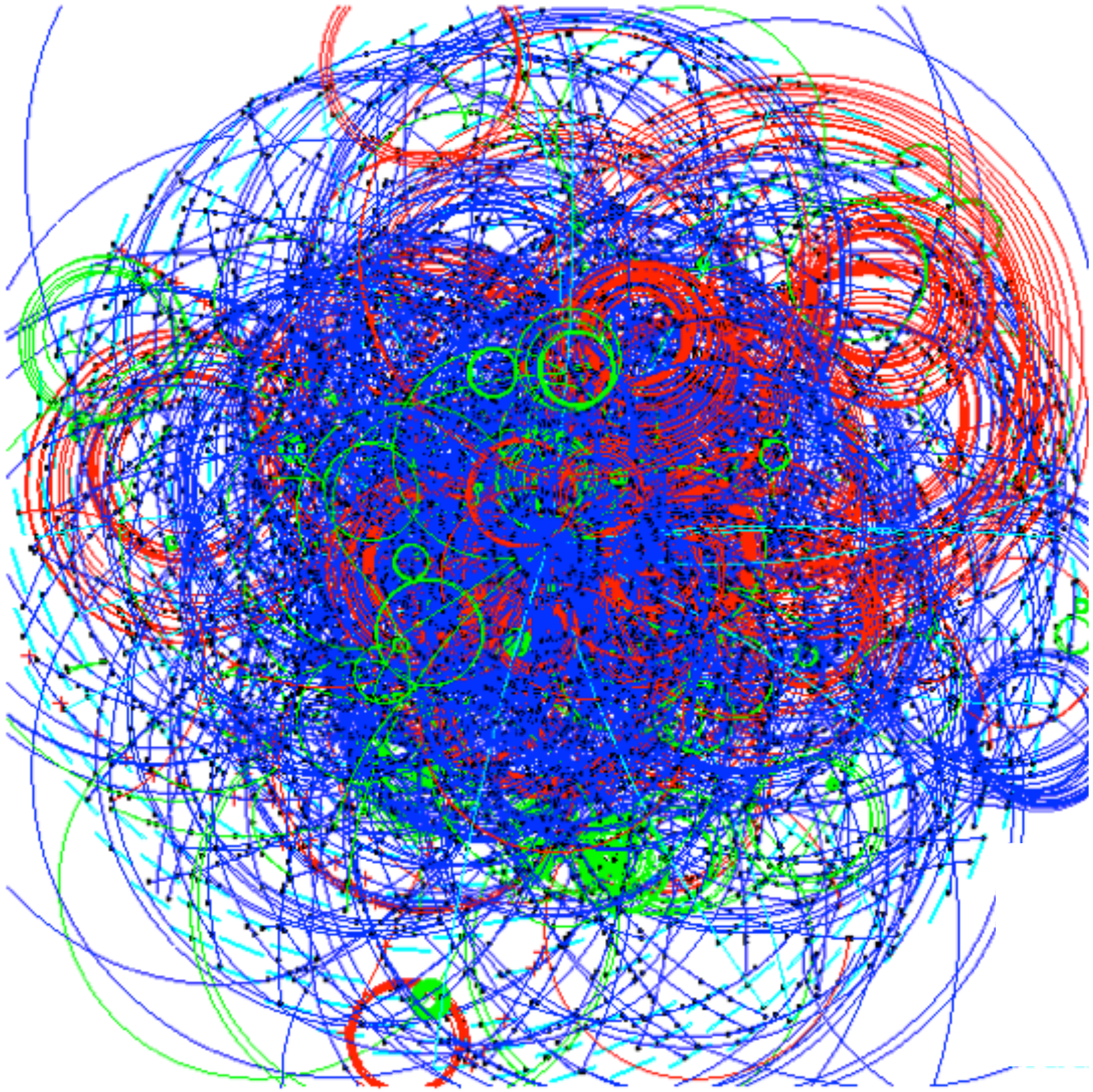


- Charged particles ionise matter along their path.
- Tracking is based upon detecting ionisation trails.
- An “image” of the charged particles in the event



