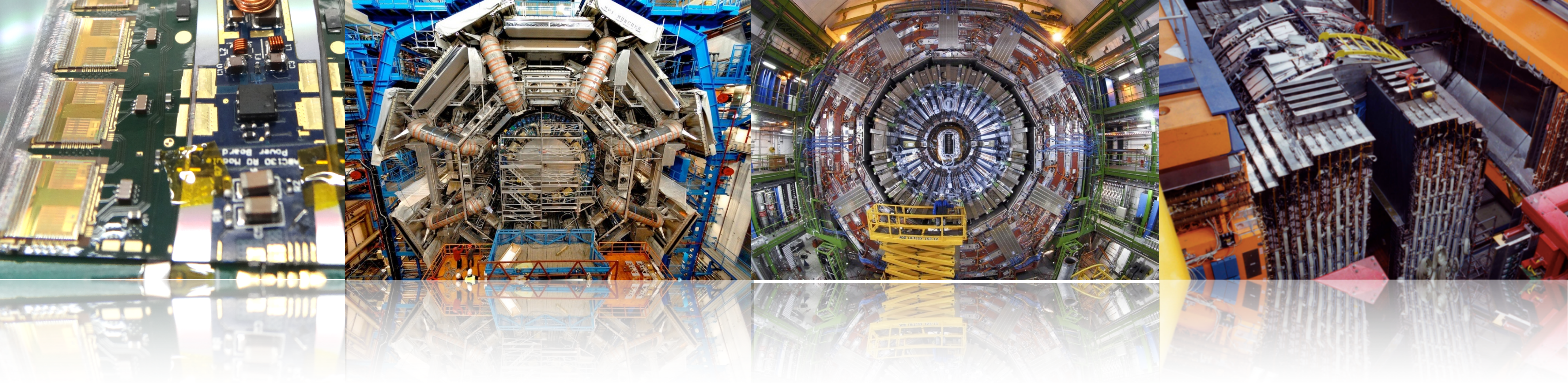


Instrumentation and Detectors

Part 1

AEPSHEP 2022

Ingrid-Maria Gregor
DESY/Universität Bonn

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**

}

Sunday

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

}

Monday

- **IV. Calorimeters**
- **V. Examples of what can go wrong**

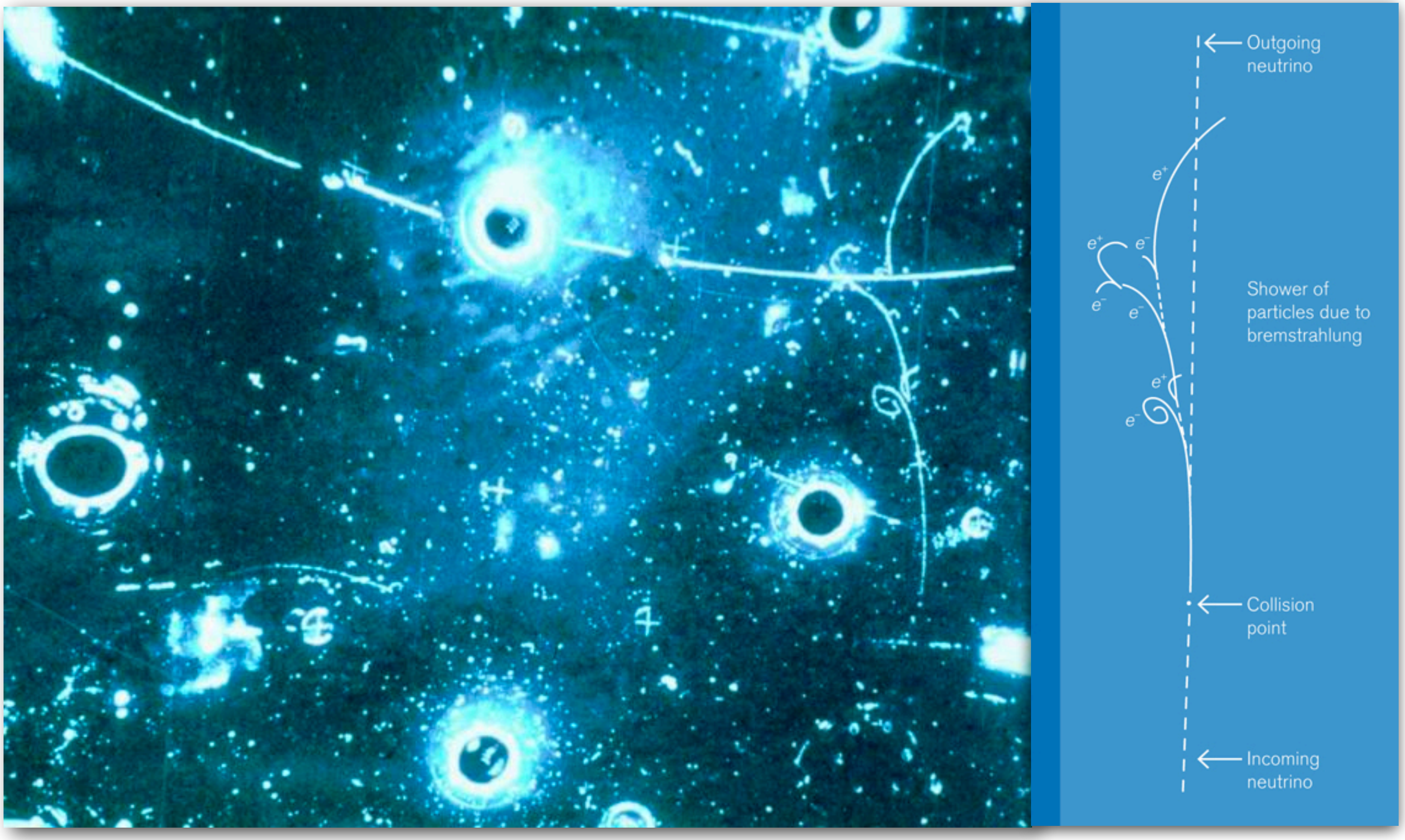
}

Wednesday

I. Overview: Detectors for particle physics

DISCOVERY OF NEUTRAL CURRENTS

Gargamelle, 1972

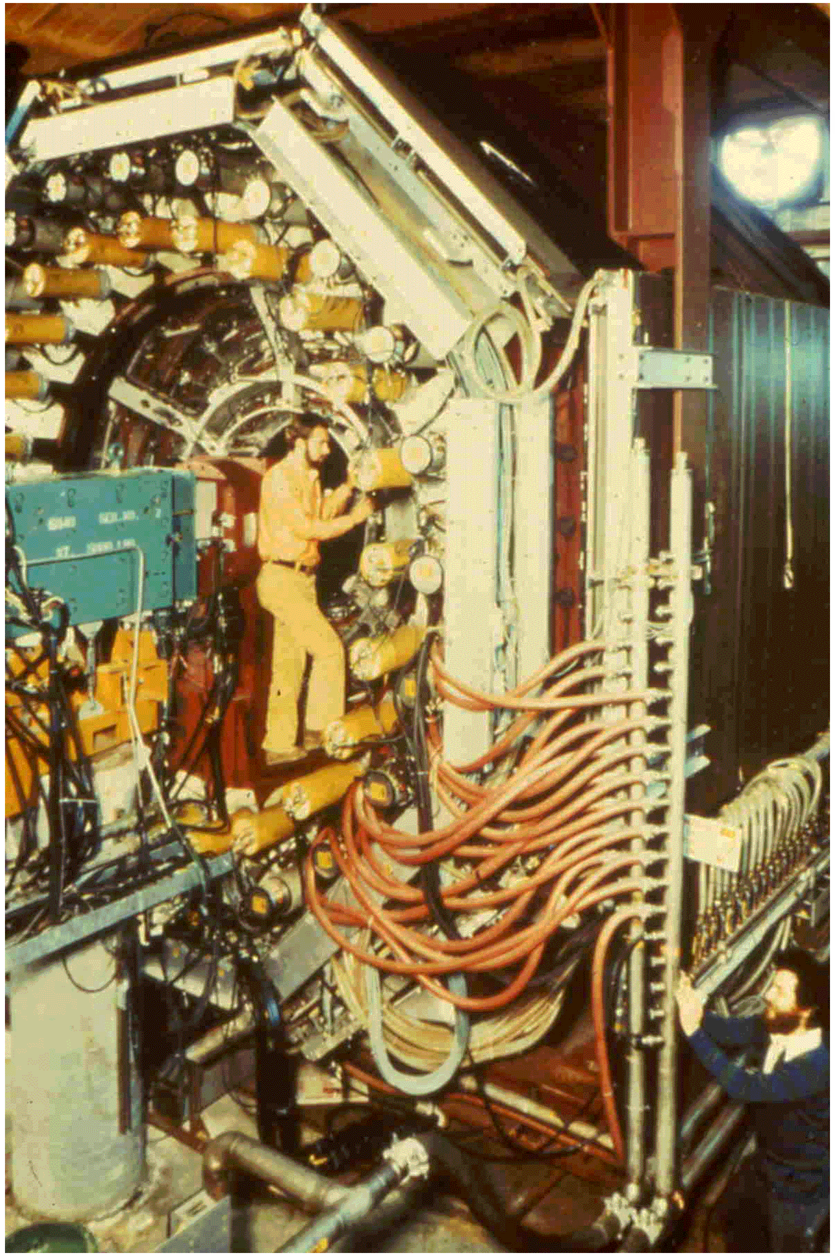


© Gargamelle/CERN

Mark-I Detectr@SLAC

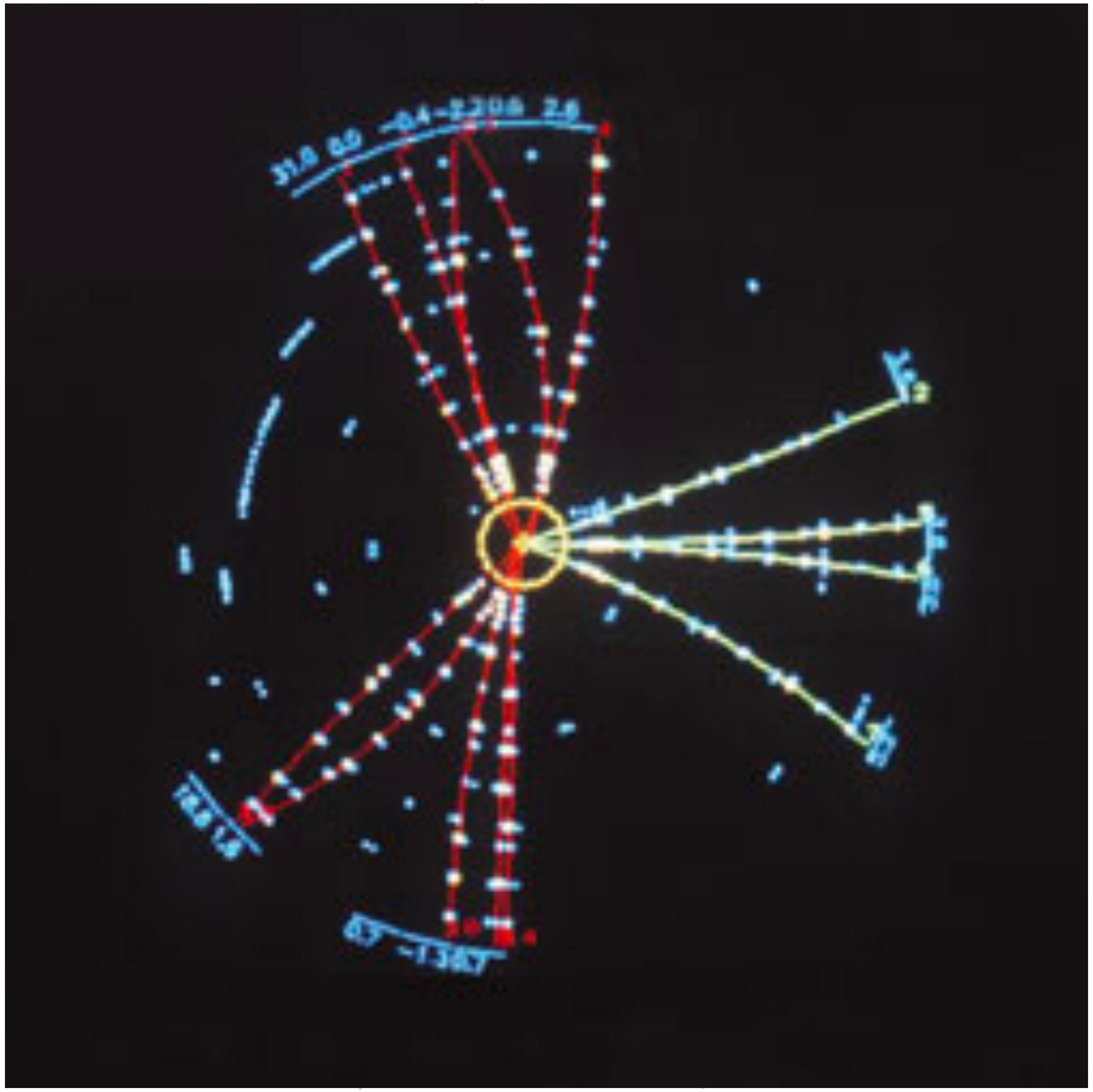
- Mark I detector: first 4 detector

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



DISCOVERY OF THE GLUON

