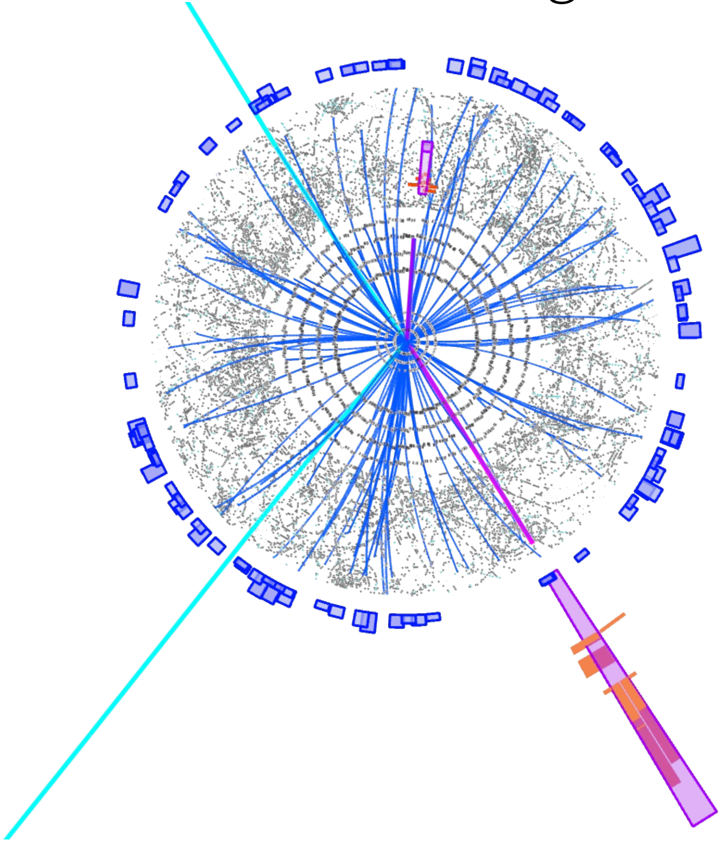
Detector Physics I

Particle Detection in High Energy Physics



Simon Spannagel, DESY

Introduction to the Terascale

17 March 2025

Event-Display:

ATLAS EXPERIMENT http://atlas.ch

Table of Contents

Prologue: Units

- Elementary charge: $e = 1.602\ 176\ 6208 \times 10^{-19}$ C
- Energy unit eV: $1\ \mathrm{eV} = 1.602\ 176\ 6208 \times 10^{-19}$ J (CV)
  Energy of an electron, accelerated through 1V
- Electron mass: $m_e = 9.1 \times 10^{-31}$ kg
  $= 511\ \mathrm{keV} / c^2$
- Factor c^2 often dropped, units defined with $c = 1$ (and $\hbar = 1$):
  MeV, GeV, TeV…
  for energy, momentum, (rest-) mass
- Scientific notation: Mantissa plus exponent to Base 10: $a \times 10^b$

What do we measure?

Determination of particle properties

Which particles can we measure?

- Particles have to be long-lived enough to reach the detectors…
  - Many elementary particles have very short life time (Higgs, W, Z…)
  - Measuring their decay products

$$d = c\tau\gamma, \quad \gamma = \frac{1}{\sqrt{(1-\beta^2)}}, \quad \beta = \frac{v}{c}$$

- Particles have to interact with detector material!
  - Not every particle participates in every force
  - Possibilities of detection depends strongly on forces
- Elementary particles: $e^{\pm}$, $\mu^{\pm}$, ν^{e}, $\bar{\nu}^{e}$, ν^{μ}, $\bar{\nu}^{\mu}$, ν^{τ}, $\bar{\nu}^{\tau}$, γ
- Baryons: $p^{\pm}$, n, $\Sigma^{\pm}$, Ξ_0, Ξ^-, Ω^-
- Mesons: $\pi^{\pm}$, $K^{\pm}$, K_0 (K_0^S, K_0^L)

$$\tau_n \approx 15\,min$$
$$\tau_\mu \approx 2\cdot 10^{-6}\,s$$

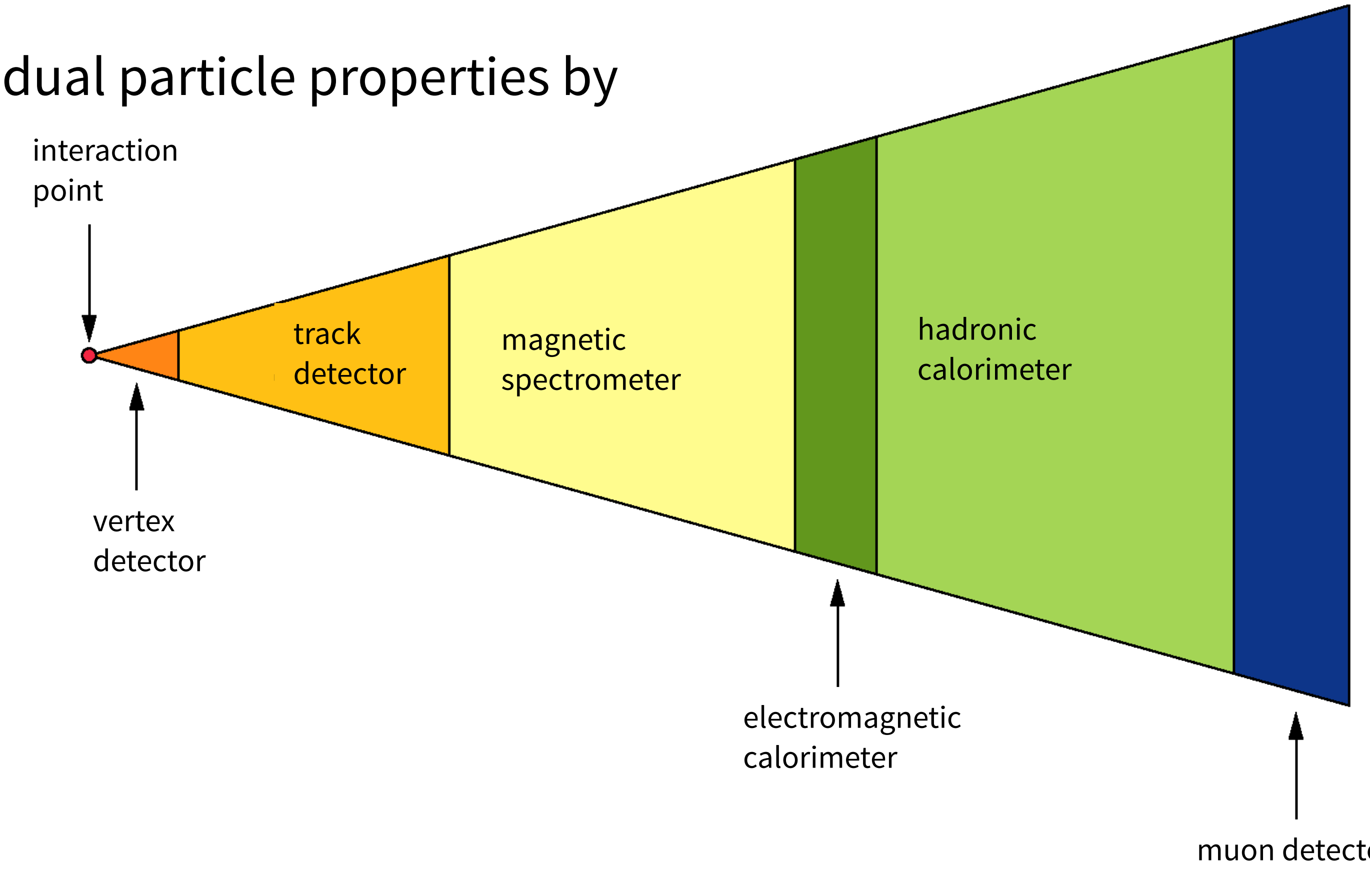
Observables

- Momentum **p** — Bending radius of track in magnetic field
- Velocity **v** — Time of flight, RICH, etc.
- Charge **Q** — Bending radius in magnetic field
- Lifetime **τ** — Measurement of decay length
- Energy **E** — Absorption in calorimeters
- Rest mass **m** — Indirect measurement e.g. from momentum and energy or velocity

$$E^2 = m^2 c^4 + p^2 c^2 \qquad p = \gamma m v = \frac{m v}{\sqrt{(1 - v^2/c^2)}}$$

Typical Design of an Experiment

- Combination of complementary detection methods
- Measurement of individual particle properties by separate detectors
- Order is important! Some measurements are “destructive“
- Design of many experiments is very similar



Detector Terminology

- **Dead time:**
  Time period immediately after the detection of a particle during which the detector is not yet ready again to detect another particle.
  - *Non-paralyzable detector: newly occurring event does nothing*
  - *Paralyzable detector: newly occurring event extends dead time*
- **Resolution:**
  Achievable uncertainty on the observable
- **Efficiency:**
  Number of recorded/detected events divided by number of events that occurred

Interaction of Radiation with Matter

Energy loss and interaction processes

Interaction with Matter

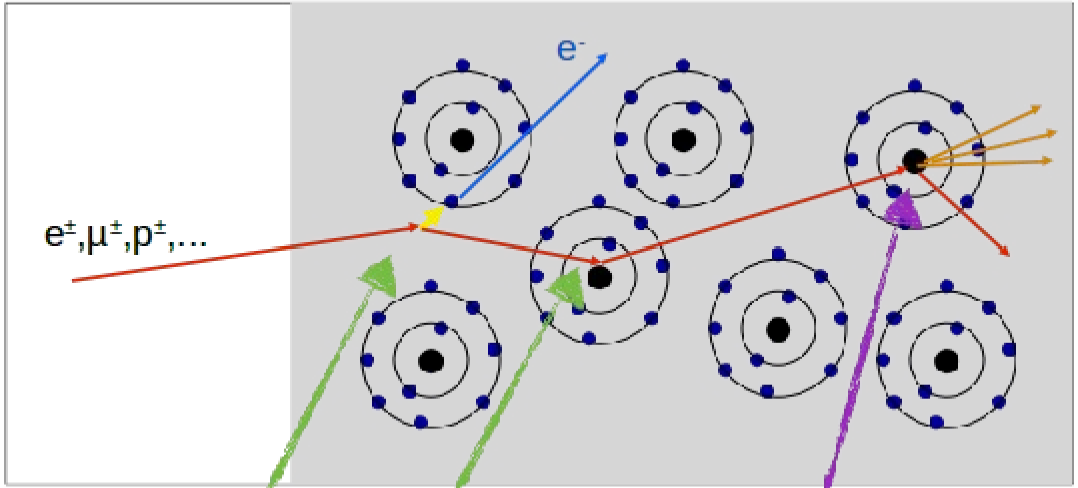
- High energy particles interact via different processes with matter, depending on
  - Particle type
  - Energy
  - Material
- Energy loss of the particles via interaction
  - Energy transfer to material or other (free) particles
  - In Detectors: ***Energy loss = signal!***

