How do we "see" ?

- All macroscopic interactions are electromagnetic
  - chemical bonds making molecules
- Effects of the chemical bonds describe the macroscopic physics
  - crystal made by lattices of ions, held together by
    - different polarity of the ions: ionic crystals
    - or by the electron gas: metals
  - liquids are bound by the Van der Waals forces
  - gases are defined by the repulsion of the electron shells
- friction is just the stretching or ripping of these chemical bonds
- Gravity only matters at the cosmic scale
  - Planetary orbits, stellar orbits, galaxies, etc. . . .
  - Earths gravity gives "only" a background for particle physics

How do we "see" subatomic particles ?

- Since all macroscopic interactions are electromagnetic
  - ⇒ we have to see them with their electromagnetic interactions !

⇒ We only see charged particles directly !

  - – neutral particles have to interact somehow else, that we can see their charged reaction products

- Subatomic particles follow Quantum Mechanics

- Detectors are macroscopic devices
  - ⇒ Subatomic particles interact with the detector "classically"
    - ∗ they behave like a small charged ball
  - – they loose energy and momentum in passing through material
    - ∗ this is how we can detect them

Particle Detection — Basics

How do we "see" subatomic particles ?

- charged particles are "ionizing"
  - when a charged particle passes through a material, it can strip off electrons from the atoms
    - they are part of the ionizing radiation

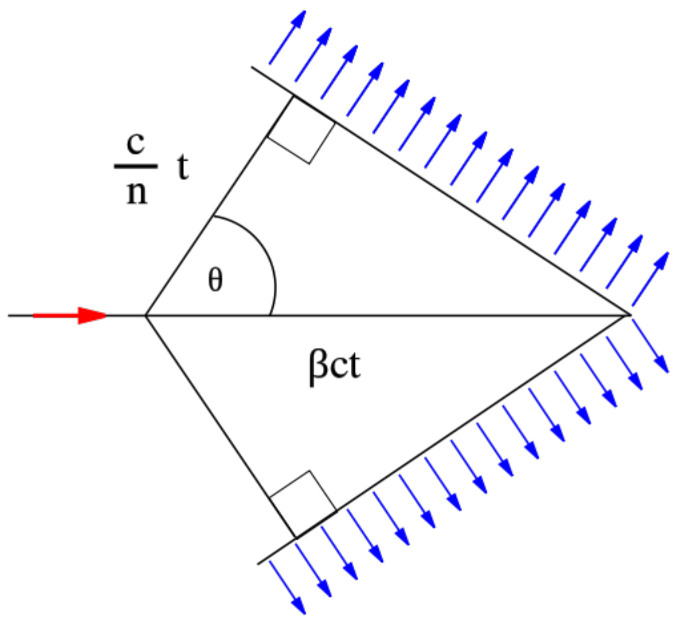
  ⇒ Geiger counters
  - development of Geiger counters gives
    - Wire chambers
    - Spark chambers
    - modern semiconductor detectors
  - other uses of the ionizing nature of charged particles
    - Cloud chamber
    - Bubble chamber

- if a charged particles moves faster than c_{material}:

