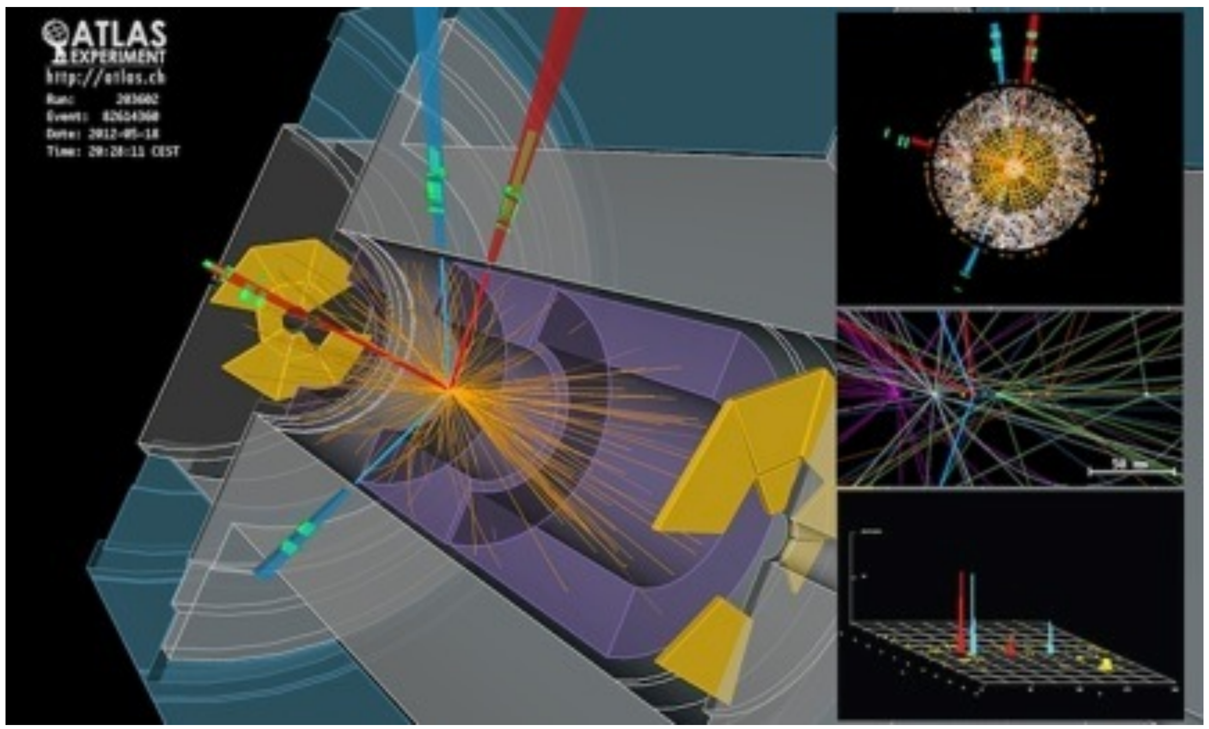
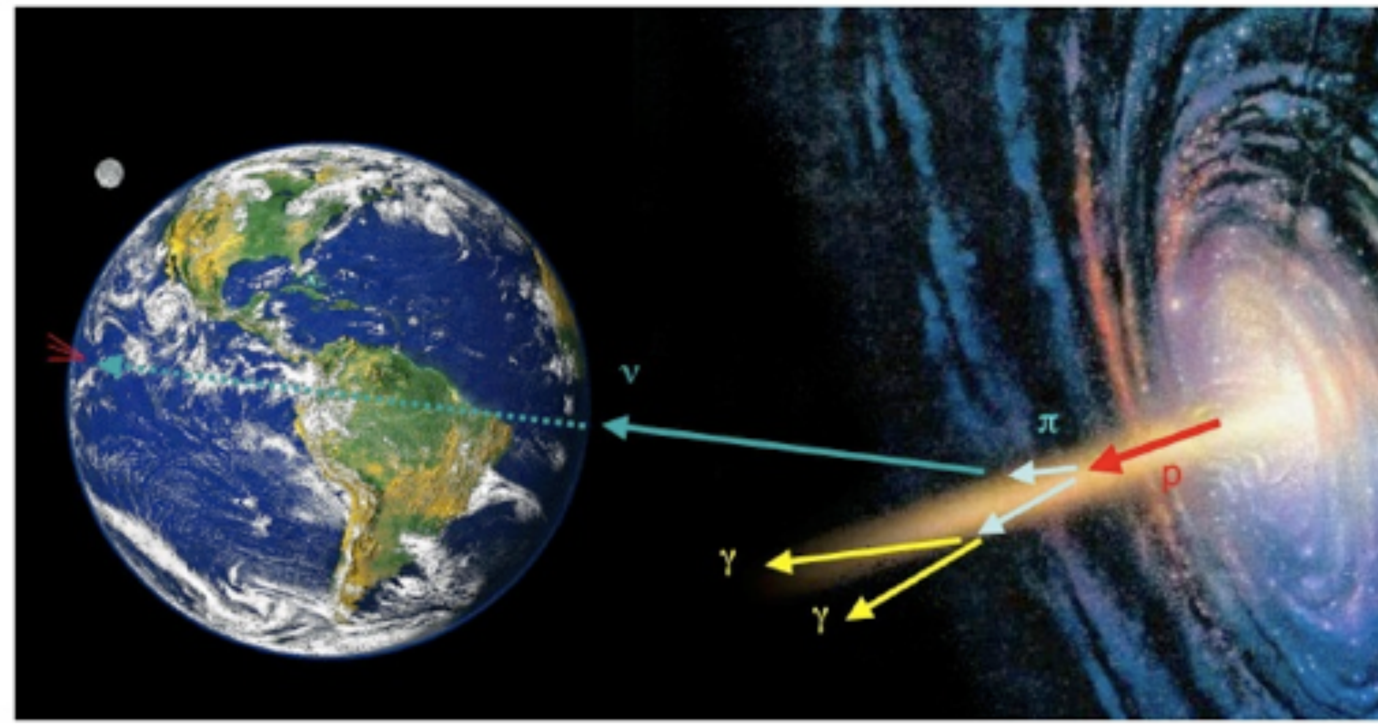
Particle Physics at Colliders and in the High Energy Universe





12. Collider Detectors

20.01.2020

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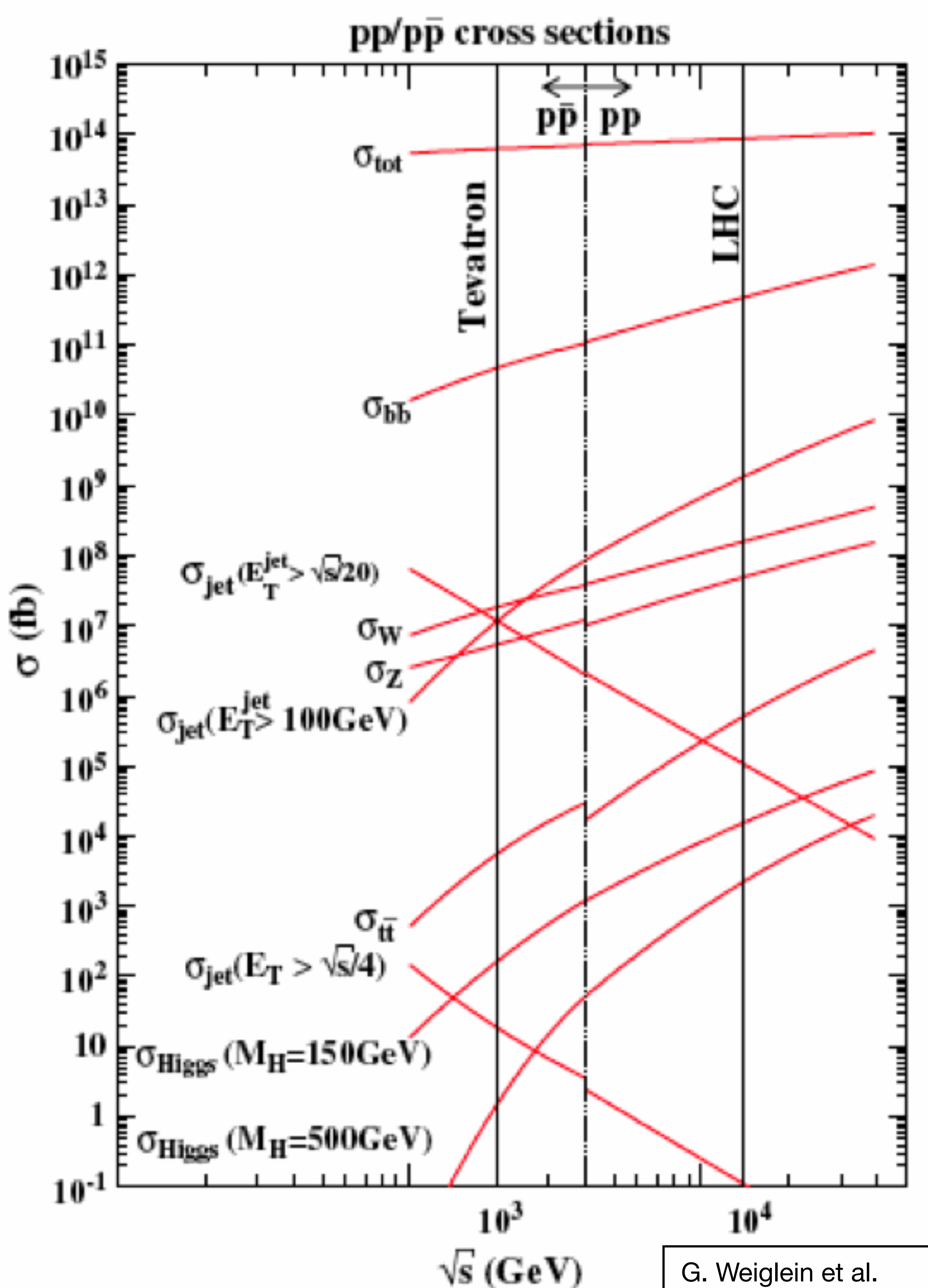
Detectors: Overview

- **Basics**
  - Introduction, overall detector concepts
  - Detector systems at hadron colliders
  - Basics of particle detection: Interaction with matter
  - Methods for particle detection
- **Selected Details**
  - Tracking Detectors
  - Calorimeters

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:

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

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

- 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

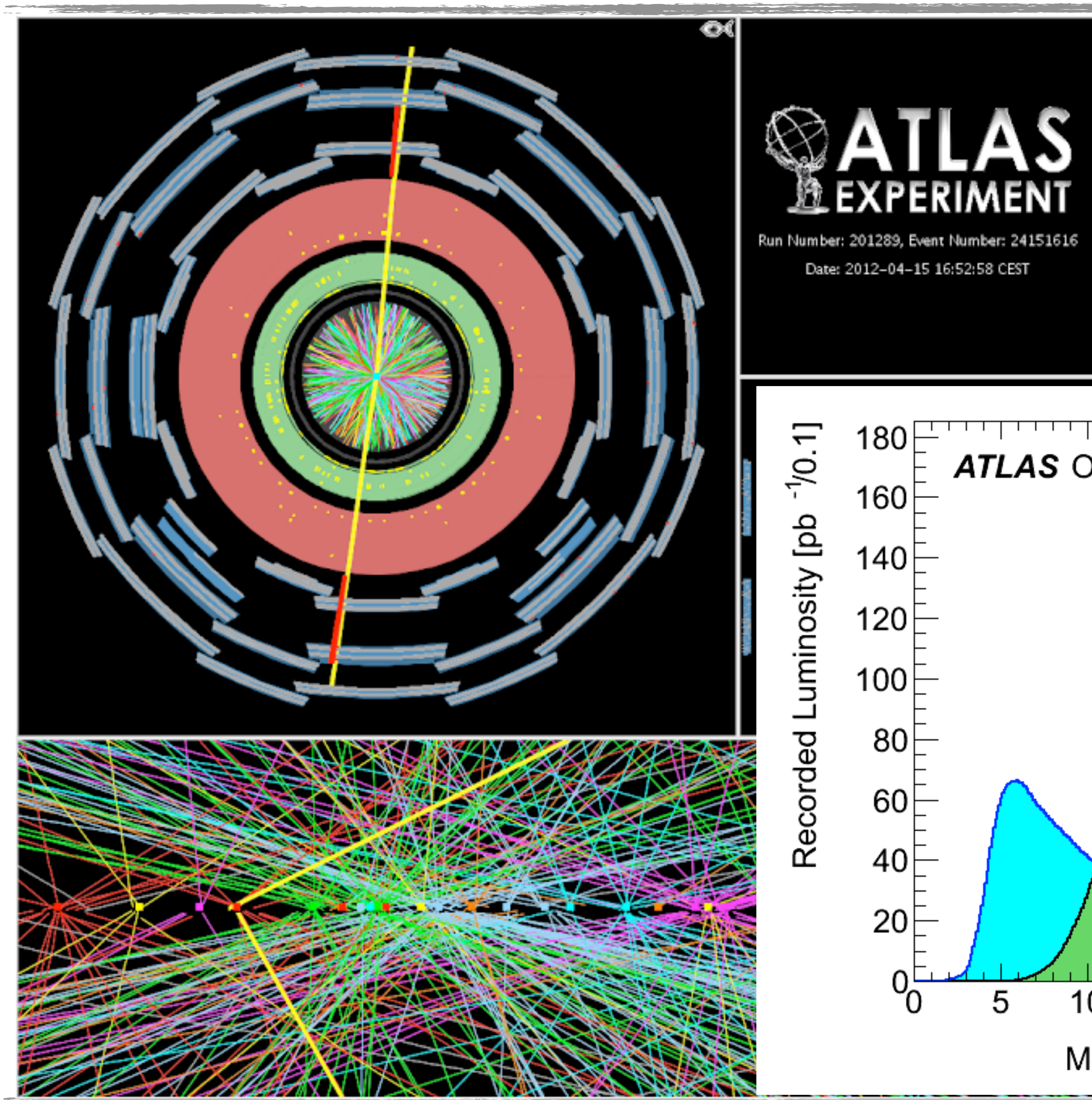
Detector Requirements

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

➠ Interaction rate ~ 1 GHz, approx. 25 p+p - reactions per bunch-crossing

- 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!

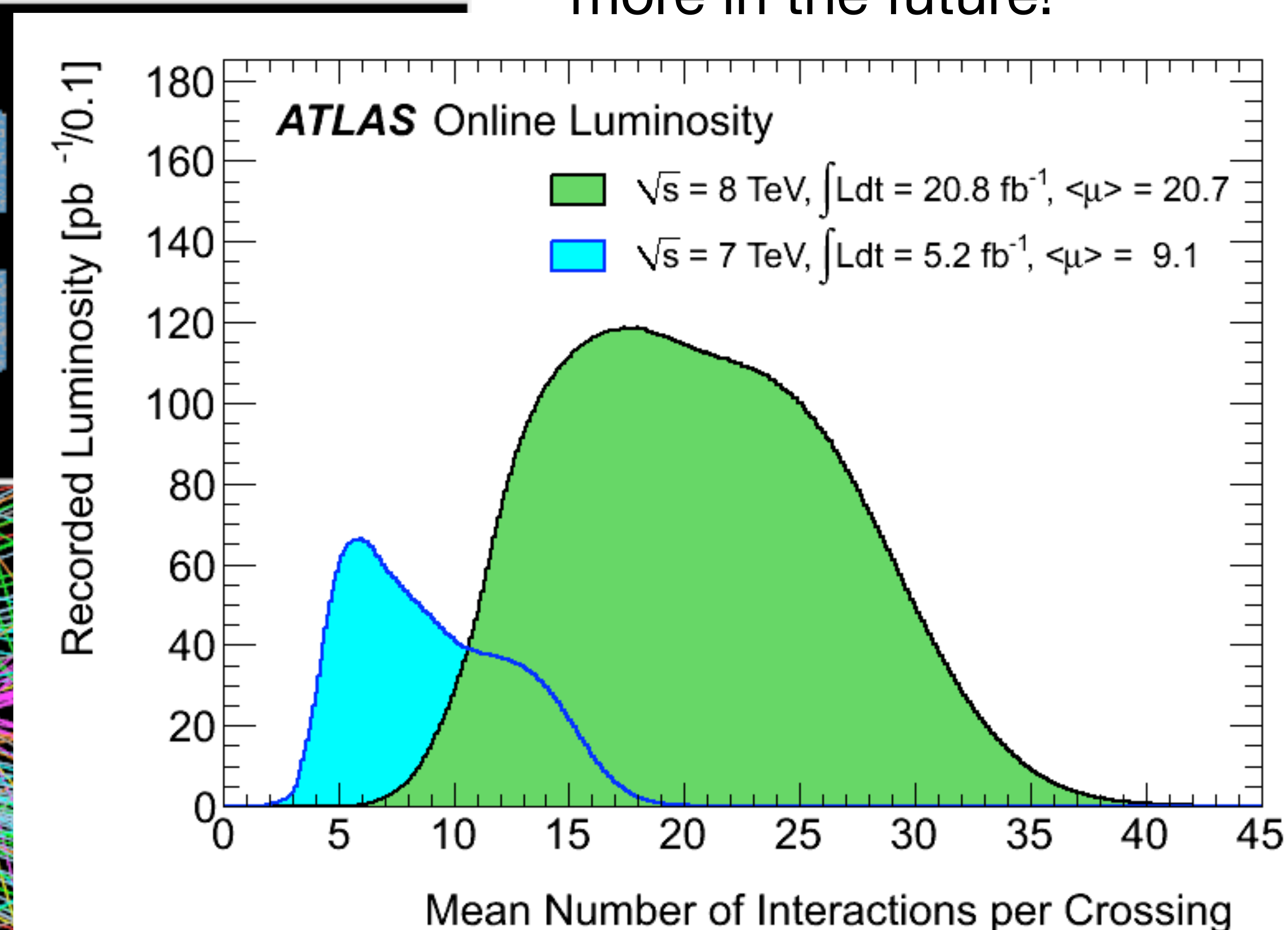
LHC: Extreme Conditions



Z -> μμ

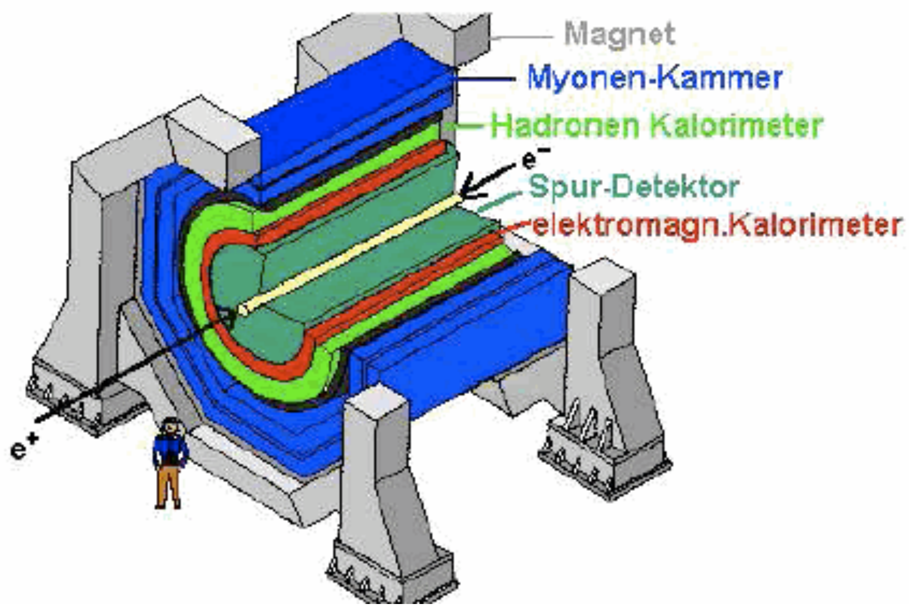
... and 25 other collisions

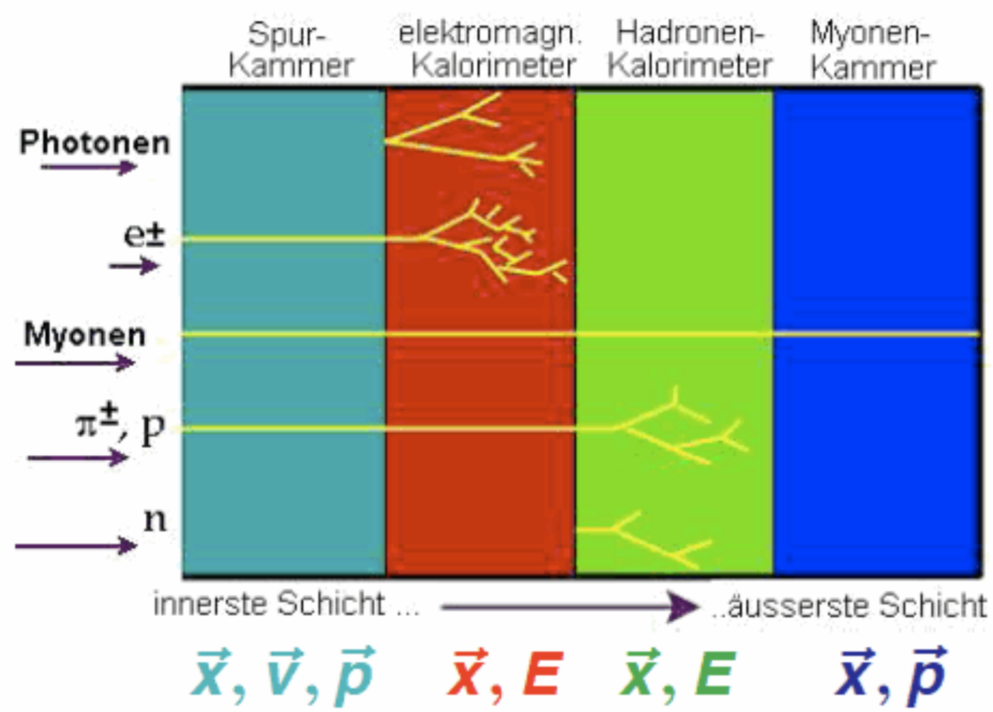
Normal LHC conditions in 2012 data taking - will get more in the future!