Charged Particles

Ionization

Elastic scattering
Recoil from atom lattice → photons

Inelastic scattering



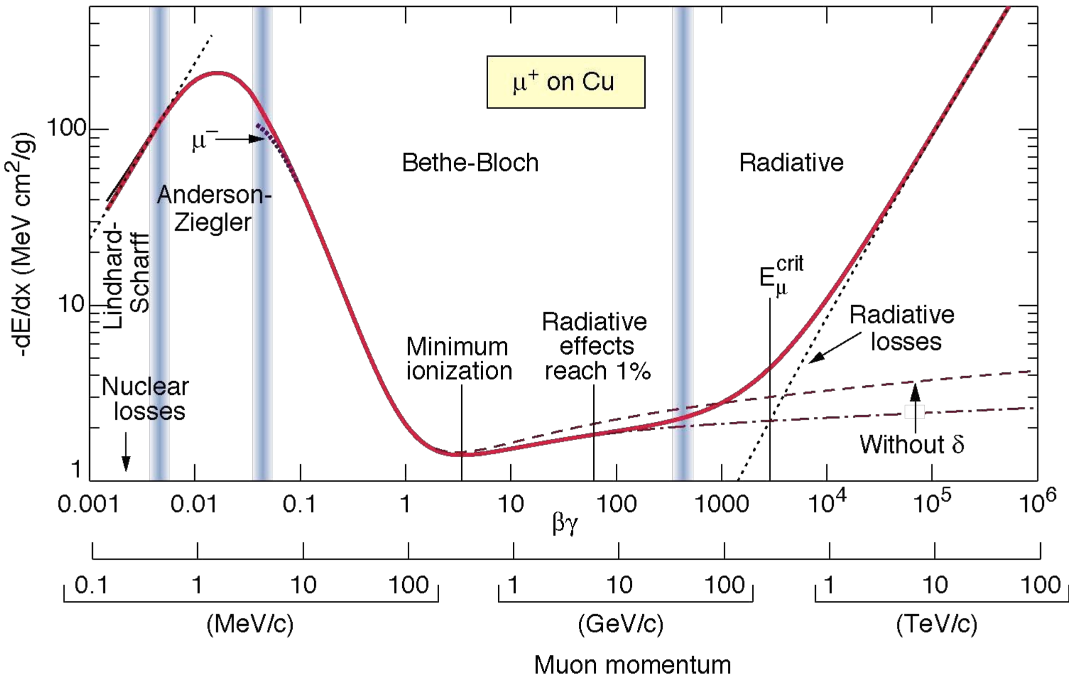
Electromagnetic interaction

Electromagnetic, weak or strong Interaction

Mean Energy Loss

- Charged particles interact with electrons in matter
- For heavy charged particles **Bethe-Formula**

$$-\left\langle \frac{dE}{dx} \right\rangle \approx K q^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\ln\left(\frac{2 m_e c^2}{I} \beta^2 \gamma^2 \right) - \beta^2 \right]$$



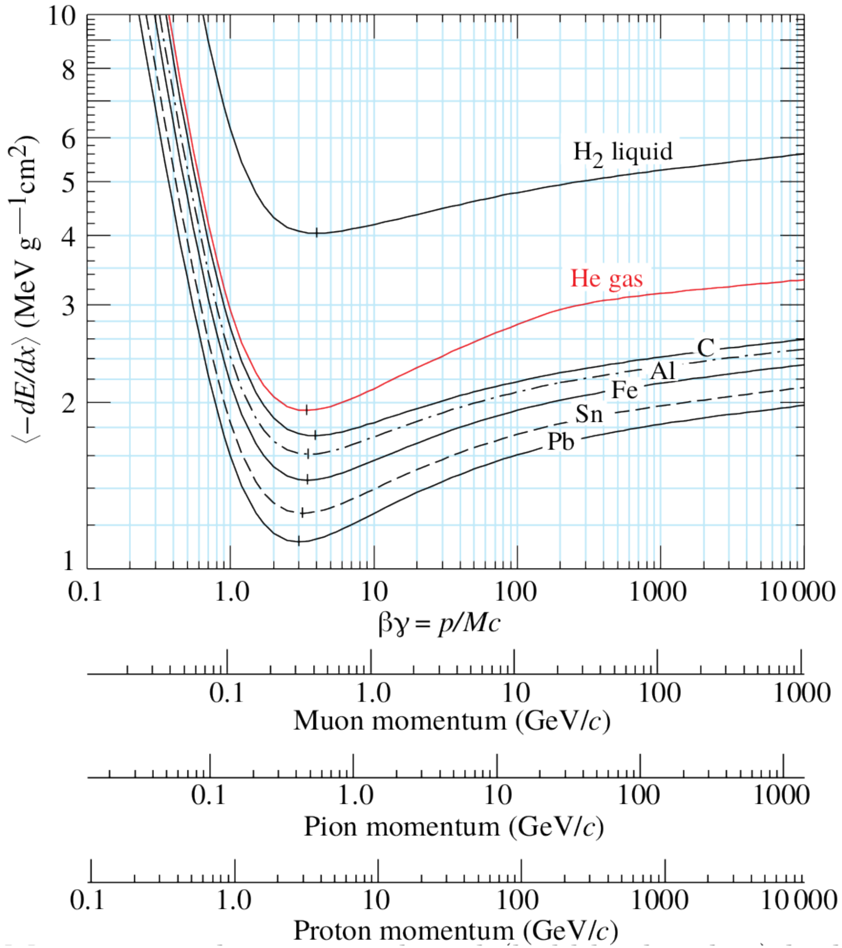
- Energy loss depends on
  - Properties of projectile: charge, energy
  - Target properties: atomic number, ionization energy, density

Mean Energy Loss

- Different components are dominating:
  - At low energies: ~ $1/\beta^2$
  - At high energies: ~ $\ln \gamma$

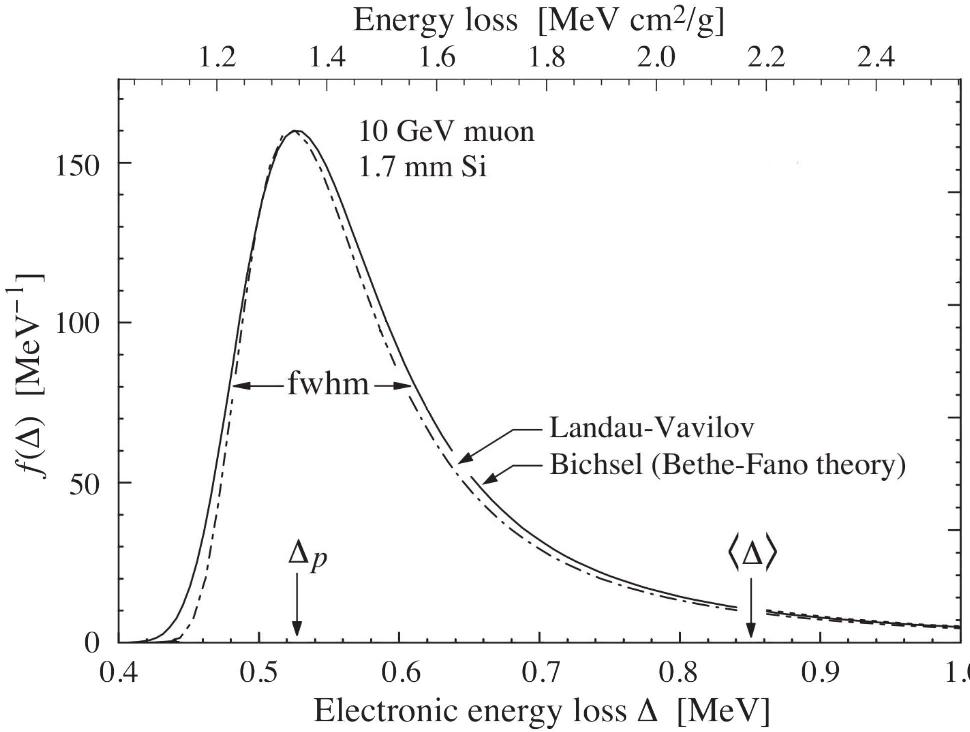
$$-\left\langle \frac{dE}{dx} \right\rangle \approx K q^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\ln\left(\frac{2 m_e c^2}{I} \beta^2 \gamma^2 \right) - \beta^2 \right]$$

- Minimal energy loss for ~ $\beta\gamma = 3$
  MIP: Minimum Ionizing Particle
- $[dx] = g / cm^2 = cm \times g / cm^3$

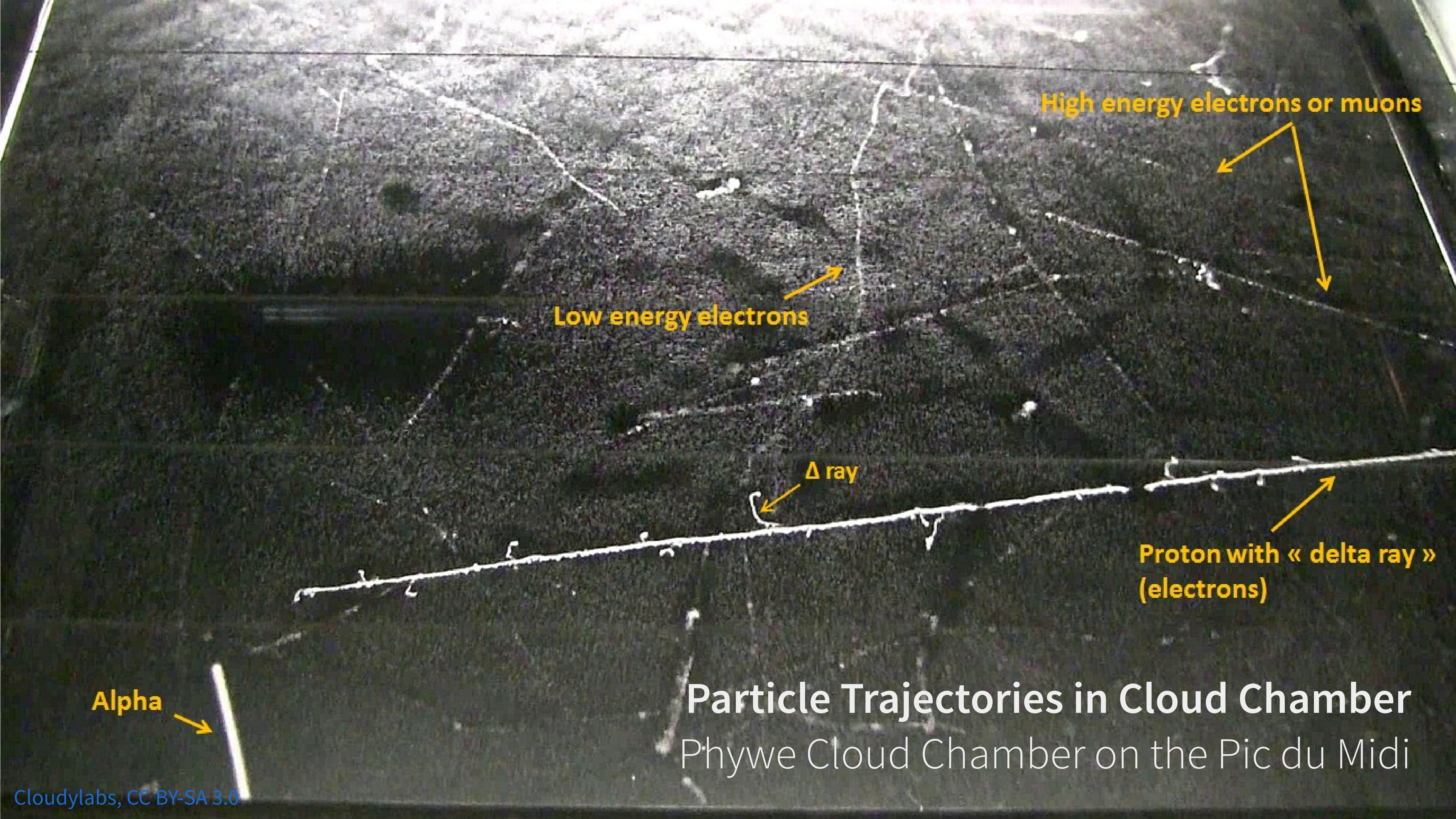


Fluctuations in Energy Loss

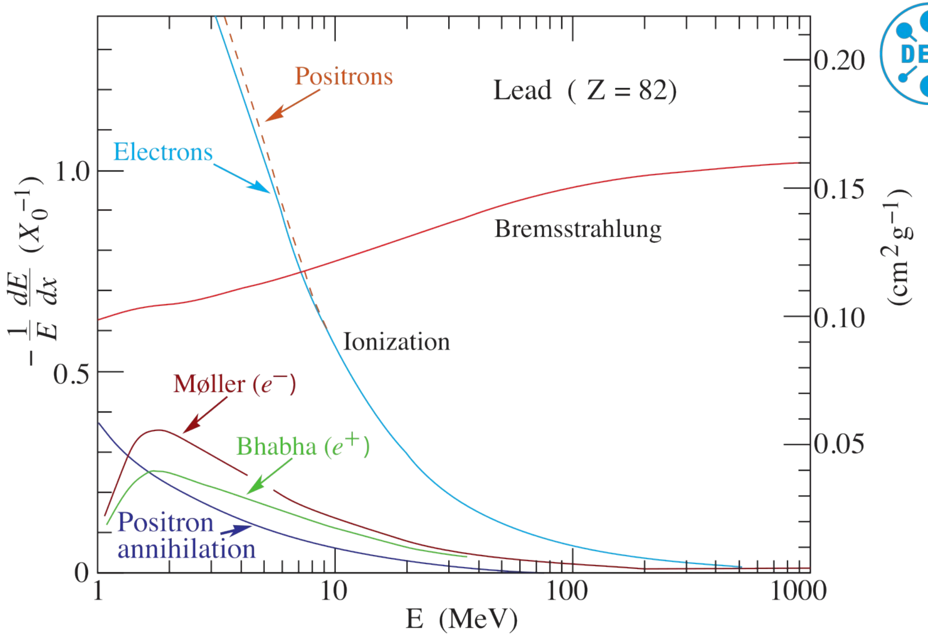
- Actual energy loss fluctuates around mean value
- **Landau-Vavilov distribution** with long tails to high energies
  - Most probable value << mean value



