Introduction

Summer Student Lecture Series 2002

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EP / TA1

From (very) basic ideas

1 + 1 = 2

1 + 1 \approx 2

to

rather complex
detector systems
Outline + timing

- Introduction, basics
- Tracking (gas, solid state)
  Thu/Mon (2x45 min)
- Scintillation and light detection
  Tue/Wed (2 x45 min)
- Calorimetry
- Particle Identification
- Electronics and Data Acquisition
  Thu (45 min)
- Detector Systems
- Discussion session I  Fri, 5 June, 11:15
- Discussion session II  Wed, 10 June, 11:15
  = Detector Exhibition
Literature on particle detectors

◆ Text books
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
  - W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
  - K. Kleinknecht, Detektoren für Teilchenstrahlung, 3rd edition, Teubner, 1992

◆ Review articles
  - Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

◆ Other sources
  - R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - Proceedings of detector conferences (Vienna VCI, Elba, IEEE)
**Introduction**

A $W^+W^-$ decay in ALEPH

$e^+e^- (\sqrt{s}=181 \text{ GeV})$

$\rightarrow W^+W^- \rightarrow qq\mu\nu_{\mu}$

$\rightarrow 2$ hadronic jets

$+ \mu + \text{missing momentum}$
A 4-jet event in DELPHI (a Higgs candidate)

Possible underlying reaction:
\[ e^+e^- (\sqrt{s}=205.5 \text{ GeV}) \rightarrow H^0Z^0 \rightarrow qqqq \rightarrow 4 \text{ hadronic jets} \]
Reconstructed B-mesons in the DELPHI micro vertex detector

\[ \tau_B \approx 1.6 \text{ ps} \quad l = c \tau \gamma \approx 500 \text{ \mu m} \cdot \gamma \]
Introduction

Particle identification methods

$B^- \rightarrow K^* \pi^-$

$1 \ K + 2 \pi$ in final state

DELPHI Vertex Display

DELPHI RICH

Average $\Delta s_0$ (rad)

Normalized $dE/dx$

Particle momentum (GeV/c)

Particle momentum (GeV/c)
NA49 Pb-Pb
158 GeV/nucleon

≈ 13 m
A simulated event in ATLAS (CMS)

\[ H \rightarrow ZZ \rightarrow 4\mu \]

pp collision at \( \sqrt{s} = 14 \text{ TeV} \)

\( \sigma_{\text{inel.}} \approx 70 \text{ mb} \)

Interested in processes with \( \sigma \approx 10^{-100} \text{ fb} \)

\( L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}, \text{ bunch spacing 25 ns} \)

\( \approx 23 \) overlapping minimum bias events / BC

\( \approx 1900 \) charged + 1600 neutral particles / BC
Introduction

Idealistic views of an elementary particle reaction

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

(+ 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!
Introduction

The ‘ideal’ particle detector should provide…

- coverage of full solid angle (no cracks, fine segmentation)
- measurement of momentum and/or energy
- detect, track and identify all particles (mass, charge)
- fast response, no dead time

Practical limitations (technology, space, budget)

Particles are detected via their interaction with matter.

Many different physical principles are involved (mainly of electromagnetic nature).

Finally we will always observe...

Ionization and excitation of matter.
Some important definitions and units

\[ E^2 = \vec{p}^2 c^2 + m_0^2 c^4 \]

- energy \( E \): measure in eV
- momentum \( p \): measure in eV/c
- mass \( m_0 \): measure in eV/c^2

\[ \beta = \frac{v}{c} \quad (0 \leq \beta < 1) \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad (1 \leq \gamma \leq \infty) \]

\[ E = m_0 \gamma c^2 \quad p = m_0 \gamma \beta c \quad \beta = \frac{pc}{E} \]

1 eV is a tiny portion of energy. 1 eV = \( 1.6 \cdot 10^{-19} \) J

\[ m_{\text{bee}} = 1 \text{g} = 5.8 \cdot 10^{32} \text{eV/c}^2 \]

\[ v_{\text{bee}} = 1 \text{m/s} \quad \rightarrow \quad E_{\text{bee}} = 10^{-3} \text{J} = 6.25 \cdot 10^{15} \text{eV} \]

\[ E_{\text{LHC}} = 14 \cdot 10^{12} \text{eV} \]