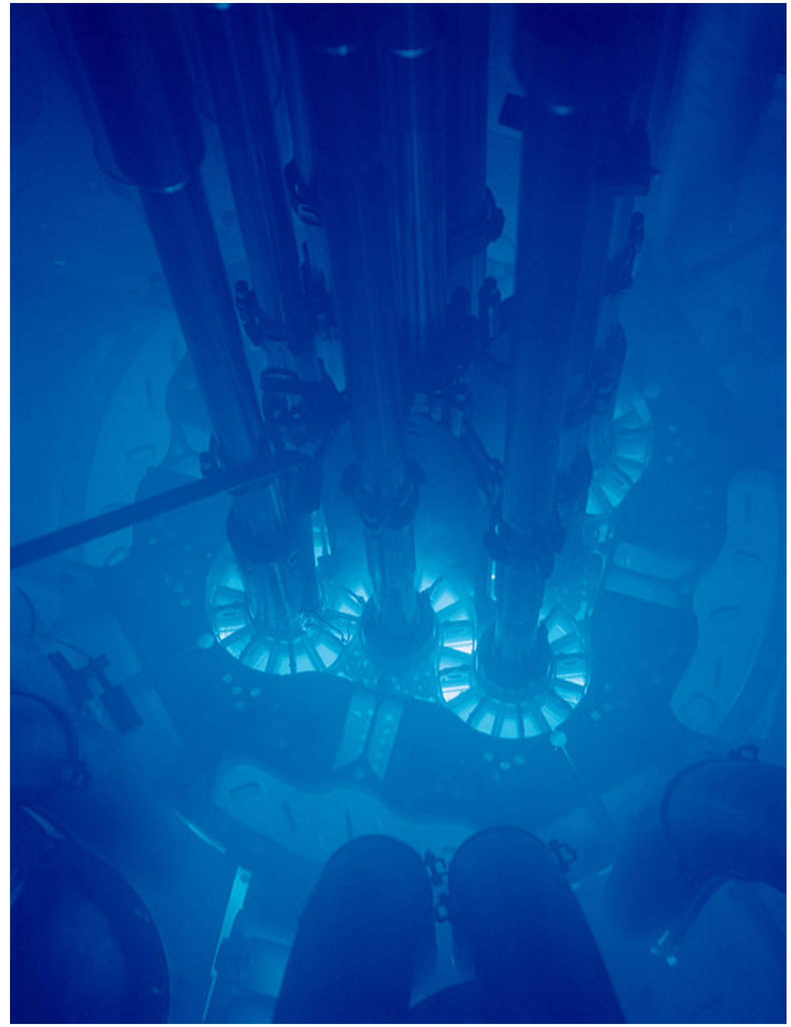
  ⇒ Cherenkov radiation ⇒ Cherenkov counters

Schematic and picture of Cherenkov radiation

- used in detectors
  - Neutrino detectors
  - Cosmic Ray detectors
  - Particle detectors



The geometry of the Cherenkov radiation
(shown for the ideal case of no dispersion)



Cherenkov radiation glowing in the core of the Advanced Test Reactor (ATR) at the Idaho National Laboratory, USA

Particle Detection — charged particles

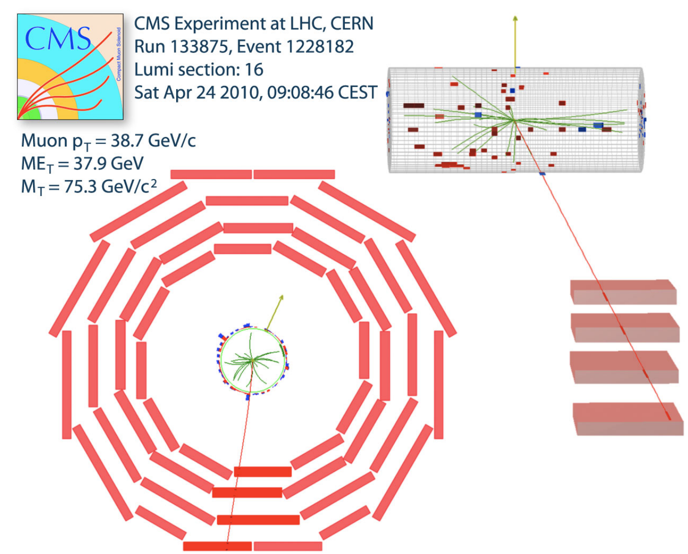
How do we "see" subatomic particles ?

- unstable particles decay ... but when?
  - they still might leave a track
  - if they live long enough
    - they interact with the macroscopic surrounding, i.e. the detector, before they decay
  - that depends on the lifetime of the respective particle
  - and the construction details of the detector
- in the CMS detector
  - the required distance is about 3 m
    - for reaching the calorimeters

  ⇒ the length of the track

  $s = vt \approx c\gamma\tau > 3\,\mathrm{m}$

    - or $\gamma\tau > 10\,\mathrm{ns} = 10^{-8}\,\mathrm{s}$



How do we "see" subatomic particles ?