Pictures: U. Husemann

Requirements



E.g. search for
$H \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

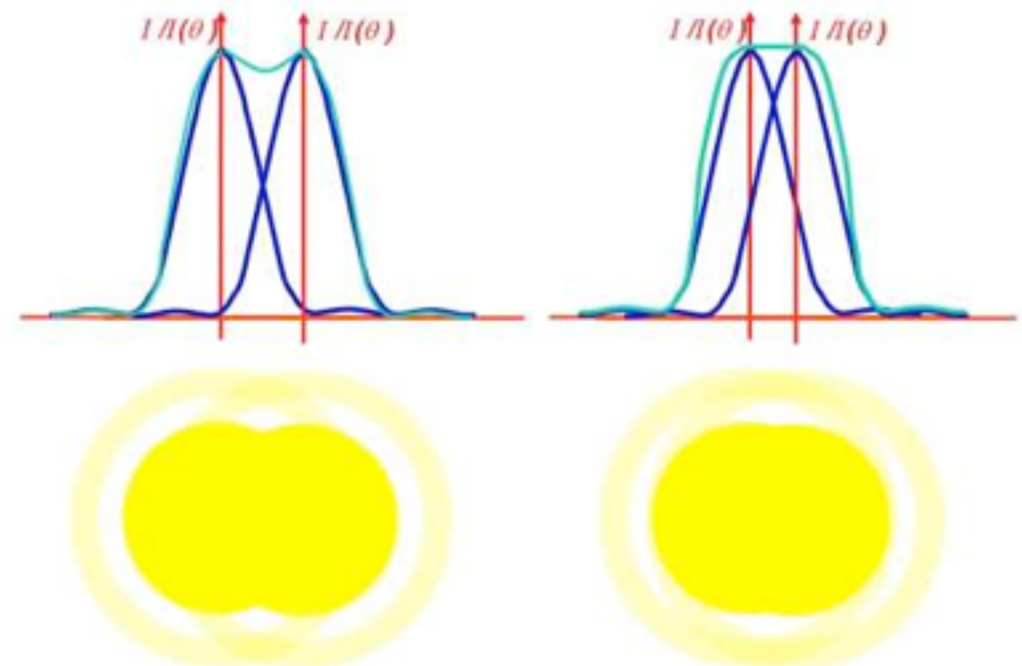
with $\Delta m_Z < 2$GeV
up to $p_z \sim 500$GeV

=> reconstruction of high p_t tracks with

+ high efficiency
  - single track $\varepsilon > 95\%$
  - in jet $\varepsilon > 90\%$
+ momentum resolution
  - $\Delta p_t / p_t = 0.01$ pt [GeV]

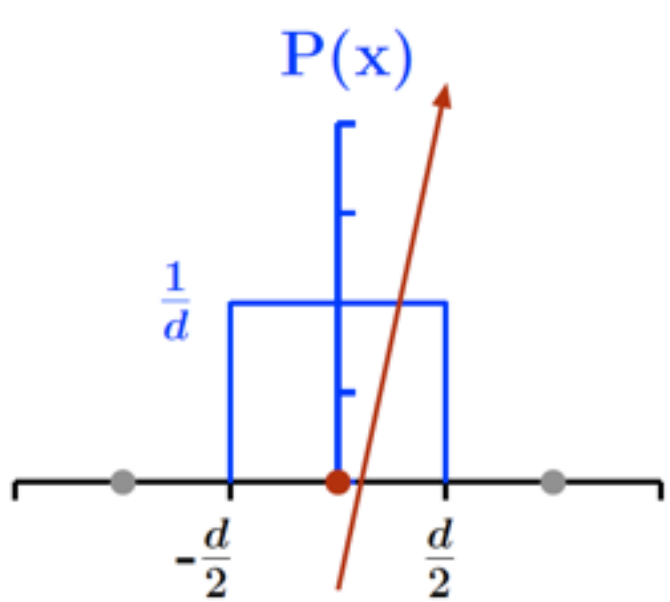
Resolution of Tracking Detectors

- An important figure of merit is the **spacial resolution**
- Depending on detector geometry and charge collection
  - Pitch (distance between channels)
  - Charge sharing between channels