- Orbital electrons can receive very large energy transfers
  - Creation of delta electrons
  - Delta electrons have enough energy for further ionization

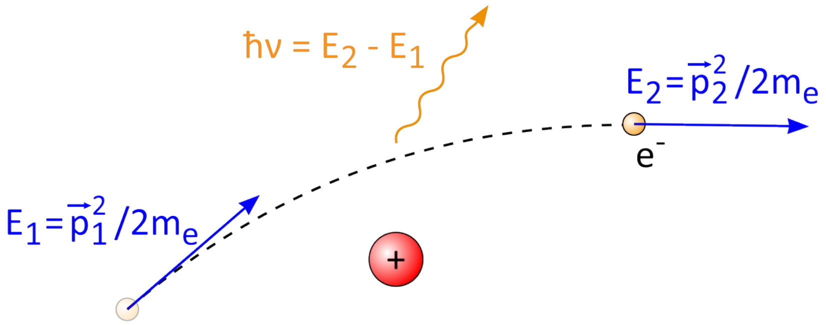

High energy electrons or muons
Low energy electrons
Δ ray
Proton with « delta ray » (electrons)
Alpha
Particle Trajectories in Cloud Chamber
Phywe Cloud Chamber on the Pic du Midi

Exception: Electron & Positron



- Special case: low mass
  $m_e = 0.511$ MeV / c^2
  $m_\mu = 106$ MeV / $c^2 \approx 200\ m_e$

- At high energies: Bremsstrahlung
  - occurs when the momentum of a charged particle changes, e.g.
    ...in the Coulomb field of a nucleus
    ...in the magnetic field: synchrotron radiation
  - Here: particles slowed down in matter
  - Relevant for electrons: $-\frac{dE}{dx} \sim E \cdot \frac{1}{m^2}$



Cherenkov Radiation

- Is emitted, when particle velocity > speed of light

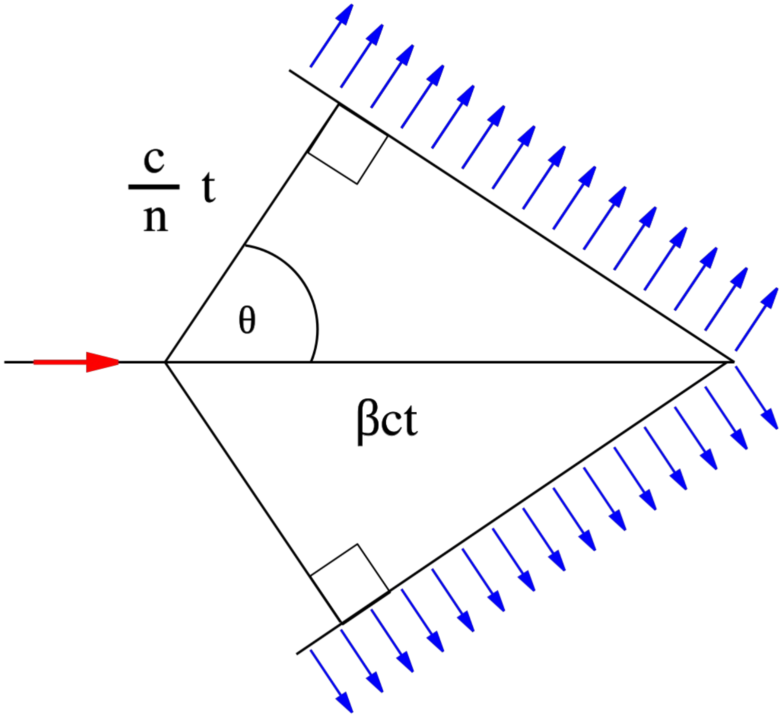
$$c_{Medium} = \frac{c_{Vacuum}}{n} < v_{Particle} < c_{Vacuum}$$

n: refractive index of medium

- Electromagnetic shockwave with conical shape is emitted under angle θ:

$$\cos(\theta) = \frac{1}{\beta n}, \qquad \beta = \frac{v}{c}$$

- Very low energy loss (ca. 1% of total energy loss)

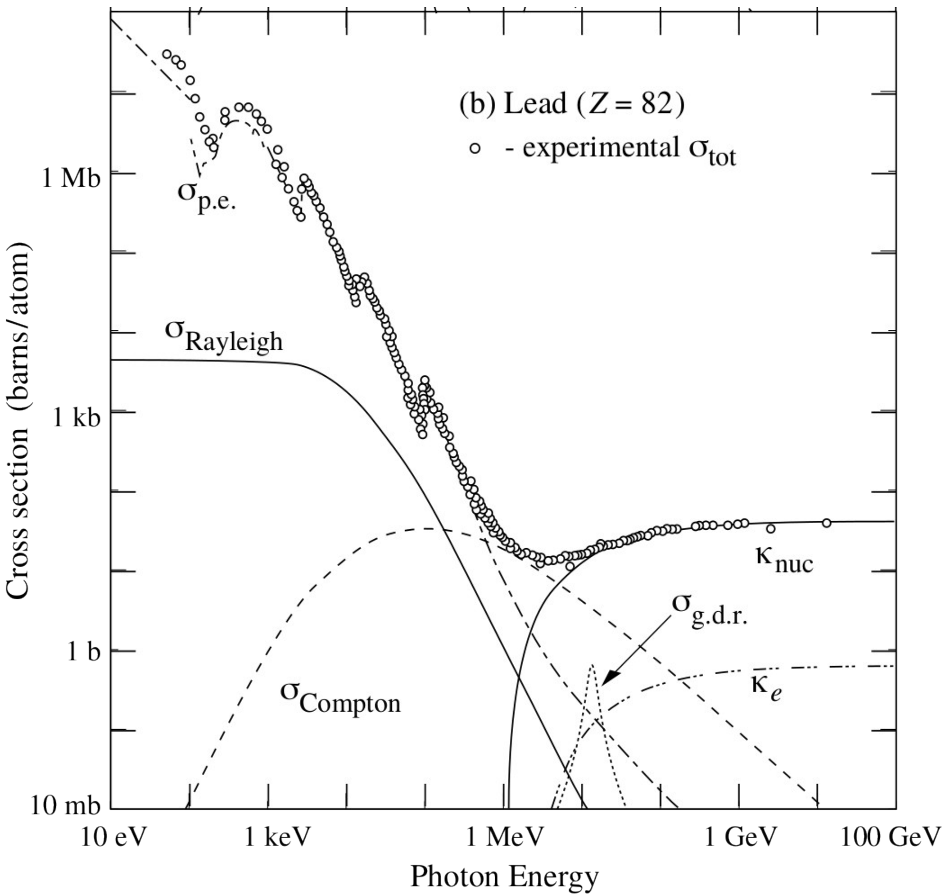


Cherenkov Radiation of a Nuclear Reactor

Advanced Test Reactor, INL

Photons

- Electromagnetic interaction
- Different processes dominate, depending on the photon energy:
  - Photo(electric) effect
  - Rayleigh scattering
  - Compton effect
  - Pair production

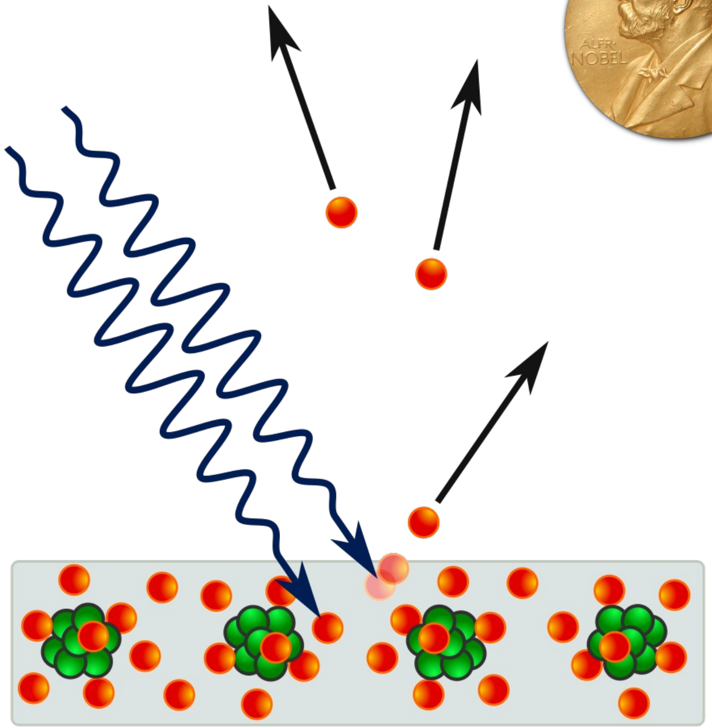


Photoelectric Effect

- Theoretical description of photo effect: Nobel price 1921 for Albert Einstein
- Photon is absorbed by electron in atomic shell
- Transferred energy releases/frees electron

$$\gamma + Atom = e^- + Ion$$

- Process only possible in the field of the nucleus:
  - Momentum conservation
  - Nucleus absorbs recoil
- Cross section of the photoelectric effect shows shell structure of the atom



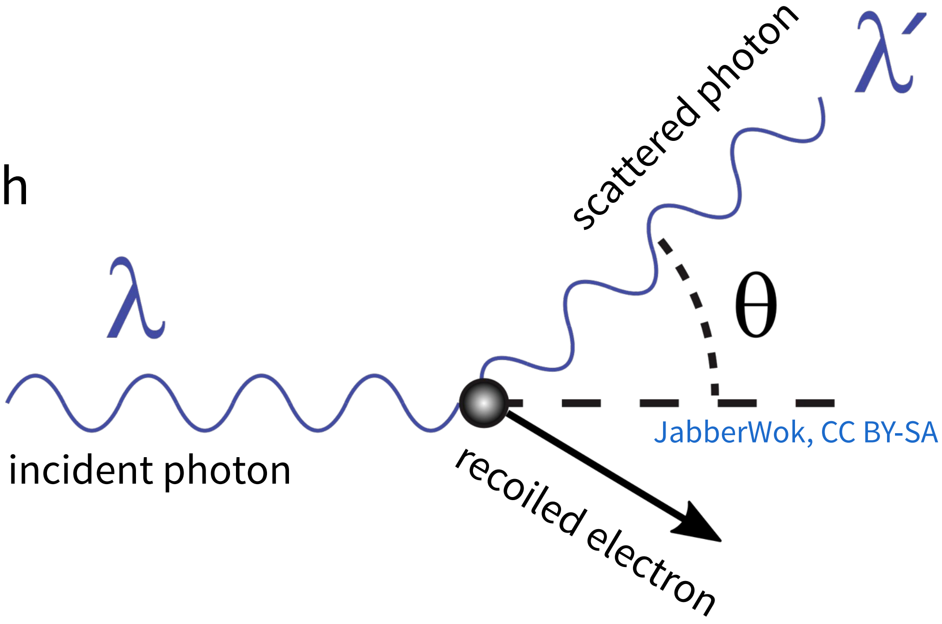
Compton Effect

- Describes scattering of photon on “quasi-free” electron

$$\gamma + Atom = \gamma + e^{-} + Ion$$

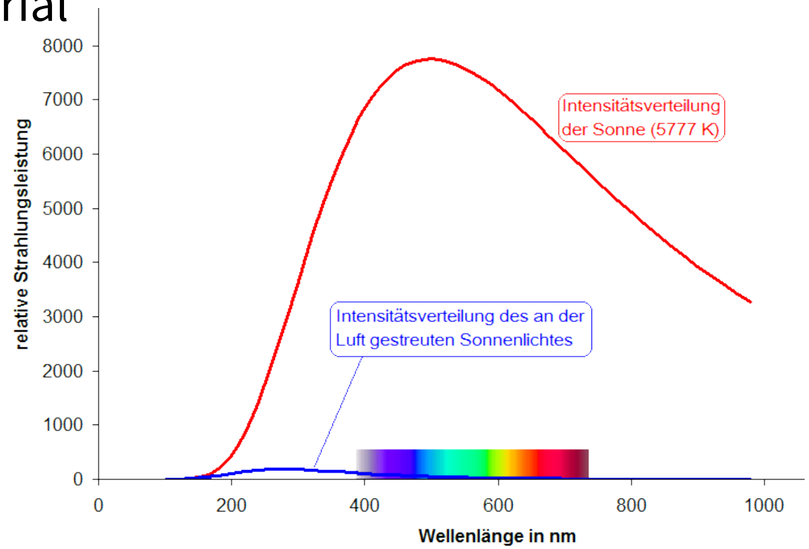
- Photon is deflected from its original path