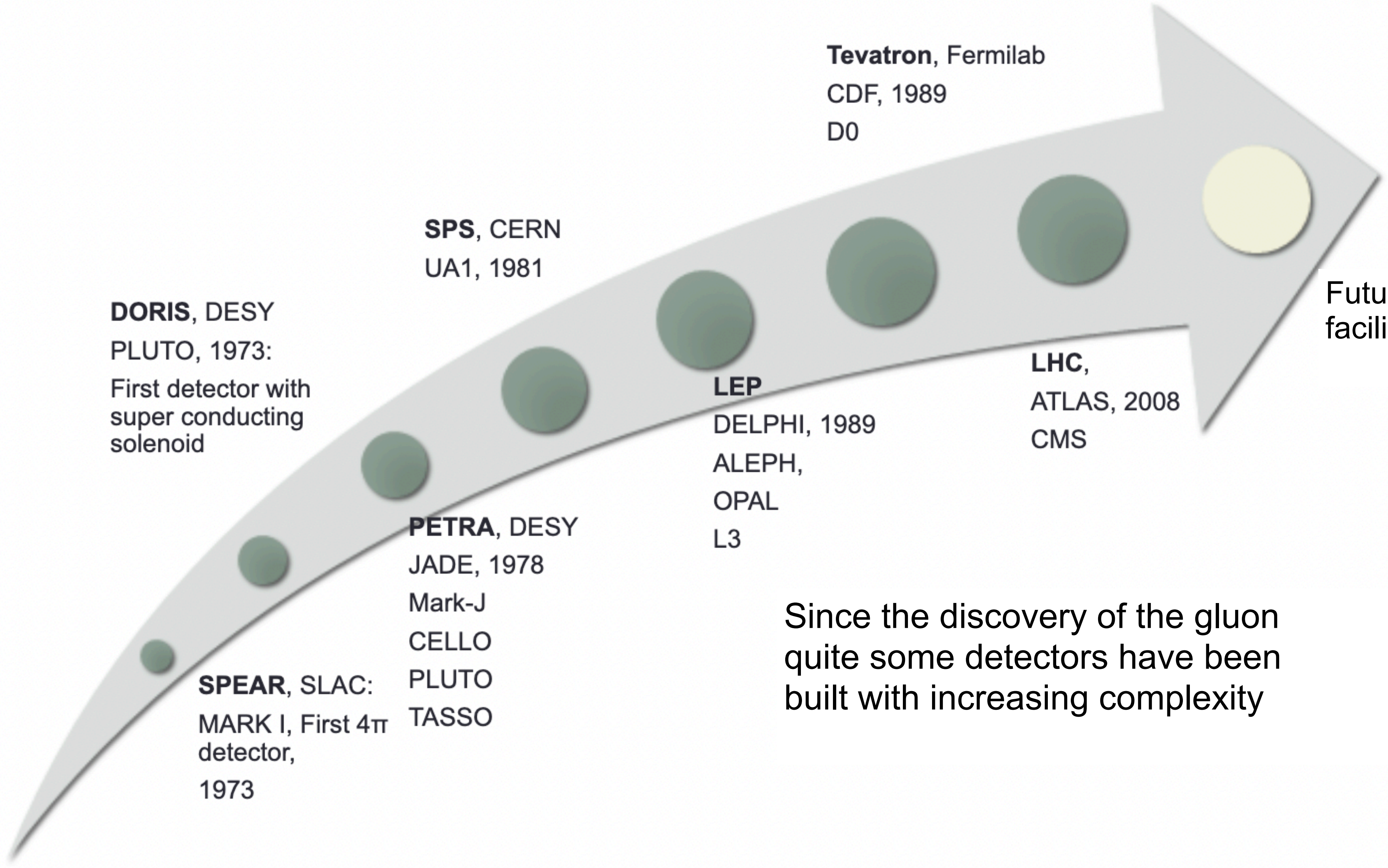
18.06.1979



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

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

EVOLUTION OF DETECTORS



SPEAR, SLAC:
MARK I, First 4π detector,
1973

DORIS, DESY
PLUTO, 1973:
First detector with super conducting solenoid

PETRA, DESY
JADE, 1978
Mark-J
CELLO
PLUTO
TASSO

SPS, CERN
UA1, 1981

LEP
DELPHI, 1989
ALEPH,
OPAL
L3

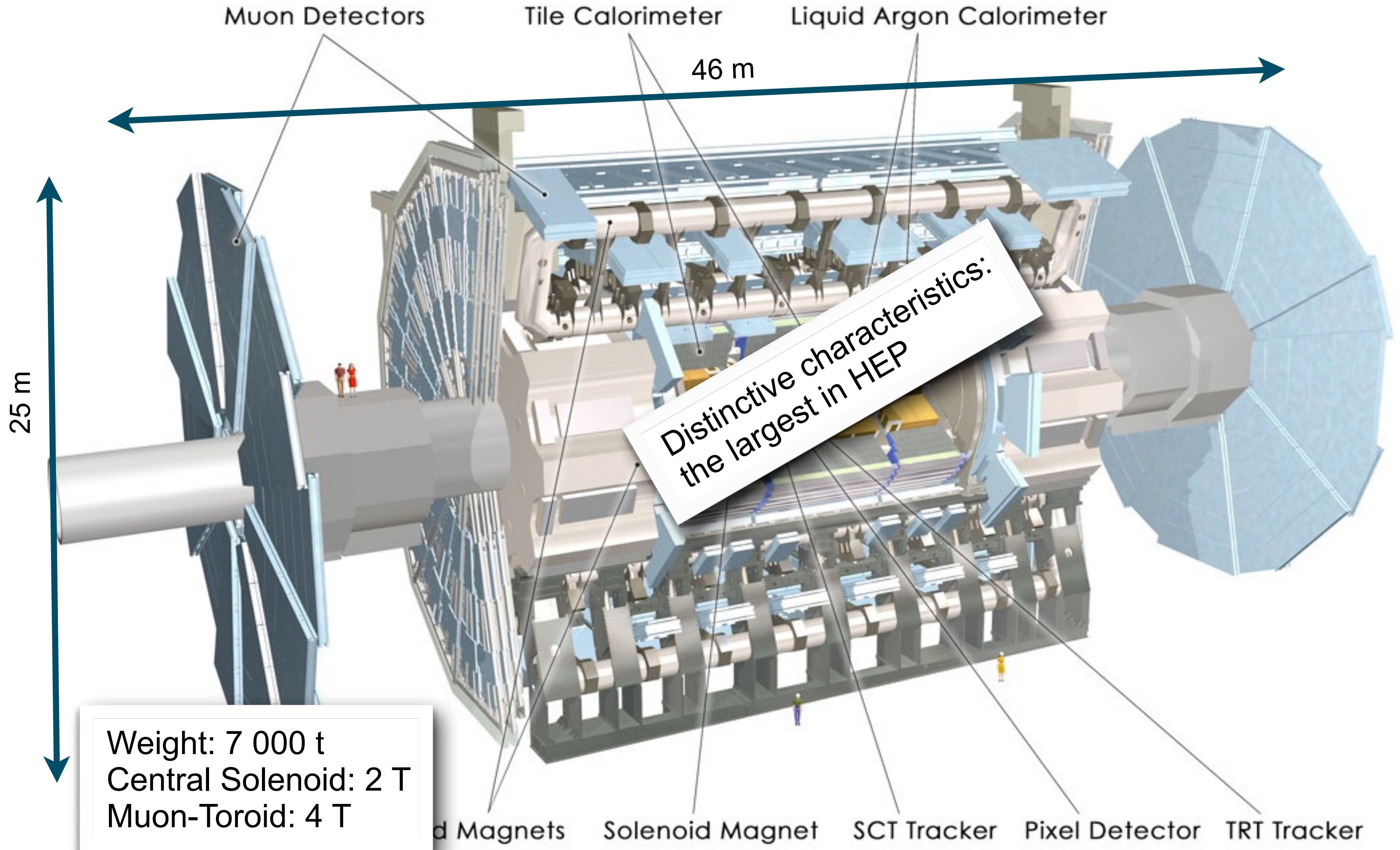
Tevatron, Fermilab
CDF, 1989
D0

LHC,
ATLAS, 2008
CMS

Future facilities

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

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

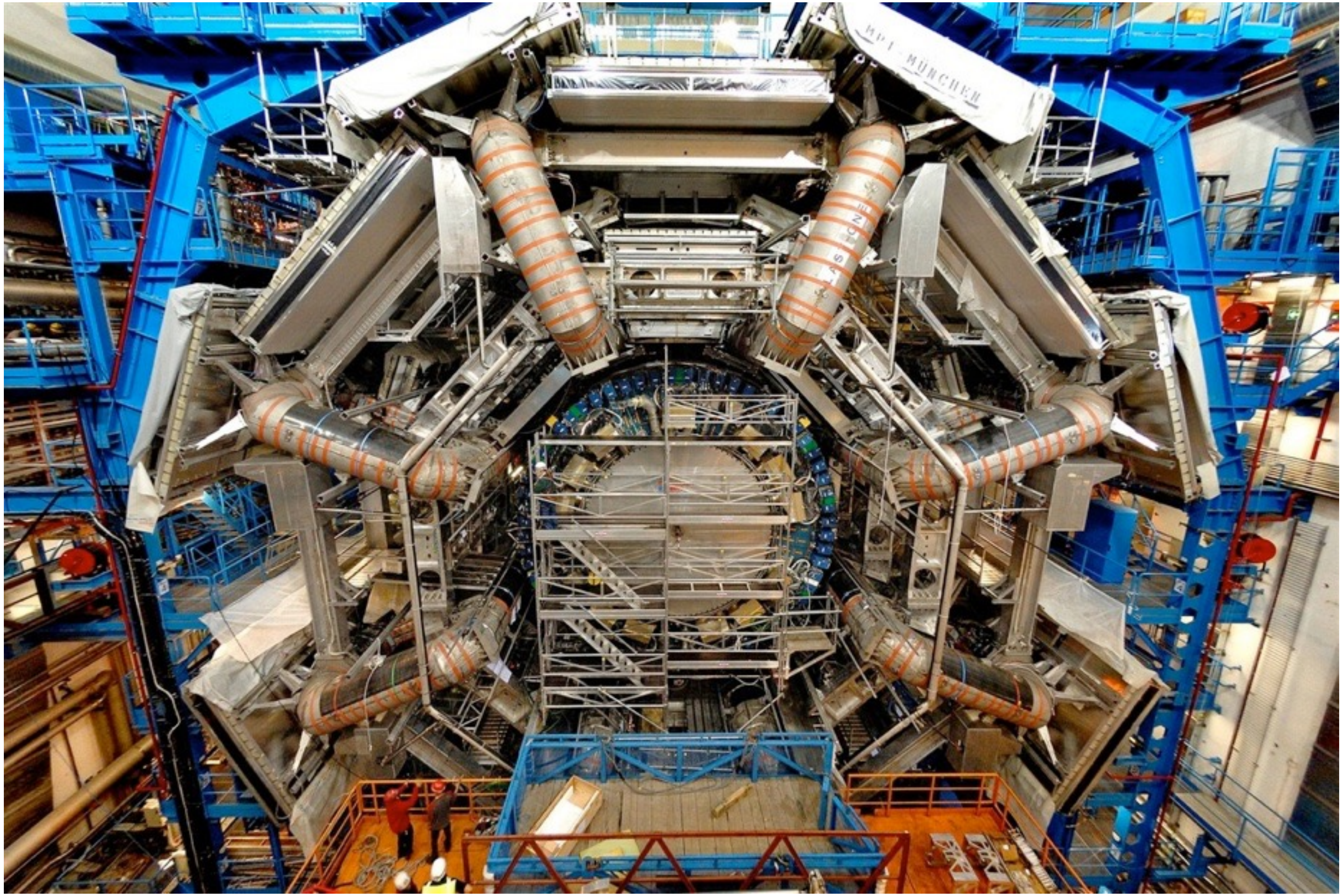
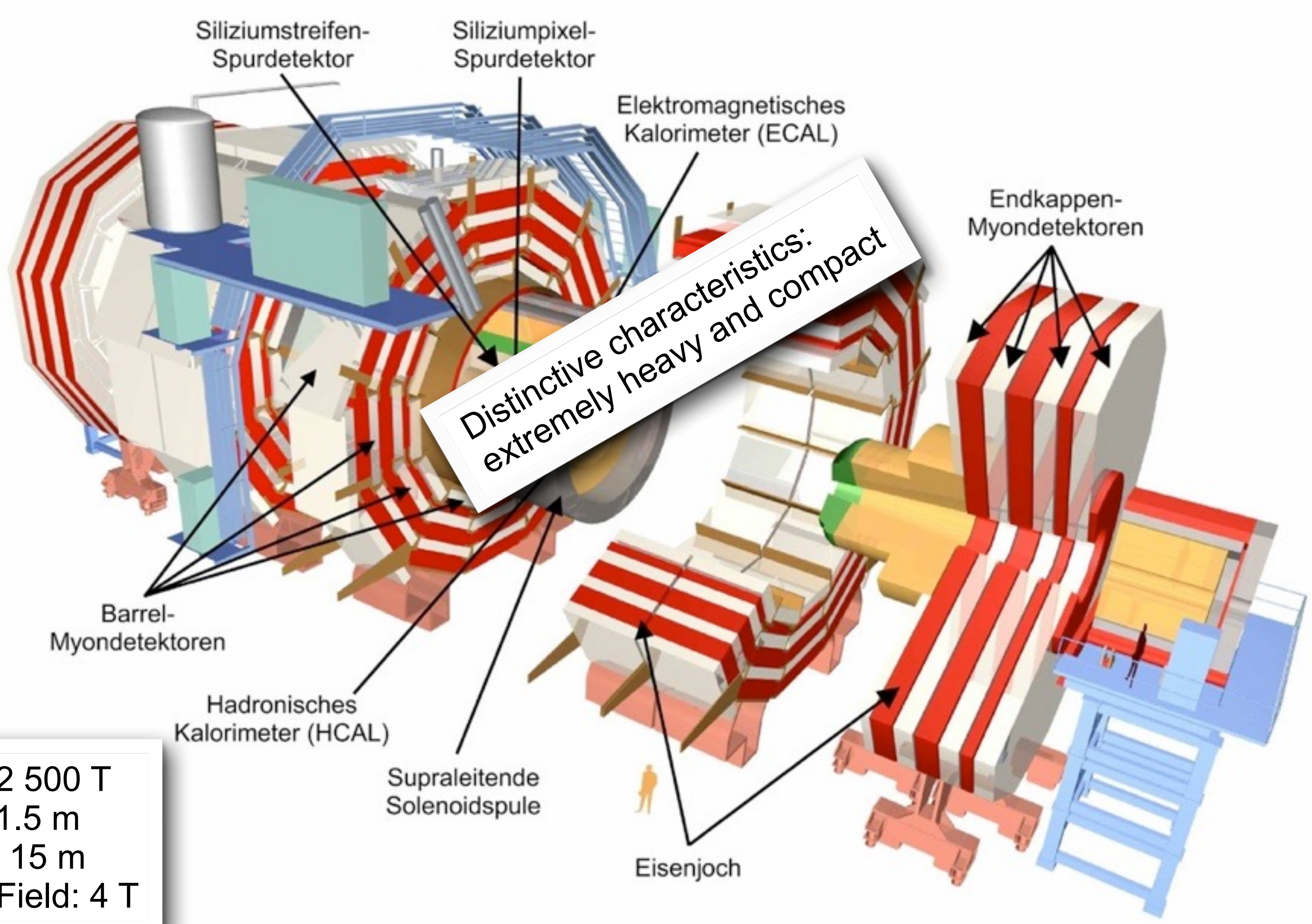


