Lecture 15

Particle detection

“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained”

Freeman Dyson

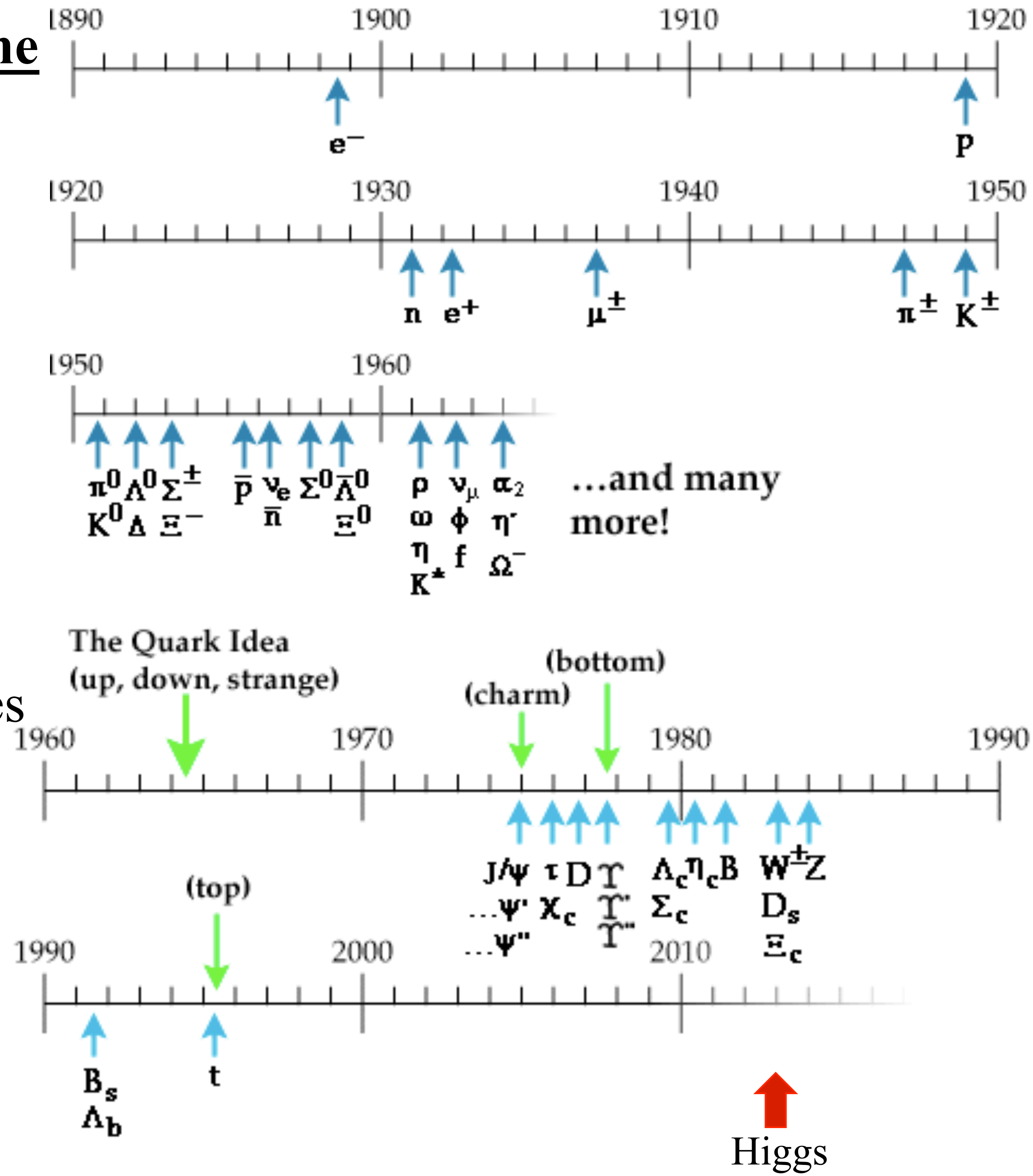
Particle Physics Timeline

>200 particles

27 have cτ > 1mm
Leave tracks in the detector

13 have cτ < 500 μm
Have displaced vertices

c – speed of light
τ – mean lifetime



Literature on particle detectors

- Text books
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - G. Knoll, Radiation Detection and Measurement, 3rd Edition, 2000
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments
  - R.S. Gilmore, Single particle detection and measurement
  - W. Blum, L. Rolandi, Particle Detection with Drift Chambers
  - K. Kleinknecht, Detectors for Particle Radiation
