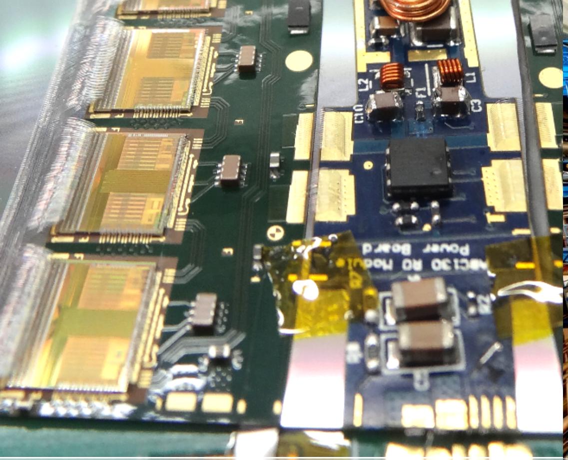
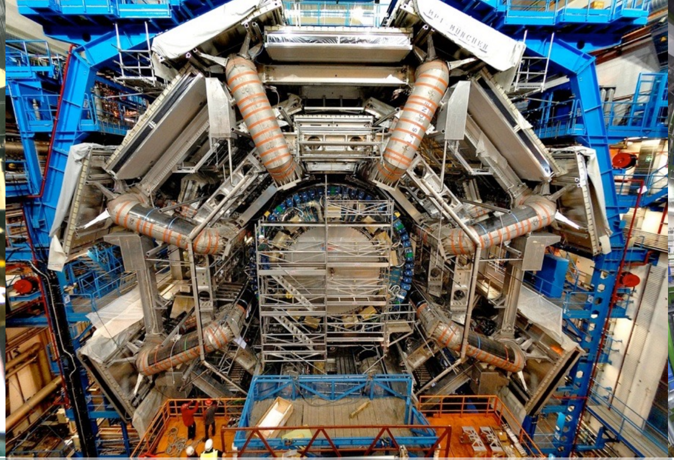
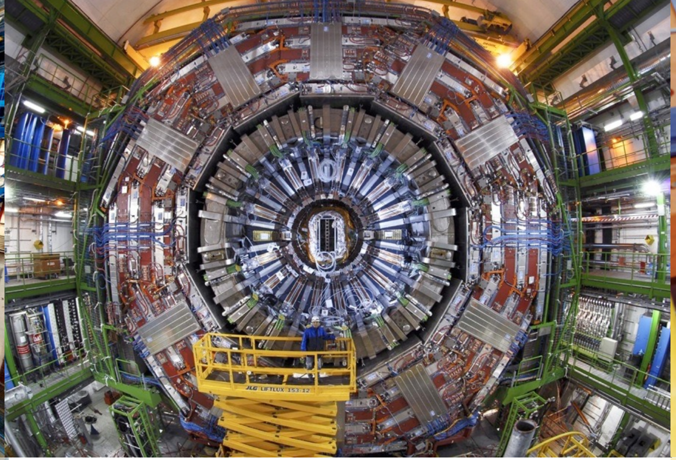





Detectors for High energy Physics

Part 1

Ingrid-Maria Gregor
DESY/Universität Bonn
Summerstudents 2022
08.08.2022

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**

Tuesday

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

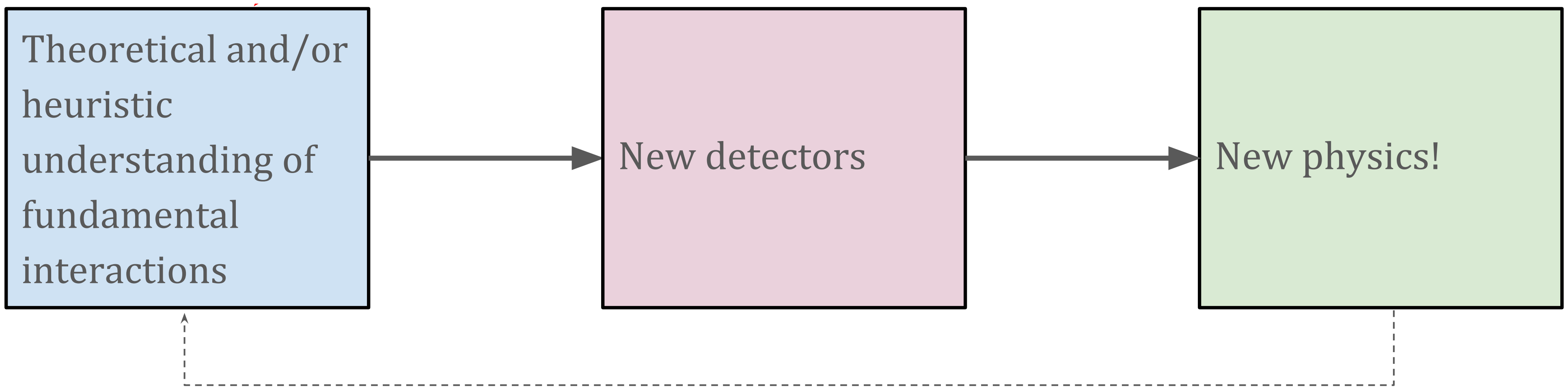
V. **Examples from the real life**

Wednesday

I. Overview: Detectors for particle physics

Why Study Detector Physics ?

- Particle and nuclear physics discoveries are driven by **detector innovation**.
- And you need *fundamental understanding* to drive innovation



Instruments = Detectors

for particle physics / photon science / medicine / societal applications

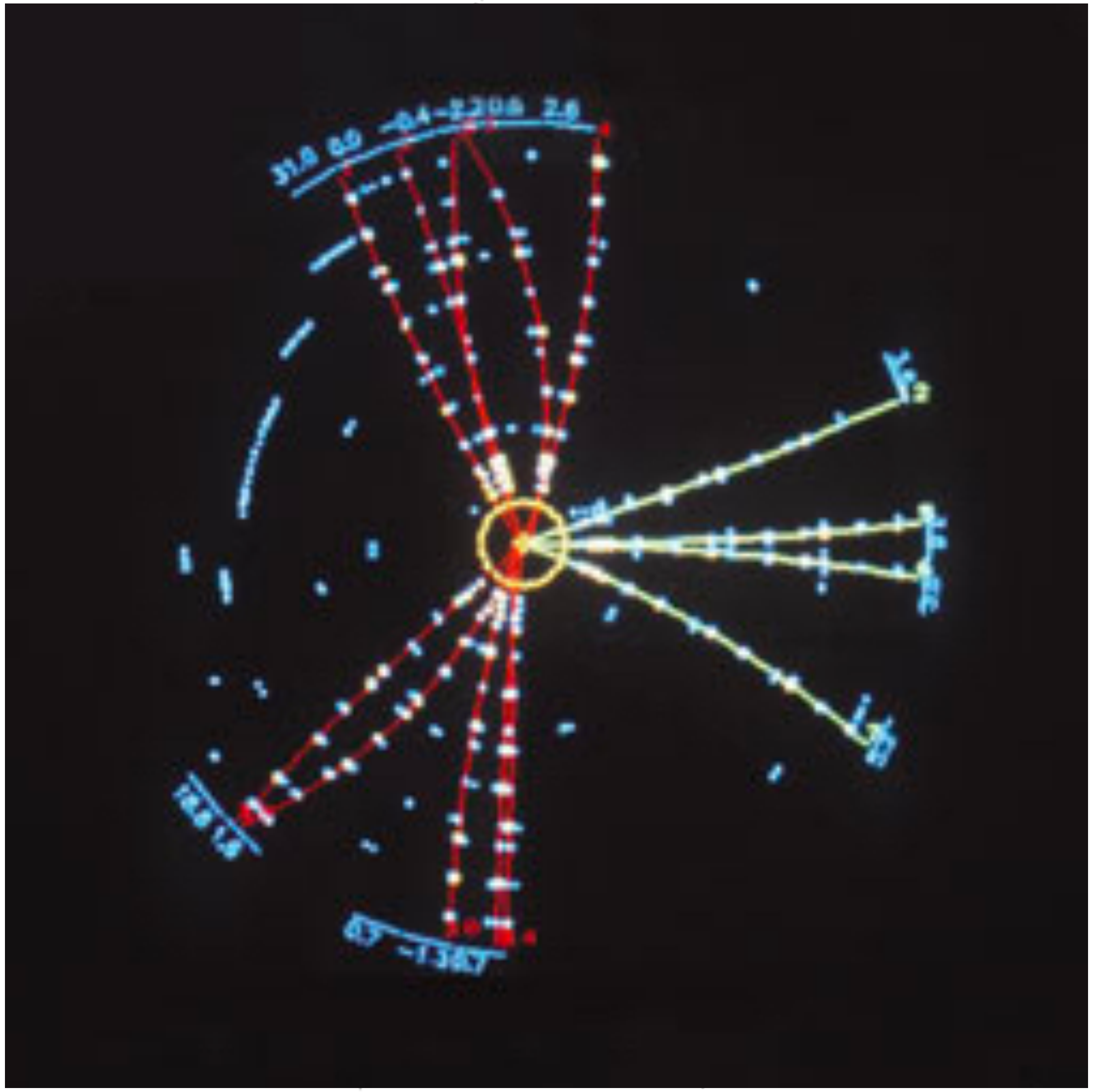
- what is the underlaying principle
- how do they work
- how precise can they measure

