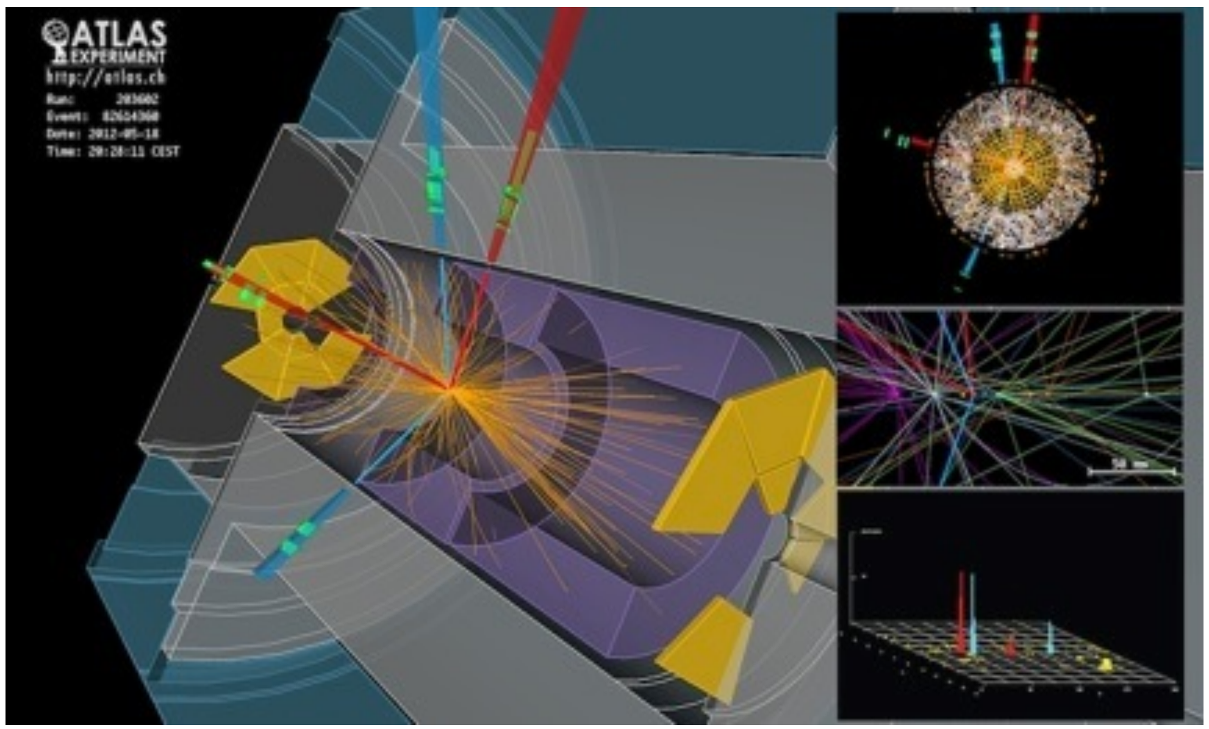
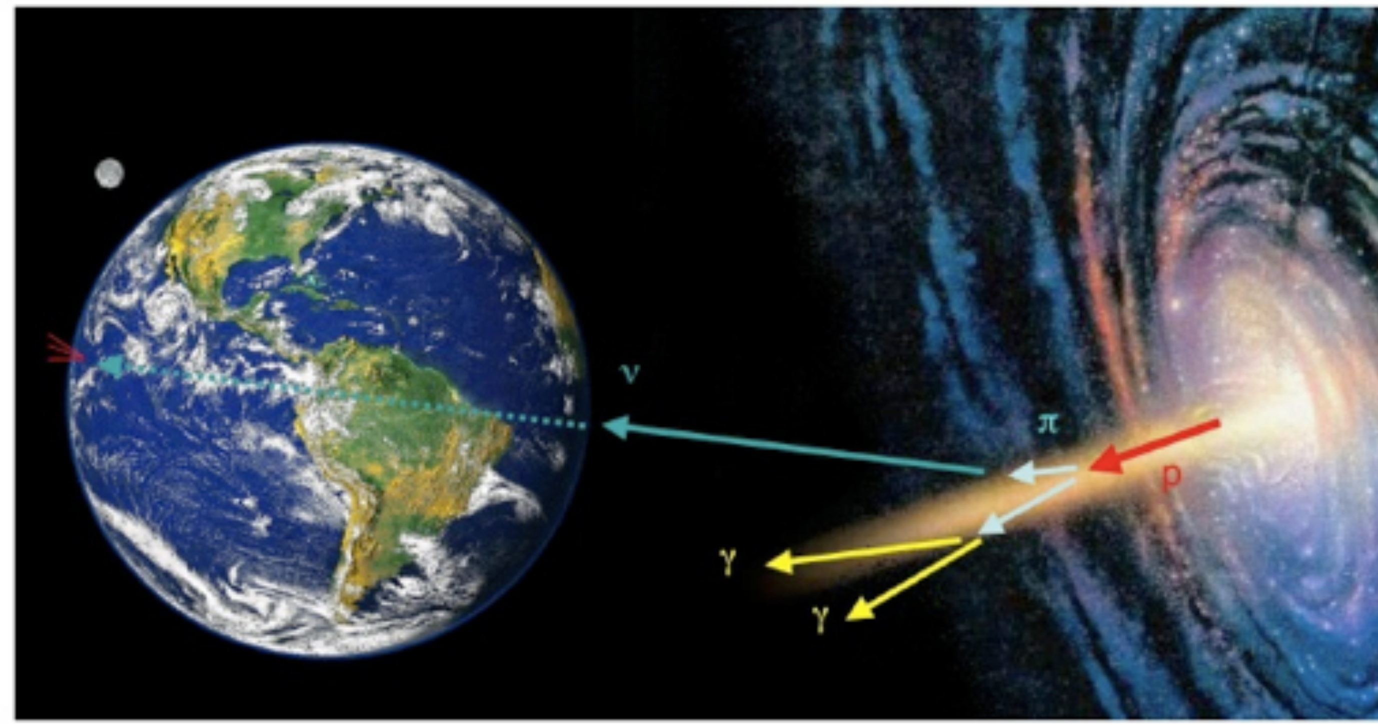
Particle Physics at Colliders and in the High Energy Universe





10. Collider Detectors I

17.12.2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Detectors: Overview

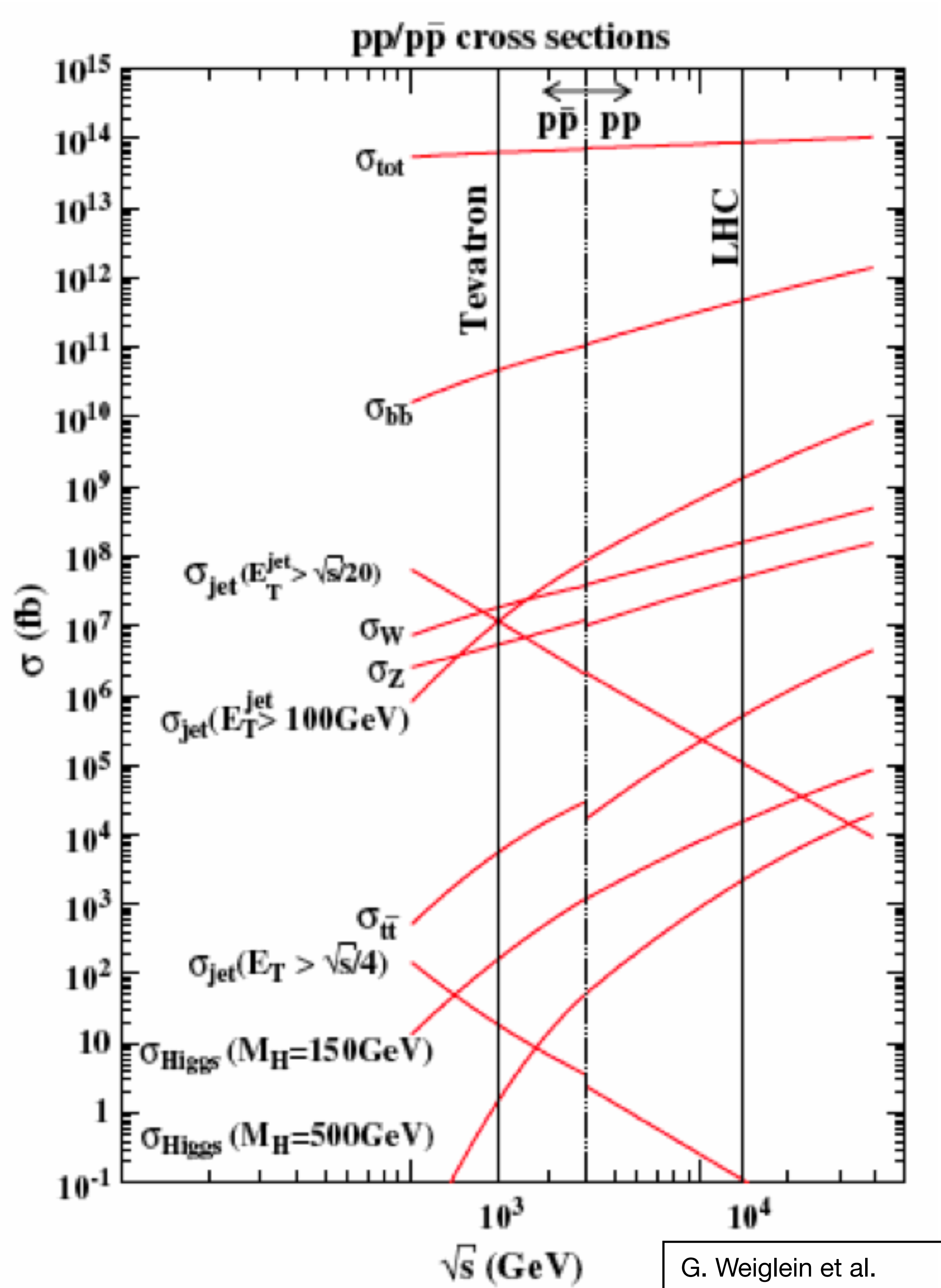
- **Lecture Detectors I**
  - Introduction, overall detector concepts
  - Detector systems at hadron colliders
  - Basics of particle detection: Interaction with matter
  - Methods for particle detection

  - And *special feature*: Novel acceleration techniques

- Lecture Detectors II
  - Tracking detectors: Basics
  - Semiconductor trackers
  - Calorimeters
  - Muon systems

Introduction, Overall Concepts

The Conditions at Hadron Colliders



G. Weiglein et al.
Physics Reports 426 (2006) 47–358

- Interesting processes are rare compared to the overall cross section:

$$\sigma(t\bar{t})/\sigma_{tot} \sim 10^{-8}$$

$$\sigma(H, M_H = 150\,\mathrm{GeV})/\sigma_{tot} \sim 10^{-10}$$

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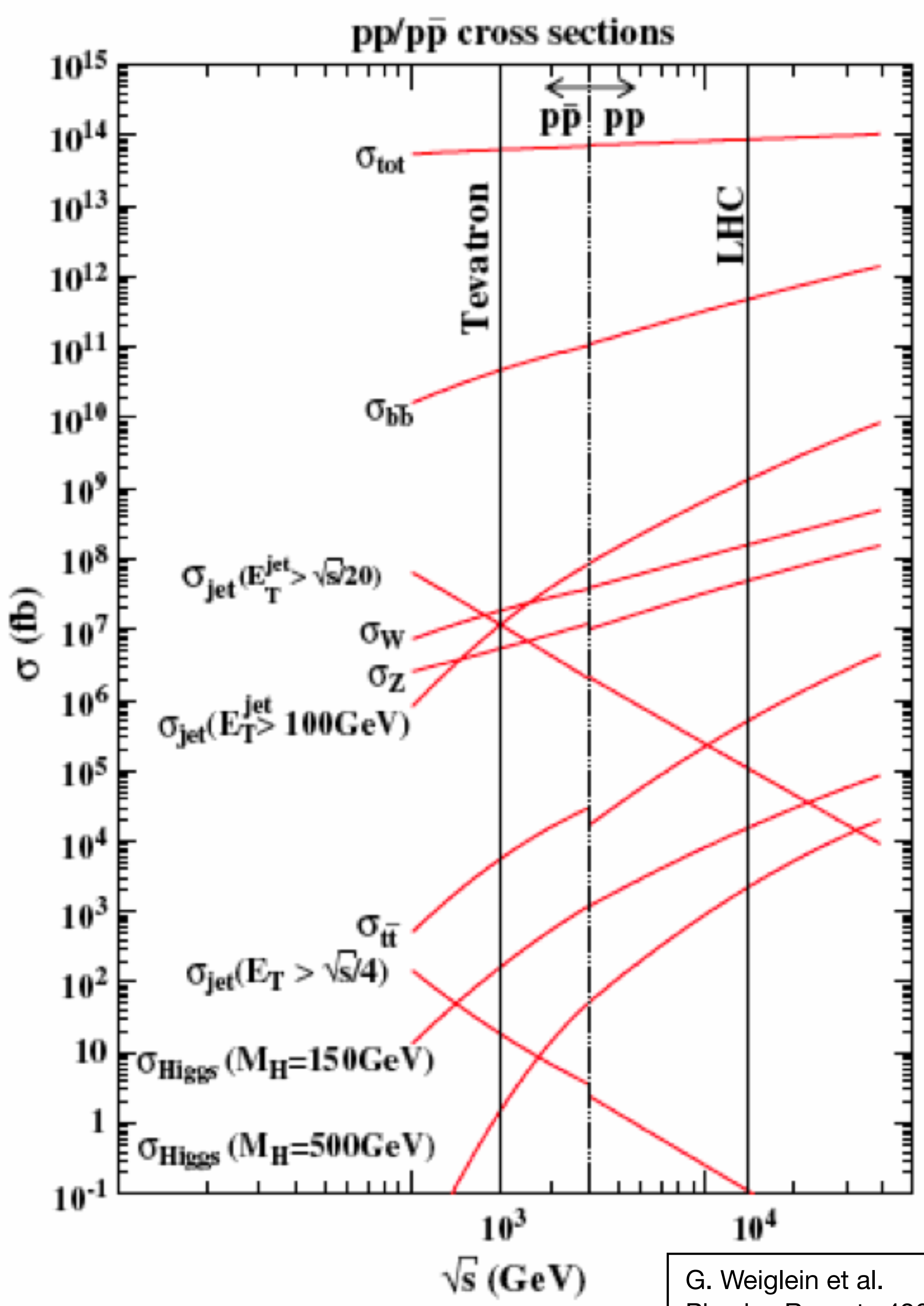

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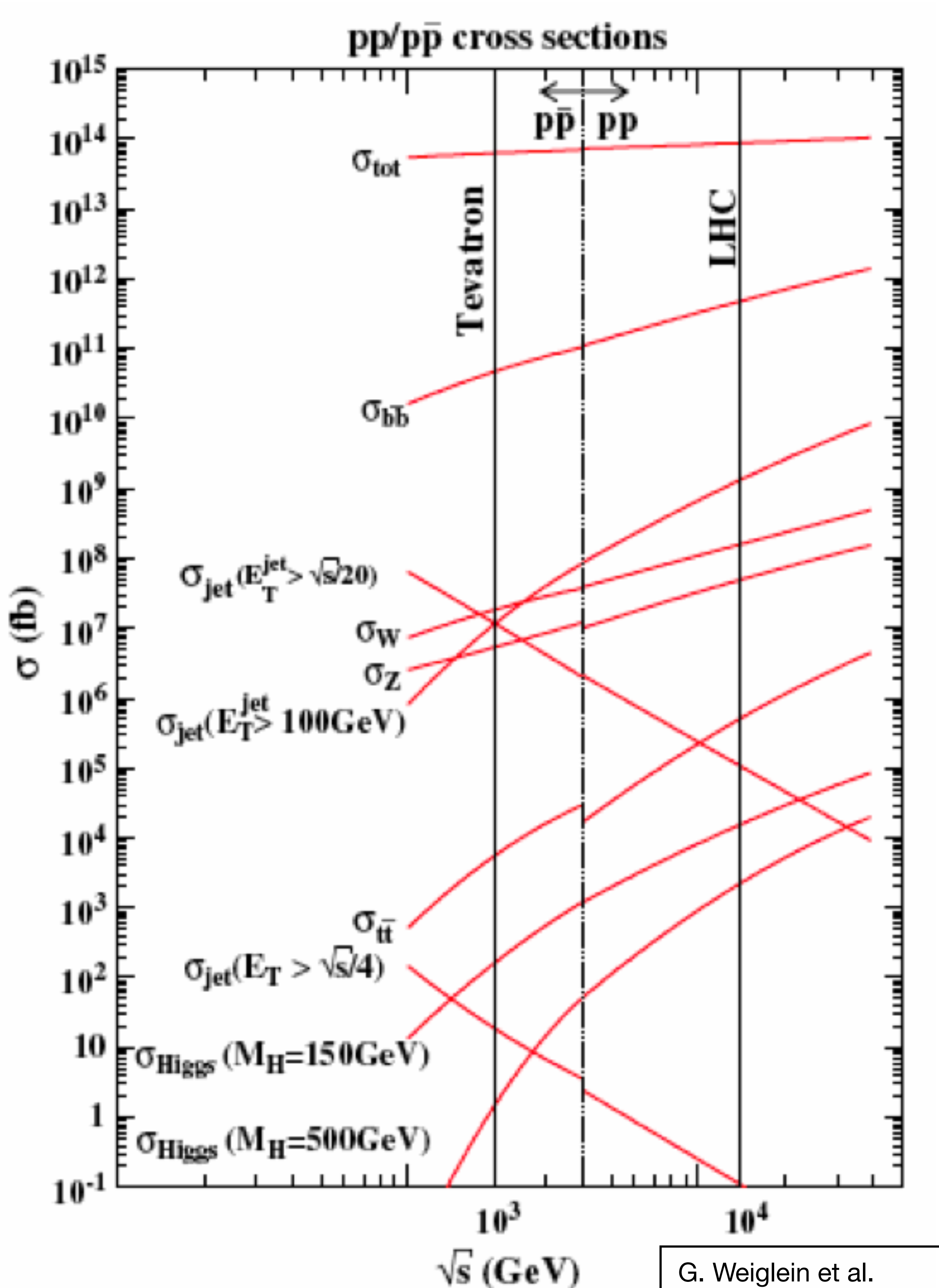

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- Very high event rates required!
- Detectors have to be able to cope with high particle rates and corresponding large amounts of data
- They have to be able to select (“trigger on”) interesting events

Detector Requirements

- Conditions at LHC:
  - Bunch crossing rate: 40 MHz (each 25 ns)
  - Design Luminosity: $L = 10^{34} cm^{-2} s^{-1}$
  - pp - cross section: $\sigma_{pp} \approx 100\, mb = 10^{-25}\, cm^2$

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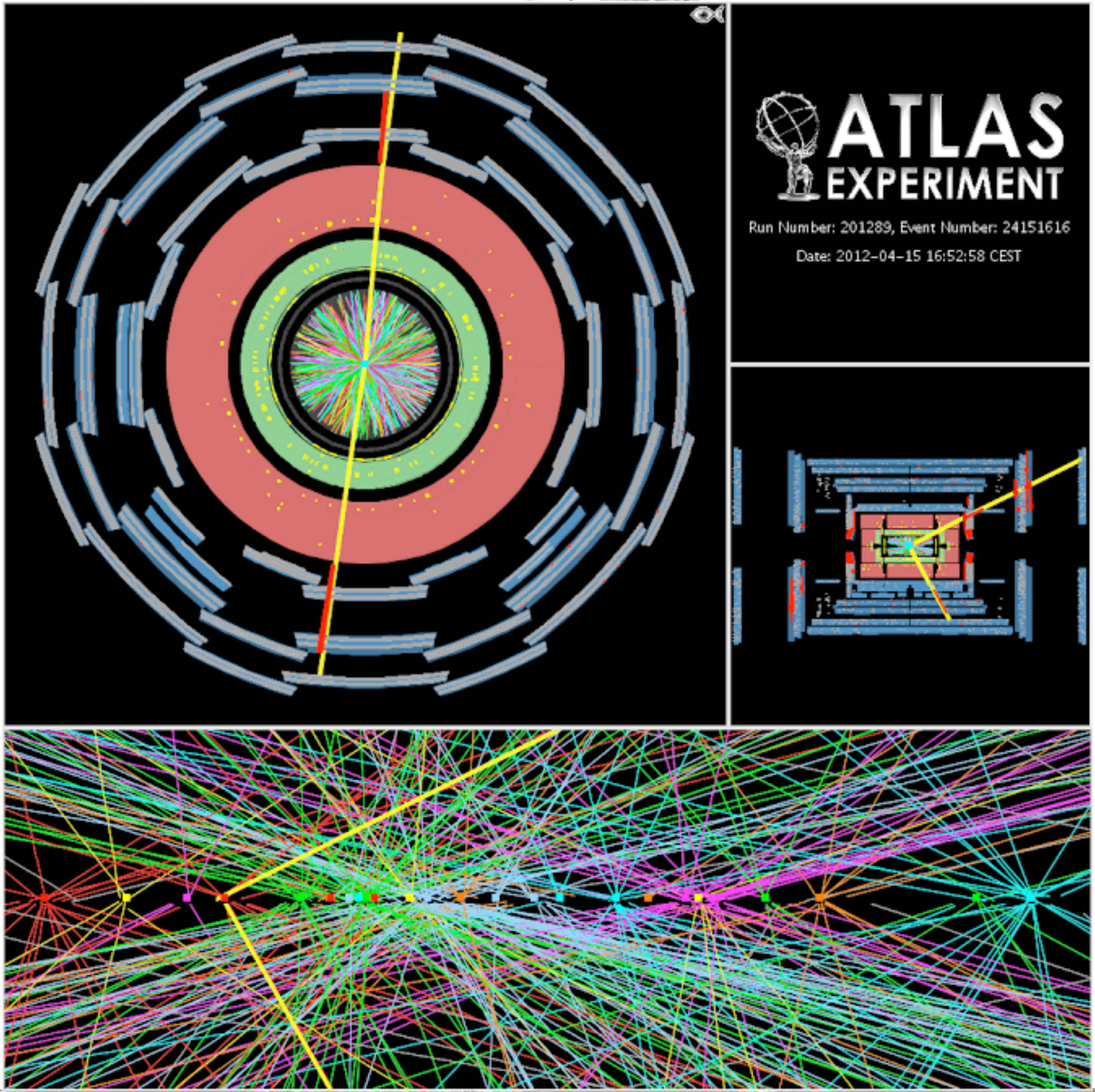
- Detector requirements:
  - high granularity to resolve high particle density
  - Fast readout, data buffering directly on detector (“pipelines”), typically 128 BX deep
  - Needs a fast decision, if an event is interesting and should be read out for further processing: a maximum of 3.2 μs to decide
  - High granularity results in high data volume: Maximum rate that can be stored ~ 100 Hz ➠ requires complex triggers!

LHC: Extreme Conditions



Z -> μμ

... and 25 other collisions

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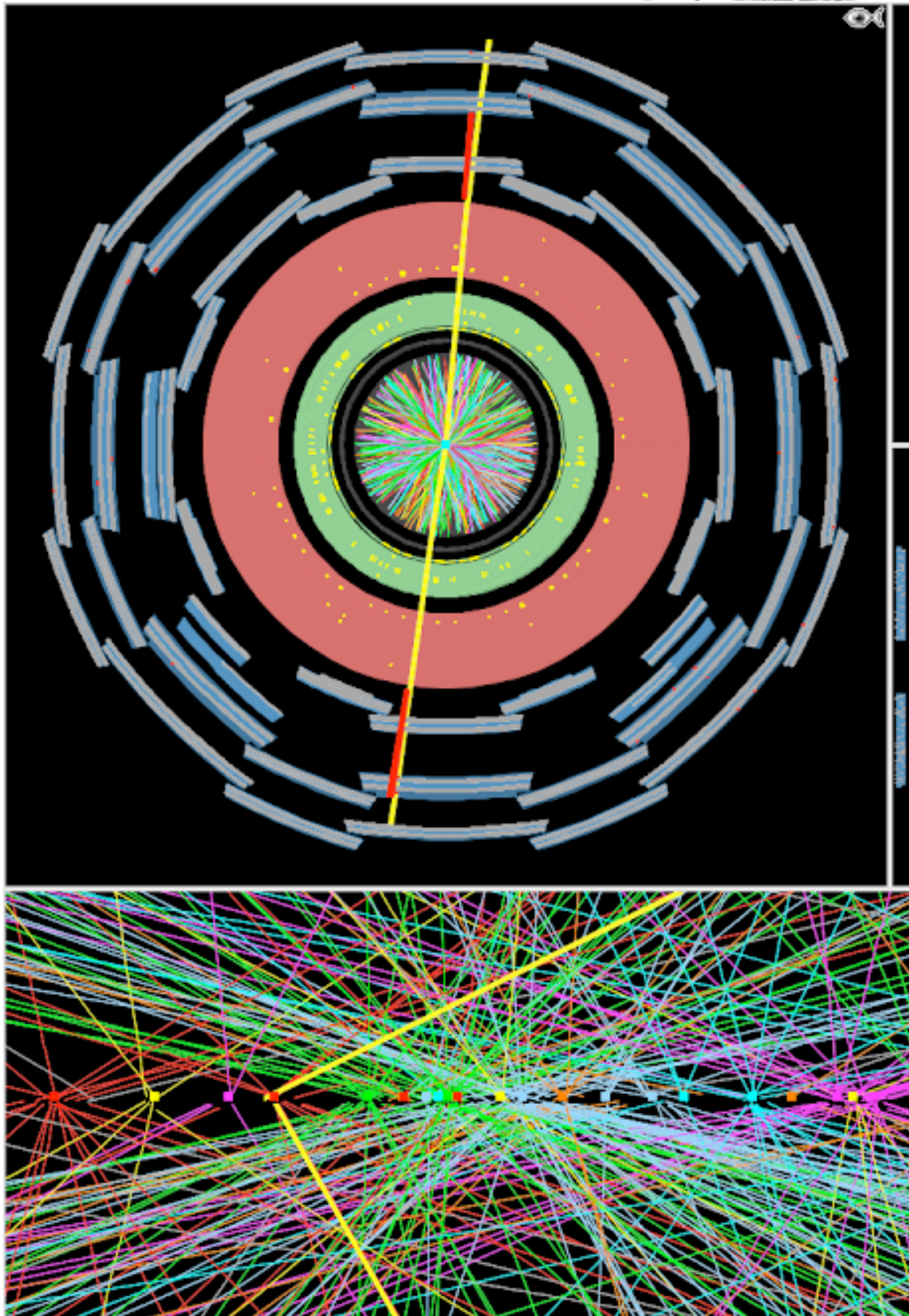