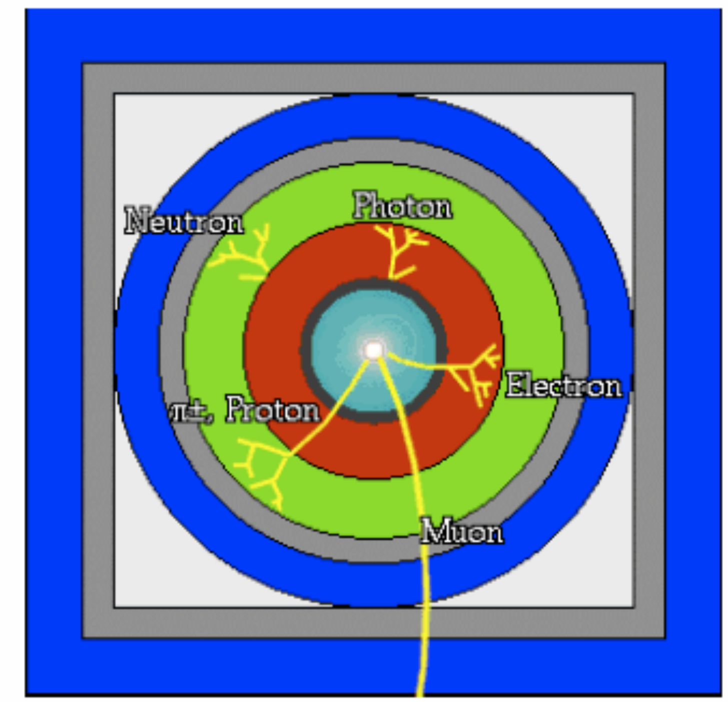


Collider Detectors

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







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

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

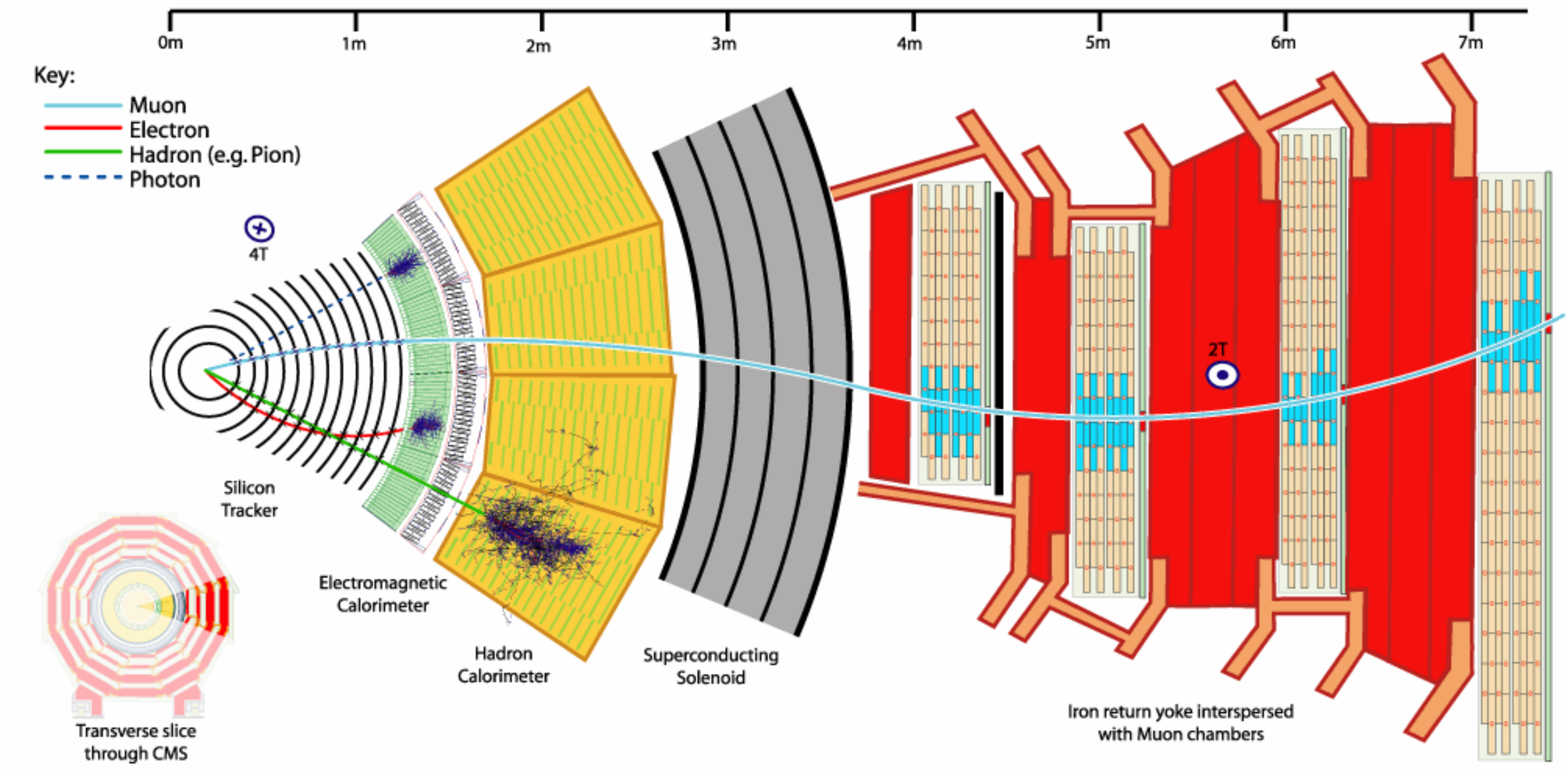
1. Vertex Tracker as close as possible to interaction point: Identification of secondary decays, for example from b-Quarks
2. Main Tracker: Measurement of location and momentum of all charged particles, some times also with particle ID
3. Particle ID: Time-of-flight measurement, Cherenkov detectors,... (optional)
4. Calorimeter (electromagnetic, hadronic): Energy measurement of charged and neutral particles
5. Muon Detectors: Improved tracking and identification of muons

- 1. - 3. have to be inside of a magnet to measure momentum
- Ideally also include the calorimeters inside of the magnet to limit (dead) material in front of the detectors

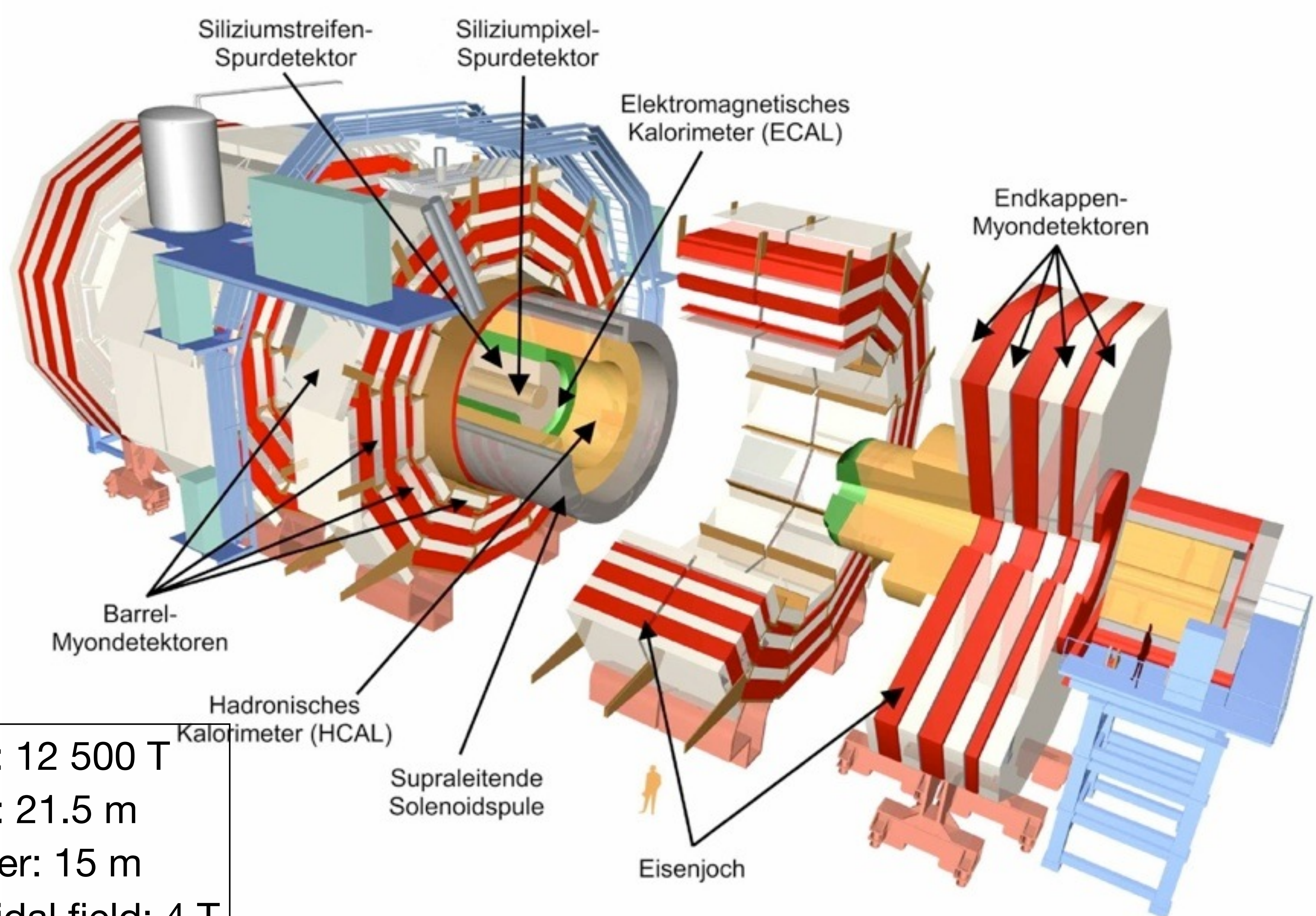
‣ 6. A big (and strong) magnet!

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

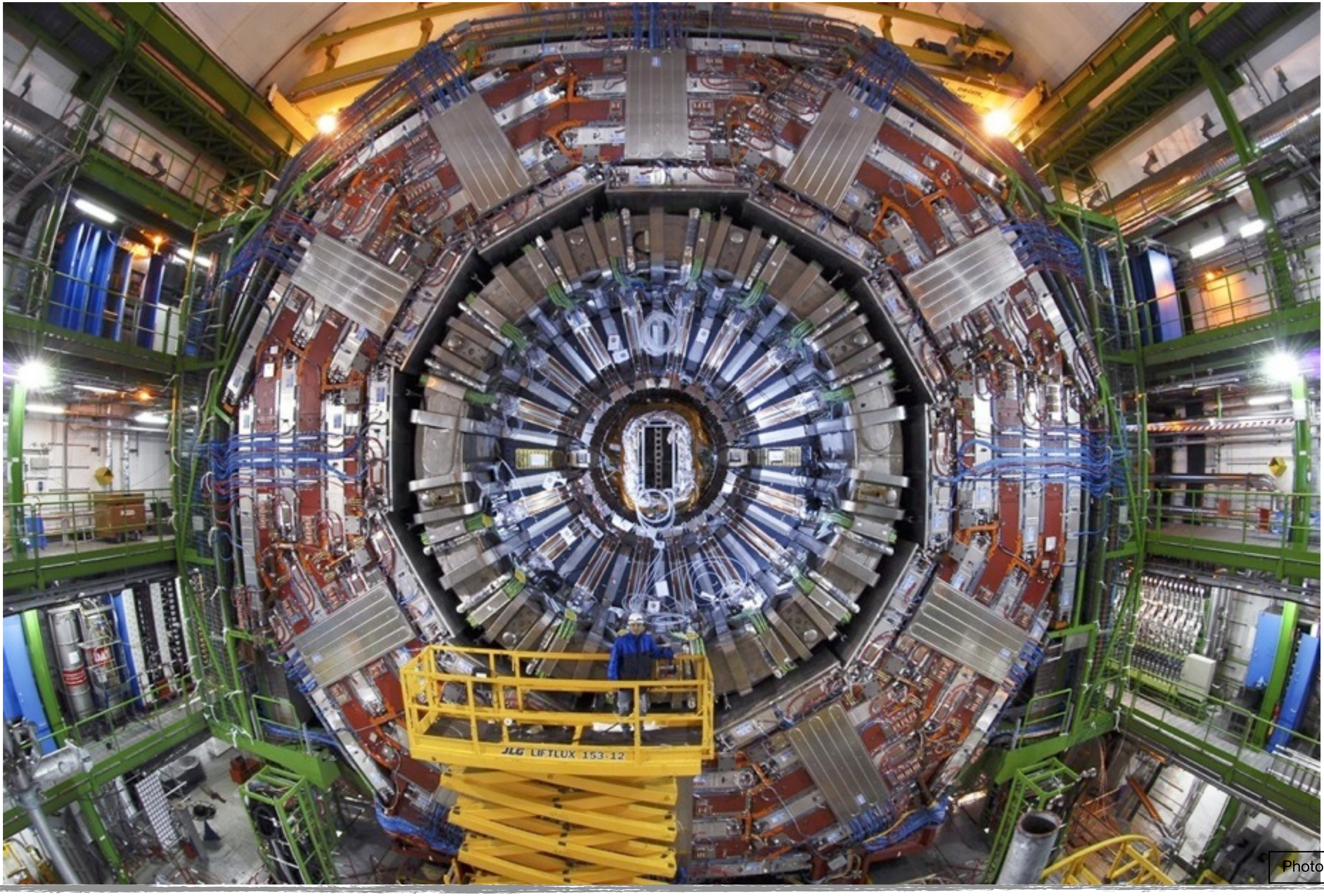
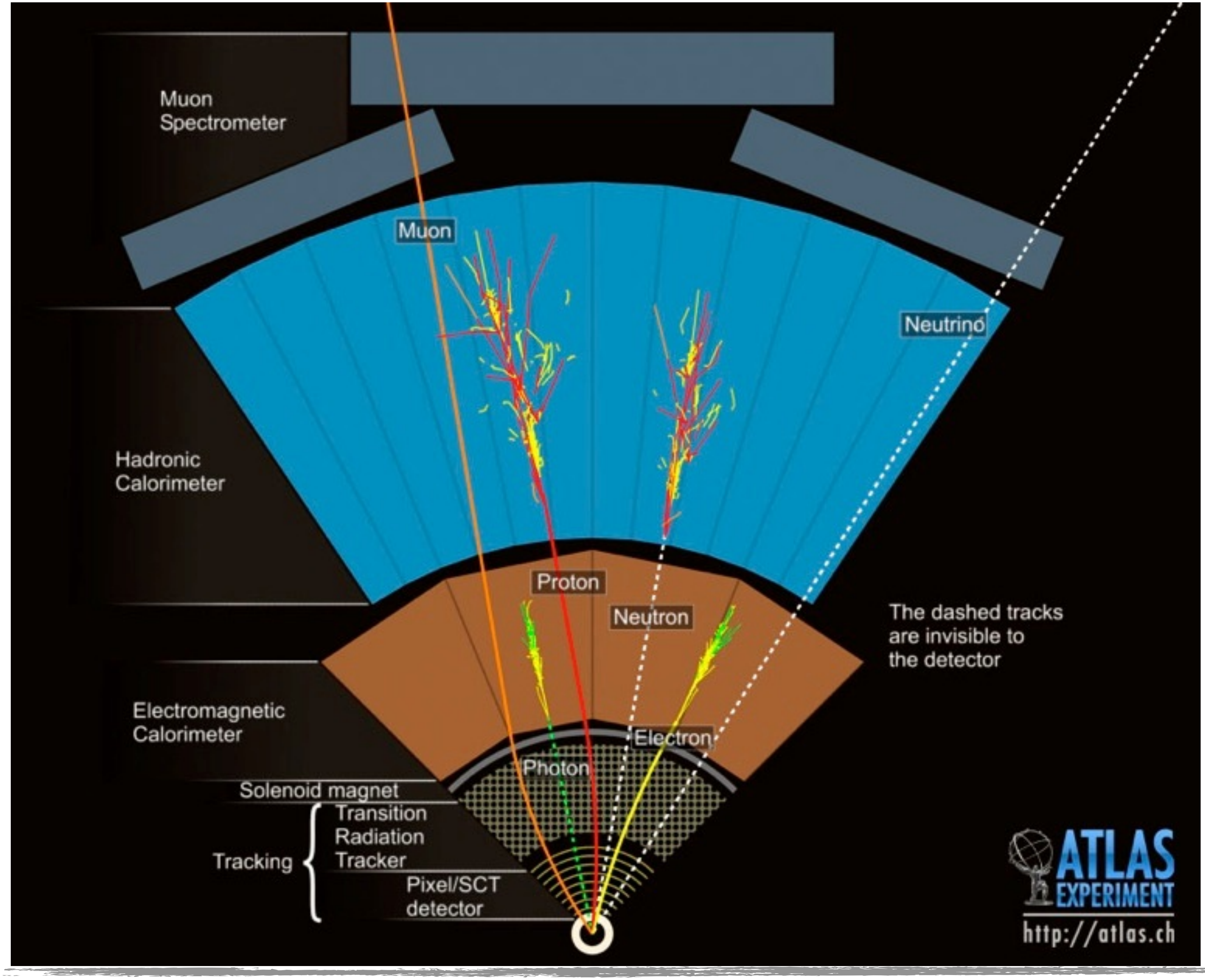
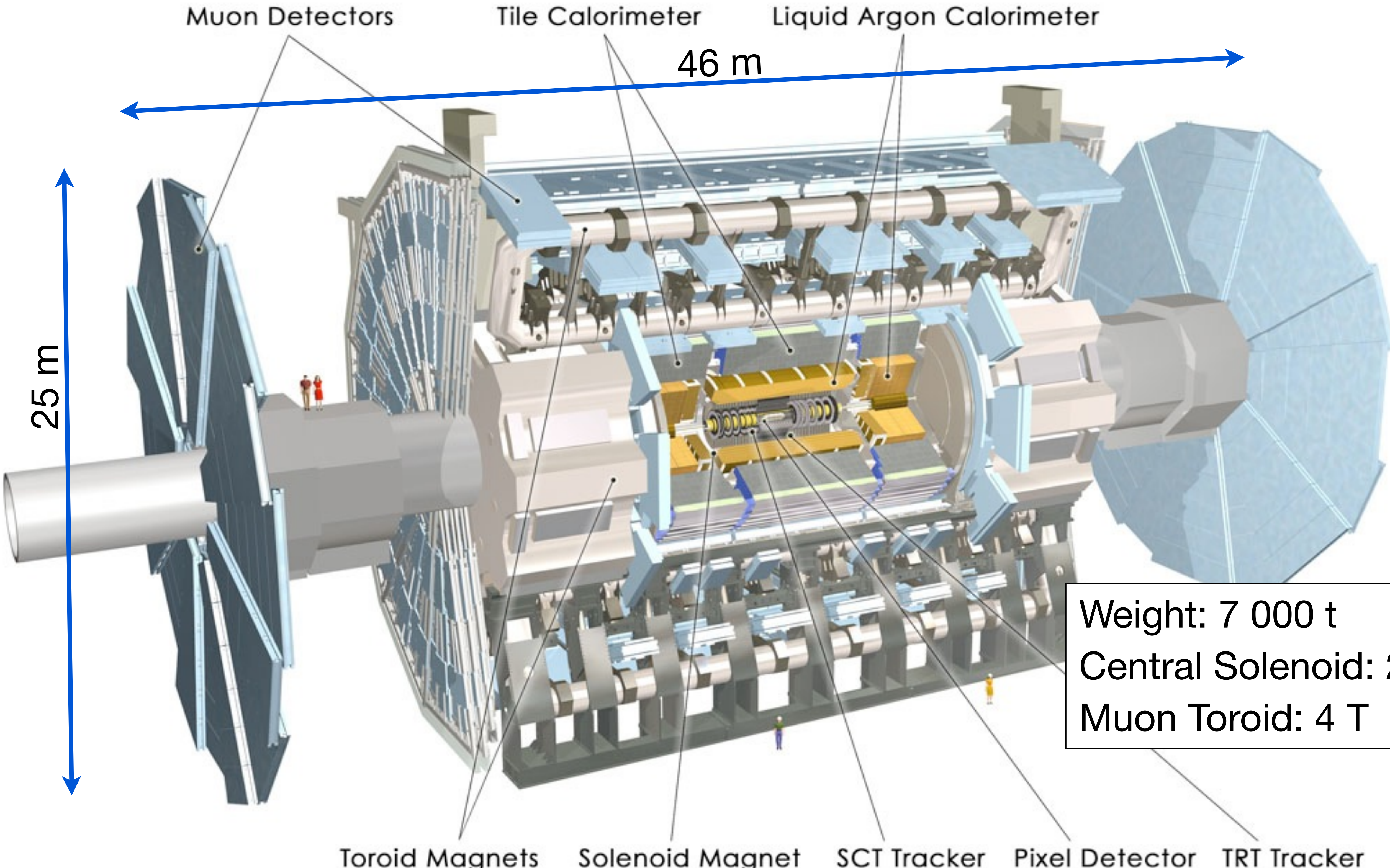