- the average lifetime of an unstable particle depends on
  - its possible interactions
    * the coupling constant for each decay channel
    * the number of possible decay channels
  - its mass
    * determining the phase space for the decay

- the γ-factor increases the seen lifetime: $\gamma = E/m$

  $\Rightarrow$ the more energy the longer the track of a specific particle

- LHC is planned to provide a maximal CM energy of 14 TeV
  - the maximal energy of a particle flying away is 7 TeV

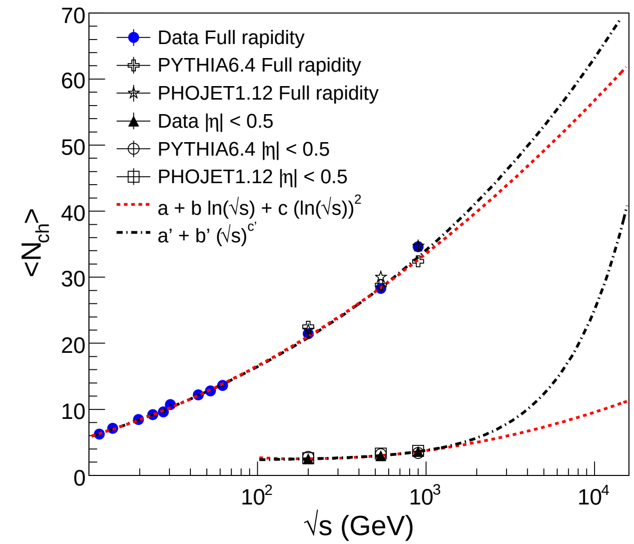
    $\Rightarrow$ the maximal boost factor is 7 TeV / m :

    * for a muon with $m_\mu = 105$ MeV, $\gamma \sim 70.000$

Particle Detection — charged particles

charged elementary particles

- in pp collisions one expects an increasing number of charged particles with c.m.-energy
  - $\Rightarrow$ the average energy of a particle increases less than linearly with energy
    - $*$ at 0.9 TeV there were $\sim$35 charged particles
    - $*$ at 7 TeV we expect $\sim$52 charged particles
    - $*$ at 14 TeV we expect 70-90 charged particles
  - $\Rightarrow$ we can assume an upper average energy of 100 GeV for a charged particle



Leptons	symbol	mass	ave. lifetime	ave. track @ 100 GeV	visible
electron	e^-	511 keV	stable	∞	yes
muon	μ^-	105 MeV	2.2 μs	630 km	yes
tau	τ^-	1.78 GeV	291 fs	4.9 mm	not really

Vector boson	symbol	mass	ave. lifetime	ave. track @ 100 GeV	visible
W-boson	$W^\pm$	80.4 GeV	$3.2 * 10^{-25}$ s	$1.2 * 10^{-16}$ m	no

charged elementary particles

scalar Mesons	symbol	mass	ave. lifetime	ave. track @ 100 GeV	visible
Pion	π^+	139 MeV	29 ns	6.26 km	yes
Kaon	K^+	494 MeV	12 ns	0.73 km	yes
D-meson	D^+	1.78 GeV	1 ps	16 mm	no
B-meson	B^+	5.28 GeV	1.6 ps	9 mm	no

Vector Mesons	symbol	mass	ave. lifetime	ave. track @ 100 GeV	visible
rho meson	ρ^+	775 MeV	$4.5 * 10^{-24}$ s	$1.7 * 10^{-13}$ m	no
Kaon*	K^{*+}	892 MeV	$7.4 * 10^{-20}$ s	$2.5 * 10^{-9}$ m	no
D*-meson	D^{*+}	2.01 GeV	$6.9 * 10^{-21}$ s	10^{-10} m	no
B*-meson	B^{*+}	5.33 GeV	?? s	$< 10^{-10}$ m	no