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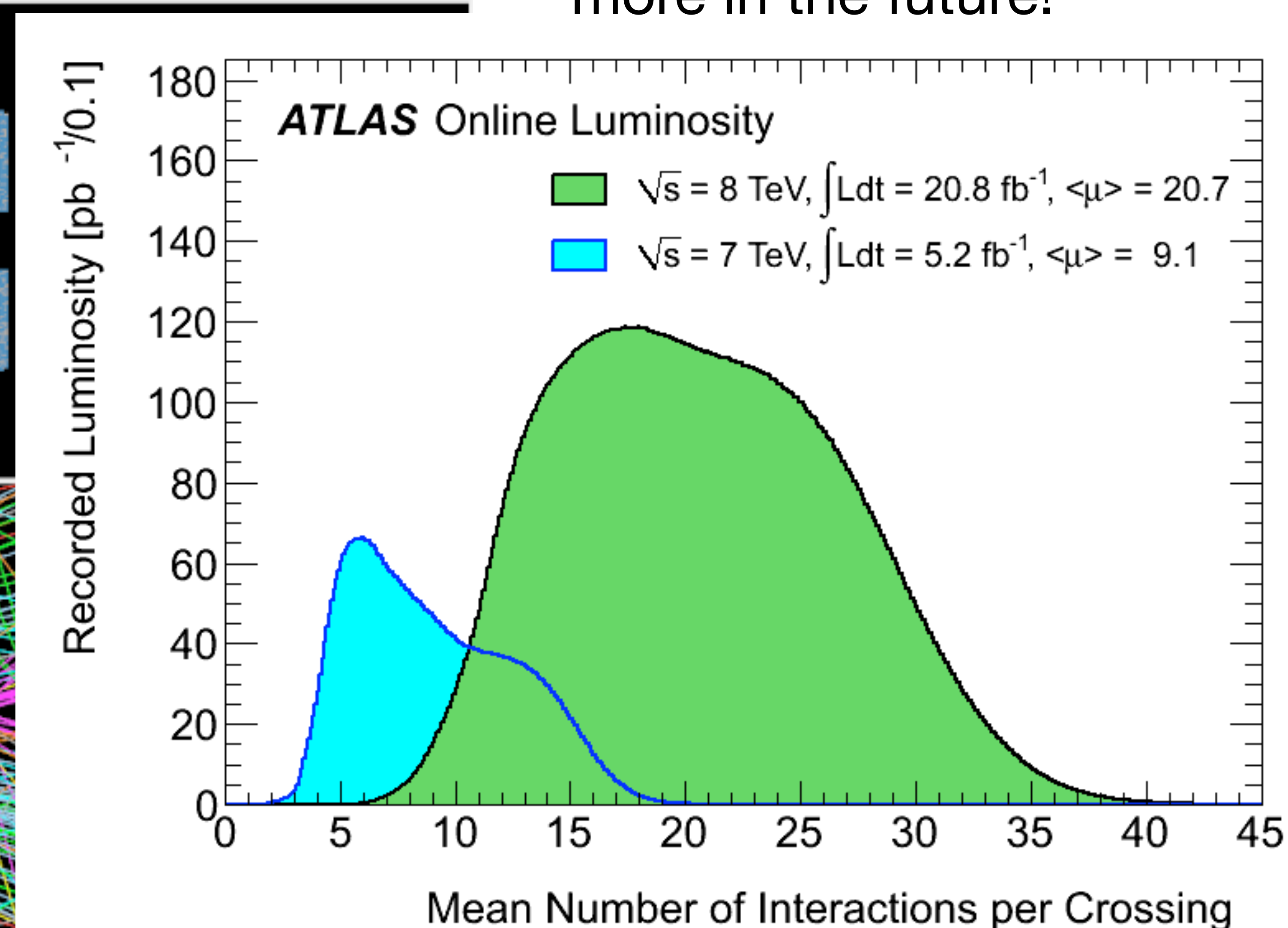
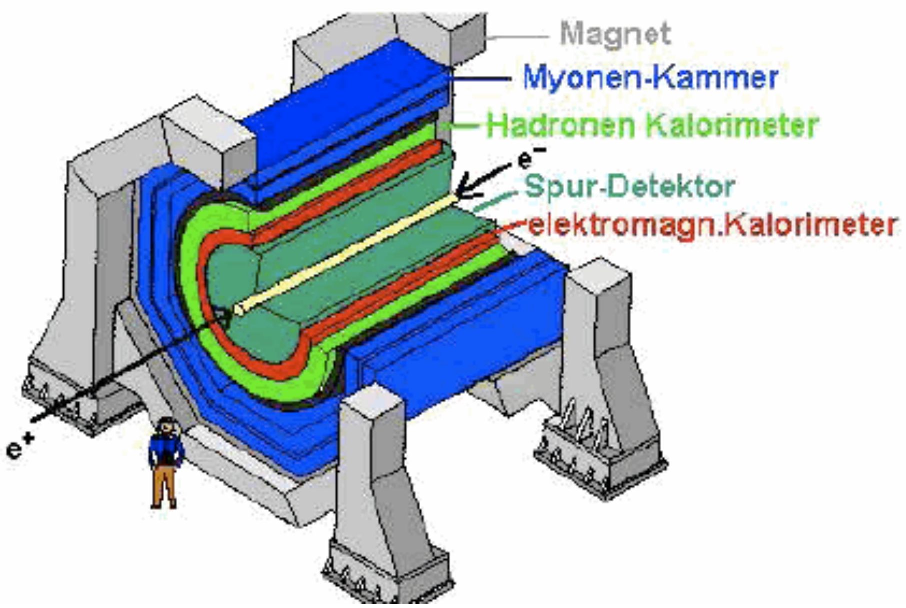
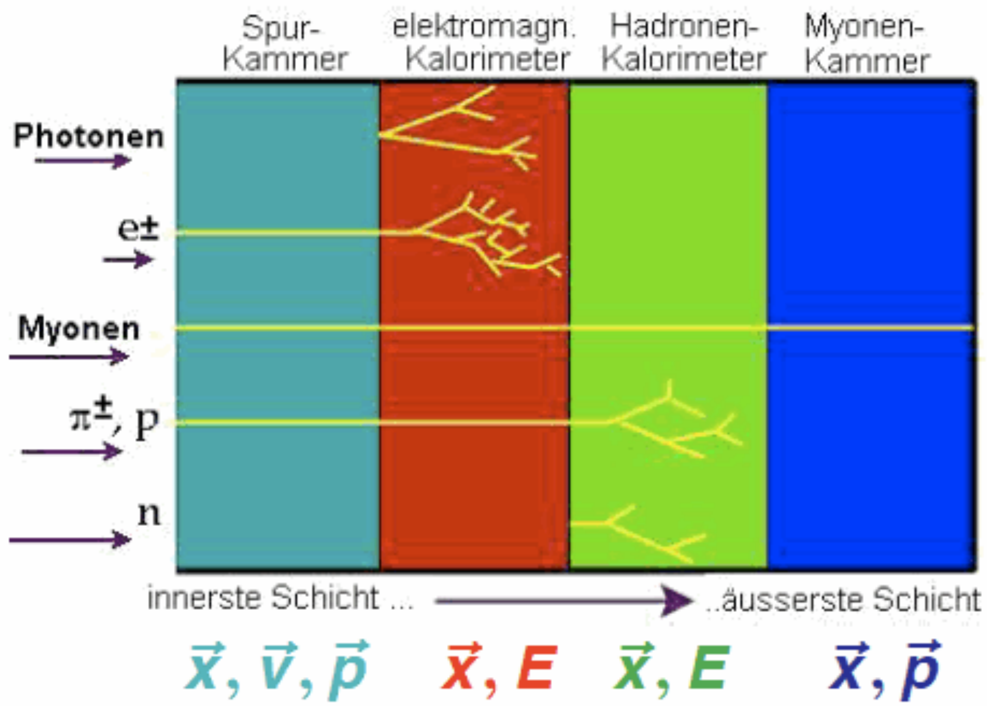
Normal LHC conditions in 2012 data taking - will get more in the future!

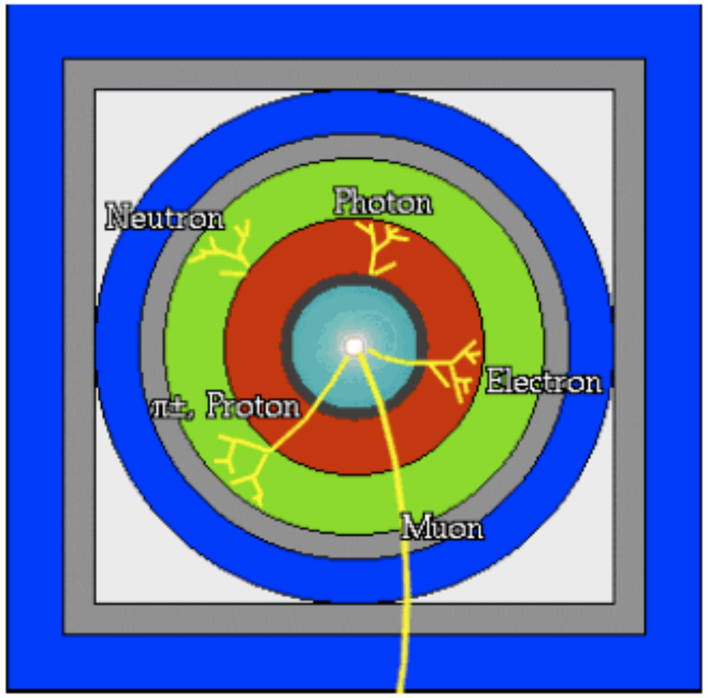


Collider Detectors

- Detection of the final-state particles of the interaction
  - Signals generated via electromagnetic interaction with the detector material







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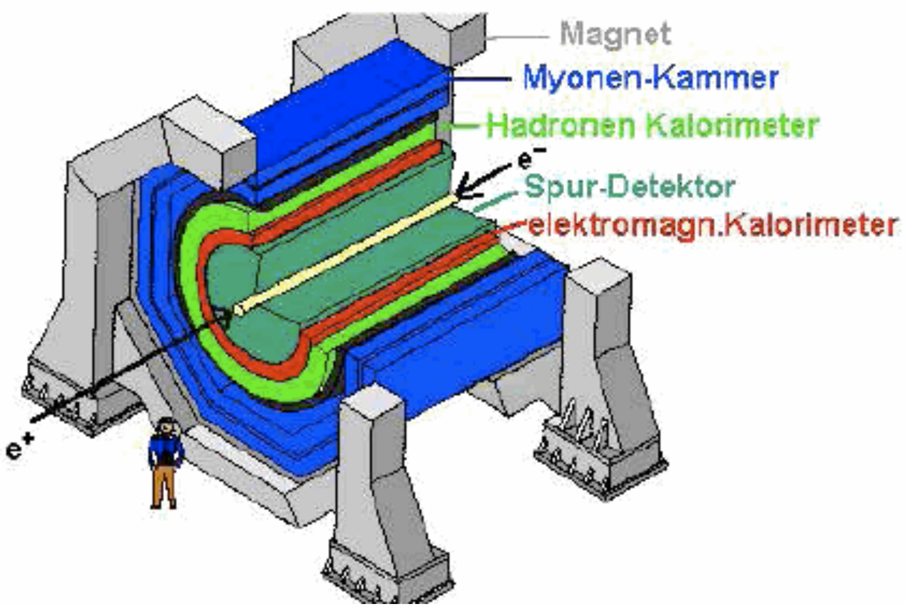

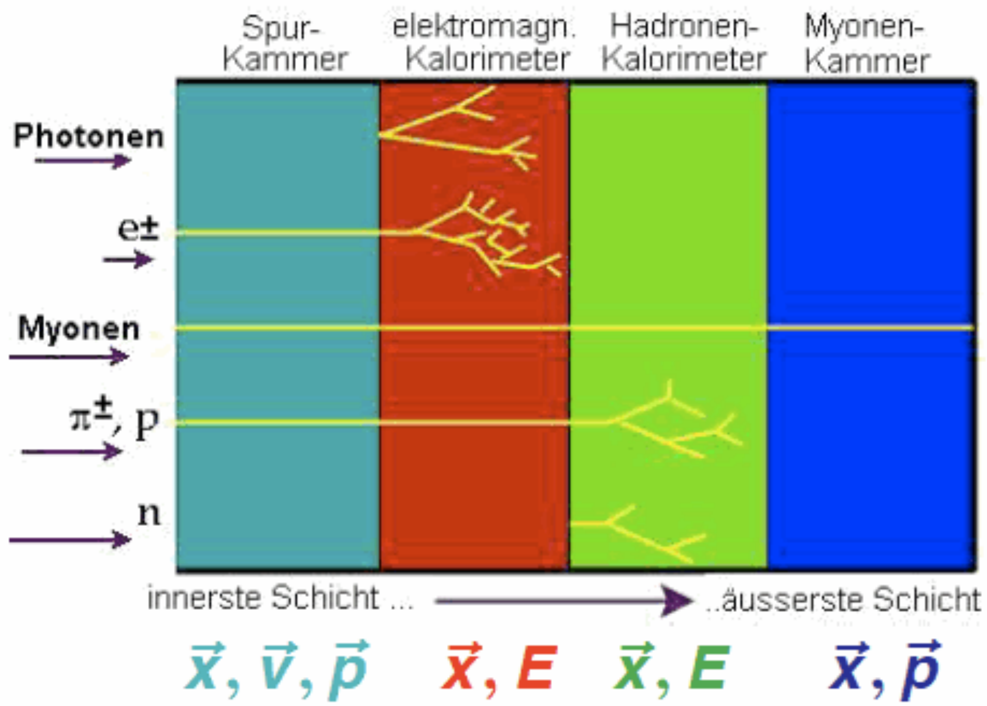

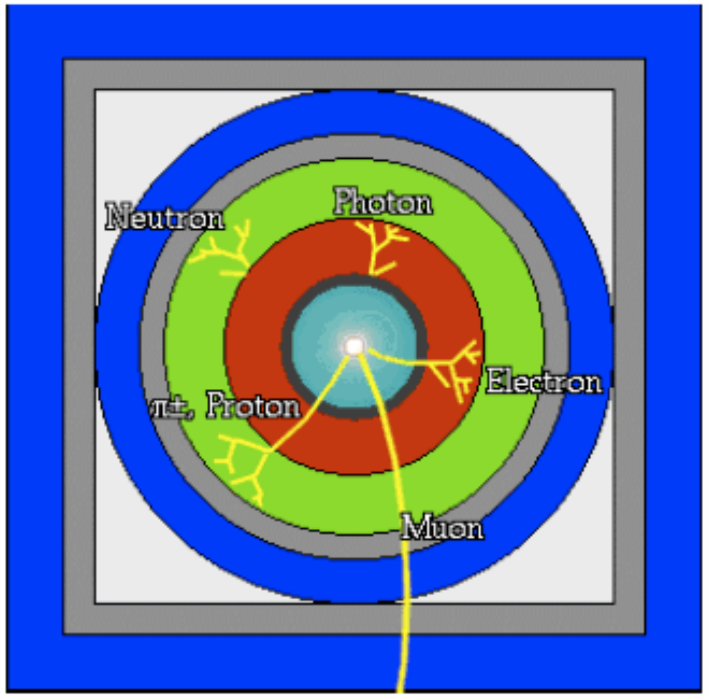

Tracker: Momentum of charged particles via precise measurement of deflection in magnetic field

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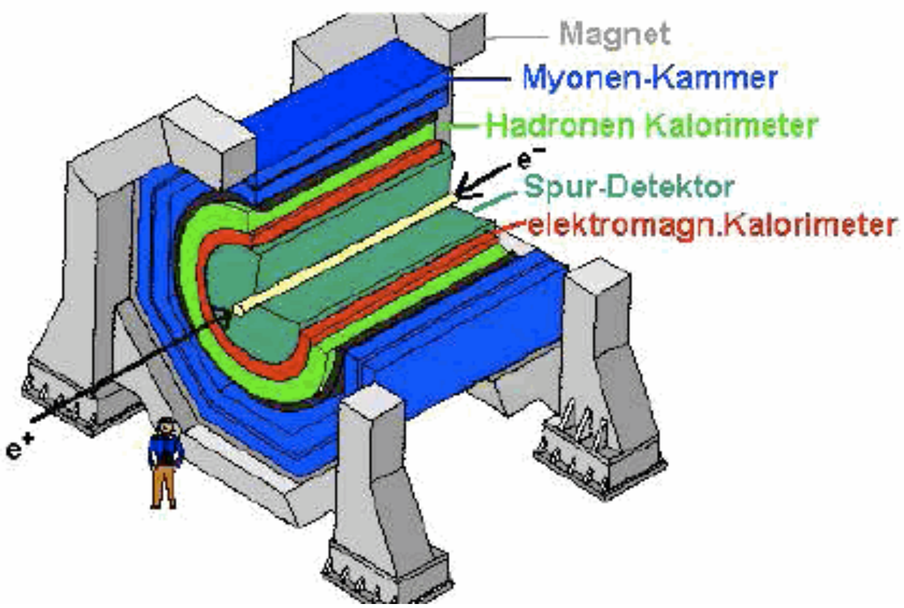

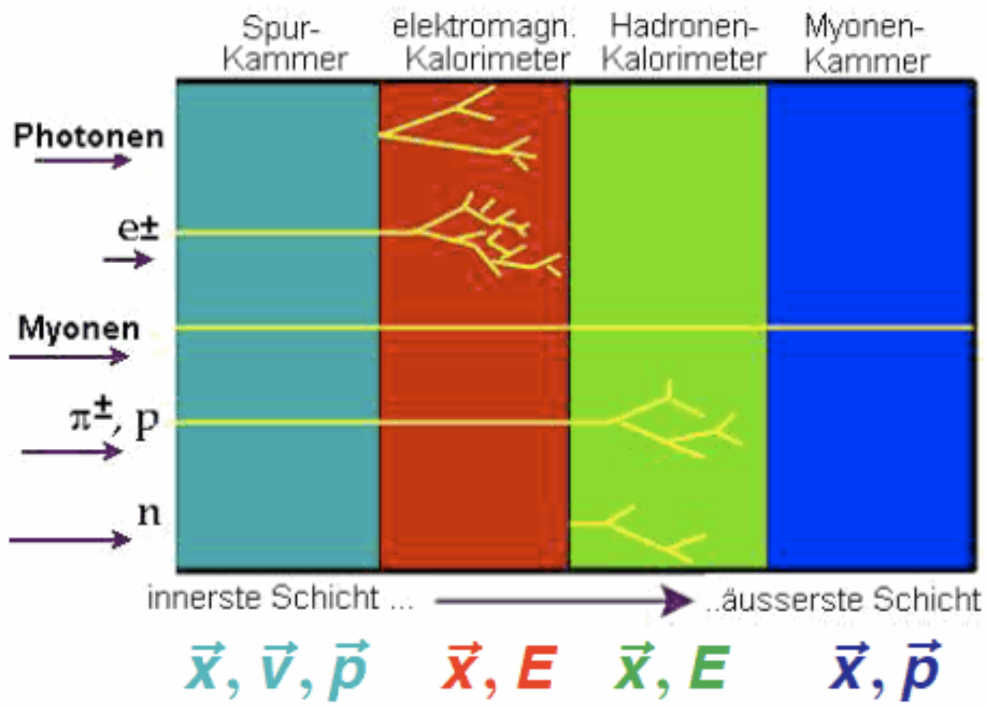

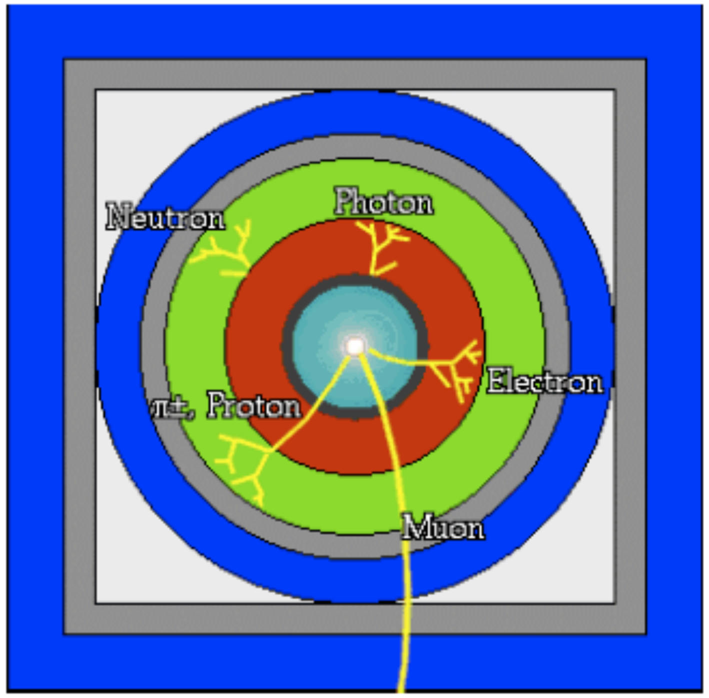

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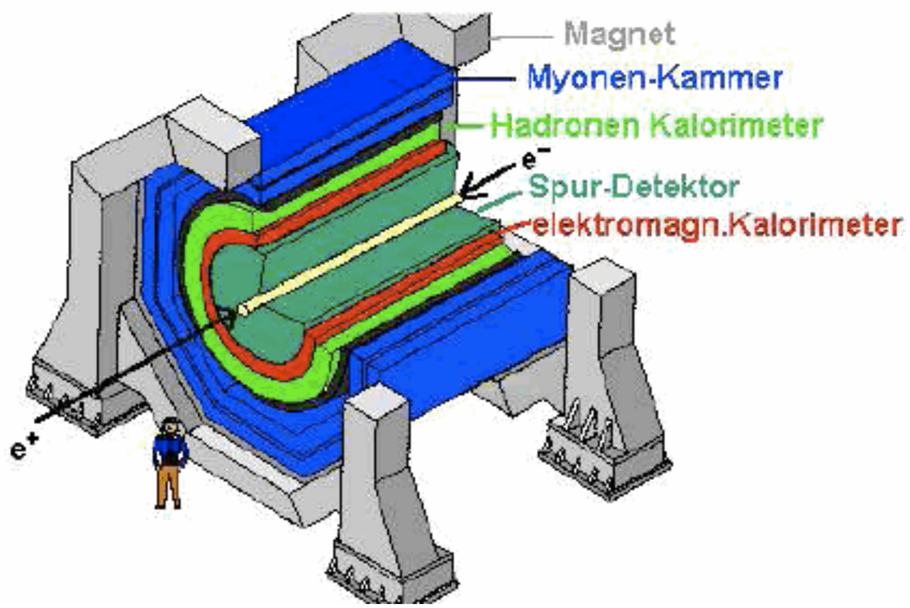

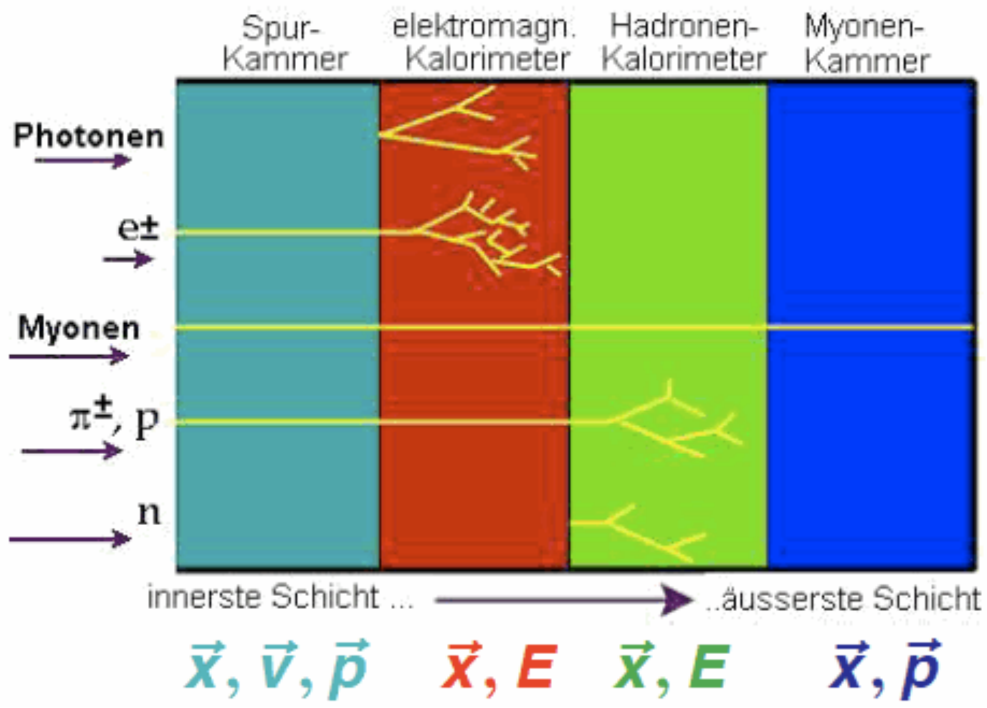

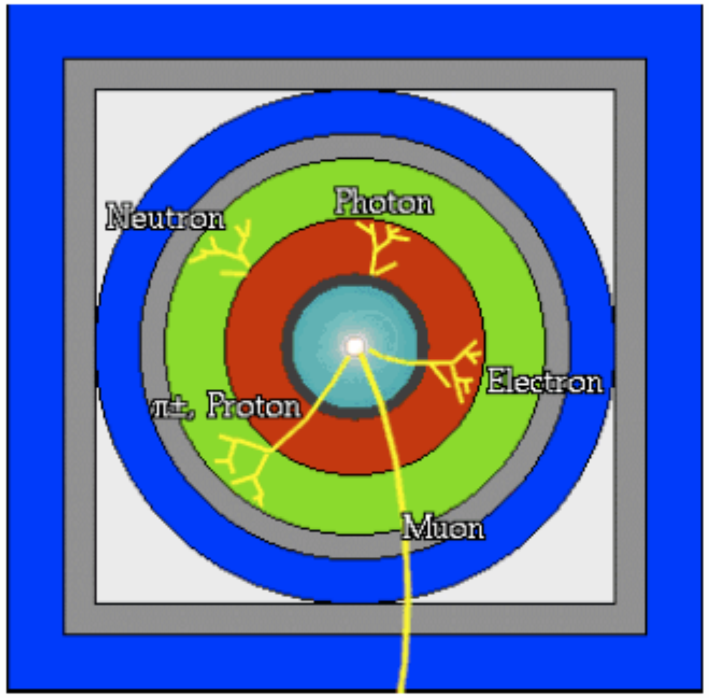

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Calorimeters: Energy measurement for photons, electrons and hadrons by total absorption

Muon detectors: Identification and precise momentum measurement outside of the main magnet