Foto: CERN

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

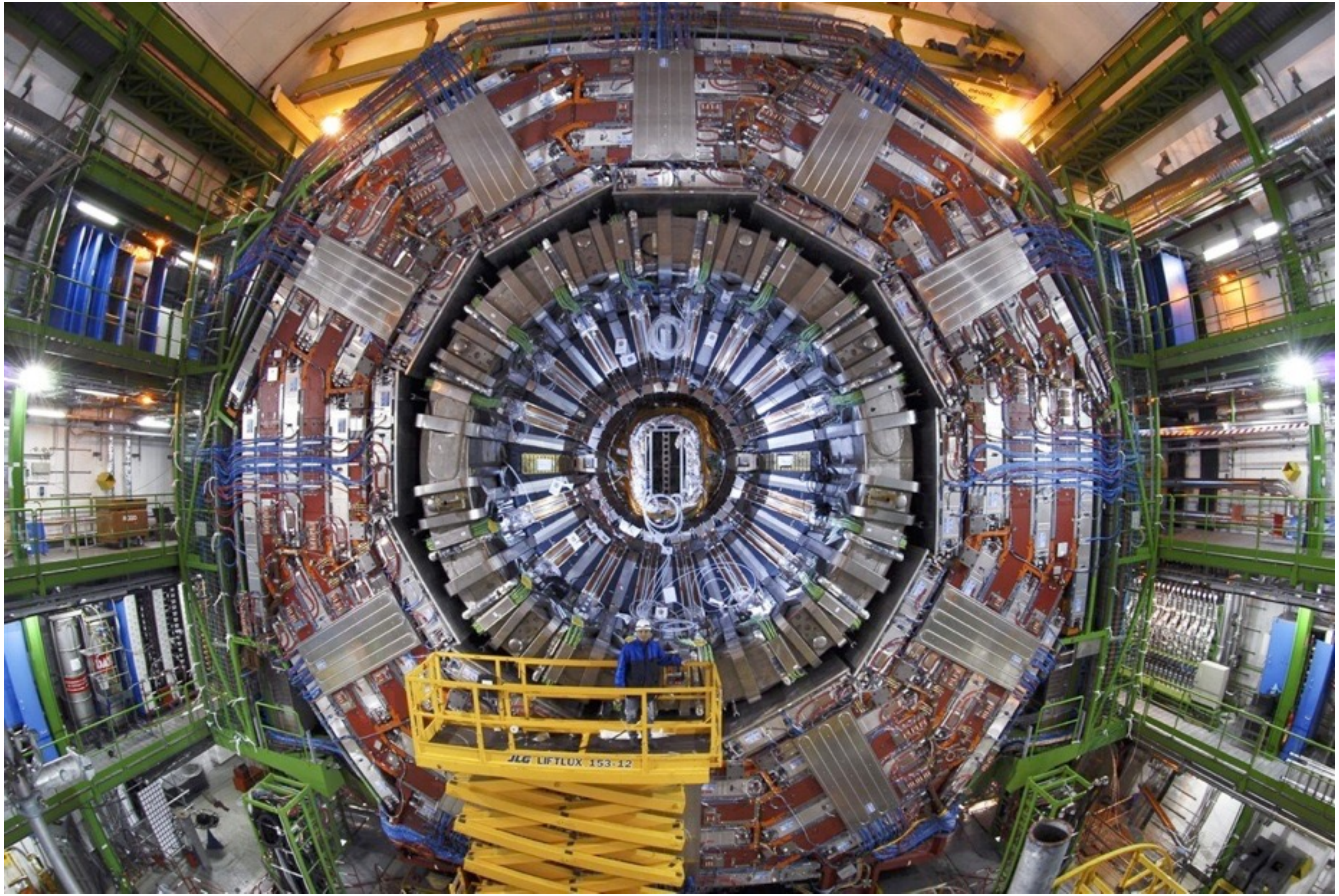
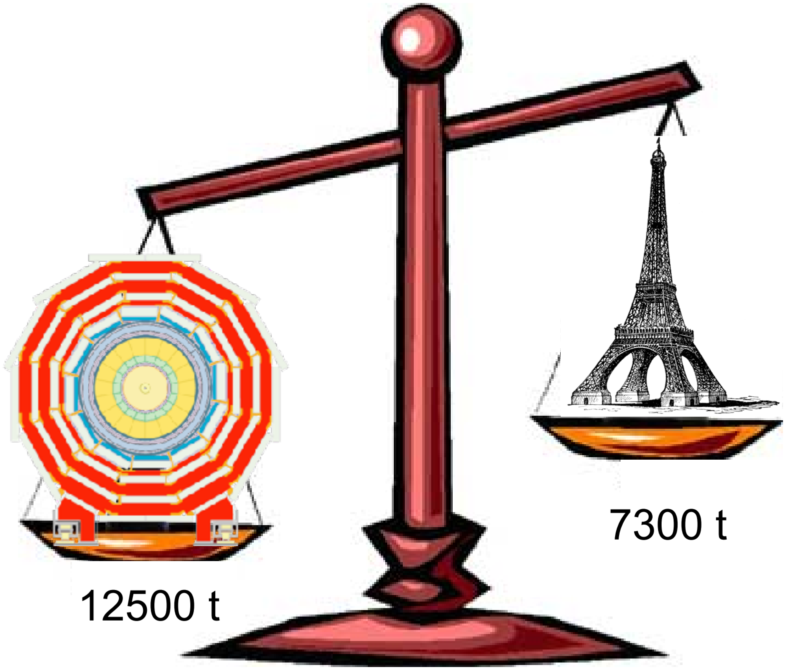


Foto: CERN

SIZE AND WEIGHT

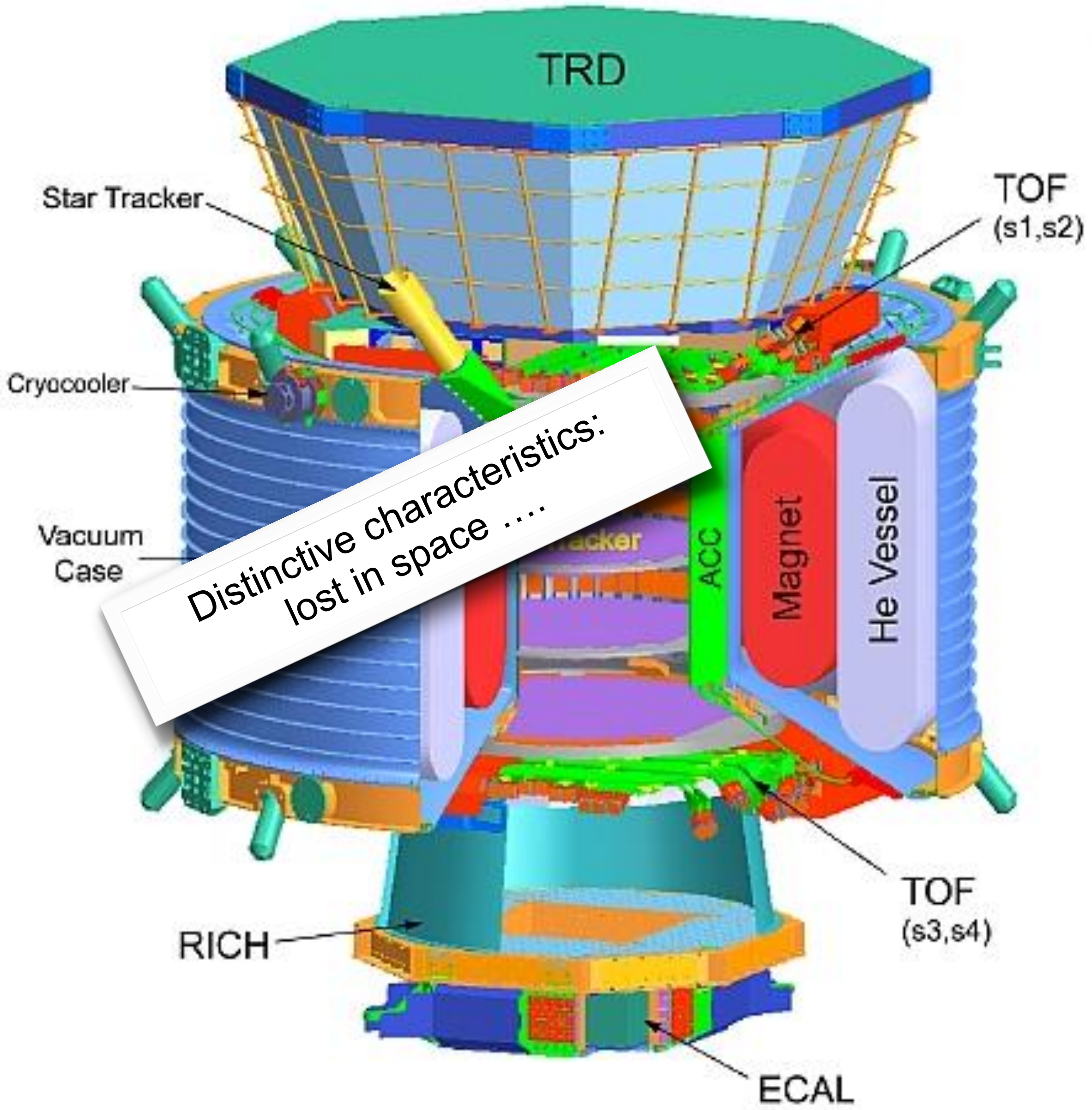
Brandenburger Tor in Berlin



CMS is 65% heavier than the Eiffel tower

AMS@ISS

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



Distinctive characteristics:
lost in space ….

picture: AMS collaboration

ICECUBE EXPERIMENT

Distinctive characteristics: Sharing the space with penguins

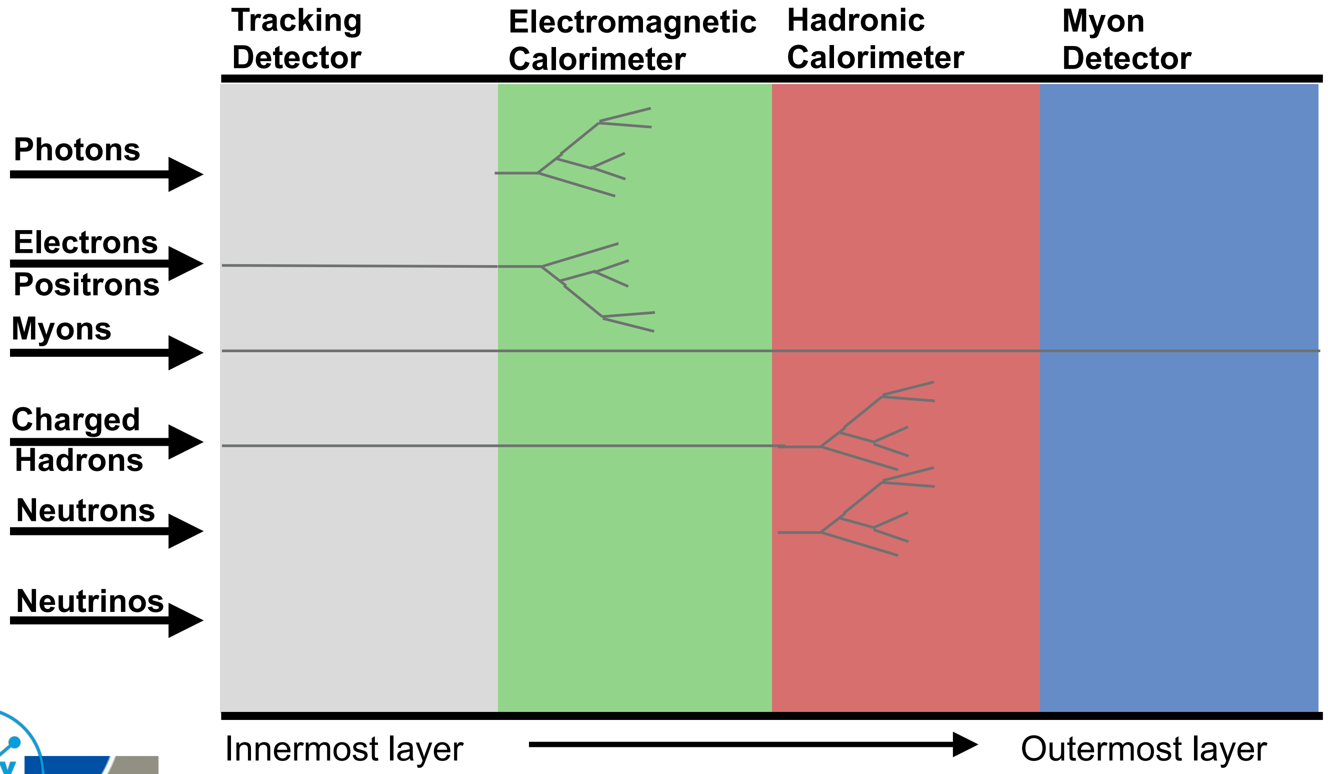
Example: ATLAS at CERN

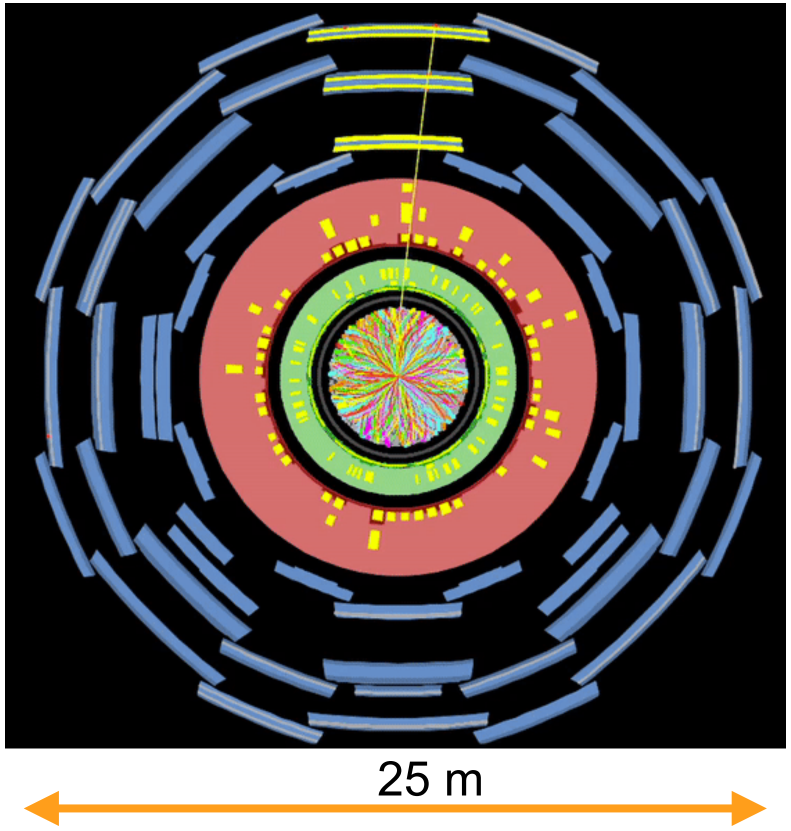
Full movie: ATLAS experiment - Episode 2 - The Particles Strike Back