Discovery of neutral currents

Gargamelle, 1972

Discovery of the Gluon

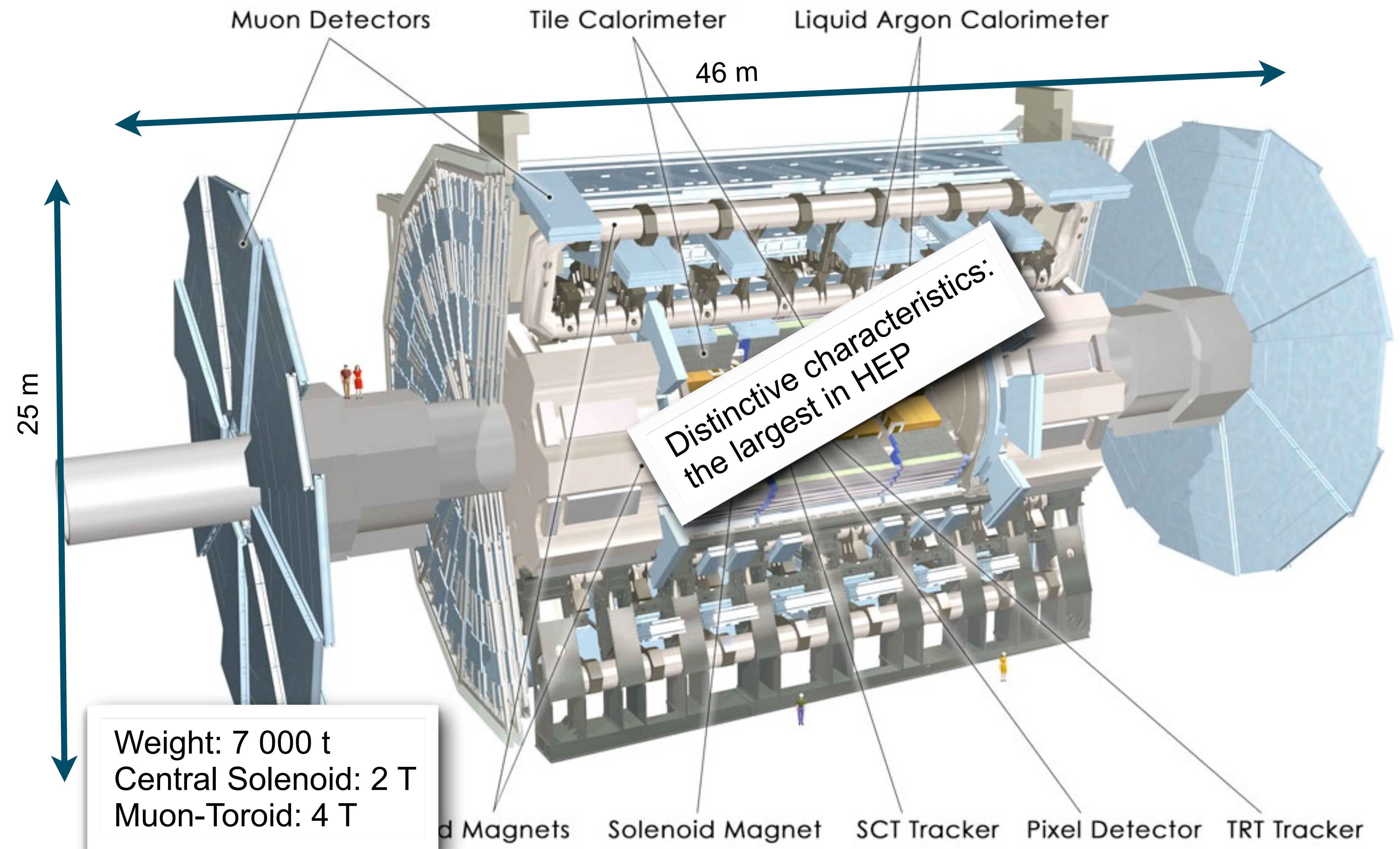
18.06.1979



- 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

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

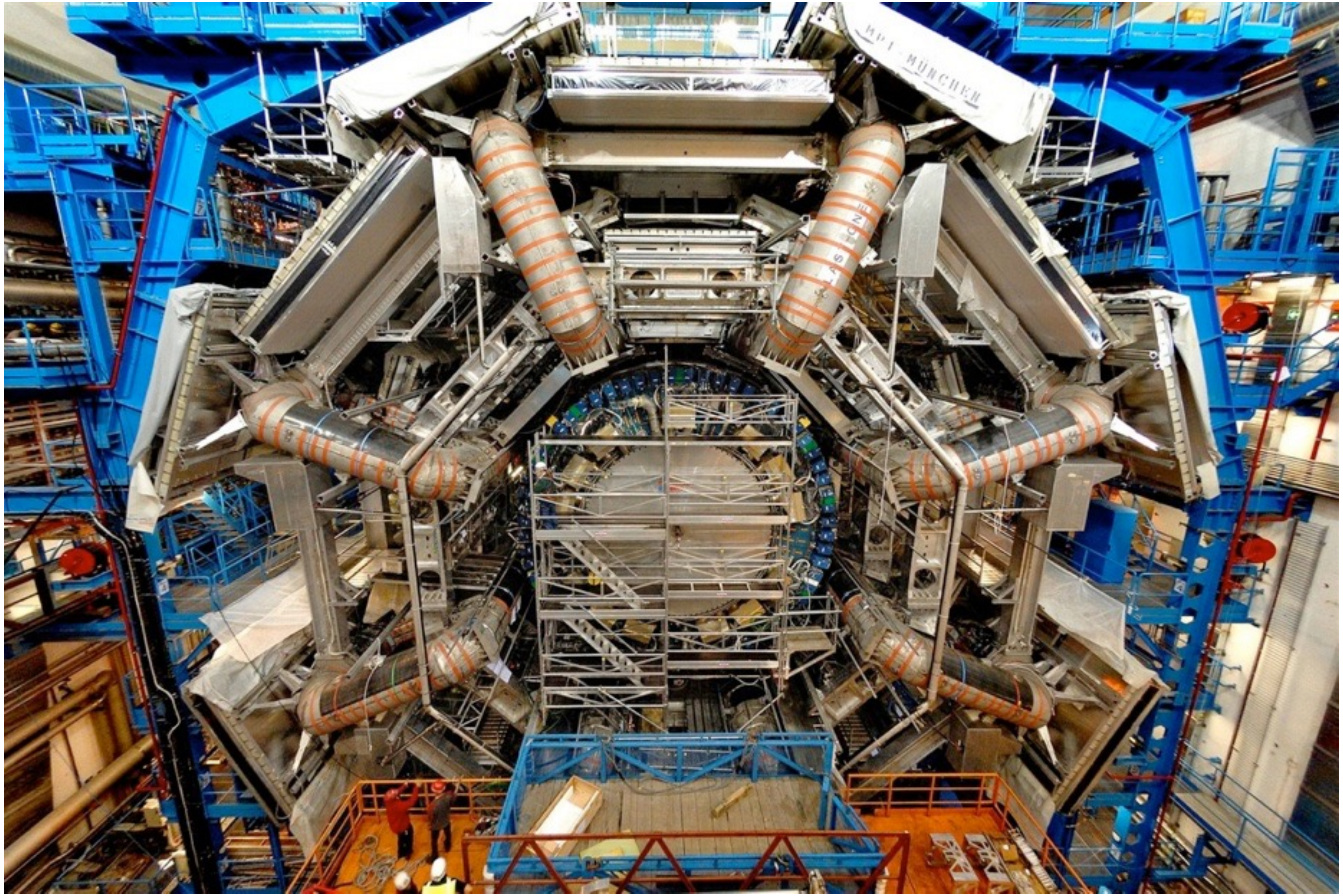
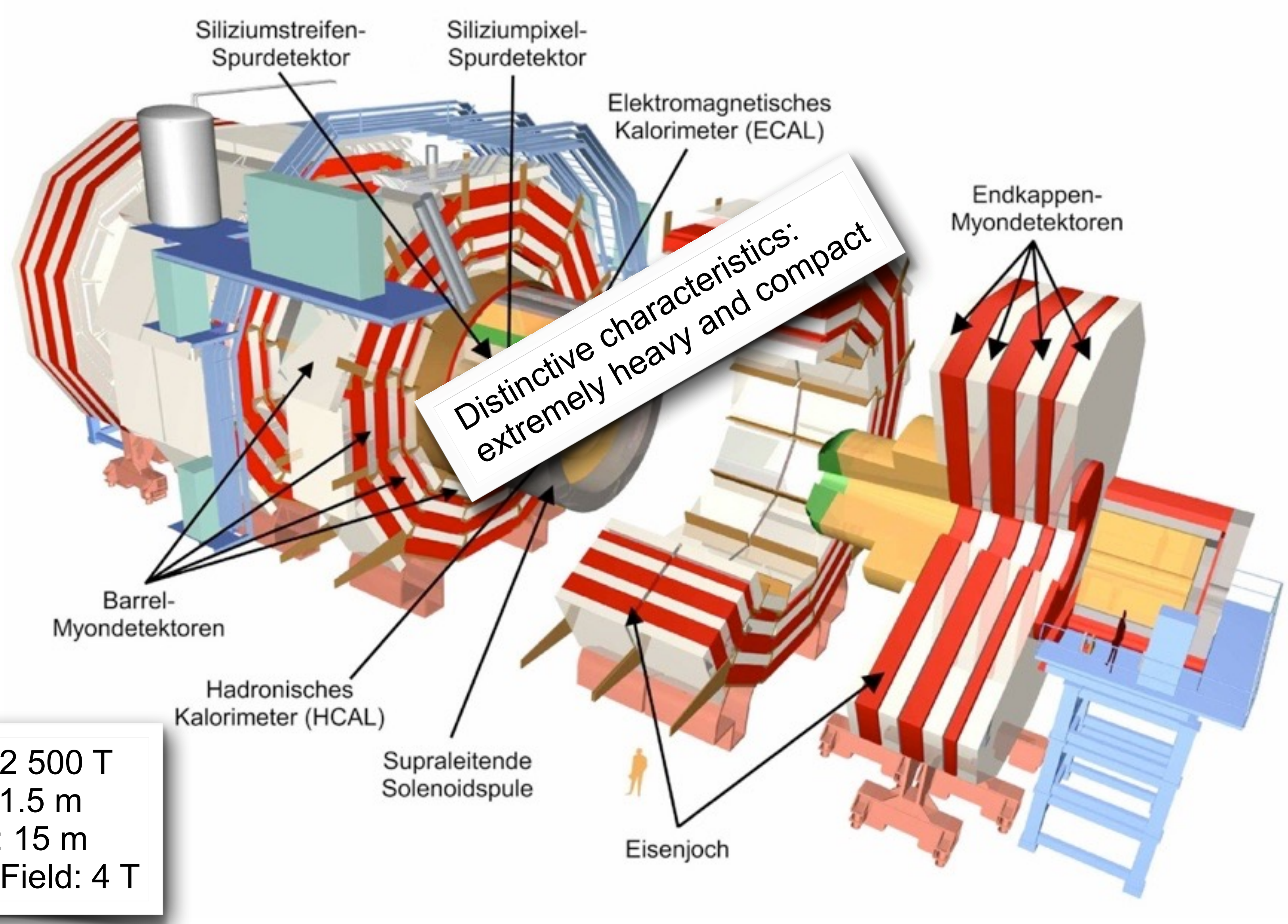


Foto: CERN

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

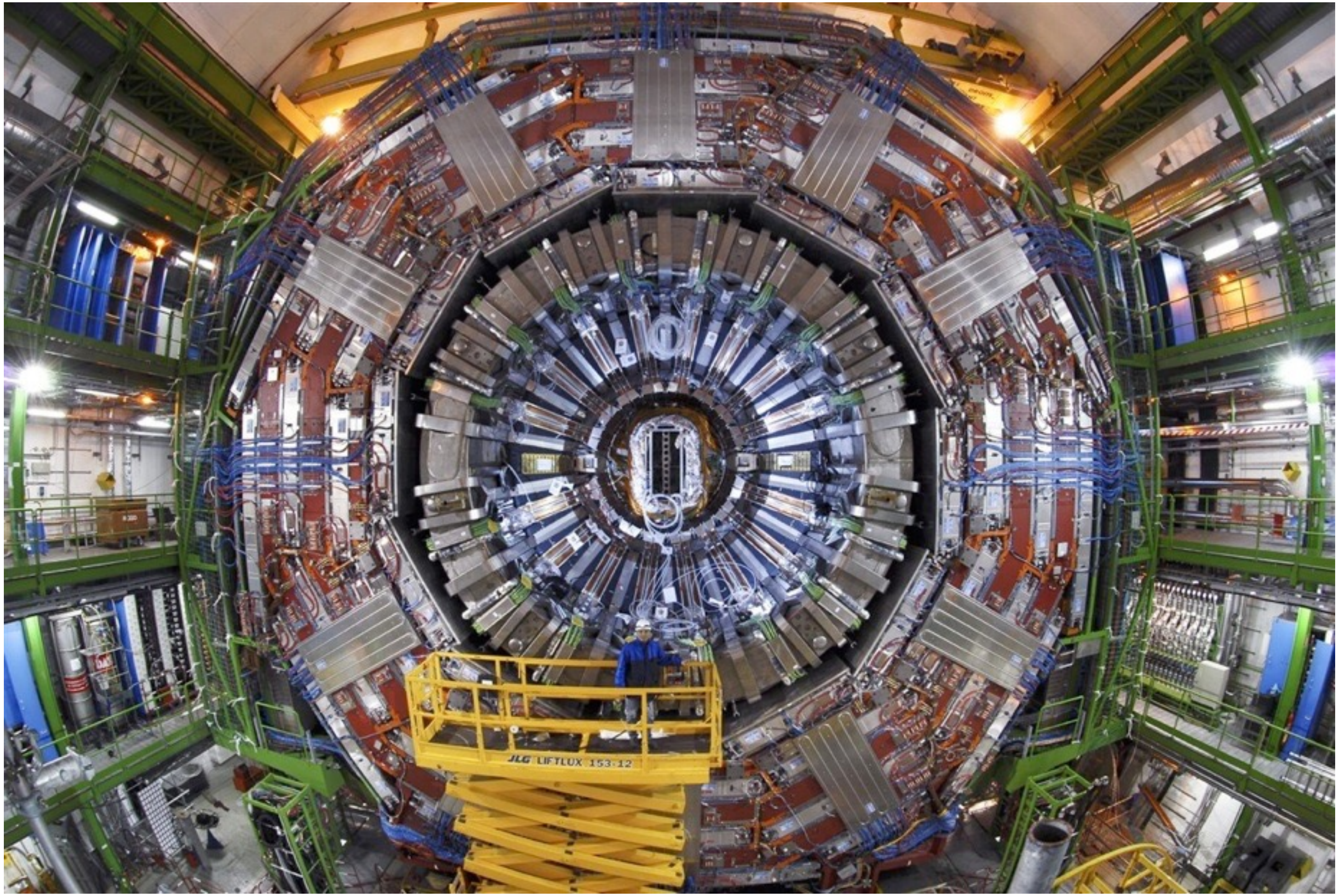
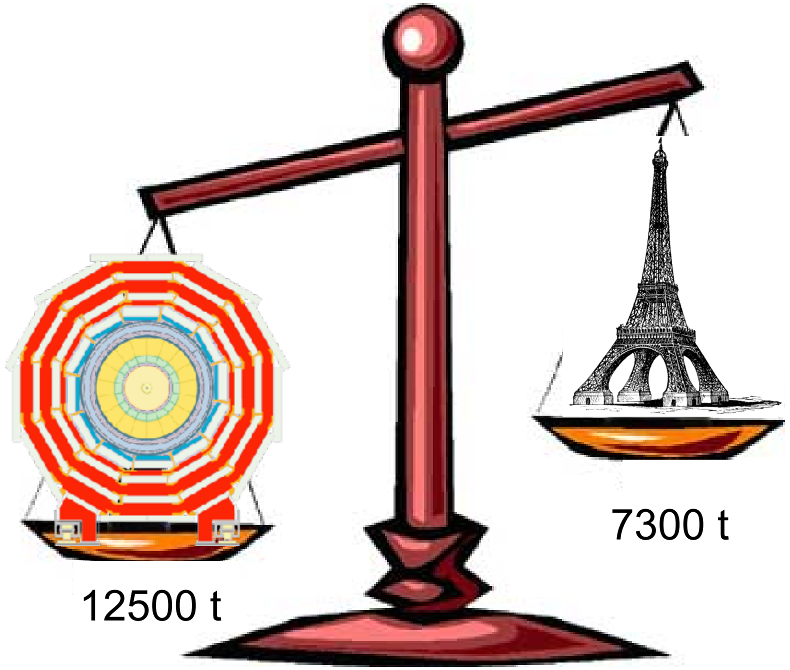