Generic Detector Construction Guide

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- 1. - 3. have to be inside of a magnet to measure momentum
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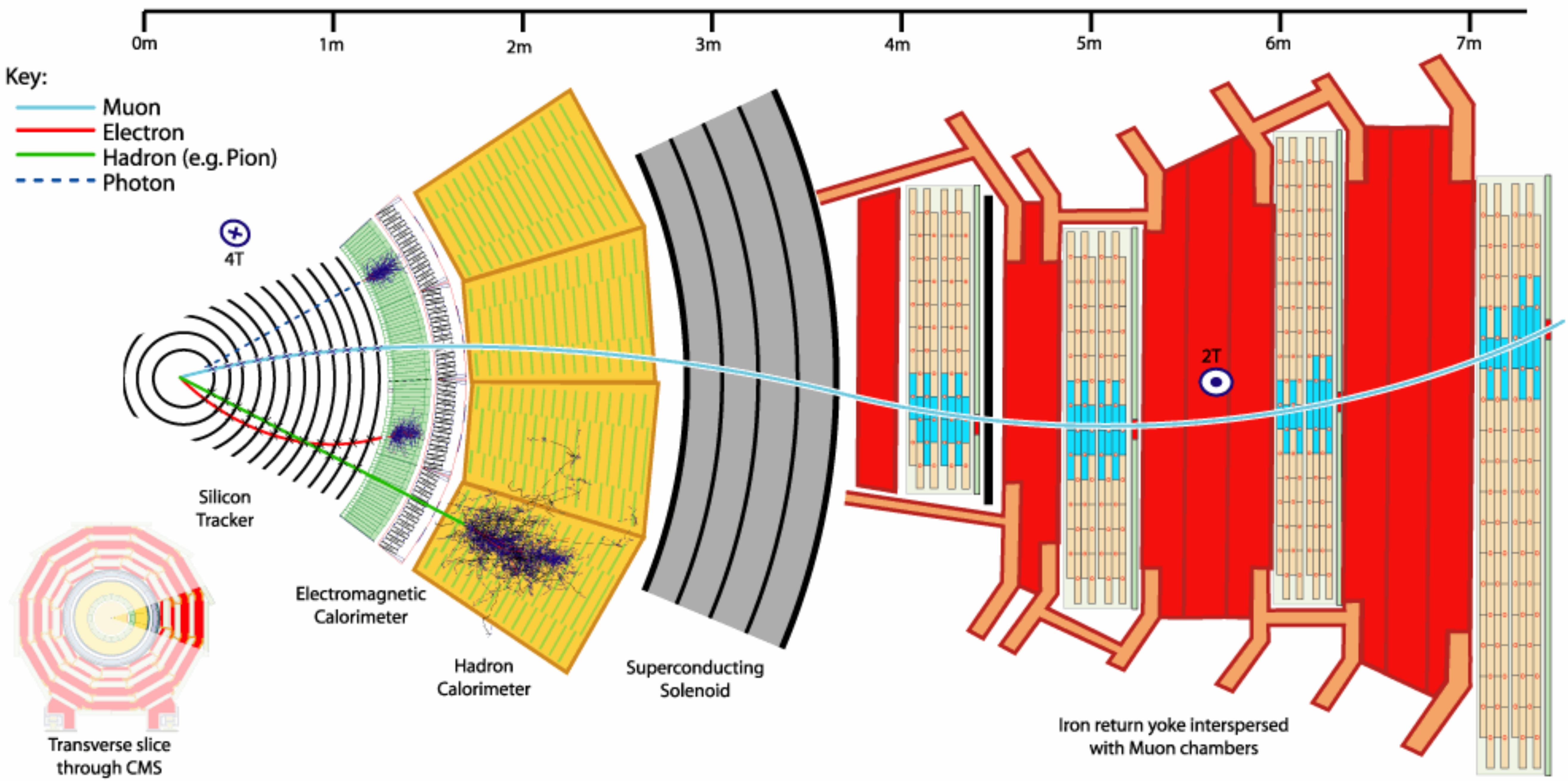
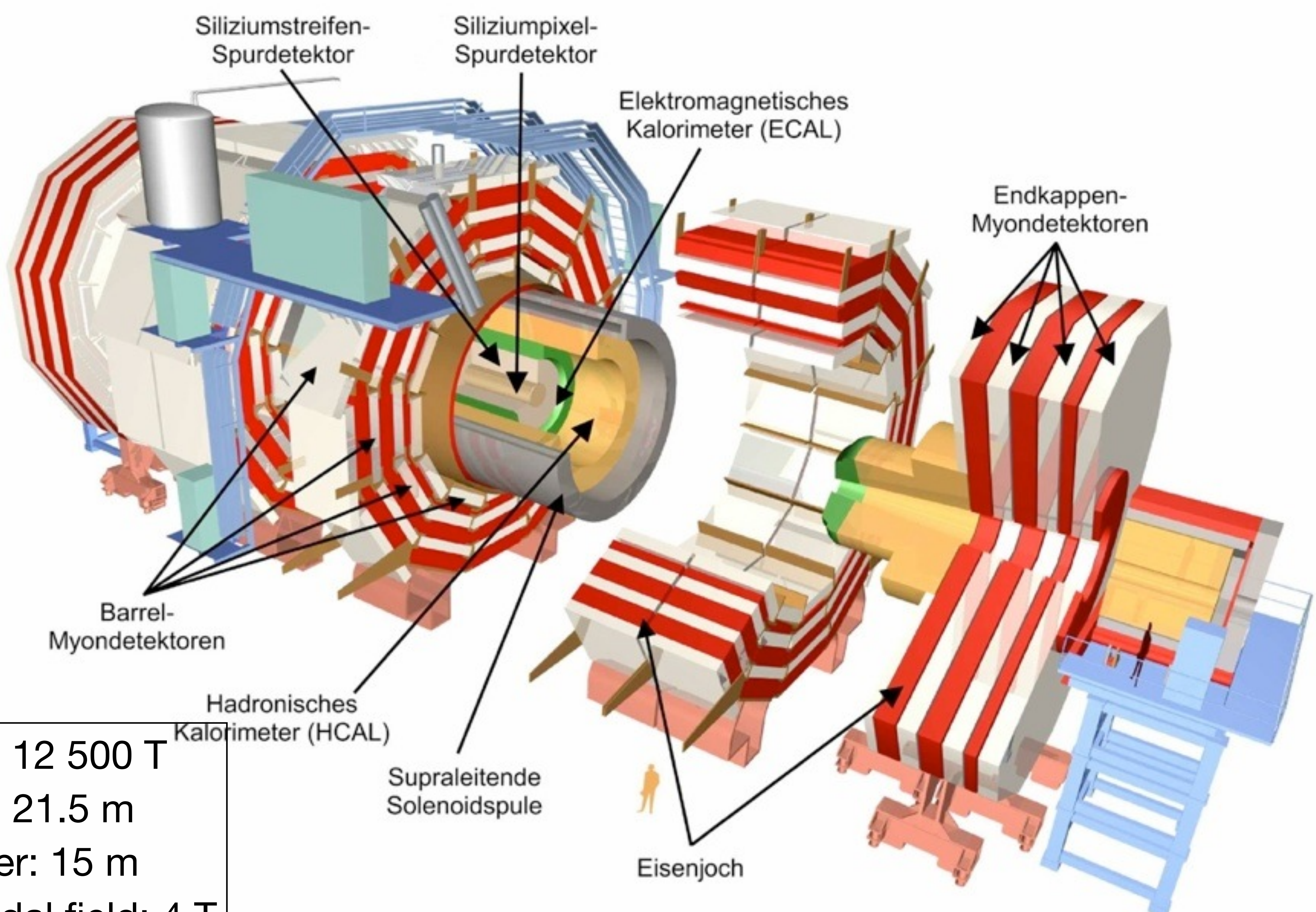
  - 6. A big (and strong) magnet!

Detector Systems at Hadron Colliders

Collider Detectors: Cross Section [CMS]



CMS: The Heavy Weight



Weight: 12 500 T
Length: 21.5 m
Diameter: 15 m
Solenoidal field: 4 T

CMS

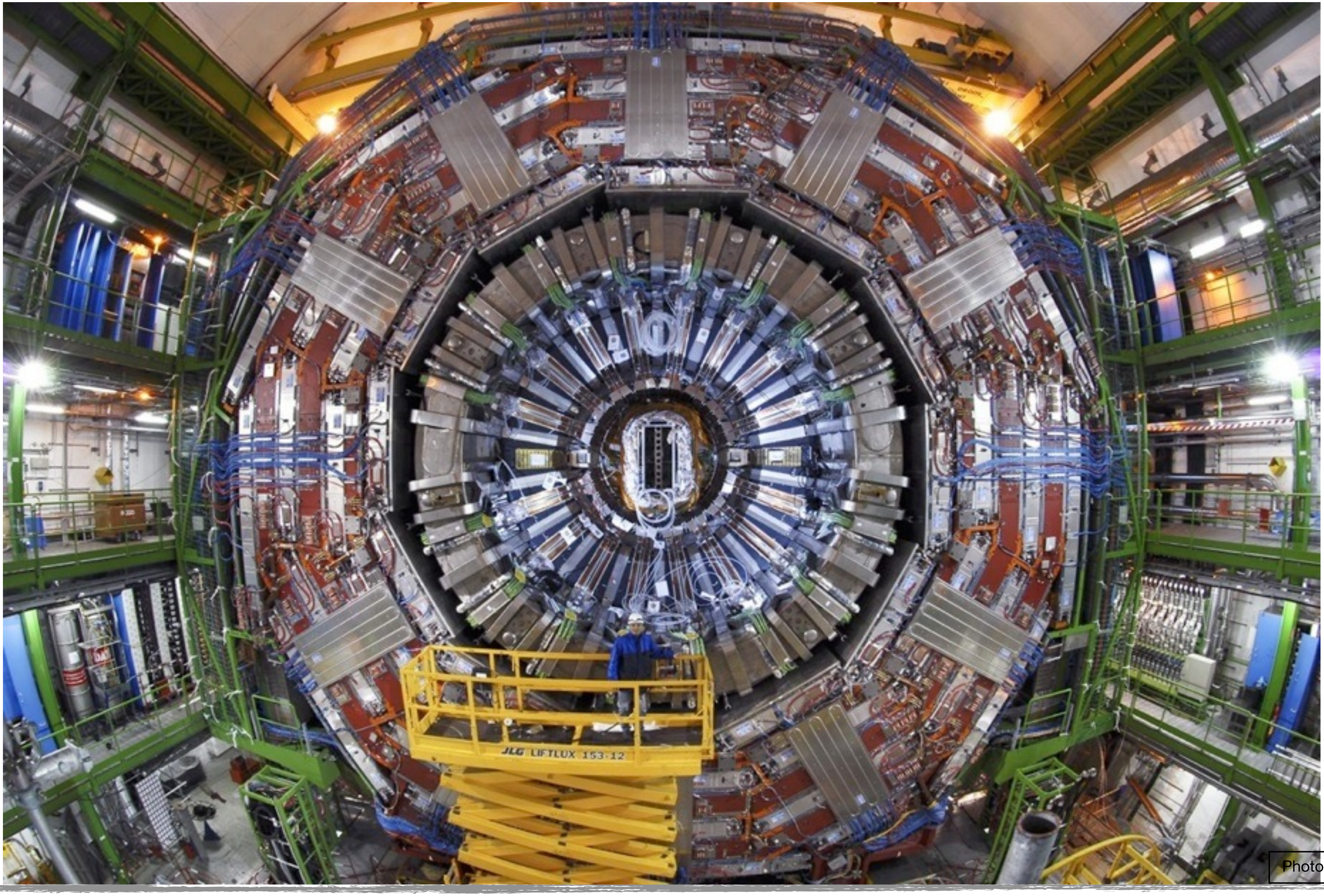
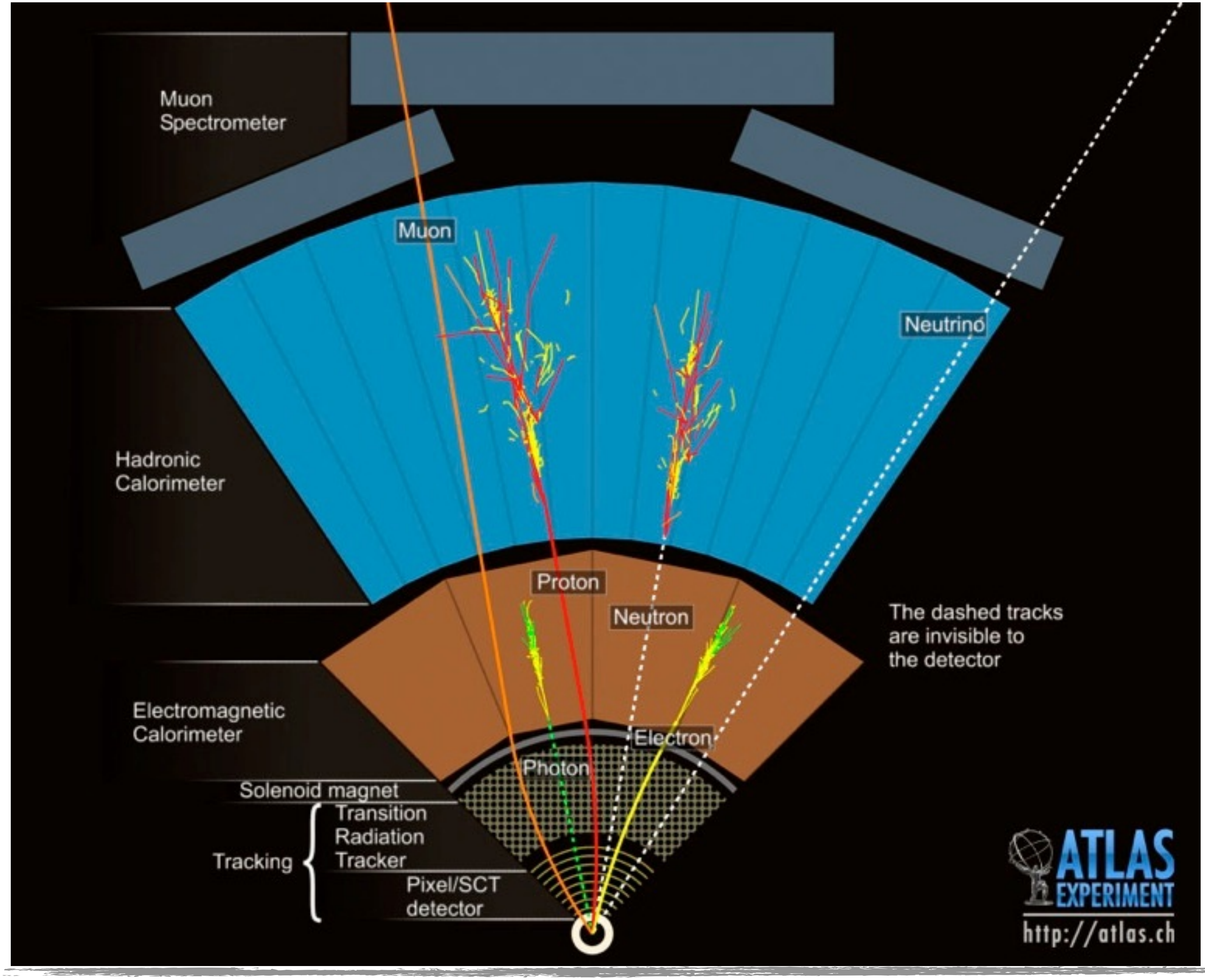
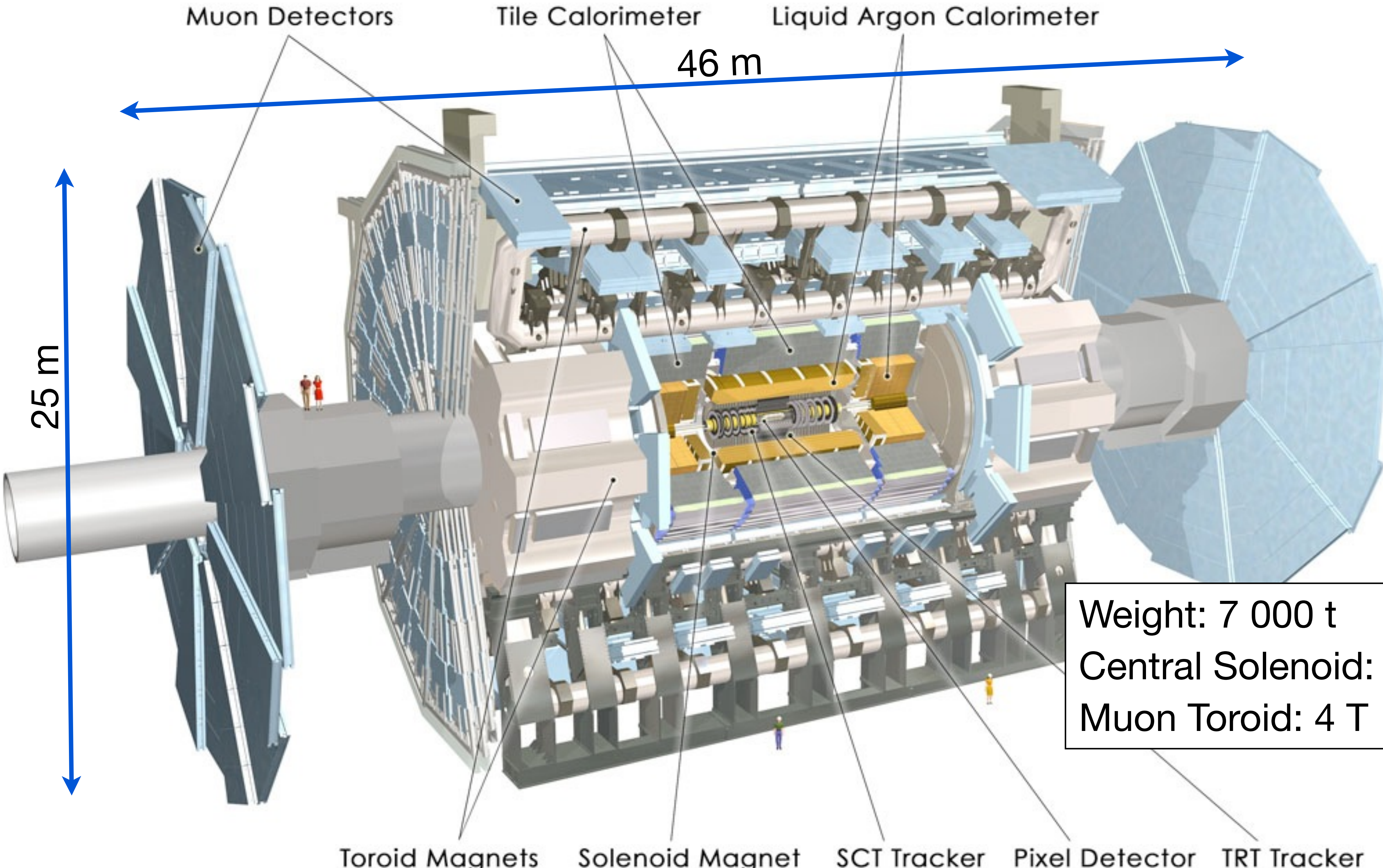


Photo: CERN

Particles in ATLAS



ATLAS: The biggest Detector in Particle Physics



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

Illustration: CERN

ATLAS

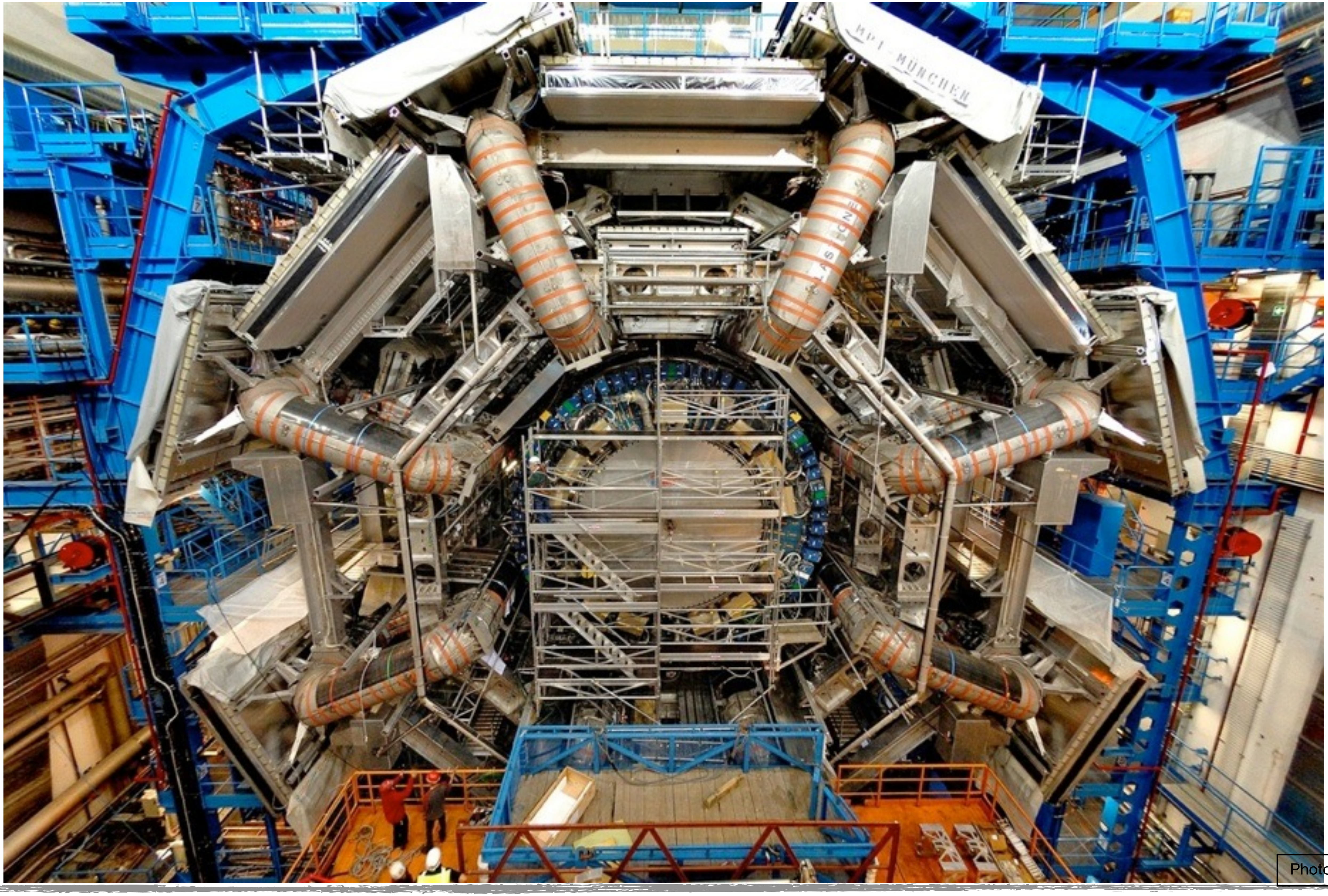


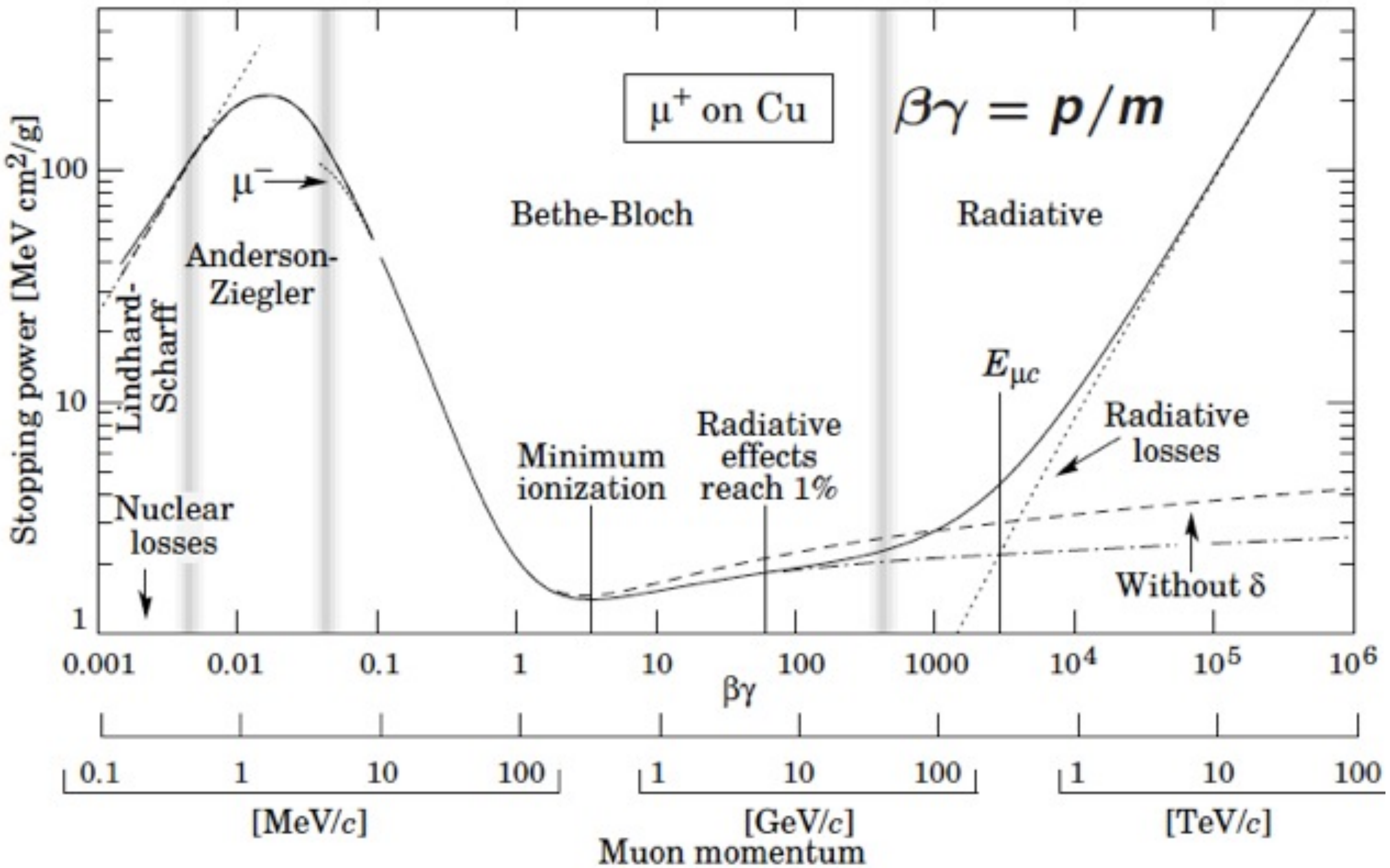
Photo: CERN

Basics of Particle Detection: Interaction with Matter

Energy Loss in Matter: Bethe-Bloch

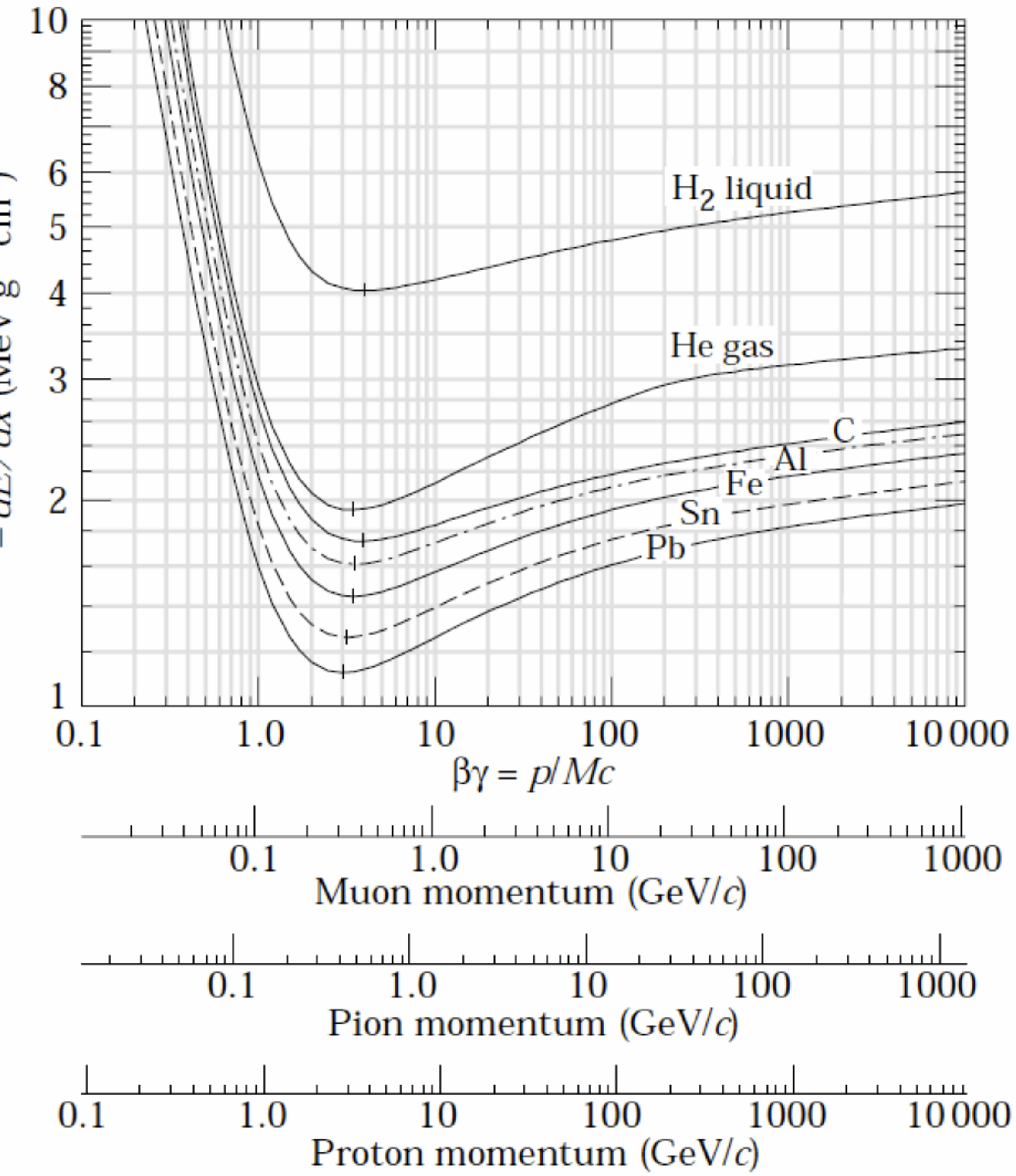
- The Bethe-Bloch Formula describes energy loss by ionization