To rehabilitate LHC…

Total stored beam energy:

\[ 10^{14} \text{ protons} \times 14 \cdot 10^{12} \text{eV} \approx 1 \cdot 10^8 \text{J} \]

this corresponds to a \( m_{\text{truck}} = 100 \text{T} \)

\[ v_{\text{truck}} = 120 \text{ km/h} \]
Definitions and units

Some important masses/energies

- **1 MeV**
  - $M_e = 0.5$ MeV
  - $M_{\mu} = 105$ MeV
  - $M_{\pi} = 140$ MeV
  - $M_{p,n} = 1$ GeV
- **1 GeV**
  - $M_Z = 91$ GeV
  - $E_{\text{LEP}} = 200$ GeV
- **1 TeV**
  - $E_{\text{LHC}} = 14$ TeV

For **lengths** we will often use units like:
- $1 \mu m$ ($10^{-6}$ m), e.g. spatial resolution of detectors
- $1$ nm ($10^{-9}$ m), wavelength of green light $\lambda = 500$ nm
- $1$ A ($10^{-10}$ m), size of an atom
- $1$ fm = 1 fermi ($10^{-15}$ m), size of a proton

For **times** practical units are:
- $1 \mu s$ ($10^{-6}$ s), an electron drifts in a gas 5 cm
- $1$ ns ($10^{-9}$ s), a relativistic $e^-$ travels 30 cm
- $1$ ps ($10^{-12}$ s), mean life time of a B meson

- Very useful relation: $\hbar c \approx 200$ MeV $\cdot$ fm
  - e.g. convert $\lambda \leftrightarrow E$ of a photon $E = \frac{hc}{\lambda} = \frac{2\pi \hbar c}{\lambda} \approx \frac{1240}{\lambda}$

- To make the formulae less bulky, particle physicists set $\hbar = c = 1$
  - e.g. $E^2 = \sqrt{p^2 + m^2_0}$ $[E] = [p] = [m] = 1$ eV
The concept of cross sections

Cross sections $\sigma$ or differential cross sections $d\sigma/d\Omega$ are used to express the probability of interactions between elementary particles.

**Example** 2 colliding particle beams

$$\Phi_1 = \frac{N_1}{t} \quad \Phi_2 = \frac{N_2}{t}$$

What is the interaction rate $R_{\text{int}}$?

$$R_{\text{int}} \propto \frac{\Phi_1 \Phi_2}{A} = \sigma \cdot L$$

Luminosity $L$ [cm$^2$ s$^{-1}$]

**Example:** Scattering from target

$$N_{\text{scat}}(\theta) \propto N_{\text{inc}} \cdot n_A \cdot d\Omega$$

$$= \frac{d\sigma}{d\Omega} (\theta) \cdot N_{\text{inc}} \cdot n_A \cdot d\Omega$$

$\sigma$ has dimension area!

Practical unit:

1 barn (b) = $10^{-24}$ cm$^2$.
Tracking

- Momentum measurement
- Multiple scattering
- Bethe-Bloch formula / Landau tails
- Ionization of gases
- Wire chambers
- Some derivatives of wire chambers
- Drift and diffusion in gases
- Drift chambers
- Micro gas detectors
- Silicon as a detection medium
- Silicon detectors strips/pixels
- Radiation hardness
Momentum measurement
Momentum measurement

\[ p_T = qB\rho \]
\[ p_T \text{ (GeV/c)} = 0.3B\rho \text{ (T} \cdot \text{m)} \]
\[ \frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \rightarrow \theta \approx \frac{0.3L \cdot B}{p_T} \]
\[ \Delta p_T = p_T \sin\theta \approx 0.3L \cdot B \]
\[ s = \rho(1 - \cos\theta/2) \approx \rho \frac{\theta^2}{8} \approx \frac{0.3L^2B}{8p_T} \]

The sagitta \( s \) is determined by 3 measurements with error \( \sigma(x) \):
\[ s = x_2 - \frac{x_1 + x_3}{2} \]
\[ \frac{\sigma(p_T)}{p_T} \bigg|^{\text{meas.}} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x) \cdot 8p_T}{0.3BL^2} \]