Photo: CERN

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

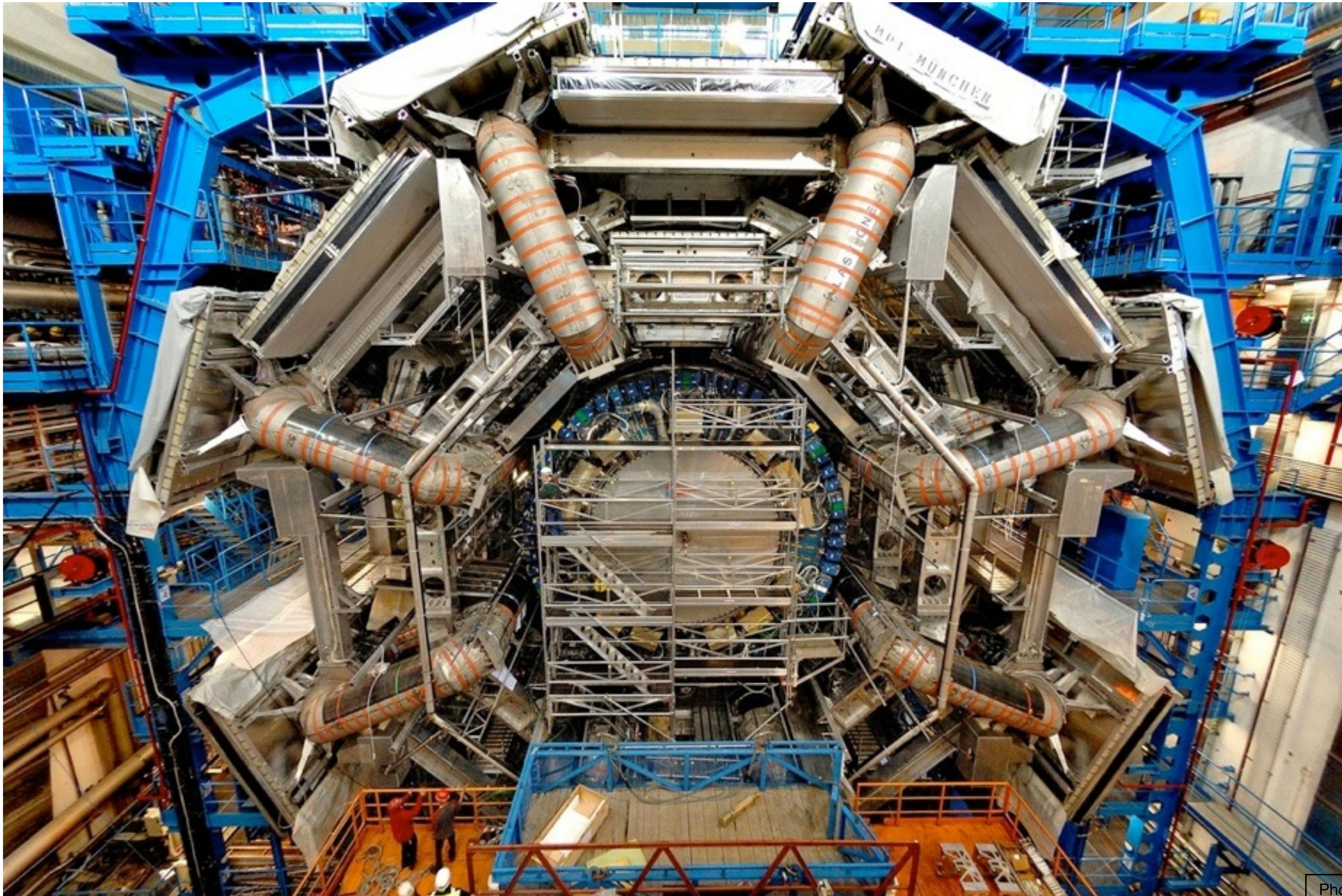


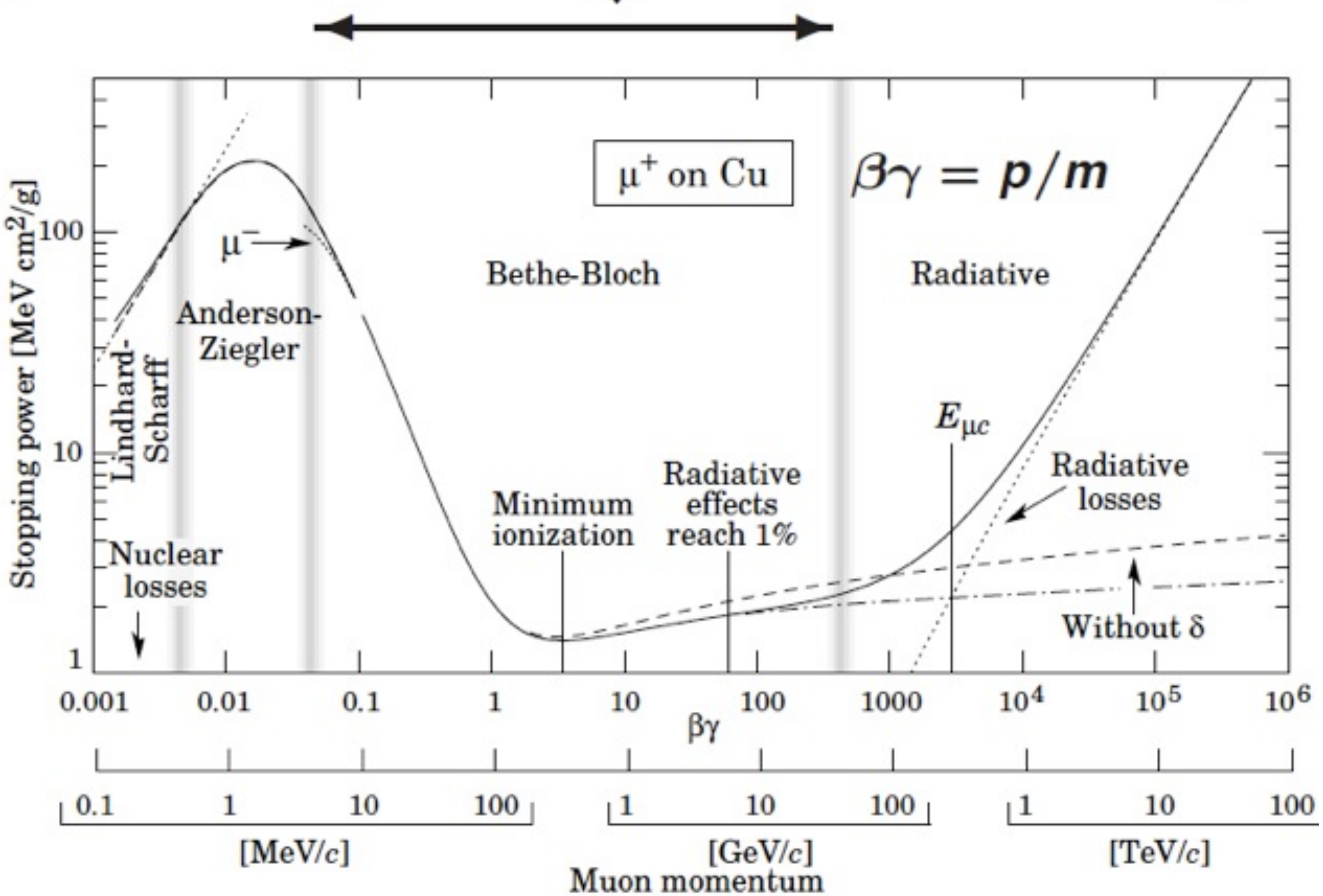
Photo: CERN

Basics of Particle Detection: Interaction with Matter

Energy Loss in Matter: Bethe-Bloch

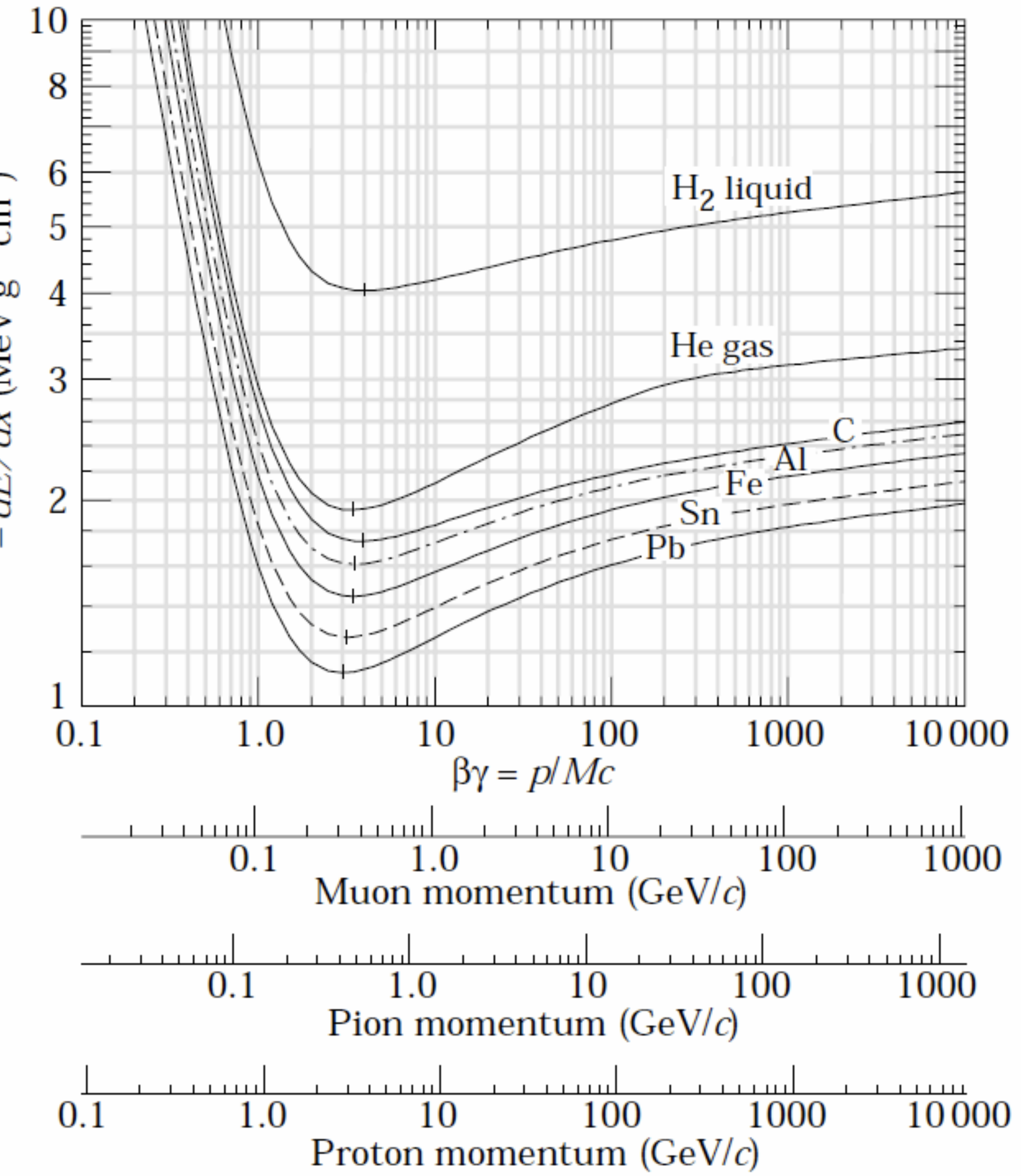
- The Bethe-Bloch Formula describes energy loss by ionization

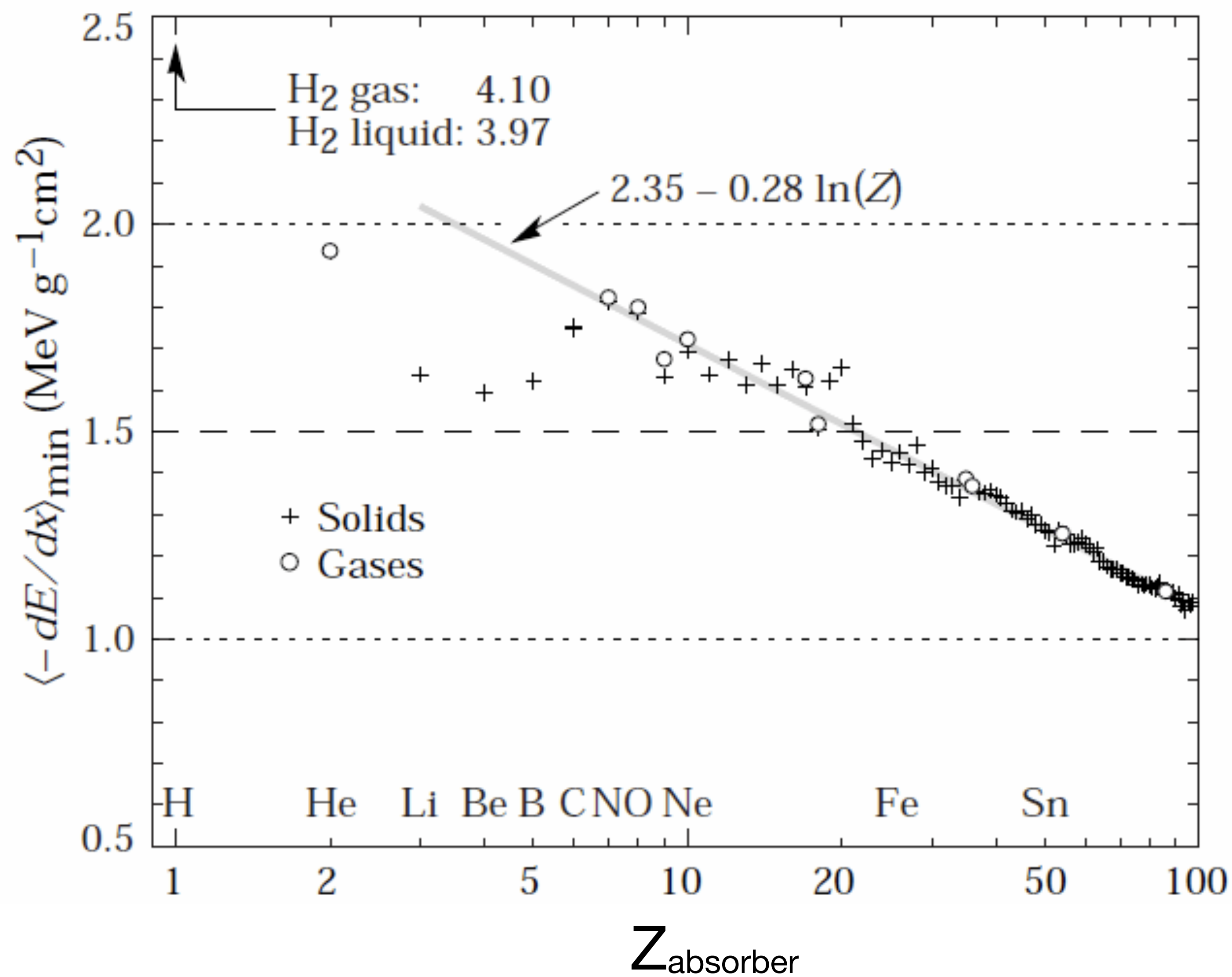
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$



- 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)

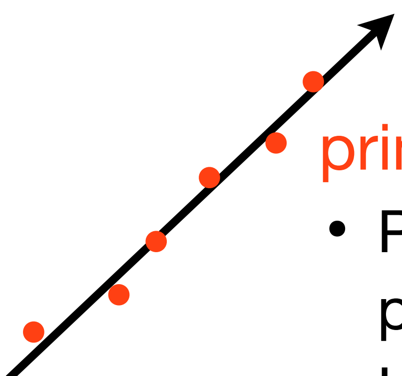
Energy Loss: A Closer Look

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

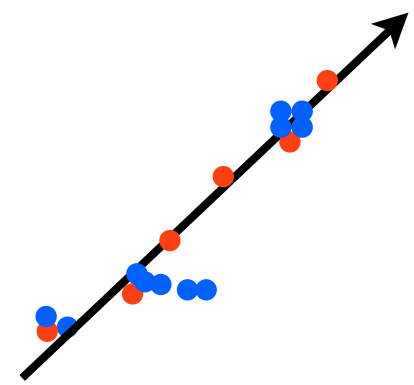
On the microscopic level: discrete scatterings, leading to ionization