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

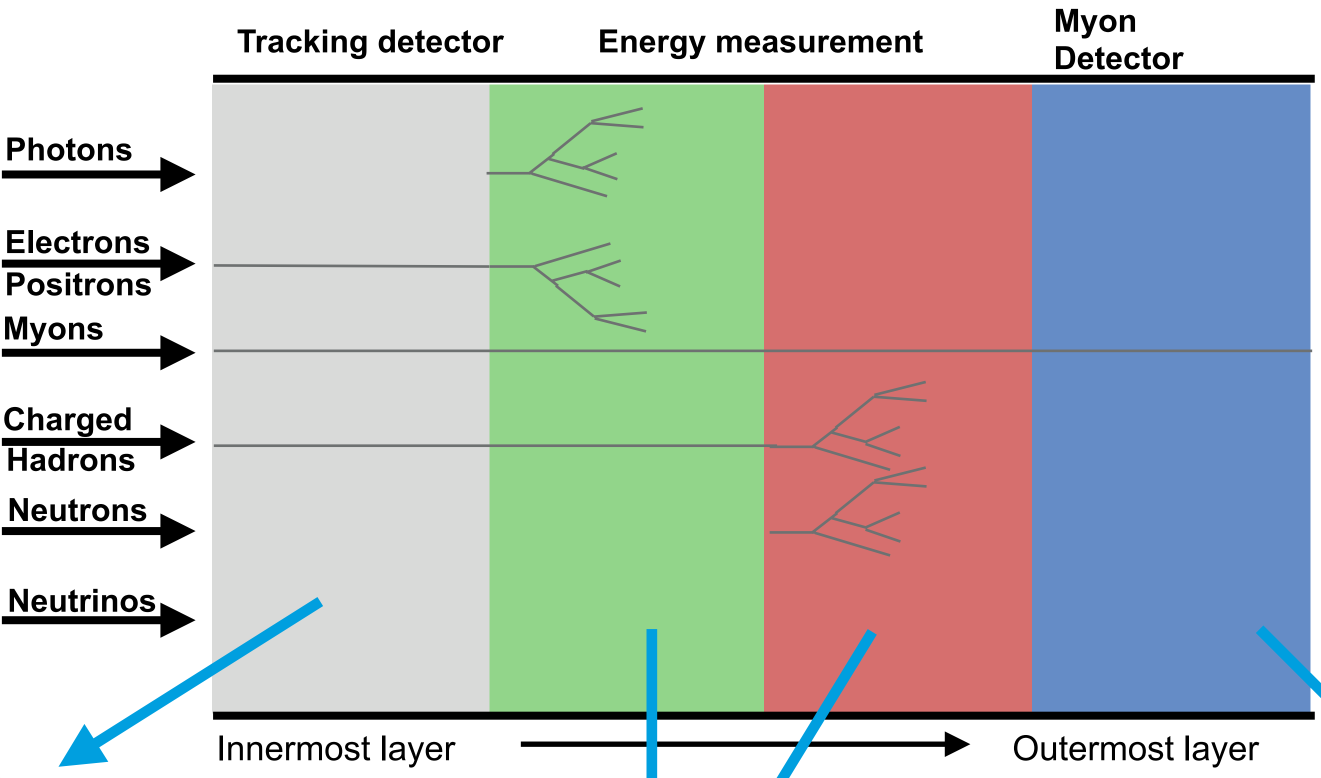
PARTICLE PHYSICS DETECTORS

- 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





PARTICLE PHYSICS DETECTORS



Tracking detectors

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

Calorimeter

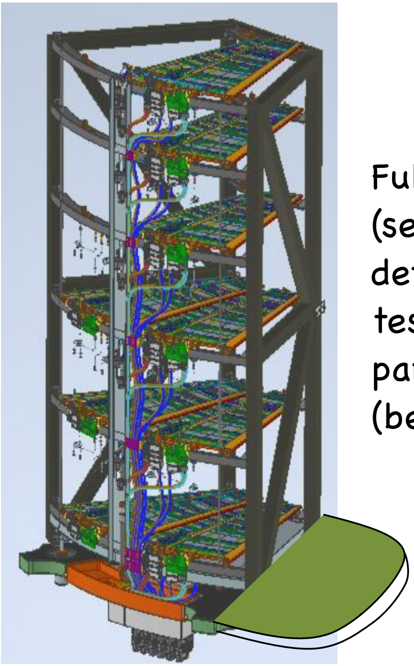
- Electromagnetic cal
- Hadronic cal

- Homogeneous
- Sampling

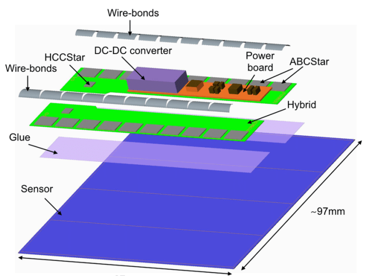
Muon detectors
= outside tracker

- Gas detectors
  - Wire chambers
  - …

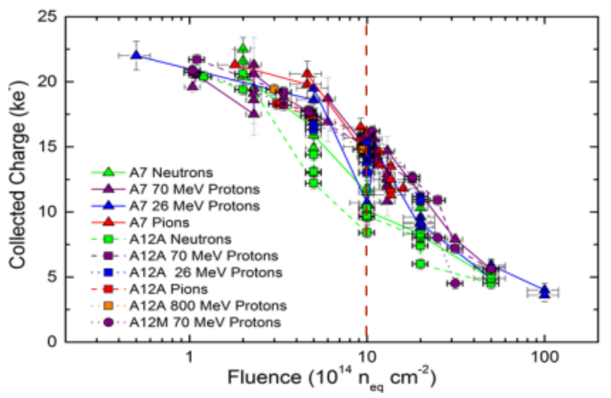
DETECTOR DEVELOPMENT CYCLE



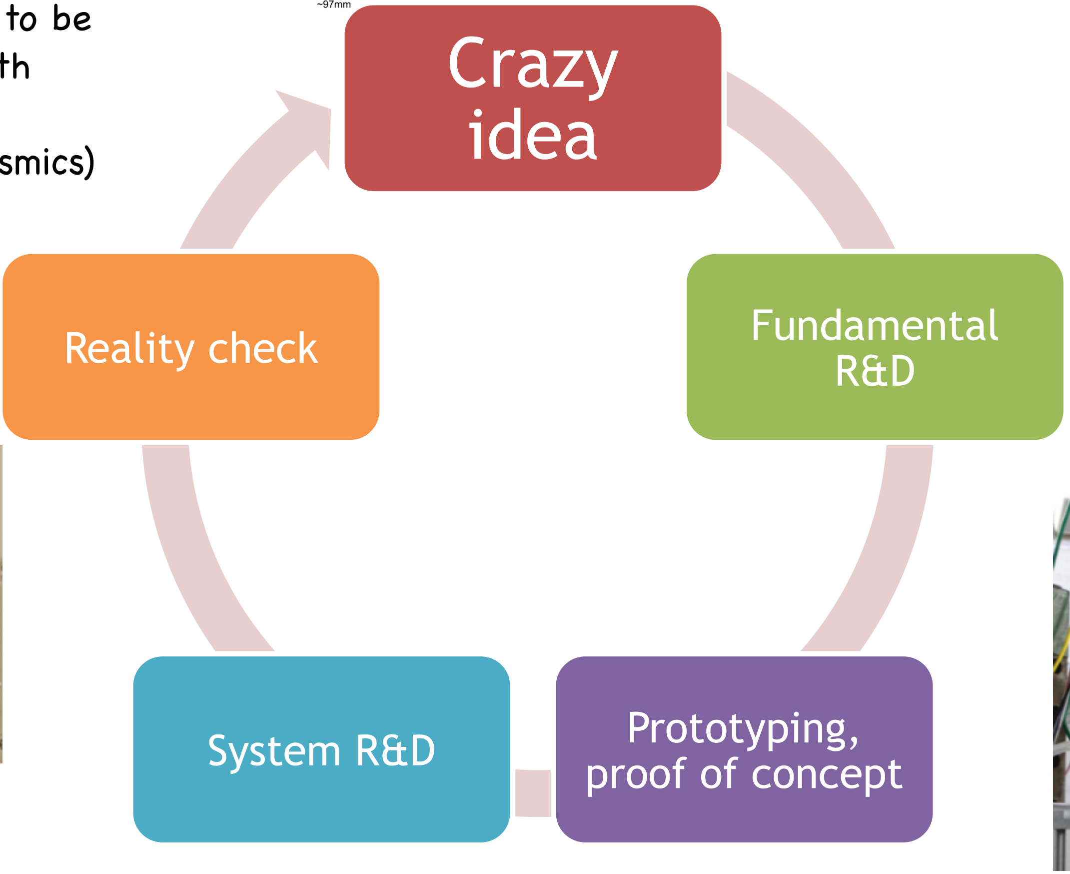
Full system (segment of detector) to be tested with particles (beam, cosmics)



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



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



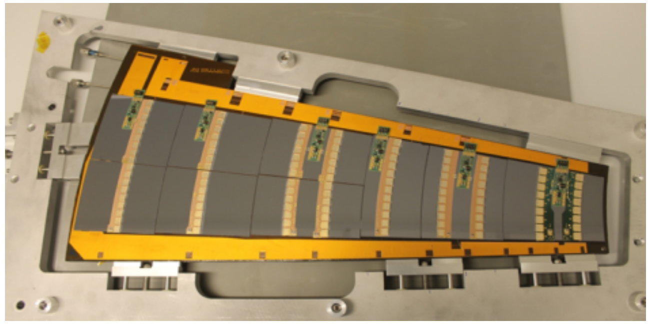
Crazy idea

Fundamental R&D

Prototyping, proof of concept

System R&D

Reality check



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

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

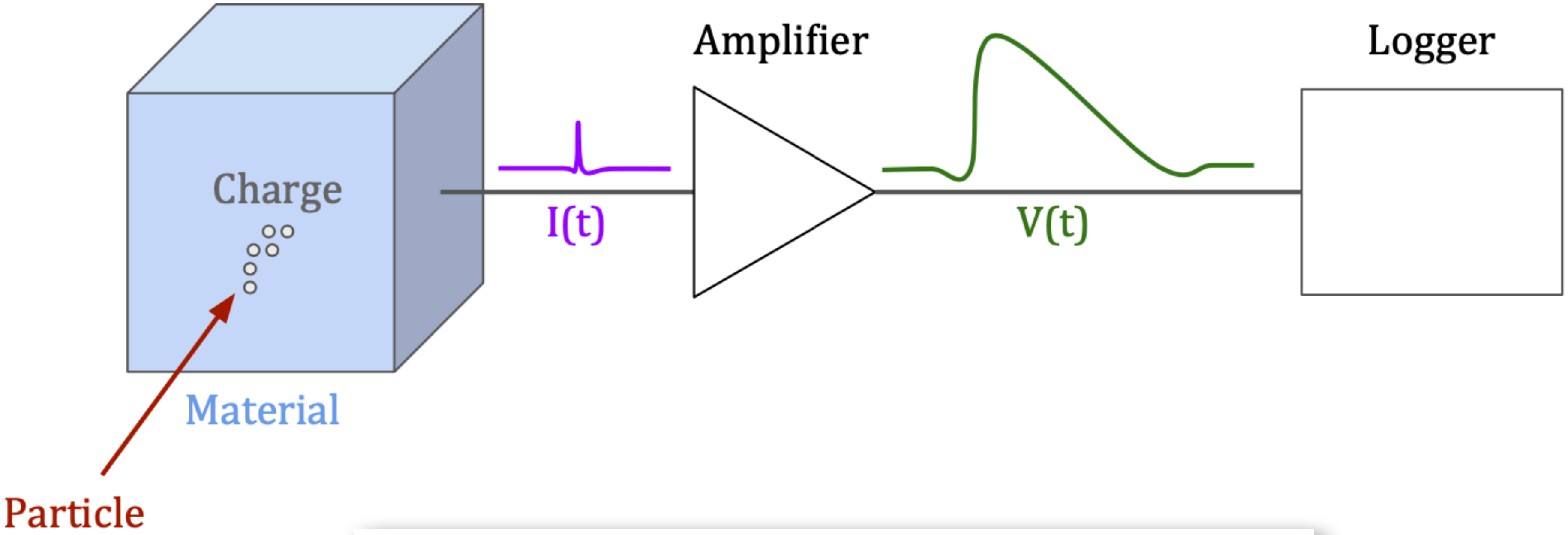
II. THE BASICS OF ALL DETECTION PROCESSES:

INTERACTIONS WITH MATTER

ANALOGY

- Planes leave tracks in sky under certain conditions ….

BASIC DETECTION PRINCIPLE

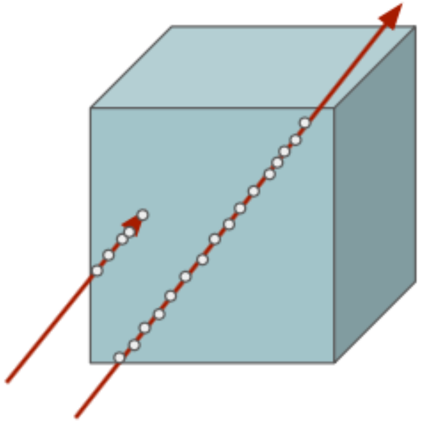


To interpret the result, we need to know **how particles interact with matter**. So that’s where we start.