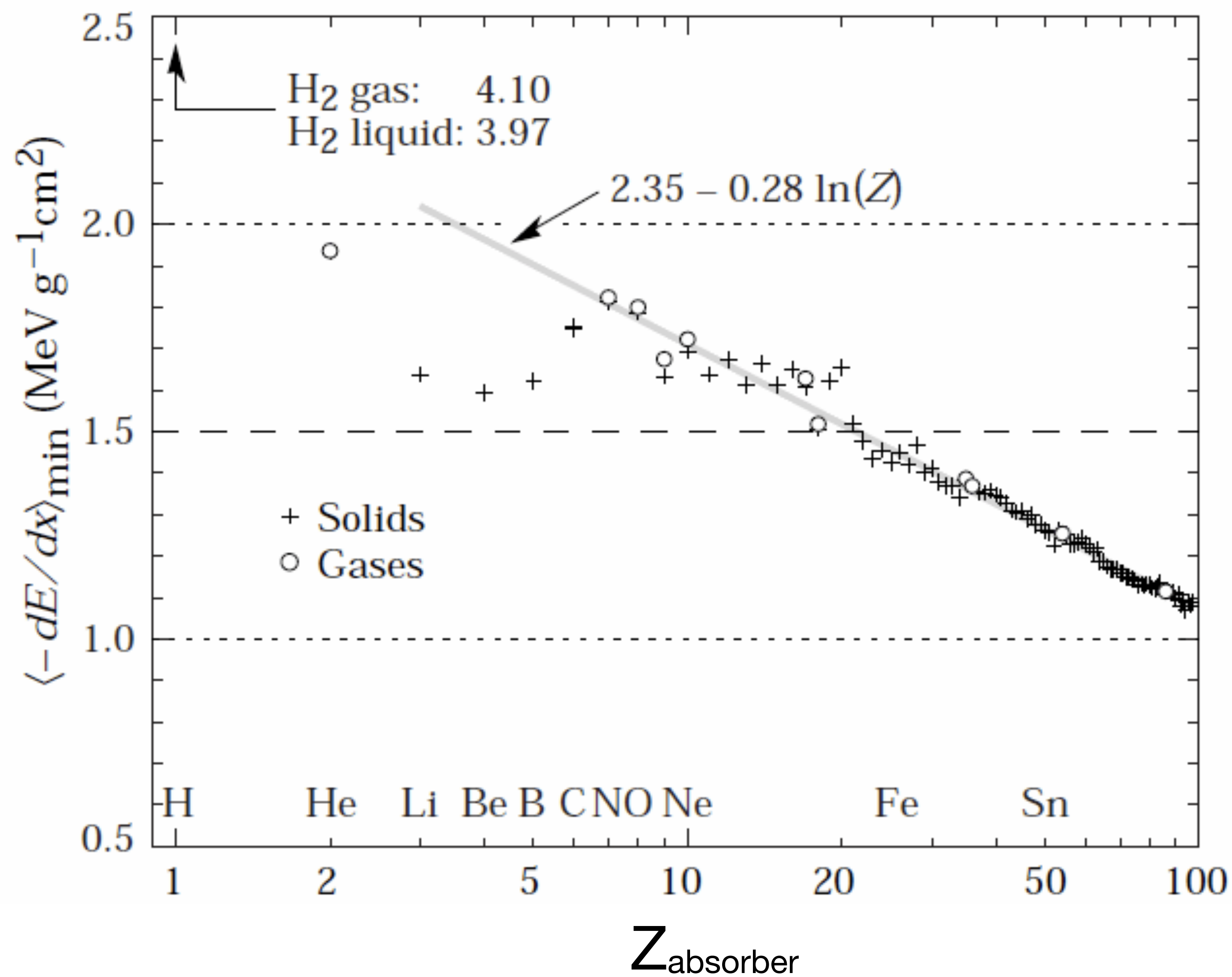
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$



- Applicable in intermediate energy range
  - Atomic effects at low energies and Bremsstrahlung at high energies separately
- Z/A dependence: large energy loss in H
- $1/\beta^2$ at low momenta: Heavy particles loose more energy
- Minimum at p/m ~ 3-4: minimum ionizing particle MIP
- logarithmic rise for high momentum
- Density effect due to polarization of medium

Material Dependence of Energy Loss





- Simple approximation: Energy loss of MIPs ($\beta\gamma$ ~ 3): 1-2 MeV g^{-1} cm^2 (exception: H)

Energy Loss: A Closer Look

- Bethe-Bloch only gives the mean value!
  - Energy loss is a statistical process

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On the microscopic level: discrete scatterings, leading to ionization

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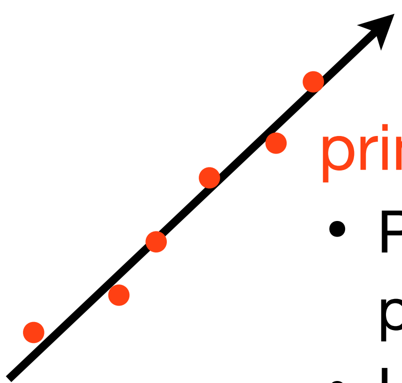
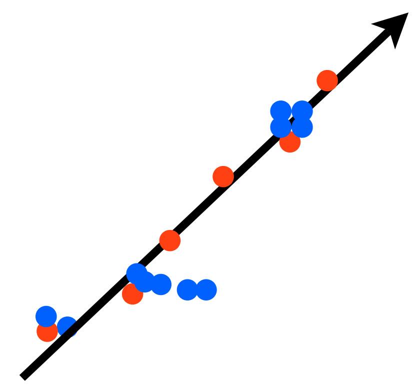
⇨ Distinguishing primary and secondary ionization:



primary ionization

- Poissonian distributed per unit length
- Large fluctuations of energy loss per collision



secondary ionization

‣ originating from high-energy primary electrons

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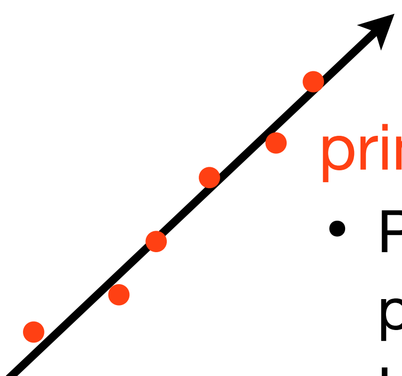

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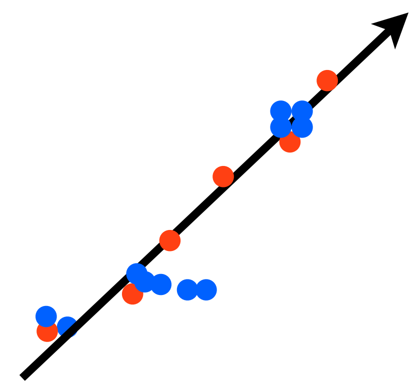

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total ionization = primary ionization + secondary ionization

In gases (STP) typically 30 primary reactions per cm, 90 electrons per cm

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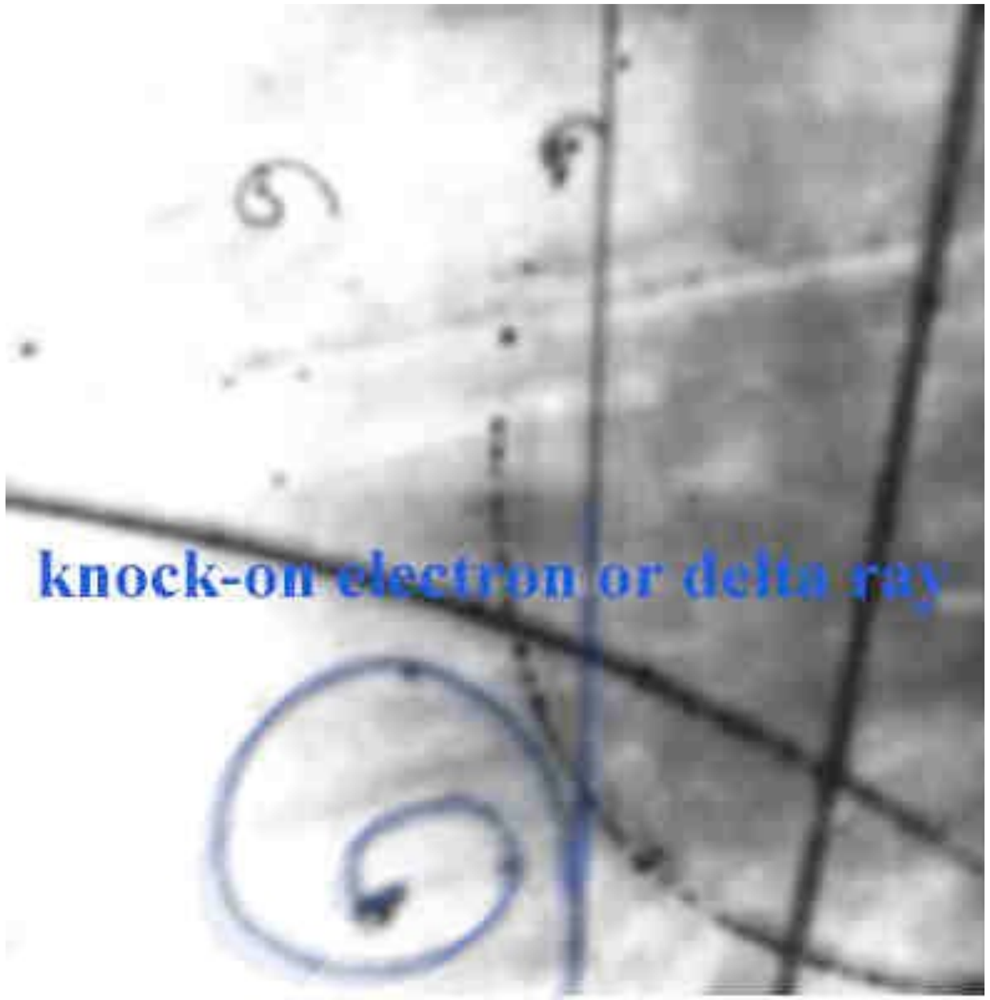
Energy Loss: A Closer Look



- Example for a delta electron in a bubble chamber: clearly visible range!

Energy Loss in Thin Layers

- The large range of the energy loss in individual reactions results in large variations of the energy loss in thin detectors:
  - A broad maximum: Collisions with relatively small energy loss
  - A long tail to high energy loss: few collisions with large energy loss, δ electrons

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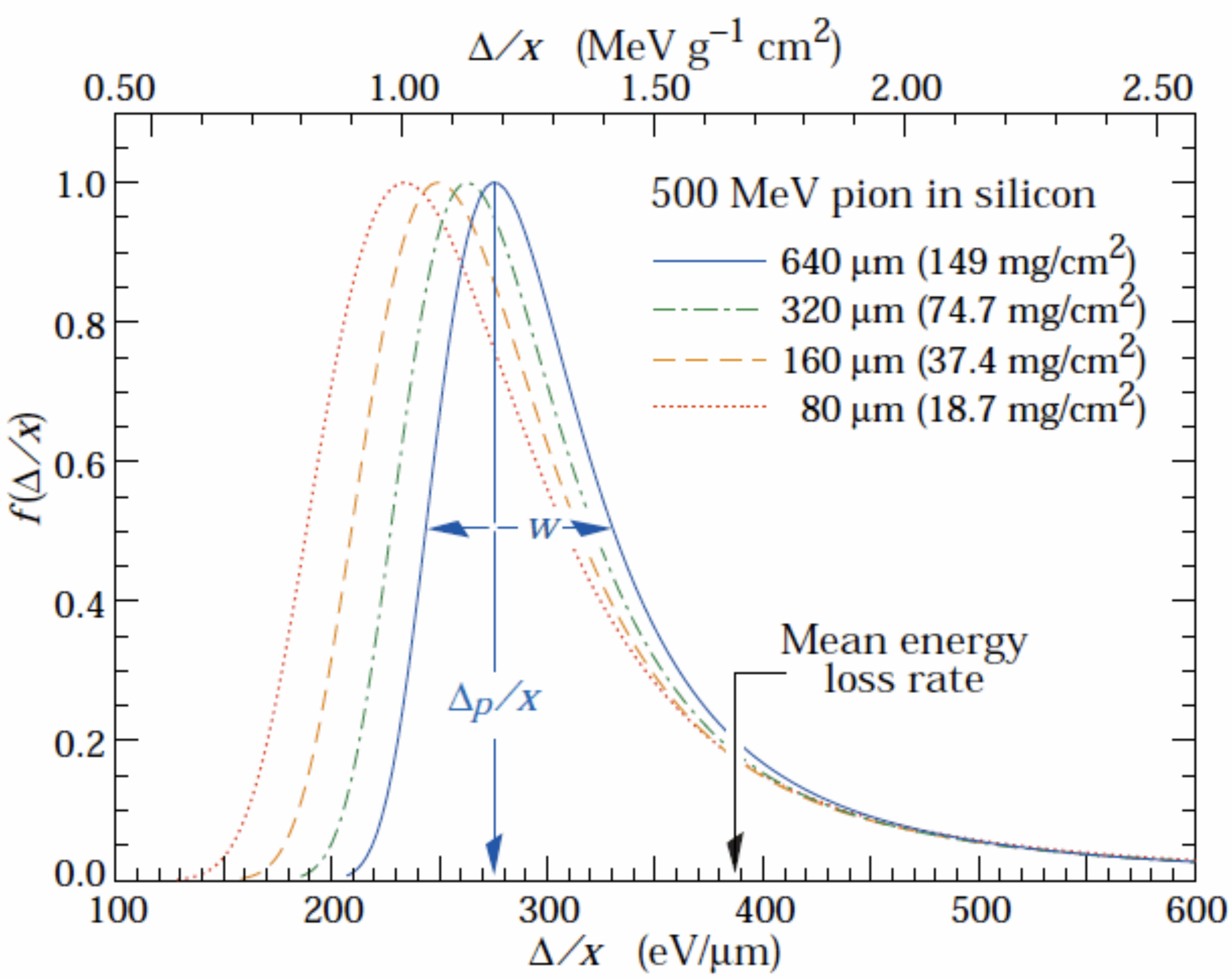


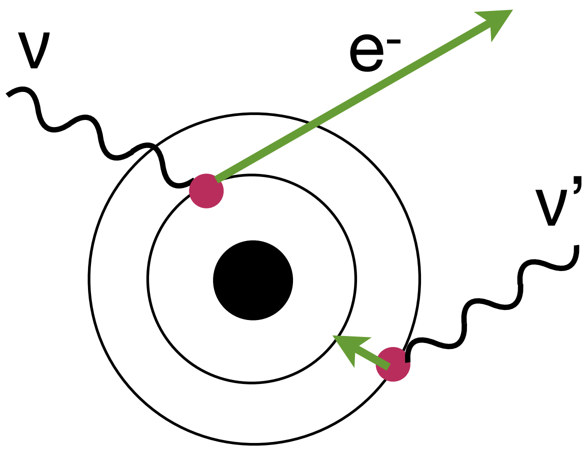
The energy loss in thin layers was first described by Landau: **Landau distribution**

Thin absorber:
$\langle \Delta E \rangle < \sim 10\ T_{max}$

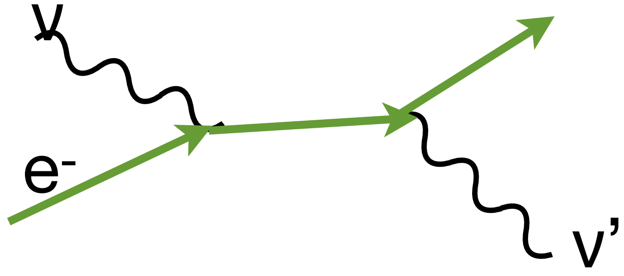
For 500 MeV pions: T_{max} ~ 9 MeV
(Mean energy loss in 9 mm of Si)

Photons: Interactions

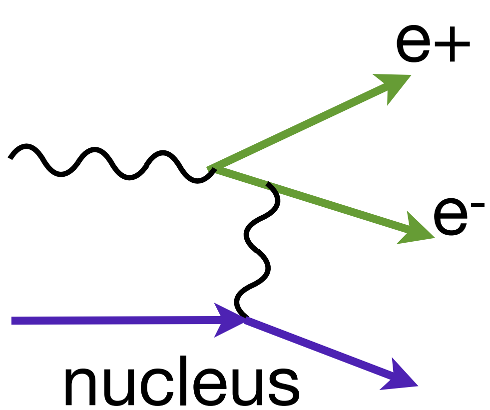
photo effect



Compton scattering



pair creation



energy threshold:

$2\ m_e = \sim 1.022$ MeV

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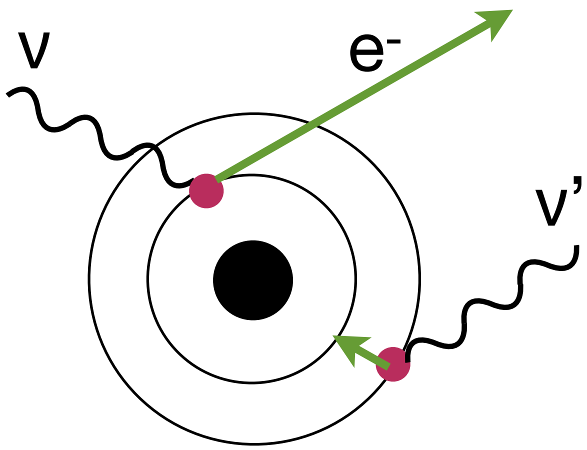

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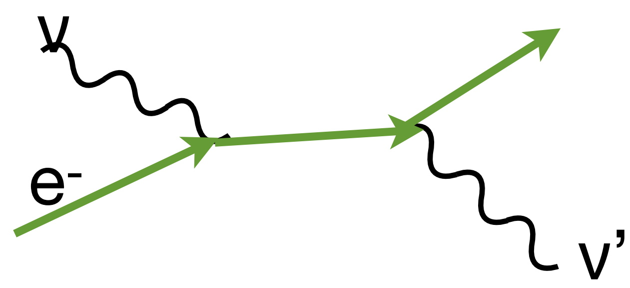

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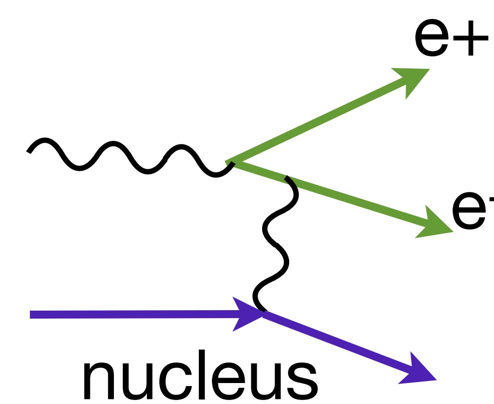

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  "All or nothing" reactions

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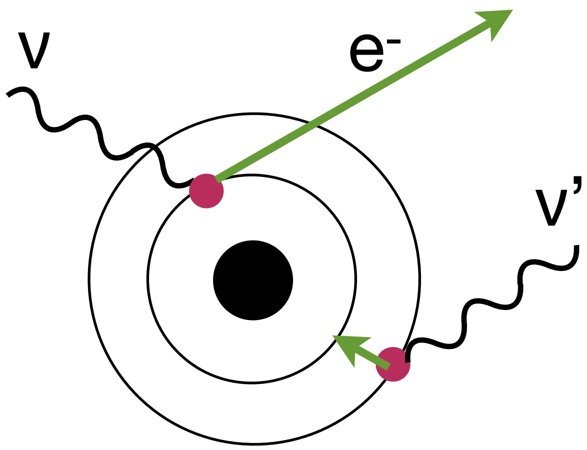

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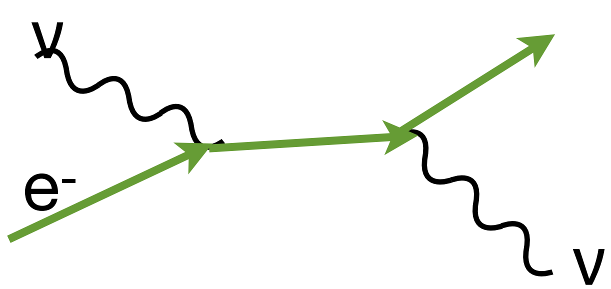

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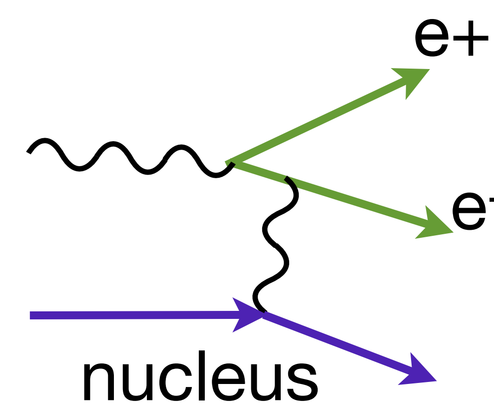


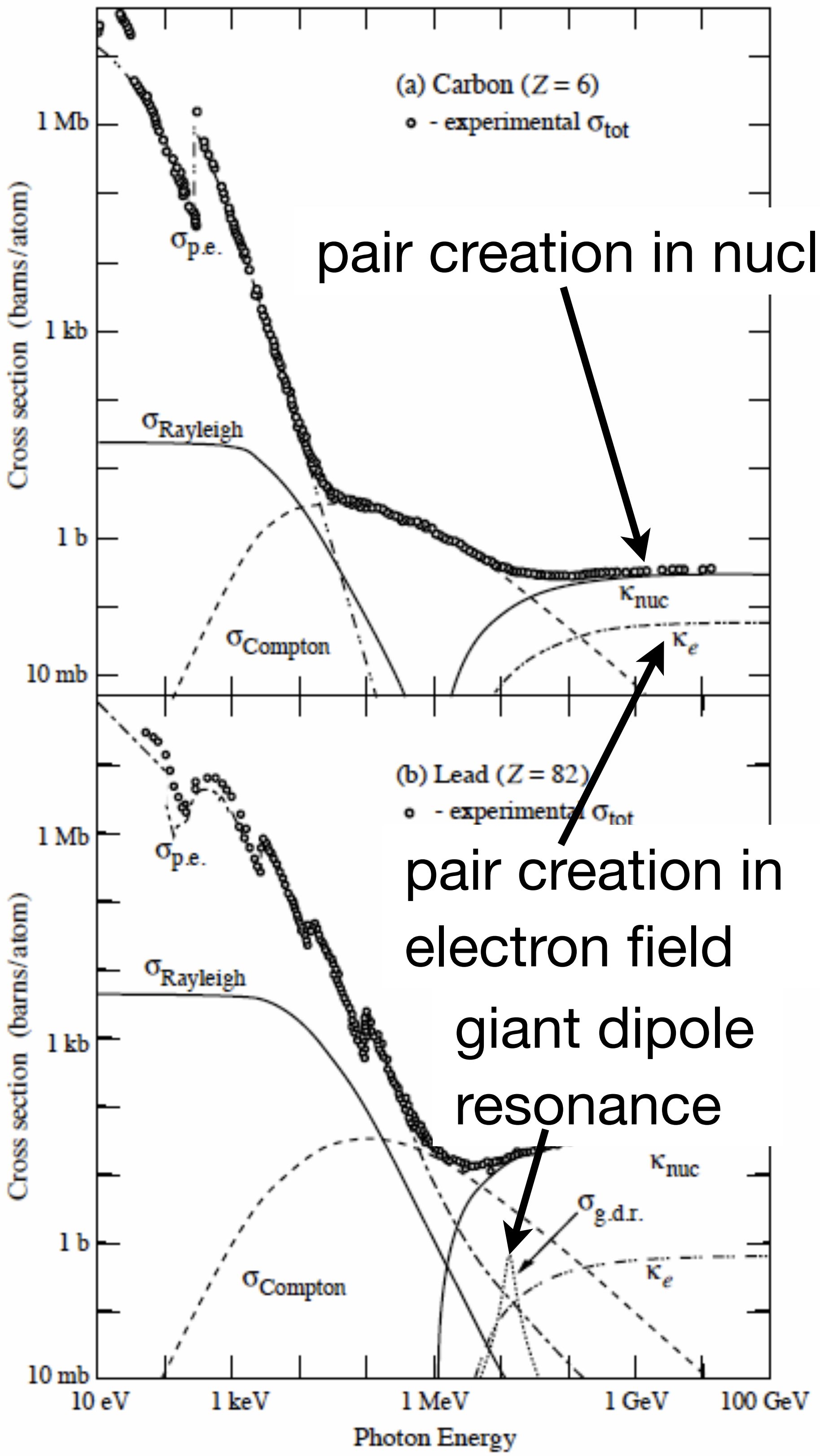
energy threshold:
2 m_e = ~1.022 MeV

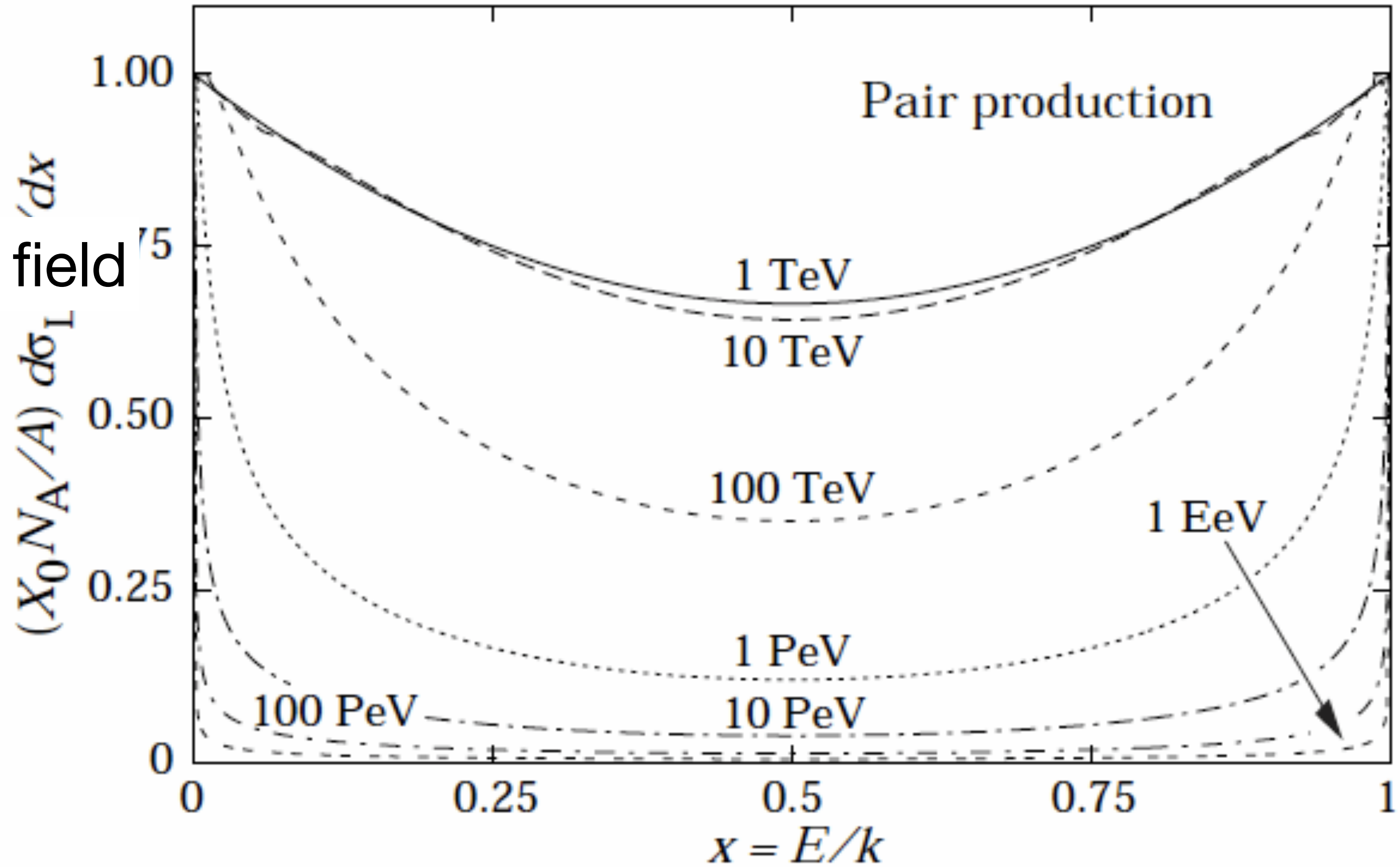
- In contrast to dE/dx for charged particles:
  “All or nothing” reactions

