Outline

Lecture 1
1. Interaction of charged particle with matter
2. Momentum measurement
3. Drift and Diffusion in Gases
4. History of Tracking Detectors (not shown)
5. Proportional Chambers

Lecture 2
6. Drift Chambers
7. Micro Pattern Gas Chambers
8. Limitations of Gaseous Detectors

Lecture 3
9. Vertex Reconstruction
10. Semiconductor Detectors
11. Silicon Strip and Pixel Detectors
12. Radiation Damage of Silicon Detectors
13. New Semiconductor Detector Concepts
14. Tracking Systems: ATLAS, CMS
I. Interaction of Particle with Matter
Challenge in Tracking

**e+ e- collision in the ALEPH Experiment/LEP.**

**Au+ Au+ collision in the STAR Experiment/RHIC**
Up to 2000 tracks

**Pb+ Pb+ Kollision in the ALICE Experiment/LHC**
Simulation for
Angle $\Theta = 60$ to $62^\circ$
Up to 40 000 tracks/collision
A charged particle passing through matter suffers
1. energy loss
2. deflection from incident direction

Main type of reactions:
1. Inelastic collisions with atomic electrons of the material.
2. Elastic scattering from nuclei.

Less important reactions are:
3. Emission of Cherenkov radiation
4. Nuclear reactions
5. Bremsstrahlung

Classification of charged particles with respect to interaction with matter:
1. Low mass: electrons and positrons
2. High mass: muons, pions, protons, light nuclei.

Energy loss:
• mainly due to inelastic collisions with atomic electrons.
• cross section $\sigma \approx 10^{-17} - 10^{-16} \text{ cm}^2$!
• small energy loss in each collision, but many collisions in dense material. Thus one can work with average energy loss.
• Example: a proton with $E_{\text{kin}}=10$ MeV loses all its energy after 0.25 mm of copper.

Two groups of inelastic atomic collisions:
• soft collisions: only excitation of atom.
• hard collisions: ionization of atom. In some of the hard collisions the atomic electron get such a large energy that it causes secondary ionisation ($\delta$-electrons).

Elastic collisions from nuclei cause very small energy loss. They are the main cause for deflection.
I. Bethe-Bloch Formula

Bethe-Bloch formula gives the mean rate of energy loss (stopping power) of a heavy charged particle.

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

with

\[ A \text{ : atomic mass of absorber} \]
\[ \frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1}\text{cm}^2, \text{ for } A = 1\text{g mol}^{-1} \]
\[ z \text{: atomic number of incident particle} \]
\[ Z \text{: atomic number of absorber} \]
\[ T_{max} \text{ : Maximum energy transfer in a single collision} \]
\[ T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \]
\[ \delta(\beta \gamma) \text{ : density effect correction to ionization loss.} \]
\[ x = \rho \text{ s}, \text{ surface density or mass thickness, with unit g/cm}^2, \text{ where s is the length.} \]
\[ \frac{dE}{dx} \text{ has the units MeV cm}^2/\text{g} \]
1915: Niels Bohr, classical formula, Nobel prize 1922.
1930: Non-relativistic formula found by Hans Bethe
1932: Relativistic formula by Hans Bethe

Bethe’s calculation is leading order in perturbation theory, thus only $z^2$ terms are included.

**Additional corrections:**

- $z^3$ corrections calculated by Barkas-Andersen

- $z^4$ correction calculated by Felix Bloch (Nobel prize 1952, for nuclear magnetic resonance). Although the formula is called Bethe-Bloch formula the $z^4$ term is usually not included.

- Shell corrections: atomic electrons are not stationary

- Density corrections: by Enrico Fermi (Nobel prize 1938, for discovery of nuclear reaction induced by slow neutrons).
I. Examples of Mean Energy Loss

Bethe-Bloch formula:

\[- \frac{dE}{dx} = K z^2 Z \frac{1}{A} \beta^2 \left[ \frac{1}{2} \ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]\]

Except in hydrogen particles of the same velocity have similar energy loss in different materials.

Figure 27.3: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for \(\beta\gamma \gtrsim 1000\), and at lower momenta for muons in higher-Z absorbers. See Fig. 27.21.

The minimum in ionization occurs at 
\(\beta\gamma=3.5\) to 3.0, 
as \(Z\) goes from 7 to 100

PDG 2008
A simultaneous measurement of dE/dx and momentum can provide particle identification.
I. Fluctuations in Energy Loss

Real detector (limited granularity) can not measure $<dE/dx>$!
It measures the energy $\Delta E$ deposited in a layer of finite thickness $\delta X$.