Foto: CERN

Size and Weight

Brandenburger Tor in Berlin



CMS is 65% heavier than the Eiffel tower

In Hamburg

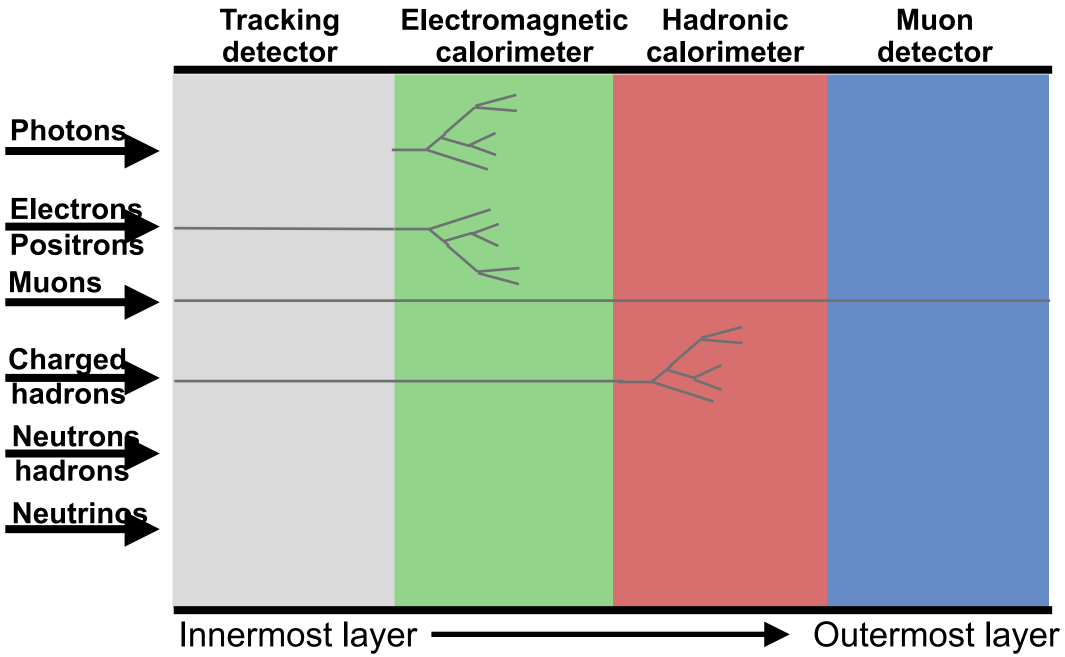
Example: ATLAS at CERN

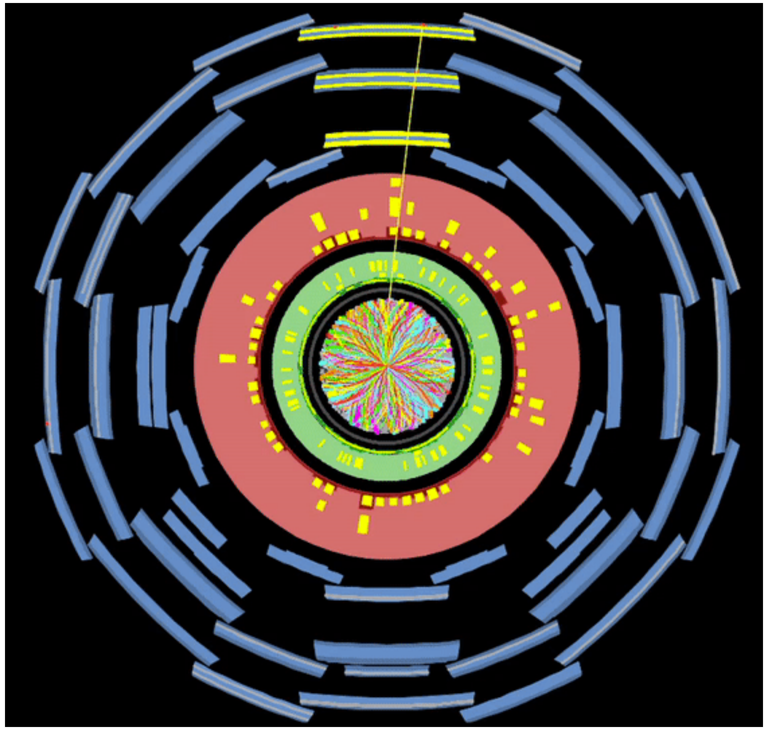
Full movie: ATLAS experiment - Episode 2 - The Particles Strike Back

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

Cameras for Particle Physics

- There is not one type of **detector** which provides all measurements we need (track, momentum, energy, PID)
  - "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





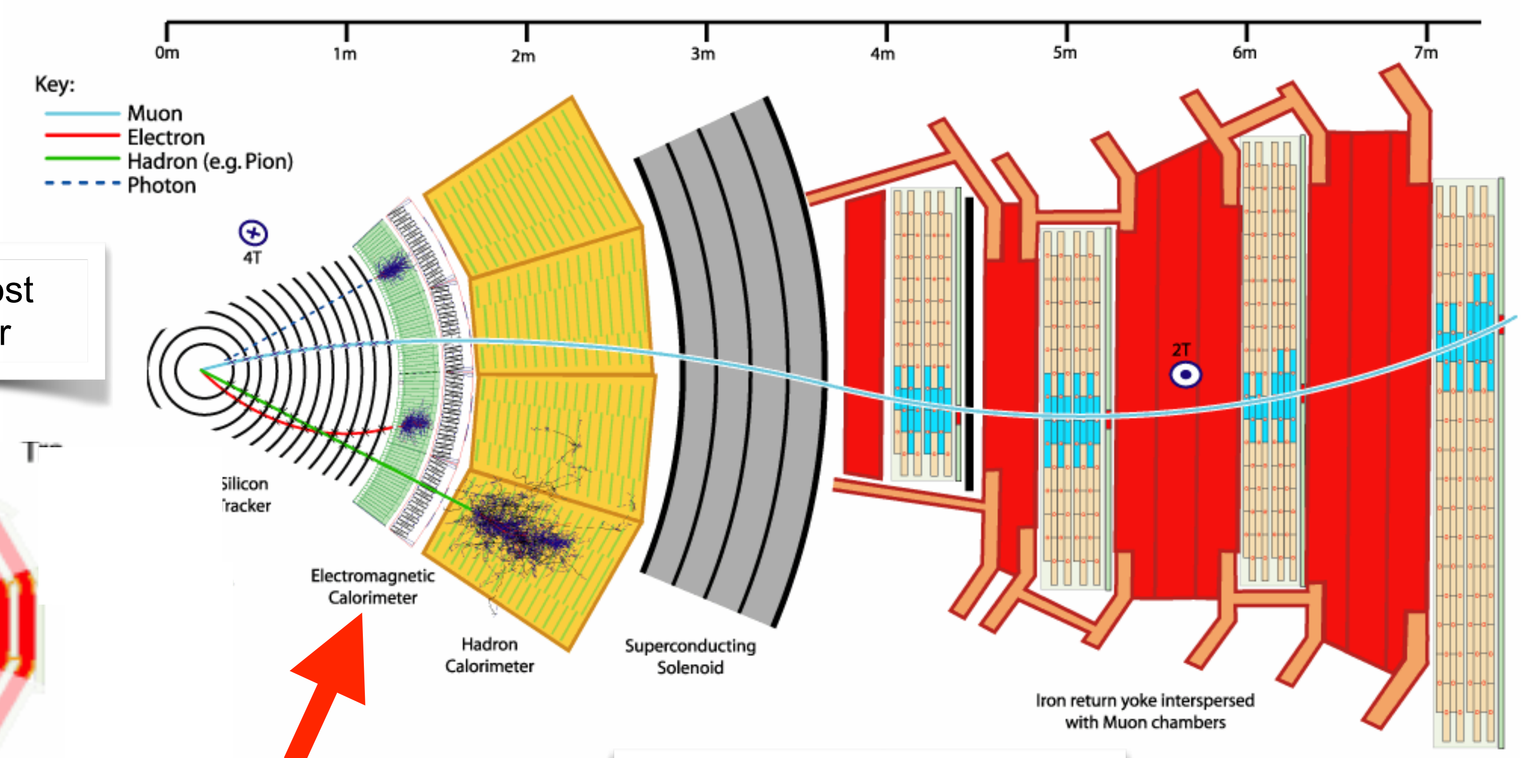
HEP Detector Overview

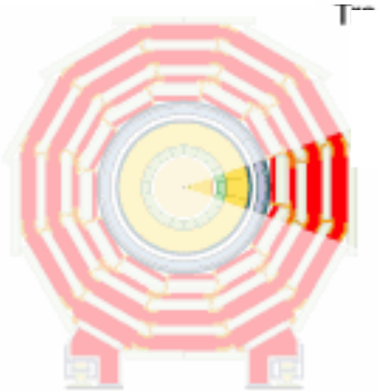
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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

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 ….

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

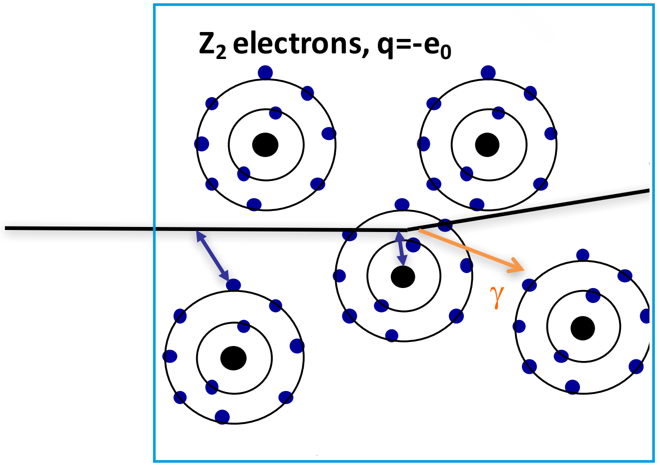
photons

neutrons

http://www.particlezoo.net/

Interactions of charged particles

Interaction of Charged Particles



- 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**

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

or

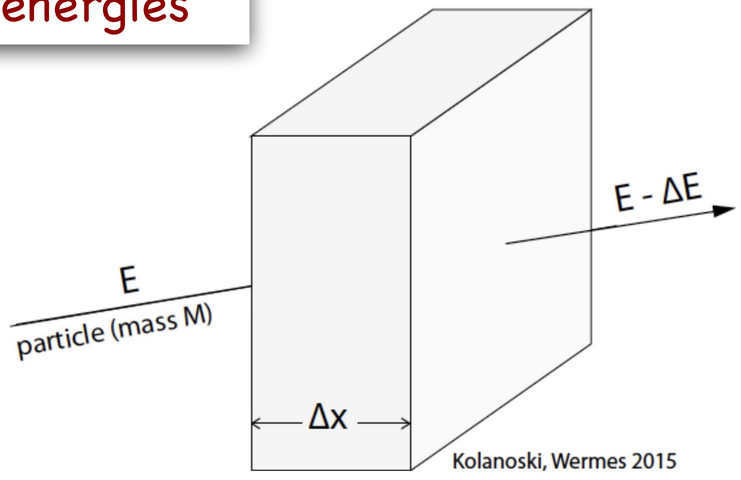
$$\left[\left\langle\frac{\mathrm{dE}}{\mathrm{d\tilde{x}}}\right\rangle\right] = \frac{\mathrm{MeV}}{\mathrm{gcm}^{-2}}$$ *Mass* stopping power