⇰ Depending on the momentum transfer, a single or multiple free electrons are created

⇰ Distinguishing primary and secondary ionization:



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

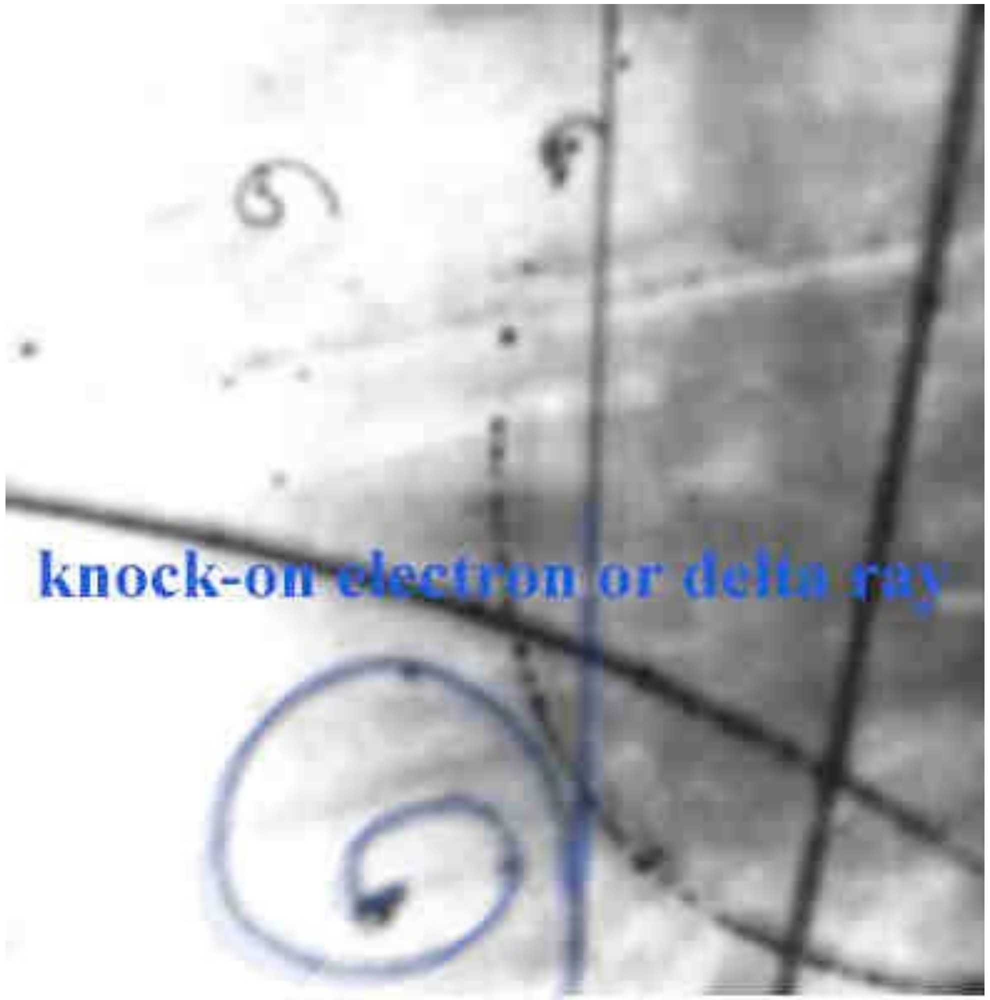


secondary ionization
- originating from high-energy primary electrons
- Sometimes the energy is sufficient for a clearly visible secondary track: δ electron

total ionization = primary ionization + secondary ionization

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

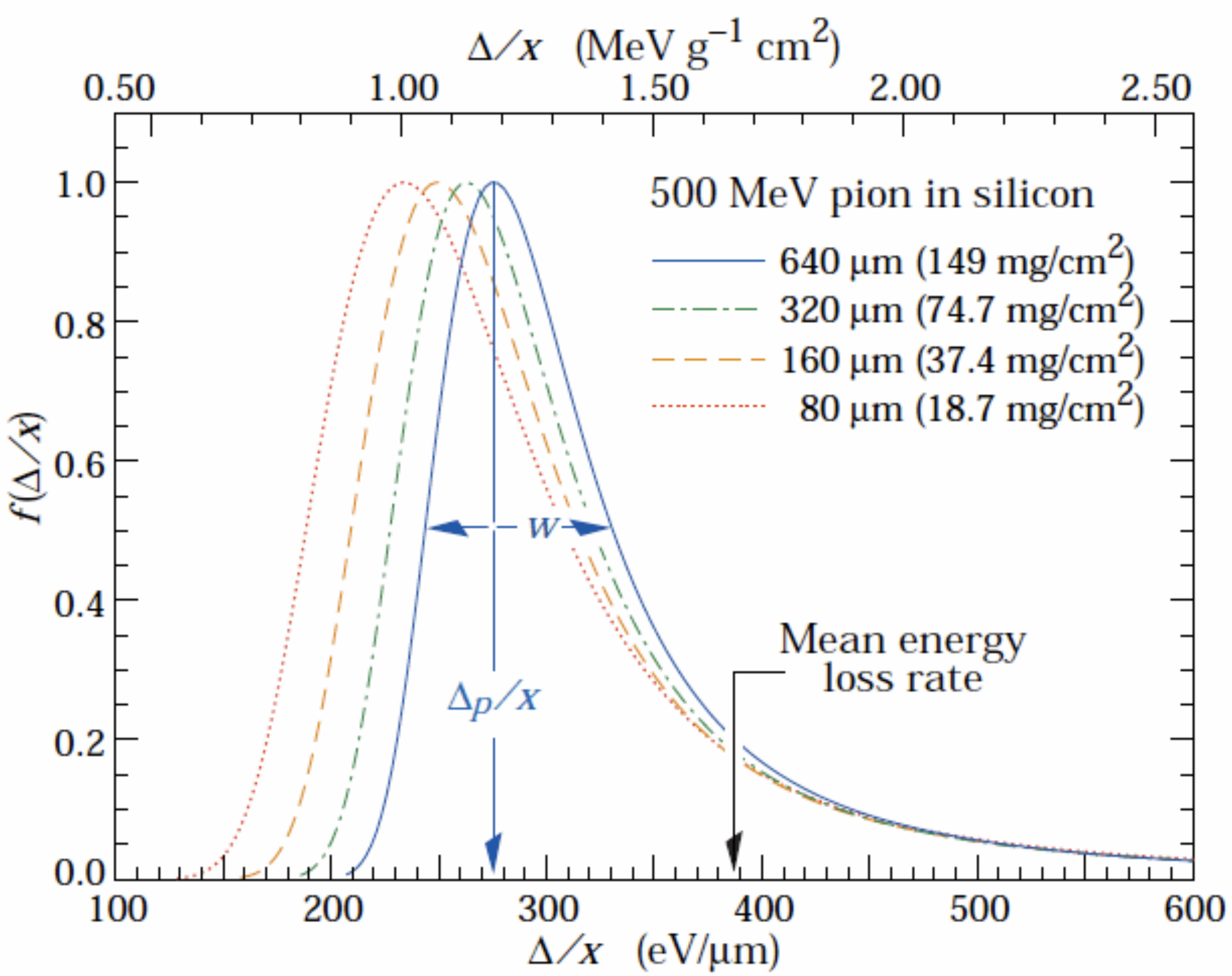
Energy Loss: A Closer Look



- 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



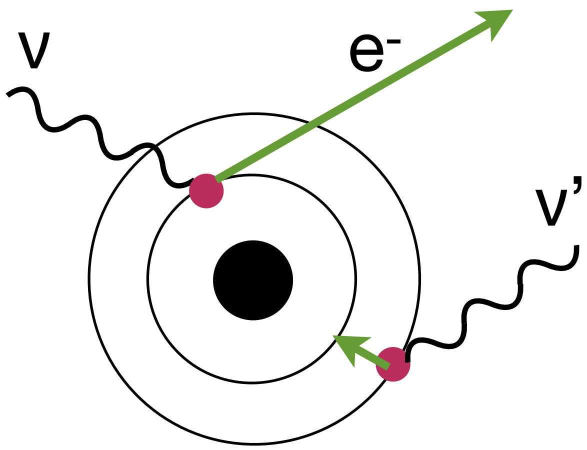
The energy loss in thin layers was first described by Landau: **Landau distribution**

Thin absorber:
<ΔE> < ~ 10 T_{max}

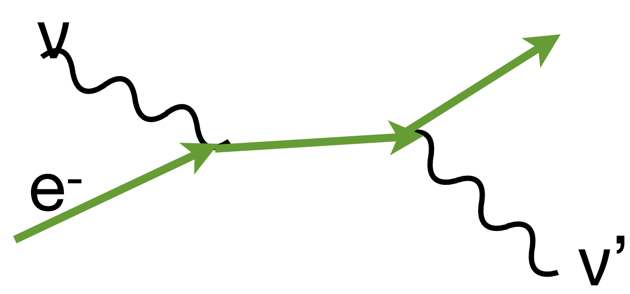
For 500 MeV pions: T_{max} ~ 9 MeV
(Mean energy loss in 9 mm of Si)

Photons: Interactions

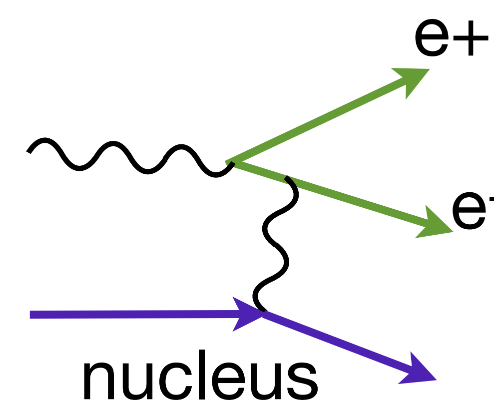
photo effect



Compton scattering



pair creation



energy threshold:
2 m_e = ~1.022 MeV

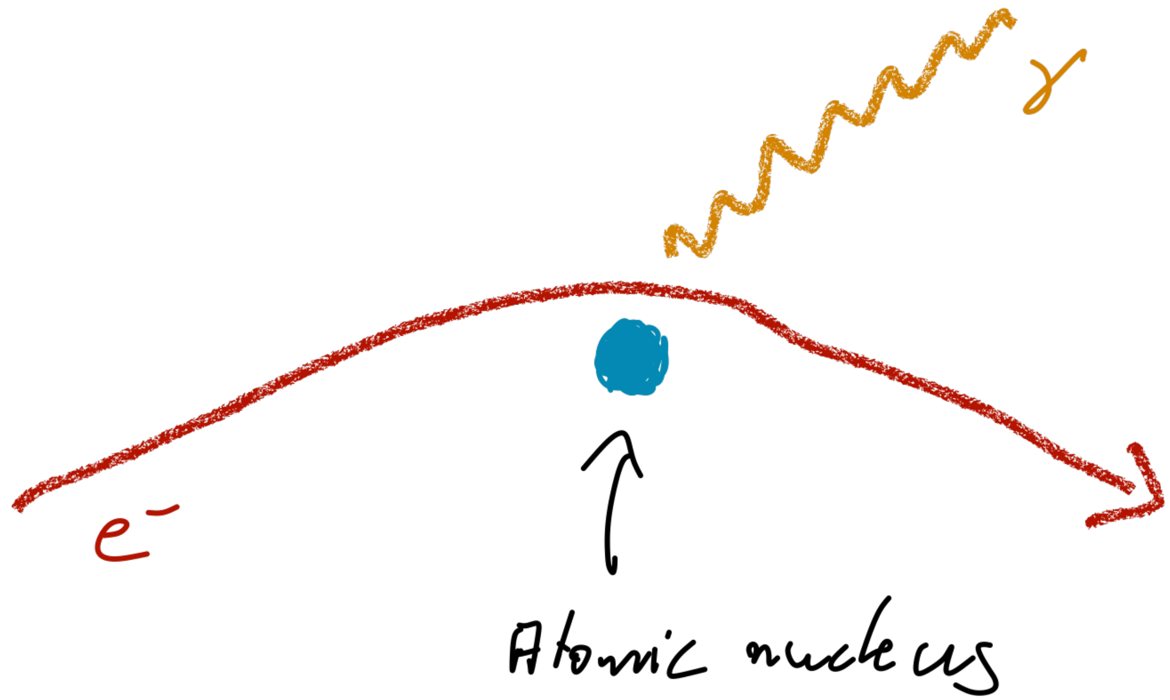
- In contrast to dE/dx for charged particles:
  "All or nothing" reactions

➩ Reduction of photon intensity when traversing matter:

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

Electrons: Interactions

- Closely related to “normal” charged particles - and to photons
  - Ionisation
  - Radiative energy loss: 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)
  - Defined as the amount of matter that has to be traversed such that
    - an electron loses all but 1/e of its energy via Bremsstrahlung
    - 7/9 of the mean free path for pair creation for high-energy photons

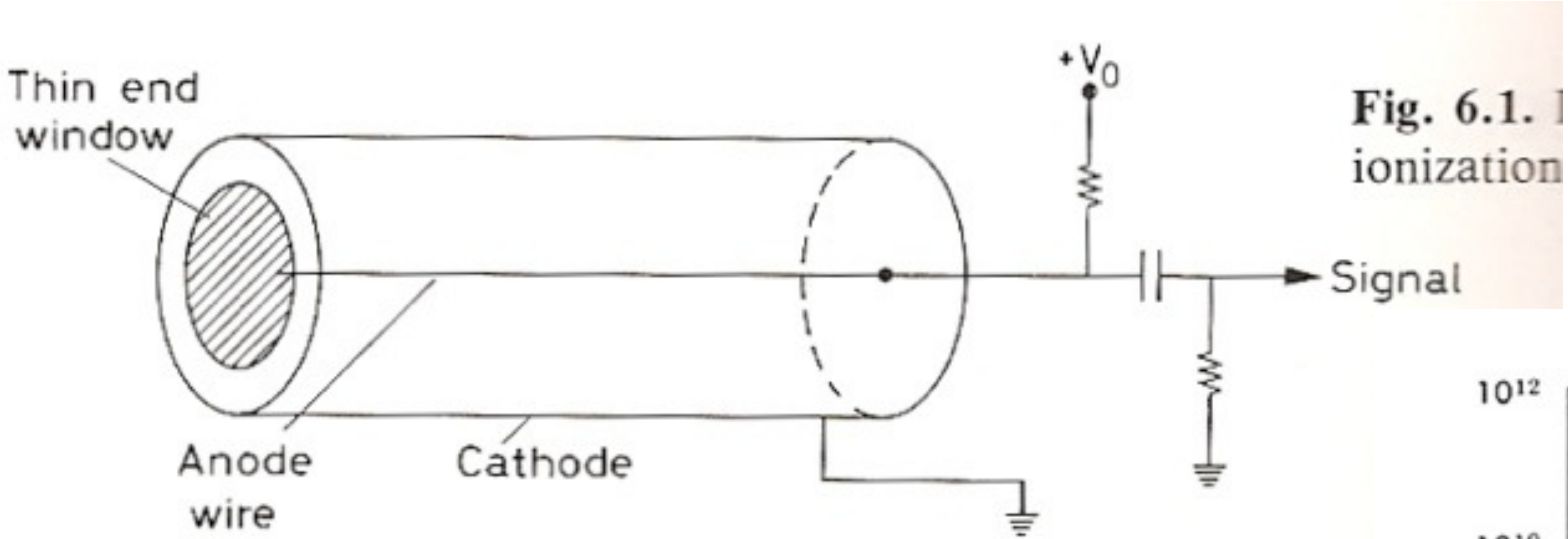
empirical: $$X_0 = \frac{716.4\,A}{Z(1+Z)\,ln(287/\sqrt{Z})}\,\frac{g}{cm^2} \propto \frac{A}{Z^2}$$

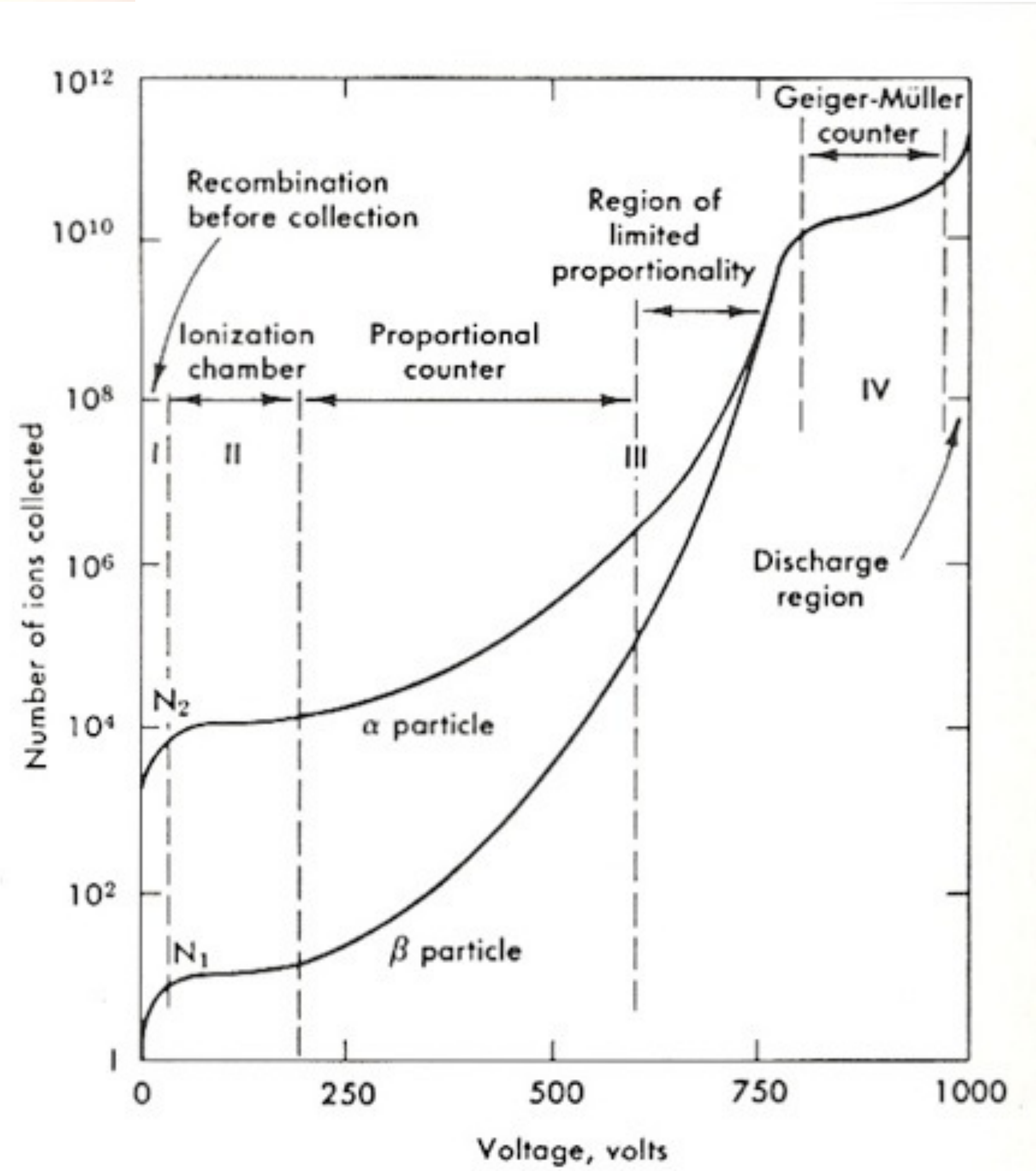
- Also relevant for the description of multiple coulomb scattering