- Review articles
  - Experimental techniques in high energy physics, T. Ferbel (editor)
  - Instrumentation in High Energy Physics, F. Sauli (editor)
  - Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.
- Other sources
  - Particle Data Book
  - R. Bock, A. Vasilescu, Particle Data Briefbook
    http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - Proceedings of detector conferences

All detection techniques are based on observing effects of electromagnetic interactions

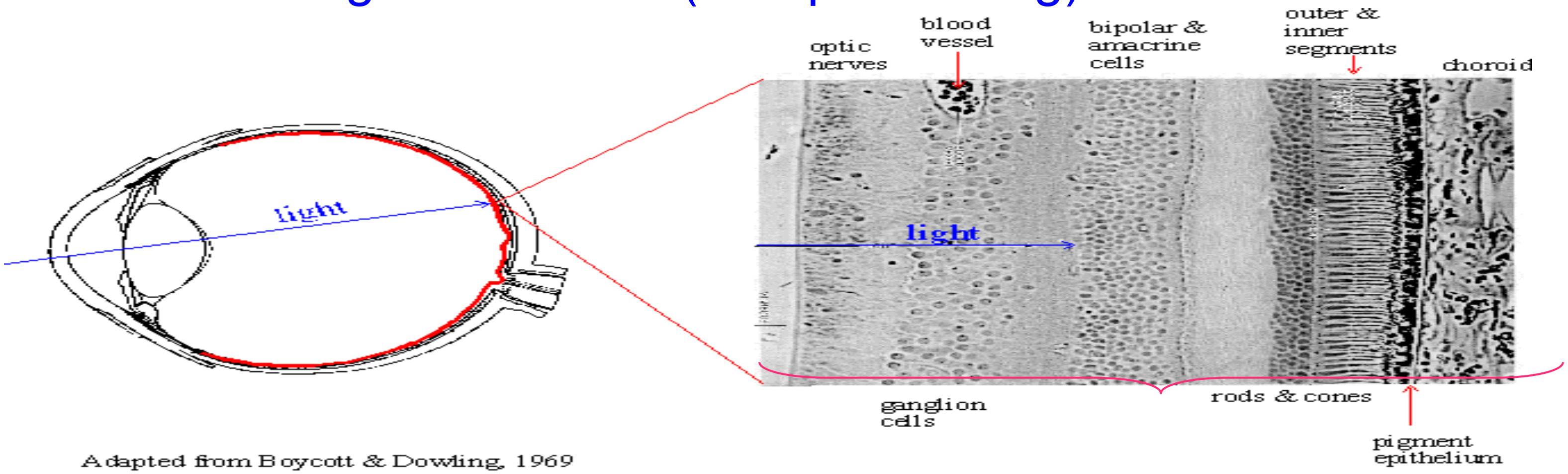
We can detect light, ionization, radiation…… – all related to passage of charged particles.

Neutral particles are detected **indirectly** via decays to charged particles, absence of expected signal,…..