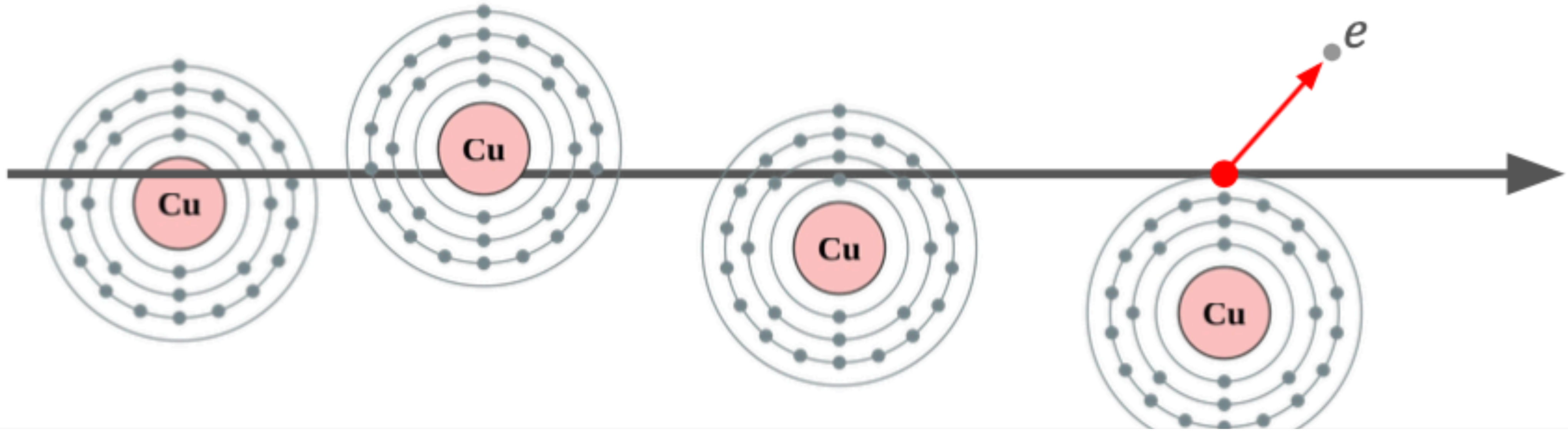
$$\tilde{x} = \rho x$$

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





- 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

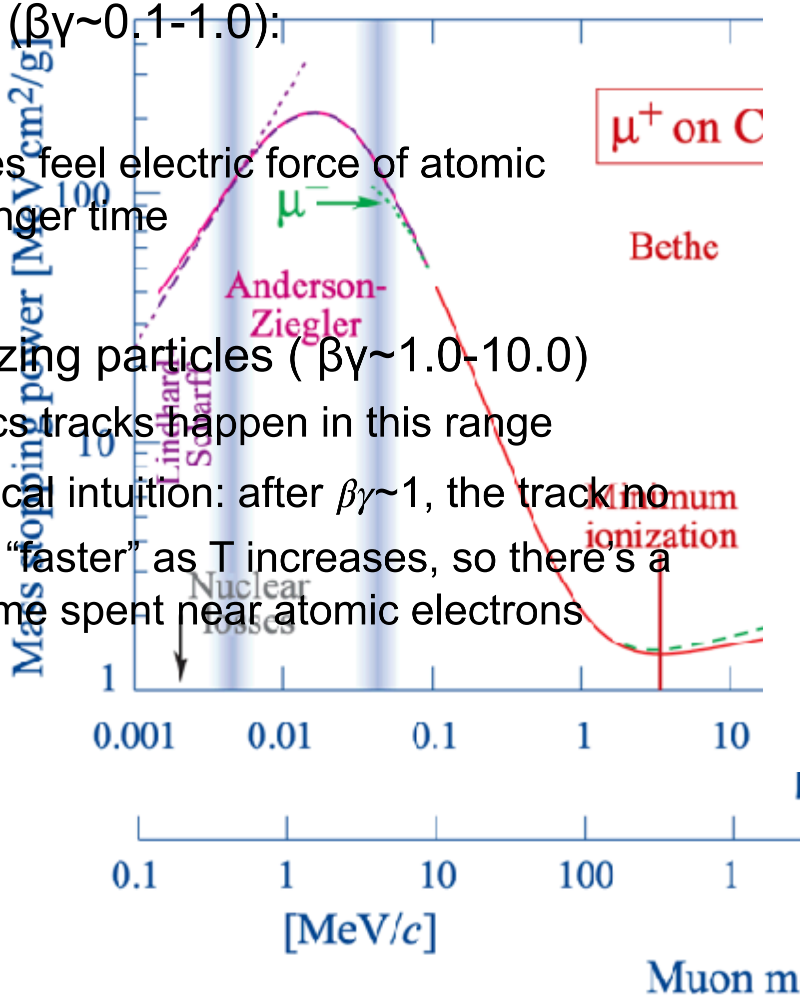
z : charge of incident particle in units of e

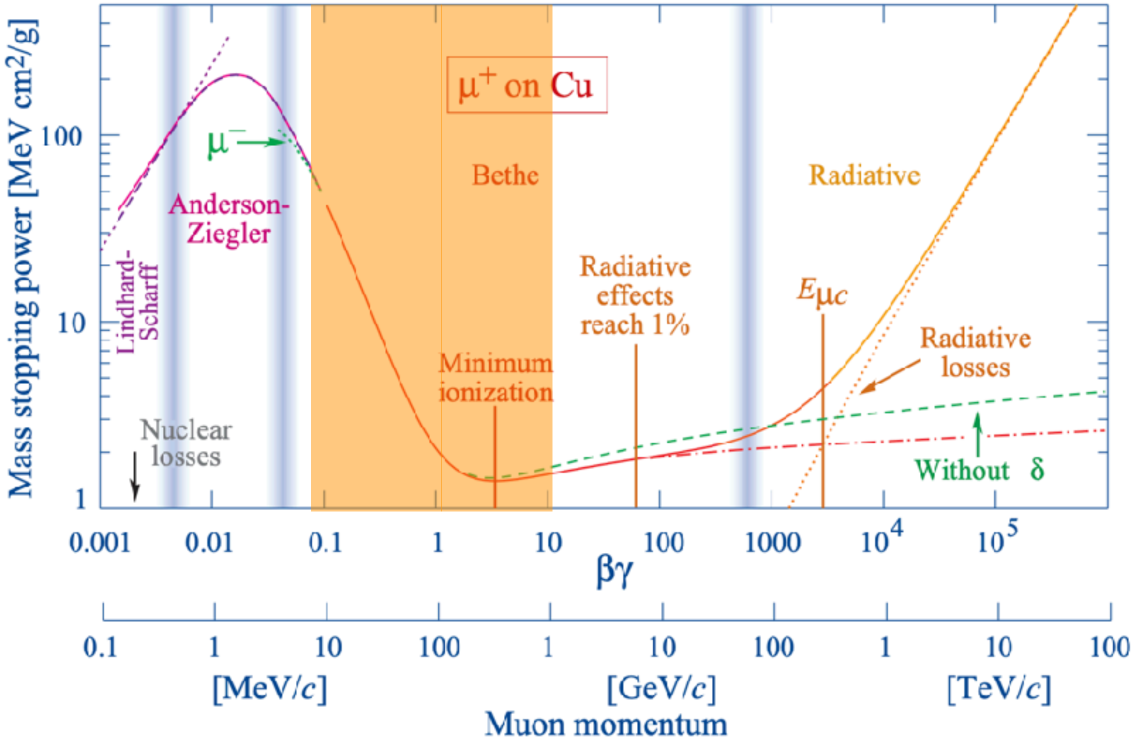
β : v/c of the incident particle

γ : $1/\sqrt{1-\beta^2}$

Understanding Bethe Bloch

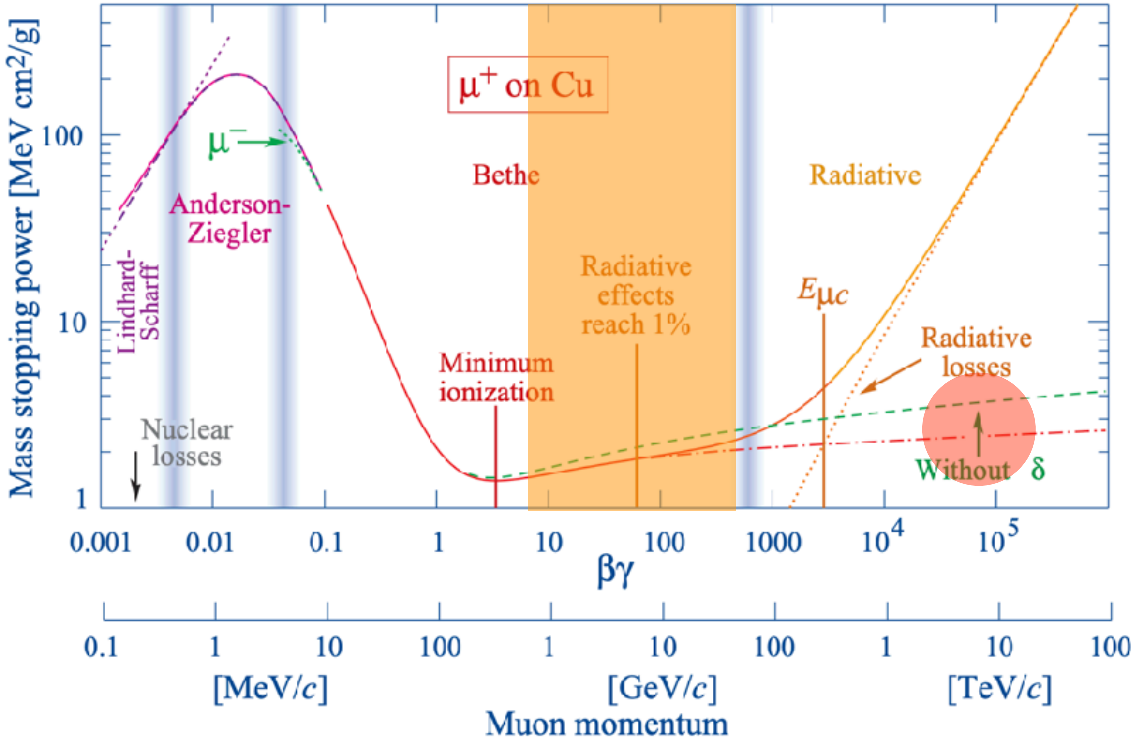
- Kinematic term (βγ~0.1-1.0):
  - dE/dx ~ β^{-2}
  - slower particles feel electric force of atomic electron for longer time
- Minimum ionizing particles (βγ~1.0-10.0)
  - Most physics tracks happen in this range
  - Semi-classical intuition: after $\beta\gamma$~1, the track no longer gets "faster"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



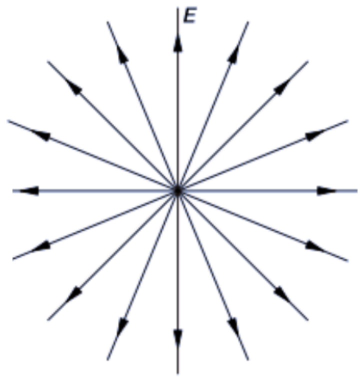


Understanding Bethe Bloch

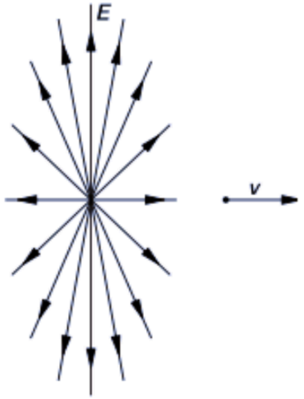
- Rise after βγ~5:
  - dE/dx~ln(βγ)2
  - due to more energy transfer from rare high-dE collisions
  - logarithmic rise due to lateral extension of electric field due to Lorentz transform Ey→γEy