- 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

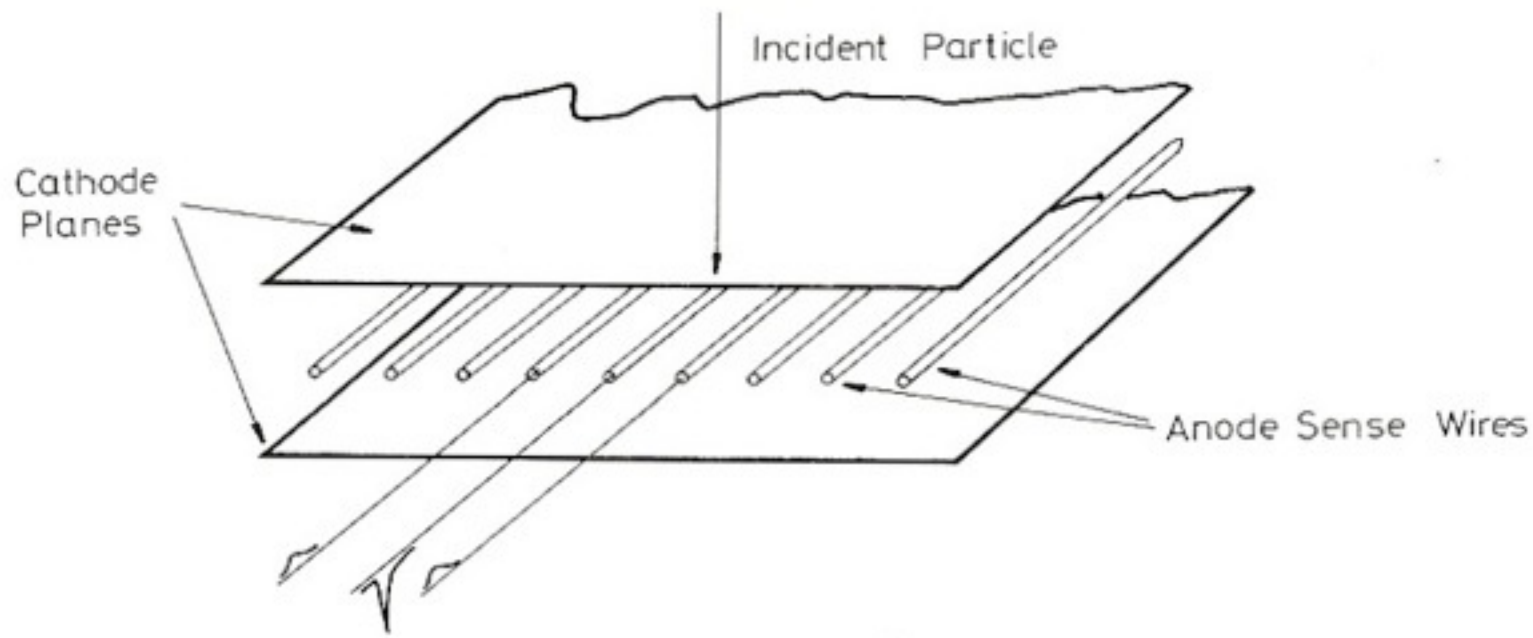
Ionization Chamber: A Classic

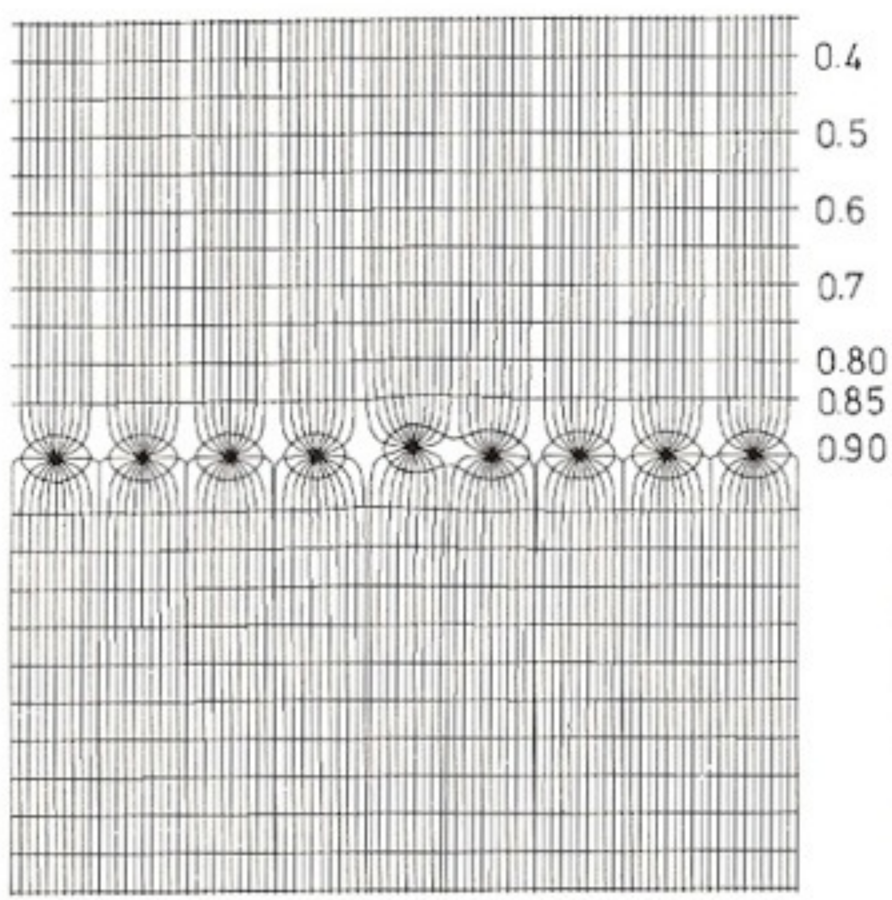


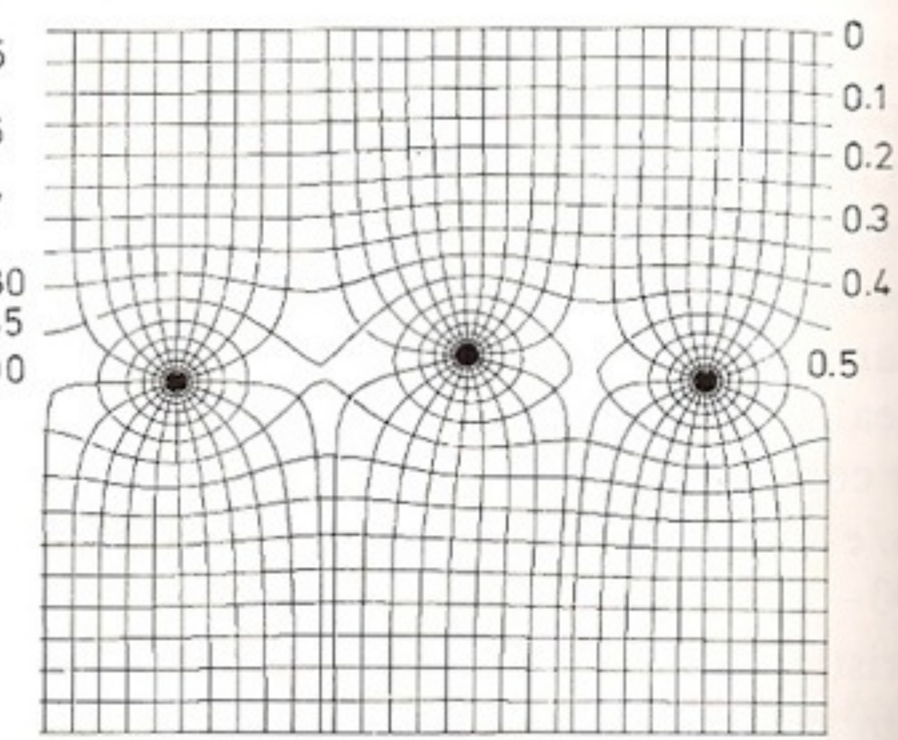


- Particles create electron-ion pairs in gas volume
- Electrons are accelerated in strong electric field, resulting in avalanche amplification
- Depending on the applied voltage the signal is proportional to the deposited energy or saturates

Spatial Resolution







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

Spatial Information through Timing: Drift Chamber

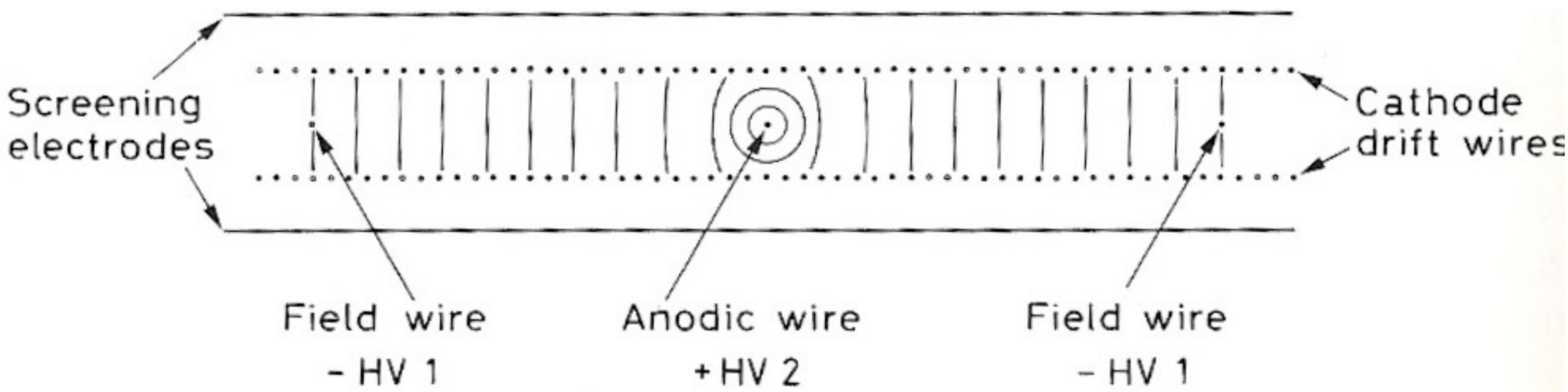


Fig. 6.16. Drift chamber design using interanode field wires (from *Breskin* et al. [6.22])

- 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

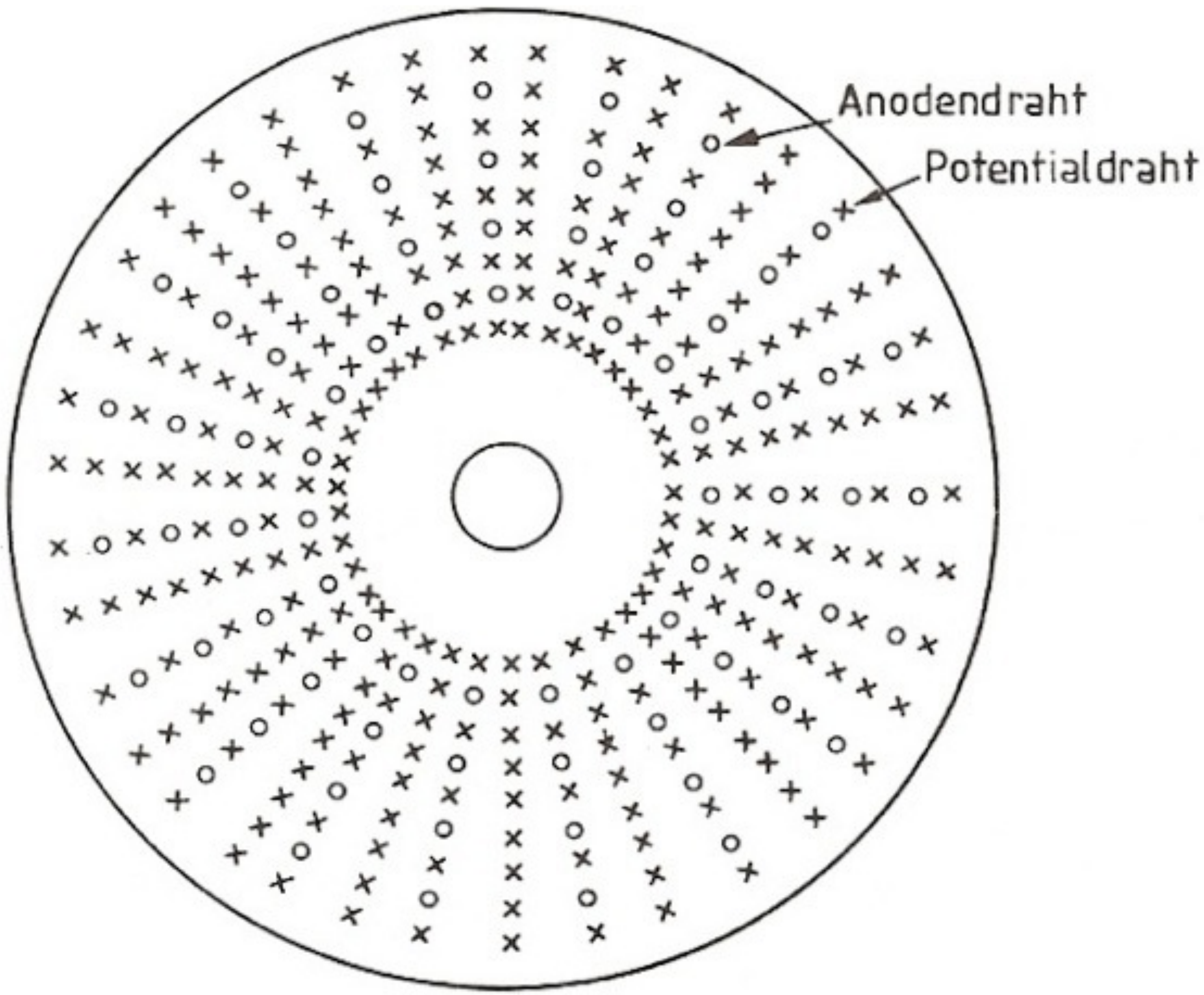
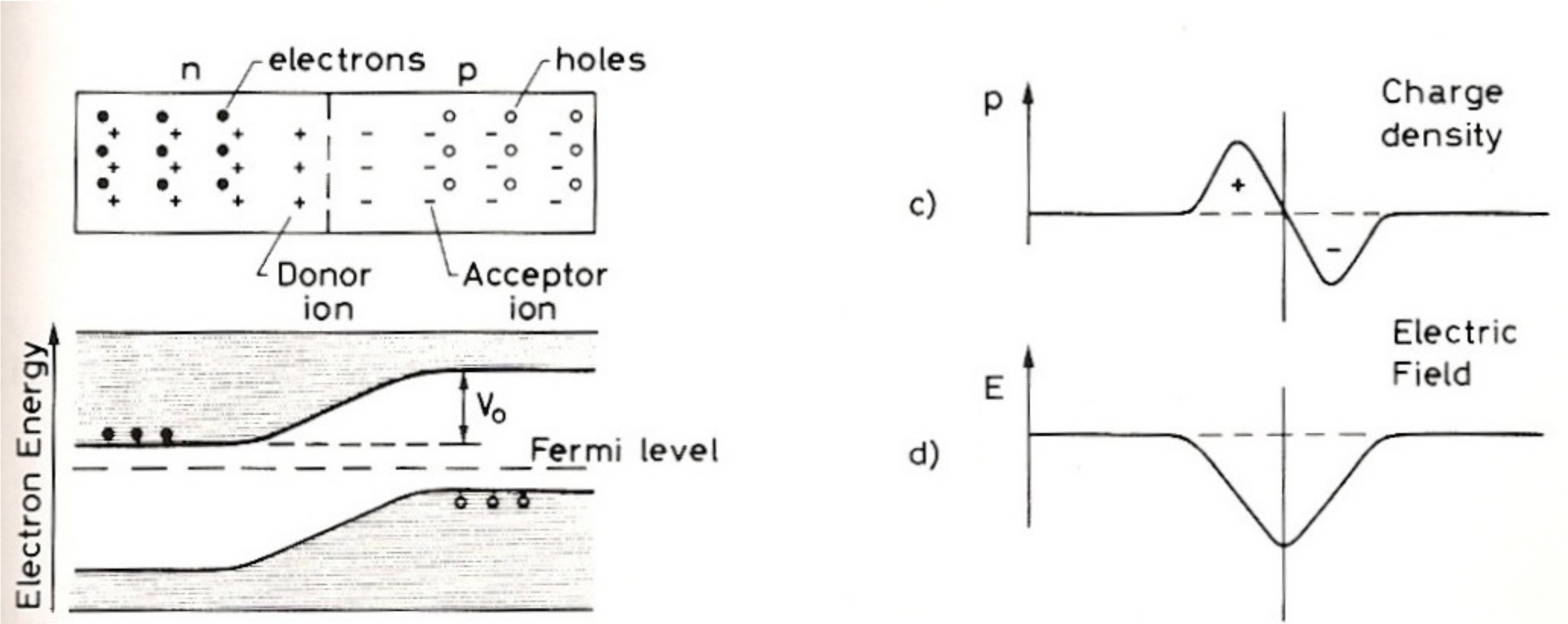


Abb. 4.41 Prinzipieller Aufbau einer zylindrischen Driftkammer. Die Abbildung zeigt einen Schnitt durch die Kammer senkrecht zu den Drähten.