- Wavelength of photon changes through energy transfer to electron



Photons: Thomson/Rayleigh Scattering

- Elastic scattering: almost no energy transfer to material
- Thomson scattering:
  Photon scattering on free electron
  - Low-energy limit of Compton scattering
- Rayleigh scattering:
  Photon scattering off an entire atom
  - Scattering cross section $\sigma_{Rayleigh} \sim f^4$



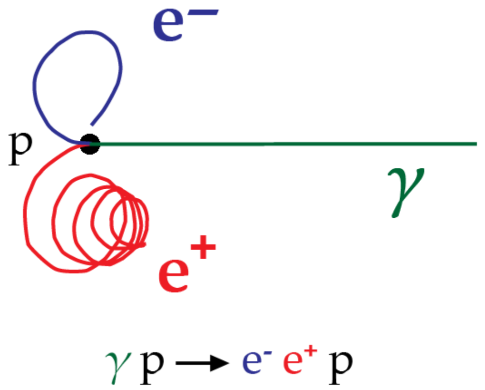
- Reason for blue / red coloration of the sky depending on the zenith angle
  - Noon: short path through atmosphere, hardly any blue light scattered
  - Morning/evening: long path through atmosphere, much blue light scattered

$$\frac{\sigma_{blue}}{\sigma_{red}} = \frac{1/\lambda_{blue}^4}{1/\lambda_{red}^4} = \left(\frac{650\,nm}{450\,nm}\right)^4 \approx 4.4$$

Photons: Pair Production

- Pair production is the generation of an electron-positron pair by the photon
- Pair production occurs in the field of a partner, which absorbs the recoil (atomic nucleus, but also shell electron)

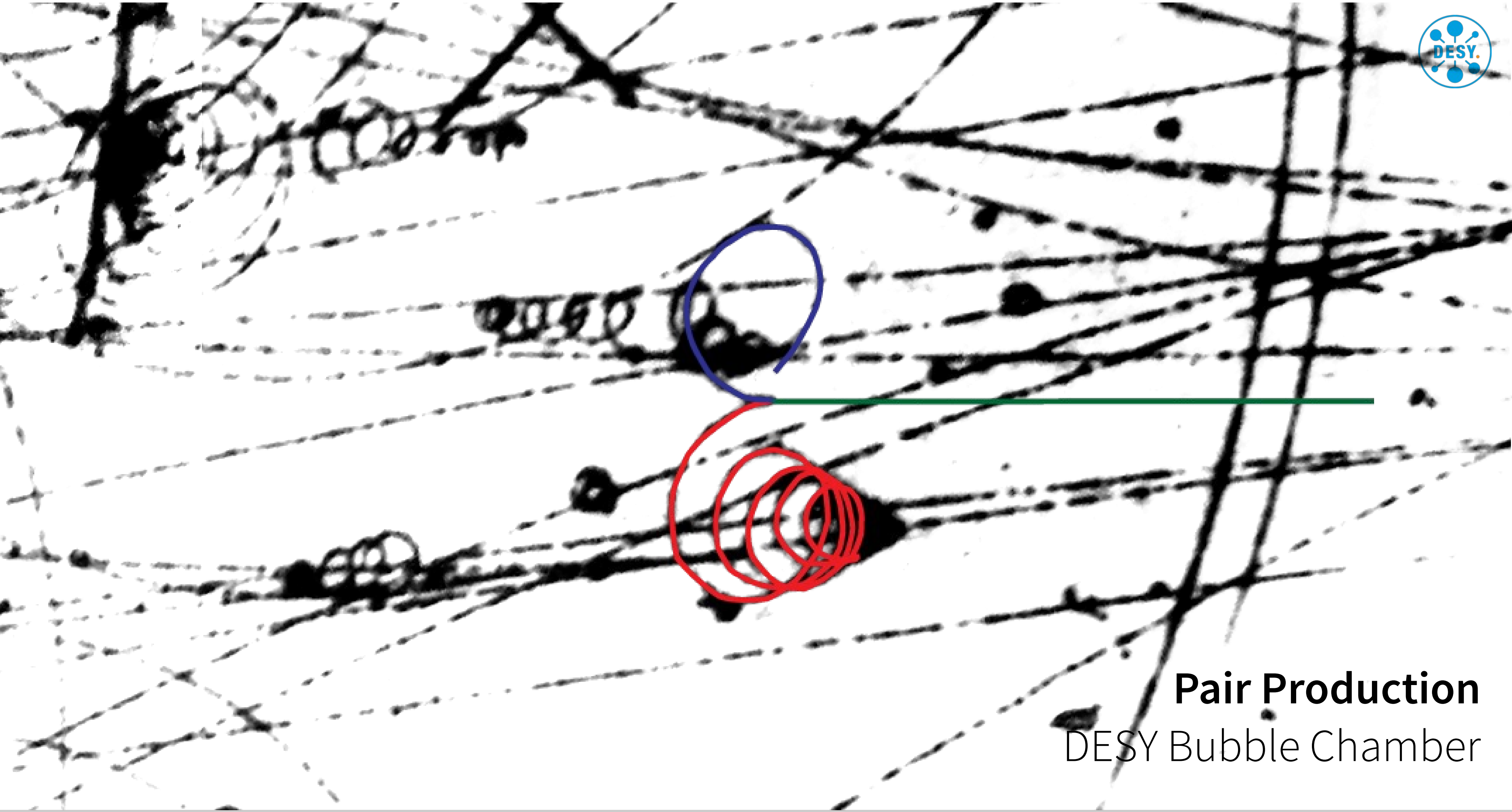
$$\gamma + p = e^{+} + e^{-} + p$$



- Photon must provide at least rest mass of e+e- pair plus recoil energy:

$$E_{\gamma} \geq 2 m_e c^2 \left(1 + \frac{m_e}{M}\right)$$

- Recoil energy can often be neglected, e.g. Ge detector: $\frac{m_e}{M} \approx 7.6 \cdot 10^{-6}$



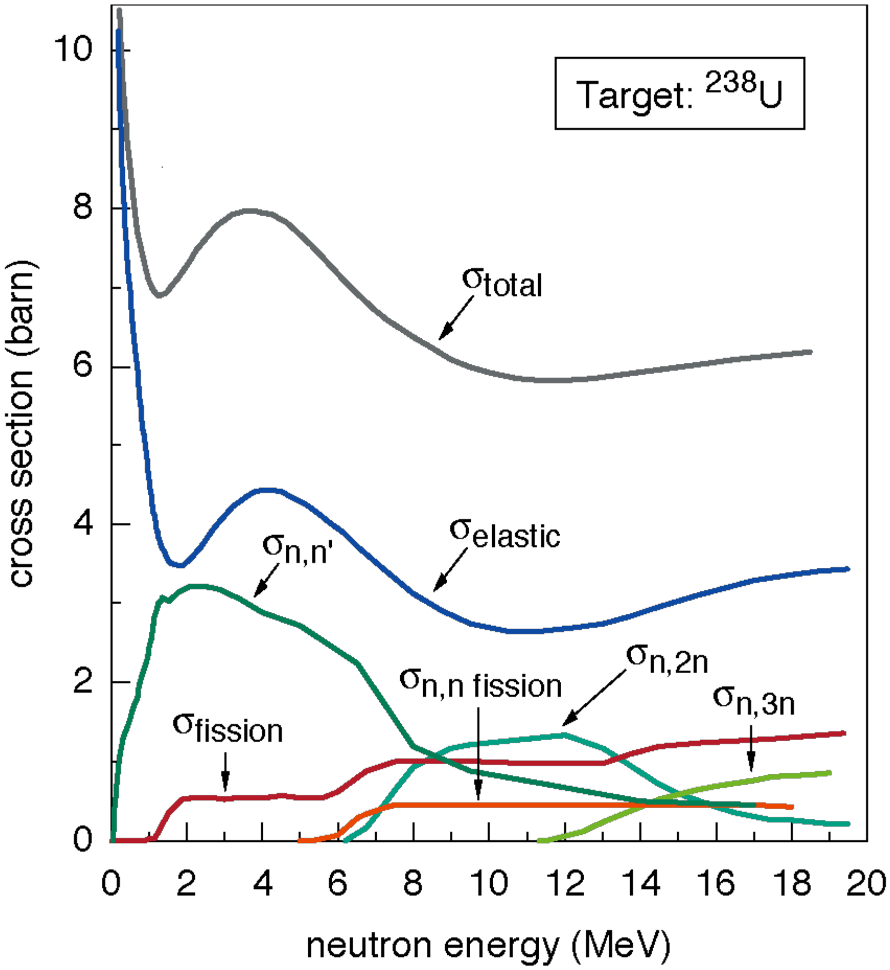
Pair Production

DESY Bubble Chamber

Hadronic Interaction

- Interactions of hadrons with nuclei
- Based on the **strong interaction, QCD**
  - Low range
  - Low probability of hadronic reactions
  - Neutrons can only interact strongly: very penetrating
- Many possible processes (energy dependent)

  Elastic, inelastic scattering; neutron capture; reactions with radiation of charged particles; nuclear fission.