INTERACTIONS OF CHARGED PARTICLES

CHARGED PARTICLES

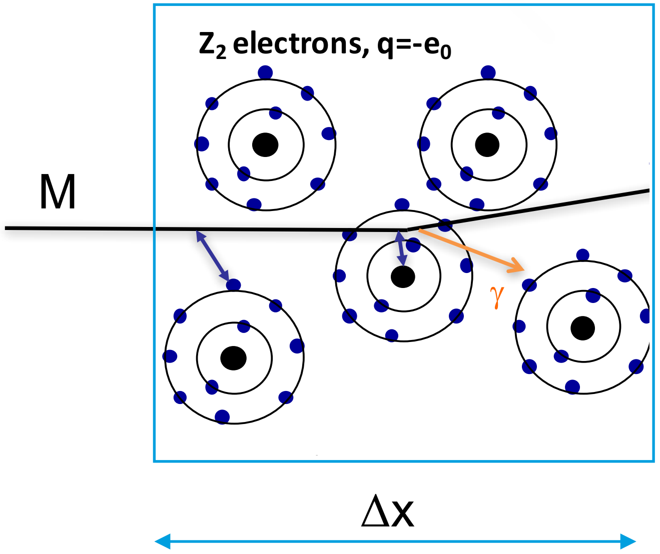
- For charged particles the electromagnetic interaction is dominating
- Charged particles penetrating matter can initiate the following processes:
  - Ionisation of atoms
  - Excitation of atoms
  - Bremsstrahlung (only relevant for electrons and positrons)
  - Cherenkov radiation
  - Transition radiation



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

INTERACTION OF CHARGED PARTICLES

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



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

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

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

Linear stopping power

or

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

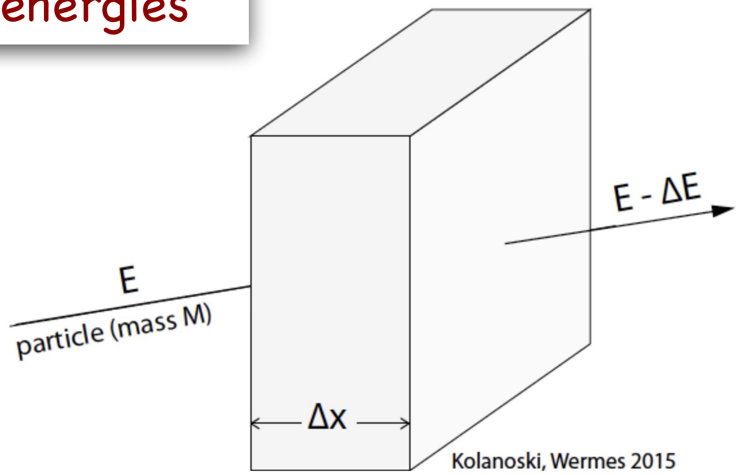
$$\tilde{x} = \rho x$$

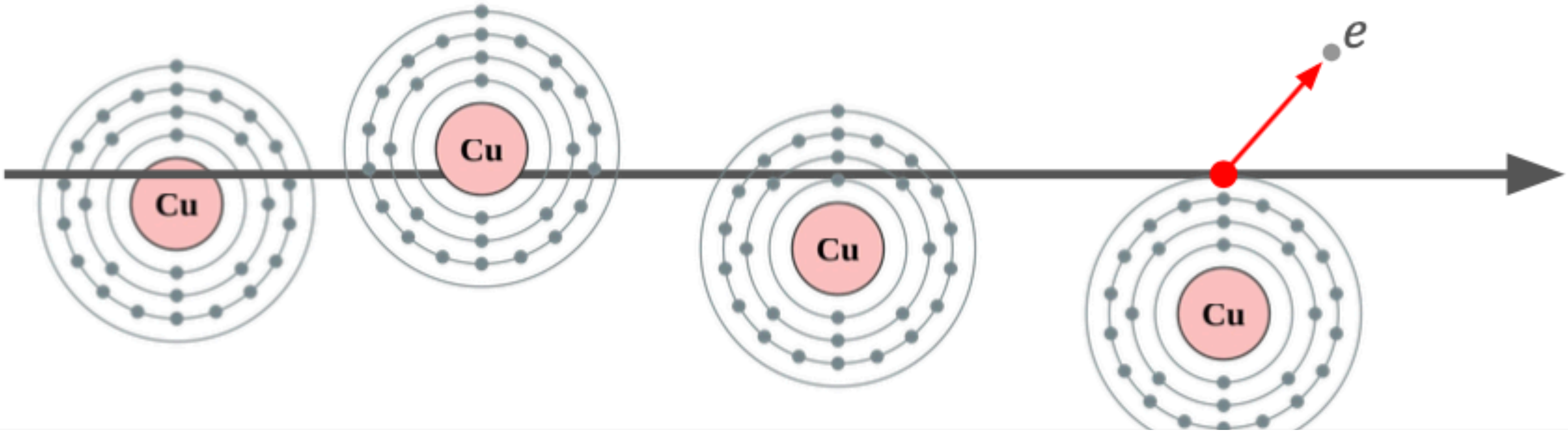
Mass stopping power

IONISATION

The primary contributor to dE/dx at typical energies

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





INTERACTIONS OF “HEAVY” PARTICLES WITH

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

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

◯ 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

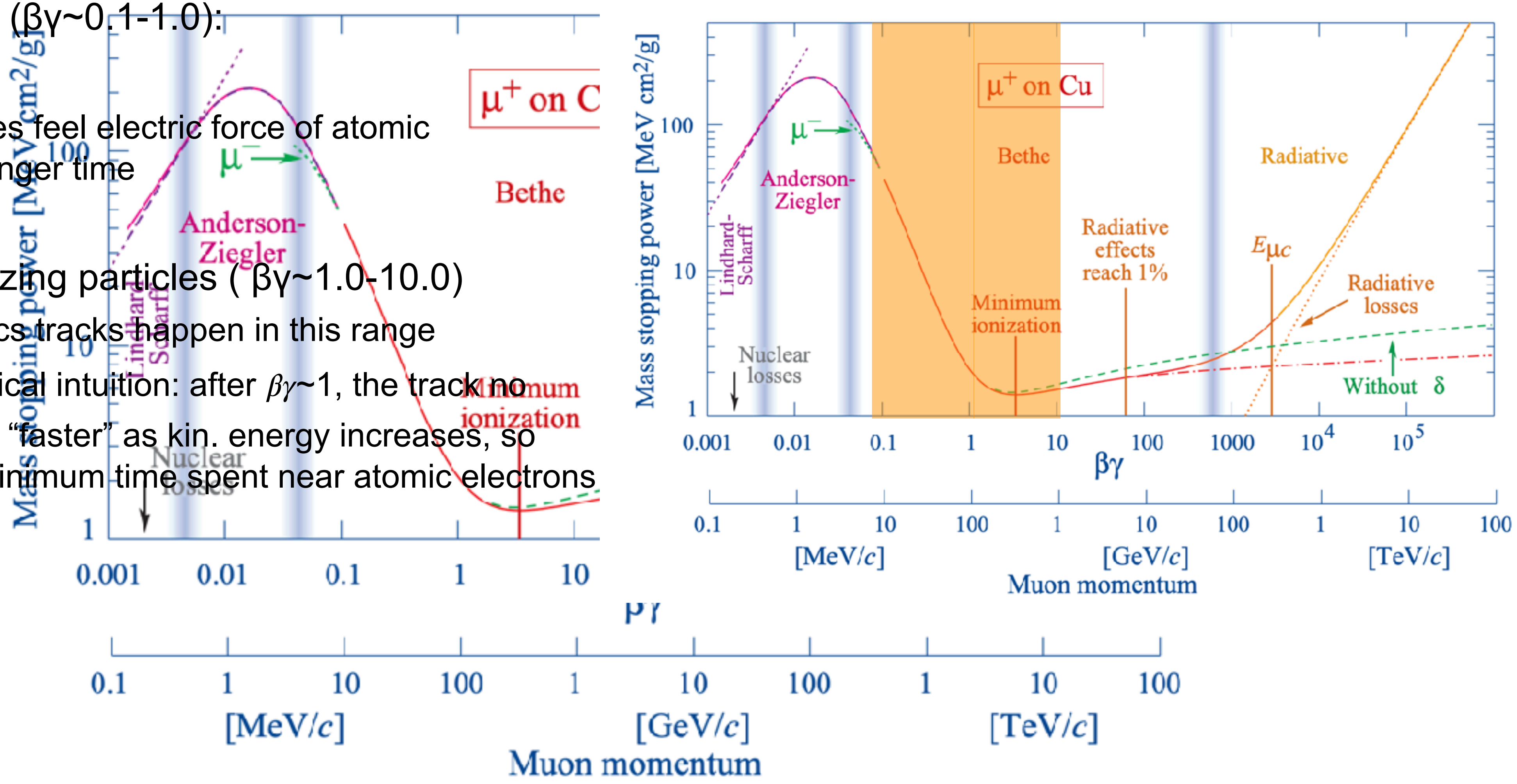
z : charge of incident particle in units of e

β : v/c of the incident particle

γ : $1/\sqrt{1-\beta^2}$

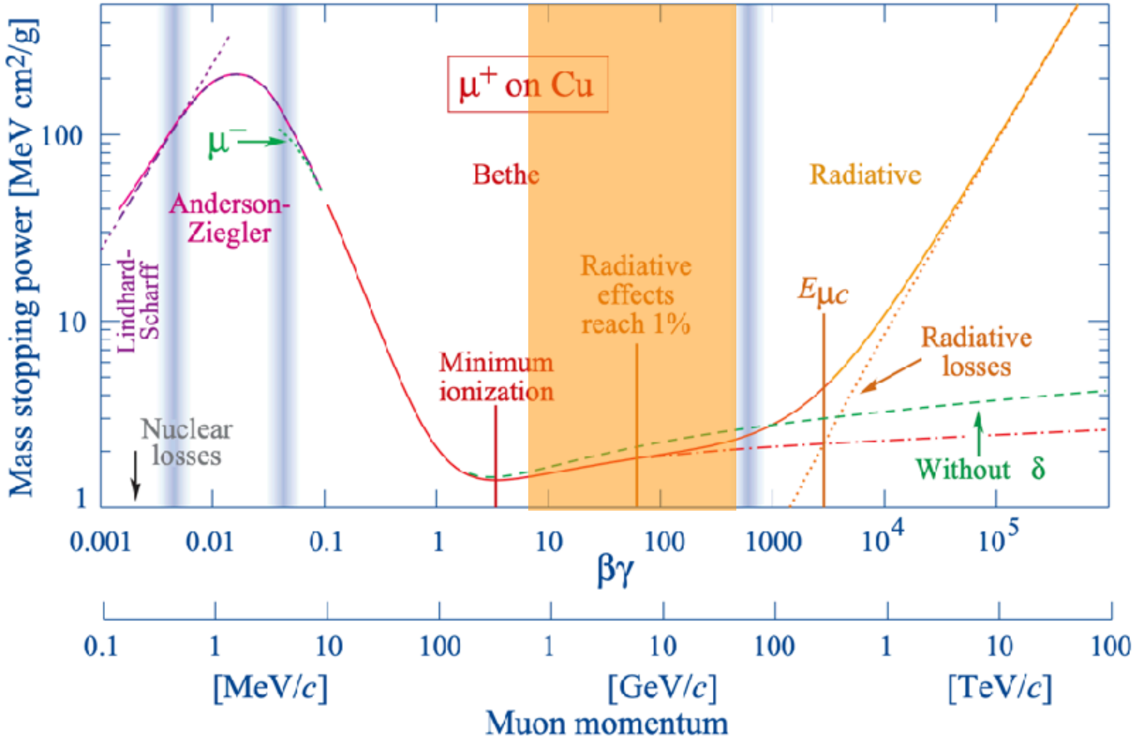
UNDERSTANDING BETHE BLOCH

- 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 kin. energy increases, so there’s a minimum time spent near atomic electrons



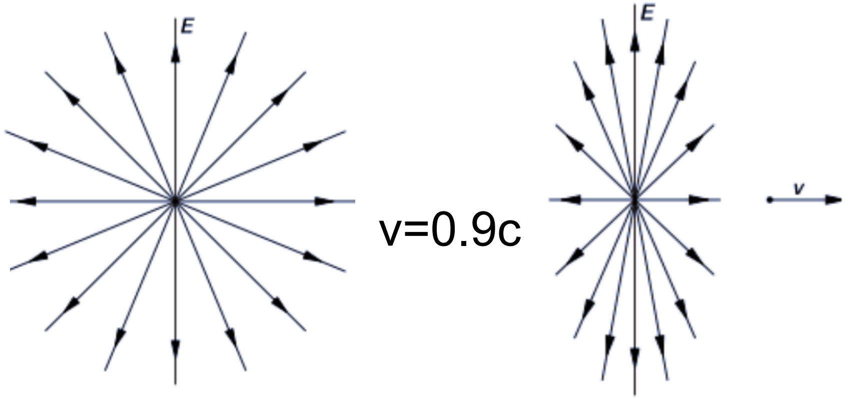
UNDERSTANDING BETHE BLOCH

- Rise after βγ~5:
  - $dE/dx \sim \ln(\beta\gamma)2$
  - due to more energy transfer from rare high-dE collisions
  - logarithmic rise due to lateral extension of electric field due to Lorentz transform $E_y \rightarrow \gamma E_y$

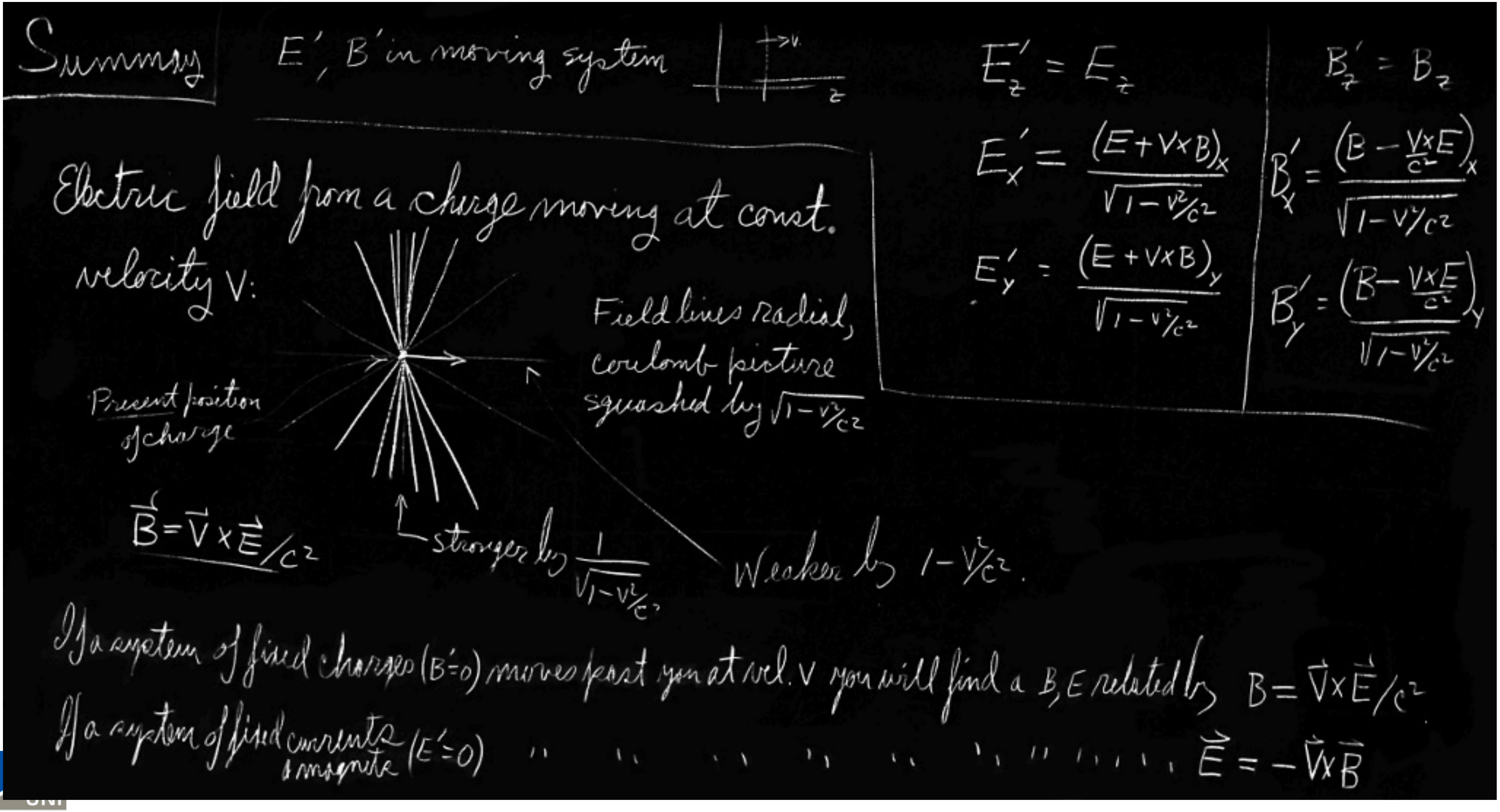


v=0

v=0.9c



FEYNMAN LECTURE



Summary

E′, B′ in moving system

$$E'_z = E_z \qquad B'_z = B_z$$

$$E'_x = \frac{(E + v\times B)_x}{\sqrt{1-v^2/c^2}} \qquad B'_x = \frac{\left(B - \frac{v\times E}{c^2}\right)_x}{\sqrt{1-v^2/c^2}}$$

$$E'_y = \frac{(E + v\times B)_y}{\sqrt{1-v^2/c^2}} \qquad B'_y = \frac{\left(B - \frac{v\times E}{c^2}\right)_y}{\sqrt{1-v^2/c^2}}$$

Electric field from a charge moving at const. velocity v:

Present position of charge

Field lines radial, coulomb picture squashed by $\sqrt{1-v^2/c^2}$

$\vec{B} = \vec{v} \times \vec{E}/c^2$

stronger by $\frac{1}{\sqrt{1-v^2/c^2}}$

Weaker by $1-v^2/c^2$.