- **Simple case:** all charge is collected by one channel
- Traversing particle creates signal in hit strip
- Flat distribution along strip pitch; no area is pronounced

➔ Probability distribution for particle passage:



$$P(x) = \frac{1}{d} \qquad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

The reconstructed point is always the middle of the strip:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\,P(x)\,dx = 0$$

Resolution of Tracking Detectors

- Calculating the resolution orthogonal to the strip:

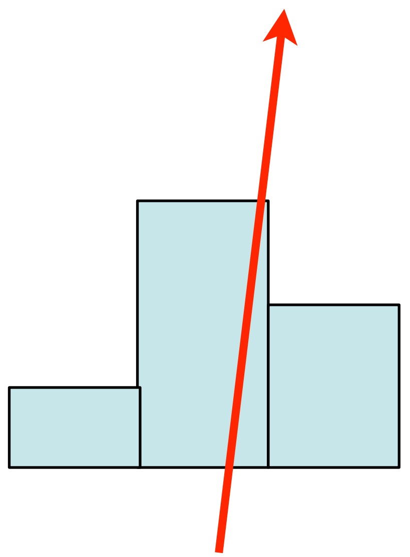
$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

- Resulting in a general term (also valid for wire chambers):

$$\sigma = \frac{d}{\sqrt{12}}$$

very important !

- For a silicon strip detector with a strip pitch of **80 µm** this results in a minimal resolution of **~23µm**
- In case of charge sharing between the strip
  - Signal size decreasing with distance to hit position
  - Resolution improved by center of gravity calculation



Momentum in Magnetic Field

- A tracking detector is typically placed within a B-field to enable momentum measurements
- Charged particles are deflected in a magnetic field:
  - takes only effect on the component perpendicular to the field