For thin layers or low density materials:

→ Few collisions, some with high energy transfer.

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

Example: Si sensor: 300 $\mu$m thick. $\Delta E_{m.p} \sim 82$ keV $<\Delta E> \sim 115$ keV

For thick layers and high density materials:

→ Many collisions.
→ Central Limit Theorem → Gaussian shaped distributions.

from L. Ropelewski
High energy electrons lose their energy predominantly through radiation (bremsstrahlung).

The electron is decelerated (accelerated) in the field of the nucleus. Accelerated charges radiate photons. Thus the bremsstrahlung is strong for light charged particles (electrons), because its acceleration is large for a given force. For heavier particles like muons bremsstrahlung effects are only important at energies of a few hundred GeV.

The presence of a nucleus is required to restore energy-momentum conservation. Thus the cross section is proportional to $Z^2$ and $\alpha^3$ ($\alpha = $ fine structure constant).

The characteristic length which a electron travels in material until a bremsstrahlung happens is the radiation length $X_0$. 

Cross section:

$$\sigma \sim (Z e^3)^2 \sim Z^2 \alpha^3$$
I. Radiation Length $X_0$

The radiation length is the characteristic length scale to describe electromagnetic showers in material. It is usually measured in g/cm$^2$.

The radiation length is:
- the mean distance over which a high energy electron loses all but 1/e of its energy.
- 7/9 of the mean free path for pair production by a high energy photon.

The radiation length is given by:

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 [L_{rad} - f(Z)] + Z L'_{rad} \right\}$$

For $A = 1$ g mol$^{-1}$, $4\alpha r_e^2 N_A / A = (716.408 \text{ g cm}^{-2})^{-1}$.

$$f(Z) = a^2 [(1 + a^2)^{-1} + 0.20206$$

$$- 0.0369 a^2 + 0.0083 a^4 - 0.002 a^6]$$

where $a = \alpha Z$

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<td>&gt; 4</td>
<td>$\ln(184.15 Z^{-1/3})$</td>
<td>$\ln(1194 Z^{-2/3})$</td>
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I. High Energy Muon Bremsstrahlung

Bremsstrahlung off muons starts to be important for momenta of a few hundred GeV.

Cosmic muon bremsstrahlung event in the ALEPH detector at LEP.
A particle which traverses a medium is deflected by small angle Coulomb scattering from nuclei. For hadronic particles also the strong interaction contributes.

The angular deflection after traversing a distance $x$ is described by the Molière theory. The angle has roughly a Gauss distribution, but with larger tails due to Coulomb scattering.

Defining: $\theta_0 = \theta_{\text{rms plane}} = \frac{1}{\sqrt{2}} \theta_{\text{rms space}}$

Gaussian approximation:

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right]$$

$x/X_0$ is the thickness of the material in radiation length.
2. Momentum measurement in B-Fields

The momentum is measured from the sagitta $s$, which gives the curvature $\rho$ of the track in the magnetic field.

Transverse momentum:

$$p_T = qB\rho$$

$$p_T [\text{GeV}] = 0.3 \ B [\text{T}] \ \rho [\text{m}]$$

$$\frac{L/2}{\rho} = \sin \frac{\theta}{2} \approx \frac{\theta}{2} \ (\text{for small } \theta) \ \Rightarrow \ \theta \approx \frac{L}{\rho} = \frac{0.3BL}{p_T}$$

$$s = \rho(1 - \cos \frac{\theta}{2}) \approx \rho \left(1 - \left(1 - \frac{1}{2} \frac{\theta^2}{4}\right)\right) = \rho \frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

Example: 3 measurements

$$s = x_2 - (x_1 + x_3)/2 \rightarrow ds = dx_2 - dx_1/2 - dx_3/2$$

assume uncorrelated errors: $\sigma(x) \approx dx_i$

$$\sigma_s^2 = \sigma^2(x) + 2 \frac{\sigma^2(x)}{4} = \frac{3}{2} \sigma^2(x)$$
2. Relative Momentum Error

For 3 points the relative momentum resolution is given by:
\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}} \sigma(x) \cdot \frac{8p_T}{0.3BL^2}
\]

- degrades linearly with transverse momentum
- improves linearly with increasing B field
- improves quadratically with radial extension of detector

In the case of \( N \) equidistant measurements according to Gluckstern [NIM 24 (1963) 381]:
\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma(x) \cdot p_T}{0.3BL^2} \sqrt{\frac{720}{N+4}}
\]
(for \( N \geq 10 \), curvature \( \kappa = 1/\rho \))