Particle Detection — charged particles

charged elementary particles

Baryons	symbol	mass	ave. lifetime	ave. track @ 100 GeV	visible
Proton	p^+	938 MeV	stable	∞	yes
Lambda-c	Λ_c^+	2.3 GeV	0.2 ps	2.7 mm	no
Sigma$^+$	Σ^+	1.19 GeV	80 ps	2 m	rarely
Sigma$^-$	Σ^-	1.2 GeV	148 ps	3.7 m	rarely
Xi	Ξ^-	1.3 GeV	164 ps	3.8 m	rarely
Xi-c	Ξ^+	2.5 GeV	442 fs	5.3 mm	no
Xi-b	Ξ_b^-	5.8 GeV	1.56 fs	8 μm	no
Omega	Ω^-	1.67 GeV	82 ps	1.4 m	rarely
Omega-b	Ω_b^-	6.2 GeV	1.13 fs	5.5 μm	no
Delta	$\Delta^{(++,+,-)}$	1.23 GeV	$5.6 * 10^{-24}$ s	$1.4 * 10^{-13}$ m	no

Particle Detection — visible particles

''Seeing'' charged particles

- there are only very few (i.e. five) ''visible'' charged particles
  - two Leptons: the electron e^- and the muon μ^-
  - three Hadrons: the proton p^+, the pion π^+, and the kaon K^+

- the other charged particles are seen only
  - through their decay products
  - or with their decay products

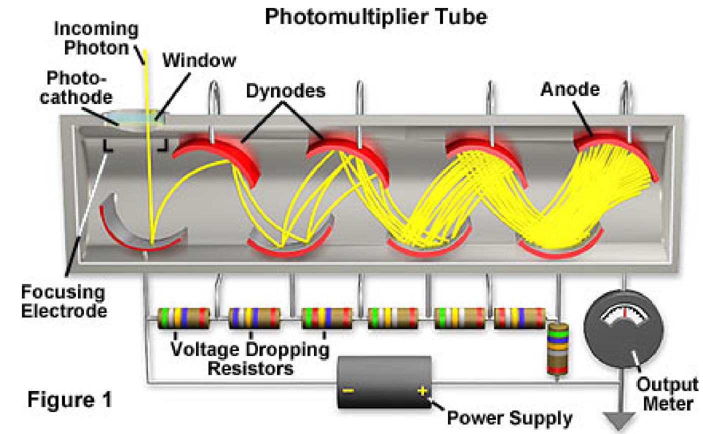
- but we can definitely ''see'' also the photon
  - with our eyes
  - or through their electromagnetic interactions

$\Rightarrow$ we should also consider neutral particles
  - we still might see them by their interactions