$$F = qvB$$

$$ma = qvB$$

$$m(\frac{v^2}{r}) = qvB$$

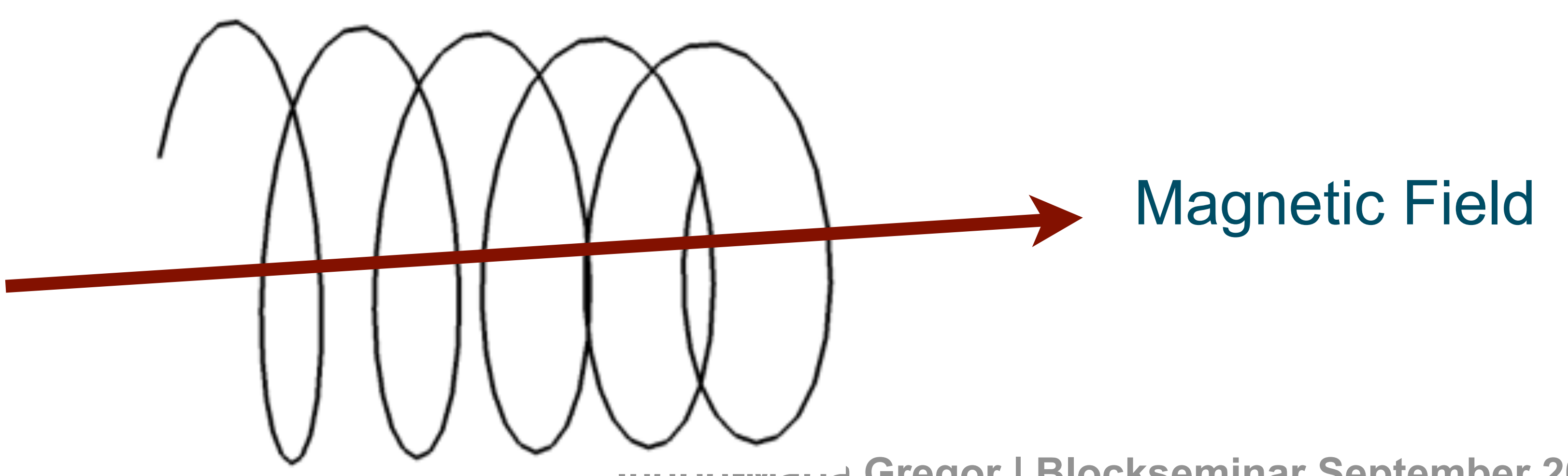
$$p = 0.3Br$$

Radius of the circular path is proportional to the transversal momentum

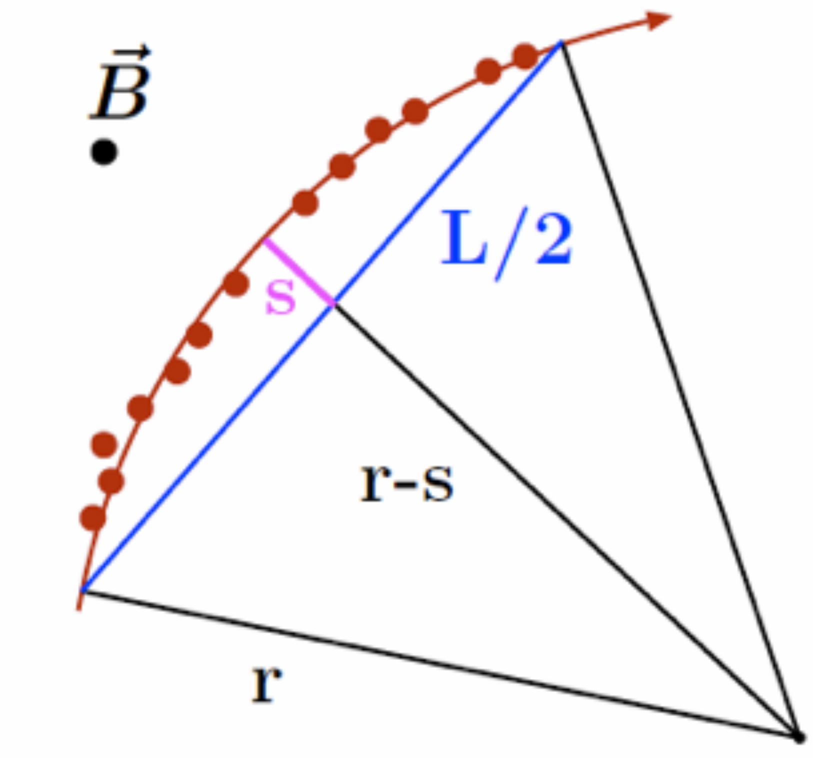
- parallel to the field is no deflection:

when converting in HEP units and assuming that all particles have the |electron charge|

➩ particle is moving on a helix, the radius is determined by the field and p_T



Momentum in Magnetic Field II



- In real applications usually only slightly bent track segments are measured
  - Figure of merit: sagitta

Segment of a circle: $$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

$$\Rightarrow r = \frac{s}{2} + \frac{L^2}{8s} \approx \frac{L^2}{8s} \quad (s \ll L)$$

With the radius-momentum-B-field relation: $r = \frac{p_T}{0.3\,B} \Rightarrow s = \frac{0.3\,B\,L^2}{8\,p_T}$

Momentum resolution due to position measurement:

Gluckstern $$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}$$

NIM, 24, P381, 1963

➠ The larger the magnetic field **B**, the length **L** and the number of measurement points n, and the better the spatial resolution, the better is the momentum resolution