➯ Reduction of photon intensity when traversing matter:

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

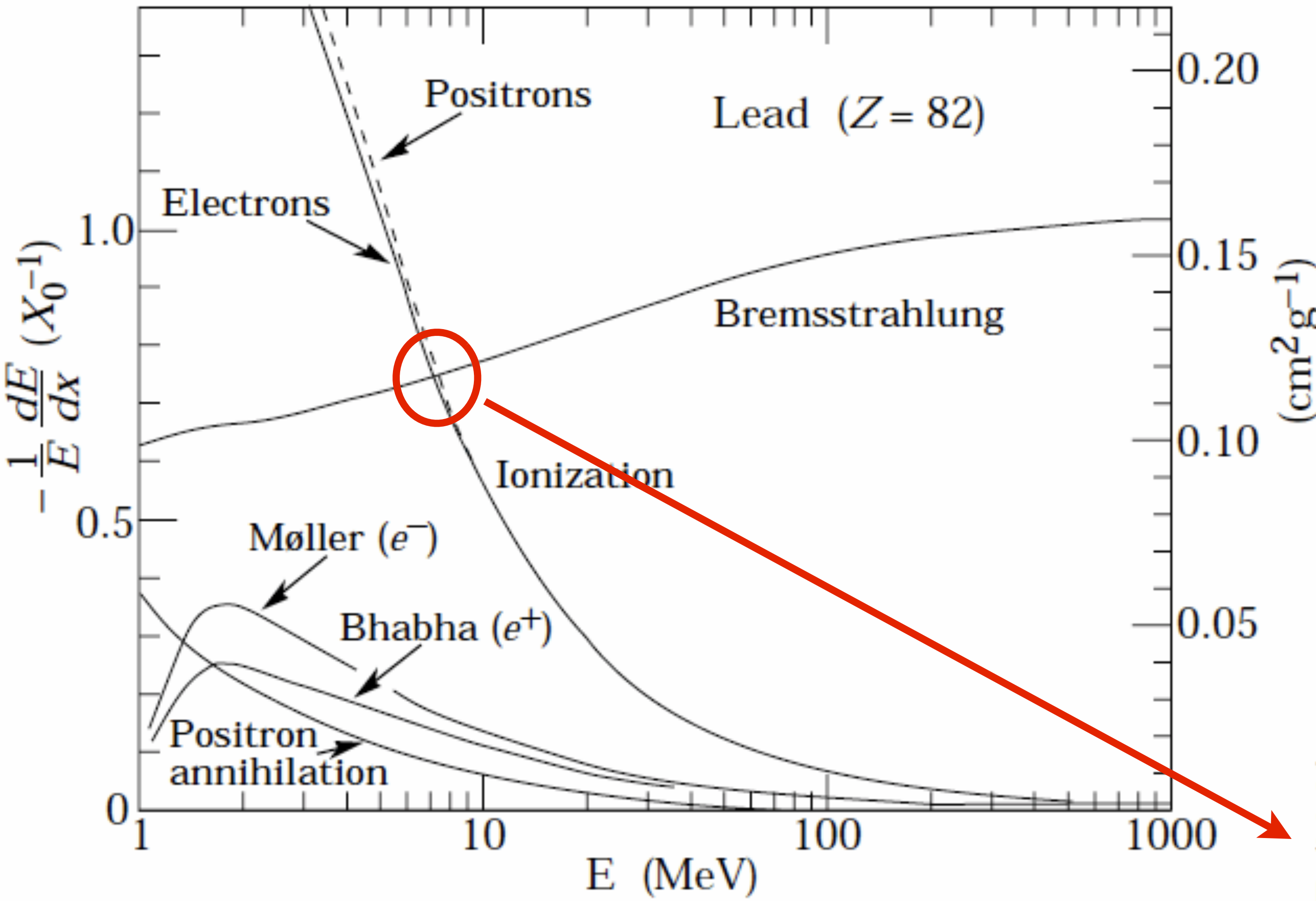
Photons in Matter



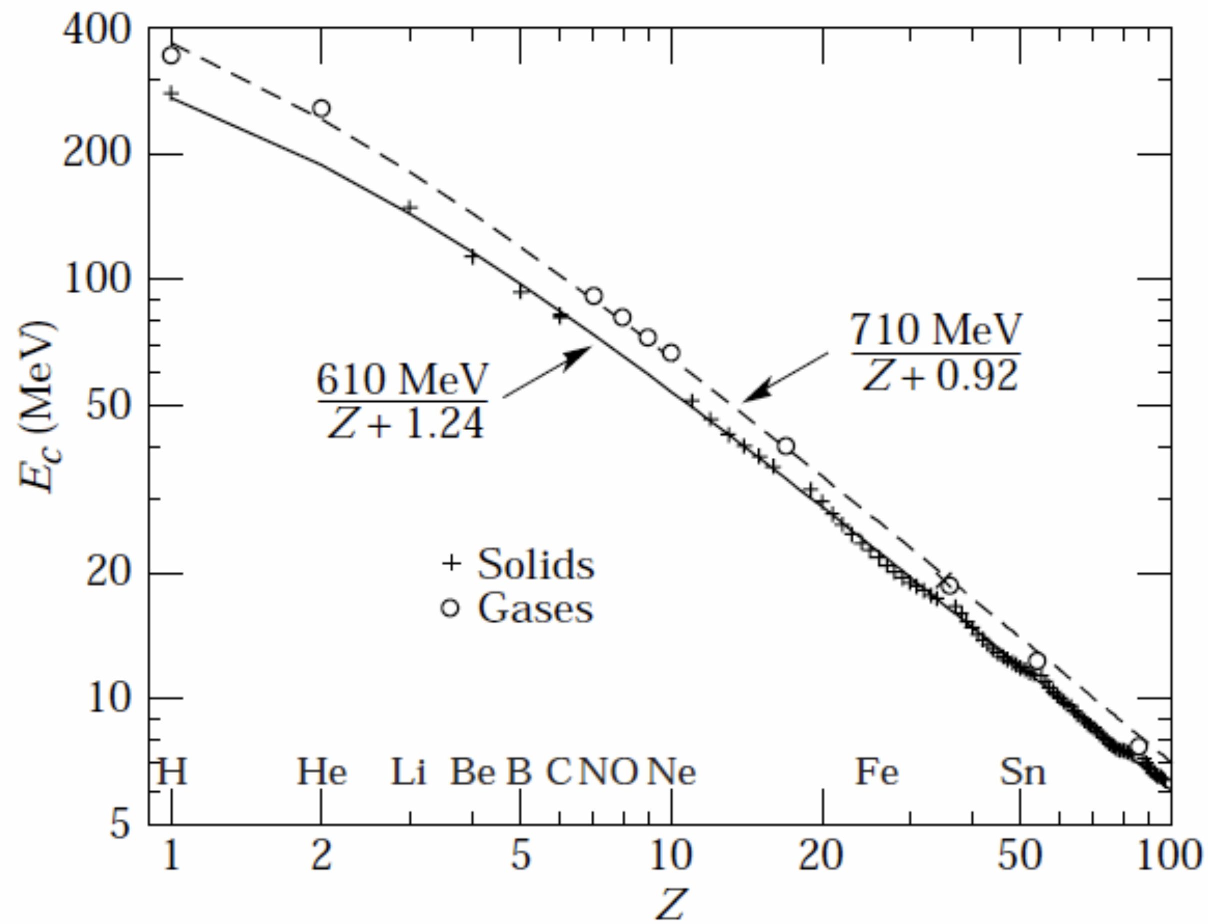


- At high energies pair creation dominates by far
- Low energies:
  - photoelectric effect
  - Coherent scattering: Rayleigh scattering
  - Compton scattering
  - nuclear excitation

Electrons: Energy Loss



- Bremsstrahlung dominates at high energies
- At low energy: Ionization, scattering



- Critical energy: The energy where ionization energy loss equals radiative losses through Bremsstrahlung

Electrons and Photons: Radiation Length

- The relevant length scale: one radiation length
  - Describes high-energy electrons and photons (Energy loss via Bremsstrahlung and e^+e^- - pair creation, respectively)

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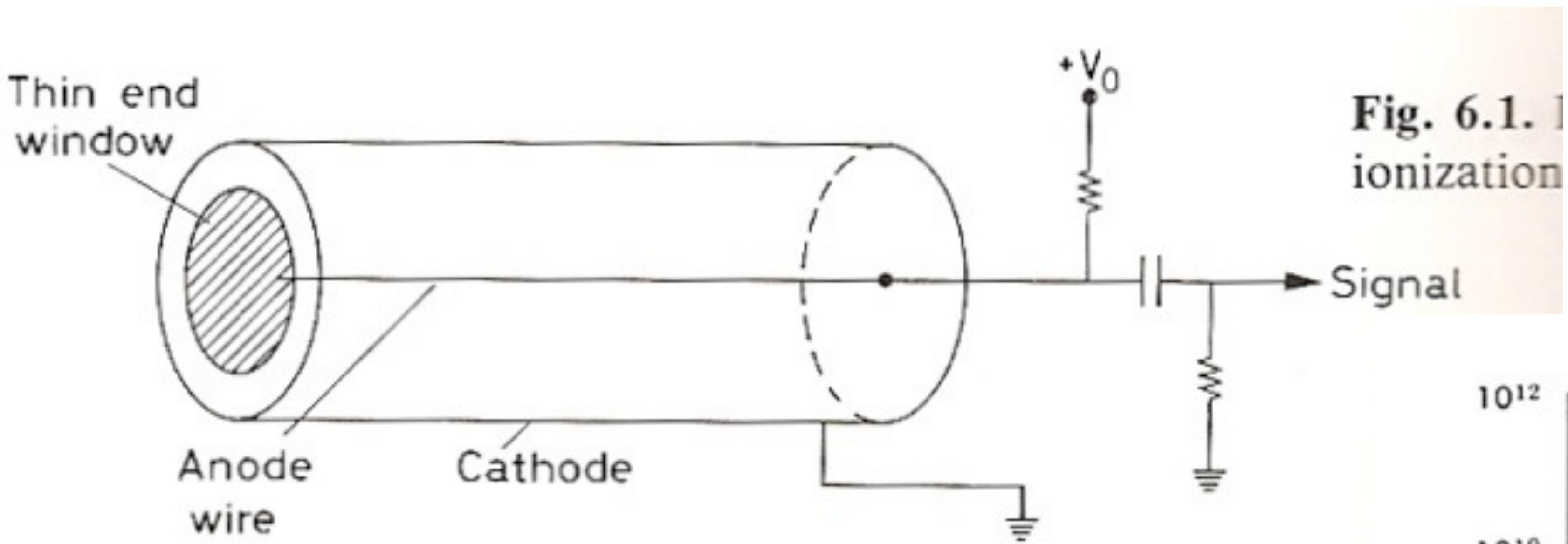
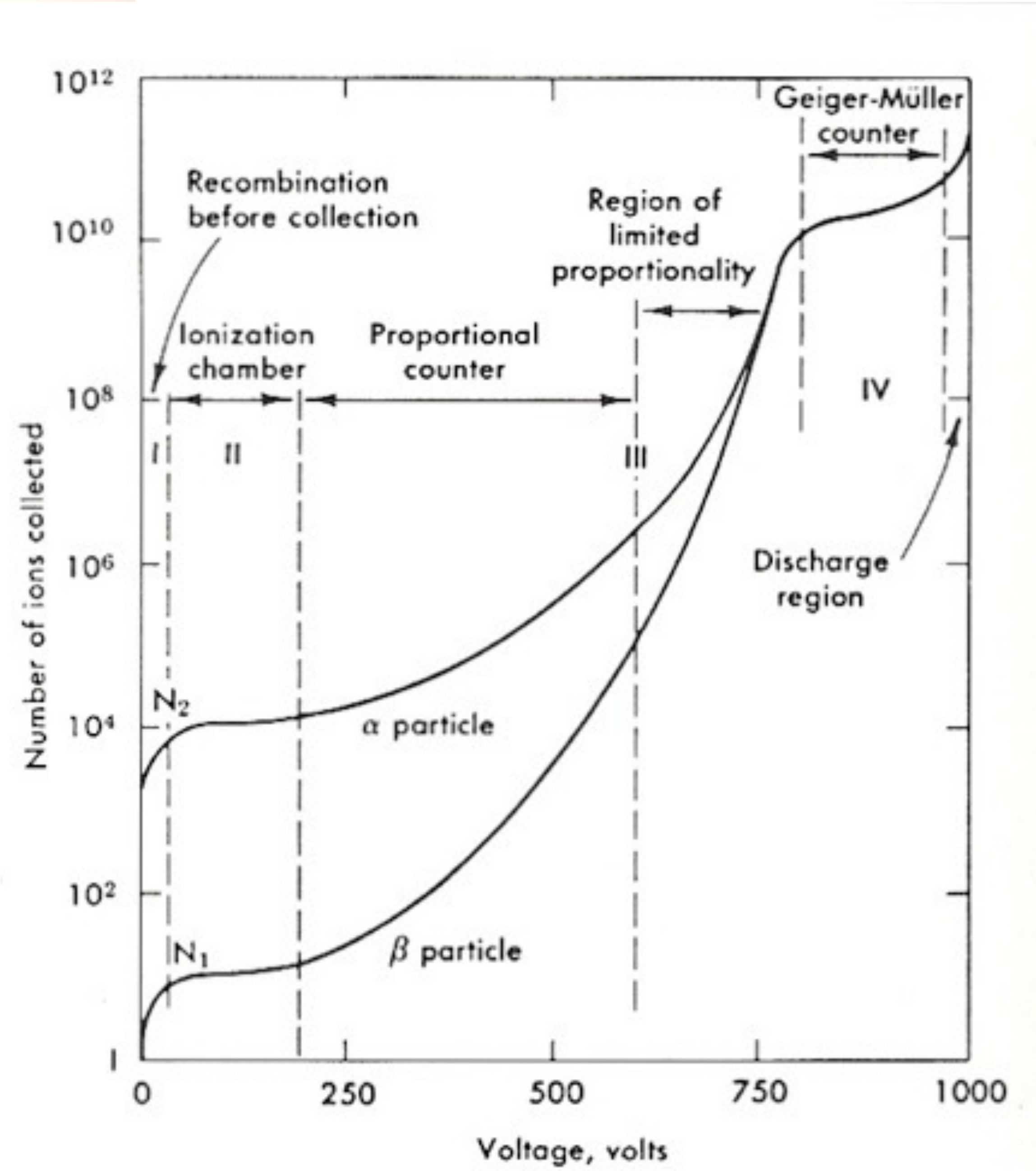
- Also relevant for the description of multiple coulomb scattering

- Is usually given in g/cm^2, typical values:
  - Air: 36.66 g/cm^2, corresponds to ~ 300 m
  - Water: 36.08 g/cm^2, corresponds to ~ 36 cm
  - Aluminium: 24.01 g/cm^2, corresponds to 8.9 cm
  - Tungsten: 6.76 g/cm^2, corresponds to 0.35 cm

Methods of Particle Detection

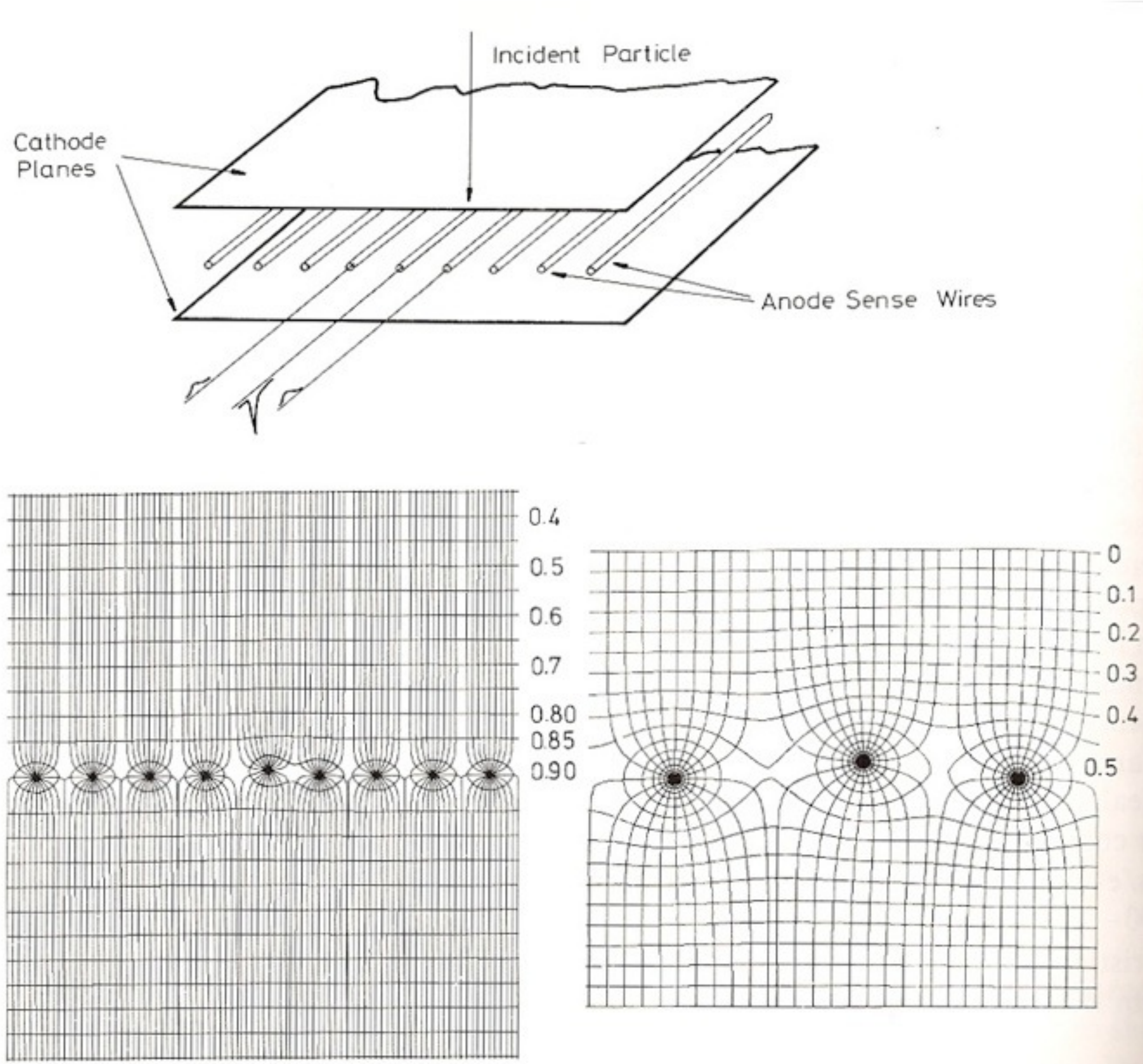
Ionization Chamber: A Classic





- Particles create electron-ion pairs in gas volume
- Electrons are accelerated in strong electric field, resulting in avalanche amplification
- Depending on the applied voltage the signal is proportional to the deposited energy or saturates

Spatial Resolution



- **M**ulti-**W**ire **P**roportional **C**ounter MWPC
- G. Charpak 1968 (NP 1992)

Spatial Information through Timing: Drift Chamber

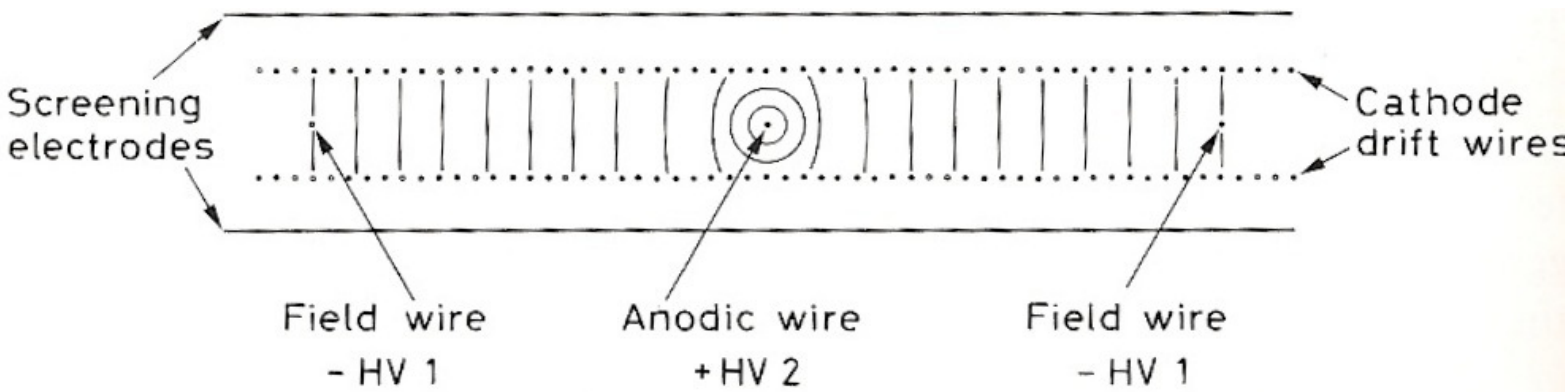


Fig. 6.16. Drift chamber design using interanode field wires (from *Breskin* et al. [6.22])

- If the time of passage of a particle is known from external measurements (trigger!) one can determine the location based on the arrival time of the charge cloud at the anode wire
- Prerequisite: Field distribution, and through that also drift velocity profile in gas volume well known

Cylindrical Drift Chamber for Collider Detectors

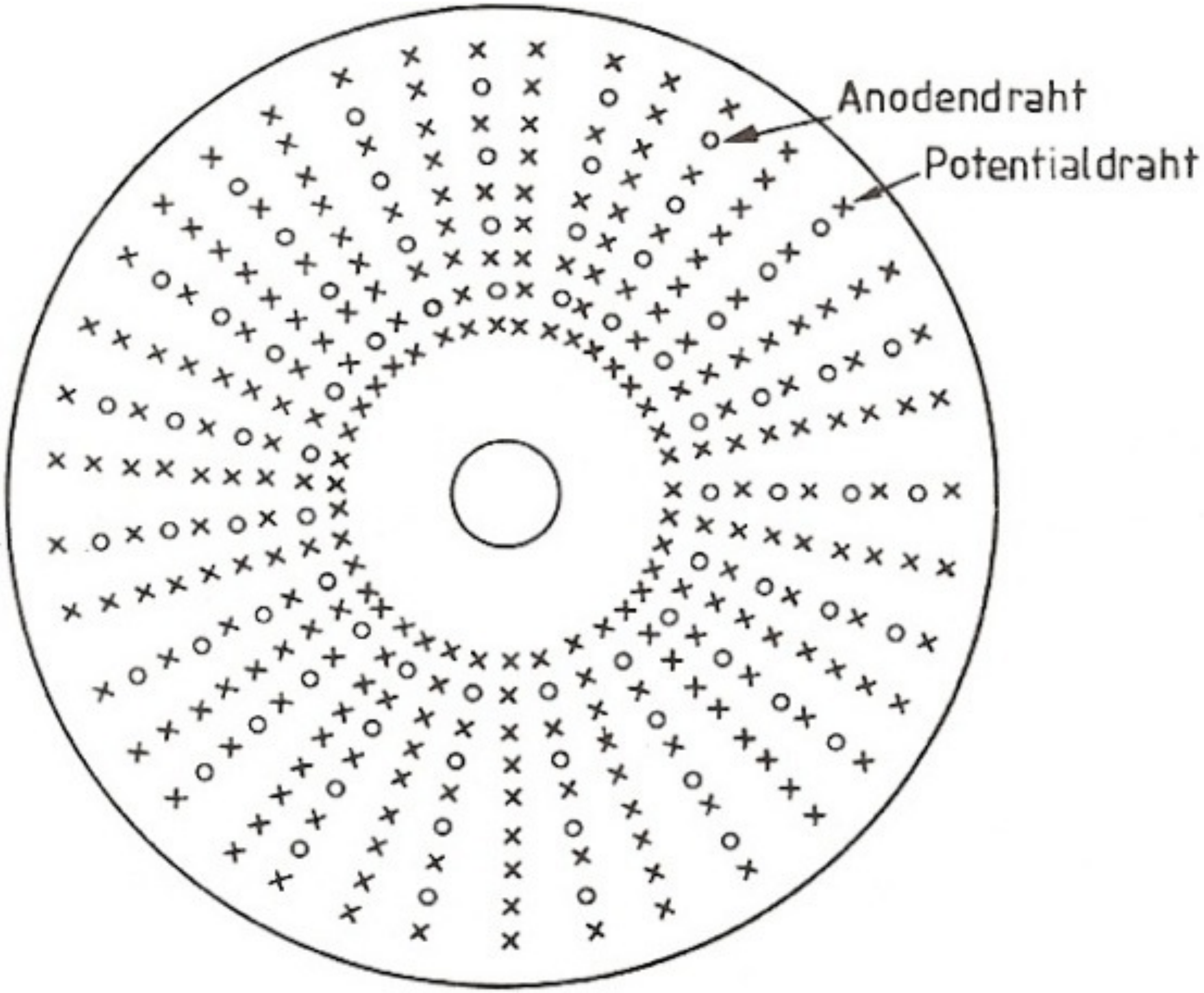
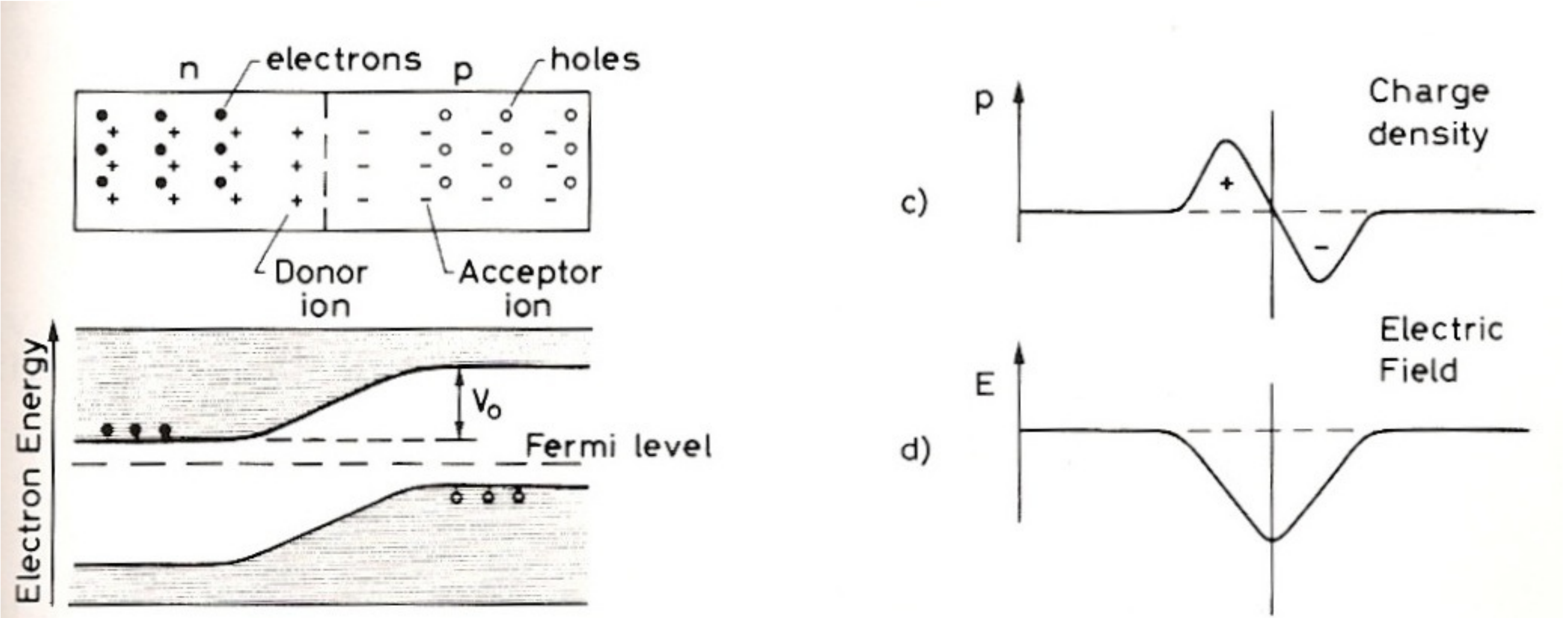


Abb. 4.41 Prinzipieller Aufbau einer zylindrischen Driftkammer. Die Abbildung zeigt einen Schnitt durch die Kammer senkrecht zu den Drähten.