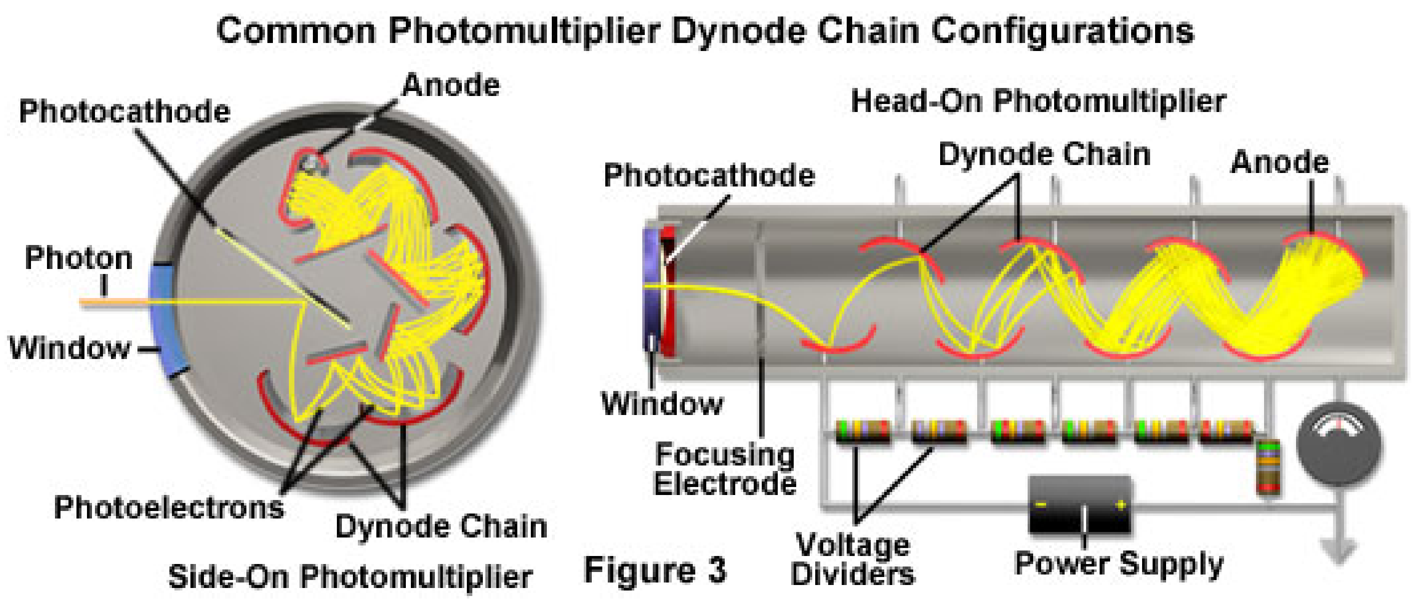
Particle Detection — Photon

"Seeing" neutral particles: the photon

- We see the photons with our eyes . . .
  - but not single photons
  - and not photons of every energy



- single photons can be seen by photomultipliers
  - using the photoeffect to produce electrons, that are then amplified through a cascade
  - not usable for the highest energy photons