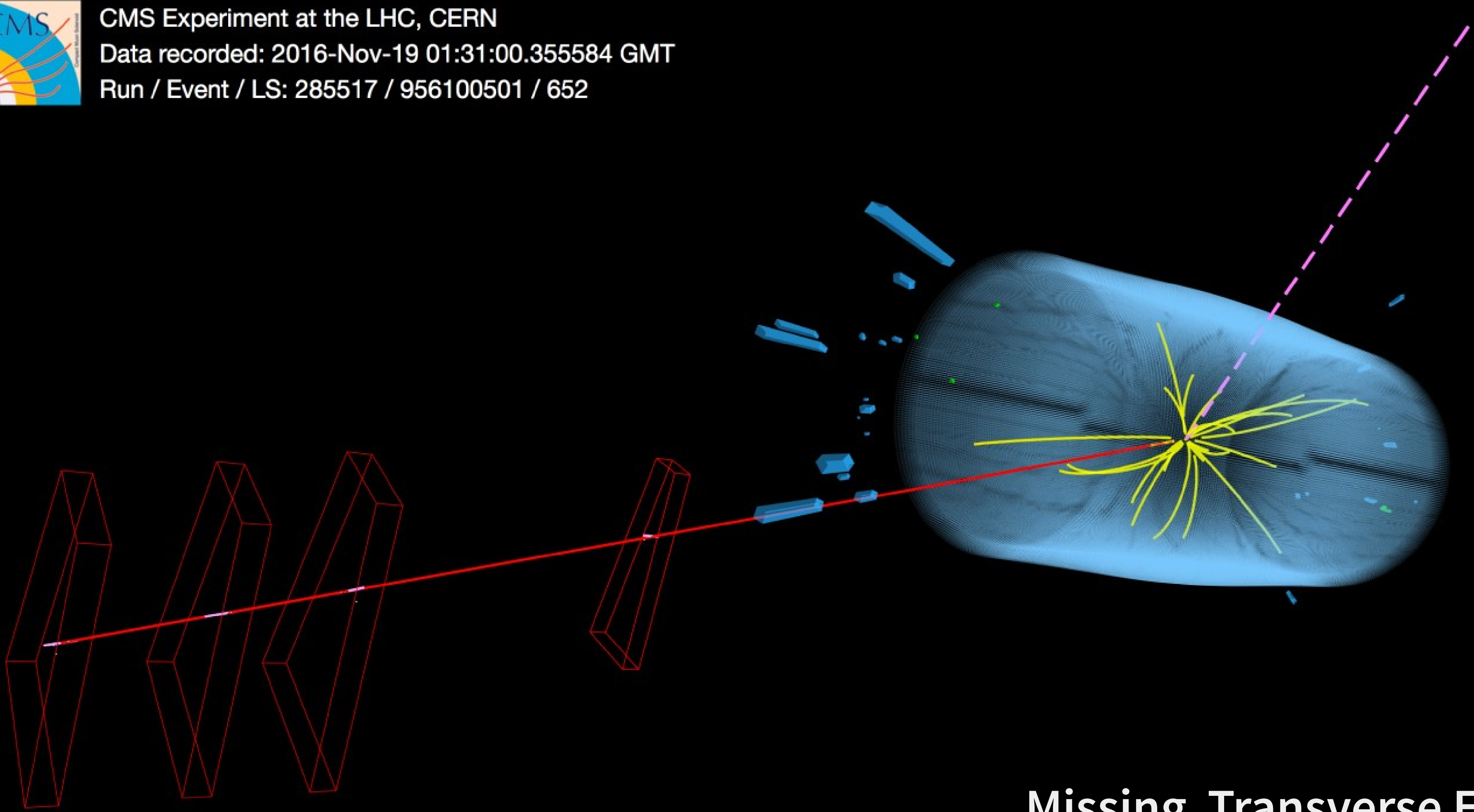
Interaction of Neutrinos

- Neutrinos are exclusively subject to the weak interaction
- Possible Interactions

$$\bar{\nu}_l + p \rightarrow n + l^+$$

$$\nu_l + n \rightarrow p + l^-$$

- Neutrino interactions have very (very!) low cross sections
- Detection of neutrinos requires
  - Very large detector and high neutrino fluxes (direct detection) or
  - Hermetic detector for measurement of missing energy (indirect evidence)



Missing Transverse Energy

Detection of Neutrinos

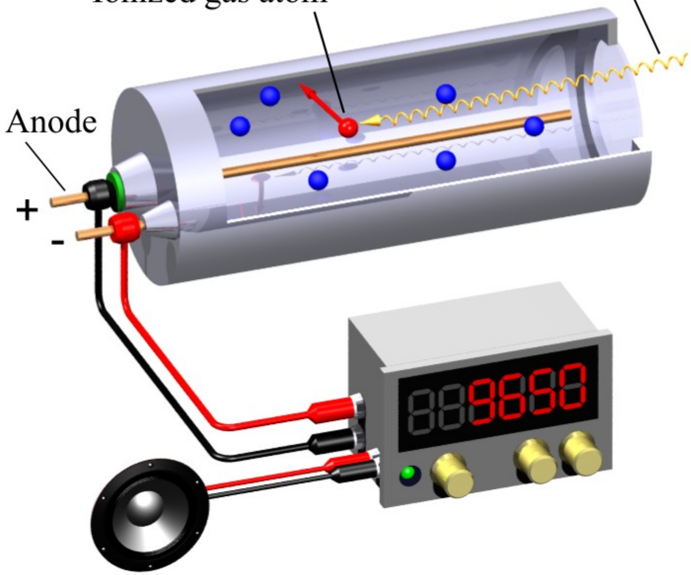
Particle Detectors

Historic Overview

Geiger-Müller Counter

- „Click" = Particle passing
- „Many Click" = Many particles
- „A Great Many Click" = Run…!

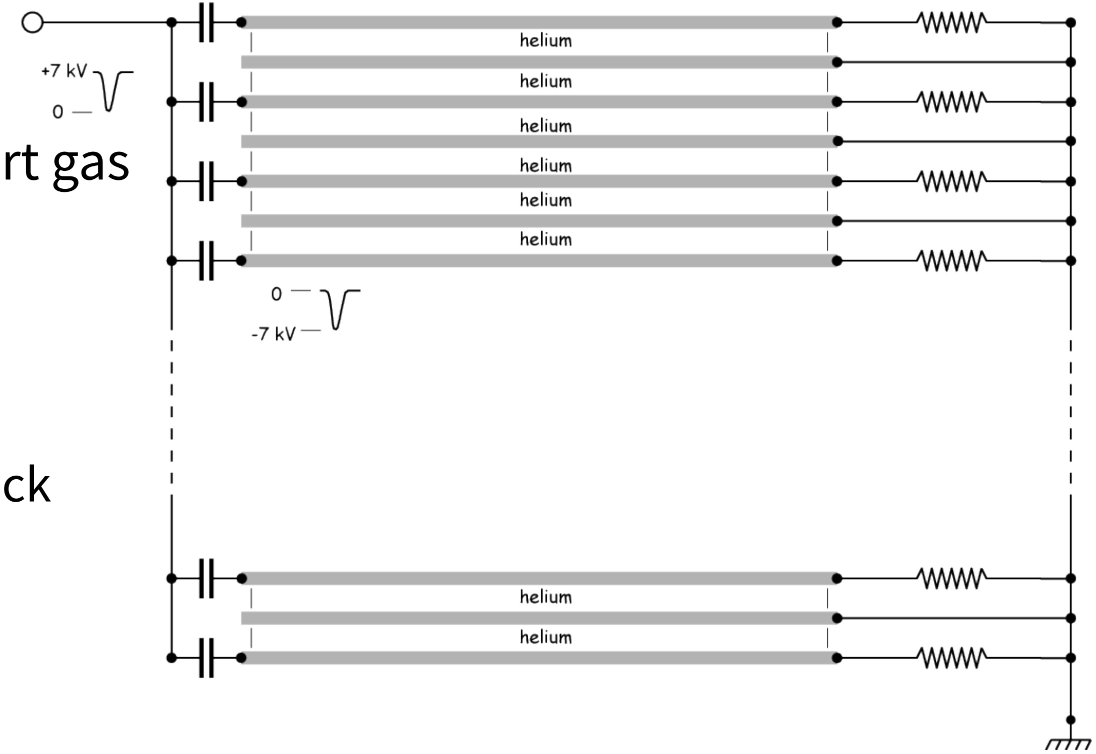
- Detector filled with noble gas
  - Charged particles ionize noble gas atoms
  - High voltage applied between electrodes amplifies
- Signal: Current pulse to loudspeaker: Click!



Geiger's lab device

Spark Chamber

- „Many Geiger counters“
- Transparent chamber filled with inert gas and many parallel plates
  - Voltage (~ kV) between plates
  - Particles ionize noble gas atoms
  - Small sparks along the particle track
- Analysis by photos or microphones
- Relatively large dead time: quenching time of the avalanche
- Used during the 1930s-1960s



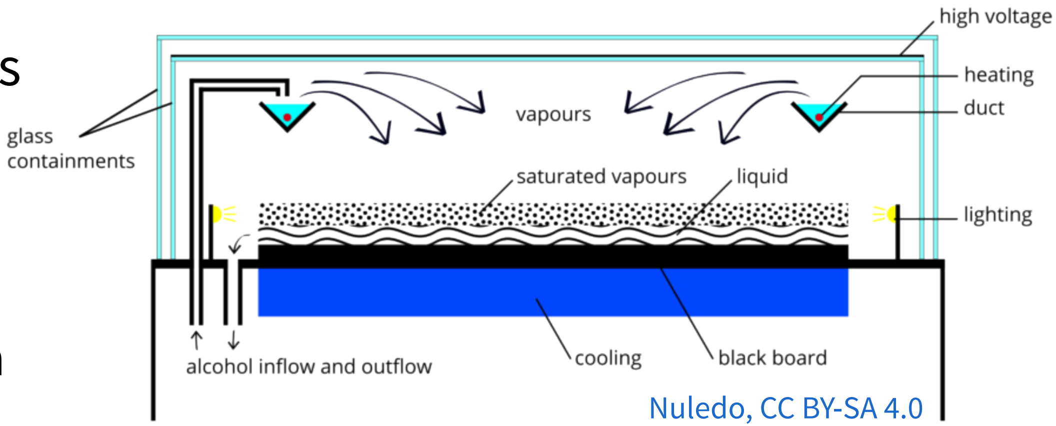
Spark Chamber

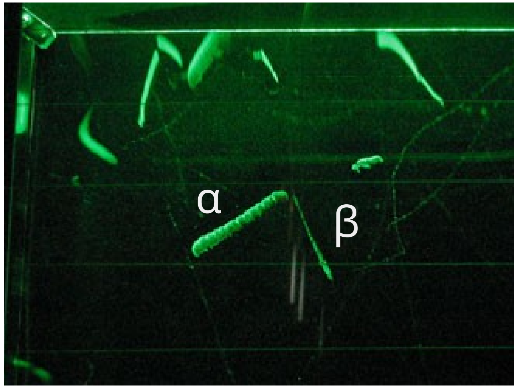
Melvin Schwartz at BNL AGS

BNL

Cloud Chamber

- Optical detection of charged particles
  - Transparent chamber with supersaturated air-alcohol mixture
  - High-energy charged particle generates ions by impact ionization
  - Ions act as condensation nuclei, droplet formation in the gas mixture
- Type of traces can (sometimes) be identified & assigned to particles
- Nobel Prize 1927 for Charles Thomson Rees Wilson





Cloud Chamber Image

Rendering of particle interaction

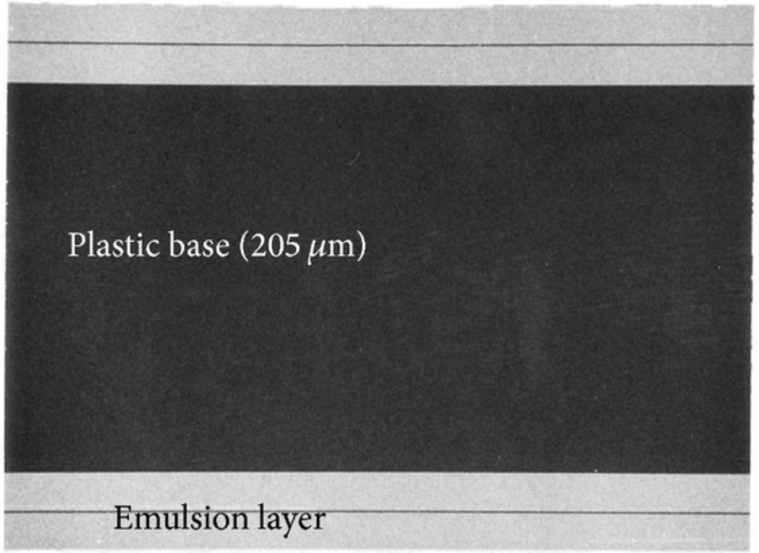
Donald Arthur Glaser

Detail of droplets

Cloud chamber tracks after Radon injection

Photo emulsion / Nuclear emulsion

- Photographic plate with thick sensitive layer and very uniform grain size.
  - Ionizing radiation leaves traces
  - Development of the plate
  - Trajectories of particles (blackened by silver) visible with microscope