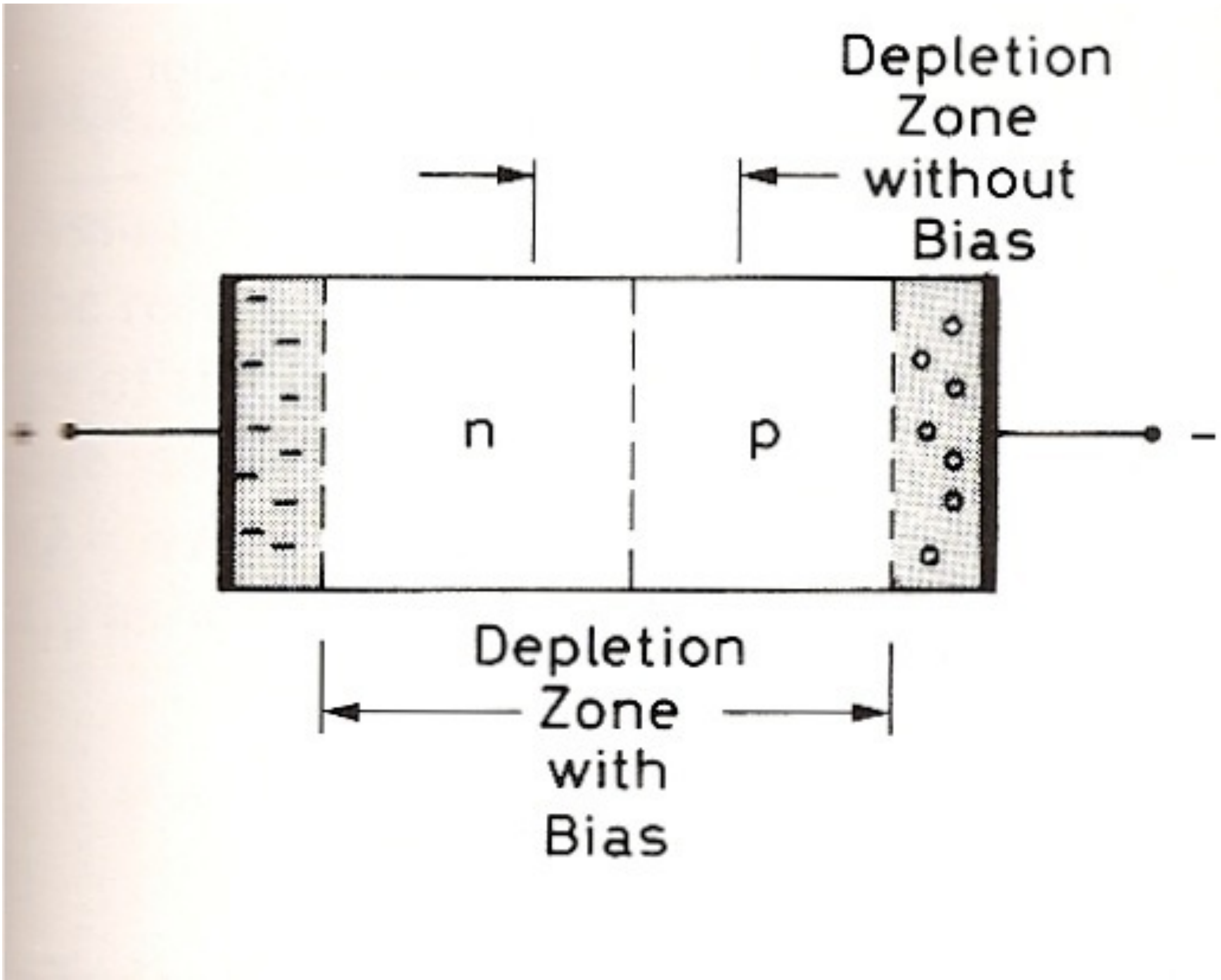
- Solenoidal magnetic field for momentum measurement parallel to chamber wires

Semiconductor Detectors: PN Junction



- By combining silicon with different dopants you get a PN junction
  - Donor (e.g. Phosphorus) provides electrons: n-doping
  - Aceptor (e.g. Boron) provides holes: p-doping
  - The charge excess gets neutralized on contact, a depletion zone and a corresponding electric field develops at the junction

Semiconductor Detectors: Charge Collection



- An external bias voltage increases the depletion zone by removing all charge carriers
  - Created electrons and holes move to the contacts without recombining with the Si: development of a signal

- Through-going particles produce electron-hole pairs (in Si: 3.6 eV required per pair, for comparison: 20 eV - 40 eV in gas)
  - The high density and low ionization threshold allows to build compact detectors with excellent spatial resolution

Semiconductor Strip Detectors

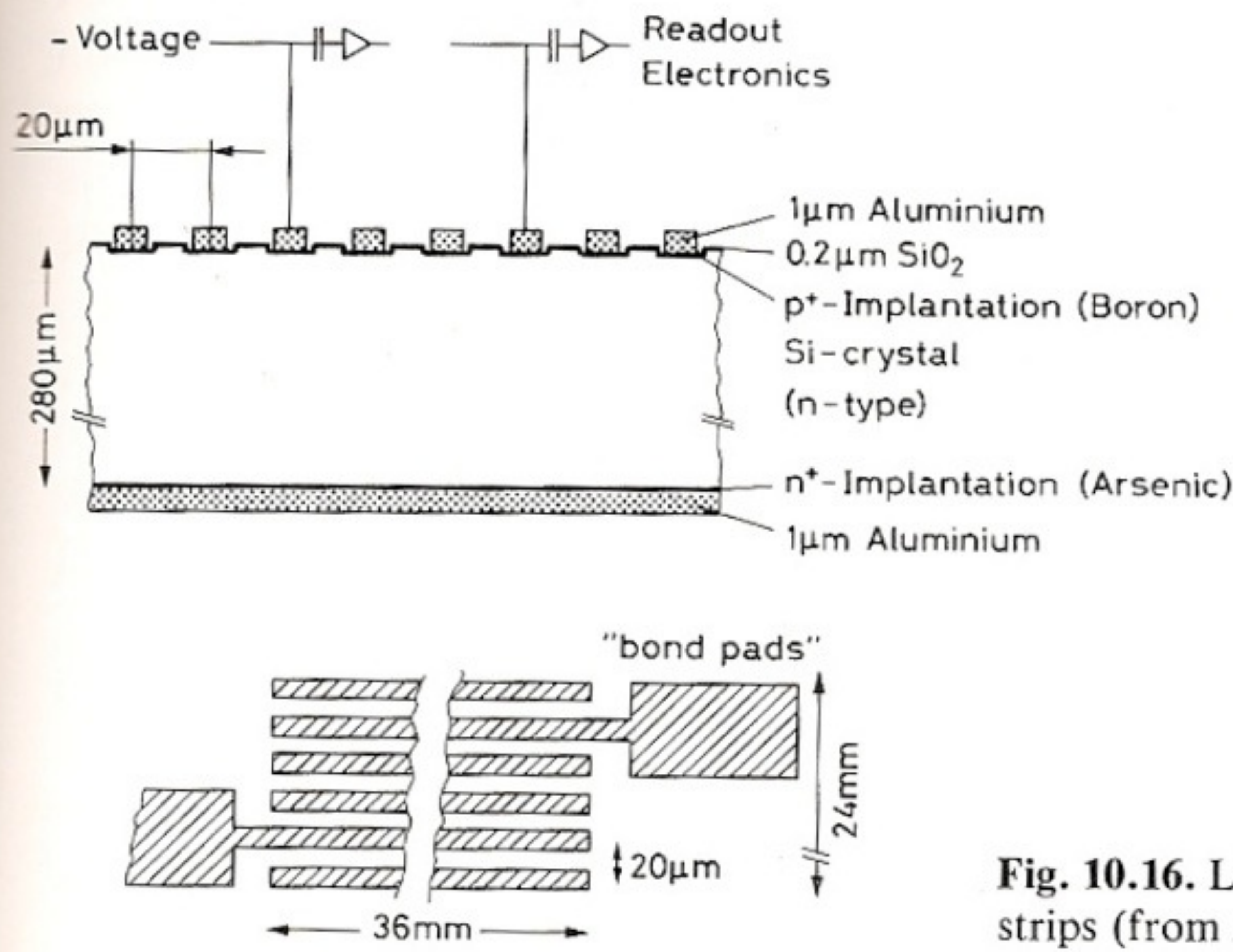
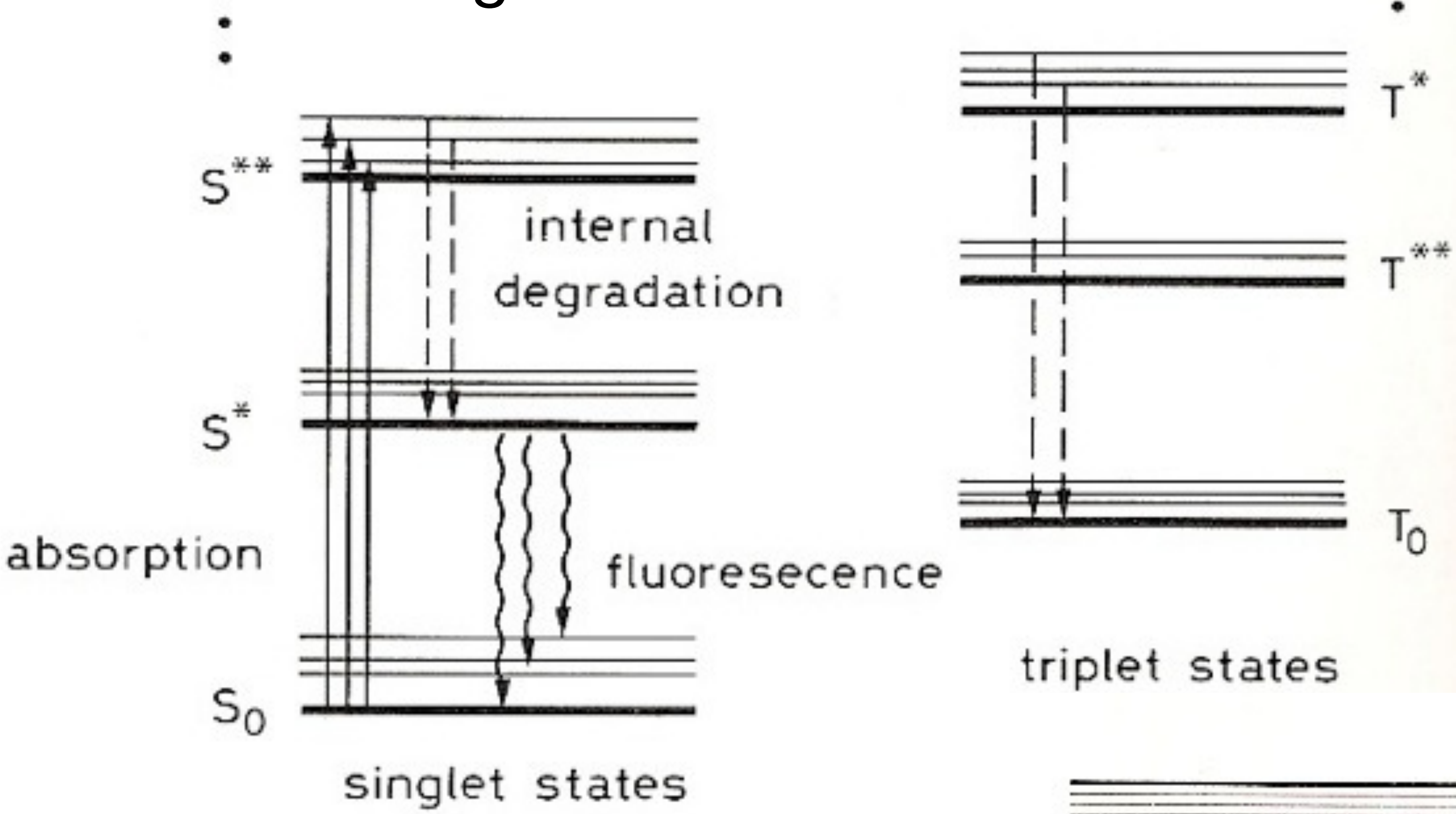


Fig. 10.16. Layout of a micro-strip detector and readout strips (from *Hyams* et al. [10.14])

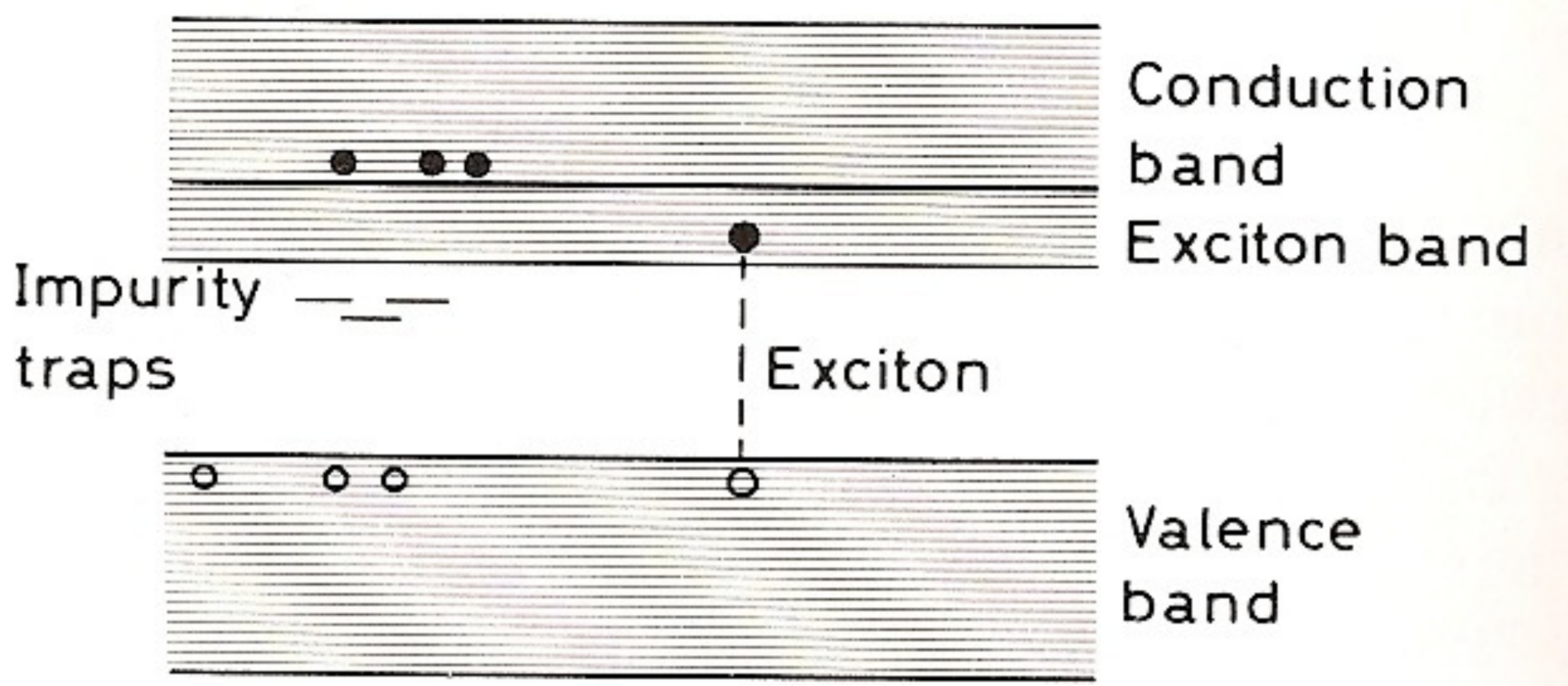
Scintillators

organic



- Scintillators emit light when traversed by ionizing particles
    - Excitation of metastable states (organic scintillators) or Defects in Crystals (inorganic scintillators)

inorganic:



Scintillation Detectors

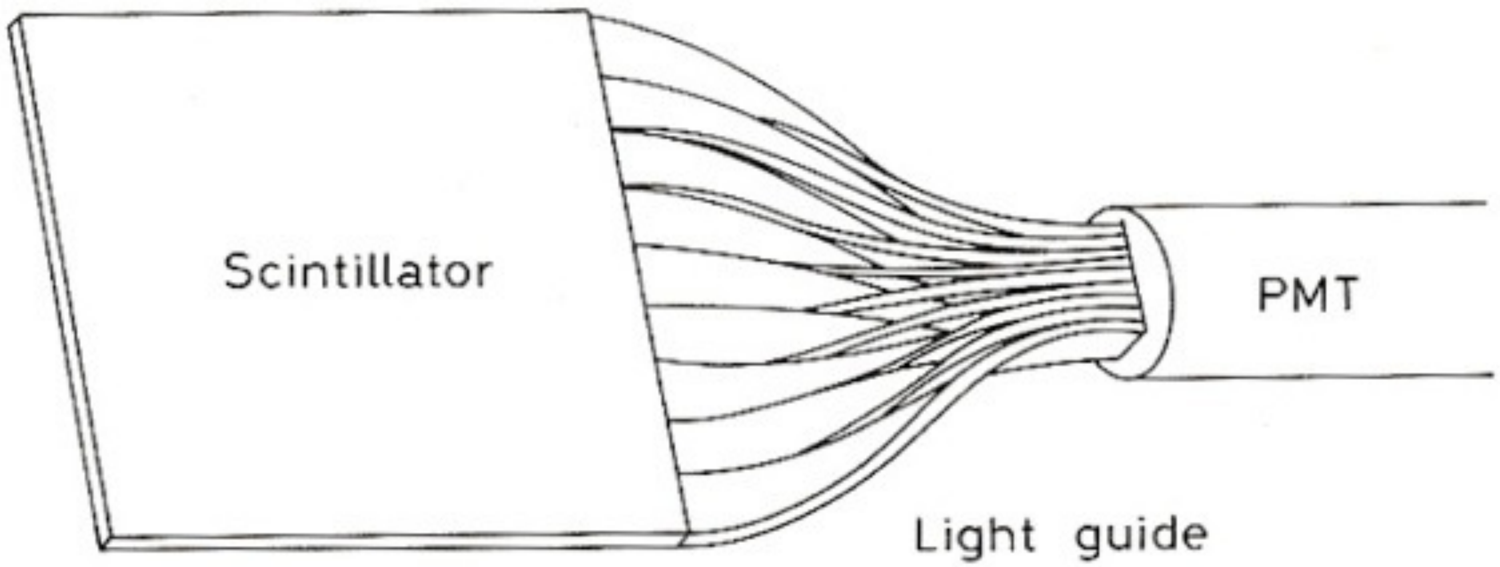


Fig. 9.7. The *twisted* light guide. Many strips of light guide material are glued on to the edge of the scintillator and then twisted 90° so as to fit onto the PM face

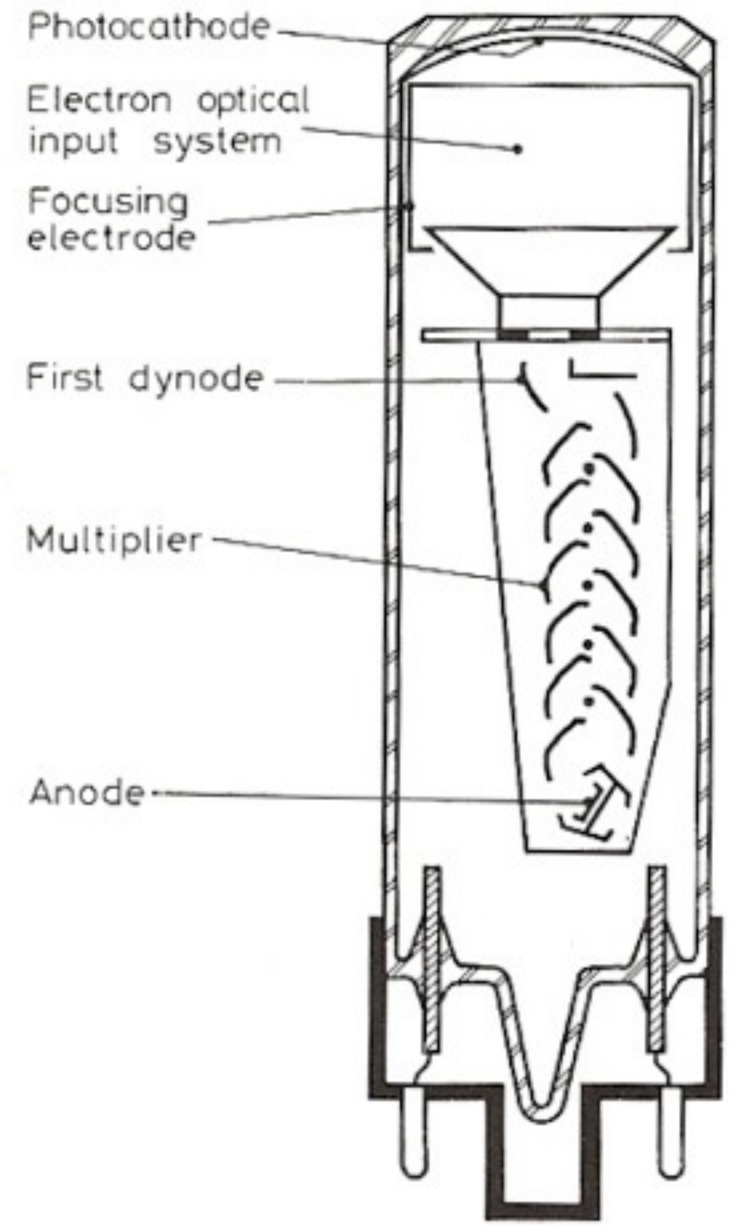


Fig. 8.1. Schematic diagram of a photomultiplier tube (from *Schonkeren* [9.1])

- Classical principle: Detection of scintillation light with photo multipliers
  - today these are more and more replaced by silicon-based photon detectors
  - Scintillators (in particular plastic scintillators) provide a fast signal, ideal for trigger detectors

Silicon-Based Photon Detection

- Silicon detectors can also be used to detect visible photons, but:
  - Photo effect only creates a single electron-hole pair (very different from the situation with charged particles): Amplification is crucial!
  - The usual charge amplification of up to ~100 reachable in silicon is insufficient to detect single photons with high efficiency n

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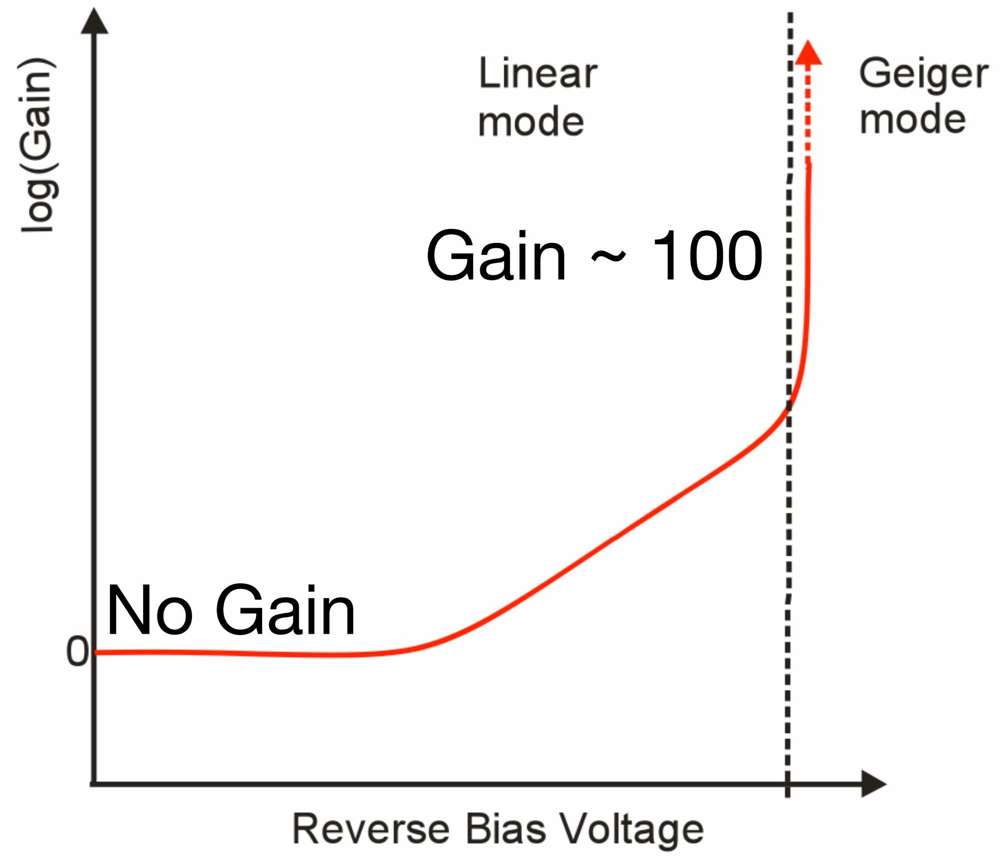
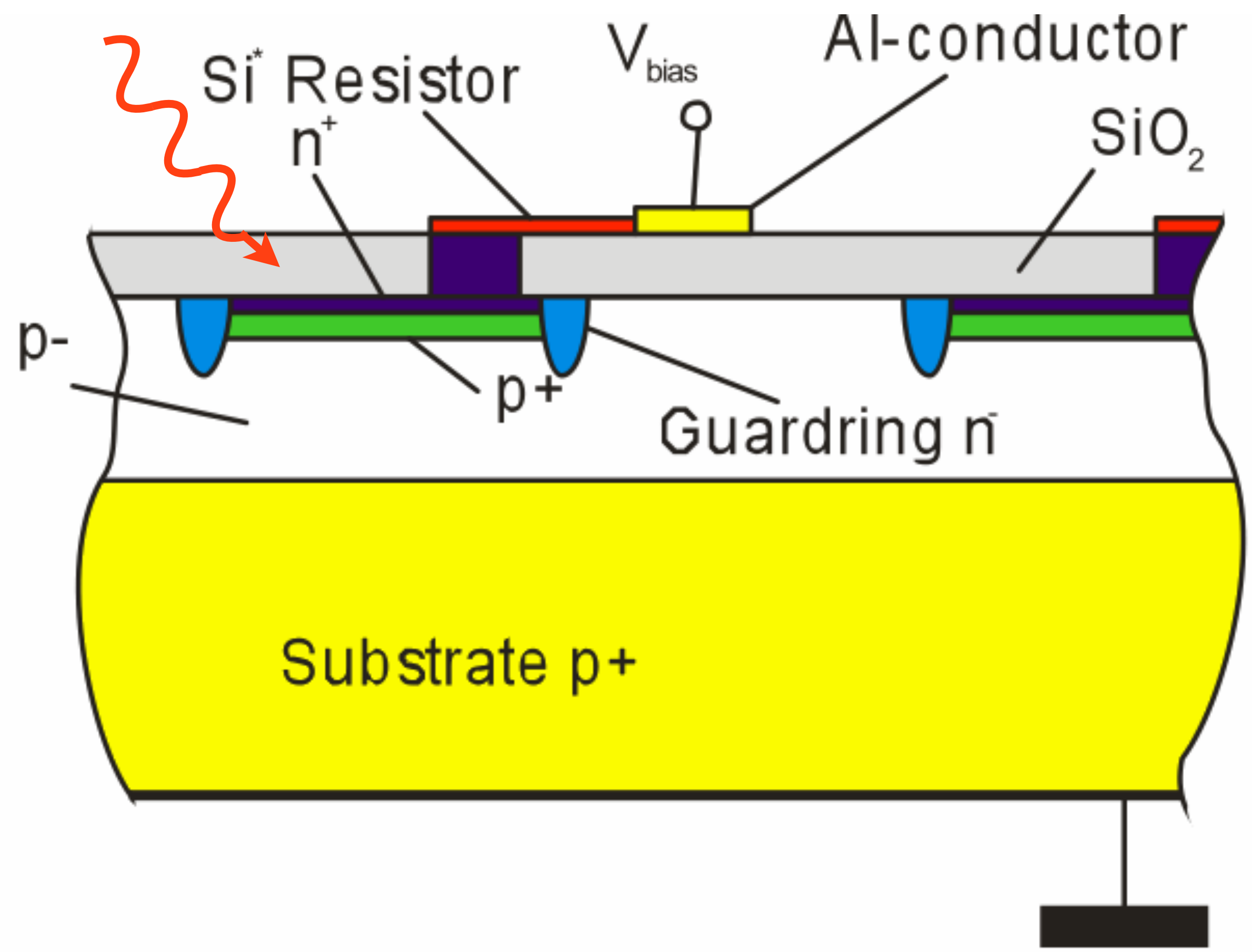
Avalanche Photo Diode APD