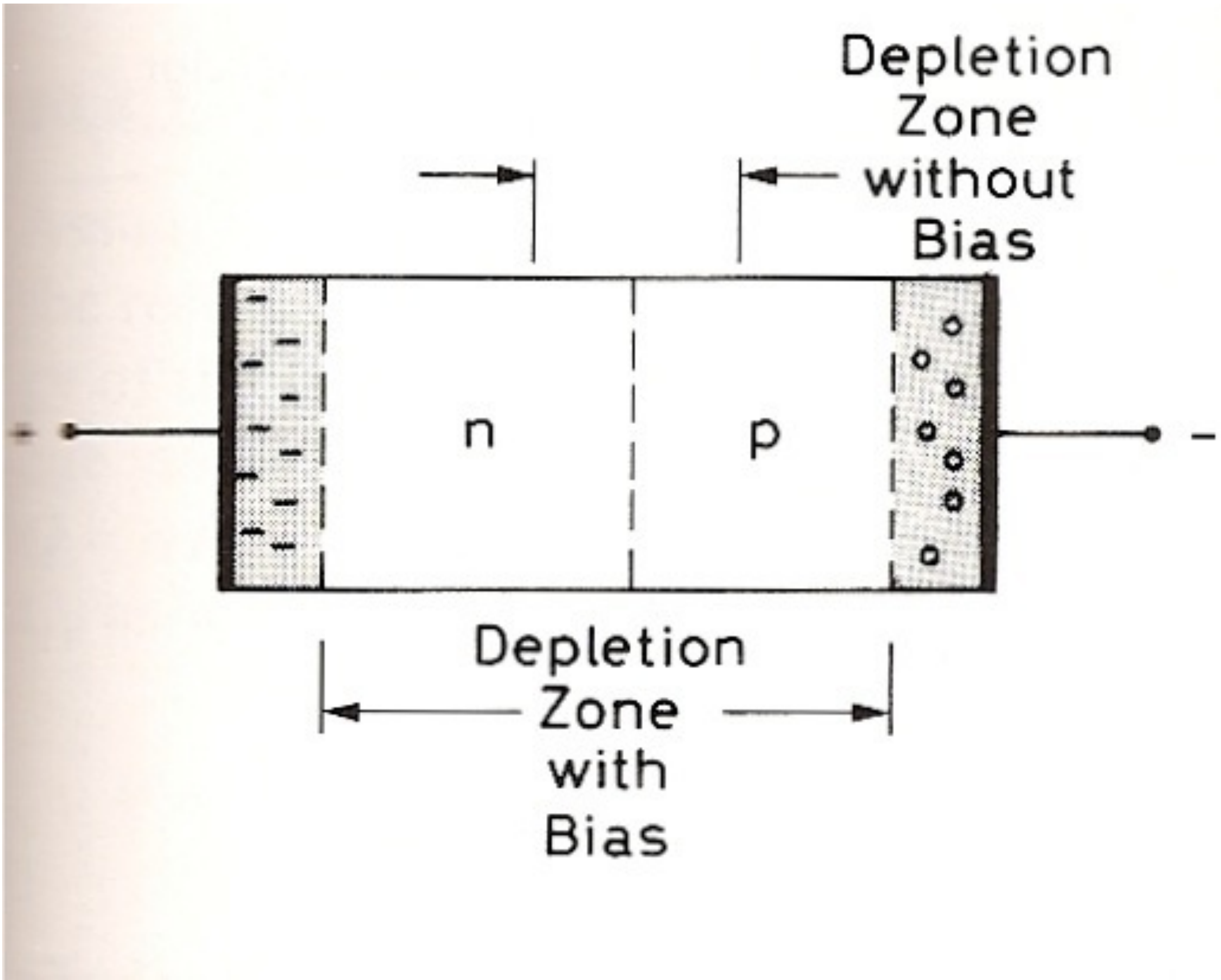
- Solenoidal magnetic field for momentum measurement parallel to chamber wires

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: Position Resolution

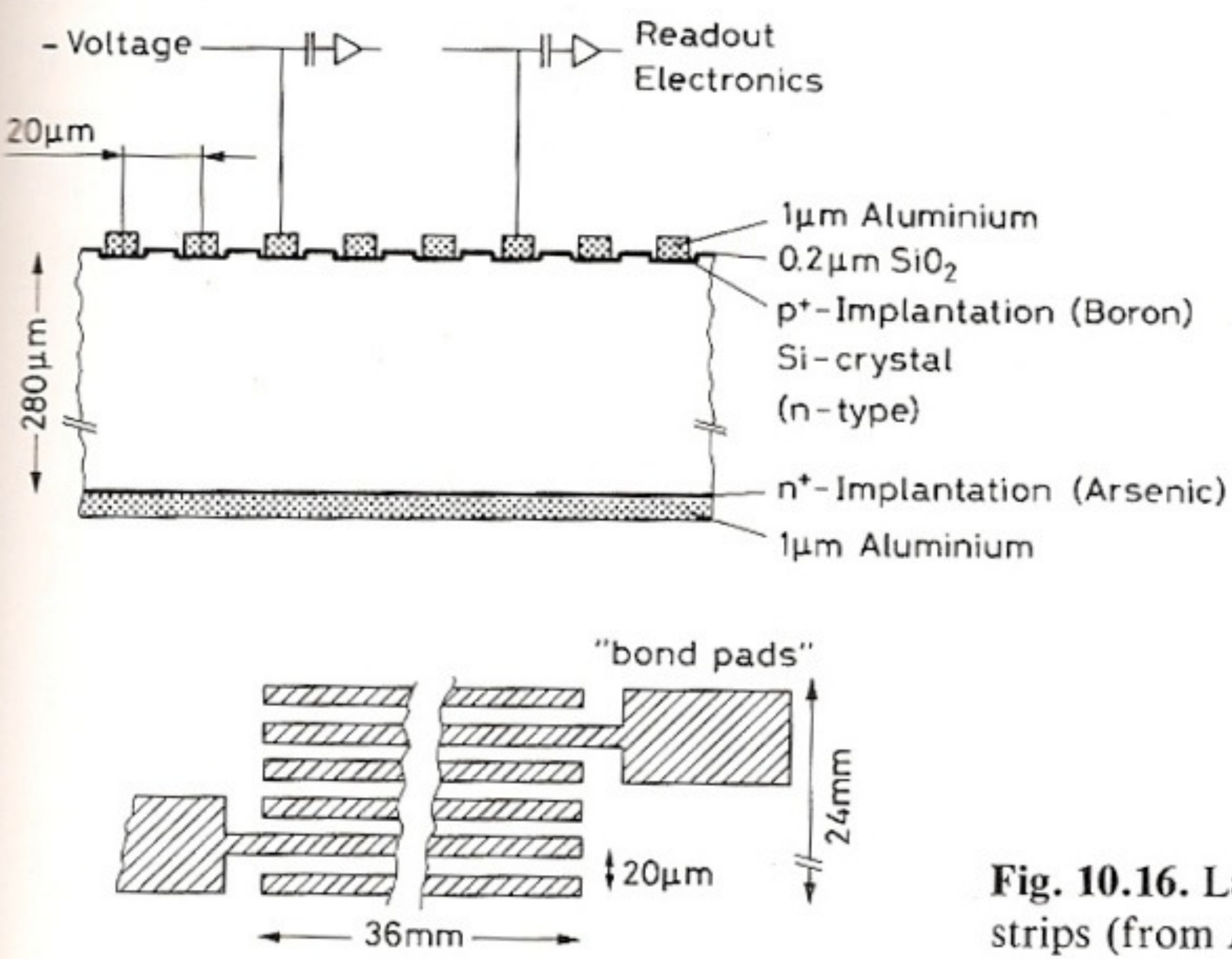
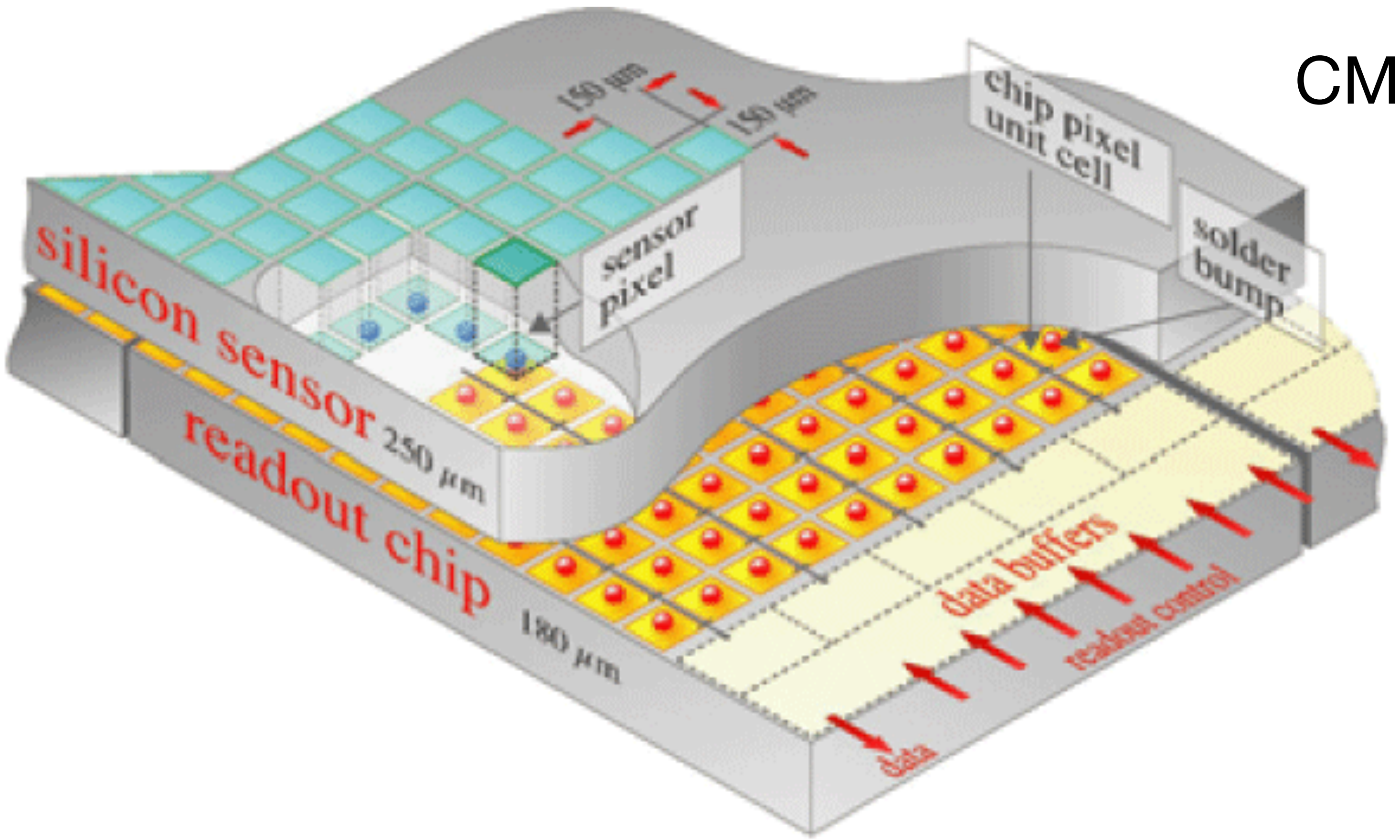


Fig. 10.16. Layout of a micro-strip detector and readout strips (from *Hyams* et al. [10.14])

Semiconductor Pixel Detectors: Higher Resolution



CMS pixel scheme

"Hybrid Pixels"

- CMS Pixels: ~65 M channels
  150 x 150 µm
- ATLAS Pixels: ~80 M channels
  50 x 400 µm (long in z or r)

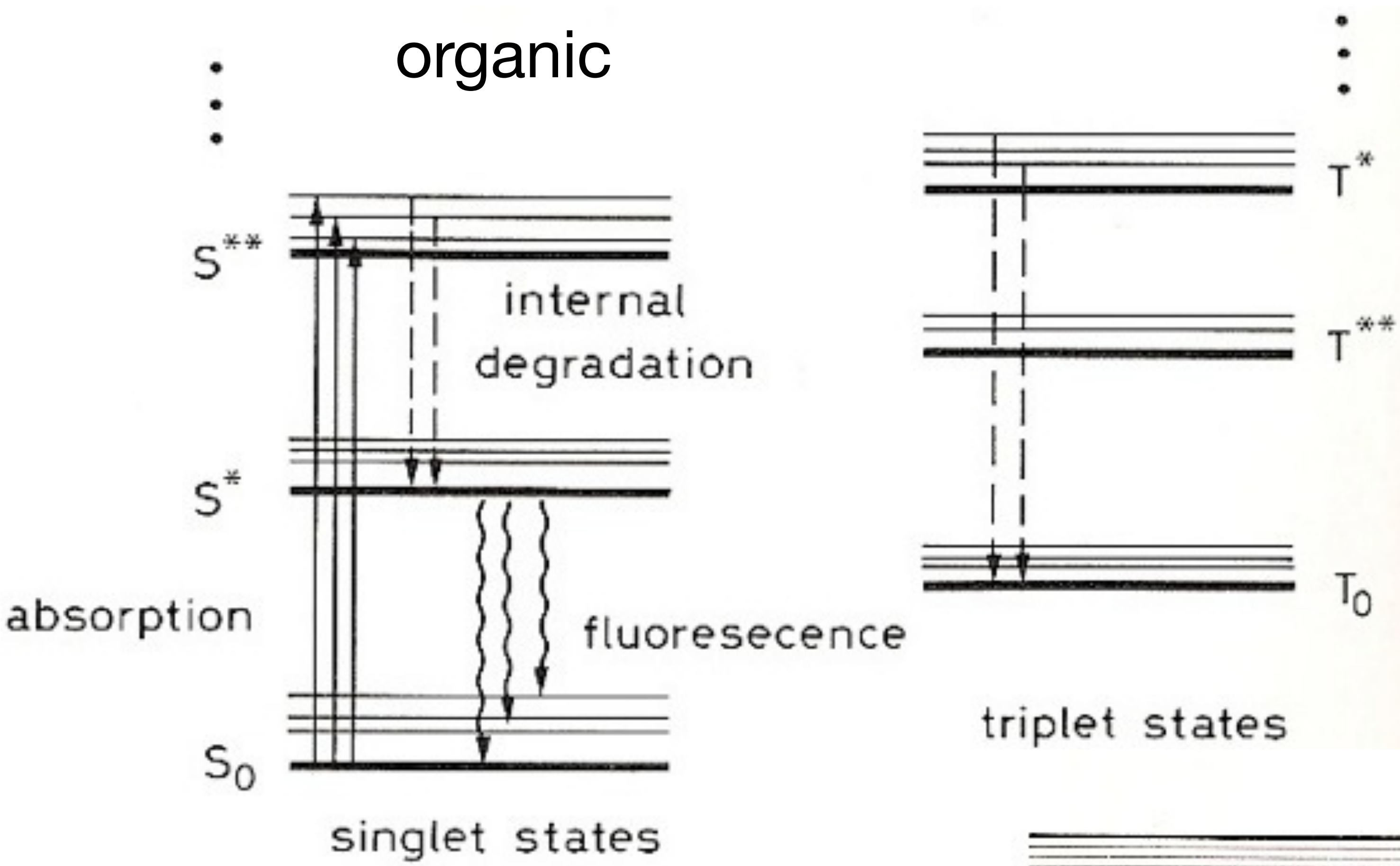
- Pixel-detectors allow tracking in environments with high particle density without ambiguities
- Good spatial resolution in two coordinates with a single layer (depending on pixel size and charge sharing between pixels)

▸ Very high channel count -> Challenging readout, in particular if it needs to be fast

... relatively high material budgets with fast readout: separate electronics layer!

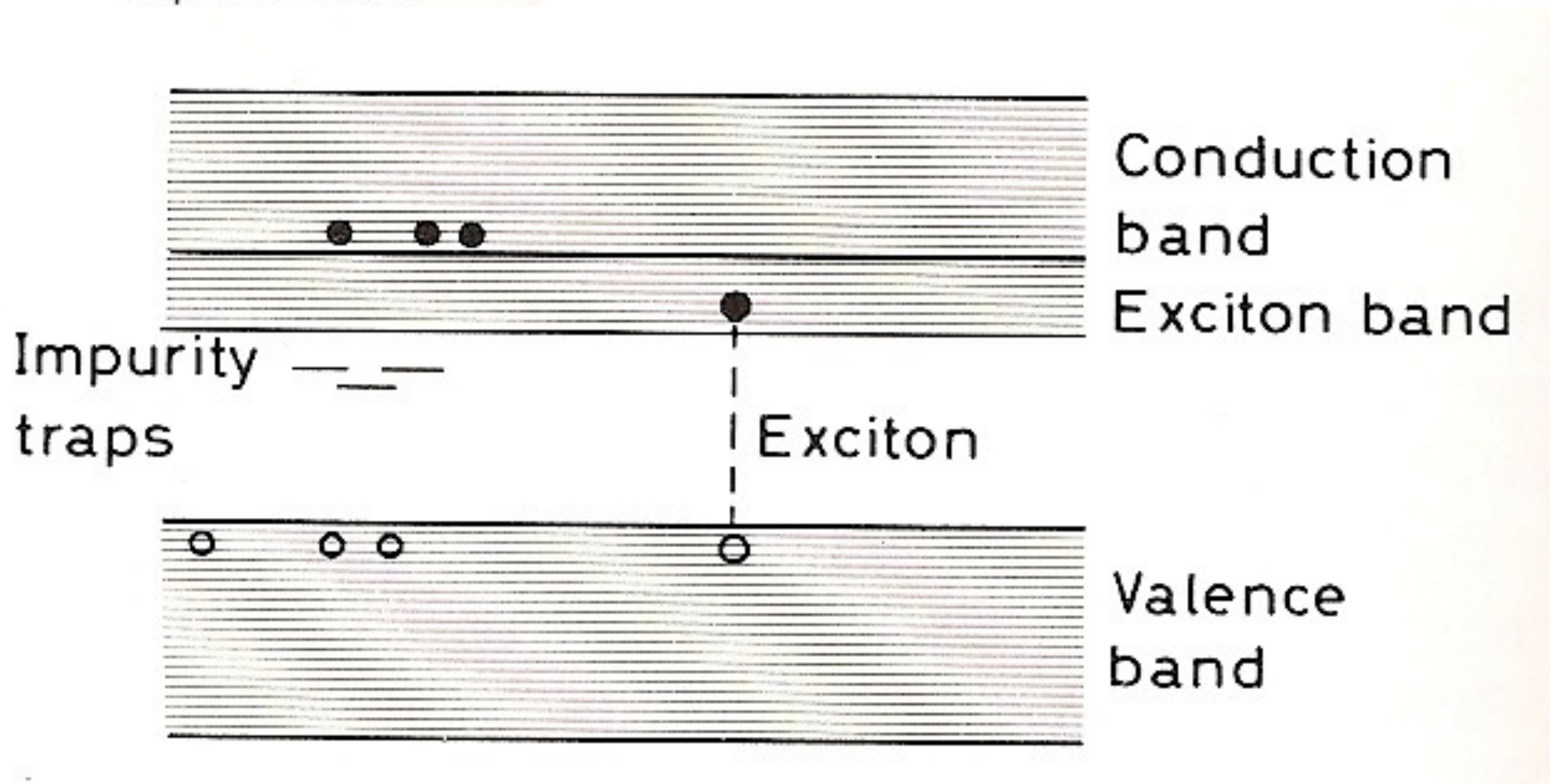
Scintillators

organic



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

inorganic:



Scintillation Detectors

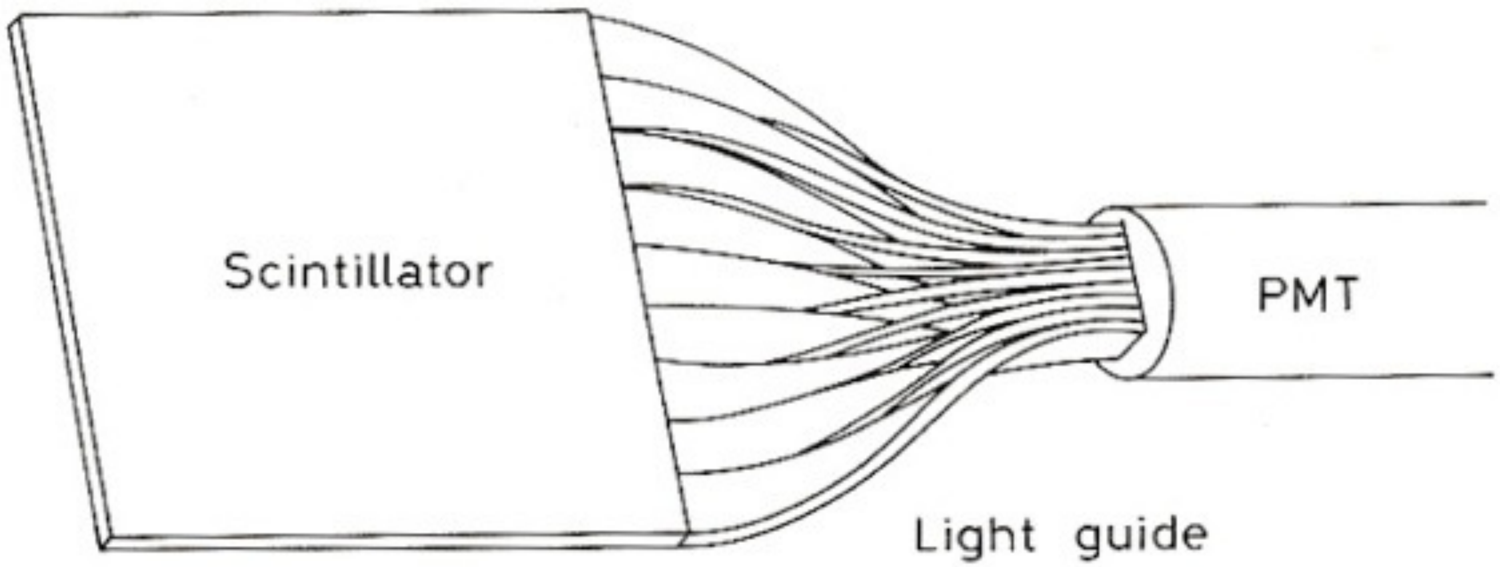


Fig. 9.7. The *twisted* light guide. Many strips of light guide material are glued on to the edge of the scintillator and then twisted 90° so as to fit onto the PM face