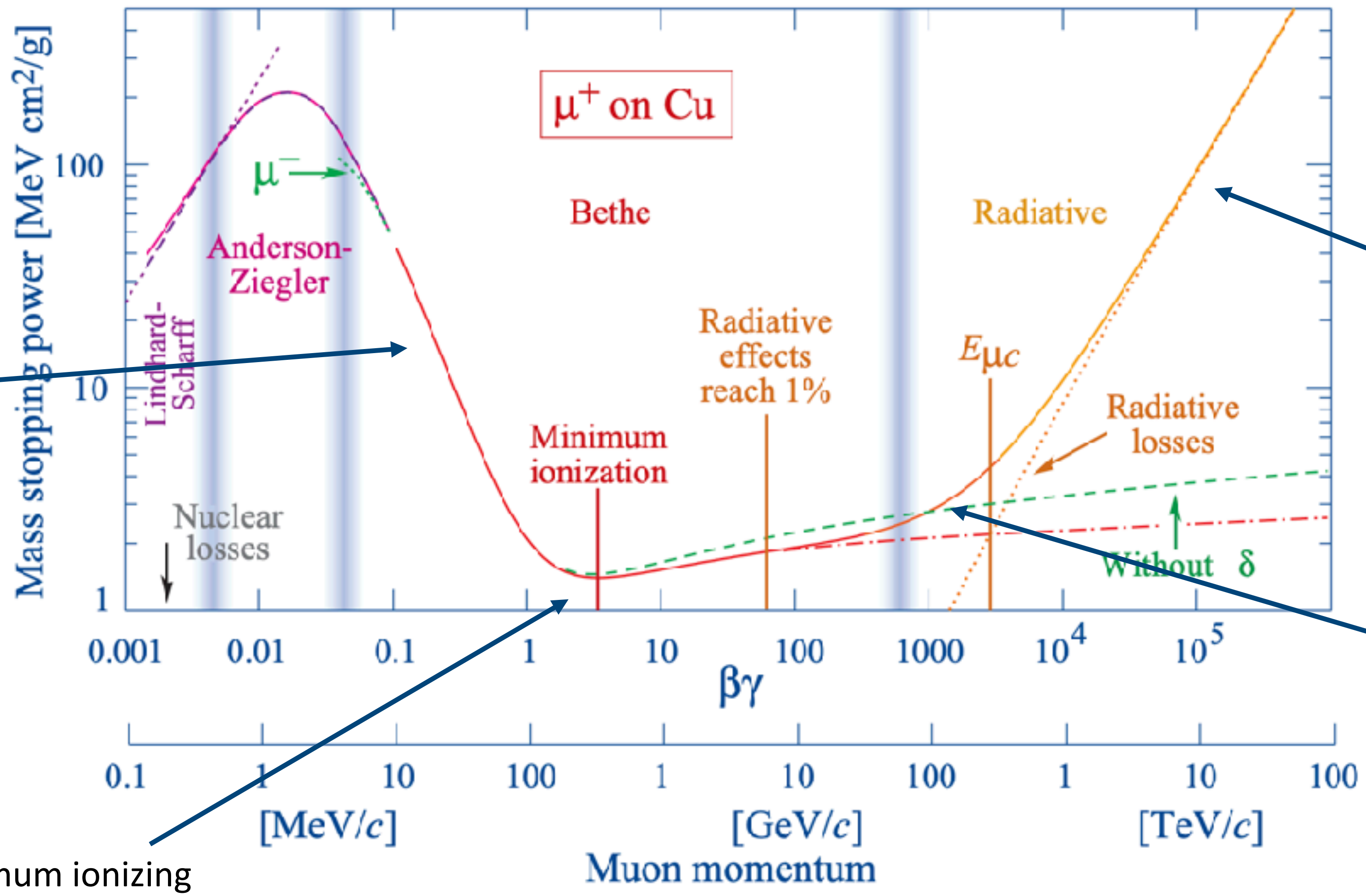
v=0



v=0.9c



Interactions of "heavy" Particles with Matter



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

"kinematic term"

Bremsstrahlung

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

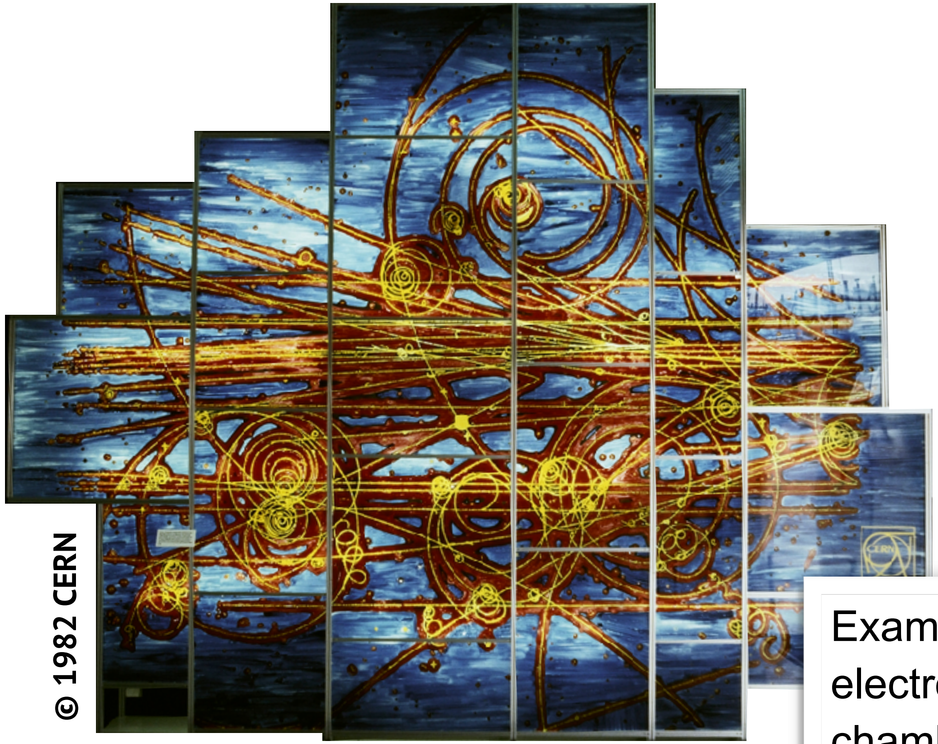
"relativistic rise"

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

Plot: PDG, June 2018

A Closer Account of Energy Loss

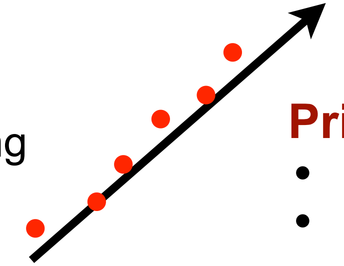
- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



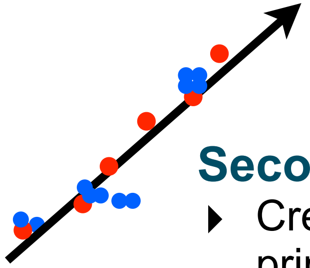
© 1982 CERN

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

Liquid hydrogen bubble chamber 1960 (~15cm).



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

- 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

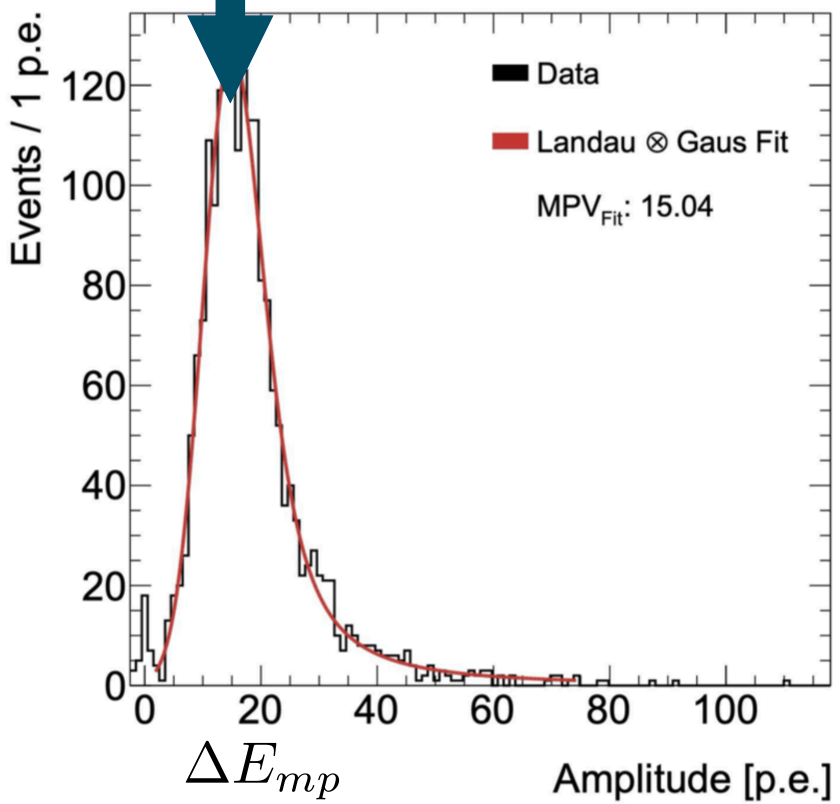
The Landau distribution is used in physics to describe the fluctuations in the energy loss of a charged particle passing through a thin layer of matter

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

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

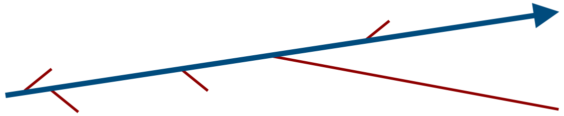
ξ is a material constant

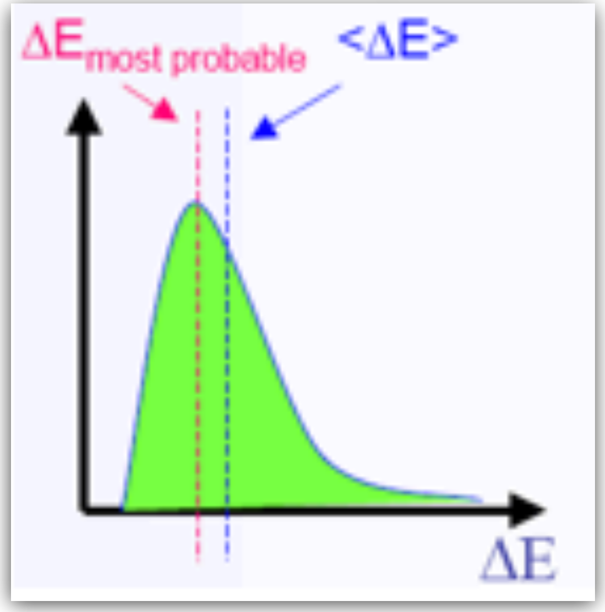
most probable peak!



Landau Tails

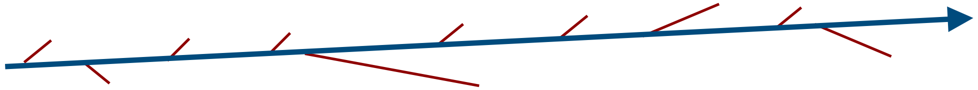
- Real detector measures the energy ΔE deposited in a layer of finite thickness δx
- For thin layers or low density materials
  - few collisions; some with high energy transfer

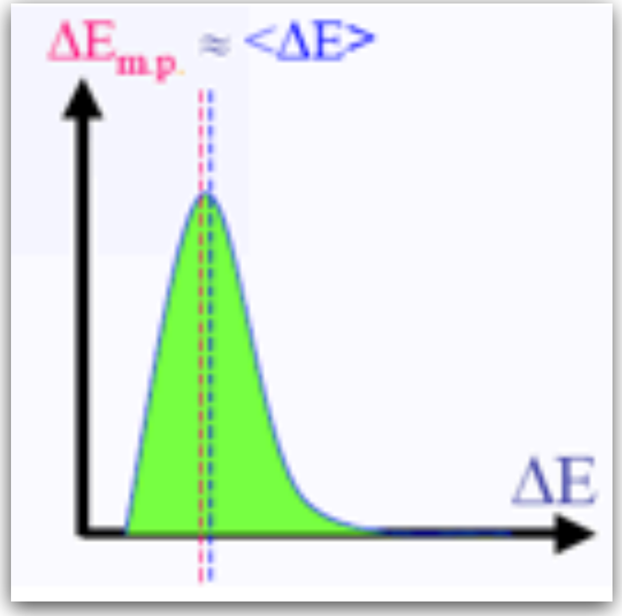




  - Energy loss distributions show large fluctuations towards high losses
  - Long Landau tails