Prehistory

"The oldest particle detector"
(made many billion times)

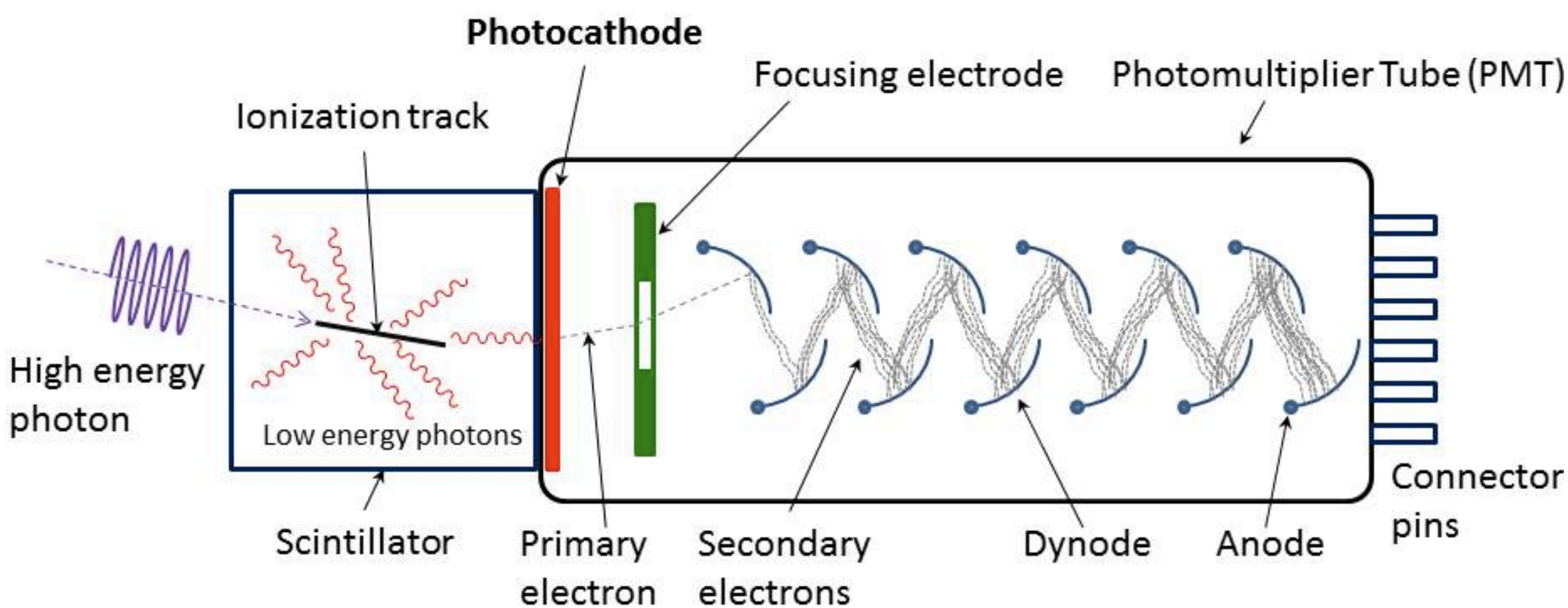
- High sensitivity to photons
- Good spatial resolution
- Very large dynamic range (1:10^{14})
  + automatic threshold adaptation
- Energy (wavelength) discrimination
- Modest speed.
  Data taking rate ~ 10Hz (incl. processing)



retina

Photon detection

Human eye cannot distinguish individual photon from ambient noise
The light flashes that you may see in total darkness are due to Cherenkov radiation in your eyeball generated by passage of cosmic rays.
Technical solution - signal amplification provided by **photomultiplier**.