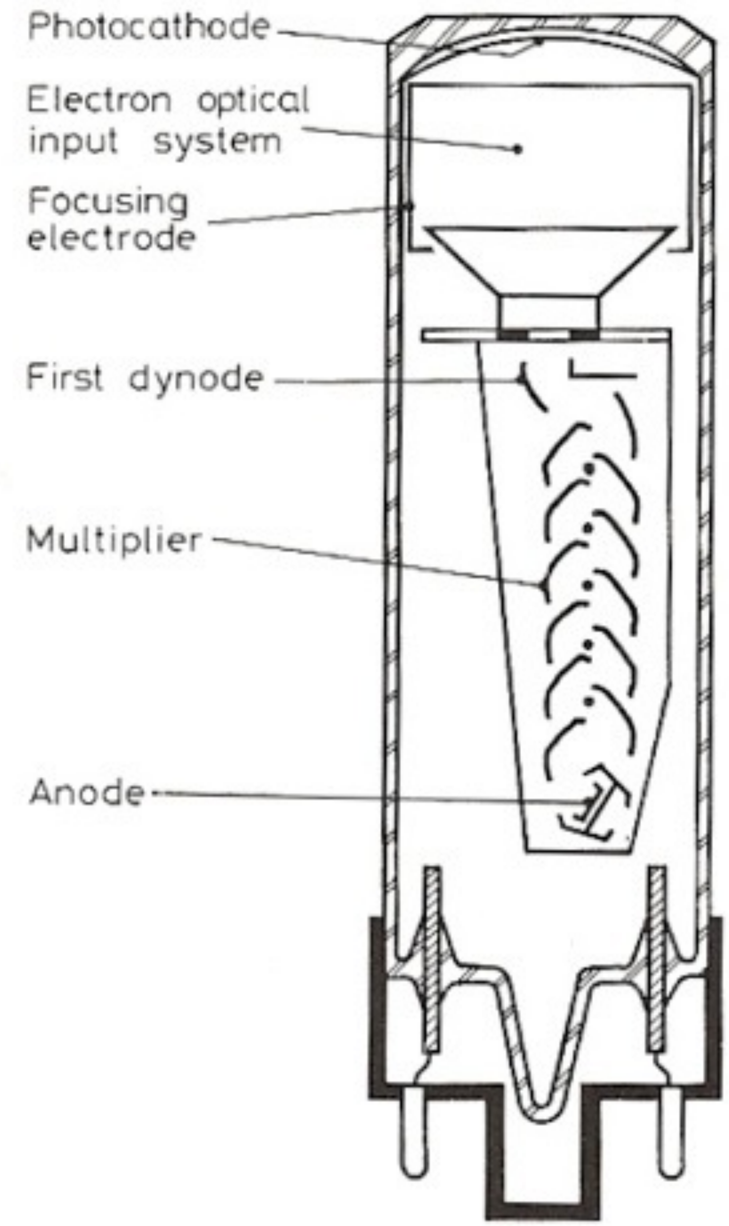


Fig. 8.1. Schematic diagram of a photomultiplier tube (from *Schonkeren* [9.1])

- 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

Selected Details: Tracking Detectors

Tracking: Momentum Measurement in B-Field

- Charged particles are deflected in magnetic field
  - only acts on the component transverse to the field

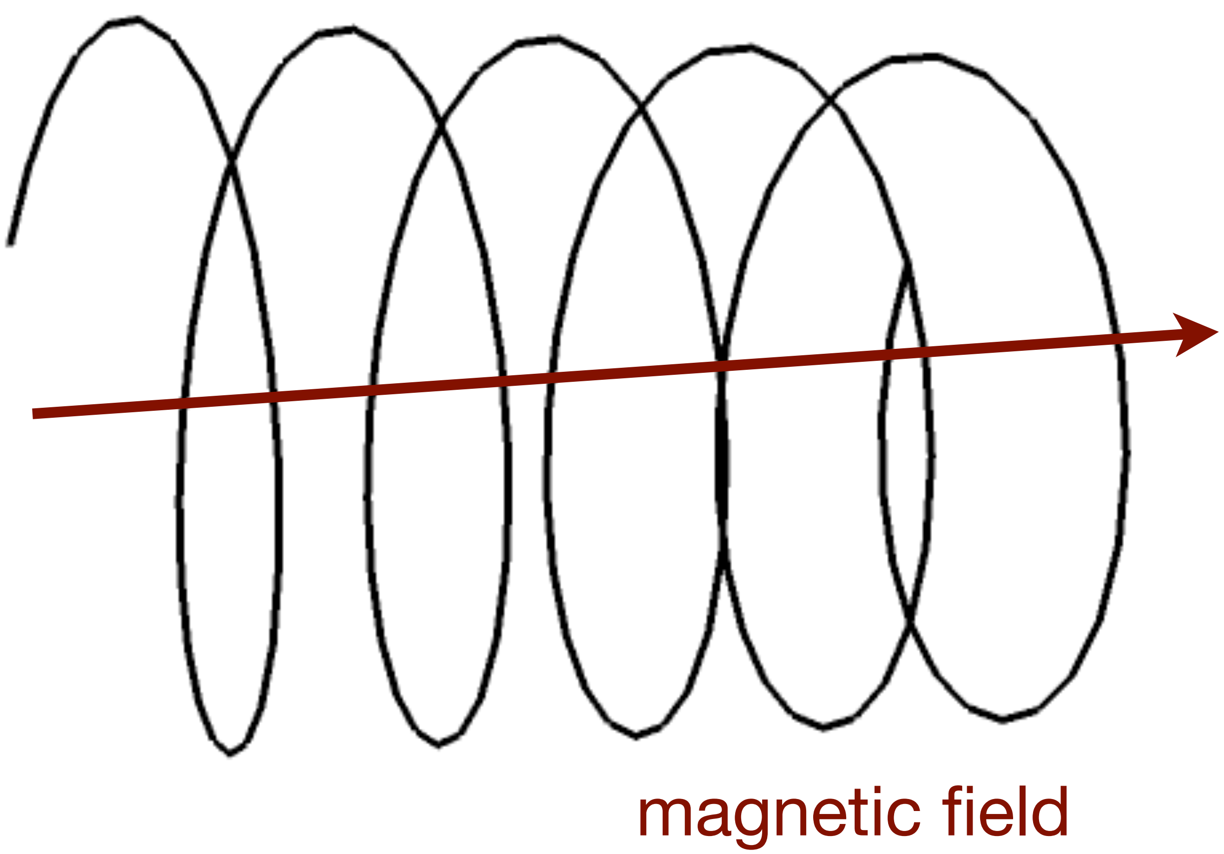
The radius of the trajectory gives transverse momentum:

$$\frac{p_T}{\mathrm{GeV}/c} = 0.3 \frac{B}{\mathrm{T}} \frac{r}{\mathrm{m}}$$

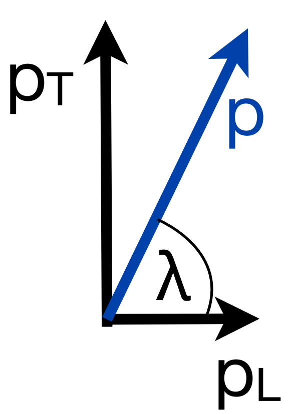
Example:
45 GeV μ, 4 T field:
r = 37.5 m

- parallel to the field there is no deflection

➯ the particle moves on a helix given by field and p_T



The total momentum is determined with the "dip angle" in addition to p_T:



$p = p_T/\sin\lambda$

Key Factors for Momentum Resolution

- Two main, often competing effects
  - Spatial resolution of the tracking detectors: Determine precision of the measurement of the helix parameters
  - Since the curvature is inversely proportional to the momentum, the momentum resolution gets worse with increasing momentum:

$$\frac{\sigma(p_T)}{p_T} \propto p_T$$

  - Measurement gets better with:
    - better spatial resolution of measurements on particle track
    - more measurements on particle track = number of detector layers

$$\frac{\sigma(p_T)}{p_T} \propto \sigma(x) \cdot \frac{1}{\sqrt{N_{layers}}}$$

spatial resolution of detector layer

Key Factors for Momentum Resolution

- Multiple scattering of particles in detector materials: Deflects particles, creates uncertainty of momentum measurement by changing particle trajectory

Deflection angle $\propto \sqrt{x/X_0}$

x: Thickness of detector layer in X_0

- “slow” particles get deflected more - linearly with 1/p
- since curvature is also proportional to 1/p, multiple scattering results in a “constant term” on momentum resolution: Important at low energy, when curvature measurement is very good

$$\left.\frac{\sigma(p_T)}{p_T}\right|_{MS} = const$$

Momentum Resolution: Competing Effects

- Momentum resolution gets better with more measurements: More detector layers!

$$\left.\frac{\sigma(p_T)}{p_T}\right|_{meas} \propto \frac{1}{\sqrt{N_{layers}}}$$

- More detector layers mean more material: More multiple scattering, increases constant term of resolution

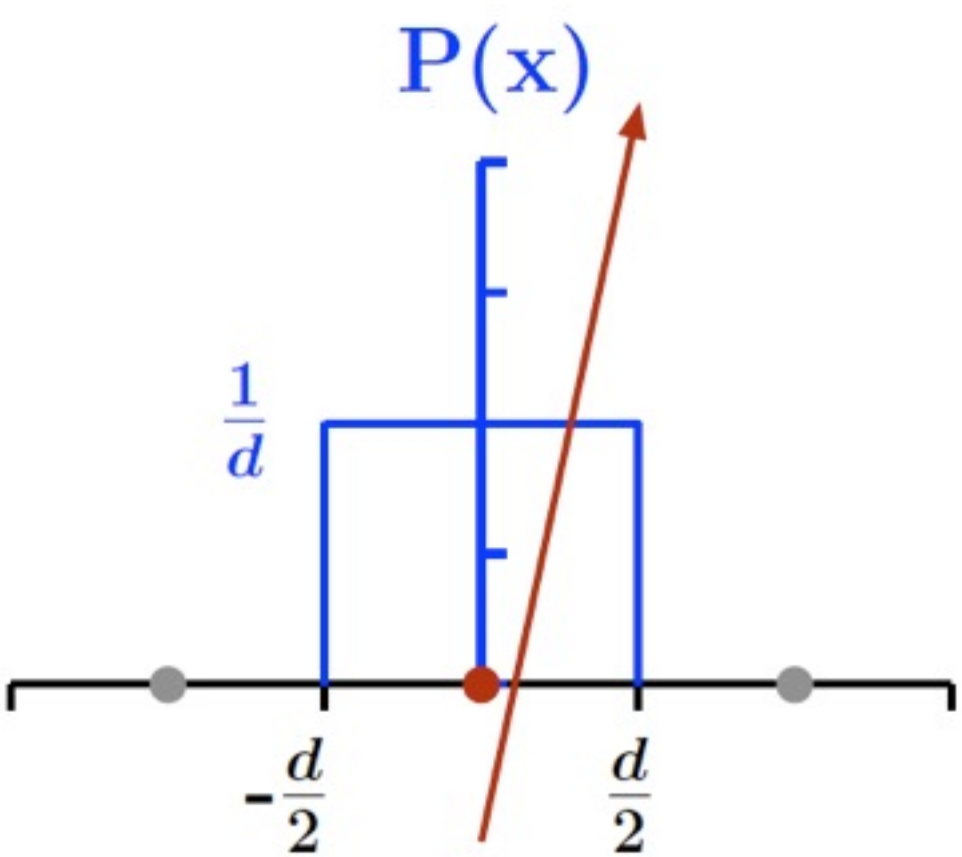
$$\left.\frac{\sigma(p_T)}{p_T}\right|_{MS} \propto \frac{\sqrt{N_{layers}}}{p} \cdot p_T$$

- An optimisation question: Depends on typical momentum of particles - for high energy, more layers win, for low energy, minimum material is crucial

Spatial Resolution of Tracking Detectors

- Depends on detector geometry and charge collection:
  - distance between strips
  - charge sharing between neighboring strips

Easiest case: The full charge is collected on a single strip:



- Particle impact generates a signal in the hit strip
  - The response does not depend on impact point, no point on the strip is "special"
  - Equal probability distribution for particle position:

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

The reconstructed impact position is always the strip center:

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

Spatial Resolution of Tracking Detectors

- The spatial resolution orthogonal to the strip direction is thus:

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

- General law for tracking detectors (also applies to wire chambers, pixels, ...) without signal sharing across several channels:

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

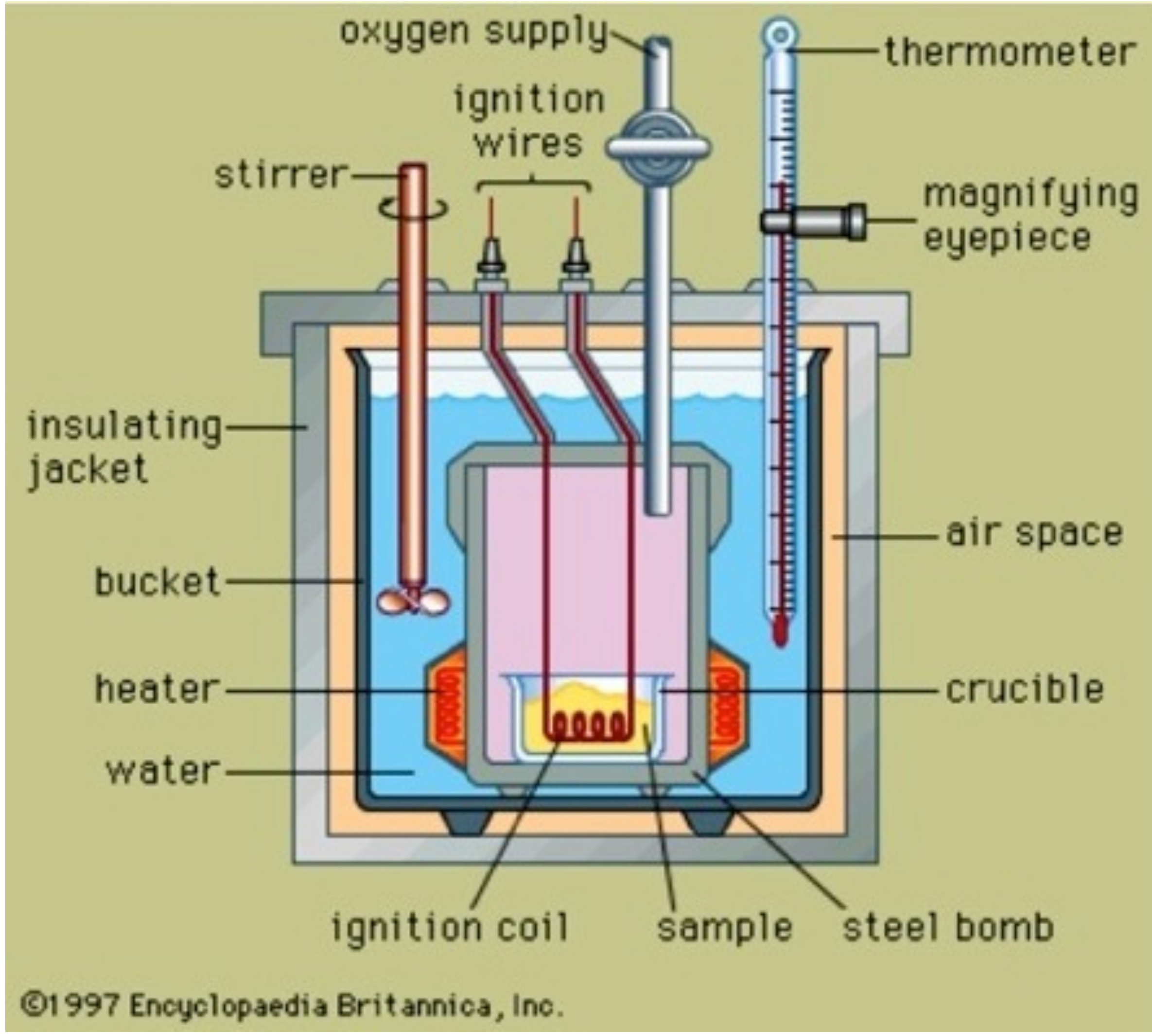
- For silicon detectors with a strip pitch of 80 μm (ATLAS) the minimum resolution is ~ 23 μm
- If the charge is collected by more than one strip, and if the charge sharing depends on the position of the particle impact the resolution can be substantially improved by calculating the center of gravity of the total signal

Selected Details: Calorimeters

The Concept

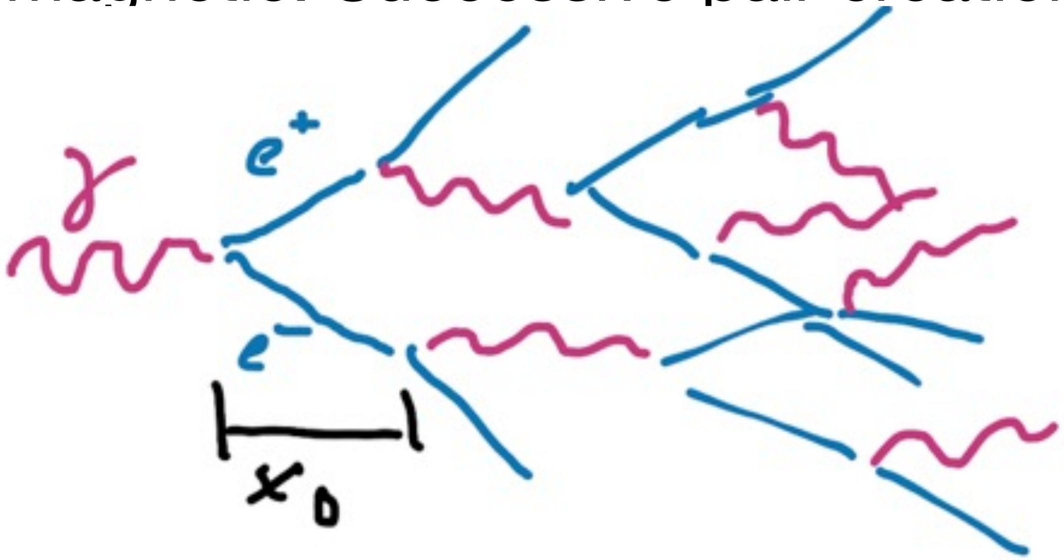
- Originally from chemistry: Measurement of the released heat by a chemical reaction: Here increase of temperature of a well-known amount of water

- For elementary particles: Measurement of the energy of a particle by total absorption
  - 1 cal = 10^7 TeV: Very small energies, no temperature increase!
    - Somewhat more sophisticated strategy for energy measurement needed