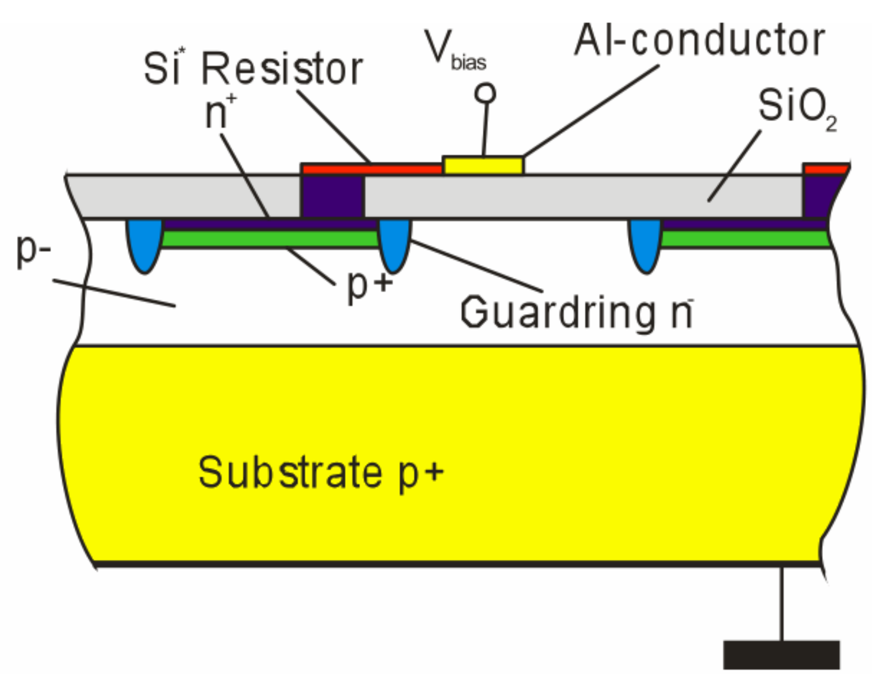
New Photon Sensors: Silicon Photomultipliers

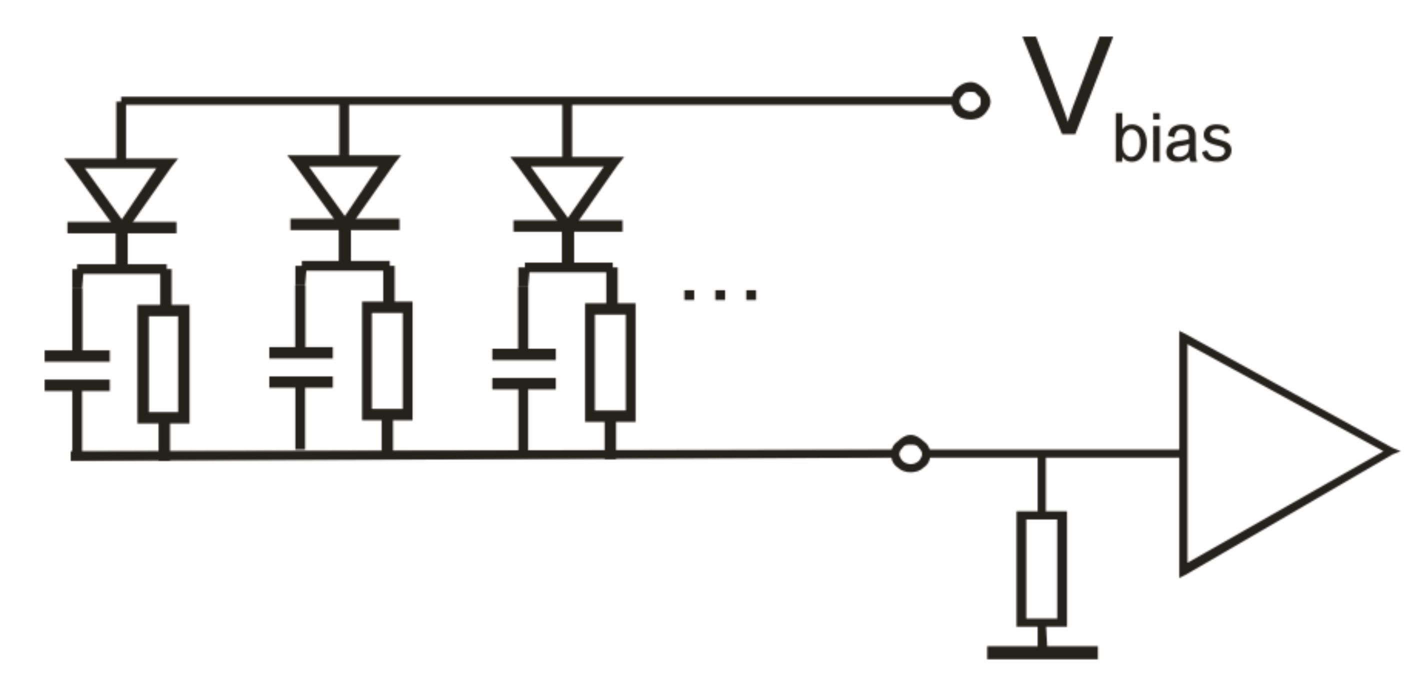
- Highest amplification (~ 10^6) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons

New Photon Sensors: Silicon Photomultipliers

- Highest amplification (~ 10^6) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons
- The trick: Put many small APDs on a chip, read out the summed-up signal
  - Easy handling: Only one channel (as a PMT, hence the name)
  - Extreme amplification: Detection of single photons not a problem!

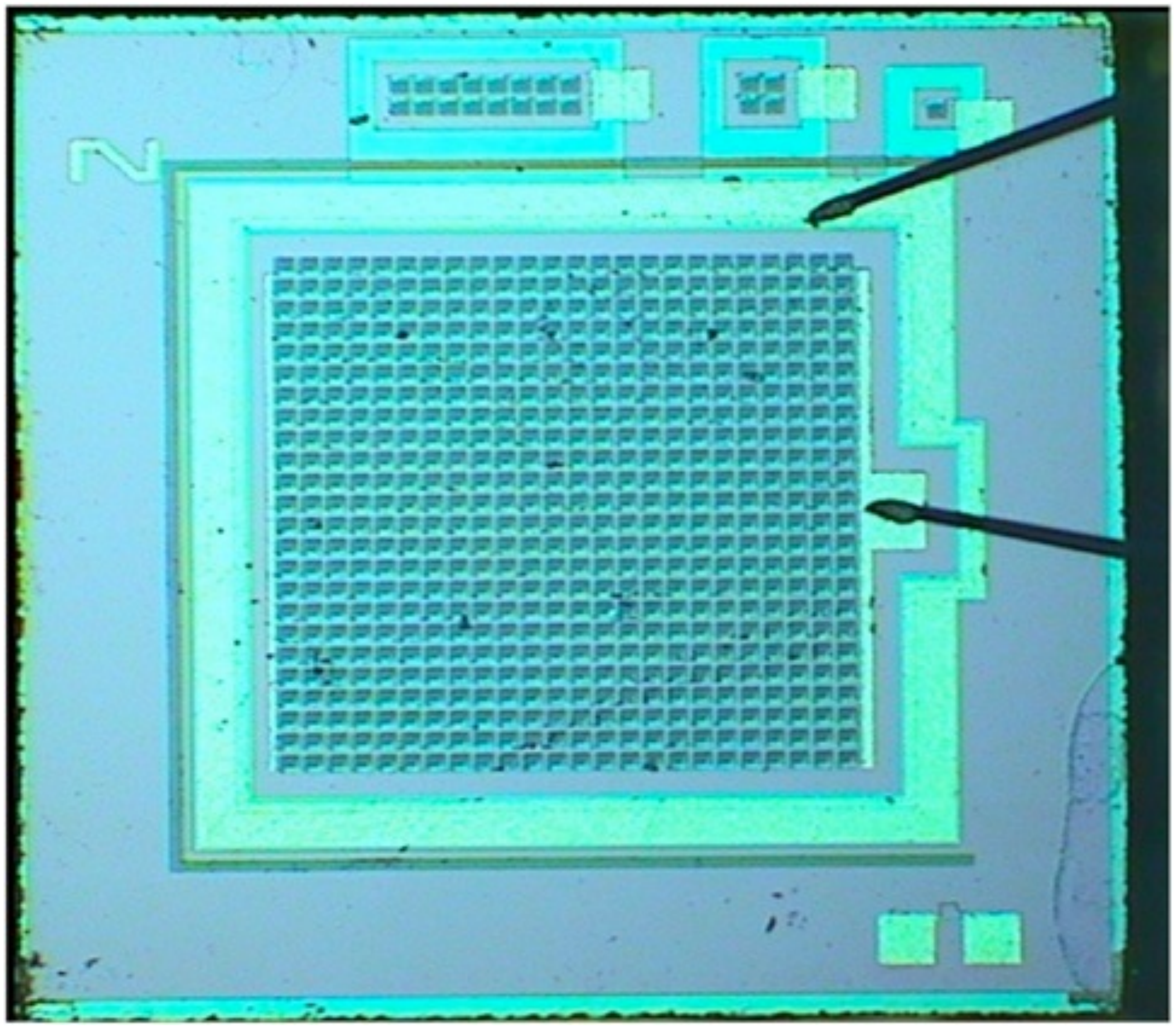
N x

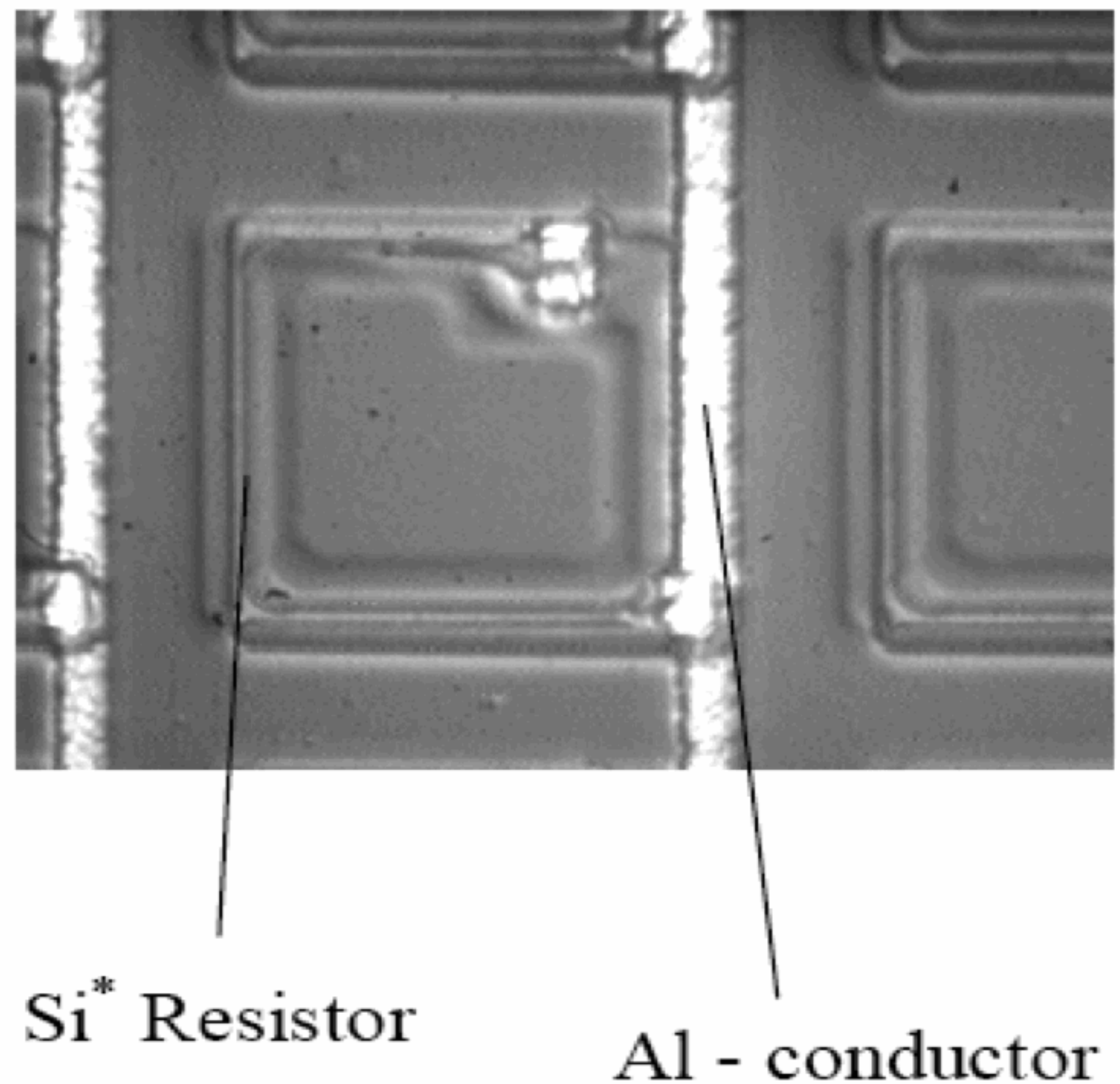




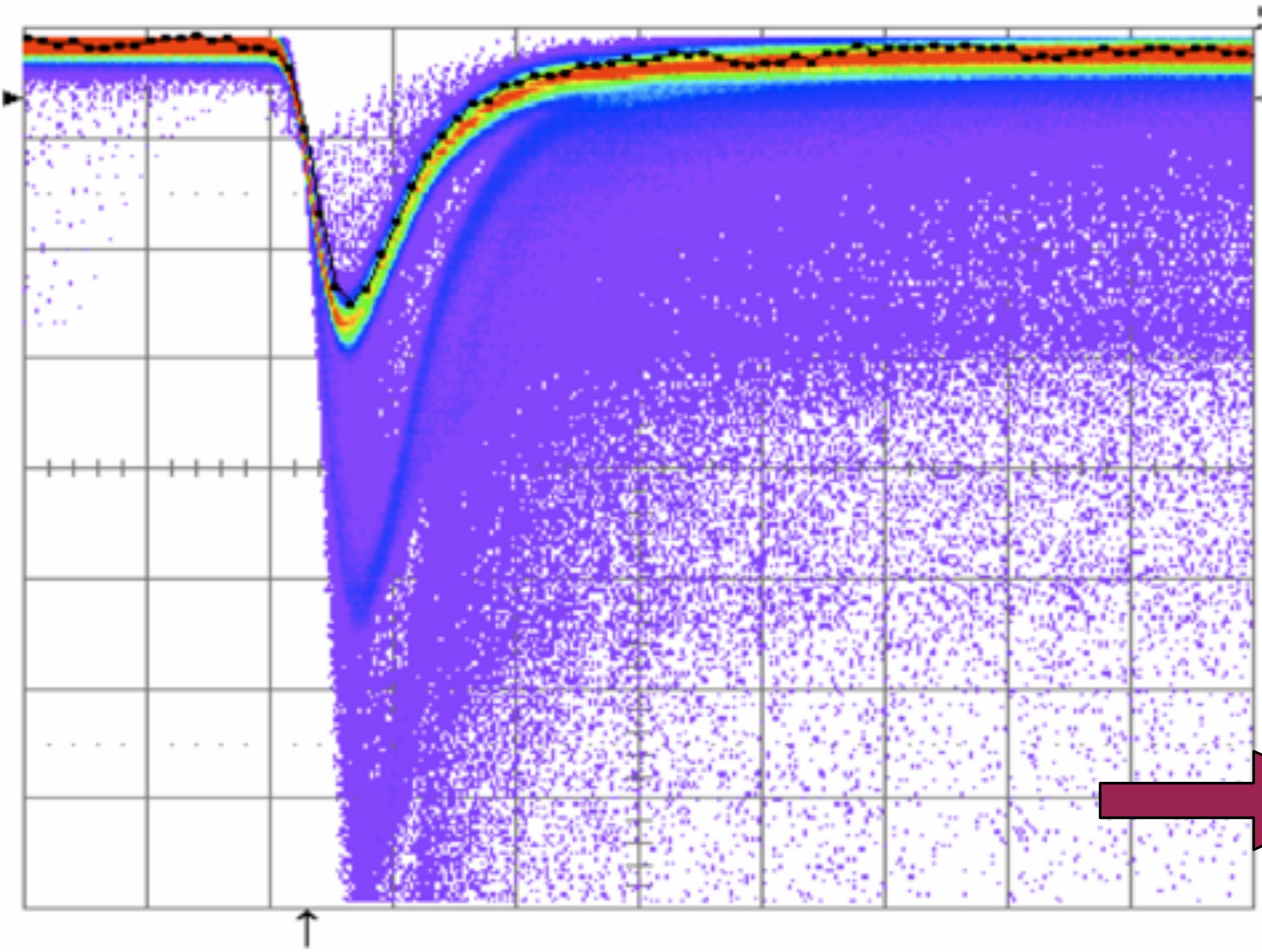
Silicon Photomultiplier (SiPM)

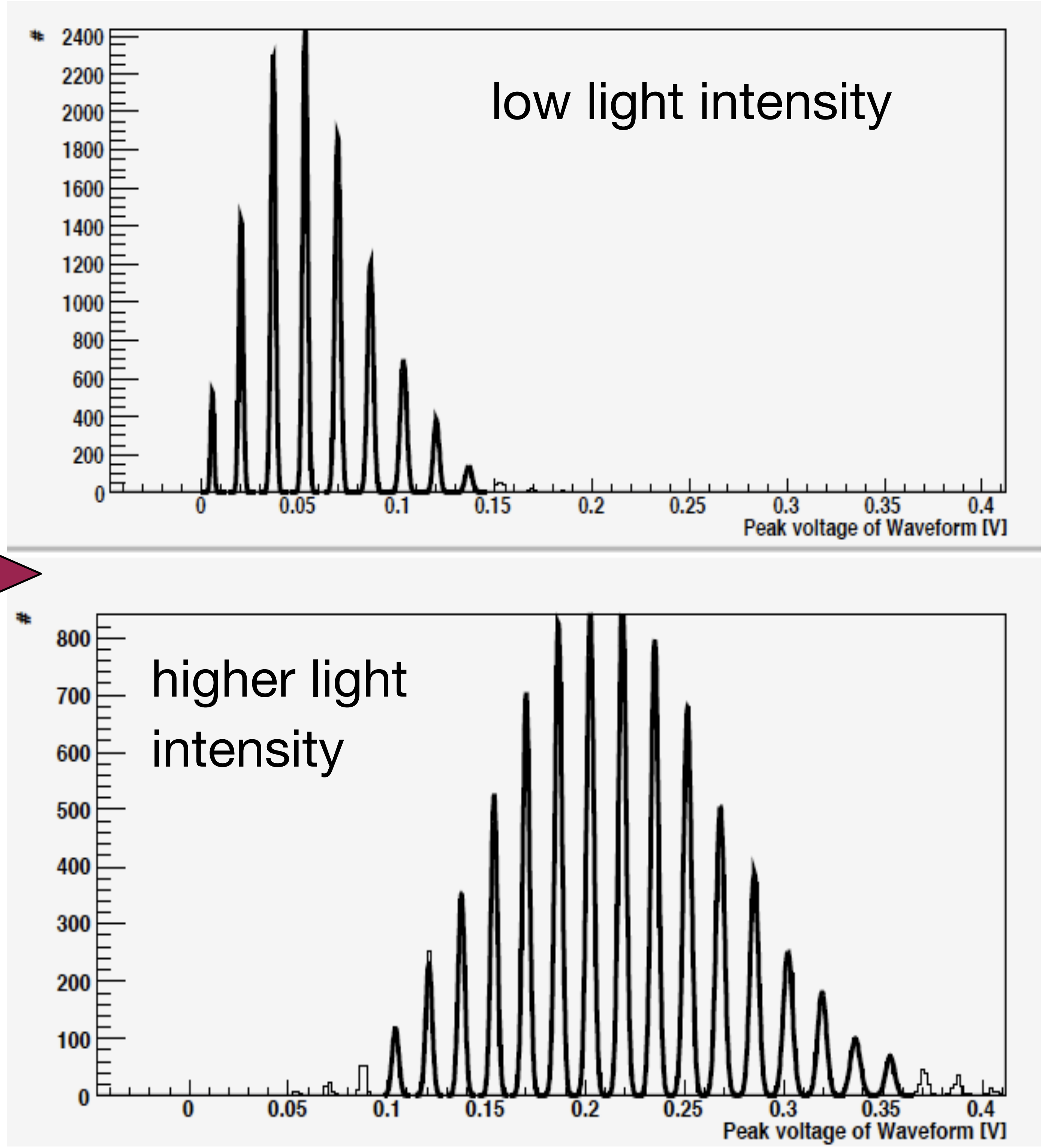
- 10 years ago still “exotic”: CALICE the first HEP instrumentation collaboration to adopt these devices (more next lecture)
- Today: Well-established manufactures, wide use also outside of HEP





SiPM Signals





Single photons can be resolved

Other Methods for Particle Detection

- Almost no limit for your creativity - Various effects originating from the interaction of particles with matter can be exploited:
  - Cherenkov light for the accurate measurement of particle velocity
  - Transition radiation for velocity measurement
  - ...

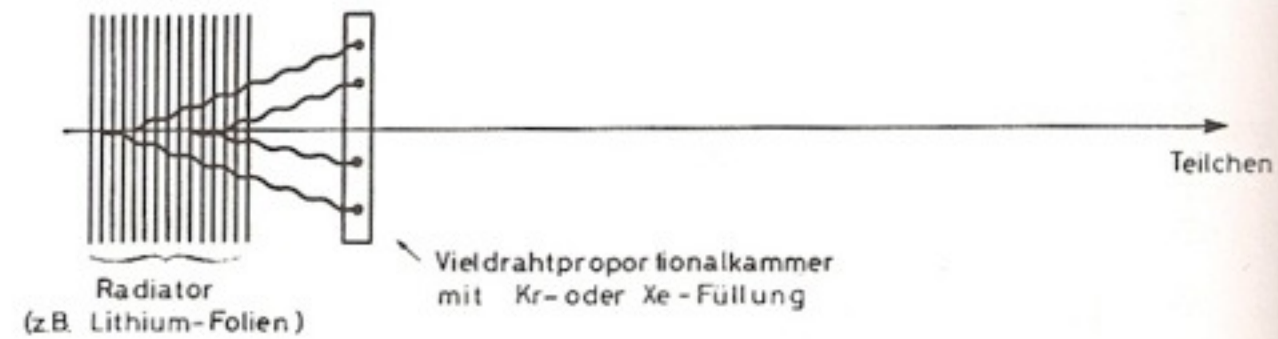


Abb. 6.22 Prinzipieller Aufbau eines Übergangsstrahlungsdetektors.

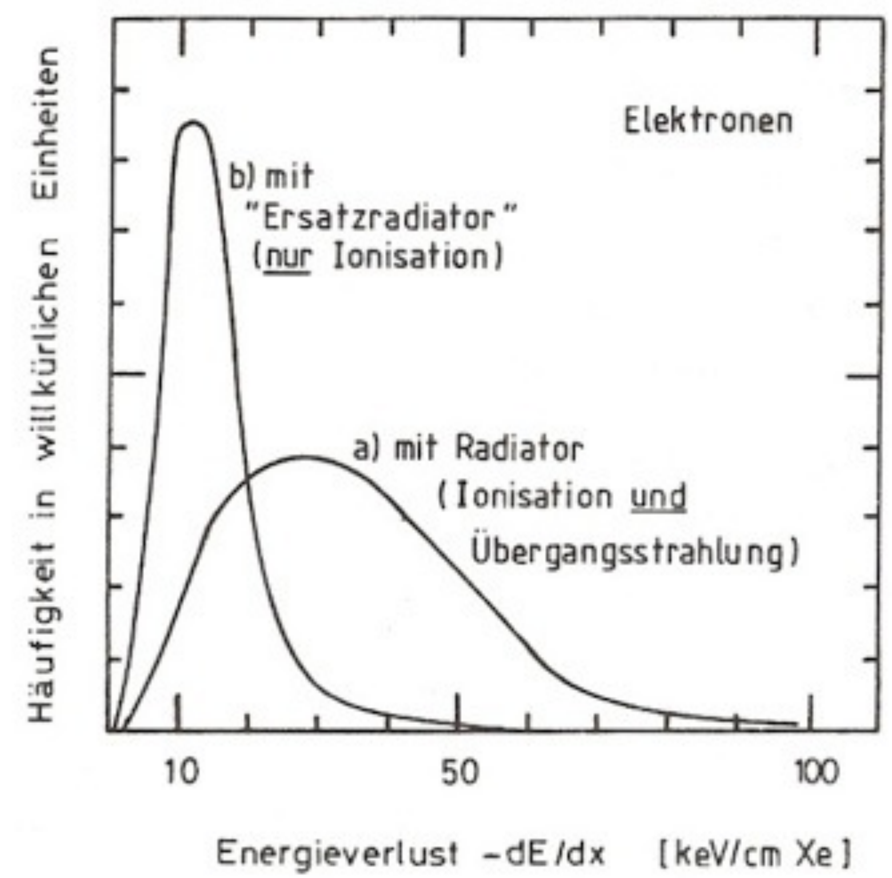


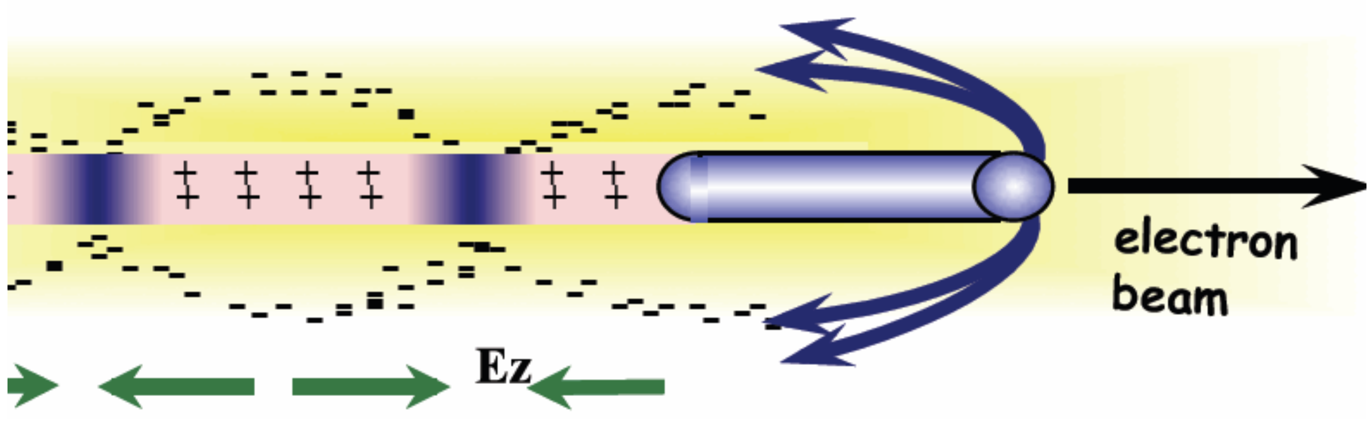
Abb. 6.23 Prinzipieller Verlauf der Häufigkeitsverteilung des Energieverlustes hochenergetischer Elektronen für einen Übergangsstrahlungsdetektor mit Radiator und "Ersatzradiator" (nach [143]).