First particle/hidden objects detection

Use of photographic paper as detector
➠ Detection of photons / x-rays

W. C. Röntgen, 1895
Discovery of the ‘X-Rays’

Photographic paper/film

e.g. AgBr / AgCl

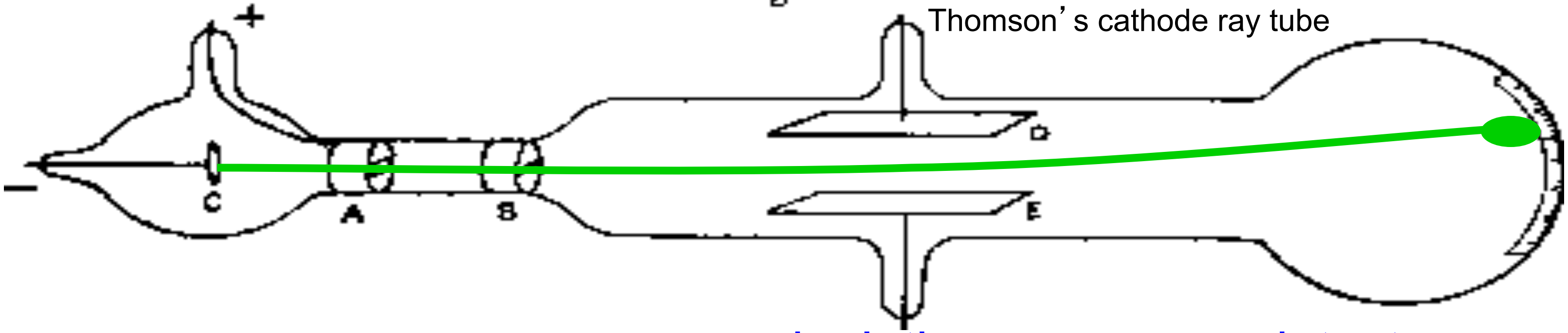
AgBr + ‘energy’
➠ metallic Ag (blackening)

+ Very good spatial resolution
+ Good dynamic range
- No online recording
- No time resolution

Observation of the electron

J. Plücker 1858 ➠ J.J. Thomson 1897

Fig. 2.



accelerator

manipulation
By E or B field

detector

From: J.J. Thomson: Cathode Rays.
Philosophical Magazine, **44**, 293 (1897).

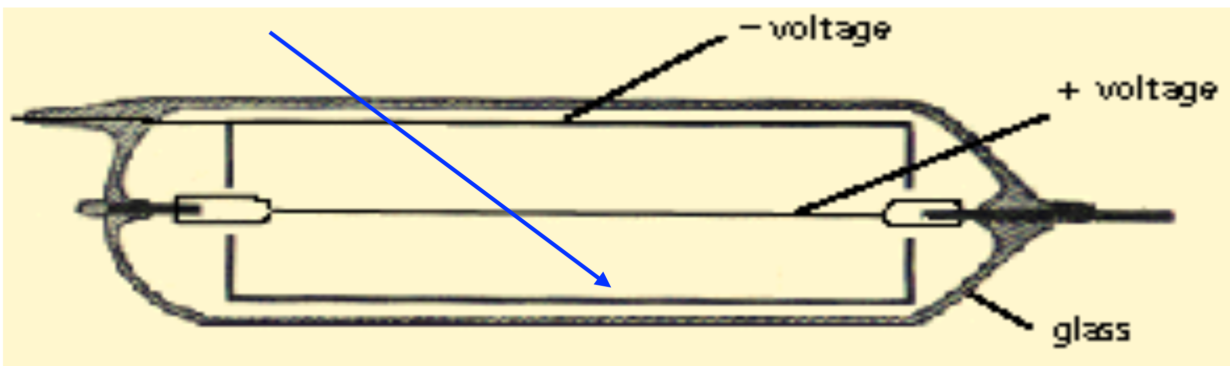
"… The rays from the cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminium plates about 5 cm. long by 2 broad and at a distance of 1.5 cm. apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflexion of this patch…."