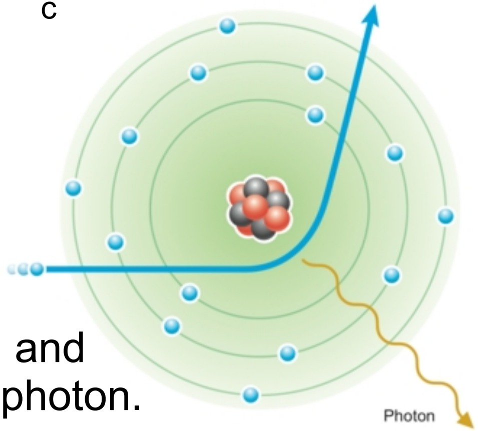
If a system of fixed charges ($B'=0$) moves past you at vel. v you will find a B, E related by $B = \vec{v}\times\vec{E}/c^2$

If a system of fixed currents & magnets ($E'=0$) " " " " " " " " " " " " $\vec{E} = -\vec{v}\times\vec{B}$

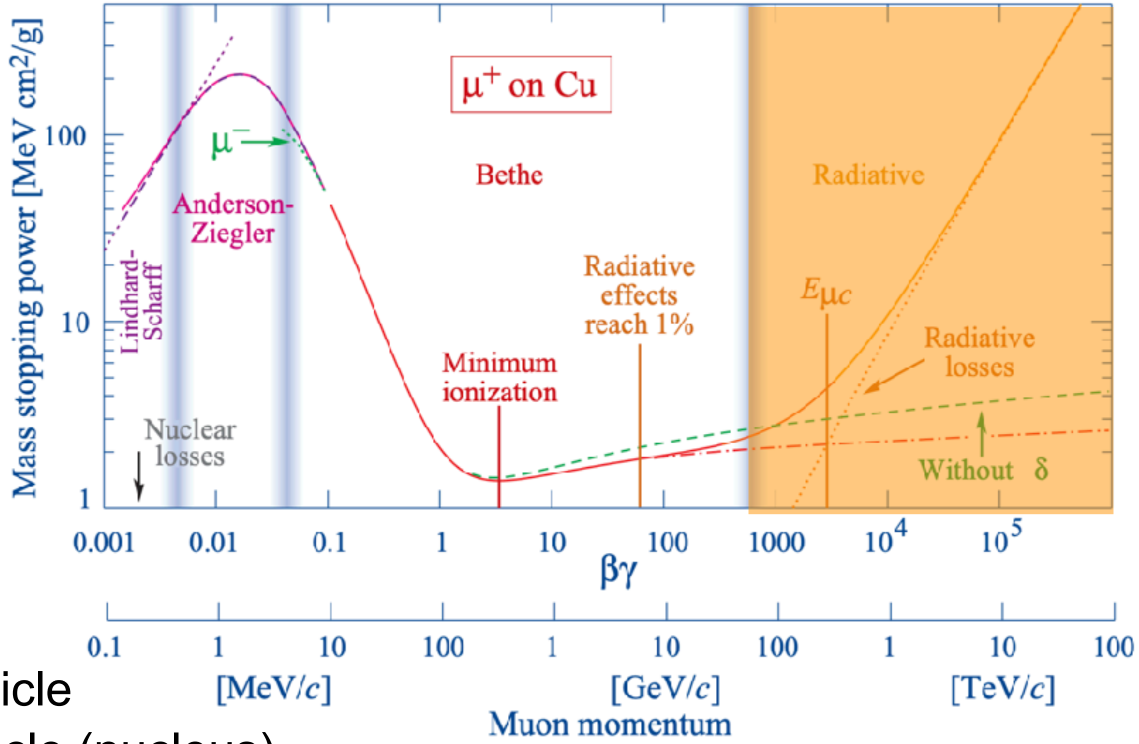
https://www.feynmanlectures.caltech.edu/II_26.html

UNDERSTANDING BETHE BLOCH - LARGE βγ

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



Incident electron and Bremsstrahlung photon.



- Bremsstrahlung: photon emission by an charged particle accelerated in Coulomb field of another charged particle (nucleus)
  - due to conservation of energy (with *hν=dE*)

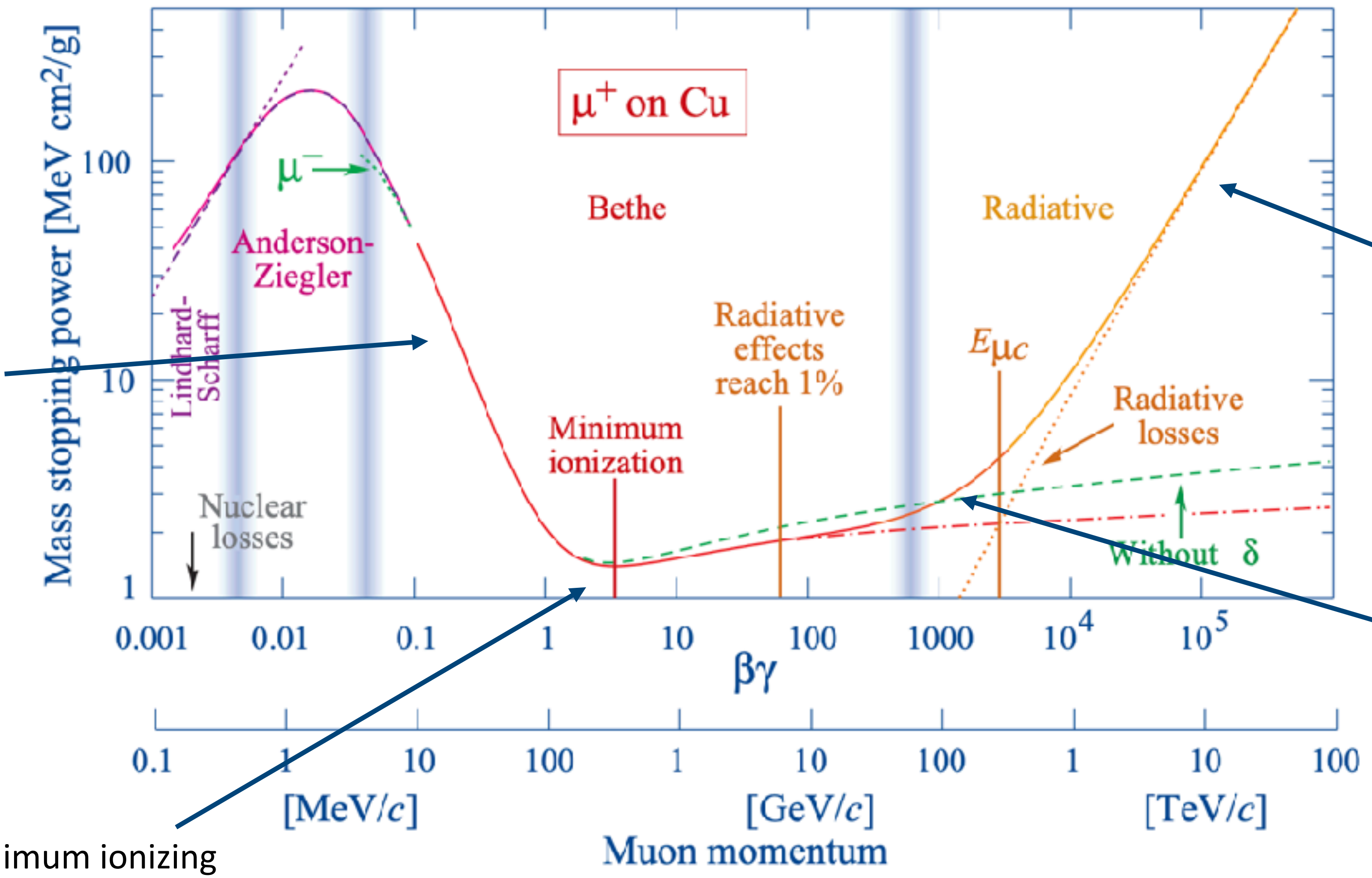
$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \boxed{\frac{Z^2 E}{m^2}}$$

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

Summary Bethe Bloch

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

"kinematic term"



Bremsstrahlung

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

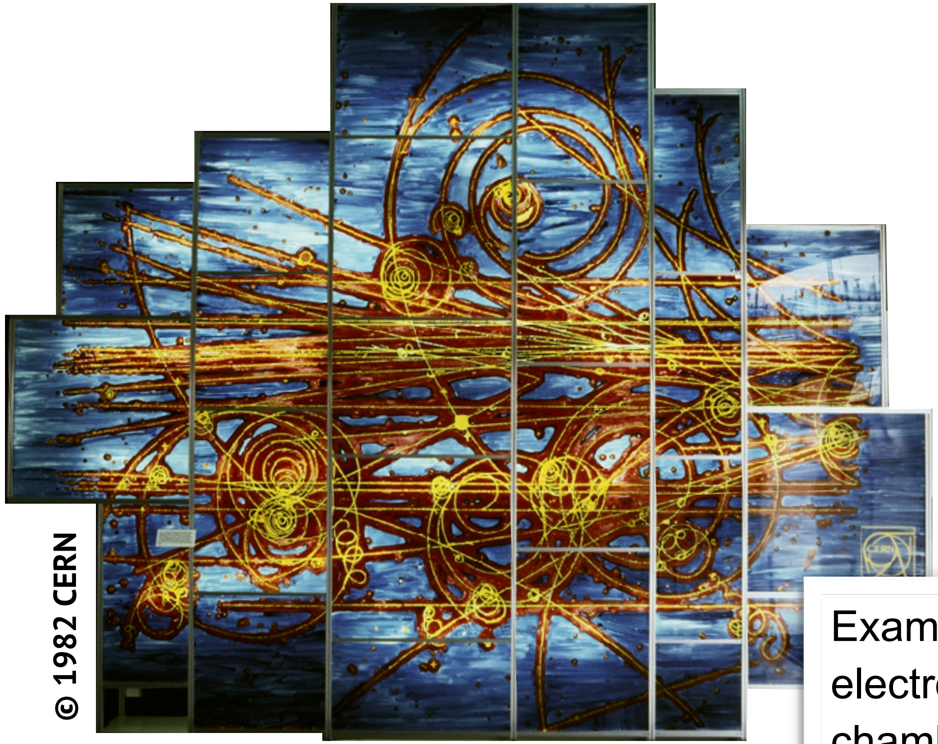
"relativistic rise"

"minimum ionizing particles" βγ ≈ 3-4

Plot: PDG, June 2018

A CLOSER ACCOUNT OF ENERGY LOSS

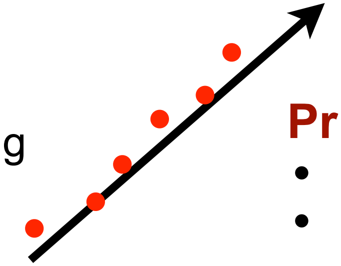
- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



© 1982 CERN

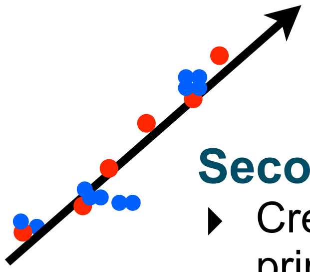
Example of a delta electron in a bubble chamber: visible path

Liquid hydrogen bubble chamber 1960 (~15cm).