**Example:** For \( p_T = 1\text{GeV}, L = 1\text{m}, B = 1\text{T}, \sigma(x) = 200\mu\text{m} \) and \( N = 10 \) one obtains:

\[
\frac{\sigma(p_T)}{p_T} \approx 0.5\% \quad \text{for a sagitta} \quad s \approx 3.8\text{cm}
\]

Important track detector parameter: \( \frac{\sigma(p_T)}{p_T^2} \) (%/GeV)
2. Contributions from Multiple Scattering

The contribution to the momentum error from $MS$ is given by:

$$\frac{\sigma(p_T)}{p_T} \bigg|_{MS} = \frac{\sigma^{MS}(s)}{s} = \frac{L'}{4 \sqrt{3}} \frac{13.6 \times 10^{-3}}{p \beta} \frac{z}{0.3B L^2 z / (8 p_T)} = \frac{52.3 \times 10^{-3}}{\beta B \sqrt{LX_0 \sin \theta}}$$

with $L' = L / \sin \theta$ total path $p_T = p \sin \theta$

for $\beta \rightarrow 1$ this part is momentum independent!

The combined total momentum error is:

$$\left( \frac{\sigma_p}{p} \right)^2 = \left( \sqrt{\frac{720}{N+4} \sigma_x p \sin \theta} \right)^2 + \left( \frac{52.3 \times 10^{-3}}{\beta B \sqrt{LX_0 \sin \theta}} \right)^2 + (\cot \theta \sigma_\theta)^2$$

Example for momentum dependence of individual contributions

from K. Niebuhr
3 Drift and Diffusion in Gases: Ionization

Fast charged particles ionize atoms of gas. Often resulting primary electron will have enough kinetic energy to ionize other atoms.

\[ n_{\text{total}} = \frac{\Delta E}{W_i} = \frac{dE}{dx} \frac{\Delta x}{W_i} \]

\[ n_{\text{total}} \approx 3 \ldots 4 \cdot n_{\text{primary}} \]

\[ \Delta E = \text{total energy loss} \]

\[ W_i = \text{effective } <\text{energy loss}>/\text{pair} \]

Number of primary electron/ion pairs in frequently used gases.

from L. Ropelewski

Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992
The actual number \( m \) of primary electron/ion pairs is Poisson distributed.

\[
P(m) = \frac{\bar{n}^m e^{-\bar{n}}}{m!}
\]

, where the average number of electron/ion pairs is \( \bar{n} = \frac{L}{\lambda} = LN\sigma_i \)

Detection efficiency \( \epsilon \): Depends on the minimum number of measurable electron/ion pairs

Example: \( m > 0 \)

\[
\epsilon = 1 - P(0) = 1 - e^{-\bar{n}}
\]

For thin detector layers the efficiency can be significantly smaller then 1.

Example: 1 mm of Ar ; \( \bar{n} = 2.5 \rightarrow \epsilon = 0.92 \)

Considering: Electronic noise in amplifier is typically 1000 e\(^-\) (ENC):

Conclusion: signal amplification in gas is needed!
3. Diffusion in Gases

Electrons and ions, produced by the ionization process, loose their energy by multiple collisions and thermalize with the temperature of the gas.

At room temperature: \( \varepsilon = (3/2) \, kT \approx 0.04 \, \text{eV} \)

The energy distribution follows a Maxwell-Boltzmann-Distribution

\[
F(\varepsilon) = const \cdot \sqrt{\varepsilon} \exp\left(-\frac{\varepsilon}{kT}\right)
\]

Due to multiple collisions (diffusion) there is a statistical distribution of charge, which is found in the length interval \( dx \) at distance \( x \) at a time \( t \) according to:

\[
\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right) dx
\]

Linear diffusion: \( \sigma_x = \sqrt{2Dt} \)

Volume diffusion: \( \sigma_{vol} = \sqrt{3} \, \sigma_x = \sqrt{6Dt} \)

Average mean free path in diffusion:

\[
\lambda = \frac{1}{N \sigma(\varepsilon)}
\]
3. Drift and Diffusion in Gases

Average mean free path in diffusion:

\[ \lambda = \frac{1}{N \sigma(\epsilon)} \]

where \( \sigma(\epsilon) \) is energy dependent collision cross section

\[ N = \left( \frac{N_A}{A} \right) \rho : \text{number of molecules per unit volume.} \]

If charge carriers are in an electric field the ordered drift due to the E-field is superimposed by the statistical disordered movement due to diffusion. The drift velocity of the charge carriers inside the gas can be defined as:

\[ v_{drift} = \mu(E) \ \vec{E} \ \frac{p_0}{p} \]