Scintillation of glass

First electrical signal

E. Rutherford 1909

H. Geiger

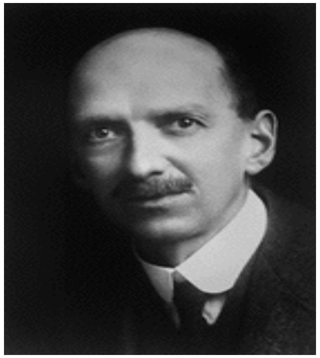


pulse

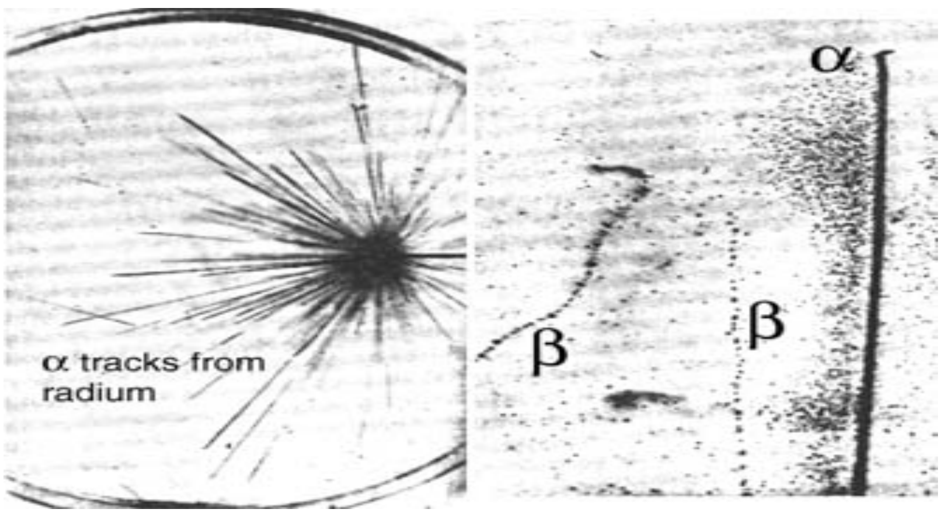
The Geiger counter, later further developed by Muller and then called Geiger-Müller counter

First electrical signal from a particle
No information about direction, poor timing information
Still used today as radiation detector, very good movie prop

First track detection



C. T. R. Wilson,
1912, Cloud chamber

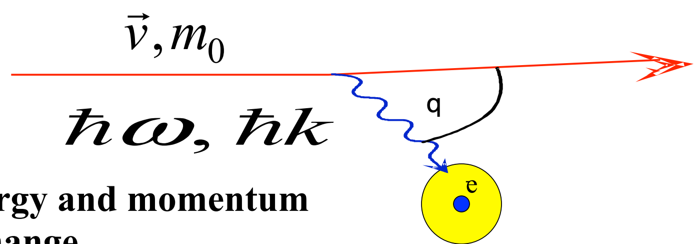


First tracking detector

The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a super-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path.

Mechanisms of energy loss in passage of charged particles through matter

•Discrete collisions with the atomic electrons of the absorber material.



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^{\infty} NE \frac{d\sigma}{dE} \hbar \, d\omega$$

N : electron density

Transfer of energy and momentum via photon exchange
hω – energy transfer
hk – momentum transfer

•If $\hbar\omega, \hbar k$ are large ⇨ ionization

•Collisions with nuclei not important ($m_e << m_N$)

Instead of ionizing an atom, under certain conditions the photon can escape from the medium