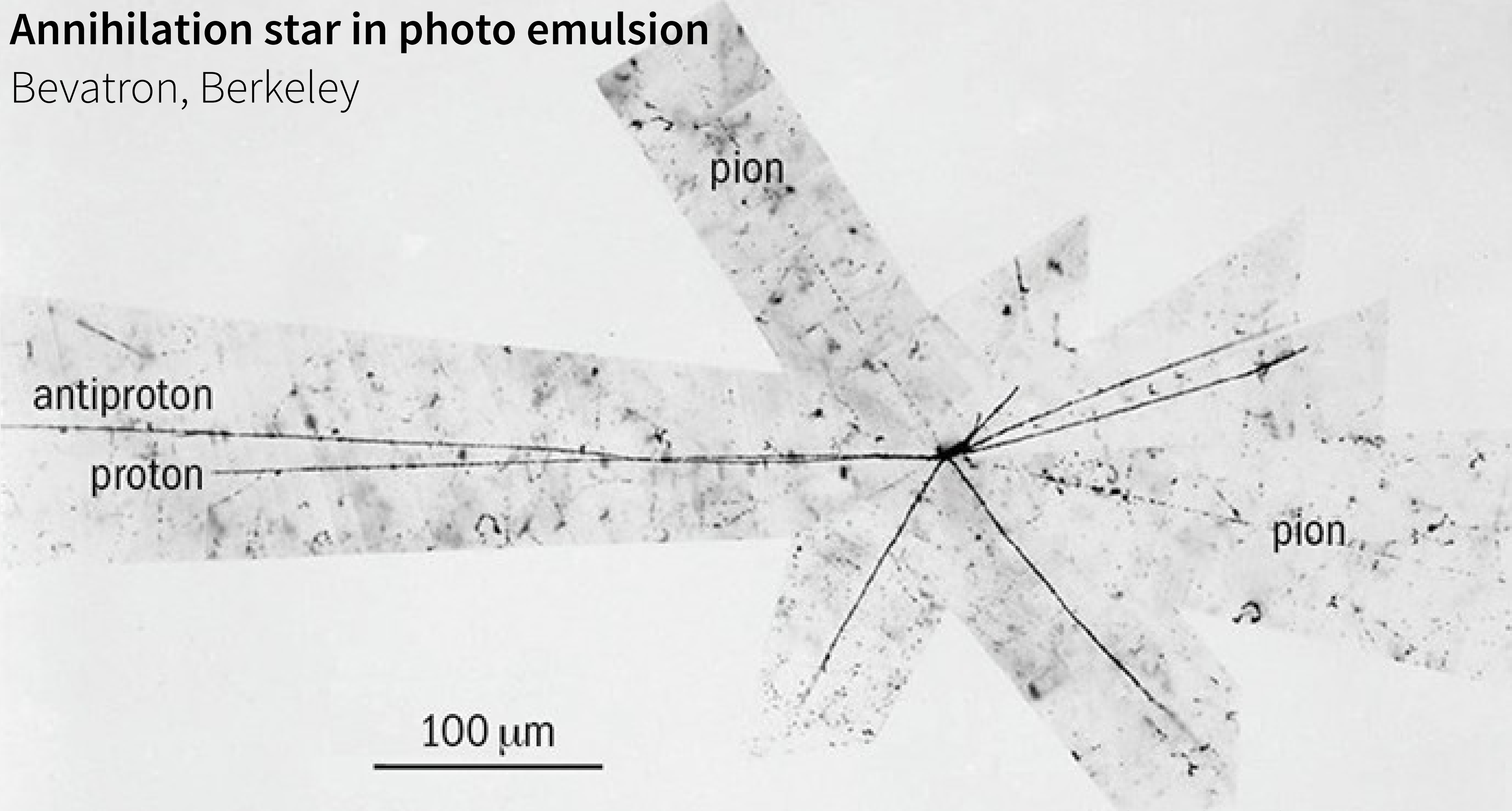
OPERA

- Nobel Prize 1950 for Cecil Powell

- OPERA experiment in Gran Sasso
  - Photoemulsion plates for particle reconstruction
  - AgBr emulsion, cooperation with Fuji Film: 9 million films, each about 10 x 12 cm

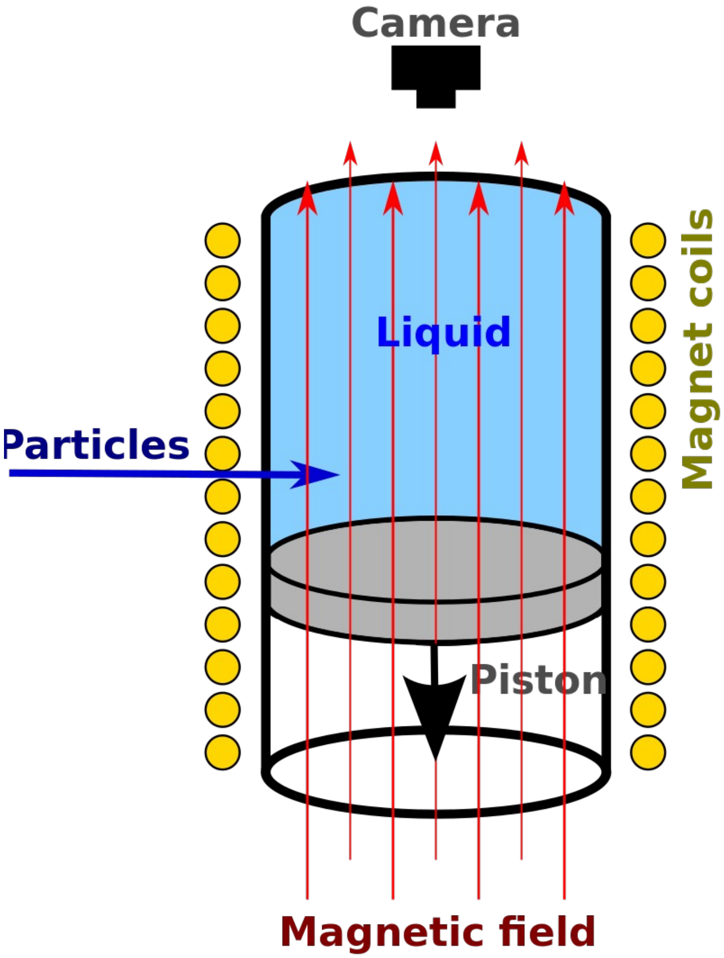
Annihilation star in photo emulsion

Bevatron, Berkeley



O Chamberlain et al. 1956 Nuo. Cim. 3 447

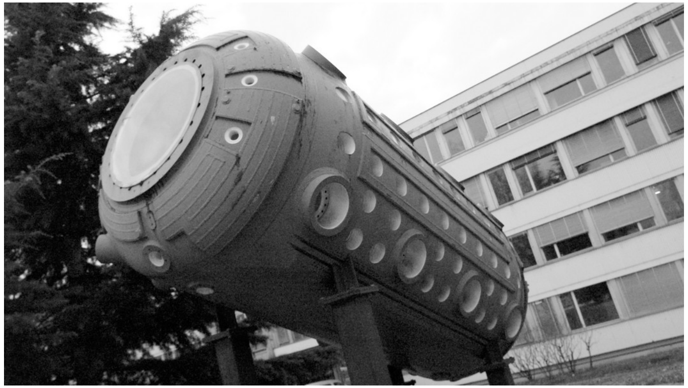
Bubble Chamber

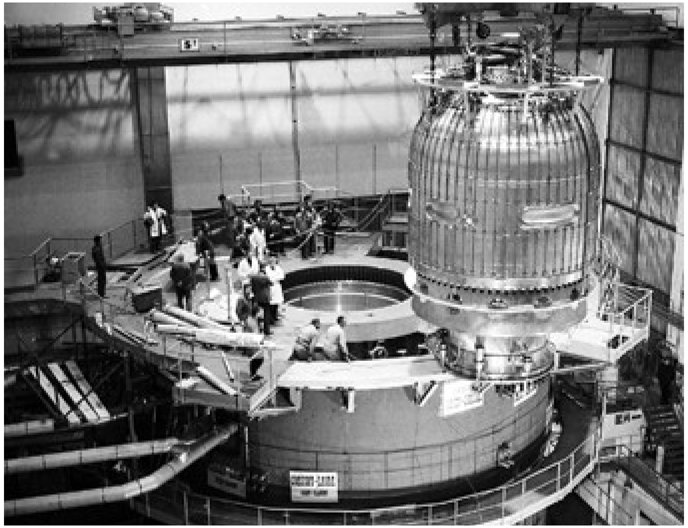


- Optically transparent chamber filled e.g. with liquid hydrogen
  - Temperature of the liquid close to the boiling point
  - Reduction of chamber pressure with piston
  - Temperature of liquid is now above boiling point
  - Charged particles generate ions along track
  - Ions serve as nuclei for gas bubbles
- Analysis of photos of the traces

- Nobel Prize 1960 for Donald A. Glaser

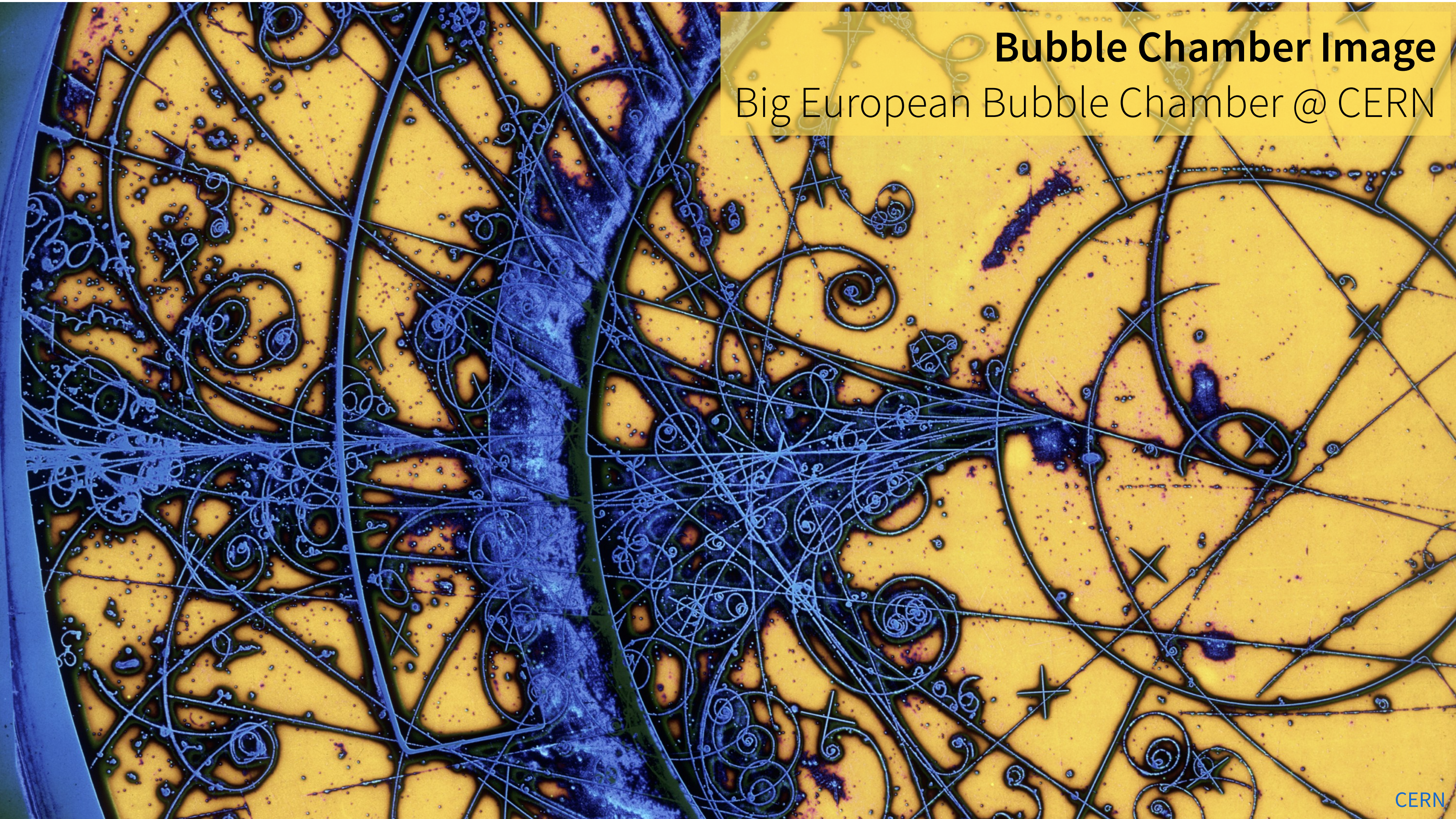
Prominent Bubble Chambers





- Most important particle detector type in the 1970s
- Particle source: proton synchrotron