Tracker: Important Parameter

- **Detector efficiency** ϵ: probability to detect a transversing particle
  - should be as close to 100% as possible
  - i.e. 12 layer silicon detector with 98% efficiency per layer -> overall tracking efficiency is only 78%
  - needs to be measured in test beam

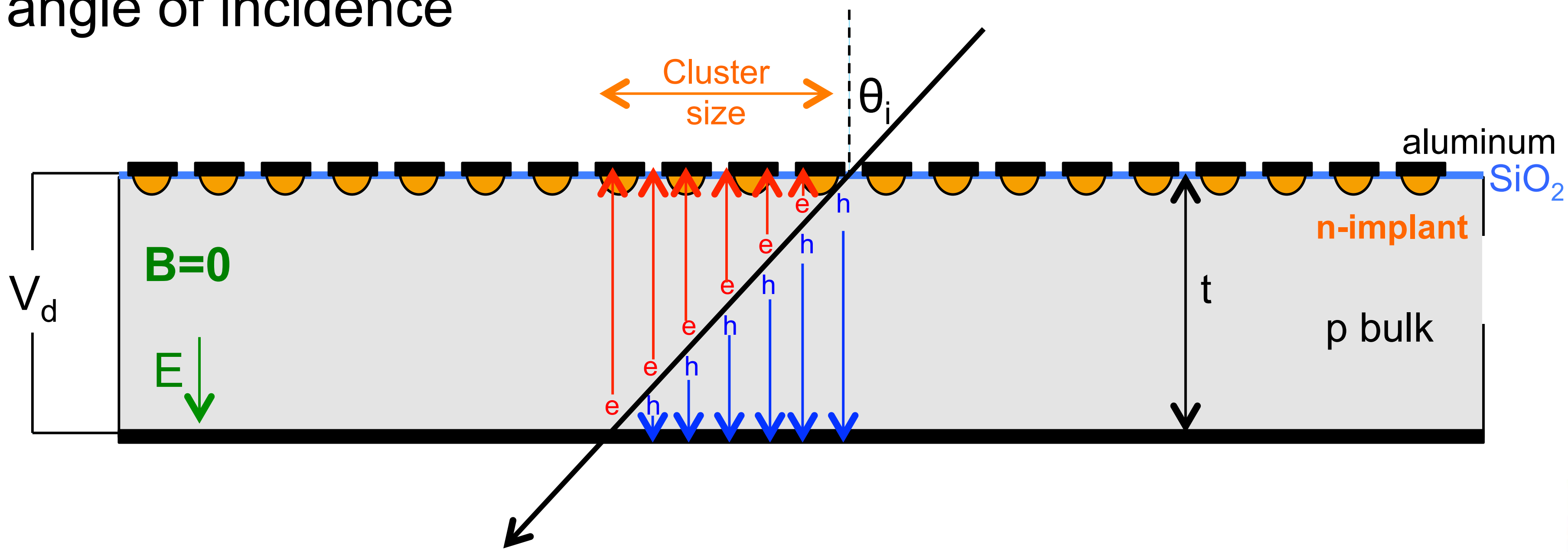
$$\epsilon_{\text{track}} = (\epsilon_{\text{layer}})^n$$

n = number of layer is tracking system

$\epsilon = 0.99$ $\epsilon = 0.98$

$\epsilon^7 = 0.93$ $\epsilon^7 = 0.87$

- **Cluster size** : number of hit pixels/strips belonging to one track
  - usually given in unit of strips or pixels
  - depending on angle of incidence



Signal/Noise Ratio

- **Signal/noise ratio**: signal size for a certain input signal over the intrinsic noise of the detector
  - parameter for analog signals
  - good understanding of **electrical noise charge** needed
  - leakage current (ENC_I)
  - detector capacity (ENC_C)
  - det. parallel resistor (ENC_{Rp})
  - det. series resistor (ENC_{Rs})