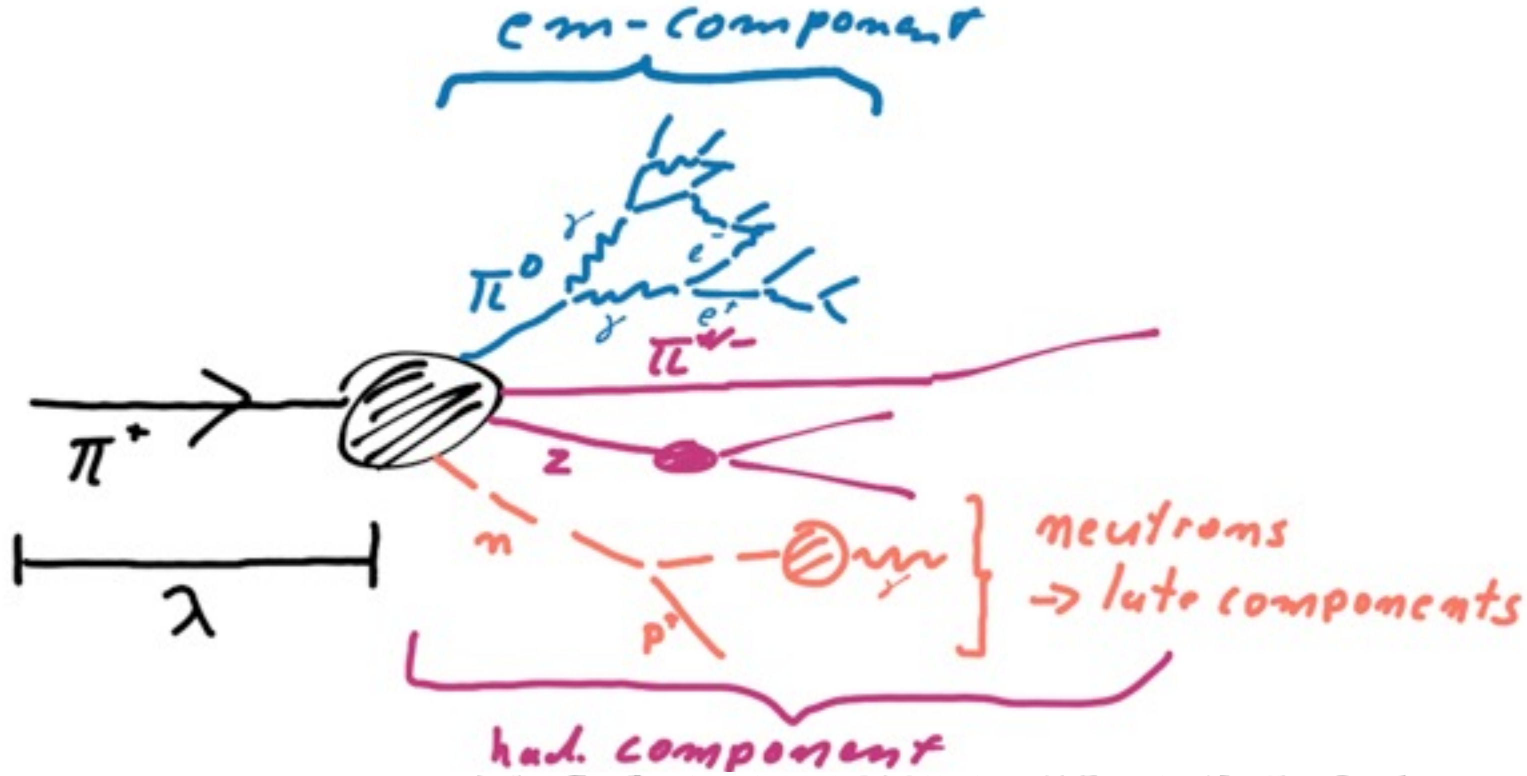


Particle Showers

- Measurement of highly energetic particles: Showers
  - Electromagnetic: Successive pair creation / Bremsstrahlung

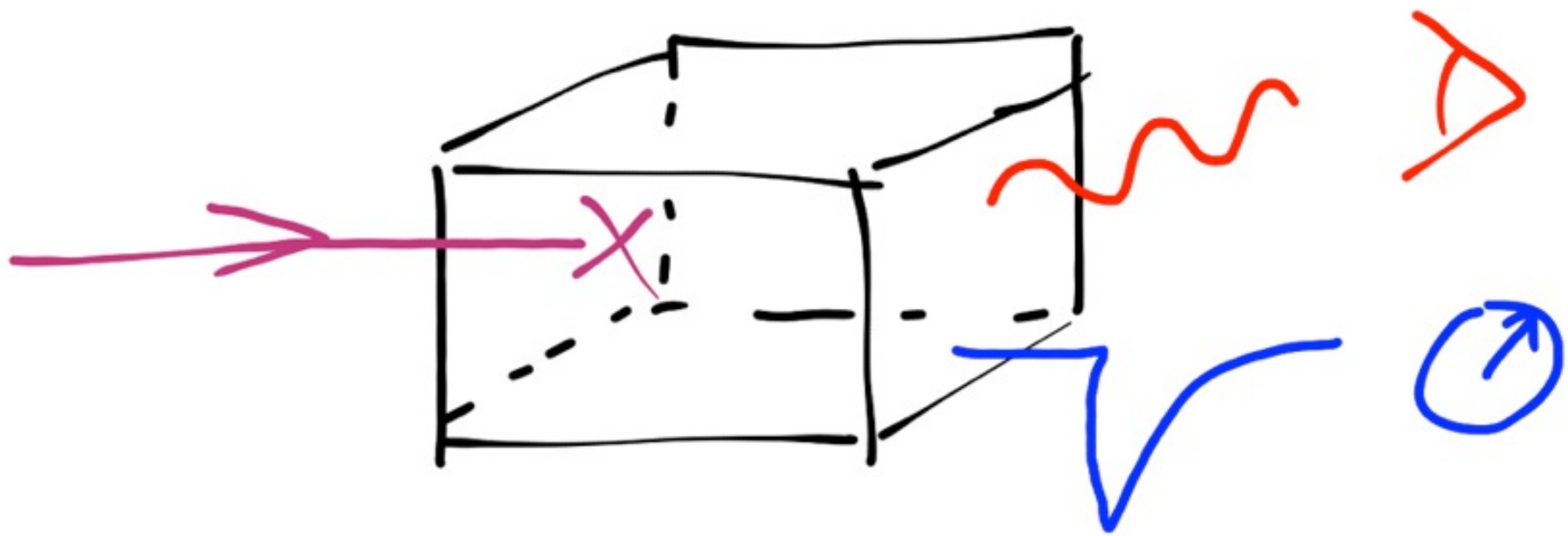


  - Hadronic: Hadronic cascade with hadronic and em content



Measuring Energy with a Calorimeter

- Convert the energy of the incident particle to a detector response
- Choose something that is easily detectable also for “small” energies
    - Electric charge
    - Photons (in or close to visible range)



N.B.: Also other channels are used - thermal for example in cryogenic DM-search experiments, acoustic measurements, ... Not covered here!

Measuring Energy with a Calorimeter

- Calorimetric processes are stochastic:
  - Counting of photons / created charge carriers
  - Number of secondary particles in showers induced by high-energy particles

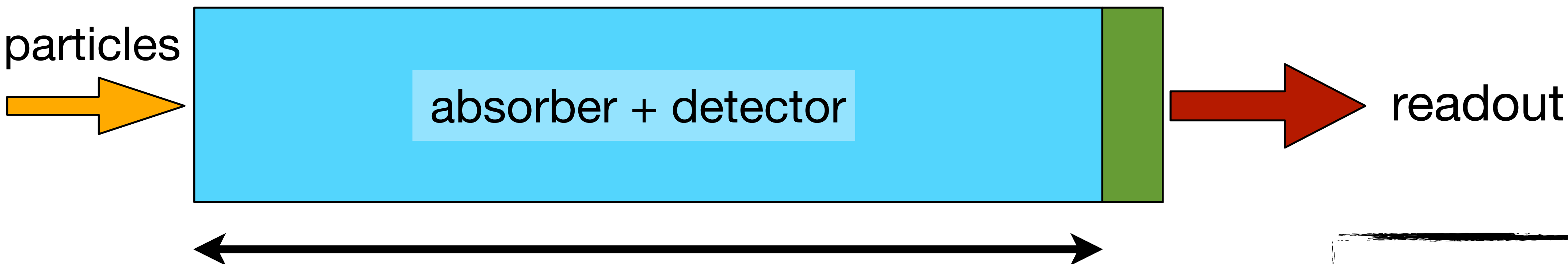
Energy resolution often well-described by $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Three components:
  - *a*: The **stochastic** term: The counting aspect of the measurement: Simple statistical error: scales with the square root of the number of particles
    ➩ Resolution term scales with $1/\sqrt{E}$
  - *b*: The **noise** term: Constant, energy-independent noise contribution to the signal -
    ➩ Resolution term scales with 1/E
  - *c*: The **constant** term: Contributions that scale with energy: Influence of inhomogeneities in the detector material, un-instrumented or dead regions, ...
    ➩ Resolution term is independent of energy

Calorimeter Types

- The dream: Contain the full energy of one particle, convert all energy into a measurable signal which is linear to the deposited energy
  - Reality is often different, in particular when measuring hadrons

Two types: ***homogeneous calorimeters*** and *sampling calorimeters*



sufficiently deep to absorb the shower

crystals as active medium

- The shower develops in the sensitive medium
  - Potentially optimal energy resolution: Complete energy deposit is measured
  - Challenging readout: No passive readout structures in detector volume

Calorimeter Types

- The dream: Contain the full energy of one particle, convert all energy into a measurable signal which is linear to the deposited energy
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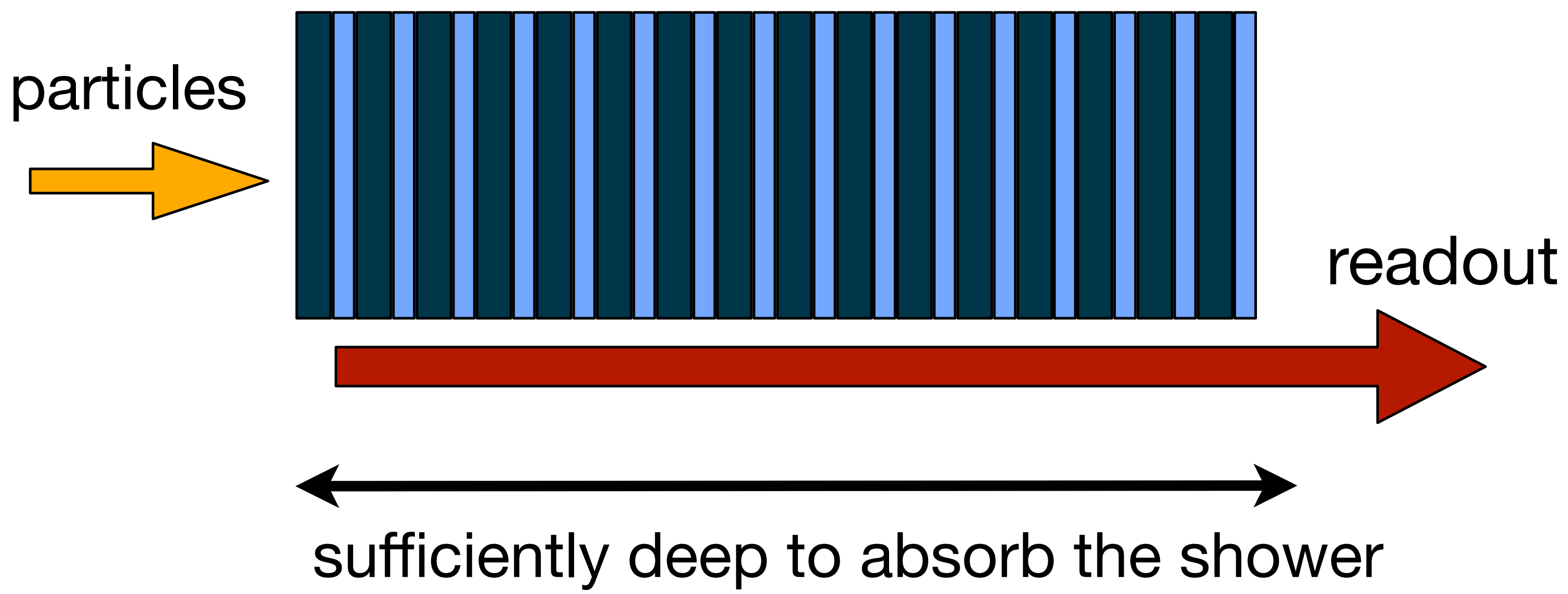
Two types: *homogeneous calorimeters* and ***sampling calorimeters***

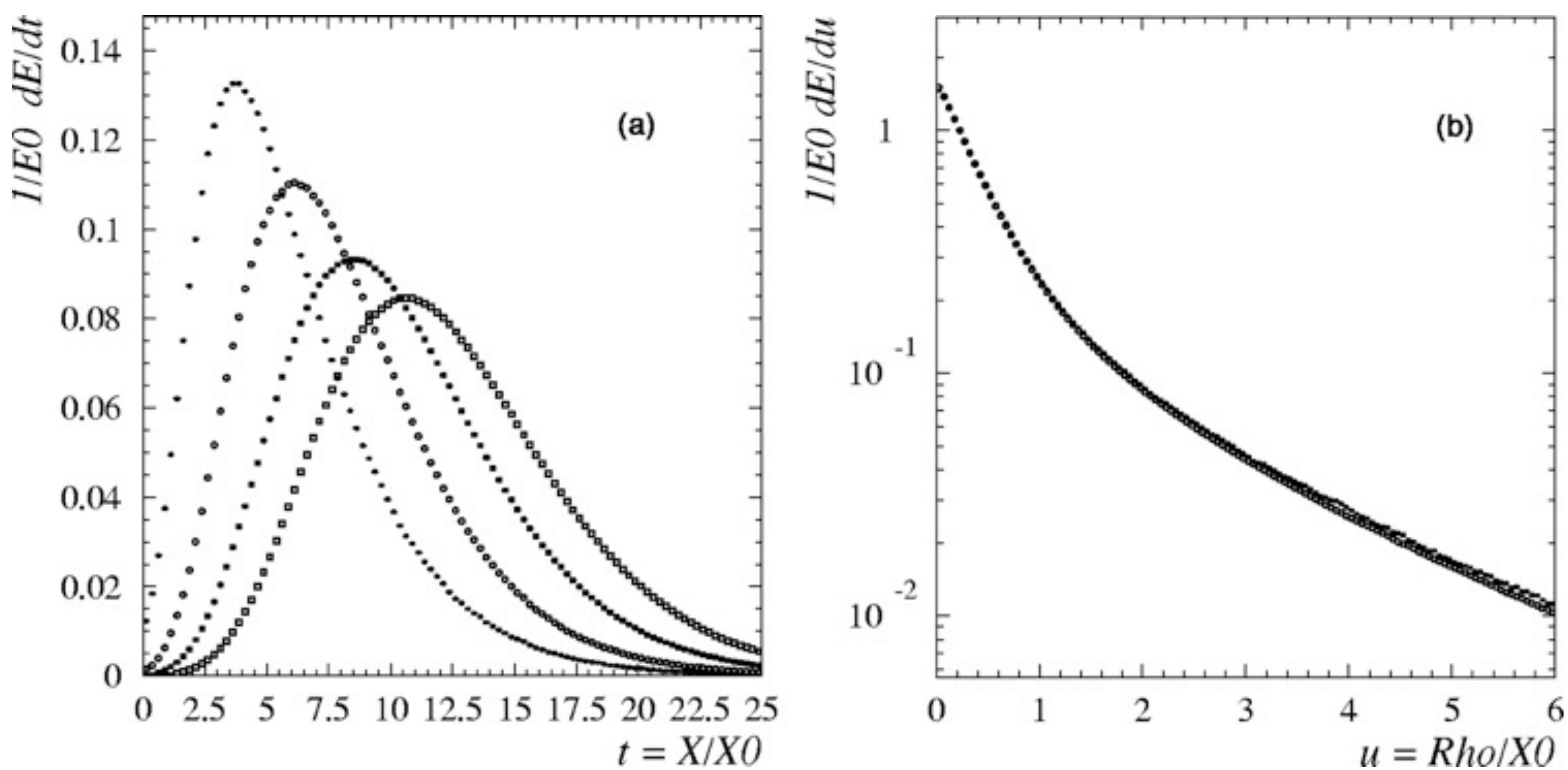


highly flexible in choice of absorbers and active medium

- The shower develops (mostly) in dense absorber medium, particles are detected in interleaved active structures
- Potentially reduced energy resolution: Only a fraction of the deposited energy is detected

Characteristic Parameters of Showers - EM

- Longitudinal development described by X_0
- Lateral shower size given by Moliere Radius ρ_M (also depends on X_0)
  90% of all energy is contained in a cylinder with a radius of 1 ρ_M around the shower axis
- Shower maximum: Depth where number of particles in the shower is maximal
  - $t_{max} \sim \ln(E_0/\varepsilon) + t_0$ in X_0, with $t_0 = -0.5$ für e^-, $+0.5$ für γ



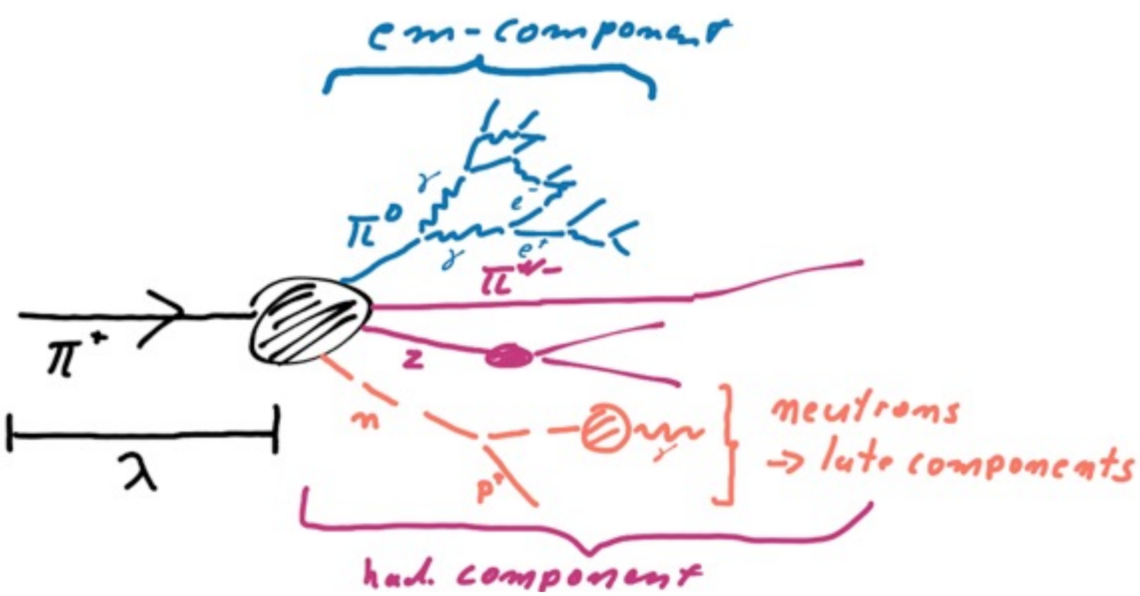
Characteristic Parameters of Showers - Hadronic

- The length scale of hadronic showers is given by the **nuclear interaction length λ_I** (mean free path between hadronic interactions)

$\lambda_I > X_0$ for all materials with $Z > 4$

	λ_I	X_0
Polystyrene	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

Hadronic showers are complicated:



- Relativistic hadrons created in interactions with nuclei, carry a sizeable fraction of momentum of original particle [*O* GeV]
- About 1/3 of all pions created are π^0: instantaneous decay to photons, em subshower
- Neutrons created in evaporation/spallation, photons from neutron capture -> MeV (or lower)
- Energy loss due to binding energy, ...

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, ...

Next Lecture: Searching for New Physics at the Energy Frontier, F. Simon, 27.01.2020

Lecture Overview

14.10.	Introduction, Particle Physics Refresher	*F. Simon*
21.10.	Introduction to Cosmology I	*B. Majorovits*
28.10.	Introduction to Cosmology II	*B. Majorovits*
04.11.	Particle Collisions at High Energy	*F. Simon*
11.11.	The Higgs Boson	*F. Simon*
18.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
25.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
02.12.	Particle Colliders	*F. Simon*
09.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
16.12.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
	Christmas Break	
13.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
20.01.	Detectors for Particle Colliders	*F. Simon*
27.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
03.02.	Physics beyond the Standard Model in the Early Universe	*B. Majorovits*