- \( \mu(E) \) energy dependent charge-carrier mobility
- \( \vec{E} \) electric field
- \( p/p_0 \) pressure normalized to standard pressure

Note that the drift velocity scales with \( E/p \) (if \( \mu \) is constant).
3. Drift and Diffusion in Gases

- **E=0** thermal diffusion
  \[ \langle v \rangle_t = 0 \]

- **E>0** charge transport and diffusion
  \[ \langle v \rangle_t = v_D \]

\[
\begin{align*}
v_D &= \frac{\Delta s}{\Delta t} \\
\sigma_x &= \sqrt{2D\tau} = \sqrt{2D \frac{s}{v_D}}
\end{align*}
\]

from L. Ropelewski
3. Lorentz Angle in Magnetic Fields

Lorentz angle (deflection angle of drift electrons due to magnetic field)

\[ \tan \alpha = \frac{v_{\text{drift}}}{E} \]

Fig. 1.21. Dependence of the electron drift velocity \( v_{\text{drift}} \) and the Lorentz angle \( \alpha \) on the magnetic field for low electric field strengths (500 V/cm) in a gas mixture of argon (67.2%), isobutane (30.3%) and methylal (2.5%) [51, 95].
In cloud chambers a charged particle causes condensation of a supersaturated gas.

The picture (left) shows an electron with 16.9 MeV initial energy.

It spirals about 36 times in the magnetic field.

Nobel prizes related to cloud chamber development:
C. T. R. Wilson, 1927
P.M.S. Blackett, 1948 (triggered chambers)
4. History of Tracking Detectors: Nuclear Emulsion

Discovery of muon and pion

Emulsion detectors are still used today: Opera experiment at Gran Sasso for the identification of tau decays.
Cloud chamber: supersaturating a gas with a vapor.
Bubble chamber: superheated liquid. Invented by Donald A. Glazer, Nobel Prize 1960. A particle depositing energy along its path makes the liquid boil and forms bubbles.

BNL, First Pictures 1963, 0.03s cycle
4. Bubble Chamber : BEBC

3.7 meter hydrogen bubble chamber at CERN, equipped with the largest superconducting magnet in the world at that time.

During its working life from 1973 to 1984, the "Big European Bubble Chamber" (BEBC) took over 6 million photographs.

Can be seen outside the Microcosm Exhibition
The excellent position (5\(\mu\)m) resolution and the fact that target and detecting volume are the same (H chambers) makes the Bubble chamber almost unbeatable for reconstruction of complex decay modes.

The drawback of the bubble chamber is the low rate capability (a few tens/second). E.g. LHC \(10^9\) collisions/s.

The fact that it cannot be triggered selectively means that every interaction must be photographed.

Analyzing the millions of images by ‘operators’ was a quite laborious task.

That’s why electronics detectors took over in the 70ties.
The Spark Chamber was developed in the early 60ies.

Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino.

A charged particle traverses the detector and leaves an ionization trail.

The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.
4. History: Multi Wire Proportional Chambers

Tube, Geiger- Müller, 1928

Multi Wire Geometry, in H. Friedmann 1949

G. Charpak 1968, Multi Wire Proportional Chamber, readout of individual wires and proportional mode working point.
Electrons produced by ionization drift to the anode wire.

### Avalanche:
- Close to the wire (∅ about few tens of μm) the E-field is very large (> 10 kV/cm).
- Between collisions electrons gain enough energy to ionize gas.
- Exponential increase of number of electron/ion pairs (gas amplification)

\[ n = n_0 e^{α(E)x} \]

\( α \) is the first Townsend coefficient.

**Electric field:**
\[ E(r) = \frac{CV_0}{2\pi\varepsilon_0} \frac{1}{r} \]

**Potential:**
\[ V(r) = \frac{CV_0}{2\pi\varepsilon_0} \ln \frac{r}{a} \]

\( V_0 = \) voltage between anode-cathode

**Capacitance per length**
\[ C = \frac{2\pi\varepsilon}{\ln(b/a)} \]
5. Single Wire Proportional Chamber

**SWPC OPERATION MODE**

- **ionization mode**
  - full charge collection
  - no multiplication
  - gain ~ 1

- **proportional mode**
  - multiplication of ionization
  - signal proportional to ionization measurement of $dE/dx$
  - secondary avalanches have to be quenched;
  - gain $\sim 10^4 \text{ to } 10^5$

- **limited proportional mode**
  - (saturated, streamer)
  - strong photoemission
  - secondary avalanches require strong quenchers or pulsed HV;
  - gain $\sim 10^{10}$

- **Geiger mode**
  - massive photoemission; full length of the anode wire affected;
  - discharge stopped by HV cut
5. Single Wire Proportional Chamber

Avalanche formation happens near the wire within time $< 1$ ns.