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



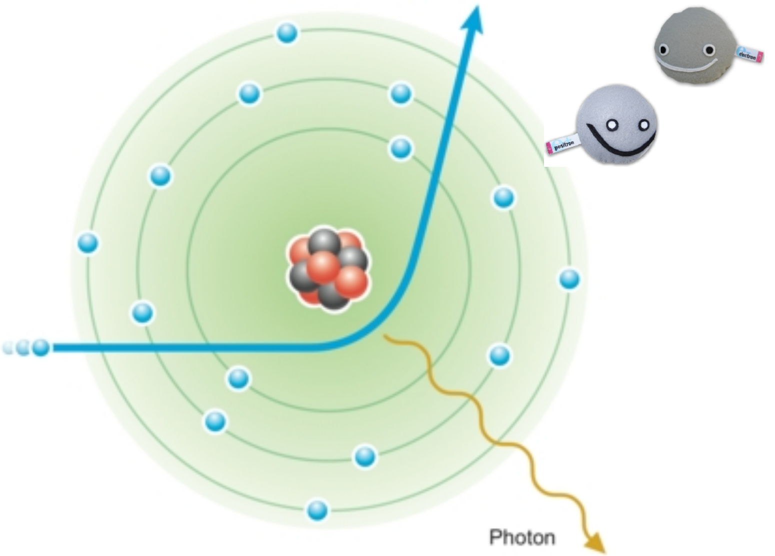


Energy Loss for Electrons

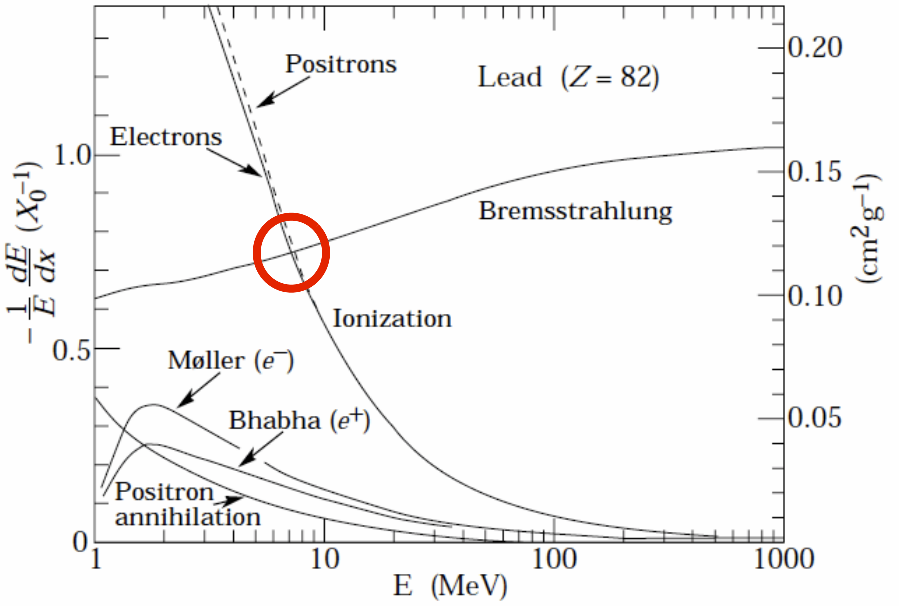
- Incident and target electron have same mass m_e
- Scattering of identical, undistinguishable particles
- Bremsstrahlung: photon emission by an electron accelerated in Coulomb field of nucleus

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

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



Incident electron and Bremsstrahlung photon.



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

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

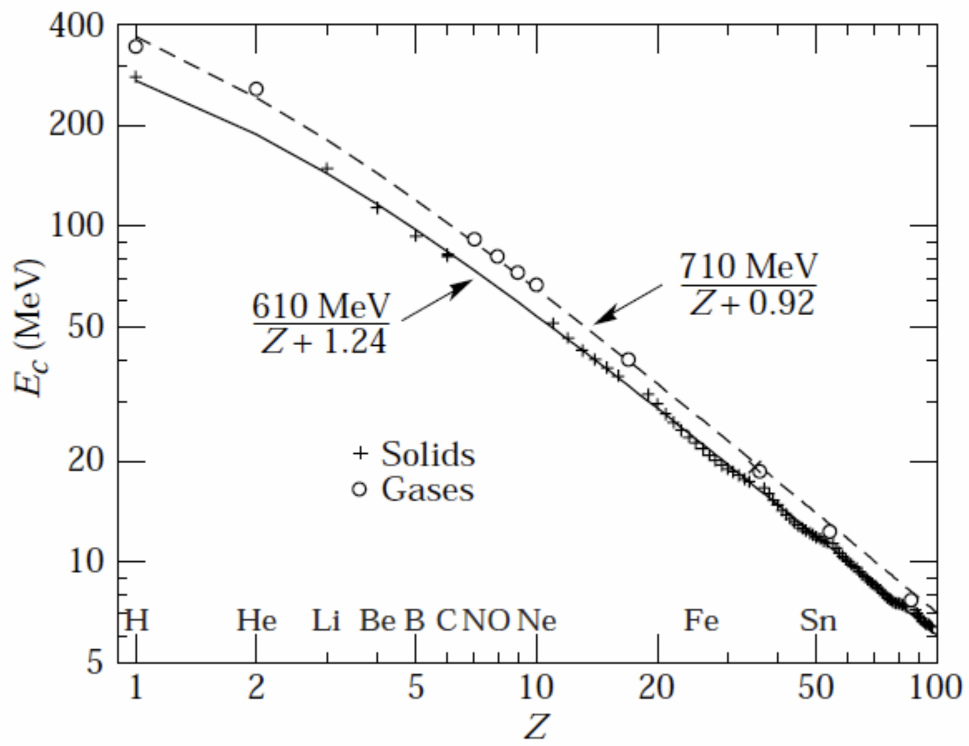
Electrons: Energy Loss

- **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:

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



For electrons

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

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

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

→

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

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

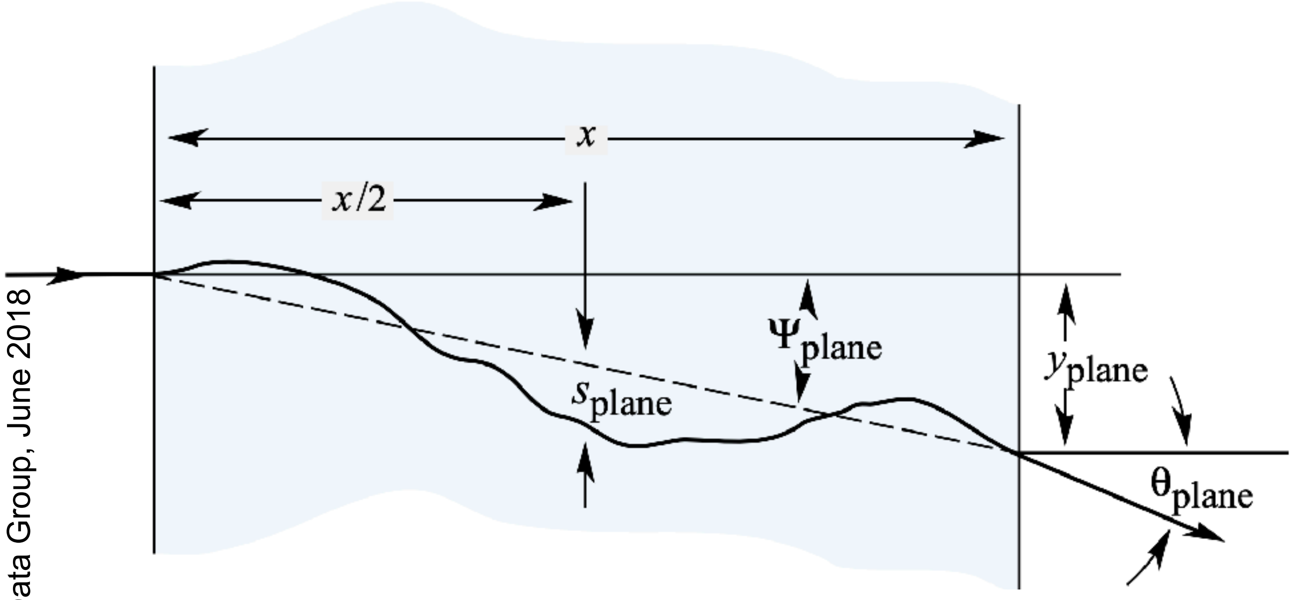
empirical: $$X_0 = \frac{716.4\,A}{Z(1+Z)\,ln(287/\sqrt{Z})}\,\frac{g}{cm^2} \propto \frac{A}{Z^2}$$

- 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/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

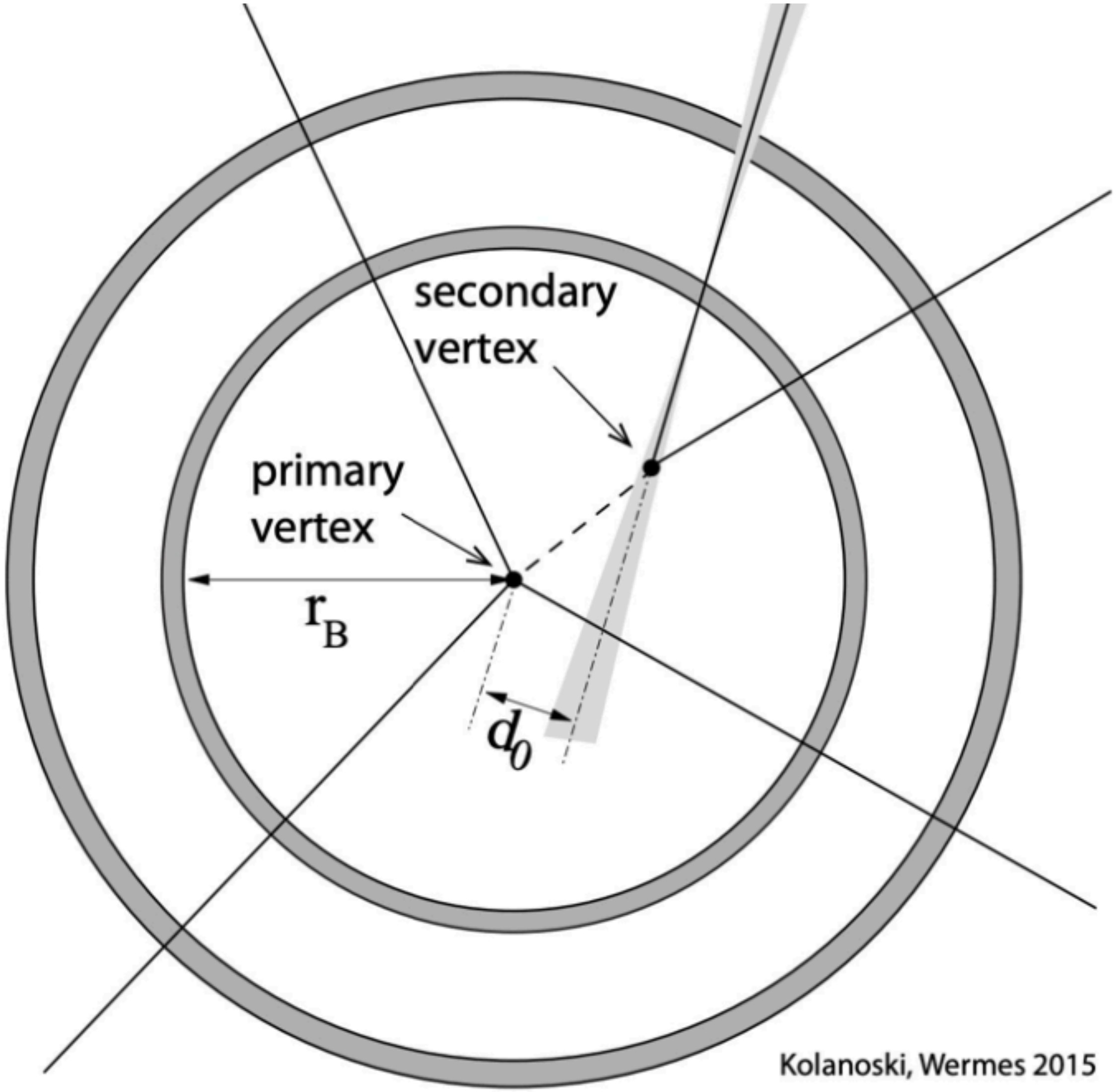
$$\theta_0 = \theta_{\rm plane}^{\rm rms} = \frac{1}{\sqrt{2}}\theta_{\rm space}^{\rm rms}$$

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

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

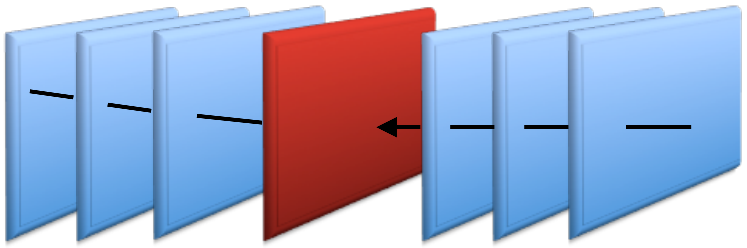
Gaussian approximation sufficient for many applications.

