Detectors for High Energy Physics

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Disclaimer

- Particle Detectors are very complex, a lot of physics is behind the detection of particles:
  - particle physics
  - material science
  - electronics
  - mechanics, ....

- To get a good understanding, one needs to work on a detector project ...

- This lecture can only give a glimpse at particle detector physics, cannot cover everything

- Biased by my favorite detectors!

Maybe not the ideal detector physicist
Overview

I. Detectors for Particle Physics

II. Interaction with Matter

III. Calorimeters

IV. Tracking Detectors
   - Gas detectors
   - Semiconductor trackers

V. Examples from the real life

Wednesday

Thursday
I. Overview:

Detectors for particle physics
Particle Physics Detectors

- There is not one type of detector which provides all measurements we need -> “Onion” concept -> different systems taking care of certain measurement

- Detection of collision production within the detector volume

- Resulting in signals (mostly) due to electro-magnetic interactions
Weight: 7,000 t
Central Solenoid: 2 T
Muon-Toroid: 4 T

Distinctive characteristics: the largest in HEP
Distinctive characteristics: extremely heavy and compact
Size and Weight

CMS is 65% heavier than the Eiffel tower

Brandenburger Tor in Berlin

12500 t

7300 t
Blue sky!
The Big Ones at LHC ....
The ZEUS Detector@HERA

Weight: 3600 T
Length: 19 m
Diameter: 11 m
Solenoid-Field: 1.5 T

Distinctive characteristics: Uranium calorimeter
The DELPHI Detector @LEP

Distinctive characteristics:
Ring Imaging Cherenkov Counter

Weight: 3500 T
Length: 10 m
Diameter: 10 m
Solenoid-Field: 1.2 T
Weight: 1200 T
Length: 6 m
Diameter: 6 m
Solenoid-Field: 1.5 T

Distinctive characteristics: lost in space ....
**HEP Detector Overview**

**Tracker**: Precise measurement of track and momentum of charged particles due to magnetic field.

**Calorimeter**: Energy measurement of photons, electrons and hadrons through total absorption.

**Muon-Detectors**: Identification and precise momentum measurement of muons outside of the magnet.

**Vertex**: Innermost tracking detector.

**Transverse slice through CMS**

Good energy resolution up to highest energies.

**Radiation hard (hadron collider)**
II. The Basics of All Detection Processes: Interactions with Matter
Planes leave tracks in sky under certain conditions ....
Particles Leave Signals in Matter

Different effects are involved when a particle passes through matter, depending on mass, charge and energy of the particle.

Following the effects will be explained for:

- Heavy charged particles (with masses $>m_{\text{electron}}$)
- Electrons/positrons
- Photons
- Neutrons

http://www.particlezoo.net/
Three type of electromagnetic interactions:
1.Ionization (of the atoms of the traversed material)
2. Emission of Cherenkov light
3. Emission of transition radiation

1) Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

2) Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

3) In case the particle’s velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability in the order of 1% to produce an X ray photon, called Transition radiation.
**Heavy Charged Particle**

- Incoming particle interacts elastically with a target of nuclear charge Z.

**Cross section**

\[ \frac{d\sigma}{d\Omega} = 4Z^2 r_e^2 \frac{m_e c}{\beta p} \left( \frac{m_e c}{\beta p} \right)^2 \frac{1}{\sin^4 \frac{\theta}{2}} \]

Rutherford Formula

- Heavy charged particles transfer energy mostly to the atomic electrons causing ionisation and excitation.

\[ \langle \frac{dE}{dx} \rangle = - \int_0^\infty NE \frac{d\sigma}{dE} h d\omega \]

N: electron density

- Simple model (M>>m_e):
  - consider energy transfer of particle to single electron (distance b)
  - multiply with the number of independent electrons passed (Z)
  - integrate over all distances b

**Bethe-Bloch Formula**
Interactions of “heavy” Particles with Matter

Mean energy loss is described by the Bethe-Bloch formula

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

- Maximum kinetic energy which can be transferred to the electron in a single collision
- Density term due to polarisation: leads to saturation at higher energies
- Excitation energy
- Shell correction term, only relevant at lower energies

Plot: PDG, July 2012

Bremsstrahlung

“minimum ionizing particles” $\beta \gamma \approx 3-4$

“kinematic term”

“relativistic rise”
Bethe-Bloch displays only the average energy loss is a statistical process. Discrete scattering with different results depending on strength of scattering. Primary and secondary ionisation.