Primary ionisation

- Poisson distributed
- Large fluctuations per reaction

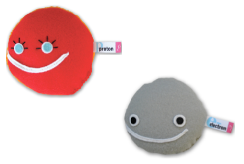


Secondary ionisation

- 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



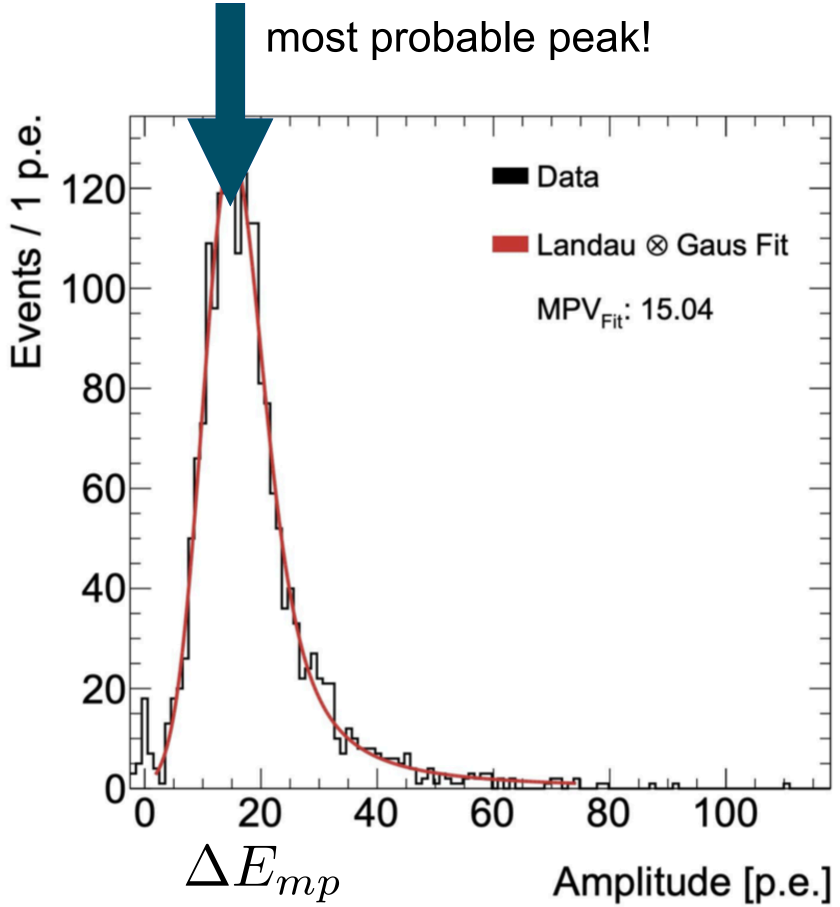
- Bethe Bloch formula describes average energy loss
- Fluctuations about the mean value are significant and non-Gaussian
  - A broad maximum: collisions with little energy loss (more probable)
  - A long tail towards higher energy loss: few collisions with large energy loss T_{max}, δ-electrons.
   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

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

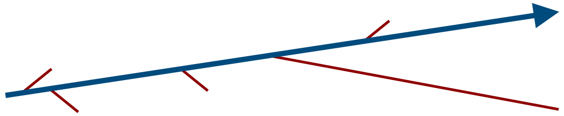
$$\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$$

ξ is a material constant

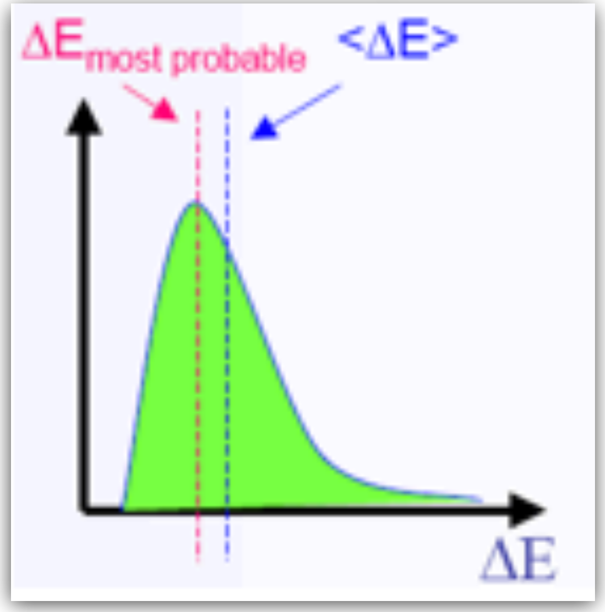

most probable peak!

LANDAU TAILS

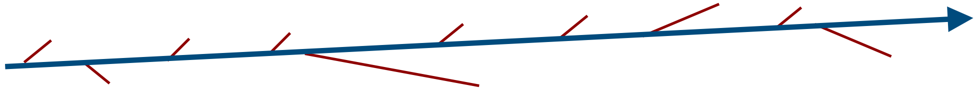
- Real detector measures the energy ΔE deposited in a layer of finite thickness δx
- For thin layers or low density materials
  - few collisions; some with high energy transfer

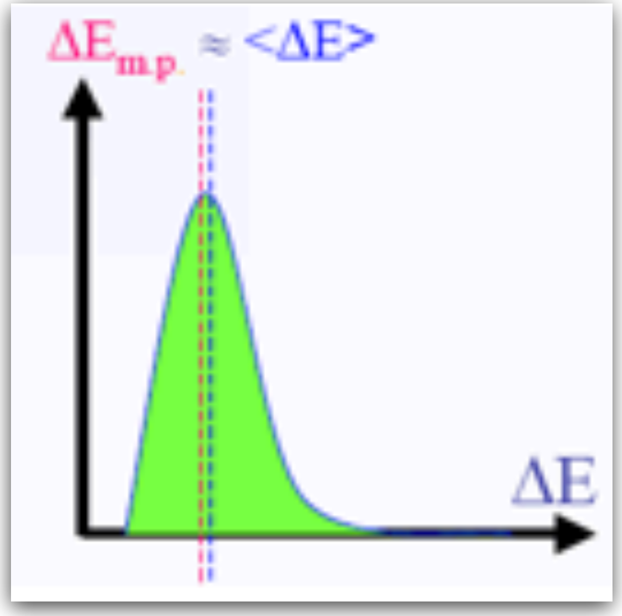


    - Energy loss distributions show large fluctuations towards high losses
    - Long Landau tails



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





RADIATION LENGTH X0

dE/dx for an electron

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

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

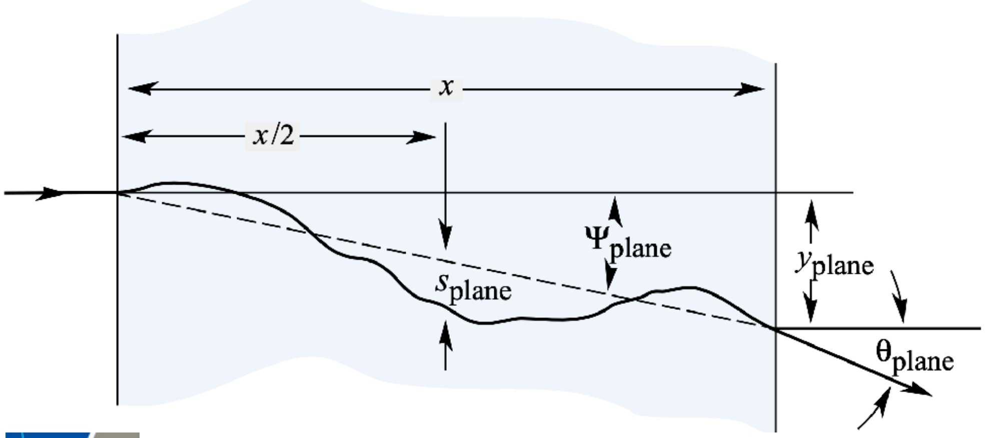
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^{\,2} \ln\frac{183}{Z^{1/3}}}$$

Parameters only depending on material the electron is passing through.

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

- 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

- 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



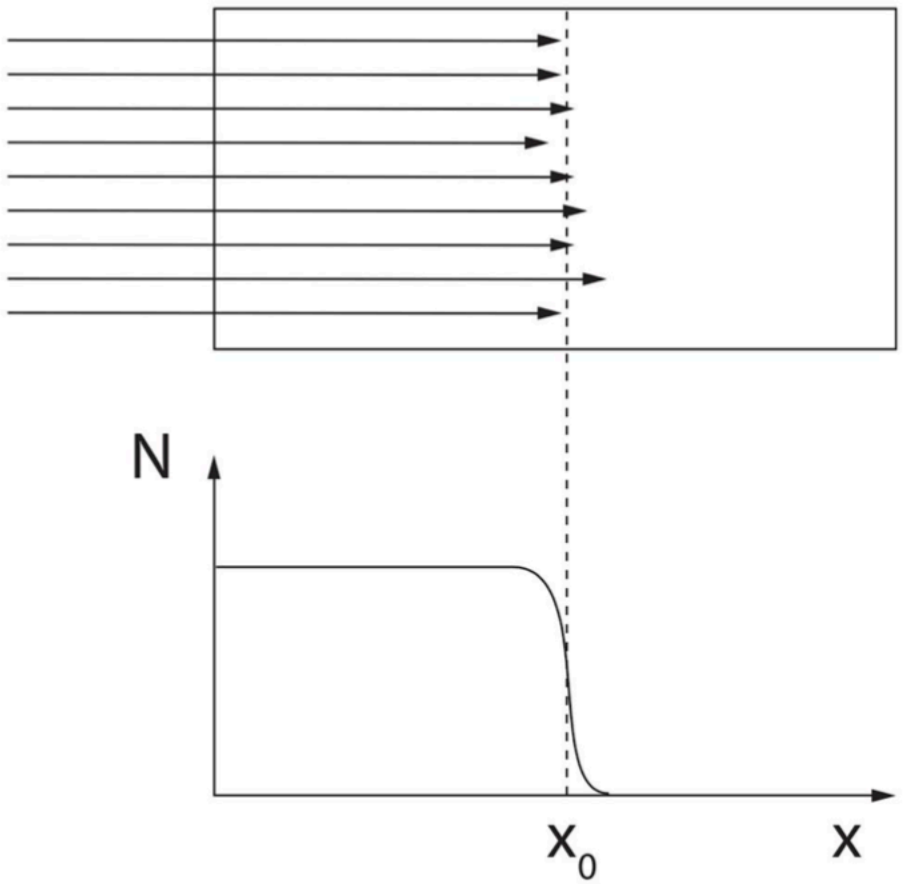
$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}}\theta^{\rm rms}_{\rm space}$$

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

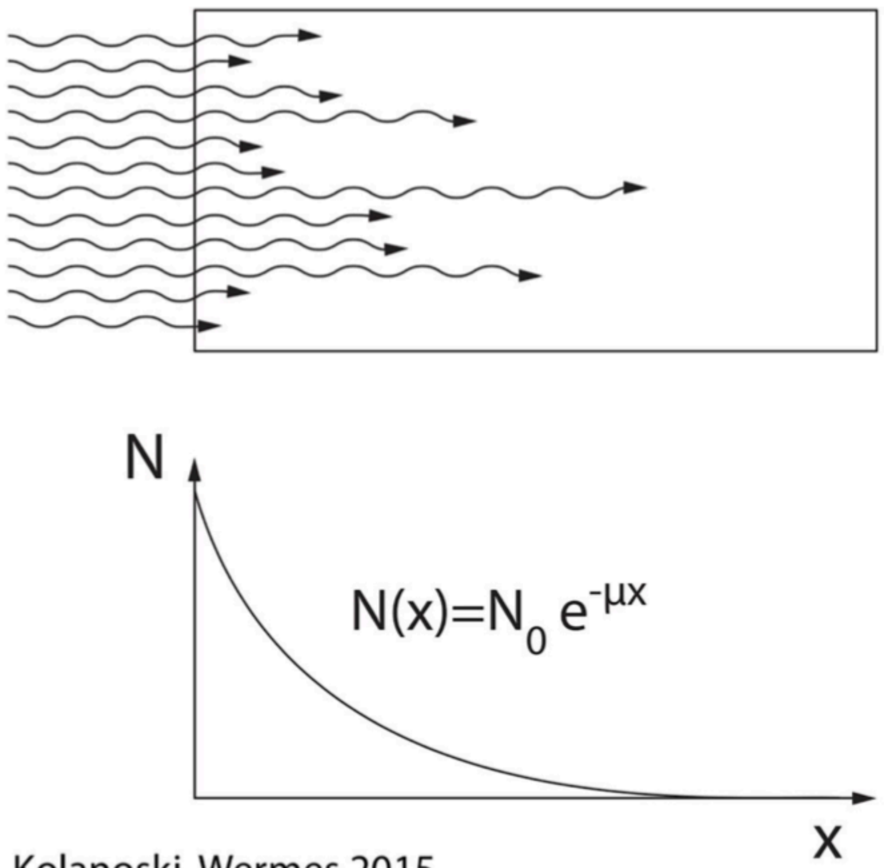
INTERACTIONS OF PHOTONS

Big Difference

Charged particles



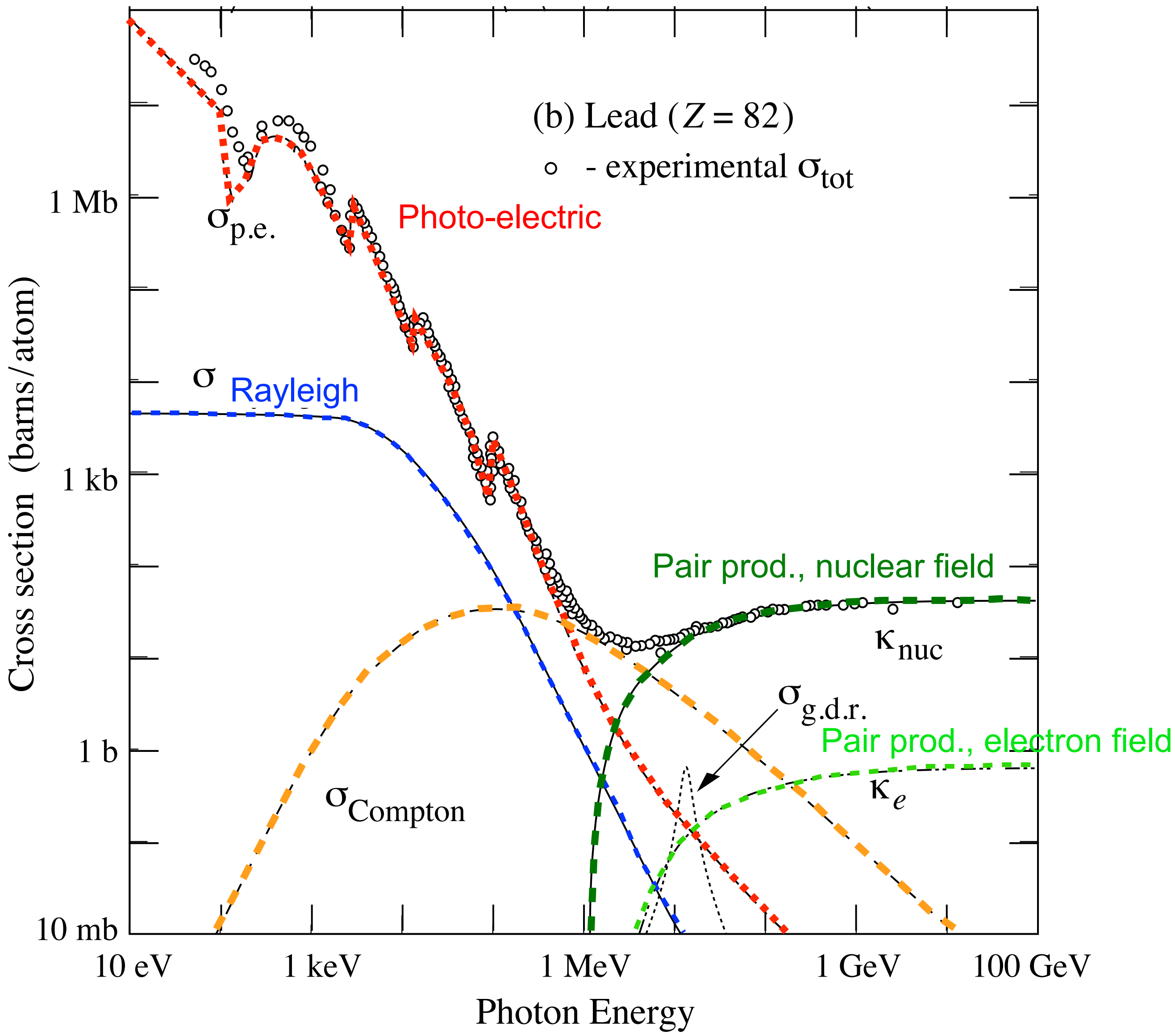
Photons



Kolanoski, Wermes 2015

PHOTONS: INTERACTIONS

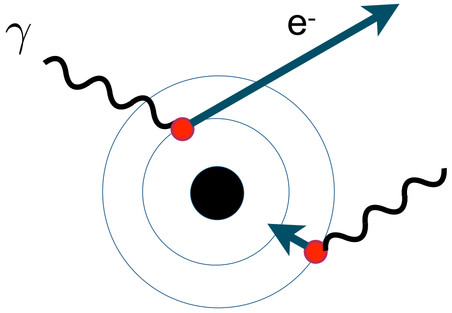
- Photons appear in detector systems
  - as primary photons,
  - created in Bremsstrahlung and de-excitations
- Photons are also used for medical applications, both imaging and radiation treatment.
- Photons interact via **six** mechanisms depending on the photon energy:
  - < few eV: molecular interactions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



PHOTONS: MAIN INTERACTIONS

- Most dominating effects:

Photo-Effect

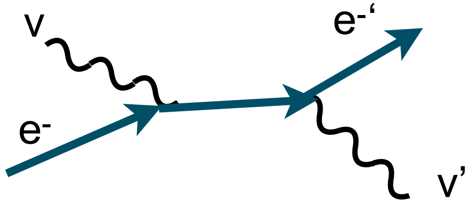


A γ is absorbed and photo-electron is ejected.