Consequence of Multiple

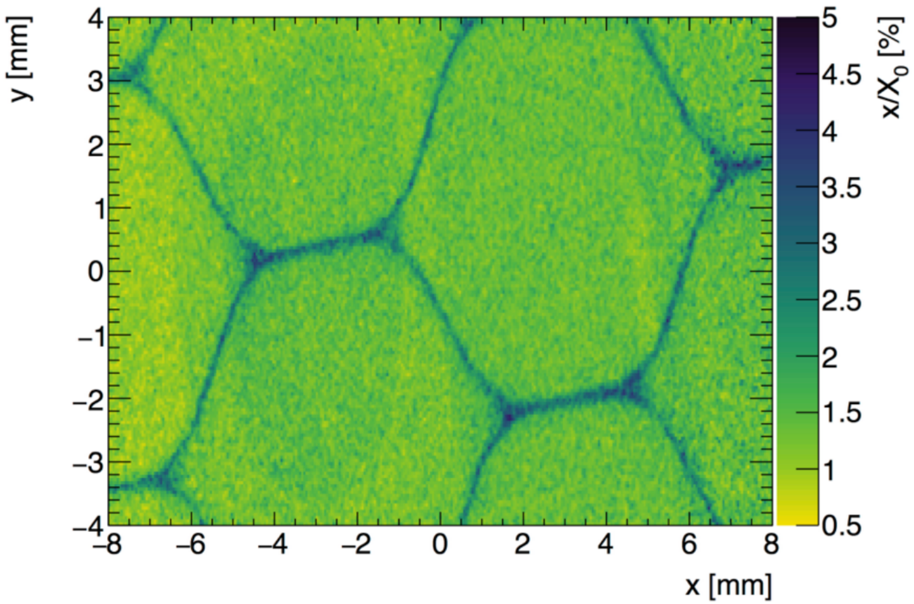


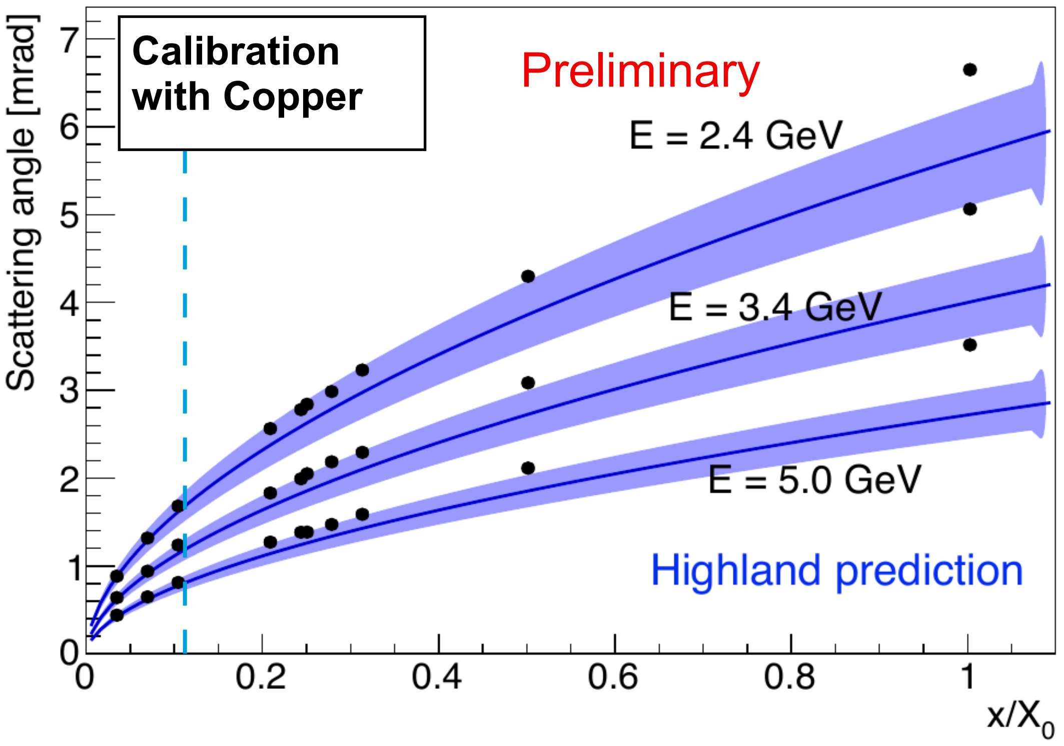
Using Multiple Scattering

- 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

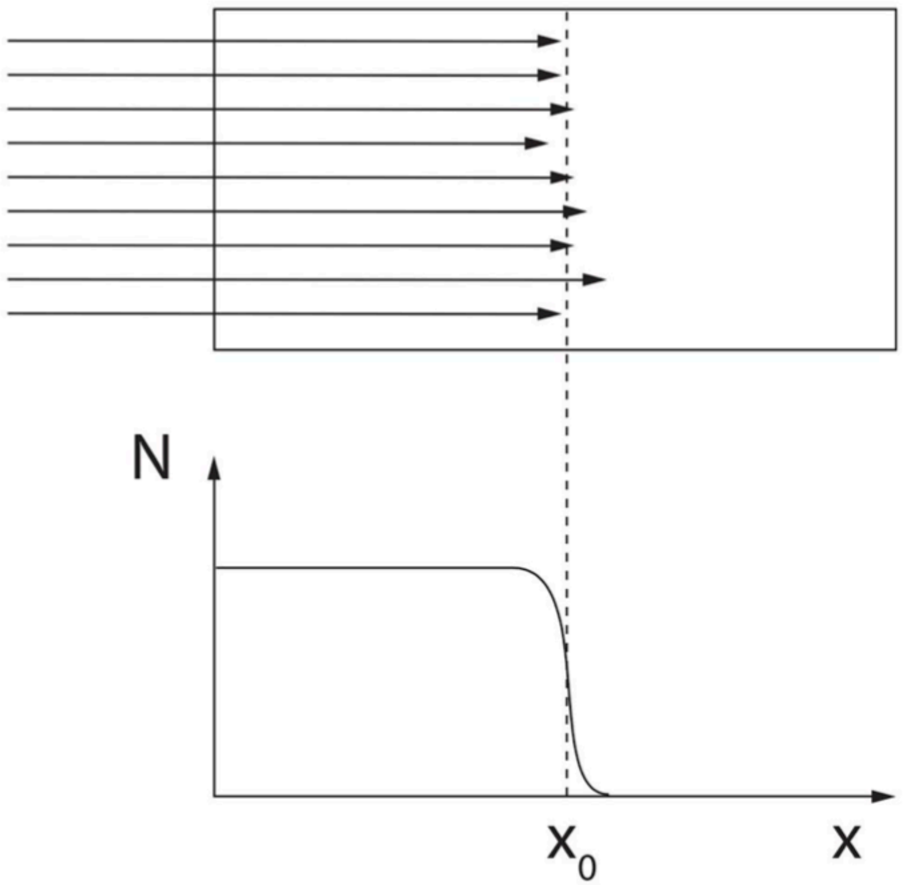




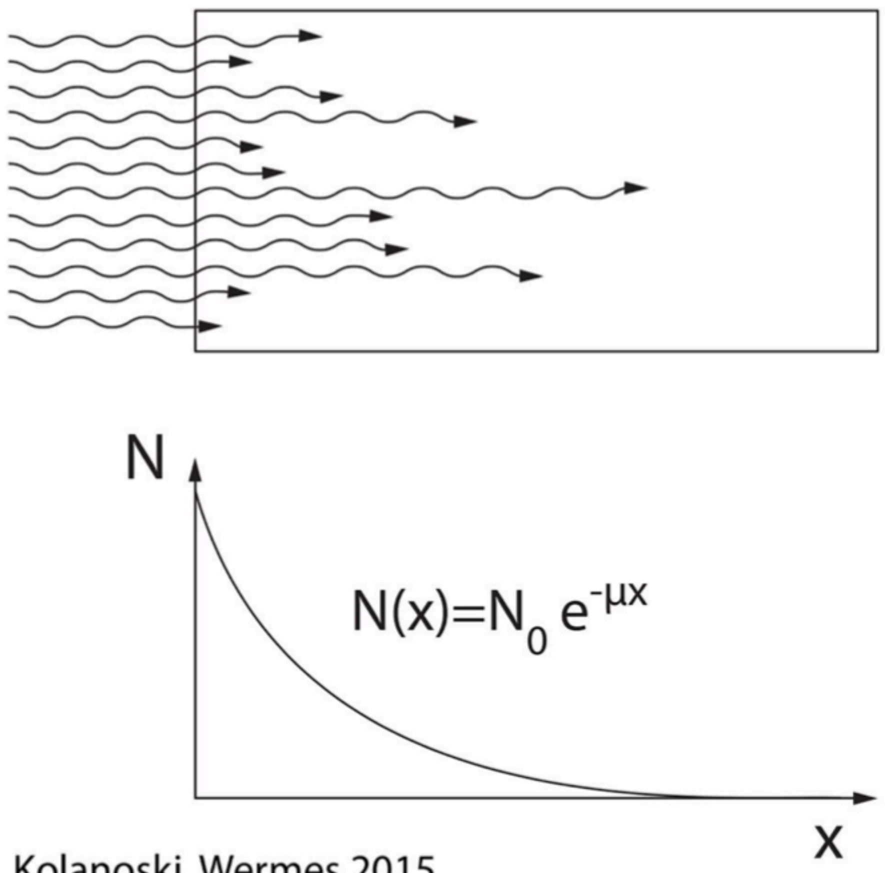
Interactions of Photons, Neutrons and Neutrinos

Big Difference

Charged particles



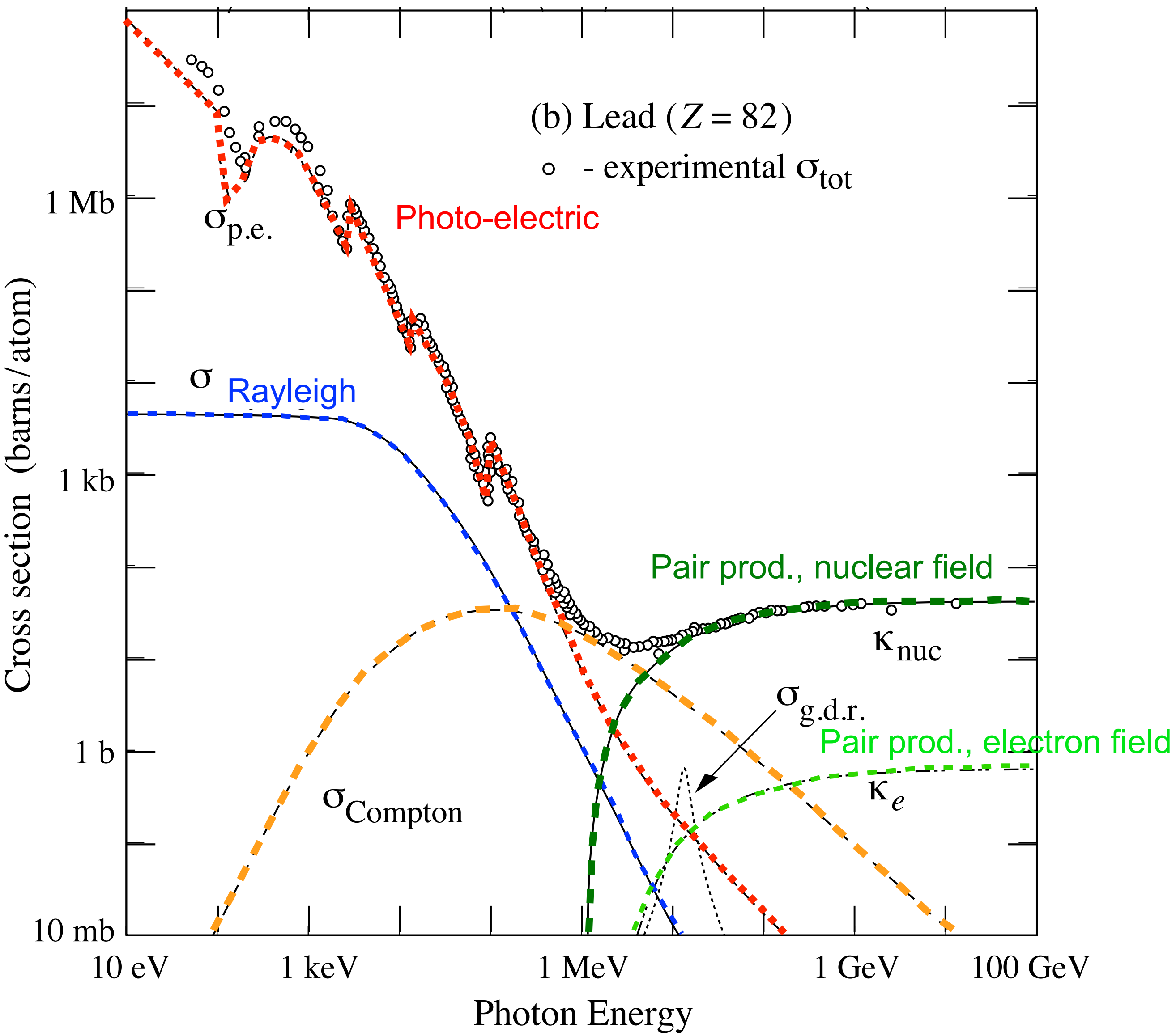
Photons



Kolanoski, Wermes 2015

Photons: Interactions

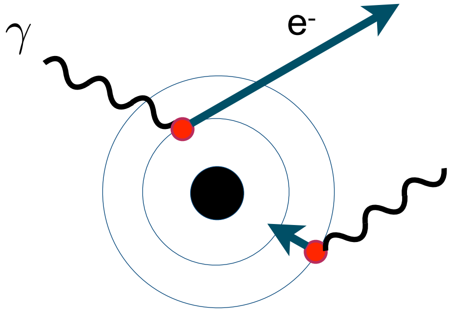
- Photons appear in detector systems
  - as primary photons,
  - created in Bremsstrahlung and de-excitations
- Photons are also used for medical applications, both imaging and radiation treatment.
- Photons interact via **six** mechanisms depending on the photon energy:
  - < few eV: molecular interactions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