For \( N \) equidistant measurements, one obtains
(R.L. Gluckstern, NIM 24 (1963) 381)
\[ \frac{\sigma(p_T)}{p_T} \bigg|^{\text{meas.}} = \frac{\sigma(x) \cdot p_T}{0.3BL^2 \sqrt{720/(N + 4)}} \quad \text{(for } N \geq 10) \]

Ex: \( p_T = 1 \text{ GeV/c}, L = 1 \text{m, B = 1T, } \sigma(x) = 200 \mu\text{m, N = 10} \)
\[ \frac{\sigma(p_T)}{p_T} \bigg|^{\text{meas.}} \approx 0.5\% \quad (s \approx 3.75 \text{ cm}) \]
Scattering

An incoming particle with charge $z$ interacts with a target of nuclear charge $Z$. The cross-section for this e.m. process is

$$\frac{d\sigma}{d\Omega} = 4zZe^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \theta / 2}$$

- Average scattering angle $\langle \theta \rangle = 0$
- Cross-section for $\theta \to 0$ infinite!

Multiple Scattering

Sufficiently thick material layer → the particle will undergo multiple scattering.

$$\theta_0 = \theta_{\text{RMS plane}} = \sqrt{\left(\theta_{\text{plane}}\right)^2} = \frac{1}{\sqrt{2}} \theta_{\text{RMS space}}$$

$$P(\theta_{\text{plane}}) = \frac{1}{\sqrt{2\pi \theta_0}} \exp\left\{-\frac{\theta_{\text{plane}}^2}{2\theta_0^2}\right\}$$
Momentum measurement

Approximation

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

\( X_0 \) is radiation length of the medium (discuss later)

\( \text{(accuracy } \leq 11\% \text{ for } 10^{-3} < L/X_0 < 100) \)

Back to momentum measurements:

contribution from multiple scattering

\[ \Delta p^{MS} = p \sin \theta_0 \approx p \cdot 0.0136 \frac{1}{p} \sqrt{\frac{L}{X_0}} \]

\[ \sigma (p) \bigg|_{p_T}^{MS} = \Delta p_T^{MS} = \frac{0.0136}{0.3BL} \frac{L}{X_0} = 0.045 \frac{1}{B \sqrt{LX_0}} \text{ independent of } p ! \]

ex: Ar \( (X_0=110m) \), \( L=1m \), \( B=1T \)

\[ \frac{\sigma (p)}{p_T} \bigg|^{MS} \approx 0.5\% \]
Momentum measurement in experiments with solenoid magnet:

\[ p_T = p \sin \theta \]

Polar angle has to be determined from a straight line fit \( x = x(z) \).

\( \text{N equidistant points with error } \sigma(z) \)

\[ \sigma(\theta)_{\text{meas.}} = \frac{\sigma(z)}{L} \sqrt{\frac{12(N-1)}{(N(N+1))}} + \text{multiple scattering contribution} \]

\[ \text{normally small} \]

*In practical cases:*

\[ \frac{\sigma(p)}{p} \approx \frac{\sigma(p_T)}{p_T} \]

*In summary:*

\[ \frac{\sigma(p)_{\text{meas.}}}{p} \propto \frac{\sigma(x) \cdot p}{BL^2} \frac{1}{\sqrt{N}} \]
Interaction of charged particles

Detection of charged particles

How do they loose energy in matter?

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

\[ \langle \frac{dE}{dx} \rangle = - \int_0^\infty N E \frac{d\sigma}{dE} \hbar \omega \ d\omega \]

\( N \): electron density

Collisions with nuclei not important \((m_e<<m_N)\).

- If \( \hbar \omega, \hbar k \) are big enough \(\Rightarrow\) ionization.

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

\(\Rightarrow\) Emission of Cherenkov and Transition radiation. (See later).
Bethe-Bloch formula

Average differential energy loss $\langle \frac{dE}{dx} \rangle$

Ionisation only $\rightarrow$ Bethe - Bloch formula

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

- $dE/dx$ in [MeV g$^{-1}$ cm$^2$]
- $dE/dx$ depends only on $\beta$, independent of $m$
- Formula takes into account energy transfers

$I \leq dE \leq T_{\text{max}}$  
$I$ : mean excitation potential

$I \approx I_0 Z$ with $I_0 = 10$ eV  
(rough approximation, $I$ fitted for each element)

- Bethe-Bloch formula only valid for “heavy” particles ($m \geq m_\mu$).
- Electrons and positrons need special treatment ($m_{\text{proj}} = m_{\text{target}}$), in addition Bremsstrahlung!