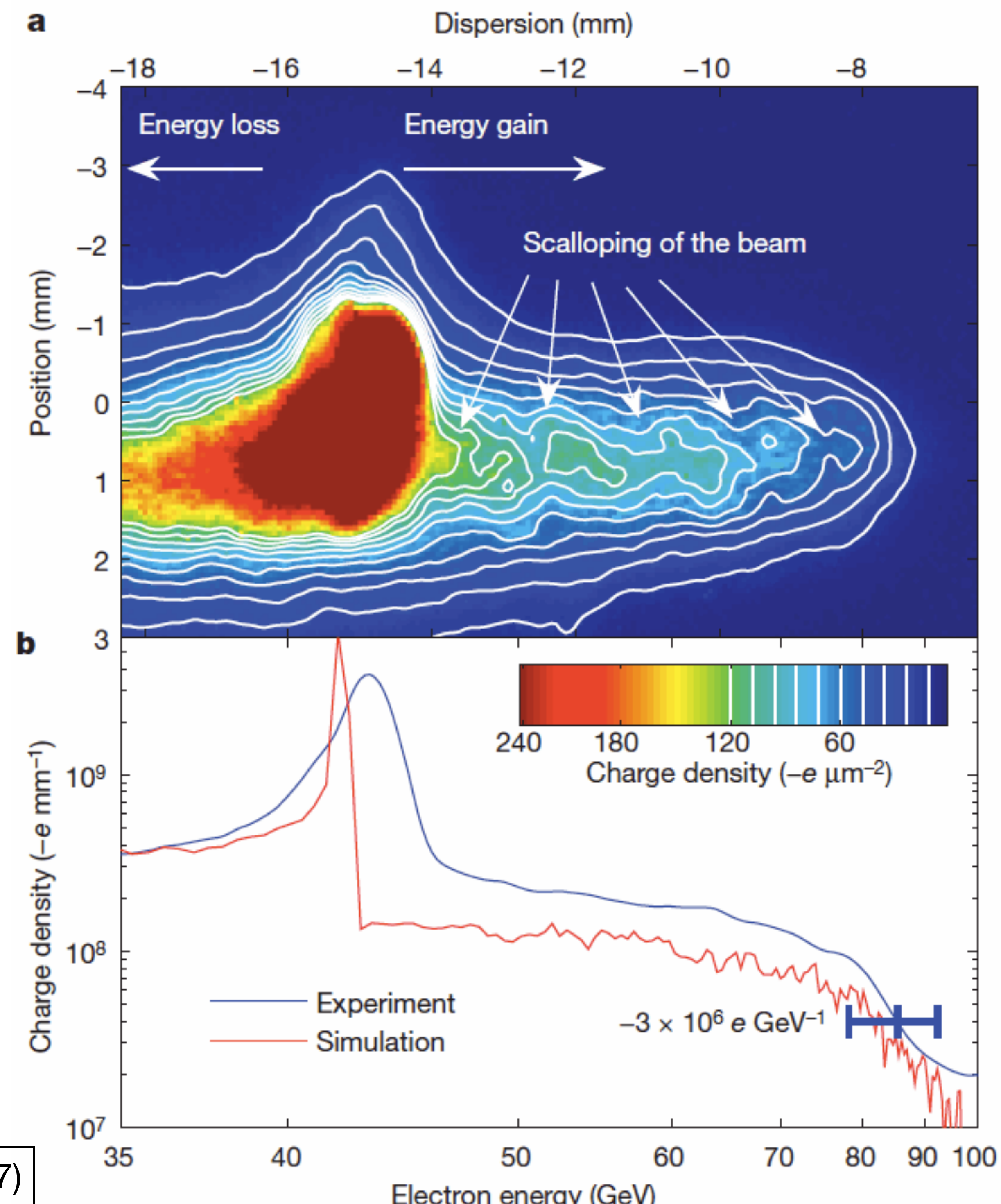
Novel Acceleration Techniques

- Special Feature, by popular demand…

Plasma Wakefield Acceleration

- For high-energy linear colliders: Need much higher acceleration gradient to go significantly beyond ~ 1 TeV beams
    - Conventional accelerating structures limited at ~ 100 MV/m or below



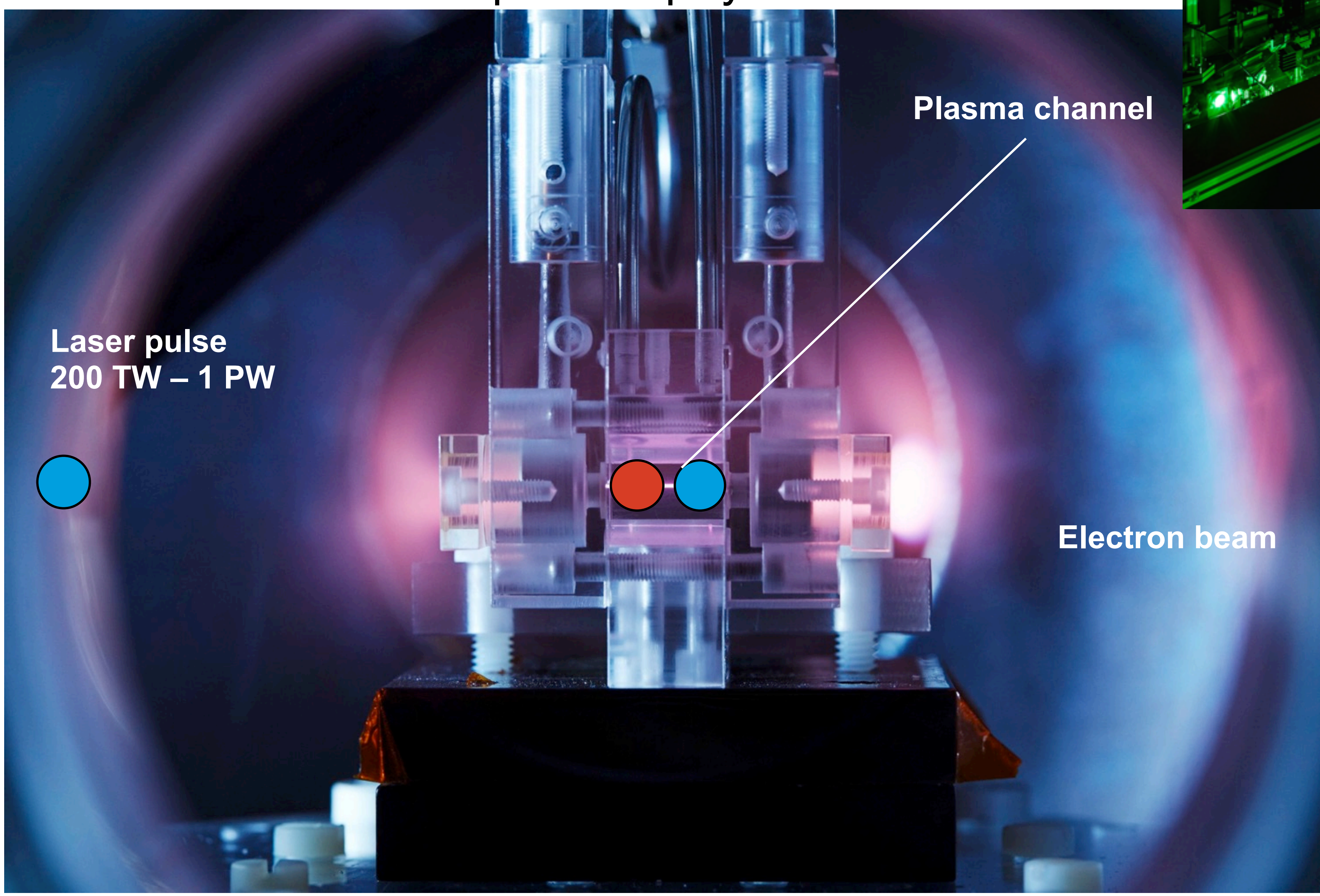


- Demonstration of high energy acceleration of electrons at SLAC: E-164X
- doubling of beam energy observed: 40 GeV energy gain over less than 1 m of plasma -> **~50 GV/m**

Nature 445, 741 (2007)

Laser Plasma Accelerator

- Today: can routinely produce ~ GeV beams with good quality with industrial lasers
  - but: low power - 50 J in a laser pulse, vs MJ beams for particle physics

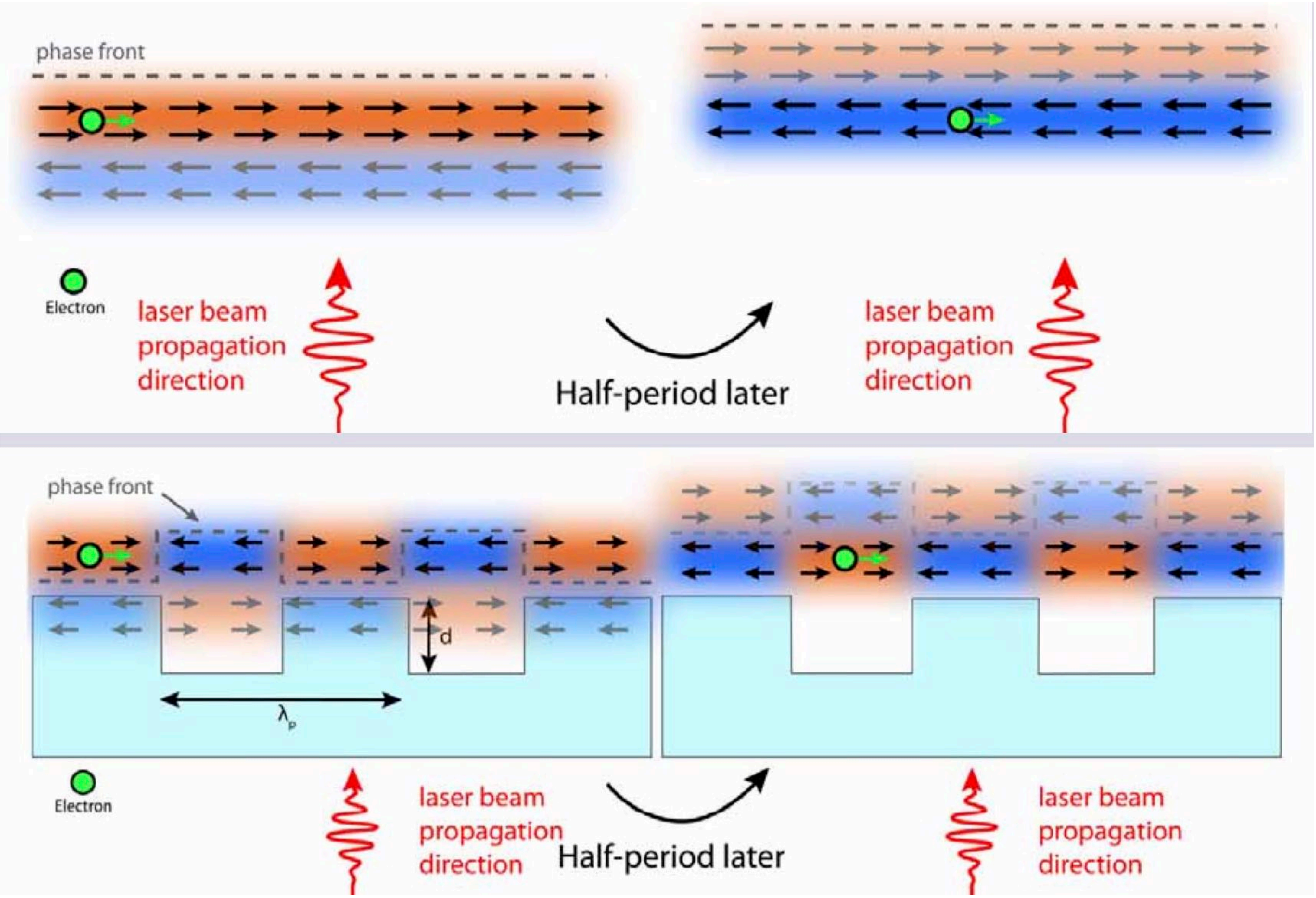


Amazingly compact

- A few cm of plasma give the same energy of 100 m of superconducting LINAC

Even smaller: Accelerator on a Chip

Dielectric Accelerator



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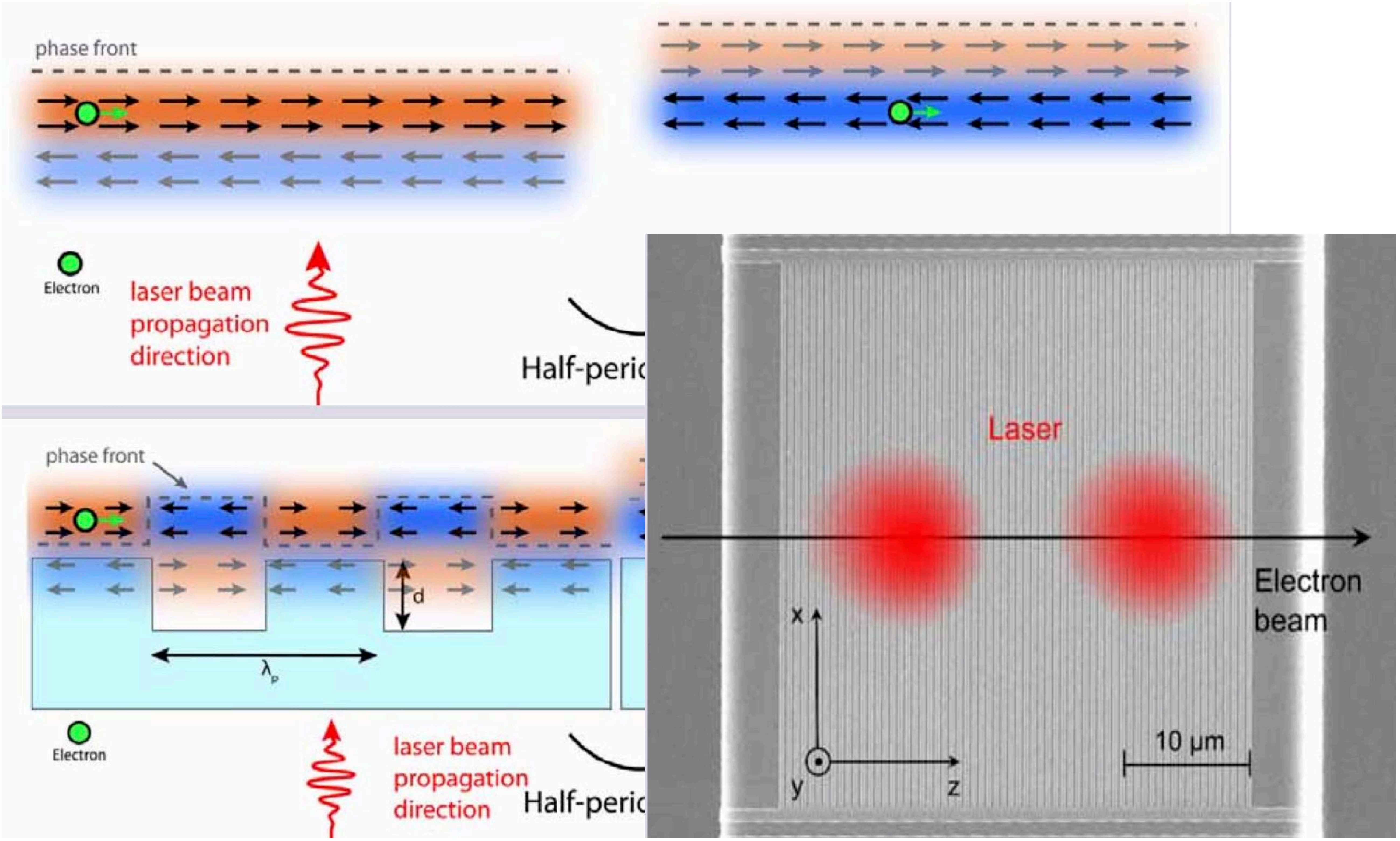
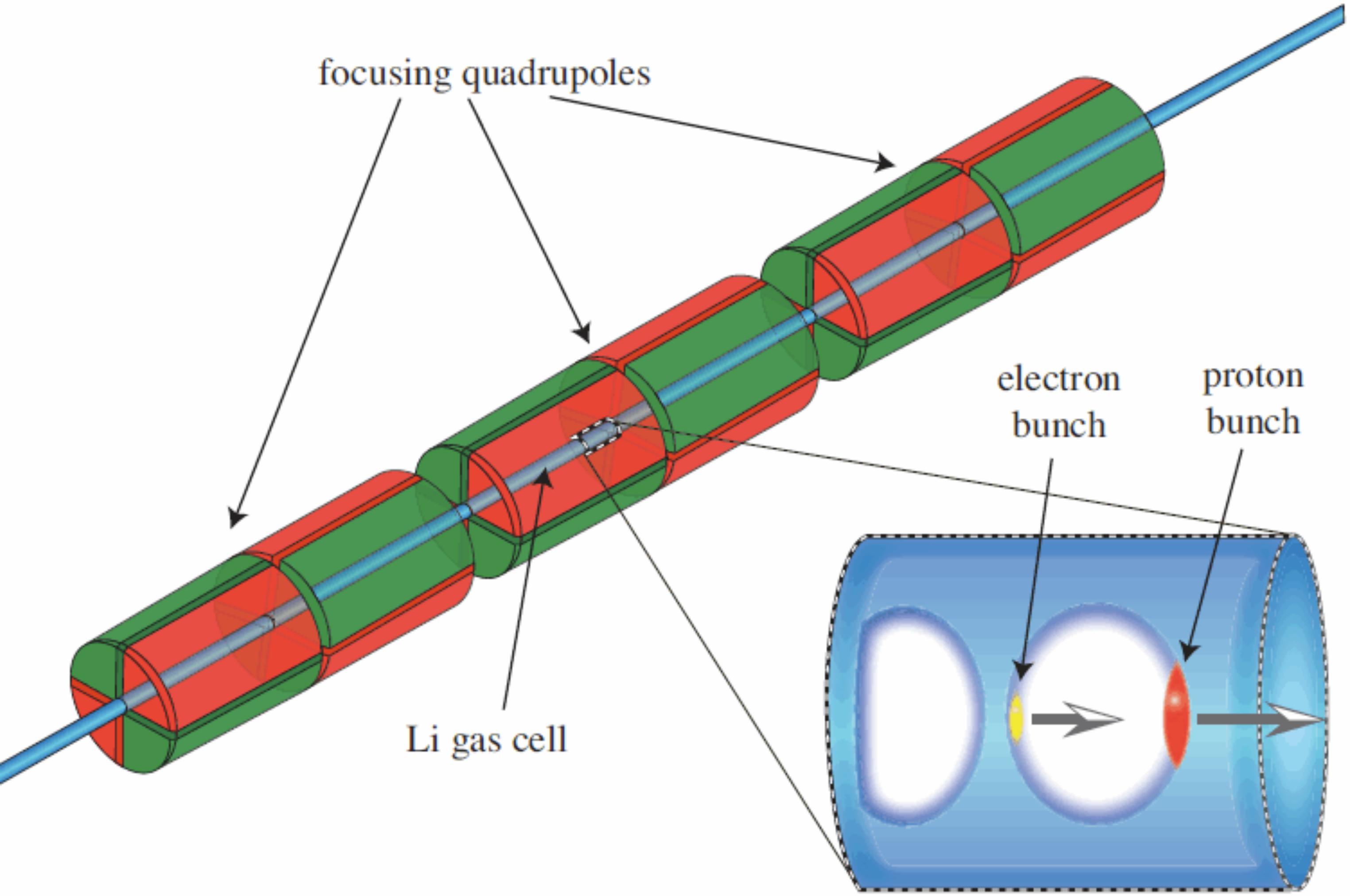
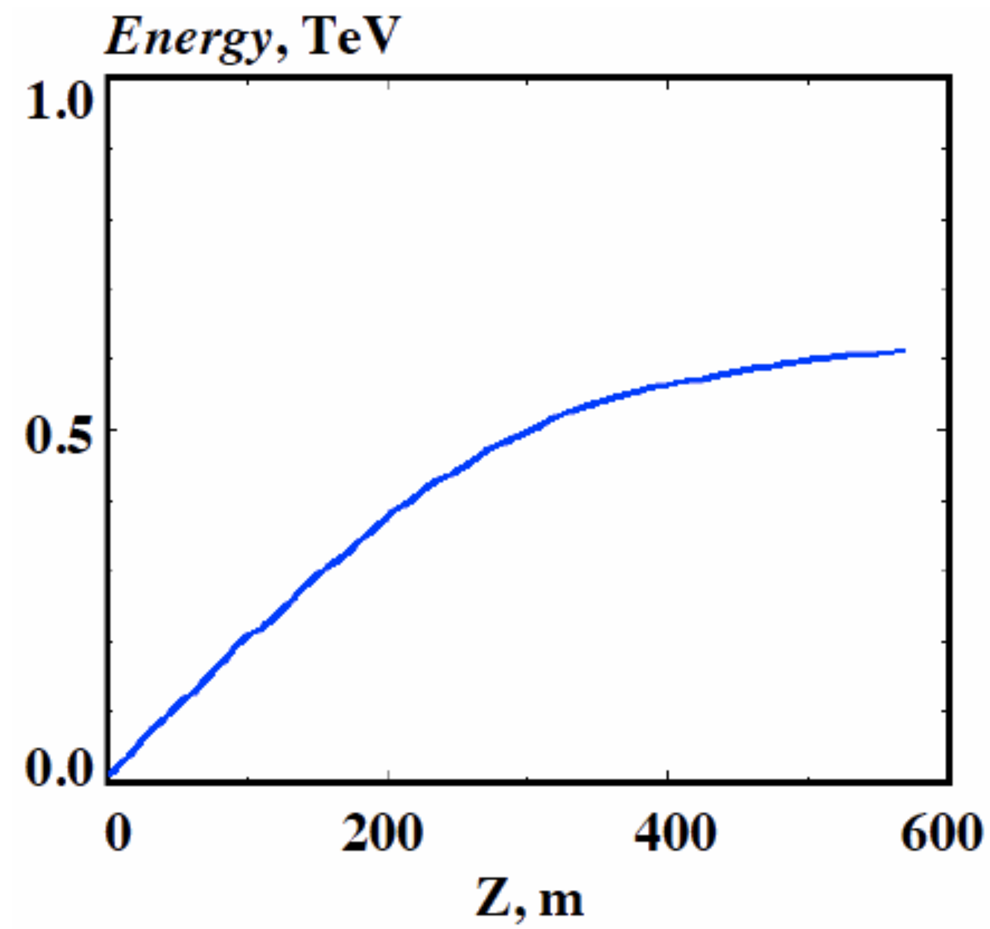


Plasma Wakefield Acceleration

- Need to get the energy into the plasma
  - Lasers - used for extreme gradients over very short distances (~ mm)
  - Beams - Much higher power - Long acceleration distances possible
    - Idea followed at MPP: Use protons to drive plasma: Very high energy available!



Simulation with 1 TeV proton beam



Plasma Wakefield Acceleration

- Need to get the energy into the plasma
  - Lasers - used for extreme gradients over very short distances (~ mm)

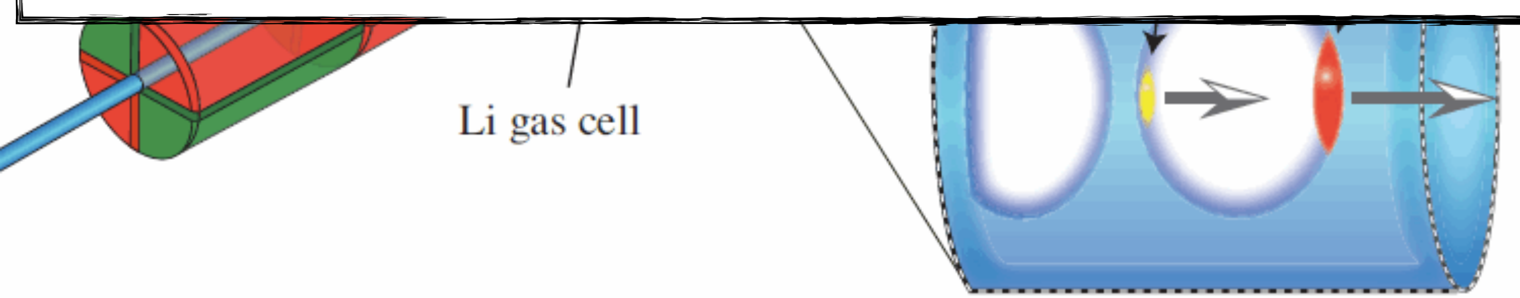
Key challenges (so far unsolved) for all techniques:

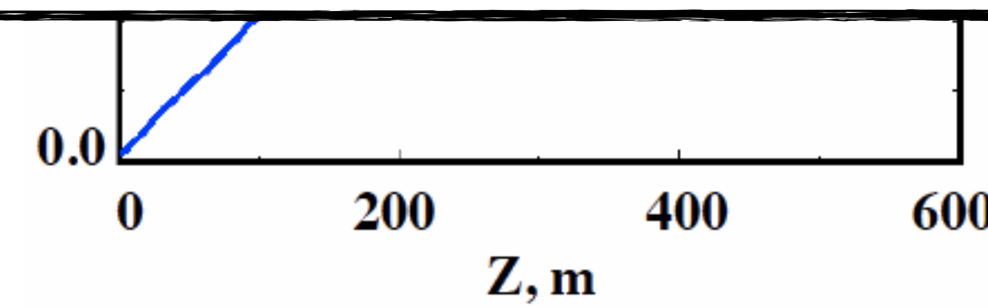
How to get very sharp energy distributions, high repetition rate, high currents and good focusing?

How to accelerate positrons with a comparably high gradient?

Or, in short:

How to get high luminosity for a collider?





Summary

- Detector systems at colliders detect stable and long-lived particles Observables are energy, momentum, time of flight; tracks and secondary vertices and particle identification
- A central component of all detectors is the magnetic field - Solenoids are standard, but other solutions are used as well
- The most commonly used mechanism is ionization by charged particles
  - Described by the Bethe-Bloch Equation
- Many different techniques are used for particle detection
  - Gas-filled ionization chambers, multi-wire chambers and drift chambers
  - Semiconductor detectors
  - Scintillators with suitable photon detectors
  - Transition radiation detectors, Cherenkov detectors, ...

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Next Lecture: Collider Detectors II, F. Simon, 07.01.2019

Lecture Overview

15.10.	Introduction, Particle Physics Refresher	*F. Simon*
22.10.	Introduction to Cosmology I	*B. Majorovits*
29.10.	Introduction to Cosmology II	*B. Majorovits*
05.11.	Particle Collisions at High Energy	*F. Simon*
12.11.	The Higgs Boson	*F. Simon*
19.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
26.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
03.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
10.12.	Particle Colliders	*F. Simon*
17.12.	Detectors for Particle Colliders I	*F. Simon*
	Christmas Break	
07.01.	Detectors for Particle Colliders II	*F. Simon*
14.01.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
21.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
28.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
04.02.	Baryogenesis via Leptogenesis	*B. Majorovits*