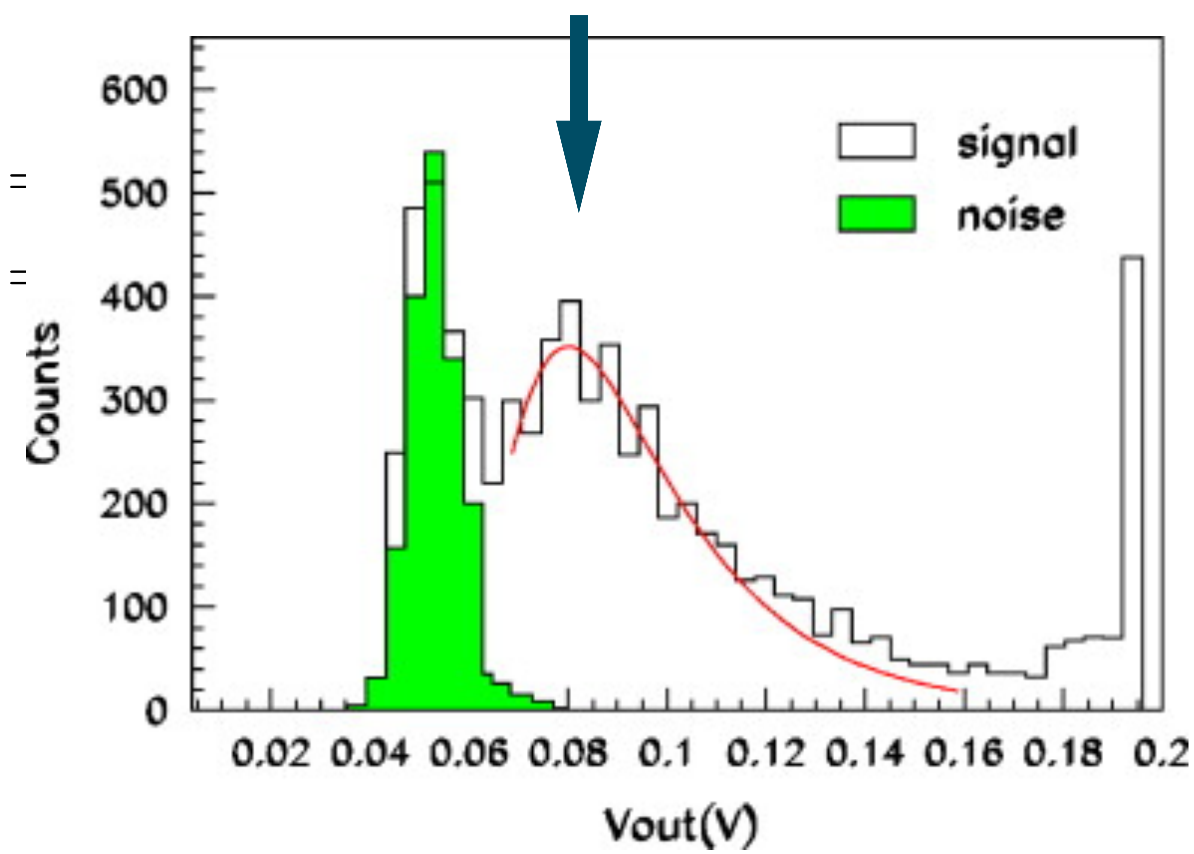
$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}_{R_p}^2 + \mathrm{ENC}_{R_s}^2}$$

example for silicon detector

most probable peak! = Signal

ϵ =

ϵ^7 =



  - signal induced by source or laser (or test beam particles)
  - optimal S/N for a MiP is larger than 20

Summary Part 1

Ionisation and Excitation:

- Charged particles traversing material are **exciting and ionising** the atoms.
- The average energy loss of the incoming particle by this process is to a good approximation described by the **Bethe Bloch** formula.
- The energy loss fluctuation is well approximated by the **Landau distribution**.

Multiple Scattering and Bremsstrahlung:

- The 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….

… and after the break more details on how we use this ….