**Primary ionisation**
- Poisson distributed
- Large fluctuations per reaction

**Secondary ionisation**
- Created by high energetic primary electrons
- Sometime the energy is sufficient for a clear secondary track: $\delta$-Electron

Total ionisation = **primary ionisation** + **secondary ionisation**

Example of a delta electron in a bubble chamber: visible path.
Energy Loss in Thin Layers

In case of thin detectors the variation width within the energy transfer of the reactions leads to a large variation of the energy loss:

- A broad maximum: collisions with little energy loss
- A long tail towards higher energy loss: few collisions with large energy loss $T_{\text{max}}$, $\delta$-electrons.

The Landau distribution is used in physics to describe the fluctuations in the energy loss of a charged particle passing through a thin layer of matter.

Thin absorber: $<dE> < \sim 10T_{\text{max}}$
The energy loss as a function of particle momentum $p = mc\beta\gamma$ is depending on the particle's mass.

By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass.

**Particle Identification at low energies** ($p<2\text{GeV/c}$)

**Example:** DELPHI@ LEP
Bremsstrahlung

Deflection of a charge in a strong nuclear E-field \( \rightarrow \) emission of a photon.

\[
- \frac{dE}{dx} = 4 \alpha N_A \frac{Z^2}{A} \left( \frac{1}{4 \pi \varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183 Z^{1/3}}{N} \propto \frac{E}{m^2}
\]

Effect plays a role only for \( e^\pm \) and ultra-relativistic \( \mu \) (>1000 GeV).

Energy loss for anything heavier than an electron is dominated by ionisation.

Bremsstrahlung is dominating at high energies

At low energies: ionisation, additional scattering
**Electrons: Energy Loss**

- **Critical energy**: the energy at which the losses due to ionisation and Bremsstrahlung are equal
  \[
  \frac{dE}{dx}(E_c) = \frac{dE}{dx}(E_c)
  \]

For electrons approximately:

- \( E_{c}^{\text{solid+liq}} = \frac{610 \text{MeV}}{Z + 1.24} \)
- \( E_{c}^{\text{gas}} = \frac{710 \text{MeV}}{Z + 1.24} \)

For electrons

- \( -\frac{dE}{dx} = 4\alpha \frac{N_A Z^2 r_e^2}{A} E \ln \frac{183}{Z^{1/3}} \)
- \( -\frac{dE}{dx} = \frac{E}{X_0} \)

\[
X_0 = \frac{A}{4\alpha \frac{N_A Z^2 r_e^2}{A} \ln \frac{183}{Z^{1/3}}}
\]

\( E = E_0 e^{-x/X_0} \)

Parameters only depending on material the electron is passing through.

\( X_0 \): Radiation length
Electrons and Photons: Radiation Length

- Radiation length: an important parameter for particle detectors
- Thickness of material an electron travels through
  - until the energy is reduced by Bremsstrahlung to 1/e of its original energy

\[ X_0 = \frac{716.4 A}{Z(1+Z) \ln(287/\sqrt{Z})} \frac{g}{cm^2} \propto \frac{A}{Z^2} \]

- The radiation length is also an important quantity in multiple scattering
- A very important number when building detectors, one always has to keep in mind how much material is within the detector volume

- Usually quoted in [g/cm\(^2\)], typical values are:
  - Air: 36.66 g/cm\(^2\) -> ~ 300 m
  - Water: 36.08 g/cm\(^2\) -> ~ 36 cm
  - Silicon: 21.82 g/cm\(^2\) -> 9.4 cm
  - Aluminium: 24.01 g/cm\(^2\) -> 8.9 cm
  - Tungsten: 6.76 g/cm\(^2\) -> 0.35 cm
**Multiple Scattering!**

- Charged particles are forced to deviate from a straight track when moving through a medium: multiple scattering mostly due to Coulomb field.
- Cumulative effect of these small angle scatterings is a net deflection from the original particle direction.

\[ \theta_0 \approx \theta_{\text{rms}}^{\text{plane}} = \frac{1}{\sqrt{2}} \theta_{\text{rms}}^{\text{space}} \]

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

- The smaller the momentum the larger the effect
- Kind of Gaussian around original direction

**Gaussian approximation sufficient for many applications.**
AND Now ... ?

10 minutes coffee break ....

KEEP CALM AND TAKE A BREAK