⇨ Emission of Cherenkov and Transition radiation

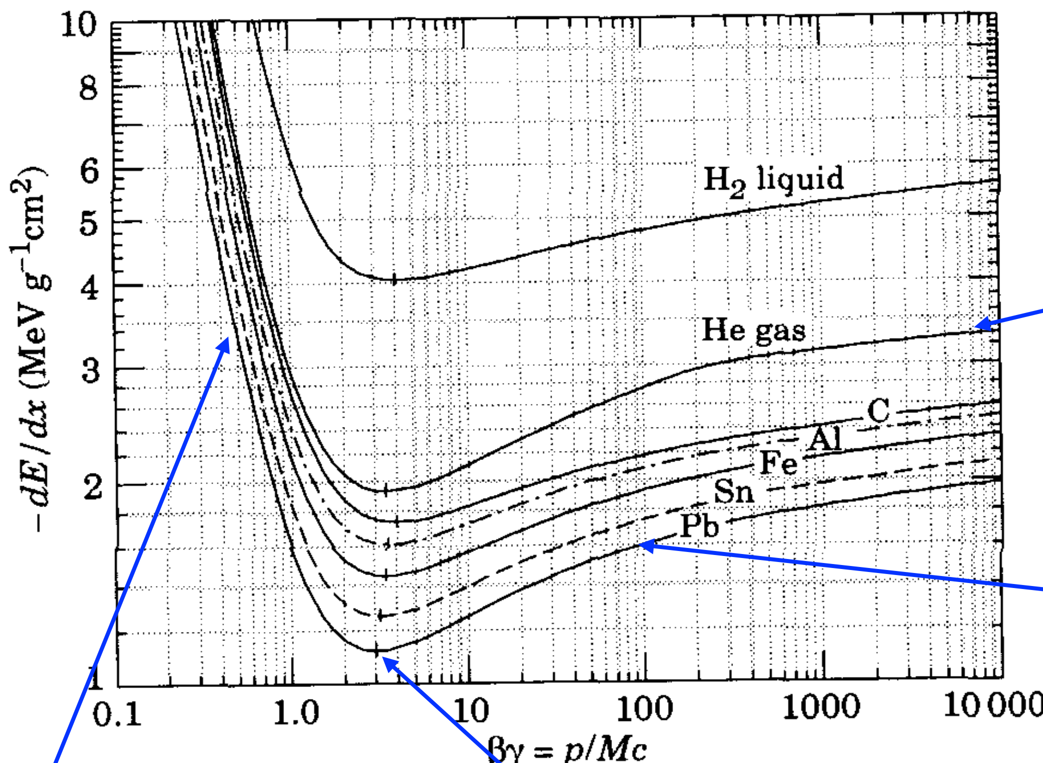
Bethe-Bloch formula

Average differential energy loss

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- **N_A – Avogadro number**
- **Z, A – atomic and mass numbers of the materia**
- **r_e = 2.8 fm -clssical radius of electron**
- **z – charge of the particle**
- **I – ionization potential**
- **$\beta = v/c$**
- **dE/dx in [MeV g^{-1} cm^2]**
- **Bethe-Bloch formula only valid for "heavy" particles ($m > m_\mu$).**
- **dE/dx depends only on β, independent of mass**
- **First approximation: medium characterized by Z/A ~its electron density**
- **ρ = mass/area →** $\frac{dE}{dX} = \frac{1}{\rho} \frac{dE}{dx}$

dE/dx ~ few MeV g^{-1} cm^2



Z/A = 1

"Fermi plateau"

Z/A~0.5

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

"relativistic rise"

βγ ≈ 3-4
minimum ionizing particles, MIPs

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

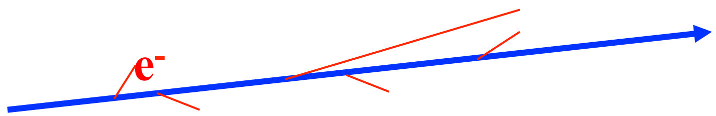
"kinematical term"

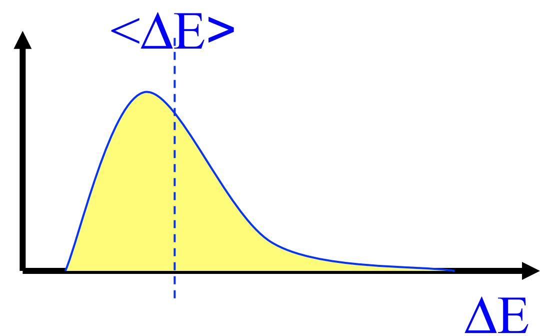
Landau tails

Real detectors have limited granularity and can not measure <dE/dx>

We measure energy ΔE deposited in a layer of finite thickness dx.

In a thin layer and low density material we have few collisions (some with high energy transfer).