Signal induced on anode and cathode due to moving charges (electrons and ions).

Work to move charge $q$ by $dr$:

$$dW = lCV_0 \, dV = q \frac{dV(r)}{dr} \, dr$$

Induced voltage:

$$dV = \frac{q}{lCV_0} \frac{dV(r)}{dr} \, dr$$

Total voltage induced in a cylindrical tube $(a < r < b)$ for gas multiplication at distance $d$ from anode, from electrons ($V^-$) and ions ($V^+$):

$$V^- = \frac{-q}{lCV_0} \int_{a+d}^{a} \frac{dV(r)}{dr} \, dr = - \frac{q}{2\pi\epsilon l} \ln \left( \frac{a + d}{a} \right)$$

$$V^+ = \frac{q}{lCV_0} \int_{a+d}^{b} \frac{dV(r)}{dr} \, dr = - \frac{q}{2\pi\epsilon l} \ln \left( \frac{b}{a + d} \right)$$

Ratio:

$$\frac{V^-}{V^+} = \frac{\ln[(a + d)/a]}{\ln[b/(a + d)]} < 1\%$$

for $a=10\ \mu m$ $b=10\ mm$ $d=1\ \mu m$
5. Multi Wire Proportional Chamber (MWPC)

Simple idea to multiply SWPC cell: Nobel Prize 1992

First electronic device allowing high statistics experiments!!

Typical geometry
5mm, 1mm, 20 μm

Normally digital readout:
spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

for $d=1$ mm
$$\sigma_x = 300 \, \mu m$$

$$\langle x^2 \rangle = \frac{d^{1/2}}{0} \int_{d/2}^{d/2} x^2 \, dx = \frac{2}{d} \frac{x^3}{3} \bigg|_0^{d/2} = \frac{d^2}{12}$$

G. Charpak, F. Sauli and J.C. Santiard, 1970
Two coordinates \((x,y)\) of the track hit can be determined from the position of the anode wire and the signal induced on the cathode strips (or wires).
With this experimental set-up based on MWPC an event rate of about 100 000 Hz can be processed. The position resolution in each layer is about 1 mm.
MWPC with many wire planes.
Precise measurement of the second coordinate by interpolation of the signal induced on pads. Closely spaced wires makes CSC fast detector.

Center of gravity of induced signal method.

From L. Ropelewski

\( \sigma = 64 \, \mu \text{m} \)

Space resolution

CMS
5. CMS Muon System
5. CMS Cathode Strip Chamber Occupancy

**BEAM HALO**

ME-1  ME-2  ME-3  ME-4

CSC Sectors
5. CMS Cathode Strip Efficiency

Average measured efficiencies for each station/ring.

Endcap Muon CSC chambers performed well during cosmics run.

F. Cavallari, Elba 2009
5. Resistive Plate Chamber

Rate capability strong function of the resistivity of electrodes in streamer mode.

Multigap RPC - exceptional time resolution suited for the trigger applications
5. CMS Muon Barrel RPC Efficiency

RPC efficiency vs impact point measured extrapolating DT segment on the RPC. The low efficiency points (in step of 10 x 10 cm$^2$) are due to the spacers. A slight degradation in efficiency is observed in the single gap zone.

F. Cavallari, Elba 2009
### The ATLAS Muon Spectrometer

A complex system:

- **4 different technologies** (MDT, CSC, RPC, TGC)
- **Large area** ($10,000 \text{ m}^2$)
- **Many channels** (1M)

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Difficult environment: Large magnetic field variations in toroid.
• High statistics collected in autumn 2008 (full ATLAS)
• Few high statistics runs studied in great detail
• Subdetectors runs in 2009: RPC runs in January
• “muon slice” runs at the end of April
Dead strips < 2%
Noisy channels < 1%

In 2008 problems with
• Synchronization
• Gas
• Temperature (reduced HV in top sectors)
Affected the overall efficiency (70% of trigger coverage)

Most of the problems were fixed during the winter shutdown, current trigger coverage is 95.5%
5. ATLAS RPC Trigger Coverage

- Commissioning ongoing
- Trigger coverage increased from 70% in 2008 to current 95.5% (better timing)
- Full detector for 2009 run.

Note: The figure shows hit maps of the strips involved in Low and High Pt triggers.