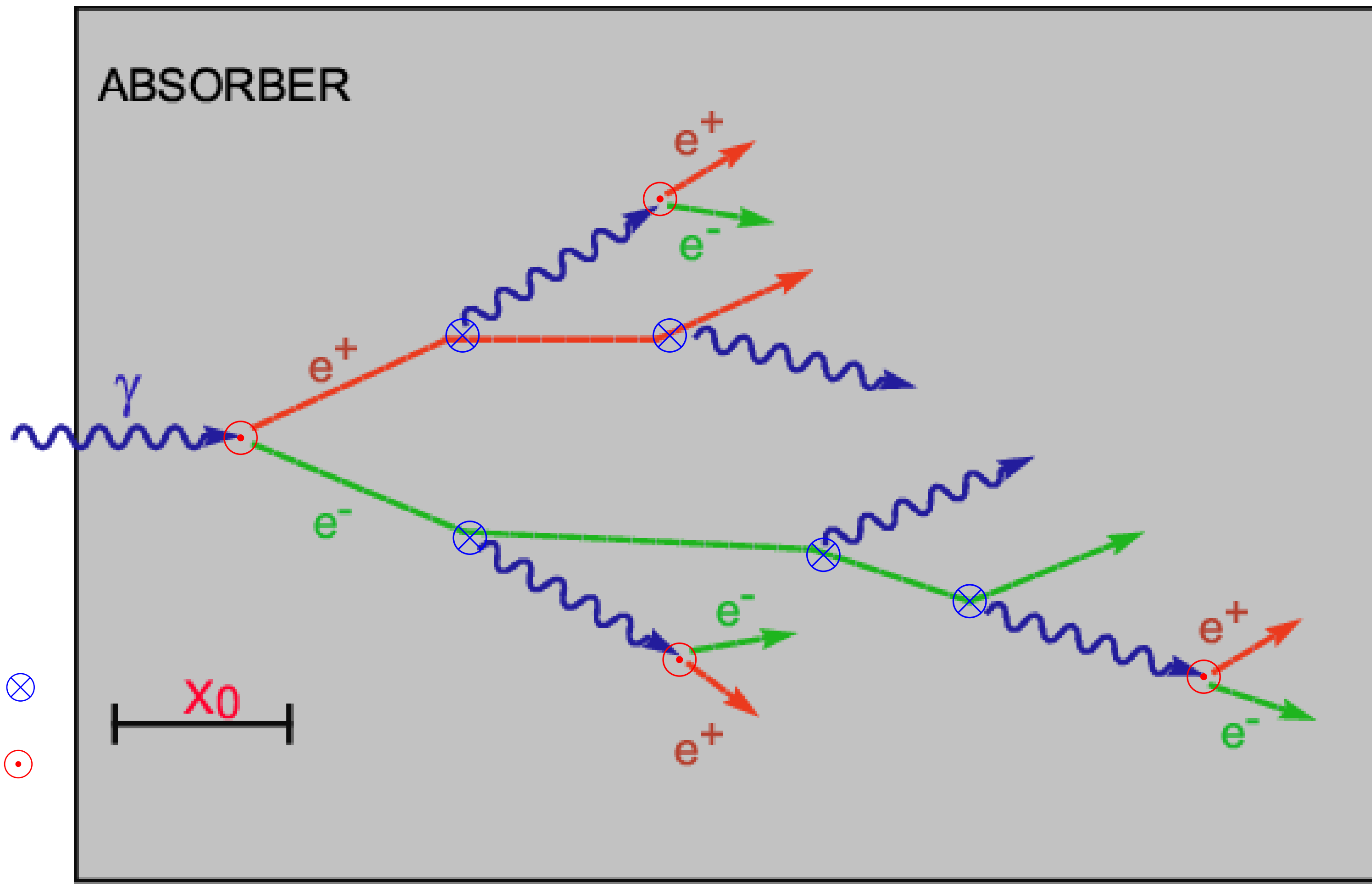
"Seeing" neutral particles: the photon

- in matter photons can convert into electron-positron pairs
  ⇒ Pair conversion

- a heavy nucleus is necessary for momentum conservation
- a single photon in vacuum cannot decay

the mechanism of the cascade uses

- Bremsstrahlung ⊗
- Pair production ⊙



Particle Detection — neutral particles

"Seeing" other neutral particles

- Hadrons interact with nuclear matter
  - with the protons and neutrons of atomic nuclei
  - mediated by the nuclear interaction
    * a residual strong interaction
      (similar to the van der Waals force in electromagnetism)
    * mediated mainly by pions

- the nuclear interaction is short ranged: $r < 2$ fm
  - the range of the EM field of the nucleus: $r \sim 10^5$ fm

  $\Rightarrow$ much smaller effective cross section: $\frac{\sigma_{\text{nucl}}}{\sigma_{\text{em}}} = \frac{g^2_{\text{nucl}} r^2_{\text{nucl}}}{g^2_{\text{em}} r^2_{\text{em}}} \sim \frac{1 * 4}{4\pi/137 * 10^{10}} \sim 10^{-8}$

  $\Rightarrow$ much larger radiation length

- the "radiation" products are also Hadrons
  - mostly pions, since they are the lightest hadrons ...
  - charged pions can be directly seen in scintilators
  - neutral pions decay into 2 photons with $\tau = 8.4 * 10^{-17}$ s

Particle Detection — visible particles

"directly visible" particles

	charged	neutral
"leptons"	$e^{\mp}$	photon (γ)
muon	$\mu^{\mp}$	
baryons	proton (p)	neutron (n)
mesons	$\pi^{\pm}$, $K^{\pm}$	K_L^0