Photons: Interactions

- Most dominating effects:

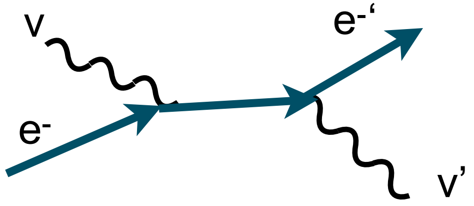
Photo-Effect



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

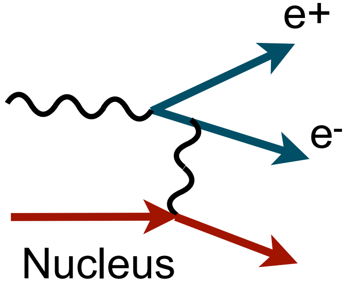


$$\gamma + e \rightarrow \gamma' + e'$$

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

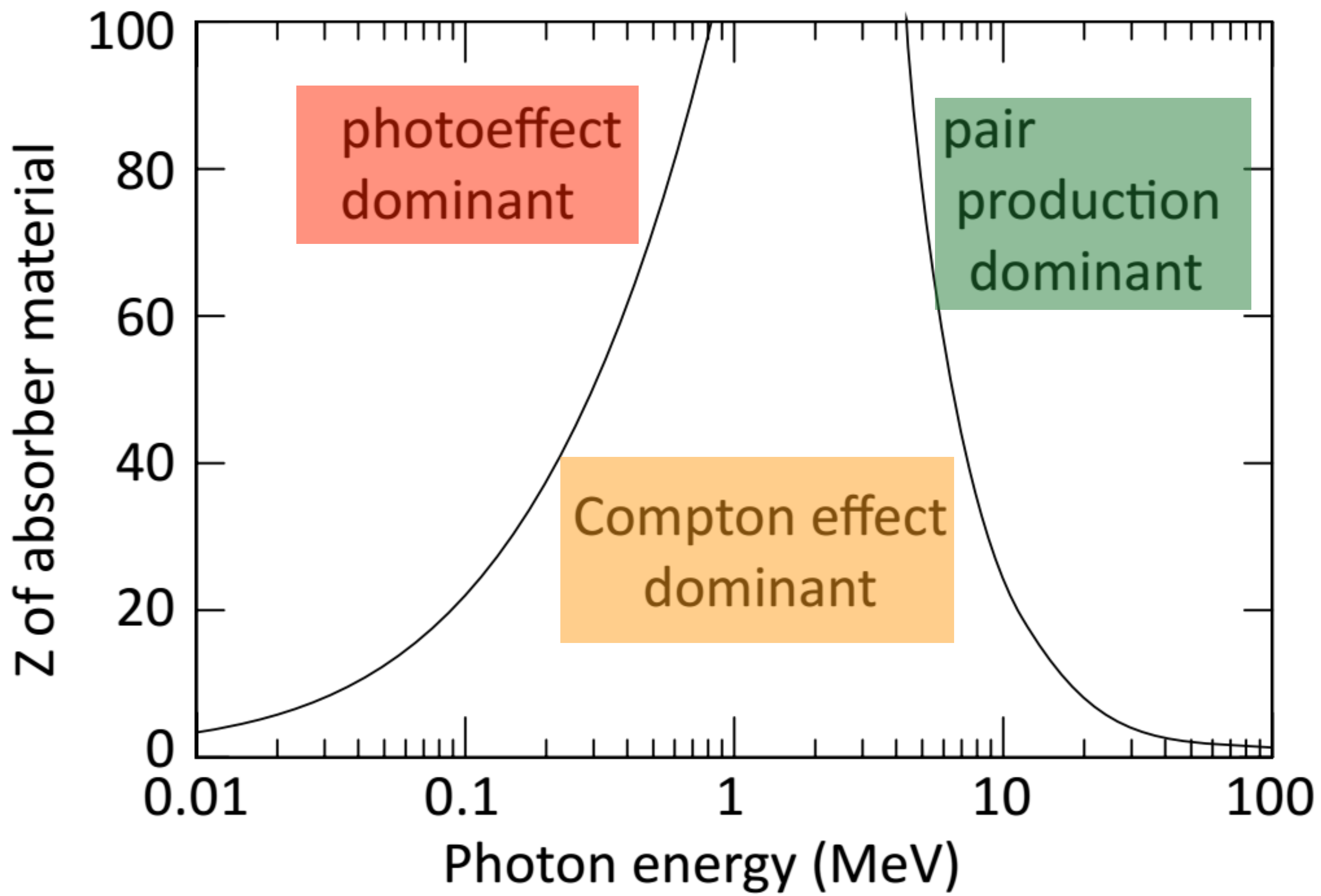
$$E_\gamma \geq 2m_ec^2$$

~1.022 MeV

➩ Reduction of photon intensity with passage through matter:

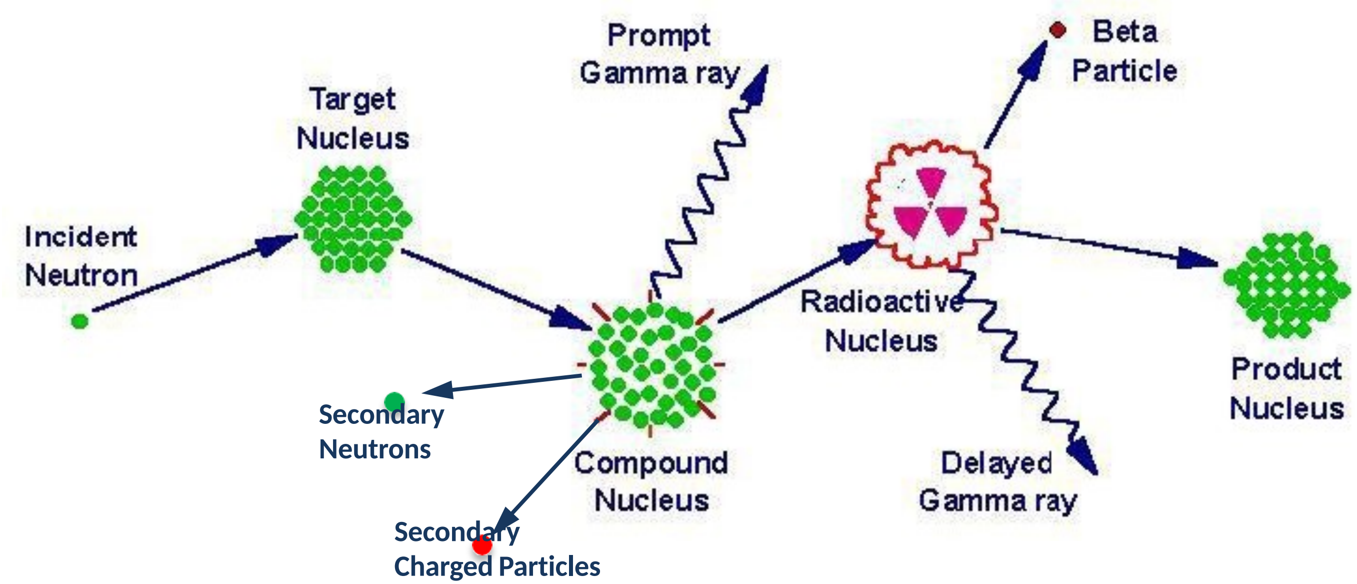
$$I(x) = I_0 e^{-\mu x}$$

Dominant Regions



General Detection Principles

- Neutron detectors do not detect neutrons but products of neutron interactions!



- Almost all detector types can be made neutron sensitive:
  - external converter (radiator)
  - converter = detector

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….

A short summary

$\pi^- + p$

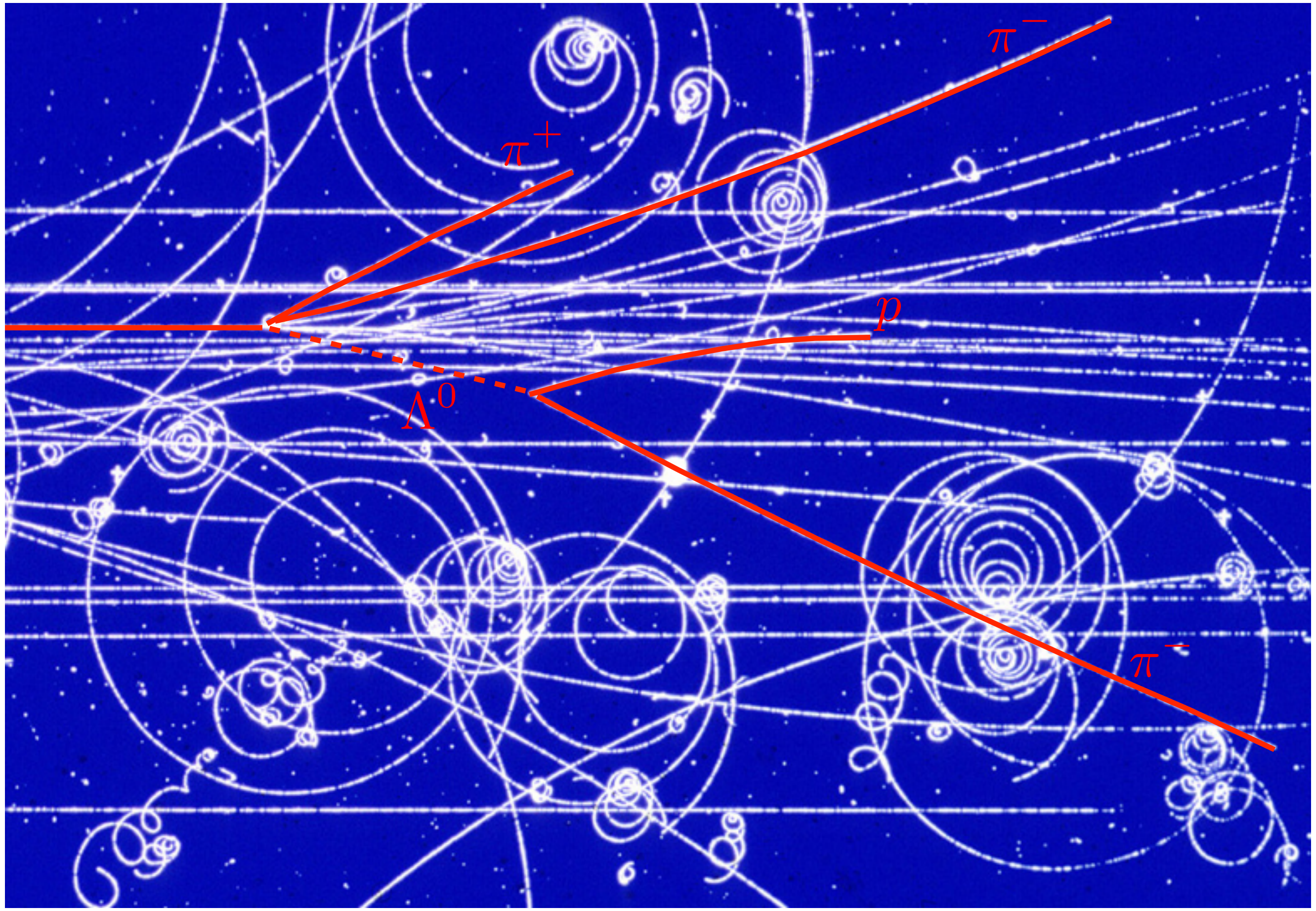
16 GeV

.

.

.

.



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