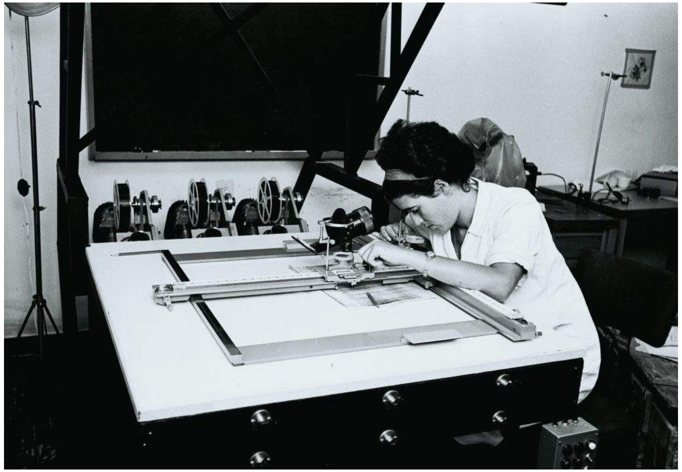
- **Gargamelle** - 1970-1978
  - 4.8 m x 1.88 m, 12 000 l
  - First detection of the Z boson
- **BEBC** - 1971-1984
  - Big European Bubble Chamber
  - 3.5 T magnetic field of superconducting coils
  - Discovery of the D meson


Bubble Chamber Image
Big European Bubble Chamber @ CERN
CERN

Problems of Early Particle Detectors

- Many based on photographic images
  - Data evaluation complex and only possible by hand
  - Limitation of the amount of data

- Long detector dead times
  - No further measurement possible until gas avalanche has been quenched/bubbles have disappeared
  - Only low particle rates possible
- Only little information in measurement
  - Information about particle location (& momentum), but no energy/time measurement



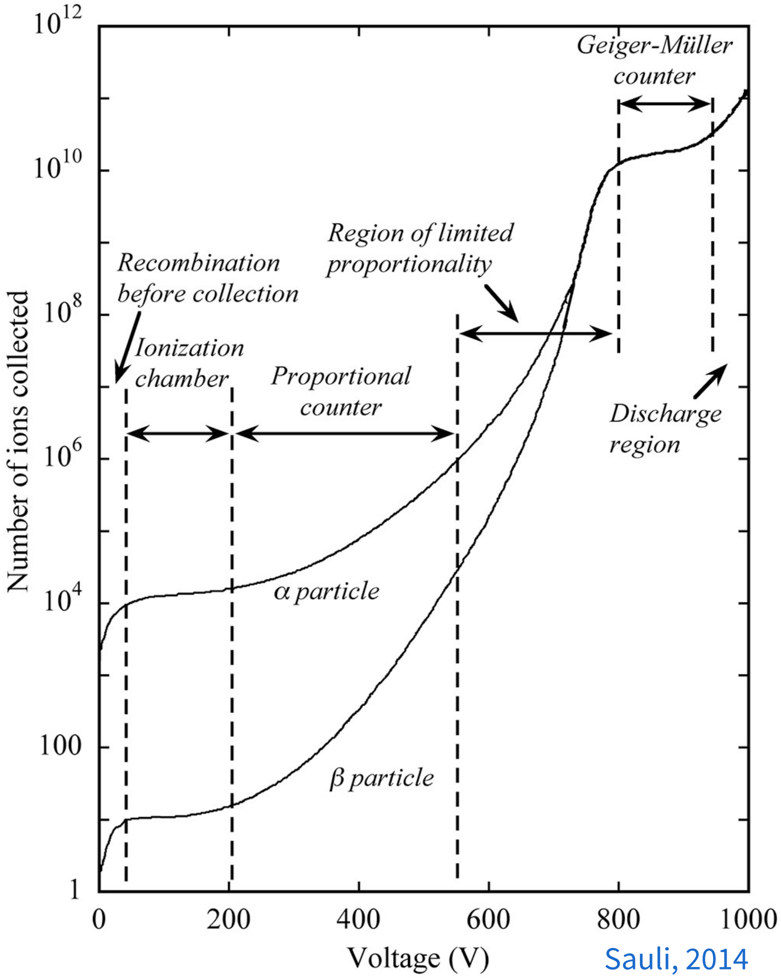
Weizmann Institute Archives

Gaseous Detectors

Primary & secondary ionization of gas atoms

Gaseous Detectors: Operating Principle

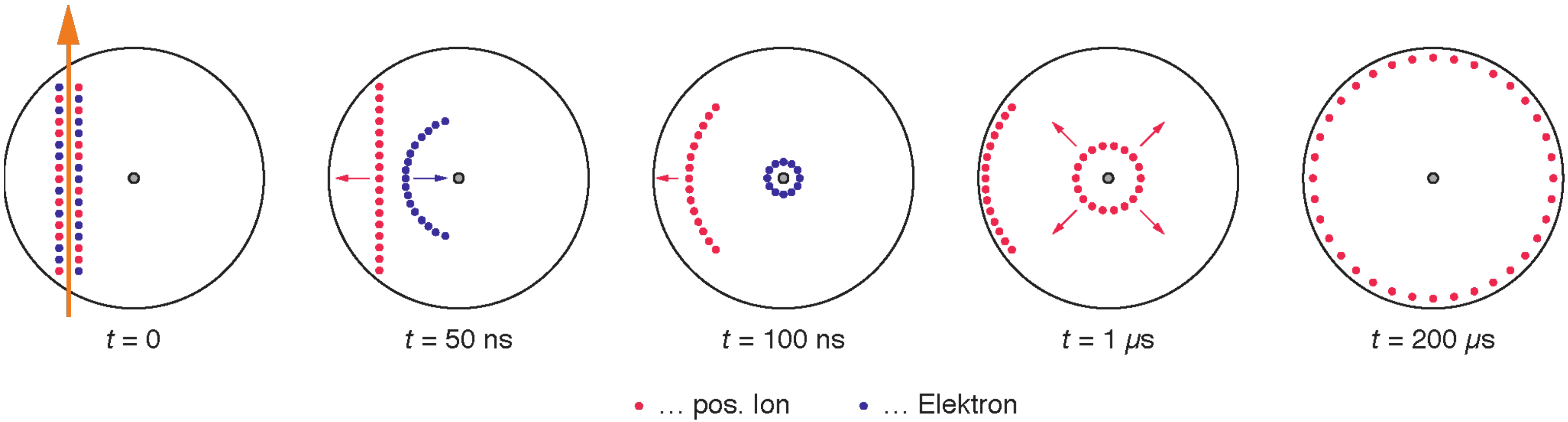
- **Primary signal:** charged particle generates electron-ion pairs by ionization
  - Noble gases: relatively low ionization energy
  - Average energy to generate a pair ~30 eV
  - Number proportional to deposited energy
- **Amplification:** different working ranges depending on applied voltage
  - Medium voltages: proportional amplification
  - High voltages: Avalanche formation due to secondary ionizations



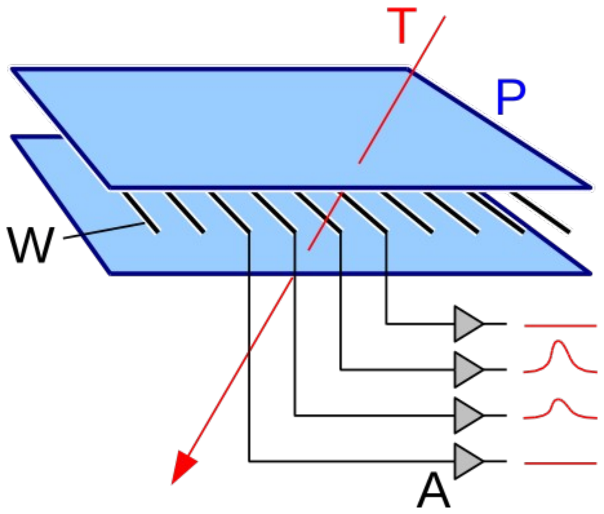
Sauli, 2014

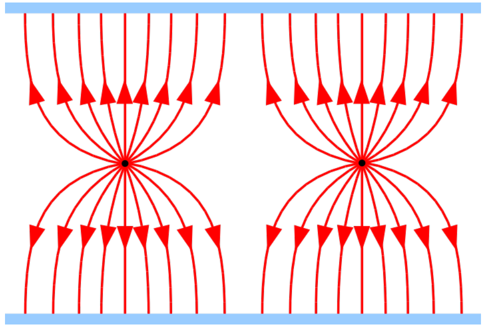
Proportional Counter

- Very similar to the Geiger counter: anode in the form of thin wire
- High field near wire leads to electron multiplication / signal amplification
- Choice of voltage: proportional range
  - Output signal proportional to original number of ionizations



Multi Wire Proportional Chamber (MWPC)

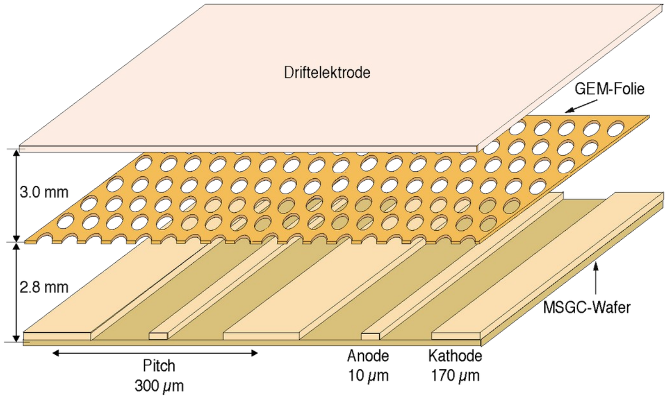




- Essentially many proportional counters next to each other, without separating walls
- Wires spaced a few millimeters apart
  - Good spatial resolution of a traversing particle
  - Large areas possible
  - Electronic selection
- High rates possible: 1000 particles/s
  for comparison, bubble chamber: 1-2 particles/s
- Nobel Prize 1992 for Georges Charpak

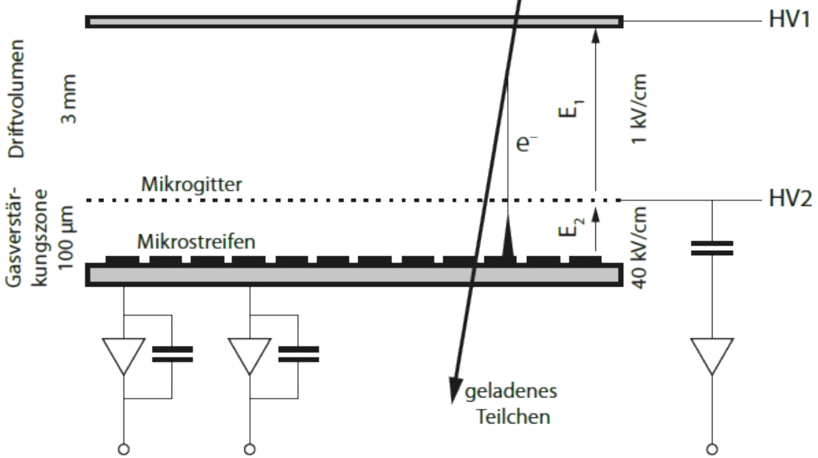
Micropattern Gas Detectors

- Replacement of fragile wires by micro structures
- Potentially better spatial resolution and applicable for higher particle rate



Gas Electron Multiplier (GEM)

- Perforated, metalized Kapton foil,
  High voltage between electrodes
- Strong dipole field in perforation holes:
  Gas amplification