Z/A does not differ much for the various elements, except for Hydrogen!
Bethe-Bloch formula

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

- \( dE/dx \) first falls \( \propto 1/\beta^2 \) (more precise \( \beta^{-5/3} \)), kinematic factor
- then minimum at \( \beta \gamma \approx 4 \) (minimum ionizing particles, MIP) \( (dE/dx \approx 1 - 2 \text{ MeV g}^{-1} \text{ cm}^2) \)
- then again rising due to \( \ln \gamma^2 \) term, relativistic rise, attributed to relativistic expansion of transverse E-field \( \rightarrow \) contributions from more distant collisions.
- relativistic rise cancelled at high \( \gamma \) by “density effect”, polarization of medium screens more distant atoms. Parameterized by \( \delta \) (material dependent) \( \rightarrow \) Fermi plateau
- many other small corrections

Measured and calculated \( dE/dx \)
Real detectors (limited granularity) do not measure $\langle dE/dx \rangle$, but the energy $\Delta E$ deposited in a layer of finite thickness $\delta x$.

For thin layers (and low density materials):
→ 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.

data: Harris et al. (1977)
dotted curve: Landau (1944)
solid curve: Allison and Cobb (1980)
Primary and total ionization

Fast charged particles ionize the atoms of a gas.

Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

\[
\begin{align*}
    n_{\text{total}} &= \frac{\Delta E}{W_i} = \frac{dE}{dx} \frac{\Delta x}{W_i} \\
    n_{\text{total}} &\approx 3\ldots4 \cdot n_{\text{primary}}
\end{align*}
\]

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

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992)
\( \approx 100 \) electron-ion pairs are not easy to detect!
Noise of amplifier \( \approx 1000 \text{ e}^- \) (ENC)!
We need to increase the number of e-ion pairs.

**Gas amplification**

Consider cylindrical field geometry (simplest case):

Electrons drift towards the anode wire (\( \approx \) stop and go!).
More details in next lecture!.

Close to the anode wire the field is sufficiently high (some kV/cm), so that \( e^- \) gain enough energy for further ionization \( \rightarrow \) exponential increase of number of \( e^- \)-ion pairs.
Proportional Counter

\[ n = n_0 e^{\alpha(E)x} \quad \text{or} \quad n = n_0 e^{\alpha(r)x} \]

\( \alpha \): First Townsend coefficient

\( \lambda \): mean free path

\[ M = \frac{n}{n_0} = \exp \left[ \int_a^{r_c} \alpha(r)dr \right] \]

Gain \( M \approx ke^{CV_0} \)

(O. Allkofer, Spark chambers, Theimig München, 1969)

(F. Sauli, CERN 77-09)
Choice of gas:
Dense noble gases. Energy dissipation mainly by ionization! High specific ionization.

De-excitation of noble gases only possible via emission of photons, e.g. 11.6 eV for Argon.
This is above ionization threshold of metals, e.g. Copper 7.7 eV.

→ new avalanches → permanent discharges!
Solution: Add poly-atomic gases as quenchers. Absorption of photons in a large energy range (many vibrational and rotational energy levels).

Energy dissipation by collisions or dissociation into smaller molecules.

Methane: absorption band 7.9 - 14.5 eV
Avalanche formation within a few wire radii and within $t < 1 \text{ ns}$!

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

$$dv = \frac{Q}{lCV_0} \frac{dV}{dr} dr$$

Electrons collected by anode wire, i.e. $dr$ is small (few $\mu$m). Electrons contribute only very little to detected signal (few %).

Ions have to drift back to cathode, i.e. $dr$ is big. Signal duration limited by total ion drift time!

Need electronic signal differentiation to limit dead time.
Operation modes:

- **ionization mode**: full charge collection, but no charge multiplication.

- **Proportional mode**: above threshold voltage multiplication starts. Detected signal proportional to original ionization $\rightarrow$ energy measurement ($dE/dx$). Secondary avalanches have to be quenched. Gain $10^4 - 10^5$.

- **Limited Proportional $\rightarrow$ Saturated $\rightarrow$ Streamer mode**: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain ($10^{10}$), large signals $\rightarrow$ simple electronics.

- **Geiger mode**: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well.