- only a finite number of particles

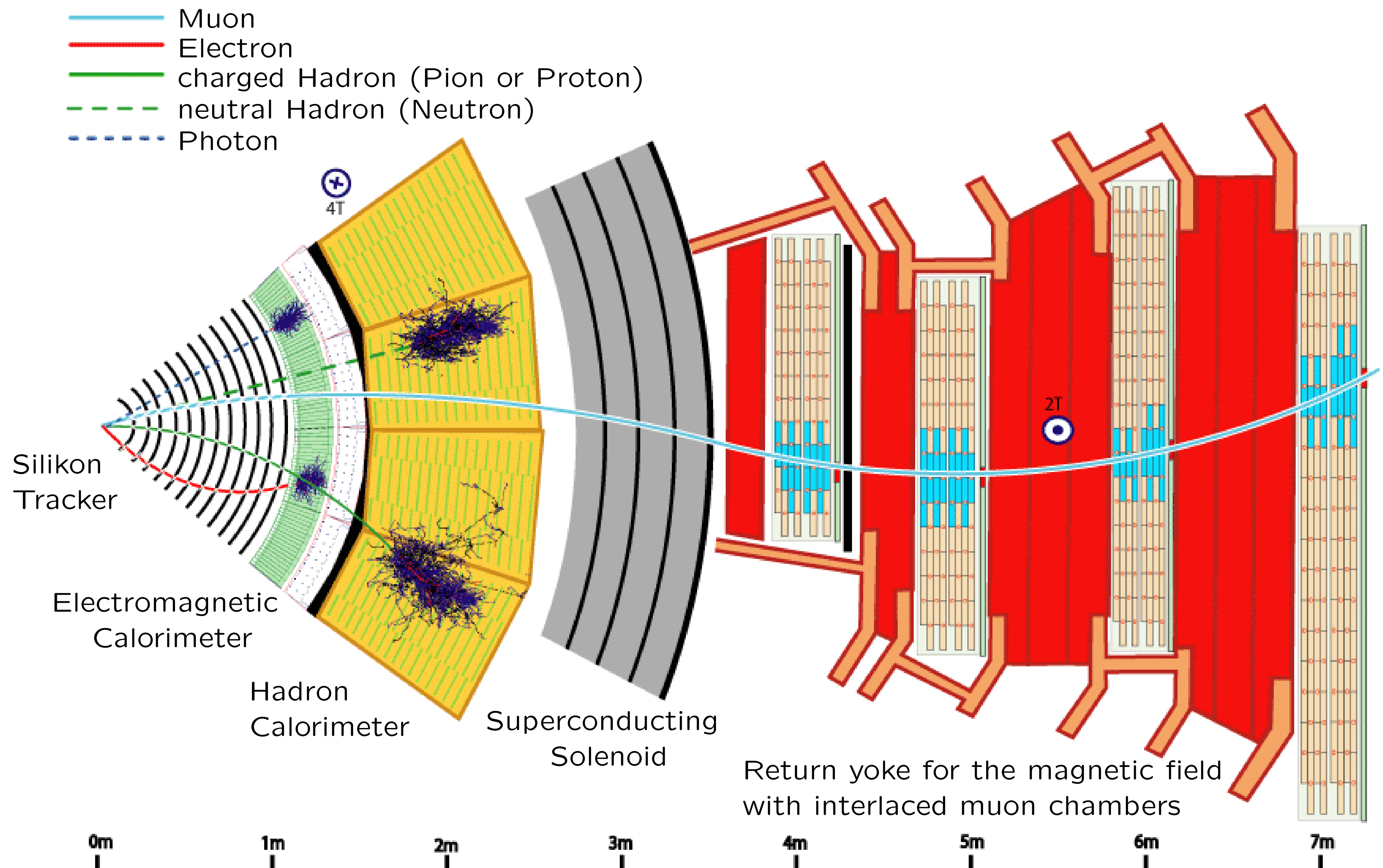
$\Rightarrow$ individual studies of interaction with matter is possible:

GEANT4

(a toolkit for the simulation of the passage of particles through matter)

http://geant4.cern.ch/

CMS: a moden detector



Particle Detection — modern detectors

Why so many layers ?

- charged particles leave tracks in the Silikon tracker
  - without loosing energy
    - energy loss due to the magnetic field (synchotron radiation) is bigger than the energy lost to scattering with the tracker
- $e^{\mp}$ and γ are stopped in the electromagnetic calorimeter (EMC)
  - their deposited energy is measured
  - all other particles fly through with minimal energy loss
    - because their mass is much bigger than the mass of the electron
- Hadrons are stopped in the Hadron calorimeter (HC)
  - their deposited energy is measured
    - with jets often a lot of particles hit the same calorimeter cell

    $\Rightarrow$ jet-energy measurements
  - muons pass through the HC: they do not feel the nuclear interaction
- Muons are detected with the muon system in Drift Tubes

  $\Rightarrow$ all particles are measured — except neutrinos

CMS: a moden detector