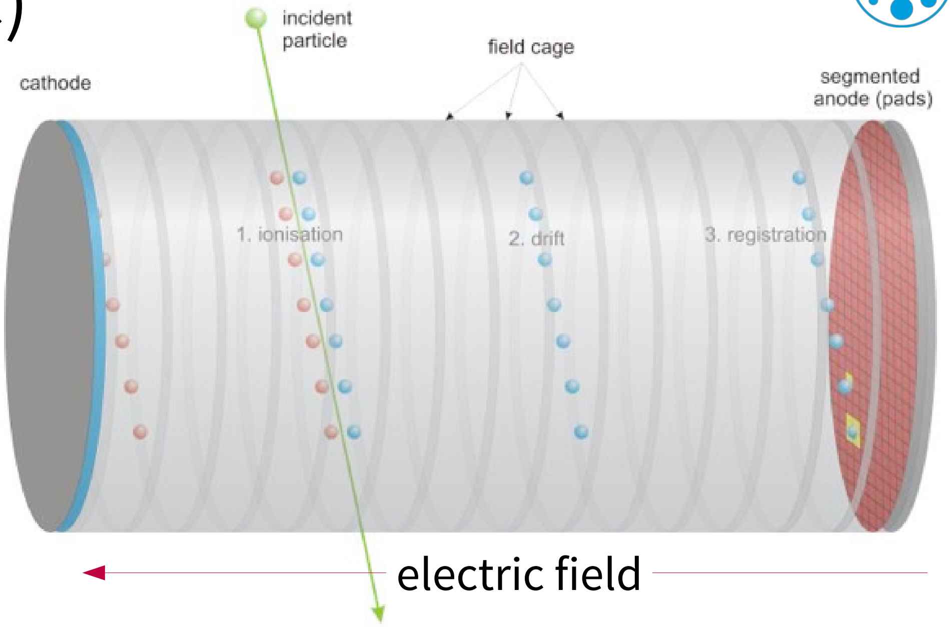


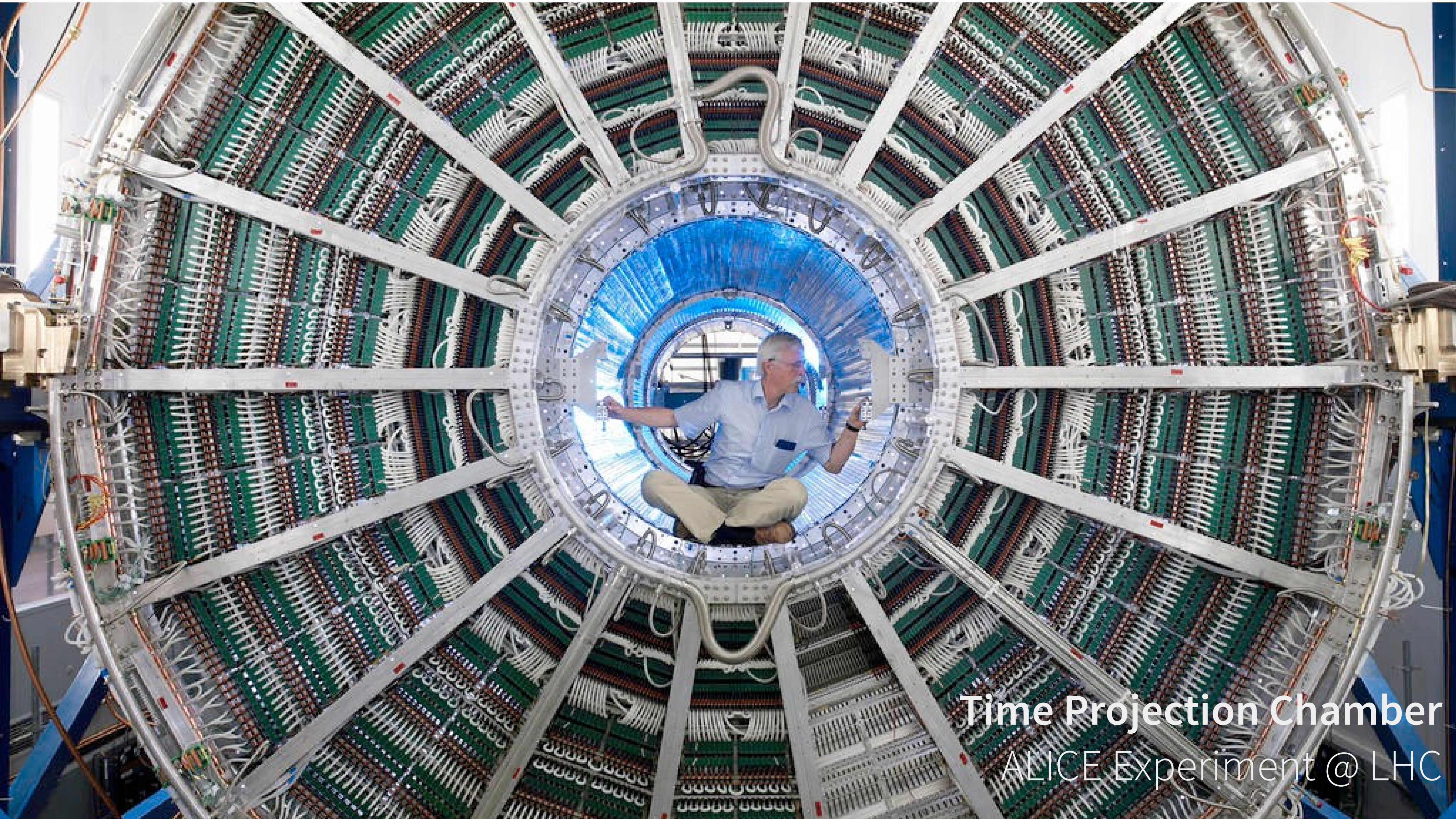
Micro-Mesh Gas Detectors (Micromegas)

- Metallic micro-grid
- Electron avalanche evolution near the lattice:
  Gas amplification

Time Projection Chambers (TPC)

- Large gas detector system
- Ionization along the particle track
  - Electrons and ions drifting in the E-field
  - Segmented anode: 2D information
  - Measurement of drift time:
    3D information
- Readout at anode side e.g. via
  multi-wire proportional chamber, GEMs, …

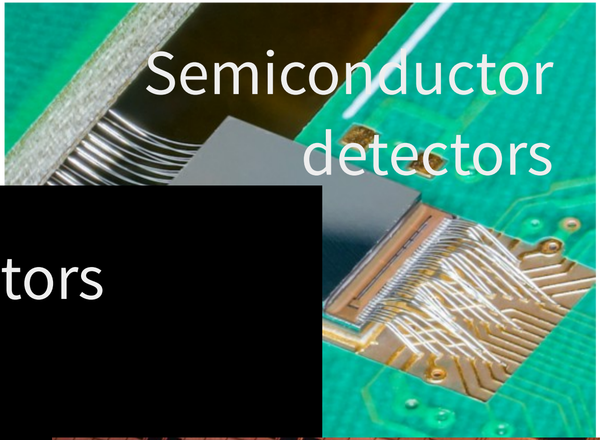



Time Projection Chamber
ALICE Experiment @ LHC

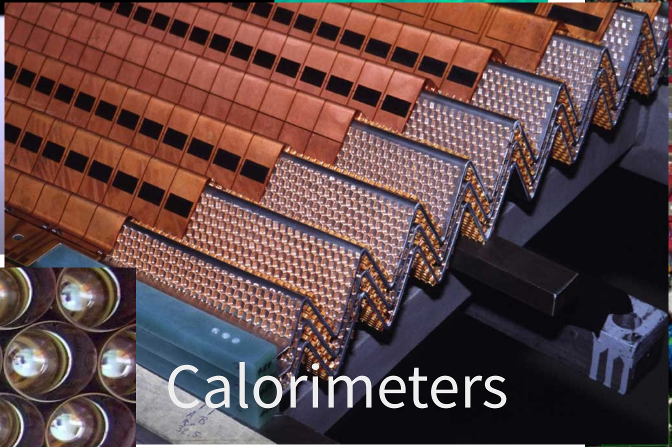
Summary

- Particle detection
  - Measurement is performed by interaction of the particle to be measured with detector material
  - There is no single detector concept that can detect all particle types / properties
  - One needs several detector technologies and concepts
- Interaction of radiation and matter
  - Ionization and excitation of detector atoms, Bremsstrahlung, Cherenkov radiation
  - Photoelectric effect, Compton effect, pair production,
  - Hadronic interaction, missing energy, ...
- Historical detectors
  - Cloud chamber, photo emulsion, bubble chamber, spark chamber
- Gas detectors
  - Operating principle
  - Proportional counters, multi-wire proportional chamber
  - Micropattern gas detectors
  - Time Projection Chamber

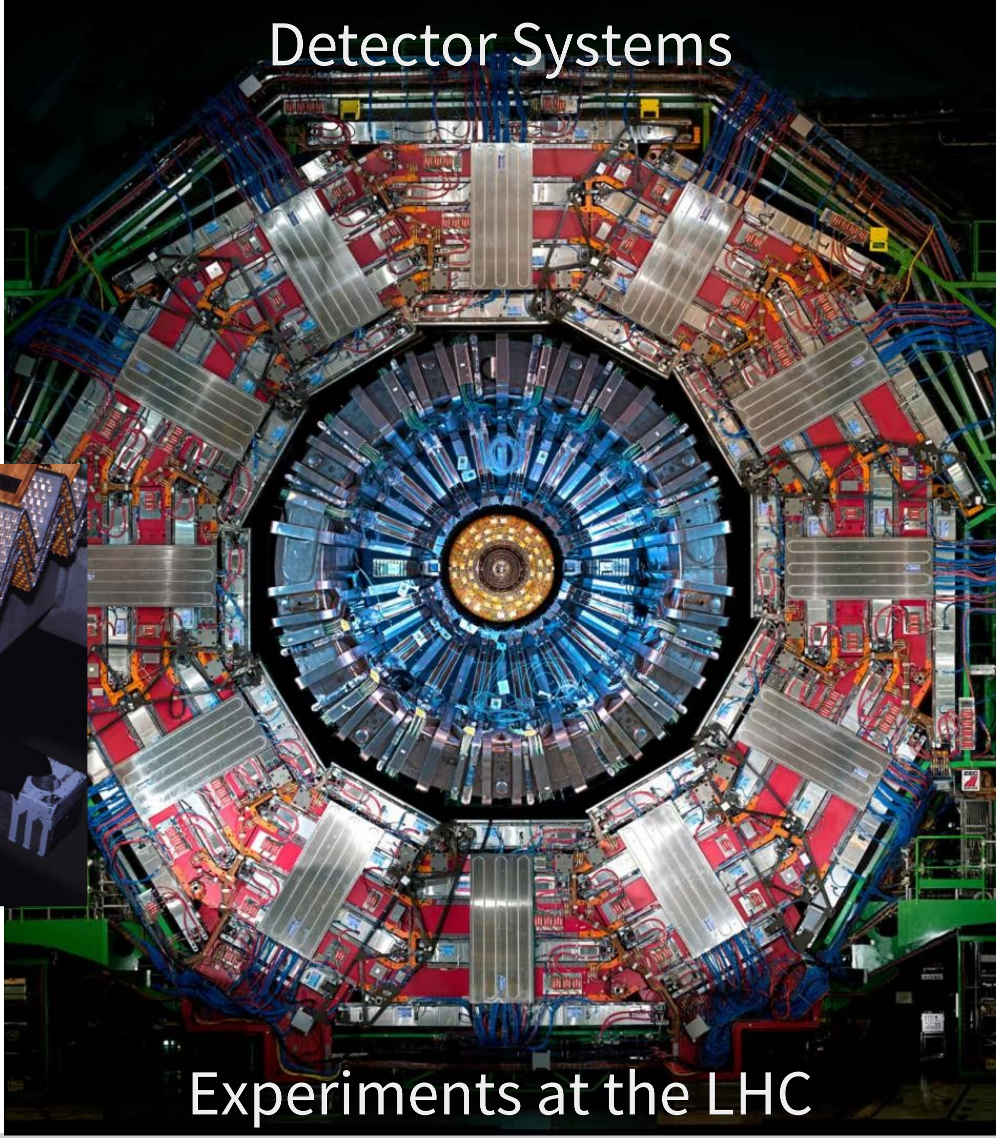
Outlook


Semiconductor
detectors


Scintillators


Calorimeters


Cherenkov Detectors


Detector Systems
Experiments at the LHC

DESY.