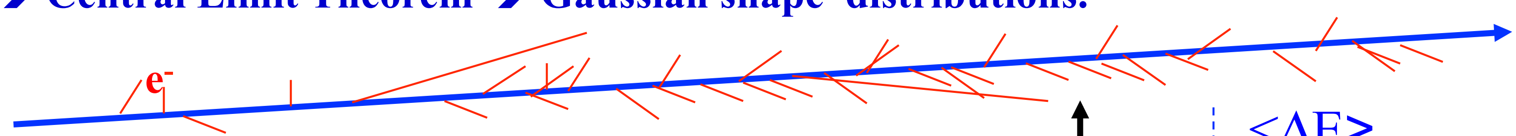


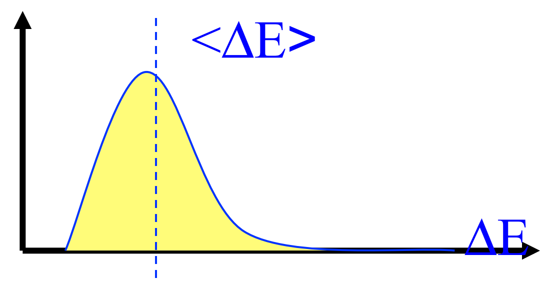
➔ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

For thick layers and high density materials:

➔ Many collisions.

➔ Central Limit Theorem ➔ Gaussian shape distributions.

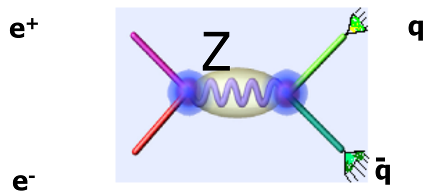


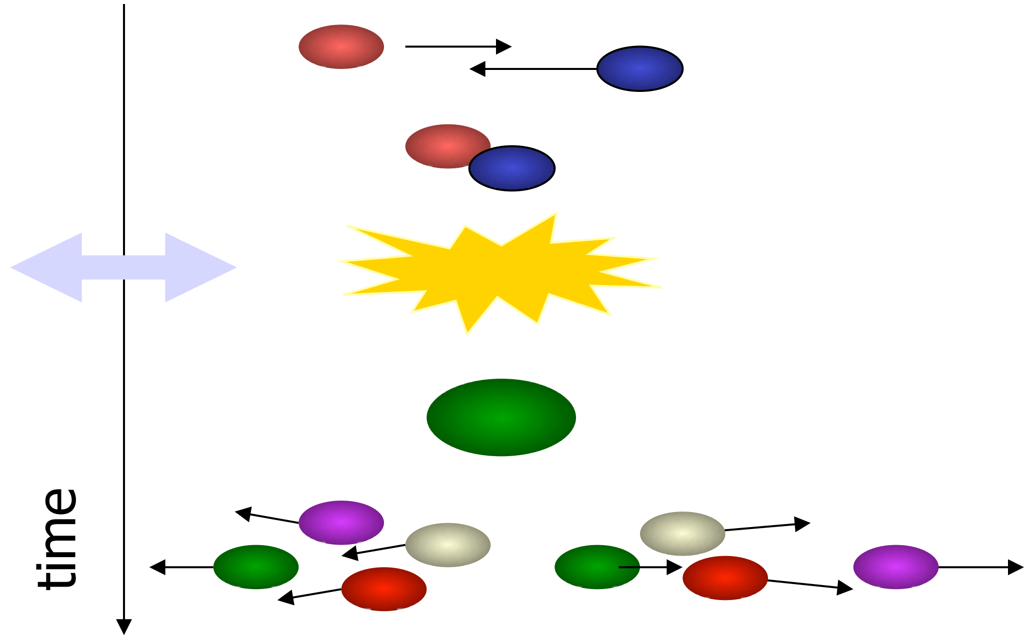


Idealistic views of an elementary particle reaction

$$e^{+} + e^{-} \rightarrow Z^{0} \rightarrow q\bar{q}$$

$$(+\,\text{hadronization})$$





- Usually we can only 'see' the end products of the reaction, but not the reaction itself.

- In order to reconstruct the reaction mechanism and the properties of the involved particles, we want the maximum information about the end products !