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

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

Compton-Scattering

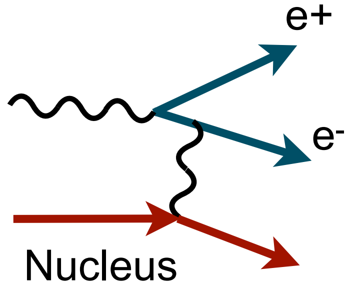


$$\gamma + e \rightarrow \gamma' + e'$$

Elastic scattering of a photon with a free electron

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

Pair creation



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

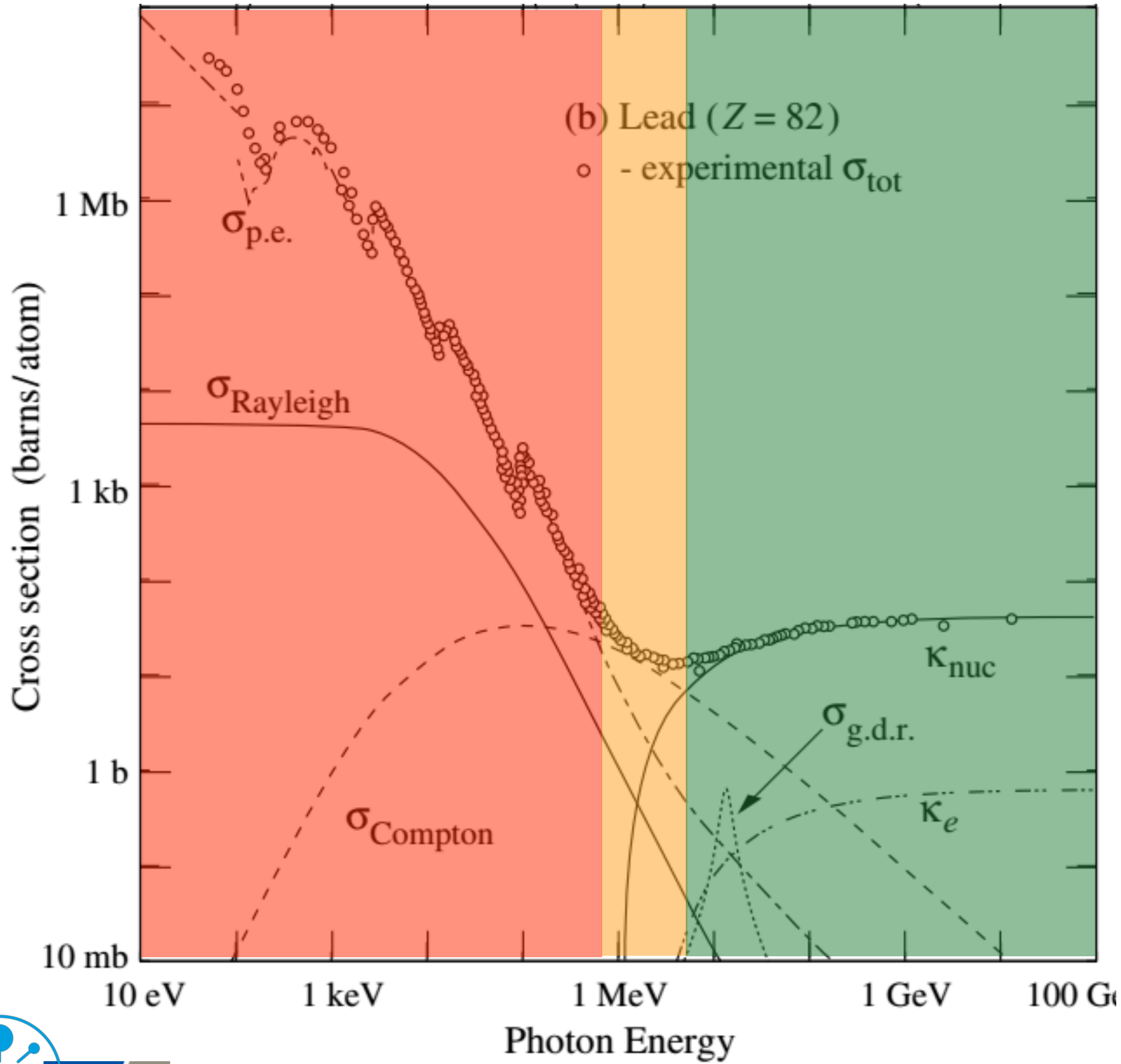
$$E_\gamma \geq 2m_ec^2$$

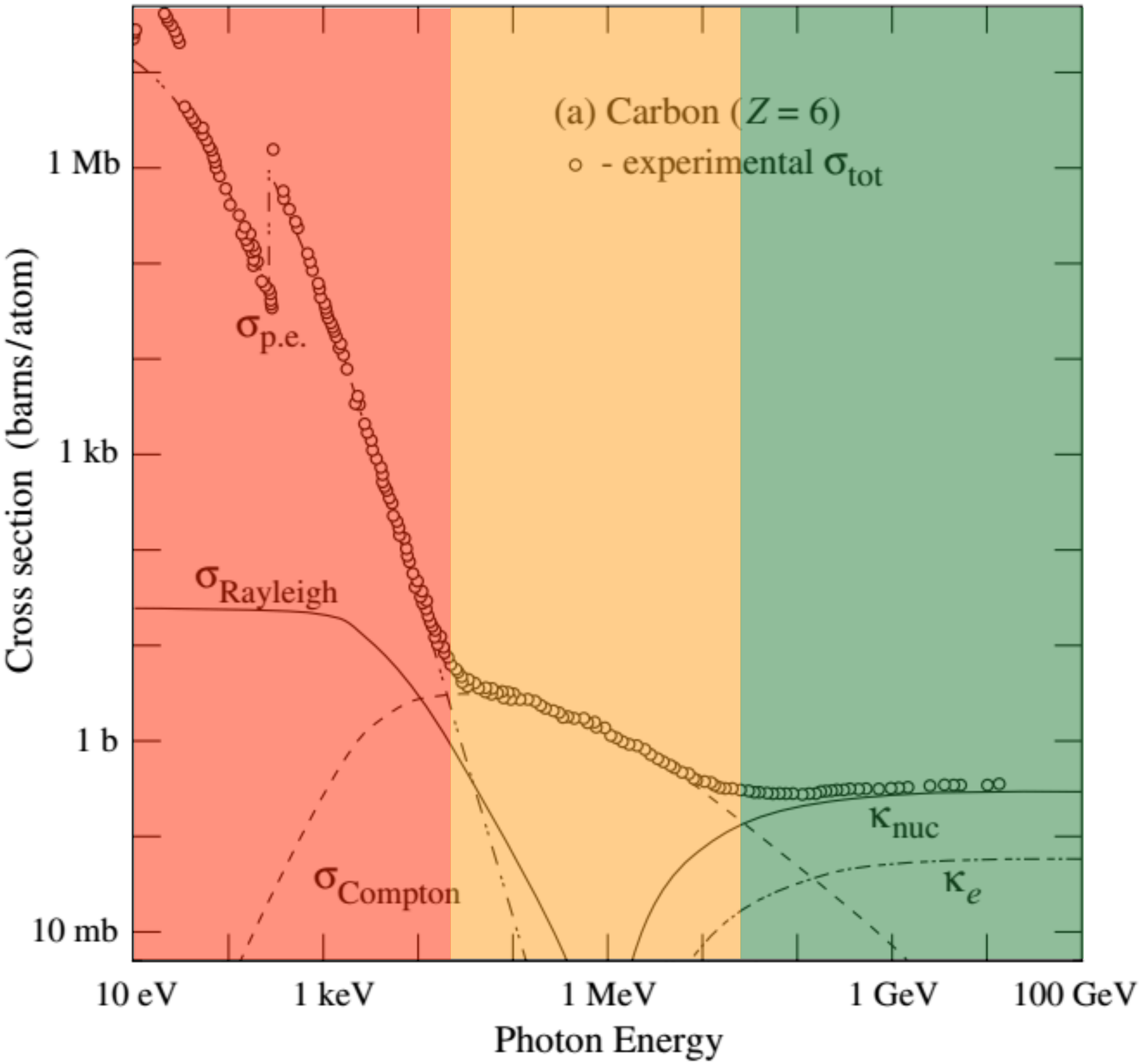
~1.022 MeV

➩ Reduction of photon intensity with passage through matter:

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

PHOTONS: CLEAR DEPENDENCE ON Z OF MATERIAL





A SHORT SUMMARY

$\pi^- + p$

16 GeV

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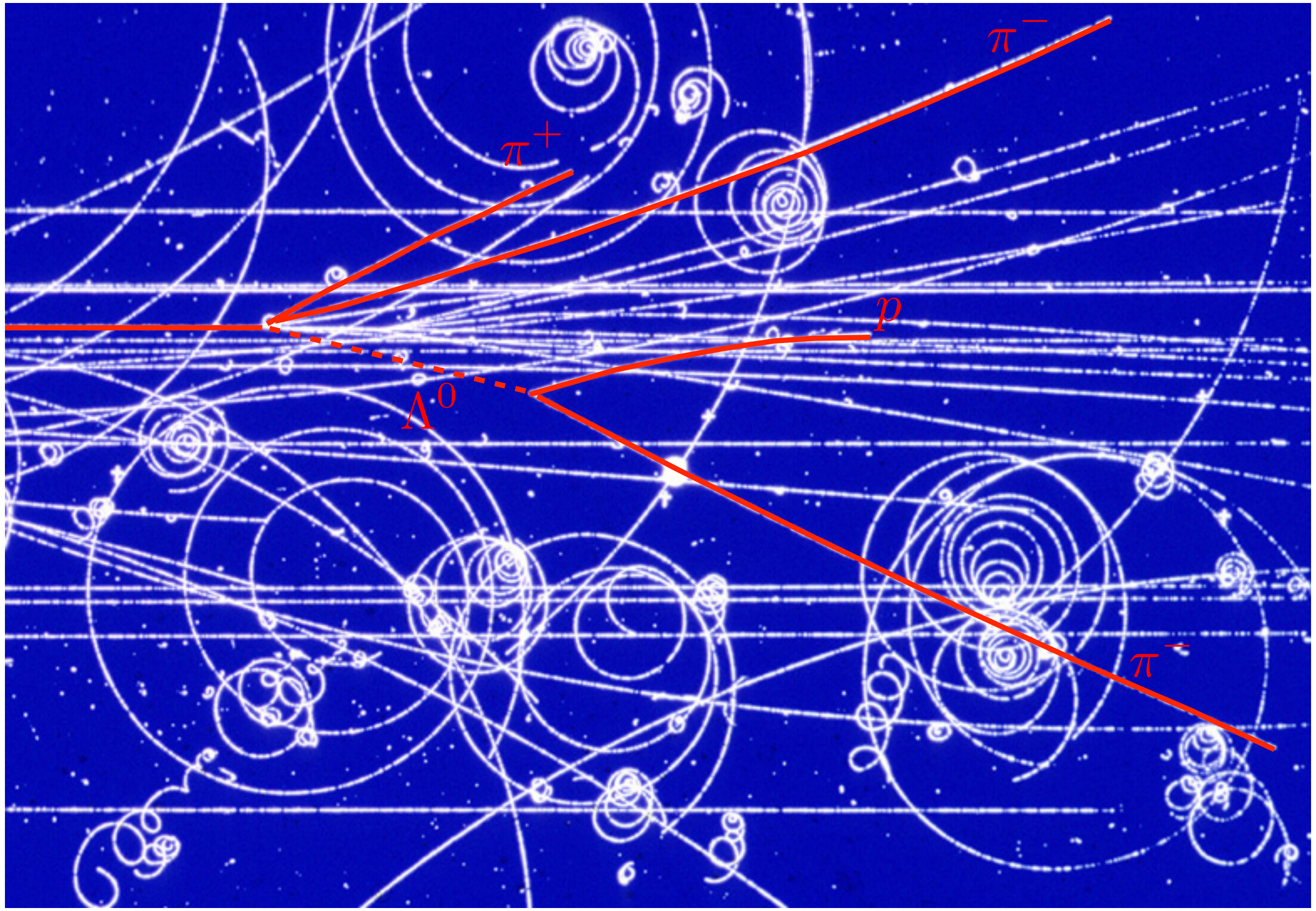

Lifetime of lambda:
2.6 10^{-10} sec
-> a few cm

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

?

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

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….

OVERVIEW

I.	**Detectors for Particle Physics**	*Sunday*
II.	**Interaction with Matter**	
III.	**Tracking Detectors** Gas detectors Semiconductor trackers Muon Detectors	*Monday*
IV.	**Calorimeters**	*Wednesday*
V.	**Examples of what can go wrong**	